**THE PHOTOFISSION CROSS SECTIONS OF URANIUM AND THORIUM NEAR THRESHOLD**

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ABSTRACT

Using monochromatic gamma rays from (n,γ) reactions, the photofission cross sections behaviour for natural Uranium and Thorium have been determined in the 5 to 10 MeV energy interval.

"Bumps" around the energies of 6 MeV and 6.6 MeV for Uranium and around 6.7 MeV and 7.6 MeV for Thorium have been found. The existence of this structure in the photofission cross section near the threshold is in accordance with Bohr's prevision about the excitation of rotational states.

## I - INTRODUCTION

The photodesintegration of a lot of elements has been studied with a variety of gamma ray energies. However, the research in photonuclear reactions has always been restricted by the gamma ray sources. It is not always possible to obtain monochromatic gamma radiation with enough intensity and resolution to permit significant experimental work.

The first experiments in photodesintegration had been performed with proton capture reactions (p.γ). This kind of source is still utilized[1,2] although it has only a few lines available and the resolution is about a hundred KeV.

The lack of monochromatic gamma rays has forced experimental workers for many years[3,4] to use the Bremsstrahlung spectra from Betatrons, Syncrotrons and Linear accelerators. The continuous distribution of photon energies up to the maximum energy of the incident eletrons is of course an unavoiadable disadvantage. This was one of the reasons for the search of new gamma radiation sources with better resolution in energy.

Recently the anihilation of positrons in flight[5] and neutron capture gamma reactions (n,γ)[6,7] have been used bringing some advantages in relation to the primary techniques permiting the obtention of more precise date.

The anihilation of positrons in flight is used mainly for research in the giant ressonance region, because its intensity is very low near the threshold where the cross sections are smaller. The neutron capture gamma rays have sufficient intensity to be used near the threshold of the photonuclear reactions and can be used only there because the energies from the (n,γ) reaction do not go beyond 11 MeV.

Recently Knowles et al.[8] have used the Compton scattered-neutron capture gamma rays obtaining a practically continuous variation of the gamma rays energies around the known (n,γ)lines which can not be obtained with the direct neutron capture radiation, but the gamma rays intensities and resolution are lower than the neutron capture gamma rays.

A comparison of the resolution and intensity for various gamma rays sources is shown in tables I and II.

The nuclear fission of heavy elements following nuclear absortion of eletromagnetic radiation was first predicted by Bohr and Wheeler in 1939[9] and the first experimental measurement were made in 1942[10] by Haxby using proton capture gamma rays in Uranium and Thorium targets.

The first measurements of photofission cross section curve for Uranium and Thorium near threshold found in the literature[4,5,11] are those made with Bremsstrahlung spectra which are low precision experiments because of the complex calculations that had to be done in order to obtain the cross sections.

In 1966 Manfredini and co-workers[12] measured the photofis sion cross section for Uranium in the 5 to 10 MeV energy interval using neutron capture gamma rays and nuclear emulsions as detectors. They found some structure in the cross section behaviour that could not be seen in the Bremsstrahlung results.

The existence of discrepancies about the photofission cross section near threshold led us to the measurement of the cross section curve trying to get more precise results using neutron capture gamma rays as source.

In the present paper we report the measurements of the photofission cross sections for Natural Uranium and Thorium and show that peaks really exist, although we can not precise exactly their width because of the few points that can be measured.

Table I

| Source | $E_\gamma$(MeV) | $\Delta E$(KeV) |
|---|---|---|
| Reaction | | |
| $^{19}F(p,\alpha\gamma)$ | 7.12 | 130 |
| $^{7}Li(p,\gamma)$ | 17.6 | 12.2 |
| Betatron | 19 (Maximum energy) | 500 |
| Positrons anihilation | 19 | 500 |
| Bremsstrahlung Monochromator | 19 (Maximum energy) | 100 |
| Reaction | | |
| $^{58}Ni(n,\gamma)\ ^{59}Ni$ | 9.00 | 0.011 |
| $^{207}Pb(n,\gamma)\ ^{208}Pb$ | 7.38 | 0.0045 |
| Compton Scattered Neutron Capture radiation | 9.00 | 255 |

Comparison between widths of gamma radiation sources.

