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CROSS SECTION OF TERNARY FISSION OF Al, Ti, Co, AND Zr NUCLEI INDUCED BY 0.8-1.8 GeV PHOTONS**

by

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A research on ternary fission of Al, Ti, Co, and Zr nuclei induced by bremsstrahlung photons of 0.8, 1.0, 1.4, and 1.8 GeV end-point energies has been carried out using makrofol polycarbonate and CR-39 polymer as fission-track detectors. Thick target metal foils were used in contact with the plastic detectors. From the observation and analysis of double divergent, etched fission tracks from a common point inside the target the number of events of ternary fission has been evaluated. Absolute mean cross sections per photon of ternary fission in the range 0.8-1.8 GeV have been obtained as 0.3±0.7, 1.7±1.5, 0.5±0.5, and 1±1μb, respectively, for Al, Ti, Co, and Zr nuclei. A probability of ternary fission of $\sim 10^{-4}$ has been deduced. Results are discussed and compared with other ternary fission data.

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Key-words: Ternary fission; Al, Ti, Co, Zr natural targets; 0.8-1.8 GeV bremsstrahlung; Makrofol detector; CR-39 detector; Photofission.

1. Introduction

Ternary fission, the decay process by which a nucleus breaks-up into three fragments of comparable masses, has shown to be a rare nuclear decay mode as compared with ordinary, binary fission mode. Ternary fission has been investigated mostly for medium-weight and heavy nuclei excited by high-energy protons as incident particles [1-13]. Several papers have reported ternary fission yields and/or angular, energy, and mass distributions of fragments in the bombardment of nuclei of $A \gtrsim 200$ by intermediate--energy pions and antiprotons [14,15], as well as deuteron-, alpha-particle-, nitrogen-, argon-, iron-, kripton-, and xenon--ion beams of different energies in the range 0.23-29 GeV [16-26].

Most experiments on ternary fission have been carried out by using the solid state nuclear track detection method through mica and makrofol sandwiches (see, for instance, Refs. [3,6,12-14,18,19,25]). An alternative arrangement frequently used is the 2π-forward geometry with polycarbonates, cellulose nitrates, and muscovite mica as fission-track detectors [17,21,23,24]. Uranium-loaded nuclear-track emulsion was the detection method used by de Carvalho and Schechter [7] in ternary fission experiments with high-energy incident protons. The technique known as "hole detector" in a mica surface has been introduced by Vater and Brandt [20] in a study of ternary fission of uranium induced by 414 MeV argon-ions. Fleischer et al. [16] were successful in detecting for the first time events of ternary fission by bombardment of 414-MeV argon-ions in a thorite crystal which served both as target and detector. Investigations on ternary fission of heavy nuclei induced by thermal neutrons were conducted by Muga and co-workers [27,28] who used a system of three fission--fragment detectors in coincidence. Also, radiochemical methods were used in many experiments to show the existence of ternary fission as, for instance, the results by Iyer and Cobble [29] when ^{238}U was bombarded with 39-MeV alpha-particle beams.

From the theoretical point of view, Muzychka et al. [30] have considered the "cascade fission" as a possible mechanism for ternary fission, and Diehl and Greiner [31] developed a direct ternary fission model (an extension of the liquid drop model) according to which the nucleus can undergo prolate and oblate ternary fission. A review to early works with detailed discussions on both experimental methods and theoretical aspects on this subject can be found in Ref. [32].

Only a few works, however, have been carried out on ternary fission of nuclei induced by photons as incident particles. Medveczky et al. [33] and Medveczky and Somogyi [34] published in 1970 the results of their investigations on ternary photofission of ^{232}Th, ^{238}U, and ^{239}Pu induced by 27.5-MeV bremsstrahlung. The events were detected by using sandwiches made of solid state nuclear track detectors of different sensitivity (plastics and mica) so making it possible to distinguish between symmetrical and asymmetrical ternary fission events. More recently, Pinheiro Filho [35] reported the observation of ternary fission events recorded on nuclear-track emulsion plates which had been exposed to bremsstrahlung of maximum energies in the range 1-6 GeV. It was shown that these events were produced by the interaction of high-energy incoming photons with Ag and Br nuclei of the emulsion.

The scope of the present work is to contribute to new data by investigating the ternary fission of Al, Ti, Co, and Zr nuclei induced by 0.8-1.8 GeV bremsstrahlung photons. The experiment, which involved thick metal foils of these elements in a 2π-forward geometry with CR-39 and makrofol track detectors, has given, among other etched tracks, double divergent tracks from a point inside the target materials. These events may be related to the occurrence of ternary fission. Based on the fission mechanism and track registration properties of the detectors used, the methods to ascertain and to discriminate ternary fission events against other types of events have been established, thus making it possible to evaluate the ternary fission cross sections and fissilities. The present work reports part of the results of a systematic research on fission of light- and medium-weight nuclei induced by intermediate-energy photons. Results of the binary fission studies have been reported elsewhere [36-39].

