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Fission of ^{27}Al Nucleus by 69-MeV Monochromatic Photons

by

O.A.P. Tavares, J.B. Martins,
E.L. Moreira, M.L. Terranova,
M. Capogni, L. Casano, A. D'Angelo,
D. Moricciani, C. Schaerf, B. Girolami,
F. Ghio and D. Babusci

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ABSTRACT - Monochromatic photon beams have been used to investigate the photofission of ^{27}Al at 69 MeV with plastic nuclear-track detectors. The measured fissility was found $(5.7\pm1.1)\times10^{-2}$. This result, along with the available data for ^{154}Sm and ^{174}Yb nuclei taken at the same energy, have been interpreted within the framework of a two-step model for the photofission reaction. According to this model the incoming photon is considered to be absorbed by a neutron-proton pair, and then followed by an evaporation-fission competition for the excited residual nucleus. The measured fissility values are seen in satisfactory agreement with the calculated ones, and the predictions from the model are confirmed, specially in the region of light fissioning systems.

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Key-words: Fission reactions; Photofission; Monochromatic photons; Plastic detectors; Nuclear photoabsorption; Fission-evaporation competition.

I. INTRODUCTION

The calculation by Myers and Swiatecki [1] of the height of the fission barrier of nuclei throughout the Periodic Table based on the Liquid Drop Model has shown a smooth trend which exhibits a maximum of ~ 55 MeV in the mass region $60 \lesssim A \lesssim 120$ (about the nickel-tin region). Structures have been evidenced when shell effects have been taken into account in these calculations, and nuclei with neutron number $N \approx 50$ (mass number $A \approx 90$) have shown the highest energy value against fission, lighter and heavier nuclei being expected to break up into two fragments of comparable masses more easily [1]. The consequent, expected variation of the nuclear fissility (ratio of fission cross section to total reaction cross section) throughout the Periodic Table was examined for the first time by Nix and Sassi [2] who considered, in an approximate way, the competition between fission and emission of neutrons and protons during the de-excitation of the excited compound nuclei. Their analysis indicated, although in a rough manner, that the fissilities of nuclei lighter than silver ($Z^2/A \approx 20$) should increase with decreasing Z^2/A. This predicted trend of fissility was experimentally verified later on by Methasiri and Johansson [3], who used intermediate-energy bremsstrahlung to induce fission in a number of medium-weight target elements. Other data obtained in this line [4-10] have confirmed the predictions by Nix and Sassi [2], although results of two experiments (one on fission induced by 167-MeV alpha particles [11], and another one by 1-GeV protons [12]) did not show such an increase of fissility with decreasing Z^2/A from about 20. Most of the experiments referred above have been performed using the track-etch technique with dielectric solid-state materials (glass, mica, and plastics) as fission fragment detectors, the exceptions being those reported in Refs. [5,12] (coincidence with silicon detectors and parallel plate avalanche counters) and Ref. [10] (nuclear-track emulsion technique).

Subsequent detailed analyses by Iljinov et al. [13] on the dependence of the fissility on parameter Z^2/A of nuclei from the actinides down to about zinc ($Z^2/A = 13.5$) by using Monte Carlo calculations, and based on the cascade-evaporation model of nuclear reactions and the liquid-drop model of fission, have again indicated a clear trend of increasing fissility with decreasing Z^2/A for nuclei lighter than silver. The authors [13] have examined in some details, also showing comparisons with experimental data, fission reactions induced by protons, alpha particles and photons of energies less than 1 GeV and incident stopped π^- mesons. These results have motivated researchers to obtain new experimental fissility data, mainly for the lightest elements of the aluminium-cobalt region, such as was done in Ref. [9], where the results have confirmed the theoretical predictions.

During the last thirty years or so, important investigations have produced, although in a fragmentary way, a number of fission data involving light systems with $A \lesssim 30$. These data have been obtained from excited states of the break-up system identified in inelastic-scattering experiments [14-19] and in resonant elastic scattering [20], electrofission[21-23], photofission [24], and alpha-particle-induced fission [25] experiments. The yield for the break-up channel of these light fissioning systems results to be very low (tens of nb [26]), and the nature of the process, known as "quasi-molecular" resonance states, appears to be entirely different in character from the process governing the fission of more complex systems, suggesting the existence of highly clustered states of the fissioning system (see, for instance, Ref. [21]). The prominent resonance states have been observed in the range 20-30 MeV of excitation energy for these light systems.

The present work was motivated by both the theoretical and experimental results summarized above. It originated in an attempt to measure the fission cross section (and, hence, the fissility) of ^{27}Al nucleus using the monochromatic and polarized incident photon beam of mean energy of 69 MeV produced at the LADON facility of the Frascati National Laboratories (Frascati, Italy), and dielectric plastic materials (CR-39 polymer and makrofol polycarbonate) as fission-track detectors. The present work is also part of a systematic experimental investigation on photofission reactions of complex nuclei in the quasi-deuteron energy-range of photonuclear absorption [27-31]. The previous results have been successfully interpreted on the basis of a model in which the incoming photon has been assumed to be absorbed by a neutron-proton pair, followed by a mechanism of evaporation-fission competition for the excited residual nucleus [32]. This approach seems to be still valid in interpreting the measured fissility value for aluminium and other intermediate-mass nuclei, as we shall see in the next paragraphs.