Table II

| Source | $E_\gamma$ (MeV) | Gamma flux in $cm^{-2}$ $sec^{-1}$ |
|---|---|---|
| Proton Current | | 30 cm from the target |
| 1 mA | | $1 \times 10^5$ |
| $^{19}F(p,\alpha\gamma)$ | 7.12 | |
| $^{7}Li(p,\gamma)$ | 17.6 | $1 \times 10^4$ |
| Betatron | 10 | 50 cm from the target |
| Maximum Energy 31 MeV | | $1 \times 10^6$ |
| Positrons aniquilation in flight | 19 | $1 \times 10$ |
| Reactor $\phi$ = $3.73 10^{11} n/cm^2 sec$ 1500 g | | 400 cm from the target |
| $^{58}Ni(n,\gamma)^{59}Ni$ | 8.997 | $2.49 \times 10^5$ |
| 1000 g | | |
| $^{207}Pb(n,\gamma)^{208}Pb$ | 7.38 | $1.6 \times 10^4$ |
| Compton Scattered Neutron Capture radiation | | |
| $^{58}Ni(n,\gamma)$ Ni | 8.997 | $2 \times 10^{-1}$ |

Comparison between gamma ray fluxes from different sources.

## II - EXPERIMENTAL SET-UP

The gamma rays used have its origin in the neutron in targets placed near the IEAR-1 reactor core in a tangencial beam-hole. The thermal neutron flux incident in the target with the reactor power at 2 Mw is about $4 \times 10^{11} n/cm^2/sec$.

The monochromatic gamma radiation thus obtained is then collimated and filtered to prevent neutron contamination. The schematic diagram of the collimator can be seen in the fig. nº 1. The gamma rays are detected by a NaI(Tl) crystal of 3 x 3 inch

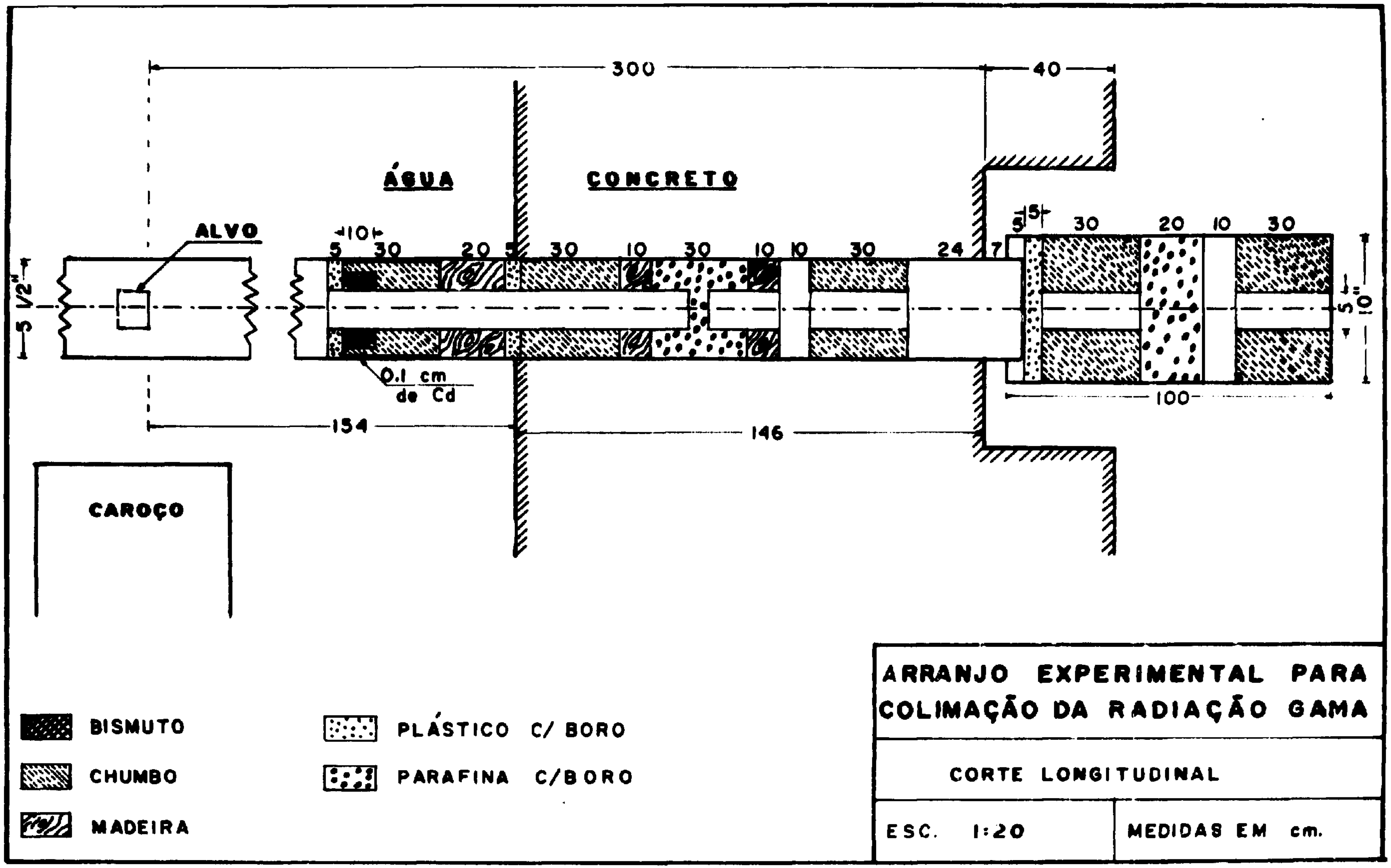


Figure 1

Schematic diagram of the collimator

and analysed by a 1024 multichannel analyser.

