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EVALUATION OF ^{246}Cm NEUTRON CROSS SECTIONS FROM 10^{-5} eV TO 15 MeV

G. Maino, E. Menapace, M. Vaccari, A. Ventura

RELAZIONE TECNICA INTERNA

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Work performed under CNEN-IAEA research agreement No. 2714/CF

RIASSUNTO

Dopo una breve rassegna dei dati sperimentali più importanti, è descritta una valutazione delle sezioni d'urto neutroniche dell'isotopo Cm-246 nell'intervallo energetico 10^{-5} eV - 15 MeV.

ABSTRACT

After a short review of the most important experimental data, Cm-246 neutron cross section evaluation in the energy range 10^{-5} eV - 15 MeV is described.

CONTENTS

EVALUATION OF ^{246}Cm NEUTRON CROSS SECTIONS FROM 10^{-5} eV TO 15 MeV (°)

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1. INTRODUCTION

The neutron cross sections of higher Curium isotopes are of interest in power reactor fuel cycle problems and mainly in the production chain of Californium 252.

This report describes an evaluation of ^{246}Cm neutron cross sections in the energy range 10^{-5} eV - 15 MeV, of interest to both thermal and fast reactors, and supersedes a previous evaluation limited to the resonance region /1/.

(°) Work performed under CNEN-IAEA research agreement No. 2114/CF.

2. GENERAL INFORMATION

A survey of experimental literature on ^{246}Cm neutron cross sections up to 1979 has already been given in ref. /1/.

In the present work, papers published in 1980-81 are taken into account, too. Thus, our main sources of experimental information are now the following:

a) Measurements analyzed by Moore and Keyworth /2/: fission and capture cross sections of five Cm isotopes were determined in the energy range 20 eV - 3 MeV. As for ^{246}Cm, 9 resonances were identified in the interval 84 eV - 381 eV; for 8 of them Γ_n and Γ_f values were attributed, with the assumption Γ_γ = 37 meV.

b) The total cross section measurements by Berreth et al. /3/ in the energy range 0.01 - 30 eV: two resonances were attributed to ^{246}Cm and their Γ_n^o and Γ_γ parameters determined.

c) Five resonances of ^{246}Cm up to 158 eV were observed by Benjamin et al. /4/ in an experiment aimed at determining the total cross section of ^{248}Cm. Values for the reduced neutron widths, Γ_n^o, were determined after deriving $\overline{\Gamma_\gamma}$ = (31 ± 6) meV from a Breit-Wigner shape analysis.

d) The same resonances as in ref. /4/ were reported by Belanova et al. in a number of papers on measurements of neutron transmission through Cm targets /5/, /6/, /7/. Average resonance parameters $\bar{D}$, $\overline{\Gamma_\gamma}$, S_o, and the absorption resonance integral were presented at the Knoxville Conference in 1979 /8/.

e) The fission thermal cross section and resonance integral ($E_n \gtrsim 0.625$ eV) were determined by Benjamin et al. /9/ with two different techniques and using ^{235}U as a reference standard.

f) σ_{nf} (0.0253 eV) and I_{nf} ($E_n \geq 0.52$ eV) were also determined by Zhuravlev et al. /10/, with ^{235}U as a standard.

g) The capture thermal cross section and resonance integral were recently measured by Gavrilov and Goncharov /11/.
To these papers, already quoted in /1/, we add two recent measurements of the fission cross section.

h) Fomushkin et al. /12/ measured σ_{nf} in the range 0.3 - 4.5 MeV by the time-of-flight method using a nuclear explosion as a pulsed neutron source. The fission cross section was measured relative to $^{235}U(n,f)$. The absolute values of σ_{nf} above the threshold turn out to be lower than those published in /2/.

i) A recent accurate measurement of σ_{nf} in the energy range 1 eV - 100 keV is due to Block et al. /13/.

The neutron flux was produced by the RINS system (linac plus neutron spectrometer) at the Rensselaer Polytechnic Institute. The ^{246}Cm target weighed 17 μg and was of high purity (96.89%). Resonances were clearly observed at 4.3 , 15.3 and 158 eV, together with the doublet at 84.4 and 91.8 eV. Clusters of non-resolved resonances were observed near 400 and 800 eV. The area analysis method made it possible to determine the fission widths of the two resonances at 4.3 and 15.3 eV, never before measured.

These results in resolved and unresolved resonance regions allowed us to improve our previous evaluation /1/.

3. RESOLVED RESONANCE REGION

The resolved resonance region extends up to 390 eV. The main difference with respect to ref. /1/ lies in the choice of parameters for the first two resonances, at 4.3 and 15.3 eV, now taken from ref. /13/: the fission widths there given are 0.4 and 0.43 meV, respectively, in agreement with the average of the remaining 9 resonances, taken from ref. /2/.

In ref. /1/ a much higher Γ_f had been attributed to the first resonance in order to reproduce the experimental fission resonance integrals /9/, /10/. This arbitrariness is now removed by the results of ref. /13/. As a consequence, we obtain a resonance contribution to the fission integral much lower that the experimental values. This disagreement is partly reduced by adding the continuum contribution ($E_n \geq 10$ keV) to the fission integral. In our opinion, new accurate measurements of the fission cross section in the resolved resonance region and new integral data could throw light on this problem. Table I shows the set of 11 resonances adopted, in the interval 4 - 381 eV. The symbols are the same as in ENDF/B formats. Although the resonance parameters were obtained from Breit-Wigner single-level analysis, we were forced to give a recommended Breit-Wigner multilevel representation in our data file in ENDF/B format, in order to avoid negative values of the computed elastic cross section.

Table II contains the calculated resonance contribution to thermal cross sections and resonance integrals.

Finally, figs. 1a-b-c-d show total, elastic, capture and fission cross sections in the resolved resonance region, calculated by means of the CRESO code /14/.

4. AVERAGE PARAMETERS FOR THE UNRESOLVED REGION

The unresolved resonance region ranges from 390 eV to 10 keV. In this interval, statistical calculations were carried out by means of the strength function formalism. The list of adopted average parameters as well as their energy dependence in this interval, is given in table III in a format slightly modified with respect to the ENDF/B rules; however, the ENDF/B symbols written above the numerical values make it possible to identify them unambiguously.

Comments on these parameters have already been made in ref. /1/, and will not be repeated here. We only quote the recommended values and point out the changes made in the fission parameters in order to reproduce the fission cross section of ref. /13/.

a) Average s-wave spacing $\bar{D}$: a list of $\bar{D}$ values estimated from the resolved resonances is given in table IV. Our previously recommended value $\bar{D} = 21.3$ eV is maintained.

b) s-wave strength function S_o : the value adopted in /1/, $S_o = 0.77 \times 10^{-4}$, has not been modified.

c) p-wave strength function S_1 : there is no experimental information about S_1 , for which the value $S_1 = 2.6 \times 10^{-4}$ of ref. /1/ has been retained.

d) Average radiation width $\overline{\Gamma_\gamma}$: a list of values of $\overline{\Gamma_\gamma}$ $(J^\pi = \frac{1}{2}^+)$, assumed or measured in resolved resonance analysis, is given in table V. They range from (27.1 1.8) meV /5/ to 37 meV /2/. As in ref. /1/, we adopt $\overline{\Gamma_\gamma} = 33$ meV over the whole unresolved region for $J = 1/2, 3/2$ and both parities.

e) Average fission width $\overline{\Gamma_f}$: the absolute values and energy dependence of $\overline{\Gamma_f}$ (J^π) have been modified with respect to ref. /1/ in order to reproduce the experimental fission cross section of ref. /13/. At the lower end of the unresolved region, $E = 390$ eV , we have adopted the average width of the resonances in ref. /2/, $\overline{\Gamma_f} = 0.48$ meV for both s- and p-wave neutrons ($J^\pi = 1/2^+$ and $J^\pi = 1/2^-$, $3/2^-$, respectively).

The fission widths are assumed to increase linearly with energy up to the upper end, $E = 10$ keV, where the following values

Γ_f $(1/2^+) = 1.7$ meV
Γ_f $(1/2^-) = 2.0$ meV
Γ_f $(3/2^-) = 1.7$ meV

allowed us to obtain a fission cross section in reasonable agreement with the experiment /13/.

5. THERMAL CROSS SECTIONS AND RESONANCE INTEGRALS

Experimental fission and capture cross sections at $E_n = 0.0253$ eV are given in table VI, the corresponding resonance integrals in table VII. Good agreement is obtained between experimental and calculated capture data, while the computed fission integral is lower than the experimental one, as pointed out in Section 3. The main contribution to the fission integral is given by the continuum region (Sect. 7) and turns out to be of the order 5.50 b, while the resonance contribution is only 1.44 b, thus giving an integral of the order 6.94 b, to be compared with experimental values $I_f \simeq 10 \div 13$ b.

6. AVERAGE NUMBER $\bar{\nu}$ OF NEUTRONS EMITTED PER FISSION

The procedure and results of ref. /1/ have not been modified: the estimate of the average number of neutrons emitted per fission by the compound nucleus ^{247}Cm versus neutron energy is obtained through an empirical formula of Howerton /15/, normalized at the thermal value $\bar{\nu}_{th}$ = 2.98 ± 0.12 of ref. /16/; the resulting function has the form:

$$\bar{\nu}(E_n) = 2.98 + 0.196\, E_n \qquad (E_n \text{ in MeV}) .$$

7. THE CONTINUUM REGION

In the energy range 10 keV - 15 MeV direct and compound nucleus contributions to various processes have been estimated through coupled channel optical model calculations and statistical Hauser-Feshbach calculations, respectively.

The reactions taken into account are the following: elastic (direct plus compound contributions), total and level inelastic (direct plus compound), capture, first and second chance fission, and (n,2n). Reactions having a threshold above 10 MeV, like (n,3n) and third chance fission have been neglected. Pre-equilibrium competitions are not taken into account since they are expected to become important above 15 MeV.

7.1. OPTICAL MODEL CALCULATIONS

Compound channel calculations have been performed by means of the JUPITOR /17/ and ADAPE /18/ codes; the former in the range 10 keV - 8 MeV, the latter from 8 to 15 MeV, where the adiabatic approximation seems to be good enough.

The states actually coupled in our non-adiabatic calculations are the 0^+, 2^+, 4^+ members of the ground state rotational band. Table VIII gives the parameters of our deformed optical potential, already used for ^{241}Am /19/ and lower mass Cm isotopes /20/.

The quadrupole and hexadecapole deformations adopted in the present work, $\beta_2 = 0.245$ and $\beta_4 = 0.03$, respectively, were obtained in studies of the equilibrium shape of various actinides by means of Woods-Saxon potentials /21/. They are consistent with our choice of the nuclear radius parameter in table VIII.

Coupled channel calculations give the direct contribution to elastic and inelastic scattering: we have evaluated integral and differential cross sections (angular distributions) for the elastic scattering and excitation of the first two levels in the ground state band. The compound nucleus contributions to these processes have been obtained through Hauser-Feshbach calculations (see the next subsection) and added to the direct contributions in order to obtain a complete description of elastic and inelastic scattering.

7.2. STATISTICAL MODEL CALCULATIONS

The compound nucleus contributions to the reactions of interest in the continuum region have been evaluated by means of a modified version of the HAUSER*4 code /22/.

