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EVALUATION OF Cm-248 NEUTRON CROSS SECTIONS FROM 10^{-5} eV TO 15 MeV

G. MAINO, M. ROSETTI, M. VACCARI, A. VENTURA

WORK PERFORMED UNDER ENEA-IAEA
RESEARCH AGREEMENT N. 2114/CF

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CONTENTS

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RIASSUNTO - Dopo una breve rassegna dei dati sperimentali più importanti, è descritta una valutazione delle sezioni d'urto neutroniche dell'isotopo Cm-248 nell'intervallo energetico 10^{-5} e V - 15 MeV.

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SUMMARY - After a short review of the most important experimental data,a Cm-248 neutron cross section evaluation in the energy range 10^{-5} eV - 15 MeV is described.

1. INTRODUCTION

The neutron cross sections of heavier Curium isotopes are very important in the description of the ^{252}Cf production chain by plutonium irradiation in high-flux reactors.

The present work describes an evaluation of ^{248}Cm neutron cross sections in the energy range 10^{-5} eV - 15 MeV, and supersedes a previous work /1/, limited to the resonance region.

2. GENERAL INFORMATION

This section is devoted to a concise review of the experimental literature taken into account in the present evaluation.

Since measurements of ^{248}Cm neutron data published up to 1979 have already been discussed in ref./1/, they will be merely quoted here, with more emphasis on the most recent experiments.

Thus, our main sources of experimental information are listed below:

a) The fission cross section was analysed by Moore and Keyworth /2/ in the energy range 20 eV - 3 MeV. A single-level resonance analysis, carried out between 20 and 800 eV, made it possible to identify 8 resonances

and assign fission widths to 3 of them, assuming an average radiative width $\overline{\Gamma}_\gamma = 37$ meV.

b) An accurate measurement of the total cross section in the range 0.5 eV - 3 KeV is due to Benjamin et al./3/. The results of this experiment still constitute the corner stone of our evaluation in the resonance region. In this experiment, 47 resonances were identified and their reduced neutron widths, Γ°_n, determined by assuming $\overline{\Gamma}_\gamma = 26$ meV. The shape analysis of the first 3 resonances made it possible to determine Γ°_n and Γ_γ simultaneously. The Authors of ref./3/ computed also the resonance contribution to the thermal capture cross section and resonance integral.

c) $\sigma_{n\gamma}$ (E_n = 0.0253 eV) and $I_{n\gamma}$ were measured by various Authors, with widely different results, often in strong mutual disagreement.
This is the case of the thermal capture cross section, $\sigma_{n\gamma}$, with an old experimental value of (7.0±2.0)b/4/, replaced by somewhat lower figures, of the order 2-3 b in successive experiments /5/, /6/, and raised again to (10.7±1.5) b by a measurement due to Gavrilov and Goncharov /7/. The values of $I_{n\gamma}$ given in /5/, /6/, /7/ are in reasonable agreement.

d) σ_{nf} (0.0253 eV) and I_{nf} (E_n > 0.625 eV) were measured by Benjamin et al. /8/, using ^{235}U as a standard.

A more recent experiment, carried out by Zhuravlev et al./9/, using again ^{235}U as a reference, provided values of σ_{nf} (0.0253 eV) and I_{nf} ($E_n > 0.5$ eV) in good agreement with the results of ref./8/.

A recent review of experimental values of thermal cross sections, resonance integrals and resolved resonance parameters is due to Belanova and Kolesov /10/.

e) A recent measurement of the fission cross section in the energy range 0.3 - 5.5 MeV is due to Fomushkin et al. /11/, by means of the time-of-flight method, using a nuclear explosion as a pulsed neutron source. The fission cross section, relative to ^{235}U (n,f) agrees well with ref./2/ up to about 2 MeV, and shows a decreasing trend above that energy, while the data of ref./2/ are more or less constant up to 3 MeV.

g) A very recent and accurate measurement of σ_{nf} between 0.1 eV and 80 KeV is due to a Rensselaer - Knolls - Oak Ridge-Livermore collaboration /12/, /13/. The preliminary measurement described in ref./12/ was performed by using the Rensselaer Intense Neutron Spectrometer (RINS), consisting of a lead slowing-down spectrometer coupled to an electron linac, which produces an intense photoneutron flux in the 1 eV - 100 Kev range. The target was a 27 μg deposit of highly enriched ^{248}Cm. Use was made of the time-of-flight method. The fission cross section was provisionally normalized by setting

the low-energy half-area of the 76 eV resonance equal to that calculated from a set of resonance parameters deduced from scientific literature. A subsequent measurement, described in ref. /13/, used the same experimental facility to determine simultaneously $^{244-246-248}Cm$ and ^{235}U fission cross sections from 0.1 eV to 80 KeV. The results were normalized to the ENDF/B-V $^{235}U(n,f)$ cross section.

The ^{248}Cm sample consisted of a 31.16 μg deposit of highly - enriched ^{248}cm (96.89% in mass).

The experiments /12/, /13/ provide us with the first measurement of σ_{nf} in the 0.1-20 eV range, not covered by ref./2/. Moreover, the data from 20 eV to 80 KeV can be taken as more reliable than those of ref./2/ in the same range, which had been obtained using a nuclear explosion as the pulsed neutron source.

3. RESOLVED RESONANCE REGION

The resolved resonance region extends up to 1.3 KeV, as in our previous work, /1/, whose list of single-level Breit-Wigner parameters has been modified at a few points, to take into account new experimental results, /13/, as shown in Table I of the present work. The list still contains 37 resonances, in the range 7.3-1300 eV, plus

a bound level at E_o = -9 eV, to reproduce experimental thermal cross sections. Energies, E_o, neutron widths, Γ_n, radiative widths, Γ_γ, still come from ref./3/. As for the fission widths, Γ_f, essential changes refer to two resonances at 7.3 eV and 35 eV, for which the Authors of ref. /13/ have obtained values of 0.06 and 0.07 meV, respectively, on the basis of their fission measurements and of neutron and gamma widths taken from ref./3/. These results fill an important gap in experimental data, but, being so small, cause further difficulties in reproducing the thermal fission cross section and resonance integral. This point will be further discussed in Section 5. For resonances whose Γ_f's are not deduced from experiment, we have retained the average value $\overline{\Gamma_f}$ = 1.3 meV, suggested in ref. /14/, which agrees with our statistical model calculations in the KeV region.

Cross sections in the resolved resonance region are shown in fig. 1a-b-c-d. The calculations have been carried out by means of the CRESO code /15/, using a multilevel Breit-Wigner formalism in order to avoid the possible appearance of negative values of the interference dips in the elastic cross section.

4. UNRESOLVED RESONANCE REGION

In the energy range 1.3-10 KeV the neutron cross sections have been calculated by means of average resonance parameters, whose values are those deduced from the resolved resonance set, or change slowly with energy, so as to smoothly join the resonance region to the continuum, above 10 KeV, where cross sections have been derived from optical and statistical model calculations. Table II lists, in ENDF/B-IV format, the average parameters for the unresolved region. Since there are no changes with respect to ref. /1/, the reader is referred to our previous work for a critical discussion. Here, we only quote the most important parameters:

a) the average s-wave resonance spacing, $\overline{D}$, keeps the value 24.5 eV estimated in /1/;

b) the s- and p-wave neutron strength functions are still $S_o = 1.2\times10^{-4}$ and $S_1 = 3\times10^{-4}$, as in /1/;

c) the average radiation width for s-wave resonance is $\overline{\Gamma}_\gamma(J^\pi = 1/2^+) = 27$ meV;

d) the average fission widths for s-waves ($J^\pi = 1/2\ +$) and p-waves ($J^\pi = 1/2^-$, $3/2^-$) slightly increase with neutron energy, so as to reproduce the results of Hauser-Feshbach calculations in the same energy range.

5. THERMAL CROSS SECTIONS AND RESONANCE INTEGRALS

Experimental and calculated values of thermal capture and fission cross sections are listed in Table III, the corresponding resonance integrals in Table IV.

As already mentioned in Section 2, there are serious discrepancies in the experimental capture cross sections, ranging from 2 to 10 b, while the measured fission cross sections agree within experimental errors, with a mean value 0.35 b.

If one adopts the lower limit 2 b for $\sigma_{n\gamma}$, it is possible to reproduce it in calculations based on experimental resonances, without resorting to a bound level: such a result had already been obtained in ref. /3/. On the other hand, there is no way of reproducing σ_{nf}. Therefore, we have preferred to keep a bound level at E_o = -9 eV, increasing its fission width from 1 meV (ref./1/) to 1.3 meV, to compensate for the smaller fission width assigned to the first resonance, at E_o = 7.3 eV, for which one now has Γ_f = 0.06 meV, value taken from ref./13/, instead of 1 meV as assumed in ref./1/. Thus, we obtain σ_{nf} (0.0253 eV) = 0.393 b, in good agreement with experimental values /8/, /9/, and $\sigma_{n\gamma}$ (0.0253 eV) = 9.808 b, which agrees with the most recent datum, in ref. /7/.

As for the capture resonance integral, we obtain $I_{n\gamma}$ (E_n >0.5 eV) = 270 b, which compares well with a number of

literature values in refs. /3/, /5/, /7/. The agreement with experiments is poorer for the fission resonance integral: in this case, one sums these two contributions: the first, which comes from the resonance region, is I_{nf} (0.5 eV < E_n < 10 KeV) = 3.398 b, the second, from the continuum, is I_{nf} (10 KeV < E_n < 15 MeV) = 6.216 b, thus giving I_{nf} (0.5 eV < E_n <15 MeV) = 9.614 b, to be compared with experimental values of the order 13 b (refs /8/ and /9/). This discrepancy could be reduced if the fission cross section reached a high plateau $\bar{\sigma}$ above 15 MeV, up to e.g. 30 MeV. In this case one could add to I_{nf} a further contribution of the order $\bar{\sigma}\cdot\ln(30/15)$, but eliminating the discrepancy with experimental data would require $\bar{\sigma} \simeq 4 \div 9$ b. Therefore, the matter remains unsolved.

6. 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.

Cross sections have been evaluated for the following reactions: elastic, total and level inelastic, first and second chance fission, and (n,2n). Reactions having a threshold above 10 MeV, like (n, 3n) and (n,2nf), have been

neglected. Preequilibrium competitions to various processes are not taken into account, because they are expected to become important only above 15 MeV.

6.1. Optical model calculations

Coupled-channel calculations have been performed by means of the JUPITOR /16/ and ADAPE /17/ codes: the former in the energy range from 10 KeV to 6 MeV, the latter from 6 MeV to 15 MeV, where the adiabatic approximation, on which ref. /17/ is based, seems to be good enough. The states actually coupled in our non-adiabatic calculations are the $0_1+, 2_1+, 4_1+$ members of the ground-state rotational band. The parameters of our optical potential are given in Table V.

The Coupled-channel calculations give the direct contribution to elastic and inelastic scattering: total cross sections and angular distributions have been evaluated for elastic scattering and for excitation of the 2_1+ level. The compound nucleus contributions to these processes have been obtained by means of Hauser-Feshbach calculations, described in the next subsection, and added to the direct contribution to elastic and inelastic scattering cross sections.

6.2. 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 /18/.

Three competing decay channels, neutron, gamma, and fission, are considered; the decay of the compound nucleus ^{249}Cm in the three channels makes it possible to evaluate the compound elastic, radiative capture and first-chance fission cross sections, respectively.

The formation of a compound nucleus ^{248}Cm, via neutron emission from ^{249}Cm, and its subsequent decay in neutron, gamma and fission channels allows us to compute cross sections for (n,2n), (n,n'γ), (n,n'f), respectively, with the assumption that these reactions can be described as two-step compound nucleus processes, thus neglecting any non--equilibrium contribution.

The decay channels of ^{248}Cm and ^{249}Cm are labelled with 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. Level densities are described by a back-shifted Fermi gas formula: since such a simple expression cannot give a realistic description of excited nuclei, its parameters do not have 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 one specifies height and curvature of the two saddle points. Our choice of barrier parameters for the compound nucleus ^{249}Cm is con-

sistent with the results of the analysis of experimental fission probabilities for odd-mass actinides in ref./19/. The barrier parameters for the compound nucleus ^{248}Cm are in agreement with the results of ref. /20/.

Level density parameters in the same fission channel have been indirectly checked by reproducing the experimental fission cross section of the target nucleus ^{247}Cm /21/.

All the parameters relevant to the description of the three decay channels for both ^{248}Cm and ^{249}Cm are given in Tables VI to VIII.

The results of our calculations in the continuum region are given in graphic form: Fig. 2 shows the evaluated fission cross section, together with experimental data from refs. /2/, /11/, /13/, Fig. 3 the main evaluated cross sections in the range 10 KeV - 15 MeV. Examples of angular distributions of scattered neutrons, leaving ^{248}Cm in 0_1+, and 2_1+ states at incident neutron energies 5,8,11,14 MeV are given in Figs. 4a-b-c-d, respectively. Finally, Fig. 5a-b-c-d show elastic, capture, fission and total cross sections over the complete evaluation range, 10^{-5} eV - 15 MeV.

