Fission of U, Th, Bi, Pb, and Au induced by 200 and 300 GeV protons

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The cross sections for the binary and ternary fission of U, Th, Bi, Pb, and Au induced by 300 GeV protons have been measured with Makrofol polycarbonate detectors. We deduce that the ternary events and most of the binary events with a projected angle $\alpha_{12} < 170°$ in the plane perpendicular to the beam direction proceed by the same mechanism which characterizes fission induced by very high energy protons.

[NUCLEAR REACTIONS Binary and ternary fission of U, Th, Bi, Pb, and Au; E_p=200 GeV, 300 GeV; measured cross sections σ_B, $\sigma_{\bar{\pi}}$, σ_T.]

INTRODUCTION

The interaction of GeV protons with heavy nuclei has been analyzed theoretically and compared with experimental results in many articles.[1-4] Experimentally, the fission of heavy nuclei induced by multi-GeV protons has been investigated by radiochemical methods[5-7,9,10] and by mica[11,12] and polycarbonate (Makrofol)[13-18] fission fragment detectors. The excitation energy deposited in the target nucleus does not change significantly with proton energy between 10 and 300 GeV.[1,2] In the present work the cross sections for binary and ternary fission of U, Th, Bi, Pb, and Au induced by 300 GeV protons were determined by use of the Makrofol sandwich technique. We measured two kinds of binary events, those with and without transverse momentum, and compared these results with those obtained with 10–20 GeV protons. The variation of the fission cross section as a function of energy and the parameter Z^2/A of the target has been investigated.

EXPERIMENTAL PROCEDURE

Each detector consisted of two 200 μm thick Makrofol sheets in the form of a sandwich.[19] The targets were prepared by evaporation of UF_4, ThF_4, Bi, Pb (nat.), and Au in a high vacuum directly upon one of the sheets of Makrofol through a circular diaphragm. The second foil was pressed and partially glued to the first one, the target layer being thus enclosed between the two detector sheets. The target thickness was determined by weighing and also by an optical method.

The sandwiches were irradiated with 300 GeV protons at the Fermi National Accelerator Laboratory. The proton flux of 10^{11} particles/cm^2 was measured in the reaction $^{27}Al(p,3pn)^{24}Na$ by activation techniques.[20] The irradiations were performed with protons incident perpendicularly upon the surfaces of the sandwiches. Heavy reaction fragments were stopped inside the Makrofol sheets and could thus be detected in a 4π geometry. After bombardments, the target layer was dissolved in an appropriate acid and the sandwich was etched for 40 min in a 5N sodium hydroxyde solution at 60 °C. With this etching process, the registration threshold of Makrofol is about 8 MeV mg^{-1}cm^2. After development a mechanical system allowed reconstitution of the sandwich to within an accuracy of a few microns of its previous configuration. Then, the sandwiches were put in a polyethylene bag under vacuum and observed with a magnification of 220 × for scanning and 2500 × for measurements.

The following four types of events were found. (a) Single tracks which could not be related to any other tracks. (b) Binary events (B); i.e., two correlated tracks corresponding to heavy fragments emitted in the same interaction. The identification criterion for such an event is that the trajectories of the two registered particles intersect at the same point in the target plane. Events in this class were further subdivided as follows.

(1) Events appearing as two fragments directed in opposite directions with an angle between the two tracks (α_{12}) of between 180° and 170°. These are called π events.

(2) Events with an angle between the two tracks of less than 170°. These are called $\bar{\pi}$ events and have a non-negligible transverse momentum.[13] (c) Ternary events (T) resulting from the disintegration of target nuclei into three heavy fragments. (d) Four pronged events resulting from the disintegration of the target nuclei into four heavy fragments. The identification criterion of (c) and (d) is the same as in (b). Only events with two and three tracks were analyzed.

When using a detector such as that employed in the present work, it is necessary to apply corrections to the observed number of events because of a systematic removal of material from the detector surface layer in the course of the chemical treatment and for the coincidence of individual events. The chemical etching leads to a loss of about 2% of the events. Accidental coincidence of two single tracks or of a single and a binary event have been calculated under the assumption that the spatial distribution of these kinds of events follows Poisson distribution.[19] It turns out that coincidence events of two single tracks may be neglected and the upper limit to a single and a binary coincidence event is $\simeq 4\%$.

RESULTS AND DISCUSSION

Binary fission

The cross section for the production of all binary events was calculated using the relation $\sigma_B = F/NP$, where F is the number of binary events per cm^2, N the number of target atoms per cm^2, and P the number of incident protons per cm^2. For the determination of the cross section for the production of ternary events, use was made of the relation $\sigma_T = (T/B)\sigma_B$, where T/B is the ratio of ternary to binary events. The values of the cross sections for binary and ternary events and the T/B ratios are given in Table I. The values correspond to an average obtained from four sandwiches for Th, three each for U and Pb, two for Bi, and one for Au. The errors presented in Table I are due to statistical and scanning errors, uncertainties in the thickness of the target layers (5–10%), and the errors in the integrated proton fluxes (10%).

