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TERNARY FISSION OF URANIUM NUCLEI INDUCED BY HIGH-ENERGY PROTONS

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Résumé. — Nous avons utilisé la technique des « sandwiches » de mica pour l'étude de la fission ternaire de l'uranium. L'existence de ce processus a été établie sans ambiguïté pour des protons incidents de 23 GeV.

Les valeurs mesurées des sections efficaces de fission ternaire pour des protons de 23 GeV et 18 GeV sont respectivement de $(3,5 \pm 1,2)$ mb et de $(1,5 \pm 1,1)$ mb.

Abstract. — Ternary fission of uranium has been studied with the mica sandwich technique. The existence of this process has been firmly established at the proton bombarding energy of 23 GeV.

The cross-section for ternary fission has been found to be (3.5 ± 1.2) mb at 23 GeV and (1.5 ± 1.1) mb at 18 GeV.

1. Introduction. — Several papers [1-7, 11] have been recently published on ternary fission of heavy nuclei induced by various incident particles. "Ternary fission" means here a nuclear break-up into three frag-

ments, every one with a mass exceeding a certain cut-off value that depends on the properties of a detector. Solid state semiconductor and track detectors, as well as radiochemical techniques, were used. Thermal neutrons, alpha particles, heavy ions, and fast protons served as bombarding particles. The ratio of the observed numbers of ternary T to binary B fission events, T/B , and other relevant details of the experiments performed until now, are set out in Table I.

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TABLE I

SUMMARY OF STUDIES ON TERNARY FISSION

REFERENCE	TARGET NUCLEUS	INCIDENT PARTICLES	DETECTOR	APPROXIMATE MASS NUMBER CUT-OFF	TERNARY TO BINARY FISSION EVENTS RATIO T/B
C.E.R.N., Heidelberg-Naples-Warsaw Collaboration [1]	U	18 GeV protons	Natural mica	30	1.9×10^{-3} (see the text)
M. Debeauvais <i>et al.</i> [2]		18 GeV protons	Plastics	14	$(1 - 2) \times 10^{-2}$
R. L. Fleischer <i>et al.</i> [6]	Th	400 MeV Ar ions	Synthetic thorite crystal ThSiO ₄	40	3.3×10^{-2}
G. N. Flerow <i>et al.</i> [4]	²³⁸ U	190 MeV Ne ions	Semiconductor detectors	20	$< 10^{-4}$
S. A. Karamian <i>et al.</i> [3]	²³⁸ U	270, 310 MeV Ar ions	Semiconductor detectors	20	$10^{-3} \cdot 10^{-4}$
	²⁰⁹ Bi	310 MeV Ar ions	"		$(1 \pm 0.4) \times 10^{-4}$
	¹⁹⁷ Au	185 MeV Ne ions	"		7×10^{-6}
M. L. Muga <i>et al.</i> [5]	$\left\{ \begin{matrix} ^{235}\text{U} \\ ^{233}\text{U} \end{matrix} \right\}$	Thermal neutrons	Semiconductor counters	20	$(1 - 30) \times 10^{-6}$
R. H. Iyer and J. W. Cobble [7] (*)	U	20-120 MeV ⁴ He ions	(Radiochemical methods give evidence for the production of fragments with $24 \leq A < 47$ for alpha-particle energies above 20 MeV.)		
V. P. Pereygin <i>et al.</i> [11]	Au, Bi, U	230-380 MeV Ar ions	Mica	> 30	$10^{-4} \cdot 10^{-2}$

(*) This article contains references to radiochemical work concerned with the study of ternary fission induced by thermal neutrons in ²³⁵U. No evidence was found to confirm the results of Muga *et al.* [5].

The present work is concerned with ternary fission of natural uranium bombarded with 23 GeV protons incident on uranium layers sandwiched between mica sheets as detectors. In mica, nuclear fragments with mass numbers exceeding about 30 can be recorded [8]. Various experimental biases have been investigated, and corrected T/B values are given for this experiment and for the previous one at 18 GeV proton energy [1].

2. Experimental procedure. — The experimental technique has been described in detail elsewhere [9], so it is sufficient to mention it here only briefly. A thin target layer was obtained by electro-spraying uranium onto a supporting aluminium foil of about $200 \mu\text{g}/\text{cm}^2$. It was then inserted between two sheets of a partially cleaved piece of natural mica of about $100 \mu\text{m}$ thickness, thus forming a sandwich.