The detection of the fission fragments is made by ionization chambers[13] of multiparallel plates in which Uranium and Thorium had been electrolitically deposited in an oxide form. The plates containing about 2.5 $mg/cm^2$ of $UO_2$ and 1.4 $mg/cm^2$ of $ThO_2$ are in number of 12 in each chamber, in order to increase the detector sensibility; it is known that the cross sections at these energies ar of the order a few milibarns.

The pulses produced in the chamber by the fission fragments are larger than the pulses produced by the alfa particles emitted by the Uranium and Thorium so the discrimination is very easy to be done. The experimental arrangement is shown in fig. nº 2.

In order to prevent a variation caused by the reactor power flutuations a $BF_3$ detector is used as a monitor. Moreover the measurements of the gamma rays intensity, fission counts is the chamber and background are alternated, having in view the possibility of reactor power variation.

## III - EXPERIMENTAL DATA HANDLING

The gamma rays intensity can be obtained by integrating the counts under the photopeak assumed to be a gaussian curve and using the total efficiency for the NaI(Tl) 3" x 3" crystal

$$I\left(\frac{\text{gammas}}{\text{sec}}\right) = \frac{A}{K\,p(1 - e^{-\mu x})}$$

were:

A is the photopeak area in counts/sec;

p is the photofraction that can be calculated by the Monte Carlo method[14] or measured experimentaly[15];

$(1-e^{-\mu x})$ is the crystal intrinsic efficiency and

K  is a correction factor because the intensity measured 2m away from the chamber position.

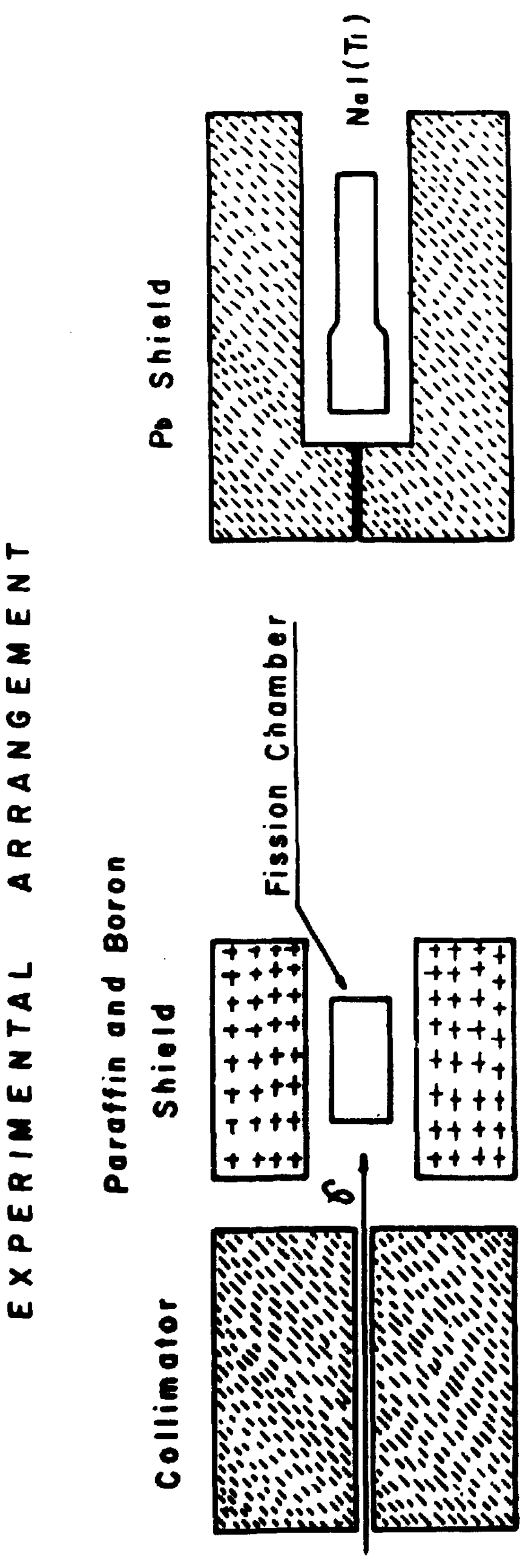


Fig. 2

Experimental arrangement

The mean gamma-ray intensity for the elements used as targets, the mean counting rate obtained with the two chambers and the statistical errors are calculated by a computer program named Carcarã and are given in table III.