Three competing decay channels, neutron, gamma and fission, are considered: the decay of the compound nucleus ^{247}Cm in the above-mentioned channels makes it possible to evaluate the compound elastic, radiative capture and first chance fission cross sections, respectively. The decay of the compound nucleus ^{246}Cm gives (n,2n), (n,n'γ) and (n,n'f) cross sections, respectively. The decay channels of both systems are described by various parameters: energy, spin and parity of discrete levels, and, for excitation of the continuum, level density parameters, to which calculated cross sections are very sensitive. We describe level densities by means of a back-shifted Fermi gas formula: since such a simple expression cannot give a realistic description of excited nuclei, its parameters do not have a physical meaning, but only allow us to fit experimental cross sections.

Moreover, the fission channel is characterized by a two-humped fission barrier, for which height and curvature of the two saddle points are specified. Our choice of barrier parameters for the compound nucleus ^{247}Cm is consistent with the results of the analysis of experimental fission probabilities for odd-A actinides given in ref. /23/; the barrier parameters for the compound nucleus ^{246}Cm are in agreement with those described for ^{244}Cm and ^{248}Cm in ref. /24/. Level density parameters in the same fission channel have been indirectly checked by reproducing the experimental fission cross section of ^{245}Cm /20/.

All the parameters relevant to the description of the three decay channels for both ^{246}Cm and ^{247}Cm are given in table IX and fol.-

7.3. RESULTS AND COMMENTS ON THE CONTINUUM

The results of our calculations in the continuum region are presented in graphic form: fig. 2 shows the fission cross section together with experimental data from refs. /2/, /12/ and /13/; fig. 3 all the evaluated cross sections in the range 10 keV - 15 MeV. Finally, figs. 4a-b-c-d-e show the elastic, capture, fission and total cross sections over the complete evaluation range, 10^{-5} eV to 15 MeV.

If we compare our results with another recent evaluation due to Caner et al. /25/, we find their underthreshold fission lower than ours by a factor $5 \div 6$ in the interval 10 - 50 keV, the disagreement being reduced at higher energy: this is due to the fact that their evaluation could not take into account the experimental data of ref. /13/. As a counterbalance, their capture cross section is higher than ours all over the energy range and the disagreement gets quickly worse with increasing energy above 0.5 MeV. On the other hand, our direct contributions to elastic and inelastic scattering are stronger, because our elastic and total inelastic cross sections are systematically higher. It has to be pointed out that direct contributions were evaluated in ref. /25/ by means of a spherical optical model.

8. ENERGY SPECTRA OF EMITTED NEUTRONS

In describing the energy distributions of neutrons emitted in various reactions, we have made the somewhat crude hypothesis that these distributions can be represented by simple evaporative formulae, thus neglecting the pre-equilibrium competition, expected to become important for emitted neutron energies of the order of 10 MeV or more.

The first chance fission spectrum has been approximated by a standard Maxwellian formula:

$$f(E,E') = \alpha \sqrt{E'} \exp(-E'/\theta(E))$$

Here, E is the incident neutron energy, E' the emitted neutron energy, $\theta(E)$ an effective temperature (in energy units), which has been taken as a function of E according to the data of ref. /37/.

The energy spectra for neutrons emitted in the following reactions: $(n,n'\gamma)$ with continuum excitation, $(n,2n)$, $(n,n'f)$ are represented by evaporation formulae of the kind

$$g(E,E') = \beta E' \exp(-E'/\theta(E))$$

The "effective" thresholds for these three reactions have been taken at $E_1 = 0.51$ MeV, $E_2 = 6.6$ MeV, $E_3 = 6.3$ MeV, respectively.

$\theta(E)$ can be interpreted in these cases as the excitation temperature of the residual nucleus after emission of an $E' \simeq 0$ neutron: it has been evaluated for the residual nuclei ^{246}Cm and ^{245}Cm through the microscopic procedure of ref. /38/. $\theta(E)$ versus E is plotted in fig. 5 for all the reactions taken into account, from their effective threshold up to 15 MeV.

9. CONCLUSIONS

The main problem encountered in the present evaluation is the discrepancy between experimental and calculated fission resonance integrals: further analysis of the fission cross section in the resolved resonance region and new integral measurements could probably throw light on this problem.

The evaluated data have been compiled and written in files according to the ENDF/B-IV format rules /26/, by means of the SYSMF system of codes /27/.

ACKNOWLEDGEMENTS

We are grateful to Dr. R.C. Block for providing us with his fission data (/13/) before publication. Thanks also to Mr. G.C. Panini for useful graphical and computing codes.

REFERENCES

/1/ T. Martinelli, E. Menapace, M. Motta, M. Vaccari, A. Ventura: CNEN Report, RT/FI(80)7 (1980).

/2/ M.S. Moore and G.A. Keyworth: Phys. Rev. C3, 1656 (1971).

/3/ J.R. Berreth, F.B. Simpson and B.C. Rusche: Nucl. Sci. and Eng., 49, 145 (1972).

/4/ R.W. Benjamin, C.E. Ahlfeld, J.A. Harvey and N.W. Hill: Nucl. Sci. and Eng. 55, 440 (1974).

/5/ T.S. Belanova et al.: Proc. of a Conf. on Neutron Physics, Kiev, 3, 224 (1975) (in Russian).

/6/ T.S. Belanova et al.: Sov. At. En. 39, 1020 (1976).

/7/ T.S. Belanova et al.: Proc. of a Conf. on Neutron Physics, Kiev, 2, 260 (1977) (in Russian).

/8/ T.S. Belanova et al.: Proc. of the Int. Conf. on Nuclear Cross Sections for Technology, Knoxville, 1979, NBS Spec. Publ. 594, p. 908 (1980).

/9/ R.W. Benjamin, K.W. Mac Murdo and J.D. Spencer: Nucl. Sci. and Eng., 47, 203 (1972).

/10/ K.D. Zhuravlev, N.J. Kroshin and A.P. Chetverikov: Sov. At. En. 39, 907 (1976).

/11/ V.D. Gavrilov and V.A. Goncharov: Sov. At. En. 44, 274 (1978).

/12/ E.F. Fomushkin, G.F. Novoselov, Yu. J. Vinogradov, V.V. Gavrilov and V.A. Zherebtsov: Sov. J. of Nucl. Phys. 31, 19 (1980).

/13/ H.T. Maguire, Jr., C. Stopa, D.R. Harris, R.C. Block, R.E. Slovacek, R.W. Hoff, R.W. Lougheed, J.W.T. Dabbs: Contr. to the 1981 Ann. Meet. of the Ann. Nucl. Sci., San Francisco, Nov. 29 - Dec. 4, 1981.

/14/ G.C. Panini: CNEN Report, RT/FI(81)30 (1981).

/15/ R.J. Howerton: Nucl. Sci. and Eng. 62, 438 (1977).

/16/ K.D. Zhuravlev, Yu.S. Zamyatnin and N.I. Kroshin: Proc. of a Conf. on Neutron Phys., Kiev, 4, 57 (1974).

/17/ T. Tamura: Rev. of Mod. Phys. 37, 679 (1965).

/18/ F. Fabbri and L. Zuffi: CNEN Report, RT/FI(69)7 (1969).

/19/ G. Maino, E. Menapace, M. Motta, A. Ventura: Proc. of the Int. Conf. on Nucl. Cross Sect. for Technology, Knoxville, 1979, N.B.S. Special Publication 594, p. 500 (1980).

/20/ G. Maino et al.: report in course of publication.

/21/ K. Adler, quoted by C.E. Bemis, Jr., et al.: Phys. Rev. C8, 1466 (1973).

/22/ F.M. Mann: Hanford Report HEDL-TME 76-80 (1976).

/23/ B.B. Back, H.C. Britt, O. Hansen, B. Leroux: Phys. Rev. C10, 1948 (1974).

/24/ B.B. Back, O. Hansen, H.C. Britt, J.D. Garrett: Phys. Rev. C9, 1924 (1974).

/25/ M. Caner, Y. Bartal, S. Yiftah: IAEC Report IA-1358 (1980).

/26/ D. Garber et al.: BNL Rep. BNL-NCS-50496 (ENDF 102) (1975).

/27/ G.C. Panini and M. Vaccari: "SYSMF System of Codes", unpublished.

/28/ M.S. Moore: Proc. of the Meeting on Transactinium Isotope Nuclear Data, Karlsruhe, 1975, IAEA-186, 2, 161 (1976).

/29/ R.E. Coté, R.F. Barnes, H. Diamond: Phys. Rev. 134B, 1281 (1964).

/30/ S.M. Kalebin: Proc. of the Meeting on Transactinium Isotope Nuclear Data, Karlsruhe, 1975, IAEA-186, 2, 121 (1976).

/31/ V. Benzi: Proc. of an Int. Conf. on Neutron Physics and Nuclear Data, Harwell, 1978, p. 288.

/32/ M.C. Thompson, M.L. Hyder and R.J. Reuland: Journ. of Inorg. Nucl. Chem. 33, 1553 (1971).

/33/ J. Halperin, R.E. Druschel and R.E. Eby: Progr. Rep. ORNL-4437, Oak Ridge Nat. Lab., 20 (1969).

/34/ R.P. Schuman: USAEC Rep. WASH-1136, 54 (1969).

/35/ Present work.

/36/ Table of Isotopes, edited by C.M. Lederer and V.S. Shirley, 7th edition, Wiley-Interscience (1978).

/37/ V.P. Kovalev and V.S. Stavinsky: Sov. At. En. 5, 166 (1958).

/38/ V. Benzi, G. Maino and E. Menapace: Nuovo Cimento A66, 1 (1981).

TABLE I

PARAMETERS FOR THE RESOLVED RESONANCE REGION

FKEY# 6. PRINT OF THE RECALLED FILE <CM246>

ZAI	ABN	b	LFW	NER	b
9.62460E+04	1.00000E+00	0.00000E+00	1.00000E+00	1.00000E+00	0.00000E+00
EL	EH	LRU	LRF	b	b
1.00000E-05	3.90000E+02	1.00000E+00	2.00000E+00	0.00000E+00	0.00000E+00
SPI	AP	b	b	NLS	NE
0.00000E+00	9.50000E-01	0.00000E+00	0.00000E+00	1.00000E+00	0.00000E+00
AWRI	AM	L	b	6*NRS	NRS
2.43953E+02	0.00000E+00	0.00000E+00	0.00000E+00	6.60000E+01	1.10000E+01
ER	AJ	GT	GN	GG	GF
4.31000E+00	5.00000E-01	3.57600E-02	3.30000E-04	3.50000E-02	4.30000E-04
1.52900E+01	5.00000E-01	3.59500E-02	5.50000E-04	3.50000E-02	4.00000E-04
8.44300E+01	5.00000E-01	5.96607E-02	2.19607E-02	3.70000E-02	7.00000E-04
9.18400E+01	5.00000E-01	5.61449E-02	1.89749E-02	3.70000E-02	1.70000E-04
1.58400E+02	5.00000E-01	6.66771E-02	2.89471E-02	3.70000E-02	7.30000E-04
2.50700E+02	5.00000E-01	4.67217E-02	9.34177E-03	3.70000E-02	3.80000E-04
2.78300E+02	5.00000E-01	4.53065E-02	7.00657E-03	3.70000E-02	1.30000E-03
2.88200E+02	5.00000E-01	9.67275E-02	5.94175E-02	3.70000E-02	3.10000E-04
3.13400E+02	5.00000E-01	6.19343E-02	2.47843E-02	3.70000E-02	1.50000E-04
3.61000E+02	5.00000E-01	9.29837E-02	5.56700E-02	3.70000E-02	3.13700E-04
3.81100E+02	5.00000E-01	1.54310E-01	1.17130E-01	3.70000E-02	1.80000E-04