7. AVERAGE NUMBER, $\bar{\nu}$, OF NEUTRONS PER FISSION

The procedure and results of ref./1/ have not been modified: the estimate of the average number, $\bar{\nu}$, of neutrons emitted per fission by the compound nucleus ^{249}Cm is obtained as a function of incident neutron energy by means of a semiempirical formula worked out in ref./22/, normalized to the experimental value $\bar{\nu}_{th} = 3.14 \pm 0.12$, obtained in ref./23/ for thermal-neutron induced fission. The resulting function has the form:

$$\bar{\nu}(E_n) = 3.14 + 0.24\ E_n \quad (E_n \text{ in MeV})$$

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

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

Here, E is the incident neutron energy, E' the emitted neutron energy, $\vartheta(E)$ an effective temperature, in energy units, whose dependence on E has been estimated by extrapolation of data in ref. /24/.

The energy spectra for neutrons emitted in the reac-

tions $(n,n'\gamma)$ with excitation of the continuum, (n,2n), (n,n'f) are represented by evaporation formulae of the kind:

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

The effective thresholds for these three reactions have been taken at E_1 = 0.51 MeV, E_2 = 6.21 MeV, E_3=6.10 MeV, respectively.

$\vartheta(E)$ can be interpreted in these cases as the excitation temperature of the residual nucleus after emission of an $E' \simeq 0$ neutron: ϑ has been evaluated for the residual nuclei ^{248}Cm (emission of the first neutron in (n,2n)) and ^{247}Cm (emission of the second neutron in (n,2n)) by means of the NUDENS code /25/, which is based on a finite - temperature Nilsson - Bardeen - Cooper - Schrieffer (NBCS) formalism. ϑ as a function of E is plotted in fig. 6 for all the reactions considered, from their effective threshold up to 15 MeV.

9. CONCLUSIONS

^{248}Cm neutron data may be considered satisfactory in resonance region, thanks to the measurement of total cross section in ref./3/ and of fission cross section in refs./12/, /13/. Thermal data leave us two unsolved problems, namely the discrepancies of capture cross sections (/5/, /6/, /7/) and the difficulties in reproducing the fission resonance

integral (/8/, /9/). The only two fission measurements in the continuum (/2/, /11/) show discrepancies above 2 MeV. New experiments in this region are, therefore, desirable and could lead to a number of modifications in our evaluated parameters.

The data obtained in the present work 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/.

ACKNOWLEDGEMENT

We thank Prof. R.C.Block for providing us with the data of ref. /13/ before publication.

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TABLE I

PARAMETERS FOR THE RESOLVED RESONANCE REGION

CURIUM-248

NIS 1
ISOTOPE 1 ZAI= 96248. ABN= 1.000 LFW= 1 NER= 2
RANGE 1 EL= 0.000010 EH= 1300.0 LRU= 1 LRF= 2

SPI= 0.0 AP= 0.950000 NLS= 1

L-STATE 1 AWRI= 245.9410 AM= 0.0 L= 0 NRS= 33

	ER	AJ	GT	GN	GG	GF
1	-9.00000E+00	5.00000E-01	4.43000E-02	1.59999E-02	2.70000E-02	1.30000E-03
2	7.24700E+00	5.00000E-01	2.51367E-02	1.77673E-03	2.33000E-02	6.00000E-05
3	2.69000E+01	5.00000E-01	5.16421E-02	1.95531E-02	3.20000E-02	8.90000E-05
4	3.50100E+01	5.00000E-01	4.19655E-02	1.17155E-02	3.02000E-02	7.00000E-05
5	7.61000E+01	5.00000E-01	1.26731E-01	9.68311E-02	2.60000E-02	3.90000E-03
6	9.89500E+01	5.00000E-01	1.75810E-01	1.49210E-01	2.60000E-02	6.00000E-04
7	1.40300E+02	5.00000E-01	2.88279E-02	1.52798E-03	2.60000E-02	1.30000E-03
8	1.86400E+02	5.00000E-01	3.15460E-02	4.24603E-03	2.60000E-02	1.30000E-03
9	2.37900E+02	5.00000E-01	4.38036E-02	1.65036E-02	2.60000E-02	1.30000E-03
10	2.58700E+02	5.00000E-01	9.00281E-02	6.27281E-02	2.60000E-02	1.30000E-03
11	3.21800E+02	5.00000E-01	5.36700E-02	2.63700E-02	2.60000E-02	1.30000E-03
12	3.80600E+02	5.00000E-01	1.20943E-01	9.36430E-02	2.60000E-02	1.30000E-03
13	4.15700E+02	5.00000E-01	7.72523E-02	4.99523E-02	2.60000E-02	1.30000E-03
14	4.57700E+02	5.00000E-01	1.02820E-01	7.55205E-02	2.60000E-02	1.30000E-03
15	4.84900E+02	5.00000E-01	3.69889E-02	9.68899E-03	2.60000E-02	1.30000E-03
16	5.41800E+02	5.00000E-01	4.11363E-01	3.84063E-01	2.60000E-02	1.30000E-03
17	6.05300E+02	5.00000E-01	1.01108E-01	7.38085E-02	2.60000E-02	1.30000E-03
18	6.47000E+02	5.00000E-01	1.36675E-01	1.09375E-01	2.60000E-02	1.30000E-03
19	6.88600E+02	5.00000E-01	6.40376E-02	3.67376E-02	2.60000E-02	1.30000E-03
20	6.94300E+02	5.00000E-01	2.30191E-01	2.02891E-01	2.60000E-02	1.30000E-03
21	7.21500E+02	5.00000E-01	1.18626E-01	9.13265E-02	2.60000E-02	1.30000E-03
22	7.69400E+02	5.00000E-01	8.83237E-02	6.10237E-02	2.60000E-02	1.30000E-03
23	8.65900E+02	5.00000E-01	5.18717E-01	4.91417E-01	2.60000E-02	1.30000E-03
24	8.87100E+02	5.00000E-01	1.25587E-01	9.82879E-02	2.60000E-02	1.30000E-03
25	9.58600E+02	5.00000E-01	1.35664E-01	1.08364E-01	2.60000E-02	1.30000E-03
26	9.94200E+02	5.00000E-01	1.50270E-01	1.22970E-01	2.60000E-02	1.30000E-03
27	1.04200E+03	5.00000E-01	2.17752E-01	1.90452E-01	2.60000E-02	1.30000E-03
28	1.10330E+03	5.00000E-01	2.46525E-01	2.19225E-01	2.60000E-02	1.30000E-03
29	1.19360E+03	5.00000E-01	3.55510E-01	3.28210E-01	2.60000E-02	1.30000E-03
30	1.20970E+03	5.00000E-01	6.20807E-02	3.47807E-02	2.60000E-02	1.30000E-03
31	1.26200E+03	5.00000E-01	2.97287E-01	2.69987E-01	2.60000E-02	1.30000E-03
32	1.27660E+03	5.00000E-01	2.05947E-01	1.78647E-01	2.60000E-02	1.30000E-03
33	1.28810E+03	5.00000E-01	8.11351E-02	5.38351E-02	2.60000E-02	1.30000E-03

MULTI-LEVEL BREIT-WIGNER FORMULA REQUIRED

TABLE II

AVERAGE PARAMETERS FOR THE UNRESOLVED RESONANCE REGION

CURIUM-248

```
NIS        1
ISOTOPE    1      ZAI= 96248.          ABN=      1.000  LFW= 1  NER= 2

 RANGE     2       EL=  1300.00000      EH=  10000.0    LRU= 2  LRF= 1

                   SPI=  0.0   A= 0.950000  NLS= 2


   GROUP NO.  1

   L-STATE  1    AWRI=   245.9410                          L= 0  NJS= 1
   (ES(I),I=1,  2)
     1.30000E+03 1.00000E+04
    J-STATE 1      MUF= 1
        D            AJ           AMUN         GNO          GG
     2.45000E+01 5.00000E-01 1.00000E+00 2.94000E-03 2.70000E-02
   (GF(I),I=1,  2)
     1.20000E-03 1.30900E-03
 UNRESOLVED FORMULA REQUIRED.ONLY FISSION WIDTHS ARE ENERGY DEPENDENT


   GROUP NO.  2

   L-STATE  2    AWRI=   245.9410                          L= 1  NJS= 2
   (ES(I),I=1,  2)
     1.30000E+03 1.00000E+04
    J-STATE 1      MUF= 1
        D            AJ           AMUN         GNO          GG
     2.45000E+01 5.00000E-01 1.00000E+00 7.35000E-03 2.73000E-02
   (GF(I),I=1,  2)
     9.17000E-04 1.00000E-03
    J-STATE 2      MUF= 1
        D            AJ           AMUN         GNO          GG
     1.22500E+01 1.50000E+00 1.00000E+00 3.67500E-03 2.68000E-02
   (GF(I),I=1,  2)
     8.98000E-04 9.80000E-04
 UNRESOLVED FORMULA REQUIRED.ONLY FISSION WIDTHS ARE ENERGY DEPENDENT
```

TABLE III

Thermal cross sections

Capture (b)	Year	Ref.	Comments
7.2±2.0	1965	|4|	Experimental
2.63±0.26	1973	|5|	Experimental
2.51±0.26	1974	|3|	Calculated from 47 resonances
10.7±1.5	1978	|7|	Experimental
2.47	1980	|1|	Calculated from the resonances of |2| and |3|
9.81	1980 1983	|1| |28|	Calculated, with a bound level at E_o=-9 eV

Fission (b)	Year	Ref.	Comments
0.34±0.07	1972	|8|	Standard: $^{235}U(n,f)$
0.39±0.07	1976	|9|	Standard: $^{235}U(n,f)$
0.036	1980	|1|	Calculated, from the resonances of |2| and |3|
0.393	1983	|28|	Calculated, with a bound level at E_o=-9 eV

TABLE IV

Resonance integrals

Capture (b)	Year	Ref.	Comments
350±40	1965	|4|	Experimental
267±26.7	1973	|5|	Experimental
259±12	1974	|3|	Calculated from 47 resonances
250±24	1978	|7|	Experimental
270	1983	|28|	Evaluated from the adopted resonances (E> 0.5 eV)

Fission (b)	Year	Ref.	Comments
13.2±0.8	1972	|8|	Standard: $^{235}U(n,f)$; E> 0.625 eV
13.1±1.5	1976	|9|	Standard: $^{235}U(n,f)$; E> 0.5 eV
3.398	1983	|28|	Calculated from the adopted resonances. E> 0.5 eV
9.614	1983	|28|	Calculated, with contribution from the continuum. E> 0.5 eV

TABLE V

DEFORMED OPTICAL MODEL POTENTIAL

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

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

$R_{a,b} = R^{(o)}_{a,b}(1 + \beta_2 Y^o_2(\theta') + \beta_4 Y^o_4(\theta'))$ (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)

$W = 0$

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

$V_{SO} = 7.2$ MeV

$R^{(o)}_a = 1.259$ fm ; $R^{(o)}_b = 1.237$ fm ;

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

$\beta_2 = 0.246$; $\beta_4 = 0.02$

TABLE VI

Discrete levels and level density parameters for Cm-248 as decaying nucleus

A) Neutron channel (Cm^*-248 → Cm-247 + n) [21]

Discrete levels

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 > 318 KeV, level density described by the formula:

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

where [21] :

$$\sigma^2 = cT$$

$$E-\Delta = aT^2 - T$$

$$a = 25.2 \text{ MeV}^{-1}$$

$$\Delta = -0.69 \text{ MeV}$$

$$c = 100 \text{ MeV}^{-1}$$

B) Gamma channel (Cm^*-248 → Cm-248 + γ)

Discrete levels

E(KeV)	J^{π}
0.0	0^+
43.4	2^+
143.6	4^+
297.0	6^+
510.0	8^+

(continues)

Table VI (continued)

Continuum

E > 510 KeV, level density formula as in the neutron channel, with parameters [21] :

$$a = 24.5\ \mathrm{MeV}^{-1}$$
$$\Delta = -1.0\ \mathrm{MeV}$$
$$c = 100\ \mathrm{MeV}^{-1}$$

C) Fission channel (Cm^*-248(f))

Transition states at the first barrier peak described by a level density formula as before, with parameters [21] :

$$a = 28.0\ \mathrm{MeV}^{-1}$$
$$\Delta = -1.0\ \mathrm{MeV}^{-1}$$
$$c = 98\ \mathrm{MeV}^{-1}$$

Table VII

Discrete levels and level density parameters for Cm-249 as decaying nucleus

A) Neutron channel ($\overset{*}{\text{Cm}}$-249 → Cm-248 + n)

Discrete levels and continuum are the same as in the gamma channel of Table VI.

B) Gamma channel ($\overset{*}{\text{Cm}}$-249 → Cm-249 + γ)

Discrete levels

E(KeV)	J^{π}
0.0	$1/2^+$
26.2	$3/2^+$
42.4	$5/2^+$
52.2	$7/2^+$
110.0	$9/2^+$
110.1	$7/2^+$
146.0	$9/2^+$
208.0	$3/2^+$
220.0	$5/2^+$
242.0	$5/2^+$
289.0	$7/2^+$

Continuum

E > 289 KeV, level density formula as in Table VI, with parameters:

$$a = 25.2\ \text{MeV}^{-1}$$
$$\Delta = -1.0\ \text{MeV}$$
$$c = 100\ \text{MeV}^{-1}$$

C) Fission channel ($\overset{*}{\text{Cm}}$-249 (f)):

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

$$a = 26.5\ \text{MeV}^{-1}$$
$$\Delta = -2.05\ \text{MeV}$$
$$c = 98\ \text{MeV}^{-1}$$

Table VIII

Fission barrier parameters

Fissioning nucleus: Cm-248 |21|

First peak		Second peak	
Height, E_A(MeV)	Curvature, $\hbar\omega_A$(MeV)	E_B(MeV)	$\hbar\omega_B$(MeV)
6.1	0.90	4.2	0.55

Fissioning nucleus: Cm-249

First peak		Second peak	
E_A(MeV)	$\hbar\omega_A$(MeV)	E_B(MeV)	$\hbar\omega_B$(MeV)
5.7	0.65	4.2	0.55

Figure Captions

1. Neutron Cross Sections in resolved resonance region:
   a) total; b) elastic; c) capture; d) fission.

2. Fission cross section in the range 1 KeV-15 MeV.
   Continuous curve: present evaluation. Experimental data,
   Δ,◇ : ref. /2/; O : ref./11/; □ : ref./13/.

