685

International Atomic Energy Agency

INDC(SEC)-45/U

INDC

INTERNATIONAL NUCLEAR DATA COMMITTEE

Reprint from

NEUTRON STANDARD REFERENCE DATA

Proceedings of a Panel, Vienna, 20-24 November 1972

VI. Summaries, Conclusions and Recommendations

January 1975

IAEA NUCLEAR DATA SECTION, KÄRNTNER RING 11, A-1010 VIENNA

SUMMARIES, CONCLUSIONS AND RECOMMENDATIONS

1. METHODS AND TECHNIQUES OF NEUTRON FLUX MEASUREMENTS

Neutron flux measurements are divided into two groups: those methods that may be called absolute because they do not depend on the knowledge of any cross-section and those that are relative in that the flux determination depends upon a known cross-section.

1.1. Absolute methods

The absolute methods can be subdivided into three groups: associated-particle, associated-activity, and total-absorption methods.

1.1.1. Associated-particle method

This method makes use of neutron-producing reactions in which the neutron is produced in conjunction with an associated charged particle of unique type and energy. In the frequently used reactions $D(d,n)^3He$, $T(p,n)^3He$ and $T(d,n)^4He$, the neutron production is associated with the production of a uniquely characterized ^3He, ^3He or ^4He charged particle, respectively. With these reactions, the associated-particle method can be used in either a 'tagged' mode, where the neutron and charged particle are detected in coincidence, or in an 'untagged' mode, where the neutron and charged-particle fluxes are measured independently.

The $T(p,n)^3He$ reaction has been extensively used recently at Cadarache and at the Central Bureau for Nuclear Measurements (CBNM), Geel, for absolute calibration of detectors for use in neutron cross-section measurements. The method is successful from 100 or 200 keV up to about 6 MeV. Much effort has been expended on the development of the method, and about 2% accuracy can be achieved in flux determinations. No single error dominates, and improvements must be along several lines. Among the limitations are charge exchange and scattering in the target at low incident particle energies, solid-angle determinations and backgrounds. Conceivably, 1.3% accuracy could be reached.

The $D(d,n)^3He$ reaction can be used with the same apparatus and similar accuracy as the $T(p,n)^3He$ reaction. Below about 100 keV deuteron energy, a simpler apparatus can be used successfully.

The $T(d,n)^4He$ reaction has been used with the associated-particle method for accurate flux determination at 14 MeV neutron energy, but no measurements were reported at this meeting. One or two per cent accuracy is possible.

1.1.2. Associated-activity method

In this method the residual radioactivity left in the neutron-producing target by the source reaction is used to determine the total neutron production in the target. It is capable of good accuracy, 1% or 2%, in determining neutron production but it is limited to a small number of suitable reactions

Generally, it is used for spot checks at a few energies and in cases in which a considerable neutron energy spread is acceptable. Examples are the reactions $^{7}Li(p,n)^{7}Be$ at threshold which produces 30-keV neutrons, $^{51}V(p,n)^{51}Cr$ which produces neutrons up to 600-700 keV, $^{65}Cu(p,n)^{65}Zn$ and $^{57}Fe(p,n)^{57}Co$. This method has been used recently in neutron standard determination by several groups for detector calibrations and cross-section measurements.

1.1.3. Total-absorption method

The total-absorption method depends upon absorption of essentially all neutrons incident upon a detector, and upon detection of those neutrons with an efficiency which is independent of neutron energy. While some detectors of this type, such as long counters, are often used only as relative flux monitors and are calibrated by other means, many total-absorption detectors are absolute flux monitors. Those in use at present include the manganese and vanadium baths and various detectors described as 'black' or 'gray' detectors.

An ancient example of the use of the total-absorption method as an absolute flux monitor is the manganese bath method in which incident neutrons are thermalized by scattering in the bath, captured by ^{55}Mn, and detected by the induced ^{56}Mn activity. In an alternative application, neutron sources which have been calibrated absolutely by the manganese bath technique are used to establish detector calibrations.

A recent version of the total-absorption method is the black detector of Poenitz in which a collimated neutron beam falls into a well in a large liquid or plastic scintillator where the neutron loses essentially all of its energy by scattering before it can escape. The proton and carbon recoil atoms produce a prompt scintillation for nearly 100% of the incident neutrons.

The best accuracy with a total-absorption technique has probably been achieved with the manganese bath method. However, it should be noted that while the experts claim 0.3% accuracy, cross-section measurements usually give other errors that are much larger. The various total-absorption detectors which respond promptly, such as the so-called black and gray detectors, often have 2% accuracy.

1.2. Relative methods

Many neutron flux determinations rely on well known cross-sections. Commonly used for reference are the light-element reactions $^{1}H(n,p)$, $^{6}Li(n,\alpha)T$, $^{10}B(n,\alpha)^{7}Li$ and $^{3}He(n,p)T$.

1.2.1. $^{1}H(n,p)$

Observation of recoil protons following neutron scattering from hydrogen is commonly used for measurement of fast neutron flux. At the low-energy end, counters filled with hydrogenous gas are used, and protons recoiling at all angles are detected. The lower-energy limit of a few keV is determined by the small amount of energy available for observation of the recoiling proton. Above 50 keV, 2% or 3% accuracy can be achieved if considerable care is used. A similar proton-recoil arrangement is often used with solid or liquid scintillation counters, but the non-linearity of pulse height with particle energy complicates their application. An accuracy of 4% to 10% is commonly

For neutron energies above 1-2 MeV the counter telescope is frequently used. In this system a small fraction of the recoil protons from a solid proton radiator of hydrogenous material is selected by means of an aperture located at some distance from the radiator and usually positioned to select protons near zero degrees to the neutron beam. A suitable detector behind the aperture counts with 100% efficiency those protons which pass the aperture. The fraction of protons counted is determined by the easily measured geometry factor of the aperture relative to the radiator. The accuracy of flux measurements with proton telescopes is about 2%. At low energies, background problems and determination of hydrogen masses limit the accuracy, and at high energy the error in the cross-section for production of forward-scattered protons dominates. At 14 MeV this latter error is about 2%.

