reaction. Those data also appear to follow the logarithmic derivative of the differential cross section, a result frequently noted in the comparison of elastic scattering cross-section and polarization distributions. This suggests that a simple method of calculation such as the diffraction method may be successful in describing these proton-polarization data. Reasonably good fits were obtained for the elastic scattering of protons and deuterons and the polarization of the scattered protons in order to supply the optical-model parameters at the appropriate nuclei for the stripping calculations. The deuteron stripping angular distribution was well described by the DWBA calculations using these parameters, but the proton polarization, in general, was not. Recent deuteron-polarization measurements[23] on other nuclei show that the deuteron distortion may be a sensitive function of the spin-orbit geometrical parameters which were not determined in this experiment. For the 1.05-MeV state, the DWBA calculations presented here fit the data well, out to about 60°, but not well at larger angles. The $^{90}Zr(d, p)^{91}Zr$ polarization for the ground state ($l_n = 2$) was found to be small out to 100° and the DWBA calculations did not reproduce the data even at forward angles.

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High-Energy-Proton Fission Cross Sections of U, Bi, Au, and Ag Measured with Mica Track Detectors*

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The interaction of 0.6–29-GeV protons with U, Bi, Au, and Ag was studied with mica track detectors. Binary fission events were identified as correlated pairs of tracks. A fragment registered an acceptable track if its mass was ≥ 30 and its kinetic energy > 6–8 MeV. The results show: The U fission cross section σ_f(U) is 1400 mb up to 1.0 GeV and decreases monotonically to 670 mb at 29 GeV; σ_f(Bi) increases from 125 mb at 150 MeV to a broad maximum of 215 mb at $\sim$600 MeV, and then decreases to 105 mb at 29 GeV; σ_f(Au) varies little, 59–76 mb, in the energy region 0.6–29 GeV (the highest values appear at 2 and 3 GeV); no binary events were observed from Ag targets: upper limits are 0.3 mb at 0.6 GeV, 2 mb at 1.0 GeV, 5 mb at 2–13 GeV, and 6 mb at 29 GeV. Effects of secondary particles were shown to be negligible; the experimental uncertainty varies from ± 10 to $\pm 20\%$. Ternary fission events (140) were seen for U starting at 1.0 GeV, and for Bi and Au starting at 2.0 GeV. The yields are about 1–2 per 1000 binaries. Many single unpaired tracks were also observed, and their yield increases with beam energy. From U, most of these seem to be from a small fraction of asymmetric fissions where one of the partners is below recording threshold. From Bi and Au, most of the single tracks are high-energy spallation residues.

INTRODUCTION

ALTHOUGH many measurements have been made of the proton fission cross sections of various elements at energies up to about 600 MeV, relatively few determinations have been carried out at higher incident proton energies.[1–4] One reason for the lack of such data is that in the GeV region, fission is no longer so clearly distinguishable from other types of processes. For example, at low and medium energies, radiochemical measurements of the yields of specific products give yield-versus-mass curves with well-defined peaks near half the target mass. At very high energies,[1] the peak may become very broad and its limits poorly defined (U^{238} at 28 GeV) or the peak may disappear altogether (Bi at 3 and 28 GeV). These observations indicate that other processes, such as spallation and fragmentation, may yield products in and near the fission-product mass region.

A technique in which two complementary heavy fragments are detected is superior to the radiochemical method for characterizing fission. In principle, multiparameter counter experiments[5] with Si detectors are well suited for the detailed study of high-energy fission. However, the complex nature of these experiments makes it impractical, at present, to use this method for measuring fission cross sections of a series of targets at a series of energies. The nuclear emulsion technique has been used[2,3] for measuring a few fission cross sections

* Research performed under the auspices of the U.S. Atomic Energy Commission.

[1] G. Friedlander, in *Physics and Chemistry of Fission* (International Atomic Energy Agency, Vienna, 1965), Vol. II, p. 265.

[2] H. G. de Carvalho, G. Cortini, N. Muchnick, G. Potenza, R. Rinzivillo, and W. O. Lock, Nuovo Cimento **27**, 468 (1963).

[3] N. A. Perfilov, V. F. Darovskikh, G. F. Denisenko, and A. I. Obukhov, Zh. Eksperim. i Teor. Fiz. **38**, 716 (1960) [English transl.: Soviet Phys.—JETP **11**, 517 (1960)].

[4] E. S. Matusevich and V. I. Regushevskii, Yadern. Fiz. **7**, 1187 (1968) [English transl.: Brookhaven National Laboratory Transl. No. BNL-TR-235 (unpublished)].