3. Neutron cross sections in the continuum region (10 KeV-15 MeV).

4. Angular distributions of neutrons leaving Cm-248 in the 0_1^+ and 2_1^+ states: for E_n (incident neutron energy) = 5, 8, 11, 14 MeV.

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

6. 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.

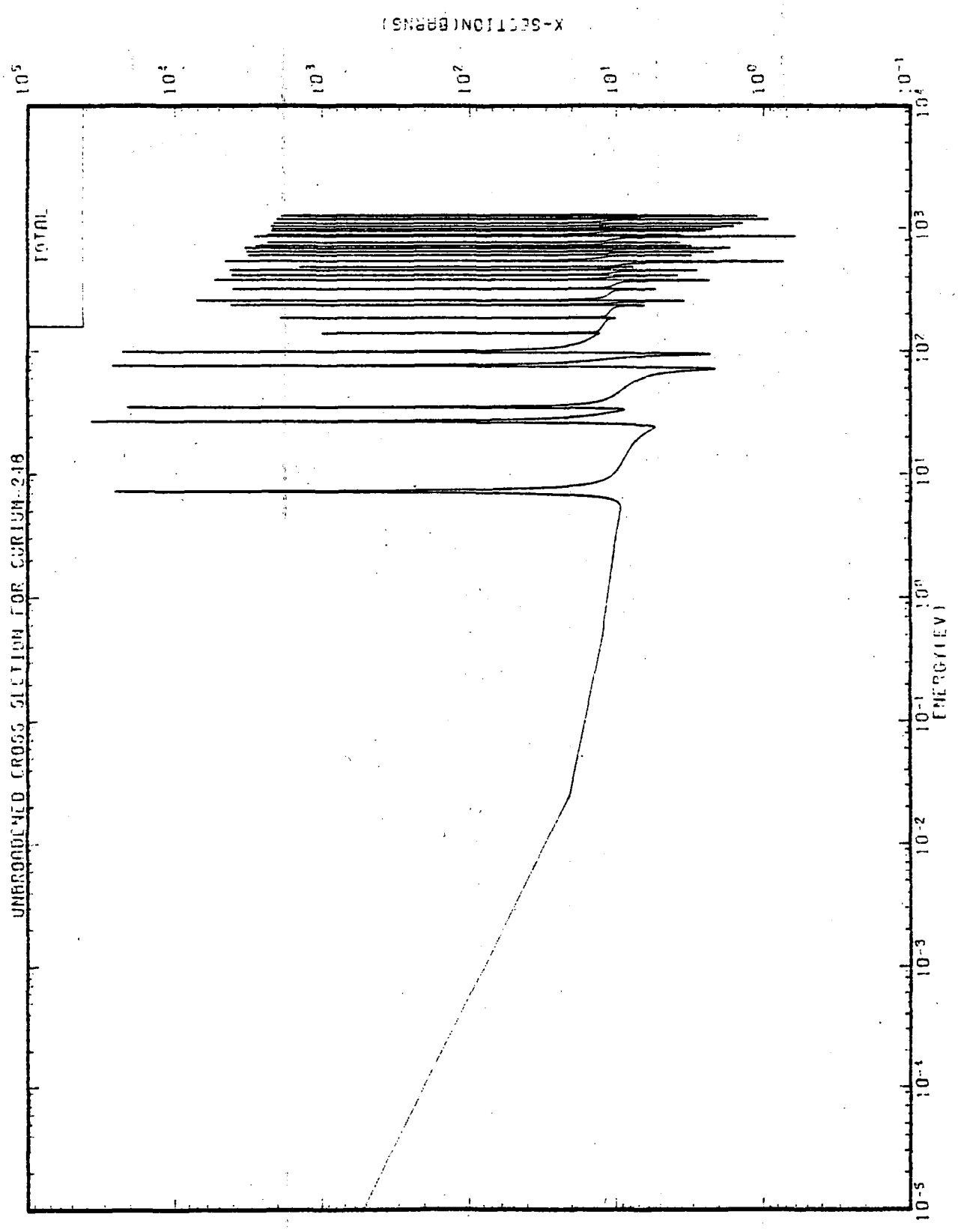

UNBROADENED CROSS SECTION FOR CURIUM-248
TOTAL
X-SECTION(BARNS)
ENERGY(EV)

Fig. 1a

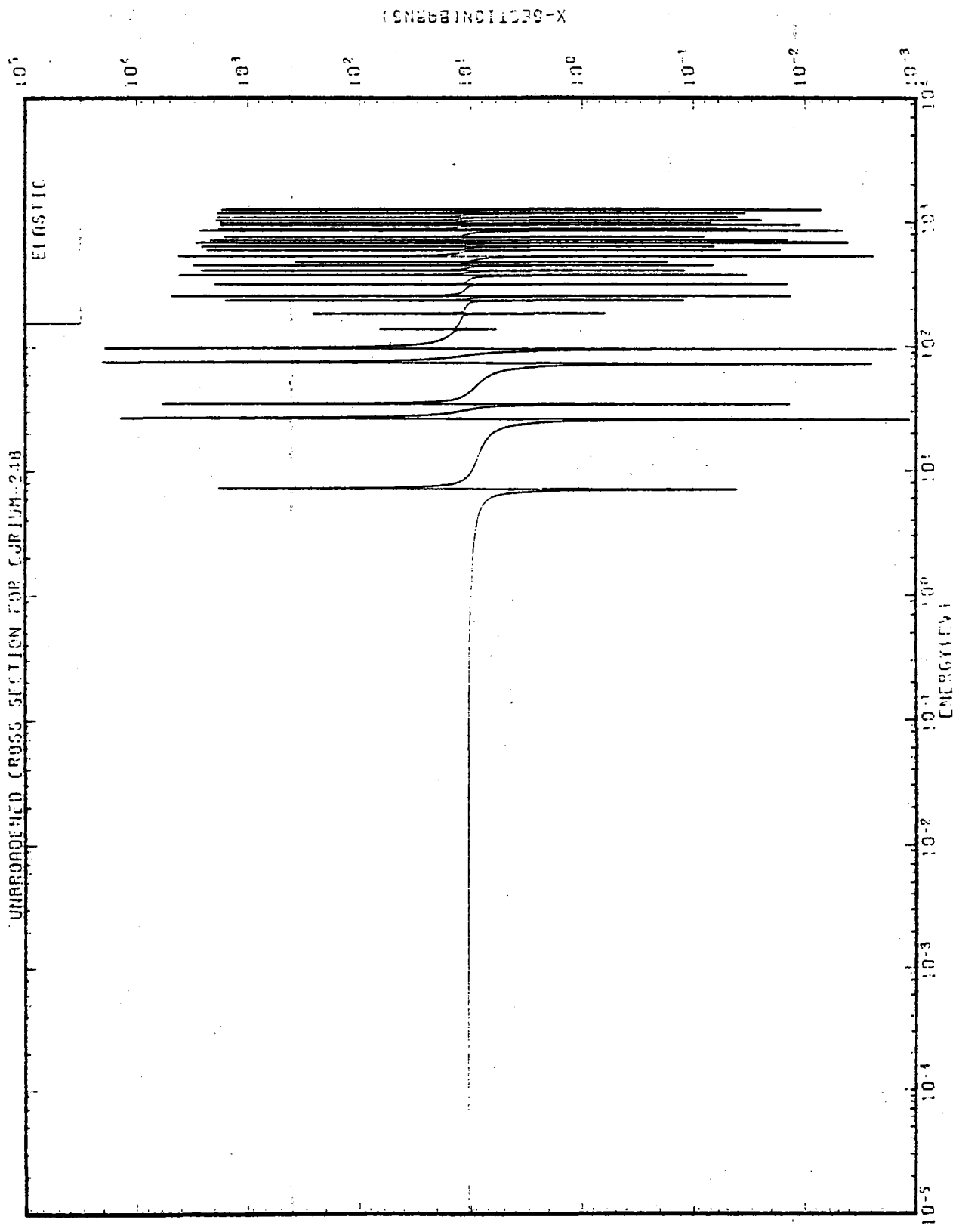

UNBROADENED CROSS SECTION FOR CORIUM-248
ELASTIC
X-SECTION(BARNS)
ENERGY(MEV)

Fig. 1b

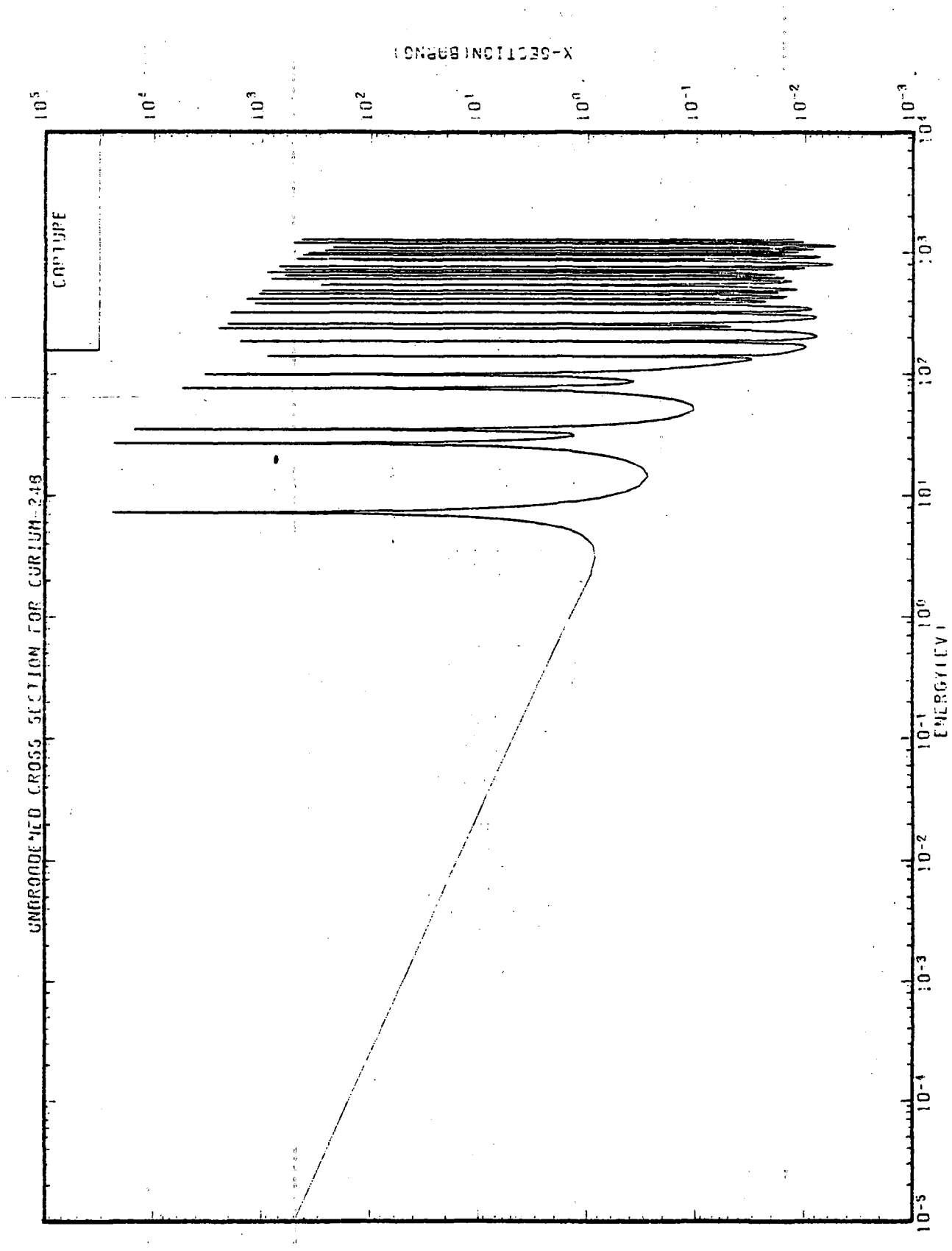

UNBROADENED CROSS SECTION FOR CURIUM-248
CAPTURE
X-SECTION(BARNS)
ENERGY(EV)
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5