1.2.2. $^{6}Li(n,\alpha)T$

For neutrons of energy below 100 keV the $^{6}Li(n,\alpha)T$ reaction is one of the most commonly used. Although solid lithium compounds can be introduced into counters for measurement of fluxes with this reaction, this method is not in common use because of the convenience of lithium glass scintillators, which are nearly 100% efficient for the detection of the charged reaction products. Care must be taken that corrections for neutron scattering in the glass and its surroundings are accurate and that the lithium content of the glass is known. The lithium content is commonly determined by measuring the transmission of the glass at low neutron energy where $^{6}Li(n,\alpha)$ absorption dominates. Aside from errors in the $^{6}Li(n,\alpha)T$ cross-section, about 2% accuracy can be achieved below 100 keV with these detectors.

1.2.3. $^{10}B(n,\alpha)$

The $^{10}B(n,\alpha)$ cross-section is well known below about 50 keV. Below about 10 keV, neutron flux is monitored using this reaction by detection of alpha particles; above 10 keV, the detection of the gamma rays from one branch of the reaction seems to be more popular. The detection efficiency for the gamma rays can be determined by a coincidence measurement, but this is seldom done. The reaction usually is used for shape determination and is sometimes normalized at thermal energy. Detectors based on the $^{10}B(n,\alpha)$ reaction can be calibrated to about 2% excluding error in the cross-section.

1.2.4. $^{3}He(n,p)$

This reaction is seldom used as a standard. Probably the unavailability of pure ^{3}He was initially a problem. Recent developments suggest that this reaction will be used more frequently in the future.

Recommendation

Absolute measurements of neutron flux by the associated-activity method are dependent upon absolute measurements of activities from radionuclides such as ^{7}Be, ^{51}Cr, ^{65}Zn and ^{57}Co. Standards laboratories should undertake an international comparison of the absolute calibration of such activities in order

TABLE I. SUMMARY OF RECENT RESULTS ON THE $^{6}Li(n,\alpha)$ CROSS-SECTION

Measurement	Energy range	Flux measurement	Normalization
Fort and Marquette [1] ^{6}Li glasses	15 keV - 1.7 MeV	Flat response detector and associated particle	Absolute
Coates et al. [2] ^{6}Li glasses	1.5 keV - 400 keV	Harwell black detector	Between 2 keV and 10 keV to $149.5/\sqrt{E}$ b
Poenitz and Meadows [3] ^{6}Li glasses	90 keV - 600 keV	Gray detector	Absolute
Clements and Rickard [4] ^{6}Li sandwich	160 keV - 3.9 MeV	Harwell long counter and ^{238}U cross-section	Uttley and Diment value between 300 keV and 500 keV

2. LIGHT-ELEMENT STANDARDS

2.1. The $^{6}Li(n,\alpha)$ cross-section

Four recent determinations of the $^{6}Li(n,\alpha)$ cross-section have been reported at this meeting. These are summarized in Table I. Considering first the common energy region across the 250-keV resonance, the ^{6}Li glass results [1] agree to an accuracy of ± 4% between about 150 keV and about 400 keV if systematic energy shifts of up to about 5 keV are accepted and if the data of Poenitz and Meadows [3] are renormalized down by approximately 5%. (This latter shift is acceptable since Poenitz's ^{6}Li-mass assay is preliminary.) The ^{6}Li sandwich detector results [4] in this energy region are known to be inaccurate because of resolution effects and may be ignored. Further work is needed to establish more accurately the ^{6}Li content of the glasses used in the Van de Graaff experiments, and there are some differences of detail in the multiple scattering corrections used by different authors. The correct energy scale in this region must be established by further experiments.

As far as the experimental (n,α) data are concerned, these represent a considerable improvement since the 1970 Argonne Symposium when, due to lack of agreement among the (n,α) data coupled with likely experimental deficiencies, it was recommended that the value of the $^{6}Li(n,\alpha)$ cross-section calculated by Uttley and Diment [5] from accurate total cross-section measurements represented the best available value. Uttley and Diment's cross-section was given some support by a preliminary measurement by Coates et al. The revised data of these authors, however, together with the other data referred to above, are approximately 12% below the Uttley and Diment value at the peak of the cross-section. These results cast doubt on the validity of deriving the (n,α) cross-section from total cross-section measurements with a theory which treats the resonance around 250 keV as

total cross-section which correctly represents the experimental total cross-section always results in a calculated (n,α) value which is too high compared with experiment. This is illustrated in Figs 2 and 3 of the paper of Fort and Marquette in these Proceedings [1] and is also confirmed by some calculations of Meadows and Whalen [6]. It appears likely that a more sophisticated attack is needed before the theoretical prediction of the (n,α) cross-section over the resonance peak is capable of being consistent with the most accurate experimental values. A possible refinement is to consider the likelihood of interference from the just-bound level at 6.64 MeV in ^{7}Li.

Turning now to the energy region below 100 keV, it is considered that the reservations on the reliability of the prediction of the (n,α) cross-section using the simple theory do not significantly alter the value of the (n,α) cross-section recommended at the 1970 Argonne Symposium for energies below approximately 50 keV. At 100 keV, the uncertainty in the P-wave contribution is not likely to be greater than 2%. Unfortunately, the spread in the experimental data is about ± 8% near this energy.

Above 300 keV, the accuracy of the cross-section is difficult to evaluate. The Fort and Marquette [1] data are substantially higher than those of Clements and Rickard [4] which are normalized to the Uttley and Diment [5] value between 300 and 500 keV. No reasonable renormalization helps the situation significantly. It should be noted that the values of σ(n,α) obtained by subtracting the σ(n, n) data from the total cross-section data in this energy region support the Fort and Marquette data [1] although the values obtained are not accurate to better than about 15%. It must be concluded that in this energy region more measurements are urgently needed.

Recommendations

(a) Work should be continued to establish the ^{6}Li(n,α) cross-section to the accuracy requested for nuclear energy programmes (see WRENDA). A further incentive lies in the need for measurements of the lower-energy (less than 500 keV) portion of the fission neutron spectrum where ^{6}Li glass detectors may have to be used.