Mica sandwiches were irradiated at the C.E.R.N. PS in an extracted proton beam of 23 GeV, incident perpendicularly onto the mica surface. Similar exposures were made with protons of 590 MeV from the C.E.R.N. SC.

After exposure, the sandwiches were opened to remove the target foils and placed for 20 to 40 minutes in 50 % hydrofluoric acid at room temperature to reveal the tracks. After rinsing in water and alcohol and after drying, the sandwiches were observed under an ordinary optical microscope.

The process of ternary fission gives rise to three-prong events in mica (a typical example is shown in ref. [1], fig. 1 f). Scanning for such events was made in these parts of mica sandwiches in which the number of binary fission events per 1 mm^2 was less than 160. Only those three-prong events were taken into account for which the distance, l , between the common intersect of the projected directions onto the mica plane of the three tracks and the beginning of each track was less than $20 \mu\text{m}$ and for which the range of every track was longer than about $3 \mu\text{m}$.

3. Results and discussion. — Among 21900 B events at 23 GeV, 100 three-prong events fulfilling the above scanning criteria have been found, for which all tracks have such points of entry into the mica as to indicate that they may have emerged from a common centre (T^+ events, see fig. 1 a). In addition, 29 events have been observed whose three tracks have in each case such points of entry that they cannot have a common point of intersection in space (T^- events, see fig. 1 b). While the examples of genuine ternary fission are among T^+ events, T^- events are accidental coincidences of binary fissions with single tracks [1].

Scanning was also made for three-prong events in uranium sandwiches exposed to thermal neutrons from a reactor [9]. In all, $2T^+$ and $3T^-$ events were found among about 7500 B events. Since ternary fission in this case, if occurring, has a very low T/B ratio [5, 7], it follows from this observation that the possibility of observing T^+ events which are due to a scattering process of one of the binary fission fragments can be ruled out. In this case both types of T events must be due to accidental coincidences of B events with single tracks. The origin of these single tracks, occurring with a ratio of a few per cent of all B events, has been discussed in ref. [9].

Contrary to the previous observation [1] further, very careful scanning in uranium sandwiches exposed

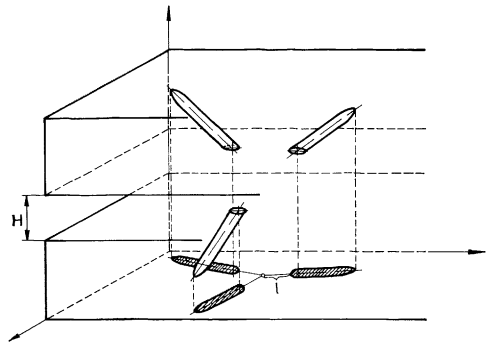


FIG. 1 a. — Schematic drawing of a T^+ event as registered in a mica sandwich.

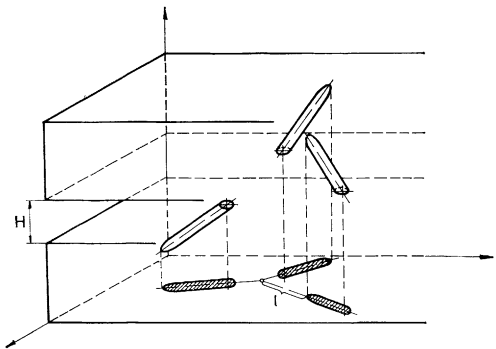


FIG. 1 b. — Schematic drawing of a T^- event as registered in a mica sandwich.

to protons of 590 MeV revealed 10 T^+ and 2 T^- events among some 4100 B events. Although the statistical significance is low, this observation may indicate the existence of ternary fission process at this energy.