Fig. 1c

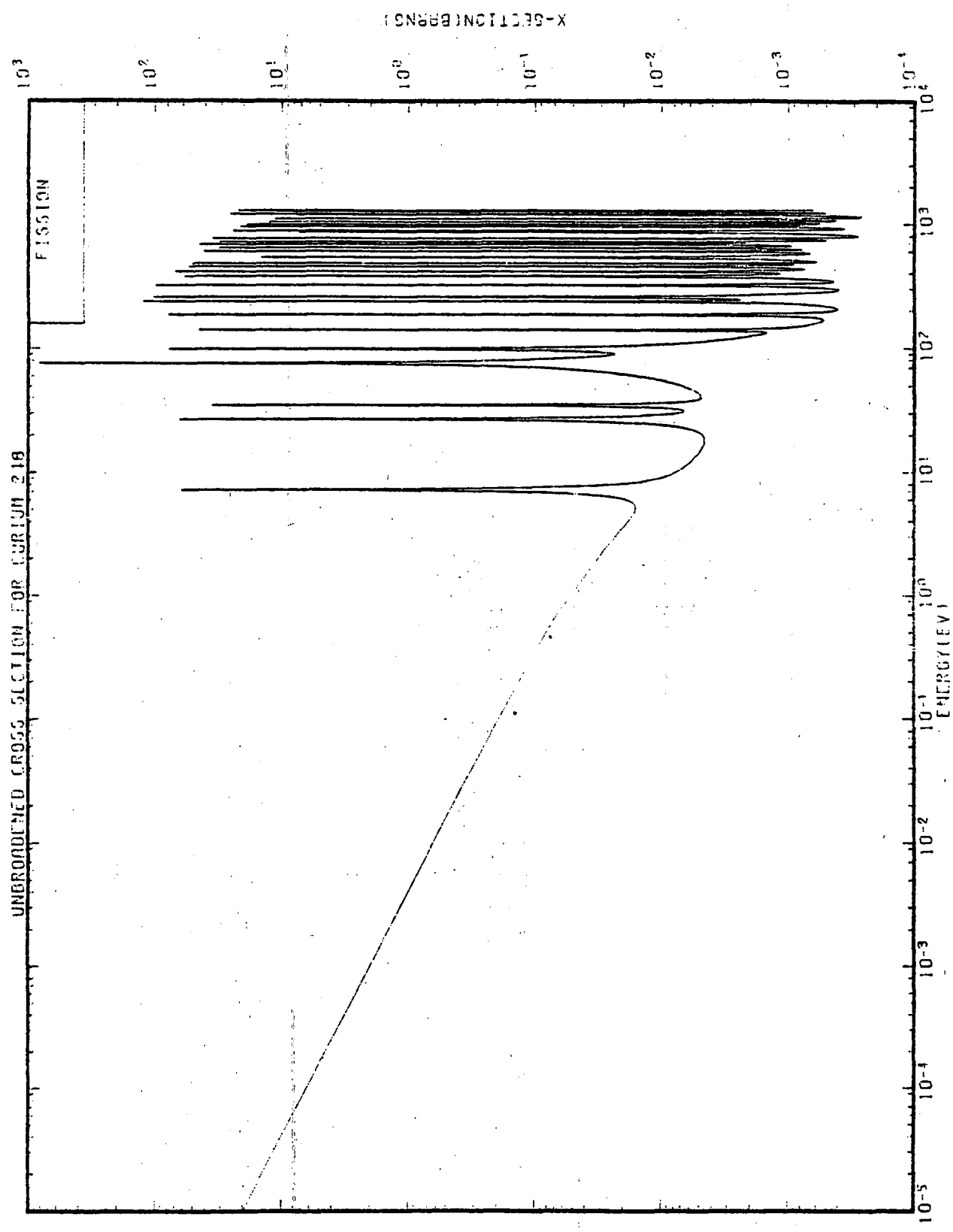

UNBROADENED CROSS SECTION FOR CURIUM 210
FISSION
X-SECTION(BARNS)
EMERGY(EV)
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}

Fig. 1d

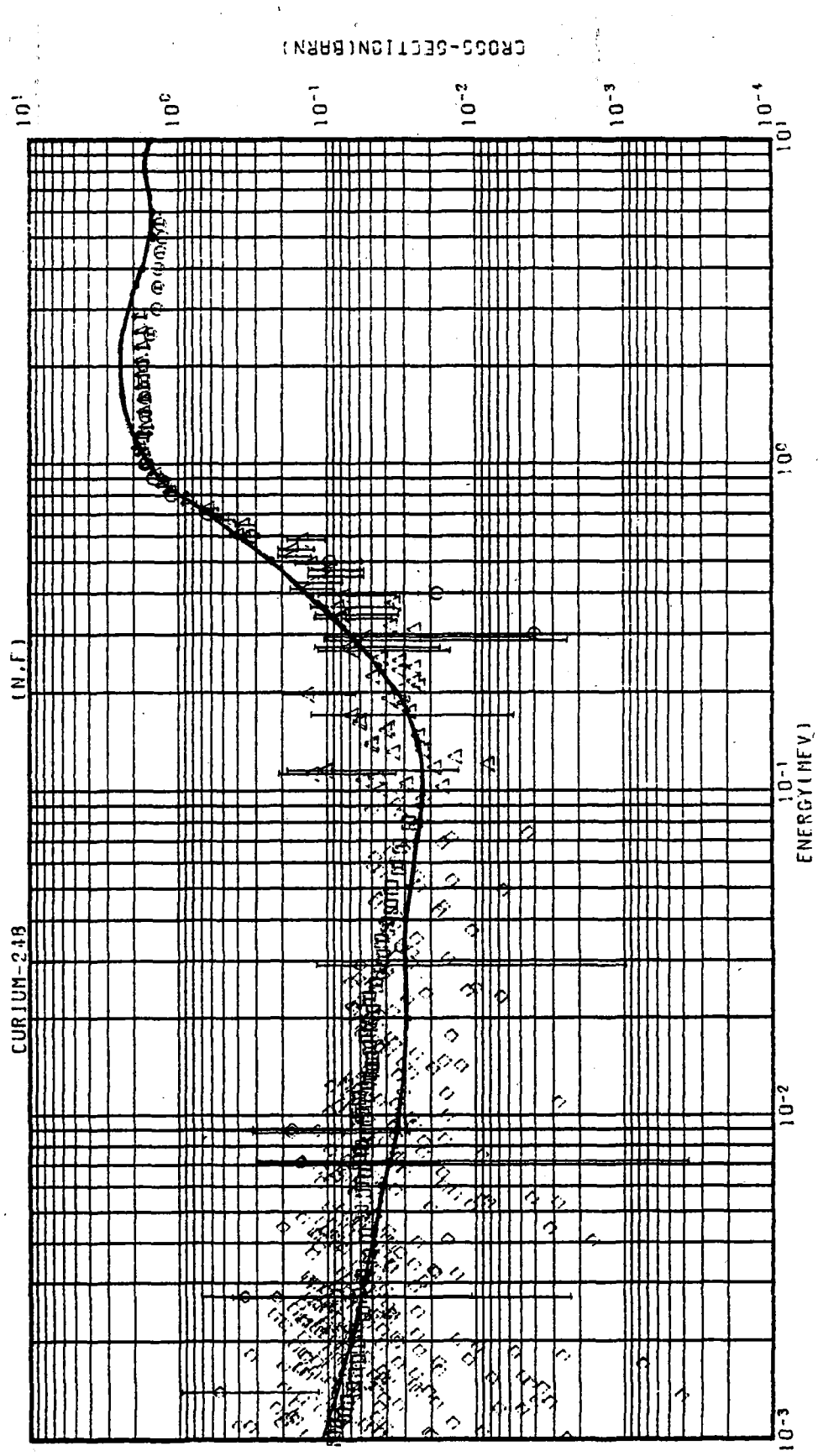

CROSS-SECTION(BARN)
CURIUM-248
(N,F)
ENERGY(MEV)
10¹
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴

Fig. 2

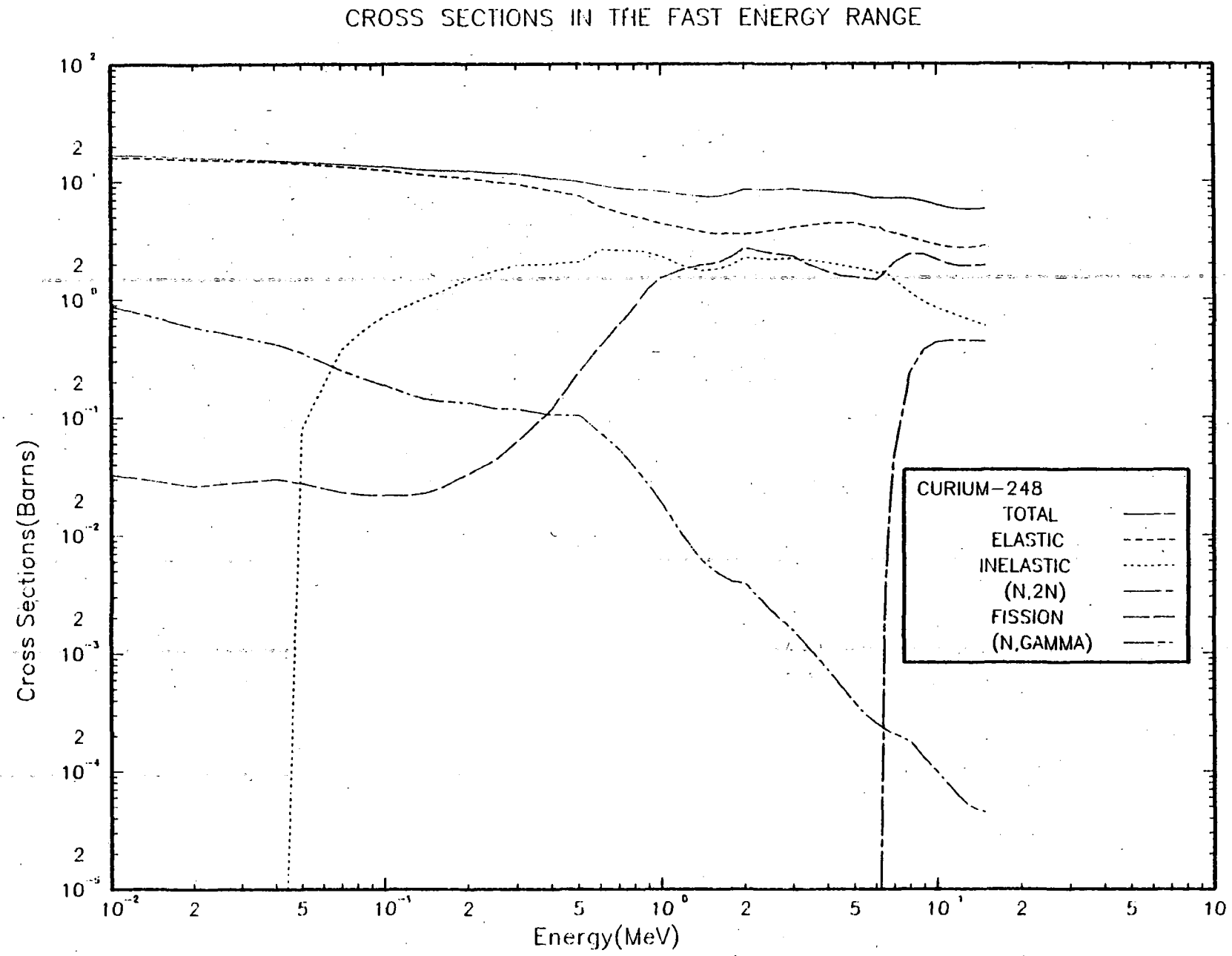
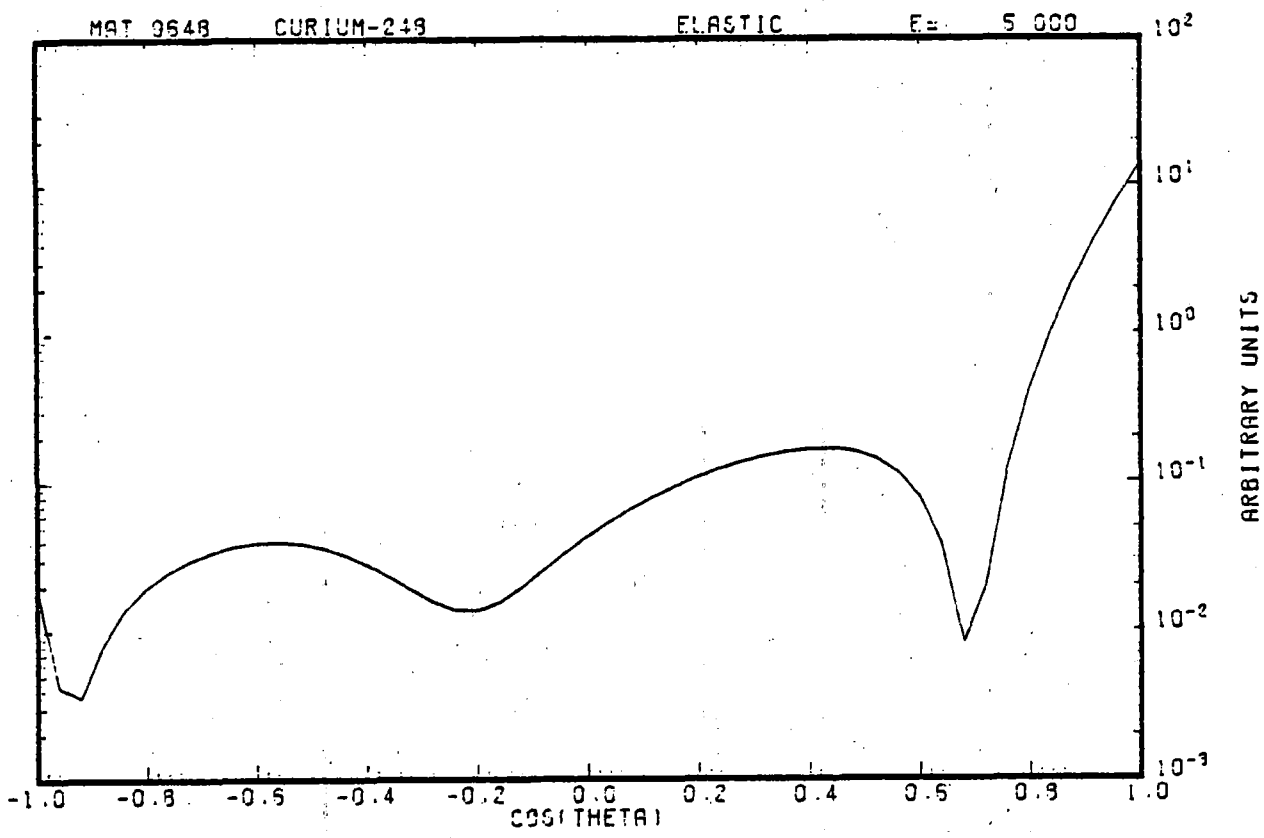