[5] L. P. Remsberg, Jr., J. B. Cumming, F. Plasil, and M. L. Perlman (unpublished).

at GeV energies but there was some difficulty in distinguishing between those events originating in the small amount of heavy element loading from those originating in the Ag and Br of the emulsion.

The development of solid-state track detectors,[6] such as plastics, glass, and mica, provides a relatively simple technique to measure fission cross sections. Mica and glass detectors are useful for high-energy measurements because fragments lighter than about mass 30 will not register. Thus much of the background arising from light-fragment emission is eliminated. Glass[4,7] has been used as a detector to measure fission cross sections of heavy elements at energies up to 9 GeV. Both mica[8] and plastic[9] were used to measure the range and angular distributions of fission tracks from binary and ternary events at energies up to 24 GeV. These last two groups of authors have also measured fission cross sections in the same energy region.[10]

In the present work, a sandwich technique was used in which a thin layer of target was placed between two sheets of mica. Cross sections were measured for the binary fission of U, Bi, and Au induced by 0.6-, 1.0-, 2.0-, 3-, 13-, and 29-GeV protons. In addition, the cross sections were determined for those events in which only a single track was recorded and for those events having three tracks.

EXPERIMENTAL

1. Target Preparation

Clear pieces of muscovite mica were cleaved and cut to rectangles of $1\times\frac{1}{2}$ in., 0.1 mm thick. Care was exercised to avoid scratching and contaminating the newly exposed surfaces. Thin target layers of Ag, Au, Bi, and UF_4 were evaporated onto the mica in vacuum. The thickness deposited was usually $\sim$100 μg/cm^2 for Ag and Au, $\sim$40 μg/cm^2 for Bi, and $\sim$10 μg/cm^2 for U. When sandwich targets were desired, a blank piece of mica was used to cover each metal-coated mica. Typical target stacks are shown in Fig. 1.

In order to achieve intimate contact between the cover mica and the evaporated metal target, pressure was applied. In the preliminary experiments $\frac{1}{4}$-in. aluminum plates were used. However, all of the cross-section data reported in this paper were obtained from mica sandwiches which were enclosed only between two sheets of heat-sealable Mylar 0.1 mm thick. The air between the Mylar foils was evacuated and the package was sealed. This technique of using atmospheric pressure to compress the target stacks was suggested by de Carvalho. The great advantage of this method is that one introduces a minimal amount of extraneous material in which secondary particles may be produced during the irradiations. Tests showed that the plastic seal maintains a sufficiently good vacuum in the target sandwiches for at least a week. In practice, the stacks were used within a few days after evacuation.

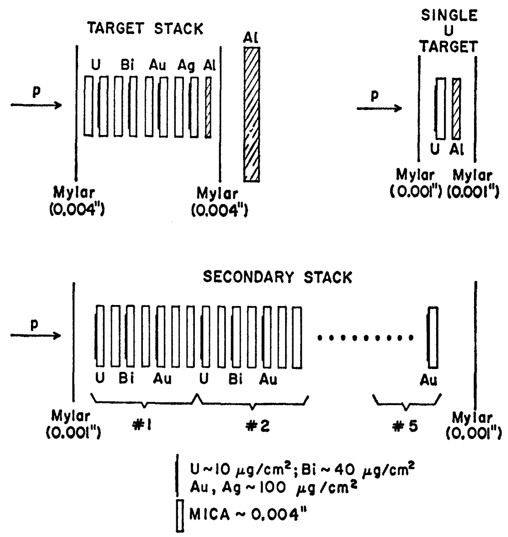

FIG. 1. Target and mica track detector stacks used in various experiments.

2. Etching and Realignment

After irradiation of a mica sandwich, three 1-mm-diam holes were drilled through a stack, near the edges, with a standard jig. It was at this time that the vacuum seal was first broken. The metal target was next quantitatively dissolved off the mica with nitric acid or aqua regia and its exact amount was determined by chemical analysis. The mica was etched with 27 N HF at room temperature for 30 min (standard time) and washed thoroughly with water and ethanol. After drying, the pair of mica foils from a sandwich was mounted on a lucite microscope slide in which 1-mm holes had been drilled with the same jig as that used for drilling the holes in the mica. Thus the two pieces of a sandwich could be repositioned, one over the other, with the aid of three 1-mm-diam pins. The two members were separated with narrow spacers 0.5 mm thick placed along the edges to allow only one mica surface to be in focus in the microscope at a time.