(b) Effort should be directed towards obtaining a more sophisticated theoretical treatment with close collaboration among the laboratories chiefly concerned (Argonne, Cadarache and Harwell).

(c) The present efforts to establish the correct energy scale over the approximately 250-keV resonance should be continued.

(d) Another white-spectrum measurement of the total cross-section should be made to cover the energy range from about 100 eV to about 5 MeV. At present, the only white-spectrum measurement is that of Uttley and Diment [5] which should be confirmed because it has been heavily relied upon. It is important that the proposed measurement covers the energy range which is accessible to Van de Graaff accelerators using monoenergetic neutron sources and, in addition, extends to lower energies which are inaccessible with Van de Graaffs.

(e) Further total cross-sections should be measured by suitable methods to resolve the discrepancy at higher energies (above 500 keV).

(f) The accuracy to which the ^{6}Li content of glasses is known should be improved.

(g) More angular distribution measurements for the (n,α) reaction are

2.2. The $^{10}B(n,\alpha)$ cross-section

Since absolute proton recoil counting with good time resolution has not been demonstrated for neutron energies below 100 keV, other light-element standards are required to extend the energy range up to 1 MeV. Because of the resonance structure near 250 keV in the $^{6}Li(n,\alpha)T$ reaction, a boron standard would also receive useful application up to 1 MeV.

The $^{10}B(n,\alpha)$ reaction (ground-state plus excited state) seems potentially useful to about 1 MeV but is not well established above 80-100 keV. Recent data do not indicate changes since the 1970 Argonne Symposium in the status of the cross-section below 40 keV, but the new measurements of Friesenhahn et al. [7] for the (n,α) reaction are approximately 5% higher at 10 keV and up to 50% higher around 420 keV.

The $(n,\alpha_1\gamma)$ reaction seems potentially more useful at the higher energies (10 keV - 1 MeV), provided the 478-keV gamma ray can be resolved. Above 100 keV the new data of Friesenhahn et al. for the $(n,\alpha_1\gamma)$ reaction and the preliminary results of Coates et al. [8] agree with each other but show systematic disagreement with current evaluated data files and with earlier measurements. This disagreement is approximately 7% at 100 keV and increases with increasing energy.

Recommendation

Further experimental work is recommended in order to establish the total (n,α) and the $(n,\alpha_1\gamma)$ cross-sections to the necessary precision up to approximately 1 MeV. In consideration of the recent experiments of Coates et al. and of Friesenhahn et al., recommended values of the ^{10}B cross-sections above 100-200 keV are difficult to determine.

2.3. The $^{3}He(n,p)T$ cross-section

The cross-section for this reaction is known to 2% below 100 eV, to about 5% below 10 keV and less accurately above 10 keV.

Recommendation

Further measurements at energies above 100 keV are recommended to achieve the accuracy requested for this standard cross-section.

2.4. The $^{1}H(n,p)$ cross-section

This cross-section is reasonably well known from 1 to 14 MeV, but since forward-scattered protons only are detected in the upper energy range, the angular distribution of the reaction is needed.

Recommendation

It is recommended that the absolute cross-section as a function of angle be measured at several energies above 8 MeV with the object of allowing the determination of the cross-section for forward-scattered protons to an

3. FISSION AND CAPTURE STANDARDS

3.1. The fast-fission cross-section of ^{235}U

Because of considerable structure as a function of energy, the usefulness of the ^{235}U fission cross-section as a standard below 100 keV is questionable. However, if this cross-section is to be used as a standard above 100 keV, the available data sets should be examined below this energy as well as above. Furthermore, cases of usefulness as a standard below 100 keV may occur. The data base in this region continues to improve, but between absolute values at thermal energies and absolute values above 20 keV, differences in the shape of the cross-section among various experiments leave uncertainties of the order of ± 5%.

Since the 1970 Argonne Symposium [9], new measurements and modifications of earlier results have contributed significantly to an improved knowledge of the fission cross-section. These new results include the following:

(a) New relative measurements have been made with ORELA [10] from 100 eV to 100 keV by Perez et al. [11] and from thermal energies to 100 keV by Gwin et al. [12]. Both measurements are normalized at low energies.

(b) Szabo et al. [13] have modified previous absolute measurements made with a Van de Graaff and have obtained new data above 1 MeV. Data based on White's fission chamber and reported previously at the 1970 Argonne Symposium [14] remain unchanged. Data reported at the 1971 Knoxville Conference [15] are currently being reassessed as a result of a foil recalibration.

(c) Relative measurements in the 1-keV to 1-MeV region have been made by Gayther et al. [16] using the Harwell linac. These data are normalized to the 1972 evaluation by Sowerby et al. [17] in the 10- to 30-keV range and have been reported previously only with preliminary flux measurements.

(d) New absolute data of Poenitz [18], obtained with a Van de Graaff, replace the low preliminary values reported previously [19]. The new data cover the range from about 35 keV to 3.5 MeV and are subject to final confirmation of the foil assay.

(e) Both absolute and relative data in the energy range 0.5 - 1.2 MeV have been obtained by Käppeler [20] using the Karlsruhe Van de Graaff.

(f) New but preliminary absolute data in the range 1 - 6 MeV obtained by Hansen et al. with the Los Alamos Van de Graaff were reported by Diven [21].

The new data presented at the Panel are plotted in Fig. 1. A comparison of the data reveals the following features:

(a) From 35 keV to 1 MeV where measurements partially overlap, the ORELA data, the data of Szabo et al. based on White's fission chamber, and the data of Poenitz and of Gayther et al. are in reasonable agreement when the errors of approximately 3 - 4% in the individual data sets are considered.

(b) Of the 19 data points of Käppeler, the five between 500 and 700 keV lie consistently about 6% higher than the data of Poenitz and of Gayther while the data of Szabo et al. have intermediate values.