2. Experimental Procedure

The experiment consisted firstly of stacking thick metal foils of aluminum and titanium target elements, each facing a plate of $\sim$ 1 mm thick CR-39 polymer* track detector (2π-forward geometry) and, similarly, cobalt and zirconium target elements placed in contact with sheets of 100 μm thick makrofol polycarbonate† track detectors. The stacks were exposed perpendicularly to high-intensity bremsstrahlung beams of 0.8, 1.0, 1.4, and

*Allyl diglicol carbonate polymer by American Acrylics & Plastics, Inc. (Stratford, Conn., USA).
†Makrofol N, Auftrag 90002 (0.7 Kg) by Bayer AG (Germany).

1.8 GeV end-point energies at the Bonn 2.5-GeV Elektronen Synchrotron with typical photon doses in the range 10^{12}-10^{13} equivalent quanta/cm^2 measured by a quantameter.

In order to make fission tracks visible for track analysis under an optical microscope the CR-39 plates were submitted later to a 6.25 N NaOH etching at 60°C during two or three periods of 1 h each without stirring. Under these conditions, a bulk etch rate v_G = 0.5±0.1 μm/h was obtained by measuring the thickness of material removed by etching with time. In the case of makrofol sheets an identical etching solution was used, this time at 70°C during three periods of 20 min each. By the same method as for CR-39 plates, a bulk etch rate v_G = 1.9±0.1 μm/h was obtained.

The scanning of the detector surfaces and the measurements of the geometrical quantities of etched tracks were carried out by using an Olympus CB213 microscope fitted out with oculars of 10X and a dry objetive of 60X magnification. Calibrated eye--pieces allowed for determination of the scanning areas and track--length measurements.

2.1. Ternary Fission Events

Under the conditions of the present experiment a large number of single tracks has been observed the origin of which is due to binary fission events, nuclear recoils, background particles, and others. The binary fission tracks were previously identified, and the number of such tracks allowed the determination of photofission cross sections already reported [36-38]. In addition, a small, but non negligible, number of double divergent fission tracks from a common point inside the target material has been also recognized in subsequent analyses of the plates. These events may be considered as strongly indicative of being due to ternary fissions and, therefore, a careful analysis of such events proceeded. The identification of ternary fission events has been done based on the simplified assumption that the excited fissioning nucleus is at rest, and that the ternary fission mode is the symmetrical one, i.e., equal masses and kinetic energies of fragments, and angles of 120^{o} between fragment trajectories which, in this case, lie on a same plane.

In order to get a ternary fission event recorded and recognized it is necessary to have two of the fragments entering the detector, and the fragment trajectory having the smallest dip angle should become visible at the microscope after etching (Fig. 1-a). This dip angle must be in the range ϕ_c-30^{o}, which results from the assumption of symmetrical nuclear break-up and the limitations imposed by the critical angle of incidence for fragment detection, ϕ_c. Besides, a minimum etched track length, C_r, is required in order to make observation of tracks possible.

The differentiation between events originated by true ternary fissions and other types of double events has been achieved by fitting the measured quantities of a two-pronged event to the following limiting criteria: i) the upper value for the angle β indicated in Fig. 1-a should be given by

$$\beta \le \arcsin(4\cos^2\phi_c - 3)^{1/2} \quad , \quad \phi_c \le 30^{o} \quad ; \qquad (1)$$

ii) the maximum distance d_0 between double, divergent etched tracks (Fig. 1-b) should be given by

$$d_0 = d - 2b \quad , \qquad (2)$$

where

$$d = 3^{1/2}\left\{a_0\left[1 - (2v_G+C_r)/R_0\right] + 2v_G t\right\} \qquad (3)$$

$$b = v_G t(1 - \sin\phi_c/\sin\phi)/\sin(\phi-\phi_c) \quad . \qquad (4)$$

Equation (4) is the one reported by Fleischer et al. [40] in their analysis of track-etch geometry applied to a track tilted at an angle ϕ measured from the detector surface, where t is the etching time. In (3), a_0 and R_0 denote the full residual ranges, respectively, in the target and detector materials of a typical nuclear fragment of a ternary fission event. Based on the cascade-evaporation model developed by Barashenkov et al. [41] to describe the interaction of intermediate-energy photons with complex nuclei it has been possible to estimate the charge, mass, and kinetic energy of typical ternary fission fragments for the target nuclei under study. Hence, from energy-loss rate curves constructed for these fragments in both target and detector materials, values of a_0 and R_0 have been evaluated. To give an example, $a_0 \approx 4.5$ μm and $R_0 \approx 7.2$ μm for the case of titanium target and CR-39 detector. The other quantities appearing in (3) and (4) resulted as $C_r \approx 0.7$ μm and $\phi_c \approx 6^{\circ}$. Finally, the location of the origin point of a double divergent event, the angle between tracks, as well as the angle between the projected tracks on the detector surface have been considered as additional parameters of identification of a true ternary fission event.