3. Observation and Counting of Tracks

The etched tracks could be seen clearly at magnifications of 150×, or higher. Matched pairs could be identified easily when the total track density was not

[6] R. L. Fleischer, P. B. Price, and R. M. Walker, Ann. Rev. Nucl. Sci. **15**, 1 (1965).
[7] V. A. Kon'shin, E. S. Matusevich, and V. I. Regushevskii, Yadern. Fiz. **2**, 682 (1965) [English transl.: Soviet J. Nucl. Phys. **2**, 489 (1966)].
[8] R. Brandt, F. Carbonara, E. Cieslak, M. Dakowski, Ch. Gfeller, H. Piekarz, J. Piekarz, W. Riezler, R. Rinzivillo, E. Sassi, M. Sowinski, and J. Zakrzewski, Nucl. Phys. **A90**, 177 (1967).
[9] M. Debeauvais, R. Stein, J. Ralarosy, and P. Cuer, Nucl. Phys. **A90**, 186 (1967).
[10] R. Brandt and M. Debeauvais (private communication).

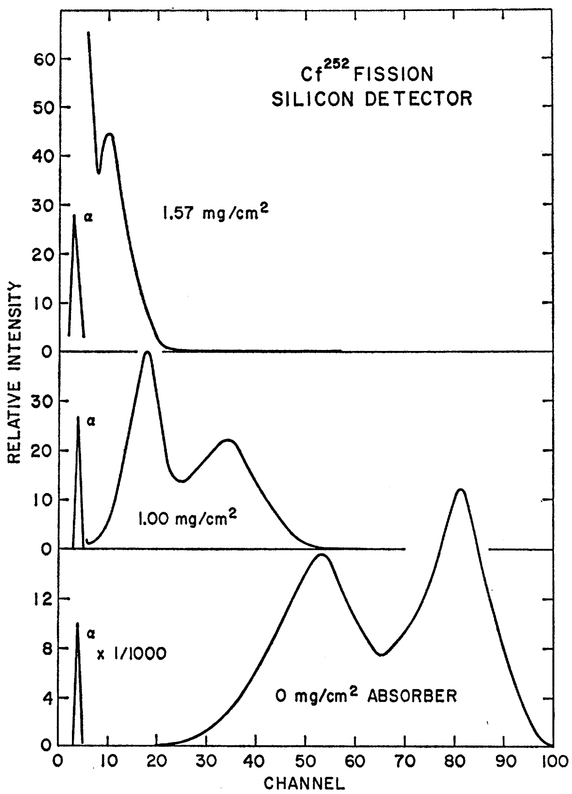

FIG. 2. Typical spectra of Cf^{252} fission fragments degraded with Mylar absorbers and observed with a Si detector. The intensity of the α-particle peak is reduced by 1000 in each case.

too high and when the relative number of unpaired tracks was not excessive.

The observation of pairs was greatly facilitated by the use of a photographic method. The inner surfaces of the two pieces of mica, which had been in contact with the target, were photographed separately on 35-mm film at a magnification of 25 or 40×. About 30 to 60 fields were selected which were uniformly distributed over the central 12×6 mm of the mica. The 35-mm negatives were further enlarged onto 8×10-in. high contrast film, yielding a total magnification of 150 or 230×. The paired sheets of film were examined on a light box, where, after slight adjustment, correlated pairs of tracks were found to be in alignment. These events were identified as binary fission. For quantitative measurement of the number of events per unit area, a scale calibration in 0.010-mm divisions was photographed at the beginning and end of each set of photos.

4. Irradiations with Thermal Neutrons

In order to test this method for measuring fission cross sections, several uranium-mica sandwiches (~60-μg/cm² U) were irradiated for a few minutes in the thermal column of the Brookhaven Graphite Reactor. Neutron fluxes were determined by means of small gold monitors. The 412-keV γ-ray intensity of Au^{198} was measured with a standardized 3×3-in. NaI crystal. A value of 99 b was used for the activation cross section, and a value of 0.04 for the conversion coefficient of the 412-keV transition.