II. EXPERIMENTAL

The experiment consisted in exposing stacks of aluminium foils in close contact with plastic track detectors perpendicularly to the monochromatic and polarized incident photon beams of maximum photon energy of 78.8 MeV produced from the scattering of a laser light by the high-energy electrons circulating in the storage ring ADONE [33]. Some experimental details are listed in Table I. The integral photon doses were measured by a large NaI(Tl) crystal detector, and the energy spectra were continuously monitored by a magnetic pair spectrometer. The spectra did not show significant deviations from the mean energy profile (Fig. 1). Since the expected mean characteristics of the fission-like fragments from aluminium are $\overline{Z}$=7, $\overline{A}$=13, full kinetic energy $\overline{T}$=4.7 MeV, and $\overline{T}/\overline{A}$=0.36 MeV/u, the current range-energy and energy-loss-rate tables indicate for such fragments an ionization rate $-dE/dx \le 1.2$ MeV/μm, and a residual range $R \le 6$μm in the plastic detectors used in the experiment.

Therefore, it became necessary to search the best conditions of track revelation in order to correlate as well as possible the physical parameters of the fragments with their track-etch images seen under the given optics. A number of preliminary etching trials were carried out after the exposure of CR-39 plates and makrofol sheets in 2π-geometry to fission fragments and alpha particles from a laboratory ^{252}Cf source. In some cases a 15 µm-thick makrofol was used to reduce the kinetic energy of the fission fragments in order to obtain fragment ionization rates not greater than ~ 1.2 MeV/µm. In this way, the geometrical aspect of the etched tracks is seen by conventional optical microscopy as a cone-shaped track, the etch pit opening (track-diameter) being the quantity used in track analysis. The most appropriate etching procedures to track analysis in the main experiment are those reported in Table I. Under these etching conditions the maximum mean track-diameter of fission fragments of aluminium should be expected as 5-6 µm for CR-39 with 5 h etching, 11-12 µm for CR-39 with 16.5h etching, and ~ 4 µm for makrofol track-detector with 1.5h etching. Track counting and track diameter measurements in the main experiment were done by two observers, and then checked by a third one. The true number of fission tracks was estimated from the mapping of the recorded events, the application of the statistical method of double scan (counting efficiency), the analysis of the track-diameter distributions and background subtraction. Besides, to obtain the final values of the physical quantities of interest and associated errors, the data have been treated taking into account the appropriate corrections coming from energy-absorption effects of fragments by the target material itself (thick-target geometry). This was done by the method described in detail in Ref.[34]. The final values so obtained for the aluminium photofission yield, as well as the various quantities necessary to determine the yield, are reported in Table II. The efficiency-values reported in column five represent the total, combined efficiency of the detection system, i.e., etching efficiency multiplied by observation (track identification) efficiency, averaged over the values deduced for each detector analysed under given optics. The derivation of the total efficiency, as well as the "effective" thickness of the target material (2nd column in Table II), takes into account i) the average residual range of full energy of the median fission fragment in both the target and detector materials ; ii) the thickness of the surface layer of detector material removed by etching ; iii) the minimal etch pit opening capable of being observed under given optics. All these quantities have been handled appropriately to obtain the values for total efficiency. The details of the method can be found in Ref.[34].

In the exposure in which CR-39 was used as detector, it was not possible, unfortunately, to identify any event ascribable to fission of aluminium with a reasonable degree of confidence. The high sensitivity of the CR-39 polymer to registration of charged particles of low ionization rate, together with a high population of tracks which resulted from defects of the detector itself, produced such a level of background that it was not possible to identify the fission signal. In addition, in this attempt to detect the fission of aluminium, the integral photon dose available was four times smaller than that used in the exposure with makrofol (Table II). Therefore, under the conditions reported, only an upper limit for the fission yield could be extracted from the data collected with the CR-39 detector. This problem was overcome with the use of makrofol detector which is known to be insensitive to registration of both charged particles and nuclear recoils of very low ionization rate expected from the interaction of 69-MeV photons with the constituents C, H, O of the plastic material [28,29].