(c) The data of Käppeler also appear to differ in shape from the other measurements in the 500-keV to 1-MeV region although both he and Poenitz

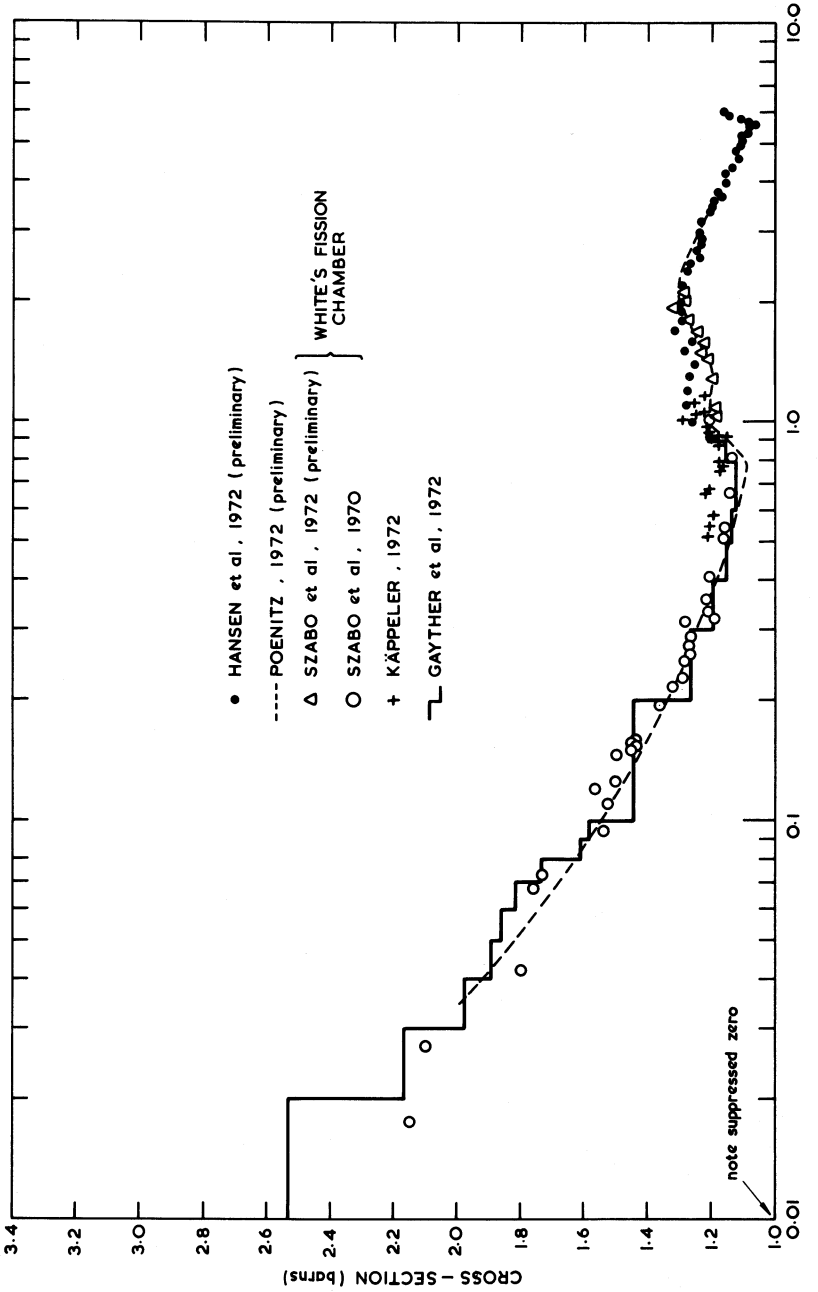

FIG. 1. Recent measurements of the ^{235}U fission cross-section. (Figure prepared by M.S. COATES and D.B. GAYTHER.)

(d) From 1 to 2 MeV the data of Szabo and Poenitz agree while the data of Käppeler are somewhat higher, and the new Los Alamos data are approximately 6% higher.

(e) From 2 to 3.5 MeV the Los Alamos data and those of Poenitz agree.

Recommendations and observations

(a) In the last two years, overall knowledge of the $^{235}U(n,f)$ cross-section has improved considerably. Below 500 keV the new data appear to agree sufficiently well so that an evaluation would be fruitful.

Above 500 keV there appear to be differences of up to 6% among the new data. In the important energy range 0.5 to 2 MeV it remains somewhat difficult to determine the shape of the cross-section, and a more detailed examination of this range is suggested. Although an evaluation would best await a final assay of the foils used by Poenitz and the Los Alamos group, even now an evaluation might achieve an estimated accuracy of about ± 3%.

(b) Turning attention to lower energies, standard fission cross-section integrals should be established and evaluated periodically as suggested by Deruytter in 1971 [22] in order to supplement the standard thermal fission cross-section of ^{235}U (as well as the thermal cross-sections of all other major fissile isotopes).

(c) For those cases in which the $^{235}U(n,f)$ cross-section must be used as a standard below 50 - 100 keV, it will be important for the experimenter to determine what additional uncertainties must be assigned to his experiment because of fluctuations in the standard cross-section.

(d) For accurate measurement of the standard fission cross-section of ^{235}U it is necessary to have detailed information concerning the angular distribution of fission fragments over the whole range of energies and angles of interest.

3.2. Fast-neutron capture cross-section of ^{197}Au and other appropriate capture standards

The most important advantage in the use of gold as a capture standard is the high accuracy with which the capture rate can be determined from the induced activity of ^{198}Au. This outweighs the disadvantage of the large proportion of gamma transitions to low-lying levels, which may disturb the detection of prompt capture gamma rays (from other materials) with split-tank scintillators. However, such detectors are used at present in only a small number of laboratories.

New absolute measurements of the capture cross-section of ^{197}Au by Fort et al. [23] support previous values reviewed at the 1970 Argonne Symposium and also agree well with the evaluation presented by Poenitz [24]. Preliminary measurements by Fort et al. [23] using the activation technique reveal some discrepancies of the order of 15% which should be resolved.