TABLE II

CONTRIBUTION OF RESOLVED RESONANCES TO THERMAL CROSS SECTIONS AND RESONANCE INTEGRALS

Cm-246 resolved region - 12/02/1982

FKEY# 9: RESONANCE INTEGRAL CALCULATION

DATA ON <ENDFA> FILE HAVE BEEN RECALLED FROM DISK

Res.#	RI CAPTURE	SUM RI CAPTURE	RI FISSION	SUM RI FISSION
1	7.21152E+01	7.21152E+01	8.85987E-01	8.85987E-01
2	9.48140E+00	8.15966E+01	1.08359E-01	9.94346E-01
3	7.90136E+00	8.94980E+01	1.49485E-01	1.14383E+00
4	6.12950E+00	9.56275E+01	2.81626E-02	1.17199E+00
5	2.64628E+00	9.82738E+01	5.22105E-02	1.22420E+00
6	4.86102E-01	9.87599E+01	4.99240E-03	1.22920E+00
7	3.05055E-01	9.90649E+01	1.07181E-02	1.23991E+00
8	1.13123E+00	1.00196E+02	9.47790E-03	1.24939E+00
9	6.22613E-01	1.00819E+02	2.52411E-03	1.25192E+00
10	7.02268E-01	1.01521E+02	5.95409E-03	1.25787E+00
11	7.98320E-01	1.02319E+02	3.88372E-03	1.26175E+00

```
CAPTURE RES.INTEGRAL = :        102.31936  between .5  and 390
FISSION RES.INTEGRAL = :        1.2617545  between .5  and 390
1/v part of CAPTURE =           .63331919 (th.capture= 1.46 barns)
1/v part of FISSION =           6.0729238E-02 (th.fission= .14 barns)

TOTAL CAP. RES. INTEGRAL =      102.95268  between .5  and 390
TOTAL FIS. RES. INTEGRAL =      1.3224837  between .5  and 390
```

