NEANDC (E) 227 «L»
INDC (FR) 54/L

STATUS OF ACTIVITIES ON ACTINIDE NUCLEAR DATA AT BRUYERES-LE-CHATEL

Service de Physique Neutronique et Nucléaire
Centre d'Etudes de Bruyères-le-Châtel
B.P. N° 561
92542 MONTROUGE CEDEX, France

– MARCH 1982 –

COMMISSARIAT A L'ENERGIE ATOMIQUE
FRANCE

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CONTENTS

INTRODUCTION AND SUMMARY

J. SALVY

This report which complements the previous one [1] presents new developments and perspectives in activities dealing with actinide nuclear data at Bruyères-le-Châtel (BRC). A brief description is given of recent progress concerning measurements, calculations and evaluations or data processing in this heavy nuclei region. Part of them devoted to evaluation purposes has been undertaken in the framework of the IAEA-BRC Research Agreement 2072/CF and preliminarily reported on [2] at the fourth Meeting of the IAEA-NDS Coordinated Research Project (CRP) on the "Intercomparison of Evaluations of Actinide Neutron Nuclear Data" which took place in Vienna, 12-13 October 1981.

In chapter 1 results are given of the average number of prompt neutrons $\bar{\nu}_p$ and average total prompt γ-ray energy $\bar{E}_\gamma$ measured for the fission of ^{232}Th induced by neutrons in the energy range from 1.5 to 15 MeV. Large fluctuations of $\bar{\nu}_p$ have been observed from high neutron energy resolution measurements performed in the threshold region. Just above the second chance fission threshold a strong increase of $\bar{\nu}_p$ is explained from energy balance considerations and is connected with the positive slope observed for the energy dependence of the average total fission fragment kinetic energy $\bar{E}_K$ for the Thorium isotopes. New measurements of the same type are planned for the near future.

Chapter 2 gives only indications on some actinide fission and (n,2n) cross section measurements planned for 1982.

Chapter 3 is devoted to the status of the BRC activities concerning neutron scattering data. A synthesis of measurements and analyses performed at BRC on an extensive set of Thorium, Uranium and Plutonium isotopes is to be published. It concerns differential cross sections for elastic and inelastic scattering to low-lying excited levels measured at incident neutron energies between 0.6 and 3.4 MeV. A high energy buncher is being installed in order to improve the experimental resolution of the spectrometer at higher neutron energies. Thus new measurements are planned for the near future at neutron energies between 5 and 7 MeV. Experimental and theoretical aspects of "fast neutron scattering on actinide nuclei" have been reviewed at the Specialists' Meeting which took place in Paris (OECD, Château de la Muette, 23-25 Nov. 1981).

With regard to this Meeting an extensive compilation of actinide nuclear data was prepared in collaboration with the Nuclear Data Bank at Saclay for considerations by the working groups.

Recent improvements of the data retrieval system SYNOPSIS are described in chapter 4. A portable version of this system is being tested and will be made available in the near future for use on IBM machines.

Chapter 5 gives a brief description of the code NRLY which is available to calculate the fast neutron cross sections of fissionable nuclei within an energy range from about 10 keV to 2 or 3 MeV when consideration of a number of discrete fission channels is needed.

Coupled channels optical model calculations have been proved to be useful for predicting neutron cross sections in the actinide region. Results of such calculations are about to be completed for an extensive set of isotopes (cf chapter 6). It has been shown that interpolations between such "realistic" results are expected to be practical and save prohibitive computation time for evaluation purposes within a wide mass range. In this context it is necessary to evaluate the importance of how to take account of the nuclear deformations. Some comments about this problem are also given in chapter 6.

Finally in chapter 7 are gathered some deformation characteristics as obtained for a set of actinide isotopes from recent microscopic calculations based on the Hartree-Fock-Bogolyubov methods. Comments are given about a comparison between calculated and experimental results.

Other recent progress related to our knowledge of the actinide nuclear data will be found in the next BRC Annual Progress Report to be published as an NEANDC-INDC report.

References

[1] "Progress Report of recent works on actinide nuclear data at Bruyères-le-Châtel", NEANDC(E) 211 "L" , INDC(FR) 41/L (March 1981).

[2] "Status of Activities on actinide nuclear data at Bruyères-le-Châtel (preliminary)", note PNN-809/81.

1 - MEASUREMENTS OF $\bar{\nu}_p$: RESULTS FOR ^{232}Th, AND SHORT TERM PROGRAMME

J. Fréhaut, A. Bertin, R. Bois, J. Trochon

The measurements of $\bar{\nu}_p$ made to date on the main isotopes of U, Np and Pu at BRC have recently been completed by a measurement on ^{232}Th in the incident neutron energy range from 1.35 MeV up to 15 MeV.

In the fission threshold region, between 1.35 and 3 MeV, measurements were made with an energy resolution of ± 20 keV. The results are plotted in Fig. 1b. The existing high energy resolution fission fragment total kinetic energy measurements [1,2] are plotted in Fig. 1c. Large fluctuations are observed for $\bar{\nu}_p$ and $\bar{E}_K$, especially around 1.8 and 2.3 MeV where the fission cross section exhibits broad structures. Above 2.3 MeV the fission cross section is a relatively smooth function of incident energy, and $\bar{\nu}_p$ and $\bar{E}_K$ are linear functions of energy with slopes of 0.104 neutron/MeV and 0.35 MeV/MeV, respectively. In Fig. 1a are plotted the partial fission cross sections for the relevant values of the quantum number K. These cross sections were obtained from a calculation based on the Hauser-Feshbach formalism [3].

The comparison of the $\bar{\nu}_p$ and $\bar{E}_K$ data with the behaviour of the partial fission cross sections suggests that $\bar{\nu}_p$ and $\bar{E}_K$ differ from a value of the quantum number K to another.

In a first approach, we have assumed that $\bar{\nu}_p$ and $\bar{E}_K$ were linear functions of the incident energy E_n with slopes independant of K and equal to those measured at higher energies (0.104 n/MeV for $\bar{\nu}_p$ and 0.35 MeV/MeV for $\bar{E}_K$). Then the zero energy values of $\bar{\nu}_p$ and $\bar{E}_K$ were determined for each value of K by fitting the experimental data using the calculated partial cross sections for weighting. These are, respectively for the K values of $^1/_2$, $^3/_2$ and $^5/_2$:

for $\bar{\nu}_p$: 2.005 , 1.905 and 1.805 (neutron)

for $\bar{E}_K$: 162.25 , 162.25 and 164.15 (MeV)

This fit corresponds to the lines drawn in Fig. 1b and 1c which agree fairly well with the behaviour of experimental data.

These results suggest that the quantum number K is not changed during the passage from saddle point to scission and that the repartition of the available

energy between the different degrees of freedom of the compound nucleus is determined by the K value of the fission channel.

The data obtained at higher incident energies for $\bar{\nu}_p$ and $\bar{E}_\gamma$ (the average total prompt γ-ray energy) are plotted in Fig. 2 and 3, respectively. Like in previous measurements [4] the behaviour of $\bar{E}_\gamma$ can be interpreted in terms of a competition between neutron and γ-ray emission in the desexcitation process of the fission fragments. Below the second chance fission threshold, one can deduce that :

$$\bar{E}_\gamma = 0.65\ \bar{\nu}_p + 4.45 \quad \text{(MeV)}$$

The value of 4.45 MeV corresponds to the statistical theory calculations, and the linear relation between $\bar{E}_\gamma$ and $\bar{\nu}_p$ results from an increase of the average angular momentum of the fission fragments with excitation energy.

Contrary to the nuclei measured to date, the occurence of the second chance fission results in a strong increase of $\bar{\nu}_p$. This behaviour can be understood very well in terms of energy balance and is mainly a consequence of the increase of $\bar{E}_K$ with excitation energy for Thorium isotopes. In the (n,n'f) process, the fissioning nucleus will have about 6 MeV less excitation energy than in direct fission, and consequently the fragment total kinetic energy will be about 2 MeV less. These 2 MeV will appear as intrinsic excitation energy of the fragments, and thus will lead to an increase of $\bar{\nu}_p$.

Measurements planned in the near future

Similar measurements of $\bar{\nu}_p$ as performed for ^{232}Th are planned on ^{230}Th in 1982. They will include a high incident neutron energy resolution measurement in the threshold region and measurements up to 15 MeV.

A $\bar{\nu}_p$ measurement is also planned for ^{243}Am within the incident neutron energy range from 1 MeV to 15 MeV.

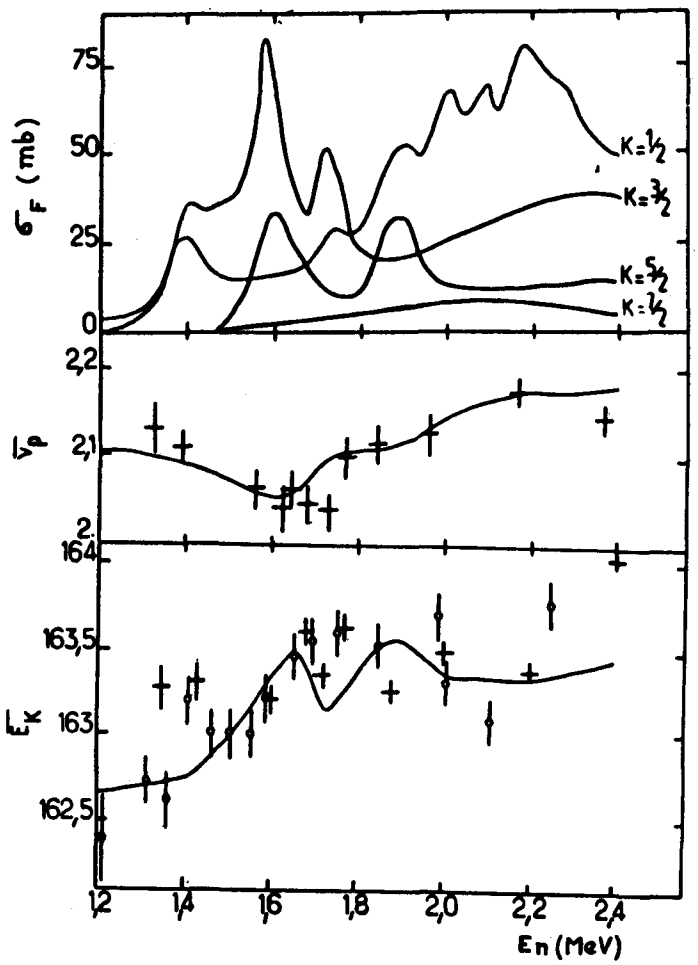
References of chapter 1

[1] J. Trochon et al., Nucl. Phys. A318 (1979) 63

[2] N. Dyachenko et al., Sov. J. Nucl. Phys. 26 (1977) 365.

[3] H. Abou Yehia et al., NEANDC(E) 204 "L" (1979)

[4] J. Fréhaut et al., NEANDC(E) 211 "L" (1981) 7.



Variation as a function of incident neutron energy :

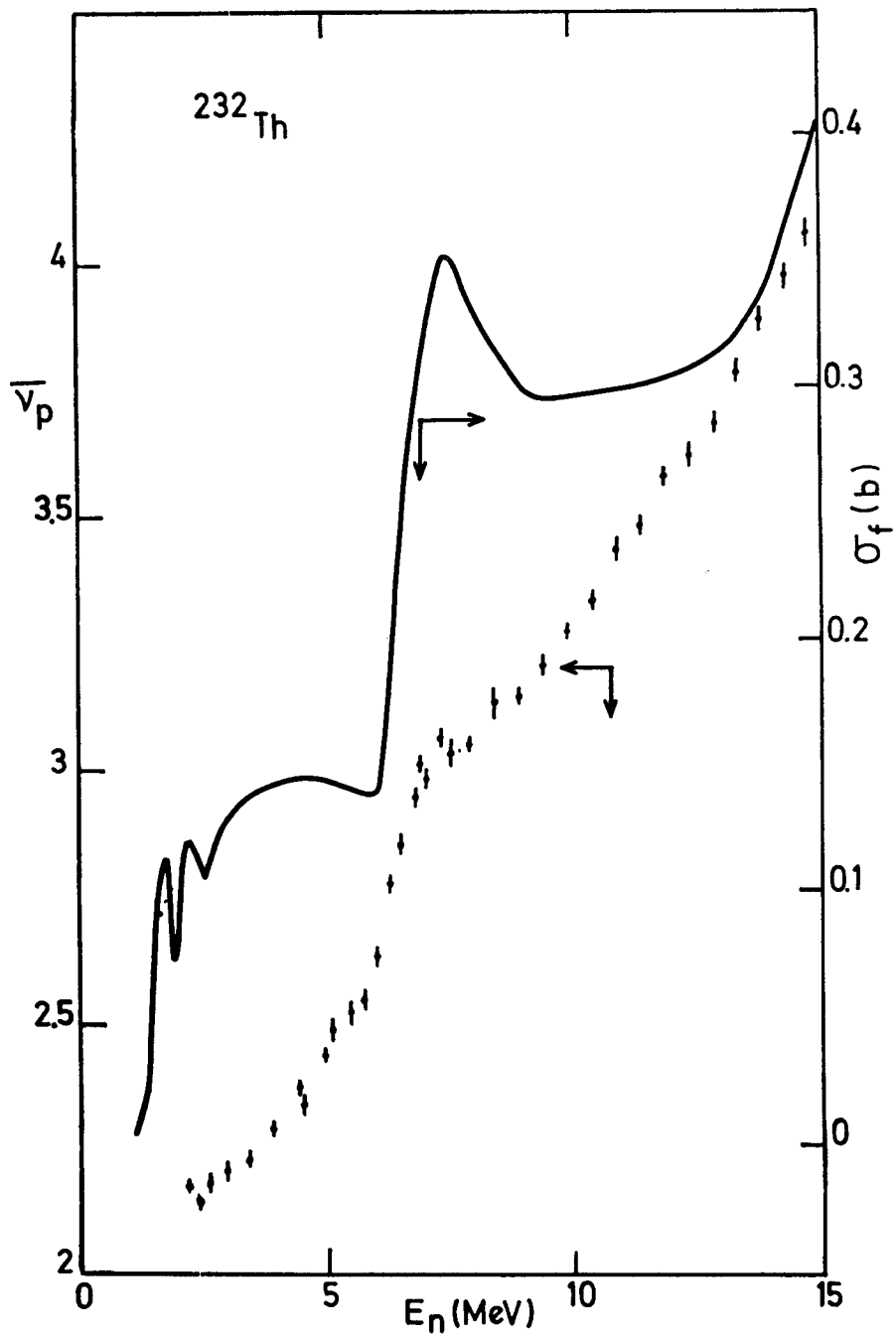
a) of the partial fission cross sections calculated for different values of the quantum number K [3].

b) of the average number of prompt neutrons $\bar{\nu}_p$.

c) of the average total kinetic energy of the fission fragments

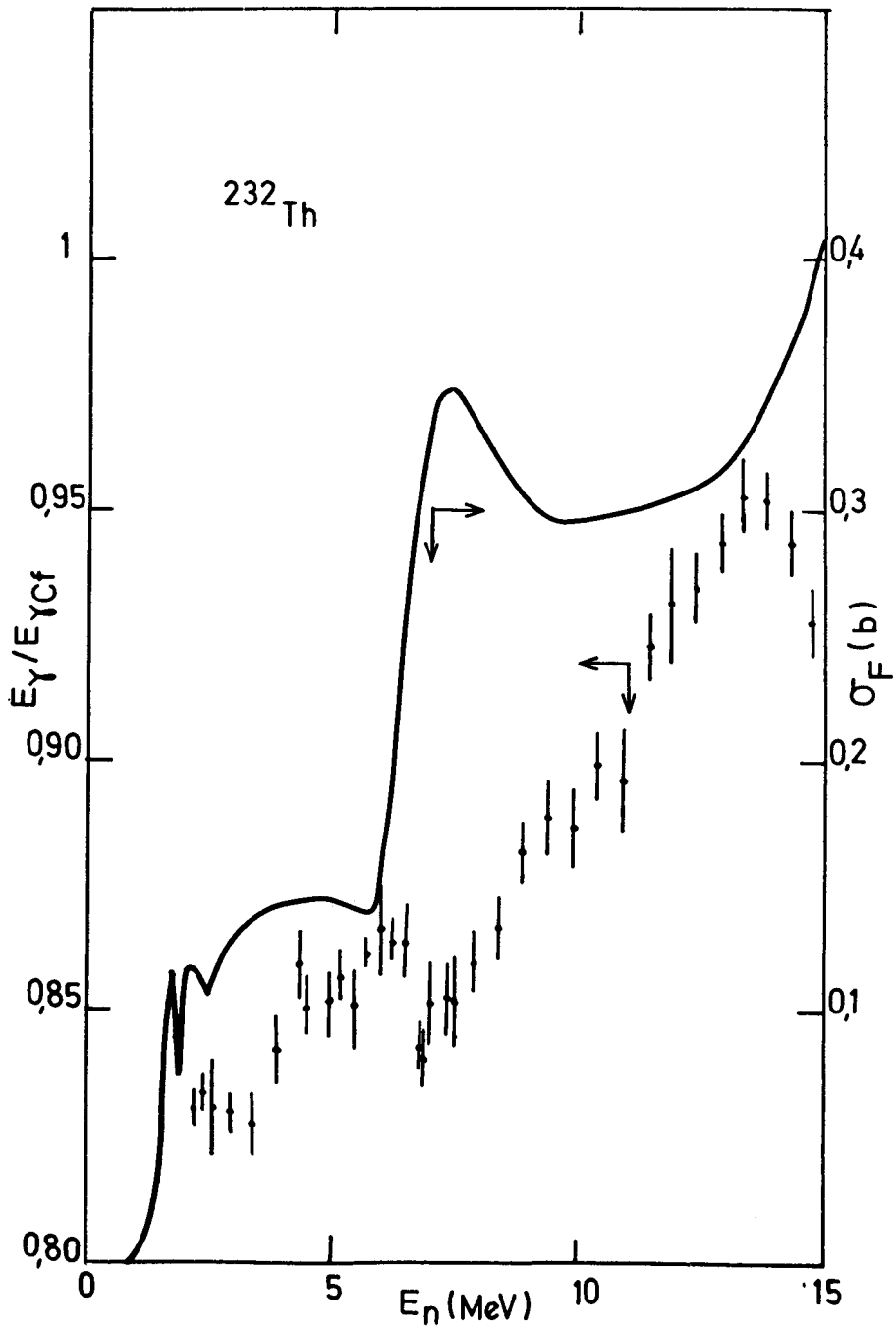
+ ref. [1] o ref. [2]

Fig. 1



Variation of $\bar{\nu}_p$ and of the fission cross section for the fission of ^{232}Th induced by neutrons in the energy range from 2 MeV to 15 MeV.