III. RESULTS AND DISCUSSION

The measured photofission yield, $Y(k_{max})$, was converted into absolute photofission cross section, σ_f, by summing the contributions to fission events due to all photons of energy between the photofission threshold, k_{th}, and the end-point energy, k_{max}, in the energy spectrum of the incident photons. Since the peak shape pf the spectra is reasonably narrow (Fig.1) it follows that

$$\sigma_f(\overline{k}_{eff}) = \frac{Y(k_{max})}{\int_{k_{th}}^{k_{max}} n(k,k_{max})\,dk} , \qquad (1)$$

where $n(k,k_{max})dk$ represents the fraction of photons in the energy interval dk, and $\overline{k}_{eff}$ is the effective mean energy of the photon spectrum calculated in the range k_{th}-k_{max}. The photofission threshold was evaluated from the average total kinetic energy released in fission, and from the Q-value for the nearly symmetric break-up of the fissioning system after absorption of the incoming photon by the aluminium target nucleus, $k_{th} = \langle E_k^t \rangle - Q$, where Q is a negative quantity. The $\langle E_k^t \rangle$ value was calculated from the systematics reported in

Ref.[35]. In this way, it was found $k_{th} \approx 40$ MeV, $\bar{k}_{eff} \sim 69$ MeV, and $\sigma_f(\bar{k}_{eff}) \approx 1.1Y(k_{max})$, which shows that under the present experimental conditions the absolute photofission cross section does not differ practically from the reaction yield.

Finally, the fissility-value for aluminium at 69 MeV was obtained by calculating the ratio $f = \sigma_f/\sigma_a^T$, where the total nuclear photoabsorption cross section, σ_a^T, was evaluated by using Levinger's modified quasi-deuteron model [36]

$$\sigma_a^T = L \frac{NZ}{A} \sigma_d(k) \ e^{-D/k} \quad , \qquad (2)$$

where $\sigma_d(k)$ is the total photodisintegration cross section of the free deuteron measured at k = 69 MeV [37] and L and D are, respectively, the so-called "Levinger's" and "damping" parameters, the values of which are calculated from the expressions $L = 6.8 - 11.2 \ A^{-2/3} + 5.7 \ A^{-4/3}$ and $D = 0.72 \ A^{0.81}$ MeV. These come from the recent analysis by Terranova et al.[38] of the total nuclear photoabsorption cross section data taken in the quasi-deuteron energy region, and the study of the photoabsorption mechanism by Tavares and Terranova [39]. The uncertainties associated with σ_a^T-values have been estimated from typical deviations of Eq.(2) from the measured total photoabsorption cross sections. At photon energies in the range 60-80 MeV these uncertainties amount, on the average, to 20% for ^{27}Al, and 11% for the lanthanides.

Values of σ_a^T and the measured ones for σ_f and f at 69 MeV are reported in Table III for ^{27}Al nucleus (this work) as well as for ^{154}Sm and ^{174}Yb nuclei taken from the paper by Moretto et al.

[40]. All these data have been interpreted on the basis of a simplified description for the photofission reaction as discussed below.

The photofission reactions in the quasi-deuteron energy region (~ 30-140 MeV) have been currently described with a two-step model, according to which the reaction begins with the primary photointeraction taking place with a neutron-proton pair thus leading to an excited residual nucleus, followed by a mechanism of de-excitation in which fission and emission of neutrons and protons compete. The details of the model have been reported in Ref.[32], from which has been deduced the following general formula to calculate the nuclear fissility:

$$f(k) = \frac{\int_{E_F^n}^{k+(1/5)[3E_F^n-2E_F^p]} \sum_{i=1}^{4} p_i P_f(E_i^*)\, dT_{n^*}}{[k - \frac{2}{5}(E_F^n+E_F^p)]} \qquad (3)$$

Here, $k = \bar{k}_{eff}$ = 69 MeV is the incident photon energy, E_F^n =28.8 MeV is the Fermi energy for neutrons in ^{27}Al, E_F^p =27.4 MeV is that for protons, p represents the probability of formation of a residual nucleus at an excitation energy E^*, and $P_f(E^*)$ is the total fission probability for this residual. Both p and E^*, and so P_f, are functions of T_n^*, the neutron kinetic energy inside the nucleus after the primary quasi-deuteron photoreaction. The subscript i refers to the four different modes of formation of residual nuclei at the end of the first, rapid stage of the reaction; for the present case of ^{27}Al target these are ^{25}Mg (i=1), ^{26}Al (i=2), ^{26}Mg (i=3), and ^{27}Al (i=4). The p-values are obtained from the calculated nuclear transparencies of ^{27}Al to neutron (τ_n) and proton (τ_p) through the relationships $p_1=\tau_n\tau_p$, $p_2=\tau_n(1-\tau_p)$, $p_3=\tau_p(1-\tau_n)$, and $p_4=(1-\tau_n)(1-\tau_p)$ (see [32]). For the three first residuals, calculations have indicated either $P_f \ll 1$ or $P_f = 0$ (for a range of values of T_n^*, p=0 also). The product pP_f results thus either negligible or null, in such a way that the referred residual nuclei do not contribute to fission.