In the following, results obtained at 23 GeV will be discussed in greater detail. Figures 2 a and 2 b show the distributions of the largest angle, φ_{max} , between the projections of the tracks onto the mica plane, observed for T^+ and T^- events at 23 GeV (broken lines). The distributions expected for accidental coincidences are also shown (solid lines). They are calculated from the known projected angle distributions of binary events on the assumption that the distribution of the projections on the mica plane of the third track is isotropic. Both distributions are similar in the case of T^- events; however, the observed distribution for T^+ events exhibits a relative excess of events with the angle $\varphi_{\text{max}} < 160^\circ$ ($T^+(\varphi_{\text{max}} < 160^\circ)$ events). A χ^2 test comparing the shapes of the curves gives for 12 degrees of freedom the value of 379 for T^+ distribution ($P(\chi^2) < 0.01 \%$), and for T^- distribution 11 ($P(\chi^2) = 57 \%$), in support of the above interpretation of T^+ events. For comparison, the distributions of φ_{max} for events found in uranium sandwiches exposed to thermal neutrons and 590 MeV protons are shown in figures 2 c and 2 d.

The ratio of the number of T^+ ($\varphi_{\text{max}} < 160^\circ$) events to that of binary fissions, B , found in the same scanning area at 23 GeV is :

$$T^+(\varphi_{\text{max}} < 160^\circ)/B = (1.6 \pm 0.3) \times 10^{-3}.$$

This is to be considered as the lower limit of the true T/B ratio, since there may be T^+ events with

the angle $\varphi_{\max} > 160^\circ$. Figure 3 illustrates the difference, $T^+ - T^-$, between the distributions of the angle φ_{\max} for T^+ and T^- events given previously in figures 2 a and 2 b.

The scanning conditions described in Section 2 introduce a certain loss of events. This depends on the distance, H , between the mica sheets at the moment

of exposure, and on the effect of the supporting foil of aluminium.

For every sandwich used in this work, the distance H was estimated by a method similar to that described by Cieślak *et al.* [9] and Carbonara and Rinzivillo [10] (colinear binary events were used in this analysis). Values ranging from $2 \mu\text{m}$ to $8 \mu\text{m}$ were obtained. It is clear that the distance l , as defined in Section 2, depends on the value of H , leading in certain cases to the loss of those events for which l becomes longer than $20 \mu\text{m}$.

The observed range distributions of fission fragments that do not pass through the supporting foil are shown in figure 4 separately for ($T^+ - T^-$) and binary events, by broken and solid lines. It is seen that the track length distribution appears to be wider for ternary than for binary fission. The range, R , of a fragment that passes through the foil is shorter by ΔR as the result of the foil absorption [9]. This effect