2.2. Ternary Fission Yield

The ternary fission yield, i.e., the cross section per equivalent quantum σ_Q at an end-point energy E_0, is obtained by

$$\sigma_Q = N_e/(QN_a) \quad , \tag{5}$$

where N_e is the number of true ternary fission events identified per unit area, Q is the number of equivalent photons incident on the target-detector stacks per unit area, and N_a is the "effective" number of target nuclei of the thick sample per unit area, i.e., the number of target nuclei which contribute effectively to the observed number of ternary fission events. N_a is related to the "effective thickness", x_{ef}, by

$$N_a = (\rho N_0/M)x_{ef} \quad , \tag{6}$$

where ρ is the density of the sample material (g/cm^3), N_0 is Avogadro's number, and M is the atomic weight (g). The evaluation of x_{ef} has been done based on Fig. 1-a. Accordingly, for the branch "a" (fragment trajectory with smallest dip angle) it can be shown that the target thickness x_a within which ternary fissions contribute to double divergent tracks is given by

$$x_a(\alpha,\beta) = a_0\left[(R_0-C_r)\sin\alpha\cos\beta - v_G t\right]/R_0 \quad , \tag{7}$$

while for the branch "b" (fragment trajectory with greatest dip angle) it is

$$x_b(\alpha,\beta) = a_0\left[(R_0-C_r)\sin(\pi/3-\alpha)\cos\beta - v_G t\right]/R_0 \quad . \tag{8}$$

The effective thickness is then obtained by taking the average value of x_a within the limits allowed for α and β, i.e.,

$$x_{ef} = 3/(\Delta\alpha\Delta\beta) \int_0^{\pi/2} \int_{\pi/6}^{\phi_c} x_a(\alpha,\beta)d\alpha d\beta \quad , \qquad (9)$$

where the factor 3 adds up the contributions coming from the three fragments. The evaluation of x_{ef} was considered in detail in Refs. [42,43] which the reader is referred to.

3. Results and Discussion

Table 1 summarizes the main data from which the ternary fission yields (last column) have been obtained. Errors indicated are statistical ones. It is remarked on the very low values obtained for the yield of ternary fission induced by intermediate-energy photons in Al, Ti, Co, and Zr nuclei (order of units of μb or less). It is noted that, for the etching times indicated in Table 1, the effective thicknesses obtained whenever CR-39 has been used as detector appear to be about one order of magnitude greater than the effective thicknesses obtained in the cases of makrofol detector. This result is a clear indication of the superior degree of sensitivity to track registration of CR-39 when compared with makrofol.

In bremsstrahlung-induced reactions the measured yields (σ_Q) represent the sum of the contributions to a particular type of event due to all photons of the bremsstrahlung spectrum of maximum energy E_0. This is expressed by the relationship

$$\sigma_Q(E_0) = \int_0^{E_0} \sigma(k)n(k,E_0)dk \quad , \qquad (10)$$

where $\sigma(k)$ is the cross section "per photon" at photon energy k, and $n(k,E_0)dk$ is the number of photons in the energy interval dk; $n(k,E_0)$ is the bremsstrahlung spectrum normalized to 1 equivalent photon. Taking the commonly used 1/k approximation for bremsstrahlung spectra produced by intermediate-energy electrons on thin radiators, i.e., $n(k,E_0) = 1/k$ for $k \leq E_0$, and assuming $\sigma(k)$ constant within a small energy range, Eq. (10) can be easily handled to give the absolute cross section as

$$\sigma = \frac{d\sigma_Q}{d(\ln E_0)} \quad . \tag{11}$$

Therefore, it suffices to calculate the slope of the curve $\sigma_Q = f(\ln E_0)$ in order to obtain σ. In Fig. 2 we have plotted the ternary fission yields of Al, Ti, Co, and Zr target nuclei as a function of $\ln E_0$. Since we have only a few measured yields in the E_0-range considered, the linear dependence of σ_Q with $\ln E_0$ is the most appropriate one to fit the yield data. Some points (those enclosed by parentheses in Fig. 2) show to be far from the expected increasing trend defined by the remaining points. This might be caused by some systematic errors the origin of which has been not easy to identify. By using the standard least-squares analysis, and rejecting the disaligned points, the absolute mean cross sections per photon in the range 0.8-1.8 GeV (the slopes of the straight lines of Fig. 2) have been obtained. Results are presented in Table 2 (third column) and they can be compared with binary fission data (second column) obtained for the same nuclei. Apart from large errors, which are due to mainly poor statistics, the ratio of ternary to binary fission cross sections (fourth column) has shown to increase with the increasing of mass number of nuclei under study.

The data available enable us to infer considerations about the probability of ternary fission (nuclear fissility of the ternary fission mode). This can be estimated by calculating the ratio $f = \bar{\sigma}/\bar{\sigma}_t$ of mean ternary fission cross section ($\bar{\sigma}$) to mean total nuclear photoabsorption cross section ($\bar{\sigma}_t$). For 0.8-1.8 GeV photons, $\bar{\sigma}_t$ has been evaluated by a simple model of nuclear photoabsorption according to which $\bar{\sigma}_t = A\,\bar{\sigma}_{\gamma N}\,\delta \approx 180A$ μb, where A denotes the mass number, $\bar{\sigma}_{\gamma N}$ is the mean total cross section for absorption of 0.8-1.8 GeV photons by a single nucleon [44], and δ is a factor which takes into account the screening effects caused by the nuclear surface [45,46]. Moreover, the quantity $\bar{\sigma}_{\gamma N}$ has been corrected for the nucleon Fermi momentum distribution within the nucleus. Table 2 lists mean values of fissility of the ternary fission mode so obtained (last column). Mean values of nuclear fissility of the binary fission mode from our previous work are also shown (fifth column) to allow a direct comparison. For the nuclei considered in the present work, and within the large experimental errors reported, results lead to the conclusion that ternary fission is a very rare de-exciting mode after absorption of intermediate-energy photons by the nucleus. In fact, as reported in Table 2, the probability of ternary fission of Al, Ti, Co, and Zr nuclei amounts to $\sim 10^{-4}$ only, and seems to be independent of mass number. This result agrees with the data obtained by Pinheiro Filho [35] for Ag,Br nuclei of nuclear-track emulsions exposed to bremsstrahlung photons in the range 1.0-1.8 GeV. From his work a probability of ternary fission of $\sim 10^{-4}$ has been also infered (from Ref. [35] we calculate a mean absolute cross section $\bar{\sigma} \approx 2$ μb, which can be compared with data of Table 2).