Therefore, for the particular case of 69-MeV photons interacting with ^{27}Al target, we have

$$f = \frac{1}{46.5}\int_{28.8}^{75.3} p_4 P_f^t(69)\,dT_{n^*} = \overline{p}_4 \times P_f^t(69) = 0.458\times P_f^t(69) \quad (4)$$

(energy-values in MeV), where $\overline{p}_4$ denotes the probability of formation of ^{27}Al residual averaged over the energy-interval allowed for T_n^*, and $P_f^t(69)$ denotes the total fission probability for the residual excited to 69 MeV. This latter quantity should include all the successive chance-fission probabilities, i.e., $P_f^t = P_{f_1} + P_{n_1} P_{n_f} + P_{p_1} P_{p_f} + \ldots$ where subscript 1 indicates the first chance probability for fission, neutron emission and proton emission, P_{n_f} denotes the fission probability after emission of the first neutron, and so forth. However, since the emission of a nucleon causes, on the average, an excitation energy decrease of ~ 20 MeV, and in view of the relatively high values of the fission barrier for the new residuals, (about 40 MeV according to [1]), it follows that not all the subsequent chance-fission probabilities contribute significantly to the total fission probability, and thus

$$f(^{27}Al,69MeV) = 0.458\times P_{f_1}(^{27}Al,69MeV) \quad . \qquad (5)$$

In order to calculate P_{f_1} by means of the general, usual expressions from the statistical fission-evaporation model as reported in [32], it was necessary to decide how to evaluate the chief quantities a_n (level density parameter of the residual nucleus after neutron evaporation) and $r = a_f/a_n$ (ratio of the level-density parameter at the fission saddle point to a_n). We chose to calculate the a_n values by the expression

$$a_n = \left[\alpha A+\beta A^{2/3}b_s\right]\cdot\left\{1+\left[1-\exp[-\gamma(E^*-\Delta)]\right]\frac{\Delta M}{(E^*-\Delta)}\right\} \quad MeV^{-1} \;, \qquad (6)$$

recently proposed by Iljinov et al.[41] on the basis of a statistical analysis of level densities of several hundreds excited nuclides. In Eq.(6) A is the mass number, $\Delta = 12\,\chi/A^{1/2}$ MeV is the pairing energy ($\chi = 0$, 1, or 2, respectively, for odd-odd, odd-even, or even-even nuclei), ΔM is the shell correction in the calculated nuclear mass, E^* is the excitation energy, $b_s \approx 1$, and $\alpha = 0.114$, $\beta = 0.098$, and $\gamma = 0.051$ are adjustable parameters resulting from the phenomenological level-density systematics without collective effects considered (for details see [41]). Finally, since there not exist in the literature indications about the values of the ratio a_f/a_n for reactions like the one studied in the present work, we determined a_f/a_n in a semiempirical way by assuming the model described above and by making use of a number of available experimental data on fission probability for intermediate-mass fissioning systems in the range $6 < Z^2/A < 31$ obtained in the excitation energy range 65-110 MeV [5,40,42-44].The present measurement for ^{27}Al was also included. The a_f/a_n data, presented in Fig.2, have been treated by a least-squares procedure obtaining the trend defined by

$$a_f/a_n = 0.750[1+0.2139(35.54-Z^2/A)^{1/2}] \quad , \quad 6 < Z^2/A < 31 \ , \quad (7)$$

with $\chi_\nu^2 = 6.25$. Apart from uncertainties coming from the experimental data, fluctuations due to single particle effects should also be expected, mainly in the region of low Z^2/A. However, to a first approximation, we assume the trend given by Eq.(7) as a good estimate for the ratio a_f/a_n to be used in fission analyses of intermediate-mass nuclear systems at moderate excitation energies.

Fissility values calculated by the method described above are reported in Table III (last column), where a quite satisfactory agreement with the experimental results is noted for ^{154}Sm and ^{174}Yb. In the case of ^{27}Al a factor of ~ 2 is found when comparing the calculated fissility value with the measured one (makrofol detector). The origin of such a (not large) discrepancy is not easy to identify. However, this factor certainly does not mean an incompatibility between the model and the experiment, since possible large uncertainties associated mainly with the calculated fissility may exist. The order of magnitude of the results is fairly well reproduced.

Another important information provided by the model described in the present work can be appreciated in Fig.3, where the calculated fissility for incident photons of 69 MeV is plotted against the parameter Z^2/A of nuclei extending from aluminium to iridium along the beta-stability valley. It is seen that fissility varies by ten orders of magnitude. Besides, structures due mainly to shell effects are clearly reproduced on the exact positions where they occur in the fission barrier curve (see inset graph). Also shown are the experimental points for ^{27}Al, ^{154}Sm, and ^{174}Yb nuclei to allow a direct comparison. The region of nuclei above iridium, where the double-magic ^{208}Pb is located, was not included. This region has been studied in detail in our previous papers [29,30] which evidenced the existence of shell effects in low-energy photofission in the vicinity of the Z = 82, N = 126 shell closures. In Fig.3, the trend exhibited by fissility is essentially an inverse reflection of that exhibited by the fission barrier, with the few available experimental points fairly well fitted to it. This result supports the adequacy of a quasi-deuteron primary interaction followed by the fission-evaporation competition mechanism in explaining the photofissility data obtained in the present work for ^{27}Al, as well as for ^{154}Sm and ^{174}Yb from the work by Moretto et al. [40].

