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# TRANSACTINIUM ISOTOPE NUCLEAR DATA (TND)

## VOL.II

PROCEEDINGS OF AN ADVISORY GROUP MEETING
ON TRANSACTINIUM ISOTOPE NUCLEAR DATA
ORGANIZED BY THE
IAEA NUCLEAR DATA SECTION
IN CO-OPERATION WITH THE
OECD NUCLEAR ENERGY AGENCY
HELD AT THE KERNFORSCHUNGSZENTRUM
KARLSRUHE, 3–7 NOVEMBER 1975

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# FOREWORD

The IAEA Nuclear Data Section, in cooperation with the OECD Nuclear Energy Agency, convened an Advisory Group Meeting on Transactinium Isotope Nuclear Data at Karlsruhe, FRG, from 3-7 November 1975. The meeting was attended by 45 representatives from 13 countries and 3 international organizations. It was the first international meeting on this topic.

The general conclusion of the meeting participants was that transactinium isotopes are becoming more and more important in nuclear technology, and that the present knowledge of nuclear data required to evaluate the effects of actinides in nuclear technology is not satisfactory. One of the basic recommendations, which resulted from the meeting was to initiate an internationally coordinated programme to measure, calculate, and evaluate needed transactinium isotope nuclear data which would span the next ten years. The principal aim of this effort would be to improve the status of actinide nuclear data required for nuclear technology.

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# STATUS OF MEASURED NEUTRON CROSS SECTIONS OF TRANSACTINIUM ISOTOPES FOR THERMAL REACTORS

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ABSTRACT

Experimentally determined neutron cross sections, resonance parameters, and the average number of neutrons per fission for neutron-induced fission of actinide nuclides in the production chains associated with thermal and near-thermal reactors are summarized and compared with user requests for experimental data. The primary fertile and fissile isotopes $^{232}$Th, $^{233}$U, $^{235}$U, $^{238}$U, and $^{239}$Pu are excluded from this survey. Integral data, i.e., spectrum-averaged thermal cross sections and resonance integrals, are included, but the emphasis is placed on energy-dependent differential cross sections because of their general utility with any specified neutron energy spectrum. Included with the data summaries are an extensive survey of the literature through August 1975, brief descriptions of measurements known to be in progress or firmly planned for the immediate future, and recommendations for needed measurements.

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## INTRODUCTION

Adequate transactinium nuclear data are required for calculations to provide design and operating parameters for thermal and near-thermal reactors. Properties of the major fertile and fissile nuclides $^{232}$Th, $^{233}$U, $^{235}$U, $^{238}$U, and $^{239}$Pu are of such importance to reactor core physics that they are under nearly constant examination, review, and modification. Other actinides, and particularly those of heavier mass, have been studied much less until comparatively recently. Large quantities of these heavy nuclides will be produced as byproducts in power reactors in the next few decades (see e.g., "Tons of Curium and Pounds of Californium"[1]), and their effects on reactor charge design, core lifetime, radioactive waste disposal, and stocks of currently recognized beneficial isotopes need to be known and well understood. The primary requirement for accurate calculation of these effects is a sound data base for nuclides in the reactor production path. This paper will consider the energy-dependent cross sections and average number of neutrons per fission for neutron-induced reactions in nuclides along the reactor production path from $^{232}$Th to $^{254}$Es, excluding only the primary fertile and fissile isotopes.

The nuclides involved in the reactor paths, separated into three parts for the sake of convenience, are shown in Figures 1 through 3. The nuclides surveyed, those which may be significant to reactor calculations, are enclosed in solid lines. Appreciable fission, which removes a nucleus from the chain, is denoted by bold vertical arrows; neutron capture is denoted by an arrow to the right; quantitatively significant ($\gamma$,n) or (n,2n) reactions are denoted by an arrow to the left; and significant alpha decay, beta decay, or electron capture are denoted by arrows in the appropriate directions accompanied by the pertinent half-life. With the chief exceptions of the 14.8 yr half-life of $^{241}$Pu[2] and the 314 d half-life of $^{249}$Bk,[3] the beta decays are all rapid compared with neutron-capture rates in reactors.

Although most of the actinides are alpha-unstable, alpha decay requires little consideration in reactor processes because it generally has a long half-life compared with neutron capture rates [the two exceptions are $^{242}Cm$ (163 d)[4] and $^{252}Cf$ (2.646 yr)[5]].

## SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

### Cross Section Measurement Techniques

The calculation of reactor production rates for the actinides requires as input the product of two energy-dependent quantities, the neutron flux $\phi(E)$ and the cross sections $\sigma_i(E)$. The neutron cross sections are fundamental physical quantities which must be determined experimentally, although in some instances approximations based on nuclear systematics and nuclear theory may be used. The purpose of this survey is to review the status of available actinide cross section data and to identify key nuclides in the production chains for which more experimental data are needed. Emphasis is placed on the energy region below 10 keV, which is most important for thermal and near-thermal reactors.

The cross section data are in two categories, integral and differential, which derive from fundamentally different measurement techniques. Differential cross sections, i.e., specific reaction probabilities as a function of incident neutron energy, are useful for most calculations; however, because enriched isotopic sample material is not always readily available or is available only in very small quantities, such data for many of the higher actinides are fragmentary or nonexistent. Integral measurements require only small quantities of sample material and relatively simple experimental techniques and are used to fill in the gaps as much as possible. Integral values for important nuclides should be viewed as interim values, useful to fill needs until differential data can be obtained, and as an important check on the normalization of differential data.

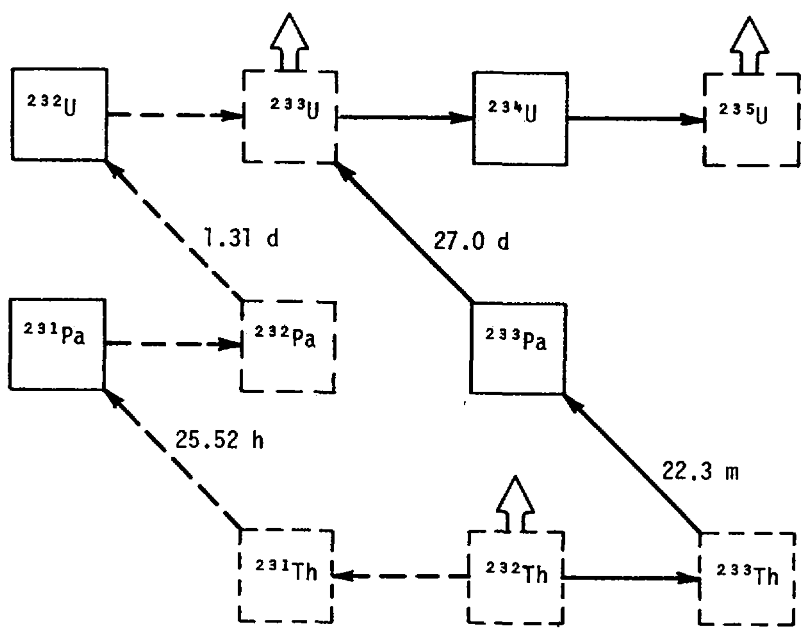


FIGURE 1. Thorium Target Path

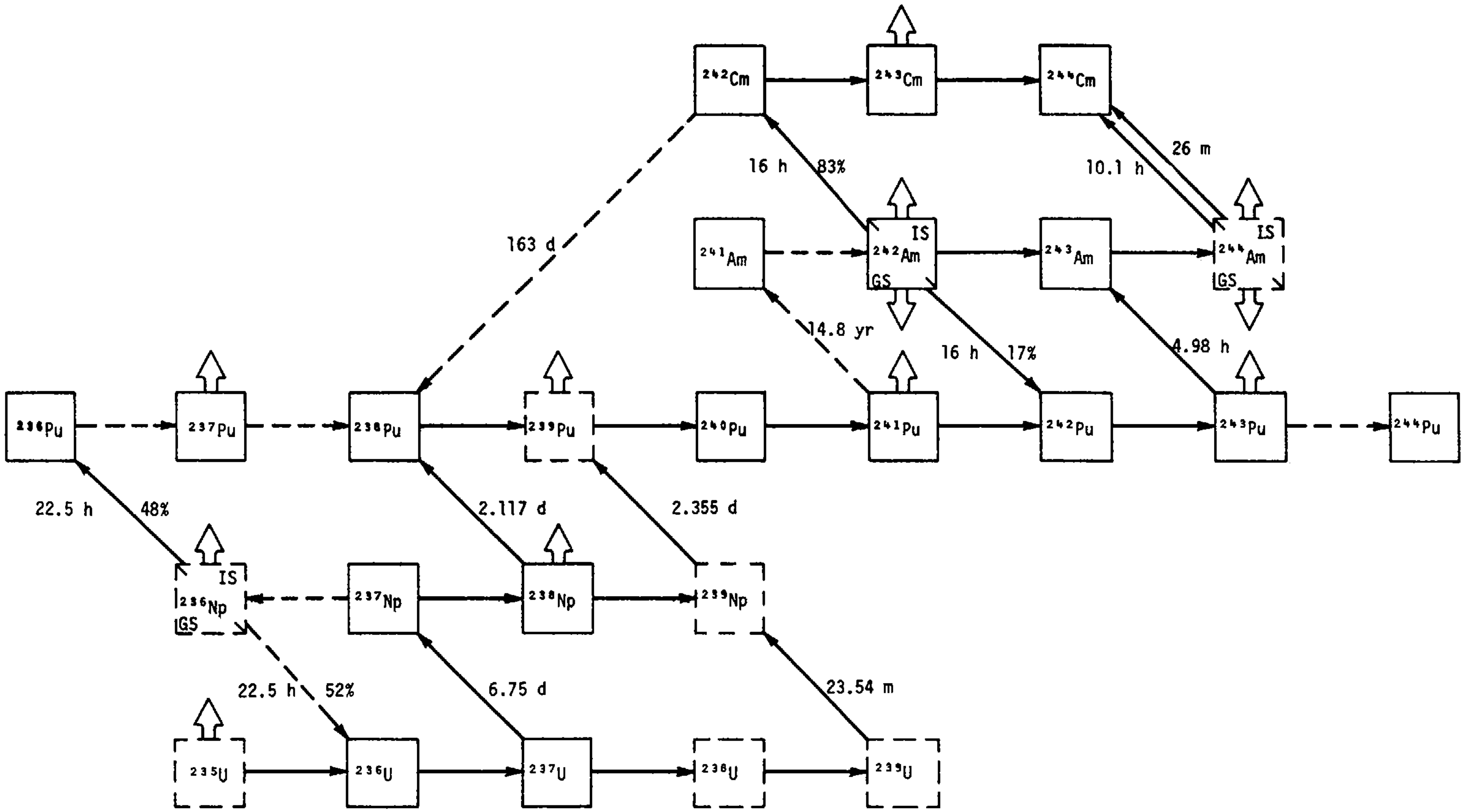


FIGURE 2. Uranium Target Path

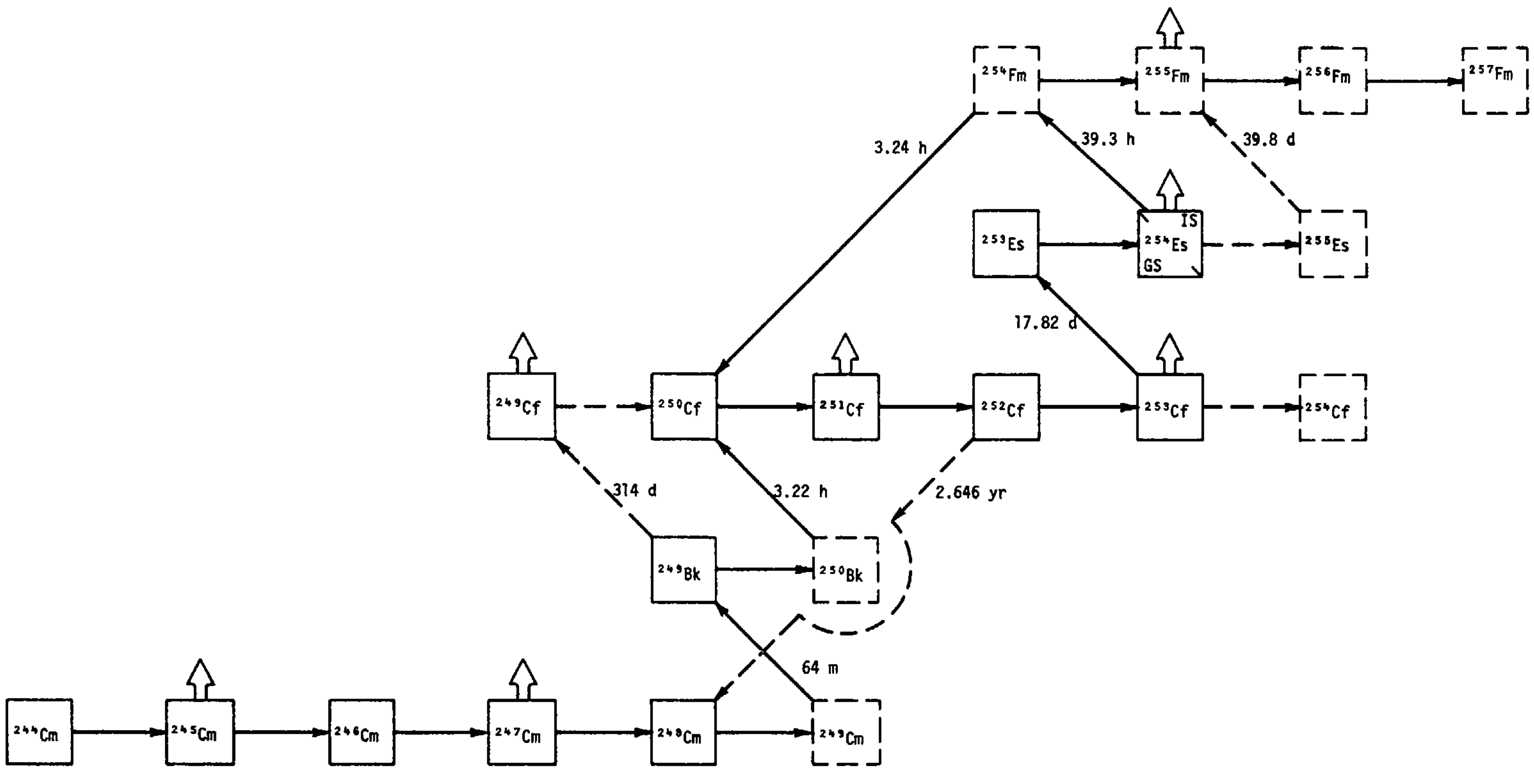


FIGURE 3. Curium Target Path

Integral cross section measurements are reaction-rate measurements and thus involve the product $\phi(E) \cdot \sigma_i(E)$. The flux as a function of energy $\phi(E)$ and the cross section of the nuclide as a function of energy $\sigma_i(E)$ interact; therefore, certain simplifying assumptions and standard conditions are conventionally used: the cross section in the thermal region varies inversely with the neutron velocity, and the neutron flux in the reactor above the thermal Maxwellian is inversely proportional to the neutron energy. The integral values obtained must be adjusted for any deviations from the assumptions or the conditions.

Integral cross sections are conventionally measured in a reactor neutron spectrum relative to a standard of well-known cross section, such as $^{235}U$ for fission measurements and $^{197}Au$ or $^{59}Co$ for capture measurements. Differentiation of the thermal and epithermal regions is made through the use of filters, such as cadmium which "cuts off" the neutron spectrum below approximately 0.5 eV. Other filters are occasionally used to vary the cutoff a few tenths of an eV to examine the effects of resonances in the vicinity of the thermal-epithermal interface. The major sources for experimental uncertainty in integral measurements are the following:

- Clear definition of the neutron spectrum.
- Determination of the cutoff energy for resonance integral measurements (this energy can vary significantly with filter material, geometry, and the resonance structure of the target material).
- Resonance self-shielding.
- The precision of the cross section for the standard used.
- Competing reactions or spontaneous activities in the target material.

The first four topics are discussed in considerable detail elsewhere (see, e.g., References 6, 7, and 8). The last is a function of the particular target material used and must be examined by the measurer. The most serious error usually encountered is lack of information concerning the cutoff energy for the resonance integral.

The major measurement techniques in current use for differential measurements are discussed in review papers by James[9] and Moore[10] at this meeting.

An additional useful approach to cross sections for the heavy actinides is the use of well-defined reactor production measurements in conjunction with evaluated multigroup neutron cross section sets and modern multigroup reactor production codes to adjust cross section sets within experimental uncertainties until they give satisfactory isotope production forecasting with a wide variety of reactor neutron spectral conditions. This approach is described and discussed in detail in Reference 11.

## Cross Section Data Summaries and User Data Requests

The current status (August 30, 1975) of experimental cross section data for nuclides outlined in solid lines in Figures 1 through 3 is summarized in Tables 1 through 4.

Table 1 gives a general summary of the status, current knowledge, and recommendations for each nuclide. Although the status for many of the nuclides is listed as "very poor," typically those so listed have little influence in current reactor operations, isotope production, or radiation shielding, and there are few user data requests for them. Thus, while more data for these nuclides would be welcome, the Recommendations for them indicate "not crucial at present."

Tables 2 and 3 list, respectively, the current situation for thermal neutron cross sections and infinite-dilution resonance integrals along with documented user data requests.[12,13] The thermal cross sections listed are 2200 m/sec values, but care must be exercised in their use because some nuclides deviate substantially from a 1/v cross section shape in the thermal region, e.g., $^{241}$Am. More is said about the interpretation of $\sigma^{2200}$ cross sections for non-1/v nuclides in the summaries which follow and in the original reference sources. The cutoff energy for infinite dilution resonance integrals is nominally ~0.5 eV, but deviations may exist because of different experimental conditions.

Table 4 lists the current status of resonance parameters for the transactinium production chain nuclides as they apply to calculations for thermal and near-thermal reactors. The experimental precision listed for $\Gamma_n$ and $\Gamma_f$ is clearly approximate because it varies from resonance to resonance; the precision is meant to be representative of the larger, low-lying resonances most influential in thermal reactor calculations.

Table 1. Summary of Transactinium Production-Chain Neutron Cross Sections

| *Element* | *Isotope* | *Status* | *Low Energy Shape* | *First Resonance, eV* | *Recommendations* |
|---|---|---|---|---|---|
| Pa(91) | 231 | Good | ~1/v <0.1 eV | 0.396 | - |
| | 233 | Acceptable | ~1/v | 0.795 | Thermal capture |
| U(92) | 232 | Good | ~1/v | 5 98 | - |
| | 234 | Good | ~1/v | 5.19 | - |
| | 236 | Good | ~1/v | 5.45 | - |
| | 237 | Very poor | Unknown | Unknown | Not crucial at present |
| Np(93) | 237 | Good | 1/v <0 15 eV | 0.489 | More (γ,n) and (n,2n) data |
| | 238 | Very poor | Unknown | Unknown | Not crucial at present |
| Pu(94) | 236 | Very poor | Unknown | Unknown | Not crucial at present |
| | 237 | Very poor | Unknown | Unknown | Not crucial at present |
| | 238 | Good | non-1/v | 2.90 | - |
| | 240 | Good | ~1/v <0.5 eV | 1.056 | Better parameters for first resonance |
| | 241 | Very good | non-1/v | 0.257 | - |
| | 242 | Very good | 1/v | 2.67 | - |
| | 243 | Poor | Unknown | Unknown | Not crucial at present |
| | 244 | Poor | Unknown | Unknown | Not crucial at present |
| Am(95) | 241 | Good | 1/v <0.06 eV | 0.308 | Capture branching ratio |
| | 242 | Very poor | Unknown | Unknown | Integral capture |
| | 242m | Poor | non-1/v | 0.173 | Capture, better resonance parameters |
| | 243 | Very good | 1/v <0.3 eV | 0.420 | - |
| Cm(96) | 242 | Very poor | Unknown | Unknown | Capture (difficult) |
| | 243 | Poor | Unknown | ~1.49 | Capture, especially thermal |
| | 244 | Good | ~1/v | 7.67 | - |
| | 245 | Acceptable | Unknown | 0.98(?) | Required measurements in progress |
| | 246 | Acceptable | 1/v | 4.32 | More data <20 eV (difficult) |
| | 247 | Poor | Unknown | Unknown | Differential fission <30 eV |
| | 248 | Good | ~1/v | 7.25 | - |
| Bk(97) | 249 | Very poor | non-1/v | 0.2 | Required measurements in progress |
| Cf(98) | 249 | Acceptable | non-1/v | 0.70 | - |
| | 250 | Poor | Unknown | Unknown | Thermal capture (difficult) |
| | 251 | Poor | Unknown | Unknown | Differential fission <30 eV |
| | 252 | Acceptable | Unknown | Unknown | Additional measurements (difficult) |
| | 253 | Very poor | Unknown | Unknown | Not crucial at present |
| Es(99) | 253 | Poor | Unknown | Unknown | Not crucial at present |
| | 254 | Very poor | Unknown | Unknown | Not crucial at present |
| | 254m | Very poor | Unknown | Unknown | Not crucial at present |

Table 2. Thermal Neutron Cross Sections

| Element | Isotope | | $\sigma_{n\gamma}^{2200}$ Recommended Experimental Value, barns | Precision, % Experimental | Precision, % Requested | $\sigma_{nf}^{2200}$ Recommended Experimental Value, barns | Precision, % Experimental | Precision, % Requested |
|---|---|---|---|---|---|---|---|---|
| Pa(91) | 231 | | 210 | 10 | 10 | 0.01 | 50 | - |
| | 233 | | 41 | 12 | 5 | ≤1 | - | - |
| U(92) | 232 | | 73.1 | 2 | - | 75.2 | 7 | - |
| | 234 | | 100.2 | 1.5 | 3 | ≤0.65 | - | - |
| | 236 | | 5.2 | 6 | 10 | - | - | - |
| | 237 | | 378 | 33 | - | ≤0.35 | - | - |
| Np(93) | 237 | | 169 | 2 | 3 | 0.019 | 16 | - |
| | 238 | | - | - | - | 2070 | 2 | - |
| Pu(94) | 236 | | - | - | 20 | 162 | 20 | 20 |
| | 237 | | - | - | - | 2200 | 20 | - |
| | 238 | | 559 | 4 | 20 | 17.3 | 3 | 20 |
| | 240 | | 289.5 | 0.5 | 3 | 0.03 | 150 | - |
| | 241 | | 362 | 3 | 3 | 1015 | <1 | 3 |
| | 242 | | 18.5 | 4-5 | 3 | 0 | - | - |
| | 243 | | 87.4 | 15 | - | 180.0 | 15 | - |
| | 244 | | 1.7 | 6 | - | - | - | - |
| Am(95) | 241 | to 242 | 748 | 3 | 10 | 3 14 | 4 | - |
| | | to 242m | 83.8 | 8 | 10 | | | |
| | 242 | | - | - | 10-20 | 2100 | 10 | 10-20 |
| | 242m | | - | - | 10 | 7600 | 4 | 10-20 |
| | 243 | | 77 | 5 | 5-10 | 0 | - | - |
| Cm(96) | 242 | | 20 | 50 | 20 | ≤5 | - | - |
| | 243 | | - | - | - | 690 | 7 | - |
| | 244 | | 10.6 | 20 | 20 | 1.1 | 50 | - |
| | 245 | | 383 | 10 | 10 | 2161 | 5 | 10 |
| | 246 | | 1.44 | 20 | 10 | 0.17 | 60 | - |
| | 247 | | 58 | 10-15 | 5-10 | 72.3 | 10-15 | 5-10 |
| | 248 | | 2.89 | 10 | - | 0.34 | 30 | - |
| Bk(97) | 249 | | 1600 | 50 | 10 | 0(?) | - | - |
| Cf(98) | 249 | | 481.4 | 6 | 10 | 1665 | 3 | 10 |
| | 250 | | 1701 | 15 | 10 | - | - | 10 |
| | 251 | | 2849 | 10 | 10 | 4801 | 10 | 10 |
| | 252 | | 20.4 | 8 | 10 | 32.0 | 10 | 10 |
| | 253 | | 12 | 20 | - | 1100 | 20 | - |
| Es(99) | 253 | to 254 | <3 | - | - | - | - | - |
| | | to 254m | 155 | 13 | - | | | |
| | 254 | | - | - | - | 2900 | 5 | - |
| | 254m | | - | - | - | 1840 | 5 | - |

Table 3. Infinite Dilution Resonance Integrals

| Element | Isotope | | $I_{n\gamma}$ Recommended Experimental Value, barns | Precision, % Experimental | Precision, % Requested | $I_{nf}$ Recommended Experimental Value, barns | Precision, % Experimental | Precision, % Requested |
|---|---|---|---|---|---|---|---|---|
| Pa(91) | 231 | | 1500 | 7 | 10 | - | - | - |
| | 233 | | 895 | 4 | 10 | - | - | - |
| U(92) | 232 | | 280 | 6 | - | 320 | 13 | - |
| | 234 | | 630 | 12 | <10 | - | - | - |
| | 236 | | 365 | 6 | 10 | - | - | - |
| | 237 | | 1200 | 18 | - | - | - | - |
| Np(93) | 237[a] | | 660 | 8 | 10 | - | - | - |
| | 238 | | - | - | - | 880 | 8 | - |
| Pu(94) | 236 | | - | - | 20 | - | - | 20 |
| | 237 | | - | - | - | - | - | - |
| | 238 | | 164 | 10 | 20 | 25 | 20 | 20 |
| | 240 | | 8013 | 12 | - | - | - | - |
| | 241 | | 162 | 0.4 | - | 570 | ∿3 | 3 |
| | 242 | | 1275 | 4 | - | 4.7 | - | - |
| | 243 | | 264 | 25 | - | 542 | 25 | - |
| | 244 | | 42.5 | 10 | - | - | - | - |
| Am(95) | 241 | to 242 | 1330 | 9 | 10 | 21 | 10 | - |
| | | to 242m | 208 | 9 | 10 | | | |
| | 242 | | - | - | 10-20 | <300 | - | 10-20 |
| | 242m | | - | - | 10-20 | 1570 | 7 | 10-20 |
| | 243 | | 1927 | 3 | 5-10 | 3 34 | - | - |
| Cm(96) | 242 | | 150 | 30 | 20 | ∿0 | - | - |
| | 243 | | - | - | - | 1860 | 21 | - |
| | 244 | | 585 | 10 | 10 | 17.9 | 10 | 10 |
| | 245 | | 104 | 7 | 10 | 766 | 5 | 10 |
| | 246 | | 117 | 7 | 10 | 9.94 | 40 | - |
| | 247 | | 500 | 15 | 5-10 | 761 | 7 | 5-10 |
| | 248 | | 251 | 10 | - | 14.7 | 15 | - |
| Bk(97) | 249 | | 4000 | 50 | 10 | 0 | - | - |
| Cf(98) | 249 | | 625 | 10 | 10 | 1610 | 10 | 10 |
| | 250 | | 11500 | 7 | 10 | - | - | - |
| | 251 | | 1590 | 4 | 10 | 5380 | 15 | 10 |
| | 252 | | 43.4 | 8 | 10 | 110 | 20 | 10 |
| | 253 | | 12.1 | 25 | - | 2000 | 25 | - |
| Es(99) | 253 | to 254 | 4299 | 5 | - | - | - | - |
| | | to 254m | 3009 | 6 | - | | | |
| | 254 | | - | - | - | 2200 | 5 | - |
| | 254m | | - | - | - | - | - | - |

*a.* Additional information of value for $^{237}$Np is $I_{n,2n}$ and $I_{\gamma,n}$
$I_{n,2n}$ = 1.46 mb ±11%  User request· 10%
$I_{\gamma,n}$ = 12.2 b ±12%  User request 10%

Table 4. Resonance Parameters

| *Element* | *Isotope* | *Resolved Resonance Range, eV* | *$\Gamma_n$ Precision, %* | | *$\Gamma_f$ Precision, %* | | *Comments on Measurements* |
|---|---|---|---|---|---|---|---|
| | | | *Experimental* | *Requested* | *Experimental* | *Requested* | |
| Pa(91) | 231 | 0-100 | ∿5 | 10 | ∿50 | - | Fission 0.396-0.743 eV |
| | 233 | 0-17 | 10 | 10 | - | - | |
| U(92) | 232 | 0-75 | 10 | - | 12 | - | |
| | 234 | 0-1500 | 5 | 6 | 10 | - | Fission 5-1500 eV |
| | 236 | 0-4100 | 5 | 10 | 30 | - | Fission 5-380 eV |
| | 237 | 45-225 | - | - | 20-50 | - | $\frac{1}{2}\pi\sigma_0\Gamma_f$ only |
| Np(93) | 237 | 0-235 | <5 | 5 | 30-100 | 30 | Fission 0 1-155 eV |
| | 238 | - | - | - | - | - | |
| Pu(94) | 236 | - | - | 20 | - | 20 | |
| | 237 | - | - | - | - | - | |
| | 238 | 0-496 | ∿10 | 20 | ∿40 | 20 | No fission <18.6 eV |
| | 240 | 1-5700 | ∿4 | 10 | ∿20 | 10 | Fission 700 eV - 3.5 keV |
| | 241 | 0-160 | ∿10 | 5 | ∿10 | 5 | |
| | 242 | 0-4000 | 5-10 | 10 | 10 | 10 | No fission <50 eV |
| | 243 | - | - | - | - | - | |
| | 244 | - | - | - | - | - | Some fission 30.7 eV - 18 keV |
| Am(95) | 241 | 0-150 | 2 | 10 | - | - | Fission 0-50 eV |
| | 242 | - | - | 10-20 | - | 10-20 | |
| | 242m[b] | 0-4 | - | 10 | - | 10-20 | Fission-errors not given |
| | 243 | 0-250 | <5 | 5-10 | - | - | |
| Cm(96) | 242 | - | - | 20 | - | - | |
| | 243[b] | 1-30 | 15 | - | 20 | - | |
| | 244 | 0-520 | 10 | 50 | ≥10 | 50 | Fission 20-972 eV |
| | 245[a] | 1.9-60 | 20 | 10 | 25 | 10 | |
| | 246 | 0-160 | 10 | 10 | 20 | - | Fission 20-382 eV |
| | 247 | 20-60 | - | 10 | - | 10 | Fission-errors not given |
| | 248 | 0-2400 | 7 | - | 20 | - | Fission 20-100 eV |
| Bk(97) | 249[a] | - | - | - | - | - | |
| Cf(98) | 249 | 0.4-70 | ∿10 | 10 | ∿10 | 10 | |
| | 250 | - | - | 10 | - | 10 | |
| | 251 | - | - | 10 | - | 10 | |
| | 252 | - | - | 10 | - | 10 | |
| | 253 | - | - | - | - | - | |
| Es(99) | 253 | - | - | - | - | - | |
| | 254 | - | - | - | - | - | |
| | 254m | - | - | - | - | - | |

*a.* New measurements in progress - applicable to thermal or near-thermal reactors.

*b.* New measurements planned - applicable to thermal or near-thermal reactors.

## Recommendations for Cross Section Measurements

The following recommendations appear both worthwhile in terms of user needs and to be within the capabilities of the current technology. The recommendations are only for measurements not in progress or firmly planned. However, documented user requests are not always indicative of measurements or experimental precision which might be required in the very near future, particularly in view of the relatively large quantities of some of the more exotic nuclides, such as $^{243}$Cm and $^{246}$Cm, which will be produced in the next few decades. Most of these nuclides are currently in such short supply that sample material of sufficient quantity and purity is difficult to obtain.

$^{233}$Pa Capture measurements from thermal to 2 eV. Differential measurements would be best, but a 5% integral thermal cross section measurement would satisfy user requirements.

$^{237}$Np Corroboration of, and better precision for, the existing integral measurements for the (n,2n) and (γ,n) reactions.

$^{240}Pu$ More differential measurements to extract resonance parameters for the first resonance at 1 eV. There has been a curious lack of interest in this resonance by recent measurers working with $^{240}Pu$. The current situation is aptly summarized by Caner and Yiftah,[14] and their evaluation should be required reading for $^{240}Pu$ measurers.

$^{241}Am$ Capture branching ratio measurements to the ground and isomeric states of $^{242}Am$. Integral measurements are available to a precision of about 10%. This branching ratio is likely to assume greater importance in the future, and additional high-precision integral measurements would be valuable. A differential measurement of the branching ratio in the low-energy region would be very worthwhile but appears to be beyond the current technology.

$^{242}Am$ Integral capture measurements. These measurements would be difficult because of the 16 hr half-life.

$^{242m}Am$ Integral capture measurements would be extremely valuable.

$^{242}Cm$ Integral capture measurements. These measurements would be difficult because of the short half-life and sample procurement.

$^{243}Cm$ Integral capture and differential total cross section measurements, particularly in the thermal region, would be valuable.

$^{246}Cm$ Higher precision capture data below 20 eV. This could be in the form of integral or differential thermal capture measurements or differential total cross section measurements. Sample procurement is a serious problem.

$^{247}Cm$ Differential fission measurements below 30 eV.

$^{250}Cf$ Thermal capture measurements of any kind.

$^{251}Cf$ Differential fission measurements from thermal energy to as high an energy as possible. This measurement would require a substantial, coordinated effort for sample procurement, isotopic separation, and measurement but is surely one of the more interesting and useful measurements which could be made.

## The Average Number of Neutrons per Fission $\bar{\nu}$

The measurement techniques, experimental values, and empirical approaches for prompt and delayed $\bar{\nu}$ from neutron-induced and spontaneous fission of the actinides have been examined in considerable detail in a recent review paper by Manero and Konshin.[15] Little, with the exception of a very few more-recent measurements, can be added to their review. The current status of $\bar{\nu}$ measurements is listed in Table 5. Most of the user data requests are at least partially fulfilled. The important measurements requested appear to be the delayed neutron measurements for $^{236}U$, $^{240}Pu$, $^{241}Pu$, and $^{242}Pu$, which are required for background corrections for fuel assays.[12] The empirical approach to $\bar{\nu}_p(E)$ presented by Manero and Konshin[15] combined with the available experimental data appear to be adequate for current and near-term requirements.

Table 5. Neutron-Induced $\bar{\nu}$ for Transactinium Production-Chain Nuclides

| | | $\bar{\nu}_p$ *(thermal)* | | | $\bar{\nu}_p(E)$ | | | | $\bar{\nu}(E)$ |
|---|---|---|---|---|---|---|---|---|---|
| | | *Measured Value,* | *Precision, %* | | *Range, MeV* | | *Precision, %* | | *Delayed* |
| *Element* | *Isotope* | *n/fission* | *Experimental* | *Requested* | *Measured* | *Requested* | *Measured* | *Requested* | *Neutrons* |
| Pa(91) | 231 | - | | - | - | - | - | - | |
| | 233 | - | | - | - | - | - | - | |
| U(92) | 232 | 3.132 | 2 | - | - | - | - | - | |
| | 234 | - | | - | 0.99-5 | 0.5-20 | ∿2 | 3 | |
| | 236 | - | | - | 0.8-6.7 | 0.5-14 | ∿2 | 3 | *a* |
| | 237 | - | | - | - | - | - | - | |
| Np(93) | 237 | - | | - | - | - | - | - | |
| | 238 | - | | - | - | - | - | - | |
| Pu(94) | 236 | - | | - | - | - | - | - | |
| | 237 | - | | - | - | - | - | - | |
| | 238 | 2.895 | 1 | - | - | 0.01-15 | - | 3 | |
| | 240 | - | | - | 0.1-15 | Thresh.-15 | 3 | 3 | *b* |
| | 241 | 2.924 | 0.4 | - | 0-15 | 0.5-15 | 3 | 3 | *c* |
| | 242 | - | | - | - | 0.5-15 | - | 3 | *d* |
| | 243 | - | | - | - | - | - | - | |
| | 244 | - | | - | - | - | - | - | |
| Am(95) | 241 | 3.121 | 0.8 | - | - | - | - | - | |
| | 242 | - | | - | - | - | - | - | |
| | 242m | 3.264 | 0.8 | - | - | - | - | - | |
| | 243 | - | | - | - | - | - | - | |
| Cm(96) | 242 | - | | - | - | - | - | - | |
| | 243 | 3.430 | 1.4 | - | - | - | - | - | |
| | 244 | - | | - | - | - | - | - | |
| | 245 | 3.832 | 1 | - | - | - | - | - | |
| | 246 | - | | - | - | - | - | - | |
| | 247 | 3.79 | 4 | - | - | - | - | - | |
| | 248 | - | | - | - | - | - | - | |
| Bk(97) | 249 | - | | - | - | - | - | - | |
| Cf(98) | 249 | 4.06 | 1 | - | - | - | - | - | |
| | 250 | - | | - | - | - | - | - | |
| | 251 | - | | - | - | - | - | - | |
| | 252 | - | | - | - | - | - | - | |
| | 253 | - | | - | - | - | - | - | |
| Es(99) | 253 | - | | - | - | - | - | - | |
| | 254 | - | | - | - | - | - | - | |
| | 254m | - | | - | - | - | - | - | |

*a.* Request for $\bar{\nu}(E)$ (delayed) at 3 and 14 MeV, 10%. No data.

*b.* Request for $\bar{\nu}(E)$ (delayed) from 0.75 to 14 MeV, 20%. Very little data.

*c.* Request for $\bar{\nu}(E)$ (delayed) from Thermal to 14 MeV, 10% Very little data.

*d.* Request for $\bar{\nu}(E)$ (delayed) at 3.14 MeV, 20%. No data.

## DATA SUMMARIES BY NUCLIDE

The nuclides are presented in order of increasing atomic number with the isotopes of each element in order of increasing atomic weight. Currently significant measurements are summarized; questionable measurements are included only if they represent a significant portion of the available data. Measurements reported through August 1975 have been surveyed. An effort has been made to include all planned or current measurements on isotopes in the chains. Information concerning any omissions or errors would be most welcome.

The cross section notation used in the following summaries conforms with that of H. Goldstein [16] with minor changes. The symbols used are:

$\sigma(E)$ The differential cross section as a function of energy

$\sigma^{2200}$ The 2200 m/sec thermal cross section

| | |
|---|---|
| I | The resonance integral $I = \int_{E_O}^{\infty} (E)/E \, dE$ |
| $\sigma_{nn}$ | The elastic scattering cross section |
| $\sigma_{nf}$ | The fission cross section |
| $\sigma_{n\gamma}$ | The capture cross section |
| $\sigma_{nT}$ | The total cross section |
| $\sigma_{na}$ | The absorption cross section |

All cross sections are given in units of barns. Terms mentioned in the discussion of the resonances are from the single-level resonance Breit-Wigner formula for neutron absorption.

Accuracies listed in the summaries are estimates of the standard deviations of both random and systematic errors. Those accuracies for the resonance widths refer specifically to the first few resonances, which are more important to thermal and near-thermal reactors. As energy increases, generally so do the uncertainties in the resonance widths, particularly those for fission.

User requirements were derived from the current (1975) compilation of requests put together by the National Neutron Cross Section Center at Brookhaven[12] and the summary sent by R. Dierckx.[13]

## PROTACTINIUM-231 (32480 yr)

This nuclide is produced by beta decay following (n,2n) or ($\gamma$,n) reactions on $^{232}$Th. A modest quantity of data is available for $^{231}$Pa and user requests appear to be satisfied. The resonance integral is very sensitive to the cutoff because of the low-lying (0.396 eV) first resonance (this problem is discussed in detail by Gryntakis and Kim [2]).

### Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* |
|---|---|---|---|
| $\sigma^{2200}$ | 210 | 0.010 | 1,3 |
| I | 1500 | - | 1,3 |

| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Requested Precision* |
|---|---|---|---|---|
| Capture | Thermal | 10% | 1,3 | 10% |
| Fission | Thermal | 50% | 1 | - |
| Resolved Resonances | | | | |
| $\Gamma_n$ | 0-100 eV | ∿5% | 1 | 10% |
| $\Gamma_f$ | 0.396-0.743 eV | ∿50% | 1 | - |
| $I_{n\gamma}$ | ≥0.5 eV | 7% | 1 | 10% |
| $I_{nf}$ | - | - | - | - |

*Nubar*

Thermal }
$\bar{\nu}$(E) No measurements known

Current or Future Measurements - None known

Recommendations - None

References

The available data, except for the recent work of Reference 3, are summarized well in the General References below.

*General References*


[1] MUGHABGHAB, S.F., GARBER, D.I., *Neutron Cross Sections, Volume 1, Resonance Parameters*, USAEC Report BNL-325, Third Edition (1973).

[2] GARBER, D.I., KINSEY, R.R., *Neutron Cross Sections, Volume 2, Curves*, USERDA Report BNL-325, Third Edition (1975).


*Integral Data*


[3] GRYNTAKIS, E.M., KIM, J.I., "The thermal cross section and the resonance integral of $^{231}Pa$: activation determination without using a Cd-filter," *J. Inorg. Nucl. Chem. 36* (1974) 1447. Careful activation measurements were made in different neutron spectra using $^{197}Au$ and $^{59}Co$ as monitors and gave the thermal cross section and resonance integral $\sigma_{n\gamma}^{2200}$ = 201 ±22 b, $I_{n\gamma}$ (excluding the 1/v contribution) = 1432 ±187 b.


## PROTACTINIUM-233 (27.0 d)

There is a modest quantity of data available for $^{233}Pa$, an important link in the Th-$^{233}U$ cycle, and a fairly recent (1970) ENDF/B evaluation has been made. Although the requested precision has not been met in the thermal region, the data are probably sufficiently good for near-term requirements.

Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* |
|---|---|---|---|
| $\sigma^{2200}$ | 41 | <1 b | 1 |
| I | 895 | - | 1 |

| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Requested Precision* |
|---|---|---|---|---|
| Capture | Thermal | 12% | 1 | 5% |
| Fission | Thermal | - | | - |
| Resolved Resonances | | | | |
| $\Gamma_n$ | 0.015-17 eV | ∿10% | 1 | 10% |
| $\Gamma_f$ | - | - | - | - |
| $I_{n\gamma}$ | ≥0.5 eV | 4% | 1 | 10% |
| $I_{nf}$ | - | - | - | - |

*Nubar*

Thermal (prompt) }
$\bar{\nu}$(E) } No measurements known

Current or Future Measurements - None known

Recommendations - A priority II request (1967) exists for capture data from 1 meV to 2 eV to 5% precision.

## References

*General Reference*


[1] MUGHABGHAB, S.F., GARBER, D.I., *Neutron Cross Sections, Vol. 1. Resonance Parameters*, USAEC Report BNL-325, Third Edition (1973).


*Differential Data*


[2] SIMPSON, F.B., CODDING, Jr., J.W., "Total neutron cross section of protactinium-233," *Nucl. Sci. Eng. 28* (1967) 133. MTR fast chopper transmission measurements were made with an initially highly enriched sample of about 700 mg $^{233}$Pa. Subsequent measurements were made to follow the decay and determine the effects of other isotopes in the sample. Data were analyzed for 0.015 eV $<E_n<$ 18 eV, and Breit-Wigner resonance parameters determined for $E_o$, $2g\Gamma_n^o$, and $\Gamma_\gamma$. Resonance absorption integral above 0.4 eV was $I_a$ = 901 ±45 b.


*Integral Data*


[3] CONNER, J.C., *Integral Measurements of the $^{233}$Pa Neutron Capture Cross Section*, USAEC Report WAPD-TM-837 (1970). The Cd-difference technique was used in a reactor irradiation of thorium wires followed by chemical separation and analysis. $\sigma_{n\gamma}^{2200}$ = 38.3 b, $I_{n\gamma}$ ($E_n$ >0.5 eV) = 857 ±35 b.

[4] CONNER, J.C., BAYARD, R.T., MACDONALD, D., GUNST, S.B., "Measurements of the protactinium-233 resonance integral," *Nucl. Sci. Eng. 29* (1967) 408. Cd-covered thorium wires were irradiated in the TRX reactor and subsequently chemically analyzed for $^{234}$U production. $I_{n\gamma}$ ($E_n$ >0.5) = 842 ±35 b.

[5] HALPERIN, J., DRUSCHEL, R.E., STOUGHTON, R.W., CAMERON, A.E., WALKER, R.L., "Thermal cross section and resonance integral of Pa$^{233}$," *Chem. Div. Ann. Prog. Rept. for Period Ending June 20, 1962*, USAEC Report ORNL-3320 (1962) 1. Cd and Gd difference measurements were made with $ThO_2$ samples in the ORR reactor. Subsequent chemical separation and analysis gave $\sigma_{n\gamma}^{2200}$ = 46 ±5 b and $I_{n\gamma}$ ($E_n$ >0.55 eV) = 920 ±90 b.

[6] EASTWOOD, T.A., WERNER, R.D., "The thermal neutron capture cross section and resonance capture integral of protactinium-233," *Can. Journ. Phys. 38* (1960) 751. Cd-difference irradiations of highly enriched samples were made in the NRX reactor followed by chemical separation and counting of the induced $^{234}$Pa (both 1.2 m and 6.7 hr activities). The results were $\sigma_{n\gamma}^{2200}$ = 39 ±5 b, $I_{n\gamma}$ (En >0.5 eV) = 930 ±134 b.


## URANIUM-232 (72 yr)

There is a modest quantity of data available for $^{232}$U. This nuclide is of importance as a precursor to the $^{228}$Th decay chain which produces several very energetic gamma rays. The data are adequate for current and near-term needs.

Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* | |
|---|---|---|---|---|
| $\sigma^{2200}$ | 73.1 | 75.2 | 1 | |
| I | 280 | 320 | 1 | |

| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Requested Precision* |
|---|---|---|---|---|
| Capture | Thermal | 2% | 1 | - |
| Fission | Thermal | 7% | 1 | - |
| Resolved Resonance | | | | |
| $\Gamma_n$ | 0-75 eV | $\sim$10% | 1 | - |
| $\Gamma_f$ | 0-75 eV | $\sim$12% | 1 | - |
| $I_{n\gamma}$ | ≥0.5 eV | 6% | 1 | - |
| $I_{nf}$ | ≥0.5 eV | 13% | 1 | - |

| *Nubar* | | *Precision* | *Reference* | |
|---|---|---|---|---|
| Thermal (prompt) | $\bar{\nu}_p$ = 3.132 | 2% | 3 | - |
| $\bar{\nu}$(E) | No measurements | known | - | - |

Current or Future Measurements - None known

Recommendations - None

References

The available cross section data for $^{232}$U are summarized well in General Reference 1.

*General References*


[1] MUGHABGHAB, S.F., GARBER, D.I., *Neutron Cross Sections, Volume 1, Resonance Parameters*, USAEC Report BNL-325, Third Edition (1973).

[2] GARBER, D.I., KINSEY, R.R., *Neutron Cross Sections, Volume 2, Curves*, USERDA Report BNL-325, Third Edition (1975).


*Nubar*


[3] JAFFEY, A.H., LERNER, J.L., "Measurement of prompt neutron fission yield ($\bar{\nu}_p$) in thermal neutron fission of $^{232}$U, $^{238}$Pu, $^{241}$Pu, $^{241}$Am, $^{242m}$Am, $^{243}$Cm, $^{245}$Cm, and in spontaneous fission of $^{244}$Cm," *Nucl. Phys. A145* (1970) 1. A coincidence technique using a gas filled ionization chamber in a thermal neutron beam with four Hornyak buttons as the neutron detectors gave $\bar{\nu}_p$ = 3.130 ±0.060.


## URANIUM-234 (2.48 x $10^5$ yr)

A substantial quantity of cross section data is available for $^{234}$U, and the quality of the data seems close to fulfilling the precision requested by the users.

Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* | |
|---|---|---|---|---|
| $\sigma^{2200}$ | 100.2 | <0.65 | 1 | |
| I | 630 | - | 1 | |

| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Requested Precision* |
|---|---|---|---|---|
| Capture | Thermal | 1.5% | 1 | 3% |
| Fission | Thermal | - | 1 | - |
| Resolved Resonances | | | | |
| $\Gamma_n$ | 0-1500 eV | ∿5% | 1,3 | 6% |
| $\Gamma_f$ | 5-1500 eV | ∿10% | 1,3 | - |
| $I_{n\gamma}$ | ⩾0.5 eV | 12% | 1 | <10% |
| $I_{nf}$ | - | - | - | - |
| *Nubar* | | *Precision* | *Reference* | |
| Thermal (prompt) | No measurement known | | - | - |
| $\bar{\nu}(E)$ (prompt) | 0.99-5 MeV | ∿2% | 8 | 3%† |

† Request for $\bar{\nu}(E)$ prompt $0.5 < E_n < 20$ MeV, priority I (1962).

Current and Future Measurements - None known.

Recommendations - The $\bar{\nu}$ measurements are still outstanding, but the existent measurements provide a substantial portion of the requested data for $\bar{\nu}_p$.

References

The available data are, for the most part, summarized succinctly in General References 1 and 2. The differential and integral references which follow are meant to be representative of the more useful and recent work, but are by no means complete.

*General References*


[1] MUGHABGHAB, S.F., GARBER, D.I., *Neutron Cross Sections, Volume 1, Resonance Parameters,* USAEC Report BNL-325, Third Edition (1973).

[2] GARBER, D.I., KINSEY, R.R., *Neutron Cross Sections, Volume 2, Curves,* USAEC Report BNL-325, Third Edition (1975).


*Differential Data*


[3] JAMES, G.D., DABBS, J.W.T., HARVEY, J.A., HILL, N.W., SCHINDLER, R.H., "Intermediate structure studies of $^{234}$U cross sections," submitted to *Nucl. Phys. A.* Fission and transmission measurements were made at ORELA for the neutron energy range from a few eV to several MeV. Neutron and fission widths for 118 resonances below 1500 eV were determined.

[4] JAMES, G.D., SLAUGHTER, G.G., "The total cross section of $^{234}$U and the parameter of its sub-threshold fission resonances," *Nucl. Phys. A 139* (1969) 471. The total cross section was measured from about 1 eV to 829 eV at the Harwell linac, and resonance parameters were extracted using these data and the data from Ref. 5. 38 resonances were analyzed for $E_o$, $\Gamma_n$ and $\Gamma_f$ from 5 eV to 587 eV.

[5] JAMES, G.D., ARE, E.R., "Fission components in $^{234}$U resonances," *Nucl. Phys. A 118* (1968)313. Differential fission measurements were made at the Harwell linac from 5 eV to about 20 MeV. Resonance analysis from 5 to 368 eV gave $E_0$ and $\Gamma_f$ for 20 resonances. Analysis superseded by Ref. 4. For additional differential data references, see References 1 and 2.

*Integral Data*

[6] CABELL, M.J., WILKINS, M., "The thermal neutron capture cross sections of $^{234}$U and $^{236}$U," United Kingdom AEA Report AERE-R 6761 (1971). Isotopically pure samples were irradiated for 2 yr in an essentially thermal spectrum and then mass-analyzed. $\sigma_{nf}^{2200}$ = 100.5 ±1.3 b.

[7] LOUNSBURY, M., DURHAM, R.W., HANNA, G.C., "Measurements of alpha and of fission cross section ratios for $^{233}$U, $^{235}$U, and $^{239}$Pu at thermal energies." *Proc. Second Int. Conf. on Nucl. Data for Reactors, Helsinki, Vol. 1* (1970) 287. Mixed samples of Pu and U isotopes were irradiated for 1 yr in a well-thermalized flux, cooled for 1 yr, and then chemically separated and mass analyzed. $\sigma_{nf}^{2200}$ = 95.6 ±2.1 b for $^{234}$U. For additional integral data references, see Reference 1.

*Nubar*

[8] MATHER, D.S., FIELDHOUSE, P., MOAT, A., "Measurement of prompt ν for the neutron-induced fission of $Th^{232}$, $U^{233}$, $U^{234}$, $U^{238}$, and $Pu^{239}$," *Nucl. Phys. 166* (1965)149. A large liquid scintillation counter and a Van de Graaff accelerator neutron source were used to measure $\bar{\nu}_p$ at several energies from 0.99 MeV to 4.02 MeV.

## URANIUM-236 (2.40 × $10^7$ yr)

Substantial differential and integral data are available for $^{236}$U. The differential cross section data are especially good and adequate for current and near-term needs.

### Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* | |
|---|---|---|---|---|
| $\sigma^{2200}$ | 5.2 | - | 1 | |
| I | 365 | - | 1 | |
| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Requested Precision* |
| Capture | Thermal | 6% | 1 | 10% |
| Fission | - | - | - | - |
| Resolved Resonances | | | | |
| $\Gamma_n$ | 0-4.1 keV | ∿5% | 1,3,4 | 10%† |
| $\Gamma_f$ | 5-380 eV | ∿30% | 1 | - |
| $I_{n\gamma}$ | ≥0.5 eV | 6% | 1 | 10% |
| $I_{nf}$ | - | - | - | - |
| *Nubar* | | *Precision* | *Reference* | |
| Thermal (prompt) | No measurements known | | | |
| $\bar{\nu}$(E) (prompt) | 0.8-6.7 MeV | ∿2% | 14 | 3%†† |

†Requires 10% accuracy in capture widths to about 1 keV; current situation is typically <11% (priority I).

††Requires: 1. $\bar{\nu}$(E) prompt from 0.5 to 14 MeV to 3% (priority I)
2. $\bar{\nu}$(E) delayed at 3 and 14 MeV to 10% (priority I).

Current or Future Measurements - None known

Recommendations - The $\bar{\nu}$ measurements need to be made, particularly for the delayed neutrons (required for background corrections in $^{235}U$ spent fuel assays).

## References

The available data are, for the most part, summarized succinctly in General References 1 and 2. The differential and integral references which follow are meant to be representative of the more useful recent work and are by no means complete.

*General References*

[1] MUGHABGHAB, S.F., GARBER, D.I., *Neutron Cross Sections, Volume 1, Resonance Parameters*, USAEC Report BNL-325, Third Edition (1973).

[2] GARBER, E.I., KINSEY, R.R., *Neutron Cross Sections, Volume 2, Curves*, USAEC Report BNL-325, Third Edition (1975).

*Differential Data*

[3] MEWISSON, L., POORTMANNS, F., ROHR, G., WEIGMANN, H., THEOBALD, J.P., VANPRAET, G., "Neutron cross section measurements on $^{236}U$ below 2 keV," *Proc. Specialists Meeting on Resonance Parameters of Fertile Nuclei and $^{239}Pu$*, Saclay, May, 1974, p 131. An analysis of GEEL linac scattering and transmission measurements gave $E_o$ and $\Gamma_n$ for 185 resonances below 4.1 keV and $\Gamma_\gamma$ for 57 of the resonances.

[4] CARRARO, G., BRUSEGAN, A., "Neutron widths for $^{236}U$ from high resolution transmission measurements at a 100 m flight path," *Proc. Specialists Meeting on Resonance Parameters of Fertile Nuclei and $^{239}Pu$*, Saclay, May, 1974, p 121. High resolution transmission measurements at the GEEL linac gave $E_o$ and $\Gamma_n$ for 188 resonances below 1.4 KeV.

[5] CARLSON, A.D., FRIESENHAHN, S.J., LOPEZ, W.M., FRICKE, M.P., "The $^{236}U$ neutron capture cross section," *Nucl. Phys. A141* (1970) 577. Capture measurements were made with Gulf General Atomic (GGA) linac on highly enriched samples for 0.01 eV $<E_n<$ 20 keV. Thermal data are good. 29 resonances were analyzed for $E_o$, $\Gamma_n$, and 12 for $E_o$, $\Gamma_n$, and $\Gamma_\gamma$ up to 415 eV. One bound level was added to fit thermal data. $\sigma_{n\gamma}^{2200} = 5.1 \pm 0.25$ b; $I_{n\gamma}$ ($E_n <0.5$ eV) = 350 ±25 b.

[6] CRAMER, J.D., BERGEN, D.W., *Fission Cross Section from Pommard*. USAEC Report LA-4420, Los Alamos Scientific Laboratory, Los Alamos, N.M. (1970) p 74. Los Alamos Scientific Laboratory (LASL) bomb shot fission data were obtained from highly enriched samples. Cross section curves were obtained for 35 eV $<E_n<$ 3 MeV with no parametric analysis and low precision.

[7] HARLAN, R.A., "Total neutron cross section parameters of $^{236}U$," *Report to the AEC Nuclear Cross Sections Advisory Committee, Oak Ridge, April 1969.* USAEC Report WASH-1127 (1969) p 60. Materials Testing Reactor (MTR) fast chopper transmission measurements were made for 0.01 eV $<E_n<$ 1000 eV. 13 resonances were analyzed for $\Gamma_n$ assuming one bound level and $\Gamma_\gamma$ = 25 mV to 400 eV.

[8] MCCALLUM, G.J., "The neutron total cross-sections of uranium-234 and uranium-236," *J. Nucl. Energy 6* (1958) 181. Harwell fast chopper transmission measurements were made with small samples enriched to $\sim$95% for 0.01 $<E_n<$ 20 eV. Small-angle scattering in the thermal region created problems. Parameters were determined for the 5.48-eV resonance. Thermal cross sections: $\sigma_{nT}^{2200}$ = 18.7 ±1.7 b, $\sigma_{n\gamma}^{2200}$ = 8.1 ±1.8 b, $\sigma_{nn}^{2200}$ = 10.6 ±0.4 b.

[9] HARVEY, J.A., HUGHES, D.J., "Spacing of nuclear energy levels," *Phys. Rev. 109* (1958) 471. Brookhaven fast chopper transmission measurements were made for samples enriched to $\sim$95%. 15 resonances were analyzed below 400 eV for $E_o$ and $\Gamma_n$ assuming $\Gamma_\gamma$ = 25 mV. No thermal data were given.

[10] CABELL, M.J., WILKINS, M., *Thermal Neutron Capture Cross Sections of $^{234}U$ and $^{236}U$.* British Report AERE-R6761, Atomic Energy Research Establishment, Harwell, England (1971). Mass spectrometric analysis was made after a two year reactor irradiation in Maxwellian spectrum at T = 119 ±9°C. $\bar{\sigma}_{n\gamma}$ = 8.47 ±4.00 b.

[11] SCHUMAN, R.P., BERRETH, J.R., *Resonance Integral Measurements.* USAEC Report IN-1296, Idaho Nuclear Corporation, Idaho Falls (1969) p 11. Samples enriched to 97.5%, both bare and cadmium-covered, received reactor irradiation. 0.208-meV gamma counting was performed after ion exchange purification. $\sigma_{n\gamma}^{2200}$ = 5.4 ±1.5 b, $I_{n\gamma}$ (no cutoff given) = 381 ±20 b.

[12] BAUMANN, N.P., HALFORD, J.D., PELLARIN, D.J., "Resonance parameters for $^{236}$U from integral measurements," *Nucl. Sci. Eng. 32* (1968) 265. Reactor activation measurements were made for samples with composition $^{236}$U-11.56 wt %, $^{235}$U-2.22 wt %, $^{27}$Al-86.22 wt %. Monitors were $^{235}$U, $^{238}$U, Au, and W. $I_{n\gamma}$ ($E_n$ >0.5 eV) = 417 ±25 b. Resonance parameters for the first resonance were adjusted to give this value. Revised values (N.P. Baumann, private communication, 6/73) are $\sigma_{n\gamma}$ = 5.3 ±0.2 b and $I_{n\gamma}$ ($E_n$ >0.625 eV) = 375 ±10.

[13] CABELL, M.J., EASTWOOD, T.A., CAMPION, D.J., "The thermal neutron capture cross sections and resonance capture integral of $^{236}$U," *J. Nucl. Energy 7* (1958) 81. Reactor activation measurements were made for bare and cadmium-covered samples enriched to $\sim$95%. A $^{59}$Co monitor was used (assumed $\sigma_{n\gamma}^{2200}$ = 36.5 b, $I_{n\gamma}$ = 48.6 b). $\sigma_{n\gamma}^{2200}$ = 5.5 ±0.3 b, $I_{n\gamma}$ ($E_n$ >0.5 eV) = 257 ±22 b.

*Nubar*

[14] CONDE, H., HOLMBERG, M., "Prompt $\bar{\nu}$ in spontaneous and neutron induced fission of $^{236}$U and its half-life for spontaneous fission," *J. Nucl. En. 25* (1971) 331. A liquid scintillator counter and a Van de Graaff accelerator neutron source were used to measure $\bar{\nu}_p$ at several energies from 0.8 to 6.7 MeV.

## URANIUM-237 (6.75 d)

Both differential and integral data for $^{237}$U are very limited because of its short half-life. For the same reason, additional data for this beta-decay precursor to $^{237}$Np are not crucial.

Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* | |
|---|---|---|---|---|
| $\sigma^{2200}$ | 378 | $\leq 0.35$ | 2,4 | |
| I | 1200 | - | 3 | |
| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Requested Precision* |
| Capture | Thermal | 33% | 2 | - |
| Fission | Thermal | - | 4 | - |
| Resolved Resonances | | | | |
| $\Gamma_n$ | | | | - |
| $\Gamma_f \times (\frac{1}{2}\pi\sigma_o)$ | 45-225 eV | 20-50% | 1 | - |
| $I_{n\gamma}$ | No cutoff given | 18% | 3 | - |
| $I_{nf}$ | - | - | - | - |

*Nubar*

Thermal (prompt) } No measurements known
$\bar{\nu}(E)$

Current or Future Measurements - None known

Recommendations - None

References

*Differential Data*


[1] MCNALLY, J. H., BARNES, J.W., DROPSKY, B.J., SEEGER, P.A., WOLFSBERG, K., "Neutron-induced fission cross section of $^{237}$U," *Phys. Rev. C9* (1974) 717. Tabulated data in USAEC Report LA-4420 (1970) p 91. LASL bomb shot fission measurements were made for samples containing 18.1 ±0.5 mg $^{237}$U with ~38% $^{237}$Np contaminant. $\sigma_{nf}(E)$ measured for 43 <$E_n$ <1000 eV and 0.1 <$E_n$ <2 MeV. A crude resonance analysis was done from 45 to 225 eV which gave $E_o$ and $\frac{1}{2}\pi\sigma_o\Gamma_f$.


*Integral Data*


[2] CORNMAN, W.R., HENNELLY, E.J., BANICK, C.J., "Neutron absorption cross section of $^{237}$U," *Nucl. Sci. Eng. 31* (1968) 149. Samples enriched to 73.08% $^{236}$U were irradiated in an SRL reactor. After chemical separation and α-counting, the effective cross section was $\sigma_{n\gamma}$ = 370 ±124 b and the inferred cross section was $\sigma^{2200}_{n\gamma}$ = 378 ±160 b.

[3] HALPERIN, J., IDOM, L.E., BALDOCK, C.R., STOUGHTON, R.W., "The neutron resonance capture integral of the 6.75-day $^{237}$U," *Chemistry Division Annual Progress Report for Period Ending May 20, 1968.* USAEC Report ORNL-4306 (1968) 1. Cd-filtered reactor irradiation followed by a mass-spectrometer analysis. $I_{n\gamma}$ (no cutoff given) = 1200 ±200 b.

[4] BARR, E.W., "Fission cross sections for $^{237}$U," *Report to the AEC Nuclear Cross Sections Advisory Committee, New York, 1968,* USAEC Report WASH 1124 (1968) 110. Reactor irradiations in three different neutron energy spectra, one of which was thermal. $\sigma^{thermal}_{nf} \leq 0.35$ b.

## NEPTUNIUM-237 ($2.14 \times 10^6$ yr)

A very large quantity of differential and integral data is available for $^{237}$Np, a key nuclide in the $^{238}$Pu chain. The lower-energy neutron cross sections for capture, scattering, and fission seem well described by the differential data. The integral data for $^{237}$Np are, however, not very useful because the first resonance is at 0.489 eV, directly in the cadmium-cutoff region. Small uncertainties in the precise cadmium cutoff lead to large differences in the resonance integral. Calculations made by F. J. McCrosson at the Savannah River Laboratory using ENDF/B Version II resonance parameters determined the effects of the cutoff on the resonance integral. The results are listed below:

| *Low Energy Cutoff, eV* | $I_{n\gamma}$, *barns* |
|---|---|
| 0.625 | 550 |
| 0.525 | 582 |
| 0.500 | 635 |
| 0.475 | 733 |
| 0.450 | 788 |
| 0.400 | 817 |

If the cadmium-difference technique is used, the thermal cross section is difficult to determine. Thus, with $^{237}$Np, only the differential data are measurable with any degree of accuracy, and integral data should be considered estimates.

Two high-energy reactions lead to $^{236}$Pu, which is a very undesirable contaminant in the $^{238}$Pu product. These reactions, both having a Q-value of about 6.8 MeV, are the n,2n and $\gamma$,n reactions, which are initiated by the high-energy fission neutron tail and by capture gammas from structural elements (such as aluminum and iron), respectively. There are only a few measurements of the $\gamma$,n and n,2n cross sections for $^{237}$Np in the energy regions of interest, and further measurements would be worthwhile.

### Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* |
|---|---|---|---|
| $\sigma^{2200}$ | 169 | 0.019 | 1 |
| I | 660 | - | 1 |

| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Requested Precision* |
|---|---|---|---|---|
| Capture | Thermal | 2% | 1 | 3% |
| Fission | Thermal | 16% | 1 | - |
| Resolved Resonances | | | | |
| $\Gamma_n$ | 0-235 eV | 5% | 1,2 | 5% |
| $\Gamma_f$ | 0.1-155 eV | 30-100% | 1,2 | 30% |
| $I_{n\gamma}$ | ≥0.5 eV | 8% | 1 | 10% |
| $I_{nf}$ | - | - | - | - |
| $I_{n,2n}$ = 1.46 mb | Threshold=6.8 MeV | 11% | 14 | 10% |
| $I_{\gamma,n}$ = 12.2 b† | Threshold=6.8 MeV | 12% | 13 | - |

| *Nubar* | | *Reference* | |
|---|---|---|---|
| Thermal (prompt) | No measurements known | - | - |
| $\bar{\nu}$(E) | Some fission spectrum measurements | 21,22 | - |

† Measured in an aluminum capture gamma ray spectrum.

Current or Future Measurements - Poortmans, et al. (NEANDC(E) 161 U (1974) p 236) are making capture, scattering, and total cross section measurements at the GEEL Linac from 7 to 250 eV.

Recommendations - Corroborative measurements of the ($\gamma$,n) and (n,2n) cross sections would be worthwhile.

## References

The available data are, for the most part, summarized succinctly in General References 1 and 2. The differential and integral references following are meant to representative of the more useful work, but are by no means complete.