After irradiation, the UF_4 was quantitatively removed from the mica with HNO_3 and submitted for chemical analysis. The mica rectangles were etched with 27 *N* HF for times varying between 10 and 60 min, mounted on lucite slides, and photographed in the manner described above. The number of matched pairs of tracks per unit area was determined for each of the various sandwiches. Mean values found for the thermal-neutron cross section of U from duplicate runs were 3.67, 4.28, and 3.98 b, respectively, for etching times of 20, 30, and 40 min. One run with a 10-min etch yielded a value of 3.25 b, while a single run with a 60-min etch resulted in a value of 4.52 b. The estimated error of the measurements is ±8%, resulting from the track identification and counting statistics (±5%), the Au^{198} activity measurement (±5%), and the U analysis (±3%). The accepted value for the natural U fission cross section[11] is 4.16±0.04 b, slightly higher than, but within the experimental error of, the mean value of 3.98±0.20 b measured here for the 20–40-min etching times. A small deficiency of paired tracks is to be expected because fragments entering close to grazing incidence may be scattered or may not register a hole in the mica. In fact, an additional (5±2)% single, unpaired tracks were observed. A correction of 5% was applied to all of the measured high-energy fission cross sections to compensate for this loss. An etching time of 30 min was used for all of the measurements.

5. Tests of Track Registration with Degraded Cf^{252} Fission Fragments

In low-energy heavy-element fission the fragment masses are 80 to 160 with energies between 50 and 120 MeV. The tests with thermal fission of U showed that

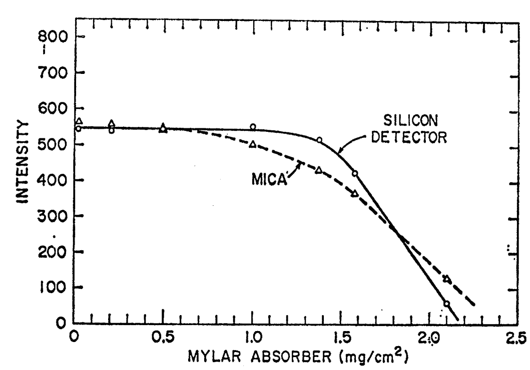

FIG. 3. Intensity of Cf^{252} fission fragments as a function of Mylar absorber thickness observed with mica track detectors and with a Si counter.

[11] D. J. Hughes and R. B. Schwartz, *Neutron Cross Sections* (U.S. Government Printing Office, Washington, D.C., 1958), 2nd ed., BNL 325.

pairs of such fragments are recorded in mica with at least 95% efficiency. In fission induced by high-energy particles, fragments can be expected which lie outside of these mass and energy ranges. Therefore a series of experiments was performed on the registration efficiency of Cf^{252} fission fragments of reduced energy.

A source of Cf^{252} in a vacuum chamber was covered, in sequence, with a series of six Mylar absorbers ranging up to 2.10 mg/cm^2 in thickness. A Si detector was placed immediately behind a 1.27-cm-diam defining hole at a distance of 10 cm from the source. The pulse-height spectrum of the fission fragments was measured with each absorber. A few of these spectra are shown in Fig. 2. All pulses above the α-particle peak were recorded as fissions. The Si counter was replaced by mica detectors positioned so that the fission fragments entered at angles of 45° and 18° to the surface. After exposure to fragments which were degraded in energy by the various absorbers, the mica detectors were etched in the standard fashion and the track densities were measured directly with a microscope. Tracks were accepted if their projected length was $\geq 1.6\,\mu$. The results at the two incident angles were identical within the statistical uncertainty of $\sim$3%.

Comparison of the number of tracks per cm^2 per minute of exposure with corresponding numbers of pulses recorded electronically is shown in Fig. 3. It is seen that the mica can record the light fission fragments down to slightly lower energy than the Si counter, while for the heavy fission fragments the situation is reversed. An estimate of the cutoff energies can be made by reference to the Cf^{252} α-particle peak in the pulse-height spectra. When a 2.10-mg/cm^2 Mylar absorber is placed over the source, the total number of fission fragments recorded in the mica is reduced to $\frac{1}{4}$ of the value with no absorber: The heavy group of fragments is absorbed completely, while about 50% of the light group is registered. With this same absorber the 6.1-MeV α particles of Cf^{252} are degraded to 4.1 MeV. The particle spectrum obtained with the Si counter exhibits a shoulder, above the α peak, which contains $\sim$25% of the light group of fission fragments. By extrapolating the shape of the fragment distribution from the shoulder it is estimated that the peak lies approximately under the α peak. From the known energy of the degraded α particles and the recent pulse-height defect experiments of Krulisch and Axtmann[12] it can be deduced that the mica efficiency for recording light fission fragments is 50% when their energy is $\sim$6 MeV. In a similar way, the 50% cutoff point for heavy fission fragments was found to be $\sim$8 MeV.