CROSS SECTIONS IN THE FAST ENERGY RANGE
Cross Sections(Barns)
Energy(MeV)
CURIUM-248
TOTAL
ELASTIC
INELASTIC
(N,2N)
FISSION
(N,GAMMA)

Fig. 3


MAT 9648 CURIUM-248 ELASTIC E= 5.000
ARBITRARY UNITS
COS(THETA)

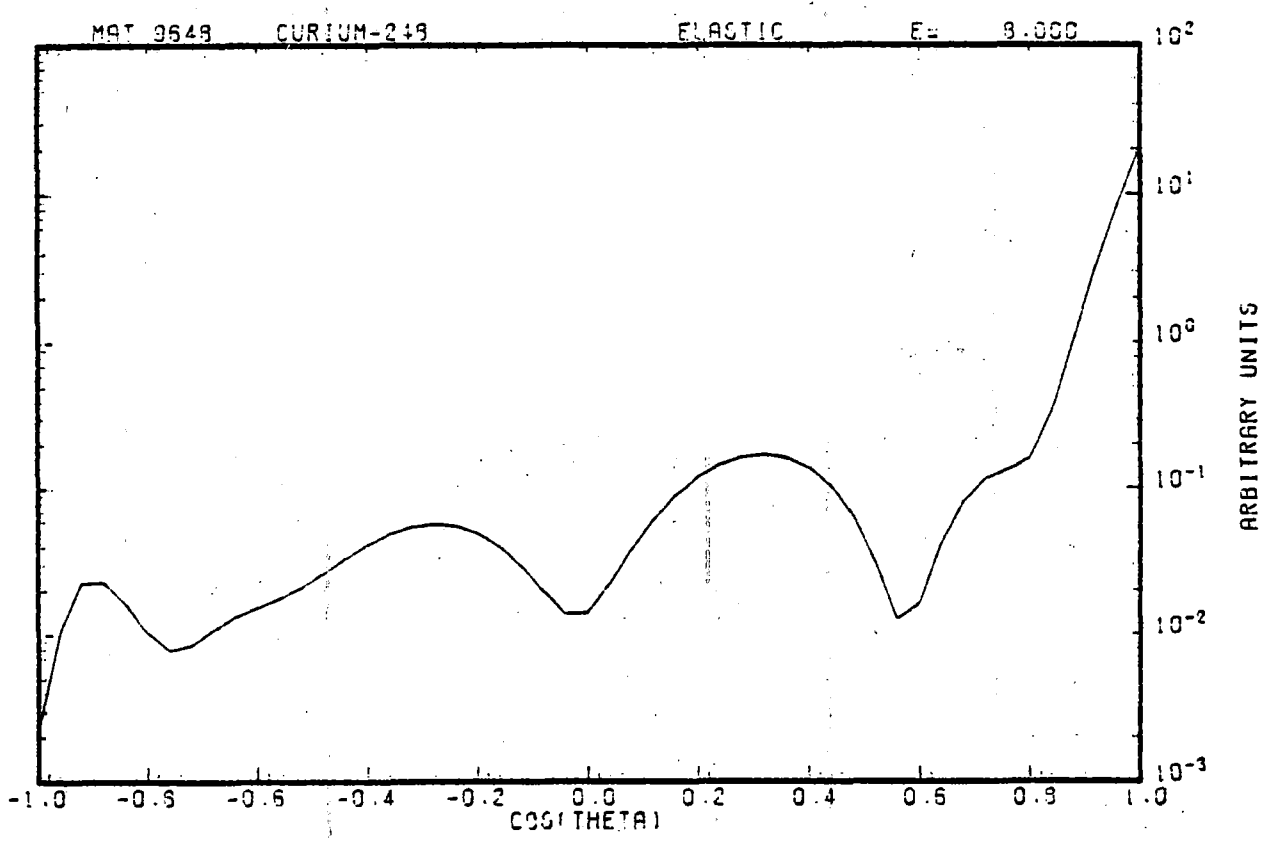

MAT 9648 CURIUM-248 ELASTIC E= 8.000
ARBITRARY UNITS
COS(THETA)

Fig. 4a

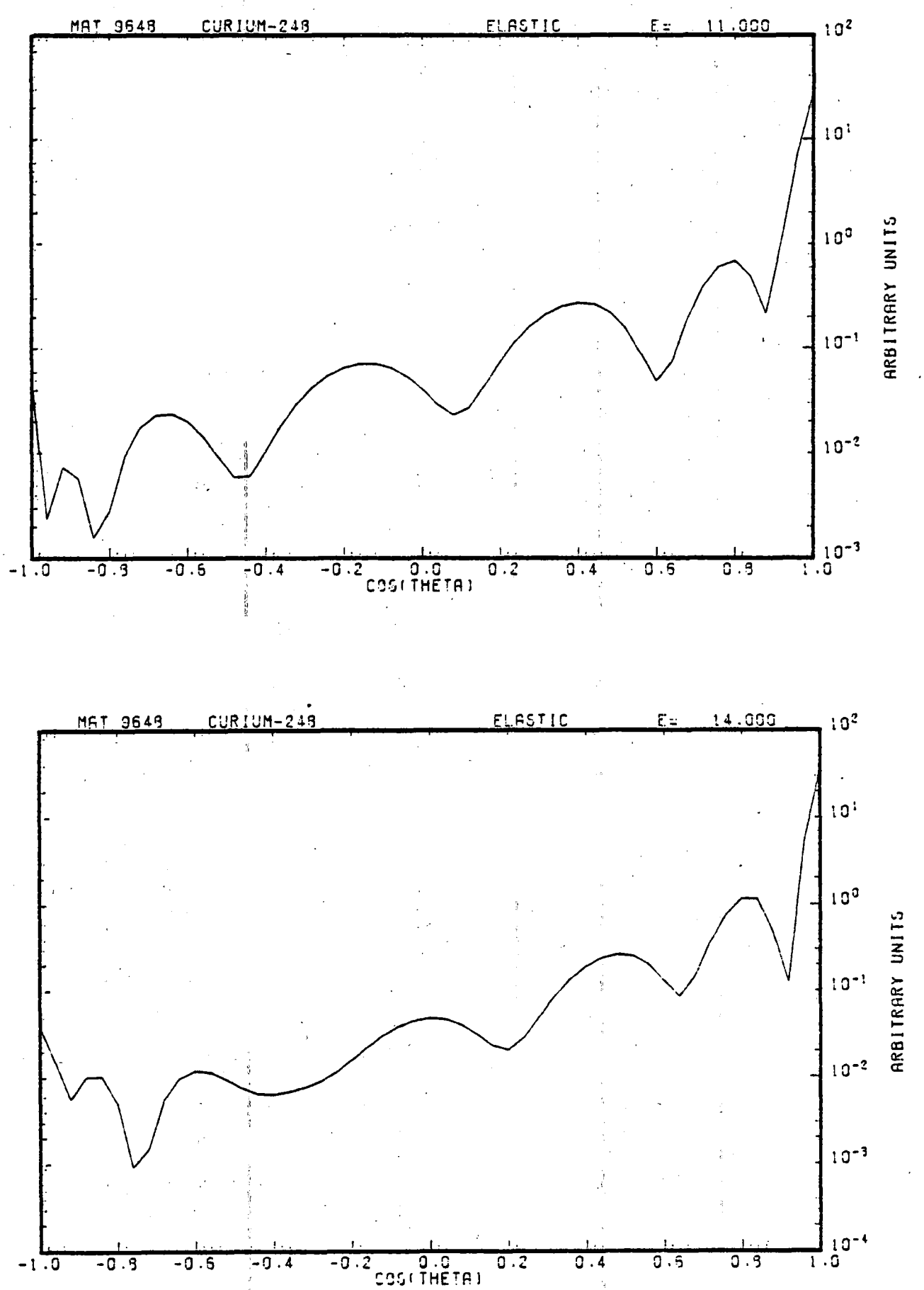
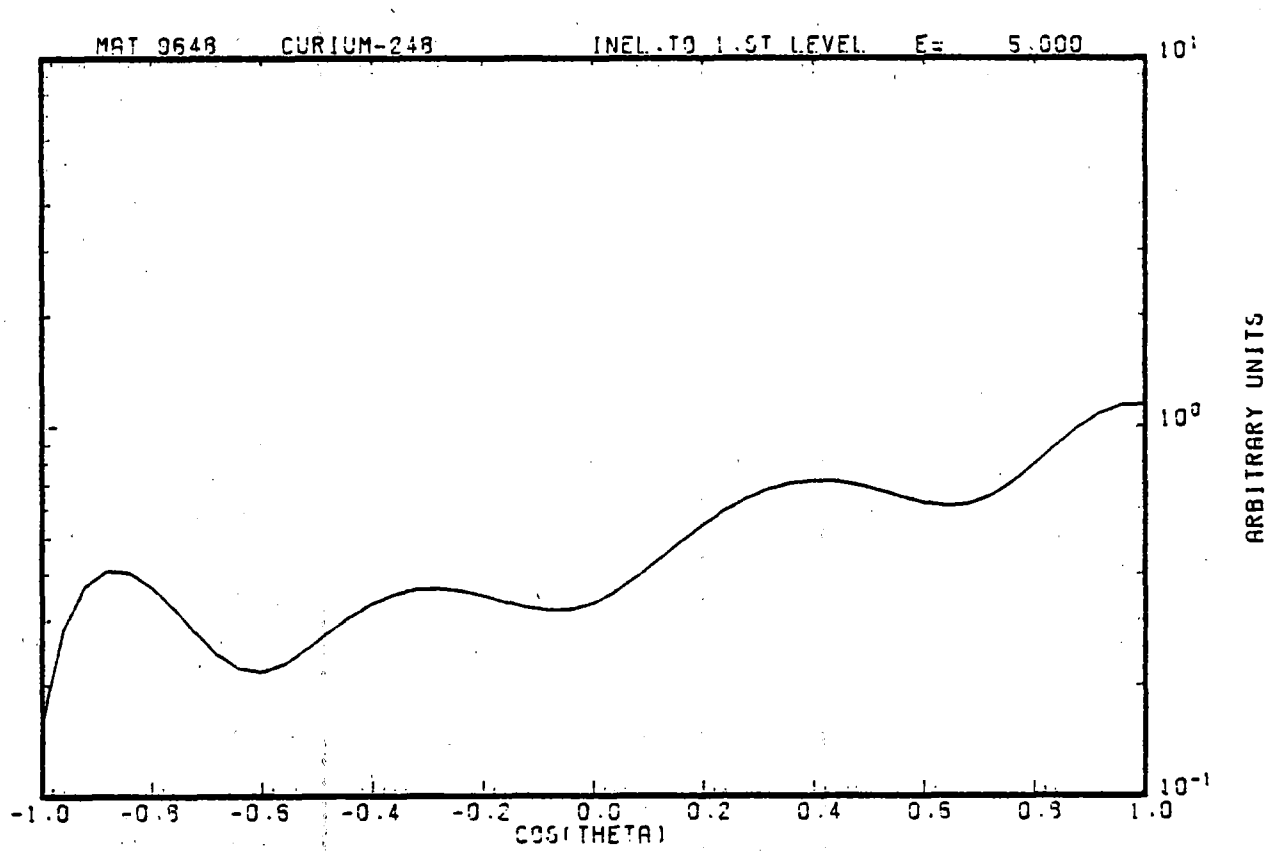

MAT 9648 CURIUM-248 ELASTIC E= 11.000
ARBITRARY UNITS
COS(THETA)
MAT 9648 CURIUM-248 ELASTIC E= 14.000
ARBITRARY UNITS
COS(THETA)

Fig. 4b


MAT 9648 CURIUM-248 INEL.TO 1.ST LEVEL E= 5.000
ARBITRARY UNITS
COS(THETA)