T A B L E III

AVERAGE PARAMETERS FOR THE UNRESOLVED REGION

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FKEY= 6: PRINT OF THE RECALLED FILE <CM246U>
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     EL           EH          LRU          LRF           b            b
 3.90000E+02 1.00000E+04 2.00000E+00 1.00000E+00 0.00000E+00 0.00000E+00
    SPI           AP           b            b           NLS           NE
 0.00000E+00 9.50000E-01 0.00000E+00 0.00000E+00 2.00000E+00 2.00000E+00
   ■ ES = 390   10000    ■
    AWRI          AM           L            b          6*NJS         NJS
 2.43953E+02 0.00000E+00 0.00000E+00 0.00000E+00 6.00000E+00 1.00000E+00
     DJ           AJ          AMUN         <GN0>        <GG>          MUF
 2.13000E+01 5.00000E-01 1.00000E+00 1.64010E-03 3.30000E-02 1.00000E+00
   ■ GF = .00048   .0017    ■
    AWRI          AM           L            b          6*NJS         NJS
 2.43953E+02 0.00000E+00 1.00000E+00 0.00000E+00 1.20000E+01 2.00000E+00
     DJ           AJ          AMUN         <GN0>        <GG>          MUF
 2.13000E+01 5.00000E-01 1.00000E+00 2.60000E-04 3.30000E-02 1.00000E+00
   ■ GF = .00048   .002    ■
 1.06500E+01 1.50000E+00 1.00000E+00 2.76900E-03 3.30000E-02 1.00000E+00
   ■ GF = .00048   .0017    ■
```

TABLE IV

AVERAGE S-WAVE RESONANCE SPACING $\bar{D}$

Value (eV)	Year	Ref.	Comments
29	1975	[28]	From $\bar{D}_{obs}$ = 38 eV, corrected for missing levels
42	1980	[1]	Staircase of resonances [2]
30	1980	[1]	Microscopic BCS calculation
20.3 ± 5.3	1980	[1]	Missing level estimator (M.L.E.) applied to res. [2]
22.4 ± 5.3	1980	[1]	Missing level estimator applied to res. [2] + [3]
21.3	1980	[1]	Adopted value: arithmetic mean of M.L.E. estimates

TABLE V.

AVERAGE RADIATIVE WIDTH $\bar{\Gamma}_{\gamma}$

Value (meV)	Year	Ref.	Comments
35 ± 5	1964	[29]	Determined from shape analysis of 1 res.
37	1971	[2]	Assumed; adopted for 9 res. in this work
35 ± 3	1972	[3]	Determined for 2 res.; assumed for the same res. in this work