A comparative study of the results of the present work with other ternary fission data which have been obtained in different irradiation conditions is presented in Fig. 3 where we chose to represent the ratio of ternary to binary fission cross sections, σ_T/σ_B, as a function of parameter Z^2/A of the system projectile plus target nucleus. As a general remark, whatever reaction we consider, binary fission always predominates over ternary fission. For the reactions selected to Fig. 3, the ratio σ_T/σ_B lies in the range $\sim 10^{-5}-10^{-1}$, and shows to vary markedly either with Z^2/A or energy of the incident particle. For the reactions studied in the present work, and within the large uncertainties referred, results indicate an increasing of the ratio σ_T/σ_B by about two orders of magnitude in going from Al to Zr (filled circles). The result represented by a cross (1.0-1.8 GeV photons on Ag, Br nuclei) suggests that the quoted value for Zr may be overestimated. It is not improbable, in fact, that the value of the ratio σ_T/σ_B for Zr may be smaller than the quoted figure. With this observation in mind, and looking at the general trend exhibited by each set of experimental points, most data in Fig. 3 show that, for a given incident projectile of fixed energy, the frequency of ternary fission relative to binary fission increases as one goes towards intermediate-mass target nuclei. An exception is clearly noted, however, in the case of the reactions induced by 305-MeV ^{40}Ar-ions in U, Th, Bi, and Au target nuclei as reported in Ref. [17] (open squares). Apart from these data points, Fig. 3 seems to indicate the existence of a broad maximum for σ_T/σ_B-ratio the width of which may be as large as $15 \leq Z^2/A \leq 30$, which is a range where medium-weight nuclei are located. Of course, a number of new, additional experimental data are required to allow for a more refined analysis which will lead to a relation between σ_T/σ_B and Z^2/A with a degree of confidence considerably better than that obtained here from a relatively small number of experimental results. Phenomenological and/or theoretical considerations on this subject must also be developed in order to understand the process of ternary fission induced by intermediate and high-energy photons, particles, and complex ions.

4. Summary and Conclusions

Although a number of investigations on ternary fission of nuclei have been undertaken during the last twenty years or so, most data have been essentially obtained for intermediate- and high-energy particles and/or complex ions. Studies on ternary fission induced by photons as incident particles are still very scanty. Therefore, we decided to contribute to new data by re-analysing some CR-39 and makrofol plates of a previous photo-fission experiment by us to search for ternary fission events in Al, Ti, Co, and Zr nuclei. Targets and detectors were arranged in a 2π-forward geometry. A careful analysis of etched tracks on these plates has shown the presence of double divergent tracks from a common point inside the target material, thus indicating the possibility of occurrence of ternary fission events in the nuclei considered. Based on track-etch-geometry and registration properties of the detectors the methods and criteria to ascertain and discriminate true ternary fission events from other types of events were established. In addition, since thick targets were used in the experiment, it was necessary to develop a method of evaluating the effective number of target nuclei which contributes to recorded events (effective target thickness). These two steps made it possible to determine the mean values of cross sections and fissilities of ternary fission of Al, Ti, Co and Zr nuclei by photons in the energy range 0.8-1.8 GeV. Cross sections resulted to be of order of units of μb or less, and a probability of ternary fission of $\sim 10^{-4}$ was obtained. These results agree with data obtained from the interaction of 1.0-1.8 GeV photons with Ag, Br nuclei. Although uncertainties are large, data of the present work indicate that the ratio of ternary to binary fission cross sections (σ_T/σ_B) varies from $\sim 10^{-3}$ to $\sim 10^{-1}$ as one goes from Al to Zr. A comparative study on a number of σ_T/σ_B-values from different combinations of target nuclei and incident particles and energies as well seems to indicate that σ_T/σ_B increases towards the intermediate-mass region of target nuclei. New experimental results in this line are called for to make many aspects of the physics of ternary fission of nuclei clear.