Based on the independent absolute measurements, the present uncertainty of the gold capture cross-section below 500 keV is less than ± 5%, probably ± 3%. Discrepancy still exists between the absolute cross-section data and values obtained relative to the $^{235}U(n,f)$ cross-section. Similar discrepancy with absolute measurements is also apparent for gold capture data based on the ^{238}U capture cross-section. Consequences of fluctuations, which are

Recommendations

(a) Gold should be retained as the capture cross-section standard. It would be a useful check to include gold in all measurements of capture cross-sections even if a different standard is used for flux measurements.

(b) The assumption of spectral independence of prompt gamma-ray detectors is a possible source of uncertainty in capture cross-section measurements. It is proposed that, in addition to the capture cross-section of gold, the ratio of gold-to-indium capture cross-sections be reliably established since the capture gamma-ray spectra from these two elements are significantly different.[1]

3.3. The value of $\bar{\nu}$ for spontaneous fission of ^{252}Cf[2]

Recommendations

(a) Based on a least-squares fit of all known absolute measurements of $\bar{\nu}$ for spontaneous fission of ^{252}Cf, the following value was derived:

$$\bar{\nu}_{total} = 3.733 \pm 0.0083 \text{ internal error}$$
$$\pm 0.0078 \text{ external error}$$

It is recommended that this value be used for normalization of future $\bar{\nu}$-measurements relative to ^{252}Cf.

Input data for the least-squares programme included the recent measurements of Boldeman [26] and all absolute measurements discussed in the reviews by Axton [27] and by Condé [28]. Weighting of the various data according to estimates of experimental error was based upon published literature cited in the review papers, upon discussions during the Panel meeting, upon preliminary correspondence with many other authors and upon

---

[1] Editor's note: In a review of the Summaries, Conclusions and Recommendations, some participants challenged the technical basis for proposing to measure or establish the ratio of the gold-to-indium cross-sections. It is the opinion of the secretary that the panel participants realized that measurements of the ratio would not resolve the primary problem of insufficient understanding of the spectral response of gamma-ray detectors but thought that reliably established ratios might help to illuminate detector problems in a user's laboratory.

In a preliminary version of this paper, owing to a typographical error, 'iodine' was written instead of 'indium'. Several interesting points arose in the ensuing correspondence.

(a) Iodine would also be useful as a secondary standard under certain circumstances. For example, iodine has a smaller thermal capture cross-section than gold and would be useful when there is a large thermal background.

(b) There are practical difficulties [25] in the use of gold for activation measurements (as opposed to capture gamma-ray measurements). If indium were to be used as a standard in place of gold in order to avoid these difficulties, then absolute values of the indium cross-section would be required — not ratios to gold.

[2] Editor's note: Because of limited time, the recommendations in sections 3.3, 3.4 and 3.5 could not be discussed in complete detail by the full panel so that the contents of these sections may represent the consensus of the working group rather than of the full panel. Some of the recommended numerical values are controversial and might have been somewhat different if they had been discussed by the full panel or by a different group of scientists. Hopefully, the implementation of the recommendations will contribute to the

the proceedings of the Consultants' Meeting on the Third Evaluation of the Thermal Fission Constants (Vienna, 15 - 17 November 1972) [29], in which several members of the present Panel had participated. Values of $\bar{\nu}$ derived from measurements of the parameter η were excluded from the present analysis.

(b) From previous discussions at the Consultants' Meeting [29], it appeared that inclusion of all data, both absolute and indirect, in the least-squares fit produced a value 0.5% higher than that recommended above and that exclusion of all absolute measurements (leaving essentially only values derived from η-measurements) produced a value approximately 1.5% higher than that recommended above.

The discrepancies among the results of the various fitting procedures can apparently be traced to the assignment of high weights to the η-experiments. Therefore, the following is recommended:

(i) either the corrections and author-estimated errors of the η-measurements should be reassessed
(ii) or η should be re-measured.

The Panel was not convinced that either of these recommendations would yield values of $\bar{\nu}$ with errors as small as those of the direct measurements.

The Panel noted that the errors assigned to the value recommended above describe only the uncertainties in the direct values and do not reflect the discrepancy of approximately 1.5% between the directly and indirectly determined values. The problem of the value of $\bar{\nu}$ for ^{252}Cf is therefore not yet satisfactorily resolved in spite of the improved agreement among the direct measurements.

3.4. The 2200-m/s fission and capture cross-sections of the fissile nuclides[3]

Recommendations

(a) Because of difficulties involved in deducing 2200-m/s values from effective cross-section measurements, it is recommended that the quantities required be measured at 2200 m/s neutron velocity.

(b) Extensive work on the alpha half-life of ^{234}U has been performed at CBNM using several counting techniques (low geometry, medium geometry and 4π alpha counting; liquid scintillation counting) and several different mass determinations (controlled-potential coulometry, isotopic dilution, weighing in ultra-high vacuum). While this work is being finalized and confirmed at Argonne National Laboratory and at Chalk River, the Panel received the working group's recommendation of the value

$$T_{1/2}(^{234}U) = 2.446 \times 10^5 \text{ a} \pm 0.3\%$$

for calculation of the amounts of ^{235}U in targets used in fission cross-section measurements. The quoted error represents three standard deviations.

(c) The difference among measured values of the alpha half-life of ^{233}U is striking. Several values from high-precision alpha counting are grouped around $T_{1/2}(^{233}U) = 1.61 \times 10^5$ a. However, recent measurements by

Keith [30] using alpha counting and by Oetting [31] using a calorimetric method both yield the value 1.55×10^5 a. The difference between the two groups of measurements is about 4%. A recent but unpublished measurement performed at Chalk River by Durham et al. using the alpha-counting method yields a value of 1.583×10^5 a.

High-accuracy measurements of the half-life of ^{233}U are recommended to resolve the discrepancy.

(d) For the half-life of ^{239}Pu the counting method yields with high consistency a value of 24 395 ± 29 a (error = 3 standard deviations) [32] while a recent calorimetric measurement by Oetting yields a value of 24 065 ± 50 a [33]. This difference of 1.3% is directly reflected in the 2200-m/s value of the fission cross-section of ^{239}Pu. Measurements of high accuracy are needed to resolve the discrepancy.

