Revista Brasileira de Física, Vol. 3, N.° 3, 1973

Angular Distribution of Photofission Fragments in ^{238}U at 5.43 MeV

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Recebido em 7 dé Junho de 1973

The angular distribution of photofission fragments of ^{238}U, produced by 543 MeV monochromatic photons from the (n,γ) reaction in sulphur, has been measured using glass plates as detectors In the analysis of the results only the contributions from the $(J^{\pi}, K) = (1^-, 0)$, $(1^-, 1)$ and $(2^+, 0)$ terms were considered The coefficients of the angular distributions of the fission fragments were obtained An analysis of the data available in the literature on the angular distribution near the photofission threshold is also presented

Foi medida a distribuição angular dos fragmentos de fotofissão do ^{238}U, induzida por fotos monocromáticas de 5,43 MeV proveniente da reação (n,γ) no enxofre. Como detetores foram utilizadas lâminas de vidro. Na análise dos resultados foram consideradas somente as contribuições dos termos $(J^{\pi}, K) = (1^-, 0)$, $(1^-, 1)$ e $(2^+, 0)$. Foram obtidos os coeficientes da distribuição dos fragmentos. Uma análise dos dados existentes na literatura a respeito da distribuição angular na região do limiar da fotofissão é também apresentada. .

1. Introduction

Strong evidence for the existence of an intermediate structure in the (γ, f) cross section near the fission threshold has been accumulated recently.

Rabotnov et al[1]., using the continuous bremsstrahlung spectra of a microtron of about 10% resolution, Knowles[2] using Compton scattered gamma-rays from the reaction $^{58}Ni(n,\gamma)\,^{59}Ni$ as a continuously variable source of gamma rays which presents an overail resolution of $\simeq 3\%$, Manfredini *et al.*[3] and Mafra *et al.*[4] using the 10 eV resolufion gamma lines from neutron capture in several elements, have found this structure in ^{238}U and ^{232}Th.

The small discrepancies between the data have been attributed to the

*Postal address: Caixa Postal 20516, 01000 - São Paulo, SP different resolutions employed. This structure in the cross section can be associated with resonances in the levels of the deformed transition state; therefore, a lot of data on the angular distributions of the fission fragments has been measured and can be found in the litterature[1,2,3,5]. In particular, the peak in the ^{238}U cross section observed by Knowles around 5 MeV can be associated to the existence of a $(2^+, 0)$ channel (quadrupole photoabsorption). It was assumed for this hypothesis that the diagram levels are the ones from Albertson and Forkman[6]. As the experimental errors involved were too high this explanation was not conclusive.

The experiment described in this paper is the measurement of the angular distribution of the fission fragments around 5 MeV (5.43 MeV) in order to investigate if there is any channel at this energy. Monochromatic gamma radiation from (n, γ) reaction in sulphur and glass detectors were used in this experiment.

An analysis of all data available in the literature on the angular distribution of fission fragments in ^{238}U from 5 to 7 MeV is also presented.

2. Theory

The energy level diagram is strangly dependent on the shape of the nucleus at the saddle point. Initially, the nucleus was assumed[7] as having a quadrupole deformation at the saddle point but later on Johansson[8] has shown that a more convenient shape is the octupolar one. This diagram of levels for heavy even-even nuclei is given by Albertsson and Forkman[6] and shown in Fig. 1.

According to this scheme, the fission threshold level is $(J^\pi; K) = (0^+, 0)$. This level is not accessible by the photoabsorption because the photons produce only levels $M = \pm 1$, so the $J^\pi = 0^+$ is forbidden.

The dominant modes of photon absorption in heavy elements (as uranium and thorium) are dipole and quadrupole since the magnetic component is very small. The levels that can be excited with photons are marked out with strong lines in Fig. 1. Each one of these levels at the the saddle point is characterized by the quantum numbers:
J – the total angular momentum,
M – the J projection over the spatial axis,
K – the J projection over the symmetry axis,
π – the wave function parity.