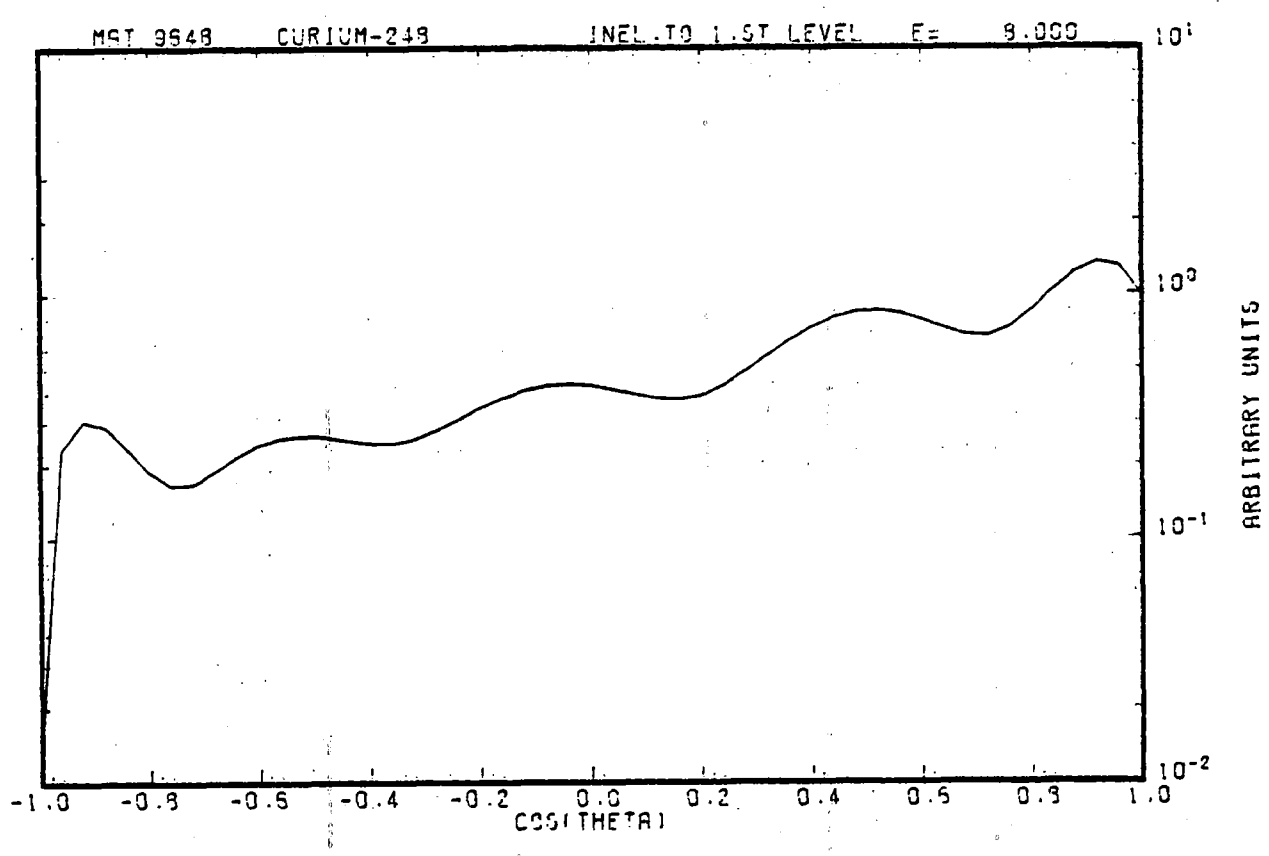

MAT 9648 CURIUM-248 INEL.TO 1.ST LEVEL E= 8.000
ARBITRARY UNITS
COS(THETA)

Fig. 4c

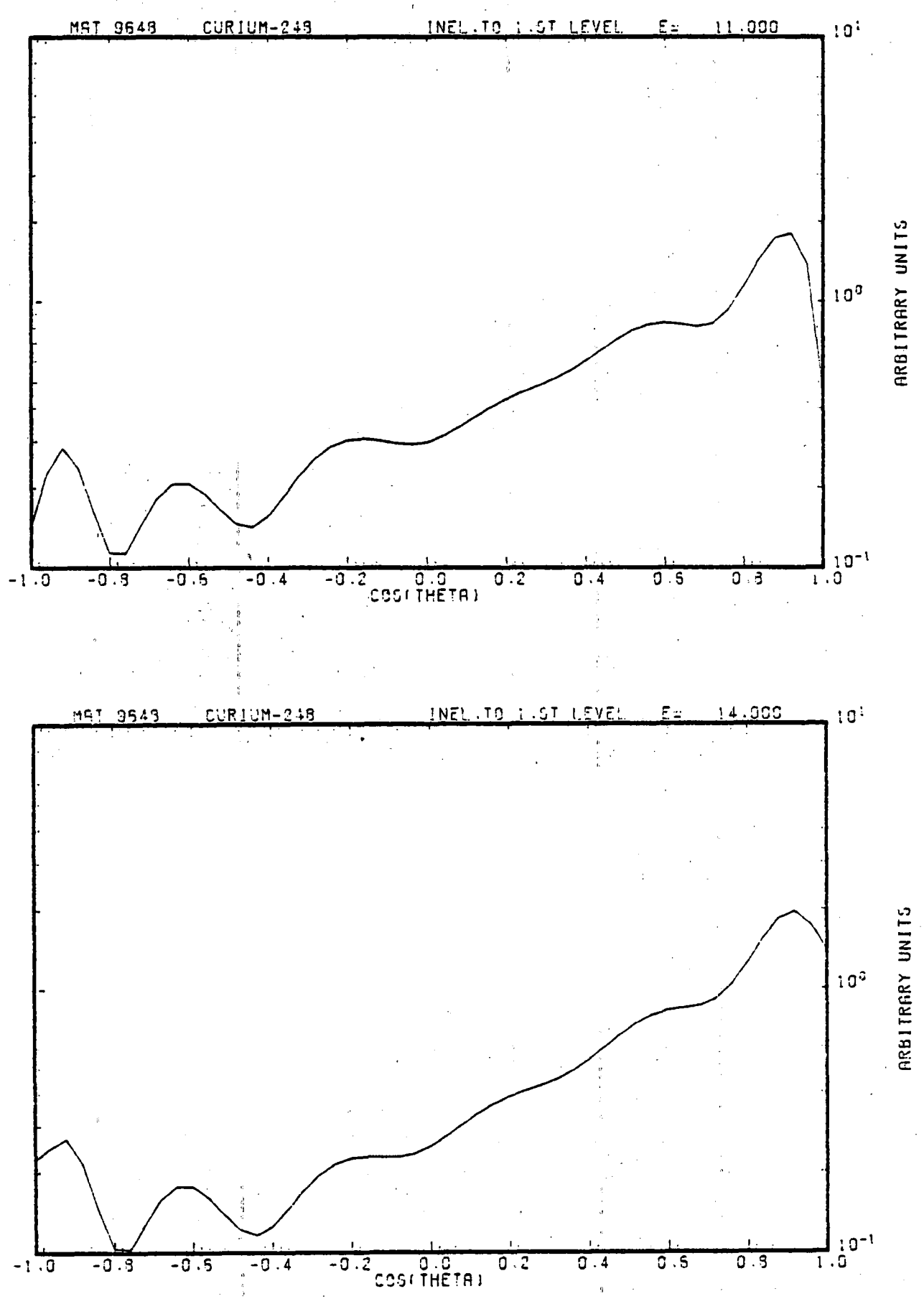

MAT 9648 CURIUM-248 INEL.TO 1.ST LEVEL E= 11.000
MAT 9648 CURIUM-248 INEL.TO 1.ST LEVEL E= 14.000
ARBITRARY UNITS
COS(THETA)
-1.0 -0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4 0.6 0.8 1.0

Fig. 4d

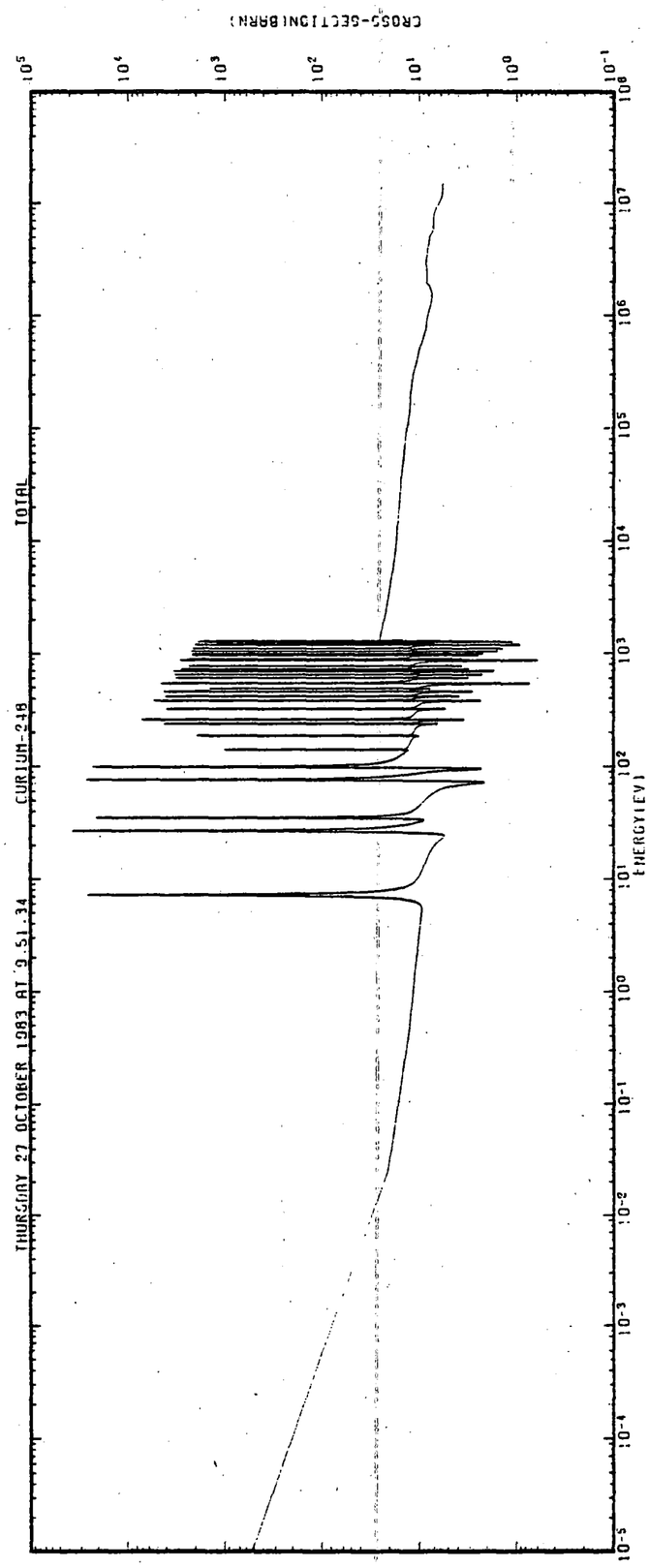

THURSDAY 27 OCTOBER 1983 AT 9.51.34
CURIUM-248
TOTAL
CROSS-SECTION(BARN)
ENERGY(EV)

Fig. 5a

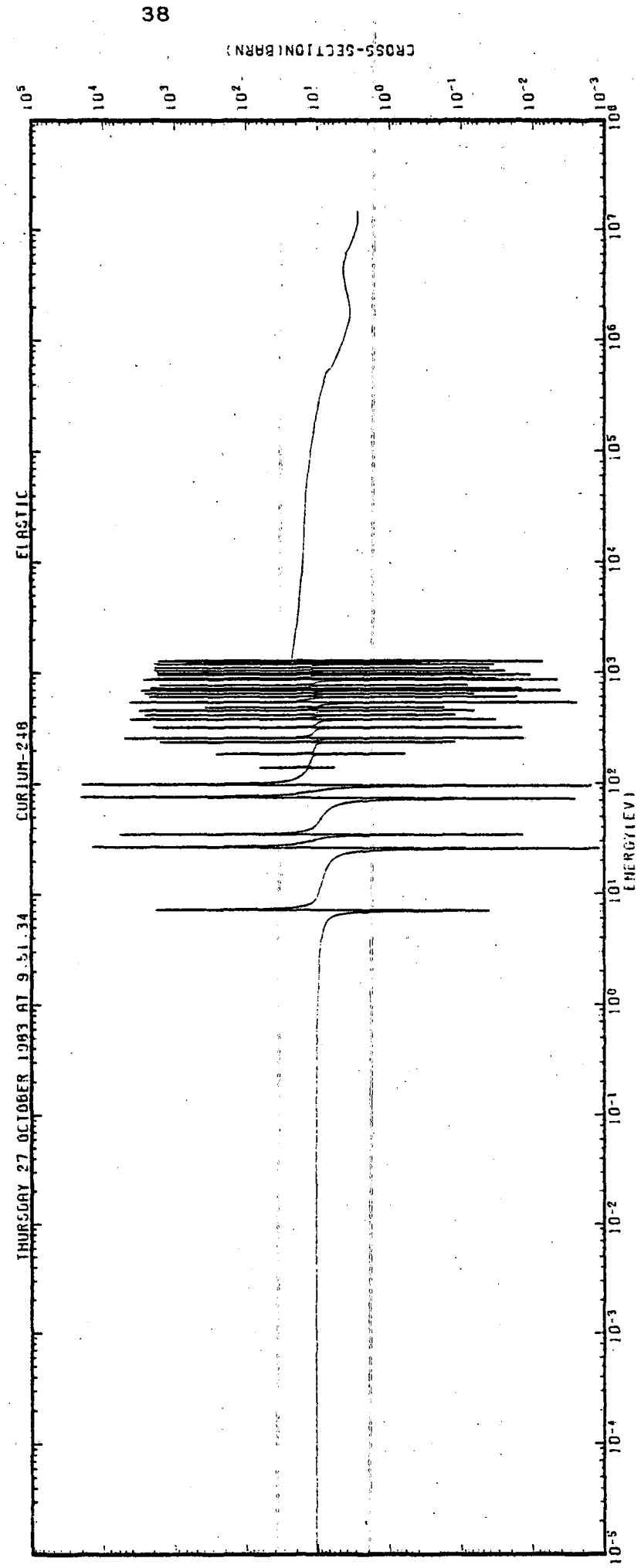

THURSDAY 27 OCTOBER 1983 AT 9.51.34
CURIUM-248
ELASTIC
CROSS-SECTION(BARN)
ENERGY(EV)
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}