*General References*


[1] MUGHABGHAB, S.F., GARBER, D.I., *Neutron Cross Sections, Volume 1 Resonance Parameters*, USAEC Report BNL-325, Third Edition, (1973).

[2] GARBER, D.I., KINSEY, R.R., *Neutron Cross Sections, Volume 2 Curves*, USAEC Report BNL-325, Third Edition (1975).


*Differential Data*


[3] KEYWORTH, G.A., LEMLEY, J.R., OLSEN, C.E., SEIBEL, F.T., DABBS, J.W.T., HILL, N.W., "Spin determination of intermediate structure in the subthreshold fission of $^{237}$Np," *Phys. Rev. C8* (1973) 2352. A polarized neutron beam and a polarized target were used to determine the spins of 15 intermediate structure groups in fission below 1 keV and of 94 resonances observed in transmission below 102 eV.

[4] JIACOLETTI, R.J., BROWN, W.K., OLSON, H.G., "Fission cross sections of neptunium-237 from 20 eV to 7 MeV determined from a nuclear explosive experiment," *Nucl. Sci. Eng. 48* (1972) 412. LASL measurements of $\sigma_{nf}$ were obtained for 20 eV $<E_n<$ 7 MeV from the Physics 8 bomb shot. The oxide was isotopically pure (contaminants <0.1%). Cross sections were presented, and only a rudimentary parametric comparison was made.

[5] KOLAR, W., THEOBALD, J.P., LANZANO, G., "Fission of $^{237}$Np + n through a double humped fission barrier," *Z. Physik 248* (1971) 355. At the Euratom linac at Geel, Belgium, fission measurements were made with a very highly enriched sample for 20 eV $<E_n<$ 60 eV. 28 resonances were analyzed for $E_o$ and $\Gamma_f$, assuming the values of Paya et al. for $2g\Gamma_n$ and $\Gamma$.

[6] POORTMANS, F., CEULEMANS, H., THEOBALD, J., MIGNECO, E., in *Proceedings of the Third Conference on Neutron Cross Sections and Technology*. CONF-710301 (1971) 667. Geel linac scattering and transmission measurements were made for samples enriched to about 99.9%. 14 resonances were analyzed for $E_o$, $2g\Gamma_n$, $\Gamma_\gamma$, and J from 5 to 51 eV.

[7] BROWN, W.K., DIXON, D.R., DRAKE, D.M., "Fission cross sections of $^{237}$Np from pommard," *Nucl. Phys. A156* (1970) 609. LASL bomb shot fission measurements were made for highly enriched samples for 35 eV $<E_n<$ 3 MeV. Only cross section curves were made. No parametric analysis was made.

[8] GAVRILOV, K.A., KOSHAEVA, K.K., KRAITOR, S.M., PIKEL'NER, L.B., "The cross section for fission of $^{237}$Np by slow neutrons," *Soviet Atomic Energy 28(4)* (1970) 464. Pulsed reactor time-of-flight measurements were made for 0.02 eV $<E_n<$ 800 eV. 7 resonances were analyzed for $E_o$, $\sigma_o$, $\Gamma_f$, and $\Gamma$ from 0.49 to 7.5 eV. Thermal data are very good.

[9] PAYA, D., DERRIEN, H., FUBINI, A., MICHAUDON, A., RIBON, P., "Total fission cross sections for $^{237}$Np," *International Atomic Energy Agency Report* INDC/156 (1966) paper 69. SACLAY transmission and fission linac measurements were made for 0.4 eV $<E_n<$100 eV. Many resonances were analyzed for $E_o$, $\Gamma_f$, and $\Gamma$ from 0.489 to 107.2 eV.

[10] ADAMCHUK, I.V., MOSKALEV, S.S., PEVZNER, M.I., "The total neutron cross section of $^{237}$Np between 2 and 10,000 eV," *J. Nucl. En. A13* (1960) 72. Fast chopper transmission measurements were made for samples enriched to about 88% for 2.5 eV $<E_n<$10 keV. Only $E_o$ was analyzed, and no parametric analysis was made. I was determined to be $\int\sigma_T\,dE/E$ = 360 b for 2.7 to 12 keV.

[11] HARVEY, J.A., BLOCK, R.C., SLAUGHTER, G.G., "Fast chopper time-of-flight spectrometer," *Reports to the AEC Nuclear Cross Sections Advisory Group, Oak Ridge, November 1958.* USAEC Report WASH-1013 (1958) p 50. Oak Ridge National Laboratory (ORNL) fast-chopper, time-of-flight transmission measurements were made for 0.40 eV $<E_n<$36 eV. 32 resonances were analyzed for $E_o$ and $2g\Gamma_n$ assuming $\Gamma_\gamma$ = 32 meV.

[12] SMITH, M.S., SMITH, R.R., JOKI, E.G., EVANS, J.E., "Neutron total cross section of $^{237}$Np from 0.02 to 2.8 eV," *Phys. Rev. 107* (1957) 525. MTR crystal spectrometer transmission measurements were made. Cross section curves are given. Thermal data are good ($\sigma_{nT}^{2200}$ = 170 ±22 b). Three resonances were analyzed for $E_o$ and $\sigma_o\Gamma$.

*Integral Data*

[13] PAULSON, C.K., HENNELLY, E.J., "Cross section measurement of plutonium-236 formation in plutonium-238 by $^{237}$Np (n,2n) reactions," *Nucl. Sci. Eng. 55* (1974) 24. Measurement of $^{236}$Pu-formation in highly enriched $^{235}$U aluminum assemblies provided data for the cross section determination of $^{237}$Np (n,2n) $^{236g}$Np. Averaged over the $^{235}$U fission spectrum >6.8 MeV, $\bar{\sigma}_{n,2n}$ = 63 ±6 mb. This gives a value for the resonance integral $I_{n,2n}$ = 1.46 ±0.15 mb.

[14] AHLFELD, C.E., BAUMANN, N.P., "Measurement of ($\gamma$,n) cross sections of $^{232}$Th, $^{233}$U, and $^{237}$Np with aluminum capture gamma rays," *Trans. Amer. Nucl. Soc. 14* (1971) 807. Reactor irradiations in the thermal spectrum were made with cadmium-covered foils in large aluminum cylinders (to produce n,$\gamma$ reaction in aluminum). $^{59}$Co monitors were used to measure $I_{\gamma n}$ = 12.2 ±1.4 b, in an aluminum capture gamma ray spectrum.

[15] EBERLE, S.H., BLEYL, H.J., GANTNER, E., REINHARDT, J., KRUCKEBERGER, C., "Cross sections," *Actinide Project: First Semi-Annual Report.* KFK-1456 Karlsruhe, West Germany (1971) p 51. Reactor irradiations were made for bare and cadmium-covered samples. $\sigma_{n\gamma}^{2200}$ = 184 ±6 b, $I_{n\gamma}$ (no cutoff given) = 805 ±10 b.

[16] HELLSTRAND, E., PHELPS, J., SASTRE, C., *Studies of the Capture Cross Section of $^{237}$Np and $^{241}$Am in Different Reactor Spectrum.* USAEC Report BNL-50242, Brookhaven National Laboratory, Upton, NY (1970). Pile oscillator techniques were used to study capture cross sections. Independent values were not obtained. Assuming $\sigma_{n\gamma}^{2200}$ = 169 ±5 b, $I_{n\gamma}$ (>0.55 eV) = 640 ±50 b. Cutoff problem was well discussed.

[17] HALPERIN, J., IDOM, L.E., BALDOCK, C.R., STOUGHTON, R.W., "Measurements of the (n,2n) cross sections of $^{233}$U, $^{235}$U, and $^{237}$Np," *Chemistry Division Annual Progress Report for Period Ending May 20, 1968.* USAEC Report ORNL-4306, Oak Ridge National Laboratory, Oak Ridge, Tenn. (1968) p 1. Reactor irradiations were made in an approximately Maxwellian neutron flux for foils in cadmium covers. The preliminary value of $I_{n,2n}$ is 1.2 mb.

[18] SCHUMAN, R.P., "Resonance integral measurements on heavy nuclides," *Reports to the AEC Nuclear Cross Sections Committee, New York, October 1968.* USAEC Report WASH-1124 (1968) p 72. Reactor irradiations were made for cadmium-covered samples. $^{197}$Au and $^{56}$Co monitors were used. $I_{n\gamma}$ (no cutoff given) = 807 ±60 b.

[19] ROGERS, J.W., SCOVILLE, J.J., "Resonance absorption integrals measured by reactivity techniques," *Trans. Amer. Nucl. Soc. 10* (1967) 259. Activation measurements were made in cadmium-shielded reactor positions. $I_{n\gamma}$ (corrected to $E_n$ >0.5) = 905 ±28 b.

[20] PERKIN, J.L., COLEMAN, R.F., "Cross sections for the (n,2n) reactions of $^{232}$Th, $^{238}$U, and $^{237}$Np with 14 MeV neutrons," *J. Nucl. Energy AB14* (1961) 69. Activation measurements were made with 14.5-MeV neutrons from a neutron generator. $\sigma_{n,2n}$ (at 14.5 ±0.4 MeV) = 0.39 ±0.07 b.

[21] TATTERSALL, R.B., ROSE, H., PATTENDEN, S.K., JOWITT, D., "Pile oscillator measurements of resonance absorption integrals," *J.Nucl. Energy A12* (1960) 32. Pile oscillator measurements were made of thermal cross sections and resonance integrals. $\sigma_{n\gamma}^{2200}$ = 169 ±3 b, $I_{n\gamma}$ (no cutoff given) = 870 ±130 b.

*Nubar*

[22] LEBEDEV, V.I., KALASHNIKOVA, V.I., "Mean number of neutrons from fast fission of Np$^{237}$," *Sov. At. En. 10* (1961) 357. Coincidence measurements similar to Ref. 25 in the RFT Reactor gave for a higher unspecified energy $\bar{\nu}_p$ = 2.96 ±0.05.

[23] KUZ'MINOV, B.D., KUSAEVA, L.S., BONDARENKO, I.I., "The number of prompt neutrons from the fast neutron fission of $^{235}$U, $^{238}$U, $^{232}$Th, and $^{237}$Np," *Journ. Nucl. En. 9* (1959) 153. Coincidence measurements in a fast neutron beam from the BR-2 reactor used enriched samples in a fission chamber and BF$_3$ counters in paraffin blocks. For a fission spectrum $\langle E_n \rangle$ = 2.5 MeV, $\bar{\nu}_p$ = 2.72 ±0.15.

## NEPTUNIUM-238 (2.117 d)

Only two measurements of the fission cross section for $^{238}$Np are available. The brief half-life of this nuclide, which is intermediate in the production of $^{238}$Pu, makes measurements difficult to perform and to interpret. More information, though useful, would be hard to obtain experimentally.

Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* |
|---|---|---|---|
| $\sigma^{2200}$ | - | 2070 | 1 |
| I | - | 880 | 1 |

| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Requested Precision* |
|---|---|---|---|---|
| Capture | - | - | - | - |
| Fission | Thermal | 2% | 1 | - |
| Resolved Resonances | | | | |
| $\Gamma_n$ } $\Gamma_f$ } | No measurements known | | | |
| $I_{n\gamma}$ | - | - | - | - |
| $I_{nf}$ | No cutoff given | 8% | 1 | - |

*Nubar*

| | |
|---|---|
| Thermal } $\bar{\nu}$(E) } | No measurements known |

Current or Future Measurements - None known

Recommendations - None

References

*Integral Data*


[1] SPENCER, J.D., BAUMANN, N.P., "Measurement of integral fission cross sections for $^{238}$Np," *Trans. Am. Nucl. Soc. 12* (1969) 284. Careful cadmium-difference measurements with back-to-back fission chambers in a reactor gave $\sigma_{nf}^{2200}$ = 2070 ±30 b, and $I_{nf}$ (no cutoff given) = 880 ±70 b. The reference foil was $^{235}$U.

[2] HENNELLY, E.J., CORNMAN, W.R., BAUMANN, N.P., in *Neutron Cross Sections and Technology, Proc. Conf., Washington, D.C., March 4-7, 1968.* NBS Special Publication 299 (1968) p 1271. Reactor irradiations were made from high-purity $^{237}$Np with cadmium and boron filters. Results were obtained from high-flux activation studies and low-flux fission chamber measurements. High flux: $\sigma_{na}^{eff}$ = 1620 ±100 b; $\sigma_{nf}^{eff}$ = 1520 ±100 b; low flux: $\sigma_{nf}^{eff}$ = 1640 ±150 b; $\sigma_{nf}^{2200}$ = 2200 ±200 b; $I_{nf}$ (no cutoff given) = 1500 ±500 b.


## PLUTONIUM-236 (2.851 yr)

Virtually no experimental data are available for $^{236}$Pu, the beta-decay daughter of $^{236}$Np (22.5 h) and an undesirable contaminant in reactor-produced $^{238}$Pu. The magnitude of the capture cross section is probably comparable to that for fission [PRINCE, A., "Thermal neutron cross sections and resonance integrals for transuranium isotopes," *Proc. Conf. Neut. Cross Sect. and Tech.*, CONF-680307-18, Washington, D.C. (1968) 951]. The primary importance of this isotope is as a contaminant in medical-grade $^{238}$Pu, through the ($\gamma$,n) and (n,2n) reactions on $^{237}$Np.

Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* |
|---|---|---|---|
| $\sigma^{2200}$ | - | 162 | 1,2 |
| I | - | - | - |

| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Requested Precision* |
|---|---|---|---|---|
| Capture | - | - | - | 20% |
| Fission | Thermal | 20% | 2 | 20% |
| Resolved Resonances | | | | |
| $\Gamma_n$ | No measurements known | | | 20% |
| $\Gamma_f$ | | | | 20% |
| $I_{n\gamma}$ | No measurements known | | | 20% |
| $I_{nf}$ | | | | 20% |

*Nubar*

| | |
|---|---|
| Thermal, $\bar{\nu}(E)$ | No measurements known |

Current or Future Measurements - None known

Recommendations - None

References

*Integral Data*


[1] HULET, E.K., WEST, H.I., COOPS, M.S., "Thermal neutron fission cross sections of $U^{232}$, $Pu^{236}$, $Pu^{237}$, and $Am^{244}$," *Reports to the AEC Nuclear Cross Sections Advisory Group, MIT and Yale, August 29-31, 1961.* USAEC Report WASH-1033 (1961) 28. Thermal fission cross sections were measured in reactor thermal columns. For $^{236}Pu$, $\sigma_{nf}^{th}$ = 162 b.

[2] GINDLER, J.E., GRAY, J., Jr., HUIZENGA, J.R., "Neutron fission cross sections of $Pu^{236}$ and $Pu^{237}$," *Phys. Rev. 115* (1959) 1271. High-purity (>98%) $^{236}Pu$ was placed in back-to-back fission chambers with $^{239}Pu$ standards and irradiated in a reactor thermal column. $\sigma_{nf}^{eff}$ = 170 ±35 b.


## PLUTONIUM-237 (45.63 d)

Virtually no experimental data are available for $^{237}Pu$. The cross sections, both capture and fission, are probably appreciable, but $^{237}Pu$ is not a significant factor in any of the production chains.

Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* | |
|---|---|---|---|---|
| $\sigma^{2200}$ | - | 2200 | 1,2 | |
| I | - | - | - | |
| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Requested Precision* |
| Capture | - | - | - | - |
| Fission | Thermal | 20% | 1,2 | - |
| Resolved Resonances | | | | |
| $\Gamma_n$ } | No measurements known | | | - |
| $\Gamma_f$ } | | | | - |
| $I_{n\gamma}$ | - | - | | - |
| $I_{nf}$ | - | - | | - |

*Nubar*

| | |
|---|---|
| Thermal } | No measurements known |
| $\bar{\nu}(E)$ } | |

Current or Future Measurements - None known

Recommendations - None

References

*Integral Data*


[1] HULET, E.K., WEST, H.I., COOPS, M.S., "Thermal neutron fission cross sections of $U^{232}$, $Pu^{236}$, $Pu^{237}$, and $Am^{244}$," *Reports to the AEC Nuclear Cross Sections Advisory Group, MIT and Yale, August 29-31, 1961.* USAEC Report WASH-1033 (1961) 28. Thermal fission cross sections were measured in reactor thermal columns. For $^{237}$Pu, $\sigma_{nf}^{th}$ = 2200 b.

[2] GINDLER, J.E., GRAY, J., Jr., HUIZENGA, J.R., "Neutron fission cross sections of $Pu^{236}$ and $Pu^{237}$," *Phys. Rev. 115* (1959) 1271. Fission plates containing plutonium enriched in accelerator-produced $^{237}$Pu were placed in back-to-back fission chambers with $^{239}$Pu standards and irradiated in a reactor thermal column. $\sigma_{nf}^{eff}$ = 2500 ±500 b.


## PLUTONIUM-238 (87.75 yr)

There are extensive differential data and limited integral data for $^{238}$Pu, the beta-decay daughter of $^{238}$Np. The differential data are adequate for a good evaluation.

Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* | |
|---|---|---|---|---|
| $\sigma^{2200}$ | 559 | 17.3 | 2,5 | |
| I | 164 | 25 | 2,5 | |
| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Requested Precision* |
| Capture | Thermal | 4% | 2 | 20% |
| Fission | Thermal | 3% | 5 | 20% |
| Resolved Resonances | | | | |
| $\Gamma_n$ | 0.005-496 eV | ∿10% <200 eV | 1,2 | 20% |
| $\Gamma_f$ | 18.6-496 eV | ∿40% | 2 | 20% |
| $I_{n\gamma}$ | ≥0.5 eV | 10% | 2 | 20% |
| $I_{nf}$ | ≥0.6 eV | 20% | 5 | 20% |
| *Nubar* | | *Precision* | | |
| Thermal (prompt) | $\bar{\nu}$ = 2.895 | 1% | 8 | - |
| $\bar{\nu}$(E) | - | | - | 3%† |

† $\bar{\nu}_p$(E) requested from 10 keV to 15 MeV.

Current or Future Measurements - None known

Recommendations - None

References

*Differential Data*


[1] SILBERT, M.G., MOAT, A., YOUNG, T.E., "Fission cross section of plutonium-238," *Nucl. Sci. Eng.* *52* (1973) 176; and SILBERT, M.G., BERRETH, J.R., "Neutron capture cross section of plutonium-238," *Nucl. Sci. Eng.* *52* (1973) 187. Fission and capture measurements were made from the LASL bomb shot "Persimmon" for 15 eV <$E_n$ <500 eV. Many resonances were analyzed for $E_o$, $\Gamma_n°$, and $\Gamma_f/\Gamma$, and some, for $E_o$, $\Gamma_f$, and $\Gamma_n$. A $\Gamma_\gamma$ of 34 meV was assumed.

[2] YOUNG, T.E., SIMPSON, F.B., BERRETH, J.R., "Neutron total and absorption cross sections of $^{238}$Pu," *Nucl. Sci. Eng.* *30* (1967) 355. MTR transmission measurements were made for highly enriched samples for 0.008 <$E_n$ <6500 eV with multiple inverse sample thicknesses from 288 to 2520 b/atom. $\sigma_{n\gamma}^{2200}$ (measured) = 559 ±20 b, $\sigma_{n\gamma}^{2200}$ (effective 1/v) = 532 b, $I_{n\gamma}$ ($E_n$ >0.5 eV) = 164 ±15 b. 14 positive energy resonances were analyzed for $E_o$ and $\Gamma_n°$, with $\Gamma_\gamma$ determined from the first 3 resonances. Thermal data were good.

[3] STUBBINS, W.F., BOWMAN, C.D., AUCHAMPAUGH, G.F., COOPS, M.S., "Neutron-induced resonance fission cross sections of $^{238}$Pu," *Phys. Rev.* *154* (1967) 1111. LLL linac time-of-flight fission chamber measurements were made for samples enriched to 99.88% and plated on both sides of 3 foils (125 μg/cm$^2$ on each side) for 2 eV <$E_n$ <300 eV. 16 resonances were analyzed for $E_o$, $\Gamma_n^o$ , and $\Gamma_f/\Gamma$.

[4] GERASIMOV, V.F., in *Nuclear Data for Reactors, Conf. Proc., Paris, 17-21, October 1966, Vol. II*, p 129 (in Russian). Fission cross sections were measured from 0.02 to 100 eV. The first 5 resonances were analyzed for $E_o$ and $\sigma_o\Gamma$. $\Gamma_f$ was determined for the first 3 resonances. Thermal data were good.

*Integral Data*

[5] EASTWOOD, T.A., et al., *2nd Int. Conf. Peaceful Uses At. Energy (Proc. Conf. Geneva,* 1958) *16,* UN, New York (1958) 54. Thermal neutron beam experiments were made with the Chalk River National Research Experiment (NRX) reactor. $\sigma_{nf}^{2200}$ = 17.1 ±0.4 b; $I_{nf}$ ($E_n$ >0.6 eV) = 25 ±5 b.

[6] BUTLER, J.P., LOUNSBURY, M., MERRITT, J.S., "The neutron capture cross section for $^{238}$Pu, $^{242}$Pu, and $^{243}$Am in the thermal and epicadmium regions," *Can. J. Phys. 35* (1957) 147. Reactor irradiations were made on bare and cadmium-covered samples, followed by chemical separation and mass spectrometry. $\sigma_{n\gamma}^{2200}$ = 403 ±8 b; $I_{n\gamma}$ ($E_n$ >0.5 eV) = 3260 ±280 b (this is very much too high).

[7] HULET, E.K., HOFF, R.W., BOWMAN, H.R., MICHEL, M.C., "Thermal-neutron fission cross sections for isotopes of plutonium, americium, and curium," *Phys. Rev. 107* (1957) 1294. Reactor thermal column fission chamber measurements were made on bare samples enriched to 99.71%. $\sigma_{nf}^{2200}$ = 18.4 ±0.9 b.

*Nubar*

[8] JAFFEY, A.H., LERNER, J.L., "Measurement of prompt neutron fission yield ($\bar{\nu}$p) in thermal neutron fission of $^{232}$U, $^{238}$Pu, $^{241}$Pu, $^{241}$Am, $^{242m}$Am, $^{243}$Cm, $^{245}$Cm, and in spontaneous fission of $^{244}$Cm," *Nucl. Phy. A145* (1970) 1. Coincidence measurements in a thermal neutron beam using an ionization chamber and four Hornyak buttons. The result for $^{238}$Pu was $\bar{\nu}$p = 2.895 ±0.027.

[9] KROSHKIN, N.I., ZAMYATNIN, YU.S., "Measurement of energy spectrum and average number of prompt fission neutrons," *Sov. At. En. 29* (1970) 790. Coincidence measurements in a thermal neutron beam using a gas scintillation chamber and a plastic scintillator. The result for $^{238}$Pu was $\bar{\nu}$p = 2.92 ±0.12.

## PLUTONIUM-240 (6537 yr)

A very large quantity of data is available for $^{240}$Pu, an extremely important factor in reactor operations. The important data for thermal and near-thermal reactors appear well in hand, though there are some significant differences in the resonance parameters of the very large resonance at 1 eV.

### Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* | |
|---|---|---|---|---|
| $\sigma^{2200}$ | 289.5 | 0.030 | 1 | |
| I | 8013 | - | 1 | |
| *Reaction* | | *Precision* | *Reference* | *Requested Precision* |
| Capture | Thermal | 0.5% | 1 | 3% |
| Fission | Thermal | 150% | 1 | - |
| Resolved Resonances | | | | |
| $\Gamma_n$ | 1 eV - 5.7 keV | ∿4% | 1 | 10% |
| $\Gamma_f$ | 700 eV - 3.5 keV | ∿20% | 1 | 10% |
| $I_{n\gamma}$ | ≥0.5 eV | 12% | 1 | - |
| $I_{nf}$ | - | - | - | - |

| *Nubar* | | *Precision* | *Reference* | |
|---|---|---|---|---|
| Thermal (prompt) | No measurements known | | - | - |
| $\bar{\nu}(E)$ (prompt) | 0.1 - 15 MeV | 3% | 9 | 3%† |

† Also a priority II request for $\bar{\nu}(E)$ (delayed), 0.750 $\leq E_n \leq$14 MeV, to 10% for Pu assay.

Current or Future Measurements - The resonance analysis of the ORELA data [4] has not yet been done.

Recommendations - Experimenters are encouraged to measure and analyze the first resonance at 1 eV whenever good values might be obtained. It is present in many transmission measurements of other heavy actinides and could be analyzed if an adequate assay has been done.

## References

The available data are, for the most part, summarized in the General References. The differential and integral references which follow are meant to be representative of the recent and more useful work, but are by no means complete.

*General References*

[1] MUGHABGHAB, S.F., GARBER, D.I., *Neutron Cross Sections, Volume 1, Resonance Parameters,* USAEC Report BNL-325, Third Edition (1973).

[2] GARBER, D.I., KINSEY, R.R., *Neutron Cross Sections, Volume 2, Curves,* USERDA Report BNL-325, Third Edition (1975).

[3] CANER, M., YIFTAH, S., "Nuclear data evaluation for plutonium-240," *Israel AEC Report IA-1243* 1972. An evaluation of the data available through early 1971.

*Differential Data*

[4] WESTON, L.W., TODD, J.H., "Measurement of the neutron capture cross sections of the actinides," *Proc. Conf. Nucl. Cross Sect. and Tech.,* Washington, D.C., March, 1975 (to be published). An ORELA time-of-flight capture measurement used NE-226 liquid scintillator as the detector over the energy range from thermal to 350 keV. Average cross sections are presented; resonance analysis will be done. Results are consistent with the results of Hockenbury [5] and ENDF/B IV.

[5] HOCKENBURY, R.W., MOYER, W.R., BLOCK, R.C., "Neutron capture, fission, and total cross sections of plutonium-240 from 20 eV to 30 keV," *Nucl. Sci. Eng. 49* (1972) 153. Capture and fission measurements were made at the RPI linac from 20 eV to 30 keV using a large liquid scintillator and the high-low bias technique. Transmission measurements were made from 30 to 500 eV. Data were analyzed to obtain $E_0$, $\Gamma_n$ and $\Gamma_\gamma$ to 500 eV.

[6] WEIGMANN, H., THEOBALD, J.P., "Resonance parameters of $^{240}$Pu," *J. Nucl. En. 26* (1972) 643. This paper provides corrections to some earlier work which brings the results into substantial agreement with Ref. 5.

[7] RAMAKRISHNA, D.V.S., NAVALKAR, M.P., "Determination of resonance parameters of $^{240}Pu$ using a crystal spectrometer," *Proc. Sec. Int. Conf. on Nucl. Data for Reactors*, Helsinki, June, 1970, Vol. 1 p 553. A transmission measurement using a crystal spectrometer with a heavy-water-moderated reactor gave resonance parameters for the first resonance.

For more information on differential data, see Refs. 1 and 3.

*Integral Data*

[8] LOUNSBURY, M., CURHAM, R.W., HANNA, G.C., "Measurements of alpha and of fission cross section ratios for $^{233}U$, $^{235}U$, and $^{239}Pu$ at thermal energies," *Proc. Sec. Int. Conf. on Nucl. Data for Reactors*, Helsinki, June, 1970, Vol. 1,p 287. A one year irradiation of mixed Pu and U samples in a Maxwellian spectrum followed by chemical separation and mass spectrometer analysis gave $\sigma_{n\gamma}^{2200}$ = 289.5 ±1.4 b for $^{240}Pu$.

For additional integral data, see Ref. 1.

*Nubar*

[9] MANERO, F., KONSHIN, V.A., "Status of the energy-dependent $\bar{\nu}$ values for the heavy isotopes (z >90) from thermal to 15 MeV and of $\bar{\nu}$ values for spontaneous fission," *At. En. Rev. 10* (1972) 637. The existing $\bar{\nu}_p(E)$ data are summarized and plotted in this review. Two measurements of $\bar{\nu}$ (delayed) are also included.

## PLUTONIUM-241 (14.8 yr)

There is a very large quantity of experimental data available for the fissionable nuclide $^{241}Pu$. The data and analyses appear to be as good as the current technology permits, although the requested precision for resonance parameters below 100 eV is not met.

### Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* | |
|---|---|---|---|---|
| $\sigma^{2200}$ | 362 | 1015 | 2 | |
| I | 162 | 570 | 1 | |
| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Requested Precision* |
| Capture | Thermal | 3% | 2 | 3% |
| Fission | Thermal | <1% | 2 | 3% |
| Resolved Resonances | | | | |
| $\Gamma_n$ | 0-160 eV | ∿10% | 1 | 5%† |
| $\Gamma_f$ | 0-160 eV | ∿10% | 1 | 5%† |
| $I_{n\gamma}$ | ≥0.5 eV | 5% | 1 | 3% |
| $I_{nf}$ | ≥0.5 eV | 3% | 1 | 3% |
| *Nubar* | | *Precision* | *Reference* | |
| Thermal (prompt) | $\bar{\nu}_p$ = 2.924 | 0.4% | 2 | - |
| $\bar{\nu}$(E) (prompt) | 0-15 MeV | ∿3% | 7,8,9 | 3%† |

† A priority II request (1972) for resonance parameters, 0-100 eV to 5%, 100-400 eV to 10%.

Current and Future Measurements - None known

Recommendations - None

References

The available data are, for the most part, summarized in the General References. The differential and integral references which follow are meant to be representative of the recent and more useful work, but are by no means complete.


*General References*

[1] MUGHABGHAB, S.F., GARBER, D.I., *Neutron Cross Sections, Volume 1, Resonance Parameters,* USAEC Report BNL-325, Third Edition (1973).

[2] LEMMEL, H.D., "The third IAEA evaluation of the 2200 m/s and 20°C Maxwellian neutron data for U-233, U-235, Pu-239, and Pu-241," *Proc. Conf. Nucl. Cross Sections and Tech.,* Washington, D.C., March 1975 (to be published).

[3] GARBER, D.I., KINSEY, R.R., *Neutron Cross Sections, Volume 2, Curves,* USERDA Report BNL-325, Third Edition (1975).

[4] CANER, M., YIFTAH, S., *Nuclear Data Evaluation for Plutonium-241,* Israel AEC Report IA-1276, 1973. An evaluation of the data available through 1971.

*Differential Data*

[5] WAGEMANS, C., DERUYTTER, A.J., "Measurement and normalization of the relative $^{241}$Pu fission cross section in the thermal and low resonance region," submitted to *Nucl. Sci. Eng.* The fission cross section was measured for 0.01 $<E_n<$50 eV at the Geel linac. Data were normalized to the 2200 m/s reference ($\sigma_{nf}^{2200}$ = 1015 ±7 b). The Westcott g-factor was determined. Cross sections are presented, but no parametric analysis. (See also "The Westcott $g_f$-factor as a function of temperature for $^{241}$Pu," by the same authors, to be published in *Ann. Nucl. En.*).

[6] WESTON, L.W., TODD, J.H., "Measurement of the neutron capture cross sections of the actinides," *Proc. Conf. Nucl. Cross Sections and Tech.,* Washington, D.C., March 1975 (to be published). An ORELA time-of-flight capture measurement used NE-226 liquid scintillator as the detector over the energy range from thermal to 350 eV. Average cross sections are presented. Results are reasonably consistent with ENDF/B IV, so no parametric analysis will be done.


For more information on differential data, see Refs. 1, 3, and 4.

*Integral Data*

The integral data available are summarized adequately in Ref. 1.


*Nubar*

[7] D'YACHENKO, N.P., KOLOSOV, N.P., KUZ'MINOV, B.D., SERGACHEV, A.I., SURIN, V.M., "Energy dependence of average number of prompt neutrons in Pu$^{241}$ fission," *Sov. At. En. 36* (1974) 406. Measurements were made using a Van de Graaff accelerator as the neutron source for 0.28 $\leq E_n \leq$5.0 MeV. Value ranged from $\bar{\nu}_p$(0.28 MeV) = 2.975 to $\bar{\nu}_p$(5.0 MeV) = 3.66 with estimated errors of typically 3% or less.

[8] FREHAUT, J., MOSINSKI, G., BOIS, R., "Mesure de $\bar{\nu}_p$ pour la fission de $^{241}$Pu induite par neutrons rapides," *Progress Report on Nuclear Data Research in the European Community for the period January 1 to December 31, 1973*, NEANDC(E) 161 "U" (1974) p 39. Coincidence measurements with a Van de Graaff accelerator as the neutron source determined $\bar{\nu}_p(E)$ for $1.5 \leq E_n \leq 15$ MeV. The values of $\bar{\nu}_p(E)$ are described by:

$$\bar{\nu}_p = (0.155 \pm 0.002)\ E_n + 2.836 \pm 0.020$$

within 1% of the relative value.

[9] MANERO, F., KONSHIN, V.A., "Status of the energy-dependent $\bar{\nu}$ values for the heavy isotopes (z >90) from thermal to 15 MeV and of $\bar{\nu}$ values for spontaneous fission," *At. En. Rev. 10* (1972) 637. The measured values for $\bar{\nu}_p(E)$ published through August 1972 are summarized. In addition, two data points are given for $\bar{\nu}(E)$ delayed, at thermal and 14.9 MeV.

## PLUTONIUM-242 ($3.87 \times 10^5$ yr)

There is an abundance of both differential and integral data for $^{242}$Pu and some very good, high precision measurements with metal samples in the thermal region [4]. A recent evaluation by Caner and Yiftah [Israel Atomic Energy Commission Report IA-1275 (1973)] summarizes the data to late 1972 from $10^{-3}$ eV to 15 MeV for the KEDAK file and puts the cross section data into a form for testing.

### Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* |
|---|---|---|---|
| $\sigma^{2200}$ | 18.5 | 0 | 1,4,10 |
| I | 1275 | 4.7 | 1,12,13 |

| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Requested Precision* |
|---|---|---|---|---|
| Capture | Thermal | 4-5% | 4,10 | 3% |
| Fission | Thermal | - | - | - |
| Resolved Resonances | | | | |
| $\Gamma_n$ | 0-4 keV | 5-10% | 4,5,6,8 | 10% |
| $\Gamma_f$ | 50 eV - 4 keV | 10% | 3,7 | 10% |
| $I_{n\gamma}$ | $\geq 0.625$ | 4% | 1,12,13 | - |
| $I_{nf}$ | $\geq 0.625$ | - | 1,12,13 | - |

| *Nubar* | | *Requested Precision* |
|---|---|---|
| Thermal | No measurements known | - |
| $\bar{\nu}(E)$ | No measurements known | 3%† |

† Priority II request (1962) for $\bar{\nu}(E)$ prompt ($0.5 < E_n < 15$ MeV) to 3%. Priority III request $\bar{\nu}(E)$ delayed at 3.14 MeV to 20%.

Current or Future Measurements - R.W. Hockenbury is currently making measurement in the keV region with the RPI linac.

Recommendations - None

## References

*Production Data*


[1] BENJAMIN, R.W., MCCROSSON, F.J., VANDERVELDE, V.D., GORRELL, T.C., *A Consistent Set of Heavy Actinide Multigroup Cross Sections*, USERDA Report DP-1394 (1975). A self-consistent set of 84-group cross sections and resonance parameters has been developed for production chain isotopes from $^{242}Pu$ to $^{253}Es$ using the results of reactor production experiments and modern multigroup reactor production codes.


*Differential Data*


[2] POORTMANS, F., ROHR, G., THEOBALD, J.P., WEIGMANN, H., VANPRAET, G.J., "Neutron resonance parameters of $^{242}Pu$," *Nucl. Phys A207* (1973) 342. Capture, elastic scattering, and total cross section measurements were performed on a $^{242}PuO_2$ sample enriched to 99.8% $^{242}Pu$ on the GEEL Linac for 20 eV $<E_n<$ 1300 eV. 71 resonances were analyzed for $\Gamma_n$ and $E_o$, and 25 of them for $\Gamma_\gamma$.

[3] AUCHAMPAUGH, G.F., BOWMAN, C.D., "Parameters of the subthreshold fission structure in $^{242}Pu$," *Phys. Rev. C7* (1973) 2085. Transmission measurements were made at the Lawrence Livermore Laboratory over the energy range 600 eV $<E_n<$ 81 keV, and resonances with significant fission widths below 4 keV were analyzed for $\Gamma_n$ and $\Gamma_f$, with $\Gamma_\gamma$ assumed to be 30 mV. Parameters are given for 72 resonances.

[4] YOUNG, T.E., SIMPSON, F.B., TATE, R.E., "The low-energy total neutron cross section of plutonium-242," *Nucl. Sci. Eng. 43* (1971) 341. MTR fast-chopper transmission measurements were made for 99.9% enriched metallic $^{242}Pu$ samples for 0.0015 eV $<E_n<$ 1 eV. Careful thermal measurements were made.

[5] SIMPSON, F.B., SIMPSON, O.D., HARVEY, J.A., HILL, N.W. *Neutron Resonance Parameters of $^{242}Pu$*, USAEC Report ANCR-1088 (1972) 32. ORELA transmission measurements were made for 15 eV $<E_n<$ 30 keV on the same samples described in the preceding reference. The samples were cooled to liquid $N_2$ temperature. 34 resolved resonances were analyzed to 500 eV for $E_o$ and $\Gamma_n$, and 13 were analyzed for $\Gamma_\gamma$.

[6] YOUNG, T.E., REEDER, S.D., "Total neutron cross section of $^{242}Pu$," *Nucl. Sci. Eng. 40* (1970) 389. MTR fast-chopper transmission measurements were made on $^{242}PuO_2$ samples for 0.0015 eV $<E_n<$ 8 keV. 8 resonances were analyze for $E_o$ and $\Gamma_n$ for 2 eV $<E_n<$ 150 eV, and some for $\Gamma_\gamma$.

[7] AUCHAMPAUGH, G.F., FARRELL, J.A., BERGEN, D.W., "Neutron-induced fission cross sections of $^{242}Pu$ and $^{244}Pu$," *Nucl. Phys. A171* (1971) 31. LASL bomb shot measurements were made on samples enriched to 99.9% in $^{242}Pu$ with $^6Li$ and $^{235}U$ monitors for 20 eV $<E_n<$ 4 MeV. Below 300 eV, fission strength is so weak that fission fragments cannot be seen over capture gammas from the same resonance. Data above 300 eV are very good.

[8] AUCHAMPAUGH, G.F., BOWMAN, C.D., COOPS, M.S., FULTZ, S.C., "Neutron total cross section of $^{242}Pu$," *Phys. Rev. 146* (1966) 840. Linac transmission measurements were made for 99.9% enriched $^{242}Pu_2O_3$ samples for 0.02 ev $<E_n<$ 400 eV. 14 resonances were analyzed <400 eV for $E_o$ and $\Gamma_n$.

[9] PATTENDEN, N.J., "$^{242}$Pu total cross section," *Nuclear Physics Division Progress Report for the Period March 1, 1965 to October 31, 1965*, British Report AERE-PR/NP9, Atomic Energy Research Establishment, Harwell, England, (1966) p 10. Time-of-flight transmission measurements were made for samples enriched to 91% in $^{242}$Pu for 4 eV $<E_n<$2000 eV. Data were analyzed for $E_0$ and $\Gamma_n^\circ$ for 17 resonances from 14.6 to 311 eV.

*Integral Data*

[10] DURHAM, R.W., MOLSON, F., "Capture cross section of $^{242}$Pu," *Can. J. Phys. 48* (1970) 716. Reactor irradiations were made on bare samples enriched to ∿90% $^{242}$Pu. $^{59}$Co monitors were used. $\sigma_{n\gamma}^{2200}$ = 18.7 ±0.7 b.

[11] FOLGER, R.L., SMITH, J.A., BROWN, L.C., OVERMAN, R.F., HOLCOMB, H.P., in *Neutron Cross Sections and Technology, Proceedings of a Conference, Washington, DC, March 4-7, 1968.* NBS Special Publication 299 (1968) p 1297. Reactor activations were made for bare and cadmium-covered samples. $^{59}$Co monitors were used. $\bar{\sigma}_a$ = 28 b, $I_a$ (no cutoff given) = 1180 b; inferred $\sigma_a^{2200}$ = 20 b.

[12] HALPERIN, J., OLIVER, J.H., "The thermal neutron capture cross section and resonance integral of $^{242}$Pu," *Chemistry Division Annual Progress Report for Period Ending June 20, 1964,* USAEC Report ORNL-3679 (1964) p 13. Reactor irradiations were made for 99.9% enriched bare and cadmium-covered $^{242}$Pu samples. $\sigma_{n\gamma}^{2200}$ = 24.9 ±4 b; $I_{n\gamma}$ (no cutoff given) = 1280 ±60 b.

[13] BUTLER, J.P., LOUNSBURY, M., MERRITT, J.S., "The neutron capture cross sections of $^{238}$Pu, $^{242}$Pu, and $^{243}$Am in the thermal and epicadmium regions," *Can. J. Phys. 35* (1957) 147. Reactor irradiations were made for bare and cadmium-covered samples enriched to 90% in $^{242}$Pu. $\sigma_{n\gamma}$ = 18.6 ±0.8 b; $I_{n\gamma}$ (E >0.5 eV) = 1275 ±30 b.

## PLUTONIUM-243 (4.955 h)

Almost no experimental data are available for $^{243}$Pu because of its very short half-life. It is, however, the path to $^{244}$Pu as well as the beta-decay precursor to $^{243}$Am. The small quantity of integral and production data does give an indication of the magnitudes of the $^{243}$Pu cross sections.

### Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* |
|---|---|---|---|
| $\sigma^{2200}$ | 87.4 | 180.0 | 1,2 |
| I | 264.0 | 542.0 | 1 |

| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Requested Precision* |
|---|---|---|---|---|
| Capture | Thermal | 15% | 1 | - |
| Fission | Thermal | 15% | 1,2 | - |
| Resolved Resonances | | | | |
| $\left.\begin{matrix}\Gamma_n\\ \Gamma_f\end{matrix}\right\}$ | No measurements known | | | |
| $I_{n\gamma}$ | ≥0.625 eV | 25% | 1 | - |
| $I_{nf}$ | ≥0.625 eV | 25% | 1 | - |

| *Nubar* | | *Reference* | |
|---|---|---|---|
| Thermal | No measurements known | - | - |
| $\bar{\nu}(E)$ | | | - |

Current or Future Measurements - None known

Recommendations - None

References

*Production Data*


[1] BENJAMIN, R.W., MCCROSSON, F.J., VANDERVELDE, V.D., GORRELL, T.C. *A Consistent Set of Heavy Actinide Multigroup Cross Sections*, USERDA Report DP-1394 (1975). A self-consistent set of 84-group cross sections and resonance parameters has been developed for production chain isotopes from $^{242}$Pu to $^{253}$Es using the results of reactor production experiments and modern multigroup reactor production codes.

[2] DIAMOND, H., HINES, J.J., SJOBLOM, R.K., BARNES, F.F., METTA, D.M., FIELDS, P.R., "Fission cross sections for $^{243}$Pu, $^{250}$Bk, $^{247}$Cm, $^{245}$Cm, $^{254m}$Es, and $^{254}$Es, and odd-odd systematics," *J. Inorg. Nucl. Chem.* *30* (1968) 2553. Fission cross sections were measured with back-to-back ion chambers in a reactor graphite thermal column. The epithermal component was not factored into the resulting cross sections. $\sigma_{nf}^{eff}$ (thermal) = 196 ±16 b.


## PLUTONIUM-244 ($8.26 \times 10^7$ yr)

Few data are available for $^{244}$Pu, a long half-lived, but peripheral isotope in the production chain. The most useful measurements are those of Druschel et al. [2] and Schuman [3] for capture.

Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* |
|---|---|---|---|
| $\sigma^{2200}$ | 1.70 | - | 2 |
| I | 42.5 | - | 2,3 |

| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Requested Precision* |
|---|---|---|---|---|
| Capture | Thermal | 6% | 2 | - |
| Fission | | | | - |
| Resolved Resonances | | | | |
| $\Gamma_n$ | No measurements known | | | - |
| $\Gamma_f$ (Areas only) | 30.7 eV - 18 keV | - | 1 | - |
| $I_{n\gamma}$ | No cutoff given | 10% | 2,3 | - |
| $I_{nf}$ | No measurements known | | | - |

*Nubar*

| | |
|---|---|
| Thermal | No measurements known |
| $\bar{\nu}(E)$ | |

Current and Future Measurements - None known

Recommendations - None

## References

*Differential Data*

[1] AUCHAMPAUGH, G.F., FARRELL, J.A., BERGEN, D.W., "Neutron-induced fission cross sections of $^{242}$Pu and $^{244}$Pu," *Nucl. Phys. A117* (1971) 31. LASL bomb-shot fission data were obtained for high-purity samples from 30.7 eV to 10 MeV. Resonances were analyzed for area from 30.7 eV to 18 keV. Good fission cross section data are shown from about 0.4 MeV.

*Integral Data*

[2] DRUSCHEL, R.E., HALPERIN, J., EBY, R.E., "The neutron capture thermal cross sections and resonance integrals of $^{244}$Pu and $^{245}$Pu," *Chemistry Division Annual Progress Report for Period Ending May 20, 1971.* USAEC Report ORNL-4706 (1971) 55. Reactor irradiations of highly pure bare and cadmium-covered $^{244}$Pu samples in a thermal neutron flux. $\sigma_{n\gamma}^{2200}$ = 1.70 ±0.10 b, $I_{n\gamma}$ (no cutoff given) = 45 ±4 b.

[3] SCHUMAN, R.P., *Thermal (Subcadmium) Capture Cross Section and Resonance Integral of* $^{244}$*Pu,* USAEC Report WASH-1136 (1969) 51. Reactor irradiations of highly pure bare and cadmium-covered $^{244}$Pu samples. $\sigma_{n\gamma}^{2200}$ = 1.6 ±0.3 b, $I_{n\gamma}$ (no cutoff given) = 35 ±7 b.

*Note:* References 2 and 3 supersede several earlier production effective cross section measurements.

## AMERICIUM-241 (433 yr)

Extensive data, both integral and differential, are available for $^{241}$Am, and further experimental work should await a new up-to-date evaluation incorporating the most recent measurements. There are some problems in determining integral cross sections because of two large resonances in the cadmium cutoff region. Particularly important are the capture branching ratios to the ground and isomeric states of $^{242}$Am. A very desirable measurement would be the determination of this branching ratio as a function of energy; this measurement, however, appears to be beyond the capabilities of current experimental techniques.

### Data Summary

| *Cross Sections* | | *Capture* | *Fission* | *Reference* |
|---|---|---|---|---|
| $\sigma^{2200}$ | to ground state | 748 | 3.14 | 8,11 |
| | to isomeric state | 83.8 | | 8 |
| I | to ground state | 1330 | 21 | 8,9,11 |
| | to isomeric state | 208 | | 8 |

| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Requested Precision* |
|---|---|---|---|---|
| Capture to ground state | Thermal | 3% | 8 | 10% |
| to isomeric state | Thermal | 8% | 8 | 10% |
| Fission | Thermal | 4% | 11 | - |
| Resolved Resonances | | | | |
| $\Gamma_n$ | 0-150 eV | 1-2% | 2 | 10% |
| $\Gamma_f$ | 0-50 eV | ? | 2,4,5 | - |
| $I_{n\gamma}$ to ground state | (≥0.369 eV) | 9% | 8 | 10% |
| to isomeric state | (≥0.369 eV) | 9% | 8 | 10% |
| $I_{nf}$ | (no cutoff given) | 10% | 9,11 | - |

| *Nubar* | | *Precision* | *Reference* | |
|---|---|---|---|---|
| Thermal (prompt) | $\bar{\nu}_p$ = 3.121 | 1% | 13,14 | - |
| $\bar{\nu}$(E) | No measurements known | | | - |

Current or Future Measurements - The analyses of the ORELA absorption measurements [1] are incomplete, and the SACLAY fission measurements are still in progress. Apparently, measurements are in progress or recently completed at the GEEL linac [NEANDC(E) U (1974) p 202].

Recommendations - A thorough evaluation of the extensive cross section data for $^{241}$Am is required as soon as possible.

References

*Differential Data*


[1] WESTON, L.W., TODD, J.W., "Measurement of the neutron capture cross sections of the actinides," *Proc. Conf. on Nuclear Cross Sections and Technology*, Washington, D.C., March 1975 (to be published). Differential absorption measurements were made with highly enriched samples and a modified Moxon-Rae detector at ORELA. The energy region was thermal to 350 keV. Analysis is not complete.

[2] DERRIEN, H., LUCAS, B., "The total cross section and the fission cross section of $^{241}$Am in the resonance region. Resonance parameters," *Proc. Conf. on Nuclear Cross Sections and Technology*, Washington, D.C., March, 1975 (to be published). Total and fission differential cross section measurements were made with highly enriched samples at the Saclay linac for 0.8 eV $<E_n<$150 eV. 187 resonances have been analyzed for $E_o$ and $\Gamma_n$ and some values of $\Gamma_\gamma$. Preliminary values are given for 38 fission widths from 1.28 eV to 39.62 eV.

[3] SEEGER, P.A., HEMMENDINGER, A., DIVEN, B.C., "Fission cross sections of $^{241}$Am and $^{242m}$Am," *Nucl. Phys. A96* (1967) 605. After a LASL nuclear detonation, time-of-flight measurements were made for 20 eV $<E_n<$1 MeV on samples enriched to 98.7%. Cross section curves are given and integrated over resonances. No parametric analysis is given.

[4] GERASIMOV, V.F., *Nuclear Data for Reactors, Conf. Proc.*, Paris, 17-21 October 1966, Vol. II, (1966) p 129. Linac fission measurements were made for 0.02 eV $<E_n<$50 eV. 15 resonances were analyzed for $E_o$ and $\Gamma_f/\Gamma$. Thermal data appear good.

[5] BOWMAN, C.D., COOPS, M.S., AUCHAMPAUGH, G.F., FULTZ, S.C., "Subthreshold neutron-induced fission cross section of $^{241}$Am," *Phys. Rev. 137* (1965) B326. Lawrence Livermore Laboratory (LLL) linac fission measurements were made for samples enriched to 99.95%. 11 resonances were analyzed for $E_o$ and $\Gamma_f/\Gamma$. One negative resonance was required.

[6] HARVEY, J.A., BLOCK, R.C., SLAUGHTER, G.G., "Fast chopper time-of-flight spectrometer," *Physics Division Annual Progress Reports for Periods Ending March 10, 1959, and February 10, 1961.* USAEC Report ORNL-2718 (1959) p 26, and "High resolution total cross section measurements on $Np^{237}$ and $Am^{241}$," ORNL-3085 (1961) p 42. ORNL fast-chopper, time-of-flight transmission measurements were made for highly enriched samples of $^{241}$AmF (solid) and $^{241}Am(NO_3)_2$ (liquid) for 0.2 eV $<E_n<$45 eV. Cross section curves were obtained. Many resonances were analyzed for $E_o$ and $g\Gamma_n^{\circ}$, and some shapes were analyzed for $\Gamma_\gamma$.

[7] ADAMCHUK, Y.B., et al. *United Nations Conf. Peaceful Uses At. Energy* (Geneva, 1955) *4*, UN, New York (1955) 216. Early chopper transmission measurements were made for 0.006 eV $<E_n<$ 100 eV. Thermal results seem good. No parametric analysis is given.

*Integral Data*

[8] MACMURDO, K.W., HARBOUR, R.M., MCCROSSON, F.J., *Nucl. Sci. Eng. 50* (1973) 364. Reactor irradiations were made for highly enriched bare and cadmium-covered samples. $\sigma_{n\gamma}^{2200}$ (to $^{242m}$Am) = 83.8 ±2.6 b; $\sigma_{n\gamma}^{2200}$ (to $^{242}$Am) = 748 ±20 b; $I_{n\gamma}$ (to $^{242m}$Am) ($E_n$ >0.369 eV) = 208 ±18 b; $I_{n\gamma}$ (to $^{242}$Am) ($E_n$ >0.369 eV) = 1330 ±117 b. The cutoff was examined in considerable detail.

[9] BAK, M.A., PETRZHAK, K.A., PETROV, YU.G., ROMANOV, YU.F., SCHLYAMIN, E.A., "Resonance fission integrals for uranium, plutonium, and americium isotopes," *Soviet Atomic Energy 28* (1970) 460. Reactor dual fission chamber measurements were made for cadmium-covered enriched samples. $^{235}$U monitors were used. $I_{nf}$ (no cutoff given) = 21 ±2 b.

[10] SCHUMAN, R.P., *Reports to the AEC National Cross Section Advisory Committee, Rice Univ., September 1969*, USAEC Report WASH-1136 (1969) p 53. High flux, cadmium-shielded reactor irradiations were made for enriched samples. $^{59}$Co monitors were used (assumed $I_{n\gamma}$ = 74.6 b). $I_{n\gamma}$ (to $^{242m}$Am, no cutoff given) = 250 ±40 b; $I_{n\gamma}$ (to $^{242}$Am, no cutoff given) = 850 ±60 b.

[11] BAK, M.A., KRIVOKHATSKII, A.S., ROMANOV, YU.R., SAROKINA, A.V., SHLYAMIN, E.A., *Soviet Atomic Energy 24* (1968) 300. Reactor burnup measurements were made for enriched samples. Alpha counting was done with $^{147}$Au monitors (assumed $\sigma_{n\gamma}^{2200}$ = 98.8 ±0.3 b and $I_{n\gamma}$ = 2300 ±200 b). $\sigma_{n\gamma}^{2200}$ (to $^{242m}$Am) = 70 ±5 b, $\sigma_{n\gamma}^{2200}$ (to $^{242}$Am) = 670 ±60 b; $I_{n\gamma}$ (to $^{242m}$Am, no cutoff given) = 300 ±30 b; $I_{n\gamma}$ (to $^{242}$Am, no cutoff given) = 2100 ±200 b; $\sigma_{nf}^{2200}$ = 3.15 ±0.10 b; $I_{nf}$ (no cutoff given) = 21 ±2 b.

[12] HULET, E.K., HOFF, R.W., BOWMAN, H.R., MICHEL, M.C., "Thermal-neutron fission cross sections for isotopes of plutonium, americium, and curium," *Phys. Rev. 107* (1957) 1294. Thermal column measurements were made in the MTR with mixed isotopic samples. $\sigma_{nf}^{2200}$ = 3.13 ±0.15 b.

*Nubar*

[13] JAFFEY, A.H., LERNER, J.L., "Measurement of prompt neutron fission yield ($\bar{\nu}_p$) in thermal neutron fission of $^{232}$U, $^{238}$Pu, $^{241}$Pu, $^{241}$Am, $^{242m}$Am, $^{243}$Cm, and $^{245}$Cm and in spontaneous fission of $^{244}$Cm," *Nucl. Phys. A145* (1970) 1. Coincidence measurements in a thermal neutron beam using an ionization chamber and four Hornyak buttons gave a result for $^{241}$Am of $\bar{\nu}_p$ = 3.219 ±0.038.

[14] LEBEDEV, V.I., KALASHNIKOVA, V.I., *Sov. At. En. 5* (1958) 1019. Coincidence measurements in a thermal neutron beam using an ionization chamber and $BF_3$ counters imbedded in a paraffin block. Data were renormalized to $^{235}$U in Ref. 13 to give $\bar{\nu}_p$ = 3.057 ±0.026.

Post-Deadline Contribution - *Integral Data*

[15] GAVRILOV, V.D., GONCHAROV, V.A., IVANENKO, V.V., SMIRNOV, V.P., KUSTOV, V.N., "Thermal cross sections and resonance integrals for capture and fission in $^{241}$Am, $^{243}$Am, $^{249}$Bk, $^{249}$Cf." (Private communication from V.I. Mostovoi, USSR). Cadmium difference measurements were made in the SM-2 reactor for capture and fission using $^{197}$Au and $^{59}$Co monitors. Glass and mica track detectors were used. Samples were 97.48% $^{241}$Am, 2% $^{237}$Np, 0.16% $^{239}$Pu. Results were: $\sigma_{n\gamma}^{2200}$ (to $^{242}$Am) = 780 ±50 b, $\sigma_{nf}^{2200}$ = 2.8 ±0.25 b, $\sigma_{n\gamma}^{2200}$ (to $^{242m}$Am) = 73 ±14 b. $I_{n\gamma}$ (to $^{242}$Am, no cutoff given) = 1570 ±110 b, $I_{nf}$ (no cutoff given) = 22.5 ±1.7 b, $I_{n\gamma}$ (to $^{242m}$Am, no cutoff given) = 230 ±80 b.

## AMERICIUM-242, Ground State (16.02 h)

Only the integral fission cross sections have been measured for the short-lived ground state of $^{242}$Am. This isotope is the precursor of both $^{242}$Pu (by electron capture) and $^{242}$Cm (by beta decay). Because of the short half-life, the cross sections are relatively less important.

### Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* |
|---|---|---|---|
| $\sigma^{2200}$ | - | 2100 | 2 |
| I | - | <300 | 2 |

| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Requested Precision* |
|---|---|---|---|---|
| Capture | Thermal | - | | 10-20% |
| Fission | Thermal | 10% | 2 | 10-20% |
| Resolved Resonances | | | | |
| $\Gamma_n$ } $\Gamma_f$ | No measurements known | | | 10-20% |
| $I_{n\gamma}$ | - | - | - | 10-20% |
| $I_{nf}$ | No cutoff given | ? | 2 | 10-20% |

| *Nubar* | | *Reference* |
|---|---|---|
| Thermal } $\bar{\nu}$(E) | No measurements known | - |

Current or Future Measurements - None known

Recommendations - Integral capture measurements would be very useful, but quite difficult to do.

### References

*Production*

[1] IHLE, H., MICHAEL, H., NEUBERT, A., BLAIR, A.J.F., DAMLE, P., BODNARESCU, M.V., "Isotopic composition of plutonium-238 from americium-241 and reactor cross sections of actinide nuclides," *J. Inorg. Nucl. Chem.* *34* (1972) 2427. Reactor irradiations of $^{241}$Am to produce $^{242}$Cm. For $^{242g}$Am, $\sigma_{nf}^{eff}$ = 2100 b.

[2] BAK, M.A., KRIVOKHATSII, A.S., PETRZHAK, K.A., PETROV, YU.G., ROMANA, YU.F., SCHLYAMIN, E.A., "Cross sections and resonance integrals for capture and fission in long-lived americium isotopes," *Soviet Atomic Energy 23* (1967) 1059. Reactor irradiations were made for $^{241}Am$ and $^{243}Am$ mixtures; alpha-counting was used. $\sigma_{nf}^{2200}$ (for $^{242}Am$) = 2100 ±200 b; $I_{nf}$ (no cutoff given) = <300 b.

## AMERICIUM-242m, Isomeric State (152 yr)

Substantial differential and integral fission data are available for the 152-yr isomeric state of $^{242}Am$, which has the unique property of having the largest thermal fission cross section known. The available fission data are reasonably complete, and through the use of nuclear systematics to determine a probable value for $\Gamma_\gamma$, the capture cross sections can be estimated with reasonable confidence. Measurements of the capture cross sections, however, would certainly be of value.

### Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* | |
|---|---|---|---|---|
| $\sigma^{2200}$ | - | 7600 | 4 | |
| I | - | 1570 | 2 | |
| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Requested Precision* |
| Capture | - | - | - | 10% |
| Fission | Thermal | 4% | 4 | 10-20% |
| Resolved Resonances | | | | |
| $\Gamma_n$ | 0-4 eV | - | 1 | 10% |
| $\Gamma_f$ | 0-4 eV | - | 1 | 10-20% |
| $I_{n\gamma}$ | - | - | | 10-20% |
| $I_{nf}$ | (≥0.5 eV) | 7% | 2 | 10-20% |
| *Nubar* | | *Precision* | *Reference* | |
| Thermal (prompt) | $\bar{\nu}p$ = 3.264 | 0.7% | 8 | - |
| $\bar{\nu}(E)$ | No measurements known | | - | - |

**Current or Future Measurements** - A fission cross section measurement from 0.01 to 14 MeV is planned by John Browne at the LLL linac. The intention is to improve substantially the work of Bowman, et al. [1].

**Recommendations** - Capture cross section measurements would be most welcome.

### References

*Differential Data*

[1] BOWMAN, C.D., AUCHAMPAUGH, G.F., FULTZ, S.C., HOFF, R.W., "Neutron-induced fission cross section of $^{242m}Am$," *Phys. Rev. 166* (1968) 1219. LLL fission chamber linac measurements were made for samples enriched to 19.8% $^{242m}Am$, 79.5% $^{241}Am$, and 0.7% $^{243}Am$ for 0.02 eV $<E_n<$ 6 MeV. Data were normalized to a thermal value of 6600 b at 0.0253 eV. Thermal data were good. 6 resonances were analyzed for $E_0$, $\Gamma_n$, and $\Gamma_f$, assuming $\Gamma_\gamma$ = 50 meV, for 0 $\le E_n <$ 4 eV.

[2] PERKINS, S.T., AUCHAMPAUGH, G.F., HOFF, R.W., BOWMAN, C.D., "Average cross sections and resonance integrals of $^{242m}$Am," *Nucl. Sci. Eng. 32* (1968) 131. LLL linac fission chamber measurements were made on $^{242m}$Am, with the same composition as in the reference above. $I_{nf}$ ($E_n$ >0.5 eV) = 1570 ±110 b.

[3] SEEGER, P.A., HEMMENDINGER, A., DIVEN, B.C., "Fission cross sections of $^{241}$Am and $^{242m}$Am," *Nucl. Phys. A96* (1967) 605. LASL nuclear detonation, time-of-flight measurements were made on enriched samples with 25% $^{242m}$Am for 20 eV $<E_n<$ 1 MeV. Cross section curves were obtained for $E_0$ and were analyzed and integrated over resonances. No parametric analysis was given.

*Integral Data*

[4] WOLFSBERG, K., FORD, G.P., "Thermal-neutron fission of $^{242m}$Am: mass and charge distribution," *Phys. Rev. C3* (1971) 1333. Reference below (Wolfsberg, et al.) was revised because of half-life refinement. $T_{1/2}$ changed from 457.7 to 432.7 yr. $\sigma_{nf}^{2200}$ = 7600 ±300 b.

[5] SCHUMAN, R.P., *Reports to the AEC Nuclear Cross Sections Advisory Committee, Rice Univ., September 1969*, USAEC Report WASH-1136 (1969) 53. High-flux, cadmium-shielded reactor irradiations were made for $^{241}$Am samples. $^{59}$Co monitors were used (assumed $I_{n\gamma}$ 74.6 b). $I_{nf}$ ($^{242m}$Am to total destruction) = 7000 ±2000 b.

[6] WOLFSBERG, K., FORD, G.P., SMITH, H.L., "Thermal neutron-induced fission cross section of $^{242m}$Am," *J. Nucl. Energy AB20* (1966) 588. Dual fission chamber reactor measurements were made of samples of 0.16% $^{242}$Cm, 79.44% $^{241}$Am, 19.70% $^{242m}$Am, and 0.7% $^{243}$Am. $^{235}$U monitor was used (assumed $\sigma_{nf}^{2200}$ = 582 ±4 b, f = 0.977). $\sigma_{nf}^{2200}$ = 7200 ±300 b (Revised, see Reference 4).

*Nubar*

[7] KROSHKIN, N.I., ZAMYATNIN, YU.S., "Measurement of energy spectrum and average number of prompt fission neutrons," *Sov. At. En. 29* (1970) 790. Time-of-flight measurements in a reactor thermal neutron beam using an americium sample enriched to 1.03% in $^{242m}$Am, a high-pressure gas scintillator, and a plastic scintillator as a neutron detector yielded a value for $^{242m}$Am of $\bar{\nu}p$ = 3.28 ±0.10.

[8] JAFFEY, A.H., LERNER, J.L., "Measurement of prompt neutron fission yield ($\bar{\nu}p$) in thermal neutron fission of $^{232}$U, $^{238}$Pu, $^{241}$Pu, $^{241}$Am, $^{242m}$Am, $^{243}$Cm, $^{245}$Cm and in spontaneous fission of $^{244}$Cm," *Nucl. Phy. A145* (1970) 1. Coincidence measurements in a reactor thermal neutron beam using an americium sample enriched to 1.32% in $^{242m}$Am, an ionization chamber, and four Hornyak buttons yielded a value for $^{242m}$Am of $\bar{\nu}p$ = 3.264 ±0.024.

See also FULTZ, et al. *Phys. Rev. 152* (1966) 1046, $\bar{\nu}p$ = 3.24 ±0.12.

## AMERICIUM-243 (7400 *yr*)

There is an abundance of production, integral, and differential data available for $^{243}$Am. This nuclide captures neutrons to the ground state and an isomeric state in $^{244}$Am, but both states decay with short half-lives (10.1 h and 26 m, respectively) to $^{244}$Cm. $^{243}$Am is a major link in the production chain to the curium isotopes and appears to be in good shape.

Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* |
|---|---|---|---|
| $\sigma^{2200}$ | 77 | 0 | 6,9 |
| I | 1927 | 3.34 | 1,2,6,7 |

| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Requested Precision* |
|---|---|---|---|---|
| Capture | Thermal | 5% | 6,9 | 5-10% |
| Fission | Thermal | - | - | - |
| Resolved Resonances | | | | |
| $\Gamma_n$ | 0-250 eV | <5% | 2 | 5-10% |
| $\Gamma_f$ | - | - | - | - |
| $I_{n\gamma}$ | ≥0.5 eV | 3% | 2,6,7 | 5-10% |
| $I_{nf}$ | ≥0.625 eV | - | 1 | - |

| *Nubar* | | *Reference* |
|---|---|---|
| Thermal (prompt), $\bar{\nu}(E)$ | No measurements known | - |

Current or Future Measurements - J. Blons and C. Mazur are making energy-dependent fission measurements from 300 keV to 5 MeV on the SACLAY linac. Results should be available in late 1975.

Recommendations - None

References

*Production Data*

[1] BENJAMIN, R.W., MCCROSSON, F.J., VANDERVELDE, V.D., GORRELL, T.C., *A Consistent Set of Heavy Actinide Multigroup Cross Sections*, USERDA Report DP-1394 (1975). A self-consistent set of 84-group cross sections and resonance parameters has been developed for production chain isotopes from $^{242}$Pu to $^{253}$Es using the results of reactor production experiments and modern multigroup reactor production codes.