6. High-Energy Irradiations; Cross Sections

For the cross-section determinations the four target elements and an aluminum monitor (20 mg/cm^2) were vacuum-sealed in Mylar (Fig. 1) as described above. The external beam of the Brookhaven Cosmotron was used for irradiations at 0.6, 1.0, 2.0, and 3 GeV; the fast extracted beam of the Brookhaven AGS was used at 13 and 29 GeV. Both beams were slightly defocused in order to obtain a more uniform distribution over the target area. Usually the Cosmotron beam diameter (as seen on Polaroid film) was $\sim$4 cm; the AGS beam was $\sim$3 cm in diam. To further ensure an even beam distribution in the area of interest the targets were oscillated 2.5 cm in both dimensions perpendicular to the beam. In each experiment the profile of the beam was measured. Each target package was backed with aluminum foil (70 mg/cm^2) which was later cut into $\frac{1}{4}\times\frac{1}{8}$-in. segments. The activity in these was measured over an area of $\frac{3}{4}\times 1$ in. In general, the beam distribution was relatively flat ($\pm$10%) over the central $\frac{1}{4}\times\frac{1}{2}$-in. target area used for measuring cross sections. In a few cases it varied by as much as $\pm$30% over the usable target area. However, the measured beam distribution always was taken into account when calculating the cross sections.

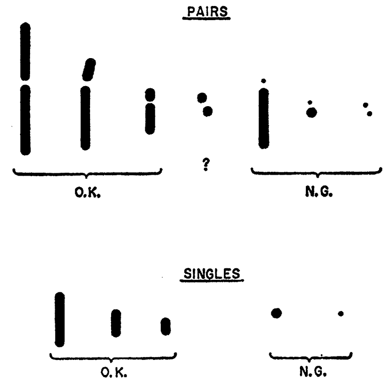

FIG. 4. Drawings of typical paired and unpaired (singles) events as seen in the mica. The smaller dots are exaggerated here; actually they were very tiny. N.G., unacceptable.

At the beginning of each experiment it was necessary to adjust the beam intensity so that a reasonable track density would be obtained in the mica for an exposure of reasonable duration. This was achieved by calibrating an ionization chamber placed in the external beam by means of the C^{11} activity induced in a 0.1-mm-thick polyethylene foil. The circulating proton beam intensity of the machine was adjusted so that irradiation times were in the range 3–30 min. Relative intensities in the external beam were monitored continuously by means of the ionization chamber. The absolute intensity was determined in each case by means of the aluminum monitor foil. The Na^{24} induced in the center $\frac{1}{2}\times\frac{1}{2}$-in. piece was counted with a calibrated end-window proportional counter. The absolute activity combined with the known values of the Na^{24} production cross sections[13] yielded the total number of protons passing through the target (typically $\sim 10^{11}$/cm^2).

[12] A. Krulisch and R. C. Axtmann, Nucl. Instr. Methods **55**, 238 (1967).

[13] J. B. Cumming, Ann. Rev. Nucl. Sci. **13**, 261 (1963).

TABLE I. High-energy fission cross sections σ_f in mb (binary events).

Target	E_p (GeV) 0.6	1.0	2.0	3.0	13	29
U	1405±160	1385±95	1053±69	969±11	814±39	668±34
Bi	216±8	191±5	165±14	161±10	122±15	105±22
Au	59±5	66±7	76±5	76±5	67±11	63±4

After each irradiation the target material was quantitatively removed, the mica etched, and the tracks photographed and counted as described above. At the lower energies identification of nearly all matched pairs of tracks was clear and unambiguous. At the higher energies many very tiny etch pits were seen and some of them were paired. The abundance of these is a steep function of the etching time, while the number of tracks is almost independent of etching time (>20 min). With a 30-min treatment, these small pits did not interfere seriously with the measurements, but they contributed appreciably to the errors at 13 and 29 GeV. An event was recorded as a binary fission if each track was $\geq 1.6\,\mu$ in projected length. In most cases at least one of the two tracks was $\geq 4\,\mu$; the longest projected lengths were $\sim 15\,\mu$. Figure 4 shows drawings of various kinds of observed events. Borderline cases amounted to a few percent and these were counted as half an event each.

In addition to the correlated tracks observed in the matched pairs of photographs, the single unpaired tracks were recorded also. These were accepted only if they were $\geq 4\,\mu$ in projected length (Fig. 4). The uncertainty of identification is considerably greater here than for the binary events.

A small number of events was observed with three tracks originating from a common point. These were recorded as ternary fission and they are discussed below.

All the photographs were scanned twice, once each by two scanners. The agreement was excellent, in most cases within 5%. During the course of the work, over a period of 2 yr, one typical set of photographs (Au at 3 GeV) was scanned periodically as a check on the stability of the scanning criteria. All of the track counts were found to be constant with a mean deviation of ±5% from the average.