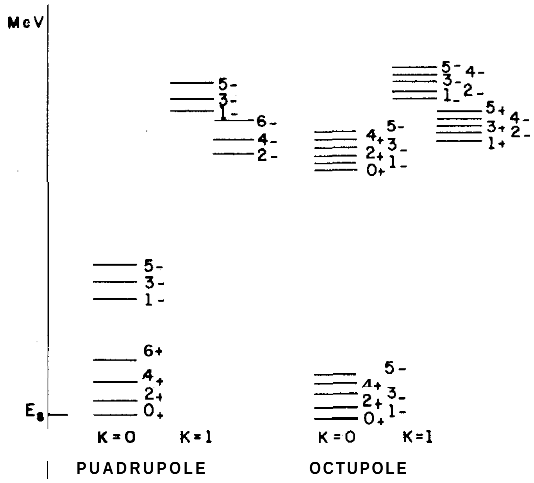

Fig. 1 - Energy levels of stable deformation.

As the fission fragments emerge in the nuclear symmetry axis, the K value, as well as J and M, define the fission fragment angular distribution. This angular distribution is given by[7]

$$P^{J}_{MK}(\theta) = (J+K)!\,(J-K)!\,(J+M)!\,(J-M)! \times \left[\sum_n \frac{(-1)^n (\cos\theta/2)^{2J+K-M-2n}}{(J-M-n)!} \right.$$

$$\left. \times \frac{(\sin\theta/2)^{2n+M-K}}{(J+K-n)!\,n!\,(n+M-K)!} \right]^2, \qquad (1)$$

where the summation is extensive to all n for which the denominator is positive and θ is the angle of the outgoing fission fragment relative to the incident beam direction.

Assuming that it is possible to observe only the dipole and quadrupole transitions, one can write the angular distribution for each transition as

$$\begin{aligned} P^{2}_{\pm 1,0}(\theta) &= (15/8)\sin^2 2\theta\,[\text{quadrupole } (2^+,0)] \\ P^{1}_{\pm 1,0}(\theta) &= (3/2)\sin^2\theta\,[\text{dipole } (1^-,0)] \qquad (2) \\ P^{1}_{\pm 1,1}(\theta) &= (3/2)(1 - 1/2\sin^2\theta)\,[\text{dipole } (1^-,1)] \end{aligned}$$

The angular distribution is connected with the differential cross section by the expression:

$$\frac{d\sigma}{d\Omega} = \sigma_1 P_{\pm 1,1}^{2} + \sigma_2 P_{\pm 1,0}^{1} + \sigma_3 P_{\pm 1,1}^{1}, \tag{3}$$

where o, , σ_2 and ***a,*** are the cross sections for the levels: (K, J") = $(0, 2^+)$, ***(0,***1^-) and *(1,* 1^-) respectively.

Equation *(3)* can be written as a function of the total cross section for fission as:

$$\frac{d\sigma_F}{d\Omega} = \sigma_F \left[\frac{\sigma_2}{\sigma_F} P_{\pm 1,0}^{1} + \frac{\sigma_3}{\sigma_F} P_{\pm 1,1}^{1} + \frac{\sigma_1}{\sigma_F} P_{\pm 1,1}^{2}\right] = \sigma_F\, \omega(\theta), \tag{4}$$

where the σ_i/σ_F coefficients are the contributions of each probability P_{MK}^{J}, and $\omega(\theta)$ is the angular distribution observed experimentally. $\omega(\theta)$ has to be normalized by:

$$\int_0^{\pi/2} \omega(\theta) \sin 0\, d\theta = 1. \tag{5}$$

Substituting (2) in *(4)* we get:

$$\frac{1}{a,} \frac{da,}{d\Omega} = \omega(\theta) = D \sin^2 8 + F\left(1 - \frac{\sin^2\theta}{?}\right) + G \sin^2 2\theta. \tag{6}$$