Fig. 2



Variation of the prompt fission gamma ray energy $\bar{E}_\gamma$ and of the fission cross section for the fission of ^{232}Th induced by neutrons in the energy range from 2 MeV to 15 MeV. The $\bar{E}_\gamma$ values are normalized to the prompt γ-ray energy $\bar{E}_{\gamma cf}$ for the spontaneous fission of ^{252}Cf.

Fig. 3

2 - FISSION AND (n,2n) CROSS SECTIONS

G. GRENIER, J. FREHAUT

Measurements planned for 1982 :

. <u>fission cross sections for</u> :

. ^{239}Pu at 2.5 MeV.
. ^{237}Np, ^{240}Pu and ^{242}Pu at 14.6 MeV.

. <u>(n,2n) cross sections for</u> :

. ^{232}Th.

3 - NEUTRON SCATTERING DATA

G.HAOUAT, Y.PATIN, J.LACHKAR, J.SIGAUD

3-1-Synthesis of measurements and analyses performed at BRC.

Fast neutron scattering data for actinide nuclei are of great importance in the optimization studies of fast breeder reactors. In particular, the balance between the elastic and inelastic scattering cross sections determines the slowing down rate of neutrons in fast reactors [1]. Nuclear data requests are expressed for several actinide nuclei in the energy range from a few keV to several MeV [2]. The evaluated data files partly fulfill the needs, but they exhibit large discrepancies for neutron scattering data at energies beyond $\simeq$ 1 MeV.

Besides the applied interest in producing accurate data for engineering purposes, the study of fast neutron scattering from actinides provides basic information for the parametrization of the deformed optical potential needed for evaluation purposes.

Therefore, an extensive experimental study of fast neutron scattering has been undertaken on the nuclei ^{232}Th, ^{233}U, ^{235}U, ^{238}U, ^{239}Pu and ^{242}Pu. Differential cross sections for elastic scattering and inelastic scattering to low-lying excited levels were measured at several incident neutron energies between 0.6 and 3.4 MeV in the angular range 15- 160 deg, utilizing a high-resolution multi-detector neutron time-of-flight spectrometer. The performances of the neutron spectrometer, the results of the measurements and their help to determine the optical potential in the actinide region are gathered in a paper to be published [3].

3-2-Compilation of nuclear data.

An extensive compilation of nuclear data for actinide nuclei in the range Z = 90 to 95 was prepared, in collaboration with the Nuclear Data Bank at SACLAY [4], and presented at the Specialists' Meeting on "Fast Neutron Scattering on Actinide Nuclei" (PARIS, 23-25 Nov. 1981) for consideration by the working groups.

The compilation includes experimental, calculated as well as evaluated data for the following cross sections :

- *Neutron nuclear data,* in the energy range 10 keV to 20 MeV
  - Elastic scattering and inelastic scattering to discrete levels (angular distributions and angle-integrated cross sections).
  - Inelastic scattering cross sections determined by (n,n'γ) reactions.
  - Energy and angular distributions of emergent neutrons.
  - Total cross sections and non-elastic cross sections.

- *Elastic and inelastic scattering cross sections for protons,* between 10 and 50 MeV.

A sample of compiled data for neutron scattering on the nucleus ^{242}Pu is given in Figs. 1-6 as an example.

3-3-Improvements of the experimental techniques and short term programme.

The optimum experimental energy resolution obtained with the neutron time-of-flight spectrometer associated with the tandem accelerator is presently $\frac{dE}{E} = 1.0\%$ [5]. This value limits neutron scattering measurements on actinide nuclei to incident energies of up to $\simeq 3.5$ MeV, if one wants to resolve the elastic and inelastic scattering neutron groups for a nucleus such as ^{238}U. Several parameters contribute to the global energy resolution of the spectrometer, in particular the burst width (Δt) and the energy dispersion (ΔE) of the charged particle pulsed beam incident on the neutron producing target. The experimental characteristics of the tandem accelerator are presently for protons or deuterons :

$$\Delta t = 0.7 - 1.0 \text{ ns} \quad \text{FWHM}$$
$$\Delta E = 7 - 10 \text{ keV} \quad \text{FWHM}$$

with a mean current of 2 to 4 μA.

In order to improve the experimental resolution of the spectrometer at high neutron energies, between 4 and 10 MeV, we have analysed the possible performances of this spectrometer by adding a "high energy buncher" to the accelerator [6]. The buncher consists in a radio-frequency single-gap cavity for which calculations and design have been performed. The expected characteristics of the pulsed beam behind the buncher are for 10 MeV protons :

$$\Delta t = 0.23 \text{ ns} \quad \text{FWHM}$$
$$\Delta E = 30 \text{ keV} \quad \text{FWHM}$$
$$\langle I \rangle = 2 \text{ to } 4 \ \mu A$$

These experimental conditions impose to optimize the neutron detector parameters. It is expected to achieve a total energy resolution $\frac{\Delta E}{E}$ of $\simeq 0.5\%$ for 10 MeV neutrons.

The high energy buncher is planned to be installed in the middle of 1982, and measurements on ^{232}Th and ^{238}U are planned to be performed at neutron energies between 5 and 7 MeV.

For a review on scattering cross section data and experimental techniques, see reference [7].

REFERENCES OF CHAPTER 3

[1] - T. CHOONG and E. KUJAWSKI, *Nucl. Sci. Eng.* 60, *326 (1976).*

[2] - D.W. MUIR, Editor, *WRENDA 79/80, INDC (SEC) 73 URSF (Oct. 1979).*

[3] - G. HAOUAT, J. LACHKAR, Ch. LAGRANGE, J. JARY, J. SIGAUD, Y. PATIN *"Neutron scattering cross sections for* ^{232}Th, ^{233}U, ^{235}U, ^{238}U, ^{239}Pu *and* ^{242}Pu *between 0.6 and 3.4 MeV", to be published in N.S.E.*

[4] - Work performed in collaboration with C. NORDBORG, T. NAKAGAWA of the OECD (Saclay), and P. NAGEL (collaborator at BRC).

[5] - G. HAOUAT, J. LACHKAR, Ch. LAGRANGE, Y. PATIN, J. SIGAUD and R.E. SHAMU, *Report NEANDC (E) 196 "L" - INDC (FR) 29/L (1978).*

[6] - J. BARDY, M.A. BEUVE, A. DANDINE, R. DEI-CAS, J.P. LAGET, *Report CEA-N-2214, NEANDC (E) 222 "L" - INDC (FR) 50/L, p. 9 (1981).*

[7] - G. HAOUAT, *"Cross section data on fast neutron elastic and inelastic scattering from actinide nuclei", invited paper at the Specialists' Meeting on "fast neutron scattering on actinide nuclei", 23-25 Nov. 1981, OECD, Château de la Muette (Paris).*

FIGURE CAPTIONS

FIG. 1 : Total cross section of ^{242}Pu between 10 keV and 1 MeV. Data referenced as follows :

E4 : ENDF/BIV
E5 : ENDF/BV
IB : INDL/A 5161 (1979)
IM : INDL/A 2025 (1979)
KFK 78 : KFK-2686 (1978)
LAS 79 : NBS-SP 594 (1980) p. 703

FIG. 2 : Total cross section of ^{242}Pu between 1 and 20 MeV. Data are referenced as follows :

E4 : ENDF/BIV
E5 : ENDF/BV
IB : INDL/A 5161 (1979)
IM : INDL/A 2025 (1979)
LAS 79 : NBS-SP 594 (1980) p. 703

FIG. 3 : Elastic scattering cross section of ^{242}Pu between 0.1 and 20 MeV. Data are referenced as follows :

E4 : ENDF/BIV
E5 : ENDF/BV
IB : INDL/A 5161 (1979)
IM : INDL/A 2025 (1979)
LAS 79 : LA/7855 (1979)
BRC 79 : NBS-SP 594 (1980) p. 672.

FIG. 4 : Inelastic scattering cross section to the first 2^+ (45 keV) state of ^{242}Pu between 0.1 and 20 MeV. Same references as in Fig. 3.

FIG. 5 : Inelastic scattering cross section to the first 4^+ (147 keV) state of ^{242}Pu between 0.1 and 20 MeV. Same references as in Fig. 3.

FIG. 6 : Elastic scattering angular distribution for ^{242}Pu at the incident neutron energy of 1 MeV. Same references as in Fig. 3.

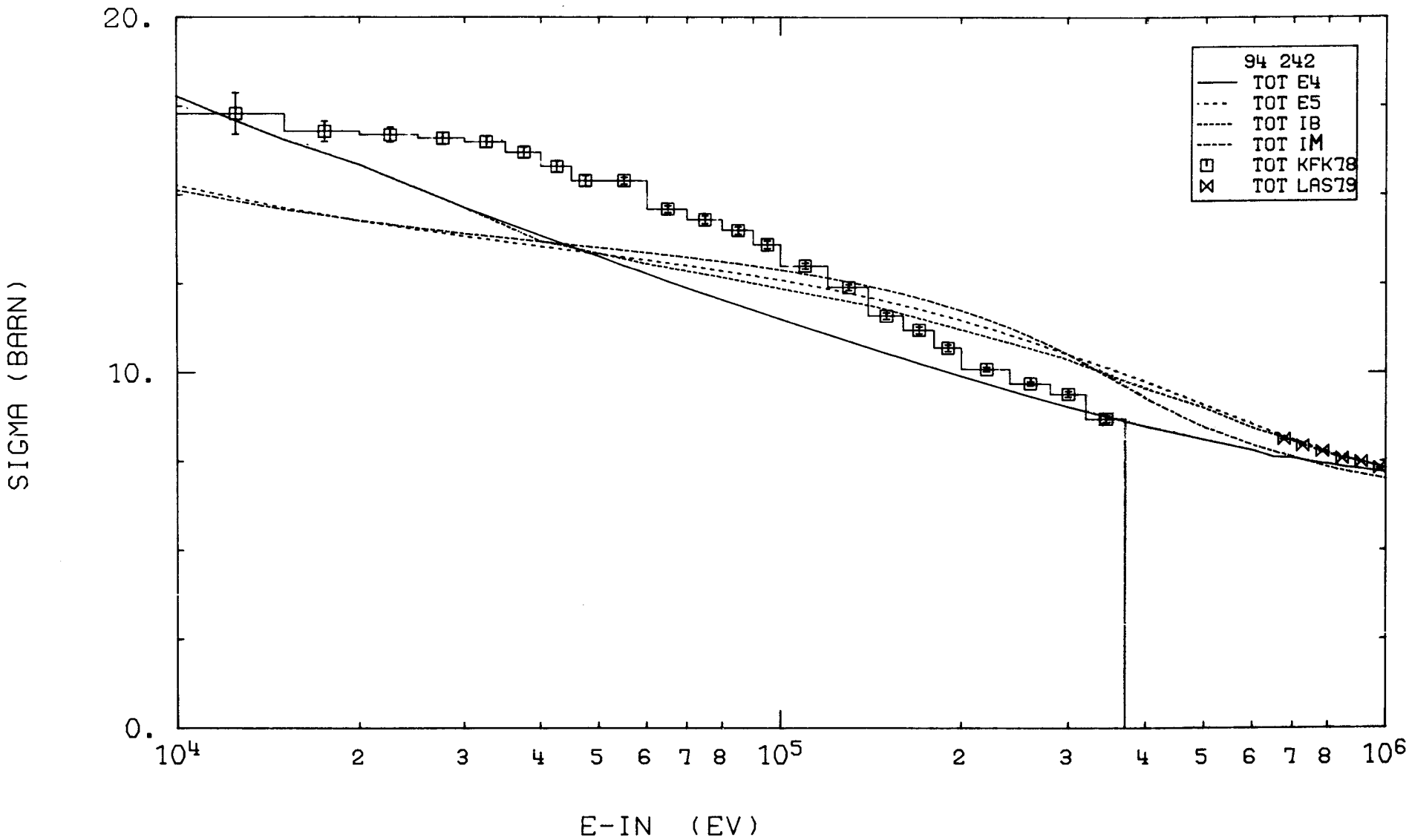

94 242
TOT E4
TOT E5
TOT IB
TOT IM
TOT KFK78
TOT LAS79
SIGMA (BARN)
20.
10.
0.
E-IN (EV)
10^4
2
3
4
5
6
7
8
10^5
2
3
4
5
6
7
8
10^6

FIGURE 1

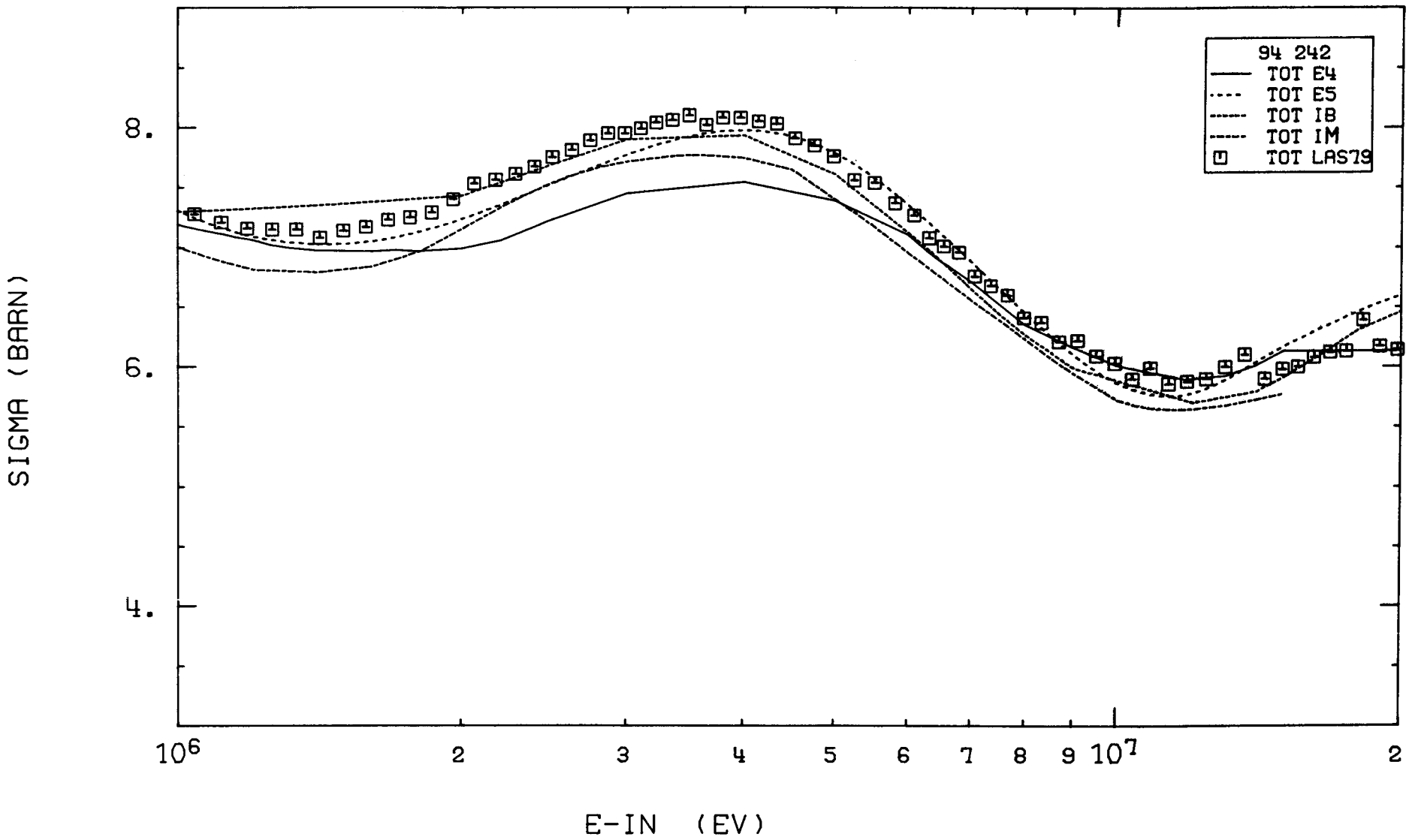

94 242
TOT E4
TOT E5
TOT IB
TOT IM
TOT LAS79
8.
6.
4.
SIGMA (BARN)
10^6
2
3
4
5
6
7
8
9
10^7
2
E-IN (EV)