7. High-Energy Irradiations; Secondary and Background Effects

In order to study the effect of secondary particles on the measured cross sections, thick stacks of targets (called "secondary stacks") and special thin targets were also irradiated (Fig. 1). These targets were not vacuum-sealed because they were intended only for the counting of single tracks. The secondary stacks had five targets each of U, Bi, and Au distributed among 33 pieces of mica. The standard cross-section stack had eight pieces of mica. The special thin targets had only one piece of mica on which was evaporated 10 μg/cm^2 of U; this was backed with an Al monitor foil (20 mg/cm^2) and covered completely with a 0.001-in. Mylar foil.

The secondary stacks and the thin U targets were exposed in the same beams as the standard targets. The intensity of the protons was measured with Al monitors as described above. After etching, each piece of mica was mounted separately for direct microscopic examination and track counting. A 20× dry objective was used with a total magnification of about 300×.

The background of tracks which did not originate in the target layer was negligible in all cases except for Ag. In several runs at 0.6 and 29 GeV the single-track densities were measured also on the mica surfaces which were not exposed to the target. The numbers corresponded to a background effect of $\ll$1% at both energies for U, Bi, and Au targets. Ag is discussed separately below.

RESULTS

1. Binary Events

The total number of binary events observed in each experiment was converted to a fission cross section by means of the expression $\sigma_f = F/NP$, where σ_f is the cross section in cm^2 for binary fission, F is the number of observed binary events per cm^2, N is the number of target atoms per cm^2, and P is the number of incident protons per cm^2. F was obtained from the number of paired tracks seen in the photographs in a known area, N from the chemical analysis of the target dissolved off the mica, and P from the amount of Na^{24} induced in the Al monitor foil.

The measured cross sections for binary events are listed in Table I. The only correction applied was for the 5% loss of real binary events as discussed above in the section on the thermal-neutron calibration experiment. No correction was necessary for fissions induced by secondary particles (see below).

The results listed in Table I are based on three to six separate determinations for each target at each energy. The errors shown are standard deviations. In addition, there are uncertainties in the value of the monitor cross section (±7%) and systematic scanning errors. The large number of unpaired tracks relative to pairs in

TABLE II. Cross sections σ_s for production of single, unpaired tracks, ratios of σ_s/σ_f, and total observed cross sections $\sigma_s+\sigma_f$.

Target		E_p (GeV) 0.6	1.0	2.0	3.0	13	29
U	σ_s/σ_f	0.14	0.16	0.26	0.43	0.53	0.45
	σ_s (mb)	196	221	273	417	431	301
	$\sigma_f+\sigma_s$ (mb)	1600	1610	1330	1390	1250	970
Bi	σ_s/σ_f	0.24	0.34	0.44	0.70	1.37	1.36
	σ_s (mb)	52	64	73	113	167	142
	$\sigma_f+\sigma_s$ (mb)	268	255	238	274	289	247
Au	σ_s/σ_f	0.29	0.53	0.73	1.13	2.27	2.27
	σ_s (mb)	17	35	55	86	152	143
	$\sigma_f+\sigma_s$ (mb)	76	101	131	162	219	206

the Au irradiations at 13 and 29 GeV make the corresponding results less certain than the others. We estimate an over-all uncertainty of ±10% for the U results, ±15% for the Bi results, and ±15 (0.6–3 GeV) to ±20% (13 and 29 GeV) for the Au data.

2. Single Unpaired Tracks

During the scanning for binary events, single unpaired tracks $\geq 4\,\mu$ in projected length were recorded also. The corresponding cross sections σ_s are listed in Table II. Also given are the ratios of singles to binaries σ_s/σ_f and the sums $\sigma_s+\sigma_f$. The observed numbers of single tracks were corrected by subtracting 5% of the binary events found in each case. This was in order to correct, in an approximate way, for those binary events which recorded as singles because the fragments entered the mica near grazing incidence. The data given on the single unpaired tracks should be considered as approximate because the observed density depends somewhat on the etching time. Relative values, of course, are more reliable than the absolute cross sections.

TABLE III. Relative intensity of single tracks measured as a function of depth in thick mica stacks. Numbers are expressed in mb; each value obtained from two experiments measured by two scanners.

0.6 GeV Position[a]	U	29 GeV Position[a]	U	Bi	Au
1	1722	1	891	195	141
2	1631	2	860	197	132
3	1607	3	978	207	139
4	1658	4	873	208	131
5	1481	5	803	205	139
Single[b]	1697	Single[b]	974		

[a] Numbers 1–5 refer to position of foil in the secondary stack (see Fig. 1).
[b] Target consisted of one piece of mica with $\sim$10 μg/cm^2 of U. Result is the average of duplicate runs at 0.6 GeV and triplicate runs at 29 GeV.