IV. CONCLUSIONS

The fission induced in ^{27}Al by monochromatic photons of mean enery 69 MeV has been successfully studied by employing dielectric plastic materials as fission-track detectors.

It is to be noted that the present paper reports the first experimental determination of photofission cross section for the ^{27}Al target necleus in the quasi-deuteron region of energy.

The value of $(5.7 \pm 1.6)\cdot 10^{-2}$ determined for the fissility of ^{27}Al seems to confirm, once again, the predictions from the fission-evaporation competition mechanism of nuclear reactions and from the Liquid Drop Model of fission, indicating an increase of nuclear fissility with decreasing Z^2/A for fissioning systems lighter than about silver. The finding of the research work here presented should stimulate further experimental and theoretical studies on fission reactions induced by low- and intermediate-energy photons as incident particles.

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FIGURE CAPTIONS

FIG. 1. Sample spectra (normalized to one photon) of the LADON photon beam obtained by a magnetic pair spectrometer for an end-point energy k_{max} = 78.8 MeV. Case 1 (effective photon mean energy $\bar{k}_{eff}$= 70 MeV) refers to the exposure in which CR-39 plates were used as track detector; case 2 ($\bar{k}_{eff}$= = 68 MeV) was for makrofol detector.

FIG. 2. The ratio $r = a_f/a_n$ of the level density parameter at the fission saddle point to that of the residual nucleus after neutron evaporation is plotted against parameter Z^2/A of the fissioning system. Points represent a semiempirical determination of r-values by assuming the fission-evaporation competition model described in the text and by making use of available data on fission probability from low-energy induced fission experiments ($65 < E^*(\mathrm{MeV}) < 110$): ● , $^{185}Re(p,f)$, $^{184}W(^3He,f)$, $^{184}W(^4He,f)$, $^{177}Hf(^3He,f)$, $^{177}Hf(^4He,f)$, $^{178}Hf(^3He,f)$, $^{180}Hf(^3He,f)$, $^{175}Lu(^4He,f)$, $^{169}Tm(^4He,f)$, $^{167}Er(^3He,f)$, and $^{170}Er(^3He,f)$ of Ref. [42]; ■ , $^{187}Re(^4He,f)$, $^{175}Lu(^4He,f)$, and $^{169}Tm(^4He,f)$ taken from the compilation of Ref. [43]; ▲ , $^{174}Yb(\gamma,f)$ and $^{154}Sm(\gamma,f)$ of Ref. [40]; ▼ , $^{108}Ag(^{14}N,f)$, $^{96}Mo(^{14}N,f)$, $^{79}Se(^{14}N,f)$, and $^{59}Ni(^{14}N,f)$ of Ref. [5]; □ , $^{40}Ca(^{12}C,f)$ of Ref. [44]; ○ , $^{27}Al(\gamma,f)$ of this work. The curve is the trend obtained by least-squares fitting of the points (Eq. (7)).

FIG. 3. Nuclear fissility plotted against parameter Z^2/A for incident photon energy (excitation energy) of 69 MeV. The broken line connects calculated values for nuclei ranging from aluminium up to iridium along the beta-stability valley; structures due mainly to shell effects are indicated, and the trend of fissility is seen as an inverse reflection of the behavior of the height of the fission barrier (see inserted graph). Experimental points are those reported in Table III: ○ , ^{154}Sm and ^{174}Yb of Ref. [40]; ● , ^{27}Al of this work.