Simplifying this expression, we obtain

$$\omega(\theta) = a + b \sin^2 0 + c \sin^2 28. \tag{7}$$

where

$$\begin{aligned}
a &= (3/2)\frac{\sigma_3}{\sigma_F}, & o, &= (8/15)\, c\sigma_F, \\
b &= (3/2)\frac{\sigma_1}{\sigma_F}(\sigma_2 - \sigma_{3/2}), & \sigma_2 &= (2/3)\left(b + \frac{a}{2}\right)\sigma_F, \\
c &= (15/8)\frac{\sigma_1}{\sigma_F}, & \sigma_3 &= (2/3)\, a\sigma_F .
\end{aligned} \tag{8}$$

The number of fissions observed experimentally per unit solid angle is proportional to the angular distribution

$$N(\theta) = K\omega(\theta) = Ka + Kb \sin^2 0 + Kc \sin^2 28.$$

Fitting the experimental points to this expression by the least squares method, one gets Ka, Kb, Kc.

The value of K is obtained by

$$\int_0^{\pi/2} N(\theta) \sin 8 \, d\theta = K \int_0^{\pi/2} \omega(\theta) \sin 6 \, d\theta = K,$$

where

$$\int_0^{\pi/2} \omega(\theta) \sin \theta d\theta = a + (2/3)\, b + (8/15)\, c = 1,$$

which is the normalization condition (5).

3. Description of the Experiment

The gamma radiation employed (5.43 MeV) is produced in a sulphur target placed near the IEAR-1 reactor core operating at 2 Mw (Fig. 2).

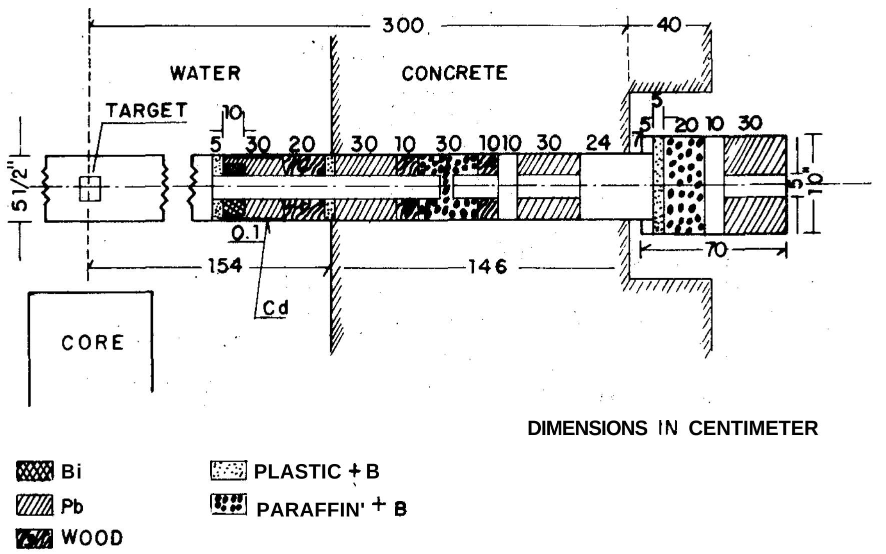

Fig. 2 · Experimental arrangement for y-radiation production.

The angular distribution is measured in a vacuum chamber covered internally with cadmium. Inside the chamber there is a cylindrical aluminum tube 7.6 cm in diameter and 9.0 cm in height. In the median plane of the cylinder there are 16 holes, 1 cm in diameter; the angle between two radial consecutive holes is 22.5".

The detectors are mounted in the outer part of this cylinder as can be seen in Fig. 3. The uranium target was a metalic cylinder 4 mm in diameter and 1 cm in height. As the average range of'the fission fragments is around 12 mg/cm^2 and the effective target mass is around 120 mg of uranium, the escape probability for the fission fragments is the same in all directions.

The detectors employed were fairly regular glass plates of 1.5 x 2.0 cm^2.