31 ± 6	1974	[4]	Determined from shape analysis of 1 res.
27.1 ± 1.8	1976	[30]	Determined from analysis of 2 res.
32.6	1980	[1]	Calculated by means of the black-body formula of ref. [31]
33.4	1980	[1]	From statistical calc. at $E_n \simeq 1$ KeV for $J^{\pi} = 1/2^{\pm}$
32.9	1980	[1]	From statistical calc. at $E_n \simeq 1$ KeV for $J^{\pi} = 3/2^{-}$

TABLE VI

THERMAL CROSS SECTIONS

Capture (b)	Year	Ref.	Comments
1.5 ± 0.5	1971	[32]	
1.2 ± 0.4	1974	[4]	Calculated from 10 res. between 4 and 380 eV
1.14 ± 0.3	1978	[11]	Measured by Cadmium difference method; rel. to ^{235}U
1.24 ± 0.41	1980	[1]	Average of [32] and [11]
1.46	1982	[35]	Calculated from resonances

Fission (b)	Year	Ref.	Comments
0.17 ± 0.10	1972	[9]	Relative to ^{235}U
0.14 ± 0.05	1976	[10]	Relative to ^{235}U
0.17	1982	[35]	Calculated from resonances Plus 1/v background

TABLE VII

RESONANCE INTEGRALS

Capture (b)	Year	Ref.	Comments
121 ± 7	1969	[33]	$E_n \geq 0.54$ eV
110 ± 40	1969	[34]	
84 ± 15	1971	[32]	No cutoff given
101 ± 11	1974	[4]	Calculated from 10 res. between 3 and 380 eV
118 ± 15	1978	[11]	No cutoff given
113.0	1982	[35]	$E_n \geq 0.5$ eV; calculated from resonances in table I

Fission (b)	Year	Ref.	Comments
10.0 ± 0.4	1972	[9]	$E_n \geq 0.625$ eV; relative to ^{235}U
13.3 ± 1.5	1976	[10]	$E_n \geq 0.52$ eV; relative to ^{235}U
6.94	1982	[35]	$E_n \geq 0.5$ eV; contribution of resonance region: 1.44 b; continuum: 5.50 b

TABLE VIII

DEFORMED OPTICAL MODEL POTENTIAL

$$\mathcal{V} = -(V+iW)\frac{1}{1+\exp[(r-R_a)/a]} - 4iW_D\frac{\exp[(r-R_b)/b]}{\{1+\exp[(r-R_b)/b]\}^2}$$

$$- V_{SO}\,\vec{\sigma}\cdot\vec{\ell}\,\frac{\lambda\!\!\!^{-}{}_\pi^2}{ar}\frac{\exp[(r-R_a)/a]}{\{1+\exp[(r-R_a)/a]\}^2}\;; \quad \text{here:}$$

$R_{a,b} = R^{(o)}_{a,b}(1 + \beta_2 Y_2^o(\theta') + \beta_4 Y_4^o(\theta'))$ (θ' refers to the body-fixed system)

$\lambda\!\!\!^{-}{}_\pi = \lambda_\pi/2\pi$ (reduced pionic Compton wavelength)

$V = 47.01 - 0.267\ E_n - 0.00118\ E_n^2$ (MeV) (E_n in MeV)

$W = 0$