*Differential Data*

[2] SIMPSON, O.D., SIMPSON, F.B., HARVEY, J.A., SLAUGHTER, G.G., BENJAMIN, R.W., AHLFELD, C.E., "The neutron total cross section of americium-243," *Nucl. Sci. Eng.* *55* (1974) 273. ORELA transmission measurements were made for multiple high-purity samples from the cadmium cutoff to 1000 eV. 238 resonances were analyzed for $E_0$, $\Gamma_n$, and $\Gamma_\gamma$ from 0.5 to 250 eV.

[3] SEEGER, P.A., in *Fission Cross Sections from Pommard.* USAEC Report LA-4420 (1970) p 138. LASL bomb shot fission data were obtained with a highly purified sample and a $^{235}$U monitor for 50 eV <$E_n$ <3 MeV. Cross section data are presented; no parametric analysis is given.

[4] BERRETH, J.R., SIMPSON, F.B., "Total neutron cross section of $^{243}$Am from 0.01 to 25 eV," *Nuclear Technology Branch Annual Progress Report for Period Ending June 30, 1970.* USAEC Report IN-1407 (1970) p 66. MTR fast chopper transmission measurements were made on multiple high-purity nuclear samples for 0.01 eV <$E_n$ <1000 eV. 36 resonances were analyzed for $E_0$ and $\Gamma_n$, and some for $\Gamma_\gamma$ from -2.00 eV (bound level) to 25 eV.

[5] COTÉ, R.E., BOLLINGER, L.M., BARNES, R.F., DIAMOND, H., "Slow neutron cross sections of $^{240}Pu$, $^{242}Pu$, and $^{243}Am$," *Phys. Rev. 114* (1959) 505. Argonne fast chopper transmission measurements were made on samples enriched to $\sim$99.5% $^{243}Am$ for 0 eV $<E_n<$16 eV. 11 resonances were analyzed for $E_o$, $\Gamma_n$, and some for $\Gamma_\gamma$ from 0.9 to 15.3 eV.

*Integral Data*

[6] EBERLE, S.H., BLEYL, H.J., GANTNER, E., REINHARD, J., KRUCKEBERG, C., "Cross sections," *Actinide Project: First Semiannual Report, 1971,* KFK-1456, Karlsruhe, West Germany (1971) p 51. Reactor irradiations were made. $\sigma_{n\gamma}^{2200}$ = 77 ±2 b; $I_{n\gamma}$ (no cutoff given) = 1930 ±50 b.

[7] SCHUMAN, R.P., "Resonance integral measurements on heavy nuclides," *Report to the AEC Nuclear Cross Sections Advisory Committee, New York, October 1968.* USAEC Report WASH-1124 (1968) p 72. Reactor irradiations were made for cadmium-covered samples. $^{197}Au$ and $^{59}Co$ monitors were used. $I_{n\gamma}$ (total capture, no cutoff given) = 2160 ±100 b; $I_{n\gamma}$ (to 10.1 hr $^{244}Am$, no cutoff given) = 111 ±15 b.

[8] FOLGER, R.L., SMITH, J.A., BROWN, L.C., OVERMAN, R.F., HOLCOMB, H.P., in *Neutron Cross Sections and Technology, Proc. Conf., Washington, D.C., March 4-7, 1968.* NBS Special Publication 299 (1968) p 1279. Reactor activations were made with bare and cadmium-covered samples. $\sigma_a^{eff}$ = 90 b, $I_a$ (no cutoff given) = 2250 b, inferred $\sigma_a^{2200}$ = 78 b.

[9] BAK, M.A., KRIVOKHATSKII, A.S., PETRZAK, K.A., PETROV, YU.G., ROMANOV, YU.F., SHLYAMIN, E.A., *Atomnaya Energija 23* (1967) 316. Reactor irradiation studies were made of buildup from $^{241,243}Am$ samples, both bare and cadmium-covered. The monitor $^{197}Au$ was used. $\sigma_a^{2200}$ = 73 ±6 b; $I_{n\gamma}$ (no cutoff given) = 2300 ±200 b.

Post-Deadline Contribution - *Integral Data*

[10] GAVRILOV, V.D., GONCHAROV, V.A., IVANENKO, V.V., SMIRNOV, V.P., KUSTOV, V.N., "Thermal cross sections and resonance integrals for capture and fission in $^{241}Am$, $^{243}Am$, $^{249}Bk$, $^{249}Cf$." (Private communication from V. I. Mostovoi, USSR). Cadmium difference measurements were made in the SM-2 reactor for capture and fission using $^{197}Au$ and $^{59}Co$ monitors. Glass and mica track detectors were used. Samples were 96.63% $^{243}Am$, 3.37% $^{241}Am$. Results were: $\sigma_{n\gamma}^{2200}$ = 83 ±6 b. $I_{n\gamma}$ (no cutoff given) = 2200 ±150 b. $\sigma_{nf}^{2200}$ = 0.2 ±11 b, $I_{nf}$ (no cutoff given) = 17.1 ±1.3 b.

## CURIUM-242 (163.0 d)

Almost no data are available for $^{242}Cm$, the alpha-decay precursor for $^{238}Pu$. Three production experiments give an indication that the cross section behaves in a manner consistent with the other even curium isotopes; i.e., the thermal capture cross section is small, the capture resonance integral moderate in size, and the fission cross section nearly negligible in both thermal and epithermal ranges. Data are required for $^{238}Pu$ production.

## Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* | |
|---|---|---|---|---|
| $\sigma^{2200}$ | 20 | $\leq 5$ | 1,3 | |
| I | 150 | $\sim 0$ | 2 | |
| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Requested Precision* |
| Capture | Thermal | 50% | 1 | 20% |
| Fission | Thermal | ? | 3 | - |
| Resolved Resonances | | | | |
| $\Gamma_n$ | No measurements known | | | 20% |
| $\Gamma_f$ | | | | 20% |
| $I_{n\gamma}$ | Not specified | 30% | 2 | 20% |
| $I_{nf}$ | | ? | - | - |

| *Nubar* | | *Reference* |
|---|---|---|
| Thermal, $\bar{\nu}(E)$ | No measurements known | |

## Current or Future Measurements - None known

**Recommendations** - Considerably more data on this nuclide are desirable, but measurements are difficult because of the short half-life and complexity in obtaining reasonably pure samples. More accurate measurements of the thermal capture cross section and the capture resonance integral would be very useful.

## References

*Production Data*


[1] IHLE, H., MICHAEL, H., NEUBERT, A., BLAIR, A.J.F., DAMLE, P., BODNARESCU, M.V., "Isotopic composition of plutonium-238 from americium-241 and reactor cross sections of actinide nuclides." *J. Inorg. Nucl. Chem. 34* (1972) 2427. A reactor irradiation of $^{241}$Am and subsequent chemical separation of the built-in actinides gave effective reactor cross sections for the nuclides involved. $\sigma_{n\gamma}^{eff}$ = 25 b, $\sigma_{nf}^{eff}$ = 5 b. The results gave inferred values of $\sigma_{n\gamma}^{2200}$ = 20 b, $\sigma_{nf}^{2200}$ = 5 b, and $I_{n\gamma}$ = 150 b.

[2] SCHUMAN, R.P., *Reports to the AEC Nuclear Cross Sections Advisory Committee, Rice Univ., September 1969*, USAEC Report WASH-1136 (1969) 53. High flux cadmium-shielded $^{241}$Am reactor irradiations were made followed by alpha pulse height and mass analysis. $I_{n\gamma}$ (no cutoff given) = 150 ±40 b.

[3] HANNA, G.C., HARVEY, B.G,. MOSS, N., TUNNICLIFFE, P.R., "Fission in $^{242}$Am." *Phys. Rev. 81* (1951) 893. Reactor irradiations were made with purified $^{241}$Am. $\sigma_{nf}^{2200} \leq 5$ b.


## CURIUM-243 (30 yr)

Sufficient data for $^{243}$Cm are available for an evaluation adequate for current and near-term needs, although the lack of capture cross sections may be a problem. This isotope is not an important participant in either the $^{252}$Cf production chain or the $^{238}$Pu production chain.

Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* | |
|---|---|---|---|---|
| $\sigma^{2200}$ | - | 690 | 4 | |
| I | - | 1860 | 3 | |
| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Requested Precision* |
| Capture | - | - | - | - |
| Fission | Thermal | 7% | 4 | - |
| Resolved Resonances | | | | |
| $\Gamma_n$ | 1-30 eV | 15% | 2 | - |
| $\Gamma_f$ | 1-30 eV | 20% | 2 | - |
| $I_{n\gamma}$ | - | - | - | - |
| $I_{nf}$ | ≥0.500 | 21% | 3 | - |
| *Nubar* | | *Precision* | *Reference* | |
| Thermal (prompt) | $\bar{\nu}p$ = 3.430 | 1.4% | 5 | - |
| $\bar{\nu}$(E) | No measurements known | | - | - |

Current or Future Measurements - J.W.T. Dabbs and C.E. Bemis, Jr. plan measurements of the differential fission cross section at ORELA beginning about October 1975. Thermal and resonance energy regions will be emphasized.

Recommendations - Since no capture measurements are currently available, integral measurements of the thermal capture cross section and capture resonance integral would help to do a proper evaluation using the resonance parameters of Berreth, et al. [2].

References


*Differential Data*

[1] FULLWOOD, R.R., private communication. LASL bomb shot fission data were obtained for samples enriched to 89% $^{243}$Cm for 20 eV <$E_n$ <1 MeV. Data were converted to cross sections versus energy curves, but the curves have not been analyzed.

[2] BERRETH, J.R., SIMPSON, F.B., RUSCHE, B.C., "The total neutron cross sections of the curium isotopes from 0.01 to 30 eV." *Nucl. Sci. Eng. 49* (1972) 145. Fast-chopper transmission data were obtained for multiple mixed samples. 15 resonances were analyzed for $E_0$, $\Gamma_n$, and $\Gamma_f$, assuming $\Gamma_\gamma$ = 40 meV, for 1 eV <$E_n$ <26 eV.

*Integral Data*

[3] THOMPSON, M.C., HYDER, M.L., REULAND, R.J., "Thermal neutron cross sections and resonance integrals for $^{244}$Cm through $^{248}$Cm." *J. Inorg. Nucl. Chem. 33* (1971) 1553. Reactor irradiations and radiochemical and mass spectrometry techniques were used for bare and cadmium-covered multiple mixed samples. $^{235}$U and $^{59}$Co monitors were used. $I_{nf}$ (no cutoff given) = 1860 ±400 b.

[4] HULET, E.K., HOFF, R.W., BOWMAN, H.R., MICHEL, M.C., "Thermal neutron fission cross sections for isotopes of plutonium, americium, and curium." *Phys. Rev. 107* (1957) 1294. MTR thermal column fission chamber measurements were made for low enrichment samples. A $^{239}$Pu monitor was used. $\sigma_{nf}^{th}$ = 690 ±50 b.

*Nubar*

[5] JAFFEY, A.H., LERNER, J.L., "Measurement of prompt neutron fission yield ($\bar{\nu}_p$) in thermal neutron fission of $^{232}U$, $^{238}Pu$, $^{241}Pu$, $^{241}Am$, $^{242m}Am$, $^{243}Cm$, $^{245}Cm$ and in spontaneous fission of $^{244}Cm$." *Nucl. Phy. A145* (1970) 1. Coincidence measurements in a thermal neutron beam using an ionization chamber and four Hornyak buttons gave a result for $^{243}Cm$ of $\bar{\nu}_p$ = 3.430 ±0.047.

## CURIUM-244 (18.1 yr)

Significant integral, differential, and production data are available for $^{244}Cm$. Sufficient data are available for a reasonable evaluation. There is a discrepancy between the integral and production data for the thermal capture cross section, 14 ±4 b vs 10.6 ±2 b, respectively. The production value is preferred.

### Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* | |
|---|---|---|---|---|
| $\sigma^{2200}$ | 10.6 | 1.1 | 1,6 | |
| I | 585 | 17.9 | 1 | |
| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Requested Precision* |
| Capture | Thermal | 20% | 1,6 | 20% |
| Fission | Thermal | 50% | 6 | - |
| Resolved Resonances | | | | |
| $\Gamma_n$ | 0-520 eV | 10% | 2 | 50% |
| $\Gamma_f$ | 20-972 eV | ≥10% | 3 | 50% |
| $I_{n\gamma}$ | ≥0.625 eV | 10% | 1 | 10% |
| $I_{nf}$ | ≥0.625 eV | 10% | 6 | 10% |

| *Nubar* | | *Reference* |
|---|---|---|
| Thermal<br>$\bar{\nu}$(E) | No measurements known | |

### Current or Future Measurements - None known

**Recommendations** - New measurements on $^{244}Cm$ are unlikely because of the relative breadth of data already available and the difficulty of obtaining sufficient sample material of the requisite purity. A careful thermal total cross section measurement with metal samples or suitable corrections for small angle scattering in oxide samples might help to resolve the differences between the integral and production data.

### References

*Production Data*

[1] BENJAMIN, R.W., MCCROSSON, F.J., VANDERVELDE, V.D., GORRELL, T.C. *A Consistent Set of Heavy Actinide Multigroup Cross Sections*, USERDA Report DP-1394 (1975). A self-consistent set of 84-group cross sections and resonance parameters has been developed for production chain isotopes from $^{242}Pu$ to $^{253}Es$ using the results of reactor production experiments and modern multigroup reactor production codes.

*Differential Data*


[2] SIMPSON, O.D., SIMPSON, F.B., YOUNG, T.E., HARVEY, J.A., BENJAMIN, R.W., Private communication. ORELA transmission measurements were made with highly enriched samples from thermal energies to 530 eV. 36 resonances were analyzed for $E_0$, $\Gamma_n$, $\Gamma_\gamma$, and $\Gamma_f$ from 0 to 520 eV using, in addition, the data from the reference below.

[3] MOORE, M.S., KEYWORTH, G.A., "Analysis of the fission and capture cross sections of the curium isotopes," *Phys. Rev. C3* (1971) 1656. LASL bomb shot capture and fission data were obtained with 98.5% enriched fission samples and 79.2% enriched capture samples for 20 eV $<E_n<$ 3 MeV. Data were analyzed for $E_0$, $\Gamma_\gamma$, $\Gamma_f$, and $\Gamma_n$. 67 resonances were analyzed for 22 eV $<E_n<$ 975 eV.

[4] BERRETH, J.R., SIMPSON, F.B., RUSCHE, B.C., "The total neutron cross sections of the curium isotopes from 0.01 to 30 eV," *Nucl. Sci. Eng. 49* (1972) 145. Fast chopper transmission data were obtained for multiple mixed samples of up to 94% $^{244}$Cm. 3 resonances were analyzed for $E_0$, $\Gamma_\gamma$, and $\Gamma_n$ for 0 $<E_n<$ 30 eV.

[5] COTÉ, R.E., BARNES, R.F., DIAMOND, H., "Total neutron cross section of $^{244}$Cm," *Phys. Rev. 134* (1964) B1281. Fast chopper transmission data were obtained for multiple mixed samples up to 96.5% $^{244}$Cm. $\Gamma_n$ and $\Gamma_\gamma$ were analyzed for 3 resonances; $\Gamma_n$, for 12 more assuming $\Gamma_\gamma$ = 37 meV. 0 $<E_n<$ 900 eV.


*Integral Data*


[6] BENJAMIN, R.W., MACMURDO, K.W., SPENCER, J.D., "Fission cross sections for five isotopes of curium and californium-249," *Nucl. Sci. Eng. 47* (1972) 203. Reactor fission chamber measurements were made with multiple bare and cadmium-covered multiple mixed samples of up to 99% enrichment in $^{244}$Cm. $^{235}$U monitors were used. $\sigma_{nf}^{2200}$ = 1.1 ±0.5 b; $I_{nf}$ ($E_n$ >0.625 eV) = 18.0 ±1.0 b.

[7] THOMPSON, M.C., HYDER, M.L., REULAND, R.J., "Thermal neutron cross sections and resonance integrals for $^{244}$Cm through $^{248}$Cm," *J. Inorg. Nucl. Chem. 33* (1971) 1553. Reactor irradiations and radiochemical and mass spectrometry techniques were used for bare and cadmium-covered multiple enriched samples. $^{235}$U and Co monitors were used. $\sigma_{n\gamma}^{2200}$ = 14 ±4 b; $I_{n\gamma}$ ($E_n$ >0.625 eV) = 650 ±50 b; $\sigma_{nf}^{2200}$ = 1.5 ±1.0 b; $I_{nf}$ (E >0.625 eV) = 12.5 ±2.5 b.

[8] SCHUMAN, R.P., *Reports to the AEC Nuclear Cross Sections Advisory Committee, Houston, September 1969*. USAEC Report WASH-1136 (1969) 54. Reactor activations were made for mixed samples with cadmium. $I_{nf}$ (no cutoff given) = 650 ±50 b.


## CURIUM-245 (8532 yr)

A substantial quantity of experimental data for $^{245}$Cm is available, and a reasonable evaluation has been made [1]. The lack of differential measurements in the low energy region is currently being remedied and, upon completion of these measurements, $^{245}$Cm should be in reasonably good shape.

Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* | |
|---|---|---|---|---|
| $\sigma^{2200}$ | 383 | 2161 | 1,4-8 | |
| I | 104 | 766 | 1,4,5,7 | |

| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Requested Precision* |
|---|---|---|---|---|
| Capture | Thermal | 10% | 1,5,7 | 10% |
| Fission | Thermal | 5% | 1 | 10% |
| Resolved Resonances | | | | |
| $\Gamma_n$ | 1.95-60 eV | ∿20% | 1-3 | 10% |
| $\Gamma_f$ | 1.95-60 eV | ∿25% | 1-3 | 10% |
| $I_{n\gamma}$ | (≥0.625 eV) | 7% | 1,7 | 10% |
| $I_{nf}$ | (≥0.625 eV) | 5% | 1,4,5 | 10% |

| *Nubar* | | *Precision* | *Reference* | |
|---|---|---|---|---|
| Thermal (prompt) | $\bar{\nu}_p = 3.832$ | 1% | 10 | - |
| $\bar{\nu}(E)$ | No measurements known | | - | - |

Current or Future Measurements - Two laboratories are currently measuring and analyzing the thermal and resonance region fission cross sections for $^{245}$Cm: LLL (John Browne) and ORNL (J.W.T. Dabbs and C. E. Bemis, Jr.). Results should be available in late 1975 or early 1976.

Recommendations - None

References

*Production Data*

[1] BENJAMIN, R.W., MCCROSSON, F.J., VANDERVELDE, V.D., GORRELL, T.C., *A Consistent Set of Heavy Actinide Multigroup Cross Sections*, USERDA Report DP-1394 (1975). A self-consistent set of 84-group cross sections and resonance parameters has been developed for production chain isotopes from $^{242}$Pu to $^{253}$Es using the results of reactor production experiments and modern multigroup reactor production codes.

*Differential Data*

[2] MOORE, M.S., KEYWORTH, G.A., "Analysis of the fission and capture cross sections of the curium isotopes," *Phys. Rev. C3* (1971) 1656. LASL bomb shot capture and fission data were obtained with fission samples enriched to ∿77% for 20 eV $<E_n<$ 3 MeV. Data were analyzed for $E_o$, $2g\Gamma_n^o$, and $\Gamma_f$ with $\Gamma_\gamma$ assumed to be 40 meV. 26 resonances were analyzed for 20 eV $<E_n<$60 eV.

[3] BERRETH, J.R., SIMPSON, F.B., RUSCHE, B.C., "The total neutron cross sections of the curium isotopes from 0.01 to 30 eV," *Nucl. Sci. Eng. 49* (1972) 145. Fast chopper transmission data were obtained for multiple mixed samples of low $^{245}$Cm enrichment. 10 resonances below 30 eV were analyzed for $E_o$, $\Gamma_n$, and $\Gamma_f$ assuming $\Gamma_\gamma$ = 40 meV.

*Integral Measurements*


[4] BENJAMIN, R.W., MACMURDO, K.W., SPENCER, J.S., "Fission cross sections for five isotopes of curium and californium-249," *Nucl. Sci. Eng. 47* (1972) 203. Reactor fission chamber and track counter measurements were made for multiple bare and cadmium-covered samples of 77% enrichment $^{245}$Cm. $^{235}$U monitors were used. $\sigma_{nf}^{2200}$ = 2018 ±37 b, $I_{nf}$ ($E_n$ >0.625 eV) = 772 ±40 b.

[5] THOMPSON, M.C., HYDER, M.L., REULAND, R.J., "Thermal neutron cross sections and resonance integrals for $^{244}$Cm through $^{248}$Cm," *J. Inorg. Nucl. Chem. 33* (1971) 1553. Reactor irradiations and radiochemical and mass spectrometry techniques were used for bare and cadmium-covered multiple enriched samples. $^{235}$U and $^{59}$Co monitors were used. $\sigma_{n\gamma}^{2200}$ = 360 ±50 b. $I_{n\gamma}$ ($E_n$ >0.625 eV) = 110 ±20 b. $\sigma_{nf}^{2200}$ = 2030 ±200 b. $I_{nf}$ ($E_n$ >0.625 eV) = 750 ±150 b.

[6] HALPERIN, J., OLIVER, J.H., STOUGHTON, R.W., "The fission thermal-neutron cross section and resonance integral of $^{245}$Cm, $^{247}$Cm, and $^{249}$Cf," *Chemistry Division Annual Progress Report for Period Ending May 20, 1970.* USAEC Report ORNL-4581 (1970) p 37. Reactor irradiations were made for bare and cadmium-covered mixed samples of ∿77% $^{245}$Cm and 23% $^{244}$Cm. $^{197}$Au monitors were used. $\sigma_{nf}^{2200}$ = 1920 ±180 b. $I_{nf}$ = 1100 ±100 b. Note: I is incorrect because the sample holder under the cadmium covers was hydrogenous.

[7] HALPERIN, J., DRUSCHEL, R.E., EBY, R.E., "Thermal neutron capture cross section and resonance integral of $^{245}$Cm and $^{246}$Cm," *Chemistry Division Annual Progress Report for Period Ending May 20, 1969.* USAEC Report ORNL-4437 (1969) p 20. Reactor activations were made for bare and cadmium-covered samples enriched to ∿77% $^{245}$Cm. $^{59}$Co monitors were used. $\sigma_{n\gamma}^{2200}$ = 340 ±20 b; $I_{n\gamma}$ (E >0.54 eV) = 101 ±8 b.

[8] DIAMOND, H., HINES, J.J., SJOBLOM, R.K., BARNES, R.F., METTA, D.N., LERNER, J.L., FIELDS, P.R., "Fission cross-sections for $^{243}$Pu, $^{250}$Bk, $^{247}$Cm, $^{245}$Cm, $^{254m}$Es, and $^{254}$Es, and odd-odd systematics," *J. Inorg. Nucl. Chem. 30* (1968) 2553. Reactor thermal column fission chamber measurements were made for samples with an enrichment purity of ∿13%. $^{235}$U monitors were used. No account was taken of epithermal neutrons. $\sigma_{nf}^{thermal}$ = 2040 ±80 b.

[9] HULET, E.K., HOFF, R.W., BOWMAN, H.R., MICHEL, M.C., "Thermal-neutron fission cross sections for isotopes of plutonium, americium, and curium," *Phys. Rev. 107* (1957) 1294. MTR thermal column fission chamber measurements were made for samples enriched to 1.62 ±0.01%. $^{239}$Pu monitors were used. $\sigma_{nf}$ = 1880 ±150 b.


*Nubar*


[10] JAFFEY, A.H., LERNER, J.L., "Measurement of prompt neutron fission yield ($\bar{\nu}_p$) in thermal neutron fission of $^{232}$U, $^{238}$Pu, $^{241}$Pu, $^{241}$Am, $^{242m}$Am, $^{243}$Cm, $^{245}$Cm, and in spontaneous fission of $^{244}$Cm," *Nucl. Phys. A145* (1970) 1. Coincidence measurements in a thermal neutron beam using an ionization chamber and four Hornyak buttons. The result for $^{245}$Cm was $\bar{\nu}_p$ = 3.832 ±0.034.

## CURIUM-246 (4820 yr)

There are sufficient production, differential, and integral data for $^{246}Cm$ to make a reasonable evaluation. The known details of the cross section, though very limited in the thermal region, seem well described by the Breit-Wigner single-level formalism using the available resonance parameters.

### Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* | |
|---|---|---|---|---|
| $\sigma^{2200}$ | 1.44 | 0.17 | 1,6,8 | |
| I | 117.0 | 9.94 | 1,6,8 | |

| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Requested Precision* |
|---|---|---|---|---|
| Capture | Thermal | 20% | 1 | 10% |
| Fission | Thermal | 60% | 6 | - |
| Resolved Resonances | | | | |
| $\Gamma_n$ | 0-160 eV | 10% | 2,4,5 | 10% |
| $\Gamma_f$ | 20-382 eV | 20% | 3 | - |
| $I_{n\gamma}$ | (≥0.625 eV) | 7% | 1,8 | 10% |
| $I_{nf}$ | (≥0.625 eV) | 40% | 6 | - |

| *Nubar* | | | *Reference* | |
|---|---|---|---|---|
| Thermal | No measurements known | | | - |
| $\bar{\nu}(E)$ | | | | - |

Current or Future Measurements - None known

Recommendations - More capture and fission data in the thermal and resonance region below 20 eV would be useful, but measurement would be difficult because of the limited amount of material available and the small thermal cross sections.

### References

*Production Data*

[1] BENJAMIN, R.W., MCCROSSON, F.J., VANDERVELDE, V.D., GORRELL, T.C., *A Consistent Set of Heavy Actinide Multigroup Cross Sections*, USERDA Report DP-1394 (1975). A self-consistent set of 84-group cross sections and resonance parameters has been developed for production chain isotopes from $^{242}Pu$ to $^{253}Es$ using the results of production experiments and modern multigroup reactor production codes.

*Differential Data*

[2] BENJAMIN, R.W., AHLFELD, C.E., HARVEY, J.A., HILL, N.W., "Neutron total cross section of Cm-248," *Nucl. Sci. Eng.* *55* (1974) 440. ORELA transmission measurements were made with liquid-nitrogen-cooled samples of 97% $^{248}Cm$ and 3% $^{246}Cm$. 5 resonances in $^{246}Cm$ were analyzed for $E_0$ and $\Gamma_n^0$ . $\Gamma_\gamma$ was determined for the first resonance.

[3] MOORE, M.S., KEYWORTH, G.A., "Analysis of the fission and capture cross sections of the curium isotopes," *Phys. Rev. C3* (1971) 1656. LASL bomb shot fission and capture data were obtained for 95% enriched fission samples and 16% enriched capture samples for 20 eV <E <3 MeV. Data were analyzed for $E_o$, $\Gamma_n$, and $\Gamma_f$, with $\Gamma_\gamma$ assumed = 37 meV; 8 resonances were analyzed for 80 eV $<E_n<$ 390 eV.

[4] BERRETH, J.R., SIMPSON, F.B., RUSCHE, B.C., "The total neutron cross sections of the curium isotopes from 0.01 to 30 eV," *Nucl. Sci. Eng. 49* (1972) 145. MTR fast chopper transmission data were obtained for multiple mixed samples of low enrichment. Two resonances were analyzed for $\Gamma_n$ assuming $\Gamma_\gamma$ = 35 meV for $E_n$ below 30 eV.

[5] COTÉ, R.E., BARNES, F.R., DIAMOND, H., "Total neutron cross section of $^{244}$Cm," *Phys. Rev. 134* (1964) B1281. Argonne fast chopper transmission data were obtained for mixed samples (mostly $^{244}$Cm). 3 resonances were resolved and analyzed for $\Gamma_n$.

*Integral Data*

[6] BENJAMIN, R.W., MACMURDO, K.W., SPENCER, J.D., "Fission cross sections for five isotopes of curium and californium-249," *Nucl. Sci. Eng. 47* (1972) 203. Reactor fission chamber measurements were made for multiple bare and cadmium-covered samples of $^{246}$Cm (enrichments to 95%). $^{235}$U monitors were used. $\sigma_{nf}^{2200}$ = 0.17 ±0.10 b; $I_{nf}$ ($E_n$ >0.625 eV) = 10.0 ±0.4 b.

[7] THOMPSON, M.C., HYDER, M.L., REULAND, R.J., "Thermal neutron cross sections and resonance integrals for $^{244}$Cm through $^{248}$Cm," *J. Inorg. Nucl. Chem. 33* (1971) 1553. Reactor irradiations, bare and cadmium-covered radiochemical, and mass spectrometry techniques were used on multiple samples of up to 94.66% enrichment. $^{235}$U and $^{59}$Co monitors were used. $\sigma_{n\gamma}^{2200}$ = 1.5 ±0.5 b; $I_{n\gamma}$ (no cutoff given) = 84 ±15 b. $\sigma_{nf}^{2200}$ and $I_{nf}$ are low.

[8] HALPERIN, J., DRUSCHEL, R.E., EBY, R.E., "Thermal-neutron capture cross section and resonance integral of $^{245}$Cm and $^{246}$Cm," *Chemistry Division Annual Progress Report for Period Ending May 20, 1969.* USAEC Report ORNL-4437 (1969) p 20. Reactor activations were made for bare and cadmium-covered highly enriched (∿97%) samples. $^{235}$U and $^{59}$Co monitors were used. $\sigma_{n\gamma}^{2200}$ = 1.2 ±0.4 b; $I_{n\gamma}$ ($E_n$ >0.54 eV) = 121 ±7 b.

[9] SCHUMAN, R.P., *Reports to the AEC Nuclear Cross Sections Advisory Committee, Rice Univ., September 1969.* USAEC Report WASH-1136 (1969) p 54. Reactor activations were made for cadmium-covered, low-enrichment mixed samples. $I_{n\gamma}$ (no cutoff given) = 110 ±40 b.

## CURIUM-247 (1.64 × $10^7$ yr)

Limited differential and integral data are available for $^{247}$Cm. More data, particularly differential data below 30 eV, are desirable, but this isotope is available in such small quantities and such low enrichments that new measurements will be very difficult.

## Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* | |
|---|---|---|---|---|
| $\sigma^{2200}$ | 58 | 72.3 | 1 | |
| I | 500 | 761 | 1 | |

| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Requested Precision* |
|---|---|---|---|---|
| Capture | Thermal | 10-15% | 1 | 5-10% |
| Fission | Thermal | 10-15% | 1 | 5-10% |
| Resolved Resonances | | | | |
| $\Gamma_n$ | 20-60 eV | Not given | 3 | 10% |
| $\Gamma_f$ | 20-60 eV | Not given | 3 | 10% |
| $I_{n\gamma}$ | ≥0.625 eV | 15% | 1 | 5-10% |
| $I_{nf}$ | ≥0.625 eV | 7% | 4 | 5-10% |

| *Nubar* | | *Precision* | *Reference* | |
|---|---|---|---|---|
| Thermal (prompt) | $\bar{\nu}_p$ = 3.79 | 4% | 8 | - |
| $\bar{\nu}$(E) | No measurements known | | - | - |

## Current or Future Measurements - None known

**Recommendations** - Differential fission measurements in the thermal and resonance regions could be made with highly enriched samples containing a few micrograms of material. This would be a worthwhile measurement if an appropriate sample could be obtained.

## References


*Production Data*

[1] BENJAMIN, R.W., MCCROSSON, F.J., VANDERVELDE, V.D., GORRELL, T.C., *A Consistent Set of Heavy Actinide Multigroup Cross Sections*, USERDA Report DP-1394 (1975). A self-consistent set of 84-group cross sections and resonance parameters has been developed for production chain isotopes from $^{242}$Pu to $^{253}$Es using the results of reactor production experiments and modern multigroup reactor production codes.

[2] SMITH, J.A., BANICK, C.J., FOLGER, R.L., HOLCOMB, H.P., RICHTER, I.B., in *Neutron Cross Sections and Technology, Proc. Conf., Washington, D.C., March 4-7, 1968.* NBS Special Publication 299, (1968) p 1285. A reactor production study was made using a $^{242}$Pu sample in a highly thermalized spectrum. $\bar{\sigma}_a$ = 457 b; $\bar{\sigma}_{nf}$ = 409 b.

*Differential Data*

[3] MOORE, M.S., KEYWORTH, G.A., "Analysis of the fission and capture cross sections of the curium isotopes," *Phys. Rev. C3* (1971) 1656. LASL bomb shot fission and capture data were obtained for 21% enriched fission samples and mixed capture samples (predominantly $^{244,246}$Cm) for 20 eV <E <3 MeV. Fission data were analyzed for $\Gamma_f$ and $\Gamma_n$ assuming $\Gamma_\gamma$. 29 resonances were resolved for 20 eV <$E_o$ <60 eV.

*Integral Measurements*

[4] BENJAMIN, R.W., MACMURDO, K.W., SPENCER, J.D., "Fission cross sections for five isotopes of curium and californium-249," *Nucl. Sci. Eng. 47* (1972) 203. Reactor fission chamber and track counter measurements were made for bare and cadmium-covered multiple samples enriched to ∿22%. $^{235}$U monitors were used. $\sigma_{nf}^{2200}$ = 82 ±5 b; $I_{nf}$ ($E_n$ >0.625 eV) = 778 ±50 b.

[5] THOMPSON, M.C., HYDER, M.L., REULAND, R.J., "Thermal neutron cross sections and resonance integrals for $^{244}$Cm through $^{248}$Cm," *J. Inorg. Nucl. Chem. 33* (1971) 1553. Reactor irradiations and bare and cadmium-covered radiochemical and mass spectrometry techniques were used for multiple enriched samples. $^{235}$U and $^{59}$Co monitors were used. $\sigma_{n\gamma}^{2200}$ = 60 ±30 b; $I_c$ (no cutoff given) = 800 ±400 b; $\sigma_{nf}^{2200}$ = 100 ±50 b; $I_{nf}$ (no cutoff given) = 935 ±190 b.

[6] HALPERIN, J., OLIVER, J.H., STOUGHTON, R.W., "The fission thermal neutron cross section and resonance integral of $^{245}$Cm, $^{247}$Cm, and $^{249}$Cf," *Chemistry Division Annual Progress Report for Period Ending May 20, 1970*. USAEC Report ORNL-4581 (1970) p 37. Reactor irradiations and track counting were used for mixed curium samples enriched to 22% $^{247}$Cm. Au monitors were used. $\sigma_{nf}^{2200}$ = 120 ±12 b; $I_{nf}$ (no cutoff given) = 1060 ±110 b. Note: I is incorrect because the sample holder under the cadmium covers was hydrogenous.

[7] DIAMOND, H., HINES, J.J., SJOBLOM, R.K., BARNES, R.F., METTA, D.N., LERNER, J.L., FIELDS P.R., "Fission cross-sections for $^{243}$Pu, $^{250}$Bk, $^{247}$Cm, $^{245}$Cm, $^{254m}$Es, and $^{254}$Es, and odd-odd systematics," *J. Inorg. Nucl. Chem. 30* (1968) 2553. Reactor thermal column fission chamber measurements were made for samples of 14% enrichment. $^{235}$U monitors were used. No account was taken of epithermal neutrons. $\sigma_{nf}^{th}$ = 108 ±5 b.

*Nubar*

[8] ZHURAVLEV, *Proc. Conf. Nucl. Phys.*, Kiev, USSR, (1973). Quoted in CINDA75, Original reference not available. $\bar{\nu}_p$ = 3.79 ±0.15.

## CURIUM-248 (3.94 × 10$^5$ yr)

Significant integral, differential, and production data are available for $^{248}$Cm, and the quality is sufficient for a good evaluation. The capture cross section of this nuclide is of particular importance because it is the precursor of the beta decay link to the californium isotopes.

### Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* |
|---|---|---|---|
| $\sigma^{2200}$ | 2.89 | 0.34 | 1,4 |
| I | 251 | 14.7 | 1,2,4,5 |

| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Requested Precision* |
|---|---|---|---|---|
| Capture | Thermal | 10% | 1,4 | - |
| Fission | Thermal | 30% | 5 | - |
| Resolved Resonances | | | | |
| $\Gamma_n$ | 0-2400 eV | 7% | 2 | - |
| $\Gamma_f$ | 20-100 eV | 20% | 3 | - |
| $I_{n\gamma}$ | ≥0.625 eV | 10% | 1,4 | - |
| $I_{nf}$ | ≥0.625 eV | 15% | 1,5 | - |

*Nubar* *Reference*

| | | |
|---|---|---|
| Thermal | No measurements known | - |
| $\bar{\nu}(E)$ | | - |

Current or Future Measurements - None known

Recommendations - None, the data are adequate for current needs.

## References

*Production Data*


[1] BENJAMIN, R.W., MCCROSSON, F.J., VANDERVELDE, V.D., GORRELL, T.C., *A Consistent Set of Heavy Actinide Multigroup Cross Sections*, USERDA Report DP-1394 (1975). A self-consistent set of 84-group cross sections and resonance parameters has been developed for production chain isotopes from $^{242}$Pu to $^{253}$Es using the results of reactor production experiments and modern multigroup reactor production codes.


*Differential Data*


[2] BENJAMIN, R.W., AHLFELD, C.E., HARVEY, J.A., HILL, N.W., "Neutron total cross section of Cm-248," *Nucl. Sci. Eng.* *55* (1974) 440. ORELA time-of-flight transmission measurements were made with liquid-nitrogen-cooled samples of 97% $^{248}$Cm and 3% $^{246}$Cm. 47 resonances in $^{248}$Cm were analyzed for $E_0$ and $\Gamma_n^0$. $\Gamma_\gamma$ was determined for the first 3 resonances.

[3] MOORE, M.S., KEYWORTH, G.A., "Analyses of the fission and capture cross sections of the curium isotopes," *Phys. Rev.* *C3* (1971) 1656. LASL bomb shot fission and capture data were obtained for high-purity fission samples and mixed $^{244,246}$Cm capture samples for 20 eV $<E<$3 MeV. 8 resonances were analyzed for capture. Capture data were not very useful.


*Integral Data*


[4] DRUSCHEL, R.E., BAYBARZ, R.D., HALPERIN, J., "The thermal neutron capture cross section and resonance integral of $^{248}$Cm," *Chemistry Division Annual Progress Report for Period Ending May 20, 1973*, USAEC Report ORNL-4891 (1973) 23. The reactor irradiation in the ORR of a sample containing 97% $^{248}$Cm plus impurities of $^{246}$Cm and $^{244}$Cm yielded $\sigma_{n\gamma}^{2200}$ = 2.63 ±0.02 b and $I_{n\gamma}$ (no cutoff given) = 267 ±27 b. The cadmium-difference technique was used.

[5] BENJAMIN, R.W., MACMURDO, K.W., SPENCER, J.D., "Fission cross sections for five isotopes of curium and californium-249," *Nucl. Sci. Eng.* *47* (1972) 203. Reactor fission chamber and track-counter measurements were obtained for bare and cadmium-covered multiple samples of up to 96% enrichment. $^{235}$U monitors were used. $\sigma_{nf}^{2200}$ = 0.34 ±0.07 b; $I_{nf}$ (E >0.625 eV) = 13.2 ±0.8 b.

[6] THOMPSON, M.C., HYDER, M.L., REULAND, R.J., "Thermal neutron cross sections and resonance integrals for $^{244}$Cm through $^{248}$Cm," *J. Inorg. Nucl. Chem.* *33* (1971) 1553. Reactor irradiations were made with bare and cadmium-covered multiple enriched samples, followed by chemical separation and mass spectrometry. $^{235}$U and $^{59}$Co monitors were used. $\sigma_{n\gamma}^{2200}$ = 3 ±1 b; $I_{n\gamma}$ (no cutoff given) = 275 ±75 b. $\sigma_{nf}^{2200}$ and $I_{nf}$ are low.

## BERKELIUM-249 (314 d)

Very little data of any sort are available for $^{249}$Bk, with the exception of some production results. These cross sections are relatively less important for production forecasts because the capture cross section is obviously very large, although better knowledge of the $^{249}$Bk cross sections would help to further delimit the $^{250}$Cf cross section. Total cross section measurements are currently in progress and should be available soon (see below).

### Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* | |
|---|---|---|---|---|
| $\sigma^{2200}$ | 1600 | 0 | 1 | |
| I | 4000 | 0 | 1 | |
| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Requested Precision* |
| Capture | Thermal | 50% | 1 | 10% |
| Fission | - | - | 1 | - |
| Resolved Resonances | | | | |
| $\Gamma_n$, $\Gamma_f$ | No measurements known | | | |
| $I_{n\gamma}$ | ≥0.625 eV | 50% | 1 | 10% |
| $I_{nf}$ | - | - | - | - |
| *Nubar* | | | *Reference* | |
| Thermal | No measurements known | | - | - |
| $\bar{\nu}(E)$ | | | - | - |

**Current or Future Measurements** - Total cross section measurements at liquid nitrogen temperature using an initially highly pure $^{249}$Bk sample weighing about 7 mg are in progress at ORELA (J.A. Harvey, R.W. Benjamin, S. Raman, and N.W. Hill). Initial results indicate a resonance spacing of 1.1 eV with the first resonance a very large one at 0.2 eV. Data will be analyzable from thermal to about 100 eV.

**Recommendations** - Additional measurements would be of interest but are very difficult and are not crucial at the present.

### References

*Production Data*

[1] BENJAMIN, R.W., MCCROSSON, F.J., VANDERVELDE, V.D., GORRELL, T.C., *A Consistent Set of Heavy Actinide Multigroup Cross Sections*, USERDA Report DP-1394 (1975). A self-consistent set of 84-group cross sections and resonance parameters has been developed for production chain isotopes from $^{242}$Pu to $^{253}$Es using the results of reactor production experiments and modern multigroup reactor production codes.

*Integral Data*

[2] FOLGER, R.L., SMITH, J.A., BROWN, L.C., OVERMAN, R.F., HOLCOMB, H.P., in *Neutron Cross Sections and Technology, Proc. Conf., Washington, D.C., March 4-7, 1968*. NBS Special Publication 299 (1968) p 1279. Reactor activations were made for bare and cadmium-covered samples. $^{59}$Co monitors were used. $\sigma_a^{eff}$ = 1150 b; $I_a$ (>~0.5 eV) = 1240 b; inferred $\sigma_a^{2200}$ = 1400 b.

[3] MAGNUSSON, L.B., STUDIER, M.H., FIELDS, P.R., STEVENS, C.M., MECH, J.F., FRIEDMAN, A.M., DIAMOND, H., HUIZENGA, J.R., "Berkelium and californium isotopes produced in neutron irradiation of plutonium," *Phys. Rev. 96* (1954) 1576. Reactor irradiations were made in MTR to provide rough cross sections. $\sigma_{n\gamma}^{\text{Pile}} \simeq 350$ b.

[4] HARVEY. B.G., ROBINSON, H.P., THOMPSON, S.G., GHIORSO, A., CHOPPIN, G.R., "Some pile neutron cross sections of isotopes of americium, berkelium, californium, and element 99," *Phys. Rev. 95* (1954) 581. Crude, early burn-up measurements were made at MTR. $\sigma_{n\gamma}^{\text{Pile}} = 1100 \pm 300$ b.

Post-Deadline Contribution - *Integral Data*

[5] GAVRILOV, V.D., GONCHAROV, V.A., IVANENKO, V.V., SMIRNOV, V.P., KUSTOV, V.N., "Thermal cross sections and resonance integrals for capture and fission in $^{241}$Am, $^{243}$Am, $^{249}$Bk, $^{249}$Cf." (Private communication from V. I. Mostovoi, USSR). Cadmium difference measurements were made in the SM-2 reactor for capture and fission using $^{197}$Au and $^{59}$Co monitors. Glass and mica track detectors were used. Samples were enriched to 65.46% $^{249}$Bk, 34.54% $^{249}$Cf. Results were $\sigma_{n\gamma}^{2200} = 1800 \pm 100$ b, $I_{n\gamma}$ (no cutoff given) = 1100 ±100 b.

## CALIFORNIUM-249 (350.6 yr)

Considerable effort has been put into cross section measurements of $^{249}$Cf; production, differential, and integral data are available. This nuclide is not directly in the $^{252}$Cf chain and is significant only to the extent of the $^{249}$Bk beta decay (314 day half-life).

Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* | |
|---|---|---|---|---|
| $\sigma^{2200}$ | 481.4 | 1665 | 1,4,6 | |
| I | 625 | 1610 | 1,2 | *Requested* |
| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Precision* |
| Capture | Thermal | 6% | 1,5 | 10% |
| Fission | Thermal | 3% | 1,4 | 10% |
| Resolved Resonances | | | | |
| $\Gamma_n$ | 0.4-70 eV | ~10% | 2,3 | 10% |
| $\Gamma_f$ | 0.4-70 eV | ~10% | 2,3 | 10% |
| $I_{n\gamma}$ | ≥0.625 eV | 10% | 1 | 10% |
| $I_{nf}$ | ≥0.625 eV | 10% | 1 | 10% |
| *Nubar* | | *Precision* | *Reference* | |
| Thermal | $\bar{\nu}_p = 4.06$ | 1% | 8 | - |
| $\bar{\nu}(E)$ | No measurements known | | - | - |

**Current or Future Measurements** - The work of Dabbs, et al. [2] has only been analyzed in a preliminary fashion. The final values are expected by early 1976. The sample used for the $^{249}$Bk total cross section measurements at ORELA will be remeasured at 2 to 3 month intervals to follow buildup of $^{249}$Cf and to determine its total cross section (see Berkelium-249).

**Recommendations** - None

## References

*Production Data*


[1] BENJAMIN, R.W., MCCROSSON, F.J., VANDERVELDE, V.D., GORRELL, T.C., *A Consistent Set of Heavy Actinide Multigroup Cross Sections*, USERDA Report DP-1394 (1975). A self-consistent set of 84-group cross sections and resonance parameters has been developed for production chain isotopes from $^{242}$Pu to $^{253}$Es using the results of reactor production experiments and modern multigroup reactor production codes.

[2] DABBS, J.W.T., HILL, N.W., BEMIS, JR., C.E., MOORE, M.S., JAMES, G.D., ELLIS, A.N., "Neutron-induced fission of $^{249}$Cf," *Physics Division Annual Progress Report for the Period Ending December 31, 1973*. USAEC Report ORNL-4937 (1974) 181. Electron linac measurements were made of $\sigma_f(E)$ for 0.3 eV $<E_n<$1.5 eV using a highly pure sample. Multilevel analysis was performed of the first 11 resonances from 0.708 to 16.82 eV to obtain $\Gamma_n^\circ$ and $\Gamma_f$. The first resonance (at 0.708 eV) is huge and dominates the resonance integral.

[3] SILBERT, M.G., "The fission cross section of $^{249}$Cf," *Nucl. Sci. Eng. 51* (1973) 376. Nuclear detonation measurements were made of $\sigma_{nf}(E)$ for 13 eV $<E_n<$3 MeV on a 101-μg sample of ∿100% $^{249}$Cf. Reich-Moore fitting of cross section data was used to extract $E_o$, $\Gamma_n{}^\circ$, and $\Gamma_f$ for 43 resonances from 16 eV to 70 eV.


*Integral Data*


[4] BENJAMIN, R.W., MACMURDO, K.W., SPENCER, J.D., "Fission cross sections for five isotopes of curium and californium-249," *Nucl. Sci. Eng. 47* (1972) 203. Reactor fission chamber and track-counter measurements were made for bare and cadmium-covered samples of high-purity. $\sigma_{nf}^{2200}$ = 1660 ±50 b; $I_{nf}$ (E >0.625 eV) = 2114 ±70 b.

[5] HALPERIN, J., BEMIS, G.E., DRUSCHEL, R.E., EBY, R.E., "The thermal cross sections and resonance integrals for neutron capture of $^{249}$Cf, $^{250}$Cf, and $^{251}$Cf," *Chemistry Division Annual Progress Report for Period Ending May 20, 1971*. USAEC Report ORNL-4706 (1971) p 47. Reactor irradiations were made of pure $^{249,250}$Cf. Mass spectrometric isotopic ratio determinations were made for bare and cadmium-covered samples. $^{59}$Co monitors were used. $\sigma_{n\gamma}^{2200}$ = 478 ±25 b; $I_{n\gamma}$ (>∿0.5 eV) = 765 ±35 b.

[6] HALPERIN, J., OLIVER, J.H., STOUGHTON, R.W., "The fission thermal-neutron cross section and resonance integral of $^{245}$Cm, $^{247}$Cm, and $^{249}$Cf," *Chemistry Division Annual Report for Period Ending May 20, 1970*. USAEC Report ORNL-4581 (1970) p 37. Reactor irradiations and track counting were used for bare and cadmium-covered samples of high purity. $^{197}$Au monitors were used. $\sigma_{nf}^{2200}$ = 1690 ±160 b; $I_{nf}$ (no cutoff given) = 2940 ±280 b. The resonance integral is incorrect because moderating polyethylene foil holders were used inside the cadmium covers.

[7] METTA, D., DIAMOND, H., BARNES, R.F., MILSTED, J., GRAY, J., Jr., HENDERSON, D.J., STEVENS, C.M., "Nuclear constants of nine trans-plutonium nuclides," *J. Inorg. Nucl. Chem. 27* (1965) 33. Fission chamber measurements in CP-5 thermal column were made for pure $^{249}$Cf samples, normalized to $^{233}$U. $\sigma_{nf}^{2200}$ = 1735 ±70 b.

*Nubar*

[8] VOLODIN, K.E., NESTEROV, V.G., NURPEISOV, B., SMIRENKIN, G.N., TURCHIN, YU.M., KOSYAKOV, V.N., CHISTYAKOV, L.V., SHVETSOV, I.K., SHUBKO, V.M., MEZENTSEV, L.N., OKOLOVICH, V.N., "Neutron yield and fragment kinetic energy in thermal-neutron-induced fission of $Cf^{249}$," *Sov. Journ. Nucl. Phys. 15* (1972) 17. Coincidence measurements in a reactor neutron beam with a highly pure sample, a fission chamber, and 24 $^3He$ detectors yielded a thermal value of $\bar{\nu}_p = 4.06 \pm 0.04$.

Post-Deadline Contribution - *Integral Data*

[9] GAVRILOV, V.D., GONCHAROV, V.A., IVANENKO, V.V., SMIRNOV, V.P., KUSTOV, V.N., "Thermal cross sections and resonance integrals for capture and fission in $^{241}Am$, $^{243}Am$, $^{249}Bk$, $^{249}Cf$." (Private communication from V. I. Mostovoi, USSR). Cadmium difference measurements were made in the SM-2 reactor for capture and fission using $^{197}Au$ and $^{59}Co$ monitors. Glass and mica track detectors were used. Samples were $\sim$100% $^{249}Cf$. Results were: $\sigma_{n\gamma}^{2200} = 530 \pm 33$ b, $I_{n\gamma}$ (no cutoff given) = 720 ±120. $\sigma_{nf}^{2200} = 1610 \pm 110$ b, $I_{nf}$ (no cutoff given) = 1800 ±200.

## CALIFORNIUM-250 (13.08 yr)

Limited integral data and some production results are available for $^{250}Cf$, and the data are somewhat inconsistent. Any measurements on $^{250}Cf$ are difficult because of the problems of obtaining enough high-purity material and the relatively short half-life. The consistent-set approach [1] to obtaining cross section data seems the only way to obtain energy-dependent data in the near term.

### Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* |
|---|---|---|---|
| $\sigma^{2200}$ | 1701 | 0 | 1 |
| I | 11500 | 0 | 1,2 |

| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Requested Precision* |
|---|---|---|---|---|
| Capture | Thermal | 15% | 1,2 | 10% |
| Fission | - | - | - | 10% |
| Resolved Resonances | | | | |
| $\Gamma_n$ | No measurements known | | | 10% |
| $\Gamma_f$ | | | | 10% |
| $I_{n\gamma}$ | ≥0.625 | 7% | 1,2 | 10% |
| $I_{nf}$ | - | - | - | 10% |

| *Nubar* | | *Reference* |
|---|---|---|
| Thermal, $\bar{\nu}(E)$ | No measurements known | |

Current or Future Measurements - None known

Recommendations - Virtually any new, well-defined cross section measurements would be welcome. However, the short half-life, paucity of material, and isotopic purity problems conspire to make measurements very difficult. The most useful measurement would be the total cross section in the thermal and low-energy region, even if the precision were only good enough to determine the gross low-energy resonance structure.

## References

*Production Data*

[1] BENJAMIN, R.W., MCCROSSON, F.J., VANDERVELDE, V.D., GORRELL, T.C., *A Consistent Set of Heavy Actinide Multigroup Cross Sections*, USERDA Report DP-1394 (1975). A self-consistent set of 84-group cross sections and resonance parameters has been developed for production chain isotopes from $^{242}$Pu to $^{253}$Es using the results of reactor production experiments and modern multigroup reactor production codes.

*Differential Data* - No data available

*Integral Data*

[2] HALPERIN, J., BEMIS, Jr., C.E., DRUSCHEL, R.E., EBY, R.E., "The thermal cross sections and resonance integrals for neutron capture of $^{249}$Cf, $^{250}$Cf, and $^{251}$Cf," *Chemistry Division Annual Report for Period Ending May 20, 1971*, USAEC Report ORNL-4706 (1971) p 47. Reactor irradiations were made for samples of pure $^{249,250}$Cf. Mass spectrometric isotopic ratio determinations were made on bare and cadmium-covered samples. $^{59}$Co monitors were used. $\sigma_{n\gamma}^{thermal}$ = 2030 ±200 b; $I_{n\gamma}$ (>∼0.5 eV) = 11,600 ±500 b.

[3] SMITH, J.A., BANICK, C.J., FOLGER, R.L., HOLCOMB, H.P., RICHTER, I.B., in *Neutron Cross Sections and Technology, Proc. Conf., Washington, D.C., March 4-7, 1968*. NBS Special Publication 299 (1968) p 1285. Reactor production studies were made with a $^{242}$Pu sample in a highly thermalized spectrum. $\bar{\sigma}_a$ = 1090 b.

[4] FOLGER, R.L., SMITH, J.A., BROWN, L.C., OVERMAN, R.F., HOLCOMB, H.P., in *Neutron Cross Sections and Technology, Proc. Conf., Washington, D.C., March 4-7, 1968*. NBS Special Publication 299 (1968) p 1279. Reactor activations were made for bare and cadmium-covered samples. $\sigma_a^{eff}$ = 1250 b; $I_a$ (>0.5 eV) = 5300 b; inferred $\sigma_a^{2200}$ = 1250 b.

[5] MAGNUSSON, L.B., STUDIER, M.H., FIELDS, P.R., STEVEN, C.M., MECH, J.F., FRIEDMAN, A.M., DIAMOND, H., HUIZENGA, J.R., "Berkelium and californium isotopes produced in neutron irradiation of plutonium," *Phys. Rev. 96* (1954) 1576. Reactor irradiations were made in the MTR to provide rough values. $\sigma_{n\gamma}^{Pile}$ = 1500 b.

## CALIFORNIUM-251 (898 yr)

Only integral and production data are available for $^{251}$Cf, but the more recent data for capture and for thermal fission seem reasonably consistent. The fission resonance integral still has a substantial uncertainty. The cross sections in the thermal region are expected to deviate markedly from the $1/\sqrt{E}$ energy dependence assumed in thermal integral measurements. Therefore, the precisions of the equivalent thermal cross sections have been increased from values of about 5% [3,4] to 10% in the table below to account for the anticipated strong spectral dependence. An all-out campaign to produce sufficient high-purity material for an energy-dependent fission cross section measurement would be worthwhile.

Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* | |
|---|---|---|---|---|
| $\sigma^{2200}$ | 2849 | 4801 | 1,3,4 | |
| I | 1590 | 5380 | 1,4 | |
| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Requested Precision* |
| Capture | Thermal | 10% | 1,4 | 10% |
| Fission | Thermal | 10% | 1,3 | 10% |
| Resolved Resonances | | | | |
| $\Gamma n$ | No measurements known | | | 10% |
| $\Gamma f$ | | | | 10% |
| $I_{n\gamma}$ | ⩾0.625 | 4% | 4 | 10% |
| $I_{nf}$ | ⩾0.625 | 15% | 1 | 10% |

*Nubar*

| | |
|---|---|
| Thermal, $\bar{\nu}(E)$ | No measurements known |

Current or Future Measurements - None known.

Recommendations - An energy-dependent fission cross section measurement should be planned in the near future to cover the thermal and (at least) the low-energy resonance regions. Such a measurement could be made with ∿1 μg of high-purity material using the techniques described by Dabbs, et al. *(Proc. Conf. Nucl. Cross Sect. and Tech.,* Washington, D. C., March 1975 - to be published). The thermal cross section shape is particularly important.

References

*Production Data*

[1] BENJAMIN, R.W., MCCROSSON, F.J., VANDERVELDE, V.D., GORRELL, T.C. *A Consistent Set of Heavy Actinide Multigroup Cross Sections,* USERDA Report DP-1394 (1975). A self-consistent set of 84-group cross sections and resonance parameters has been developed for production chain isotopes from $^{242}$Pu to $^{253}$Es using the results of reactor production experiments and modern multigroup reactor production codes.

*Integral Data*

[2] FLYNN, K.F., GINDLER, J.E., SJOBLOM, R.K., GLENDENIN, L.E., "Mass distributions for thermal-neutron-induced fission of $^{255}$Fm and $^{251}$Cf," *Phys. Rev. C 11* (1975) 1676. Cross sections were determined for $^{251}$Cf in the course of determining mass distributions. $\sigma_{nf}^{2200}$ = 5300 ±530 b.

[3] RAGAINI, R.C., HULET, E.K, LOUGHEED, R.W., WILD, J, "Symmetric fission in the neutron-induced fission of $^{255}$Fm," *Phys. Rev. C9* 1974)399. Thermal column measurements with Si detectors of $^{255}$Fm and $^{251}$Cf daughter. $\sigma_{nf}$ was determined from the fission rate. $\sigma_{nf}^{2200}$ = 4800 ±250 b.

[4] HALPERIN, J., BEMIS, Jr., C.E., DRUSCHEL, R.E., BAYBARZ, R.D., EBY, R.E., "The thermal cross sections and resonance integrals for neutron capture of $^{249}$Cf, $^{250}$Cf, and $^{251}$Cf," BEMIS, Jr., C.E., DRUSCHEL, R.E., BAYBARZ, R.D., HALPERIN, J., "Evaluation of $^{251}$Cf burnout experiment," *Chemistry Division Annual Report for Period Ending May 20, 1971.* USAEC Report ORNL-4706 (1971). Reactor irradiations were made of pure $^{249,250}$Cf. Mass spectrometric isotopic ratio determinations were made for bare and cadmium-covered samples. $^{59}$Co monitors were used. $\sigma_{n\gamma}^{th}$ = 2850 ±150 b and $I_{n\gamma}$ (>∿0.5 eV) = 1600 ±30 b. Also, $\sigma_a^{eff}$ ≃6900 ±1380 b and $\sigma_{n\gamma}^{eff}$ = 3022 ±150 b, with activation measurement, chemical separation, and alpha counting, $I_a$ ≅7000 b ±50%, $I_{n\gamma}$ = 1620 ±100 b.

[5] METTA, D., DIAMOND, H., BARNES, R.F., MILSTAD, J., GRAY, Jr., J., HENDERSON, D.J., STEVENS, C.M., "Nuclear constants of nine transplutonium nuclides." *J. Inorg. Nucl. Chem. 27* (1965) 33. Fission chamber measurements were made in the CP-5 thermal column for mixed californium samples. Data were normalized to $^{239}$Pu. $\sigma_{nf}^{2200}$ = 3000 ±260 b.

[6] SMITH, J.A., BANICK, C.J., FOLGER, R.L., HOLCOMB, H.P., RICHTER, I.B., *Neutron Cross Sections and Technology, Proc. Conf., Washington, D. C, March 4-7, 1968.* NBS Special Publication 299 (1968) 1285. Reactor production study was made in a highly thermalized spectrum with a bare $^{242}$Pu sample. $\bar{\sigma}_a$ = 4970 b; $\bar{\sigma}_{nf}$ = 3550 b.

[7] FOLGER, R.L., SMITH, J.A., BROWN, L.C., OVERMAN, R.F., HOLCOMB, H.P., *Neutron Cross Sections and Technology, Proc. Conf., Washington, D. C., 1968.* NBS Special Publication 299, Vol. II (1968) 1279. Reactor activations were made for bare and cadmium-covered samples. $\sigma_a^{eff}$ = 5300 b; $I_a$ (>∿0.5 eV) = 980 b; inferred $\sigma_a^{2200}$ = 6600 b.

## CALIFORNIUM-252 (2.646 yr)

Good differential fission data are available from 20 eV to 5 MeV, and fission resonance parameters have been extracted in the energy region from 20 to 984 eV. Several integral capture and fission measurements are available and, with the production measurements, appear to be consistent. The energy-dependent cross section of $^{252}$Cf appears to be well-behaved; i.e., there is no large resonance in the thermal-epithermal interface region. Additional energy-dependent data in the near future are unlikely because of the high alpha activity and spontaneous fission background associated with $^{252}$Cf.

### Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* |
|---|---|---|---|
| $\sigma^{2200}$ | 20.4 | 32.0 | 1,3,4,5 |
| I | 43.4 | 110.0 | 1,3,4,5 |

| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Requested Precision* |
|---|---|---|---|---|
| Capture | Thermal | 8% | 1,4,5 | 10% |
| Fission | Thermal | 10% | 1,3 | 10% |
| Resolved Resonances | | | | |
| $\Gamma_n$ | | | | 10% |
| $\Gamma_f(\frac{1}{2}\pi\sigma_o\Gamma_f)$ | 24-984 eV | 10-20% | 2 | 10% |
| $I_{n\gamma}$ | ≥0.625 | 8% | 1,4,5 | 10% |
| $I_{nf}$ | ≥0.625 | 20% | 1,3 | 10% |

*Nubar* *Reference*

| | | |
|---|---|---|
| Thermal } | No measurements known | - |
| $\bar{\nu}(E)$ | | - |

Current or Future Measurements - None known

Recommendations - None

References

*Production Data*


[1] BENJAMIN, R.W., MCCROSSON, F.J., VANDERVELDE, V.D., GORRELL, T.C., *A Consistent Set of Heavy Actinide Multigroup Cross Sections*, USERDA Report DP-1394 (1975). A self-consistent set of 84-group cross sections and resonance parameters has been developed for production chain isotopes from $^{242}$Pu to $^{253}$Es using the results of reactor production experiments and modern multigroup reactor production codes.


*Differential Data*


[2] MOORE, M.S., MCNALLY J.H., BAYBARZ, R.D., "Neutron-induced fission cross section of $^{252}$Cf," *Phys. Rev. C4* (1971) 273. Bomb shot measurements were made of $\sigma_f(E)$ for 20 eV to 5 MeV; $\frac{1}{2}\pi\sigma_0\Gamma_f$ was deduced from 24 eV to 984 eV (35 resonances), $I_{nf}$ (>20 eV) = 65 ±6 b.


*Integral Data*


[3] HALPERIN, J., OLIVER, J.H., STOUGHTON, R.W., "The thermal cross section and resonance integral for neutron fission of $^{252}$Cf," *Chemistry Division Annual Report for Period Ending May 20, 1971.* USAEC Report ORNL-4706 (1971) p 53. Fission-track measurements were made in the ORNL Research Reactor (ORR) for bare and cadmium-covered samples. Data were normalized to $^{197}$Au and $^{56}$Mn. $\sigma_{nf}^{eff}$ = 35 ±4 b; $I_{nf}$ = 110 ±30 b; inferred $\sigma_{nf}^{2200}$ = 32 ±4 b.

[4] EBERLE, S.H., REINHARDT, J., GANTNER, E., KRUCKEBERG, C., KFK-1338, Karlsruhe, West Germany (1971). Reactor activations were made for bare and cadmium-covered samples. $\sigma_{n\gamma}^{2200}$ = 20 ±1.5 b. $I_{n\gamma}$ (no cutoff given) = 40 ±4 b.

[5] HALPERIN, J., BEMIS, Jr., C.E., DRUSCHEL, R.E., STOKELY, J.R., "The thermal-neutron capture cross section and resonance integral of $^{252}$Cf," *Nucl. Sci. Eng. 37* (1969) 228. Reactor activations were made for bare and cadmium-covered samples. $\sigma_{n\gamma}^{2200}$ = 20.4 ±2 b; $I_{n\gamma}$ (>0.54 eV) = 43.5 ±3 b.

[6] FOLGER, R.L., SMITH, J.A., BROWN, L.C., OVERMAN, R.F., HOLCOMB, H.P., in *Neutron Cross Sections and Technology, Proc. Conf., Washington, D.C., March 4-7 1968.* NBS Special Publication 299, (1968) p 1279. Reactor activations were made for bare and cadmium-covered samples. $\sigma_a^{eff}$ = 7.4 b; $I_a$ (no cutoff given) = 42 b; inferred $\sigma_a^{2200}$ = 8.6 b.

## CALIFORNIUM-253 (17.82 d)

A small quantity of integral data is available for $^{253}Cf$, the beta-decay precursor to Es and Fm. The thermal fission measurement of Wild, et al. [2] combined with results for the production measurements of Benjamin, et al. [1] give a basis for reactor calculations. The nuclides above $^{252}Cf$, while of interest, are not of prime importance.

### Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* |
|---|---|---|---|
| $\sigma^{2200}$ | 12.0 | 1100 | 1,3 |
| I | 12.1 | 2000 | 1 |

| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Requested Precision* |
|---|---|---|---|---|
| Capture | Thermal | 20% | 1 | - |
| Fission | Thermal | 20% | 1,3 | - |
| Resolved Resonances | | | | |
| $\Gamma_n$, $\Gamma_f$ | No measurements known | | | - |
| $I_{n\gamma}$ | ≥0.625 | 25% | | - |
| $I_{nf}$ | ≥0.625 | 25% | | - |

| *Nubar* | | *Reference* | |
|---|---|---|---|
| Thermal | No measurements known | | - |
| $\bar{\nu}(E)$ | | | - |

Current or Future Measurements - None known

Recommendations - None

### References

*Production Data*


[1] BENJAMIN, R.W., MCCROSSON, F.J., VANDERVELDE, V.D., GORRELL, T.C., *A Consistent Set of Heavy Actinide Multigroup Cross Sections*, USERDA Report DP-1394 (1975). A self-consistent set of 84-group cross sections and resonance parameters has been developed for production chain isotopes from $^{242}Pu$ to $^{253}Es$ using the results of reactor production experiments and modern multigroup reactor production codes.