The contribution due to neutron scattering in the target container as well as the room background have been measured and subtracted. The influence of neutrons scattered in the target have been calculated and also taken into account.

The gamma ray lines obtained for an element are not exactly monochromatic, but the relative intensities of the secondary to the principal lines are well known and not very high[16].

For each target the counts measured in the fission chamber are due contributions from several gamma lines; however there is a more intense gamma line that is the main responsible for the counts.

If we had just one gamma ray line the photofission reaction rate in the fission chamber would be given by:

$$R\left(\frac{\text{reactions}}{\text{sec}}\right) = \frac{c}{\varepsilon} = \phi\,\sigma\,NV = \phi\,\sigma\,N_t$$

where:

- $C$ are the chamber counts per second
- $\varepsilon$ is the chamber intrinsic efficiency
- $\phi$ is the incident gamma flux
- $\sigma$ is the photofission cross section
- $N_t$ is the number of Uranium and Thorium atoms.

$$\frac{C}{\varepsilon\,N_t} = \frac{K\,A(E)\;\sigma(E)}{(1 - e^{-\mu(E)x})\,p(E)\,S}$$

where S is the beam area.

$$\frac{\sigma(E)}{K'} = \frac{C\ (1 - e^{-\mu x})\ p(E)}{A\ (E)} = \frac{C}{I}$$

with $K' = \frac{S}{\varepsilon N_t K}$ and I the gamma ray intensity.

Since for each target there are more than one gamma line we get:

$$\frac{C}{I} = \sigma_1' + r_2\ \sigma_2' + r_3\ \sigma_3' + \ldots \quad \text{where } \sigma_i'$$

are numbers proportional to the photofission cross section and $r_i$ are the secondary lines intensity relative to the principal ones.

Table III

| Elements | Uranium chamber counts/sec | Thorium chamber counts/sec | Gamma ray intensity $\gamma$/sec |
|---|---|---|---|
| Ti | 7.54 ± 0.07 | 2.41 ± 0.02 | $(4.9 \pm 0.5)10^4$ |
| Al | 0.97 ± 0.01 | 0.178 ± 0.002 | $(7.6 \pm 0.8)10^3$ |
| Ni | 8.73 ± 0.09 | 0.944 ± 0.009 | $(1.54 \pm 0.15)10^4$ |
| Zn | 1.12 ± 0.01 | 0.177 ± 0.002 | $(4.68 \pm 0.48)10^3$ |
| Cu | 3.73 ± 0.04 | 0.673 ± 0.007 | $(1.71 \pm 0.18)10^4$ |
| Mn | 2.66 ± 0.03 | 0.449 ± 0.004 | $(3.12 \pm 0.37)10^4$ |
| Fe | 4.73 ± 0.05 | 0.909 ± 0.008 | $(2.9 \pm 0.3)10^4$ |
| K | — | 0.0677 ± 0.0007 | $(2.31 \pm 0.26)10^4$ |
| S | 0.236 ± 0.002 | 0.0306 ± 0.0003 | $(1.4 \pm 0.1)10^4$ |
| Ca | 0.166 ± 0.002 | 0.0588 ± 0.0006 | $(4.4 \pm 0.4)10^3$ |
| Y | 0.232 ± 0.004 | 0.00572 ± 0.00006 | $(2.2 \pm 0.2)10^3$ |
| Pb | 0.130 ± 0.001 | 0.0153 ± 0.0002 | $(1.1 \pm 0.1)10^3$ |
| Be | 0.0023 ± 0.001 | 0.00011 ± 0.00005 | (1.1 ± 0.[illegible])$10^2$ |

This last equation can be written for all the targets and a linear system is obtained.

As some of the energies are not very different, approximations of the order of 50 KeV have been made to reduce the final system.

To solve this system it was first taken the quadratic system made with the principal lines of the elements. The cross section obtained were then affected by errors corresponding to the lines that had not been considered earlier.

## IV - RESULTS

The results with the errors obtained for Natural Uranium and Thorium are in table IV and fig. nº 3 and 4. The errors include statistical errors, uncertanties in the intensity measurement and the influence of the gamma ray lines that had not been considered.

The data obtained for Uranium had also been normalised to the results of Manfredini[12] showing a very good agreement (fig.5).

Looking at the cross section behaviour we see that peaks really exist near the energies of 6 MeV and 6.6 MeV for Uranium and 6.7 and 7.6 MeV for Thorium.