$$W_D = \begin{cases} 3.195\ \text{MeV} & (E_n \le 2.25\ \text{MeV}) \\ 2.25 + 0.42\ E_n\ (\text{MeV}) & (E_n\ \text{in MeV}) \end{cases}$$

$V_{SO} = 7.2$ MeV

$R_a^{(o)} = 1.259$ fm ; $R_b^{(o)} = 1.237$ fm ;

$a = 0.66$ fm ; $b = 0.48$ fm ;

$\beta_2 = 0.245$; $\beta_4 = 0.003$.

TABLE IX

DISCRETE LEVELS AND LEVEL DENSITY PARAMETERS FOR ^{245}Cm NEUTRON CHANNEL

Discrete levels /36/:

E (keV)	J^{π}
0.0	$7/2^+$
54.8	$9/2^+$
121.5	$11/2^+$
197.0	$13/2^+$
252.85	$5/2^+$
295.7	$7/2^+$
350.5	$9/2^+$
355.9	$1/2^+$
361.5	$3/2^+$
388.1	$9/2^-$
417.0	$11/2^+$
418.8	$5/2^+$
431.0	$7/2^+$
442.8	$11/2^-$
498.0	$13/2^+$
508.7	$13/2^-$
532.0	$9/2^+$
555.0	$11/2^+$

Continuum: E > 555 keV; level density described by the formula:

$$\rho(E,J) = \frac{(2J+1)}{24\sqrt{2}\sigma^3} \frac{\exp(2\sqrt{a(E-\Delta)})}{a^{1/4}(E-\Delta+T)^{5/4}} \exp\left[-J(J+1)/2\sigma^2\right]$$

where:

$$\sigma^2 = cT$$
$$E-\Delta = aT^2-T$$
$$a = 24.5\ \mathrm{MeV}^{-1}$$
$$\Delta = -0.10\ \mathrm{MeV}$$
$$\sigma^2/T = 100\ \mathrm{MeV}^{-1}$$

T A B L E X

DISCRETE LEVELS AND LEVEL DENSITY PARAMETERS FOR ^{246}Cm

Neutron channel:

Discrete levels /36/

E (keV)	J^{π}
0.0	0^+
42.9	2^+
142.0	4^+
295.5	6^+
500.0	8^+

Continuum: E > 500 keV, level density formula as in table IX, with parameters

$$a = 24.0 \text{ MeV}^{-1}$$
$$\Delta = -0.37 \text{ MeV}$$
$$\sigma^2/T = 100 \text{ MeV}^{-1}$$

Fission channel (^{246}Cm as fissioning nucleus):

Transition states at the first barrier peak described by a level density formula as in table IX, with parameters:

$$a = 26.5 \text{ MeV}^{-1}$$
$$\Delta = -0.45 \text{ MeV}$$
$$\sigma^2/T = 100 \text{ MeV}^{-1}$$

TABLE XI

DISCRETE LEVELS AND LEVEL DENSITY PARAMETERS FOR ^{247}Cm

Gamma channel (^{247}Cm as decaying nucleus):

Discrete levels /36/

E (keV)	J^{π}
0.0	$9/2^-$
61.5	$11/2^-$
133.0	$13/2^-$
217.0	$15/2^-$
227.0	$5/2^+$
266.0	$7/2^+$
285.0	$7/2^+$
309.0	$(17/2^-)$

Continuum: E > 309 keV, level density formula as in table IX, with parameters

$a = 25.2$ MeV^{-1}

$\Delta = -0.69$ MeV