FIGURE 2

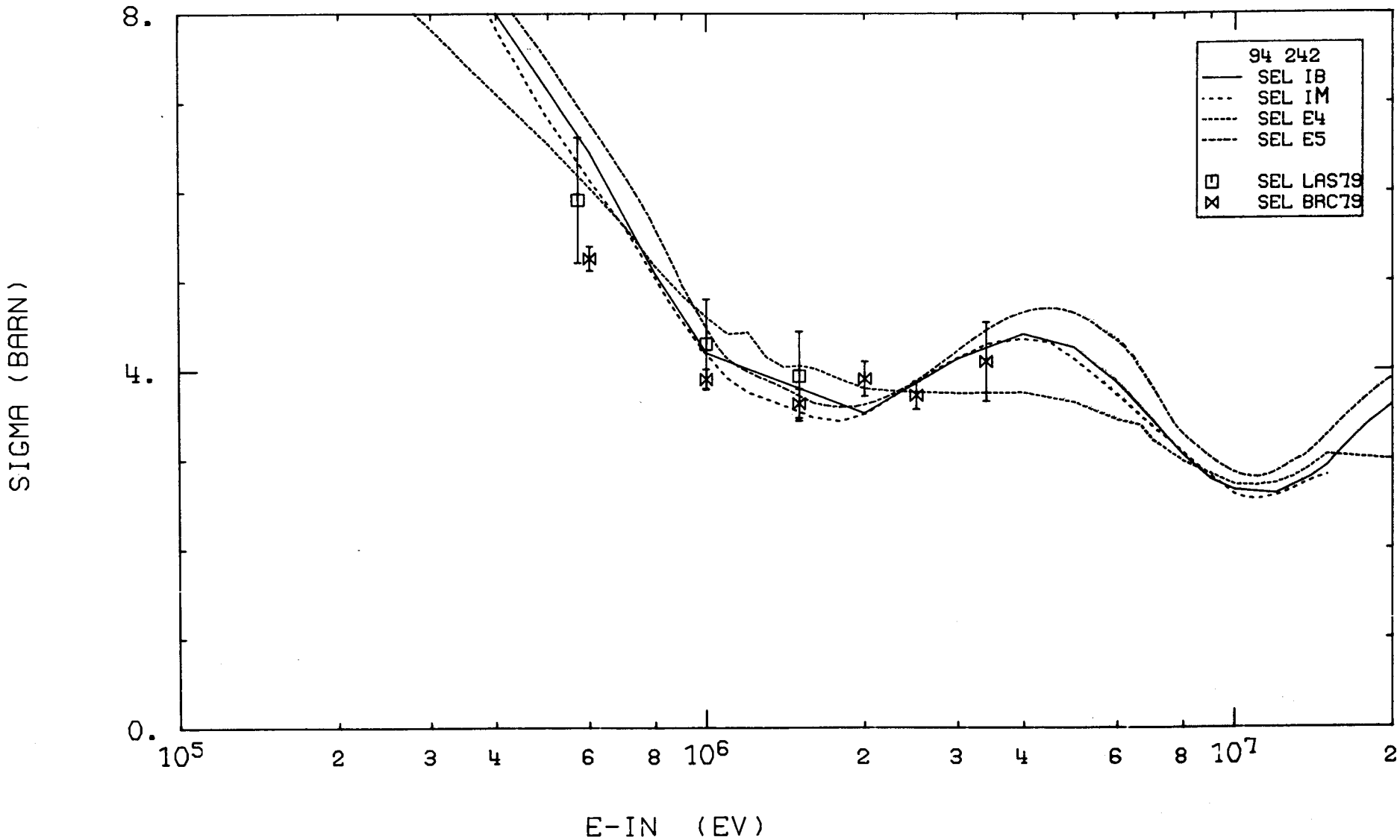

94 242
SEL IB
SEL IM
SEL E4
SEL E5
SEL LAS79
SEL BRC79
8.
4.
0.
SIGMA (BARN)
10^5
2
3
4
6
8
10^6
2
3
4
6
8
10^7
2
E-IN (EV)

FIGURE 3

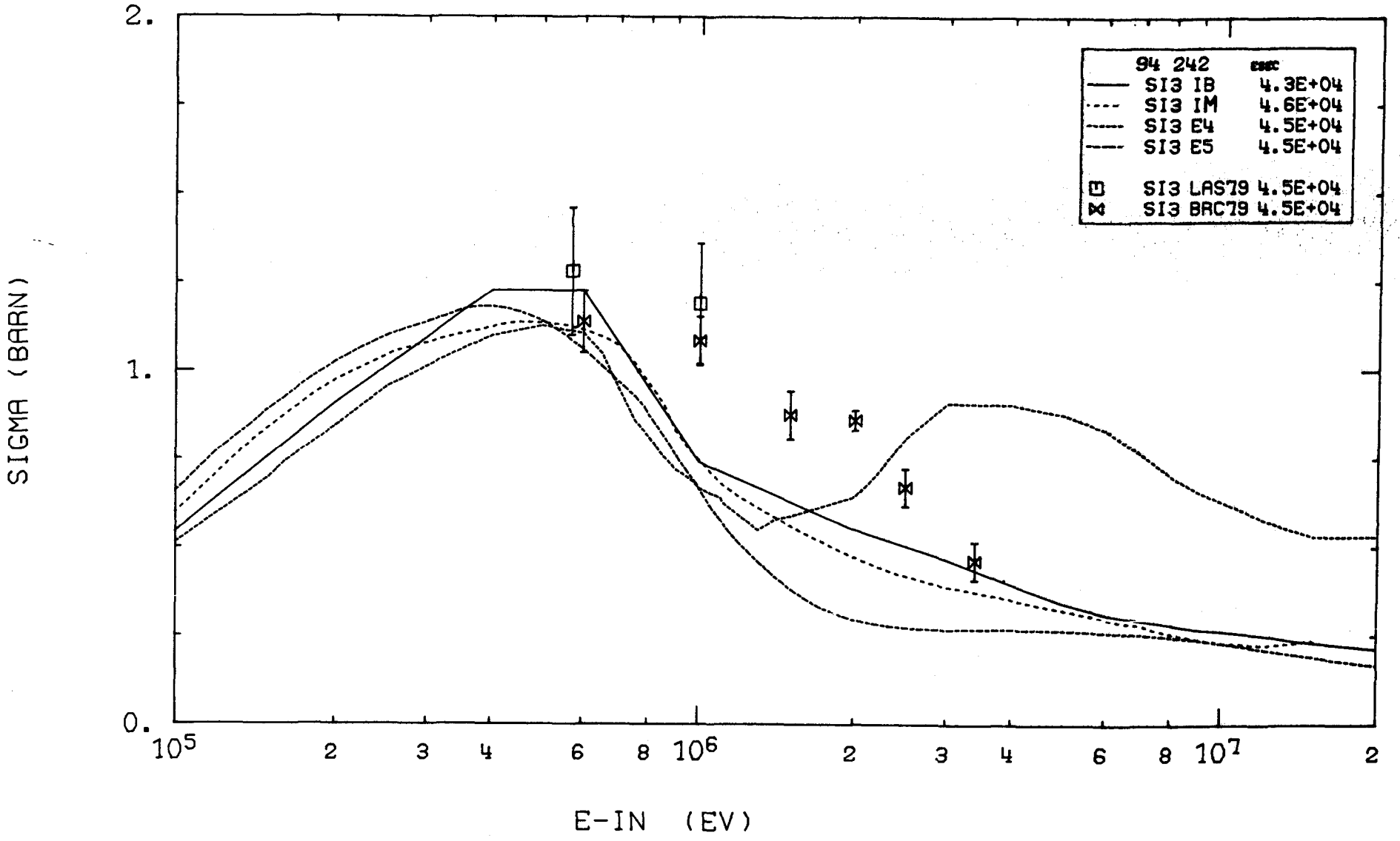
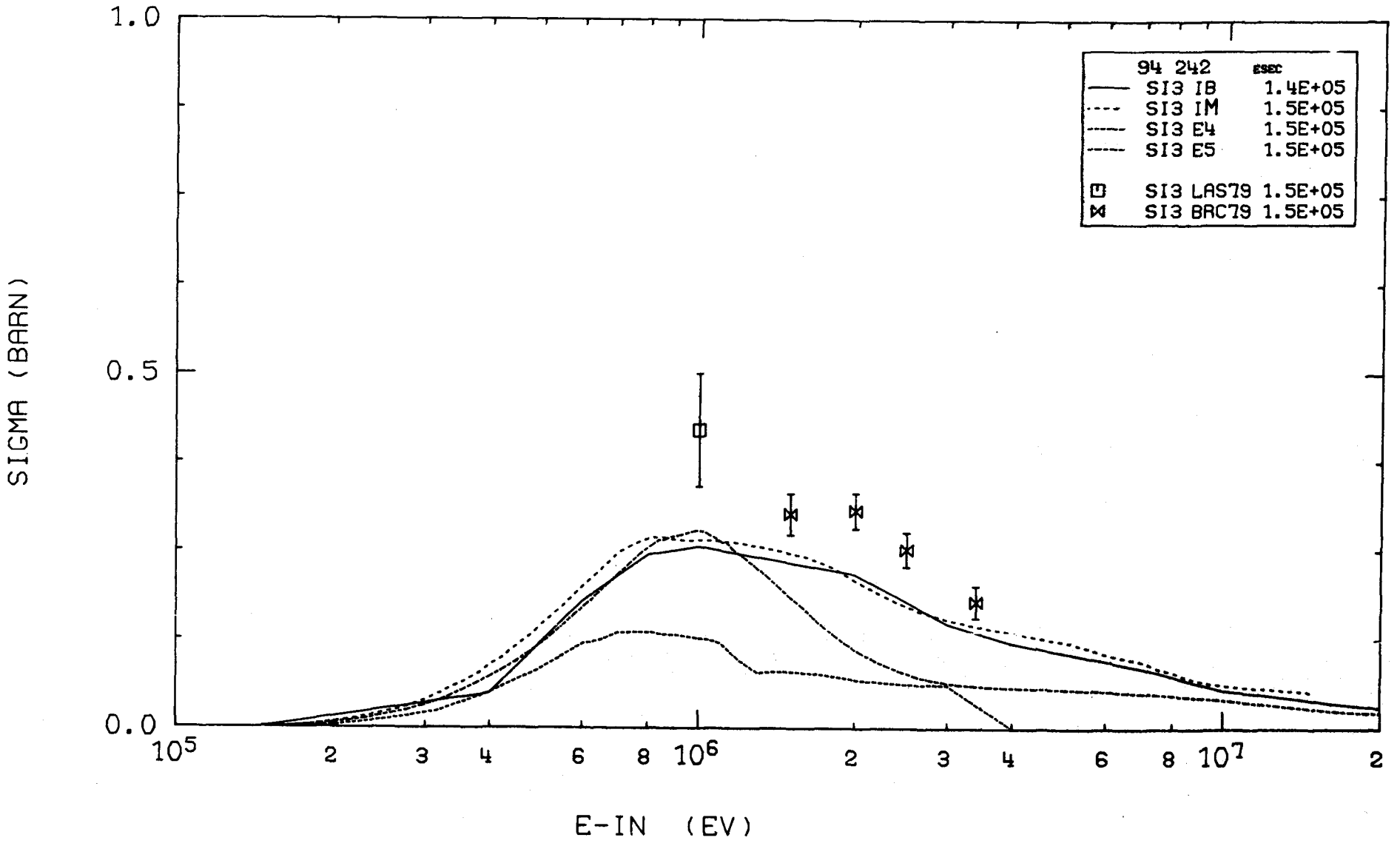

94 242
SI3 IB 4.3E+04
SI3 IM 4.6E+04
SI3 E4 4.5E+04
SI3 E5 4.5E+04
SI3 LAS79 4.5E+04
SI3 BRC79 4.5E+04
SIGMA (BARN)
2.
1.
0.
10^5
2
3
4
6
8
10^6
2
3
4
6
8
10^7
2
E-IN (EV)

FIGURE 4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0.5
0.0
SIGMA (BARN)
94 242 ESEC
SI3 IB 1.4E+05
SI3 IM 1.5E+05
SI3 E4 1.5E+05
SI3 E5 1.5E+05
SI3 LAS79 1.5E+05
SI3 BRC79 1.5E+05
10^5
2
3
4
6
8
10^6
2
3
4
6
8
10^7
2
E-IN (EV)

FIGURE 5

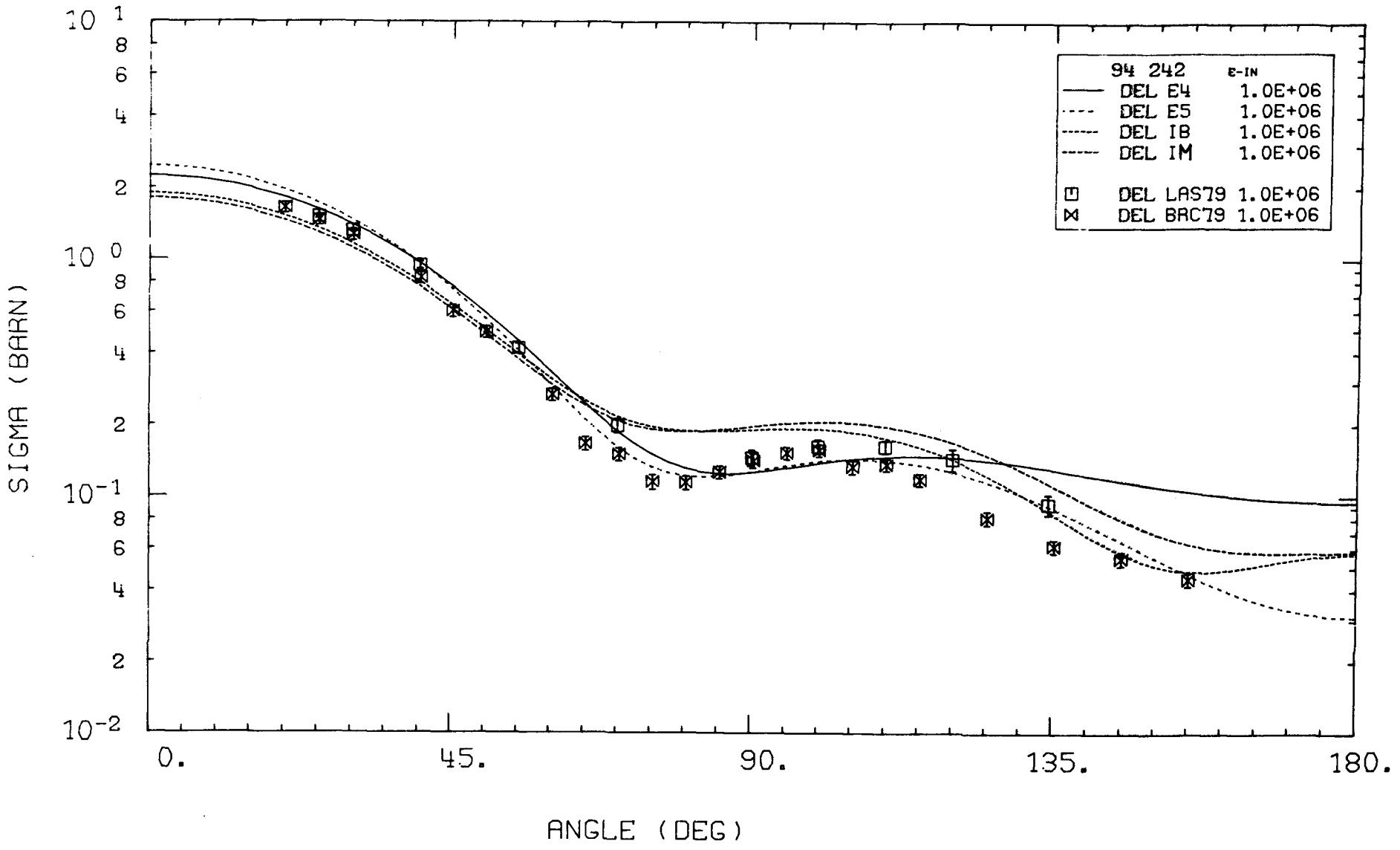

94 242 E-IN
DEL E4 1.0E+06
DEL E5 1.0E+06
DEL IB 1.0E+06
DEL IM 1.0E+06
DEL LAS79 1.0E+06
DEL BRC79 1.0E+06
SIGMA (BARN)
ANGLE (DEG)
0.
45.
90.
135.
180.

FIGURE 6

4 - SYNOPSIS : RECENT IMPROVEMENTS OF THE SYSTEM

M. Collin, D. Cotten, C. Philis

As planned in the previous report [1] many aspects of the SYNOPSIS system have been developed :

1 - The acquisition of a 300 megabyte disk to replace the original 50 Mb one has allowed us

- to store other libraries such as KEDAK and JENDL.
- to create our own library containing BRC-evaluations.
- to extend the "MINI" file system. Each user can store up to 600 data sets and compare each of them to other and/or to evaluated data libraries.

2 - The format conversion routines were extended to treat all the options of the description of angular distributions and spectra in ENDF BIV and BV formats.