[2] SMITH, J.A., BANICK, C.J., FOLGER, R.L., HOLCOMB, H.P., RICHTER, I.B., in *Neutron Cross Sections and Technology, Proc. Conf., Washington, D.C., March 4-7, 1968*. NBS Special Publication 299 (1968) p 1285. Reactor production studies were made for a highly thermalized spectrum from a bare $^{242}Pu$ sample. $\bar{\sigma}_a$ = 165 b.


*Integral Data*


[3] WILD, J.F., HULET, E.K., LOUGHEED, R.W., "Some nuclear properties fermium-257," *J. Inorg. Nucl. Chem. 35* (1973) 1063. Material from Hutch heavy-element explosion of July 1969. Used separated decay product $^{253}Cf$, fission track recorders (mica) in Livermore Pool Type Reactor (Cd-ratio for Au ∿1000). $\sigma_{nf}^{thermal}(^{253}Cf) = 1300 \pm 240b$.

[4] BEMIS, Jr., C.E., DRUSCHEL, R.E., HALPERIN, J., "Effective capture and fission cross sections for californium-253," *Nucl. Sci. Eng.* 41 (1970) 146. Reactor irradiations were made in the ORR for mixed samples of 40% $^{253}$Cf and 60% $^{252}$Cf. Determined $\sigma_{n\gamma}^{eff}$ = 17.6 ±1.8 b; $\sigma_{abs}^{eff}$ = 2550 ±400 b.

## EINSTEINIUM-253 (20.47 d)

Only production and integral data are available for $^{253}$Es, and all are capture measurements. More extensive data are not crucial and would be difficult to obtain because of the short half-life and the very small amount of material available.

### Data Summary

| *Cross Sections* | | *Capture* | *Fission* | *Reference* |
|---|---|---|---|---|
| $\sigma^{2200}$ | to $^{254}$Es | <3 | - | 2 |
| | to $^{254m}$Es | 155 | - | 2 |
| I | to $^{254}$Es | 4299 | - | 2 |
| | to $^{254m}$Es | 3009 | - | 2 |

| *Reaction* | *Energy range* | *Precision* | *Reference* | *Requested Precision* |
|---|---|---|---|---|
| Capture to $^{254}$Es | Thermal | - | - | - |
| Capture to $^{254m}$Es | Thermal | 13% | 2 | - |
| Fission | Thermal | - | - | - |
| Resolved Resonances | | | | |
| $\Gamma_n$ } $\Gamma_f$ | No measurements known | | | |
| $I_{n\gamma}$ to $^{254}$Es | ≥0.412 eV | 5% | 2 | - |
| $I_{n\gamma}$ to $^{254m}$Es | ≥0.412 eV | 6% | 2 | - |

*Nubar*

| | |
|---|---|
| Thermal } $\bar{\nu}$ (E) | No measurements known |

### Current or Future Measurements - None known

### Recommendations - None

### References

*Production Data*

[1] BENJAMIN, R.W., MCCROSSON, F.J., VANDERVELDE, V.D., GORRELL, T.C., *A Consistent Set of Heavy Actinide Multigroup Cross Sections*, USERDA Report DP-1394 (1975). A self-consistent set of 84-group cross sections and resonance parameters has been developed for production chain isotopes from $^{242}$Pu to $^{253}$Es using the results of reactor production experiments and modern multigroup reactor production codes.

*Integral Data*

[2] HARBOUR, R.M., MACMURDO, K.W., "Thermal neutron capture cross sections and capture resonance integrals of $^{253}$Es." *J. Inorg Nucl. Chem 35* (1973) 1821. Reactor activations were made with bare and cadmium-covered samples. Data were normalized to $^{59}$Co. $\sigma_{n\gamma}^{2200}$ (to $^{254m}$Es) = 155 ±20 b; $\sigma_{n\gamma}^{2200}$ ( to $^{254g}$Es) <3 b; $I_{n\gamma}$ (to $^{254m}$Es, >0.421 eV) = 3009 ±168 b; $I_{n\gamma}$ (to $^{254g}$Es, >0.421 eV) = 4299 ±218 b.

NOTE: It will be very difficult to fit a resonance structure with the use of nuclear systematics to such large resonance integrals and such small thermal cross sections.

[3] FOLGER, R.L., SMITH, J.A., BROWN, L.C., OVERMAN, R.F., HOLCOMB, H.P., in *Neutron Cross Sections and Technology, Proc. Conf., Washington, D.C., March 4-7, 1968. NBS Special Publication 299,* (1968) 1279. Reactor activations were made for bare and cadmium-covered samples. Data were normalized to $^{59}$Co. $\sigma_a^{eff}$ = 200 b. $I_a$ (no cutoff given) = 3600 b; inferred $\sigma_a^{2200}$ = 130 b.

[4] FIELDS, P.R., DIAMOND, H., FRIEDMAN, A.M., MILSTED, J., LERNER, J.L., BARNES, R.F., SJOBLOM, R.K., METTA, D.N., HORWITZ, E.P., "Some new properties of $^{254}$Es and $^{255}$Es." *Nucl. Phys. A96* (1967) 440. Reactor activations were made for bare samples. Data were normalized to $^{59}$Co. $\sigma_{n\gamma}^{Pile}$ (to $^{254g}$Es) = 13 b.

See also ANUFRIEV, V.A., et al., *Sov. At. En. 36* (1974) 359, for effective cross sections in a hard, but unspecified spectrum.

## EINSTEINIUM-254, Ground State (276 d) and Isomeric State (39.3 h)

Only integral data are available for $^{254}$Es, and all are fission measurements. The useful measurements include two consistent thermal cross sections for $^{254}$Es, one thermal cross section for $^{254m}$Es, and one resonance integral for $^{254}$Es. Further data are not crucial and would be difficult to obtain because of the very small amount of $^{254}$Es available.

### Data Summary

| *Cross Sections* | *Capture* | *Fission* | *Reference* |
|---|---|---|---|
| $\sigma^{2200}$ (254) | - | 2900 | 1,2 |
| $\sigma^{2200}$ (254m) | - | 1840 | 2 |
| I (254) | - | 2200 | 1 |

| *Reaction* | *Energy Range* | *Precision* | *Reference* | *Requested Precision* |
|---|---|---|---|---|
| Capture | - | - | - | - |
| Fission | Thermal | 5% | 1,2 | - |
| Resolved Resonances | | | | |
| $\Gamma_n$ | No measurements known | | | - |
| $\Gamma_f$ | | | | - |
| $I_{n\gamma}$ | - | - | - | - |
| $I_{nf}$ | ≥0.421 eV | 5% | 1 | - |

| *Nubar* | | *Reference* |
|---|---|---|
| Thermal, $\bar{\nu}(E)$ | No measurements known | - |

Current or Future Measurements - None known

Recommendations - None

References

*Integral Data*


[1] MACMURDO, K.W., HARBOUR, R.M., "Thermal neutron fission cross section and fission resonance integral of $^{254}$Es," *J. Inorg. Nucl. Chem. 34* (1972) 449. Fission-track measurements were made in the Savannah River Standard Pile (SP) reactor for bare and cadmium-covered samples. Data were normalized to $^{249}$Cf. $\sigma_{nf}^{2200}$ = 2830 ±130 b; $I_{nf}$ (>0.421 eV) = 2200 ±90 b.

[2] DIAMOND, H., HINES, J.J., SJOBLOM, R.K., BARNES, R.F., METTA, D.N., LERNER, J.L., FIELDS, P.R., "Fission cross sections for $^{243}$Pu, $^{250}$Bk, $^{247}$Cm, $^{245}$Cm, $^{254m}$Es, and odd-odd systematics," *J. Inorg. Nucl. Chem. 30* (1968) 2553. Fission chamber measurements were made in a reactor thermal column with bare and cadmium-covered samples. Data were normalized to $^{235}$U. $\sigma_{nf}^{2200}$ ($^{254}$Es) = 3060 ±180 b. $\sigma_{nf}^{2200}$ ($^{254m}$Es) = 1840 ±80 b.

[3] SCHUMAN, R.P., EASTWOOD, T.A., JACKSON, H.G., BUTLER, J.P., "The half-life, neutron capture, and fission cross sections of long-lived einsteinium-254," *J. Inorg. Nucl. Chem. 6* (1958) 1. Reactor burnup measurements were made with low precision. $\sigma_{nf}^{eff}$ ($^{254}$Es) = 2700 ±600 b; $\sigma_{n\gamma}^{eff}$ ≤40 b.

[4] HARVEY, B.G., ROBINSON, H.P., THOMPSON, S.G., GHIORSO, A., CHOPIN, G.R. "Some pile neutron cross sections of isotopes of americium, berkelium, californium, and element 99," *Phys. Rev. 95* (1954) 581. Crude early burn-up measurements were made at the MTR. $\sigma_{n\gamma}^{Pile}$ <15 b.

See also VANUFRIEV, V.A., et al., *Sov. At. En. 36* (1974) 359, for effective cross sections in a hard, but unspecified, spectrum.



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## BIBLIOGRAPHY


1. CRANDALL, J.L., "Tons of curium and pounds of californium," *Proc. Conf. Constructive Uses of Atomic Energy*, Washington, D.C. (1968) 193.

2. ELLIS, Y.A., "A = 241," *Nucl. Data Sheets 6* (1971) 630.

3. ELLIS, Y.A., WAPSTRA, A.H., "A = 249," *Nucl. Data Sheets 3* (1969) B3-2-61.

4. ELLIS, Y.A., "A = 242," *Nucl. Data Sheets 4* (1970) 683.

5. ELLIS, Y.A., WAPSTRA, A.H., "A = 252," *Nucl. Data Sheets 3* (1969) B3-2-85.

6. WESTCOTT, C.H., *Effective Cross Sections for Well-Moderated Thermal Reactor Spectra*, Canadian AEC Report CRRP-787 (1958).

7. BAUMANN, N.P., *Resonance Integrals and Self-Shielding Factors for Detector Foils*, USAEC Report DP-817 (1963).

8. ZIJP, W.L., "Nuclear data for neutron metrology, *Proc. Symp. Nucl. Data in Sci. and Tech.*, Paris (1973) Vol. 2, p. 271.

9. JAMES, G.D., "Status of neutron cross sections of transactinium isotopes in the resonance energy region," *Advisory Group Meeting on Transactinium Isotope Nuclear Data*, Karlsruhe, West Germany, November 3-7, 1975, Paper B-2.

10. MOORE, M.S., "Status of neutron cross sections of transactinium isotopes in the resonance and fast energy regions - underground nuclear explosion measurements," *Advisory Group Meeting on Transactinium Isotope Nuclear Data*, Karlsruhe, West Germany, November 3-7, 1975, Paper B-3.

11. BENJAMIN, R.W., MCCROSSON, F.J., VANDERVELDE, V.D., GORRELL, T.C., *A Consistent Set of Heavy Actinide Multigroup Cross Sections*, USERDA Report DP-1394 (1975).

12. *Compilation of Requests for Nuclear Data, April, 1975*, USERDA Report BNL-50444 (1975).

13. DIERCKX, R., private communication.

14. CANER, M., YIFTAH, S., *Nuclear Data Evaluation for Pu-240*, Israel AEC Report IA-1243 (1972).

15. MANERO, F., KONSHIN, V.A., "Status of the energy-dependent $\bar{\nu}$-values for the heavy isotopes (Z >90) from thermal to 15 MeV and of $\bar{\nu}$-values for spontaneous fission," *At. En. Rev. 10* (1972) 637.

16. GOLDSTEIN, H., "Nomenclature scheme for experimental monoenergetic nuclear cross sections," in *Fast Neutron Physics, Part II*, Marion, J.B., Fowler, J.K., eds., Interscience Publishers, New York (1963) p. 2227.

General References

A list of the more useful general references for transactinium cross section and $\bar{\nu}$ data follows, with a brief description of each reference.


17. MUGHABGHAB, S.F., GARBER, D.I., *Neutron Cross Sections, Volume 1, Resonance Parameters*, USAEC Report BNL 325, Third Ed., (1973). This very useful primary reference lists recommended integral cross sections, resonance properties, and resonance parameters which have been drawn from the literature. Care must be exercised, however, for integral cross sections quoted are not always experimentally measured values, e.g., the thermal capture cross section of $^{243}$Cm.

18. GARBER, D.I., KINSEY, R.R., *Neutron Cross Sections, Volume 2, Curves*, USERDA Report BNL-325, Third Ed. (to be released in 1975). This compilation shows the cross section data graphically as a function of energy and is especially useful in showing up regions where contradictory data exist.

19. BENJAMIN, R.W., MCCROSSON, F.J., VANDERVELDE, V.D., GORRELL, T.C., *A Consistent Set of Heavy Actinide Multigroup Cross Sections*, USERDA Report DP-1394 (to be released in 1975). This cross section and production study lists resonance parameters and 84-group smooth cross sections for production chain nuclides from $^{242}$Pu to $^{253}$Es.

20. MANERO, F., KONSHIN, V.A., "Status of energy-dependent $\bar{\nu}$-values for the heavy isotopes (Z >90) from thermal to 15 MeV and of $\bar{\nu}$-values for spontaneous fission," *At. En. Rev. 10* (1972) 637. This is an indispensable review article for anyone interested in $\bar{\nu}$ for the actinides.

21. *CINDA-75, Vol. 2, Z ≥53, An Index to the Literature on Microscopic Neutron Data*, International Atomic Energy Agency, Vienna (1975).

22. KING, J.L., BIGELOW, J.E., COLLINS, E.D., *Transuranium Processing Plant Semiannual Report of Production, Status, and Plans for Period Ending December 31, 1973*, USAEC Report ORNL-4965 (1974). This report contains the integral, consistent cross section set in current use at the TRU facility for HFIR irradiations.

IAEA-NEA Advisory Group Meeting on Transactinium Isotope Nuclear Data

Review Paper B2

# STATUS OF NEUTRON CROSS SECTIONS OF TRANSACTINIUM ISOTOPES IN THE RESONANCE REGION - LINEAR ACCELERATOR MEASUREMENTS

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Abstract

A review of the status of transactinium isotope cross sections in the resonance region and of resolved resonance parameters is given by summarising the work submitted by fourteen contributors and also by highlighting other work where notable progress has been made in our knowledge of neutron resonance phenomena.

## 1. INTRODUCTION

The neutron total, fission and capture cross sections of transactinium isotopes are of importance in the design and safety of nuclear reactors, in the safe handling and management of reactor fuels and in the management of nuclear waste. Cross section measurements on some transactinium isotopes, not of direct technological interest, have on occasion greatly extended our knowledge of the basic nuclear physics which, with continual improvement will enable the cross sections of technological importance to be calculated with acceptable accuracy. This report reviews the status and accuracy of existing total, fission and capture cross sections, in the resonance region, and the parameters of resolved resonances for isotopes ranging from Z=90 to Z=105 excluding the better known isotopes $^{232}$Th, $^{233}$U, $^{235}$U, $^{238}$U, and $^{239}$Pu. It also reviews the statistical methods used in obtaining, averaging and examining the resonance parameters and cross sections. As noted previously [1], the discovery of strong resonance structure near threshold in the fission cross section of some isotopes leads to a natural extension of our concept of the resonance region from the fine structure levels of the first fission potential barrier minimum towards the effects of stationary levels in the second minimum. These have an influence observable as resonance structure in fission cross sections up to and possibly beyond incident neutron energies of 1 MeV. To include such effects the review has been extended to results obtained on sources other than linear accelerators but excluding underground nuclear explosions. Some techniques of measurement or analysis are of such importance that they are considered in this review even though they have so far been applied to nuclei among the five better known fissionable isotopes.

Fourteen scientists kindly sent me reports giving the latest account of their work and these are summarised in the next section. Sections 3 and 4 are devoted to a discussion of fission cross sections for odd and even nuclei, which exhibit sub-threshold fission phenomena. It is convenient to divide the discussion into the fine structure fission data governed by narrow intermediate structure (sect.3) and a discussion (sect.4) of gross structure near the fission threshold. In these sections the data are confined to results obtained since the excellent review of Michaudon [58]. As pointed out by C.F. Powell a generation ago, new discoveries are made once the experimental techniques capable of making them are developed. Probably the most outstanding advance of recent years in the direct measurement of resonance parameters is contained in the work of Keyworth et al. [2] on the spin determination of resonances for $^{235}U$ and $^{237}Np$. Another development in technique, in the use of a lead slowing down spectrometer by Block et al. [26] , has lead to the discovery of sub-threshold fission resonances in $^{238}U$ and possibly in $^{232}Th$ also. Recently, Dabbs et al. [3] have developed a spherical fission chamber to counter alpha pile-up. These techniques and others which have advanced our knowledge of resonance neutron cross-sections are briefly discussed in sect.5. Since the early advances of Wigner [4] and Porter and Thomas [5] neutron resonance parameters and the cross-sections which they govern have undergone detailed analyses designed to ascertain their distributions, to correct average values for the effect of missed resonances, to select a quantally pure sequence of resonances and, since the discovery of narrow intermediate structure in sub-threshold fission, to search for energy dependent structure. Notable advances in the last two topics have been made in recent years and are discussed in sect.6. Finally, in sect.7, we note the areas where further work might prove most fruitful.

## 2. CORRESPONDENTS REPORTS

Fourteen correspondents sent reports of work in their laboratories which are summarised here.

2.1 Harwell, Chemistry Division (Mrs. K.M. Glover)

Measurements [6] on the integral cross sections of $^{241}Am$ leading to the production of $^{242}Cm$ have been made in ZEBRA core 12 and in ZEBRA core 14 which is a close mock-up of PFR. The results obtained for the production cross section of $^{242}Cm$ are given below.

| | Calculated | Experimental | Ratio (Exp/Calc) |
|---|---|---|---|
| Zebra core 12 | 0.970b | 1.50 $\pm$ 0.090b | 1.55 |
| Zebra core 14 | 0.810b | 1.275 $\pm$ 0.013b | 1.57 |

Measurements on the integral cross section of $^{243}Am$ leading to the production of $^{244}Cm$ are in progress.

2.2 Harwell, Linac (B.H. Patrick)

Dr. Patrick has listed the nuclear data measurement programmes of the EEC member countries. Only three TND measurements in the resonance region are planned. They are the fission cross section of $^{241}Am$ from 100 eV to 100 keV by Gayther at Harwell and from 1 eV to 1 MeV by Brusegan et al. at Geel, and $^{241}Am(n,\gamma)$ from 100 eV to 100 keV by Coates et al. at Harwell. In the energy range above about 10 keV, measurements on $^{237}Np(n,f)$, $^{240}Pu(n,f)$, $^{240}Pu(n,\gamma)$, $^{242}Pu(n,\gamma)$, $^{241}Am(n,f)$ and $^{241}Am(n,\gamma)$ are planned at Karlsruhe.

2.3 CCDN (H. Derrien)

The work of Derrien and Lucas [7] on the total and fission cross section of $^{241}Am$ supersedes the data given at the 1973 Kiev conference because of a 1% change in the $2g\Gamma_n$ values. Values of $2g\Gamma_n$ for 189 levels and values of the radiation width $\Gamma_\gamma$ for 43 levels below 150 eV are given. The s-wave strength function is found to be (0.94 $\pm$ 0.09) $10^{-4}$ and the average radiation width for 43 levels is (43.77 $\pm$ 0.72)meV. The mean level spacing below 50 eV corrected for 18% of missed levels is (0.55 $\pm$ 0.05)eV. Fission widths for 38 levels up to 39.62 eV are given based on a single level Breit-Wigner shape analysis. They have an average value $\langle\Gamma_f\rangle$ = 0.23 meV and obey a chi-squared distribution with $\nu$ = 4 degrees of freedom. The fission cross section data of Seeger et al. [8] have been analysed to provide 36 values of $\Gamma_f$ in the energy range 20 eV to 50 eV. These results give $\langle\Gamma_f\rangle$ = 0.52 meV and $\nu$ = 15 in disagreement with the Saclay data. A possible explanation is an admixture of capture ray events in the Los Alamos fission detector. The admixture would have to be large, 60%, but would represent only 0.7% of the total capture. The fission widths are in good agreement with the data of Bowman et al. [9] except for four levels where the parameters published by Bowman are ten times smaller than the Saclay data. The fission cross section measurements were performed by coincident fission neutron detection at 8% efficiency using NE213 liquid scintillator and pulse shape discrimination to eliminate $\gamma$-ray pulses. However, the high alpha activity gives a high neutron background from ($\alpha$,n) reaction in the oxide and the measurement could be improved by the use of a metal sample canned in a material of high atomic number. The reduction in neutron background would enable the neutron detection to be carried out without requiring a coincidence, thus increasing the efficiency by a large factor [10] .

2.4 CEN, Saclay (P. Ribon)

Workers at Saclay have undertaken the measurement of $^{237}$Np [11], $^{232}$Th, $^{238}$U and $^{239}$Pu [12, 13] and $^{243}$Am [14] fission cross sections with high resolution, for example 1.5 keV at 500 keV, near the fission threshold. The data on $^{237}$Np(n,f) show almost no structure between 0.1 and 2 MeV thus confirming the low value of the energy of the second minimum ($E_{II}$ = 1.84 MeV) [15] and the complete damping of possible vibrational states in the second well. The data on $^{232}$Th and $^{238}$U, although excluded from consideration at this meeting, are mentioned because they both show detailed structure in the neighbourhood of fission threshold. In the case of $^{238}$U(n,f) cross section the resonances discovered by Block et al. [26] are clearly seen and detailed structure is revealed in the cross section breaks at 1 MeV and 1.2 MeV. In the measurements on $^{232}$Th with 3 keV resolution near 1.7 MeV detailed structure is revealed in peaks at 1.4, 1.5, 1.6 and 1.7 MeV. Combined with a measurement of angular anisotropy these results are interpreted in terms of rotational bands to give $\hbar^2/2\mathcal{J}$ values of 2.5 and 2.8 for K = $^3/2$ bands and values of 3.9 and 4.5 for K = $^1/2$ bands which enable a set of double hump fission barrier parameters to be specified.

Analysis of the data on $^{243}$Am which covers the energy range 300 keV to 5 MeV will be completed this year. The data give the ratio $\sigma_f(^{243}\mathrm{Am})/\sigma_f(^{235}\mathrm{U})$ to 3% for each point above the threshold.

2.5 Tokai-Mura (S. Igarasi)

An evaluation of the $^{241}Am$ fission cross section has been carried out which fits the data over the energy range .001 MeV to 10 MeV, obtained from the NEUDADA library of CCDN, by a combined resonance term and penetrability formula in terms of 15 parameters. Another three parameters enable a peak of poor statistical quality at 0.164 MeV to be fitted also.

2.6 LLL (J.C. Browne)

Behrens et al. [16] have measured the fission cross section ratios for $^{233}U$, $^{234}U$, $^{236}U$ and $^{238}U$ relative to $^{235}U$ over the energy range 0.1 MeV to 30 MeV. The threshold cross section method of normalisation is used in which the fissionable isotope with a threshold fission cross section is mixed with the thermally fissile isotope and the data should be useful in resolving problems of normalisation. However, the resolution attained, 15 keV at 1 MeV, precludes the observation of detailed structure near threshold as reported for $^{238}U$ [12] and $^{234}U$ [59] by other workers.

Brown [17] has measured the fission cross section of $^{245}Cm$ over the energy range 0.006 eV using a 3 $\mu$g sample on a 3.5m flight path on the LLL linac. It is planned to improve the statistical quality of the data with a 10 $\mu$g sample.

There are plans at Livermore for the measurement of fission cross section for several transactinide nuclei, particularly $^{242m}Am$ so as to improve the measurements of Bowman et al [18]. It is also suggested that the thermal capture cross section of $^{242m}Am$ which, at present, has a 60% uncertainty could be remeasured to reduce the uncertainty to 15%.

2.7 Physics Division, ORNL (J.W.T. Dabbs)

Dabbs et al. [19] have developed a spherical plate ionization chamber in which the ratio of maximum to minimum track length is three. In the small sample version the maximum track length is 6 mm and the alpha to fission current pulse ratio does not exceed $^{1}/14$. This enables fissile isotopes with alpha half lives down to 30 years (e.g. $^{243}Cm$) to be studied. Preliminary fission cross section measurements on $^{245}Cm$ have been carried out and the relative heights of 12 resonances below 16 eV are given. Data of improved statistical quality are being processed.

Work at ORNL on $^{234}U$ cross sections [59] is discussed in sect.3 and sect.4.

2.8 Neutron Physics Division, ORNL (L.W. Weston)

Weston and Todd [20] have carried out capture cross section measurements on $^{240}Pu$ and $^{241}Am$ and measurements are planned for $^{242}Pu$ and possibly $^{237}Np$ and $^{243}Am$. The capture events are detected by a "total energy detector" suggested by Maier-Leibnitz and developed by Macklin [21]. In this, the $\gamma$-rays are detected in NE226, a non-hydrogenous scintillator, and sets of weighting factors dependent on pulse height force the net efficiency to be proportional to gamma-ray energy. Fission events are detected by a fast neutron counter (NE213 scintillator) with pulse shape discrimination. Data are shown for the capture cross section of $^{240}Pu$ over the energy range 0.1 keV to 300 keV which are in good agreement with those of Hockenbury et al. [22] over the more limited range of these data. The ENDF/B-IV evaluation was based in part on preliminary results of this measurement and lie consistently below the measurement above 40 keV.

In the measurement on $^{241}Am$, a high neutron background arose from $(\alpha,n)$ interactions in the oxide sample, thus the low fission cross section could not be measured and the average absorption cross section is quoted. It lies above the ENDF/B-IV evaluation at energies above 20 keV indicating that in fast reactors more $^{242}Cm$ would be produced than calculated from the ENDF evaluation. This may help to reduce the discrepancy between the measured and calculated $^{242}Cm$ production cross section found by Glover et al. [6] . In the resonance region below 10 eV, the single level parameters of ENDF/B-IV based on total cross section measurements do not fit the valleys between resonances in the measured $^{241}Am$ absorption cross section.

As a result of the $\alpha = \langle\sigma_c\rangle/\langle\sigma_f\rangle$ measurement for $^{241}Pu$ [23], the ENDF evaluation below 400 eV has been improved by taking better account of capture in missed resonances.

Gwin et al. [24] have carried out a comparison of two techniques for measuring neutron capture and fission cross sections. Method 1 is that employed by Weston and Todd [23] and method 2 consists of a multiplate pulse ionization chamber to detect fission fragments and a large liquid scintillator to detect prompt gamma rays arising from fission or capture. It is shown that over the energy range 0.1 keV to 200 keV the two methods give results which are in excellent agreement for $^{239}Pu$. It is concluded that for the measurement of $\langle\sigma_c\rangle/\langle\sigma_f\rangle$ the combination of an ionization chamber and a Macklin type 'total energy' detector would provide the most versatile system in a laboratory where a selection of flight path lengths is available.

It is emphasised that a sound waste management program for power reactors and the establishment of the feasibility and desirability of actinide transmutation in power reactors will require additional cross section measurements on transactinide nuclei because nuclear model calculations to date do not provide sufficiently accurate results.

2.9 Soreq Nuclear Research Centre (M. Caner)

Dr. Caner has provided reports on evaluated cross sections for $^{238}Pu$, $^{240}Pu$, $^{241}Pu$ and $^{242}Pu$. These are best considered in the session on evaluated data.

2.10 RPI (R.C. Block)

Results from RPI are dominated by the spectacular success of the 75-ton lead slowing down spectrometer [25] in detecting sub-threshold fission resonances at 720 eV and 1210 eV in $^{238}U$ [26] and in the ability of this instrument to determine fission widths [27] for the three resonances in $^{238}U$ below 50 eV of (10 $\pm$ 1)neV at 6.67 eV, (58 $\pm$ 9)neV at 20.9eV and (12 $\pm$ 2)neV at 36.8 eV. The thermal fission cross section is found to be 2.7 $\pm$ 0.3$\mu$b and is made up of the following contributions, 66% from the three resolved resonances below 50 eV, 6.3% from $\langle \Gamma_f \rangle$ = 19.5 $\pm$ 2.5 neV between 50 and 350 eV, 18.5% from the sub-threshold group at 720 eV and 9.2% from the sub-threshold group at 1210 eV. The fission resonance integral from 0.4 eV to 30 keV is 1.33 $\pm$ 0.15mb. Recent results on $^{232}Th(n,f)$ indicates no structure below 1 keV but a pronounced resonance is seen at 1.75 keV. The RINS produces a useable neutron flux which is $10^3$ - $10^4$ times greater than that obtained by using the linac source in conventional time-of-flight experiments at the cost of poorer resolution, $(\Delta E/E)_{FWHM}$ = 0.33. In favourable cases, fission widths of $10^{-9}$ eV in 1g samples can be measured in a few hours. There are plans to measure fission in Cm isotopes in 0.1 to 1 g samples using a fission chamber based on the design of Dabbs et al. [19].

2.11 Ghent (A. J. Deruytter)

Wagemans and Deruytter [29] have measured the fission cross section of $^{241}Pu$ over the energy ranges 0.01 eV to 20 eV and from 0.15 eV to 50 eV and have made a careful study of the discrepancies between existing measurements in terms of the methods of normalisation. All previous data were renormalised to an area 1363 $\pm$ 14 b.eV over the energy range 12 eV to 20 eV. This changes the data of Blons et al. [30] by 2.1%, the data of Migneco et al. [31] by 2.6% and the high resolution data sets of James [32] by 1.6% and Moore et al. [33] by 4.2%. For the twelve energy intervals considered between 3 eV and 52 eV the average discrepancy between previous measurements and the results of Wagemans and Deruytter is 2.7% for Blons et al. 4.4% for Migneco et al. and 5.2% and 7.7% respectively for the high resolution sets of James and Moore et al.

2.12 CBNM (H. Weigmann)

Work on $^{235}$U, $^{236}$U, $^{237}$Np, $^{240}$Pu and $^{242}$Pu is reported from Geel. Weigmann et al. [34] failed to find evidence for the fission fragment energy variations in low energy neutron resonances reported by Felvinci et al. [35]. As an example out of many, the 11.66 eV resonance which is one of the most distinct cases of strong variation in the data of Felvinci et al. shows no variation in the Geel results. In these experiments, different bands across the fragment energy curve are used to determine the fission cross section.

Capture, scattering and total cross section measurements on $^{236}$U have been made by Mewissen et al. [36] who deduce neutron widths $\Gamma_n$ for 97 levels in the range 30 eV to 1.8 keV and also deduce capture widths $\Gamma_\gamma$ for 57 of these levels. These results give a level spacing $\bar{D}$ = 16.1 $\pm$ 0.5 eV, an S-wave strength function of (1.05 $\pm$ 0.14).$10^{-4}$ and an average $\bar{\Gamma}_\gamma$ = 23.0 $\pm$ 0.3 (stat.) $\pm$ 1.5(syst.) meV in good agreement with a $\bar{\Gamma}_\gamma$ = 23.9 $\pm$ 1.0 meV derived by Carlson et al. [37] from twelve levels.

A total cross section measurement on $^{236}$U by Carraro and Brusegan [38] gives neutron widths for 185 resonances in the range 40 eV to 4.1 keV with the following average parameters. $\bar{D}$ = (16.2 $\pm$ 0.3) eV; $\bar{\Gamma}_n^o$ = (1.61 $\pm$ 0.16) meV and $S_o$ = (1.00 $\pm$ 0.1) $10^{-4}$. This paper shows an exemplary use of statistical techniques, combining the methods of Bollinger and Thomas [39] and the $\Delta_3$ and W statistics of Dyson and Mehta [40], to decide which levels are most likely to be p-wave resonances.

Since the evaluation of $^{240}$Pu neutron cross sections by L'Heriteau and Ribon [41] there have been important changes in the experimental data, notably in the parameters of the 20.45 eV resonance used in the normalisation of certain data. Careful measurements by Moxon [42] have changed the neutron and capture widths for this resonance by 29% and 58% respectively to $\Gamma_n$ = (2.65 ± 0.07)meV and $\Gamma_\gamma$=(32.2 ± 3.4)meV. Using these revised parameters, Weigmann and Theobald [43] have revised their data to give $\bar{\Gamma}_\gamma$ = (32 ± 2)meV derived from fourteen levels below 665 eV. In an evaluation of $^{240}$Pu parameters, Weigmann et al. [44] have revised the neutron widths of nine resonances below 665.1 in the data of Kolar and Böckhoff [45] which provide the most extensive set of neutron widths for $^{240}$Pu and recommend $\bar{D}(l = 0)$ = (12.7 ± 0.3) eV, $S_o = (1.04 {}^{+0.14}_{-0.12}).10^{-4}$ and $\bar{\Gamma}_\gamma$ = (30.8 ± 1) meV. There are still discrepancies of 8% between the capture widths from Geel and RPI [46] which can only be resolved by additional measurements. The evaluation of the fission widths for $^{240}$Pu has been overtaken by the measurements of Auchampaugh and Weston [47].

Work at Geel [48] on the capture, elastic scattering and total cross section of $^{242}$Pu has provided neutron widths for 71 resonances below 1300 eV and capture widths for 25 of these resonances. These give the results $\bar{D}$ = 17.02 eV, $S_o = (0.89 {}^{+0.10}_{-0.09})\ 10^{-4}$ and $\bar{\Gamma}_\gamma$ = 21.9 ± 0.4 (stat.) ± 1.0 (syst.) meV. Combined with the fission resonance integrals of Auchampaugh et al. [49], the results enable 26 fission widths between 350 eV and 950 eV to be deduced and parameters for two narrow intermediate structure resonances at 475 eV and 762 eV to be determined.

Earlier work at Geel [50] had revealed fission components in $^{236}$U neutron resonances and shown by contrast with the $^{234}$U results [51] that the outer fission barrier height changes drastically by 0.4 MeV in going from $^{235}$U to $^{237}$U. From an analysis of available data on sub-threshold fission and shape isomer decay data, they deduce that there is a marked even-odd effect in the outer barrier thickness $\hbar\omega_B$ with values of 0.68 keV for doubly even, 0.50 keV for odd and 0.40 keV for doubly odd compound nuclei.

Weigmann et al. [52] have measured capture cross sections for $^{237}$Np and $^{238}$U in the vicinity of intermediate structure groups with two different biases designed to distinguish class I capture gamma ray decays from predominantly class II capture $\gamma$-ray decays. The relative cross sections are independent of bias in these two nuclei, thus the resonance with the largest fission width is not predominantly class II and $\Gamma^{\downarrow} \ll \Gamma^{\uparrow}$ indicating that the inner barrier height $E_A$ is greater than the outer barrier height $E_B$. However, an analysis of the neutron widths of the levels with largest fission width indicates that they are very small indicating that they are probably predominantly class II levels. This disagreement between the two sources of evidence leaves the question of the relative magnitude of $\Gamma^{\downarrow}$ and $\Gamma^{\uparrow}$ unresolved.

In order to provide estimates for radiative capture widths for nuclei, such as fission products, which are not readily available, Weigmann and Rohr [53] have fitted the experimental widths in the mass range $40 \leq A \leq 247$. The model used takes into account shell corrections to the level spacing, a pairing correction term to the effective binding energy and well established non-statistical effects which are accounted for by the so called valency nucleon model. There remain four free parameters. The root mean square value of the deviation between the theoretical fit and the experimental data is 25%. Numerically this is no improvement over previous fits but it does include data for A = 50 to 60 and $A \sim 200$ which were excluded previously.

A second series of scattering, capture and total cross section measurements on $^{237}$Np have been carried out by Poortmans et al. [54] but the analysis is not complete. Values of neutron widths derived from the transmission data agree well with the Saclay data of Paya and from a shape analysis of 10 resonances between 8 eV and 18 eV, $\langle\Gamma_\gamma\rangle$ = 41.0 meV in good agreement with the Saclay value of $\langle\Gamma_\gamma\rangle$ = 40.2 meV for the same resonances. The earlier determinations of spin for 14 levels below 50 eV [76] are in disagreement with the data of Keyworth et al. [2] in eight cases because the sample used at Geel was too thin to be physically stable during the measurement.

## 2.13 Savannah River (R.W. Benjamin)

Total cross section measurements have been carried out at ORELA on a small sample system which is capable of operation with a 1.29 mm diam. beam on an 18 m flight path. Measurements on $^{243}$Am [56] have resulted in neutron widths for 219 levels below 250 eV. The average parameters obtained are $\bar{D} = 0.68 \pm 0.6$ eV, $S_o = (0.96 \pm 0.10),10^{-4}$ and $\bar{\Gamma}_\gamma = 39 \pm 1$ meV deduced from the shape analysis of 24 resonances below 18 eV.

Transmission measurements [57] on a curium sample containing 96.82% $^{248}$Cm and 3.11% $^{246}$Cm have provided neutron widths for 47 levels below 3000 eV in $^{248}$Cm and for 5 levels below 158.5 in $^{246}$Cm. The data give average parameters for $^{248}$Cm of $\bar{D} = 40 \pm 5$ eV and $S_o = (1.2 \pm 0.2)10^{-4}$. The contribution of these resonances to the thermal capture cross section and to the capture resonance integral has been calculated and found to agree well with the integral measurements of other workers.

Unpublished data are also available for $^{244}$Cm, 36 values of $\Gamma_n$, $\Gamma_f$ and $\Gamma_\gamma$ below 520 eV ($\bar{D}$ = 14.1 eV),, and for $^{249}$Bk, 47 values of resonance energy. $^{249}$Bk has a half-life of only 311 days. The sample of 7 mg will be used for measurements on $^{249}$Cf after several months decay.

2.14 Kurchatov Institute (V.I. Mostovoy)

A paper giving the results of total cross section measurements on the transactinium isotopes $^{241,243}$Am and $^{244,245,246,248}$Cm has been prepared for this meeting by S.M. Kalebin [57a]. Values of $2g\Gamma_n$ for 36 resonances below 25.6 eV are given for $^{241}$Am and for 47 resonances below 33.9 eV for $^{243}$Am. These agree within statistical accuracy with the results of previous measurements which are listed for comparison. The same remark applies to the Cm isotopes for which $\Gamma_n$ values of 11 resonances below 171 eV for $^{244}$Cm, four resonances below 157 eV for $^{246}$Cm and six resonances below 98.6 eV for $^{248}$Cm, are listed. In the case of $^{245}$Cm, 17 values of $2g\Gamma_n$ for resonances below 50.5 eV are listed. Here, agreement with previous measurements is good up to 32.4 eV. Above this energy a few resonances show $2g\Gamma_n$ values which are discrepant by more than one standard deviation not always in the same direction. For the even Cm isotopes average values of the radiation widths and resonance capture integrals are in excellent agreement with previous measurements. For the Am isotopes the following average parameters are given; for $^{241}$Am $\bar{D}$ = (0.67 $\pm$ 0.10) eV, $S_o = (0.76 \pm 0.18).10^{-4}$ and for $^{243}$Am $\bar{D}$ = (0.71 $\pm$ 0.06) eV and $S_o = (0.89 \pm 0.21).10^{-4}$.

## 3. SUB-THRESHOLD FISSION DATA

Early work on narrow intermediate structure in the sub-threshold fission cross sections of $^{237}$Np, $^{240}$Pu, $^{234}$U, $^{242}$Pu and $^{238}$Pu has been expertly reviewed by Michaudon [58]. Since then, fission components have been discovered for low energy resonances in $^{236}$U, $^{238}$U and possibly also for $^{242}$Th, definitive spin determinations have been carried out for resonances in the structure near 40 eV in $^{237}$Np and improved measurements have been made resulting in fission widths for resonances in $^{234}$U, $^{240}$Pu and $^{242}$Pu. Fission data in the region of fine structure resonances obtained since the review of Michaudon are discussed in the following sub-sections.

## 3.1 $^{234}U$

High resolution fission and total cross section measurements on $^{234}U$ have been carried out at ORNL by James et al. [59] . These cover the neutron energy from a few eV to several MeV. Neutron and fission widths for 118 resonances below 1500 eV have been determined and give $\bar{D} = 10.6 \pm 0.5$ eV and $S_o = (0.86 \pm 0.11).10^{-4}$. The fission widths are illustrated in fig. 1 which also shows the Lorentzian energy dependence of the mean fission width. The average width peaks at 550 eV and possibly also at 1092 eV. A wealth of structure, shown in fig. 2, is seen in the fission cross section up to and beyond the fission threshold. As a result, the class II level spacing below 20 keV is found to be $\bar{D}_{II} = 2.1 \pm 0.3$ keV, a considerable reduction on the previous value [59a] of 7 keV.

## 3.2 $^{236}U$

Theobald et al. [60] have discovered fission components in $^{236}U$ neutron resonances in a measurement of fission cross section which extends from 0.3 eV to 1000 eV. Fission widths have been deduced for 16 resonances below 415 eV and have an average value $\langle \Gamma_f \rangle = 0.354$ meV. There is no narrow intermediate structure level within this energy range, but, by comparison with the results on $^{234}U$ it is shown that in going from the compound state $^{235}U$ to $^{237}U$ there is a change of at least 0.4 MeV in the relative inner and outer barrier heights (or, of course, a corresponding change in barrier thickness).

## 3.3 $^{238}U$

By the use of the lead slowing down spectrometer [25] and an ionization chamber to detect fission fragments from $^{238}U$, Block et al. [26] have discovered narrow intermediate structure resonances at 0.720 keV, 1.210 keV, 2.5 keV, 7.5 keV, 11.3 keV and 15.3 keV in $^{238}U$. Fission cross section data for the first two structures are shown in fig. 3 together with values of $\Gamma_n^o$ . These resonances have since been measured with high resolution by Waretena et al. [61] who used a liquid scintillator to detect fission neutrons from a 250g sample of $^{238}U$. The measurements were performed at Geel on a 30m flight path at a nominal resolution of 1.3 ns/m. Fission widths are given for 7 resonances between 660 eV and 1272 eV. The resonances with largest fission width are at 721 eV ( $\Gamma_f = 850 \pm 130$ $\mu$eV) and at 1210.7 eV ( $\Gamma_f = 250 \pm 50$ $\mu$eV).

Blons and Mazur [12] using a gas scintillation fission fragment detector have also observed these resonances with good resolution and point out that, because only one resonance in a group has any appreciable fission width, the spreading width must be less than or at most equal to the class I level spacing (8.4 eV) and that the levels observed appear by a fortuitous close proximity of class I and class II level energies. This implies, of course, that $D_{II}$ could be much less than the value observed.

## 3.4 $^{237}$Np

Perhaps the greatest advance in resonance parameter determination in recent years has been made by Keyworth et al. [2] who made direct measurements of resonance spin for $^{237}$Np and $^{235}$U by using a polarized neutron beam and a polarized target. Experiments were carried out on a 13.4m flight path at ORELA and used to determine spins for 15 intermediate structure groups in the fission cross-section of $^{237}$Np below 1 keV and of 94 resonances observed in transmission below 102 eV. The neutron beam is polarized to about 55% polarization, by transmission through a dynamically polarized sample of protons in single crystals of lanthanum magnesium nitrate cooled to 1.15$^{\circ}$K. The $^{237}$Np is polarized, to about 20% polarization, in the ferromagnetic compound $NpAl_2$ cooled to 650mK by a $^3$He - $^4$He refrigerator. The fission data for $^{237}$Np in the region of 40 eV are shown in fig.4. The enhancement of the compound nuclear levels is distributed over nine individual resonances and the difference, $\sigma$par - $\sigma$anti, between the cross sections obtained with different relative directions of polarization show that all these levels have spin J = 3. Fig. 5 shows a sample of the transmission data in which Tpar - Tanti clearly separates resonances with J = 2 from those with J = 3. Combined with fission fragment angular distribution measurements from a polarized $^{237}$Np target by Kuiken et al. [62], the spin assignment J = 3 for the 40 eV structure implies an admixture of spin projection K = 2 and K = 3 components.

Spin assignments for 53 levels in $^{235}$U in the energy range 1.13 eV to 56.6 eV show that only the capture method of Corvi et al. [101] gives 100% agreement with the Keyworth assignments and even then only for 14 resonances. The other six methods of indirect spin determination are shown to be unreliable.

### 3.5 $^{240}$Pu

Auchampaugh and Weston [47] have measured the fission cross section of $^{240}$Pu from 500 eV to 10 keV on ORELA by detecting fission neutrons from a 10.23g sample of $PuO_2$. The detector was on a 20 m flight path and the neutron pulse width was 8 ns. A total of 82 fission widths were obtained by area and shape analysis of those resonances which define class II states at 782 eV, 1406 eV, 1936 eV and 2700 eV. Approximately 22 clusters of class I resonances are seen below 10 keV which gives $\bar{D}_{II} = 450 \pm 50$ eV. Values obtained for the average coupling matrix element, $\langle H^2 \rangle$ between class I and class II states and of the class II fission width $\Gamma_{f\,II}$ are given for the class II resonances at 782 eV, 1406 eV and 1936 eV in Table 1. These parameters lead to barrier heights of $V_A = 5.89 \pm 0.09$ MeV and $V_B = 5.54 \pm 0.03$ MeV. Values of the class I fission widths are shown in fig. 6.

### 3.6 $^{242}$Pu

Poortmans et al. [48] have measured capture, elastic scattering and total cross sections of $^{242}$Pu below 1300 eV and have used their resonance parameters to deduce fission widths for 25 levels of the 72 that are observed below 1286 eV, from the fission data of Auchampaugh et al. [63]. The fission widths associated with intermediate structure levels at 475 eV and 762 eV are illustrated in fig. 7. The parameters of the Lorentzian energy dependence of the average fission width shown in fig. 7 gives the outer barrier height as $V_B = 5.18$ MeV.

## 4. GROSS STRUCTURE NEAR FISSION THRESHOLD

It has long been known that accurate (n,f) data reveal, in most cases, some structure in the region of fission threshold. It was shown by Lynn [64] that structure in the fission cross section of $^{230}$Th could not be explained by the competition theory of Wheeler [65]. This conclusion was strikingly reinforced [66] when the $^{230}$Th fission cross section was measured with a resolution of 5 keV and showed the pronounced resonance at 715 keV, only 36 keV wide, illustrated in fig. 8. This cross section, together with fission fragment angular distribution measurements [66, 67], is explained in terms of a sharp maximum in the penetrability of the $^{231}$Th double-humped fission barrier. Since the peak is very narrow and also since no other peaks are found at lower energy, it is likely that the maximum penetrability corresponds to the first vibrational level in a shallow second well. It is found that the spin projection $K = \frac{1}{2}$ and the parity of the state is probably negative. The data can be reasonably interpreted on the assumption that this vibrational level is the head of a rotational band with effective moment of inertia $2\frac{1}{2}$ to 3 times the value for the ground state deformation of $^{231}$Th.

It seems reasonable to extend our concept of the resonance region to include discussion of fission cross section resonances near threshold which are explained in terms of vibrational states in the second fission potential minimum. Different potential barrier conditions can give rise to a variety of fission cross section structure which are being observed in detailed measurements on $^{232}$Th, $^{231}$Pa and $^{234}$U.

## 4.1 $^{228}$Th

The fission cross section of $^{228}$Th over the energy range 0.16 MeV to 1.7 MeV has been measured by Vorotnikov et al. [68] with an energy resolution of 50 keV although data seem to have been taken at 100 keV intervals. The results are reminiscent of those obtained with similar resolution by Gokhberg et al. [69] on $^{230}$Th. Peaks are observed at 0.50 MeV, 1.07 MeV and 1.63 MeV. Between 0.5 MeV and 0.6 MeV the cross section decreases by about 50% as shown in fig. 9. These results clearly call for measurements with improved resolution. This will be a difficult experiment because the plateau cross section at 2 MeV is only 0.18b and the peak cross section observed at 500 keV is only 3mb.

## 4.2 $^{232}$Th

Detailed structure in the fission cross section of $^{232}$Th, as shown in fig. 10, has been observed near fission threshold by Blons et al. [13]. In measurements on the Saclay Linac with 3 keV resolution, four well separated peaks are observed in the gross structure at 1.6 MeV and three others in the structure at 1.7 MeV. Also, the fission fragment angular anisotropy has been measured using a detector with a grid. Fig. 11 shows the anisotropy as a function of neutron energy together with the expected values for sets of (K,J). The sharp peaks are interpreted as rotational band structures and enable the values $A = \hbar^2/2\mathcal{I} = 2.5$ and 2.8 for bands with $K = {}^3/2$ and $A = 3.9$ and 4.5 for $K = {}^1/2$. The decoupling parameter, a, being 0.2 and 0.1 respectively. The data are consistent with the following barrier parameters $V_A$ = 7.2 MeV, $\hbar\omega_A$ = 0.8 MeV, $V_{II}$ = 4.55 MeV, $\hbar\omega_{II}$ = 0.5 MeV, $V_B$ = 6.9 MeV and $\hbar\omega_B$ = 0.56 MeV.

### 4.3 $^{231}$Pa

Sicre et al. [70] have measured the $^{231}$Pa fission cross section from 100 kev to 1.3 MeV on a Van de Graaff generator with a neutron energy resolution of between 10 keV and 15 keV. They have also measured fission fragment angular distributions at 34 energies between 180 keV and 854 keV. Their results are shown in fig. 12. Two gross structure resonances, observed also by earlier workers, are seen at 200 keV and 330 keV and it is found that these and their associated angular distributions cannot be explained as pure vibrational resonances.

### 4.4 $^{234}$U

The gross structure at 310 keV, first observed in the $^{234}$U fission cross section in the data of Lamphere [71] , has been resolved into a sequence of peaks about 10 keV apart by measurements on the Harwell synchrocyclotron [72] and later with improved statistical accuracy by measurements at ORELA [59] using fission fragment detection from a 180 mg sample of $^{234}$U on a 20m flight path. As seen in fig. 13 the ORELA data, which have an energy resolution of about 1 keV at 300 keV, show a wealth of structure superimposed on plateaux near 310 keV, 550 keV and 770 keV. The gross structure at 310 keV which is estimated to contribute an average cross section of 0.0725b is attributed to a vibrational level in the second minimum. Assuming a two stage process whereby the vibrational level is damped into class II levels which in turn are coupled to class I levels, the average cross section of 0.0725b is accounted for by an outer barrier height $V_B$ = 674 keV for assumed values of $\hbar\omega_A$ = 1000 keV, $\hbar\omega_B$ = 560 keV and a value $V_A$ = 101 keV deduced from $\langle\Gamma_{II(c)}\rangle$ = 115 eV at low energy. The rapid decrease of $\Gamma_{II(f)}$ due to the Lorentzian energy dependence introduced by the vibrational level results in a value $\bar{\Gamma}_{II(f)}$= 0.0075 eV at 1 keV in contrast with the average value 0.152 eV measured for seven class II levels below 13 keV. However, by direct coupling to the threshold through the Hill-Wheeler formula, $\bar{\Gamma}_{II(f)}$ = 0.152 eV at below 13 keV results in $V_B$ = 684 keV in close agreement with the value deduced via the average gross structure at 310 keV. Fluctuations on the gross structure, illustrated in fig. 14, have an average spacing of 10 keV. It is found by Monte Carlo simulation that the average properties of the fluctuations are consistent with the two stage process and with the observation of class II structures of spacing less than 1 keV, corresponding to 2.3 keV at low energy, with the resolution of the experiment (1 keV at 310 keV). Other interpretations, allowing $V_A > V_B$ or the gross structure to be a p-wave vibrational level, are possible, and high neutron energy resolution fission fragment angular distribution measurements will be required to decide between these possibilities.

## 5. EXPERIMENTAL TECHNIQUES

A number of improvements in experimental techniques have lead to an enhancement in our knowledge of neutron resonance parameters. These will be briefly mentioned here although some have already been discussed in previous sections. Keyworth's measurement [2] of resonance spins for $^{235}U$ and $^{237}Np$ using a polarized neutron beam and polarized targets is a notable achievement which not only shows that all the resonances with enhanced fission widths in the narrow intermediate structure group at 40 eV have the same spin but also indicates that other techniques adopted to determine resonance spin often give wrong answers. The discovery of low energy resonances in the fission cross section of $^{238}U$ was made by Block et al. [26] using the RPI linac as a neutron source for a lead slowing down spectrometer. The electron target used was gas (helium) cooled with a design cooling capacity of 500 watts and a source intensity of $10^{12}$n/sec. A liquid cooledtarget would enable the source strength to be increased by an order of magnitude.

In the measurement of fission cross sections, a design of large gas scintillation chamber which can be cooled to liquid nitrogen temperature [73] has been used to great advantage by the Saclay group. The reduction in Doppler broadening thereby attained enabled fission widths for $^{239}Pu$ to be determined up to an energy of 658 eV [74] . Fission fragment detectors face the problem of alpha pile up which are countered by short pulse widths and chamber design. To reduce the maximum possible alpha path length, Dabbs et al. [19] have produced a spherical design of ionization chamber which has enabled fission cross section measurements on ORELA to be carried out on an isotope of only 30y alpha half-life. Spark chambers, as used to measure the fission cross section of $^{241}Am$ by Bowman et al. [75], have the great advantage of spatial resolution in countering alpha pile up. However, they suffer from a background due to spontaneous sparking which tends to get worse under alpha bombardment of the wires. This could possibly be reduced by the correct choice of wire material. Fission neutron detectors, with pulse shape discrimination to remove pulses due to gamma-rays overcome the $\alpha$-pile up problem but, ($\alpha$,n) reactions in light elements can cause a neutron background. Thus, oxides and light element encapsulation of the fissile material should be avoided [7].

## 6. STATISTICAL ANALYSIS

The statistical analyses carried out on resonance parameter data can be divided into those carried out in the absence of energy dependent structure to correct average values for missing levels or to remove contamination by levels from another sequence and those designed to detect the presence of energy dependent structure.

### 6.1 Statistical tests in the absence of structure

In any experimental observation of resonances, there is a limit, set by the statistical quality of the data and instrumental resolution, below which levels cannot be detected. In quoting average resonance parameters a correction should be made for missing levels. A method of carrying out the correction based on the Porter-Thomas [5] distribution of neutron widths has been developed by Fuketa and Harvey [77] and, for a Wigner [4] distribution of level spacings, by Musgrove [79]. Bollinger and Thomas [80] showed how Bayes theorem [81] can be used correctly to convert the a priori probability, based on the spin dependence of level spacing, that a given resonance is a p-wave level, into an a posteriori probability, by taking the measured neutron width into account.

Clear evidence for Dyson's theory [82] of level spacing has been obtained at Columbia [83] in the resonance energy spacing of a pure sequence of 109 levels in $^{166}$Er. In developing the theory of level spacing based on the properties of the eigervalues of a random matrix of high order, the Gaussian orthogonal ensemble, a number of sensitive statistical tests have been developed to examine the agreement between data sets and theoretical expectations. These include the $\Delta$ (or $\Delta_3$) and W statistic of Dyson and Mehta [84], the F statistic of Dyson [85] and the $\Lambda$ statistic of Monahan and Rosenzweig [86] . For data on $^{232}$Th and $^{238}$U, Liou et al. [85] have carried out a selection of s-wave levels so as to fit simultaneously the Wigner nearest-neighbour spacing distribution, the spacing correlation coefficient $\rho(S_j,S_{j+1}) = -0.27$, the Dyson-Mehta $\Delta$ statistic and Dyson's F statistic. Good simultaneous fits to all these statistics were found for both isotopes. The F statistic was developed to detect the presence of spurious or missing levels in an otherwise perfect sequence of levels. The $\Delta_3$ statistic also gives an indication of spurious or missing levels and it has been used, together with the statistic W, in an analysis of 103 observed resonances in $^{236}$U below 1660 eV by Carraro and Brusegan [38] . The 103 values of $\Delta_3$ obtained by leaving out one level at a time are shown in fig. 15. Dips in the value of $\Delta_3$ give an indication of spurious levels. When these are compared with a list of resonances which have a probability exceeding 1% of being p-wave levels as deduced using Bayes theorem, it becomes possible to pick out five levels which have a high probability of being p-wave resonances.

## 6.2 Statistical tests for structure

The occurrences of intermediate structure is associated with non-random effects over limited energy ranges in the distribution of resonance parameters and in the energy dependence of cross sections. However, resonance parameters and cross sections undergo fluctuations from energy to energy which obscure the energy dependent structure and which must be removed or accounted for in any effective method of testing for intermediate structure. This can be done by the use of distribution-free tests and the first demonstration [87] was carried out using the runs statistic of Wald and Wolfowitz [88] to show that the neutron widths of $^{232}$Th have no energy dependence (as expected), that the $^{234}$U fission widths have a strong energy dependence and that a sequence of correlation coefficients derived from the fission cross section of $^{239}$Pu can be rendered featureless by the introduction of an energy dependent mean. Moore [89] applied the test to show that the $^{244}$Cm fission widths measured by Moore and Keyworth [90] over the energy range 50 eV to 1000 eV have a significant energy dependence. Moore [89] also suggested a test based on the length of the longest run above the median. The feasibility of this test was demonstrated [91] on the basis of previous work by Olmstead [92]. Baudinet-Robinet and Mahaux [93] suggested the use of the runs up and down test devised by Levine and Wolfowitz [94] and followed this suggestion by a critical survey of eight possible tests [91] . These tests are listed here with comments on the use of three of them derived from work on simulated cross sections [95] .

1. Comparison between two samples

The Wald and Wolfowitz runs test [88] was originally designed to test whether two samples are drawn from the same population. It can be applied by arranging two sets of widths taken from two energy ranges in order and testing the run sequence produced.

2. Number of runs about a reference line

It has been shown [87] how the runs test [88] can be used to test for energy dependent structure in a sequence of resonance parameters or correlation coefficients derived from energy averaged cross sections. The test can also be applied directly to cross section data. This has been done by James et al. [95] and also by Migneco et al. [96] and gives strong evidence for structure in the fission cross section of $^{235}U$ between 10 keV and 40 keV. Applied to average values of $\sigma_f$ over 100 eV intervals derived from the $^{249}Cf$ fission cross section data of Dabbs et al. [97] , it shows that $\langle \sigma_f \rangle \sqrt{E}$ has no energy dependence over the range 100 eV to 7100 eV. The observed number of runs around the mean value is 34 compared with an expectation value $35.89 \pm 4.14$ in the absence of structure.

3. Longest run above the median

This test was proposed by Moore [89] and its feasibility demonstrated in [91] . It has the advantage, in common with the next test of being able to locate the intermediate structure.

4. Longest run above the line of optimal run length

The line of optimal run length is chosen so as to maximize the shorter of the longest runs above and below the line.

5. Runs up and down

This test, proposed in [93] , is less sensitive than the two Wald and Wolfowitz tests (2 and 7) but could be more useful when the data set is small. However, as described later (7), it proved grossly insensitive to progressively increasing modulation of fission widths in a simulated fission cross section.

6. Mean-square successive difference

Based on the ratio between the sum of squares of differences between successive terms in a sequence and the sum of squares of the differences between each term and the mean, this test will indicate the existence of a variation of the mean. The test, proposed in [91] , is appliable only to the mean of a normal population.

7. Serial correlation

Wald and Wolfowitz [99] have shown that a test based on the serial correlation coefficient with lag h is equivalent (when h is prime to N) to a test based on the statistic

$$R = \sum_{1}^{N-1} x_\alpha x_{\alpha+1} + x_N x_1$$

The use of this test is suggested in [91] . It had also been discovered independently by James et al. [95] in the course of their work on $^{235}U$. These authors produced two sets of mock $^{235}U$ fission cross section data, by Monte Carlo methods, one with intense fission width modulation and one without. These data were mixed in ten varying proportions and tested for structure using R, the Wald and Wolfowitz runs statistic U and the Levine and Wolfowitz runs up and down statistic R(n) for runs of length n. The results obtained are shown in fig. 16. Values of R and U increase monotonically with increasing fraction of modulated data finally reaching deviations of about 14 and 11 standard deviations respectively for the maximum modulation. For the measured $^{235}U$ fission cross section of Perez et al. [102] averaged over 100 eV intervals between 10 keV and 40 keV, the values of R and U are at 8.94 and 6.48 standard deviation away from the expectation values for no structure. These values both indicate, from fig. 16, structure which is comparable with the simulated data containing about 50% of the maximum modulation of fission widths.

The lower curves in fig. 16 refer to the runs up and down test of run length one, R(1), and for the run length of maximum significance, $R_{max}(n)$. Neither of these statistics proves useful in detecting the structure under investigation. R(1) remains almost constant at about 1.7 standard deviation and is almost independent of the fraction of modulated data. As a function of the fraction of modulated data $R_{max}(n)$ starts at 1.6 standard deviations and increases to 3.2 only to decrease again as the fraction of modulated data increases to 100%.

8. Large adjacent values

The probability distribution of runs of length larger than or equal to a given value for random events arising from a binomial population of known probabilities p and q has been calculated by Mood [100] . As suggested in [91] this test can be applied to resonance data that have a known distribution.

## 7. CONCLUSION

Since the discovery of neutron cross section resonances a few years after the discovery of the neutron, there has been a continual improvement in our knowledge of neutron resonance phenomena. The late thirties saw an expression for resonance line shape, the beginnings of multilevel theory and the first neutron time-of-flight experiments. The late fifties brought a surmise for level spacing distributions and a representation of level width distributions. The late sixties witnessed the discovery of sub-threshold fission phenomena which opened the way for the study of nuclei in highly deformed shape isomeric states. As shown by the work considered in this review, improvement in our knowledge of neutron resonance phenomena remains unabated in the early seventies. We have seen more nuclei added to the list of those that exhibit low energy sub-threshold fission, the development of a superior method of resonance spin determination by polarization experiments requiring the unmitigated application of technical excellence, evidence for the Wigner-Dyson theory of level spacing, the development of a new design of fission chamber which will prove useful in measurements on the higher actinides, the careful remeasurement of certain widths and average values used in the normalisation of data, improvement in our knowledge of sub-threshold fission parameters and more recently high resolution measurements which reveal a welter of detailed structure in fission cross sections near the threshold, the development and application of several statistical tests, derived mainly from the work of Dyson and Mehta, which have been used in the selection of a quantally pure sequence of levels, and the introduction of distribution-free statistical tests which enable us to search for energy dependent structure in the presence of random fluctuations.

In continuing this work into the late seventies, the pathways that appear particularly inviting are further development of fission chambers to counter the increased alpha rates encountered in work on higher actinides, including more work on spark chamber design, high resolution measurements of fission cross sections near threshold together with high quality angular distribution measurements and possibly a definitive assessment of the sensitivity of the various statistical tests for structure to the kind of structure we are likely to encounter.

## REFERENCES


1 JAMES, G.D., Nuclear Data for Reactors, 1, IAEA, Vienna (1970) 267

2 KEYWORTH, G.A., LEMLEY, J.R., OLSEN, C.E., SEIBEL, F.T., DABBS, J.W.T. and HILL, N.W., Phys. Rev. 8C (1973) 2352 and Physics and Chemistry of Fission 1973, I, IAEA, Vienna (1974) 85

3 DABBS, J.W.T., HILL, N.W., BEMIS, C.E. and RAMAN, S., 4th Conf. on Nuclear Cross-Sections and Technology, Washington, 1975.

4 WIGNER, E.P., Oak Ridge National Laboratory, Report No. ORNL-2309 (1956) 59

5 PORTER, C.E. and THOMAS, R.G., Phys. Rev. 104 (1956) 483

6 GLOVER, K.M., WILTSHIRE, R.A.P. and ROGERS, F.J.G., "Measurement of the integral cross sections of $^{241}Am$", U.K. Nuclear Data Progress Report (GAYTHER, D.B., Ed) UKNDC (75) P71, page 51

7 DERRIEN, H. and LUCAS, B., "The total cross section and fission cross section of $^{241}Am$ in the resonance region Resonance parameters." 4th Conf. on Nuclear Cross Section Technology, Washington, 1975

8 SEEGER, P.A. et al. Nucl. Phys. A96 (1967) 605

9 BOWMAN, C.D., et al. Phys. Rev. 137 (1965) B326

10 LUCAS, B., DERRIEN, H. and PAYA, D., "Section efficace de fission et parameteres de resonance de $^{241}Am$" - unpublished report

11 PLATTARD, S., PRANAL, Y., BLONS, J. and MAZUR, C. National Soviet Conference on Neutron Physics, Kiev, 1975

12 BLONS, J. and MAZUR, C., "Mesures a haute resolution des sections efficaces de fission de $^{238}U$ et $^{239}Pu$ par rapport de celle de $^{235}U$" - unpublished report

13 BLONS, J., MAZUR, C. and PAYA, D. "Structures in $^{232}Th(n,f)$ and $^{238}U(n,f)$ cross sections". 4th Conf. on Nuclear Cross Sections and Technology, Washington, 1975

14 BLONS, J. and MAZUR, C., "Mesure de $\sigma_f$ de $^{243}Am$" - unpublished

15 PLATTARD, S. Thése 3éme cycle, Orsay, 1973

16 BEHRENS, J.W., CARLSON, G.W. and BAUER, R.W. "Neutron induced fission of $^{233}U$, $^{234}U$, $^{236}U$ and $^{238}U$ with respect to $^{235}U$." 4th Conf. on Nuclear Cross Section and Technology, Washington, 1975

17 BROWNE, J.C. "$^{245}Cm$ Fission cross section" - unpublished

18 BOWMAN, C.D., et al., Phys. Rev. 166 (1968) 1219

19 DABBS, J.W.T., HILL, N.W., BEMIS, C.E. and RAMAN, S. "Fission cross section measurements on short-lived alpha emitters". 4th Conf. on Nuclear Cross Section and Technology, Washington, 1975

20 WESTON, L.W. and TODD, J.H. "Measurement of the neutron capture cross sections of the actinides". 4th Conf. on Neutron Cross Sections and Technology, Washington, 1975

21 MACKLIN, R.L. and GIBBONS, J.H. Phys. Rev. 159 (1967) 1007

22 HOCKENBURY, R.W., MOYER, W.R. and BLOCK, R.C. Nucl. Sci. & Engng. 49 (1972) 153

23 WESTON, L.W. and TODD, J.H. Trans. Am. Nucl. Soc. 15 (1972) 480

24 GWIN, R., WESTON, L.W., TODD, J.H., INGLE, R.W. and WEAVER, H. "A direct comparison of different experimental techniques for measuring neutron capture and fission cross sections for $^{239}Pu$". 4th Conf. on Neutron Cross Sections and Technology, Washington, 1975

25 BLOCK, R.C., HOCKENBURY, R.W., CRAMER, D.S., BEAN, E. and SLOVACEK, R.E. "The Rensselaer intense neutron spectrometer", 4th Conf. on Neutron Cross Sections and Technology, Washington, 1975

26 BLOCK, R.C., HOCKENBURY, R.W., SLOVACEK, R.E., BEAN, E.B. and CRAMER, D.S., Phys. Lett. 31 (1973) 247

27 SLOVACEK, R.E., CRAMER, D.S., BEAN, E.B., HOCKENBURY, R.W., VALENTINE, J.R. and BLOCK, R.C., "$^{238}U(n,f)$ measurements below 30 keV" APS Meeting, Washington, D.C., April 1975

28 VALENTINE, J.R. - Private communication

29 WAGEMANS, C. and DERUYTTER, A.J. "The $^{241}$Pu neutron induced fission cross section from 0.01 eV and its normalisation" 4th Conf. on Neutron Cross Sections and Technology, Washington, 1975 also "Measurement and normalisation of the relative $^{241}$Pu fission cross section in the thermal and low resonance region" submitted to Nucl. Sci. & Engng.