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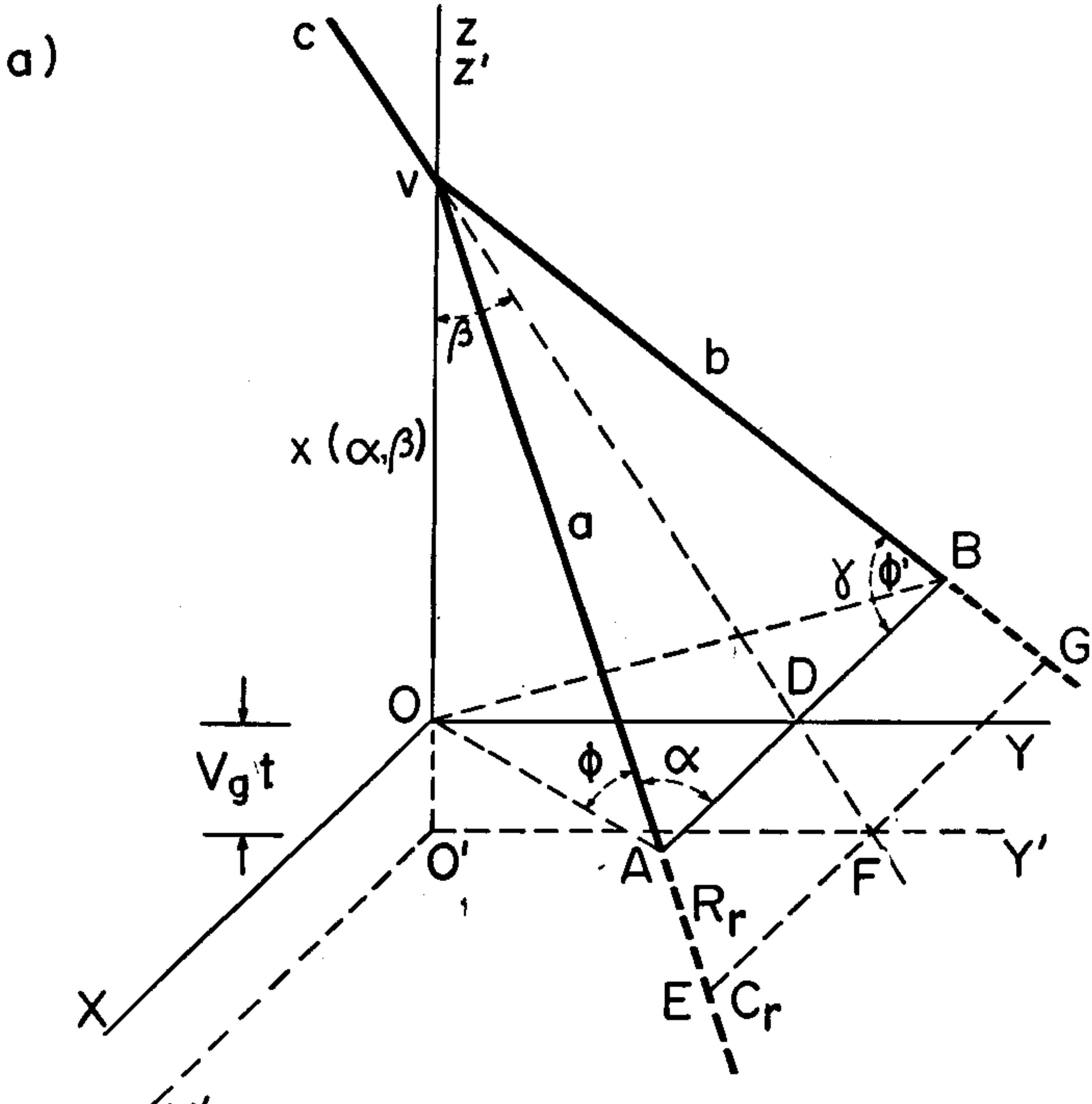
Figure Captions

Fig. 1. a - Schemmatic representation of a three-pronged event: VA, VB, and VC are the fragment trajectories from an origin point V inside the target material and located at a distance $x(\alpha,\beta)$ above the target-detector interface (XOY plane); β measures the amount of slope of the plane of the fragment trajectories from the vertical; ϕ and ϕ' are the dip angles, respectively, for branches "a" and "b"; α and γ are the angles formed by the intersection AB and the branches "a" and "b", respectively; $V_G t = 00'$ is the thickness of detector material surface removed by etching; R_r = AE is part of the track-length for branch "a" removed by etching; C_r is the minimum track-length recorded necessary to make track visible under a microscope. b - Illustrating the relative positions of a pair of double divergent tracks from an origin point located inside the target; the quantities d, d_0 and b are defined in the text.

Fig. 2. - Ternary fission yields, expressed as cross sections per equivalent quantum (σ_Q), are plotted against maximum bremsstrahlung energy E_0 (log scale). Points represent the results obtained in the present experiment for target-detector combinations as indicated. The straight lines are least-squares fits to the points.

Fig. 3. - Ratio of ternary to binary fission cross sections, σ_T/σ_B, plotted as a function of Z^2/A of the compound incident particle plus target nucleus system for some selected reactions. Points guided by a line represent measured σ_T/σ_B-values for interactions of different target nuclei with both the same incident particle and energy. Data are as follows: ◇, 414-MeV $^{40}Ar+^{232}Th$ (thorite crystal detector [16]) and $+^{238}U$ (hole detector in mica surface [20]); ◆, 27.5-MeV bremsstrahlung + ^{239}Pu, ^{238}U, and ^{232}Th (polyester sandwiches [33,34]); ◐, 300-GeV p + ^{nat}U, ^{232}Th, ^{209}Bi, and ^{nat}Pb (makrofol sandwiches [12]); □, 305-MeV $^{40}Ar+^{nat}U$, ^{232}Th, ^{209}Bi, and ^{197}Au (2π-forward geometry with mica detectors [17]); ■, 600-MeV p + ^{nat}U, ^{nat}Pb, and ^{197}Au (makrofol sandwiches [5]); ○, 7-GeV p + ^{238}U, ^{209}Bi, ^{208}Pb, ^{197}Au, ^{184}W, ^{165}Ho, and ^{108}Ag (Daicel sandwiches[13]); △, 640-MeV ^{4}He + ^{nat}U, ^{232}Th, ^{209}Bi,