3 - Editing programs allow us to obtain

- the list of one or several sections of one or several materials.
- the complete description of one or several materials.
- the translation of an ENDF BV description in BIV format permitting one to use the new data without modification of the codes.

4 - A portable version of the SYNOPSIS system for IBM machines is being tested.

We verified that the data sets (MEGA, MINI and indexes) in their binary form can be transferred from MITRA 125 to an IBM 370.

So we can save time using a copy of the data files in binary form to implement the system on a new computer.

The storage of ENDF BIV + BV + ENDL form card format needed 15 hours CPU on MITRA, and a simple copy seems easier and faster.

5 - A set of procedures was developed to allow automatisation of data plotting. Verification and publication of large sets of data will be greatly

simplified. Different samples of graphical outputs are given (Fig. 1-3) (units are barn, barn/st, and eV).

Fig. 1 - ^{242}Pu : capture cross sections (different libraries)

Fig. 2 - ^{242}Pu : Angular distribution (different incident energies) for inelastic scattering to the first excited state.

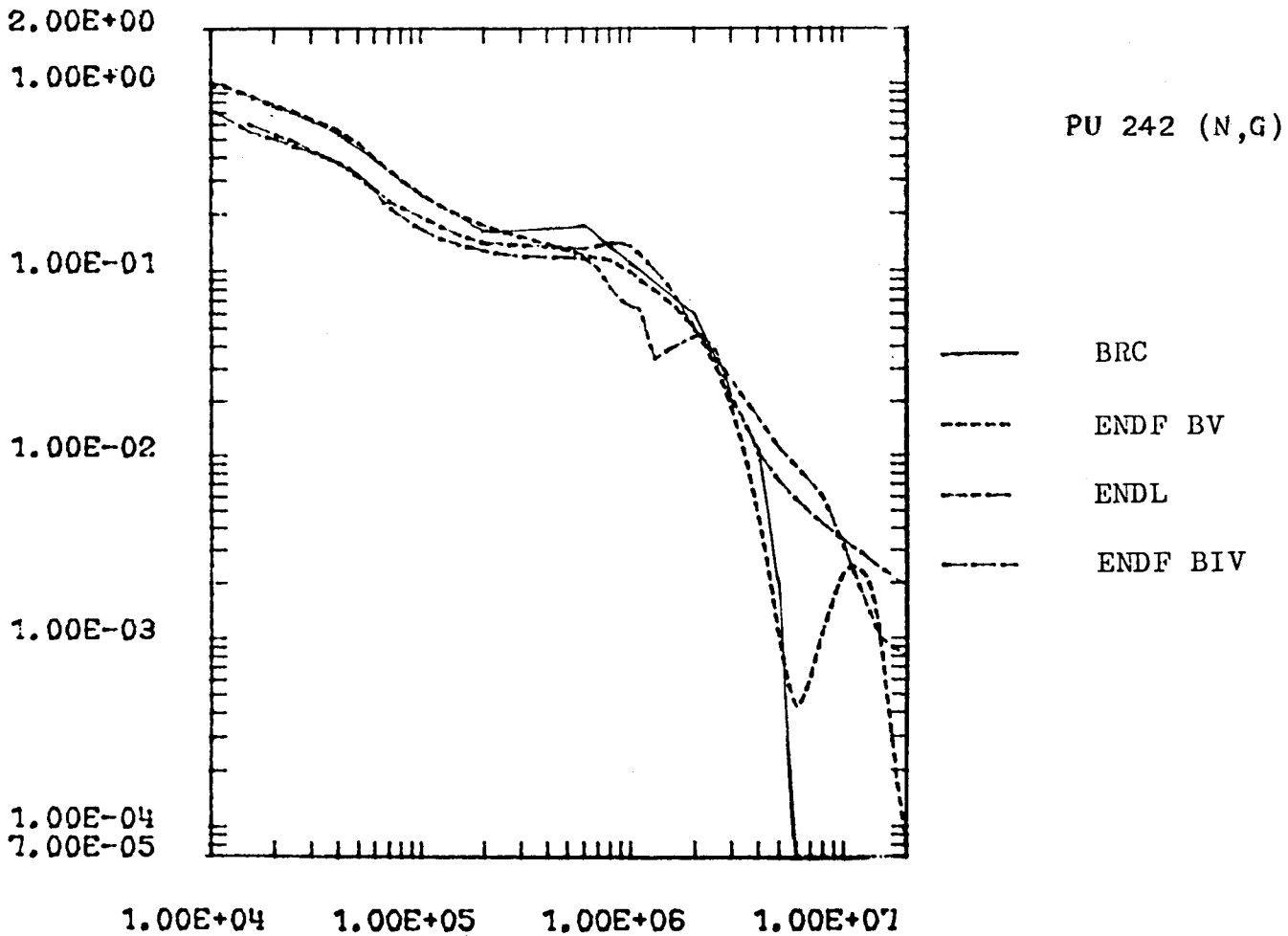
Fig. 3 - ^{242}Pu : Secondary neutron spectra (different incident energies).

We plan to write the second part of the report [2] concerning the implementation of SYNOPSIS as soon as the portable version is available.

References of chapter 4

[1] M. Collin, D. Cotten, C. Philis. : "Synopsis : an Interactive Nuclear Data Evaluation File Interface and Maintenance System", in Report NEANDC(E) 211 "L" ; INDC(FR) 41/L (1981).

[2] M. Collin, A. Schett, C. Philis : "Synopsis : an Interactive Nuclear Data Evaluation File Interface and Maintenance System : Part I, Basic Concept" Report NEANDC(E) 207 "L" ; INDC(FR) 37/L (1980).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1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
7.00E-05
1.00E+04
1.00E+05
1.00E+06
1.00E+07
PU 242 (N,G)
BRC
ENDF BV
ENDL
ENDF BIV

FIG.1

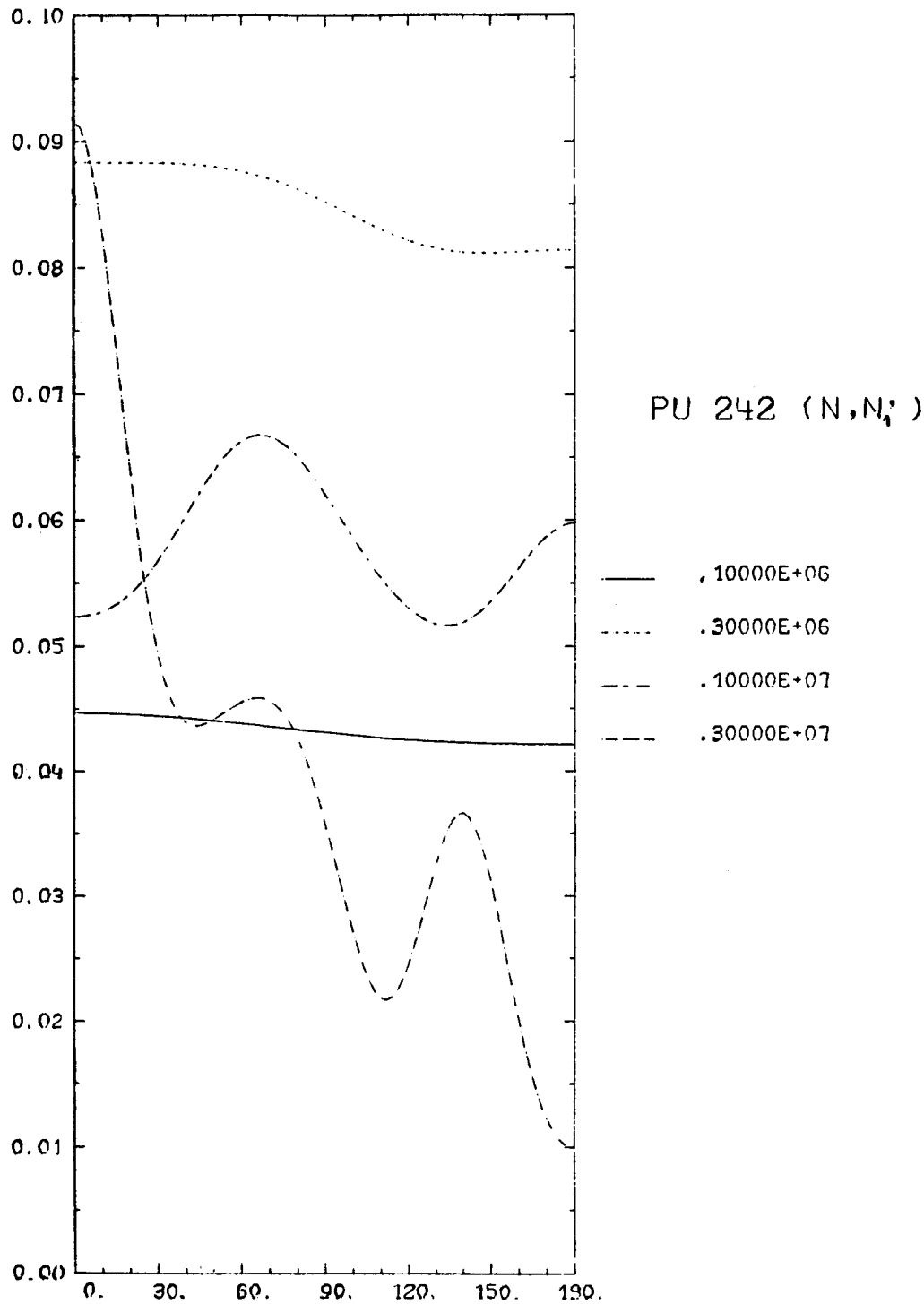
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0.
30.
60.
90.
120.
150.
180.
PU 242 (N,N1')
.10000E+06
.30000E+06
.10000E+07
.30000E+07

FIG.2

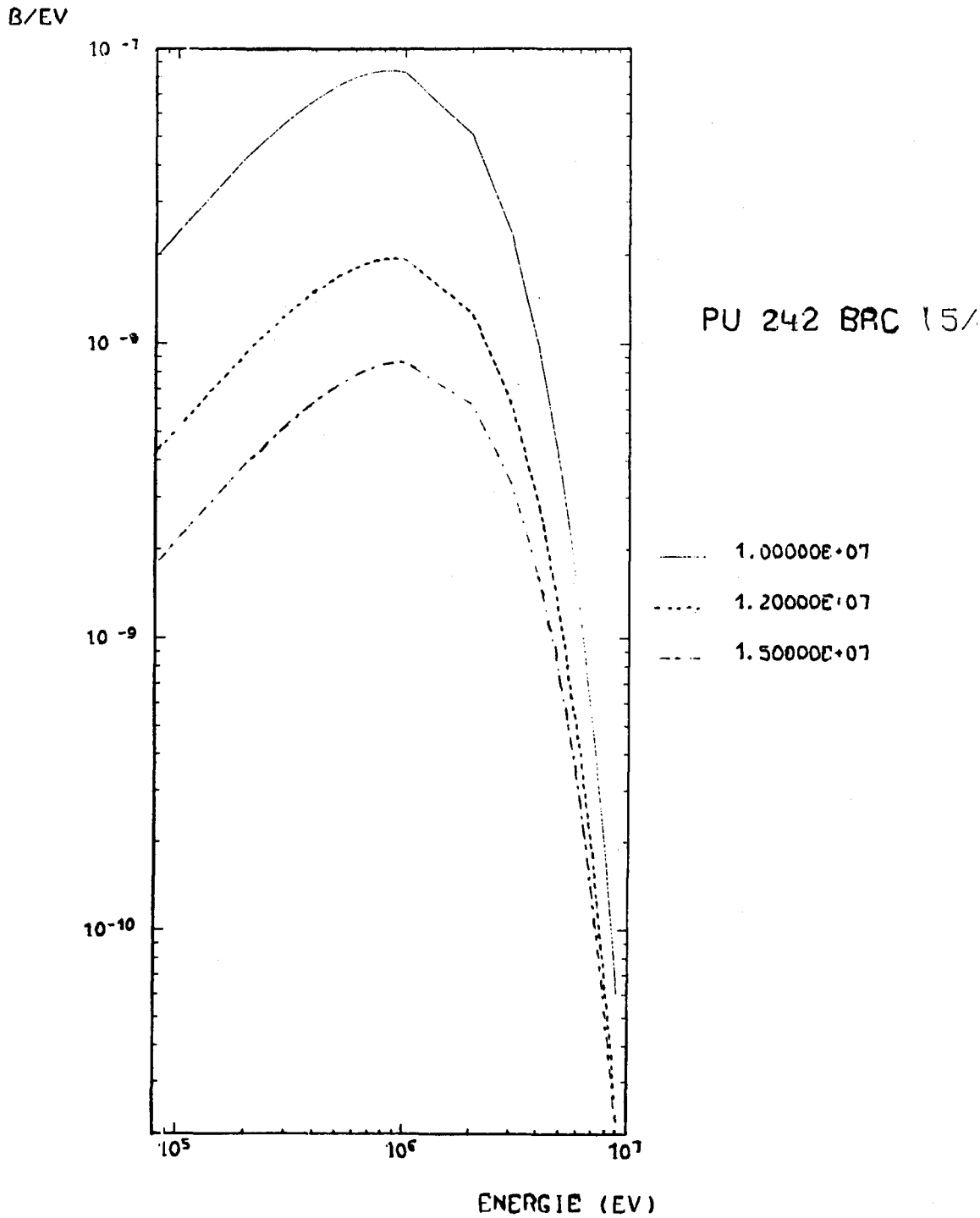
B/EV
10 -7
10 -8
10 -9
10-10
10⁵
10⁶
10⁷
ENERGIE (EV)
PU 242 BRC 15/
1.00000E+07
1.20000E+07
1.50000E+07

FIG.3

5 - NRLY : A STATISTICAL MODEL CODE FOR CALCULATING NEUTRON CROSS SECTIONS OF FISSIONABLE NUCLEI

J. JARY

The statistical model code NRLY which calculates the fast neutron cross sections of fissionable nuclei within an energy range from about 10 keV to 2 or 3 MeV has just been made available [1].

Cross sections are calculated for the following mechanisms : radiative capture, compound elastic and inelastic scattering, fission and angular distributions of fission fragments for each relevant fission channel.

The formalism upon which this code is based has been extensively described in Ref. [2].

In the neutron channels, for calculating compound nucleus formation cross section and neutron emission from this nucleus, use is made of neutron penetrabilities resulting from optical model calculations. The transmission coefficients are introduced as input data as well as the discrete level spectra and the continum level density parameters of the compound and target nuclei (Fermi gas model).

In the radiative channels, we need as input data the experimental radiative width of the compound nucleus at the neutron resonance energies, as well as the characteristics of the giant dipole resonance since the radiative capture widths can be deduced from a single particle formalism [3] or from a dipole resonance formalism (Appendix A in Ref. [2]).

For the fission channels, the input data provide the parameters of possibly different two-humped fission barriers represented by three joint parabolas. Each set of these parameters determine a rotational band head on which rotational states are automatically built. The damping in the second well of these barriers is simulated by an imaginary potential, the strength and energy dependence of which are also given as input data. Continuous fission channel density is not included, whence the upper neutron energy range limitation.

The final fission channel parameters set is generally obtained from a repeatedly use of this code so as to adjust the calculated fission cross

section and (or) angular distribution onto the corresponding available data.

As examples, this code has been used for performing the calculations described in references [2], [4] and [5].

This code is running on IBM computers.

References of chapter 5

[1] J. Jary, Internal note PNN-771/81 (available upon request).

[2] J. Jary, Ch. Lagrange, P. Thomet, Report INDC(FR)9/L - NEANDC(E)174"L" (1977).

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[5] J.W. Boldeman, D. Gogny, A.R. de L. Musgrove, R.L. Walsh, Phys. Rev. C22 (1980) 627.

6 - USE OF THE COUPLED CHANNEL OPTICAL MODEL IN THE ACTINIDE REGION

Ch. Lagrange

6-1- Results of calculations for a set of actinide nuclei

It has been shown in the previous report [1] that interpolations between results from calculations using deformed and well adapted optical potentials could be very useful for evaluation purposes within the actinide region. Such calculations have just been completed and are available for the following even-even nuclei : ^{230}Th, ^{232}Th, ^{234}U, ^{238}U, ^{242}Pu. Contrary to previous calculations (for example Ref. [2] for ^{240}Pu and ^{242}Pu) the results presented here take account of the spin-orbit term within the whole energy range from 1 keV to 20 MeV. Calculated quantities are the following ones :

1 - total cross sections
2 - compound nucleus formation cross sections
3 - shape elastic scattering cross sections
4 - direct inelastic scattering cross sections to the first and second excited levels
5 - Legendre coefficients for the angular distributions corresponding to the scattering mechanisms 3 and 4.
6 - Relevant generalized transmission coefficients $T_{\ell j}(E_n)$ associated to the ground state.

A sample of such results for the target ^{238}U is given in the Appendix 1 for the quantities 1 to 5 and in the Appendix 2 for the quantities 6. Analogous calculations are in progress for ^{248}Cm and ^{252}Cf.

6-2- Parametrisation of the optical potential

The parameters set used for the above calculations is given in Table I. The coupling basis is 0+, 2+, 4+ and complex form factors are considered. The geometric parameters are the same for all nuclei and the slight differences between the potential depths arise essentially from the isospin dependence of the optical potential. Thus, differences in the neutron scattering properties of the actinides are essentially attributable to the nuclear deformations (parameters β_2 and β_4). The global parametrization results from consideration of low energy

neutron scattering properties (strength functions S_0, S_1 ; scattering radius R') and energy dependence of the total cross sections, as well as a number of elastic and inelastic scattering angular distributions recently measured at Bruyères-le-Châtel [3].