In order do distinguish the natural glass defects which can simulate fission tracks, all the glass plates are etched in a 6% HF solution for 50 minutes before irradiation. This etching condition has been determined experimentally[10]

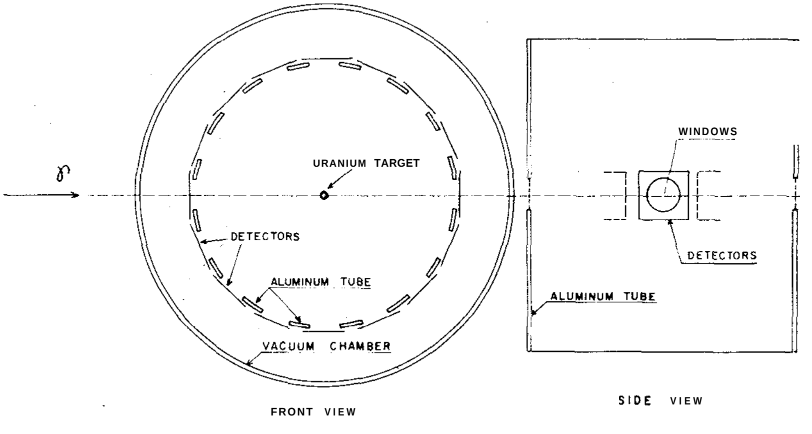

Fig. 3 - Views of the angular distribution experimental arrangement.

During the irradiation the fission fragments produce holes of a few microns in depth and $\sim$ 10Å in diameter. The glass is again etched in the fluoridric acid for 30 min and this process increases the magnitude of the holes thus permiting their identification in an optical microscope. The size of the glass defects increases again with this new chemical attack so there is no danger in confusing them with real fission tracks.

4. Experimental Results

The results obtained are the following:

θ^0	n.^{0} of tracks (average)
0 $\pm$ 7.5	2.0 $\pm$ 0.5
22.5 $\pm$ 7.5	2.5 $\pm$ 1.0
45.0 $\pm$ 7.5	4.7 $\pm$ 1.2
67.5 $\pm$ 7.5	6.0 $\pm$ 0.6
90.0 $\pm$ 7.5	5.5 $\pm$ 1i5

Fitting a second degree polynominal expression to the experimental points, the angular distribution coefficients obtained are the following:

$$a = 0.3 \pm 0.2,$$
$$b = 0.8 \pm 0.2,$$
$$c = 0.2 \pm 0.1.$$

These coefficients include the contribution of the 7.78 MeV and 8.64 MeV secondary gamma lines from the sulphur target. Although these lines have a small intensity, the cross sections at these energies are sufficiently high (9.8 $\pm$ 0.3 and 25.7 $\pm$ 0.4 mbam respectively) to make their contribution non negligible.

Taking the angular distribution coefficients at 7.78 MeV and 8.64 MeV from Rabotnov[1] and correcting for the normalization used in this paper, we obtained the following angular distribution coefficients for 5.43 MeV:

$$a = 0.03 \pm 0.59,$$
$$b = 1.2 \pm 0.7,$$
$$c = 0.6 \pm 0.3.$$

In Fig. 4, curve n.^{0} 1 is the second degree polynomial fitted to the experimental points, curve n.^{0} 2 is the normalized angular distribution for 5.43 MeV and curve n.^{0} 3 is the normalized angular distribution obtained experimentally (without corrections).

5. Analysis and Discussions

The results obtained in this paper are compared with results of other authars in terms of b/a and c/b ratios. The ratios are independent of the

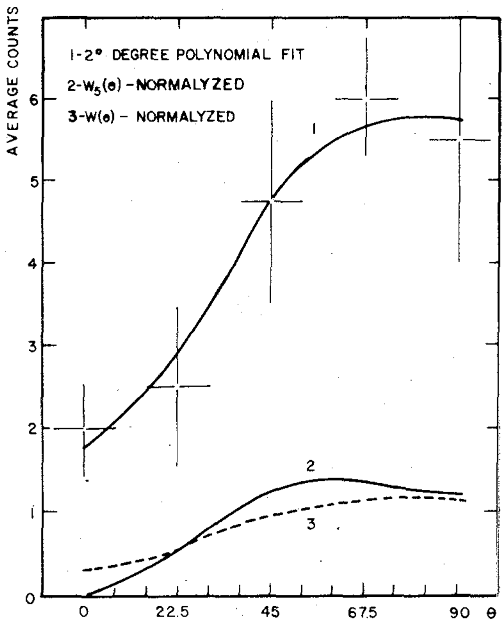

Fig. 4 - Experimental results before and after normalyzation.