3. Effect of Target Stack Thickness; Secondaries

Table III shows the relative intensity of single tracks observed as a function of depth in the mica secondary stacks (Fig. 1). The beam struck the U in position 1 after passing through only a thin Mylar cover (0.001 in.), but it encountered the U in position 5 after passing through 30 pieces of mica (0.12 in.). The numbers in the table are given in mb, since each stack was monitored with an Al foil. There is no significant trend with depth in the stack at either 0.6 or 29 GeV. Furthermore, the U results obtained with thin targets, consisting of 10 μg/cm^2 of U on a single piece of mica backed with 20 mg/cm^2 of Al, were the same, within experimental error, as those obtained with the thicker targets. Since the total thickness of the target stacks was $\frac{1}{4}$ that of the secondary stacks, the effect of secondary particles was considered negligible in the cross-section measurements.

4. Ternary Fission

During the routine scanning for binary fission events a small number of three-pronged stars was observed and recorded. These were later carefully reexamined and all doubtful cases were eliminated. Although no detailed measurements of track lengths or angles were made, events were discarded if it appeared likely that they consisted of a correlated pair of tracks and an accidental unpaired track. A total of $\sim$140 ternary fission events were seen. Their distribution among the various targets and bombarding energies is shown in Table IV. Absolute cross sections and ratios to binary events are also given.

5. Tracks from Ag Targets

Attempts to find correlated pairs of tracks from the Ag targets were not successful, although unpaired tracks were found in both the forward and backward

TABLE IV. Observations on ternary fission: numbers observed, cross sections σ_t in mb, and ratios σ_t/σ_f.

Target		E_p (GeV) 0.6	1.0	2.0	3.0	13	29
U	Number	0	5	3	13	4	7
	σ_t(mb)	≤0.1	1.1	0.4	1.7	0.6	0.4
	σ_t/σ_f ($\times 10^3$)	≤0.1	0.8	0.4	1.7	0.8	0.6
Bi	Number	0	0	12.5[a]	17.5[a]	10	3
	σ_t(mb)	≤0.02	≤0.02	0.2	0.4	0.2	0.03
	σ_t/σ_f ($\times 10^3$)	≤0.1	≤0.1	1.0	2.2	1.4	0.3
Au	Number	0	0	12	21.5[a]	6	12
	σ_t(mb)	≤0.005	≤0.006	0.1	0.2	0.1	0.1
	σ_t/σ_f ($\times 10^3$)	≤0.1	≤0.1	1.2	3.1	1.4	1.3

[a] Half-integer values result from averaging data of two scanners.

pieces of mica. These results are shown in Table V. Small background corrections were made by counting the tracks on the mica surfaces which were not in contact with Ag. The table also gives the forward-to-backward ratios, the total cross sections for production of unpaired tracks, and estimated upper limits for correlated pairs.

DISCUSSION

The results on binary fission shown in Table I have been plotted in Fig. 5, together with selected data from other work.[7,14,15] It is seen that the U fission cross section is fairly constant at 1400 mb from 150 MeV to 1.0 GeV. Above this energy there is a slow monotonic decrease in the binary fission cross section to 670 mb at 29 GeV. The Bi fission cross section increases from 125 mb at 150 MeV to a broad maximum of 215 mb centered at ~600 MeV. This is followed by a steady decrease to 105 mb at 29 GeV. The σ_f of Au increases from 25 mb at 150 MeV to 76 mb at 2 and 3 GeV; at 29 GeV the observed cross section is 63 mb. However, this apparent decrease may not be real because of the errors associated with the measurements.

A decrease in the fission cross sections of U and Bi at very high energies was reported previously by de Carvalho *et al.*[2] from nuclear emulsion data. Although our results are in reasonable agreement with theirs at 600 MeV, their values at 20 GeV are lower than our interpolated results by about a factor of 2. The discrepancies are probably due to differences in selection criteria.

Comparison of our mica experiments with the work in which glass was used also shows some substantial discrepancies. The glass data[7] up to 660 MeV are plotted as triangles in Fig. 5, and one can see that at 600 MeV the agreement is good for Bi and Au and fair for U. However, at higher energies[4] the glass experiments gave much lower values of σ_f for U: 620 mb at 1.0 GeV, decreasing slowly to 490 mb at 9 GeV. On the other hand, glass detectors gave high values of σ_f from Bi: ~280 mb, independent of energy between 1.0 and 9 GeV. We measured 191 mb at 1.0 GeV and 120 mb (interpolated) at 9 GeV. It is not clear from the reports in the literature[4,7] whether the glass technique accurately recorded all high-energy binary fission events or if binary events could be readily separated from single-track events.