Given the importance of the deformations [1], their behaviour throughout the actinide region is to be studied. It is shown in chapter 7 that microscopic calculations could be useful for evaluation purposes. In this context it is worthwhile to point out that the neglect of the β_6, β_8,.. parameters in the scattering calculations seems to induce a mass quadrupole moment q_4^m slightly larger than the one calculated from microscopic calculations. An illustration of that is given in Fig. 1 and Table II showing two equivalent parameter sets respectively with and without taking account of β_6 and describing the ^{238}U scattering differential cross sections.

A review on the use of the coupled channels optical model for predicting actinide fast neutron cross sections is given in reference [4].

References of chapter 6

[1] Ch. Lagrange, "On the usefulness of coupled channel calculations for actinide nuclei", in Report NEANDC(E) 211"L" ; INDC(FR) 41/L (1981).

[2] Ch. Lagrange, J. Jary, NEANDC(E) 198"L" ; INDC(FR)30/L (1978).

[3] G. Haouat, J. Lachkar, Ch. Lagrange, J. Jary, J. Sigaud, Y. Patin, "Neutron scattering cross sections for ^{232}Th, ^{233}U, ^{235}U, ^{238}U, ^{239}Pu and ^{242}Pu between 0.6 and 3.4 MeV", to be published in Nucl. Sci. Eng.

[4] Ch. Lagrange, "Utilisation du modèle optique en voies couplées pour la prédiction de sections efficaces de neutrons rapides, et plus particulièrement pour les actinides de nombre de masse impair", Invited paper at the Specialists' Meeting on "fast neutron scattering on actinide nuclei", OECD, Château de la Muette (Paris, 23-25 Nov. 1981).

$V = V_0 - 0.3\ E_n$		$a_0 = 0.63$ fm	$r_0 = 1.26$ fm
$W_D = \begin{cases} W_{DO} + 0.4\ E_n \\ W_{DO} + 4.0 \end{cases}$	$E_n \leqslant 10$ MeV $E_n \geqslant 10$ MeV	$a_D = 0.52$ fm	$r_D = 1.26$ fm
$V_s = 6.2$		$a_s = 0.47$ fm	$r_s = 1.12$ fm

	^{230}Th	^{232}Th	^{234}U	^{238}U	^{242}Pu
V_0	46.600	46.400	46.42	46.20	46.02
W_{DO}	3.600	3.600	3.720	3.600	3.51
β_2	0.180	0.190	0.194	0.198	0.204
β_4	0.085	0.071	0.071	0.057	0.051

Optical potential and deformation parameters (Energies and potential depths are in MeV)

TABLE I

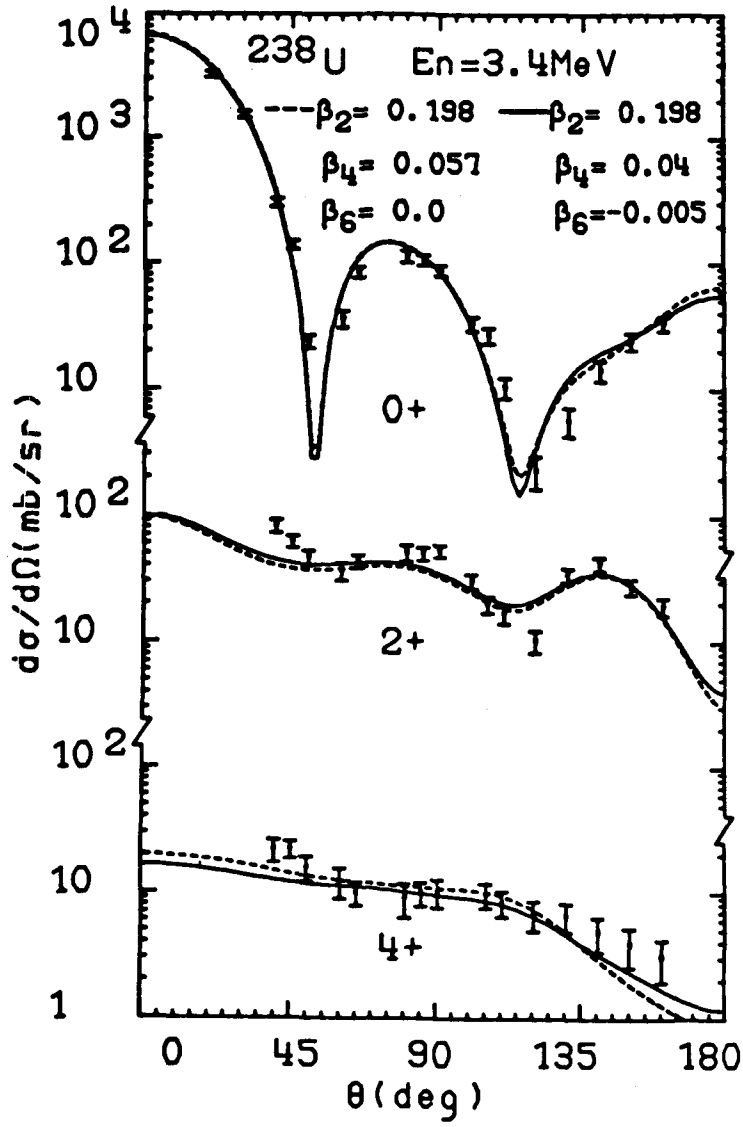

Fig. 1

	q_2^m	q_4^m	q_6^m
β_2=0.198 β_4=0.057	8.263	2.731	0.658
β_2=0.198 β_4=0.04 β_6=-0.005	8.103	2.084	0.315
HFB calculations	8.33	2.40	0.35

TABLE II

ANNEXE 1

RESULTS OF COUPLED CHANNEL CALCULATIONS FOR ^{238}U

- Cross sections and angular distribution (units are respectively barn and eV).

- The angular distributions are represented by their corresponding Legendre polynomial coefficients. The absolute differential cross sections are obtained by :

$$\frac{d\sigma}{d\Omega}(\Omega,E) = \frac{A}{2\pi} \sum_{\ell=o}^{NL} \frac{2\ell+1}{2} B_\ell(E)\, P_\ell(u)$$

with

$$A = \sigma_s\,(E) \quad \text{and} \quad B_o = 1.0$$

where : u = cosine of the scattering angle in the centre of mass system

- E, incident neutron energy in the laboratory system
- σ_s (E), the integrated scattering cross section
- $B\ell$, the ℓth legendre polynomial coefficient (tabulated)
- $\frac{d\sigma}{d\Omega}(\Omega,E)$, differential cross section in units of barns per steradian

RESULTS OF COUPLED CHANNEL CALCULATIONS FOR URANIUM 238
(CH.LAGRANGE 1981)

NEUTRON TOTAL CROSS SECTIONS

E	S(E)	E	S(E)	E	S(E)
1.0000D+03	2.4914D+01	5.0000D+03	1.7452D+01	1.0000D+04	1.5701D+01
2.0000D+04	1.4441D+01	3.0000D+04	1.3848D+01	4.0000D+04	1.3460D+01
6.0000D+04	1.2925D+01	8.0000D+04	1.2529D+01	1.0000D+05	1.2198D+01
2.0000D+05	1.0647D+01	3.0000D+05	9.6899D+00	4.0000D+05	8.9110D+00
5.0000D+05	8.2814D+00	6.0000D+05	7.7825D+00	8.0000D+05	7.0984D+00
1.0000D+06	6.7515D+00	1.2500D+06	6.6493D+00	1.5000D+06	6.7717D+00
1.7500D+06	6.9946D+00	2.0000D+06	7.2372D+00	2.5000D+06	7.6471D+00
3.0000D+06	7.8980D+00	4.0000D+06	7.9702D+00	5.0000D+06	7.5833D+00
6.0000D+06	7.0809D+00	7.0000D+06	6.5949D+00	8.0000D+06	6.2045D+00
1.0000D+07	5.7543D+00	1.2000D+07	5.6520D+00	1.4000D+07	5.7951D+00
1.6000D+07	6.0298D+00	1.8000D+07	6.2557D+00	2.0000D+07	6.4178D+00

RESULTS OF COUPLED CHANNEL CALCULATIONS FOR URANIUM 238
(CH.LAGRANGE 1981)

NEUTRON COMPOUND NUCLEUS FORMATION CROSS SECTIONS

E	S(E)	E	S(E)	E	S(E)
1.0000D+03	1.3788D+01	5.0000D+03	6.5316D+00	1.0000D+04	4.9641D+00
2.0000D+04	4.0031D+00	3.0000D+04	3.6646D+00	4.0000D+04	3.5076D+00
6.0000D+04	3.3842D+00	8.0000D+04	3.3522D+00	1.0000D+05	3.3501D+00
2.0000D+05	3.1361D+00	3.0000D+05	3.1629D+00	4.0000D+05	3.1535D+00
5.0000D+05	3.1341D+00	6.0000D+05	3.1188D+00	8.0000D+05	3.1079D+00
1.0000D+06	3.1423D+00	1.2500D+06	3.2337D+00	1.5000D+06	3.3369D+00
1.7500D+06	3.4063D+00	2.0000D+06	3.4236D+00	2.5000D+06	3.3470D+00
3.0000D+06	3.2225D+00	4.0000D+06	3.0269D+00	5.0000D+06	2.9029D+00
6.0000D+06	2.8383D+00	7.0000D+06	2.8308D+00	8.0000D+06	2.8470D+00
1.0000D+07	2.8663D+00	1.2000D+07	2.7924D+00	1.4000D+07	2.7242D+00
1.6000D+07	2.6620D+00	1.8000D+07	2.6114D+00	2.0000D+07	2.5760D+00

RESULTS OF COUPLED CHANNEL CALCULATIONS FOR URANIUM 238
(CH.LAGRANGE 1981)

NEUTRON SHAPE ELASTIC SCATTERING CROSS SECTIONS

E	S(E)	E	S(E)	E	S(E)
1.0000D+03	1.1127D+01	5.0000D+03	1.0920D+01	1.0000D+04	1.0736D+01
2.0000D+04	1.0438D+01	3.0000D+04	1.0183D+01	4.0000D+04	9.9522D+00
6.0000D+04	9.5392D+00	8.0000D+04	9.1716D+00	1.0000D+05	8.8375D+00
2.0000D+05	7.4692D+00	3.0000D+05	6.4580D+00	4.0000D+05	5.6653D+00
5.0000D+05	5.0333D+00	6.0000D+05	4.5272D+00	8.0000D+05	3.8035D+00
1.0000D+06	3.3645D+00	1.2500D+06	3.0965D+00	1.5000D+06	3.0486D+00
1.7500D+06	3.1487D+00	2.0000D+06	3.3365D+00	2.5000D+06	3.7905D+00
3.0000D+06	4.1697D+00	4.0000D+06	4.4841D+00	5.0000D+06	4.2489D+00
6.0000D+06	3.8536D+00	7.0000D+06	3.4025D+00	8.0000D+06	3.0192D+00
1.0000D+07	2.5946D+00	1.2000D+07	2.5677D+00	1.4000D+07	2.7875D+00
1.6000D+07	3.0991D+00	1.8000D+07	3.3914D+00	2.0000D+07	3.6021D+00

RESULTS OF COUPLED CHANNEL CALCULATIONS FOR URANIUM 238
(CH.LAGRANGE 1981)

NEUTRON DIRECT INELASTIC FIRST EXCITED LEVEL

E	S(E)	E	S(E)	E	S(E)
6.0000D+04	1.6101D-03	8.0000D+04	5.5082D-03	1.0000D+05	1.0580D-02
2.0000D+05	4.1398D-02	3.0000D+05	6.7926D-02	4.0000D+05	8.8526D-02
5.0000D+05	1.0556D-01	6.0000D+05	1.2123D-01	8.0000D+05	1.5347D-01
1.0000D+06	1.9018D-01	1.2500D+06	2.4039D-01	1.5000D+06	2.8878D-01
1.7500D+06	3.2944D-01	2.0000D+06	3.5936D-01	2.5000D+06	3.8685D-01
3.0000D+06	3.8388D-01	4.0000D+06	3.4495D-01	5.0000D+06	3.2963D-01
6.0000D+06	2.9745D-01	7.0000D+06	2.7962D-01	8.0000D+06	2.6674D-01
1.0000D+07	2.3971D-01	1.2000D+07	2.4256D-01	1.4000D+07	2.3873D-01
1.6000D+07	2.2902D-01	1.8000D+07	2.1801D-01	2.0000D+07	2.0886D-01

RESULTS OF COUPLED CHANNEL CALCULATIONS FOR URANIUM 238
(CH.LAGRANGE 1981)

NEUTRON DIRECT INELASTIC SECOND EXCITED LEVEL

E	S(E)	E	S(E)	E	S(E)
2.0000D+05	5.4332D-05	3.0000D+05	1.0127D-03	4.0000D+05	3.6224D-03
5.0000D+05	8.3375D-03	6.0000D+05	1.5185D-02	8.0000D+05	3.3538D-02
1.0000D+06	5.4501D-02	1.2500D+06	7.8615D-02	1.5000D+06	9.7382D-02
1.7500D+06	1.1021D-01	2.0000D+06	1.1778D-01	2.5000D+06	1.2280D-01
3.0000D+06	1.2201D-01	4.0000D+06	1.1426D-01	5.0000D+06	1.0189D-01
6.0000D+06	9.1587D-02	7.0000D+06	8.2038D-02	8.0000D+06	7.1504D-02
1.0000D+07	5.3645D-02	1.2000D+07	4.9433D-02	1.4000D+07	4.4683D-02
1.6000D+07	3.9622D-02	1.8000D+07	3.4888D-02	2.0000D+07	3.0901D-02

RESULTS OF COUPLED CHANNEL CALCULATIONS FOR URANIUM 238
(CH.LAGRANGE 1981)

LEGENDRE COEFFICIENTS FOR SHAPE ELASTIC
THE LEGENDRE COEFFICIENTS ARE IN THE ORDER 1.2...6 AND NEXT LINE 7,8..... 12

ELAB= 1.0000E+03	LMAX= 3					
	8.7301D-04	9.9217D-07	3.8838D-07	0.0	0.0	0.0
ELAB= 5.0000E+03	LMAX= 3					
	4.7203D-03	2.5275D-05	-5.5436D-07	0.0	0.0	0.0
ELAB= 1.0000E+04	LMAX= 3					
	9.9194D-03	1.0592D-04	1.2357D-07	0.0	0.0	0.0
ELAB= 2.0000E+04	LMAX= 3					
	2.1017D-02	4.2520D-04	3.0098D-06	0.0	0.0	0.0
ELAB= 3.0000E+04	LMAX= 3					
	3.2650D-02	9.5304D-04	1.1582D-05	0.0	0.0	0.0
ELAB= 4.0000E+04	LMAX= 3					
	4.4565D-02	1.6885D-03	2.6749D-05	0.0	0.0	0.0
ELAB= 6.0000E+04	LMAX= 3					
	6.8675D-02	3.7454D-03	8.9970D-05	0.0	0.0	0.0
ELAB= 8.0000E+04	LMAX= 3					
	9.2720D-02	6.5367D-03	2.1298D-04	0.0	0.0	0.0
ELAB= 1.0000E+05	LMAX= 3					
	1.1636D-01	9.9946D-03	4.1104D-04	0.0	0.0	0.0
ELAB= 2.0000E+05	LMAX= 3					
	2.0867D-01	3.2936D-02	2.8151D-03	0.0	0.0	0.0
ELAB= 3.0000E+05	LMAX= 5					
	2.9012D-01	6.2752D-02	9.2051D-03	9.9384D-04	-9.5676D-06	0.0
ELAB= 4.0000E+05	LMAX= 5					
	3.5546D-01	9.5144D-02	2.0294D-02	2.9449D-03	-3.1240D-05	0.0
ELAB= 5.0000E+05	LMAX= 5					
	4.0753D-01	1.2707D-01	3.6725D-02	6.7089D-03	-6.1456D-05	0.0
ELAB= 6.0000E+05	LMAX= 6					
	4.4871D-01	1.5742D-01	5.8630D-02	1.2948D-02	-1.5011D-05	9.5749D-05
ELAB= 8.0000E+05	LMAX= 6					
	5.0527D-01	2.1320D-01	1.1672D-01	3.4952D-02	8.5746D-04	5.7038D-04
ELAB= 1.0000E+06	LMAX= 8					
	5.3757D-01	2.6602D-01	1.8624D-01	7.1398D-02	4.8545D-03	2.2223D-03
	1.7171D-04	1.6612D-05	0.0	0.0	0.0	0.0

RESULTS OF COUPLED CHANNEL CALCULATIONS FOR URANIUM 238
(CH.LAGRANGE 1981)