If we compare the binary fission cross sections for U, Th, Bi, Pb, and Au as a function of the incident proton energy along with the data obtained by other authors,[11,15,17,21-24] we observe that the binary fission cross section is a slowly varying function of energy in the interval 10–300 GeV for U, Th, Bi, and Au, while for Pb the increase is larger but still less than the values obtained by radiochemical methods at 30 GeV.[25] Barashenkov[2] has found anomalies in the binary fission cross section in the vicinity of the doubly magic nucleus $A = 208$.

The calculated ratios, except for Pb, are close to unity. Using nuclear emulsions to study the interactions of multi-GeV protons with heavy emulsion nuclei, or heavy incorporated nuclei, it has been shown that the number of charged particles with $\beta < 0.7$ emitted was practically independent of the incident energy between 10 and 400 GeV and that the energy deposited in these nuclei was constant.[3,26,27] In the present experiments with plastic detectors, another phenomena, namely the fission cross section, was found to be approximately constant, and it is reasonable to extrapolate previous emulsion results to mean that the excitation energy deposited prior to fission is likewise constant. Barashenkov *et al.*[3] have found that for the interaction ($p + {}^{238}U$) at 10 and 20 GeV the average excitation energy of fission products after the internuclear cascade is equal to 365 ± 25 and 376 ± 25 MeV, respectively. The binary fission probability P_{2f} is defined as σ_B/σ_{in}; the value of σ inelastic at 300 GeV is deduced from the calculation of Carrol *et al.*[29] The dependence of P_{2f} as a function of the parameter Z^2/A is presented in Fig. 1 and shows an exponential increase for all the targets except Au. This rapid increase of the binary fission cross section occurs because, for U and Th fission is possible over a broad range of excitation energy whereas for lighter nuclei (Au, Pb, and Bi) the range is smaller.[31]

Ternary fission and $\bar{\pi}$ events

The ternary fission cross sections and the ratios T/B of ternary to binary fissions at 300 GeV are

TABLE I. Cross section and other experimental results.

Target	E (GeV)	σ_B (mb)	T/B (%)	σ_T (mb)	SD(α_{12})	$\bar{\pi}/B$ (%)	$T/\bar{\pi}$ (%)	$\sigma_{\bar{\pi}}$ (mb)
U	200		1.35		10°4	18	~8	
	300	866 ± 214	1.55	13.4	14°4	20	8	173
Th	200		1.70		12°1	20	9	
	300	890 ± 165	2.50	22.2	20°3	33	8	294
Bi	200				23°3	48		
	300	303 ± 44	3.50	10.6	17°4	38	9	115
Pb	200				20°9	43		
	300	241 ± 40	4.50	10.8	20°8	45	10	108
Au	200		4.90		27°5	56	9	
	300	46 ± 8						

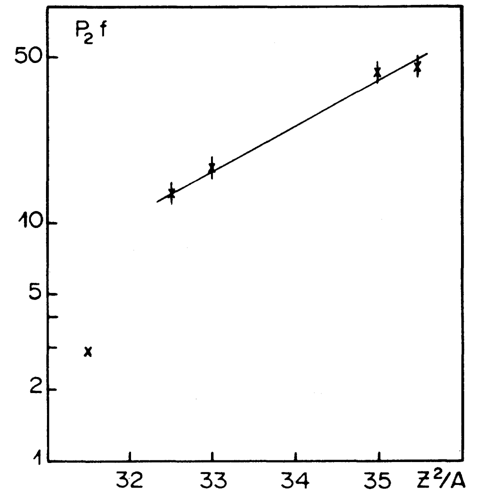

FIG. 1. Fission probability versus Z^2/A of the target.

given in Table I. We notice that for U and Th the ternary fission cross section is not changed at 300 GeV relative to that at 18 GeV, while for Pb and Bi the increase is by a factor 2 and 1.5, respectively. This indicates that for Pb and Bi there is a larger fragmentation contribution to the ternary process than in the case for U and Th. The probability for ternary fission $P_{3f} = \sigma_{3f}/\sigma_{in}$ is a weak function of Z^2/A. The same has been found true for the fragmentation probability.[30]