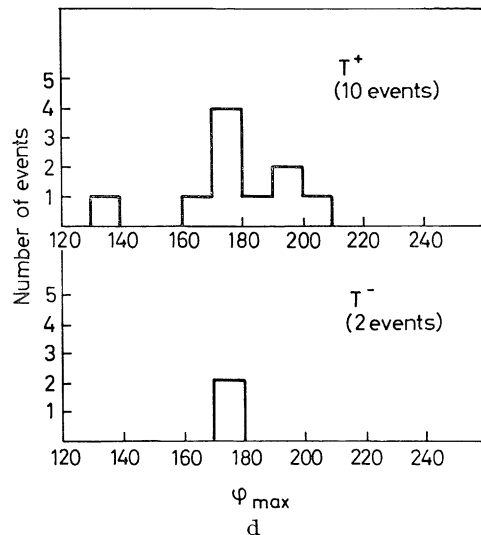
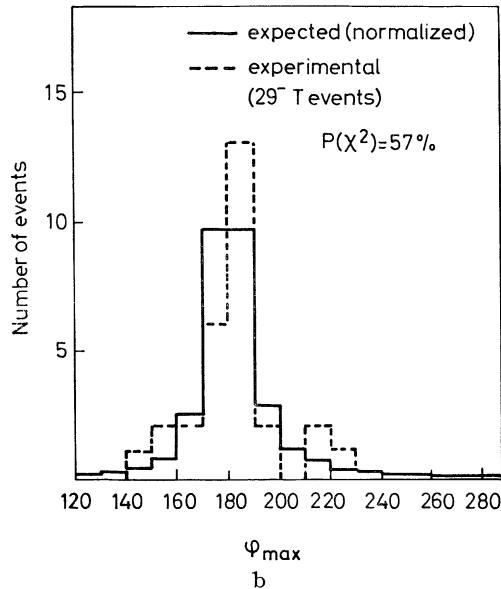
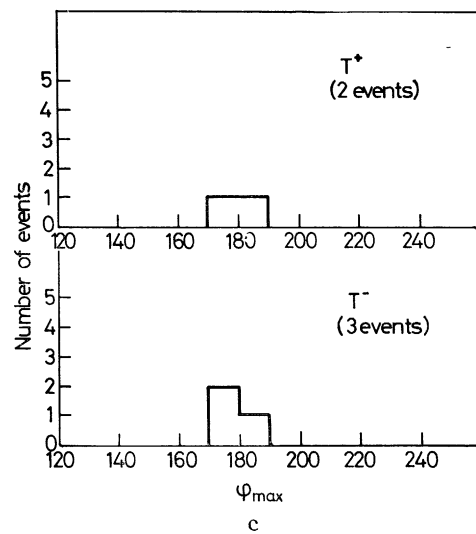
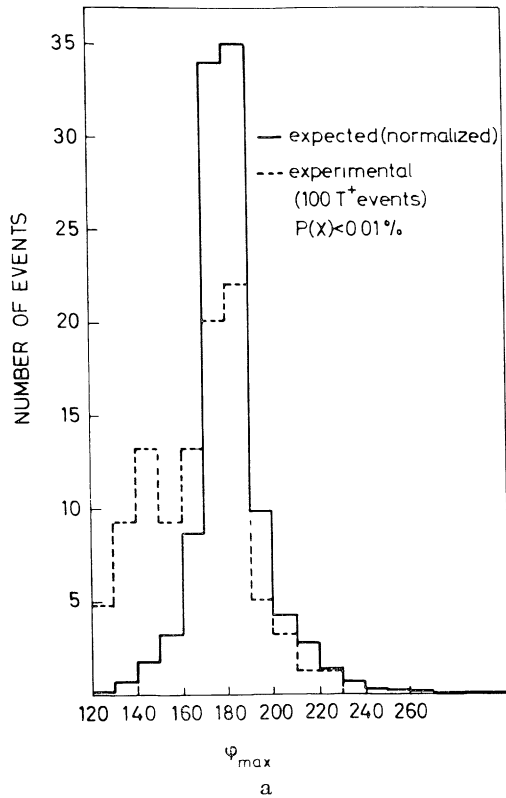


FIG. 2. — Distributions of the largest projected angle, φ_{\max} observed for three-prong events in uranium sandwiches :

- a) T^+ events as 23 GeV.
- b) T^- events at 23 GeV.
- c) T^+ and T^- events for thermal neutron exposure.
- d) T^+ and T^- events at 590 MeV.

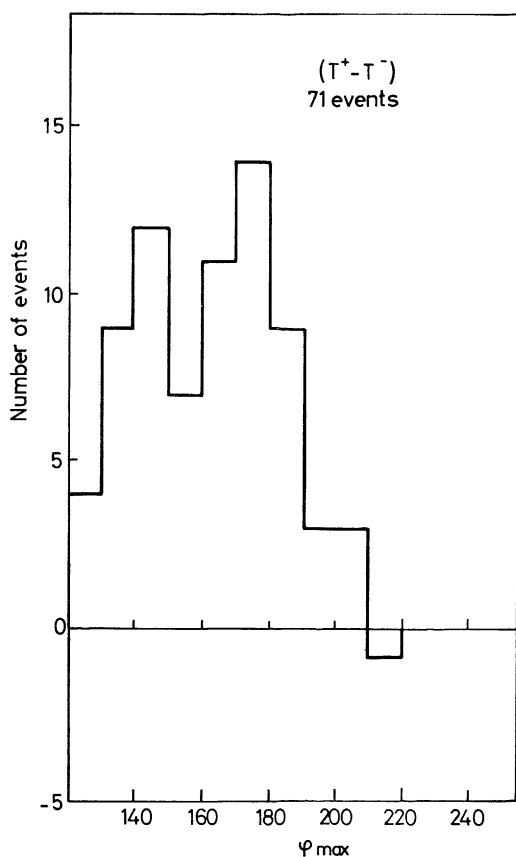


FIG. 3. — Distribution of the largest projected angle φ_{\max} , for $(T^+ - T^-)$ events at 23 GeV.