The distance between them is approximately 1 MeV and the width of the order of 300 KeV although this value is very rough because of the small number of experimental points available.

To show the importance of the gamma line width in the shape of the cross sections we have folded our experimental data with 1% and 5% resolution functions; it can be seen clearly that this last resolution function is sufficient to smear out the structure in the cross section (fig. nº 6). This can be an explanation why some authors[17] found peaks that are poorly defined near these energies.

The existence of peaks is in accord with the Bohr[18] ideas based on the liquid drop model.

According to Bohr theory the photofission in even nuclei close to the fission threshold should accur predomintly via a

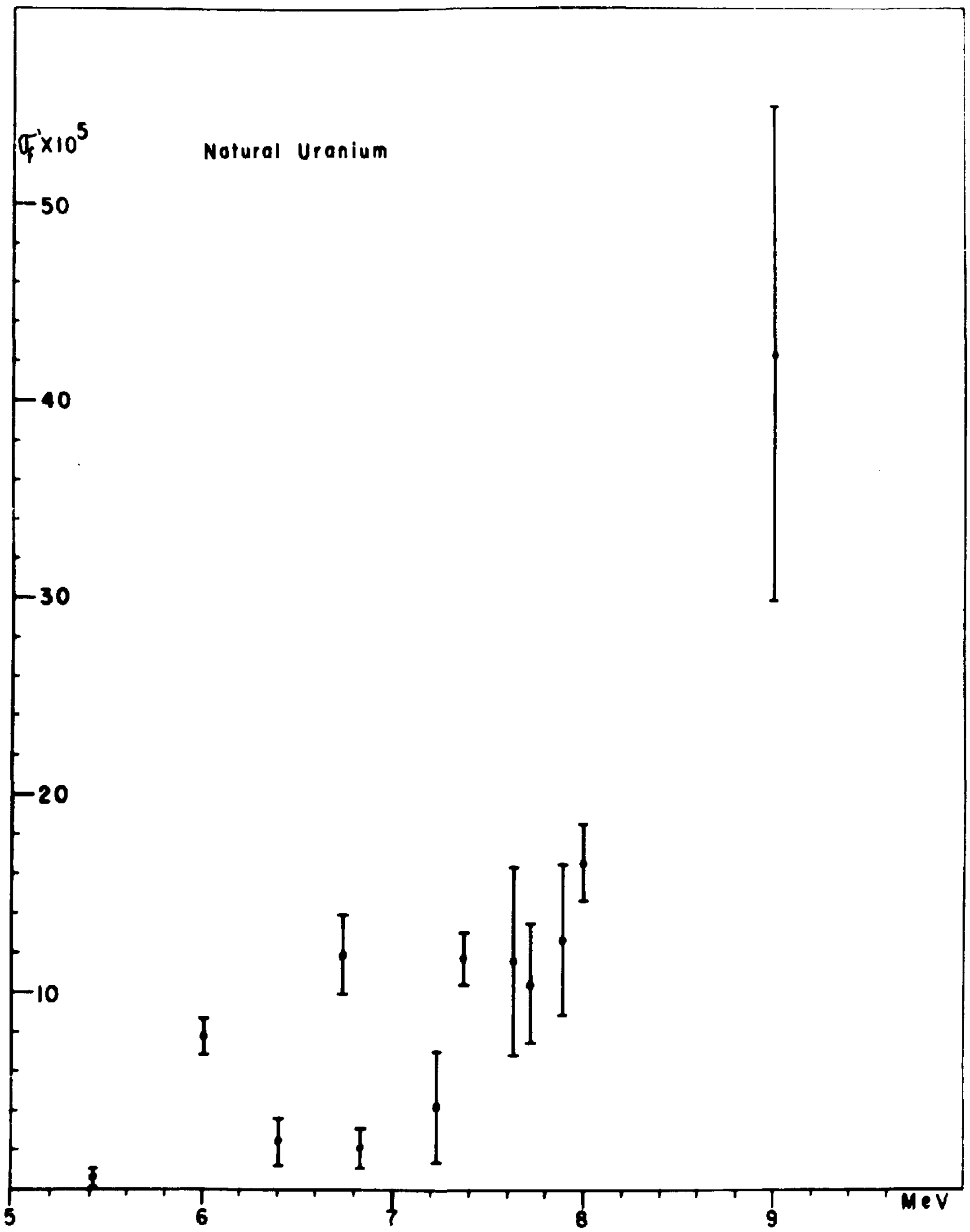


Fig. 3

Photofission cross section behaviour for Natural Uranium

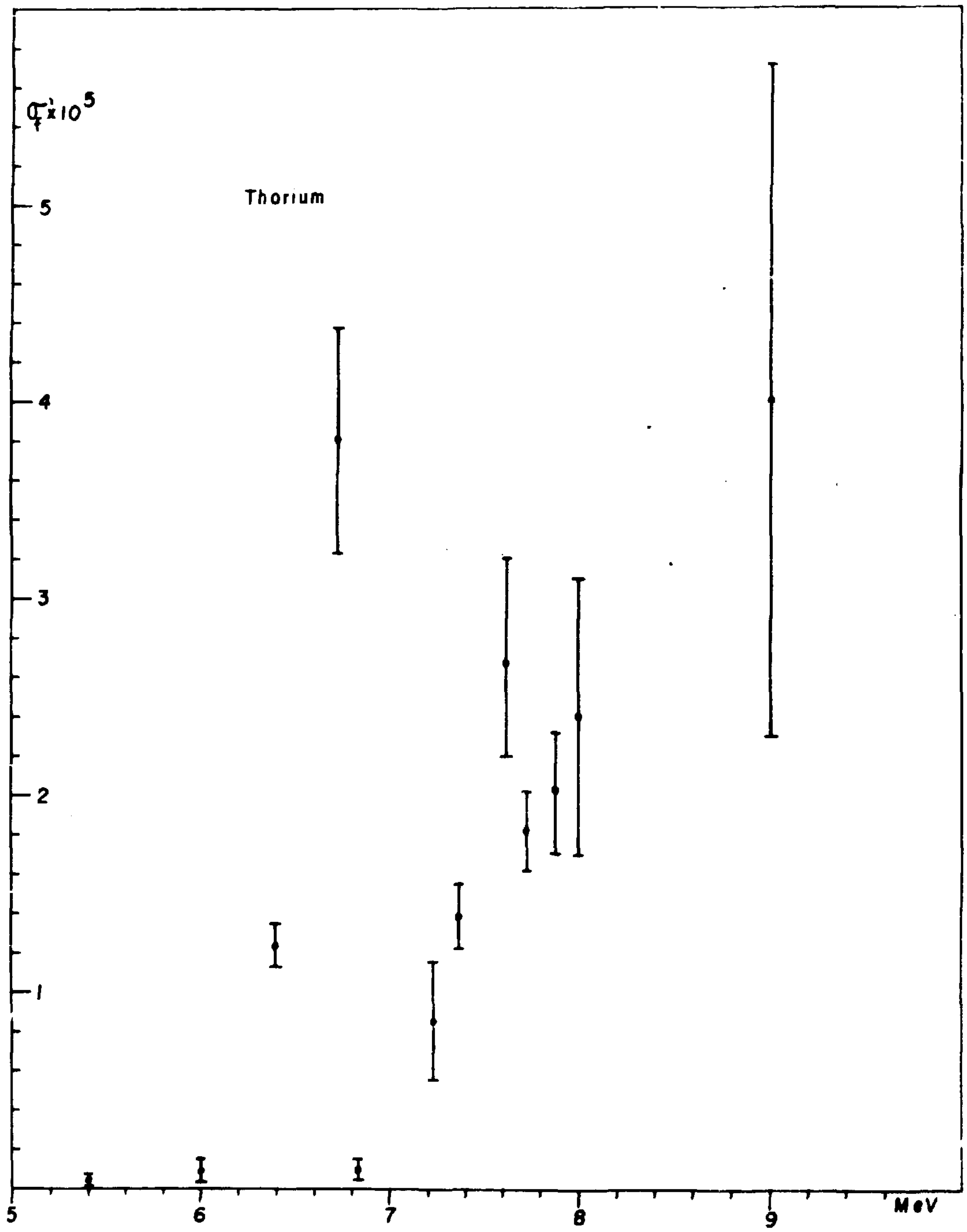


Fig. 4

Photofission cross section behaviour for Thorium single or small number of well defined low lying excited states of the compound nucleus at the saddle point configuration. In the Bohr interpretation this excitation is an odd parity state (-1) similar to the observed low energy excitations of the ground state and represents a collective mode of excitation associate with assymetric vibrations in the shape of the nuclear surface.