LEGENDRE COEFFICIENTS FOR SHAPE ELASTIC
THE LEGENDRE COEFFICIENTS ARE IN THE ORDER 1.2...6 AND NEXT LINE 7,8..... 12

ELAB= 1.2500E+06	LMAX= 8					
	5.6340D-01	3.3359D-01	2.7036D-01	1.3363D-01	1.9282D-02	7.4701D-03
	7.7417D-04	9.6920D-05	0.0	0.0	0.0	0.0
ELAB= 1.5000E+06	LMAX= 8					
	5.9199D-01	4.0136D-01	3.3464D-01	2.0177D-01	4.7396D-02	1.7561D-02
	2.3275D-03	3.3687D-04	0.0	0.0	0.0	0.0
ELAB= 1.7500E+06	LMAX= 9					
	6.2946D-01	4.6178D-01	3.7638D-01	2.6119D-01	8.5538D-02	3.2014D-02
	5.1871D-03	8.7776D-04	9.8741D-05	0.0	0.0	0.0
ELAB= 2.0000E+06	LMAX= 9					
	6.7067D-01	5.1033D-01	4.0356D-01	3.0529D-01	1.2591D-01	4.9010D-02
	9.6033D-03	1.8516D-03	2.3674D-04	0.0	0.0	0.0
ELAB= 2.5000E+06	LMAX= 11					
	7.4256D-01	5.7833D-01	4.4375D-01	3.5683D-01	1.9388D-01	8.4643D-02
	2.2724D-02	5.5291D-03	9.5894D-04	1.2169D-04	1.3926D-05	0.0
ELAB= 3.0000E+06	LMAX= 12					
	7.9135D-01	6.2580D-01	4.8198D-01	3.8661D-01	2.4075D-01	1.1760D-01
	4.0076D-02	1.2185D-02	2.6858D-03	4.1532D-04	5.8800D-05	6.3762D-06
ELAB= 4.0000E+06	LMAX= 14					
	8.4090D-01	6.9162D-01	5.5214D-01	4.3439D-01	3.0238D-01	1.7164D-01
	7.9777D-02	3.4441D-02	1.1109D-02	2.5407D-03	4.8645D-04	7.4430D-05
	6.9463D-06	-1.0029D-07	0.0	0.0	0.0	0.0
ELAB= 5.0000E+06	LMAX= 15					
	8.6043D-01	7.2932D-01	6.0300D-01	4.7693D-01	3.4870D-01	2.1651D-01
	1.1874D-01	6.4651D-02	2.8423D-02	8.9420D-03	2.2068D-03	4.5894D-04
	7.0211D-05	1.0882D-05	1.1434D-06	0.0	0.0	0.0
ELAB= 6.0000E+06	LMAX= 15					
	8.6289D-01	7.4264D-01	6.3112D-01	5.1085D-01	3.8587D-01	2.5869D-01
	1.5565D-01	9.8770D-02	5.5445D-02	2.2617D-02	7.1607D-03	1.8807D-03
	3.6731D-04	7.3998D-05	1.1738D-05	0.0	0.0	0.0
ELAB= 7.0000E+06	LMAX= 16					
	8.5961D-01	7.4418D-01	6.4574D-01	5.3750D-01	4.1976D-01	3.0231D-01
	1.9773D-01	1.3737D-01	9.2016D-02	4.6848D-02	1.8578D-02	5.9013D-03
	1.4096D-03	3.3105D-04	7.0046D-05	1.3138D-05	0.0	0.0
ELAB= 8.0000E+06	LMAX= 17					
	8.5493D-01	7.3765D-01	6.4647D-01	5.5203D-01	4.4782D-01	3.4268D-01
	2.4384D-01	1.7944D-01	1.3492D-01	8.2458D-02	3.9390D-02	1.4697D-02
	4.2217D-03	1.1494D-03	2.6223D-04	5.2609D-05	8.7873D-06	0.0

RESULTS OF COUPLED CHANNEL CALCULATIONS FOR URANIUM 238
(CH.LAGRANGE 1981)

LEGENDRE COEFFICIENTS FOR SHAPE ELASTIC
THE LEGENDRE COEFFICIENTS ARE IN THE ORDER 1.2...6 AND NEXT LINE 7,8..... 12

ELAB= 1.0000E+07 LMAX= 18

8.5427D-01	7.2086D-01	6.2409D-01	5.4845D-01	4.7335D-01	3.9686D-01
3.2348D-01	2.6178D-01	2.1860D-01	1.6798D-01	1.0508D-01	5.2057D-02
2.0829D-02	7.4074D-03	2.2270D-03	5.7984D-04	1.4670D-04	2.9601D-05

ELAB= 1.2000E+07 LMAX= 20

8.6417D-01	7.2180D-01	6.1266D-01	5.3596D-01	4.7264D-01	4.1784D-01
3.6573D-01	3.1840D-01	2.7700D-01	2.3353D-01	1.7181D-01	1.0521D-01
5.3712D-02	2.3807D-02	8.9179D-03	2.8775D-03	8.5474D-04	2.1558D-04
5.3561D-05	1.0623D-05	0.0	0.0	0.0	0.0

ELAB= 1.4000E+07 LMAX= 21

8.8738D-01	7.5734D-01	6.4617D-01	5.6021D-01	4.9249D-01	4.3991D-01
3.9319D-01	3.5186D-01	3.1089D-01	2.6894D-01	2.1406D-01	1.4919D-01
8.9645D-02	4.7144D-02	2.1296D-02	8.3892D-03	2.9960D-03	9.0250D-04
2.6203D-04	6.7730D-05	1.4397D-05	0.0	0.0	0.0

ELAB= 1.6000E+07 LMAX= 22

9.0914D-01	7.9933D-01	6.9706D-01	6.0865D-01	5.3417D-01	4.7417D-01
4.2259D-01	3.7759D-01	3.3347D-01	2.8869D-01	2.3690D-01	1.7674D-01
1.1729D-01	6.9859D-02	3.6935D-02	1.7327D-02	7.2623D-03	2.6050D-03
8.9196D-04	2.6450D-04	8.0650D-05	2.0248D-05	0.0	0.0

ELAB= 1.8000E+07 LMAX= 23

9.2491D-01	8.3336D-01	7.4412D-01	6.6034D-01	5.8308D-01	5.1585D-01
4.5683D-01	4.0436D-01	3.5453D-01	3.0498D-01	2.5257D-01	1.9539D-01
1.3788D-01	8.9457D-02	5.3359D-02	2.8850D-02	1.3948D-02	5.8637D-03
2.2710D-03	7.5231D-04	2.3702D-04	6.9196D-05	1.6115D-05	0.0

ELAB= 2.0000E+07 LMAX= 24

9.3533D-01	8.5731D-01	7.8074D-01	7.0510D-01	6.2960D-01	5.5882D-01
4.9376D-01	4.3415D-01	3.7807D-01	3.2350D-01	2.6857D-01	2.1230D-01
1.5628D-01	1.0757D-01	6.9930D-02	4.2384D-02	2.3317D-02	1.1324D-02
4.9391D-03	1.8748D-03	6.7459D-04	2.1956D-04	6.9955D-05	1.7771D-05

RESULTS OF COUPLED CHANNEL CALCULATIONS FOR URANIUM 238
(CH.LAGRANGE 1981)

LEGENDRE COEFFICIENTS FOR DIRECT INELASTIC (1 LEVEL)
THE LEGENDRE COEFFICIENTS ARE IN THE ORDER 1.2...6 AND NEXT LINE 7,8..... 12

```
ELAB= 6.0000E+04  LMAX=    3
                   3.1344D-01  4.3516D-02 -1.5214D-03  0.0         0.0         0.0

ELAB= 8.0000E+04  LMAX=    3
                   2.9256D-01  4.4232D-02 -3.0585D-03  0.0         0.0         0.0

ELAB= 1.0000E+05  LMAX=    3
                   2.8571D-01  4.2347D-02 -4.5688D-03  0.0         0.0         0.0

ELAB= 2.0000E+05  LMAX=    3
                   2.6643D-01  2.8575D-02 -1.1529D-02  0.0         0.0         0.0

ELAB= 3.0000E+05  LMAX=    5
                   2.4313D-01 -1.0833D-02 -2.1485D-02  3.4455D-03 -1.3320D-04  0.0

ELAB= 4.0000E+05  LMAX=    5
                   2.2211D-01 -3.1952D-02 -3.0261D-02  6.8105D-03 -3.2154D-04  0.0

ELAB= 5.0000E+05  LMAX=    5
                   1.9794D-01 -4.9112D-02 -3.8518D-02  1.0881D-02 -5.7654D-04  0.0

ELAB= 6.0000E+05  LMAX=    6
                   1.7204D-01 -6.2095D-02 -4.3397D-02  1.2200D-02 -9.8458D-04  5.7183D-04

ELAB= 8.0000E+05  LMAX=    6
                   1.2358D-01 -7.2810D-02 -5.4403D-02  1.3336D-02 -1.3165D-03  1.9300D-03

ELAB= 1.0000E+06  LMAX=    8
                   8.6437D-02 -7.0085D-02 -5.9137D-02  7.2533D-03 -1.4621D-04  4.2218D-03
                  -2.4601D-04  6.2572D-05  0.0         0.0         0.0         0.0

ELAB= 1.2500E+06  LMAX=    8
                   5.8639D-02 -6.0231D-02 -5.9027D-02 -7.4180D-03  2.3801D-03  8.0109D-03
                  -6.2271D-04  2.2521D-04  0.0         0.0         0.0         0.0

ELAB= 1.5000E+06  LMAX=    8
                   4.5268D-02 -5.1122D-02 -5.7298D-02 -2.3508D-02  7.0236D-03  1.1751D-02
                  -1.2183D-03  5.9790D-04  0.0         0.0         0.0         0.0

ELAB= 1.7500E+06  LMAX=    9
                   4.1987D-02 -4.2649D-02 -5.5665D-02 -3.4881D-02  1.3639D-02  1.3613D-02
                  -1.3499D-03  1.4525D-03 -1.2647D-04  0.0         0.0         0.0

ELAB= 2.0000E+06  LMAX=    9
                   4.8318D-02 -3.2651D-02 -5.3046D-02 -3.7098D-02  2.2507D-02  1.3564D-02
                  -1.3170D-03  2.6518D-03 -2.7728D-04  0.0         0.0         0.0
```

RESULTS OF COUPLED CHANNEL CALCULATIONS FOR URANIUM 238
(CH.LAGRANGE 1981)

LEGENDRE COEFFICIENTS FOR DIRECT INELASTIC (1 LEVEL)
THE LEGENDRE COEFFICIENTS ARE IN THE ORDER 1.2...6 AND NEXT LINE 7,8..... 12

```
ELAB= 2.5000E+06  LMAX=   11
                   8.4191D-02 -2.8192D-03 -3.5134D-02 -2.0380D-02  4.1426D-02  7.0786D-03
                   9.1746D-04  5.6215D-03 -7.7439D-04  4.1078D-04 -9.6874D-06  0.0

ELAB= 3.0000E+06  LMAX=   12
                   1.3035D-01  3.0771D-02 -3.2831D-03  4.2302D-03  5.6973D-02 -2.9804D-03
                   4.6037D-03  8.0726D-03 -1.2673D-03  1.3731D-03 -4.6114D-05  2.7113D-05

ELAB= 4.0000E+06  LMAX=   14
                   1.9207D-01  7.3171D-02  4.2773D-02  3.1891D-02  6.9391D-02 -1.2542D-02
                   1.4603D-03  1.1095D-03 -2.2951D-04  6.6273D-03 -4.6071D-04  3.5586D-04
                   1.5977D-05  4.6523D-06  0.0         0.0         0.0         0.0

ELAB= 5.0000E+06  LMAX=   15
                   2.3581D-01  8.3941D-02  3.5921D-02  3.2668D-02  4.7086D-02 -9.2933D-03
                  -2.0751D-02 -2.3544D-02  6.8585D-03  1.3001D-02 -1.8027D-03  1.9290D-03
                   7.6779D-05  4.0661D-05  5.9878D-06  0.0         0.0         0.0

ELAB= 6.0000E+06  LMAX=   15
                   2.6251D-01  7.9718D-02  8.8061D-03  1.4619D-02  1.2246D-02 -1.6683D-02
                  -3.6527D-02 -4.1108D-02  1.4084D-02  1.1233D-02 -3.5065D-03  6.3079D-03
                   1.4604D-04  2.2287D-04  4.1677D-05  0.0         0.0         0.0

ELAB= 7.0000E+06  LMAX=   16
                   2.8617D-01  7.8362D-02 -3.0873D-03  2.0500D-04 -7.5322D-03 -2.2156D-02
                  -3.2960D-02 -4.2204D-02  8.7730D-03 -3.1192D-03 -2.1352D-03  1.2780D-02
                  -2.6184D-05  7.3814D-04  1.9060D-04  2.9992D-05  0.0         0.0

ELAB= 8.0000E+06  LMAX=   17
                   3.0543D-01  8.3374D-02 -3.0249D-03 -6.8387D-03 -1.5794D-02 -2.5973D-02
                  -2.9594D-02 -4.4421D-02 -5.6183D-03 -1.6413D-02  3.5717D-03  1.7960D-02
                  -6.2082D-04  1.9421D-03  5.9694D-04  1.2118D-04  3.6680D-05  0.0

ELAB= 1.0000E+07  LMAX=   18
                   3.5914D-01  1.2398D-01  1.3210D-02 -8.1510D-03 -2.5155D-02 -3.9384D-02
                  -3.7595D-02 -5.3568D-02 -2.0745D-02 -1.3926D-02  1.2726D-02  1.3443D-02
                  -1.2144D-03  8.1144D-03  3.3603D-03  8.9693D-04  4.2891D-04  8.1920D-05

ELAB= 1.2000E+07  LMAX=   20
                   4.1253D-01  1.7660D-01  4.2672D-02  1.6537D-02 -1.3512D-02 -2.8154D-02
                  -3.0396D-02 -3.9483D-02 -1.7781D-02 -6.7941D-03  8.5299D-03 -1.9409D-03
                  -3.9281D-04  1.6282D-02  7.7556D-03  2.9706D-03  2.0275D-03  4.6689D-04
                   1.8440D-04  4.1573D-05  0.0         0.0         0.0         0.0

ELAB= 1.4000E+07  LMAX=   21
                   4.5781D-01  2.2360D-01  8.1184D-02  5.0214D-02  1.3403D-02 -6.6465D-04
                  -1.0514D-02 -1.7553D-02 -7.0048D-03 -1.8170D-03  1.1975D-02 -1.7585D-03
                   2.7027D-03  1.6269D-02  8.6044D-03  6.7101D-03  6.2296D-03  1.6216D-03
                   8.8445D-04  2.6011D-04  7.1296D-05  0.0         0.0         0.0
```

RESULTS OF COUPLED CHANNEL CALCULATIONS FOR URANIUM 238
(CH.LAGRANGE 1981)

LEGENDRE COEFFICIENTS FOR DIRECT INELASTIC (1 LEVEL)
THE LEGENDRE COEFFICIENTS ARE IN THE ORDER 1.2...6 AND NEXT LINE 7,8..... 12

ELAB= 1.6000E+07 LMAX= 22

4.9306D-01	2.6009D-01	1.1326D-01	7.6934D-02	4.2525D-02	2.9704D-02
1.9181D-02	9.9405D-03	1.5265D-02	1.2104D-02	2.2676D-02	7.9282D-03
1.3458D-03	3.3297D-03	2.5210D-03	1.1024D-02	1.1917D-02	3.8038D-03
2.9865D-03	8.9774D-04	3.5185D-04	9.1532D-05	0.0	0.0

ELAB= 1.8000E+07 LMAX= 23

5.2093D-01	2.8602D-01	1.3521D-01	9.0886D-02	5.8485D-02	4.6818D-02
3.9411D-02	2.9037D-02	3.1280D-02	2.2418D-02	2.5753D-02	1.0988D-02
-1.9911D-03	-8.4865D-03	-4.8226D-03	1.1205D-02	1.3485D-02	6.6193D-03
6.9778D-03	2.2389D-03	1.0514D-03	3.7281D-04	1.1130D-04	0.0

ELAB= 2.0000E+07 LMAX= 24

5.4518D-01	3.0615D-01	1.5514D-01	1.0096D-01	6.7185D-02	5.4646D-02
4.8860D-02	3.9287D-02	3.9102D-02	2.8620D-02	2.6306D-02	1.2629D-02
-7.2501D-04	-1.0341D-02	-9.7275D-03	3.6979D-03	8.4380D-03	9.8092D-03
1.2082D-02	4.4350D-03	2.7092D-03	1.0378D-03	4.3422D-04	1.2911D-04

RESULTS OF COUPLED CHANNEL CALCULATIONS FOR URANIUM 238
(CH.LAGRANGE 1981)