normalization factor used and can be given in terms of the cross sections for the difkrent fission channels as

$$\frac{b}{a} \sim \frac{\sigma(1^-,0)}{\sigma(1^-,1)} - 1/2,$$

$$\frac{c}{b} \sim \frac{5}{4}\,\frac{\sigma(2^+,0)}{\sigma(1^-,0) - 0.5\sigma(1^-,1)}$$

This kind of analysis indicates directly the fission channels.

The peaks in the b/a curve corresponds to the (1-,O) levels. Comparing the results from several authors in the 5.0 to 8.0 MeV interval (Fig. 5), one can see that the experimental points obtained by Knowles[2] have two defini-te peaks at 6.0 and 6.9 MeV. Data from Manfredini[3] and Dowdy[5] show a displacement in magnitude relative to the Knowles' data but agree generally with his results. The Rabotnov' data do not agree with the others above 6 MeV. Nevertheless, below this energy all the curves present the same tendency of showing a very well defined maximum around 5 MeV. The data obtained in the present paper using monochromatic photons agree with the data of Rabotnov in magnitude. Consequently,

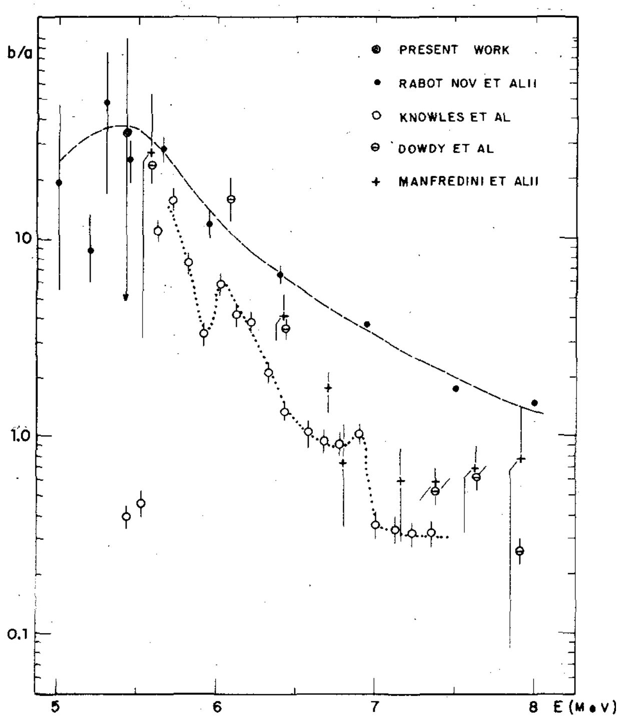

Fig. 5 - The ratio b/a, normalized, obtained from the $\sigma_i(E)$ curves as a function of the γ energy (E, MeV).

in addition to the two $(1^-, 0)$ levels in 6.0 and 6.9 MeV we can associate a level $(1^-, 0)$ to the peak in 5.43 MeV.

To verify the presence of the $(2^+, 0)$ channel, the behaviour of the c/b curve has to be analysed. Fig. 6 shows the c/b data from several authors. The experimental points do not agree even when the experimental errors are taken into account, but the behaviour is more or less the same. So there is a peak around 7 MeV and a tendence to a maximum near 5.5 MeV. Nevertheless, only the curve obtained by Rabotnov is extended to 5 MeV and presents a peak at this energy. Our data agree with a high value of c/b near 5 MeV, so it is possible to associate a $(2^+, 0)$ channel to this peak.