Table IV

| Energy | $\sigma'_U (x\ 10^5)$ | $\sigma'_{Th} (x\ 10^5)$ |
|---|---|---|
| 5.43 | 0.61 ± 0.49 | 0.05 ± 0.04 |
| 6.05 | 7.85 ± 0.86 | 0.09 ± 0.06 |
| 6.42 | 2.47 ± 1.20 | 1.23 ± 0.13 |
| 6.73 | 1.2 ± 2 | 3.8 ± 0.6 |
| 6.83 | 2.2 ± 1 | 0.1 ± 0.046 |
| 7.23 | 4.3 ± 2.8 | 0.86 ± 0.3 |
| 7.38 | 11.8 ± 1.3 | 1.4 ± 0.2 |
| 7.63 | 11.6 ± 5 | 2.7 ± 0.5 |
| 7.73 | 10.6 ± 3 | 1.8 ± 0.2 |
| 7.79 | — | — |
| 7.88 | 12.8 ± 4 | 2.2 ± 0.9 |
| 7.91 | 16.6 ± 1.8 | 2.4 ± 0.7 |
| 8.99 | 42.4 ± 13 | 4.0 ± 1.7 |

$\sigma'$ are numbers proportional to the cross sections at the various energies.

From this we can expect that rotational states of the assymetric liquid drop model (K = 0, 1, 2, ...) with odd parity would be excited in photofission just above the threshold giving this cross section behaviour.

RESUMO

Utilizando radiação gama proveniente da reação (n,γ) foram medidos os comportamentos das secções de choque de fotofissão do Urânio Natural e Tório no intervalo de energias de 5 a 10 MeV.

Foram encontrados picos nas vizinhanças das energias de 6 MeV e 6.6 MeV para o Urânio e nas vizinhanças de 6.7 MeV e 7.6 MeV para o Tório. A existência desta estrutura na secção de choque de fotofissão junto ao limiar está de acôrdo com a previsão de Bohr sôbre a excitação de estados rotacionais.