(e) There is a persistent difference among values of 2200-m/s fission cross-section ratios deduced from g-dependent experiments. For example, values of the $\sigma_f(^{239}Pu)/\sigma_f(^{235}U)$ ratio measured at Aldermaston in a thermal column are 1.277 ± 0.025 (White et al. [34]), 1.271 ± 0.015 (Keith et al. [35]); the ratio obtained with a beam extracted from the column is 1.235 ± 0.022 (White et al. [34]). Values measured at Chalk River are: 1.2970 ± 0.0075 (Bigham et al. [36]), 1.2926 ± 0.0081 (Lounsbury et al. [37]). The ratio is rather sensitive to the assumed g-factors, and results are different for different irradiation facilities. Ratio values obtained with monokinetic neutrons of 2200-m/s velocity are much more consistent.

It is therefore recommended that evaluators reassess the g-factors for the fissile isotopes to take into account recent low-energy data. In view of the inconsistency of ratio values obtained with different neutron spectra, it is recommended that the errors assigned to the Maxwellian ratios be increased to a realistic value when those ratios are used in an evaluation of all parameters at 2200 m/s.

(f) For ^{241}Pu the available information is very scarce. Further measurements of the 2200-m/s fission and absorption cross-sections are needed in connection with the least-squares evaluation by the IAEA [29].

(g) When 2200-m/s fission cross-section measurements are performed, they should be carried out in low geometry in order to avoid significant corrections for scattering and self-absorption of fission fragments in the fissile layers.

(h) It is recommended that the output parameters from the IAEA revision [29] of the 2200-m/s parameters should be used for future normalizations of relative measurements.

3.5. Fission neutron spectra[4]

Recommendations

(a) It is recommended that a standard fission neutron spectrum be included among the neutron standard reference data. The spectrum of neutrons from spontaneous fission of ^{252}Cf should be a primary standard but the fission spectrum of ^{235}U induced by neutrons below 150 keV should be regarded as an associated standard.

The choice of ^{252}Cf is derived from its wide potential utility, not only for comparison with other fission neutron spectra but also in simple integral experiments, detector calibration, etc. [38]. ^{235}U is included because of its convenience as a standard for comparison in many experimental applications involving accelerators or reactors and because at present it is comparatively well known. Over the energy range 0.5 - 7 MeV there is good consensus, and there is already at least one set of very careful measurements [39] extending to 15 MeV.

(b) While appreciating the value for discussions and scientific analysis of representations of the fission spectrum in terms of parametrized analytical formulae, the Panel insist that the definitive representation is in numerical terms, i.e. a table of intensity as a function of energy. This table should include a statement of the statistical and systematic errors.

(c) The correction of standard measurements for the effects of multiple reactions requires data for the elastic and inelastic cross-sections of all materials of importance in the experiment, e.g. ^{235}U, platinum and the components of stainless steel. It is suggested that the effect of present uncertainties in these cross-sections on the accuracy of the fission neutron spectra should be assessed.

(d) The possible existence of delayed neutron groups with half-lives less than those currently accepted makes difficult a clear definition of prompt and delayed fission neutron spectra and hence could in principle result in observation of different spectra depending on the technique or parameters used. It is recommended that attention be given to establishing the existence and intensity of such neutron groups and their associated spectra.

(e) The present state of our knowledge of the fission neutron spectrum of ^{252}Cf is regarded as far from satisfactory. The experiments are mostly rather old, and many of them require substantial corrections, as was pointed out at the Consultants' Meeting on Prompt Fission Neutron Spectra [40]. Less attention was paid to detector and energy calibration than now seems desirable. It is recommended that the results of experiments currently in progress be awaited before an evaluation of the ^{252}Cf fission neutron spectrum is attempted.

(f) It is felt that an evaluation of the ^{235}U fission spectrum could profitably be carried out as soon as all the results currently known in preliminary form have been finalized.

4. GENERAL RECOMMENDATIONS

(1) Particularly in the field of neutron standard reference data, experimenters are strongly urged to make special effort to include in the publication of their work all details required for evaluation and permanent documentation.

The reporting of sources of error and estimates of uncertainty is frequently in need of improvement. Although similar recommendations have appeared in the proceedings of numerous meetings, further improvement is necessary, and therefore the following recommendations on reporting of errors are made. Recommendations (2a) through (2c) are based on similar recommendations of the Consultants' Meeting on the Third Evaluation of the Thermal Fission Constants [29] which the Panel strongly affirm.

(2a) In general, greater care should be devoted to the identification of

(2b) Overall random and systematic errors should be reported separately, whether or not the combined uncertainty is also reported.

(2c) Component uncertainties in each of the above categories should be itemized, especially the systematic errors.

(2d) Experimenters should report precisely how components of the uncertainty correlate among various subsets of the data. For example, the full estimated variance (or relative variance) on a value might be given as a sum of terms, one of which is not shared by any other value, one of which might depend on a foil assay and be shared equally among all values given, and perhaps one of which is shared among a subset of points with correlated background or flux determination uncertainties. Such an organization of uncertainties would allow the construction, if necessary, of the full covariance matrix of the data given.

This information is needed even to determine correctly whether various sets of experimental values are discrepant, and it is further needed to allow a rational combination of results from various investigators. As pointed out by Usachev et al. [41], such detailed estimates of uncertainties are needed for final evaluated cross-sections to allow the assessment of the effects of uncertainties upon applications such as reactor design.

Evaluators cannot supply the required details about uncertainties unless measurers provide the basic information in a clear way. Of course, much relevant information is often supplied by experimentalists, but the manner of presentation is sometimes ambiguous.

When the published account of research lacks sufficiently detailed information about uncertainties, often an evaluator's only option is to revise the uncertainties to a 'realistic' value. Regrettably, such revision may in effect exclude the measurement from the evaluation.