LEGENDRE COEFFICIENTS FOR DIRECT INELASTIC (2 LEVEL)
THE LEGENDRE COEFFICIENTS ARE IN THE ORDER 1.2...6 AND NEXT LINE 7,8..... 12

```
ELAB= 2.0000E+05  LMAX=    3
                    2.7792D-01  1.2660D-01  1.3867D-02  0.0         0.0         0.0

ELAB= 3.0000E+05  LMAX=    5
                    4.3615D-01  2.1726D-01  1.8590D-02  1.2876D-03 -1.9366D-04  0.0

ELAB= 4.0000E+05  LMAX=    5
                    4.7040D-01  2.1871D-01  1.6045D-02  2.4159D-05 -2.7883D-04  0.0

ELAB= 5.0000E+05  LMAX=    5
                    4.8011D-01  2.0841D-01  1.1615D-02 -1.4253D-03 -3.0438D-04  0.0

ELAB= 6.0000E+05  LMAX=    6
                    4.8267D-01  1.8770D-01  2.3743D-03 -3.8161D-03 -2.2581D-04  1.0762D-04

ELAB= 8.0000E+05  LMAX=    6
                    4.6233D-01  1.4463D-01 -1.3194D-02 -6.0832D-03  3.3802D-04  1.9042D-04

ELAB= 1.0000E+06  LMAX=    8
                    4.3279D-01  9.2155D-02 -3.0972D-02 -7.1866D-03  2.2611D-03  1.8505D-04
                   -1.0593D-04  9.4770D-06  0.0         0.0         0.0         0.0

ELAB= 1.2500E+06  LMAX=    8
                    3.8783D-01  2.6166D-02 -4.4801D-02 -3.2815D-03  4.4311D-03 -5.5720D-05
                   -2.0749D-04  3.4659D-05  0.0         0.0         0.0         0.0

ELAB= 1.5000E+06  LMAX=    8
                    3.4410D-01 -2.6472D-02 -4.6712D-02  5.5259D-03  6.2949D-03 -7.3212D-04
                   -3.1957D-04  7.5353D-05  0.0         0.0         0.0         0.0

ELAB= 1.7500E+06  LMAX=    9
                    3.1040D-01 -5.5269D-02 -3.3842D-02  1.8004D-02  6.6120D-03 -1.9514D-03
                   -1.5601D-04  1.4698D-04 -4.0607D-05  0.0         0.0         0.0

ELAB= 2.0000E+06  LMAX=    9
                    2.9004D-01 -6.2028D-02 -1.4184D-02  2.8735D-02  4.9579D-03 -3.1804D-03
                    1.3685D-04  1.9274D-04 -8.5992D-05  0.0         0.0         0.0

ELAB= 2.5000E+06  LMAX=   11
                    2.7459D-01 -4.6590D-02  2.3499D-02  3.7736D-02 -2.6579D-03 -4.3123D-03
                    1.3320D-03 -1.2000D-04 -2.4226D-04  8.2982D-05 -4.2727D-06  0.0

ELAB= 3.0000E+06  LMAX=   12
                    2.7135D-01 -2.7443D-02  4.1211D-02  2.9452D-02 -9.7973D-03 -1.3952D-03
                    2.3635D-03 -1.4419D-03 -3.8424D-04  2.6097D-04 -2.1923D-05  8.4367D-06
```

RESULTS OF COUPLED CHANNEL CALCULATIONS FOR URANIUM 238
(CH.LAGRANGE 1981)

LEGENDRE COEFFICIENTS FOR DIRECT INELASTIC (2 LEVEL)
THE LEGENDRE COEFFICIENTS ARE IN THE ORDER 1.2...6 AND NEXT LINE 7,8..... 12

```
ELAB= 4.0000E+06  LMAX=   14
                   2.7151D-01  2.1549D-04  4.1424D-02 -6.0544D-04 -7.8496D-03  6.6554D-03
                  -3.6377D-03 -5.2863D-03  7.5403D-04  6.6959D-04 -1.9474D-04  1.0762D-04
                   9.3775D-07  8.1918D-07  0.0         0.0         0.0         0.0

ELAB= 5.0000E+06  LMAX=   15
                   2.4992D-01  1.2566D-02  3.2102D-02 -2.7025D-02 -3.4114D-04 -3.4933D-03
                  -1.6737D-02  2.0405D-03  4.3530D-03 -1.2488D-03 -6.1230D-04  5.4563D-04
                  -1.7160D-05  1.3901D-05  1.9818D-06  0.0         0.0         0.0

ELAB= 6.0000E+06  LMAX=   15
                   2.3937D-01  3.2763D-02  3.0173D-02 -3.9092D-02  2.0719D-03 -1.5552D-02
                  -1.9096D-02  2.2716D-02  6.0912D-03 -7.3363D-03 -3.1668D-04  1.4367D-03
                  -1.8069D-04  6.1786D-05  6.2595D-06  0.0         0.0         0.0

ELAB= 7.0000E+06  LMAX=   16
                   2.3742D-01  5.9424D-02  3.7574D-02 -2.9052D-02  1.4171D-02 -1.1128D-02
                  -1.0536D-02  3.1634D-02 -1.0699D-03 -1.1774D-02  2.4852D-03  2.0722D-03
                  -6.8410D-04  1.5836D-04  1.8753D-05  6.7344D-06  0.0         0.0

ELAB= 8.0000E+06  LMAX=   17
                   2.5290D-01  8.7570D-02  4.2130D-02 -1.7453D-02  2.1899D-02 -8.6071D-03
                  -6.9467D-03  1.9298D-02 -1.1426D-02 -6.9093D-03  7.5241D-03  1.2328D-03
                  -1.5925D-03  3.2308D-04  2.6414D-05  2.0350D-05  1.0070D-05  0.0

ELAB= 1.0000E+07  LMAX=   18
                   3.0898D-01  1.3357D-01  4.6634D-02 -5.7233D-03  1.8277D-02 -1.5864D-02
                  -4.8456D-03  2.7516D-03 -5.8929D-03  1.7831D-02  1.0677D-02 -5.9023D-03
                  -2.8391D-03  9.0151D-04 -1.2056D-04  7.9124D-05  1.1973D-04  1.7523D-05

ELAB= 1.2000E+07  LMAX=   20
                   3.3344D-01  1.5603D-01  5.9996D-02  2.3262D-03  2.1214D-02 -1.5815D-02
                   6.9184D-03  3.8449D-03  3.2641D-03  2.1795D-02  4.6455D-05 -7.7912D-03
                   2.1054D-03  9.0372D-04 -1.8768D-03  4.0858D-05  4.7115D-04  4.7638D-05
                   7.2098D-05  1.6733D-05  0.0         0.0         0.0         0.0

ELAB= 1.4000E+07  LMAX=   21
                   3.5754D-01  1.9131D-01  8.3342D-02  1.4765D-02  2.7299D-02 -1.4615D-02
                   1.0537D-02  2.9472D-04  2.7690D-03  1.7620D-02 -6.7691D-04  4.2148D-03
                   9.4873D-03 -3.3162D-03 -6.2598D-03  6.6397D-05  8.1874D-04 -3.2256D-05
                   3.4227D-04  1.0182D-04  3.8107D-05  0.0         0.0         0.0

ELAB= 1.6000E+07  LMAX=   22
                   3.8807D-01  2.3272D-01  1.0599D-01  3.1742D-02  3.4450D-02 -9.3050D-03
                   1.2481D-02  1.7914D-04  4.3863D-03  1.6186D-02  3.6563D-03  9.9815D-03
                   9.1289D-03 -7.9690D-03 -8.1575D-03  4.3168D-04 -7.9539D-04 -6.5148D-04
                   1.0499D-03  2.4980D-04  1.7443D-04  4.7548D-05  0.0         0.0
```

RESULTS OF COUPLED CHANNEL CALCULATIONS FOR URANIUM 238
(CH.LAGRANGE 1981)

LEGENDRE COEFFICIENTS FOR DIRECT INELASTIC (2 LEVEL)
THE LEGENDRE COEFFICIENTS ARE IN THE ORDER 1.2...6 AND NEXT LINE 7,8..... 12

ELAB= 1.8000E+07 LMAX= 23

4.1072D-01	2.6358D-01	1.2613D-01	5.2061D-02	4.1567D-02	-2.5407D-03
1.2551D-02	-2.3016D-03	2.0344D-03	7.5064D-03	-1.9003D-04	2.5738D-03
2.5131D-03	-5.4043D-03	-1.2271D-03	7.8781D-04	-6.1028D-03	-1.7157D-03
2.0054D-03	2.1599D-04	4.2291D-04	1.6270D-04	6.4577D-05	0.0

ELAB= 2.0000E+07 LMAX= 24

4.2997D-01	2.8184D-01	1.4430D-01	7.3589D-02	5.1716D-02	9.4142D-03
1.6177D-02	-2.0215D-03	1.5340D-03	3.0240D-04	-2.9901D-03	-1.5071D-03
-7.9751D-04	4.6903D-04	6.6193D-03	-1.7026D-03	-1.1688D-02	-1.5544D-03
1.9465D-03	-5.5512D-04	8.5668D-04	3.5475D-04	2.4451D-04	8.1073D-05

ANNEXE 2

RESULTS OF COUPLED CHANNEL CALCULATIONS FOR ^{238}U

Neutron transmission coefficients for the ground state.

NEUTRON TRANSMISSION COEFFICIENTS FOR URANIUM 238.000

THE COEFFICIENTS ARE IN THE ORDER (L,J): (0,1/2),(1,1/2),(1,3/2),(2,3/2),(2,5/2),(3,5/2),(3,7/2), ...

```
            E= 0.10000E-02(MEV)     LMAX=    3     JMAX=    5/2
0.20438E-01 0.10207E-03 0.13826E-03 0.41034E-07 0.26575E-07 0.47748E-11

            E= 0.50000E-02(MEV)     LMAX=    3     JMAX=    5/2
0.45098E-01 0.11327E-02 0.15344E-02 0.22785E-05 0.14786E-05 0.13362E-08

            E= 0.10000E-01(MEV)     LMAX=    3     JMAX=    5/2
0.63129E-01 0.31735E-02 0.42984E-02 0.12781E-04 0.83146E-05 0.15111E-07

            E= 0.20000E-01(MEV)     LMAX=    3     JMAX=    5/2
0.87968E-01 0.88017E-02 0.11915E-01 0.71083E-04 0.46478E-04 0.17081E-06

            E= 0.30000E-01(MEV)     LMAX=    3     JMAX=    5/2
0.10650E+00 0.15848E-01 0.21437E-01 0.19255E-03 0.12657E-03 0.70550E-06

            E= 0.40000E-01(MEV)     LMAX=    3     JMAX=    5/2
0.12176E+00 0.23909E-01 0.32307E-01 0.38843E-03 0.25678E-03 0.19296E-05

            E= 0.60000E-01(MEV)     LMAX=    3     JMAX=    5/2
0.14664E+00 0.42144E-01 0.56816E-01 0.10338E-02 0.69086E-03 0.79643E-05

            E= 0.80000E-01(MEV)     LMAX=    3     JMAX=    5/2
0.16691E+00 0.62251E-01 0.83711E-01 0.20504E-02 0.13831E-02 0.21780E-04

            E= 0.10000E+00(MEV)     LMAX=    3     JMAX=    5/2
0.18426E+00 0.83493E-01 0.11197E+00 0.34592E-02 0.23556E-02 0.47554E-04

            E= 0.20000E+00(MEV)     LMAX=    3     JMAX=    5/2
0.23894E+00 0.17584E+00 0.23258E+00 0.15544E-01 0.11503E-01 0.48937E-03

            E= 0.30000E+00(MEV)     LMAX=    4     JMAX=    7/2
0.28359E+00 0.27135E+00 0.35295E+00 0.35931E-01 0.27831E-01 0.20130E-02 0.25783E-02 0.31072E-04

            E= 0.40000E+00(MEV)     LMAX=    4     JMAX=    7/2
0.31936E+00 0.35633E+00 0.45510E+00 0.61950E-01 0.50075E-01 0.54340E-02 0.69399E-02 0.10802E-03

            E= 0.50000E+00(MEV)     LMAX=    4     JMAX=    7/2
0.34953E+00 0.43020E+00 0.53921E+00 0.91237E-01 0.76636E-01 0.11643E-01 0.14862E-01 0.28131E-03

            E= 0.60000E+00(MEV)     LMAX=    5     JMAX=    9/2
0.37563E+00 0.49357E+00 0.60706E+00 0.12195E+00 0.10595E+00 0.21542E-01 0.27507E-01 0.61040E-03 0.61969E-03 0.21789E-04

            E= 0.80000E+00(MEV)     LMAX=    5     JMAX=    9/2
0.41857E+00 0.59235E+00 0.70153E+00 0.18293E+00 0.16764E+00 0.55720E-01 0.71108E-01 0.20370E-02 0.21786E-02 0.10467E-03

            E= 0.10000E+01(MEV)     LMAX=    6     JMAX=   11/2
0.45187E+00 0.65980E+00 0.75258E+00 0.23914E+00 0.22749E+00 0.11287E+00 0.14330E+00 0.50895E-02 0.56931E-02 0.35262E-03
0.71230E-03 0.80308E-05
```

NEUTRON TRANSMISSION COEFFICIENTS FOR URANIUM 238.000

THE COEFFICIENTS ARE IN THE ORDER (L,J): (0,1/2),(1,1/2),(1,3/2),(2,3/2),(2,5/2),(3,5/2),(3,7/2), ...

E= 0.12500E+01(MEV) LMAX= 6 JMAX= 11/2
0.48291E+00 0.71119E+00 0.77613E+00 0.30006E+00 0.29378E+00 0.21635E+00 0.27108E+00 0.12422E-01 0.14563E-01 0.11822E-02
0.21965E-02 0.34497E-04

E= 0.15000E+01(MEV) LMAX= 6 JMAX= 11/2
0.50462E+00 0.73853E+00 0.77737E+00 0.35063E+00 0.34790E+00 0.34226E+00 0.42155E+00 0.25111E-01 0.30537E-01 0.31546E-02
0.53210E-02 0.11350E-03

E= 0.17500E+01(MEV) LMAX= 7 JMAX= 13/2
0.51896E+00 0.75191E+00 0.77190E+00 0.39198E+00 0.38941E+00 0.46907E+00 0.56664E+00 0.44332E-01 0.55307E-01 0.71767E-02
0.10899E-01 0.30978E-03 0.35101E-03 0.11103E-04

E= 0.20000E+01(MEV) LMAX= 7 JMAX= 13/2
0.52763E+00 0.75747E+00 0.76638E+00 0.42534E+00 0.41928E+00 0.58045E+00 0.68537E+00 0.70473E-01 0.89155E-01 0.14508E-01
0.19718E-01 0.73426E-03 0.82212E-03 0.28496E-04

E= 0.25000E+01(MEV) LMAX= 8 JMAX= 15/2
0.53409E+00 0.75754E+00 0.76023E+00 0.47254E+00 0.45240E+00 0.73918E+00 0.82428E+00 0.13988E+00 0.17642E+00 0.45752E-01
0.48639E-01 0.29969E-02 0.32490E-02 0.13529E-03 0.64193E-04 0.68510E-05

E= 0.30000E+01(MEV) LMAX= 9 JMAX= 17/2
0.53463E+00 0.75342E+00 0.75884E+00 0.50086E+00 0.46694E+00 0.82745E+00 0.86750E+00 0.21895E+00 0.26913E+00 0.11050E+00
0.89717E-01 0.88384E-02 0.92576E-02 0.46550E-03 0.23476E-03 0.31675E-04 0.23306E-04 0.54764E-06

E= 0.40000E+01(MEV) LMAX= 10 JMAX= 19/2
0.53907E+00 0.75221E+00 0.76221E+00 0.53029E+00 0.49095E+00 0.88884E+00 0.85109E+00 0.35502E+00 0.41859E+00 0.33695E+00
0.18165E+00 0.39779E-01 0.42135E-01 0.29176E-02 0.17782E-02 0.31291E-03 0.19285E-03 0.73001E-05 0.14208E-04 0.42484E-06

E= 0.50000E+01(MEV) LMAX= 11 JMAX= 21/2
0.56231E+00 0.74897E+00 0.75829E+00 0.56181E+00 0.53290E+00 0.87286E+00 0.81357E+00 0.45641E+00 0.53016E+00 0.53123E+00
0.27548E+00 0.10707E+00 0.12893E+00 0.10504E-01 0.82783E-02 0.15168E-02 0.87335E-03 0.53287E-04 0.11251E-03 0.37004E-05
0.32955E-05 0.15781E-06

E= 0.60000E+01(MEV) LMAX= 11 JMAX= 21/2
0.57998E+00 0.76056E+00 0.76619E+00 0.58178E+00 0.56491E+00 0.85584E+00 0.79112E+00 0.52413E+00 0.60890E+00 0.63568E+00
0.36140E+00 0.21121E+00 0.28614E+00 0.28394E-01 0.27298E-01 0.49125E-02 0.28758E-02 0.26388E-03 0.55402E-03 0.19756E-04
0.19082E-04 0.10867E-05

E= 0.70000E+01(MEV) LMAX= 12 JMAX= 23/2
0.59938E+00 0.77141E+00 0.77298E+00 0.60350E+00 0.59246E+00 0.84105E+00 0.77705E+00 0.58458E+00 0.67012E+00 0.67637E+00
0.43897E+00 0.35000E+00 0.48441E+00 0.61839E-01 0.69220E-01 0.13180E-01 0.75835E-02 0.10045E-02 0.18911E-02 0.76935E-04
0.82489E-04 0.54217E-05 0.63112E-05 0.38353E-06

E= 0.80000E+01(MEV) LMAX= 13 JMAX= 25/2
0.61904E+00 0.78058E+00 0.77855E+00 0.62544E+00 0.61755E+00 0.83082E+00 0.76810E+00 0.63965E+00 0.71850E+00 0.69648E+00
0.50324E+00 0.51170E+00 0.65558E+00 0.11666E+00 0.14300E+00 0.31393E-01 0.17247E-01 0.31323E-02 0.49323E-02 0.24967E-03
0.29188E-03 0.21353E-04 0.23803E-04 0.16981E-05 0.17235E-05 0.12751E-06

E= 0.10000E+02(MEV) LMAX= 14 JMAX= 27/2
0.65720E+00 0.79414E+00 0.78678E+00 0.66716E+00 0.66569E+00 0.81853E+00 0.75780E+00 0.72436E+00 0.78760E+00 0.71933E+00
0.58855E+00 0.78907E+00 0.80225E+00 0.29427E+00 0.38304E+00 0.12175E+00 0.65576E-01 0.19004E-01 0.21241E-01 0.17587E-02
0.23634E-02 0.19798E-03 0.20290E-03 0.18849E-04 0.19846E-04 0.17874E-05 0.18076E-05 0.16083E-06

NEUTRON TRANSMISSION COEFFICIENTS FOR URANIUM 238.000

THE COEFFICIENTS ARE IN THE ORDER (L,J): (0,1/2),(1,1/2),(1,3/2),(2,3/2),(2,5/2),(3,5/2),(3,7/2), ...