30 BLONS, J. et al. Nuclear Data for Reactors 1 (IAEA, Vienna, 1970) 469

31 MIGNECO, E., THEOBALD, J. and WARTENA, J. Nuclear Data for Reactors 1 (1970) 437

32 JAMES, G.D., Nucl. Phys 65 (1965) 353

33 MOORE, M. et al.,Phys. Rev. 135 (1964) B945

34 WEIGMANN, H., WARTENA, J.A. and WAGEMANS, C., "Are there fission fragment energy variations in $^{235}$U neutron resonances" submitted to Phys. Rev. Lett.

35 FELVINCI, J.P., MELKONIAN, E. and HAVENS Jr., W.W., 4th Conf. on Nuclear Cross Sections and Technology, Washington, 1975

36 MEWISSEN, L., POORTMANS, F., ROHR, G., THEOBALD, J., WEIGMANN, H. and VANPRAET, G., "Neutron cross section measurements on $^{236}$U". 4th Conf. on Neutron Cross Sections and Technology, Washington, 1975

37 CARLSON, A.D. et al., Nucl. Phys. A141 (1970) 577

38 CARRARO, G. and BRUSEGAN, A., "Total neutron cross section measurements of $^{236}$U in the energy range from 40 eV to 4.1 keV" submitted to Nucl. Phys.

39 BOLLINGER, L.M. and THOMAS, G.E., Phys. Rev. 171 (1968) 1293

40 DYSON, F.G. and MEHTA, M.L., J. Math. Phys. 4 (1963) 701

41 L'HERITEAU, J.P.L. and RIBON, P., CEA-N-1273/EANDC(E) 126AL (1970)

42 MOXON, M.C. unpublished

43 WEIGMAN, H. and THEOBALD, J.P., J. Nucl. En. 26 (1972) 643

44 WEIGMANN, H., ROHR, G. and POORTMANS, F., "An evaluation of $^{240}$Pu resonance parameters" Resonance Parameters of Fertile Nuclei and $^{239}$Pu, Saclay, 1974

45 KOLAR, W. and BÖCKHOFF, K.H., J. Nucl. En. 22 (1968) 299

46 HOCKENBURY, R.W., MOYER, W.R.,and BLOCK, R.C., Nucl. Sci. Engng. 49 (1972) 153

47 AUCHAMPAUGH, G.F. and WESTON, L.W., "Parameters of the subthreshold fission structure in $^{240}$Pu". 4th Conf. on Neutron Cross Sections and Technology, Washington, 1975

48 POORTMANS, F., ROHR, G., THEOBALD, J.P., WEIGMANN, H. and VANPRAET, G.J., Nucl. Phys. A207 (1973) 342

49 AUCHAMPAUGH, G.F., FARRELL, J.A. and BERGEN, D.W., Nucl. Phys. A171 (1971) 31

50 THEOBALD, J.P., WARTENA, J.A., WEIGMANN, H. and POORTMANS, F., Nucl. Phys. A181 (1972) 639

51 WEIGMANN, H. and THEOBALD, J.P., Nucl. Phys. A187 (1972) 305

52 WEIGMANN, H., ROHR, G., Van der VEEN, T. and VANPRAET, G., "Neutron resonance capture as a means of studying the coupling conditions in sub-barrier fission" Symposium on Neutron Capture Gamma Ray Spectroscopy, Petten, 1974

53 WEIGMANN, H. and ROHR, G., "Systematics of total radiative widths of neutron resonances" Symposium on Nuclear Physics with Thermal and Resonance Energy Neutrons, Petten, 1973

54 POORTMANS, F. - private communication

55 PAYA, D. Thesis, 1972

56 SIMPSON, O.D., SIMPSON, F.B., HARVEY, J.A., SLAUGHTER, G.G., BENJAMIN, R.W. and AHLFELD, C.E., Nucl. Sci. Engng. 55 (1974) 273

57 BENJAMIN, R.W., AHLFELD, C.E., HARVEY, J.A. and HILL, N.W., Nucl. Sci. Engng. 55 (1974) 440

57a KALEBIN, S.M., "Results of measurements of the total cross section for the transactinium isotopes $^{241,243}$Am, $^{244,245,246,248}$Cm." Moscow Institute of Theoretical and Experimental Physics. Report for the IAEA Advisory Group Meeting on Transactinium Isotope Nuclear Data, Karlsruhe, 1975

58 MICHAUDON, A., "Nuclear Fission" Chap.1 in Advances in Nuclear Physics, Baranger, M. and Vogt, E. (Editors) (Plenum Press, New York, 1973)

59 JAMES, G.D., DABBS, J.W.T., HARVEY, J.A., HILL, N.W. and SCHINDLER, R.H., "Intermediate Structure studies of $^{234}$U cross sections" submitted to Phys. Rev.

59a JAMES, G.D. and RAE, E.R., Nucl. Phys. A118 (1968) 313

60 THEOBALD, J.P., WARTENA, J.A. and WEIGMANN, H., Nucl. Phys. A181 (1972) 639

61 WARTENA, J.A., WEIGMANN, H. and MIGNECO, E., "On sub-barrier fission in $^{238}$U". 4th Conf. on Neutron Cross Sections and Technology, Washington, 1975

62 KUIKEN, R., PATTENDEN, N.J. and POSTMA, H. Nucl. Phys. A167 (1971) 225

63 AUCHAMPAUGH, G.F., FARRELL, J.A. and BERGEN, D.W. Nucl. Phys. A171 (1971) 31

64 LYNN, J.E., Nuclear Data for Reactors 2 (IAEA, Vienna, 1966) p.89

65 WHEELER, J.A., Physica 22 (1956) 1103; Fast Neutron Physics, MARION, J.B. and FOWLER, J.L. (Editors) (Interscience, New York, 1963) p.2051

66 JAMES, G.D., LYNN, J.E. and EARWAKER, L.G. Nucl. Phys. A189 (1972) 225

67 YUEN, G., RIZZO, G.T., BEHKAMI, A.N. and HUIZENGA, J.R.Nucl.Phys.A171(1971)614

68 VOROTNIKOV, P.E., GLADKIKH, Z.S., DAVYDOV, A.V., DUBROVINA, S.M., OTROSHCHENKO, G.A., PAL'SHIN, E.S., SHIGIN, V.A. and SHUBKO, V.M., Yad. Fiz. 16 (1972) 916. Sov. J. Nucl. Phys. 16 (1973) 506

69 GOKHBERG, B.M., OTROSHCHENKO, G.A. and SHIGIN, V.A., Sov. Phys. Dokl. 4 (1960) 1074

70 SICRE, A., BARREAU, G., CHASTEL, R., DOAN, T.P., LEROUX, B. and SAGEAUX, J.C. Physics and Chemistry of Fission 1 (IAEA, Vienna, 1974) 71

71 LAMPHERE, R.W., Nucl. Phys. 38 (1962) 561

72 JAMES, G.D., LANGSFORD, A. and KHATOON, A., Progress Report AERE PR/NP19 p.16

73 BLONS, J., Nucl. Sci. and Engng. 51 (1973) 130

74 BLONS, J., DERRIEN, H. and MICHAUDON, A., Nuclear Data for Reactors 1 (IAEA, Vienna, 1970) 513

75 BOWMAN, C.D., COOPS, M.S., AUCHAMPAUGH, B.F. and FULTZ, S.C., Phys. Rev. 137 (1965) B326

76 POORTMANS,F.,CEULEMANS,H.,THEOBALD,J. and MIGNECO,E.,3rd Conf. on Neutron Cross Sections and Technology, Knoxville 2 (1971) 667

77 FUKETA, T. and HARVEY, J.A., Nucl. Instrum. Meth. 33 (1965) 107

78 WIGNER, E.P., SIAM Review 9 (1967) 1

79 MUSGROVE, A.R. de L., Australian J. Phys. 21 (1968) 779

80 BOLLINGER, L.M. and THOMAS, G.E., Phys. Rev. 171 (1968) 1293

81 BAYES, T., Phil. Trans.Roy.Soc.53(1763)370 also Biometrika 45 (1958) 293

82 DYSON, F.G., J. Math. Phys. 3 (1962) 140, 157, 166, 1199

83 LIOU, H.I., CAMARDA, H.S., WYNCHANK, S., SLAGOWITZ, M., HACKEN, G., RAHN, F. and RAINWATER, J., Phys. Rev. C5 (1972) 974

84 DYSON, F.J. and MEHTA, M.L., J. Math. Phys. 4 (1963) 701

85 LIOU, H.I., CAMARDA, H.S. and RAHN, F., Phys. Rev. C5 (1972) 1002

86 MONAHAN, J.E. and ROSENZWEIG, N., Phys. Rev. C5 (1972) 1078

87 JAMES, G.D., Nucl. Phys. A170 (1971) 309

88 WALD, A. and WOLFOWITZ, J., Annals Math. Stat. 2 (1940) 147

89 MOORE, M.S., Statistical Properties of Nuclei (J.B. Gard, Editor) (Plenum Press, New York, 1972) 55

90 MOORE, M.S. and KEYWORTH, G.A., Phys. Rev. C3 (1971) 1656

91 BAUDINET-ROBINET, Y. and MAHAUX, C., Phys. Rev. C9 (1974) 723

92 OLMSTEAD, P.S., Bell. Syst. Tech. J. 55 (1958) 1

93 BAUDINET-ROBINET, Y. and MAHAUX, C., Phys. Lett. 42B (1972) 392

94 LEVINE, H. and WOLFOWITZ, J., Annals Math. Stat. 15 (1944) 58

95 JAMES, G.D., DESAUSSURE, G. and PEREZ, R.B., Am. Nucl. Soc. Trans. 17 (1973) 495

96 MIGNECO, E., BONSIGNORE, P. and LANZANO, G., 4th Conf. on Neutron Cross Sections and Technology, Washington, 1975

97 DABBS, J.W.T., BEMIS, C.E., HILL, N.W., JAMES, G.D., MOORE, M.S. and ELLIS, A.N., Physics and Chemistry of Fission 2 (IAEA, Vienna, 1973) 505

98 STRUTINSKY, V.M., and PAULI, H.C., Physics and Chemistry of Fission (IAEA, Vienna, 1969) 155

99 WALD, A. and WOLFOWITZ, J., Annals Math. Stat. 14 (1943) 378

100 MOOD, A.M., Annals Math. Stat. 11 (1940) 367

101 CORVI, F., STEFANON, M., COCEVA, C., GIACOBBE, P., Nucl. Phys. A203 (1973) 145

102 PEREZ, R.B. et al., Report ORNL-TM-3696 (1972)

TABLE 1

$^{240}$Pu + n class II resonance parameters
(after Auchampaugh and Weston [47])

| E (eV) | $\langle H^2 \rangle$ (eV)$^2$ | $\Gamma_{II(f)}$ (eV) |
|---|---|---|
| 782 | 2.24 $\pm$ 0.23 | 1.6 $\pm$ 0.4 |
| 1406 | 4.67 $\pm$ 2.33 | 3.5 $\pm$ 0.4 |
| 1936 | 5.37 $\pm$ 3.27 | 2.3 $\pm$ 0.6 |

## FIGURE CAPTIONS

<u>Fig.</u>

1 Energy dependence of class I fission widths for resonances in the fission cross section of $^{234}U$ below 1500 eV. The solid line represents the energy dependence of the mean fission width as a sum of two Lorentzian curves. A dot at 50 (40) indicates that a fission width is above (below) a median value which lies at 0.47 of the mean value for a Porter-Thomas distribution. After James et al. [59]

2 The $^{234}U$ fission cross section between 1 keV and 20 keV showing class II structures with $\bar{D} = 2.1 \pm 0.3$ keV. After James et al. [59]

3 Sub-threshold fission cross section for $^{238}U$ measured on a lead slowing down spectrometer by Block et al. [26]

4 Fission data for $^{237}Np$ in the region of the group at 40 eV. The upper curve representing the difference between the cross sections measured with the beam and target polarization parallel and anti-parallel is consistently greater than zero over each of the nine individual resonances, indicating J = 3 in each case. After Keyworth et al. [2]

5 A sample of the transmission data for $^{237}Np$ obtained by Keyworth et al. [2]. The upper curve dips below zero for resonances with J = 3 and protrudes above zero for those with J = 2.

6 Fission widths versus neutron energy for $^{240}Pu$ after Auchampaugh and Weston [47]

7 Fission widths versus neutron energy for $^{242}Pu$ measured by Poortmans et al. [48] . The two curves represent Lorentzian distributions of the mean fission width.

8 The $^{230}Th$ fission cross section from 0.6 MeV to 1.4 MeV measured by James et al. [66]

9 The $^{228}Th$ fission cross section from 0.2 MeV to 2 MeV measured by Vorotnikov et al. [68]

10 The fission cross section of $^{232}$Th from 1.2 MeV to 2.4 MeV showing structure in the resonances at 1.6 MeV and 1.7 MeV. The solid line is the calculated sum of transmission coefficients for a series of double humped barriers. After Blons et al. [13]

11 A fission fragment anisotropy function a(K,J) for $^{232}$Th derived from measurements using a detector with a grid. Calculated values of a(K,J) for a series of values of K and J are also shown. After Blons et al. [13]

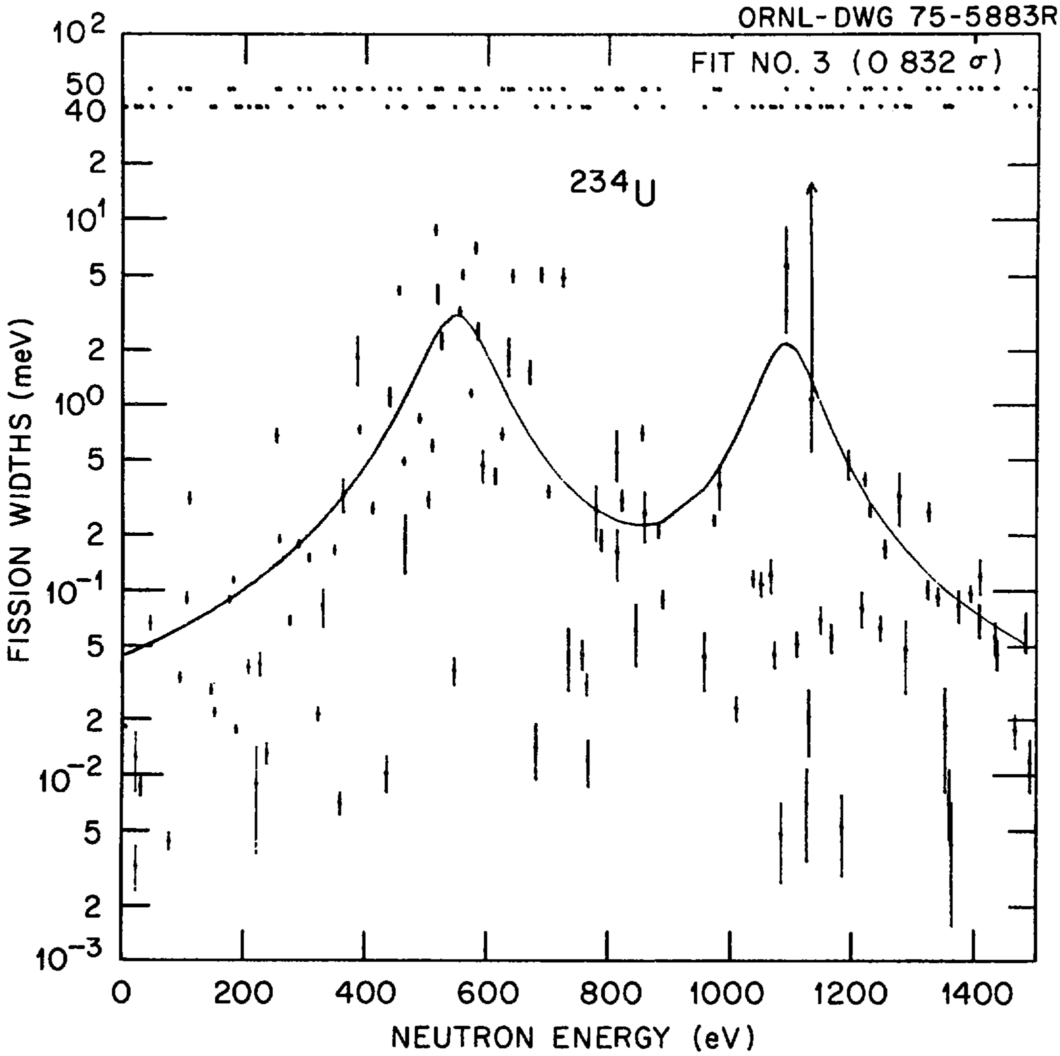
12 The $^{231}$Pa fission cross section from 0.2 MeV to 1.4 MeV and the variation of $W(0^{o})/W(90^{o})$ compared with the results of Vorotnikov et al. After Sicre et al. [70]

13 The $^{234}$U fission cross section between 20 keV and 1.6 MeV. After James et al. [59]

14 The fission cross section of $^{234}$U between 270 keV and 370 keV is shown by the full circles. Of the two solid lines through the data, one shows a running sum over twenty timing channels and the other is a guide line indicating fluctuations. The presumed contribution of the vibrational level is shown by the dashed line and again by the diagram below the data. After James et al. [59]

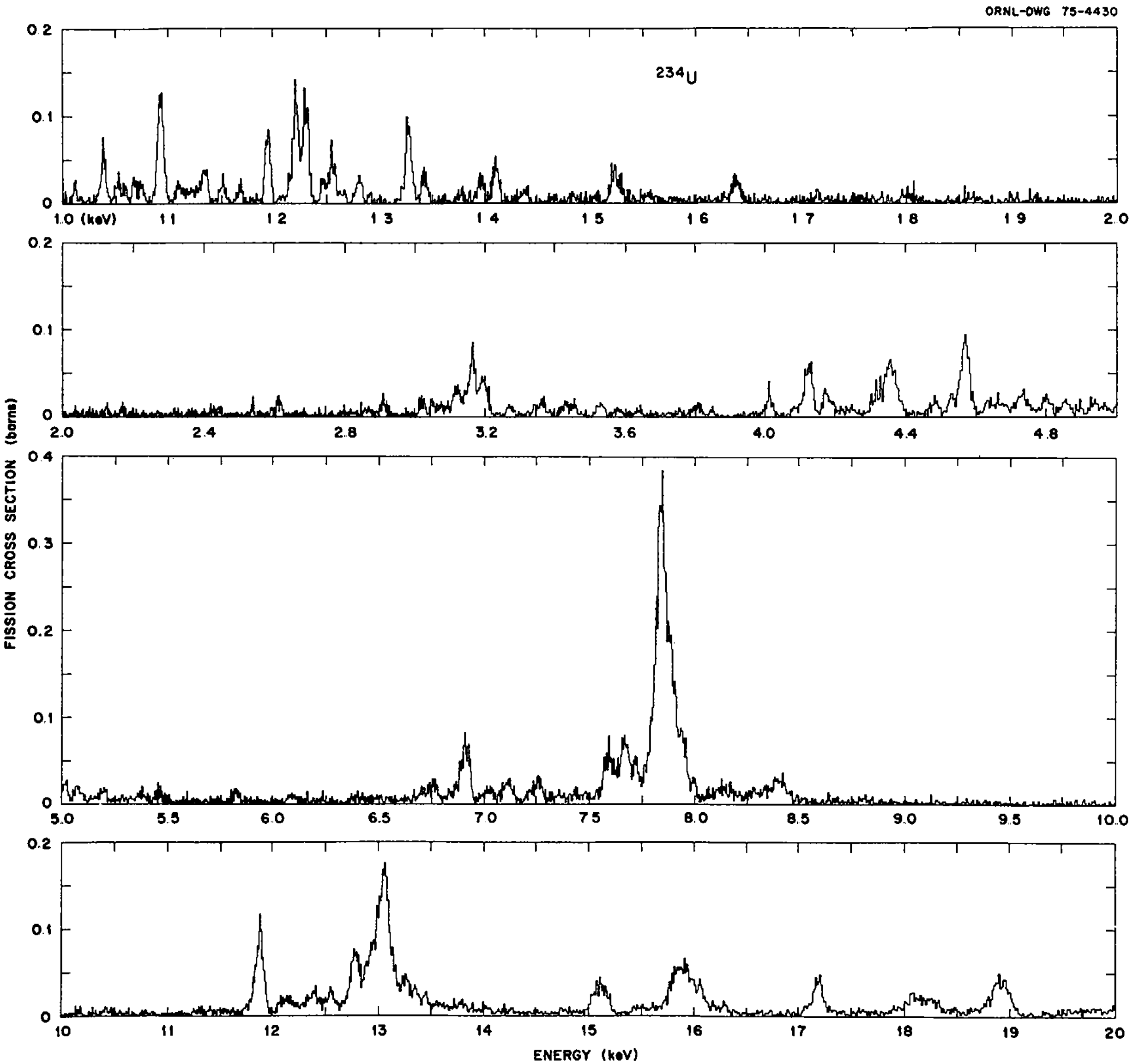
15 Observed $\Delta_3$ values for 102 levels in $^{236}$U versus energy of the excluded resonances. After Cararro and Brusegan [38]

16 Results of three statistical tests on simulated fission cross section data obtained by mixing a data set with a constant average fission width with a data set in which the fission widths are strongly modulated by class II levels. Both tests due to Wald and Wolfowitz [88] and [99] show a monotonic increase with increasing modulation of $\Gamma_f$ up to 14.2 and 10.2 standard deviations respectively. Both these tests indicate that the measured $^{235}$U fission cross section is similar to the simulated data at 50% of the maximum fission width modulation. The runs up and down test of Levine and Wolfowitz [94] gives an unreliable indication of the degree of modulation in this instance. R(1) is completely independent of the fraction of modulated data.




118 Fission Widths.

Fig. 1



ORNL-DWG 75-4430
$^{234}$U
FISSION CROSS SECTION (barns)
ENERGY (keV)
1.0 (keV)


Fig. 2

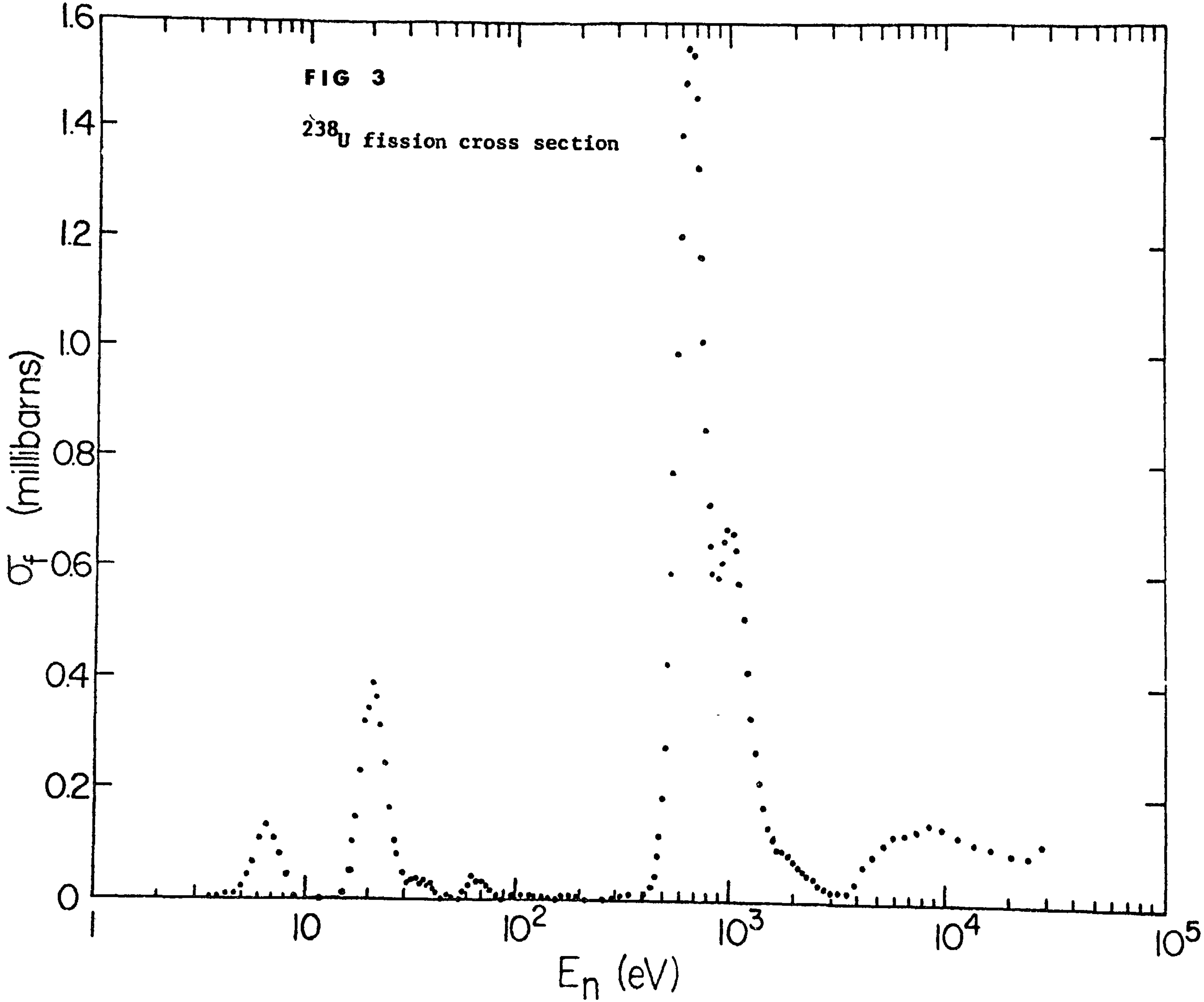
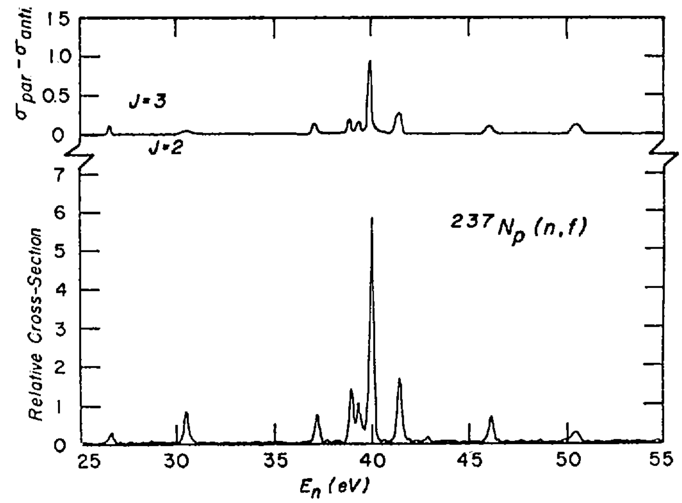


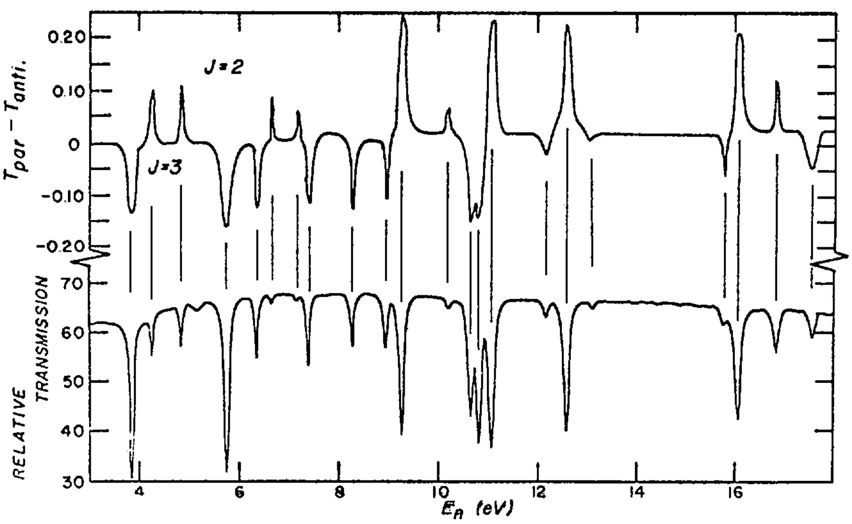

**FIG 3**

$^{238}$U fission cross section



$\sigma_{par} - \sigma_{anti.}$
J=3
J=2
$^{237}N_p\ (n,f)$
Relative Cross-Section
$E_n\ (eV)$

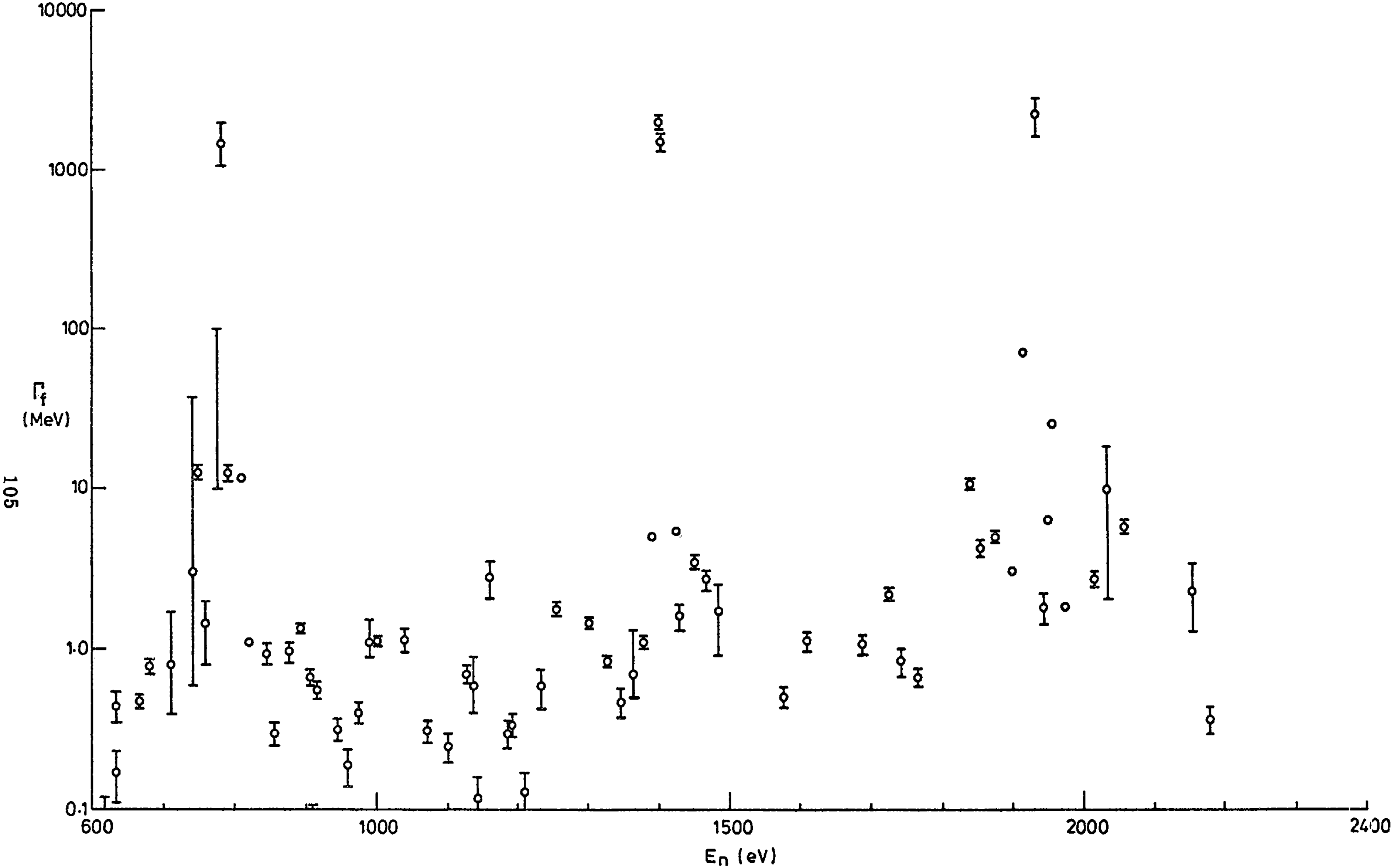

**FIG 4**



$T_{par} - T_{anti.}$
J=2
J=3
RELATIVE TRANSMISSION
$E_n\ (eV)$


**FIG 5**

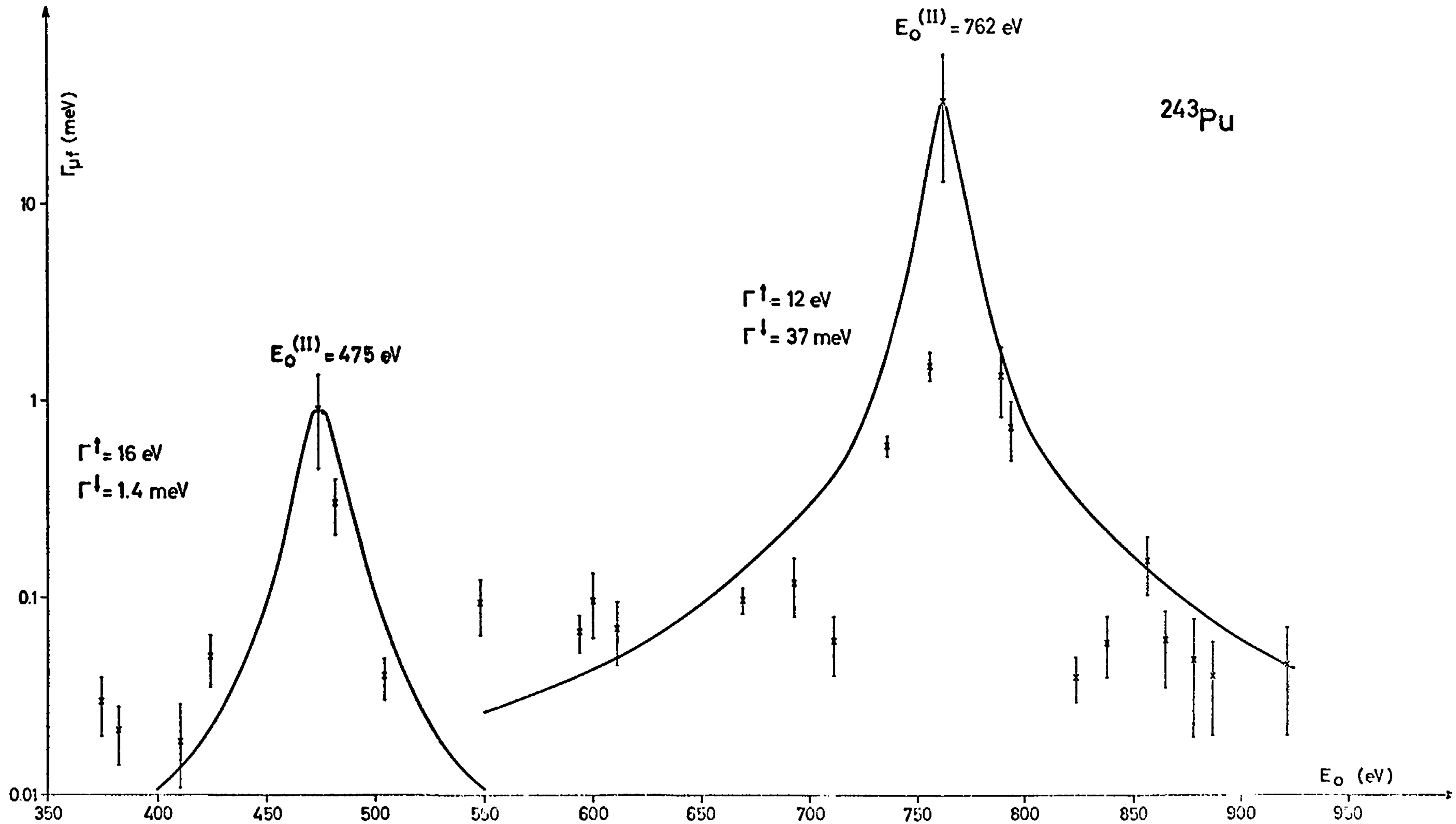
105




FISSION WIDTHS FOR RESONANCES IN $^{240}$Pu [after AUCHAMPAUGH AND WESTON]

FIG 6

106



$\Gamma_{\mu f}$ (meV)
10
1
0.1
0.01
350
400
450
500
550
600
650
700
750
800
850
900
950
$E_o$ (eV)
$^{243}$Pu
$E_o^{(II)}$ = 475 eV
$E_o^{(II)}$ = 762 eV
$\Gamma^{\uparrow}$ = 16 eV
$\Gamma^{\downarrow}$ = 1.4 meV
$\Gamma^{\uparrow}$ = 12 eV
$\Gamma^{\downarrow}$ = 37 meV


FIG. 7

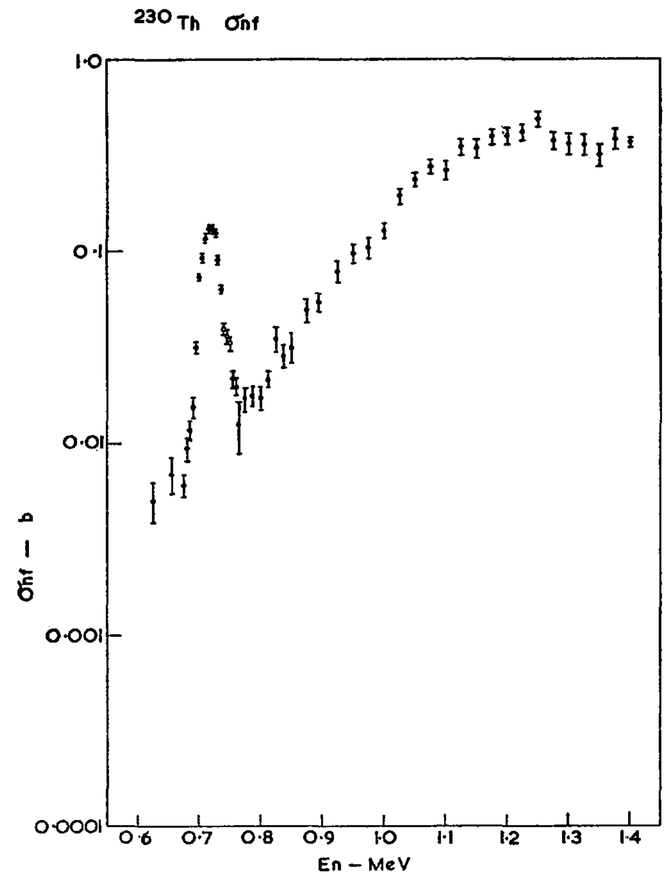

230 Th σnf
1·0
0·1
0·01
0·001
0·0001
σnf — b
0·6
0·7
0·8
0·9
1·0
1·1
1·2
1·3
1·4
En — MeV

**FIG 8**

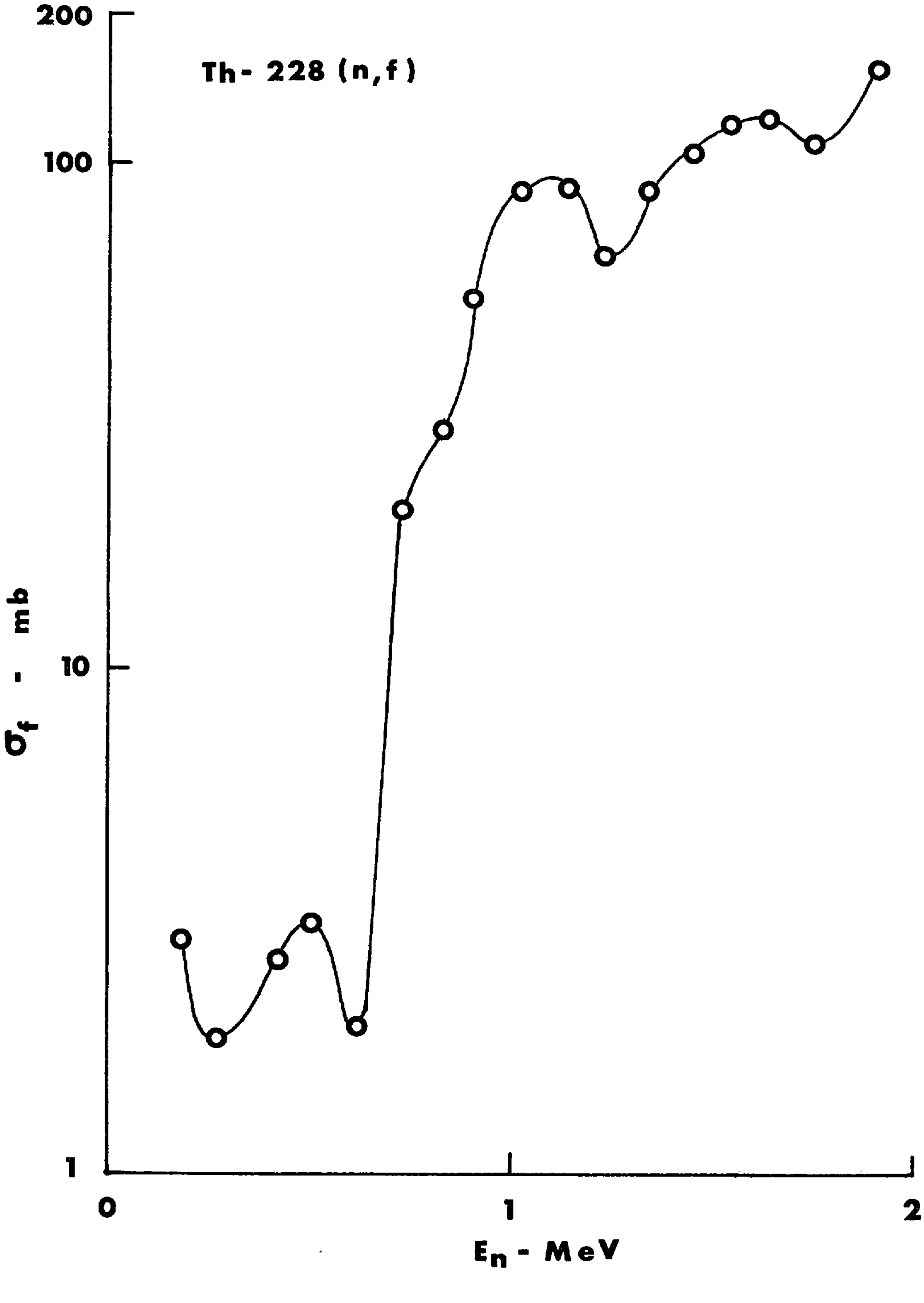
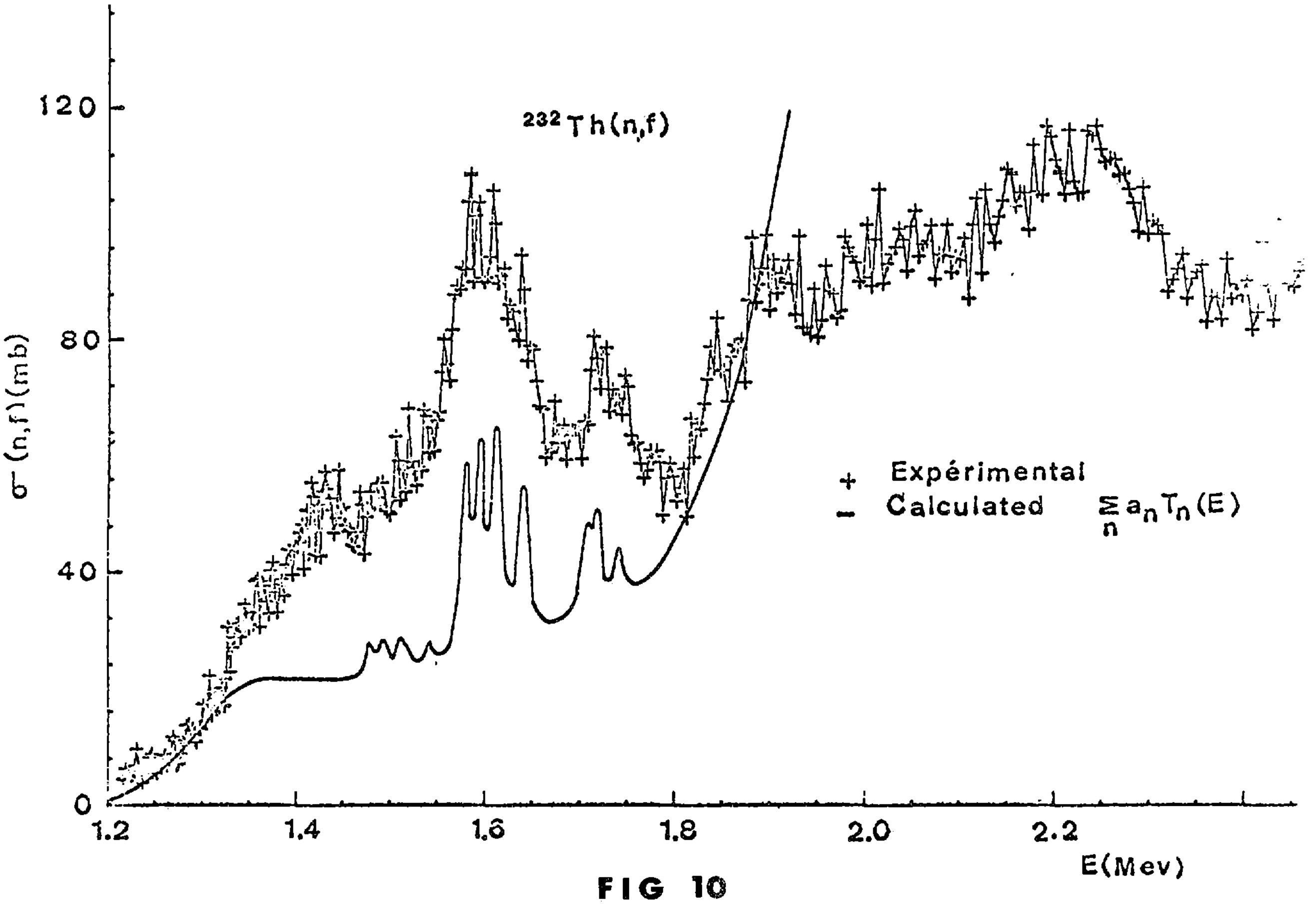
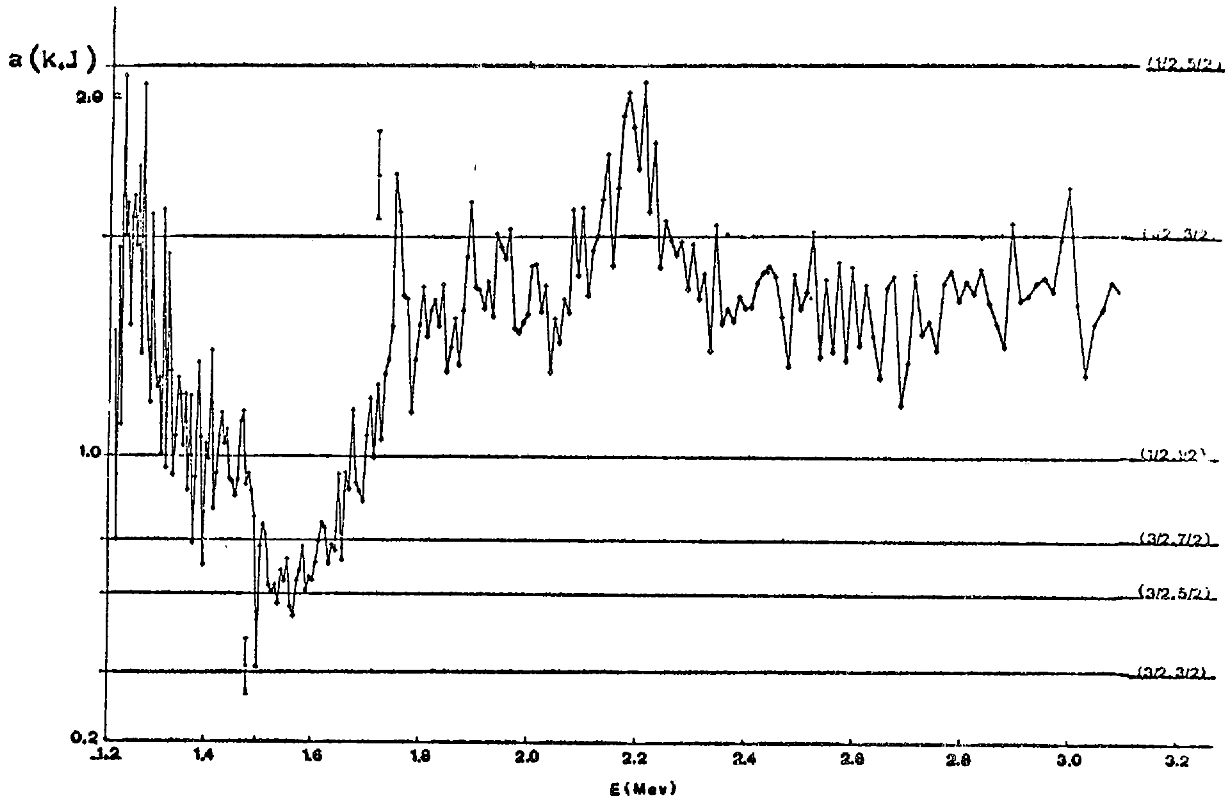



FIG 9



120
80
40
0
$^{232}$Th(n,f)
σ (n,f)(mb)
+ Expérimental
– Calculated $\sum_n a_n T_n(E)$
1.2
1.4
1.6
1.8
2.0
2.2
E(Mev)


**FIG 10**



a (K,J)
2.0
1.0
0.2
(1/2,5/2)
(3/2,7/2)
(3/2,5/2)
(3/2,3/2)
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
E(Mev)


**FIG 11**

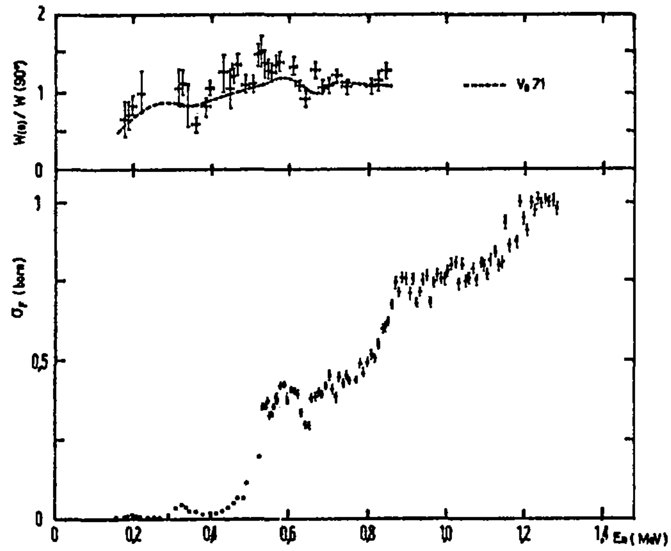

W(θ)/W(90°)
σf (barns)
V. 71
En(MeV)

FIG 12

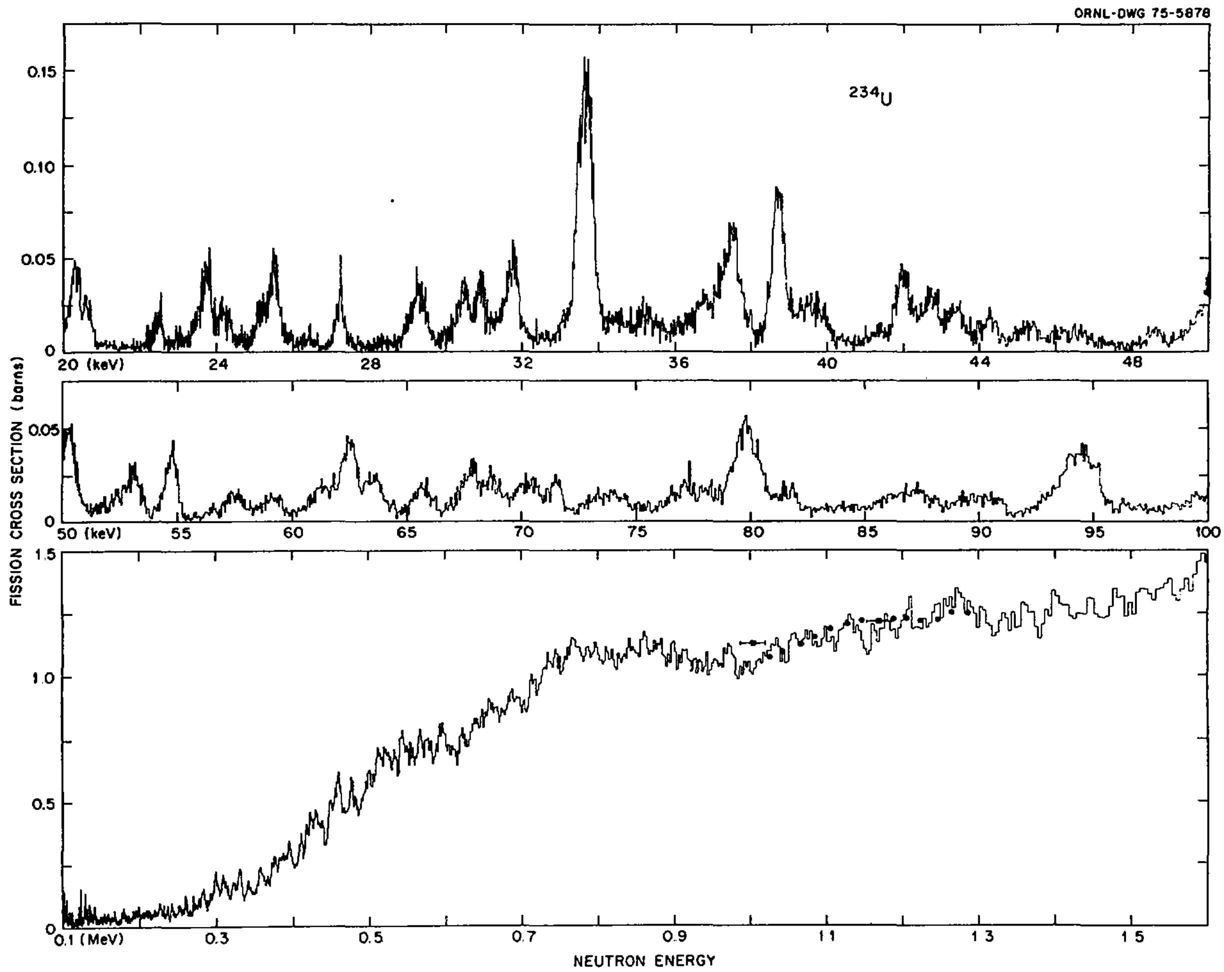
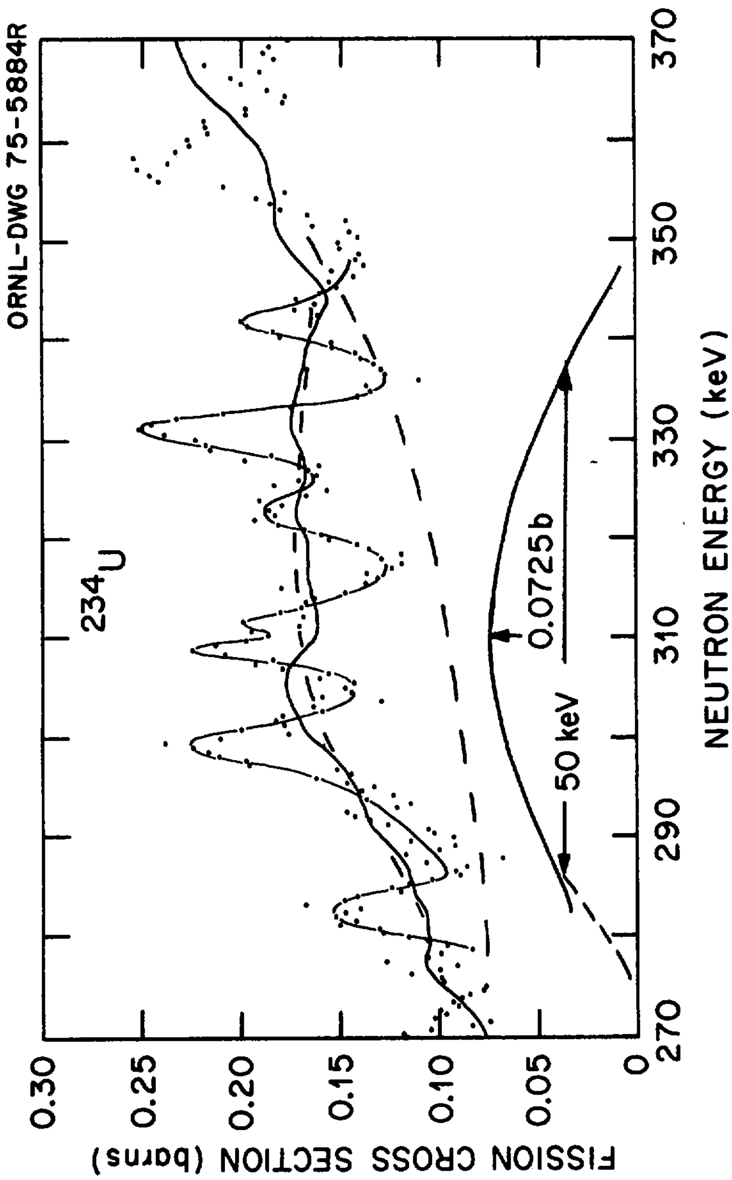

ORNL-DWG 75-5878
234U
FISSION CROSS SECTION (barns)
20 (keV)
50 (keV)
0.1 (MeV)
NEUTRON ENERGY

Fig. 13



ORNL-DWG 75-5884R
$^{234}$U
0.0725b
50 keV
FISSION CROSS SECTION (barns)
0.30
0.25
0.20
0.15
0.10
0.05
0
270
290
310
330
350
370
NEUTRON ENERGY (keV)


Fig. 14

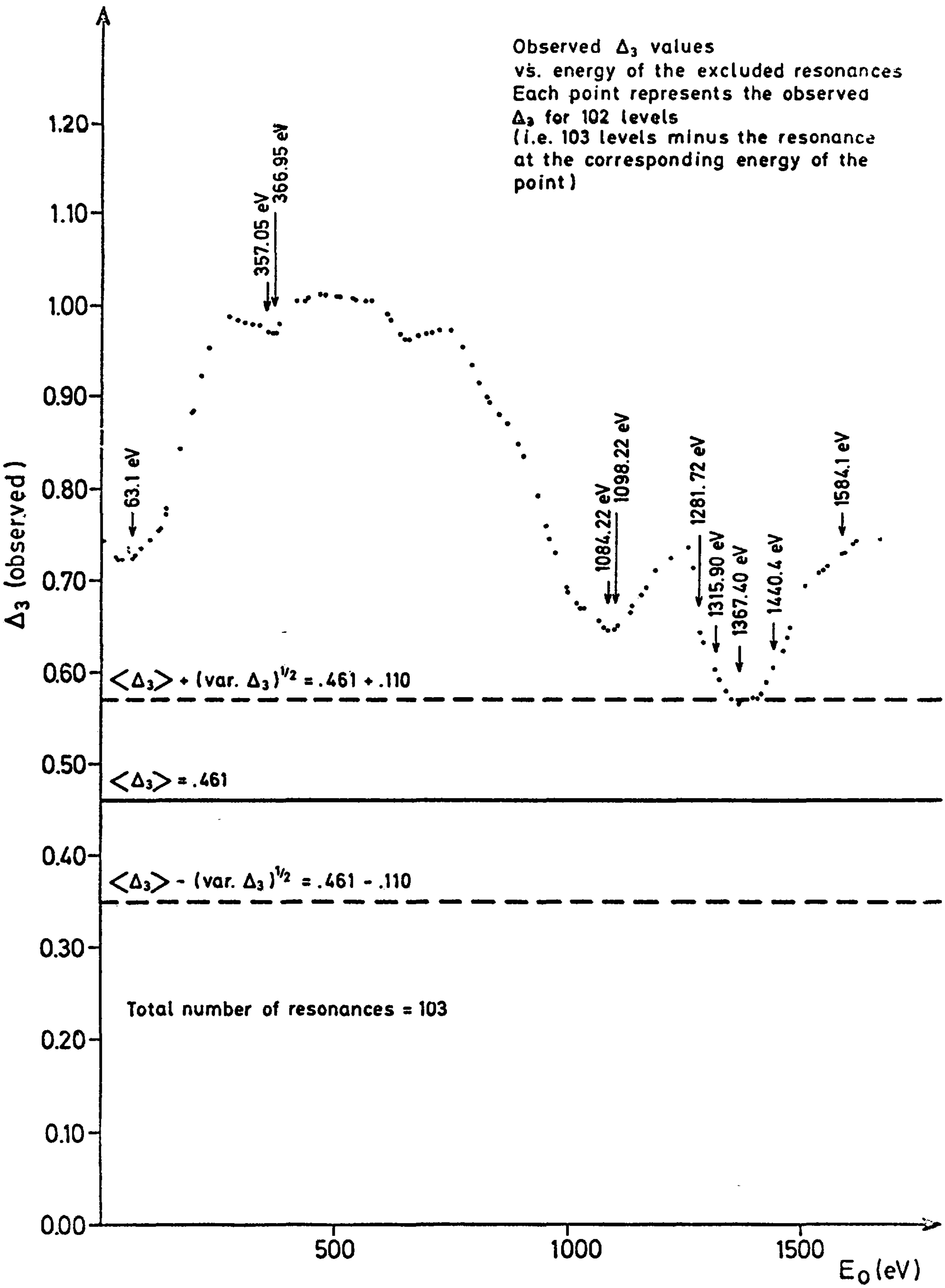

Observed Δ₃ values
vs. energy of the excluded resonances
Each point represents the observed
Δ₃ for 102 levels
(i.e. 103 levels minus the resonance
at the corresponding energy of the
point)
Δ₃ (observed)
63.1 eV
357.05 eV
366.95 eV
1084.22 eV
1098.22 eV
1281.72 eV
1315.90 eV
1367.40 eV
1440.4 eV
1584.1 eV
<Δ₃> + (var. Δ₃)^½ = .461 + .110
<Δ₃> = .461
<Δ₃> - (var. Δ₃)^½ = .461 - .110
Total number of resonances = 103
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20
500
1000
1500
E0 (eV)

**FIG 15**

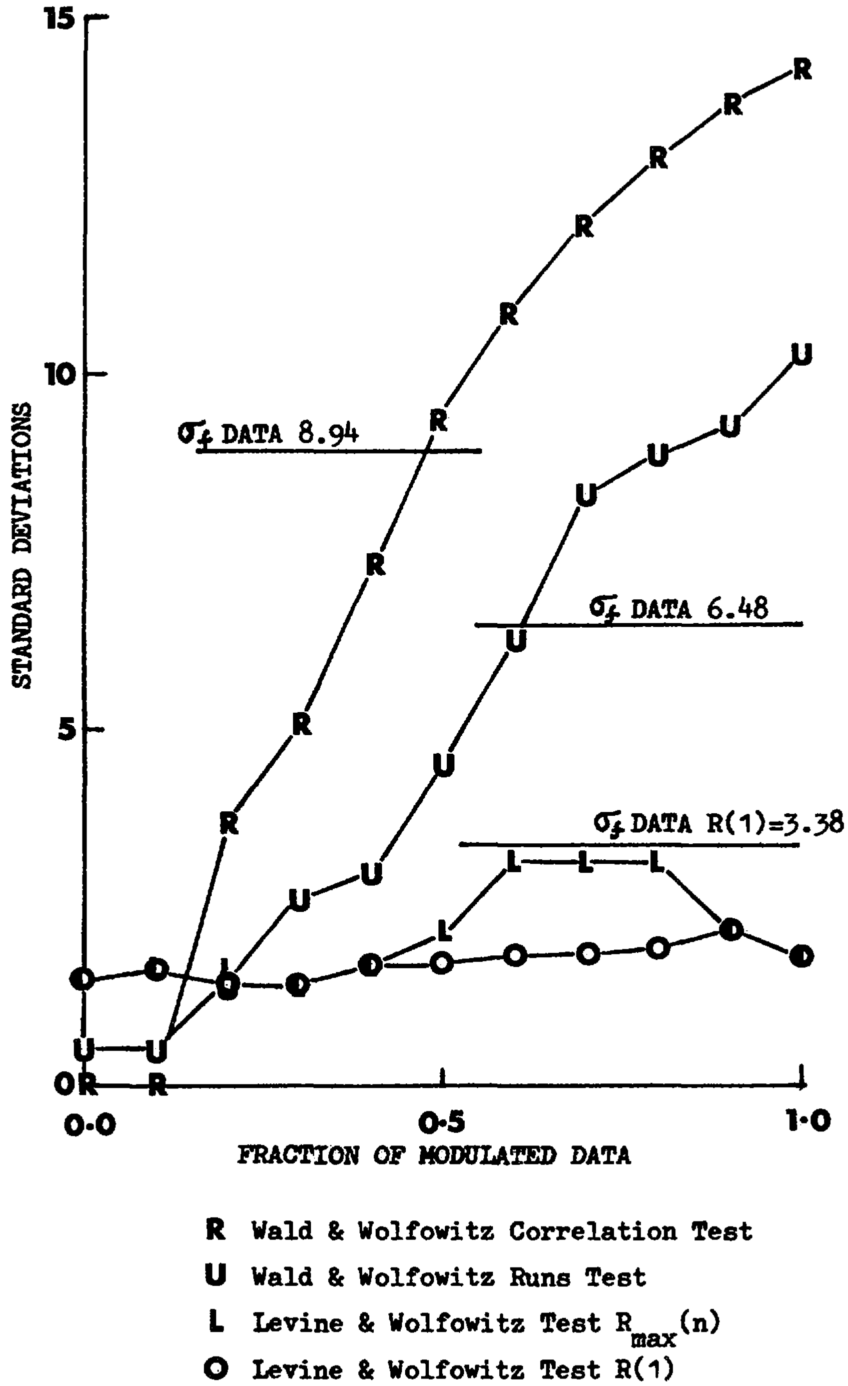

15
10
5
0
STANDARD DEVIATIONS
$\sigma_f$ DATA 8.94
$\sigma_f$ DATA 6.48
$\sigma_f$ DATA R(1)=3.38
0·0
0·5
1·0
FRACTION OF MODULATED DATA
R Wald & Wolfowitz Correlation Test
U Wald & Wolfowitz Runs Test
L Levine & Wolfowitz Test $R_{max}(n)$
O Levine & Wolfowitz Test R(1)

FIG 16

Contributed Paper to Topic B2

# NEUTRON CAPTURE CROSS SECTIONS OF THE ACTINIDES*

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## Abstract

Consideration is given to the measurement and calculations of neutron cross section of actinide isotopes, and of the importance of some of these cross sections to fast reactor calculations. The average absorption cross section of $^{241}$Am between 0.01 eV and 350 KeV is compared to the ENDF/B-IV evaluated data is presented.