^{nat}Pb, and ^{197}Au (makrofol sandwiches [25]); ▲, 2.1-GeV ^{2}H+^{nat}U, ^{232}Th, ^{209}Bi, ^{nat}Pb, and ^{197}Au (makrofol sandwiches [19]); ▽, 2.36-GeV π^{-} + ^{nat}U, ^{209}Bi, and ^{197}Au (mica sandwiches [14]); X, 1.0-1.8-GeV photons + Ag,Br (nuclear-track emulsions [35]); ●, 0.8-1.8-GeV photons + ^{27}Al and ^{nat}Ti (2π-forward geometry with CR-39 detectors, this work) and + ^{59}Co and ^{nat}Zr (2π-forward geometry with makrofol detectors, this work).


a)
c
Z
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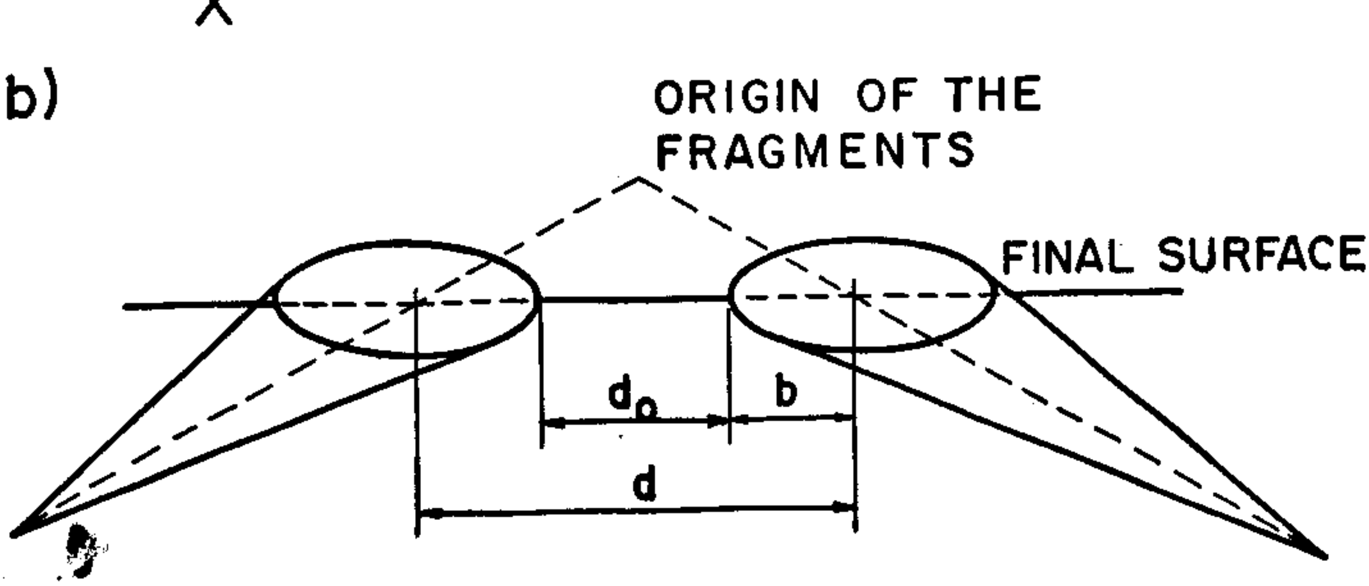
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FINAL SURFACE
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Fig. 1