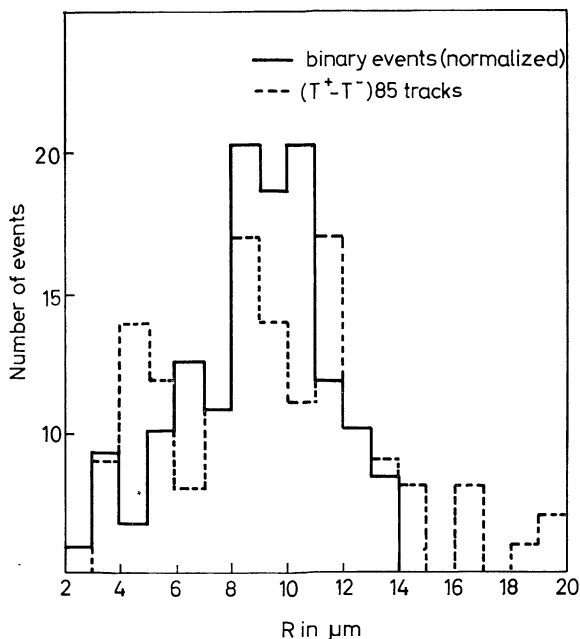


FIG. 4. — Range distributions for $(T^+ - T^-)$ and B events at 23 GeV.

can be taken into account on the assumption that the stopping power of mica is the same as for the aluminium foil. Due to scanning criteria an event would be lost

altogether if the range of any of its fragments were less than $3 \mu\text{m}$.

In order to estimate these detection losses, a simulation calculation has been performed with the use of the Gier computer. For an event with given ranges, angles between the tracks, and their position in space with respect to the mica plane, one can calculate both, the distance l and the quantities ΔR for all its tracks. Assuming a certain angular and space distribution of events one can then find the fraction of those events that fulfill the scanning criteria, i.e. the observation efficiency. Detailed calculations were made in the case of results obtained at 23 GeV. Figure 5 a shows for T^+ events the distribution of the coplanarity volume $V = \mathbf{r}_1 \cdot (\mathbf{r}_2 \times \mathbf{r}_3)$, \mathbf{r}_i ($i = 1, 2, 3$) being unit vectors in the direction of the fission tracks. A similar distribution of V can be plotted for T^- events (fig. 5 b) if for every such event the third accidental track with a given dip angle θ is rotated around its centre by the angle 2θ to make up "an accidental T^+ event" (see fig. 1 a and 1 b). Figure 5 c shows the difference between the distributions presented in figures 5 a and 5 b, respectively, i.e. the distribution for $(T^+ - T^-)$ events. Since the uncertainties in the measurement of the directions of fission tracks in space are large [9], the values of the coplanarity volume V cannot be determined accurately. In fact, the errors ΔV of V values range from 0.1 to 0.5 in this experiment, with an average value of $\overline{\Delta V} = 0.2$. Figure 6 shows the ratio of $V/\Delta V$ for $(T^+ - T^-)$ events. Keeping in mind all the reservations indicated above, one can see that the majority of the events are coplanar. Figure 7 shows the distribution of the true angle in space between pairs of tracks for $(T^+ - T^-)$ events. It has a maximum around 120° , similar to the one observed in ref. [2].

On the basis of these results, it was assumed in the calculations, that the ternary fission events are coplanar and that they are distributed isotropically⁽⁴⁾ in space. Under these assumptions, not inconsistent with the experimental data, the calculated observation efficiency e.g. for $H = 3 \mu\text{m}$ is 65%. It turns out that the observation efficiency does not change by more than 20% if an anisotropic⁽⁵⁾ distribution of T events in space is assumed and it does not depend much on the assumed range — energy relation for mica or the angles in space between the tracks.

The values of the observation efficiency were calculated with the appropriate value of H , on the assumption of isotropy, for every sandwich. These values were then used to obtain the corrected numbers of T events.

The difference between the sum of the corrected values of T events, $(T^+ - T^-)_{\text{corr}} = 128 \pm 31$, gives the true number of ternary fission events for all sandwiches used in this work.

⁽⁴⁾ The isotropic distribution means in this case that the unit vector normal to the coplanarity plane containing the tracks of ternary fission fragments has the following distribution: $N(\theta) d\theta \sim \sin(\theta) d\theta$, where θ is the angle between the normal unit vector and the plane of the mica sheet and $N(\theta) d\theta$ is the number of events with the angle θ between θ and $\theta + d\theta$.