The long-lived actinides have assumed major importance in waste management for power reactors.[1,2] A great deal of calculational effort has been applied to prediction of the build-up of these nuclides which will be a hazard for more than 250,000 years. Additional work has been done on the feasibility of transmuting these long-lived nuclides to shorter lived fission products by recycling them in reactors.

A major deterrent to accurately calculating quantitative actinide build-up and the feasibility of actinide transmutation has been the sparsity of cross section measurements for the actinide isotopes which are basically not reactor fuel. This is particularly true for fast reactors which operate with neutron energies above thermal. Fission cross section measurements are more abundant than are capture cross section measurements.[3] Normally in reactor calculations the accuracy

*Research sponsored by the Energy Research and Development Administration under contract with the Union Carbide Corporation.

of the necessary fission cross sections is more important than capture because of multiple neutrons emitted per fission. For the case of actinide build-up and transmutation, however, the fission and capture cross sections assume more of a similar correspondence in importance.

Capture cross sections in the resonance region of neutron energies and up to a few kilovolts neutron energy can often be derived from total cross section measurements when fission cross sections are not appreciable. These total cross section measurements, which are simplier than direct capture measurements because of the natural radioactivity of the actinides require about an order of magnitude less sample in the resolved resonance region of neutron energies. Above a few keV, and at lower neutron energies when fission is appreciable, direct capture cross section measurements assume great importance. Integral measurements are valuable but do not contain as complete or as versatile information as differential measurements.

Nuclear model calcualtions can be used to compute capture cross sections above a few kilovolts.[4] The reliability of such calculations varies according to the particular case. Since direct capture cross section measurements cannot be made on all the actinides, particularly the ones with very high spontaneous fission rates, nuclear model calculations must be relied upon in many cases. For the cases where capture cross sections can be measured they would enable refinements of the nuclear model calculations for these and other nuclides.

An example of a capture cross section measurement[5] with an actinide is shown in Figs. 1 and 2. This measurement with $^{241}Am$ yields the absorption cross section which is predominately capture since fission is small. This measurement indicates the cross section above 20 keV is appreciably greater than the nuclear model calculation represented by ENDF/B-IV. This difference is important to fast reactors since it would lead to increased $^{242}$Cm production. Production of $^{242}$Cm presents a fuel handling problem because of its high spontaneous fission rate. It would also indicate greater production of the higher actinides in fast reactors. Recent nuclear model calculations[6] are more consistent with the measured data. Even at thermal neutron energies and in the resonance region (see Fig. 2), information is added by such a measurement. This measurement was done with the Oak Ridge Electron Linear Accelerator using "total energy detectors"[7] to detect the prompt gamma rays following an absorption event in the sample.

A major difficulty in additional capture cross section measurements on the actinides would be obtaining pure isotopic samples. Since it is not possible to completely discriminate between capture and fission events, isotopes with high spontaneous fission rates must be excluded from the samples. Some actinides for which capture cross section measurements would be feasible if proper samples were available would be $^{237}$Np, $^{243}$Am, $^{242M}$Am, $^{245}$Cm, and $^{247}$Cm. The cost of the sample preparation for the isotopes other than $^{237}$Np and perhaps $^{243}$Am would be rather high and might need to be justified by more refined reactor sensitivity calculations than have presently been done.

In conclusion, capture cross section measurements could be carried out on some of the nuclides which are important to actinide waste disposal and transmutation. The required effort and expense would be rather high; however, the cost of surprises caused by misjudged cross sections could be much higher.

Fig. 1. The Average Absorption Cross Section of $^{241}Am$ Between 0.01 and 350 keV Compared to ENDF/B-IV, Mat 1056.

Fig. 1

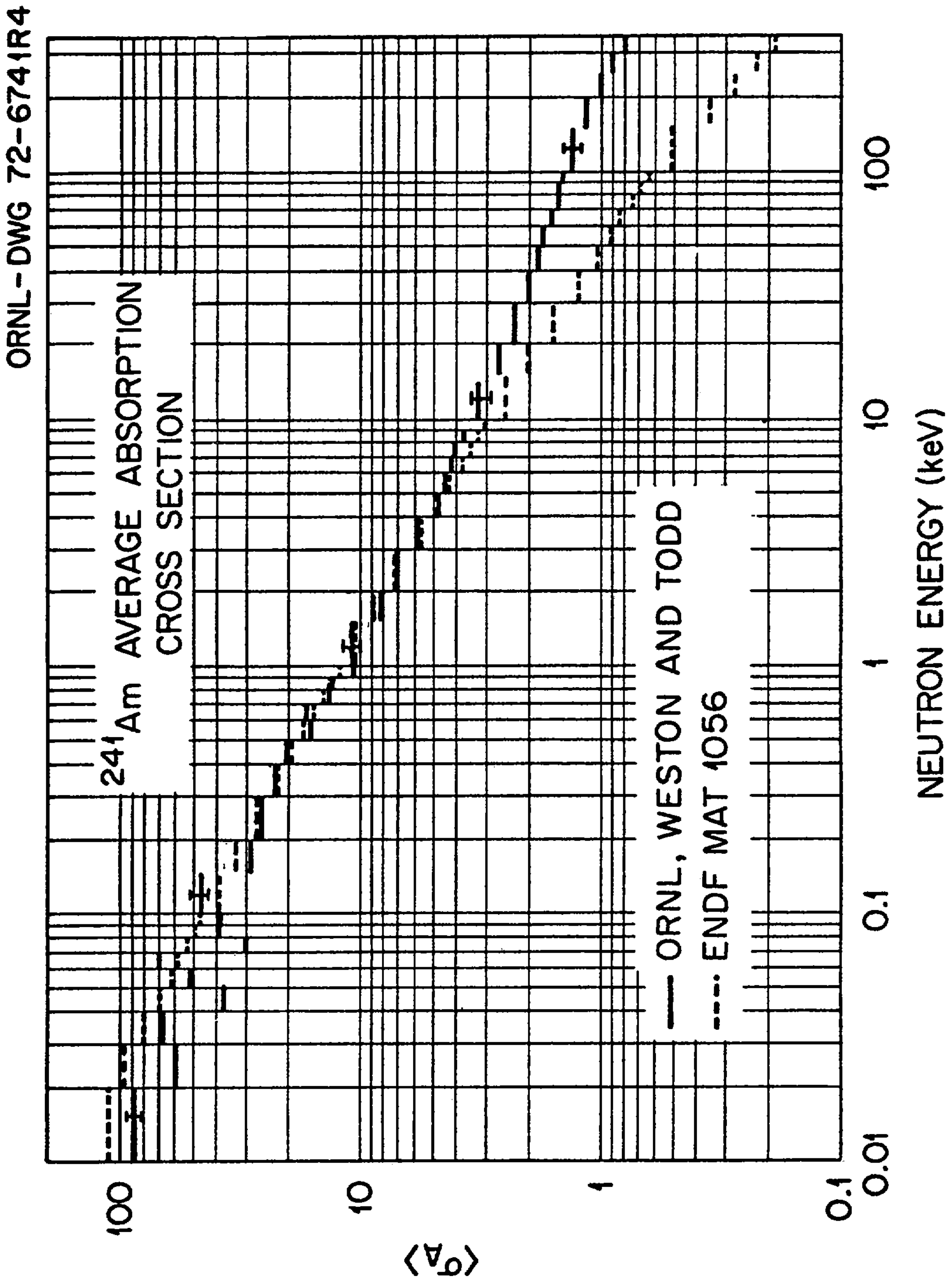
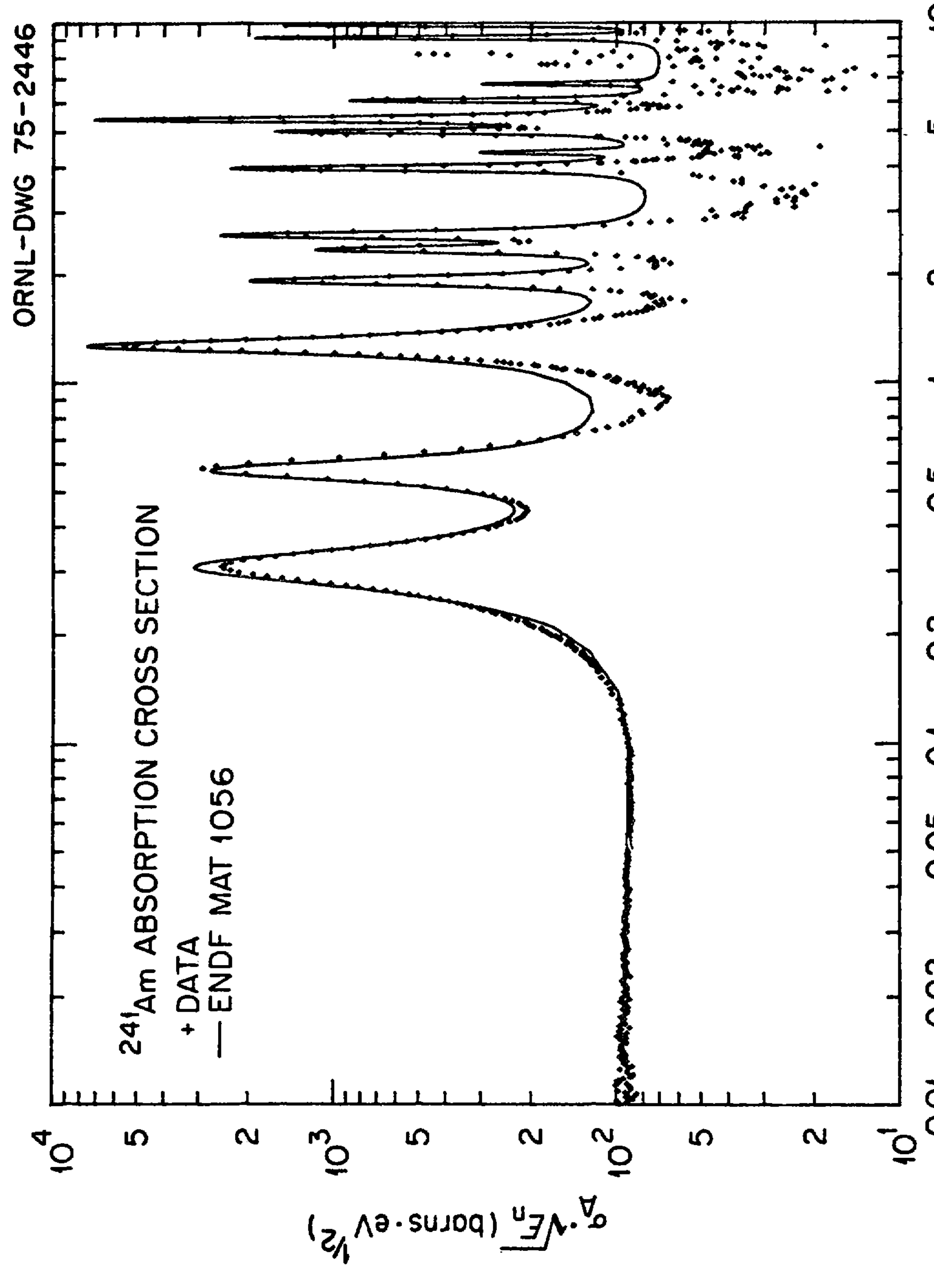


**Fig. 2.** The Absorption Cross Section of $^{241}$Am Between 0.01 and 10 eV Compared to ENDF/B-IV, Mat 1056.

Fig. 2



## REFERENCES


1. H. C. Claiborne, "Neutron-Induced Transmutation of High-Level Radioactive Waste," ORNL-TM-3964, December 1972; also ORNL-TM-4724, January 1975.

2. "High-level Radioactive Waste Management Alternatives," BNWL-1900, vols. 1-4, May 1974.

3. R. W. Benjamin, "Survey of Experimentally Determined Neutron Cross Sections of the Actinides," DP-1324, 1973.

4. J. E. Lynn, "Systematics for Neutron Reactions o: the Actinide Nuclei," AERE-R-7468, November 1974.

5. L. W. Weston and J. H. Todd, "Measurement of the Neutron Capture Cross Sections of the Actinides," Proc. Conf. Nuclear Cross Sections and Technology, March 3-7, 1975, Washington, D. C., to be published.

6. R. E. Schenter, Westinghouse - Hanford, priviate communication.

7. R. L. Macklin and J. H. Gibbons, Phys. Rev. 159, 1007 (1967).

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# Total Neutron Cross-Section Measurements on the Transactinium Isotopes $^{241,243}Am$, $^{244,245,246,248}Cm$


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## Abstract

Results obtained in in-pile measurements of the total neutron cross sections of americium and curium isotopes by the time-of-flight method are presented. Resonance parameters are derived and the results are compared with published data.


The paper discusses the results obtained in in-pile measurements (by the time-of-flight method) of the total neutron cross-sections of americium and curium isotopes. The data obtained on a neutron chopper with synchronous rotors suspended in a magnetic field [1, 2] are also to be found in Refs [3-6].

The best resolution in the measurements was 70 nsec/m, the background was not more than 4%, the statistical accuracy of the experimental data was within the limits 0.5-1.5%. The transverse cross-section of the neutron beam at the point where the target was located was 3 mm$^2$, which made it possible to perform the measurements with small amounts of the isotopes.

## Americium-241

The measurements were carried out using 99.9 mg of $AmO_2$ powder with a 99.99% content of $^{241}Am$. Thanks to the high purity of the sample a reliable energy dependence could be obtained for the total neutron cross-section of this isotope in the thermal energy range [3]. Figure 1 shows the results in the 0.0036-8 eV range. The dashed curve in this figure represents the calculated neutron capture cross-section for positive $^{241}Am$ resonances. At the thermal point (0.025 eV) this cross-section is 180 b, while the experimentally measured cross-section is 640 $\pm$ 20 b.

Calculating the neutron level parameters in the resonance energy range from the Breit-Wigner single-level formula gave a constant potential neutron scattering cross-section of 12.8 ± 1 b for $^{241}$Am. In view of the fact that the fission cross-section at the thermal point is equal to 3 b [7], it follows from the total cross-section obtained that the neutron capture cross-section for an energy of 0.025 eV is 624 ± 20 b. Table I compares this result with data obtained by integral methods of measuring the equivalent total neutron capture cross-section of $^{241}$Am.

Table I

Total capture cross-section of $^{241}$Am at 0.025 eV

| $\sigma_\gamma$, barn | 624 ± 20 | 360 | 900 | 647 ± 104 | 832 ± 20 |
|---|---|---|---|---|---|
| Reference | this work [3] | [8] | [9] | [10] | [11] |

The last value given in the table is recommended in BNL-73 [12]. The pronounced spread in the results obtained by the integral method are no doubt due to the fact that the $^{241}$Am neutron cross-section in the thermal energy range has a complicated energy dependence; this can be seen from Fig. 1. The value of 832 ± 20 b recommended in BNL-73 is not in agreement with the value of 624 ± 20 b obtained in measurements by the time-of-flight method.

Table II gives the neutron resonance parameters obtained in the measurements described in Refs [3, 4]. For purposes of comparison, this table also gives the values obtained in Refs [12, 13, 14]. The comparison shows that there is a marked divergence. The measurements in Refs [3, 4] include new resonances: 7.53, 10.11, 11.58, 12.06, 14.32, 18.00, 20.28, 25.05 eV. On the other hand, these measurements do not confirm the existence of levels at: 1.68, 4.40, 6.78, 7.97, 8.28, 16.02, 18.37. The 8.17-eV resonance shown has a neutron width an order of magnitude less, while a resonance with energy 15.66 ± 0.07 eV corresponds to the resonances 15.60 ± 0.5 eV and 15.73 ± 0.05 eV. Above an energy of 20 eV, a provisional total neutron cross-section with a high resolution was measured by Derrien et al. in 1973 [15]. The same authors also presented data starting at 1 eV [16] at the Third Neutron Conference which was held at Kiev, USSR, 9-13 June 1975. At this same conference a comparison was made between their results and those from Refs [3, 4], given in Table II, and the agreement was found to be good. In the case of $^{241}$Am a mean spacing of 0.67 ± 0.10 eV was obtained between neutron resonances, and a value of (0.76 ± 0.18) x $10^{-4}$ for the neutron strength function S. The values of these quantities, taken from Ref. [12], are 0.74 ± 0.08 eV and (1.2 ± 0.2) x $10^{-4}$, respectively.

Americium-243

The measurements were carried out using 266 mg of $AmO_2$ powder. Table III gives the isotopic composition based on mass-spectrometric analysis.

Table III

Isotopic composition of sample of $^{243}Am$ (%)

| $^{243}Am$ | $^{241}Am$ | $^{244}Cm$ | $^{242}Cm$ |
|---|---|---|---|
| 96.60 | 3.32 | 0.07 | 0.01 |

The sample also contained ~5% of inactive impurities (1.5% iron; 0.5% nickel; 0.4% sodium; 0.15% chromium and others). Since the sample was not sufficiently pure, it was not possible to study the total neutron cross-section of $^{243}Am$ in the thermal range as was done in the case of $^{241}Am$. Table IV [5] gives the neutron resonance parameters obtained. For comparison, Table IV also gives the values obtained in Refs [12, 17, 18, 19]. It can be seen from the data in the table that some of the resonances show divergences. It will be noted that the neutron widths of the resonances in the study of Belanova, Kalebin et al. [5] are as a rule rather less than those found by Simpson et al. [17] and Berreth and Simpson [18]. On the whole the data are in satisfactory agreement. The mean spacing between the neutron levels is $0.71 \pm 0.06$ eV, and the neutron strength function S is $(0.89 \pm 0.21) \times 10^{-4}$. The values for these quantities given in Ref. [12] are $0.67 \pm 0.06$ eV and $(0.096 \pm 0.10) \times 10^{-4}$, respectively.

Curium-244, -245, -246, -248

The measurements were carried out on two samples of $Cm_2O_3$, of weight 32.8 mg and 116.4 mg, with different contents of curium isotopes. The composition is given in Table V.

Table V

Isotopic composition of curium samples (%)

| No. of sample | wt (mg) | $^{242}Cm$ | $^{244}Cm$ | $^{245}Cm$ | $^{246}Cm$ | $^{247}Cm$ | $^{248}Cm$ |
|---|---|---|---|---|---|---|---|
| 1 | 82.8 | 0.31 | 88.62 | 9.57 | 1.49 | - | - |
| 2 | 116.4 | - | 39.28 | 0.47 | 51.85 | 1.61 | 6.79 |

Sample 1 contained the impurities $^{243}Am$ (2%), $^{240}Pu$ (1.6%); sample 2 contained $^{243}Am$ (0.19%), and $^{240}Pu$ (0.8%).

The neutron resonance parameters obtained by Belanova, Kalebin et al. [6] in the resonance range of energies are compared with published data in Tables VI and IX.

Comparison of the data given in Table VI shows that in the case of $^{244}Cm$ the neutron resonance parameters are in good agreement. In the case of $^{246}Cm$ there is considerable scatter in the neutron widths for the 91.5 eV resonance, and in that of $^{248}Cm$ the total neutron widths differ considerably for the 7.26 eV and 26.88 eV resonances. An indeterminate situation arises in Ref. [6] for the 84.4 eV $^{246}Cm$ resonance. Figure 2 shows the transmission for curium sample No. 2 at the energy of this resonance. Three salient points can be seen on the transmission curve corresponding to energies 85.9 eV, 84.8 eV and 84.4 eV. The first of these is due to the $^{244}Cm$ resonance, which was measured independently in sample No. 1. The third is the familiar $^{246}Cm$ resonance. The 84.8-eV anomaly in the transmission curve has not been accounted for with certainty.

In view of this situation, the 84.4-eV neutron resonance parameters for $^{246}Cm$ were not calculated and Table VI gives only the position of the resonances. Various possible alternative explanations of the 84.8-eV anomaly in the transmission curve were considered and it was assumed to be due to a $^{248}Cm$ resonance, although this resonance was not observed for $^{248}Cm$ by Moore and Keyworth [21] or by Benjamin et al. [22]. Considerable difficulties were also encountered in determining the 35.0-eV neutron resonance parameters for $^{240}Cm$.

This was due to the fact that there is a strong $^{244}Cm$ resonance at this same energy.

It should be noted that in the study of Moore and Keyworth [21] there is no 35.0-eV resonance for $^{248}Cm$.

The mean radiation widths ($\bar{\Gamma}_\gamma$) and capture resonance integrals have been calculated for the level parameters obtained and these values are given in Tables VII and VIII.

Table VII

$\bar{\Gamma}_\gamma$ (MeV) for $^{244, 246, 248}Cm$

| Reference | $^{244}Cm$ | $^{246}Cm$ | $^{248}Cm$ |
|---|---|---|---|
| This work [6] | 33.7 ± 3.2 | 27.1 ± 1.8 | 25.9 ± 2.2 |
| [22] | - | 31 ± 6 | 26 ± 2 |
| [20] | 40 assumed | - | - |

Table VIII

Capture resonance integrals for $^{244}$, $^{246}$, $^{248}$Cm (barn)

| Reference | $^{244}$Cm | $^{246}$Cm | $^{248}$Cm |
|---|---|---|---|
| This work [6] | 636 ± 32 | 105 ± 6*/ | 266 ± 18 |
| [22] | - | 101 ± 11 | 259 ± 12 |
| [20] | 605 ± 40 | - | - |

*/ This value includes the 84.4-eV resonance with parameters taken from Benjamin et al. [22].

The $^{245}$Cm-neutron resonance parameters are given in Table IX; they should be regarded in this work [6] as provisional. Comparison of the results given in the Table shows that in Ref. [6] the 25.84-, 34.59-, 39.45-, 45.74-eV resonances could not be observed. It should be noted that the 25.84-eV level was not observed by Berreth et al. [20] either. The resonances listed are relatively weak and when a thin sample is used, as in Refs [6, 20], they could easily be missed.

The strong 35.31-eV resonance is not observed because it is close to the $^{244}$-, $^{248}$Cm levels with this energy. Comparison of the 14.0-eV and 15.9-eV resonances in this work leads to the conclusion that the latter is weaker than the former, since it was difficult even to determine its parameters; according to the data of Berreth et al. [20], however, the opposite should be expected. A similar situation is observed for the 47.8-eV and 49.2-eV levels. There is a considerable discrepancy in the neutron widths of the 9.25-eV and 40.9-eV resonances. Further measurements are necessary, particularly on samples of higher purity. Apparently, it was precisely their absence from the measurements made that was the main reason for the divergences found in the data on neutron cross-sections and level parameters for transactinium isotopes.

Table II

Neutron resonance parameters for $^{241}$Am

| This work [3, 4] | | | [12, 13, 14] | | |
|---|---|---|---|---|---|
| $E_0$ (eV) | $\Gamma$(MeV) | $2g\Gamma_n$ (MeV) | $E_0'$ (eV) | $\Gamma$(MeV) | $2g\Gamma_n$ (MeV) |
| -0,425 | | $2g\Gamma_n^0$=I,0 | - | - | - |
| 0,306±0,002 | 45±I | 0,0556±0,0004 | 0,308±0,003 | 4I±4 | 0,060±0,003 |
| 0,573±0,004 | 43±I | 0,0928±0,00I6 | 0,576±0,005 | 40±5 | 0,075±0,007 |
| I,268±0,004 | 4I±2 | 0,330±0,0I6 | I,27 ±0,0I | 44±7 | 0,39 ±0,02 |
| - | - | - | I,68 ±0,02 | - | - |
| I,9I6±0,005 | 46±2 | 0,I07±0,002 | I,93±0,02 | - | 0,I25±0,006 |
| 2,358±0,008 | 4I±2 | 0,070±0,00I | 2,36±0,02 | - | 0,080±0,0I0 |
| 2,58I±0,009 | 38±2 | 0,I50±0,004 | 2,60±0,03 | - | 0,20±0,02 |
| 3,956±0,009 | 28±3 | 0,230±0,008 | 3,99±0,04 | - | 0,26±0,02 |
| - | - | - | 4,40±0,05 | - | 0,027±0,006 |
| 4,947±0,0I0 | 3I±5 | 0,I76±0,005 | 5,03±0,04 | - | 0,2I±0,04 |
| 5,390±0,0I2 | 38±7 | 0,844±0,II4 | 5,46±0,04 | - | I,08±0,05 |
| 6,I00±0,0I3 | 42±I4 | 0,II6±0,005 | 6,I0±0,04 | - | 0,I3±0,04 |
| 6,650±0,0I5 | - | 0,05±0,03 | - | - | - |
| - | - | - | 6,78±0,02 | - | 0,23±0,09 |
| 7,53±0,02 | - | 0,07±0,04 | - | - | - |
| - | - | - | 7,97±0,02 | - | 0,79±0,34 |
| 8,I7±0,02 | 42±5 | 0,096±0,004 | 8,II±0,03 | - | 0,80±0,34 |
| - | - | - | 8,28±0,04 | - | 0,I3±0,08 |
| 9,II±0,02 | 48±3 | 0,358±0,006 | 9,I3±0,05 | - | 0,42±0,06 |
| 9,84±0,03 | 48±3 | 0,370±0,007 | 9,90±0,05 | - | 0,33±0,05 |
| I0,II±0,03 | - | 0,025±0,004 | - | - | - |
| I0,39±0,03 | 45±4 | 0,294±0,007 | I0,38±0,03 | - | 0,34±0,03 |
| I0,99±0,04 | 52±4 | 0,382±0,008 | I0,99±0,03 | - | 0,36±0,05 |
| II,58±0,05 | - | 0,0I8±0,003 | - | - | - |
| I2,06±0,06 | - | 0,007±0,003 | - | - | - |
| I2,86±0,06 | 44±5 | 0,II6±0,009 | I2,86±0,04 | - | 0,I4±0,04 |
| I4,32±0,06 | - | 0,066±0,0I2 | - | - | - |
| I4,66±0,07 | 44±5 | 2,30±0,I3 | I4,75±0,07 | - | 2,4±0,5 |
| I5,66±0,07 | 32±I2 | 0,2I5±0,0I2 | I5,60±0,05 | - | 0,I7±0,I0 |
| - | - | - | I5,73±0,05 | - | 0,I6±0,I0 |
| - | - | - | I6,02±0,05 | - | 0,I4±0,09 |
| I6,35±0,07 | 44±5 | I,I85±0,033 | I6,38±0,05 | - | 0,97±0,I9 |
| I6,8I±0,07 | 3I±8 | 0,575±0,020 | I6,82±0,06 | - | 0,4I±0,I6 |
| I7,69±0,07 | 40±I0 | 0,373±0,0I6 | I7,68 | - | 0,25±0,I0 |

| I | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|
| I8,09±0,07 | - | - | - | - | - |
| - | - | - | I8,37 | - | 0,43±0,I7 |
| I9,39±0,07 | 37±I2 | 0,I82±0,0I6 | I9,48 | - | 0,I2±0,I2 |
| 20,28±0,07 | - | 0,050±0,0I0 | - | - | - |
| - | - | - | 20,64 | - | 0,27±0,I8 |
| 20,84±0,08 | - | 0,064±0,0II | - | - | - |
| 2I,72±0,08 | - | 0,067±0,0I2 | - | - | - |
| 22,74±0,09 | - | 0,070±0,0I2 | - | - | - |
| 23,08±0,09 | - | 0,39±0,05 | 23,09 | - | 0,38±0,I9 |
| 23,33±0,09 | - | 0,40±0,05 | 23,28 | - | 0,77±0,23 |
| 24,I7±0,09 | - | I,27±0,08 | 24,I7 | - | I,08±0,20 |
| 25,05±0,I0 | - | - | - | - | - |
| 25,60±0,I0 | - | I,2I±0,07 | 25,6I | - | I,0I±0,4I |

Table IV

Neutron resonance parameters for $^{243}$Am

| This work [5] | | | [12, 17, 18] | | [19] |
|---|---|---|---|---|---|
| $E_0$ (eV) | $\Gamma$ (MeV) | $2g\,\Gamma_n$ (MeV) | $\Gamma$ (MeV) | $2g\,\Gamma_n$ (MeV) | $2g\,\Gamma_n$ (MeV) |
| 0,4I6±0,003 | 39±2 | 0,00084±0,00005 | 39±2 | 0,00084±0,00006 | - |
| 0,977±0,004 | 37±2 | 0,0I34±0,0003 | 36±2 | 0,0I46±0,0007 | 0,0I7±0,003 |
| I,355±0,004 | 56±I | 0,890±0,007 | 44±2 | I,II±0,05 | 0,82±0,08 |
| I,744±0,005 | 39±I | 0,208±0,002 | 38±2 | 0,240±0,0II | 0,I8±0,0I |
| 3,I34±0,009 | 47±3 | 0,0I2±0,003 | 32±6 | 0,0II3±0,00I | - |
| 3,424±0,009 | 45±2 | 0,253±0,008 | 38±4 | 0,287±0,0II | 0,2I±0,0I |
| 3,844±0,009 | 22±5 | 0,009±0,00I | 43±6 | 0,0I3±0,00I | - |
| 5,I20±0,0I2 | 63±2 | 0,260±0,006 | 39±3 | 0,3I3±0,0I4 | 0,23±0,02 |
| 6,55I±0,0I5 | 50±3 | 0,794±0,044 | 38±3 | 0,968±0,038 | 0,83±0,04 |
| 7,063±0,0I7 | 46±3 | 0,072±0,0II | 40±6 | 0,072±0,005 | - |
| 7,86±0,02 | 36±9 | I;580±0,I30 | 40±4 | I,33±0,056 | 0,93±0,05 |
| 8,39±0,02 | 40±2 | 0,0I0±0,002 | 39±6 | 0,009±0,005 | - |
| 8,77±0,02 | 46±2 | 0,II3±0,002 | 37±I0 | 0,II2±0,006 | - |
| 9,32±0,02 | 43±2 | 0,I33±0,002 | 39±9 | 0,I53±0,009 | - |

| | | | | | |
|---|---|---|---|---|---|
| I0,3I±0,03 | 47±2 | 0,433±0,007 | 50±2 | 0,449±0,032 | 0,23±0,05 |
| I0,87±0,04 | - | 0,0I3±0,002 | - | 0,0I3±0,007 | - |
| II,27±0,04 | 49±2 | 0,267±0,003 | 4I±6 | 0,285±0,0I3 | - |
| II,68±0,06 | 35+4 | 0,094±0,002 | 26±I4 | 0,I06±0,007 | - |
| I2,I2±0,06 | 4I±3 | 0,I52±0,003 | 37±II | 0,I74±0,0I0 | - |
| I2,87±0,06 | 43±4 | 2,20±0,20 | 38±6 | 2,40±0,II | I,50±0,20 |
| I3,I5±0,06 | 45±5 | I,00±0,08 | 42±8 | I,35±0,07 | 0,80±0,20 |
| I5,I2±0,07 | 33±I5 | 0,070±0,007 | - | 0,097±0,027 | - |
| I5,39±0,07 | 37±6 | I,36±0,08 | 45±II | I,33±0,I2 | 0,63±0,30 |
| I6,20±0,07 | 39±3 | 0,5I8±0,009 | 49±9 | 0,55I±0,028 | - |
| I6,56±0,07 | 27±7 | 0,I74±005 | 36±I0 | 0,I96±0,0I6 | - |
| I7,84±0,07 | 35±8 | 0,2I0±0,007 | 42±I0 | 0,228±0,I27 | - |
| I8,I4±0,07 | 27±I5 | 0,046±0,007 | - | 0,060±0,009 | - |
| I9,50±0,07 | 27±I0 | 0,I93±0,007 | - | 0,24±0,02 | - |
| I9,88±0,07 | 40±20 | 0,085±0,006 | - | 0,I00±0,0I8 | - |
| 20,94±0,07 | 29±I5 | 0,54±0,I8 | - | 0,50±0,05 | - |
| 2I,09±0,07 | I6±I0 | 0,86±0,22 | - | I,00±0,09 | - |
| 2I,85±0,08 | 27±I0 | 0,I4±0,02 | - | 0,I68±0,0I4 | - |
| 22,0I±0,08 | - | - | - | 0,052±0,023 | - |
| 22,59±0,09 | 33±I0 | I,00±0,60 | - | 0,49±0,05 | - |
| 22,72±0,09 | I9±I0 | 0,65±0,50 | - | I,34±0,I4 | - |
| 24,38±0,09 | 22±I0 | 0,73±0,02 | - | 0,952±0,049 | - |
| 25,38±0,I0 | 40±I0 | 0,I4±0,02 | - | 0,I6I±0,025 | - |
| 26,3±0,I0 | 3I±I0 | 0,06±0,02 | - | 0,04I±0,020 | - |
| 26,75±0,I0 | - | I,I6±0,3I | - | I,66±0,I0 | - |
| 27,34±0,II | - | 0,43±0,02 | - | 0,52±0,05 | - |
| 28,73±0,I2 | - | 0,97±0,I2 | - | I,09±0,05 | - |
| 29,29±0,I2 | - | 0,68±0,I5 | - | 0,73±0,05 | - |
| 30,I2±0,I3 | - | 0,49±0,20 | - | 0,52±0,04 | - |
| 3I,06±0,I3 | - | 0,70±0,I5 | - | 0,8I±0,06 | - |
| 3I,49±0,I3 | - | 0,I2±0,05 | - | 0,I7±0,03 | - |
| 32,43±0,I4 | - | 0,I2±0,05 | - | 0,I5±0,02 | - |
| 33,I9±0,I4 | - | 0,88±0,I5 | - | 0,98±0,06 | - |
| 33,92±0,I4 | - | I,90±0,20 | - | I,83±0,09 | - |

## Table VI

Neutron resonance parameters for $^{244}$, $^{246}$, $^{248}$Cm

| Isotope | This work [6] | | | [20] | | [21] | [22] | |
|---|---|---|---|---|---|---|---|---|
| | $E_0$ (eV) | Γ (MeV) | $\Gamma_n$ (MeV) | Γ (MeV) | $\Gamma_n$ (MeV) | $\Gamma_n$ (MeV) | Γ (MeV) | $\Gamma_n$ (MeV) |
| $^{244}$Cm | 7,67±0,02 | 44±3 | I0,4±0,4 | 45±2 | 9,4±0,6 | – | | |
| | I6,77±0,07 | 37±5 | I,90±0,30 | – | I,63±0,I6 | – | | |
| | 22,85±0,08 | 36±I0 | 0,84±0,I0 | – | 0,79±0,I2 | 0,88±0,09 | | |
| | 35,00±0,I4 | 35±5 | 4,3±0,3 | – | 3,0±0,6 | 3,5±0,3 | | |
| | 52,80±0,I4 | – | 0,56±0,I5 | – | 0,52±0,II | 0,56±0,08 | | |
| | 69,80±0,20 | – | 0,44±0,25 | – | 0,52±0,I2 | 0,67±0,07 | | |
| | 85,9±0,3 | – | 26,0±4,8 | – | 22±5 | 24,5±2,3 | | |
| | 95,5±0,3 | – | 7,8±2,2 | – | – | 7,3±0,6 | | |
| | I32,0±0,6 | – | I6±8 | – | – | I5,5±2 | | |
| | I39,0±0,6 | – | 2,2±0,9 | – | – | 2,5±0,3 | | |
| | I7I,0±0,8 | – | 3,6±I,8 | – | – | 3,3±0,5 | | |
| $^{246}$Cm | 4,32±0,0I | 27±2 | 0,34±0,0I | 35±2 | 0,33±0,03 | – | 3I±6 | 0,3I±0,02 |
| | I5,29±0,07 | 28±3 | 0,52±0,0I | 35±3 | 0,55±0,08 | – | – | 0,56±0,I2 |
| | 84,4±0,3 | – | – | – | – | 22±5 | – | 26,8±2,8 |
| | 9I,5±0,3 | – | 9,9±2,5 | – | – | I9±2 | – | 9,6±2,9 |
| | I57,0±0,6 | – | 34,I±7,6 | – | – | 29±5 | – | 26,5±9 |
| $^{248}$Cm */ | 7,26±0,02 | 36±3 | I,90±0,04 | – | – | – | 25±I | I,75±0,05 |
| | 26,88±0,08 | 37±3 | 2I,7±0,7 | – | – | 25±3 | 5I±3 | I9,4±0,9 |
| | 35,00±0,I4 | 38±5 | 9,5±2 | – | – | – | 42±3 | II,7±0,5 |
| | 75,6±0,3 | – | I02,5±I3,6 | – | – | large | – | 96±5 |
| | 84,8±0,3 | – | – | – | – | no resonance | | |
| | 98,6±0,3 | – | I69±I8 | – | – | large | – | I50±6 |

*/ Resonance not clearly identified.

Table IX

Neutron resonance parameters for $^{245}Cm$

| This work [6] | | [20] | | [21] | |
|---|---|---|---|---|---|
| $E_0$ (eV) | $2g\Gamma_n$ (MeV) | $E_0$ (eV) | $2g\Gamma_n$ (MeV) | $E_0$ (eV) | $2g\Gamma_n$ (MeV) |
| I,93±0,005 | - | I,95±0,02 | 0,3I3±0,035 | - | - |
| 4,69±0,0I | I,73±0,35 | 4,67± 0,02 | 2,08± 0,03 | - | - |
| 9,25±0,02 | 0,32±0,I0 | 9,I7±0,05 | 0,67± 0,I2 | - | - |
| II,4± 0,04 | 0,50±0,20 | II,34± 0,06 | 0,7I± 0,I0 | - | - |
| I4,0± 0,07 | 0,25± 0,08 | I3,88± 0,06 | 0,335± 0,075 | - | - |
| I5,9± 0,I | - | I6,0± 0,I | I,2 ± 0,4 | - | - |
| 2I,6± 0,I | 2,6 ± 0,4 | 2I,40±0,I5 | 3,2 ± 0,9 | 2I,36 | 2,I2 |
| 25,0 | 2,4± 0,4 | 24,74±0,I5 | 4,0± I,0 | 24,90 | 2,60 |
| - | - | - | - | 25,84 | 0,036 |
| 26,9 | - | - | - | 26,83 | 0,76 |
| 27,I | I,0± 0,3 | 27,4± 0,2 | 0,9 ± 0,3 | 27,63 | 0,60 |
| 29,6 | 4,2± 0,7 | 29,3± 0,2 | 3,8±I,I | 29,42 | 3,44 |
| 3I,4 | 0,5 ± 0,2 | - | - | 3I,7I | 0,50 |
| 32,4 | 0,4 ± 0,2 | - | - | 32,99 | 0,37 |
| - | - | - | - | 34,59 | 0,23 |
| - | - | - | - | 35,3I | 7,58 |
| 36,3 | 3,6± I,8 | - | - | 36,32 | I,54 |
| - | - | - | - | 39,45 | 0,65 |
| 40,9 | I,8±0,9 | - | - | 40,44 | 4,48 |
| 42,9 | 3,0± I,5 | - | - | 42,45 | 5,37 |
| 43,5 | - | - | - | 43,I0 | I,73 |
| 44,9 | I,7± 0,5 | - | - | 44,57 | 2,6I |
| - | - | - | - | 45,74 | 0,59 |
| 47,8 | 5,7± I,4 | - | - | 47,5I | 3,56 |
| 49,2 | 2,2± I,2 | - | - | 49,20 | 5,04 |
| 50,5 | I,8 ± 0,7 | - | - | 50,48 | I,79 |

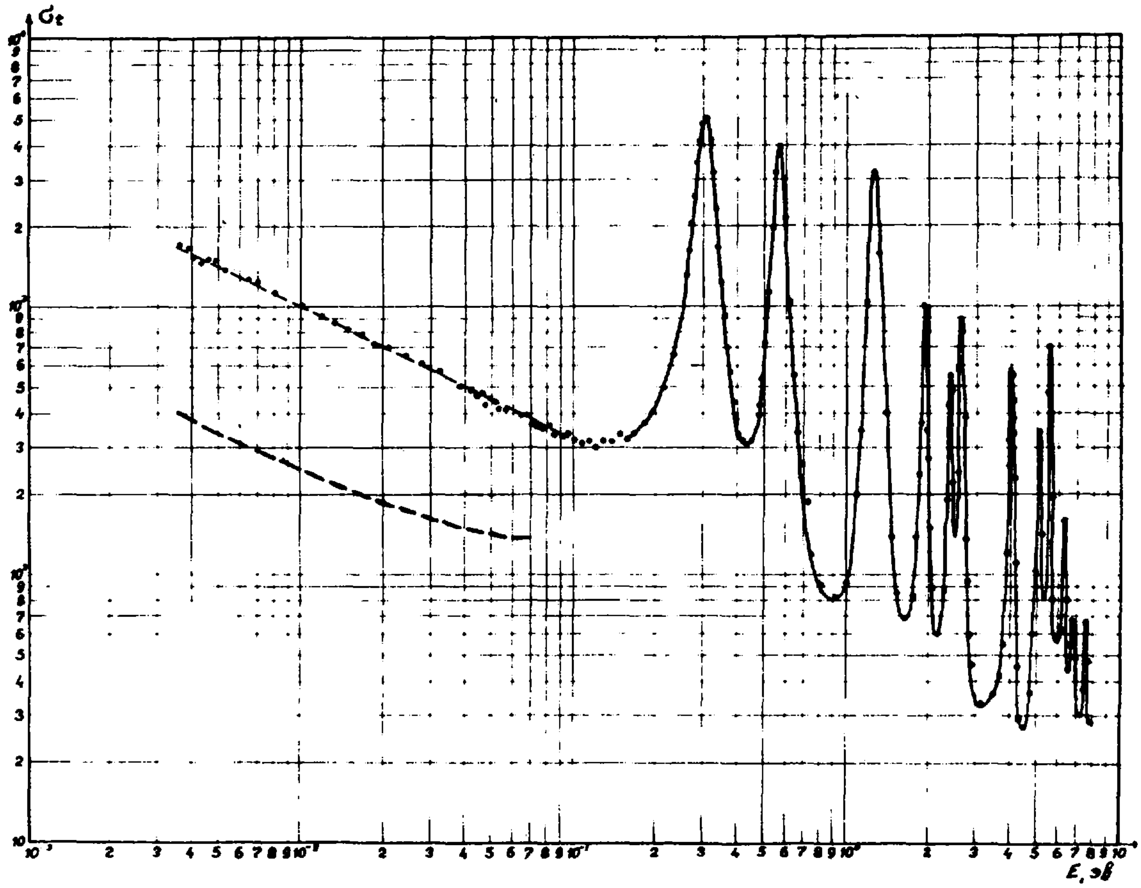


Fig. 1: Total neutron cross-section for $^{241}Am$ dashed curve: calculated contribution of positive resonances to the capture cross-section at low energy.

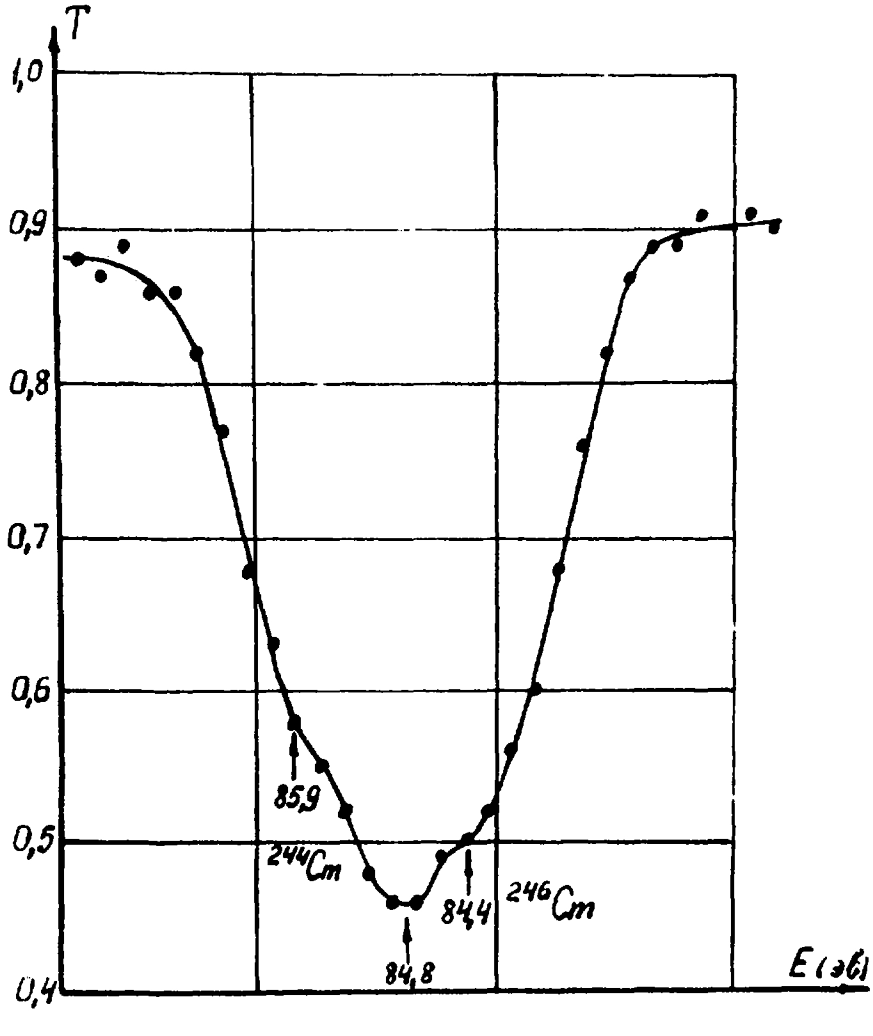


Fig. 2: Measured transmission of curium sample No. 2 in the 84-eV energy range.

## REFERENCES


[1] KALEBIN, S.M., RUKOLAJNE, G.V., ADIB, M., PTE 3, 79 (1970) (in Russian).

[2] KALEBIN, S.M. et al., in Nejtronnaya Fizika (Proc. Conf.), Part II, "Naukova Dumka", Kiev (1972) 267.

[3] BELANOVA, T.S., KALEBIN, S.M. et al., in Nejtronnaya Fizika (Proc. Conf.) Kiev (1975).

[4] BELANOVA, T.S., KALEBIN, S.M. et al., Atomnaya Energiya 38 (1975) 29.

[5] BELANOVA, T.S., KALEBIN, S.M. et al., in Nejtronnaya Fizika (Proc. Conf.) Kiev (1975).

[6] BELANOVA, T.S., KALEBIN, S.M. et al., in Nejtronnaya Fizika (Proc. Conf.) Kiev (1975).

[7] BAK, M.A. et al., Atomnaya Energiya 23 (1967) 1059.

[8] STREET, K. et al., Phys.Rev. 85 (1952) 135.

[9] THOMPSON, S.G., MUGA, M., Proc. Intern. Conf. Peaceful Uses At. Energy, United Nations, Geneva, 28 (1958) 331.

[10] DOVBENKO, A.G. et al., Byulletin Tsentra po yadernym dannym, 42 (1969).

[11] HARBOUR, R.M. et al., Nucl. Sci. Eng. 50 (1973) 264.

[12] BNL-325, Third Edition, New York (1973).

[13] BOWMAN, C.D. et al., Phys. Rev. 137 (1965) B 326.

[14] SLOUGHTER, G.G. et al., ORNL-3085, (1961) 42.

[15] DERRIEN, H. et al., in Nejtronnaya Fizika (Proc. Conf.) Part II, Obninsk (1974) 246.

[16] DERRIEN, H. et al., in Nejtronnaya Fizika (Proc. Conf.) Kiev (1975).

[17] SIMPSON, O.D. et al., Nucl. Sci. Eng. 55 (1974) 273.

[18] BERRETH, J.R., SIMPSON, F.B., IN-1407, Idaho Nuclear Corp. (1970).

[19] COTE, F.E. et al., Phys. Rev. 114 (1959) 505.

[20] BERRETH, J.R. et al., Nucl. Sci. Eng. 49 (1972) 145.

[21] MOORE, M.S., KEYWORTH, G.A., Phys. Rev. 63 (1971) 1656.

[22] BENJAMIN, R.W. et al., Nucl. Sci. Eng. 55 (1974) 440.

Contributed Paper to Topic B2

(Paper presented at the National Soviet Conference on Neutron Physics, held at Kiev from 9 to 13 June 1975)

# MEASUREMENT OF THE FISSION CROSS-SECTION OF $^{237}Np$ BETWEEN 100 keV AND 2 MeV

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J. Blons and C. Mazur
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## ABSTRACT

The 60-MeV linear accelerator at Saclay was recently used to study resonant structures in the threshold region for several actinides.

This paper discusses measurements of the fission cross-section of $^{237}Np$ carried out with a 0.3 ns/m resolution. The authors only present results between 100 keV and 2 MeV confirming the energy of the second minimum of the fission barrier determined in a previous experiment. Considerable damping of possible vibrational states in the second well of the fission barrier prevents the possibility of observing the vibrational resonances in the threshold region.

The fission cross-section of $^{237}Np$ at low energy ($E_n < 20$ keV) offers the first and most satisfactory example of an intermediate structure due to states situated in the second well of the fission barrier [1]. The mean widths and spaces of these states, together with the corresponding distributions, show that the states have a compound nucleus [2, 3] and that, just as in the first well, the collective states in the second well are completely damped. It has been deduced from this that the second minimum energy must have been fairly low [4] ($E_{II} = 1.84$ MeV), but the result has not yet been confirmed or invalidated by other experiments, more especially no shape isomer has been observed so far in $^{238}Np$. Furthermore, the fission cross-section close to the threshold, as measured by a nuclear explosion with a resolution of 5-300 keV [5] shows fluctuations which, although statistically significant, seem to indicate the presence of relatively narrow resonances at these energies. Such resonances, already observed for the case of even-even compound nuclei [6] and uneven-uneven nuclei [7], are generally construed as vibrational resonances in the second well [8, 9]. Although similar resonances exist in the case of the compound nucleus $^{238}Np^*$ with widths of the order of 10 keV, they appear to run counter to the conclusions drawn from study of the intermediate structure. It was therefore legitimate, when studying resonances in the neighbourhood of the fission threshold, to include a sample of $^{237}Np$.

The measurements made in the 60 MeV linear accelerator at Saclay (pulsed neutron source) related to the following nuclei: $^{232}Th$, $^{238}U$, $^{237}Np$ and $^{243}Am$. Here we only give the results for $^{237}Np$ between 100 keV and 2 MeV. Table 1 summarizes the experimental conditions.

The fission fragment detector, which was placed in a flight path perpendicular to the plane of the moderator, consisted of a gas scintillator already used to measure the fission cross-section of $^{233}U$, $^{235}U$, $^{239}Pu$ and $^{241}Pu$ in the resonance region [10, 11], as well as for $^{237}Np$ below the threshold [4, 12]. Neptunium in the form of acetate with a density of 2 mg/cm$^2$ in $^{237}Np$, was deposited on the two faces of an aluminium semicircle 16 cm in diameter and 10 μm thick. A deposit of $^{235}U_3O_8$ with similar characteristics was placed in the same plane as the above to determine the neutron spectrum delivered by the accelerator.

The background was assessed by the grey resonance method, using two silica screens placed in sequence in the neutron beam, the thicknesses of which were in the ratio of 1:2. To avoid the overlap of neutron pulses, a cadmium filter (1.04 g/cm$^2$) was placed in the beam.

Figure 1 shows the fission cross-section $\sigma_f$ between 100 keV and 2 MeV, with the statistical error varying from $\pm$23% at 100 keV to $\pm$1.3% at 2 MeV. Since the efficiencies for detection of the neptunium and uranium were not accurately known, $\sigma_f$ was normalized to the fission integral between 1 and 2 MeV calculated from the ENDF/B-IV evaluated data library; determination of the fission cross-section of $^{235}U$ was also derived from the ENDF/B-IV library by using logarithmic interpolation between 100 keV and 2 MeV, as recommended.

Table 2 shows the fission integral calculated at intervals of 100 keV and compared with the values determined from Refs [13, 14].

Examination of Fig. 1 appears to indicate with fair certainty the absence of resonances at the fission threshold. In particular, it seems clear that what might have been taken in Ref. [5] as a resonance structure between 300 and 350 keV was in fact due to statistical fluctuations. Behaviour as regular as this on the part of $\sigma_f$ would justify an absolute measurement between several hundreds of keV and 2 MeV (or more); the cross-section obtained in that way could then be used as a standard for normalizing other fission cross-sections over this energy range.

The relatively smooth shape of $\sigma_f$ provides a qualitative confirmation of the position of the second minimum of the fission barrier which, being much lower than the excitation energy of $^{238}Np$ ($E^* > 6.1$ MeV) prevents observation of vibrational resonances because of total damping of the states among those of the compound nucleus.

Measurement of $\sigma_f$ in the threshold region has not provided any new information on the fission barriers for $^{238}Np$. Hence, in order to improve our knowledge of the shape of these barriers, we will definitely have to direct our efforts to finding a shape isomer.

## REFERENCES


[1] D. PAYA, H. DERRIEN, A. FUBINI, A. MICHAUDON, P. RIBON, Nuclear Data for Reactors, A.I.E.A., PARIS 1966, VIENNE 1967, II, 128 ;
A. FUBINI, J. BLONS, A. MICHAUDON, D. PAYA, Phys. Rev. Lett., 20, 1373, (1968)

[2] D. PAYA, J. BLONS, H. DERRIEN, A. MICHAUDON, Physics and Chemistry of Fission , A.I.E.A., VIENNE 1969, 307

[3] S. PLATTARD, D. PAYA, Soviet National Conference on Neutron Physics, KIEV 1973, 2, 254

[4] S. PLATTARD, Thèse 3ème cycle, ORSAY 1973

[5] R.J. JIACOLETTI, W.K. BROWN et H.G. OLSON, Nucl. Sci. Eng., 48, 412, (1972)

[6] H.J. SPECHT, J.S. FRASER, J.C.D. MILTON, W.G. DAVIES, Physics and Chemistry of fission, A.I.E.A., VIENNE 1969, VIENNE 1970, 363 ;
H.C. BRITT, S.C. BURNETT, J.D. CRAMER, Ibid. P. 375 ;
B.B. BACK, J.P. BONDORF, G.A. OSTROSHENKO, J. PEDERSEN, B. RASMUSSEN, Ibid. p. 351

[7] A. SICRE, G. BARREAU, R. CHASTEL, T.P. DOAN, B. LEROUX, J.C. SAGEAUX, Physics and chemistry of fission, A.I.E.A., ROCHESTER 1973, VIENNE 1974, I, 71.

[8] S. BJØRNHOLM, V.M. STRUTINSKY, Nucl. Phys., A.136, 143, (1969)

[9] J. E. LYNN, Physics and Chemistry of fission, A.I.E.A., VIENNE 1969, VIENNE 1970, 249 ;
Rapport UKAEA, AERE -M- 2505, (1971)

[10] C. EGGERMANN, J. BLONS, M. DUMAZERT et Y. PRANAL, Nucl. Enstr. and Meth., 81, 243, (1970)

[11] J. BLONS, Nucl. Sci. Eng., 51, 130, (1973)

[12] S. PLATTARD, A. MICHAUDON et D. PAYA, Conférence Européenne de Physique Nucléaire, AIX-EN-PROVENCE, II, 21, (1972)

[13] W.K. BROWN, D.R. DIXON, D.M. DRAKE, Nucl. Phys., A.156, 609, (1970)

[14] R.J. JIACOLETTI, et W.K. BROWN, Rapport LASL, LA - 4763 - MS, (1971)

Table 1

| | |
|---|---|
| Electron pulse width | 7 ns |
| Repetition rate | 500 Hz |
| Output | 800-900 W |
| Flight distance | 22.42 m |
| Time-amplitude coder | 4096 channels of 2.5 ns in width |
| Experimental resolution | 40 eV-50 keV |
| | 130 eV-100 keV |
| | 1.5 eV-500 keV |
| | 3.2 keV-1 MeV |
| | 9 keV-2 MeV |
| Accumulation time | 307 h |

Table 2

Fission integral $I_f = \int_{\Delta E} \sigma_f(E)dE$

| $I_f$ (b.MeV) / (MeV) | Po[illegible]rd 13 | Physics 8 14 | Our experiment | Statistical error |
|---|---|---|---|---|
| .1 - 0.2 | $3.371\ 10^{-3}$ | $2.961\ 10^{-3}$ | $3.469\ 10^{-3}$ | ± 18 % |
| .2 - 0.3 | $5.803\ 10^{-3}$ | $5.362\ 10^{-3}$ | $5.151\ 10^{-3}$ | ± 11 % |
| .3 - 0.4 | $1.477\ 10^{-2}$ | $1.290\ 10^{-2}$ | $1.114\ 10^{-2}$ | ± 4 % |
| .4 - 0.5 | $3.939\ 10^{-2}$ | $3.419\ 10^{-2}$ | $2.997\ 10^{-2}$ | ± 1 % |
| .5 - 0.6 | $7.058\ 10^{-2}$ | $6.669\ 10^{-2}$ | $5.793\ 10^{-2}$ | ± 0.4 % |
| .6 - 0.7 | $1.030\ 10^{-1}$ | $1.035\ 10^{-1}$ | $8.839\ 10^{-2}$ | ± 0.2 % |
| .7 - 0.8 | $1.233\ 10^{-1}$ | $1.356\ 10^{-1}$ | $1.107\ 10^{-1}$ | ± 0.2 % |
| .8 - 0.9 | $1.393\ 10^{-1}$ | $1.488\ 10^{-1}$ | $1.275\ 10^{-1}$ | ± 0.2 % |
| .9 - 1 | $1.368\ 10^{-1}$ | $1.591\ 10^{-1}$ | $1.382\ 10^{-1}$ | ± 0.2 % |
| .0 - 1.1 | $1.457\ 10^{-1}$ | $1.661\ 10^{-1}$ | $1.486\ 10^{-1}$ | ± 0.2 % |
| .1 - 1.2 | $1.485\ 10^{-1}$ | $1.661\ 10^{-1}$ | $1.510\ 10^{-1}$ | ± 0.2 % |
| .2 - 1.3 | $1.488\ 10^{-1}$ | $1.688\ 10^{-1}$ | $1.551\ 10^{-1}$ | ± 0.2 % |
| .3 - 1.4 | $1.608\ 10^{-1}$ | $1.665\ 10^{-1}$ | $1.582\ 10^{-1}$ | ± 0.2 % |
| .4 - 1.5 | $1.543\ 10^{-1}$ | $1.713\ 10^{-1}$ | $1.596\ 10^{-1}$ | ± 0.2 % |
| .5 - 1.6 | $1.498\ 10^{-1}$ | | $1.619\ 10^{-1}$ | ± 0.2 % |
| .6 - 1.7 | $1.582\ 10^{-1}$ | $1.763\ 10^{-1}$ | $1.639\ 10^{-1}$ | ± 0.2 % |
| .7 - 1.8 | $1.651\ 10^{-1}$ | $1.764\ 10^{-1}$ | $1.653\ 10^{-1}$ | ± 0.2 % |
| .8 - 1.9 | $1.631\ 10^{-1}$ | $1.830\ 10^{-1}$ | $1.667\ 10^{-1}$ | ± 0.2 % |
| .9 - 2.0 | $1.639\ 10^{-1}$ | $1.816\ 10^{-1}$ | $1.679\ 10^{-1}$ | ± 0.2 % |

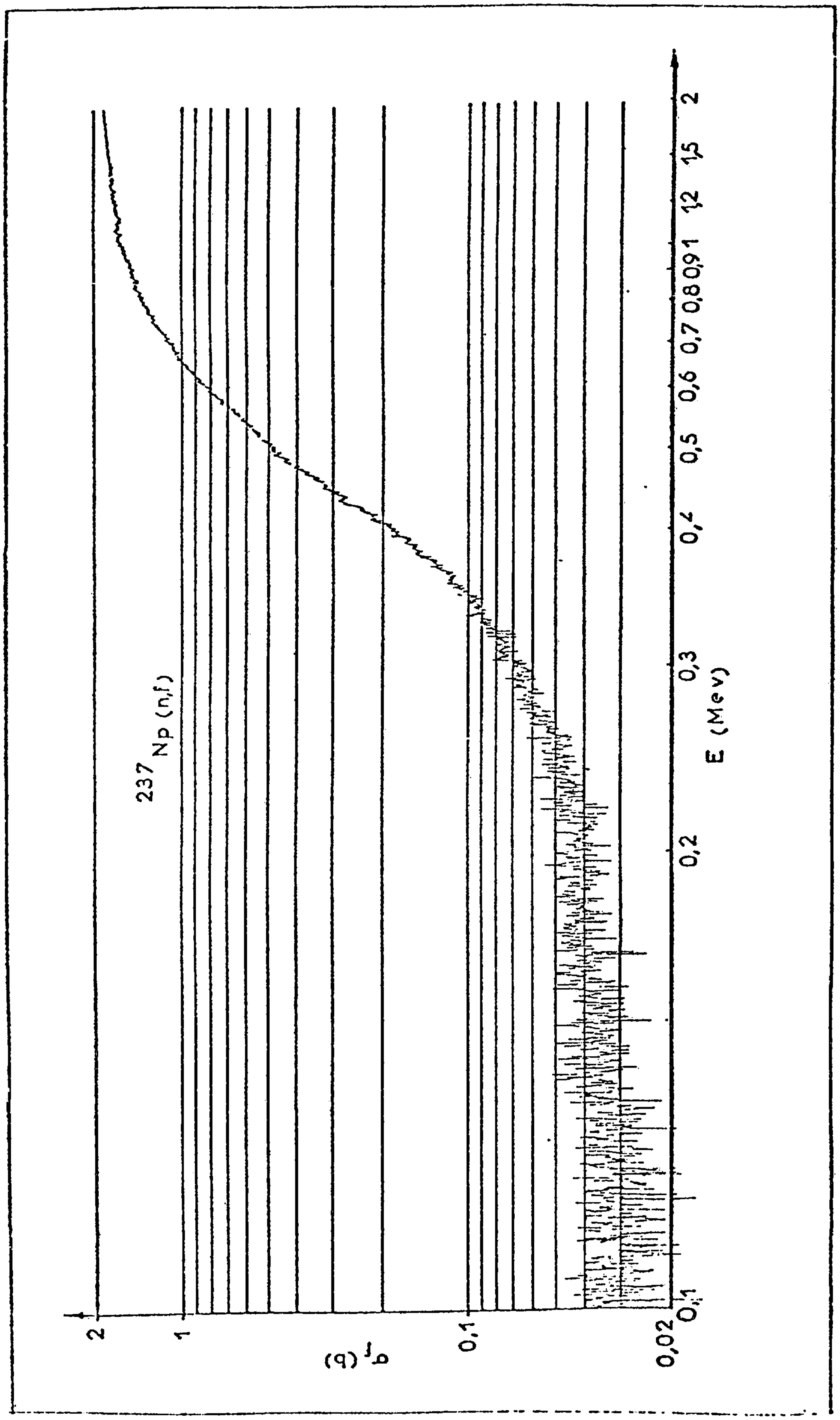


Fig. 1

Contributed Paper to Topic B2

# HIGH RESOLUTION MEASUREMENTS OF FISSION CROSS SECTIONS OF $^{238}U$ AND $^{239}Pu$ AS COMPARED WITH $^{235}U$

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Nuclear Research Centre,
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ABSTRACT

Fission cross-sections of $^{238}U$ and $^{239}Pu$ were measured relative to $^{235}U$ in the 60-MeV linear accelerator at Saclay up to a limit of 5 MeV. An intermediate structure effect was observed below the fission threshold of $^{238}U$. Moreover, because of the very good energy resolution, several structures appeared between 300 and 1200 keV for $^{238}U$ and up to 1 MeV for $^{239}Pu$.

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Time-of-flight neutron spectrometry has undergone great improvement over the last few years. The improvements have made it possible, in particular, to bring out the intermediate structure effect in fission cross-sections. Whereas linear accelerators have mainly shown their superiority in the resonance region in the past, they are now becoming highly competitive in the MeV region. Their advantages are energy resolution attaining from 1.5 keV to 1 MeV and the possibility of covering, at one fell swoop, a broad range of energy between several eV and several MeV.

These characteristics are illustrated by a series of experiments that we undertook in order to find possible resonances in the fission cross-section of heavy nuclei between 50 eV and 5 MeV. The target nuclei studied were as follows: $^{232}Th$, $^{237}Np$, $^{238}U$, $^{239}Pu$ and $^{243}Am$, the cross-sections of which are compared with that of $^{235}U$. The results for $^{232}Th$ and $^{237}Np$ have been reported in separate communications at this conference [1, 2]. The data for $^{238}U$ and $^{239}Pu$ are presented here although they are still of a preliminary nature.

The detector used is the gas scintillator already described in Refs [3, 4]. Given the range of energy under consideration, it was not necessary to heat the detector to the temperature of liquid nitrogen. By having six independent cells we were able to measure the cross-section of several fissile nuclei in one and the same experiment, the relevant samples usually being deposited in the oxide or acetate form on aluminium backing placed in the centre of each cell.