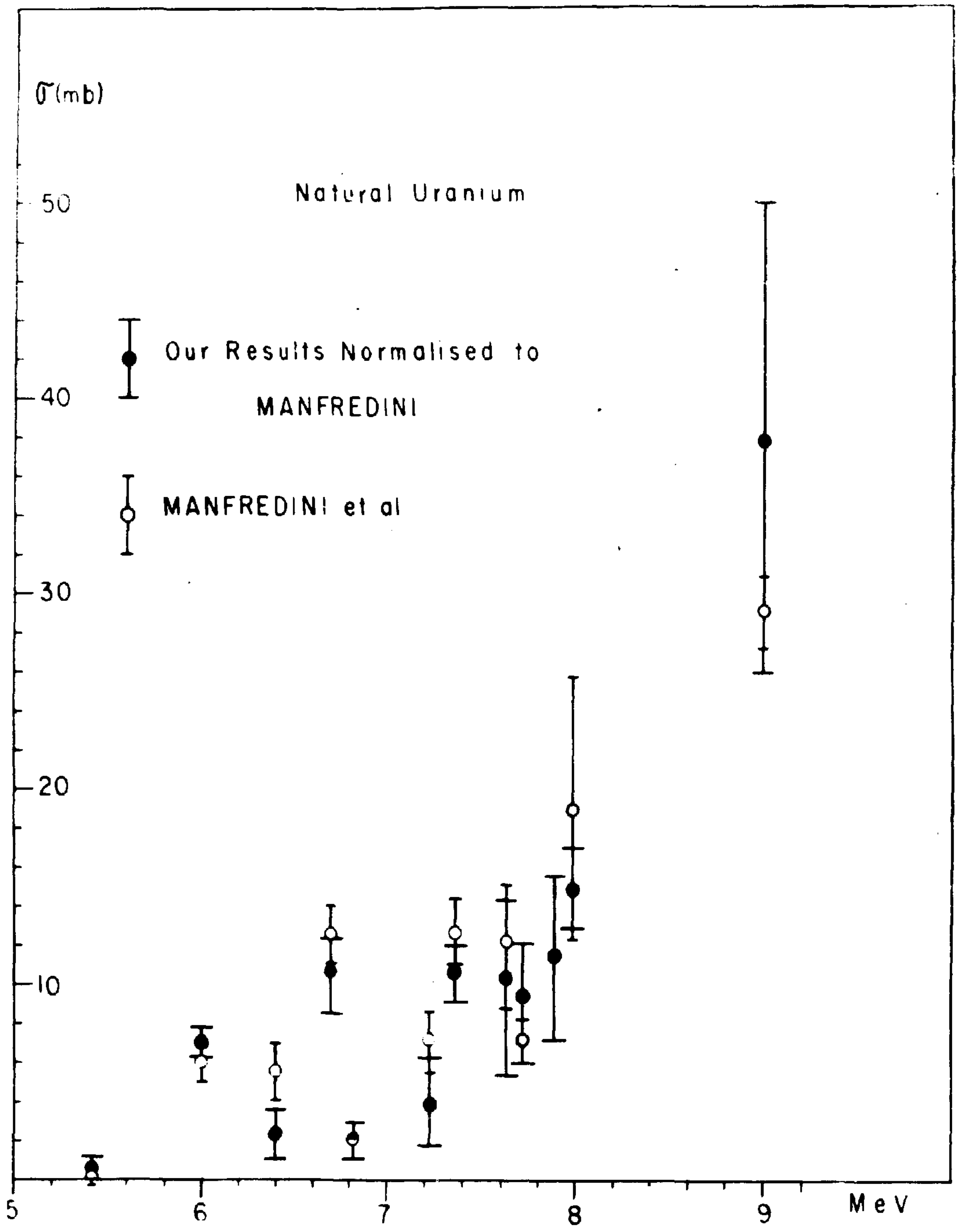


Fig. 5

**Photofission cross section for Uranium normalised to Manfredini's results**

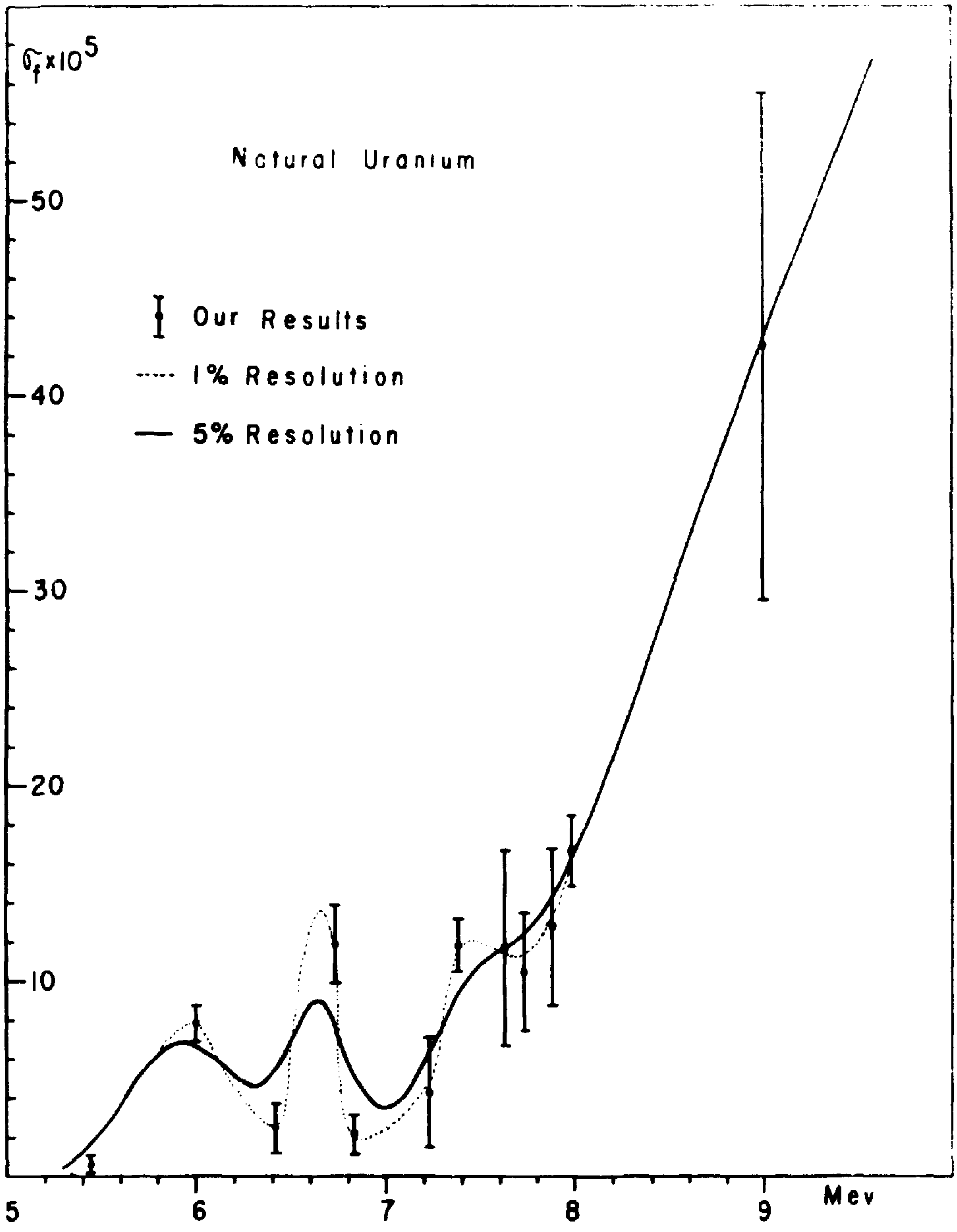


**Fig. 6**

**Photofission cross sections folded with 1% and 5% resolution functions**

## V - AKNOWLEDGEMENTS

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