(2e) Journals are urged to accept for publication the detailed information required for subsequent evaluation and documentation, especially in the case of neutron standard reference data. Many Panel members had personally encountered rejection of important information by journals on the basis of excessive detail.

(3) The Panel recognized the important role of the Central Bureau for Nuclear Measurements (CBNM) in providing targets and samples relevant to neutron standard reference data measurements, both inside and outside the European communities. They expressed hope that the same service will continue to be available in the future.

(4) The comparison of neutron flux measurements which has been undertaken by the International Bureau of Weights and Measures (BIPM) is a valuable approach which should be supported.

(5) The Euratom Working Group on Reactor Dosimetry (EWGRD) has indicated the need for rapid improvement of certain capture and threshold reaction cross-sections relevant to reactor dosimetry. In view of present concentration on only six primary standard reactions, three of which also belong to the reactor-dosimetry class, EWGRD should consider whether the adoption of the neptunium fission cross-section as a primary standard would improve the situation. This suggestion should also be brought to the attention of the International Working Group on Reactor Radiation Measurements

(6) The Panel strongly urges all participants to send their data to the Neutron Data Centre which serves their area.

(7) In consideration of the extensive efforts presently under way at many laboratories, a third panel on neutron standard reference data is recommended for spring 1975.

REFERENCES

[1] FORT, E., MARQUETTE, J.P., paper IAEA-PL-246-2/18, these Proceedings.
[2] COATES, M.S., HUNT, G.J., UTTLEY, C.A., paper IAEA-PL-246-2/20, these Proceedings.
[3] POENITZ, W.P., MEADOWS, J.W., paper IAEA-PL-246-2/16, these Proceedings.
[4] CLEMENTS, P.J., RICKARD, I.C., UKAEA Rep. AERE-R 7075 (1972).
[5] UTTLEY, C.A., DIMENT, K.M., UKAEA Repts AERE-PR/NP-14 (1968), AERE-PR/NP-15 (1969), AERE-PR/NP-16 (1969).
[6] MEADOWS, J.W., WHALEN, J.F., Nucl. Sci. Eng. 48 (1972) 221.
[7] FRIESENHAHN, S.J., CARLSON, A.D., ORPHAN, V.J., FRICKE, M.P., Gulf Radiation Technology Rep. GULF-RT-A12210 (1972).
[8] COATES, M.S., HUNT, G.J., UTTLEY, C.A., "Preliminary measurement of the relative $^{10}B(n, \alpha, \gamma)$ cross-section", paper IAEA-PL-246-2/20, these Proceedings.
[9] Neutron Standards and Flux Normalization (Proc. Symp. Argonne, 1970) CONF-701002, AEC Symp. Ser. 23, USAEC Div. Tech. Inf. Ext., Oak Ridge (1971).
[10] PEELLE, R.W., "ORELA measurements of the $^{235}U(n, f)$ cross-section to 100 keV", paper IAEA-PL-246-2/23, these Proceedings.
[11] PEREZ, R.B., DE SAUSSURE, G., SILVER, E.G., INGLE, R.W., WEAVER, H., Simultaneous Measurements of the Neutron Fission and Capture Cross-Sections for ^{235}U for Neutron Energies from 8 eV to 10 keV, Rep. ORNL-TM-3696 (1972). The preliminary results for energies above 10 keV are from a private communication.
[12] GWIN, R., SILVER, E.G., INGLE, R.W., WEAVER, H., in preparation.
[13] SZABO, I., LEROY, J.L., MARQUETTE, J.P., "Discrepancies observed in fission cross-section measurements using fission foils from different origins", paper IAEA-PL-246-2/24, these Proceedings.
[14] SZABO, I., FILIPPI, G., HUET, J.L., LEROY, J.L., MARQUETTE, J.P., Neutron Standards and Flux Normalization (Proc. Symp. Argonne, 1970), CONF-701002, AEC Symp. Ser. 23, USAEC Div. Tech. Inf. Ext., Oak Ridge (1971) 257.
[15] SZABO, I., FILIPPI, G., HUET, J.L., LEROY, J.L., MARQUETTE, J.P., Neutron Cross-Sections and Technology (Proc. Conf. Knoxville, 1971) 2, CONF-710 301, USAEC Div. Tech. Inf. Ext., Oak Ridge (1971) 573.
[16] GAYTHER, D.B., BOYCE, D.A., BRISLAND, J.B., "Measurement of the ^{235}U fission cross-section in the energy range 1 keV to 1 MeV", paper IAEA-PL-246-2/26, these Proceedings.
[17] SOWERBY, M.G., PATRICK, B.H., MATHER, D.S., UKAEA Rep. AERE-R-7273.
[18] POENITZ, W.P., "Measurements of the ^{235}U fission cross-section in the fast neutron energy range", paper IAEA-PL-246-2/25, these Proceedings.
[19] POENITZ, W.P., Neutron Cross-Sections and Technology (Proc. Conf. Washington, D.C., 1968), (GOLDMAN, D.T., Ed.), NBS Special Publ. 299, US Government Printing Office, Washington, D.C. (1968) 503.
[20] KÄPPELER, F., "Measurement of the neutron fission cross-section of ^{235}U between 0.5 and 1.2 MeV", paper IAEA-PL-246-2/27, these Proceedings.
[21] DIVEN, B.C., "Progress report on LASL measurement of the ^{235}U fission cross-section from 1 to 6 MeV", paper IAEA-PL-246-2/28, these Proceedings.
[22] DERUYTTER, A.J., WAGEMANS, C., J. Nucl. Energy 25 (1971) 263.
[23] FORT, E., LE RIGOLEUR, C., ARNAUD, A., TASTE, J., HUET, J.L., MALOIZEL, J., "Measurements of capture cross-section of ^{197}Au between 75 keV and 500 keV", paper IAEA-PL-246-2/29, these Proceedings.
[24] POENITZ, W.P., Neutron Standards and Flux Normalization (Proc. Symp. Argonne, 1970), CONF-701002, AEC Symp. Ser. 23, USAEC Div. Tech. Inf. Ext., Oak Ridge (1971) 320.