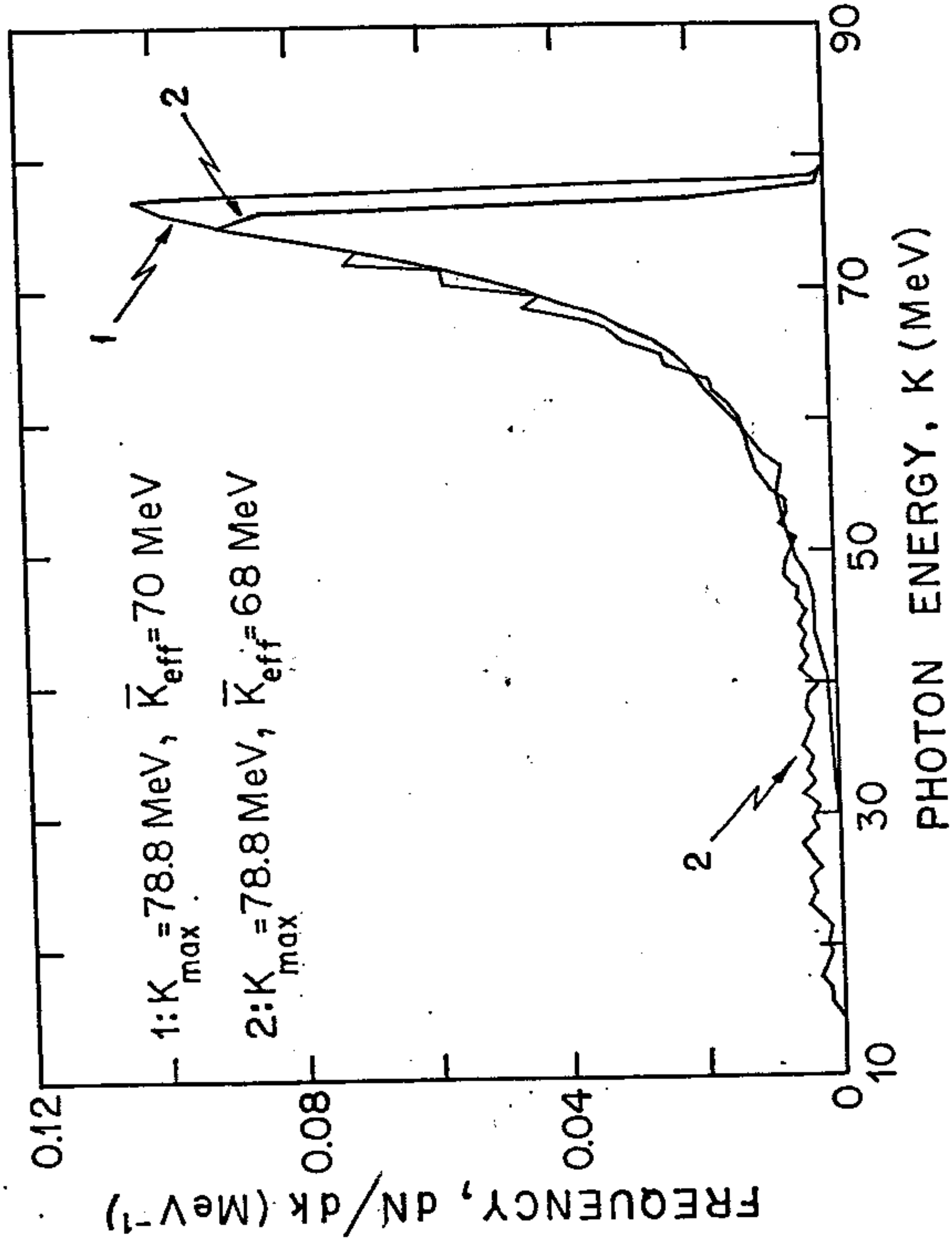

1: K_{max}=78.8 MeV, $\overline{K}_{eff}$=70 MeV
2: K_{max}=78.8 MeV, $\overline{K}_{eff}$=68 MeV
1
2
2
0.12
0.08
0.04
0
10
30
50
70
90
PHOTON ENERGY, K (MeV)
FREQUENCY, dN/dk (MeV^{-1})