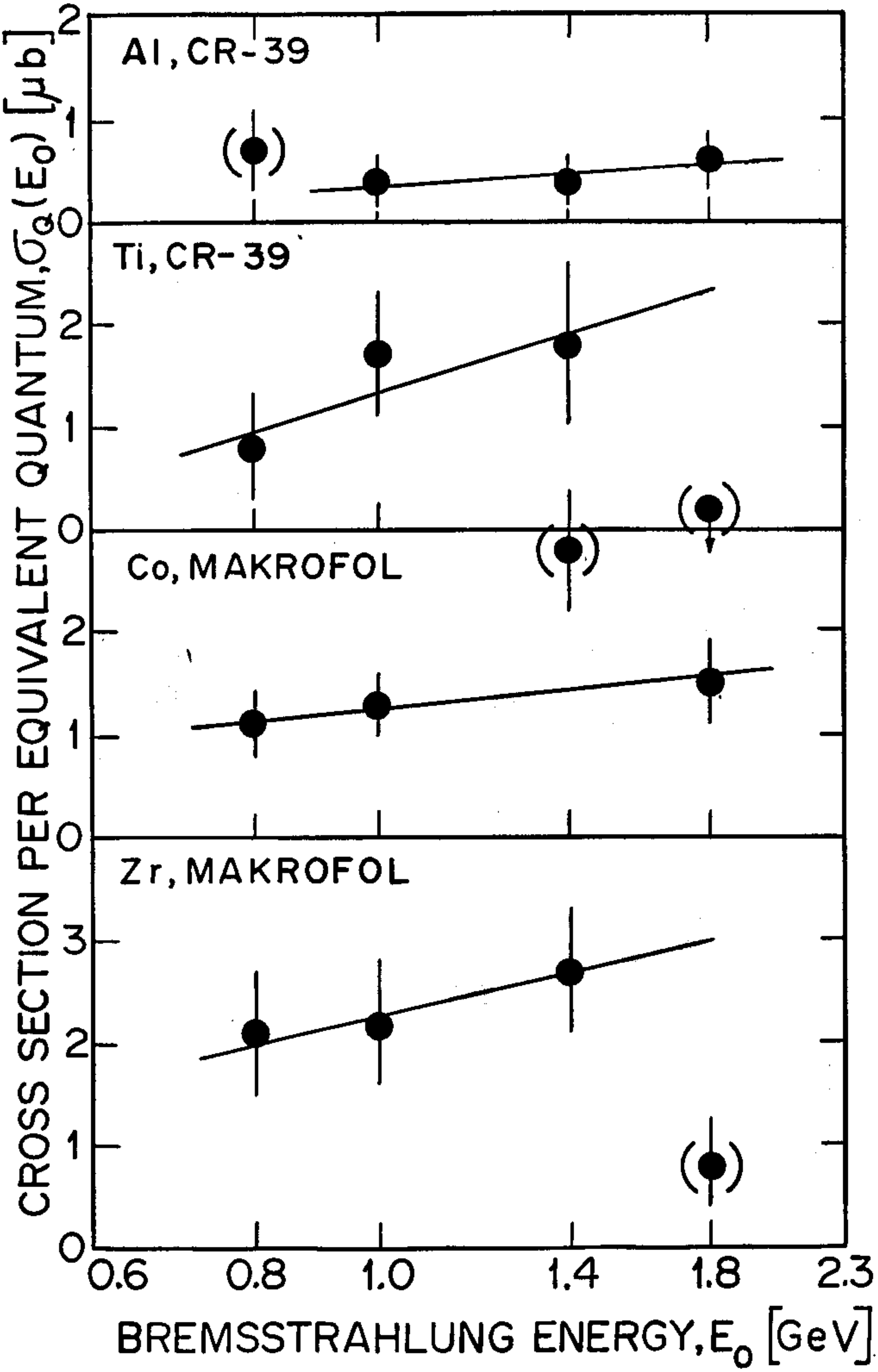
Al, CR-39
Ti, CR-39
Co, MAKROFOL
Zr, MAKROFOL
CROSS SECTION PER EQUIVALENT QUANTUM, $\sigma_Q(E_0)$ [μb]
BREMSSTRAHLUNG ENERGY, E_0 [GeV]
0.6
0.8
1.0
1.4
1.8
2.3

Fig. 2

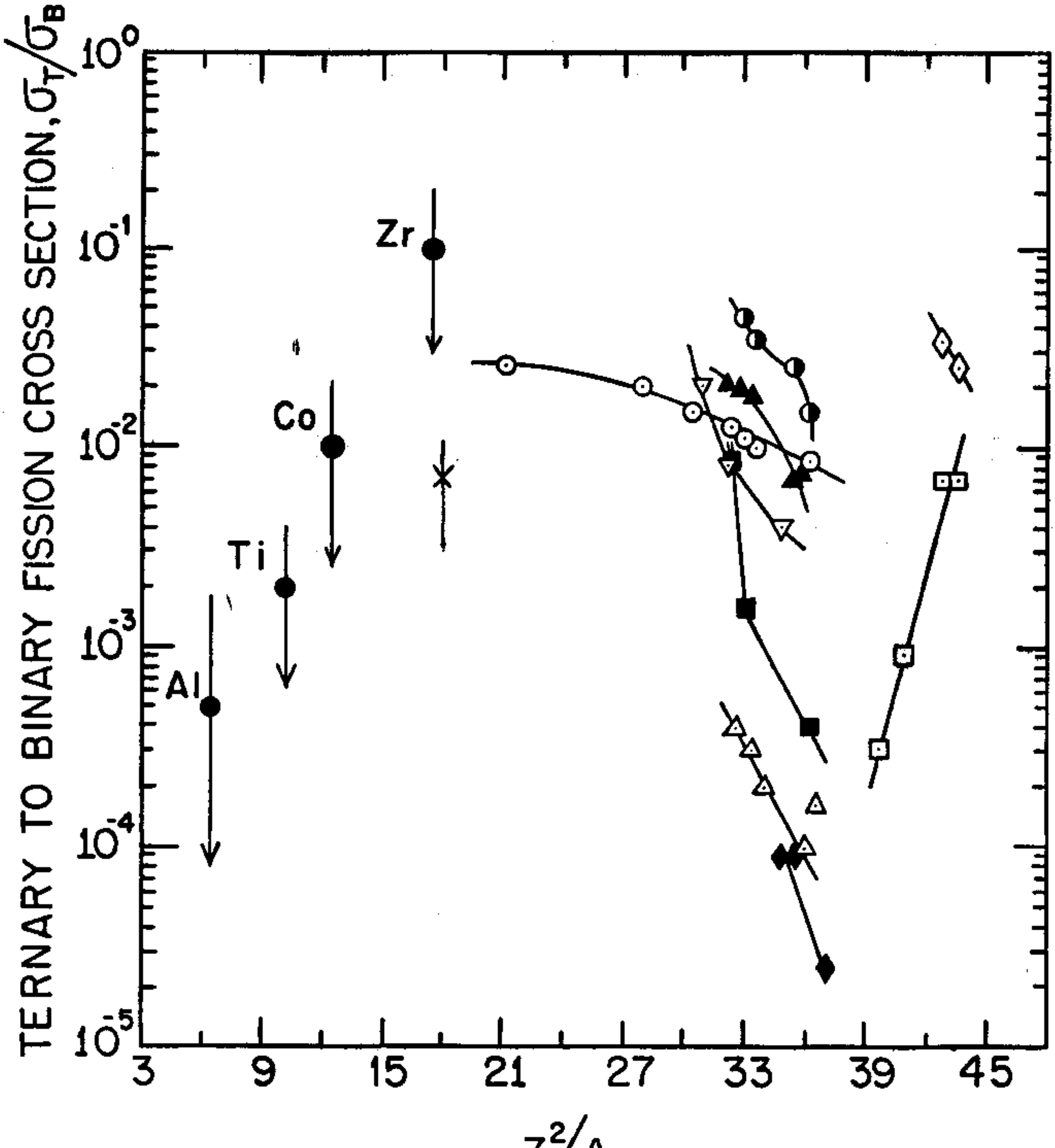
TERNARY TO BINARY FISSION CROSS SECTION, σ_T/σ_B
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Zr
Co
Ti
Al
3
9
15
21
27
33
39
45
Z^2/A