$\sigma^2/T = 100$ MeV^{-1}

Fission channel (^{247}Cm as fissioning nucleus):

Transition states at the first barrier peak described by a level density formula as in table IX, with parameters:

$a = 26.5$ MeV^{-1}

$\Delta = -1.7$ MeV

$\sigma^2/T = 98$ MeV^{-1}

TABLE XII

FISSION BARRIER PARAMETERS

Fissioning nucleus: ^{246}Cm

First peak		Second peak	
Height, E_A (MeV)	Curvature, $\hbar\omega_A$ (MeV)	E_B (MeV)	$\hbar\omega_B$ (MeV)
6.0	0.9	4.2	0.55

Fissioning nucleus: ^{247}Cm

First peak		Second peak	
Height, E_A (MeV)	Curvature, $\hbar\omega_A$ (MeV)	E_B (MeV)	$\hbar\omega_B$ (MeV)
6.0	0.63	4.2	0.55

FIGURE CAPTIONS

Fig. 1a,b,c,d — Total, elastic, capture and fission cross sections in the resolved resonance region.

Fig. 2 — Evaluated fission cross section in comparison with experimental data from: O and □ , ref. /2/; ∇, ref./12/; ◆ , ref. /13/.

Fig. 3 — Neutron cross sections in the range 10 keV - 15 MeV.

Fig. 4a,b,c,d — Neutron cross sections over the complete evaluation range 10^{-5} eV - 15 MeV: a) total; b) elastic; c) capture and d) fission.

Fig. 5a,b,c — Effective temperature $\theta(E)$ versus incident neutron energy E , relative to the energy spectra of emitted neutrons in (n,2n), (n,f), (n,n'f) and (n,n'γ) reactions.

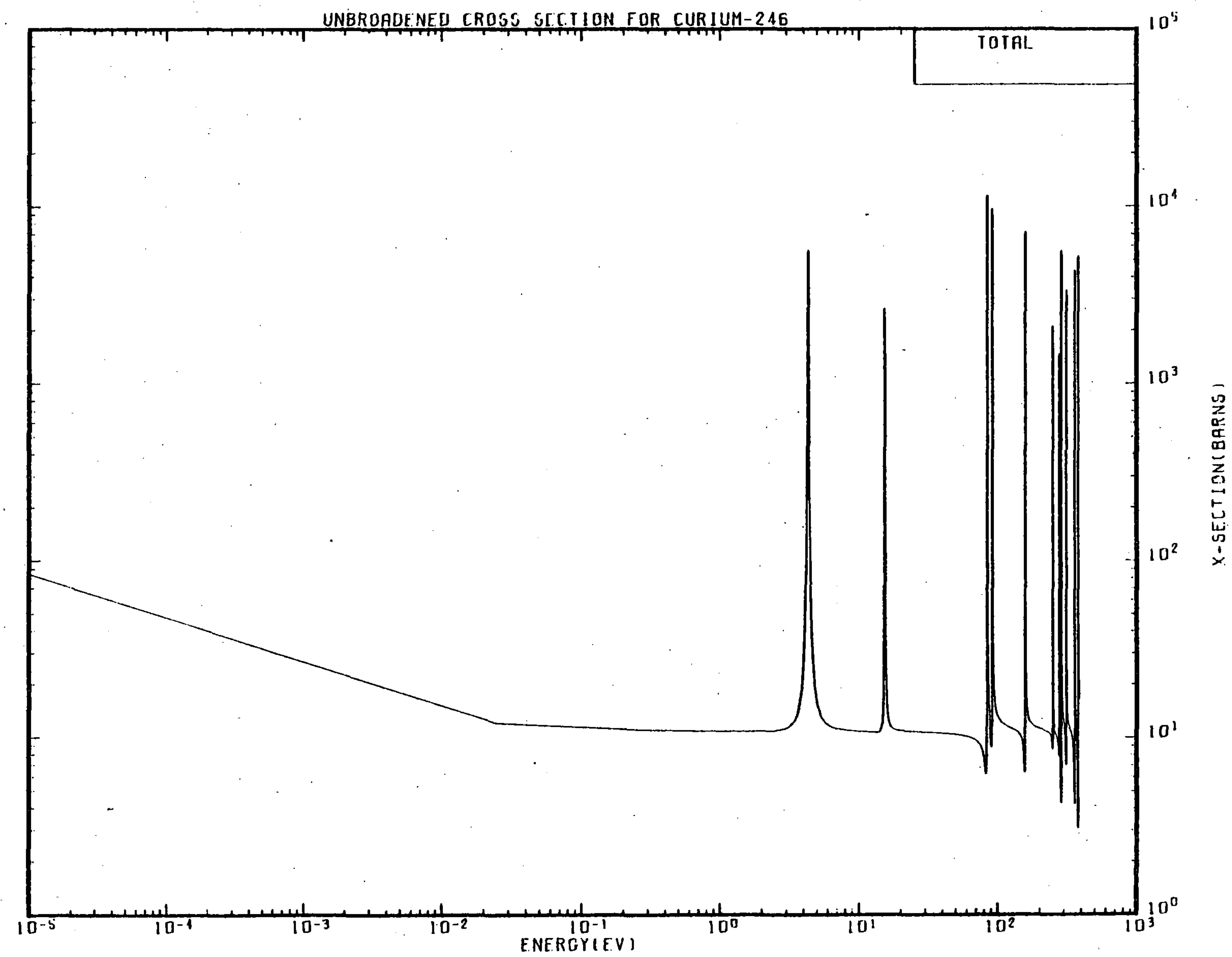

UNBROADENED CROSS SECTION FOR CURIUM-246
TOTAL
ENERGY(EV)
X-SECTION(BARNS)
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5}

Fig. 1a

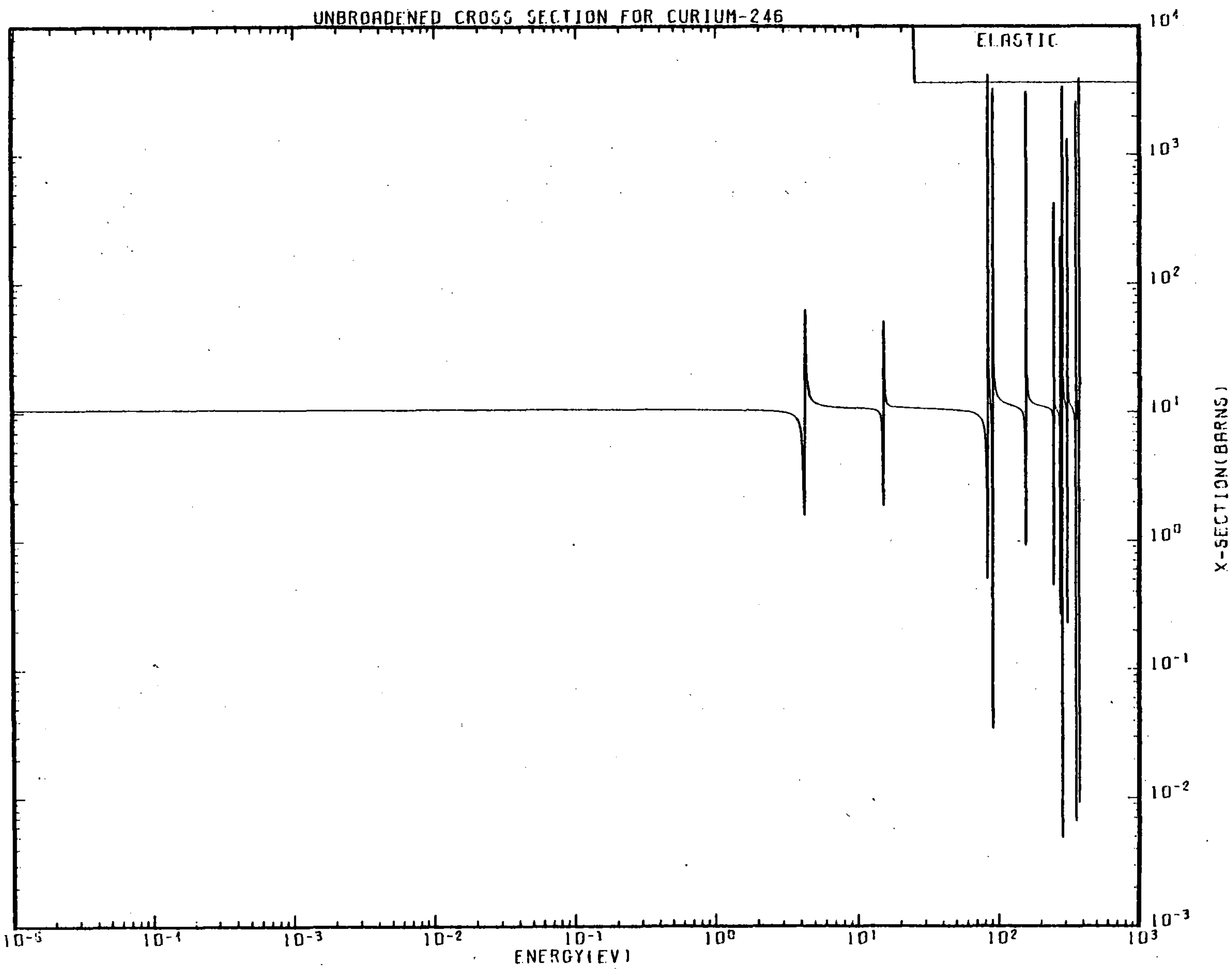
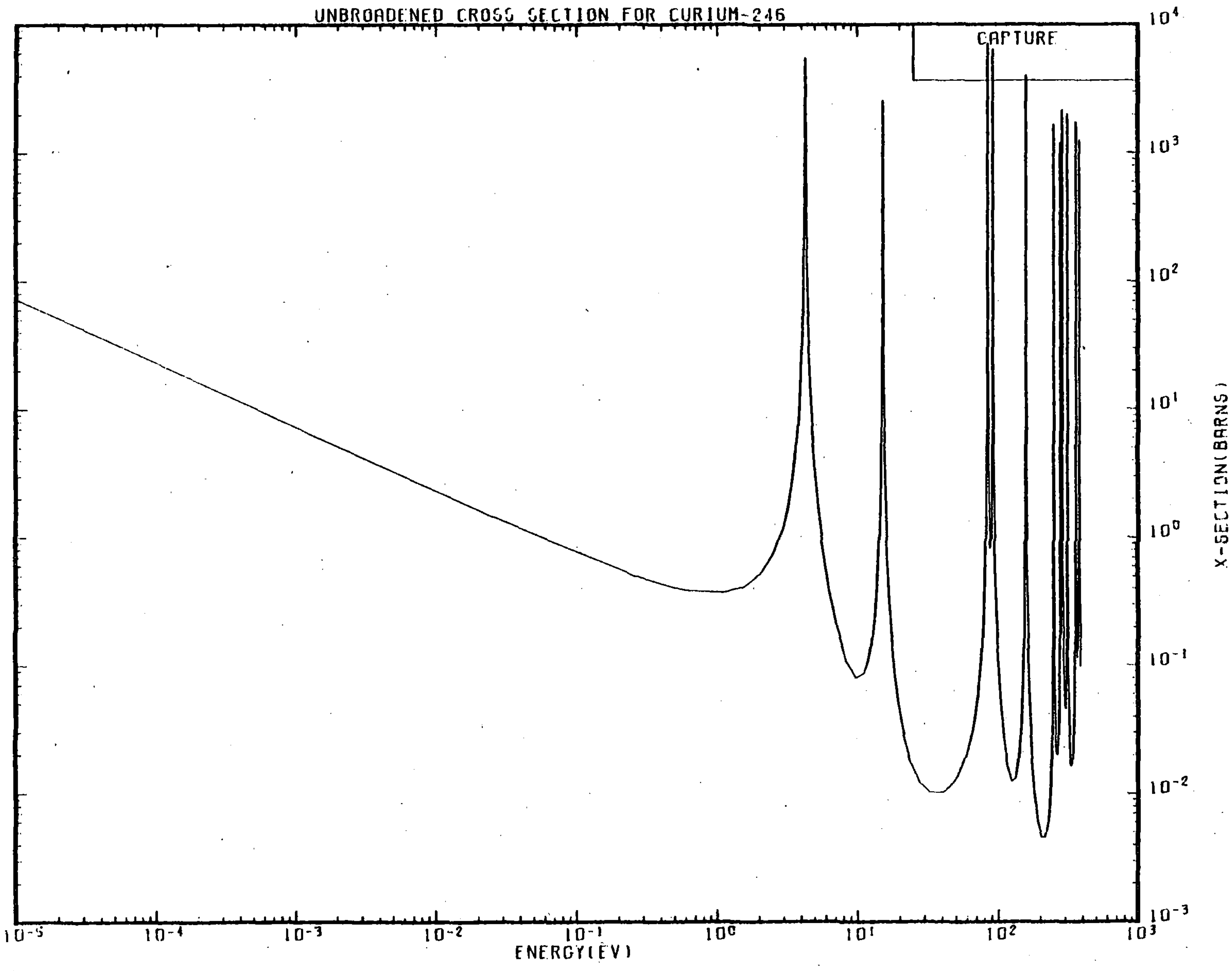
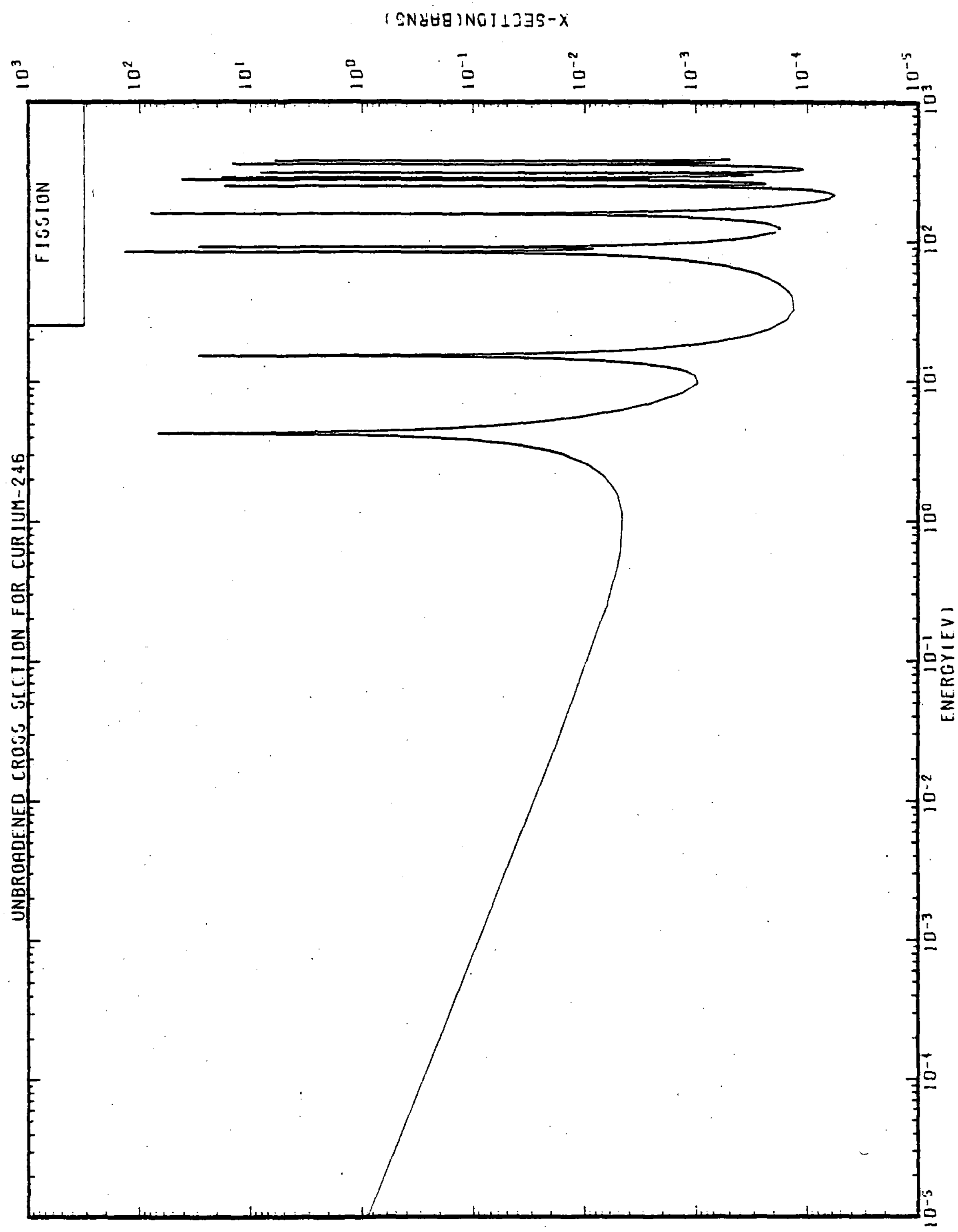

UNBROADENED CROSS SECTION FOR CURIUM-246
ELASTIC
ENERGY(EV)
X-SECTION(BARNS)
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
10^{4} 10^{3} 10^{2} 10^{1} 10^{0} 10^{-1} 10^{-2} 10^{-3}

Fig. 1b



UNBROADENED CROSS SECTION FOR CURIUM-246
CAPTURE
ENERGY(EV)
X-SECTION(BARNS)
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
10^{4} 10^{3} 10^{2} 10^{1} 10^{0} 10^{-1} 10^{-2} 10^{-3}

Fig. 1c



UNBROADENED CROSS SECTION FOR CURIUM-246
FISSION