Figure 1

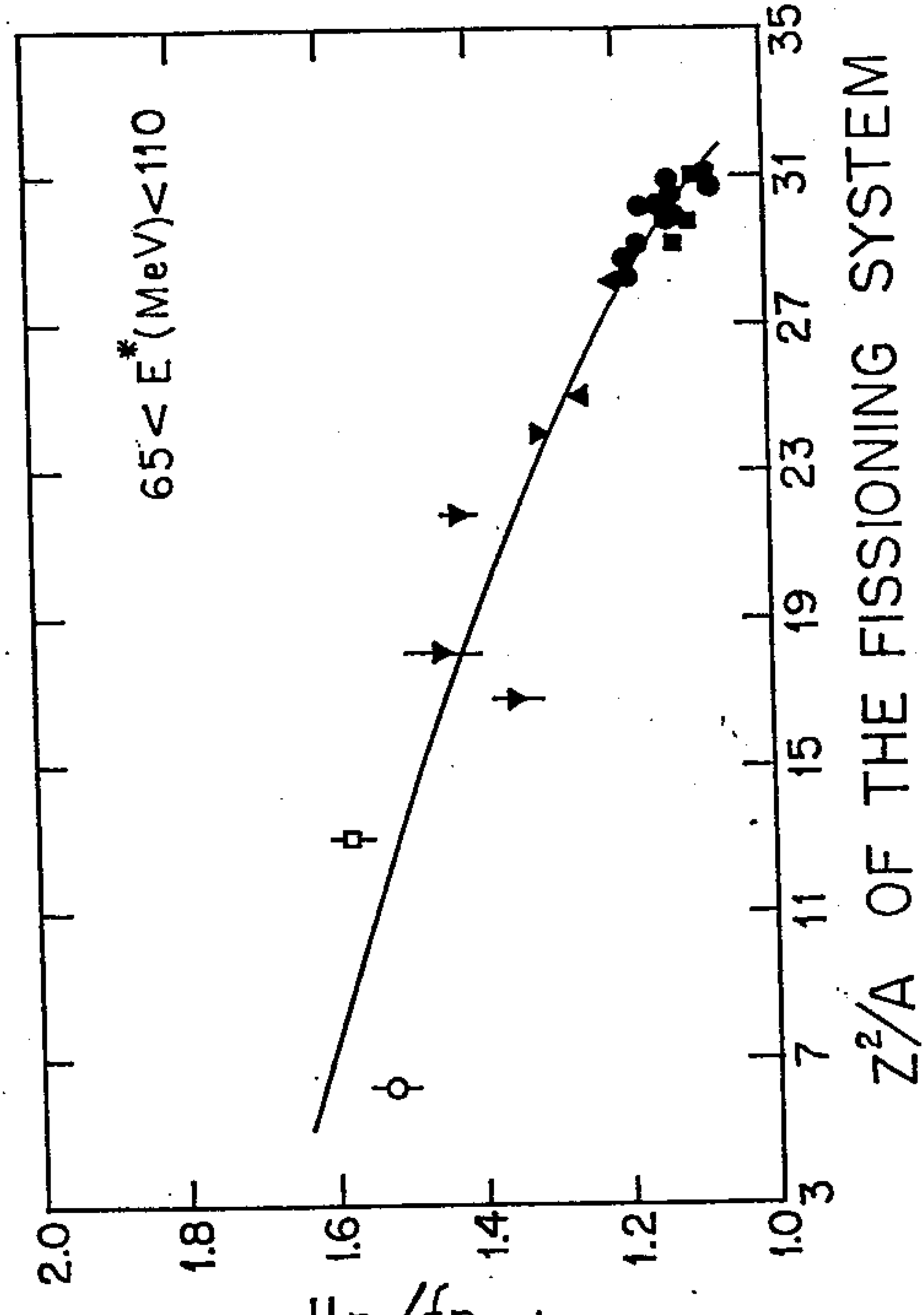
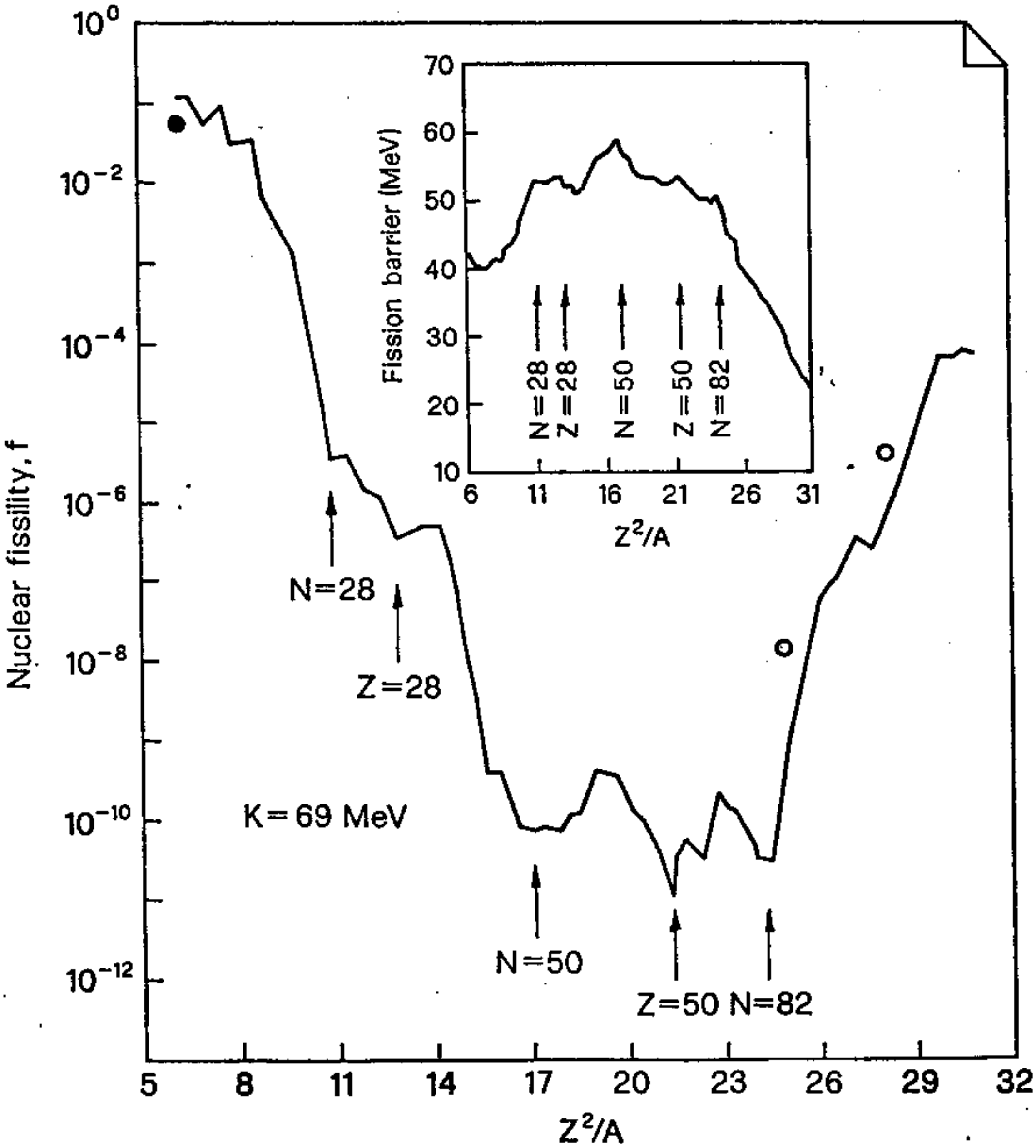