⁽⁵⁾ This change has been obtained on the assumption that the anisotropic distribution is of the form: $N(\theta) d\theta \sim \cos \theta d\theta$.

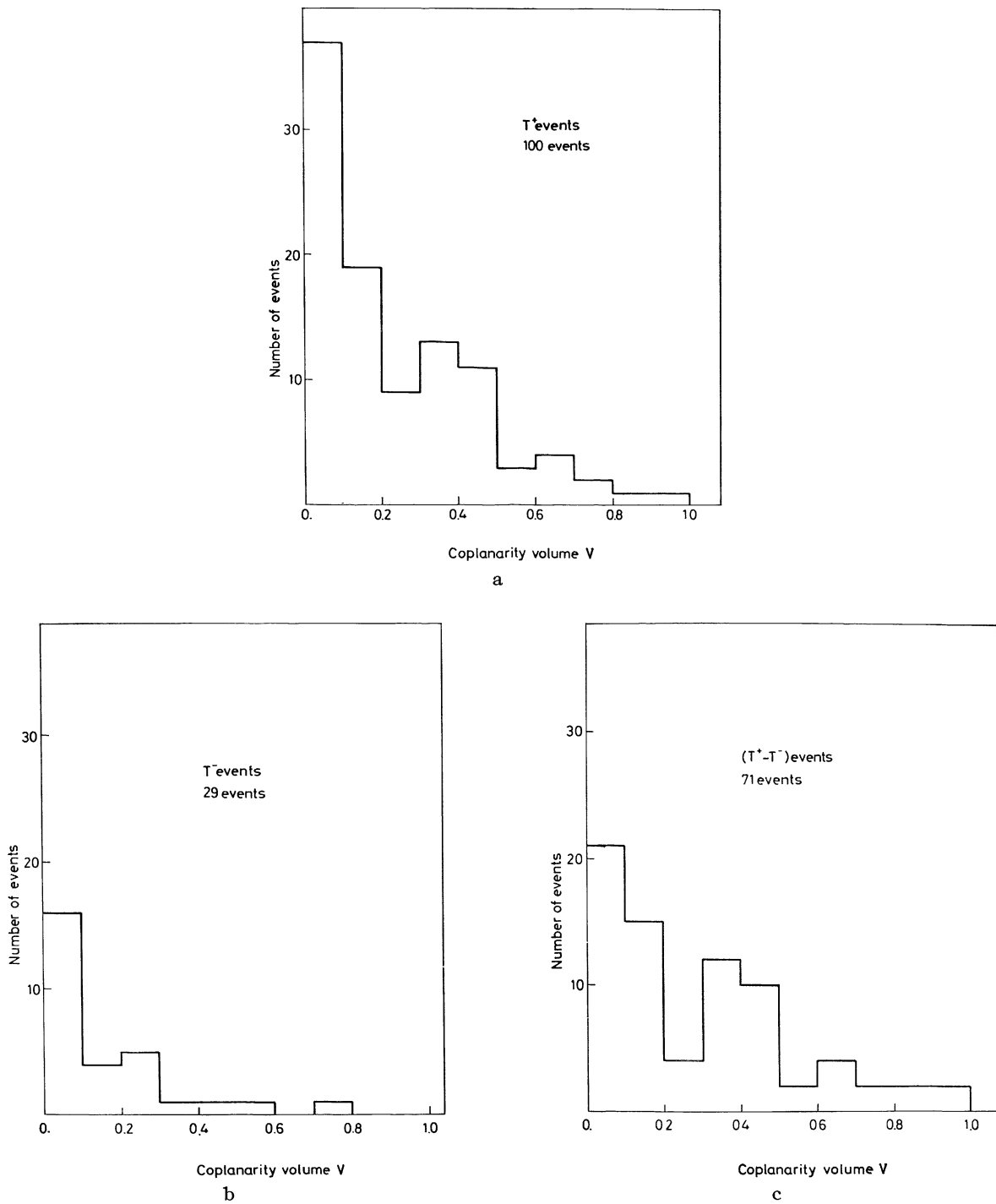


FIG. 5. — Distributions of the coplanarity volume V (see the text) at 23 GeV for :

- a) T^+ events.
- b) T^- events.
- c) $(T^+ - T^-)$ events.