The background was measured at low energy by the "black" resonance method (cobalt and manganese screens), and at high energy by the "grey" resonance method ($SiO_2$ screen). It should be pointed out that the background is very low - of the order 3% at 1 MeV in the case of a nucleus with a large thermal fission cross-section, such as a $^{235}U$. We should point out, furthermore, that an opening was made in the neutron moderator at the accelerator target level so as to harden the neutron spectrum. The other experimental conditions are summarized in the following table:

| | | |
|---|---|---|
| Accelerator | Repetition rate: 500 Hz<br>Electron pulse width: 7 ns | |
| | Energy range | Channel width (ns) |
| Time-of-flight selector | 50 eV - 2098 eV | 80 |
| | 2098 eV - 15.8 keV | 40 |
| | 15.8 keV - 5 MeV | 10 |
| | 500 keV - 5 MeV | 2.5 |
| Flight path | 22.28 m perpendicular to the plane of the moderator | |
| Filter | Cadmium (1.2 mm) | |

URANIUM-238: Figure 1 shows the count rates between 700 and 1450 eV. We see the appearance of the intermediate structure effect at 721 and 1211 eV. This result has also been reported by R.C. Block et al. [5] and J.A. Wartena et al. [6]. Other resonances, much less clear, can be traced at 1684, 2285, 3230, 4125, 5250, 7400, 10 710 and 15 140 eV. In Fig. 1 we have plotted the position of the known resonances of $^{238}U$ on the abscissa.

Although the accuracy is insufficient to say for certain, it seems that about half the resonances can be identified in the fission cross-section on account of the good resolution of the measurement; it can be said, in contrast to what occurs in the case of $^{237}Np$ or $^{240}Pu$, that the intermediate structure does not cover several class I resonances. This suggests that the width of the class II states in the second well of fission barrier is lower than, or at most equal to, the spacing of the class I states in the first well (8.4 eV). Under these conditions the very marked effect observed at 721 and 1211 eV can only be due to chance coincidence of a class II state with a class I state of the same quantum numbers. Since a coincidence of this kind has little chance of recurring very often, it is not surprising that the intermediate structure is more difficult to observe at other energies.

In the region of the opening of the fission channel, previous measurements showed slight plateaux at 650, 950 and 1200 keV. They were due to the opening of the inelastic scattering channels competing with fission [7]. Thanks to improved resolution, we can now distinguish between several resonance strucutres (Figs 2 and 3); their width half way up is of the order of 20 keV. There are probably structures of the same type between these plateaux as well, but they are masked by the unduly rapid variation in cross-section. The spacing and width of these structures suggest that they are different in nature from those observed at low energy. They might be due to the presence of vibrational states of a relatively simple type in the second well of the fission barrier.

PLUTONIUM-239: Since this nucleus can be fissioned by slow neutrons, study of the intermediate structure in channel $1^+$ (closed) is made very difficult by the presence of a strong cross-section due to channel $0^+$ (open). It is only by separating the components $0^+$ and $1^+$ that it has proved possible to demonstrate this effect below 60 eV [8].

Visual examination of the fission count rate below several keV where resolution is very good brings to light different groups of very close resonances. They might be resonances $1^+$ associated with an intermediate structure with a spacing of about 300 eV. When the width of the resolution function approaches that of the resonances $0^+ (<\Gamma_f>_{0^+} \approx 2.2$ eV), it is not possible to determine whether the modulations of the cross-section are due to the intermediate structure or to the presence of the resonances $0^+$.

At still higher energies, around 400 keV, structures of a different type appear, which have a width of about 5 keV and a spacing of the order of 20 keV (Fig. 4). They may be the same in origin as those observed in $^{238}U$ close to the threshold.

## REFERENCES

[1] J. Blons et al.,"Mise en évidence de bandes de rotation au voisinage du seuil de fission dans la réaction $^{232}Th$ (n, f)", communication à cette conférence.

[2] S. Plattard et al.,"Mesure de la section efficace de $^{237}Np$ de 100 keV à 2 MeV", communication à cette conférence.

[3] J. Blons et al.,Rev. Phys. Appl. 4 (1969) 287.

[4] C. Eggermann et al., Nucl. Inst. and Meth., 81 (1970) 243.

[5] R.C. Block et al., Phys. Rev. Lett., 31 (1973) 247.

[6] J.A. Wartena et al., "On sub-barrier fission in $^{238}U$". C.R. Nuclear cross section and technology conference Washington, 1975.

[7] L. Cranberg et al., Phys. Rev., 1968, 109, 2063.

[8] J. Blons et al., Nuclear Data for Reactions (C.R. Conf. Helsinki 1970), 1, AIEA, Vienne (1970) 513.

## CAPTIONS TO FIGURES

Fig. 1 Count rate for the reaction $^{238}U(n,f)$.

Fig. 2 Count rate for the reaction $^{238}U(n,f)$.

Fig. 3 Count rate for the reaction $^{238}U(n,f)$.

Fig. 4 Count rate for the reaction $^{239}Pu(n,f)$.

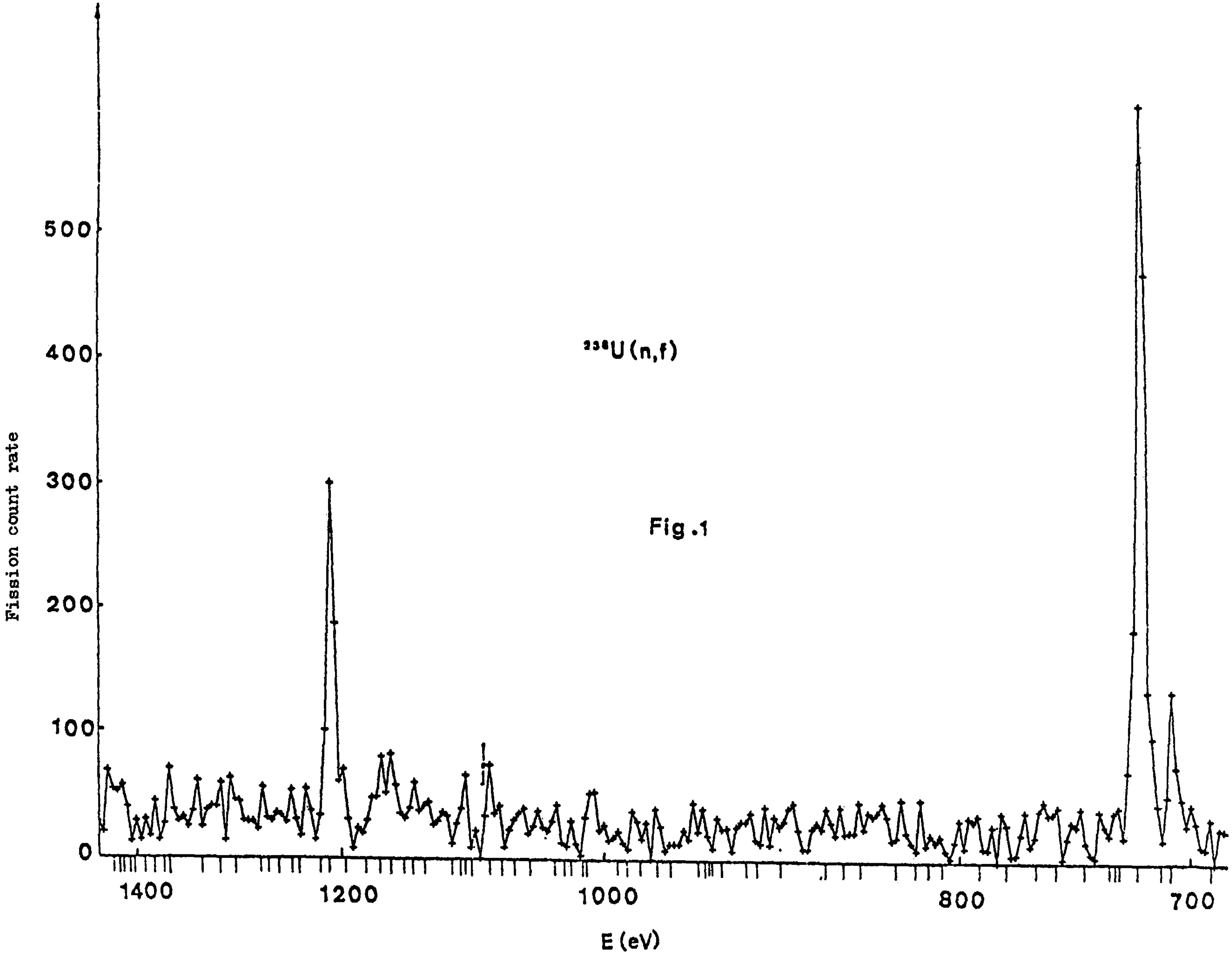

$^{238}U(n,f)$
Fission count rate
0
100
200
300
400
500
1400
1200
1000
800
700
E (eV)

Fig.1

Fig. 1

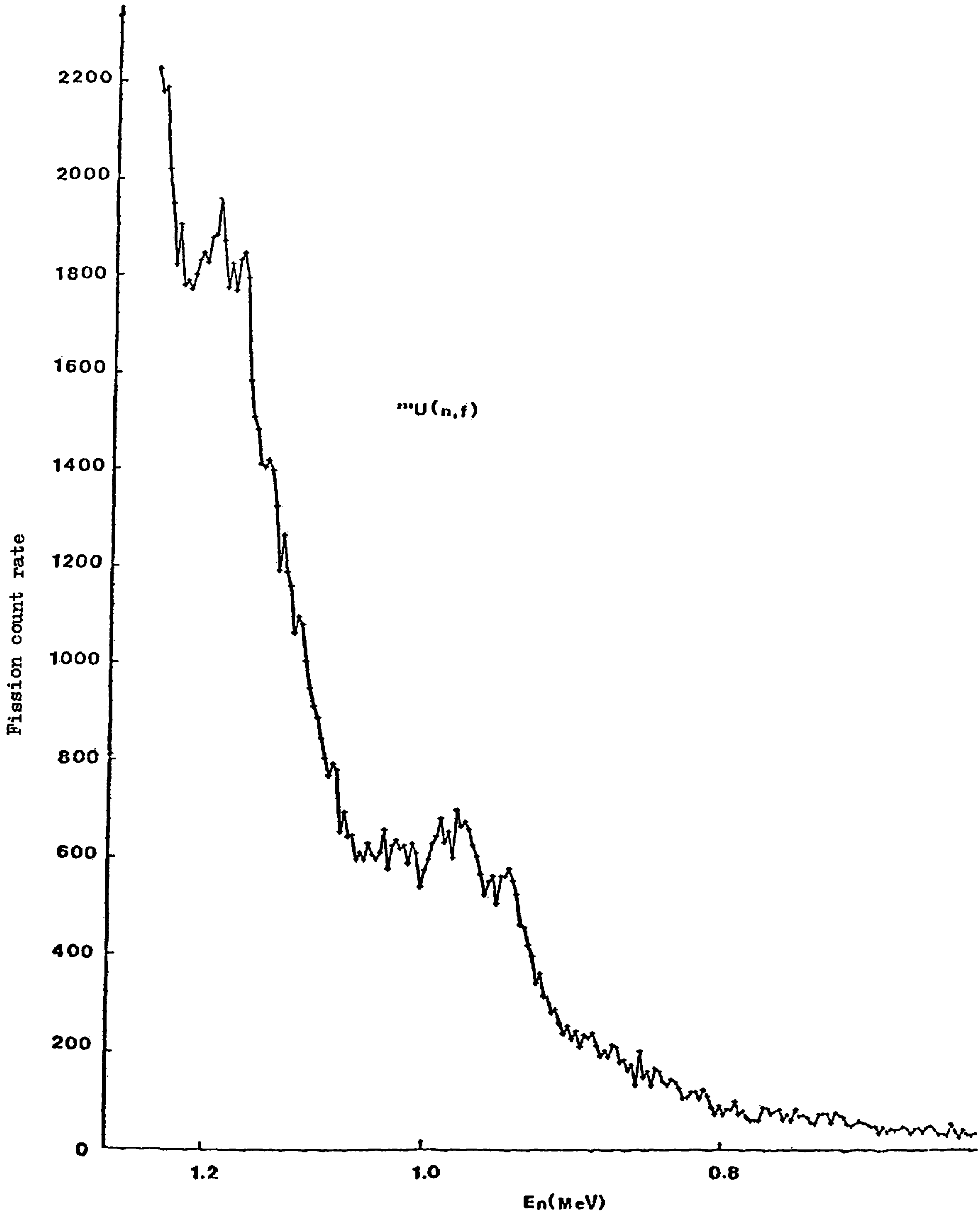
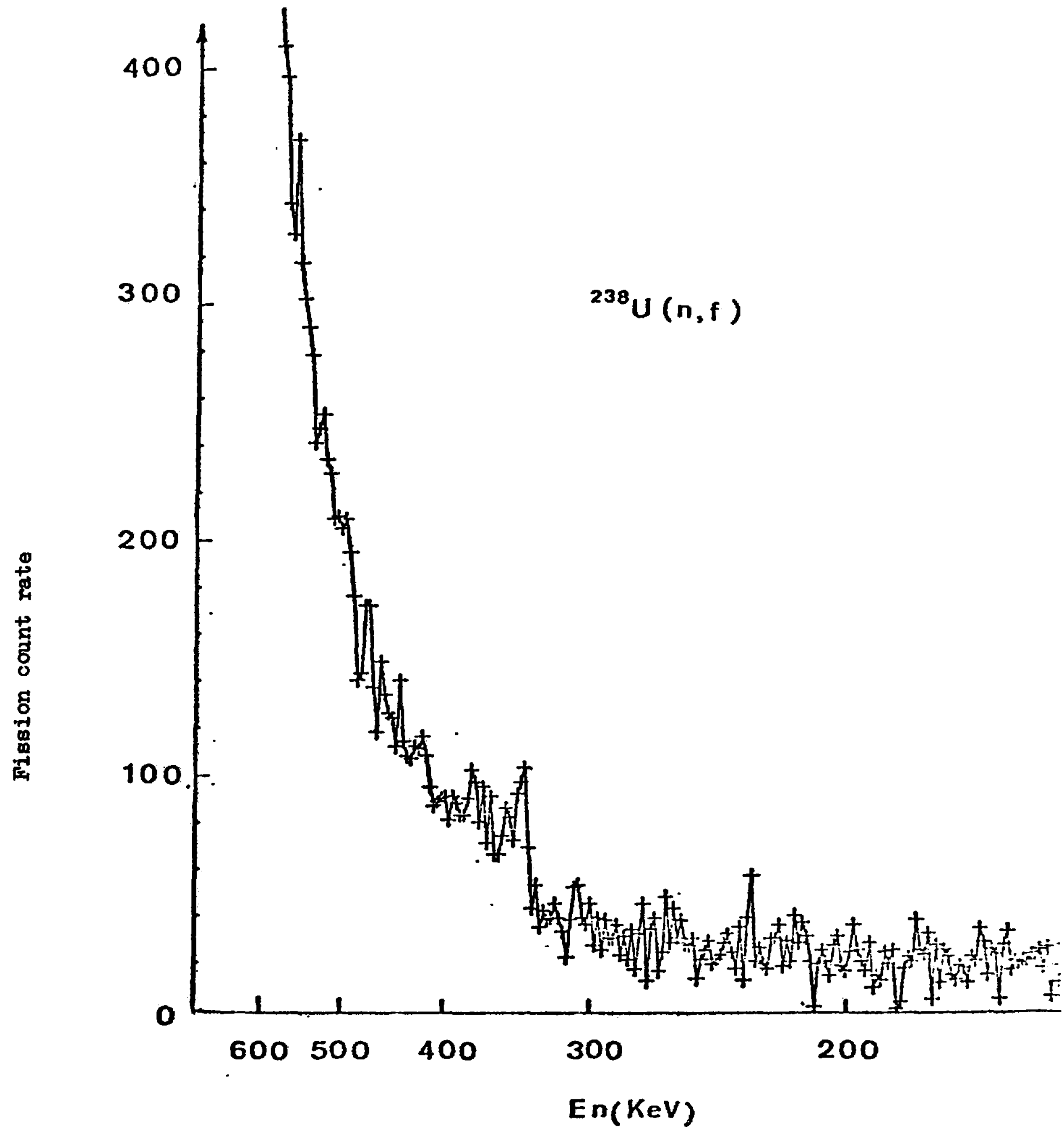

2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Fission count rate
U(n,f)
1.2
1.0
0.8
En(MeV)

Fig. 2



Fission count rate
400
300
200
100
0
$^{238}U(n,f)$
600
500
400
300
200
En(KeV)


Fig. 3

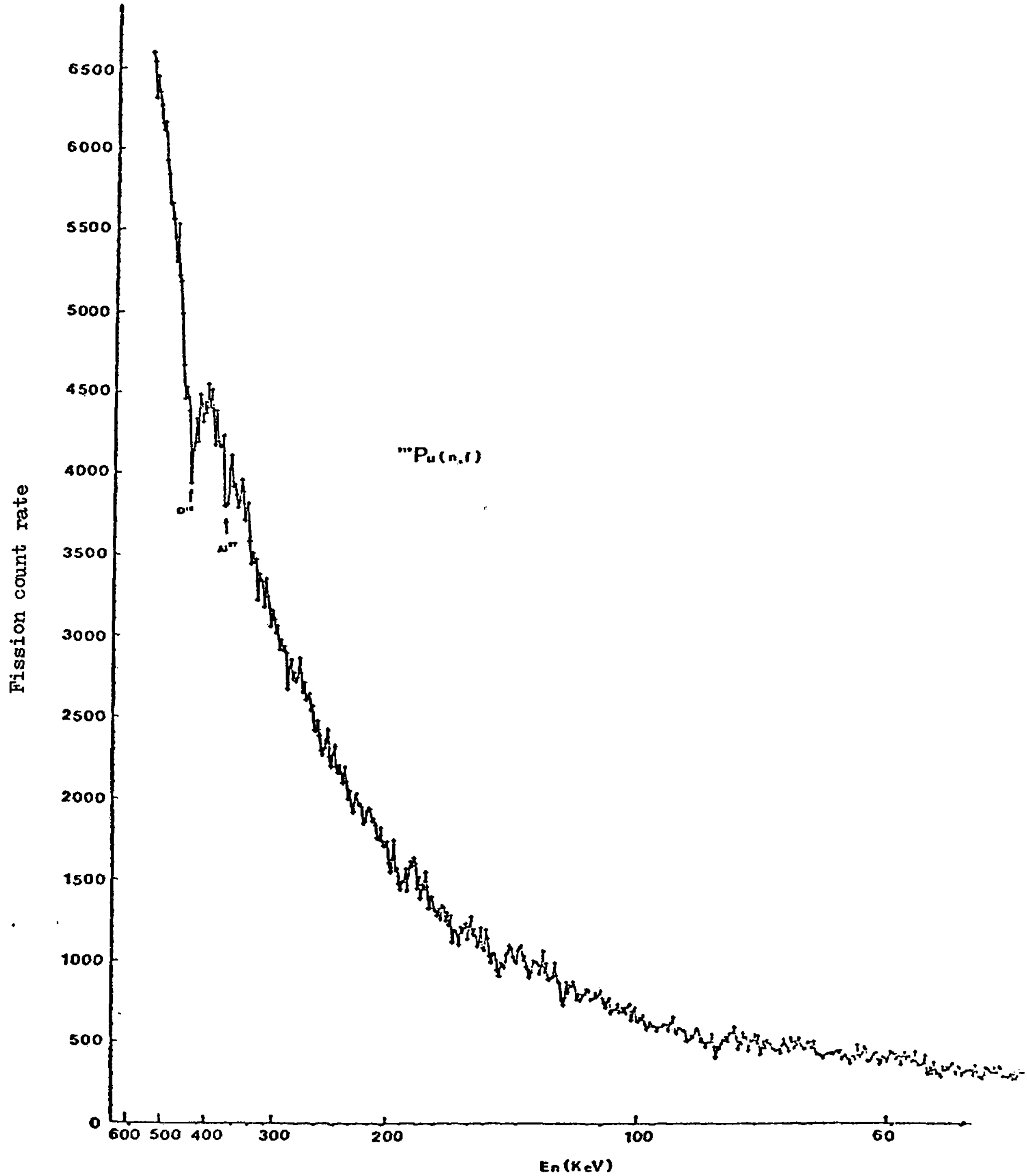

Fission count rate
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
600 500 400 300 200 100 60
En(KeV)
Pu(n,f)
O
Al

Fig.4

Contributed Paper to Topic B2

# FISSION CROSS-SECTION AND RESONANCE PARAMETERS OF $^{241}Am$

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ABSTRACT

The total cross-section of $^{241}Am$ has provided resonance parameters up to 150 eV. The fission cross-section was measured by means of a fast neutron detector. It provides the fission widths up to 40 eV. The results are compared with those based on measurements made at other laboratories.

Measurement of the fission cross-section of $^{241}Am$ was performed in order to find a possible intermediate structure similar to the one present in $^{237}Np$ and several other nuclei. Since previous measurement [1] had not shown a marked effect of this type, however, it was expected that a close analysis of the resonance parameters would have to be made. Furthermore, these resonances, despite their value in calculating reactors, were either well known in only a few cases or else not properly known. For this reason we attempted to measure, successively, the total cross-section and the fission cross-section of $^{241}Am$, using the neutron spectrometer installed in the AL60 accelerator at Saclay.

The total cross-section was measured between 0.8 eV and 1 keV. The experimental conditions were described at the previous Kiev conference [2], during which some preliminary results were presented. The analysis has now been completely finished [3]. Table 1 shows for all the resonances identified between 0 and 150 eV the following: energy E, neutron width $2\ g\ \Gamma_n$; statistical error $\Delta(2\ g\Gamma_n)_1$ and error due to background $\Delta(2\ g\Gamma_n)_2$. Moreover, whenever it was possible, the radiative widths $\Gamma_\gamma$ were calculated by the difference $\Gamma_\gamma = \Gamma - 2\ g\Gamma_n$ on the assumption that $\Gamma_n$ and $\Gamma_f$ are sufficiently small for the approximation introduced by this relationship to be better than the experimental accuracy. The values of $\Gamma_\gamma$ as well as the statistical error $\Delta\Gamma_\gamma$ also appear in Table I. Monte Carlo calculations aimed at reproducing a cross-section similar to the one measured show that $(18 \pm 4)\%$ of the levels are not observed in the experimental cross-section. Approximately 80% of these levels are lost because they have a neutron width less than one tenth of the mean width. If we take these lost resonances into account, the true mean spacing is $\langle D \rangle = (0.55 \pm 0.05)$ eV.

Measurement of the fission cross-section made it necessary to develop a new type of detector. Indeed, the strong alpha activity of $^{241}Am$ considerably reduces the amount of this element that can be put into an ionization chamber or a gas scintillator. Given the poor cross-section and the flux available to us, we had to use a sample of a few grams of americium. We therefore selected a proton recoil detector responsive to fission neutrons and insensitive to resonance neutrons and alpha particles. This detector consists of a truncated cylinder holding 45 litres of NE 213 scintilating liquid and divided into four optically independent parts. Each part is viewed by an XP 1040 photomultiplier. A tube runs along the detector axis, enabling the americium sample to be placed at the centre and permitting the incident neutron beam to pass through. A set of lead and boron screens reduce the gamma radiation and delayed neutron exchange between the liquid and samples. A pulse shape discriminator system cuts out the signals due to gamma radiation at a rejection rate of $10^5$ for an 800 keV threshold neutron energy. Preliminary experiments have been made with a sample of 1.5 g of americium oxide. Unfortunately, the reactions $(\alpha,n)$ in the oxide create a fast neutron background that can only be eliminated by imposing coincidences between two diametrically opposite parts of the detector, the disadvantage of which is that the efficiency is greatly reduced. Under the experimental conditions described in Table II, the count rate was 10 fissions per hour at the resonance peak 5.4 eV.

The cross-section was normalized to the Bowman cross-section [4] between 0 and 15 eV. Table III shows the fission widths obtained for 38 resonances below 40 eV. They were calculated on the basis of the parameters in Table I. Matching with the Bowman value is satisfactory for seven of the resonances and poor for four others. In the case of resonances at 3.97, 4.97, 6.12 and 9.11 eV, Bowman gives resonance surfaces some ten times weaker than ours, although there was no apparent disagreement in the cross-sections. The fission widths have a mean value $\Gamma_f$ = 0.23 MeV with a $\chi^2$ distribution with 4 degress of freedom (Fig. 1). Hence, there is a fairly large number of channels contributing to the fission below the threshold for the $^{242}Am$ compound nucleus; this is in fact not impossible when we think that in an uneven-uneven nucleus of this kind the transition states should be very close together.

The results in Table I have also made it possible to analyse the fission cross-section measured at Los Alamos [1](obtained through the Neutron Data Compilation Centre (CCDN) at Saclay). The fission widths obtained between 22 and 52 eV are given in Table IV. Their mean value is $< \Gamma_f >$ = 0.52 meV and has a $\chi^2$ distribution with 15 degrees of freedom. It is difficult to interpret this result within the theory of fission channels. An explanation might be found in contamination of the fission cross-section by capture. It only needs a 0.7%

contribution to fission by the total capture in order to raise the mean width from 0.23 meV to 0.52 meV. If we apply the corresponding correction of 0.30 meV at each fission width, the number of degrees of freedom drops from 15 to 3 (Fig. 2).

In view of the above remarks, neither our results, nor those of Los Alamos, show anomalies in the distribution of widths suggesting an intermediate structure effect, or at least not below 50 eV. At higher energies, there is nothing to be seen from visual examination of the cross-section, and the statistics obtained in this initial experiment are too poor to permit analysis in terms of resonance parameters.

It should be stressed, however, that although this experiment has enabled us to measure a certain number of fission widths, its aim was basically to verify, under particularly stringent experimental conditions, the capabilities of the fission neutron detector. Since the latter justified the hopes that had been based on it, it would be interesting to remake the measurement, using a sample of americium metal enclosed in a box made of a material with a high atomic number. The detector, then rid of neutrons produced by reactions (α,n), would be able to operate without coincidences. The resulting gain in the detection efficiency would thereby make it possible to work with longer flight distances and to expand the energy analysis region.

## REFERENCES


[1] P.A. Seeger et al. Nucl. Phys. A 96 (1967), 605.

[2] H. Derrien. 2nd National Soviet Conf. Kiev (1973), vol.2, p. 246.

[3] H. Derrien et B. Lucas. Conf. on Nucl. Cross Section and Technology, Washington (1975).

[4] C.D. Bowman et al. Phys. Rev. 137 B (1965) 326.


## CAPTIONS TO FIGURES

**Fig. 1** Number of resonance for which $\sqrt{\Gamma_f}$ is higher than the value given on the abscissa (this experiment).

**Fig. 2** Number of resonances for which $\sqrt{\Gamma_f}$ is higher than the value given on the abscissa: (a) analysis of data from Ref. [1]; (b) previous results after subtraction of 0.30 meV.

CAPTIONS TO TABLES

Table I: Resonance parameters for $^{241}Am$;

Table II: Experimental conditions for measuring the fission cross-section;

Table III: Fission widths for $^{241}Am$;

Table IV: Fission widths derived from data given in Ref. [1].

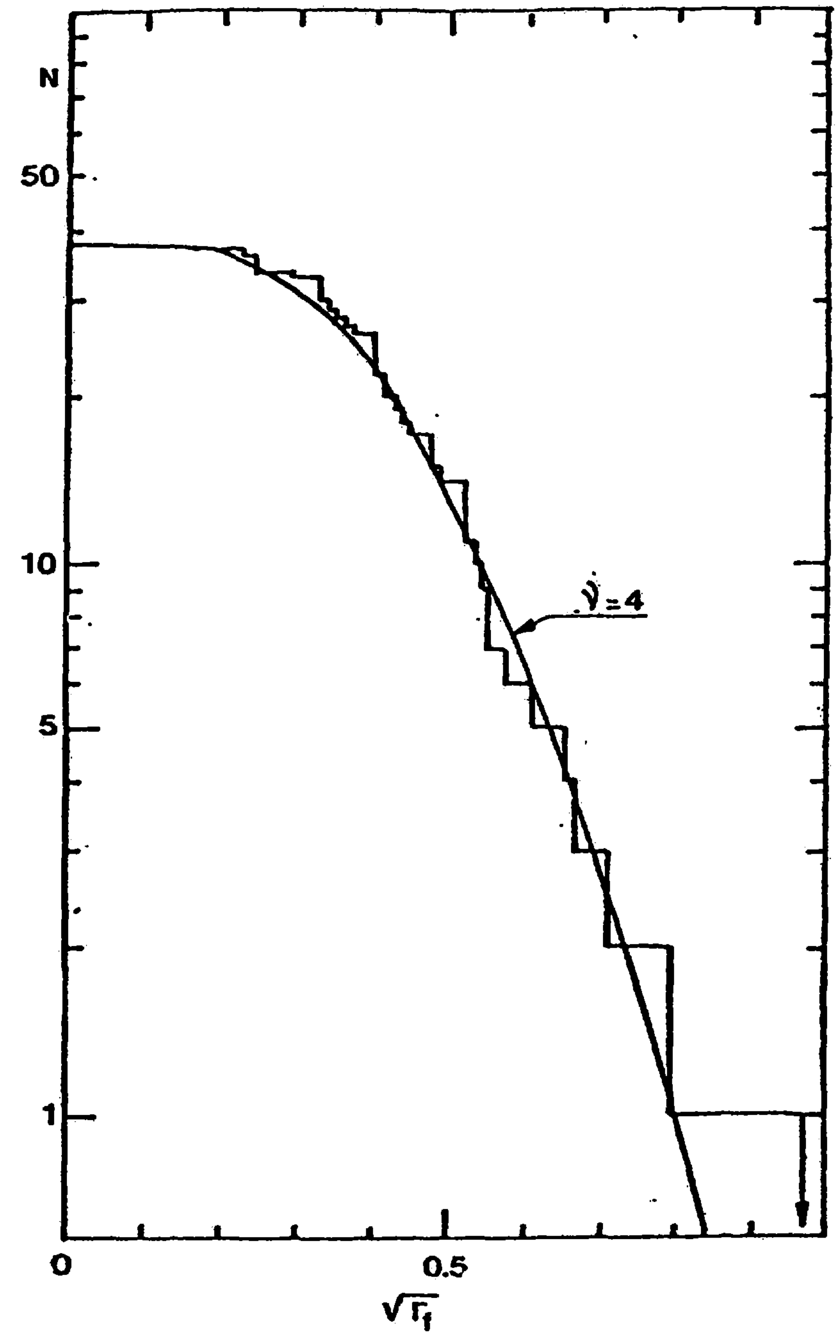


Fig.:1

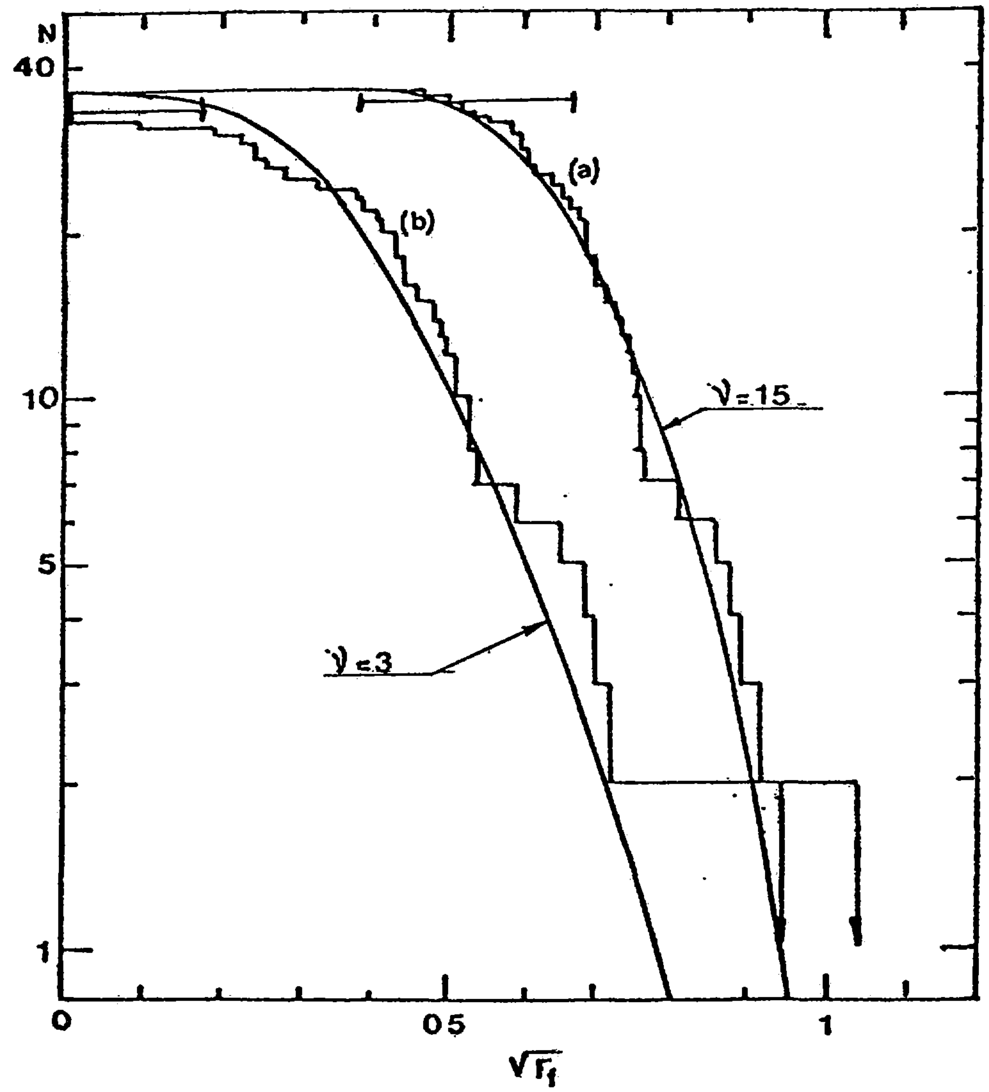


Fig.: 2

Table I

| E (eV) | $2g\Gamma_n$ (meV) | $\Delta(2g\Gamma_n)_1$ (meV) | $\Delta(2g\Gamma_n)_2$ (meV) | $\Gamma_\gamma$ (meV) | $\Delta\Gamma_\gamma$ (meV) | E (eV) | $2g\Gamma_n$ (meV) | $\Delta(2g\Gamma_n)_1$ (meV) | $\Delta(2g\Gamma_n)_2$ (meV) | $\Gamma_\gamma$ (meV) | $\Delta\Gamma_\gamma$ (meV) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.276 | 0.322 | 0.006 | 0.026 | 46.5 | 0.8 | 31.020 | 0.336 | 0.010 | 0.004 | | |
| 1.928 | 0.113 | 0.001 | 0.006 | 44.3 | 0.3 | 31.251 | 0.996 | 0.019 | 0.015 | 42.6 | 4.2 |
| 2.372 | 0.073 | 0.001 | 0.004 | 42.4 | 0.3 | 32.030 | 0.300 | 0.010 | 0.003 | 47.4 | 6.6 |
| 2.598 | 0.147 | 0.001 | 0.010 | 46.0 | 0.3 | 33.510 | 0.060 | | | | |
| 3.973 | 0.210 | 0.001 | 0.006 | 44.5 | 0.3 | 34.028 | 0.628 | 0.012 | 0.008 | 45.4 | 4.9 |
| 4.968 | 0.175 | 0.001 | 0.004 | 43.8 | 0.4 | 34.460 | 0.125 | 0.007 | | | |
| 5.415 | 0.760 | 0.003 | 0.019 | 44.2 | 0.1 | 34.928 | 0.612 | 0.012 | 0.006 | 42.8 | 5.4 |
| 5.800 | 0.002 | | | | | 35.485 | 0.427 | 0.012 | 0.004 | 50.6 | 8.1 |
| 6.117 | 0.124 | 0.001 | 0.002 | 43.8 | 0.7 | 36.250 | 0.167 | 0.007 | 0.001 | | |
| 6.745 | 0.028 | 0.001 | | | | 36.483 | 0.100 | | | | |
| 7.659 | 0.037 | 0.001 | | | | 36.979 | 2.995 | 0.017 | 0.075 | 52.0 | 1.5 |
| 8.173 | 0.108 | 0.001 | 0.001 | 42.7 | 1.2 | 38.366 | 2.260 | 0.015 | 0.044 | 47.0 | 2.0 |
| 9.113 | 0.389 | 0.002 | 0.009 | 44.2 | 0.6 | 38.830 | 0.055 | | | | |
| 9.851 | 0.406 | 0.002 | 0.009 | 43.9 | 0.6 | 39.617 | 1.295 | 0.020 | 0.020 | 40.2 | 4.2 |
| 10.116 | 0.026 | 0.001 | | | | 40.067 | 0.541 | 0.040 | 0.005 | 77.9 | 20.1 |
| 10.403 | 0.326 | 0.002 | 0.005 | 42.4 | 0.8 | 40.396 | 0.948 | 0.034 | 0.012 | 66.0 | 8.6 |
| 10.997 | 0.413 | 0.002 | 0.006 | 46.5 | 0.8 | 41.298 | 0.084 | | | | |
| 11.583 | 0.016 | 0.001 | | | | 41.791 | 0.355 | 0.009 | 0.003 | | |
| 12.137 | 0.007 | 0.001 | | | | 42.130 | 0.150 | 0.009 | 0.001 | | |
| 12.879 | 0.131 | 0.001 | 0.001 | | | 43.294 | 0.605 | 0.033 | 0.010 | 18.0 | 8.9 |
| 13.674 | 0.012 | 0.001 | | | | 43.574 | 0.582 | 0.035 | 0.006 | 36.2 | 13.6 |
| 14.360 | 0.071 | 0.002 | 0.001 | | | 44.416 | 0.118 | 0.009 | | | |
| 14.682 | 2.482 | 0.011 | 0.075 | 40.3 | 0.5 | 44.921 | 0.074 | 0.009 | | | |
| 15.689 | 0.244 | 0.003 | 0.003 | 39.3 | 2.9 | 46.073 | 0.665 | 0.019 | 0.007 | 43.8 | 6.6 |
| 16.388 | 1.277 | 0.005 | 0.034 | 41.8 | 0.9 | 46.566 | 0.371 | 0.018 | 0.003 | 27.8 | 14.0 |
| 16.849 | 0.646 | 0.004 | 0.012 | 41.2 | 1.5 | 47.535 | 1.053 | 0.017 | 0.012 | 41.6 | 5.2 |
| 17.729 | 0.391 | 0.004 | 0.006 | 37.3 | 2.4 | 48.765 | 0.713 | 0.018 | 0.007 | 40.0 | 8.0 |
| 18.167 | 0.017 | | | | | 49.332 | 0.220 | 0.011 | 0.002 | | |
| 19.445 | 0.213 | 0.003 | 0.002 | | | 50.278 | 2.442 | 0.022 | 0.042 | 51.6 | 3.0 |
| 20.333 | 0.034 | | | | | 50.847 | 0.393 | 0.020 | 0.003 | 35.8 | 16.4 |
| 20.880 | 0.089 | 0.001 | | | | 51.984 | 1.385 | 0.021 | 0.017 | 50.2 | 4.9 |
| 21.740 | 0.081 | 0.003 | | | | 53.014 | 0.165 | 0.012 | 0.001 | | |
| 22.748 | 0.069 | 0.003 | | | | 53.493 | 0.184 | 0.012 | 0.001 | | |
| 23.079 | 0.417 | 0.012 | 0.005 | 47.2 | 6.0 | 54.407 | 0.073 | 0.012 | | | |
| 23.337 | 0.445 | 0.012 | 0.006 | 42.5 | 5.8 | 54.990 | 1.443 | 0.025 | 0.002 | 108.5 | 6.9 |
| 24.192 | 1.304 | 0.007 | 0.028 | 39.2 | 1.5 | 55.595 | 0.213 | 0.014 | 0.002 | | |
| 25.008 | 0.014 | 0.001 | 0.001 | | | 55.945 | 1.432 | 0.034 | 0.018 | | |
| 25.634 | 1.258 | 0.008 | 0.025 | 37.6 | 1.7 | 56.158 | 0.949 | 0.034 | 0.010 | | |
| 26.498 | 0.487 | 0.014 | 0.006 | 22.0 | 6.1 | 57.372 | 4.146 | 0.029 | 0.082 | 81.0 | 2.7 |
| 26.669 | 0.217 | 0.010 | 0.004 | | | 59.066 | 0.589 | 0.028 | 0.004 | 107.2 | 19.4 |
| 27.575 | 0.165 | 0.021 | 0.002 | | | 60.045 | 0.285 | 0.017 | | | |
| 27.726 | 0.509 | 0.029 | 0.006 | 70.6 | 8.8 | 60.381 | 0.140 | 0.017 | 0.001 | | |
| 28.355 | 0.570 | 0.009 | 0.008 | 44.7 | 3.7 | 61.258 | 1.672 | 0.044 | 0.017 | 74.7 | 9.6 |
| 28.903 | 0.467 | 0.009 | 0.006 | 48.6 | 4.7 | 61.613 | 0.434 | 0.025 | 0.004 | | |
| 29.504 | 0.701 | 0.009 | 0.009 | 44.6 | 3.2 | 62.549 | 0.222 | 0.016 | 0.001 | | |
| 29.956 | 0.050 | | | | | 63.507 | 0.199 | 0.018 | 0.001 | | |
| 30.822 | 0.150 | 0.010 | 0.002 | | | 64.039 | 4.042 | 0.049 | 0.074 | 47.1 | 4.6 |

Table I
(continued)

| E (eV) | $2g\Gamma_n$ (meV) | $\Delta(2g\Gamma_n)_1$ (meV) | $\Delta(2g\Gamma_n)_2$ (meV) | $\Gamma_\gamma$ (meV) | $\Delta\Gamma_\gamma$ (meV) | E (eV) | $2g\Gamma_n$ (meV) | $\Delta(2g\Gamma_n)_1$ (meV) | $\Delta(2g\Gamma_n)_2$ (meV) | $\Gamma_\gamma$ (meV) | $\Delta\Gamma_\gamma$ (meV) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 64.539 | 1.954 | 0.052 | 0.025 | 38.3 | 9.2 | 106.396 | 3.352 | 0.180 | 0.054 | | |
| 65.264 | 5.187 | 0.048 | 0.109 | 49.7 | 3.7 | 107.615 | 1.925 | 0.038 | 0.019 | | |
| 65.733 | 1.090 | 0.046 | 0.010 | 18.8 | 14.0 | 109.824 | 3.756 | 0.144 | 0.042 | | |
| 66.314 | 1.036 | 0.052 | 0.010 | 75.2 | 19.6 | 110.093 | 3.337 | 0.144 | 0.043 | | |
| 66.874 | 2.105 | 0.044 | 0.025 | 71.9 | 8.1 | 111.170 | 0.374 | 0.059 | 0.003 | | |
| 68.525 | 0.431 | 0.019 | 0.003 | | | 111.627 | 5.200 | 0.102 | 0.068 | 94.3 | 10.4 |
| 69.585 | 1.116 | 0.051 | 0.013 | | | 112.752 | 0.414 | 0.042 | 0.003 | | |
| 69.824 | 2.661 | 0.053 | 0.040 | | | 113.280 | 0.300 | | | | |
| 71.253 | 0.583 | 0.085 | 0.006 | | | 113.907 | 1.741 | 0.078 | 0.014 | 77.6 | 23.0 |
| 71.463 | 1.109 | 0.079 | 0.011 | | | 115.084 | 1.800 | 0.081 | 0.014 | 79.3 | 23.8 |
| 71.841 | 1.034 | 0.025 | 0.010 | | | 115.777 | 0.701 | 0.049 | 0.004 | | |
| 72.276 | 0.226 | 0.021 | 0.001 | | | 116.396 | 2.623 | 0.081 | 0.023 | 42.0 | 15.6 |
| 74.969 | 0.481 | 0.020 | 0.004 | | | 117.656 | 0.030 | | | | |
| 75.715 | 0.378 | 0.034 | 0.003 | | | 118.522 | 0.806 | 0.046 | 0.005 | | |
| 75.943 | 0.515 | 0.027 | 0.003 | | | 119.823 | 2.237 | 0.131 | 0.022 | | |
| 76.779 | 0.109 | | | | | 120.123 | 1.930 | 0.131 | 0.026 | | |
| 78.191 | 1.486 | 0.099 | 0.015 | 10.3 | 17.4 | 121.982 | 3.216 | 0.138 | 0.033 | 36.9 | 19.0 |
| 78.551 | 1.179 | 0.105 | 0.011 | 60.8 | 26.0 | 122.662 | 3.893 | 0.222 | 0.040 | 64.2 | 27.6 |
| 79.555 | 0.730 | 0.023 | 0.005 | | | 123.283 | 3.534 | 0.166 | 0.035 | 56.3 | 20.5 |
| 80.050 | 0.546 | 0.029 | 0.004 | | | 124.946 | 1.640 | 0.054 | 0.013 | | |
| 80.393 | 0.588 | 0.029 | 0.004 | | | 125.819 | 1.035 | 0.055 | 0.007 | | |
| 81.077 | 0.106 | 0.039 | | | | 126.441 | 2.035 | 0.057 | 0.017 | | |
| 81.458 | 1.042 | 0.081 | 0.008 | 104.6 | 35.0 | 127.415 | 0.250 | | | | |
| 82.089 | 1.454 | 0.054 | 0.015 | 26.7 | 14.0 | 127.994 | 1.688 | 0.056 | 0.013 | | |
| 82.900 | 0.439 | 0.024 | 0.003 | | | 129.677 | 0.225 | | 0.002 | | |
| 83.370 | 0.431 | 0.024 | 0.003 | | | 130.720 | 1.358 | 0.072 | 0.009 | | |
| 84.906 | 1.456 | 0.027 | 0.015 | 38.1 | 8.7 | 131.319 | 3.121 | 0.132 | 0.032 | 56.0 | 23.2 |
| 84.695 | 2.141 | 0.044 | 0.022 | | | 132.180 | 0.875 | 0.062 | 0.006 | | |
| 86.610 | 0.225 | 0.025 | 0.001 | | | 132.754 | 1.180 | 0.059 | 0.008 | | |
| 87.481 | 0.126 | 0.029 | | | | 133.657 | 1.784 | 0.100 | 0.014 | 52.1 | 30.5 |
| 87.984 | 3.918 | 0.053 | 0.055 | 70.7 | 6.3 | 134.867 | 8.015 | 0.317 | 0.104 | | |
| 89.297 | 0.332 | 0.061 | 0.002 | | | 135.449 | 4.131 | 0.348 | 0.042 | | |
| 89.602 | 2.364 | 0.093 | 0.024 | 86.7 | 16.1 | 136.435 | 5.757 | 0.145 | 0.068 | 45.7 | 14.1 |
| 93.412 | 6.296 | 0.055 | 0.115 | 53.7 | 4.0 | 137.103 | 1.294 | 0.077 | 0.009 | | |
| 94.610 | 0.754 | 0.030 | 0.006 | | | 137.613 | 1.628 | 0.064 | 0.012 | | |
| 95.285 | 0.360 | 0.035 | 0.003 | | | 138.774 | 3.886 | 0.108 | 0.040 | 40.6 | 15.4 |
| 95.686 | 2.863 | 0.041 | 0.034 | | | 139.963 | 1.253 | 0.071 | 0.008 | | |
| 96.100 | 2.906 | 0.048 | 0.037 | | | 140.498 | 2.436 | 0.073 | 0.021 | | |
| 96.450 | 2.834 | 0.052 | 0.035 | | | 141.310 | 4.229 | 0.108 | 0.055 | | |
| 97.423 | 0.277 | 0.030 | 0.001 | | | 141.520 | 3.256 | 0.106 | 0.039 | | |
| 98.356 | 0.265 | 0.030 | 0.001 | | | 143.036 | 0.331 | 0.066 | 0.002 | | |
| 100.156 | 1.075 | 0.033 | 0.009 | | | 144.869 | 1.421 | 0.068 | 0.010 | | |
| 101.598 | 2.825 | 0.058 | 0.028 | 51.1 | 10.0 | 145.438 | 0.350 | | | | |
| 102.555 | 0.248 | 0.035 | 0.001 | | | 146.436 | 1.739 | 0.070 | 0.012 | | |
| 103.203 | 6.980 | 0.063 | 0.120 | 40.2 | 4.5 | 148.031 | 12.302 | 0.138 | 0.198 | | |
| 104.788 | 2.196 | 0.059 | 0.022 | 40.2 | 12.8 | 149.141 | 3.926 | 0.076 | 0.039 | | |
| 106.148 | 6.824 | 0.185 | 0.136 | | | | | | | | |

Table II

| Energy limits (eV) | Channel length for time-of-flight sector | - Accelerator pulse width: 100 ns |
|---|---|---|
| 0.8 - 3.8 | 800 | - Repetition rate - 500 Hz |
| 3.8 - 9.7 | 400 | |
| 9.7 - 23.6 | 200 | - Flight path length: 13 945 m |
| 23.6 - 86.7 | 100 | |
| 86.7 - 152 | 50 | - Accumulation time: 200 h. |

Table III

| E (eV) | $\Gamma_f$ (meV) | E (eV) | $\Gamma_f$ (meV) | E (eV) | $\Gamma_f$ (meV) |
|---|---|---|---|---|---|
| 1.28 | 0.37 | 10.12 | 0.16 | 24.19 | 0.14 |
| 1.93 | 0.08 | 10.40 | 0.06 | 25.63 | 0.29 |
| 2.37 | 0.18 | 10.99 | 0.13 | 26.50 | 0.05 |
| 2.60 | 0.17 | 12.88 | 0.06 | 26.67 | 0.19 |
| 3.97 | 0.16 | 14.68 | 0.27 | 28.36 | 0.16 |
| 4.97 | 0.44 | 15.69 | 0.10 | 28.90 | 0.16 |
| 5.42 | 0.63 | 16.39 | 0.11 | 29.50 | 0.10 |
| 6.12 | 0.42 | 16.85 | 0.32 | 31.25 | 0.22 |
| 6.74 | 0.22 | 17.73 | 0.30 | 32.03 | 0.28 |
| 7.66 | 0.10 | 19.44 | 0.03 | 36.98 | 0.51 |
| 8.17 | 0.12 | 21.74 | 0.27 | 38.37 | 0.30 |
| 9.11 | 0.18 | 23.08 | 0.27 | 39.62 | 0.23 |
| 9.85 | 0.95 | 23.34 | 0.17 | | |

Table IV

| E (eV) | $\Gamma_f$ (meV) | E (eV) | $\Gamma_f$ (meV) | E (eV) | $\Gamma_f$ (meV) |
|---|---|---|---|---|---|
| 22.75 | 0.58 | 30.82 | 1.20 | 40.07 | 0.79 |
| 23.08 | 0.77 | 31.02 | 0.51 | 40.41 | 0.34 |
| 23.34 | 0.31 | 31.25 | 0.57 | 43.29 | 0.35 |
| 24.19 | 0.48 | 32.03 | 0.56 | 43.57 | 0.49 |
| 25.63 | 0.82 | 34.03 | 0.22 | 46.07 | 0.27 |
| 26.50 | 0.47 | 34.46 | 0.74 | 46.57 | 0.28 |
| 26.67 | 0.48 | 34.93 | 0.41 | 47.54 | 0.25 |
| 27.57 | 2.54 | 35.49 | 0.36 | 48.76 | 0.49 |
| 27.73 | 0.44 | 36.25 | 0.57 | 49.33 | 0.54 |
| 28.36 | 0.55 | 36.99 | 0.66 | 50.28 | 0.37 |
| 28.90 | 0.36 | 38.37 | 0.53 | 50.85 | 0.47 |
| 29.50 | 0.45 | 39.62 | 0.56 | 51.98 | 0.38 |

75-9906
Translated from French

Contributed Paper to Topic B2

# MEASUREMENT OF $\sigma_f$ FOR $^{243}Am$

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Abstract

The measurement of the fission cross section of $^{243}Am$ in progress at the 60 MeV linear electron accelerator at Saclay is described briefly. Analysis of the data is planned for the end of 1975.

## Principal characteristics relating to the experiment carried out in the 60-MeV linear electron accelerator at Saclay

Measured quantity: ratio $\sigma_f(^{243}Am)/\sigma_f(^{235}U)$

Energy range: 300 keV-5 MeV

Resolution conditions:

- Wavelength: 22 m
- Accelerator width: 8 ns
- Time-of-flight channel width: 3 ns
- Deposit: 140 mg onto 300 $cm^2$, spread over four independent cells

Impurities:

- $^{241}Am < 1\%$
- $^{244}Cm < 2\text{-}10^{-5}$

## Comments

The experiment was carried out under the same conditions as for $^{237}Np$, $^{238}U$ and $^{239}Pu$ (the preliminary results were presented at the Kiev conference in 1975).

Analysis of $^{243}Am$ data is planned for the end of 1975. The statistical accuracy of the ratio $\sigma_f(^{243}Am)/\sigma_f(^{235}U)$ will be of the order of 3% for each point above the threshold; the measurement is a relative one and will not give the absolute value of $\sigma_f(^{243}Am)$.

# STATUS OF NEUTRON CROSS SECTIONS OF TRANSACTINIUM ISOTOPES IN THE RESONANCE AND FAST ENERGY REGIONS — UNDERGROUND NUCLEAR EXPLOSION MEASUREMENTS

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ABSTRACT

The nuclear explosion technique as a means of obtaining neutron cross-section data of actinide isotopes with half-lives of the order of days or longer is reviewed. The status of measurements previously made in this region (except for $^{232}$Th, $^{233}$U, $^{235}$U, $^{238}$U, and $^{239}$Pu) is discussed. Some suggested corrections which may be in order for previously published data are described, and recommendations are made for possible future work by this technique.

## 1. INTRODUCTION

The measurement of neutron cross sections by time of flight with a nuclear explosion as a neutron source is ideally suited for samples which are highly radioactive. It is perhaps the only technique presently available which will give partial cross sections of isotopes having half lives as short as a few days. The neutron beam intensity is high enough that backgrounds from radioactive decay can be easily overridden, and the amount of sample material necessary for the measurement can be minimal (e.g., ~1 μg for a fission cross-section determination, or ~30 mg for radiative capture). The accuracy of the data obtained is not high (~10% systematic error is to be expected), although the uncertainties can be reduced substantially by fielding several samples and making multiple recordings of each signal on a given shot. The method is most useful in providing cross-section data in the intermediate and fast neutron energy regions for isotopes which are not required to high accuracy but which are of interest to the nuclear energy program in such areas as waste management and isotope production.

The purpose of the present paper is to assess the nuclear explosion technique as a means of providing nuclear data for transactinium isotopes ($Z \geqslant 90$), with the exception of $^{232}$Th, $^{233}$U, $^{235}$U, $^{238}$U, and $^{239}$Pu. We shall review the technique, the status of existing data, and make some recommendations about future work.

Concerning future work, the question naturally arises, "What is the probability that there will be future nuclear explosion events for neutron data measurements?" The last such event was Physics 8, carried out in 1969. Over the last six years, the activity has been minimal, restricted to a few isolated measurements done on a non-interference basis in the U.S. underground testing program. Several years ago, the International Data Committee, an advisory committee to the International Atomic Energy Agency, assessed interest in participating in a nuclear explosion event for the measurement of neutron data, by soliciting proposals from the international community. The proposals received were evaluated and forwarded to the USAEC, but because of competition for funding, no action was taken at that time. At present, however, there are strong indications that serious consideration is being given to implementing a physics shot. This would not necessarily be open to outside participants. It is appropriate that advanced planning should begin for this event and we should like to provide enough detail in this review to give interested persons an idea of what is required in fielding an experiment and what can reasonably be expected in the way of results.

## 2. DEVELOPMENT OF THE TECHNIQUE

In the latter part of the 1960's, the use of a nuclear explosion as a neutron source for nuclear data was developed in the Los Alamos Scientific Laboratory series of physics shots to the point that the data obtained are comparable in quality with those from more familiar laboratory time-of-flight methods. Several general reviews traced the development of the technique [1-7]; perhaps the most detailed of these is a two part Laboratory report, LA-3478, by Hemmendinger et al. [6] and by Seeger and Bergen [7]. The first part deals with the procedures involved in fielding an experiment, and the second with data reduction. Both parts of this report are quite comprehensive, and would be especially useful to those interested in participating in a future measurement. Another report, LA-4095, by Brown et al. [8], is concerned with the special problem of determining the flux.

The first three physics shots were carried out with the very limited objective of demonstrating that signals capable of giving nuclear data over a wide dynamic range could be observed. Physics 1 and Physics 2 were the first attempts, which were inconclusive. In April 1964, on an event code-named Pipefish (Physics 3), fission fragments from a $^{235}U$ foil were detected by solid-state p-n junction detectors; the signals were amplified and recorded from oscilloscope traces with plate cameras. This event demonstrated the feasibility of making fission cross-section measurements. A second feasibility experiment (Physics 4) was carried out on the Parrot event in December 1964. We showed that radiative capture cross sections could be measured with a modified Moxon-Rae detector. We also found that the simplest possible laboratory measurement, that of the total cross section, was not going to be at all easy with a nuclear explosion, where one gets only a single pulse of neutrons. The data from Physics 4 were processed but never published; the instrumentation we used was still not quite adequate.

The latter four physics shots not only taught us how to use this technique, but they also produced a significant amount of nuclear data. New data obtained on the transactinium isotopes on the Petrel event (Physics 5) in June 1965 included measurements of the fission cross sections of $^{240}Pu$, $^{241}Pu$, $^{241}Am$, and $^{242m}Am$, and of the radiative capture cross section of $^{240}Pu$. The Persimmon event (Physics 6), in February 1967, yielded new data on fission of $^{238}Pu$ and $^{244}Cm$, and radiative capture of $^{238}Pu$. There was also fielded on Physics 6 a 1 μg sample of $^{239}Pu$, in a successful demonstration that useful data can be obtained with very limited quantities of material. The Pommard event (Physics 7), in March 1968, was the first in which we had available more than one collimated beam for nuclear data measurements. Fission data were obtained on $^{233}Pa$, $^{232}U$, $^{234}U$, $^{236}U$, $^{237}U$, $^{237}Np$, $^{238}Pu$, $^{242}Pu$, $^{243}Am$, and $^{243}Cm$. A radiative capture measurement was fielded for $^{233}Pa$, using a 2 g sample, but the sample ruptured and was lost as it was being installed, so no data were obtained. There were also severe noise problems: the calibration system was triggered by noise during data acquisition, and much of the data was lost. Physics 8, in the summer of 1969, was an unqualified success. Four collimated beams for cross section measurements were available, and fission data were obtained for $^{234}U$, $^{236}U$, $^{237}Np$, $^{242}Pu$, $^{244}Pu$, $^{243}Am$, $^{243}Cm$, $^{244}Cm$, $^{245}Cm$, $^{246}Cm$, $^{247}Cm$, $^{248}Cm$, $^{249}Bk$, $^{249}Cf$, $^{252}Cf$, and $^{253}Es$. A capture measurement was made for a sample of mixed Cm isotopes, which gave good data for $^{244}Cm$ and limited data for certain resonances of $^{246}Cm$ and $^{248}Cm$.

Several developmental measurements were made on Physics 8. We tried a different technique for measuring total cross sections: recording the difference signal between two matched detectors placed below and above a sample, to provide greater sensitivity. The results were not completely satisfactory, but the data were useful in making multiple scattering corrections.

Auchampaugh showed that elastic scattering cross sections of fissile targets can be measured. The detector was a high pressure $^3He$ cell in which 10 totally depleted solid state detectors were placed, spaced 1.9 mm apart. Backgrounds were determined with matched cells containing $^4He$, and the difference signal was recorded.

Ellis et al. [9] also fielded an experimental measurement of the Moxon-Rae detector efficiency. The Moxon-Rae detectors used in the physics shots are modified by the addition of bismuth to the graphite, to flatten the response, and by using p-n junction solid-state detectors instead of plastic scintillant to detect the emitted electrons and electromagnetic radiation. The response of these detectors is difficult to determine, and on Physics 8, Ellis fielded a spinning drum containing 50 mg/cm$^2$ thick gold and $^{238}U$ ribbons, through which the neutron beam passed. The modified Moxon-Rae detectors viewed the ribbons, and the signals were recorded in the usual way. After the event, the ribbons were recovered, and the number of $^{198}Au$ and $^{239}Np$ atoms produced by the neutron beam at various strong resonances was determined, which in effect, calibrates the detector in the current mode absolutely for the $^{197}Au$ and $^{238}U$ capture gamma spectra. Within the errors, the efficiencies were found to be the same ($\sim$0.1%) for the two spectra.

Finally, on Physics 8, Brown and Furnish [10] demonstrated the feasibility of recording the analog data on a magnetic disc. This had the enormous advantage that it obviates the necessity of reading film; the first step in data reduction can be done by digitizing the recorded analog signal with a computer.

While Physics 8 was the last of the large-scale shots with a line-of-sight pipe to the surface, we should note that nuclear data of interest have subsequently been measured as add-on experiments to the Laboratory's test program. These include measurements of the fission cross sections of $^{230}Th$ and $^{231}Pa$ in 1970, and an exploratory measurement of the absorption cross section of $^{241}Am$ in 1974.

At this point, we might summarize what we had found to be the requirements for a measurement to be carried out with an underground nuclear explosion. First, the device must be placed underground a distance which is roughly proportional to the cube root of the expected yield, far enough that the explosion will be contained, but not so far that cavitation will fail to occur after the underground fireball cools. We want to be able to recover the samples afterward for post-shot assay, so the measurements are done at the surface, with an evacuated pipe leading to the underground neutron source. A collimator and anti-scattering baffles are provided in the line-of sight pipe to prevent off-energy neutrons from reaching the samples. The samples are generally oriented at 45° to the neutron beam. At higher energies, one expects to see angular anisotropies in the reaction products to be detected. The beam-target-detector geometry is shown in Fig. 1. It has the feature that all detectors view the sample at 45°. In this way, differences in the energy degradation of the reaction products by the sample from one angular position to another are minimized. The reaction products strike the detector, and the current produced develops a voltage across a nominal 50Ω load, which is amplified and displayed on one or more oscilloscopes located in a recording station a few hundred meters away from the line-of-sight pipe (outside the cavitation perimeter). Each sample views the same neutron flux, and enough redundance is provided for samples of $^{235}U$ and $^6Li$ (from which the flux is determined) that the uncertainty in the flux determination is small compared to the uncertainty in the other sample signals. A comparison of the neutron flux for various physics shots is shown in Fig. 2. No moderator was used on Physics 4; we relied on the high explosive used to detonate the device as a moderating medium. A cold moderator was used in Physics 5 and subsequent shots, to extend the lower energy limit to which useful data could be obtained. The Physics 7 flux recording is effectively missing between 0.4 and 70 keV because of the calibration signal superimposed on the data. From Fig. 2, it is apparent that the flux of neutrons observed at the surface depends strongly on the design of the device and moderator and their relative locations. In each of the spectra, one sees resonance structure which gives the characteristic signature of the material used in the vacuum windows and, for the earlier shots, the sample backings: Ni and Pt for Physics 4-6, Al for Physics 7 and Physics 8. The bulk motion of the moderator up the line-of-sight pipe sets a lower limit to the velocity of neutrons which can be observed.

The signals to be expected span a large dynamic range — several decades. The amplifiers used are linear at the low end of the range, permitting observation of single fission fragments in the absence of background, and logarithmic at higher input levels. After the neutron pulse has passed through the samples, the signal amplitudes are calibrated by impressing a known stair-step voltage at the input of the amplifier, and recording the output. A writing speed check can also be provided to allow one to account for possible distortions in the data due to the time response of the amplifiers and the long cable runs.

The neutron energy over which useful data can be obtained also spans about six decades. The attaining of sufficiently high timing resolution at all energies requires partially redundant recordings of the signals. The highest resolution recordings are obtained with plate cameras and fast sweep oscilloscopes, but the range of neutron energies is severely limited. Going to moving film introduces additional broadening due to the decay of the cathode-ray tube phosphor. The P-16 phosphor adopted for these measurements has a decay which is comparable to the amplifier and cable length responses of ~100 nsec. This timing resolution is also comparable to that introduced by the spot size on the developed film (~20 μm) in the fast drum cameras used; in these cameras, the film is moved at 250 m/sec. The drum cameras contain roughly 1 m of film, and so could be used down to neutron energies of ~10 eV for a nominal 200 m flight path. These records are rarely used below a few hundred eV, because the experimental resolution is usually determined in this region by the moderator hold-up time. The temperature of the "cold" moderator is variable, depending on its location relative to the center of the device, the device output, and the moderator design, but the temperature is usually about $10^6$ K, so that the thermal neutron distribution extends up to ~300 eV. In the thermal region, moderator hold-up times are several μsec, and lower resolution recordings are completely adequate. We use a second type of camera which pulls the last half of a 30 m reel of 35 mm film at a 30 m/sec (called streak recordings). This camera gives an effective time resolution of 700 nsec.

We should also mention the accuracy one can expect. In the region of logarithmic response of the amplifiers, the accuracy is determined by the uncertainty in reading the film. If we assume that the center of a 20 μm wide trace can be determined to ± 4 μm, and use typical parameters of 4 V/cm for the oscilloscope sensitivity, 2.5 V/decade for the logarithmic amplifier gain, and an object/image ratio of 22, we find that the film reading uncertainty amounts to ~3%, for each signal used in the cross-section determination.

The fielding of a large number of measurements as was done on Physics 8 is a large effort, which includes sample fabrication by many groups, shipping and assembly of equipment, and innumerable dry runs (in which everything is tested except the device itself). Only one pulse of neutrons is obtained, so that everything must work perfectly and automatically during the pulse. Much of the electronic equipment has the function of providing the required timing and control. A typical timing sequence is given in Table I. Timing signals at intervals >1 sec are provided as requested from the Control Point, some miles away. Zero time is obtained locally, by monitoring the device output. Timing signals shorter than 1 sec are generated by the experimental electronics. The items listed in Table I are self-explanatory, with the possible exception of "bias on" and "bias off." In order to avoid noise pulses generated by the detector power supplies, the detector bias during data collection is maintained passively, using a capacitor bank which is charged prior to the shot.