65 < E*(MeV) < 110
Z²/A OF THE FISSIONING SYSTEM
r = af/an
3
7
11
15
19
23
27
31
35
1.0
1.2
1.4
1.6
1.8
2.0

Figure 2



Nuclear fissility, f
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
5 8 11 14 17 20 23 26 29 32
Z^2/A
N=28
Z=28
K= 69 MeV
N=50
Z=50 N=82
Fission barrier (MeV)
70 60 50 40 30 20 10
6 11 16 21 26 31
Z^2/A
N=28
Z=28
N=50
Z=50
N=82

Figure 3

TABLE I. Data regarding the samples, exposures, etching procedures, and detector analysis of the present aluminium photofission experiments.

Exposure	Sample stack[a] Target	Sample stack[a] Detector	Total thickness (g/cm²)	Irradiation conditions: Effective photon mean energy[d] $\bar{k}_{eff}$ (MeV)	Irradiation conditions: Total photon dose[e] Q($10^9\gamma$)	Irradiation conditions: Beam spot at the stacks[f] ϕ(mm)	Etching conditions	Total area scanned[g] (cm²)
1º run	19 foils of 13-μm thick aluminium 4cm×4cm	20 sheets of 750-μm thick CR-39 polymer[b] 4cm×4cm	2.05	70	3.36	∼ 10	6.25-N NaOH, 60ºC 5h, gentle stirring 16.5h, no stirring	2.0cm×2.0cm over 13 detectors
2º run	36 foils of 13-μm thick aluminium 3cm×3cm	72 sheets of 100-μm thick makrofol poly carbonate[c] 3cm×3cm	1.01	68	13.8	∼ 11	6.25-N NaOH, 70ºC 1h 30min, gentle stirring	1.5cm×1.5cm over 30 detectors.

[a] Aluminium target placed in intimate contact with the detector material forming a stack.
[b] Allyl diglicol carbonate polymer supplied by "Track Analysis Systems Limited", Bristol (England), November 1989.
[c] Makrofol N (Auftrag 90002, 0.7 Kg) supplied by Bayer AG (Germany).
[d] Photon maximum energy of 78.8 MeV in all runs (see Fig. 1).
[e] Average beam intensity of $\sim 10^5 \gamma/s$.
[f] Estimated from exposure geometry.
[g] Leitz Ortholux microscopes (objective 25X and oculars 10X, 12.5X, and 25X).

TABLE II. Data regarding the determination of the photofission yield.

Detector	Effective total number of target nuclei $N_{\dot{a}}$ $(10^{20}cm^{-2})$[a]	Number of incident photons $Q(10^9\gamma)$	Number of photon-induced fission tracks N[b]	Mean total efficiency $\bar{\epsilon}$ (%)	Photofission yield Y (mb)[c]
CR-39	0.76±0.09	3.36	1±18	2.6±0.5	<0.15
Makrofol	3.8±0.5	13.8	137±15	14±2	0.18±0.04

[a] These correspond to 6 aluminium foils for CR-39 and 30 ones for makrofol.

[b] Corrected for counting loss and background.

[c] Statistical plus systematic errors.

TABLE III. Absolute photofission cross section and comparison between experimental and calculated fissility at 69-MeV photon mean energy.

Target nucleus	Z^2/A	Total nuclear photoabsorption cross section $\sigma_a{}^T$ (mb)	Photofission cross section σ_f (mb)	Nuclear Fissility Experimental	Nuclear Fissility Calculated[d]
^{27}Al	6.26	3.5±0.7	< 0.15[a] 0.20±0.04[b]	$< 4.3\cdot10^{-2}$ $(5.7\pm1.6)\cdot10^{-2}$	0.12±0.04
^{154}Sm	24.96	13.8±1.5	$(1.8\pm0.4)\cdot10^{-7}$[c]	$(1.3\pm0.3)\cdot10^{-8}$	$(1.8\pm1.0)\cdot10^{-8}$
^{174}Yb	28.16	14.7±1.6	$(6\pm1)\cdot10^{-5}$[c]	$(4\pm1)\cdot10^{-6}$	$(2.6\pm1.7)\cdot10^{-6}$

a CR-39 detector.
b Makrofol detector.
c Reference [40].
d Estimated uncertainties by considering the standard deviation of 0.044 for a_f/a_n from data of Fig. 2.

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