For 300 GeV incident energy, the ratio T/B is a decreasing function of the target mass. Similar results were obtained by Remy *et al.*[11] and Rahimi *et al.*[23] The present results for polycarbonate[13,14] are higher than those obtained by mica detectors.[6] This can be explained on the basis that Makrofol is sensitive to particles with $Z \geq 9$, but mica is sensitive only to those with $Z \geq 15$. Therefore, our ternary fission events contain a more important contribution of lighter fragments than events visualized in mica. Thus the cross section values σ_T measured in this work must be considered to be underestimated relative to the total probability of ternary phenomena, and suggest that some of the events classified as binary were in fact reactions with three or more fragments involving one or more especially fast or light products. Their detection was not possible because of the registration threshold of the Makrofol detector. The expected configuration for such events in Makrofol would correspond in general to the configuration of binary events but would be characterized by a projected angle α_{12} perceptible different from 180° to conserve momentum. These events have been observed and are called $\bar{\pi}$ events. Figure 1 shows the normalized distribution $dN/d\alpha$ for binary events induced in U, Th, Bi, Pb, and Au by 300 and 200 GeV protons and, for comparison, binary events in ^{235}U induced by thermal neutrons. In this latter case $^{235}U(n,f)$, which is our reference reaction, the experimental distribution of the projected angle α_{12} has a Gaussian-type shape centered at 180° as expected. We note that in this reaction 98% of the events are situated between 170° and 180°. Therefore we have called π events all those with a projected angle $\alpha_{12} > 170°$ and $\bar{\pi}$ events all binary ones with $\alpha_{12} < 170°$. The calculated standard deviations [$SD(\alpha_{12})$] relative to $\alpha = 180°$ for these distributions are represented in Table I and in Fig. 2. As can be seen, the standard deviation $\sigma_{\alpha 12}$ and the T/B ratio decrease with mass of the target nucleus. The relative abundance of detectable ternary events is higher as the distribution is wider.

In Table I we present the two classes of binary events: π/B and $\bar{\pi}/B$, where $\pi + \bar{\pi} = B$. The variations of $\sigma_{\bar{\pi}}$ and σ_T versus Z^2/A of the target are the same. Similar results have been found by Rémy.[17] Another important fact is that the ratio T/B to $\bar{\pi}/B$ is approximately constant for four of the targets (Table I). We must recall that the ratios T/B and $\bar{\pi}/B$ have been established independently. The $T, \bar{\pi}$ value may be a characteristic of the detector sensitivity.

If we make a rough comparison between the results of radiochemical studies and our results, we can suggest the following parallels:

π events correspond to neutron rich fragments,
$\bar{\pi}$ events correspond to neutron poor fragments.

These correlations are based on the one hand on excitation function properties and on the other hand on the properties of fragment recoils. This has also been seen by Rémy[17] with the same techniques for U and Pb targets bombarded with protons from 0.6 to 23 GeV energy. We also note

TABLE II. Ratio of binary fission cross sections

$\sigma_{300\ GeV}/\sigma_{10-20\ GeV}$	Au	Pb	Bi	Th	U	Experimental technique
σ_{300}/σ_{18}	0.75	2.06	1.08	1.05	1.04	Makrofol, this work and Refs. 17, 18, 21.
σ_{300}/σ_{13}	1.0		1.07		0.95	Mica, Ref. 11
$\sigma_{300}/\sigma_{11.5}$					0.90	Radiochemistry, Ref. 15
$\sigma_{300}/\sigma_{11.5}$					0.99	Radiochemistry, Ref. 7

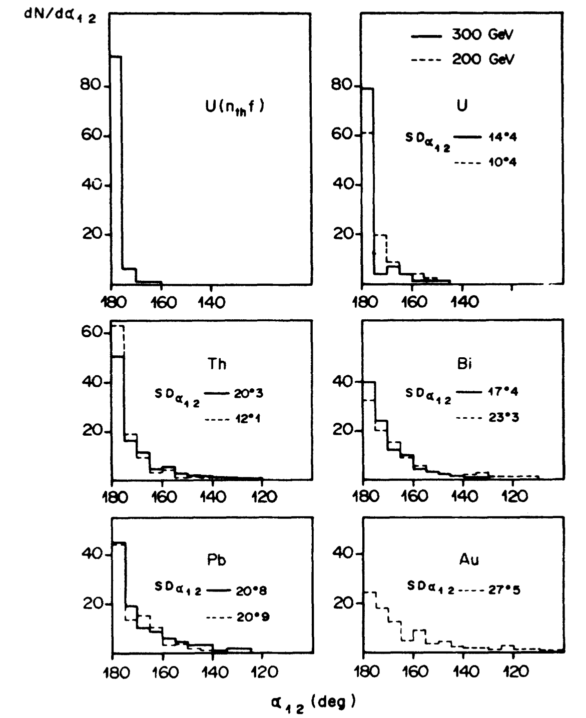

FIG. 2. Distribution of the projected angle α_{12} between tracks in the detector plane.

that the breakup into more than three fragments is more important at 300 GeV than at 20 GeV.[21]

CONCLUSIONS

(1) The binary fission cross section for U, Th, Bi, and Au does not vary between 18 and 300 GeV. For Pb, it varies by a factor of 2.

(2) The probability for binary fission increases approximately exponentially with the parameter Z^2/A.

(3) The ternary fission cross section increases for Pb and Bi between 18 and 300 GeV, while for U and Th it does not change.

(4) Ternary fission seems to appear as a typical high energy reaction. The probability of finding three fragments of about equal mass is rare, and ternary fission with a large dispersion of masses is important.

(5) The ratio of ternary to binary fission, T/B, presents a fundamental difference of behavior compared to fission induced by heavy ions which shows an increase with Z^2/A of the compound nucleus.[32]

(6) The ratio of binary events with a projected angle $\alpha_{12} < 170°$ to the total binary events shows the same behavior at the T/B ratio B and T events from the same kind of mechanism, which is a characteristic of high energy reactions with very heavy target nuclei.

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