After the shot, the exposed film is recovered, developed, spliced, copied, and eventually digitized, either automatically or manually. These x-y data sets are then edited to remove reading errors and computer processed to give signal in mV vs time in μsec. The s(t) data sets are further processed, either against a reference cross-section set to produce a neutron flux, or against a flux data set to produce a cross section vs neutron energy. Next, the f(E) or σ(E) sets are combined, renormalized, and averaged as appropriate to produce the final output and plots suitable for analysis. A complete description of the usual procedures for data reduction and analysis have been given by Seeger and Bergen [7], Brown et al. [8], and Auchampaugh [11].

## 3. STATUS OF TRANSACTINIUM NUCLEAR DATA OBTAINED WITH NUCLEAR EXPLOSIONS

### 3.1. $^{230}$Th

Fission cross sections from 0.3 to 3 MeV at 15° and 80° with respect to the neutron beam were reported by Muir and Veeser [12] at the 1971 Conference on Neutron Cross Sections and Technology. The data were measured relative to $^{239}$Pu(n,f) according to the evaluation by Davey [13], and lie ~30% lower than the 1972 data of James et al. [14], although a measurement of $^{232}$Th(n,f) done at the same time (and used for a background correction) is in satisfactory agreement with currently accepted evaluations. These data are on file at the four centers.

### 3.2. $^{231}$Pa

Fission cross sections from 0.1 to 3 MeV at 15° and 80° with respect to the neutron beam were also reported by Muir and Veeser [12]. The data lie ~20% higher than the earlier measurements of Dubrovina and Shigin [15] between 0.5 and 2 MeV; this disagreement is somewhat larger than the quoted error. These data are on file at the four centers.

### 3.3. $^{233}$Pa

A fission cross section sample containing 126 μg of material was fielded by D. K. Oestreich, F. B. Simpson, and J. R. Berreth on Physics 7 (Pommard), and signals were recorded at 15°, 55°, and 90° to the incident neutron beam. Because of the $^{233}$U content of the sample, the energy region over which significant data were obtained was limited to the $^{233}$Pa fission threshold and above. In this region, the 55° signal gave a cross section a factor of 2 larger than the 90° signal, and the 15° signal gave an even higher apparent cross section. Because of this inconsistency, these data were never published. However, subsequent experience suggests that the data can be salvaged, the discrepancy being due to the presence of a significant amount of hydrogenous material in the sample. (This effect led to our discarding certain forward-angle signals from a number of Physics 8 samples.) We show the fission cross section of $^{233}$Pa from 0.9 to 4 MeV, as determined from only the 90° signal, as Fig. 3.

### 3.4. $^{232}$U

The fission cross section from 40 eV to 22 keV at 55° to the neutron beam was measured by Farrell [16] on Physics 7 (Pommard). The data were normalized to earlier work by Auchampaugh et al. [18] at the peak of the 74 eV resonance, because the sample was not assayed prior to the shot and afterward showed evidence of flaking and loss of material. The data show a much better signal-to-noise ratio in the valleys than do the data obtained by Auchampaugh et al. or by James [18] using conventional techniques. Data above 22 keV were lost because of noise, as were the 90° data. Farrell carried out a preliminary multilevel analysis of the data, which gives the average parameters shown in Table II. The data are on file at the four centers.

### 3.5. $^{234}U$

M. G. Silbert fielded fission samples on both Physics 7 and Physics 8. The cross section obtained from Physics 7 at 90° showed a significant discrepancy with earlier work, lying ~25% higher at 1 MeV. The 55° data were lost. The Physics 8 data were not reduced to obtain cross sections, because the effect of capture gamma radiation on the fission detectors is large enough to make the resonance data a sum of capture and fission.

### 3.6. $^{236}U$

Cramer and Bergen [19] reported fission cross section data taken with a 4.4 mg sample at both 55° and 90° on Physics 7. The data agree well with older data above 1 MeV, but show what appears to be a timing discrepancy in the region of threshold. Data were also obtained between 30 eV and 2 keV which suggest subthreshold fission. However, because of the presence of a significant quantity of $^{235}U$ in the sample (0.12%) and because of the sensitivity of the detectors to gamma radiation, for which no correction was made, one should not accept the subthreshold results as definitive. A sample having much lower $^{235}U$ content was fielded by G. F. Auchampaugh on Physics 8, but the data have not been reduced. The data of Cramer and Bergen are on file at the four centers.

### 3.7. $^{237}U$

McNally et al. [20] fielded a fission cross-section sample containing 18 μg of material on Physics 7, and have reported results at 55° and 90° to the beam between 40 and 1000 eV and between 0.1 and 2 MeV. Data between 1 and 100 keV were lost because of calibration interference. A multilevel analysis was carried out below 200 eV; the average parameters are given in Table II. The data are on file at the four centers.

### 3.8. $^{237}Np$

Fission cross section measurements at 55° and 90° to the beam with a 6.1 mg sample were reported by Brown et al. [21] from Physics 7, and by Jiacoletti et al. [22] from Physics 8. Over threshold, both sets of data agree well with current evaluations. The results at lower energies indicate the presence of subthreshold fission, but should not be taken as definitive because of the sensitivity of the detectors to gamma radiation. Jiacoletti et al. attempted to correct for this effect in their analysis. Both sets of data are on file at the four centers.

### 3.9. $^{238}Pu$

Silbert et al. have reported both fission [23] and radiative capture [24] cross-section measurements from Physics 6 (Persimmon). The fission data were taken at both 55° and 80° to the beam, with a sample containing 5.1 mg of $^{238}Pu$. The radiative capture sample consisted of pressed $^{238}PuO_2$ in an aluminum-lead matrix, canned in Ni, and contained 84 mg/cm$^2$ of $^{238}Pu$. Drake et al. [25] repeated the fission measurement at 55° and 90° with a sample containing 1.1 mg of higher purity material on Physics 7, looking for broad Class II states in the valleys. The two sets of data agree well, and, because the subthreshold fission widths are quite large, no correction for gamma-ray sensitivity of the detectors is necessary. Average parameters given by the analysis of Silbert et al. [24] are shown in Table II. Both sets of data are on file at the four centers.

### 3.10. $^{240}Pu$

Byers et al. [26] reported both radiative capture and fission cross-section measurements from Physics 5 (Petrel). The radiative capture sample was a metal disc, 750 mg/cm$^2$ thick, canned in Al; the fission sample contained 2.3 mg of material. Fission data were taken at 55° and 90° to the beam; capture data at 90°. The Moxon-Rae detector efficiency was determined by the black resonance technique. The data agree, within the errors, with current evaluations of the fission cross section in the region above threshold. In the larger (Class II) clumps of resonances, the fission widths are large enough that no correction need be made for gamma-ray sensitivity of the detectors. No analysis of the data obtained has been carried out, and only the fission cross sections are on file at the four centers.

### 3.11. $^{241}Pu$

Simpson et al. [27] have reported fission cross sections at 55° and 90° to the beam using a sample containing 6.53 mg of material, from Physics 5 (Petrel). Average parameters from the multilevel analysis carried out by Simpson et al. are listed in Table II. The data are on file at the four centers.

### 3.12. $^{242}Pu$

Fission cross sections were measured at 55° and 90° to the beam with a 5.0 mg sample by Bergen and Fullwood [28] on Physics 7, and at the same angles with a 9.56 mg sample by Auchampaugh et al. [29] on Physics 8. The two sets of data agree well with one another and with older data in the threshold region. From a few hundred eV to 5 keV, the Physics 7 results lie significantly higher than those from Physics 8 in the valleys; this is most likely due to incomplete recovery of the base-line from the noise-induced calibration during data acquisition in Physics 7. Both sets of data are on file at the four centers.

### 3.13. $^{244}Pu$

The fission cross section was measured by Auchampaugh et al. [29] on Physics 8 at 55° and 90° to the beam with a sample containing 573 μg of material. The data have been submitted to the National Neutron Cross Section Center (NNCSC) at the Brookhaven National Laboratory for distribution to the other three data centers.

### 3.14. $^{241}Am$

The fission cross section was measured at 55° and 90° to the beam with a 774 μg sample on Physics 5 (Petrel) and has been reported by Seeger et al. [30]. The data show good agreement in the threshold region with current evaluations and recent measurements. These data are on file at the four centers. In 1974, Forman et al. [31] showed that one can carry out short flight-path measurements with this technique, by placing a sample of $^{241}Am$ at 20 m and recording signals from Moxon-Rae detectors, to give the gamma-ray production cross section of $^{241}Am$ from 0.3 to 6 MeV. Underground measurements of this type do not, of course permit the sample to be recovered.

### 3.15. $^{242m}Am$

The fission cross section was measured on Physics 5 by Seeger et al. [30] at 55° and 90° to the beam using a sample containing 88 μg of $^{242m}Am$, 355 μg of $^{241}Am$, 3.1 μg of $^{243}Am$, and 0.7 μg of $^{242}Cm$. No analysis of the resonance structure was carried out, because of the high level density and large fission widths of the resonances observed. The data are on file at the four centers.

### 3.16. $^{243}$Am

Seeger [32] measured the fission cross section at 55° and 90° to the beam with a 5.7 mg sample on Physics 7; these data are on file at the four centers. Seeger repeated the measurement on Physics 8 with the same sample. The data obtained agreed well with the earlier Physics 7 data and were combined into the final fission cross-section curve shown in Fig. 4. These data have not yet been analyzed or published, although they have been sent to the NNCSC for distribution.

### 3.17. $^{243}$Cm

A fission cross section sample with 228 μg of $^{243}$Cm was fielded by R. R. Fullwood on Physics 6 (Persimmon). The signal recordings were marginal in quality, and the data were never reduced. The same sample, which had decayed to 216 μg of material, was fielded on Physics 7 (Pommard). The drum camera signals were lost when the film failed to rotate with the drum, but the cross section from 100 keV to 3 MeV was obtained by Fullwood et al. [33] from plate camera recordings of both the 55° and 90° signals. These data are on file at the four centers. A different sample, containing 178 μg of $^{243}$Cm and 22 μg of $^{244}$Cm, was fielded on Physics 8. The data obtained have been reduced by M. G. Silbert. The preliminary 90° cross section is shown in Fig. 5. The data will soon be sent to the NNCSC for distribution. A multilevel fit from 15 to 100 eV is in progress.

### 3.18. $^{244}$Cm

The fission cross section was measured at 55° and 90° to the beam by Fullwood et al. [34] with a sample containing 204 μg of $^{244}$Cm, on Physics 6. The data obtained are on file at the four centers. The fission cross section from 20 eV to 3 MeV and the radiative capture cross section from 20 eV to 10 keV were measured on Physics 8. The fission sample contained 82 μg of material; the radiative capture sample was pressed curium oxide in an aluminum matrix, and contained 0.54 g/cm$^2$ of $^{244}$Cm. We excluded the 55° signal from the fission data reported above threshold because of organic content in the sample. These data are also on file at the four centers. Table II contains average parameters from an analysis of the data reported by Moore and Keyworth [35].

### 3.19. $^{245}$Cm

The fission cross section was determined from 20 eV to 3 MeV on Physics 8. The sample contained 34 μg of $^{245}$Cm; data were taken at 55° and 90° to the beam. Average parameters from an analysis of the data by Moore and Keyworth [35] are listed in Table II. The data are on file at the four centers.

### 3.20. $^{246}$Cm

The fission cross section from 20 eV to 3 MeV, and the radiative capture cross section for the first few resonances were determined on Physics 8. The fission sample contained 16 μg of $^{246}$Cm; the 55° signal was excluded above 0.1 MeV because of organic content in the sample. The capture sample contained 106 mg/cm$^2$ of $^{246}$Cm. Average parameters from an analysis by Moore and Keyworth [35] are listed in Table II. The data are on file at the four centers.

### 3.21. $^{247}$Cm

The measurement of the fission cross section was carried out at 55° and 90° on Physics 8 with a sample which contained 21 μg of $^{247}$Cm, and which required significant corrections for each of the other Cm isotopes: it contained 50 μg of $^{244}$Cm, 0.6 μg of $^{245}$Cm, 26 μg of $^{246}$Cm, and 2 μg of $^{248}$Cm. The average parameters, from the multilevel analysis of Moore and Keyworth [35], are given in Table II. Subsequent to the reporting of the data, which are on file at the four centers, the sample was reanalyzed, mass spectroscopically by J. E. Rein and R. Abernathy, and by gamma spectroscopy by G. M. Matlack. We determined that the sample also contained ~23 μg of $^{243}$Am, implying that the apparent large rise in the fission cross section near 1 MeV is completely spurious and should be ignored.

### 3.22. $^{248}$Cm

The 77 μg sample used for the fission cross section measurement on Physics 8 was prepared from material obtained in the decay of $^{252}$Cf, but it also contained significant amounts of the other even Cm isotopes and $^{245}$Cm, for which corrections were made. Fission data at 55° and 90° to the beam are included. Radiative capture cross sections were also determined for the lowest three resonances; the mixed Cm sample used was reported to contain 6 mg/cm$^2$ of $^{248}$Cm. The average parameters are given in Table II, based on the analysis reported by Moore and Keyworth [35] for these three resonances. The data obtained are on file at the four centers.

### 3.23. $^{249}$Bk

The sample used on Physics 8 for the fission cross section was freshly prepared, but still contained enough $^{249}$Cf that data only above the fission threshold are significant. Preliminary results have been obtained by M. G. Silbert, but the final data reduction has not yet been done. Apparent inconsistencies in the 55° and 90° signals suggest that the 55° signal should be excluded.

### 3.24. $^{249}$Cf

Fission cross section measurements with a 101 μg sample at 55° and 90° to the neutron beam from Physics 8 were reported by Silbert [36], and the data have been submitted to NNCSC for distribution. Average parameters from the multilevel analysis of Silbert are listed in Table II.

### 3.25. $^{252}$Cf

The sample fielded on Physics 8 contained 60 μg of $^{252}$Cf such that the fission fragment background in the detector amounted to $10^6$/sec. This sample (and the Cm radiative capture sample) were located at the top of the tower, and the collimator just below these samples was badly misaligned. Neither sample was completely in the beam, and in order to determine the $^{252}$Cf cross section, the data were normalized using the strong fission resonance at 76 eV in $^{248}$Cm measured on the same event. Average parameters, determined from the area analysis of the fission resonance carried out by Moore et al. [37], are listed in Table II. The data are on file at the four centers.

### 3.26. $^{253}$Es

The sample fielded by M. G. Silbert on Physics 8 for the determination of the fission cross section contained 3.3 μg of material. Contamination from decay products is so large that useful data can probably be obtained only above the threshold. These data have not yet been reduced.

## 4. POSSIBLE CORRECTIONS AND UNCERTAINTIES

In all the above measurements, the data reported are measured relative to the fission cross section of $^{235}$U at energies above 100 keV. For Physics

6-8, the reference $^{235}U$ cross section used was the evaluation of Davey [13]. For Physics 5, we used a reference cross section given in LA-3586, which differs significantly from the Davey evaluation only in the region from 500 to 700 keV, where it is ~5% higher.

For Physics 8, we used the $^{6}Li(n,\alpha)$ cross section as a standard below 100 keV. This normalization is dependent upon the angular distribution of the reaction products, which we assumed to be isotropic, but which has recently been shown by Schröder et al. [38] to be quite strongly angular dependent at neutron energies as low as 25 keV. However, because our signal consists of both reaction products (tritons and alphas) at a given angle, and because the final flux is determined by averaging both 90° and 55° signals at energies below 100 keV, the net effect of the strong angular distribution is fairly small. Calculations based on the angular distribution coefficients in the evaluation by Hale [39] for ENDF/B show that the error we made by assuming isotropy reaches its maximum of 3.1% at 100 keV. We could also renormalize the data above 100 keV to the $^{235}U$ fission cross section of ENDF/B-IV. The resulting energy-dependent renormalization for Physics-8 data is shown in Fig. 6; it is consistent with the uncertainty of ± 3% assigned to the reference cross section. There seems to be little purpose in carrying out the renormalization exercise, however, because the changes are negligible compared to the uncertainties in the Physics-8 data from other sources.

The uncertainties associated with nuclear data obtained with nuclear explosions depend on a number of factors. The assigned uncertainties are standard deviations, and in the data reduction are divided into two categories. Correlated errors are uncertainties which are common to all signals from a given sample; they include target thickness, average energy deposition, and flux normalization. Uncorrelated errors are uncertainties which are different for each signal; they include statistical and film-reading uncertainties and calibration uncertainties (some of these may be correlated in redundant recordings of the same signal). In averaging different recordings to obtain a final set of results on a given isotope, the correlated error is removed before averaging, then recombined with the statistical and other uncorrelated error of the average. Typical total uncertainties assigned to fission cross sections of fissile nuclei (with relatively high fission cross sections at all energies) are listed in Table III. One notes that accuracies of ~10 to 30% can generally be expected over the whole energy region, and that the uncertainties are at least to some extent due to statistics; they are higher for smaller samples and in energy regions where the neutron flux is lower. The uncertainty can, of course, be considerably reduced by fielding multiple samples and recording more signals, as was done for example, in the measurement of the fission cross section of $^{235}U$ reported by Lemley et al. [40].

## 5. RECOMMENDATIONS FOR FUTURE WORK

With a few exceptions, the transactinium isotopes for which nuclear data are required for waste management, plutonium recycle, the thorium breeding cycle, isotopic heat sources, or californium production are also those which can be produced by neutron irradiation in sufficient quantities to permit the measurements. A review paper by Raman [41] discusses the problems associated with production of such samples. One exception is $^{236}Pu$, which was recognized nearly ten years ago by Snyder [42] as being a potentially troublesome isotope in fast-reactor-produced plutonium.

Before assigning priorities for future work, we should summarize the requirements for making nuclear data measurements by the nuclear explosion technique. The shortest half-life isotope for which successful data were obtained was 6.7 day $^{237}U$. The lower limit for samples which might be considered is perhaps 1 day. For fission cross section measurements, the samples should contain 10-100 μg of material, although we have shown that useful data can be obtained with 1 μg. Moxon-Rae detector signals per capture event are ~3 x $10^{-5}$ as large as signals per fission event in a fission detector. This implies that useful radiative capture cross sections can be obtained with 30 mg of material; however, one would prefer 0.3 to 3 g. We have not been successful in obtaining total cross section data comparable to those which can be measured by the usual laboratory techniques, but if thick capture samples are fielded, transmission data are required for multiple scattering and self-absorption corrections. Table III shows that accuracies of 10-30%, depending on sample size, are to be expected, and the energy range covered is ~20 eV to several MeV. (This could be extended to lower energies if necessary, at some sacrifice in intensity, by relocating and redesigning the moderator.) Analysis of the data indicates that for fissile targets, a fission cross section measurement is probably sufficient. For non-fissile targets, the radiative capture cross section is required as well. Finally, our experience on Physics 8 suggests that a practical upper limit to the number of signals to be recorded is about 100.

One of the primary considerations in arriving at a set of recommended measurements for future work is sample availability. We show in Table IV estimates of production rates for the transactinium isotopes which might be candidates for such measurements. The estimates in Table IV were based on four kinds of production mechanism: Radioactive decay, high flux thermal reactor irradiation (HFIR), 800 MeV proton irradiation at LAMPF, and isotope production using a nuclear explosion. Esimates of the production rates at LAMPF use the 330 μb cross section for production of $^{236}$Pu measured by C. J. Orth et al. [43] at 600 MeV. Estimates for sample production by a nuclear explosion are based on results from the Par, Barbel, and Hutch events as reported by Bell [44] and by Hoff and Hulet [45] and involve the chemical processing of a large quantity (~1 metric ton) of radioactive debris.

In Table IV, we also attempt to estimate the status of existing data and to assign a priority for future work based both on known requirements, and on the existence of adequate available data. From Table IV, we arrive at the following list of measurements which should be considered:

1. Fission cross sections of $^{250}$Cf, $^{251}$Cf, $^{252}$Cf, and $^{253}$Cf. The cross section of highest priority is $^{251}$Cf, produced by reactor irradiation of $^{250}$Cf. Both $^{250}$Cf and $^{252}$Cf will be present in the samples and in order to make corrections for isotopic contamination, they should be measured on the same event. The $^{253}$Cf measurement has much lower priority, but might be included to complete the set.

2. Radiative capture cross sections of $^{250}$Cf and $^{252}$Cf.

3. Radiative capture cross sections of $^{246}$Cm and $^{244}$Cm. Although little improvement is to be expected for $^{244}$Cm, the low isotopic purity of the $^{246}$Cm sample material available requires a complementary $^{244}$Cm sample to be fielded.

4. Radiative capture cross sections of $^{233}$Pa and $^{233}$U. As above, the $^{233}$U data are required to permit corrections due to sample decay prior to the event. The effort and expense of preparing the $^{233}$Pa capture sample suggests that a remeasurement of the fission cross section be included on the same event, which also requires a $^{233}$U fission sample.

5. Radiative capture and fission cross sections of $^{232}$U and $^{228}$Th. The necessity of chemical purification of the $^{232}$U prior to the event suggests that the capture and fission cross sections of $^{228}$Th should be determined at the same time.

6. Radiative capture and fission cross sections of $^{242}$Cm and $^{238}$Pu. While no improvement in the data for $^{238}$Pu is expected, samples must be fielded to correct for decay of the $^{242}$Cm.

7. Fission cross section of $^{236}$Pu. This is the only LAMPF-produced sample of applied interest, but the effort of producing it suggests that samples of $^{235}$Np, $^{236m}$Np, and $^{237}$Np should also be fielded at the same time.

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## REFERENCES


[1] DIVEN, B.C., "Neutron experiments with underground nuclear explosions," Nuclear Structure Study with Neutrons, (NEVE DE MEVERGNIES, M., VAN ASSCHE, P., VERVIER, J., Eds.) North Holland Amsterdam (1966) 441.

[2] HEMMENDINGER, A., "Cross-section measurements made with neutrons from a nuclear detonation," Physics Today 18 8 (1965) 17.

[3] HEMMENDINGER, A., "New time-of-flight measurements made with an intense source," in Nuclear Data for Reactors II, IAEA, Vienna (1967) 219.

[4] DIVEN, B.C., "Nuclear explosions as a nuclear physics tool," Ann. Rev. Nuc. Sci. 20, (1970) 79.

[5] DIVEN, B.C., "Measurements of neutron cross sections with nuclear explosives," in Peaceful Nuclear Explosions III IAEA, Vienna (1974) 463.

[6] HEMMENDINGER, A., DIVEN B.C., BROWN, W.K., ELLIS, A., FURNISH A. SHUNK, E.R., FULLWOOD, R.R., USAEC Rep. LA-3478, Part I (1968).

[7] SEEGER, P.A., BERGEN, D.W., USAEC Rep. LA-3478, Part II (1967).

[8] BROWN, W.K., SEEGER, P.A., SILBERT, M.G., USAEC Rep. LA-4095 (1970).

[9] ELLIS, A.N., BROWN, W.K., FARRELL, J.A., FULLWOOD R.R., A method of calibration of Moxon-Rae detectors, IEEE Trans. Nuc. Sci. NS-18 (1971) 205; see also USAEC Rep. LA-4445 (1970).

[10] BROWN, W.K., FURNISH, A.P., "A high resolution recording system for neutron cross section measurements using an underground nuclear explosive source," IEEE Trans. Nuc. Sci. NS-16 (1969) 411; see also ARLOWE, H.D., FURNISH, A.P., USAEC Rep. LA-4277 (1969).

[11] AUCHAMPAUGH, G.F., "The role computers play in LASL's neutron cross-section program using neutrons from an underground nuclear explosion," USAEC Rep. LA-DC-11806 (1970) unpublished.

[12] MUIR, D.W., VEESER, L.R., "Neutron-induced fission cross sections of $^{230}$Th and $^{231}$Pa," Neutron Cross Sections and Technology, USAEC Rep. CONF-71031 (1971) 292.

[13] DAVEY, W.G., Nuc. Sci. Eng. 32 (1968) 35.

[14] JAMES, G.D., LYNN, J.E., EARWAKER, L.G., Nuc. Phys. A189 (1972) 225.

[15] DUBROVINA, S.M., SHIGIN, V.A., Dok. Akad. Nauk SSSR 157 (1964) 561.

[16] FARRELL, J.A., as reported by SEEGER, P.A., USAEC Rep. LA-4420 (1970) 3.

[17] AUCHAMPAUGH, G.F., BOWMAN, C.D., EVANS, J.E., Nuc. Phys. A112 (1968) 329.

[18] JAMES, G.D., Nuc. Phys. 55 (1964) 517.

[19] CRAMER, J.D., BERGEN, D.W., as reported by SEEGER, P.A., USAEC Rep. LA-4420 (1970) 74.

[20] McNALLY, J.H., BARNES, J.W., DROPESKY, B.J., SEEGER, P.A., WOLFSBERG, K., Phys. Rev. C 9 (1974) 717; see also USAEC Rep. LA-4420 (1970) 91.

[21] BROWN, W.K., DRAKE, D.M., DIXON, D.R., Nuc. Phys. A156 (1970) 609.

[22] JIACOLETTI, R.J., BROWN, W.K., OLSON, H.G., Nuc. Sci. Eng. 48 (1972) 412; see also JIACOLETTI, R.J., BROWN, W.K., USAEC Rep. LA-4763-MS (1971).

[23] SILBERT, M.G., MOAT, A., YOUNG, T.E., Nuc. Sci. Eng. 52 (1973) 176; see also SILBERT, M.G., USAEC Rep. LA-4108-MS (1969).

[24] SILBERT, M.G., BERRETH, J.R., Nuc. Sci. Eng. 52 (1973) 187; see also SILBERT, M.G., USAEC Rep. LA-5024-MS (1972).

[25] DRAKE, D.M., BOWMAN, C.D., COOPS, M.S., HOFF, R.W., as reported by SEEGER, P.A., USAEC Rep. LA-4420 (1970) 101.

[26] BYERS, D.H., DIVEN, B.C., SILBERT, M.G., "Capture and fission cross section of $^{240}$Pu," Neutron Cross-Section Technology, USAEC Rep. CONF-660303 (1966) 903; see also USAEC Rep. LA-3586 (1966) 59, 173.

[27] SIMPSON, O.D., FLUHARTY, R.G., MOORE, M.S., MARSHALL, N.H., DIVEN, B.C., HEMMENDINGER, A., "The fission cross section of $^{241}$Pu from 20-200 eV as determined from a nuclear explosion," Neutron Cross-Section Technology, USAEC Rep. CONF-660303 (1966) 910; see also USAEC Rep. LA-3586 (1966) 72, 188.
[28] BERGEN, D.W., FULLWOOD, R.R., Nuc. Phys. A163 (1971) 577; see also USAEC Rep. LA-4420 (1970) 123.
[29] AUCHAMPAUGH, G.F., FARRELL, J.A., BERGEN, D.W., Nuc. Phys. A171 (1971) 31.
[30] SEEGER, P.A., HEMMENDINGER, A., DIVEN, B.C., Nuc. Phys. A96 (1967) 605; see also USAEC Rep. LA-3586 (1966) 86, 204.
[31] FORMAN, L., SILBERT, M.G., SCHELBERG, A.D., Nuc. Inst. Methods, to be published (1975).
[32] SEEGER, P.A., USAEC Rep. LA-4420 (1970) 138.
[33] FULLWOOD, R.R., DIXON, D.R., LOUGHEED, R.W., as reported by SEEGER, P.A., USAEC Rep. LA-4420 (1970) 157.
[34] FULLWOOD, R.R., McNALLY, J.H., SHUNK, E.R., "Neutron-induced fission cross-section measurements in $^{244}$Cm," Neutron Cross Sections and Technology, NBS Spec. Pub. 299, Vol 1 (1968) 567.
[35] MOORE, M.S., KEYWORTH, G.A., Phys. Rev. C3 (1971) 1656; see also BAYBARZ, R.D. et al., USAEC Rep. LA-4566 (1971).
[36] SILBERT, M.G., Nuc. Sci. Eng. 51 (1973) 376; see also SILBERT, M.G., LOUGHEED, R.W., EVANS, J.E., HOFF, R.W., USAEC Rep. LA-5042-MS (1972).
[37] MOORE, M.S., McNALLY, J.H., BAYBARZ, R.D., Phys. Rev. C4 (1971) 273.
[38] SCHRÖDER, I.G., McGARRY, E.D., DE LEEUW, S., DE LEEUW-GIERTS, G., "Angular anisotropy in the $^{6}$Li(n,$\alpha$)$^{3}$H reaction at 25 keV," Nuclear Cross Sections and Technology, to be published (1975).
[39] HALE, G.M., "R-matrix analysis of the light element standards," Nuclear Cross Sections and Technology, to be published (1975).
[40] LEMLEY, J.R., KEYWORTH, G.A., DIVEN, B.C., Nuc. Sci. Eng. 43 (1971) 281.
[41] RAMAN, S., "U.S. programmes in the waste management (incineration) of actinides," Proceedings of the Advisory Group Meeting on Transactinium Isotope Nuclear Data (TND), IAEA (1975).
[42] SNYDER, T.M., "Future cross section needs of the nuclear power industry," Neutron Cross-Section Technology, USAEC Rep. CONF-660303 (1966) 1025.
[43] ORTH, C.J., SCHILLACI, M.E., OBRIEN, H.A., JR., private communication (1975).
[44] BELL, G.I., Phys. Rev. 139 (1965) B1207.
[45] HOFF, R.W., HULET, E.K., "Recovery and study of heavy nuclides produced in a nuclear explosion: the Hutch event," Symposium on Engineering with Nuclear Explosives, USAEC Rep. CONF-700101 (1971) Vol 2, 1283.

Table I. Typical Timing and Control Sequence

| | |
|---|---|
| - 10 min | Start drum cameras.<br>Open solenoid valve to drum camera vacuum pump.<br>Turn on "bias on" relay. |
| - 15 sec | Run out radioactive samples (e.g., $^{232}U$). |
| - 2 sec | Unlock camera controllers.<br>Activate "bias off" relay.<br>Release "bias on" relay.<br>Activate coaxial relays to enable time marks. |
| - 1 sec | Trigger digital delays to start countdown.<br>Open camera and detector shutters.<br>Start streak cameras.<br>Intensify streak and timing oscilloscopes.<br>Turn on streak pinlights for reference trace. |
| - 50 msec | Intensify drum oscilloscopes for one revolution of prebase record and time marks.<br>Trigger plate camera for prebase and time mark recording. |
| - 10 msec | Turn on drum pinlights. |
| 0 | Intensify drum cameras to collect data for 0.93 revolution.<br>Trigger plate cameras. |
| ~ + 20 msec | Intensify drum cameras for calibration signal recording in other 0.07 revolution. (Exact timing is done by counting pulses from drum speed sensors for each drum camera.) |
| + 24 msec | Close drum camera shutters, and repeat calibrate every ~5 msec for multiple recording on streak cameras. |
| + 60 msec | Stop calibrator pulser. |
| + 1 sec | Reset all timing signals. |
| + 10 sec | Drop instrument power. |

Table II. Average parameters of transactinium isotopes deduced from nuclear explosion measurements. In this table, $d_{obs.}$ is the observed spacing (both spin states included), $d_{corr.}$ is the spacing corrected for missed levels, (2J+1)*D is the corrected spacing per spin state multiplied by (2J+1), $\langle \Gamma_n^o \rangle$ is the reduced neutron width corrected for missed levels, $S_o$ is the neutron strength function $\langle \Gamma n^o \rangle /D$, $\langle \Gamma_f \rangle$ is the average fission width, $\langle \Gamma_\gamma \rangle$ is the average radiative capture width, and the last column gives the energy range over which the analysis of average parameters was carried out. Values in parentheses are assumed.

| Isotope | $d_{obs.}$ (eV) | $d_{corr.}$ (eV) | (2J+1)*D (eV) | $\langle \Gamma n^o \rangle$ (MeV) | $S_o$ $(10^{-4})$ | $\langle \Gamma_f \rangle$ (MeV) | $\langle \Gamma_\gamma \rangle$ (MeV) | Energy Range (eV) |
|---|---|---|---|---|---|---|---|---|
| $^{232}U$ | 5.0 | 4.2 | 8.4 | .40 | 0.95 | 345 | (40) | 65-165 |
| $^{237}U$ | 4.5 | 3.8 | 15.1 | - | (1.0) | ~70 | (37) | 43-120 |
| $^{238}Pu$ | - | 9.5 | 19.0 | 1.21 | 1.27 | 17[a] | (34) | 18-500 |
| $^{241}Pu$ | - | 0.98 | 11.8 | 0.20 | 0.99 | 314 | (40) | 20-64 |
| $^{244}Cm$ | 13.7 | 11.4 | 22.8 | 1.37 | 1.20 | 1.4 | (37) | 20-500 |
| $^{245}Cm$ | 1.54[b] | 1.18 | 18.9 | 0.34 | 1.42 | 600 | (40) | 20-60 |
| $^{246}Cm$ | 38 | 29 | 58 | 1.8 | 0.6 | 0.5 | (37) | 20-400 |
| $^{247}Cm$ | 1.38[b] | 1.06 | 21.2 | 0.17 | 0.80 | 140 | (40) | 20-60 |
| $^{248}Cm$ | 28 | 22 | 44 | - | - | 1.3 | (37) | 20-200 |
| $^{249}Cf$ | - | 1.07 | 21.4 | 0.31 | 1.45 | 180 | (40) | 15-70 |
| $^{252}Cf$ | 27 | 21 | 42 | - | (1.0) | ~60 | (37) | 20-500 |

a Consists of 30 levels with $\Gamma_f$ =5.3 MeV and 18 levels with $\Gamma_f$ =36 MeV as reported in ref. [24].

b Erroneously reported in ref [35]; the error propagates to the value of So as well.

Table III. Typical estimated relative uncertainties in the fission cross sections ($\Delta\sigma_f/\sigma_f$) as a function of neutron energy for six fissile nuclides which have been measured by the nuclear explosion technique.

| E | $^{237}U$ (18 μg) | $^{241}Pu$ (6.5 mg) | $^{242m}Am$ (88 μg) | $^{245}Cm$ (34 μg) | $^{247}Cm$ (21 μg) | $^{249}Cf$ (101 μg) |
|---|---|---|---|---|---|---|
| 20 eV | — | .20 | .16 | .20 | — | .22 |
| 50 | .72 | .12 | .11 | .07 | .07 | .14 |
| 100 | .20 | .10 | .12 | .10 | .14 | .10 |
| 200 | .24 | .12 | .16 | .17 | .18 | .09 |
| 500 | .40 | .13 | .34 | .11 | .20 | .23 |
| 1 keV | .41 | .14 | .36 | .15 | .20 | .18 |
| 2 | — | .14 | .24 | .27 | .32 | .16 |
| 5 | — | .15 | .27 | .33 | .20 | .18 |
| 10 | — | .16 | .20 | .24 | .30 | .17 |
| 20 | — | .18 | .28 | .35 | .20 | .14 |
| 50 | — | .13 | .18 | .22 | .18 | .11 |
| 100 | .27 | .14 | .14 | .21 | .15 | .10 |
| 200 | .13 | — | .15 | .13 | .12 | .09 |
| 500 | .11 | .14 | .11 | .08 | .14 | .09 |
| 1 MeV | .12 | .14 | .40 | .10 | .33 | .10 |
| 2 | .09 | — | — | .10 | — | .09 |

Table IV. Estimates of sample availability, status, and priority for transactinium isotopes.*

| Isotope | Availability | Status | Priority |
|---|---|---|---|
| 18.7 d $^{227}Th$ | $^{227}Ac \rightarrow$ 2.3 μg/mg. | U | 3 |
| 1.9 y $^{228}Th$ | $^{232}U \rightarrow$ 26 μg/mg. | D | 2 |
| 7340 y $^{229}Th$ | $^{233}U \rightarrow$ 6.2 μg/g-y. | C | 3 |
| 8 x $10^4$ y $^{230}Th$ | Available in g quantities > 90%. | C | 3 |
| 25.5 h $^{231}Th$ | HFIR $\rightarrow$ 23 μg/mg $^{230}Th$. | U | 3 |
| 24.1 d $^{234}Th$ | HFIR $\rightarrow$ 0.5 μg/mg $^{232}Th$. | U | 3 |
| 26 h $^{228}Pa$ | LAMPF $\rightarrow$ 0.3 μg/g $^{232}Th$. | U | 3 |
| 1.4 d $^{229}Pa$ | LAMPF $\rightarrow$ 0.5 μg/g $^{232}Th$. | U | 3 |
| 17.4 d $^{230}Pa$ | LAMPF $\rightarrow$ 5 μg/g $^{232}Th$. | U | 3 |
| 3 x $10^4$ y $^{231}Pa$ | Available in 10 g quantities. | B | 3 |
| 1.3 d $^{232}Pa$ | HFIR $\rightarrow$ 60 μg/mg $^{231}Pa$. | U | 2 |
| 27 d $^{233}Pa$ | HFIR $\rightarrow$ 30 μg/mg $^{232}Th$. | C | 1 |
| 20.8 d $^{230}U$ | LAMPF $\rightarrow$ 4 μg/g $^{231}Pa$. | U | 3 |
| 4.2 d $^{231}U$ | LAMPF $\rightarrow$ 0.6 μg/g $^{231}Pa$. | U | 3 |
| 72 y $^{232}U$ | Available, 100 mg quantities. | C | 2 |
| 2.4 x $10^5$ y $^{234}U$ | Available, g quantities > 99%. | A | |
| 2.3 x $10^7$ y $^{236}U$ | Available, g quantities > 89%. | A | |
| 6.7 d $^{237}U$ | HFIR $\rightarrow$ 8 μg/mg $^{236}U$. | C | 2 |
| 4.4 d $^{234}Np$ | LAMPF $\rightarrow$ 1 μg/g $^{238}U$. | U | 3 |
| 400 d $^{235}Np$ | LAMPF $\rightarrow$ 40 μg/g $^{238}U$. | U | 3 |
| 22 h $^{236}Np$ | LAMPF $\rightarrow$ 0.2 μg/g $^{238}U$. | U | 3 |
| $10^6$ y $^{236m}Np$ | LAMPF $\rightarrow$ 30 μg/g $^{238}U$. | U | 3 |
| 2 x $10^6$ y $^{237}Np$ | Available in 100 g quantities. | | |
| 2.1 d $^{238}Np$ | HFIR $\rightarrow$ 50 μg/mg $^{237}Np$. | U | 2 |
| 2.4 d $^{239}Np$ | HFIR $\rightarrow$ 3 μg/mg $^{238}U$. | U | 2 |

Table IV. (continued)

| Isotope | Availability | Status | Priority |
|---|---|---|---|
| 2.8 y $^{236}Pu$ | LAMPF → 30 μg/g $^{238}U$. | U | 2 |
| 46 d $^{237}Pu$ | LAMPF → 12 μg/g $^{238}U$. | U | 3 |
| 87 y $^{238}Pu$ | Available in g quantities > 97%. | A | |
| 6540 y $^{240}Pu$ | Available in 10 g quantities > 98%. | A | |
| 13.2 y $^{241}Pu$ | Available in 10 g quantities > 93%. | A | |
| $3.9 \times 10^5$ y $^{242}Pu$ | Available in g quantities > 99%. | A | |
| $8 \times 10^7$ y $^{244}Pu$ | Available in 100 mg quantities > 98%. | C | 2 |
| 10.9 d $^{246}Pu$ | HFIR → 0.2 μg/mg $^{244}Pu$. | U | 3 |
| 51 h $^{240}Am$ | LAMPF → 0.6 μg/g $^{242}Pu$. | U | 3 |
| 433 y $^{241}Am$ | Available in 100 g quantities > 98%. | A | |
| 152 y $^{242m}Am$ | HFIR → 10 μg/mg $^{241}Am$. | B | 2 |
| 7400 y $^{243}Am$ | Available in 100 g quantities. | A | |
| 27 d $^{240}Cm$ | LAMPF → 5 μg/g $^{243}Am$. | U | 3 |
| 35 d $^{241}Cm$ | LAMPF → 6 μg/g $^{243}Am$. | U | 3 |
| 163 d $^{242}Cm$ | HFIR → 70 μg/mg $^{241}Am$. | U | 2 |
| 32 y $^{243}Cm$ | Available in 10 mg quantities, 55%. | B | 2 |
| 18 y $^{244}Cm$ | Available in 100 g quantities, 95%. | A | |
| 8500 y $^{245}Cm$ | Available in 10 μg quantities > 70%. | A | |
| 4700 y $^{246}Cm$ | Available in g quantities > 60%. | C | 1 |
| $1.6 \times 10^7$ y $^{247}Cm$ | Available in 10 μg quantities > 20%. | C | 1 |
| $4 \times 10^5$ y $^{248}Cm$ | Available in 10 mg quantities > 97%. | A | |
| $1.7 \times 10^4$ y $^{250}Cm$ | Heavy element shot → 10 μg/ton of debris or HFIR → 1 μg/g of $^{248}Cm$. | U | 3 |
| 5 d $^{245}Bk$ | LAMPF → 1 μg/g of $^{248}Cm$. | U | 3 |
| 1.8 d $^{246}Bk$ | LAMPF → 0.4 μg/g of $^{248}Cm$. | U | 3 |
| 1400 y $^{247}Bk$ | LAMPF → 4 μg/g of $^{248}Cm$. | U | 3 |
| > 9 y $^{248}Bk$ | LAMPF → 2 μg/g of $^{248}Cm$. | U | 3 |
| 314 d $^{249}Bk$ | Available in 10 mg quantities. | A | |

Table IV. (continued)

| Isotope | Availability | Status | Priority |
|---|---|---|---|
| 36 h $^{246}Cf$ | LAMPF → 0.2 μg/g $^{249}Bk$. | U | 3 |
| 350 d $^{248}Cf$ | LAMPF → 10 μg/g $^{249}Bk$. | U | 3 |
| 360 y $^{249}Cf$ | Available in 10 mg quantities. | B | 2 |
| 13 y $^{250}Cf$ | HFIR → 200 μg/mg $^{249}Bk$. | U | 1 |
| 900 y $^{251}Cf$ | HFIR → 170 μg/mg $^{250}Cf$. | U | 1 |
| 2.6 y $^{252}Cf$ | Available in 10 mg quantities. | C | 1 |
| 17.6 d $^{253}Cf$ | HFIR → 12 μg/mg $^{252}Cf$. | U | 2 |
| 60 d $^{254}Cf$ | HFIR → 1 μg/mg $^{252}Cf$. | U | 2 |
| 33 h $^{251}Es$ | LAMPF → 0.2 ng/mg $^{252}Cf$. | U | 3 |
| 140 d $^{252}Es$ | LAMPF → 2 ng/mg $^{252}Cf$. | U | 3 |
| 20 d $^{253}Es$ | HFIR → 2 μg/mg $^{252}Cf$. | D | 2 |
| 276 d $^{254}Es$ | HFIR → 2 ng/μg $^{253}Es$. | U | 2 |
| 40 d $^{255}Es$ | HFIR → 0.2 ng/μg $^{253}Es$. | U | 2 |
| 23 h $^{252}Fm$ | LAMPF → 0.1 pg/μg $^{253}Es$. | U | 3 |
| 3 d $^{253}Fm$ | LAMPF → 0.1 pg/μg $^{253}Es$. | U | 3 |
| 20 h $^{255}Fm$ | HFIR → 5 pg/μg $^{253}Es$. | U | 2 |
| 80 d $^{257}Fm$ | Heavy element shot → 5 x $10^{11}$ atoms/ton of debris. | U | 2 |
| 55 d $^{258}Md$ | None by techniques considered. | U | 2 |

*HFIR calculations assumed a maximum flux of 5 x $10^{15}$ n/cm$^2$-sec;

LAMPF calculations assumed production by (p,xn) reactions at 1 mA average current for short lived samples (a few days) and 0.67 mA average for longer-lived samples.

Status symbols are defined as follows:

A - Probably known well enough to meet current needs.
B - Improved data probably needed, but it is doubtful that the nuclear explosion technique could contribute significantly.
C - A measurement or remeasurement by the nuclear explosion technique could significantly improve existing data.
D - Very little is known.
U - Unknown except for integral measurements.

Priority symbols are defined as follows:

1. Data improvements probably required for applied purposes.
2. Data of interest in applications.
3. Data of interest to nuclear systematics.

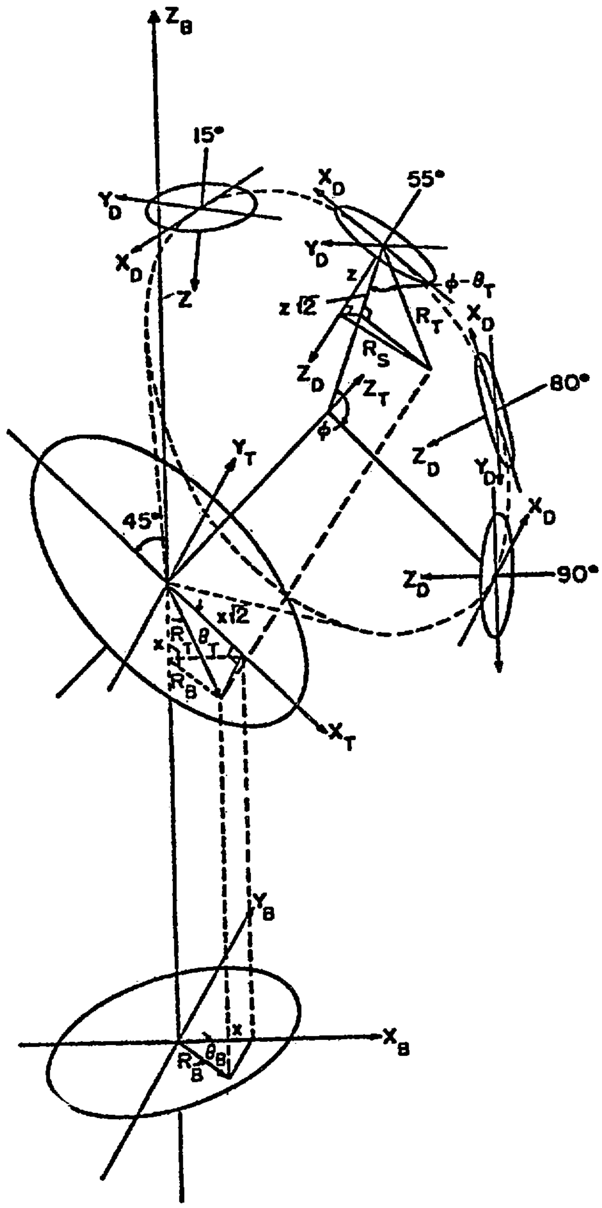


Fig. 1. Beam-target-detector geometry. Each detector axis in inclined at 45° to the target plane, forming a cone with axis $Z_T$ and apex angle 90°. The target plane is inclined at 45° to the beam axis $Z_B$.

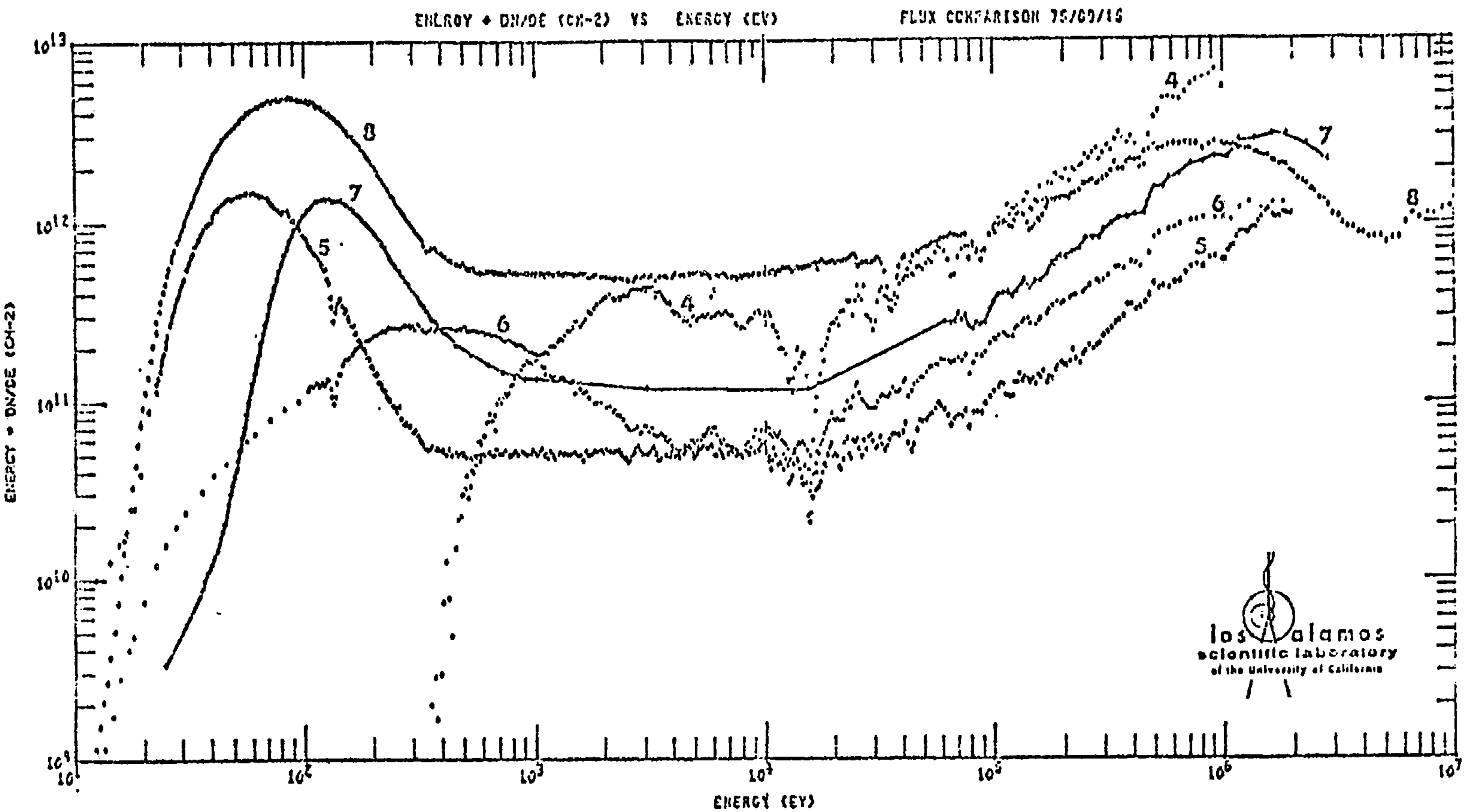


Fig. 2. Comparative neutron spectra observed from various physics events. The ordinate is given in units of neutrons/cm$^2$ per logarithmic energy interval. Physics 4 (Parrot) had no moderator other than the high explosive used to detonate the device; all the other physics shots show a thermal maxwellian near 100 eV. Flux recordings on Physics 7 (Pommard) are missing between ~10$^3$ and 10$^5$ eV because of calibrator interference; a few points were inserted by hand.

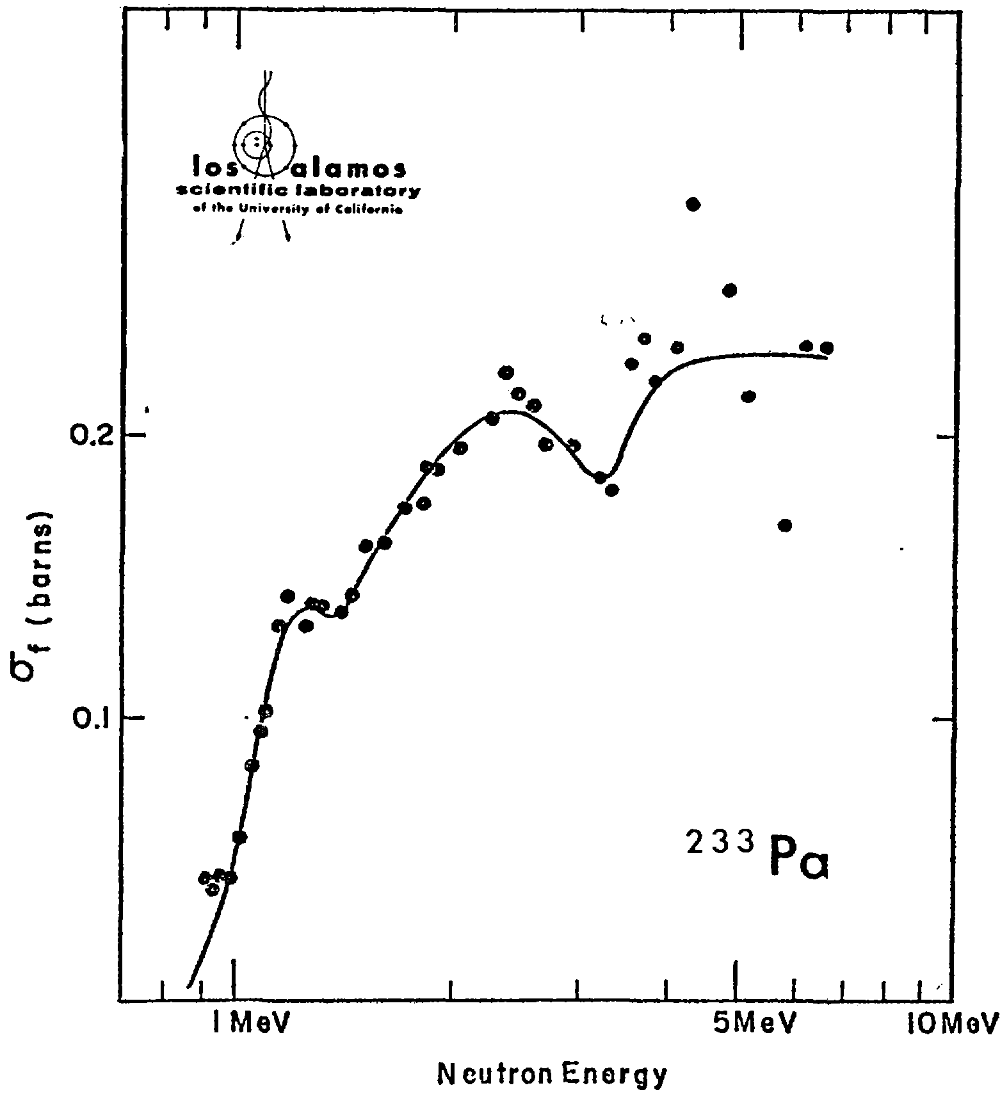


Fig. 3. The fission cross section of $^{233}Pa$, as measured by D. K. Oestreich et al. with a detector at 90° to the beam on Physics 7 (Pommard).

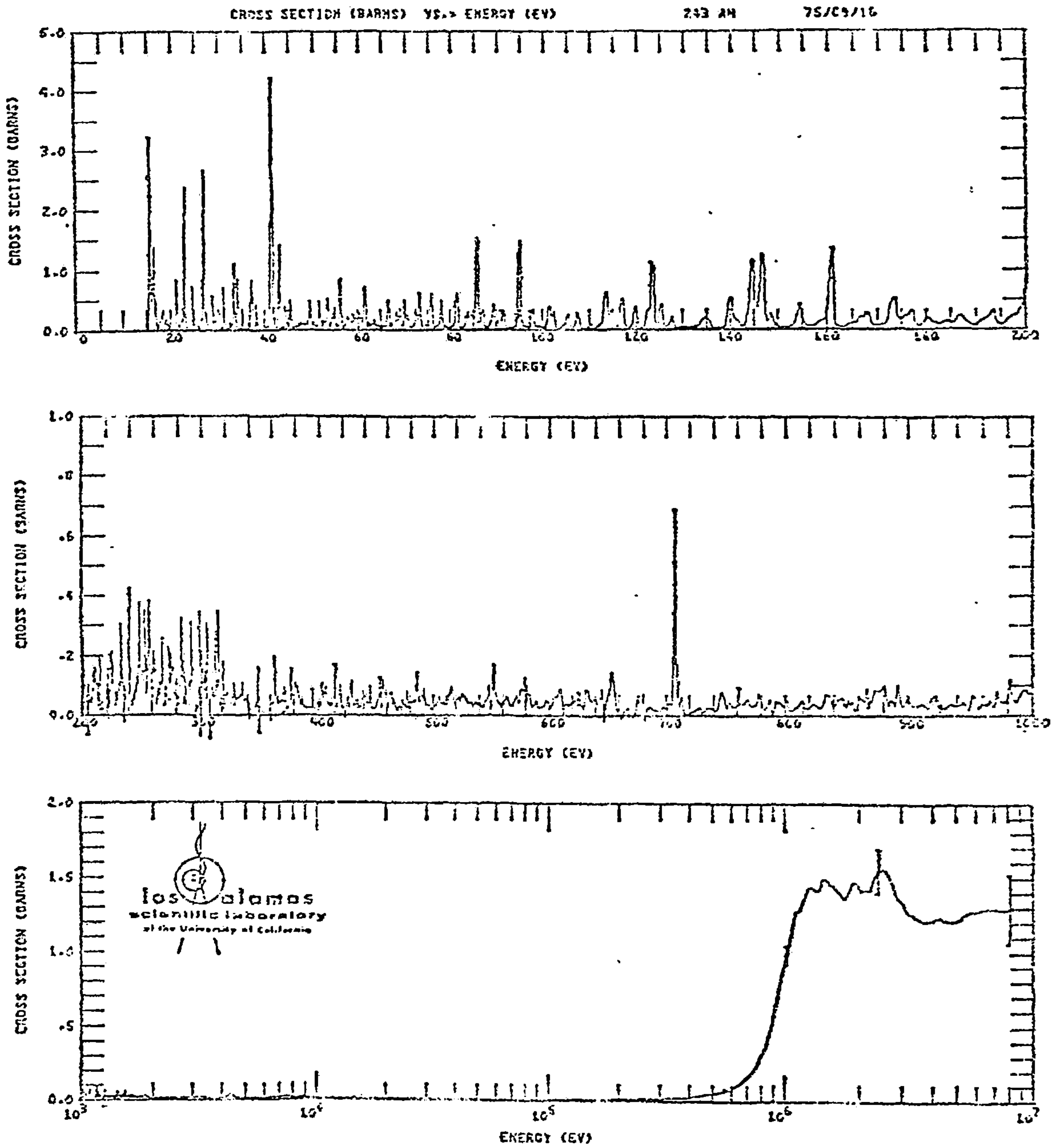

Fig. 4. The fission cross section of $^{243}Am$, as measured by P. A. Seeger on Physics 7 and Physics 8.

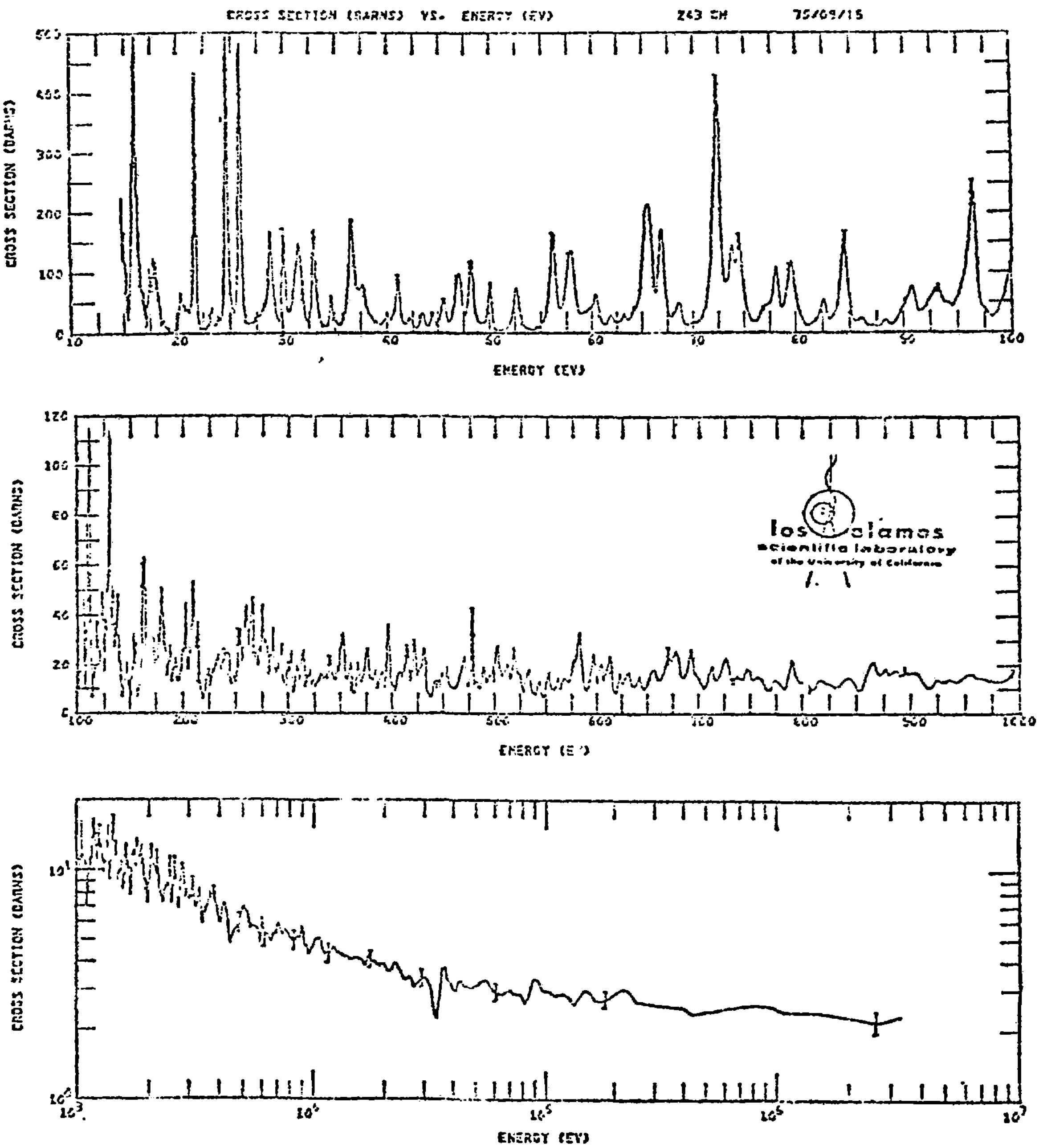


Fig. 5. The fission cross section of $^{243}$Cm, as measured by M. G. Silbert with a detector at 90° to the beam on Physics 8.

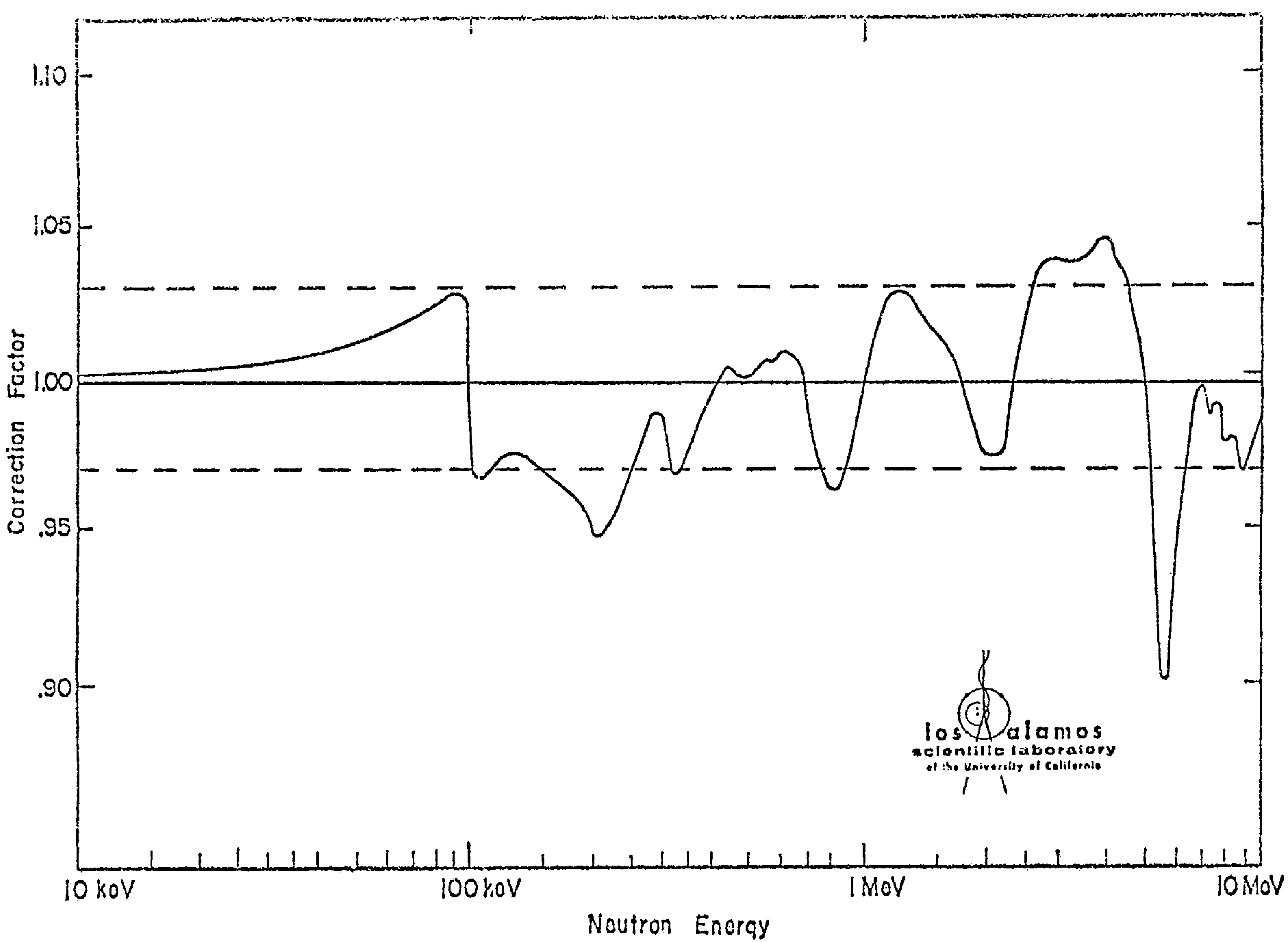


Fig. 6. Energy dependent correction factor which might be applied to Physics-8 data to accomplish a renormalization to ENDF/B-IV. Assumed uncertainty of ± 3% on the reference sets chosen are given by the dashed lines.