In a similar manner one can obtain the observation efficiency of B events⁽⁶⁾. The final result for the corrected T/B ratio is $[(T^+ - T^-)/B]_{\text{corr}} = (4.9 \pm 1.3) \times 10^{-3}$. The corrected T/B ratio at 18 GeV has also been calculated from the data given in ref. [1] and found to be $(1.9 \pm 1.2) \times 10^{-3}$. On the assumption that the

cross-sections for the binary fission of uranium induced by 18 GeV and 23 GeV protons are respectively⁽⁷⁾ : $\sigma_B = (800 \pm 100)$ mb and (720 ± 100) mb, one obtains the cross-sections for ternary fission of uranium at these energies :

$$\sigma_T = (1.5 \pm 1.1) \text{ mb} \quad \text{and} \quad (3.5 \pm 1.2) \text{ mb.}$$

⁽⁶⁾ The details of the calculations will be given in a forthcoming publication on cross-sections for high energy nuclear fission.

⁽⁷⁾ To be published elsewhere.

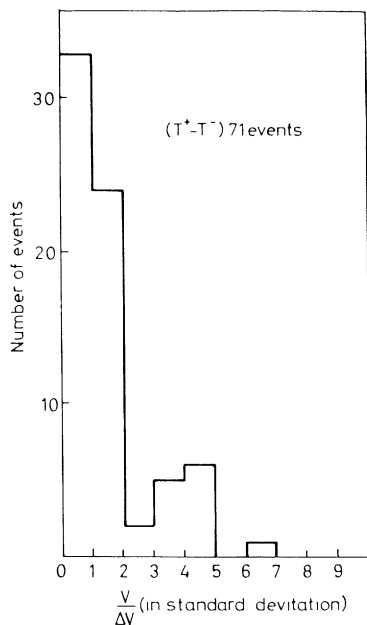


FIG. 6. — Distribution of the ratio of the coplanarity volume V to its error ΔV for $(T^+ - T^-)$ events.

4. **Summary.** — *a)* The observation of the process of ternary fission of uranium bombarded with high energy protons reported previously at 18 GeV [1] has been confirmed at 23 GeV.

b) The corrected ratios of ternary to binary fission events have been found to be $(1.9 \pm 1.2) \times 10^{-3}$ at 18 GeV and $(4.9 \pm 1.3) \times 10^{-3}$ at 23 GeV.

c) The majority of ternary fission events are coplanar within large experimental errors.

d) The distribution of the true angle in space between every pair of tracks of ternary fission events exhibits a maximum around 120° .

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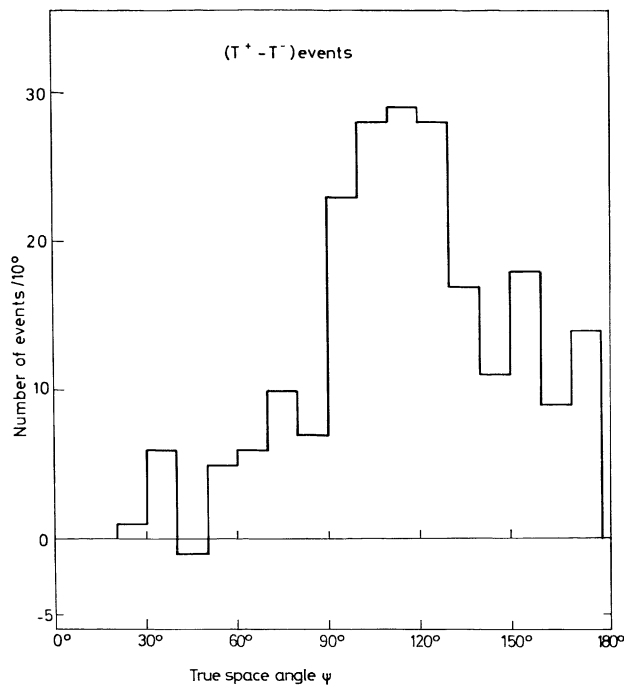


FIG. 7. — Distribution of the true space angle ψ between pairs of tracks for $(T^+ - T^-)$ events (see the text).

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Note added in proof: Recently, a publication appeared by J. Hudis and S. Katcoff, *Phys. Rev.*, 1969, **180**, 1120. It contains information concerning ternary fission induced by high-energy protons.

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