The peak around 7 MeV could be produced by a resonance of the $(1^-, 0)$ level giving a minimum around 6 MeV but the fact that Rabotnov's results also present a peak at this energy could indicate the presence of a $(2^+, 0)$ level because Rabotnov's curve for b/a shows no structure in this energy interval.

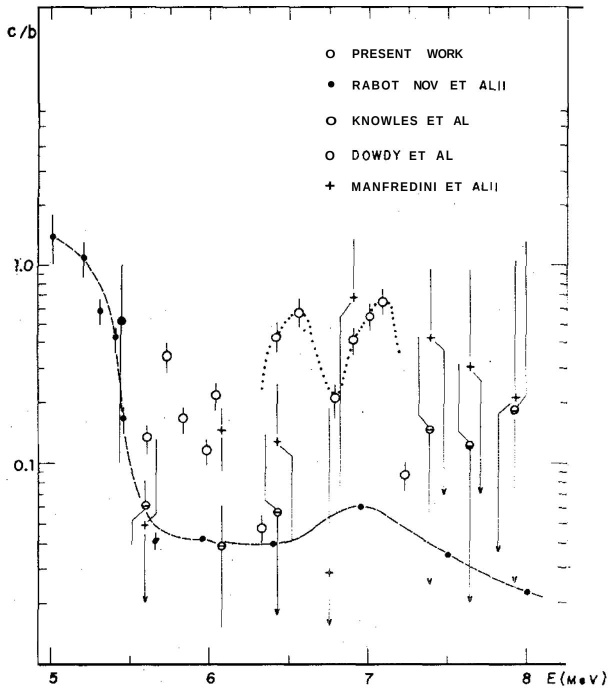

Fig. 6 - The ratio c/b, normalized, obtained from the $\sigma_i(E)$ curves as functions of the γ energy (E, MeV).

With the levels found, the energy level diagram for uranium in the 5 to 7 MeV energy interval can be organized and is shown in Fig. 7. In this figure we can also see the levels distribution proposed by Albertsson and Forkman[6] for quadrupole and octupole deformation at the saddle point.

Although the first level $(2^+, 0)$, expected for the octupole deformation, is not clearly observed experimentally, we can see in Fig. 6 a possible indication of this level even though the results are not in good agreement.

The fact that the b/c and c/b maxima coincide with the peaks of the observed cross section does not permit to conclude that the deformation potential is double humped. Nevertheless, if we admit the existence of a double humped barrier it can be said that the height of the second barrier (higher deformation) is greater or has the same height of the first one. If the opposite occurs, the nucleus going through the first barrier during the deformation would arrive at the second barrier with a greater excita-

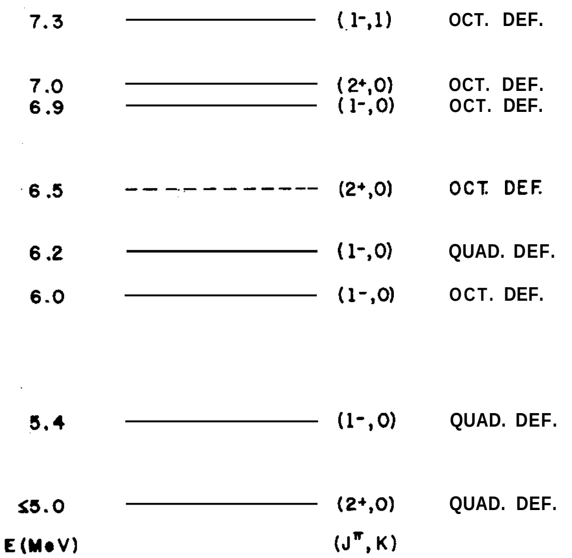

Fig. 7 - Energy level diagram for ^{238}U in the 5 to 7 MeV energy interval.

tion energy. This implies in several outgoing channels each one with a characteristic angular distribution. Consequently, one would expect an anisotropic angular distribution which definitely is not in agreement with the experimental results shown by this paper.

The authors would like to thank Prof. A. F. R. de Toledo Piza and Dr. F. A. B. Coutinho for valuable discussions.

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