E= 0.12000E+02(MEV) LMAX= 16 JMAX= 31/2

0.65836E+00	0.77073E+00	0.76021E+00	0.67218E+00	0.67595E+00	0.78305E+00	0.72499E+00	0.75064E+00	0.79857E+00	0.70680E+00
0.61383E+00	0.90909E+00	0.80000E+00	0.48380E+00	0.63409E+00	0.28829E+00	0.16699E+00	0.69090E-01	0.63155E-01	0.75443E-02
0.11867E-01	0.10339E-02	0.10351E-02	0.11416E-03	0.12587E-03	0.13078E-04	0.13176E-04	0.13993E-05	0.14156E-05	0.14241E-06
0.14289E-06	0.13473E-07								

E= 0.14000E+02(MEV) LMAX= 17 JMAX= 33/2

0.65991E+00	0.74778E+00	0.73547E+00	0.67699E+00	0.68391E+00	0.75272E+00	0.69982E+00	0.76201E+00	0.79432E+00	0.69177E+00
0.63127E+00	0.92030E+00	0.76332E+00	0.62255E+00	0.79986E+00	0.46162E+00	0.31785E+00	0.17925E+00	0.13578E+00	0.24772E-01
0.43304E-01	0.38158E-02	0.40224E-02	0.49860E-03	0.56477E-03	0.65881E-04	0.66665E-04	0.81535E-05	0.82847E-05	0.96684E-06
0.97144E-06	0.10742E-06	0.10761E-06	0.11029E-07						

E= 0.16000E+02(MEV) LMAX= 18 JMAX= 35/2

0.66163E+00	0.72607E+00	0.71292E+00	0.68121E+00	0.68914E+00	0.72759E+00	0.68017E+00	0.76496E+00	0.78203E+00	0.68223E+00
0.64794E+00	0.89272E+00	0.72864E+00	0.71460E+00	0.87268E+00	0.56943E+00	0.47121E+00	0.35041E+00	0.22389E+00	0.67558E-01
0.11439E+00	0.10893E-01	0.12908E-01	0.17204E-02	0.19191E-02	0.25091E-03	0.25966E-03	0.35525E-04	0.36149E-04	0.47912E-05
0.48231E-05	0.61074E-06	0.61212E-06	0.72325E-07	0.72390E-07	0.78855E-08				

E= 0.18000E+02(MEV) LMAX= 19 JMAX= 37/2

0.66313E+00	0.70603E+00	0.69271E+00	0.68420E+00	0.69152E+00	0.70657E+00	0.66468E+00	0.76177E+00	0.76574E+00	0.67713E+00
0.66274E+00	0.85772E+00	0.70130E+00	0.77851E+00	0.88570E+00	0.61776E+00	0.59638E+00	0.53930E+00	0.31211E+00	0.15573E+00
0.22307E+00	0.26121E-01	0.35858E-01	0.49124E-02	0.52387E-02	0.77595E-03	0.83131E-03	0.12411E-03	0.12579E-03	0.18708E-04
0.18883E-04	0.26853E-05	0.26935E-05	0.36033E-06	0.36075E-06	0.44684E-07	0.44706E-07	0.50903E-08		

E= 0.20000E+02(MEV) LMAX= 20 JMAX= 39/2

0.66397E+00	0.68787E+00	0.67485E+00	0.68551E+00	0.69116E+00	0.68874E+00	0.65260E+00	0.75424E+00	0.74779E+00	0.67449E+00
0.67445E+00	0.82367E+00	0.68023E+00	0.81740E+00	0.86912E+00	0.63910E+00	0.69020E+00	0.69292E+00	0.39601E+00	0.29872E+00
0.35034E+00	0.55978E-01	0.88004E-01	0.11865E-01	0.12494E-01	0.20649E-02	0.22797E-02	0.36384E-03	0.36916E-03	0.60649E-04
0.61418E-04	0.96547E-05	0.96942E-05	0.14466E-05	0.14488E-05	0.20121E-06	0.20134E-06	0.25779E-07	0.25786E-07	0.30303E-08

7 - MICROSCOPIC CALCULATION OF DEFORMATION PROPERTIES IN THE ACTINIDE REGION

M. Girod and D. Gogny

In the last decade, Hartree-Fock (HF) type calculations with density dependent effective interactions have been performed in the whole chart of nuclides. The calculations, first undertaken for spherical nuclei, have been extended with a great success to the description of deformed ones.

The calculations, presented here, have been performed with Gogny's D1 density dependent force [1]. This finite range interaction has been fitted in such a way as to permit the correct simultaneous treatment of the mean field and the pairing field in the framework of the Hartree-Fock-Bogolyubov approximation (HFB). The D1 interaction makes possible the description of a lot of spherical-nuclei properties (binding energy, charge radius, charge densities...) in the HF, HFB and HF + RPA approximations. We have also calculated many deformed nuclei from ^{8}Be to ^{248}Cm with this interaction [2].

We give here the preliminary results of HFB calculations for fifteen even nuclei going from ^{230}Th to ^{258}Fm.

The techniques of HFB calculations with a finite range interaction are evidently more complicated than HF calculations with zero-range force, where one avoids the time-consuming building up of matrix elements of the two body hamiltonian. But due to the separation method we developed in Ref. [3], we were, in fact, able to construct a very fast algorithm for the calculation of the matrix elements.

The HFB solutions are expanded in a deformed oscillator basis. The conserved symmetries are the axial symmetry and the left-right one. This basis is troncated with the usual prescription :

$$(2n_\perp + m + 1)\,\hbar\omega_\perp + (n_z + 1/2)\hbar\omega_z \leqslant (N + 2)\hbar\omega_o$$

where $\hbar\omega_o^3 = \hbar\omega_\perp^2 \,.\, \hbar\omega_z$.

The parameters of the basis are $\hbar\omega_o$ and $q = \hbar\omega_\perp/\hbar\omega_z$. We must choose these parameters in order to minimize the HFB energy. However, for a sufficiently

large number of shells N, the solutions are practically independant of these parameters.

The multipole moments are defined by the relation

$$q_\lambda = \int \rho(\vec{r})\ r^\lambda\ Y_{\lambda o}\ d\vec{r}$$

where $\rho(\vec{r})$ is the HFB charge (protons) or mass (protons + neutrons) density. They can be connected to the β_λ parameters given in the literature. However these quantities are rather model dependent and we prefer to compare directly our multipole moments with the intrinsic deformation deduced from the $B(E_\lambda)$ data or with the multipole moments of the deformed optical model potential which are less sensitive to the detailed values of the optical parameters used in calculations.

The first column of the Table I gives the HFB binding energies calculated with a large oscillator basis (N = 13 major shells). The differences between theoretical and experimental binding energies are no more than 3 MeV. We have estimated the lack of binding energy due to the truncation effect. This effect varies linearly from 3.8 MeV for ^{230}Th up to 4.3 MeV for ^{258}Fm. With addition of this truncation energy, the HFB binding energies are too large, but no more than 3 MeV.

The next columns of the Table I display the pairing energy and the gaps for protons and neutrons obtained by self consistent HFB procedure without any free parameter. For the protons, these values are systematically over-estimated by about 10-20% due to the neglect of the Coulomb force in the pairing field.

The last column gives the moment of inertia calculated to the Cranking approximation.

The charge and mass multipole moments q_λ, $\lambda = 2,4,6$ and the charge radius are displayed in the Table II. The mass multipole moments are normalized for Z particles. Except for the $^{230-232}$Th, all the mass moments are smaller than the charge moments. The largest difference is .07b for q_2, .06b^2 for q_4 and .03b^3 for q_6. These differences are relatively much smaller than the corresponding differences between the deformation paramters β_λ obtained from electromagnetic measurements (charge-β_λ) and from nuclear inelastic scattering (mass-β_λ). Such relatively large differences are not observed when multipole moments are considered.

The comparison of the HFB results with the experiment is difficult because the experimental results for the actinides beyond ^{238}U are very scarce.

For these nuclei the main reference is the Bemis et al. paper [4] (Fig. 1a, 1b). The q_2 moments extracted from the ($\alpha\alpha'$) scattering are systematically larger than the HFB ones by $\sim$ .3b. Concerning the q_4 moments, they are seen in this paper to be vanishing (with large incertainties) close to A = 244-248 while the theory predicts this cancellation close to A = 260-262. Let us point out that in the HF calculations with Skyrme III interaction [5] this cancellation at A = 260-262 is also predicted.

On the other hand, the experimental results concerning the ^{232}Th and ^{238}U nuclei are more numerous [6,7]. It can be remarked that most of them exhibit q_2 moments smaller than those from Ref. [4] and also closer to the H.F.B. results. It is tempting to suppose that the same situation could occur for the Pu and Cm isotopes.

It must be emphasized that a more recent experiment [7] on ^{232}Th, ^{234,236,238}U is in excellent agreement with our predictions not only for the quadrupole and hexadecapole moments, but also for the hexacontatetrapole one (q_6) (Fig. 1a, 1b, 1c).

For all these reasons, it seems to us that more accurate experiments on the Pu and Cm isotopes would be desirable before drawing a definite conclusion about the comparison between theory and experiment.

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Nucleus	B_{HFB} (MeV)	B_{exp} [a] (MeV)	E pairing (MeV) p	E pairing (MeV) n	Gap (MeV) p	Gap (MeV) n	I_x ($\hbar^2$/MeV)
^{230}Th	1753.5	1755.152	8.3	9.3	1.2	1.1	36
^{232}Th	1764.9	1766.709	8.8	8.8	1.2	1.0	38
^{234}U	1777.3	1778.592	8.4	8.3	1.1	1.0	42
^{236}U	1788.7	1790.435	8.8	8.6	1.1	1.0	42
^{238}U	1799.3	1801.713	9.6	8.4	1.2	.90	40
^{236}Pu	1787.8	1788.423	7.9	8.2	1.1	1.0	44
^{238}Pu	1800.2	1801.294	7.9	8.0	1.2	1.0	46
^{240}Pu	1811.8	1813.475	8.5	8.2	1.2	.90	43
^{242}Pu	1822.9	1825.026	9.5	7.7	1.2	.90	42
^{244}Pu	1833.4	1836.081	10.7	6.0	1.2	1.1	45
^{244}Cm	1834.1	1835.869	9.2	7.5	1.1	.90	43
^{246}Cm	1845.7	1847.846	9.7	6.8	1.1	1.1	45
^{248}Cm	1856.1	1859.215	10.7	8.3	1.2	.90	39
^{252}Cf	1878.3	1881.294	11.1	10.0	1.2	1.0	36
^{258}Fm	1910.9	-	11.3	10.5	1.2	1.0	34

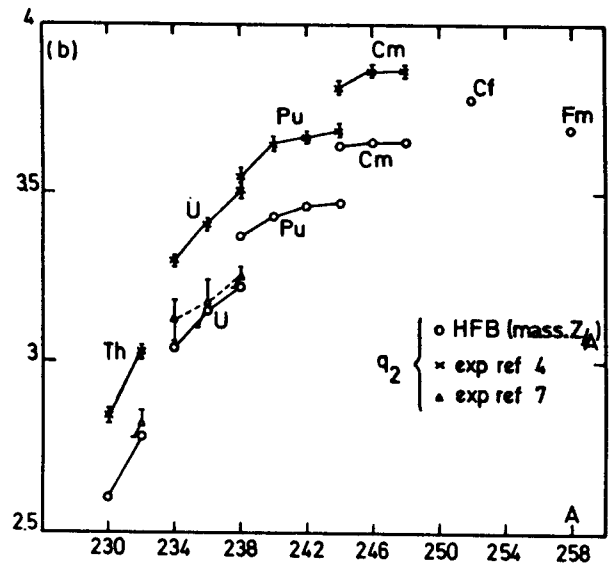
[a] Atomic Data and Nuclear Data Tables 19 (1977) 177.

TABLE I

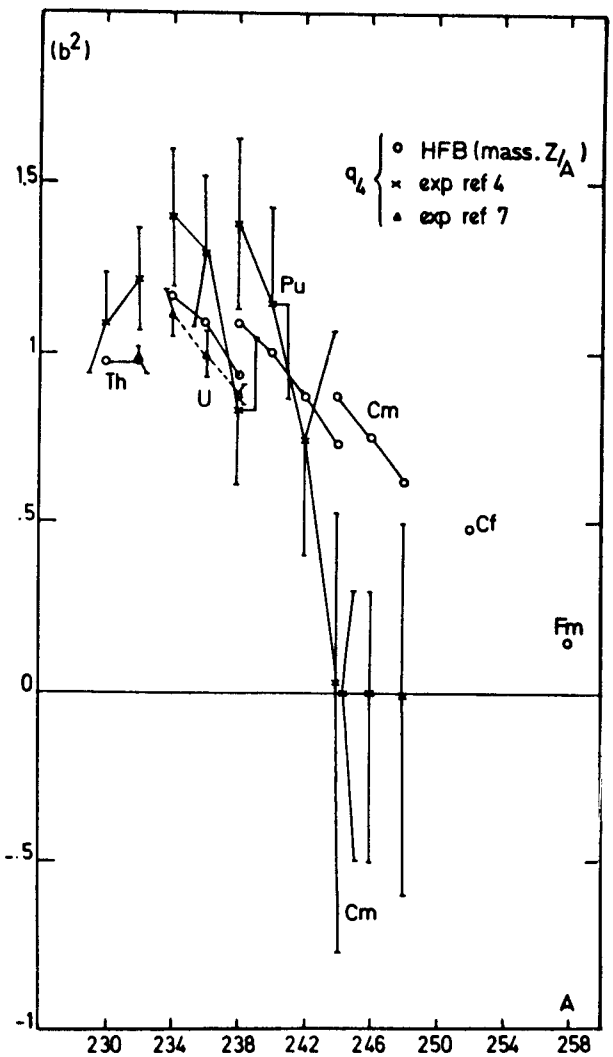
Nucleus	q_2^C (b)	$q_2^M \times \frac{Z}{A}$	q_4^C (b^2)	$q_4^M \times \frac{Z}{A}$	q_6^C (b^3)	$q_6^M \times \frac{Z}{A}$	r_{ch} (fm)
^{230}Th	2.57	2.60	.94	.97	.23	.23	5.714
^{232}Th	2.74	2.78	.96	.97	.22	.22	5.730
^{234}U	3.05	3.04	1.17	1.17	.30	.28	5.764
^{236}U	3.16	3.15	1.10	1.09	.23	.21	5.777
^{238}U	3.21	3.22	.94	.93	.16	.14	5.792
^{236}Pu	3.31	3.26	1.19	1.18	.28	.26	5.796
^{238}Pu	3.42	3.37	1.11	1.09	.24	.22	5.810
^{240}Pu	3.47	3.43	1.02	1.00	.18	.15	5.823
^{242}Pu	3.48	3.46	.89	.87	.11	.08	5.833
^{244}Pu	3.49	3.47	.77	.73	.05	.02	5.843
^{244}Cm	3.70	3.64	.90	.87	.09	.06	5.862
^{246}Cm	3.70	3.65	.80	.75	.007	-.004	5.872
^{248}Cm	3.67	3.65	.67	.62	-.003	-.04	5.882
^{252}Cf	3.85	3.78	.54	.48	-.07	-.10	5.918
^{258}Fm	3.75	3.69	.20	.15	-.14	-.16	5.960

TABLE II

(a)


(b)
Cm
Cf
Fm
Pu
Cm
U
Pu
U
Th
q_2
o HFB (mass. Z/A)
× exp ref 4
▲ exp ref 7
A
4
3.5
3
2.5
230
234
238
242
246
250
254
258

(b)


(b^2)
q_4
o HFB (mass. Z/A)
× exp ref 4
▲ exp ref 7
Pu
Th
U
Cm
Cf
Fm
Cm
A
1.5
1
.5
0
-.5
-1
230
234
238
242
246
250
254
258

(c)

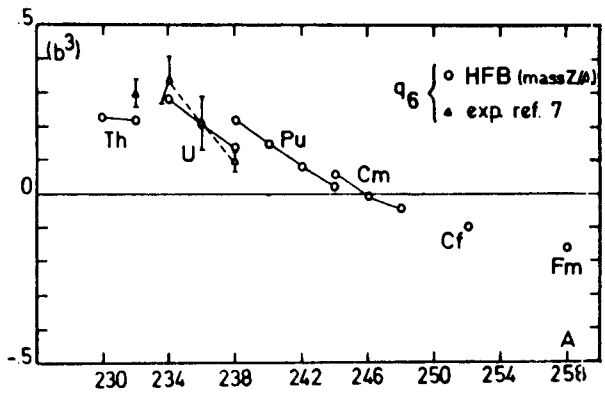

(b^3)
q_6
o HFB (mass Z/A)
▲ exp. ref. 7
Th
U
Pu
Cm
Cf
Fm
A
.5
0
-.5
230
234
238
242
246
250
254
258

Figure 1