X-SECTION(BARNS)
ENERGY(EV)

Fig. 1d

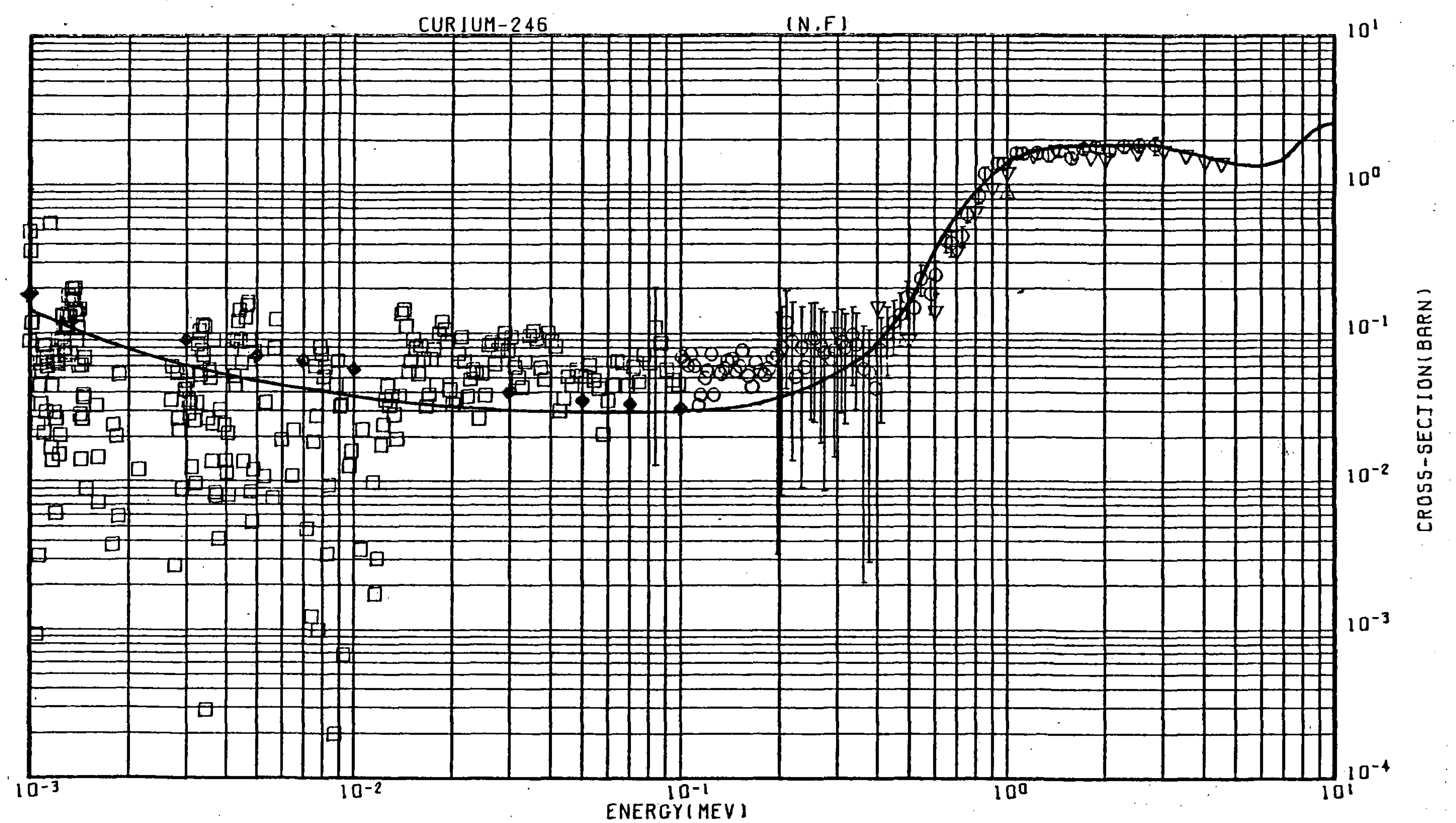

CURIUM-246
(N,F)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
CROSS-SECTION(BARN)
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
ENERGY(MEV)

Fig. 2

CROSS SECTIONS IN THE FAST ENERGY RANGE

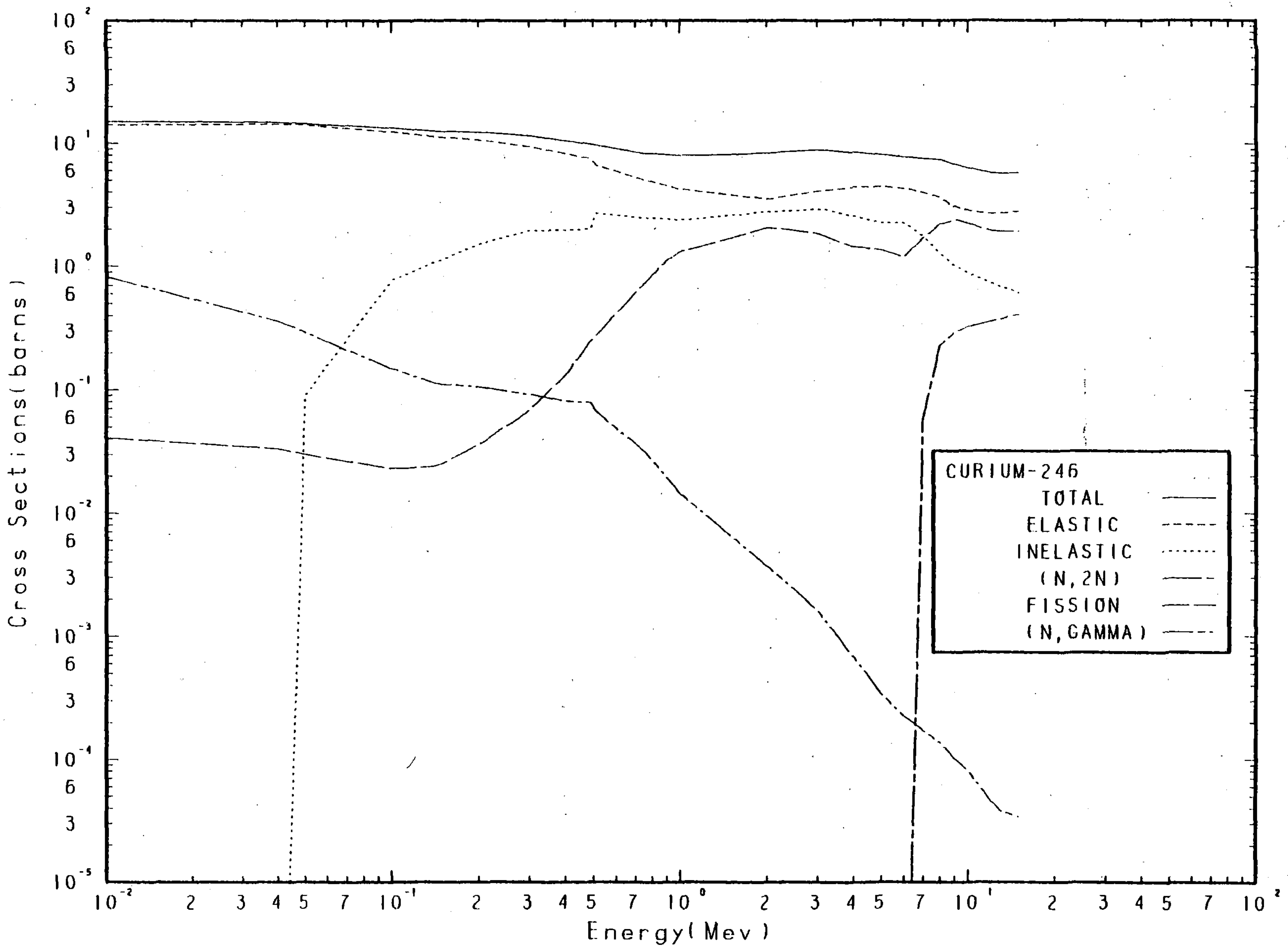


Fig. 3

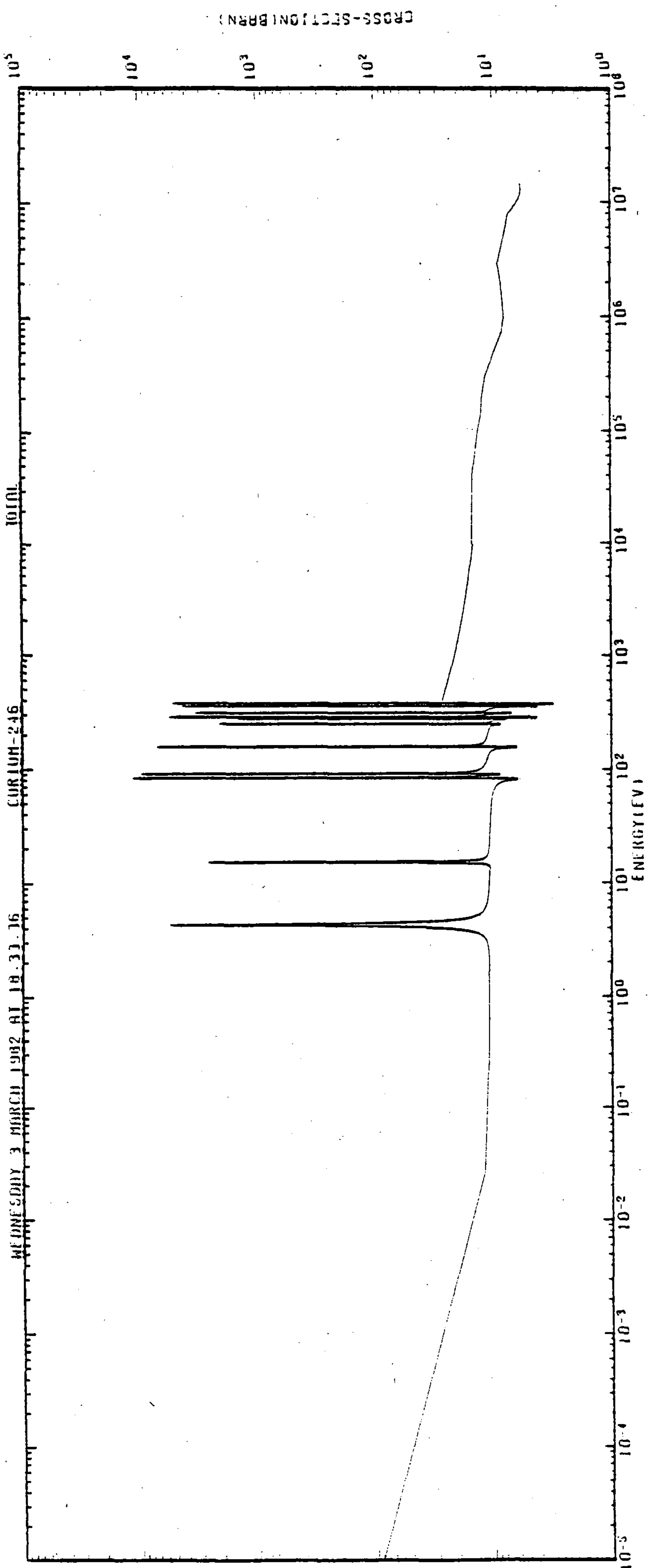

CROSS-SECTION(BARN)
TOTAL
CURIUM-246
WEDNESDAY 3 MARCH 1982 AT 18.33.16
ENERGY(EV)

Fig. 4a

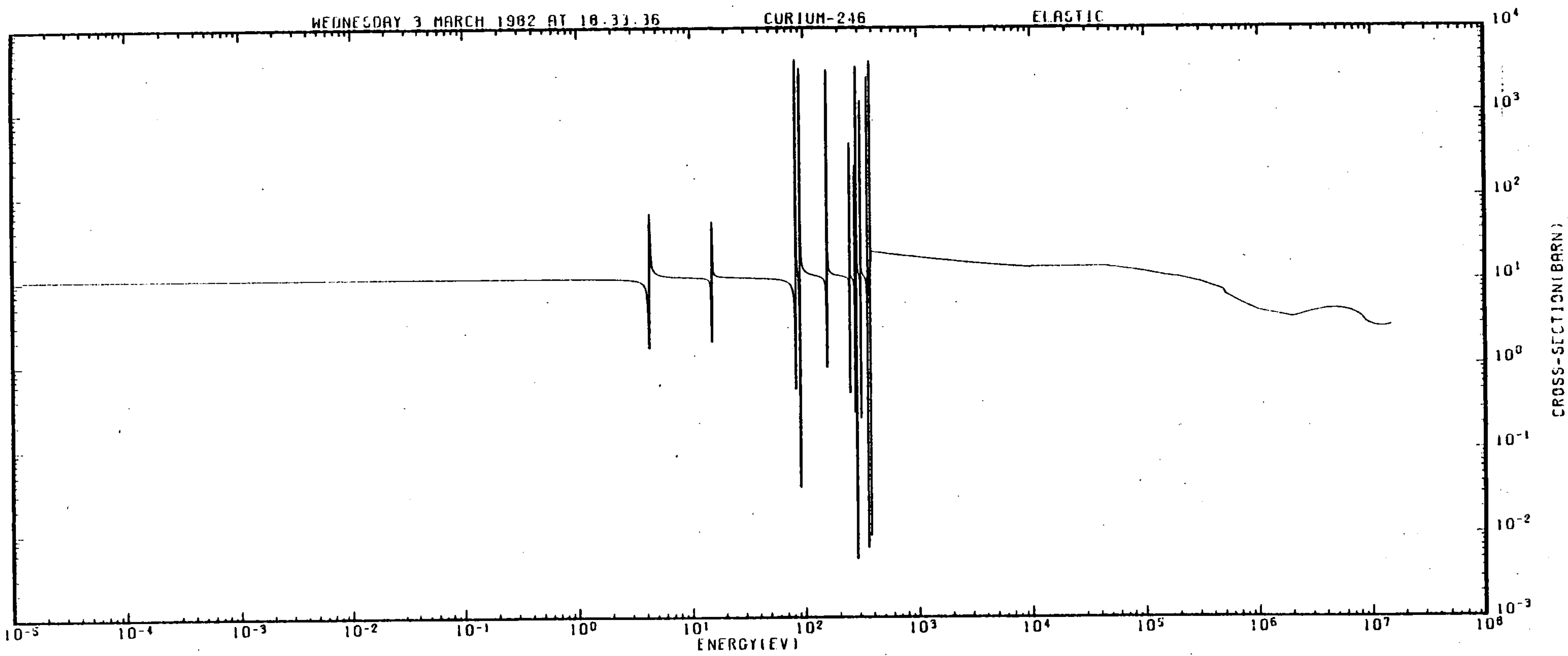

WEDNESDAY 3 MARCH 1982 AT 18.33.36
CURIUM-246
ELASTIC
ENERGY(EV)
CROSS-SECTION(BARN)
10⁻⁵ 10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 10⁰ 10¹ 10² 10³ 10⁴ 10⁵ 10⁶ 10⁷ 10⁸
10⁴ 10³ 10² 10¹ 10⁰ 10⁻¹ 10⁻² 10⁻³

Fig. 4b

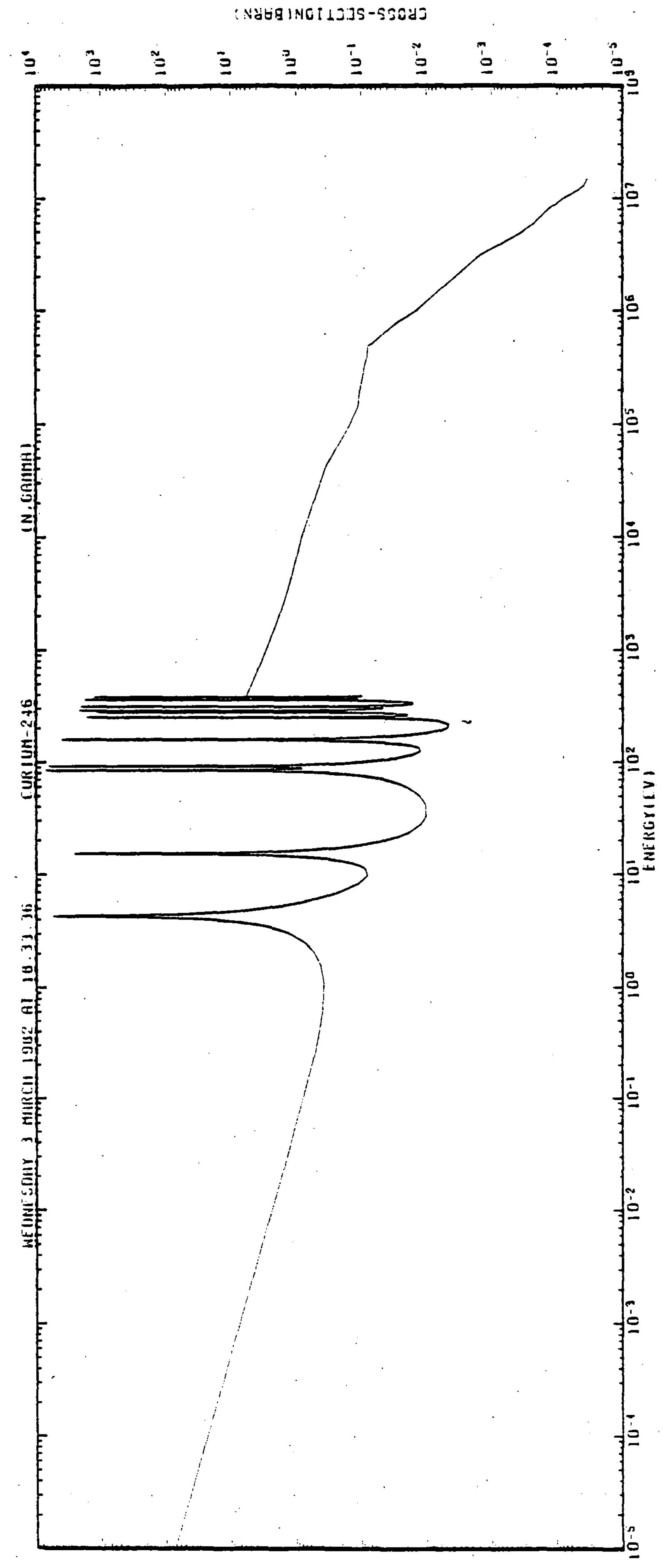


Fig. 4c

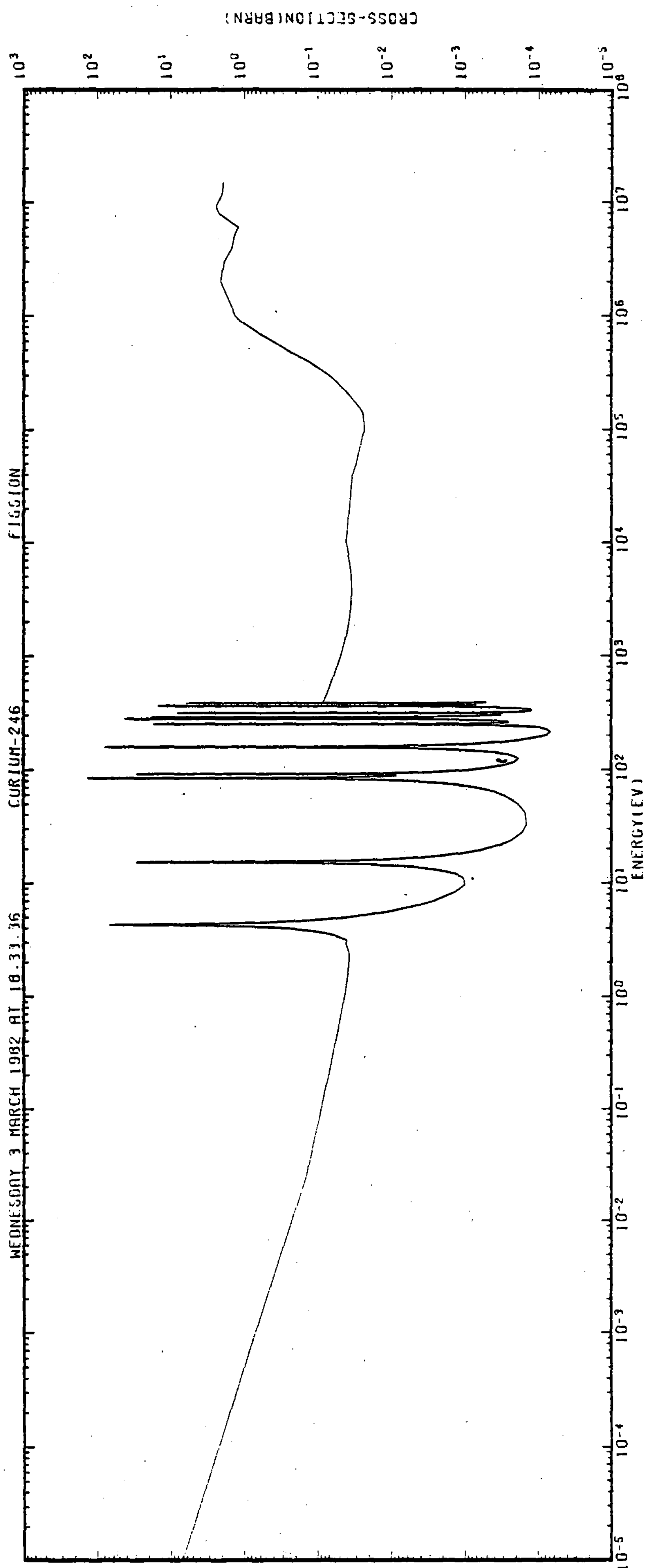
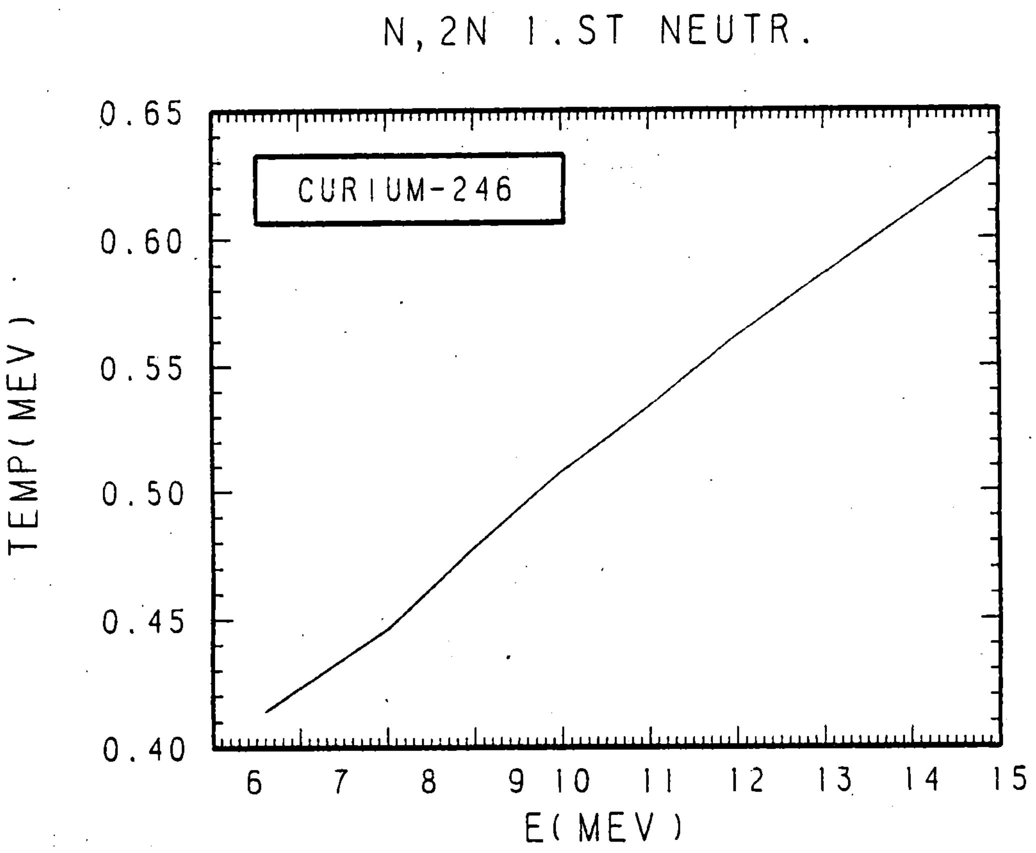

WEDNESDAY 3 MARCH 1982 AT 18.33.36
CURIUM-246
FISSION
CROSS-SECTION(BARN)
ENERGY(EV)
10^{3} 10^{2} 10^{1} 10^{0} 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5}
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8}

Fig. 4d


N, 2N 1.ST NEUTR.
CURIUM-246
TEMP(MEV)
0.65
0.60
0.55
0.50
0.45
0.40
6
7
8
9
10
11
12
13
14
15
E(MEV)

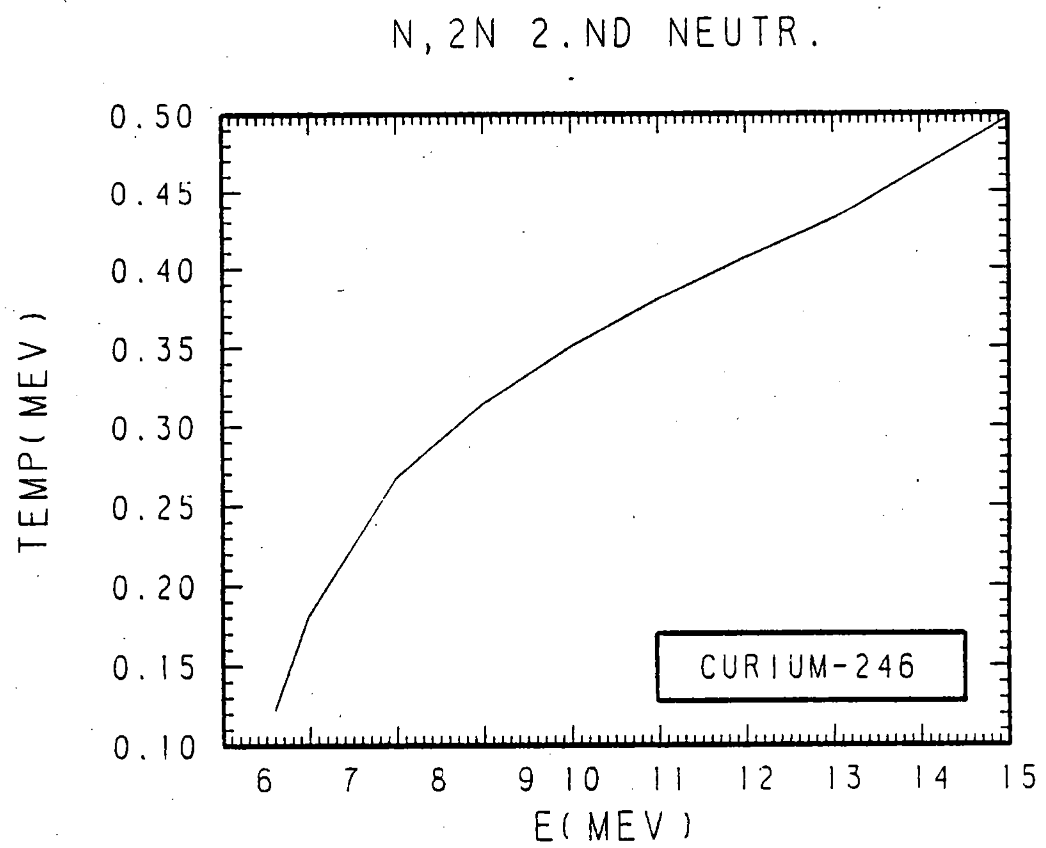
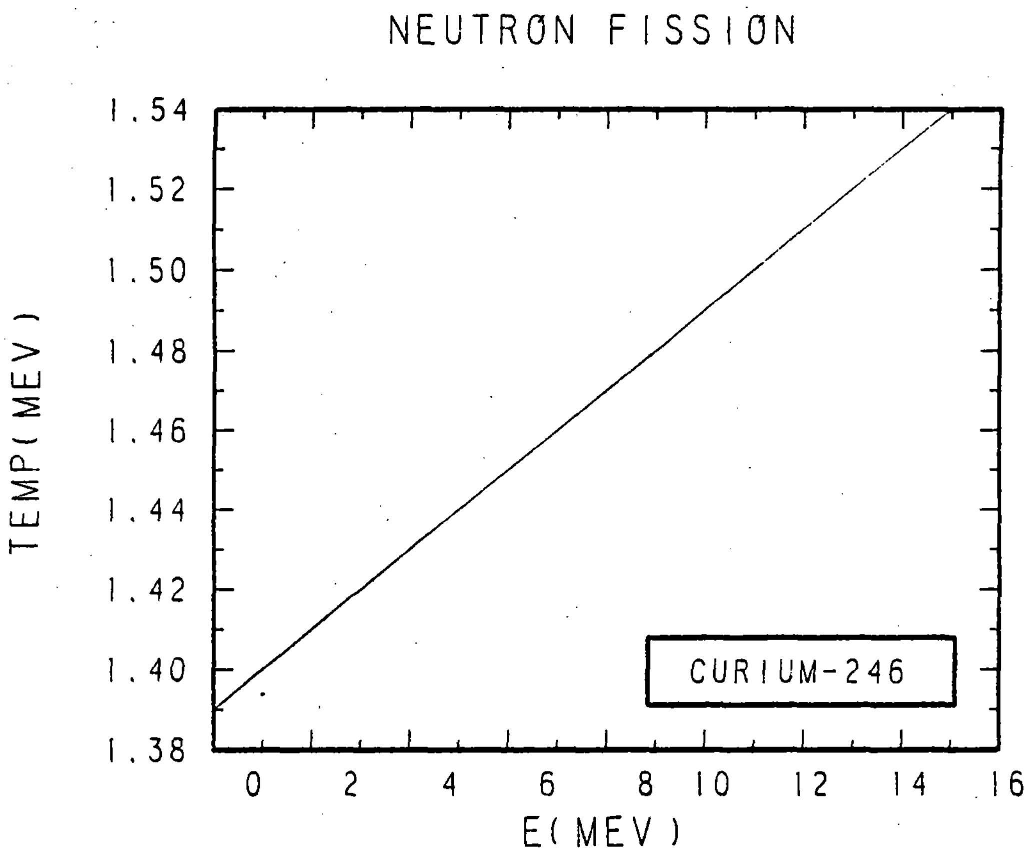

N, 2N 2.ND NEUTR.
CURIUM-246
TEMP(MEV)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
6
7
8
9
10
11
12
13
14
15
E(MEV)

Fig. 5a


NEUTRON FISSION
TEMP(MEV)
1.54
1.52
1.50
1.48
1.46
1.44
1.42
1.40
1.38
CURIUM-246
0
2
4
6
8
10
12
14
16
E(MEV)

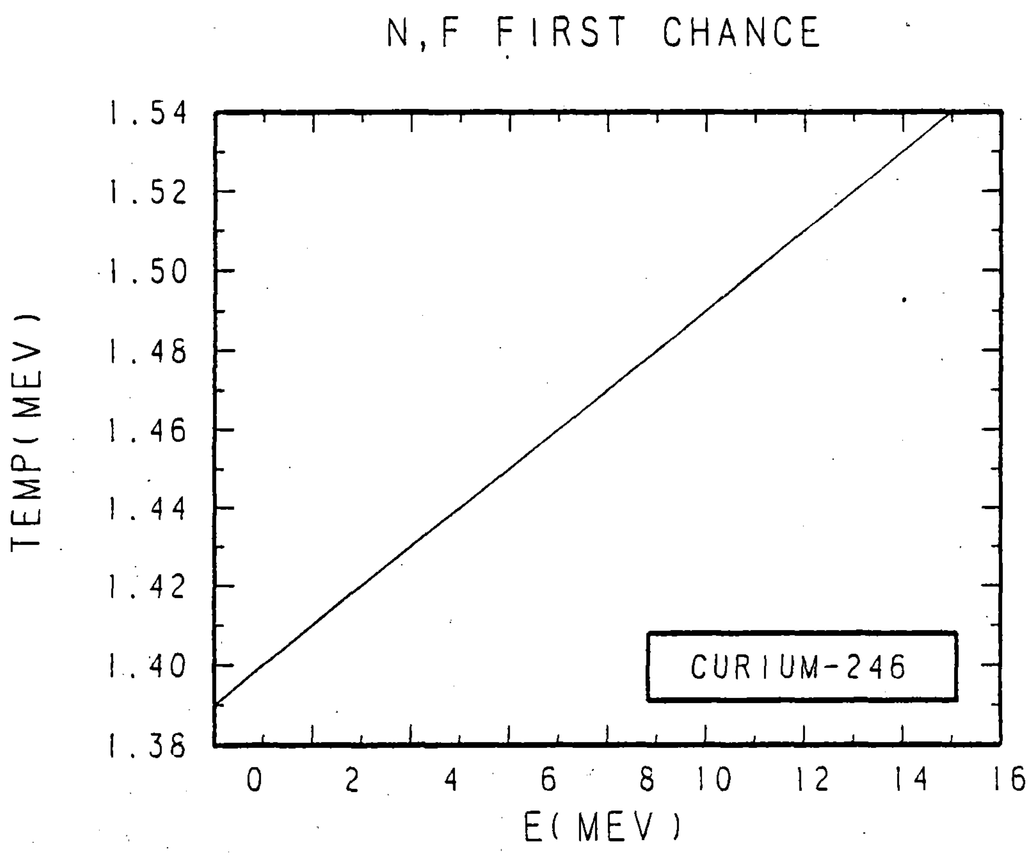
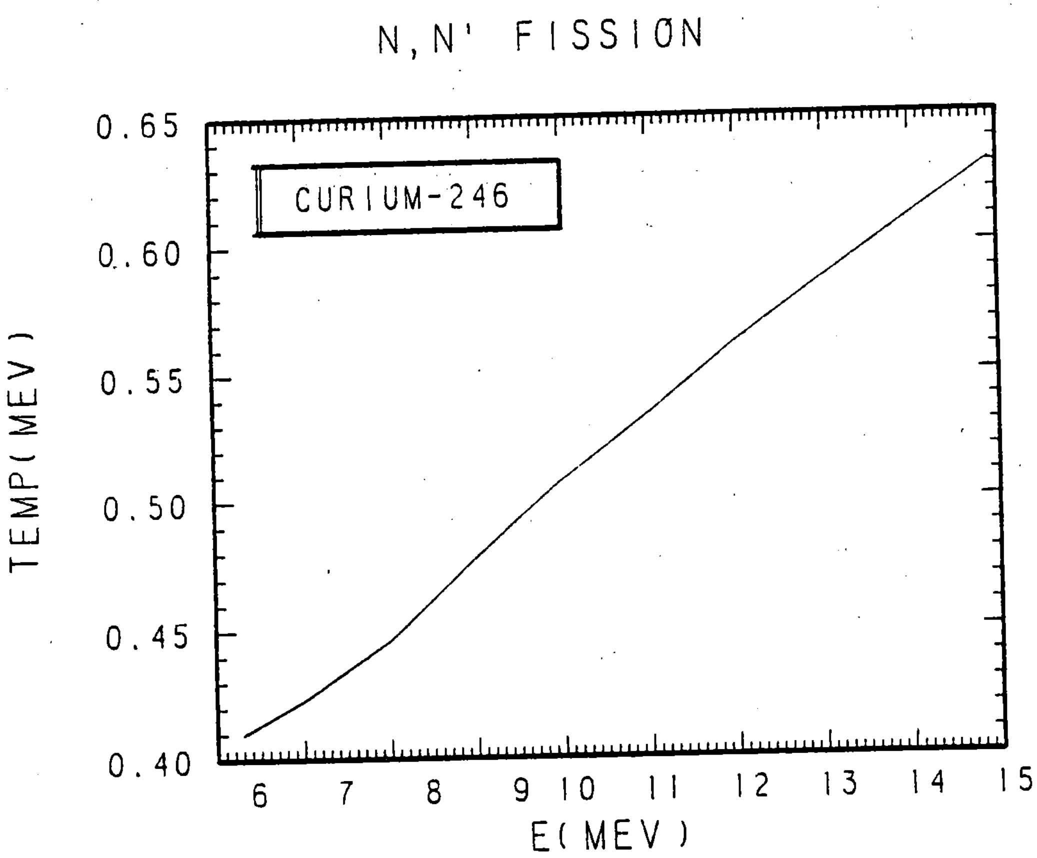

N,F FIRST CHANCE
TEMP(MEV)
1.54
1.52
1.50
1.48
1.46
1.44
1.42
1.40
1.38
CURIUM-246
0
2
4
6
8
10
12
14
16
E(MEV)

Fig. 5b


N, N' FISSION
CURIUM-246
TEMP(MEV)
E(MEV)
0.65
0.60
0.55
0.50
0.45
0.40
6
7
8
9
10
11
12
13
14
15

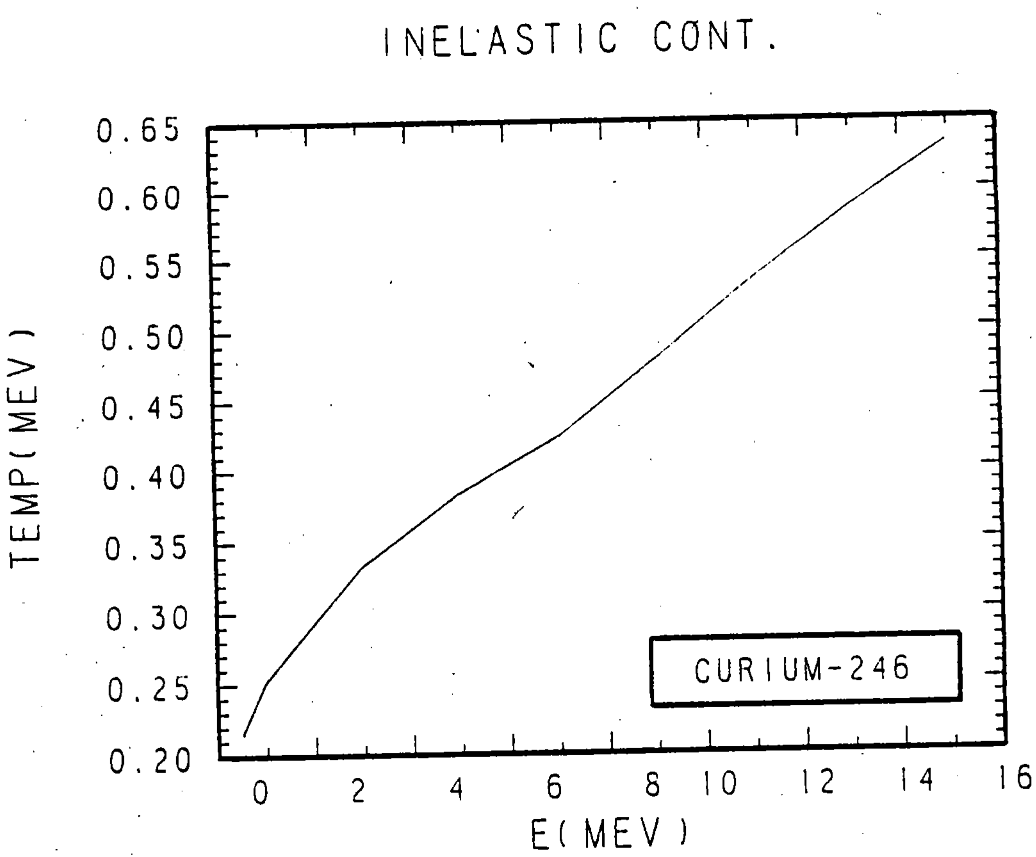

INELASTIC CONT.
CURIUM-246
TEMP(MEV)
E(MEV)
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0
2
4
6
8
10
12
14
16

Fig. 5c