Fig. 5b

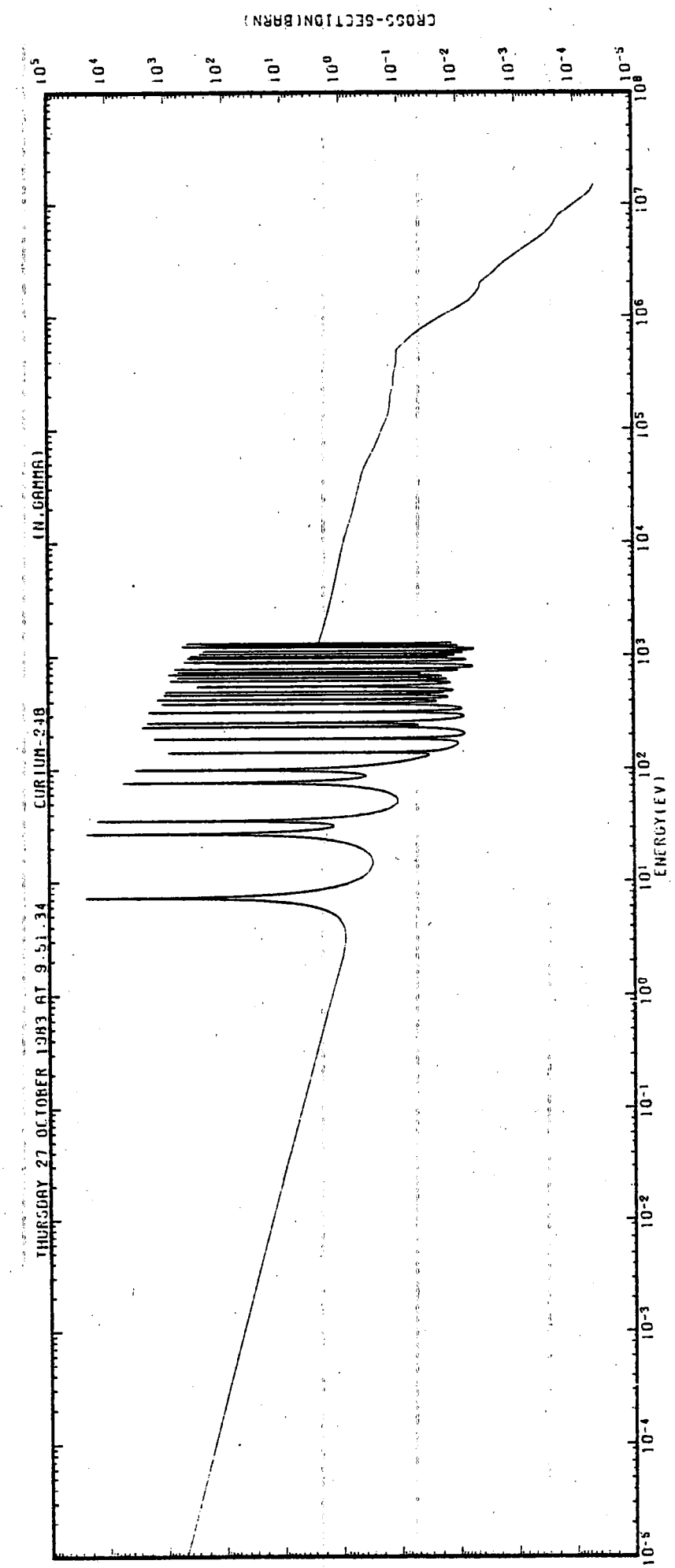

CURIUM-248
(N,GAMMA)
THURSDAY 27 OCTOBER 1983 AT 9.51.34
CROSS-SECTION(BARN)
ENERGY(EV)

Fig. 5c

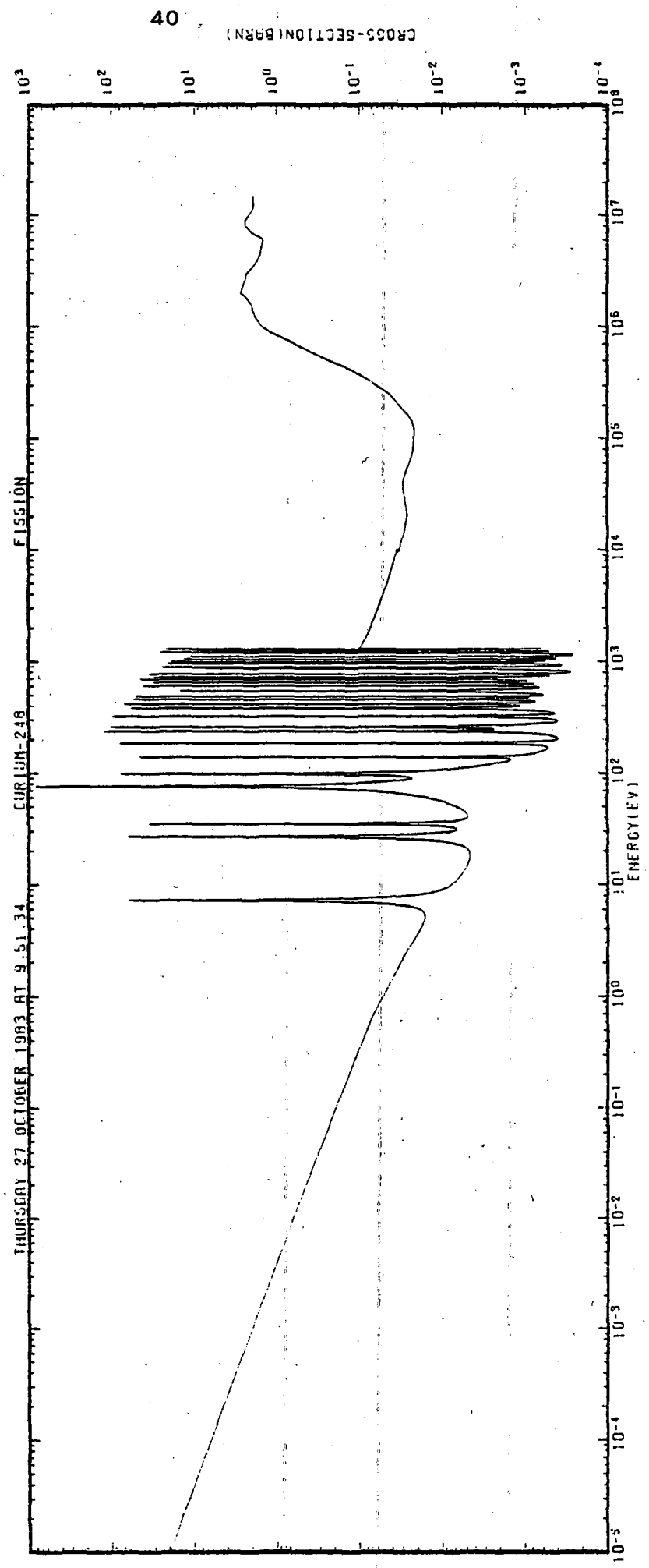
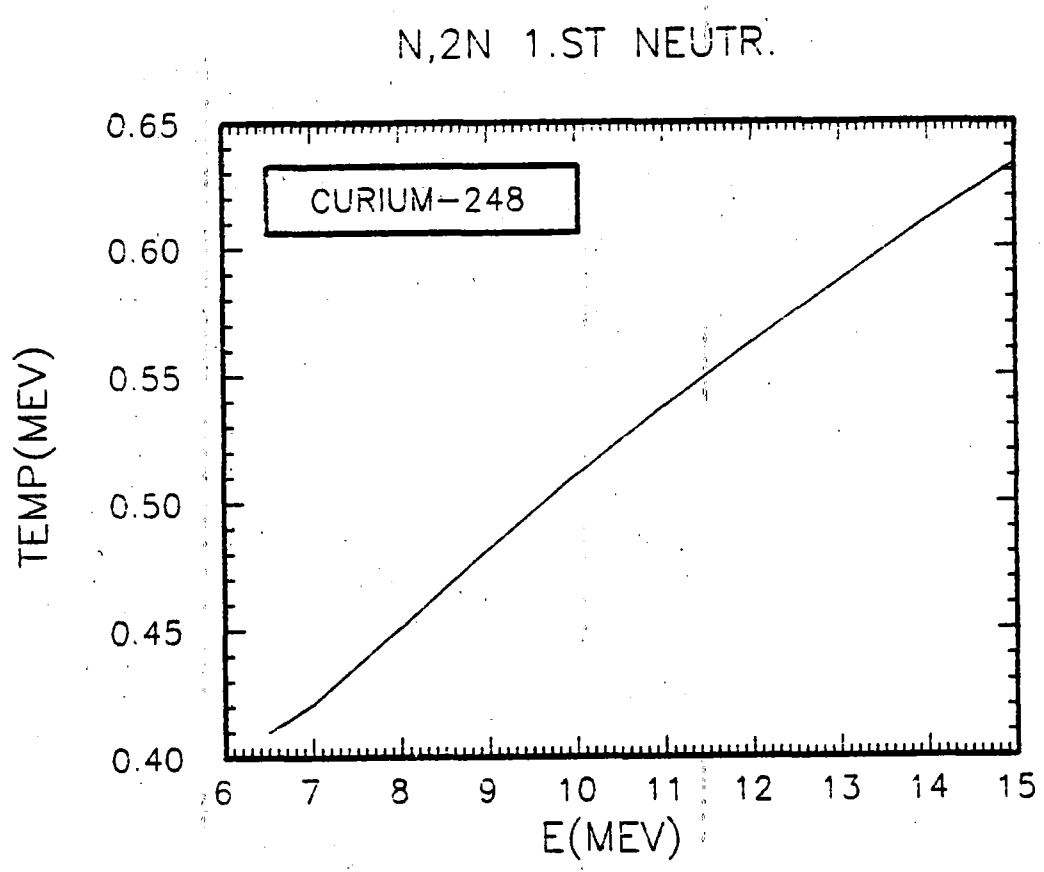

THURSDAY 27 OCTOBER 1983 AT 9.51.34
CURIUM-248
FISSION
CROSS-SECTION(BARN)
ENERGY(EV)

Fig. 5d


N,2N 1.ST NEUTR.
CURIUM-248
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)