[26] BOLDEMAN, J.W., "Prompt neutron yield from the spontaneous fission of ^{252}Cf", paper IAEA-PL-246-2/33, these Proceedings.
[27] AXTON, E.J., "The value of $\bar{\nu}$ for ^{252}Cf", paper IAEA-PL-246-2/31, these Proceedings.
[28] CONDE, H., "Summary of the absolute measurements of $\bar{\nu}$ for the spontaneous fission of ^{252}Cf", paper IAEA-PL-246-2/32, these Proceedings.
[29] Third Evaluation of the Thermal Fission Constants (Proc. Consultants' Meeting Vienna, 1972) to be published.
[30] KEITH, R.L.G., J.Nucl.Energy 22 (1968) 471.
[31] OETTING, F.L., Thermodynamics of Nuclear Materials (Proc.Symp.Vienna, 1967) IAEA, Vienna (1968) 55.
[32] DERUYTTER, A.J., BECKER, W., The accurate fission cross-section of ^{239}Pu from 0.005 eV to 0.1 eV and its reference value at 2200 m/s, to be published (J.Nucl.Energy).
[33] OETTING, F.L., Rocky Flats Rep.RFP-1469 (1971).
[34] WHITE, P.H., REICHELT, J.M.A., WARNER, G.P., Nuclear Data for Reactors (Proc.Conf.Paris, 1966) 2, IAEA, Vienna (1967) 29.
[35] KEITH, R.L.G., McNAIR, A., ROGERS, A.L., J.Nucl.Energy 22 (1968) 477.
[36] BIGHAM, C.B., HANNA, G.C., TUNNICLIFFE, P.R., CAMPION, P.J., LOUNSBURY, M., MACKENZIE, D.R., 2nd Int.Conf.Peaceful Uses At.Energy (Proc.Conf.Geneva, 1958) 16, UN, New York (1959) 125.
[37] LOUNSBURY, M., DURHAM, R.W., HANNA, G.C., Nuclear Data for Reactors (Proc.Conf.Helsinki, 1970) 1, IAEA, Vienna (1970) 287.
[38] FERGUSON, A.T.G., "Standard fission neutron spectra", paper IAEA-PL-246-2/37, these Proceedings.
[39] FERGUSON, A.T.G., private communication.
[40] INTERNATIONAL ATOMIC ENERGY AGENCY, Prompt Fission Neutron Spectra (Proc.Consultants' Meeting Vienna, 1971), IAEA, Vienna (1972).
[41] USACHEV, L.N., BOBKOV, Yu.G., Proposals on RENDA — A World-wide Compilation of Requests for Neutron Data Measurements for Reactors, IAEA Rep. INDC(CCP)-25 (1972).

LIST OF PARTICIPANTS

AXTON, E. J.	Division of Radiation Science, Ministry of Technology, National Physical Laboratory, Teddington, Middlesex, United Kingdom
BOLDEMAN, J. W.	Australian Atomic Energy Commission, Research Establishment, New Illawarra Road, Lukas Heights, NSW, Australia
BOWMAN, C. D.	Center for Radiation Research, National Bureau of Standards, Washington, D. C. 20234, United States of America
COATES, M. S.	United Kingdom Atomic Energy Authority, Atomic Energy Research Establishment, Harwell, Didcot, Oxfordshire, United Kingdom
CONDE, H.	Research Institute of National Defense, 10450 Stockholm 80, Sweden
DERUYTTER, A. J.	Central Bureau for Nuclear Measurements, Euratom, Steenweg Naar Retie, 2440 Geel, Belgium
DIVEN, B. C.	Group P-3, Los Alamos Scientific Laboratory, P. O. Box 1663, Los Alamos, N. Mex. 87544, United States of America
FERGUSON, A. T. G.	Nuclear Physics Division, H8, United Kingdom Atomic Energy Authority, Atomic Energy Research Establishment,

FORT, E.
CEN de Cadarache,
B. P. N° 1,
13 St. Paul-lez-Durance,
France

GAYTHER, D. B.
United Kingdom Atomic Energy Authority,
Atomic Energy Research Establishment,
Harwell, Didcot, Oxfordshire,
United Kingdom

KÄPPELER, F.
Kernforschungszentrum Karlsruhe,
Institut für Angewandte Kernphysik,
Postfach 3640,
Karlsruhe,
Federal Republic of Germany

KUZMINOV, B. D.
Institute of Physics and Energetics,
Obninsk, Kaluga Region,
USSR

LEROY, J. L.
CEN de Cadarache,
B. P. N° 1,
13 St. Paul-lez-Durance,
France

LISKIEN, H.
Central Bureau for Nuclear Measurements,
Euratom,
Steenweg Naar Retie,
2440 Geel,
Belgium

MIGNECO, E.
Istituto di Fisica,
Università di Catania,
Corso Italia 57,
95129 Catania,
Italy

MOTTA, E.
Comitato Nazionale per l'Energia Nucleare,
Centro di Calcolo, Via Mazzini,
Bologna,
Italy

PEELLE, R. W.
Oak Ridge National Laboratory,
P. O. Box X,
Oak Ridge, Tenn. 37830,
United States of America

POENITZ, W. P.
Argonne National Laboratory,
9700 South Cass Avenue,
Argonne, Ill. 60439,

SCHETT, A.
OECD,
P.O. Box N° 9,
91 Gif-sur-Yvette,
France

SOLEILHAC, M.
Service de physique nucléaire,
Centre d'études de Bruyères le Châtel,
B.P. N° 515,
92 Paris,
France

STEWART, Leona
Los Alamos Scientific Laboratory,
P.O. Box 1663,
Los Alamos, N. Mex. 87544,
United States of America

TSUKADA, K.
Japan Atomic Energy Research Institute,
Tokai Research Establishment,
Tokai-Mura, Naka-Gun,
Ibaraki-Ken,
Japan

Scientific Secretaries

BYER, T.A.
Division of Research and Laboratories,
IAEA, Vienna

LEMLEY, J.R.
Division of Research and Laboratories,
IAEA, Vienna

Printed by the IAEA in Austria