Fig. 3

Table 1. Relevant data regarding the determination of the ternary fission yields.

Target nucleus and Detector	Effective thickness of the target sample x_{ef} (μm)	Effective number of target nuclei N_a (10^{18} cm^{-2})	Bremsstrahlung end-point energy E_0 (GeV)	Number of equivalent photons Q (10^{12} cm^{-2})	Area of scanning (cm^2)	Number of ternary fission events	Ternary fission yield, σ_Q(μb)
^{27}Al	0.26±0.03[a]	1.6±0.2	0.8	1.0	1.7±0.2	2±1	0.7±0.4
CR-39	0.50±0.05[b]	3.0±0.3	1.0	1.0	1.8±0.2	2±1	0.4±0.2
			1.4	1.0	1.9±0.2	2±1	0.4±0.2
			1.8	1.0	2.1±0.2	4±2	0.6±0.3
$^{47.9}$Ti*	0.37±0.04[b]	2.1±0.2	0.8	1.0	1.8±0.2	3±2	0.8±0.5
CR-39			1.0	1.0	1.7±0.2	6±2	1.7±0.6
			1.4	1.0	1.9±0.2	7±3	1.8±0.8
			1.8	1.0	2.0±0.2	0	< 0.2
^{59}Co	0.025±0.003[c]	0.23±0.02	0.8	28.4	2.0±0.2	14±4	1.1±0.3
Makrofol			1.0	29.6	2.1±0.2	18±4	1.3±0.3
			1.4	30.0	1.2±0.1	23±5	2.8±0.6
			1.8	30.0	1.7±0.2	18±4	1.5±0.4
$^{91.2}$Zr*	0.029±0.003[c]	0.13±0.01	0.8	28.4	1.7±0.2	13±4	2.1±0.6
Makrofol			1.0	29.6	1.9±0.2	16±4	2.2±0.6
			1.4	30.0	2.2±0.2	23±5	2.7±0.6
			1.8	30.0	1.9±0.2	6±3	0.8±0.4

*Mean mass number taking into account the isotopic abundances of the naturally occurring isotopes.
[a]For 3h etching; [b]for 2h etching; [c]for 1h etching.

Table 2. Comparison between mean values of binary and ternary fission cross sections and fissilities by photons in the energy-range 0.8-1.8 GeV.

Nucleus	Mean cross section per photon, $\bar{\sigma}$ (μb)			Mean nuclear fissility, $\bar{f}$	
	binary fission[a]	ternary fission	ratio (ternary/binary)	binary fission[a]	ternary fission
^{27}Al	$(6\pm2)\times10^{2}$	0.3 ± 0.7	$\sim 5\times10^{-4}$	$(1.2\pm0.4)\times10^{-1}$	$(0.6\pm1.4)\times10^{-4}$
$^{47.9}$Ti	$(8\pm3)\times10^{2}$	1.7 ± 1.5	$\sim 2\times10^{-3}$	$(0.9\pm0.3)\times10^{-1}$	$(2.0\pm1.8)\times10^{-4}$
^{59}Co	34 ± 7	0.5 ± 0.5	$\sim 1\times10^{-2}$	$(3.2\pm0.6)\times10^{-3}$	$(0.5\pm0.5)\times10^{-4}$
$^{91.2}$Zr	7 ± 4	1 ± 1	$\sim 1\times10^{-1}$	$(4\pm2)\times10^{-4}$	$(0.6\pm0.6)\times10^{-4}$

[a] Refs. [36-38].

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