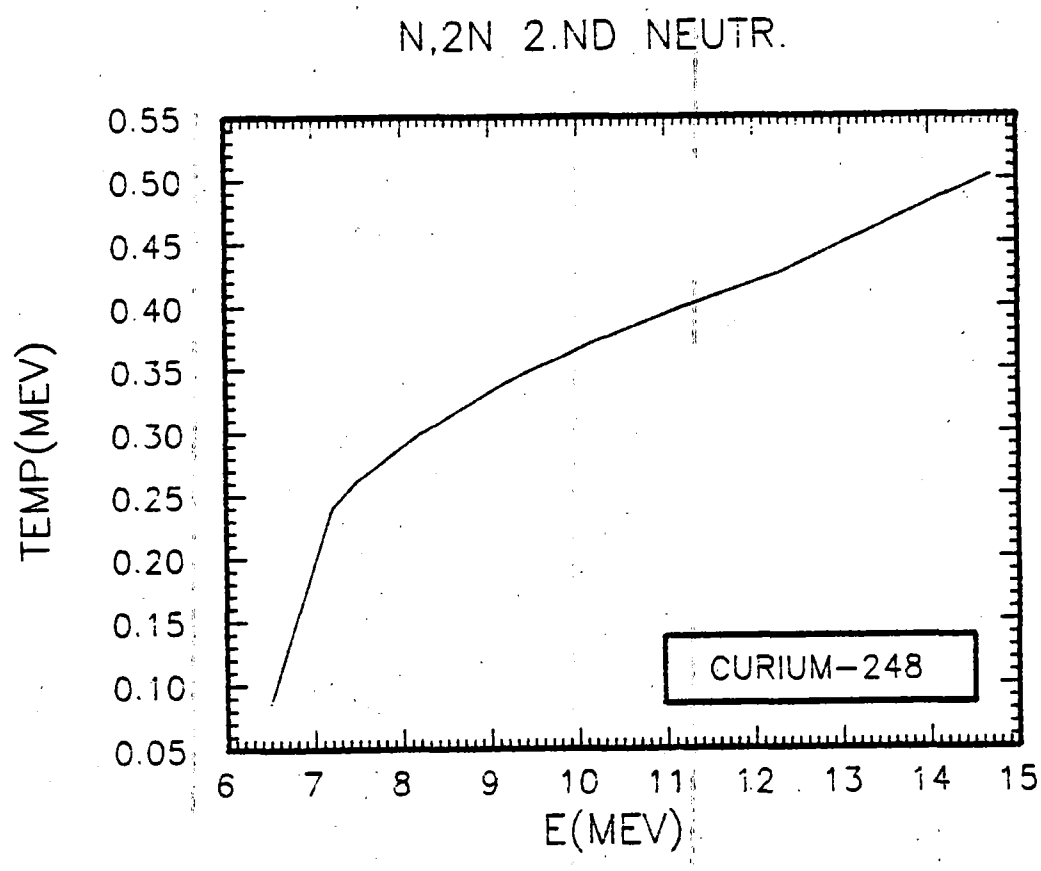
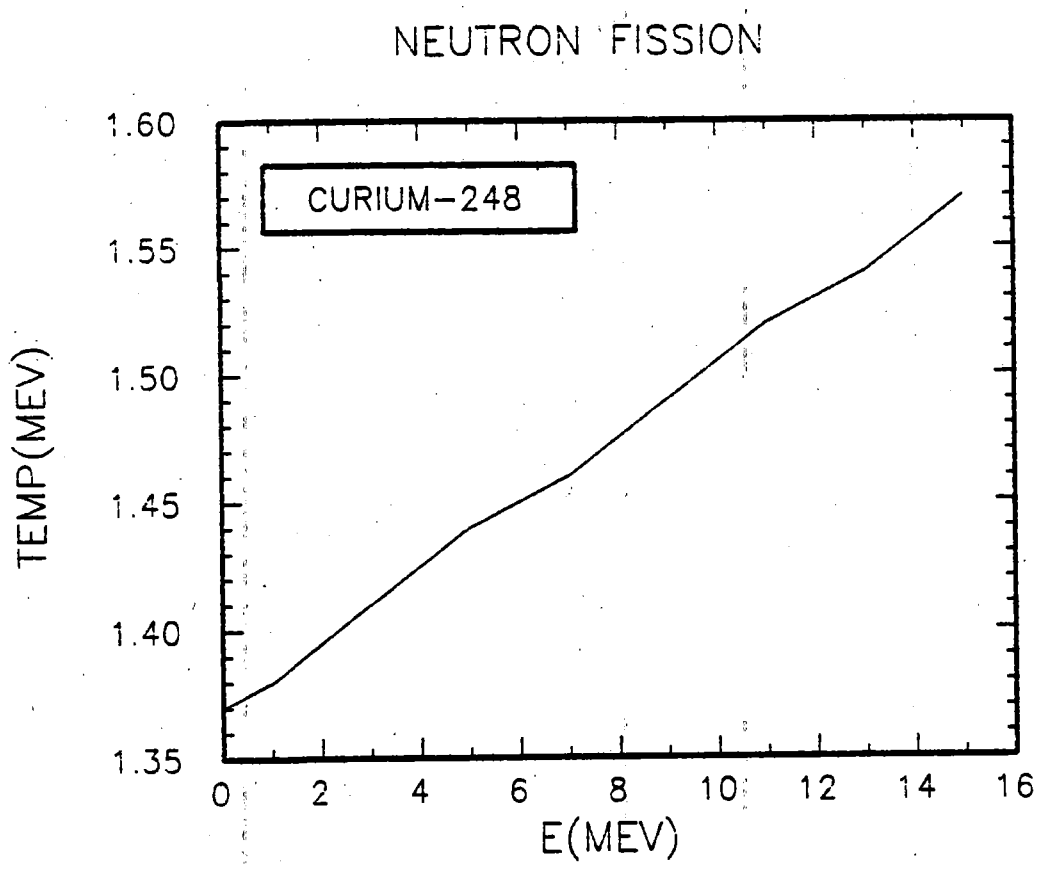

N,2N 2.ND NEUTR.
CURIUM-248
TEMP(MEV)
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
6
7
8
9
10
11
12
13
14
15
E(MEV)

Fig. 6a


NEUTRON FISSION
CURIUM-248
TEMP(MEV)
1.60
1.55
1.50
1.45
1.40
1.35
0
2
4
6
8
10
12
14
16
E(MEV)

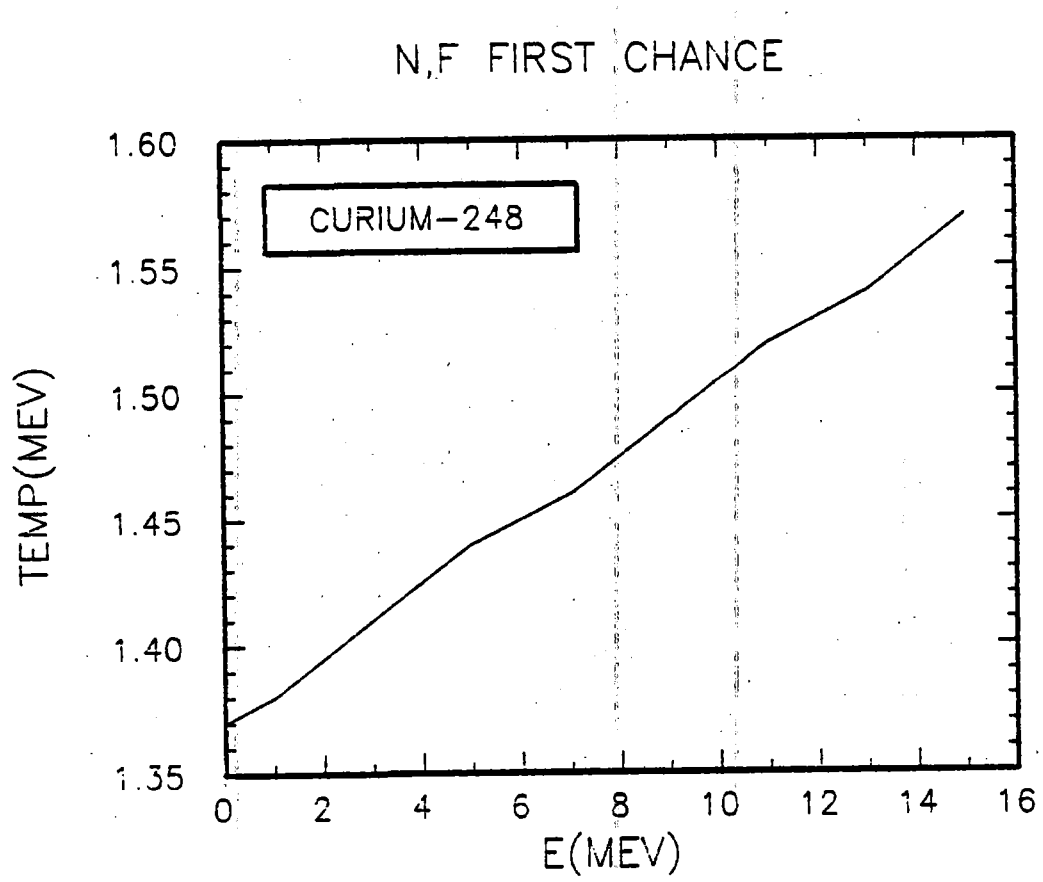
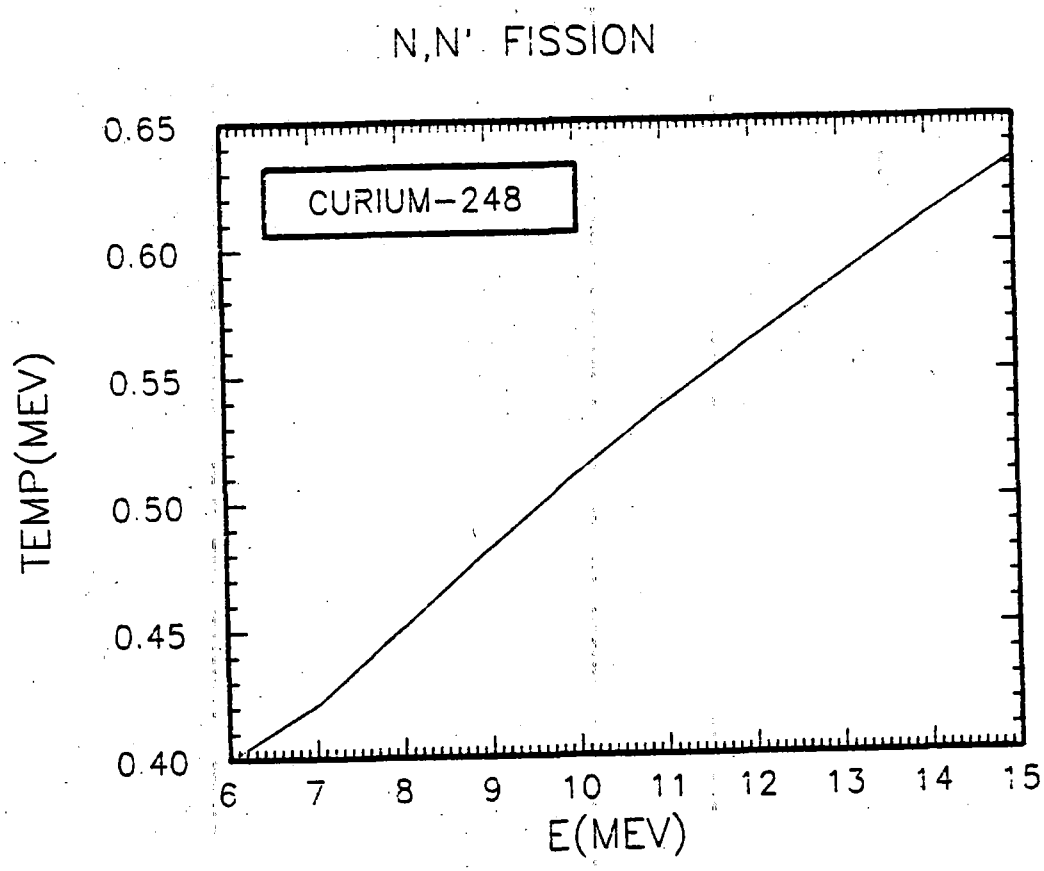

N,F FIRST CHANCE
CURIUM-248
TEMP(MEV)
1.60
1.55
1.50
1.45
1.40
1.35
0
2
4
6
8
10
12
14
16
E(MEV)

Fig. 6b


N,N' FISSION
CURIUM-248
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)

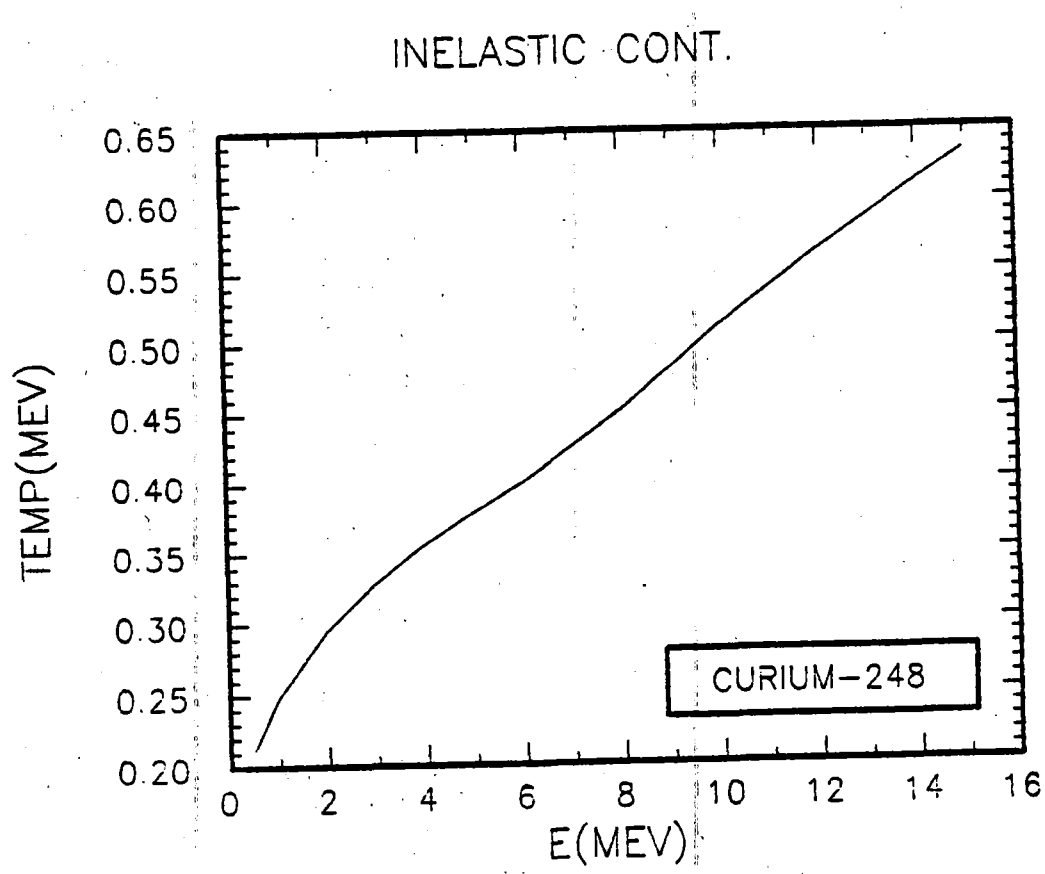

INELASTIC CONT.
CURIUM-248
TEMP(MEV)
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0
2
4
6
8
10
12
14
16
E(MEV)

Fig. 6c