Friedlander[1] has made estimates of the U and Pb fission cross sections at high energies from radiochemical measurements. Upper limits for U at 2.9 and 28 GeV are 1280 and 1210 mb, respectively; lower limits are 830 and 480 mb, respectively (arrows in Fig. 5). The uncertainty is in the identification of the fission products from the yield-versus-mass curves. For Pb, only upper limits could be estimated because the yield-versus-mass curves show no fission peaks. The values are 270 and 310 mb, respectively, at 2.9 and 28 GeV.

The observed decrease in the fission cross sections at very high beam energy may be related to the gradual increase in mean excitation energy of the target nuclei. Monte Carlo calculations[16] have shown that the average ratio of neutrons to protons emitted during the cascade is similar to the ratio of neutrons to protons in the struck nucleus and that the average excitation energy of the cascade products increases with the complexity of the cascade. Thus, as the incident proton energy is increased, the spectrum of cascade products shifts towards regions of lower mass, lower values of Z^2/A,

[14] L. Kowalski and C. Stephan, J. Phys. Radium **24**, 901 (1963).
[15] M. Maurette and C. Stephan, in *Physics and Chemistry of Fission* (International Atomic Energy Agency, Vienna, 1965), Vol. II, p. 307.
[16] N. Metropolis, R. Bivens, M. Storm, J. M. Miller, G. Friedlander, and A. Turkevich, Phys. Rev. **110**, 204 (1958).

TABLE V. Track production cross sections, in mb, from Ag targets. The uncertainty in the mica results is ±20%.

Proton energy (GeV)	0.6	1.0	2.0	3	13	29
Pairs in mica	≤0.3	≤2	≤5	≤5	≤5	≤6
Pairs in emulsion[a]		7±2	30±7	50±10		
Unpaired forward	2.8	8.2	28	27	28	30
Unpaired backward	≤0.3	2.2	9.9	10.7	14.9	19
Forward+backward	3	10.4	38	38	43	49
Forward/backward	≥9	3.7	2.8	2.5	1.9	1.6

[a] Reference 21.

and higher excitation energy. Although it is difficult to separate the dependence of σ_f on Z^2/A and on E^*, there is evidence[17] that Z^2/A is the predominant factor. The values of σ_f shown in Table I combined with the results of the cascade calculations mentioned above support this hypothesis.

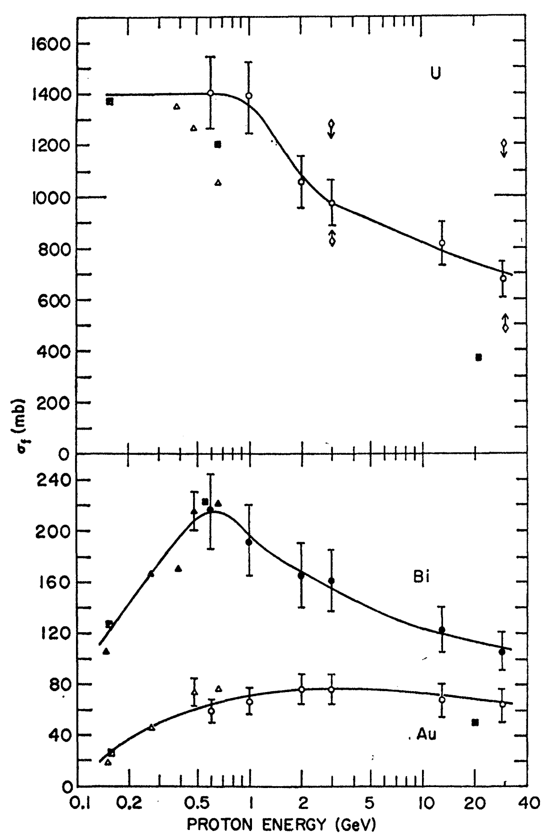

FIG. 5. Binary fission cross sections of U, Bi, and Au as a function of incident proton energy, 150 MeV to 29 GeV. Circles (●, ○), present work with mica track detectors; triangles (▲, △), glass detectors, Ref. 7; solid squares (■), U- and Bi-loaded emulsions, Ref. 2; half-filled squares (◩), mica track detectors and Si counters, Refs. 14 and 15; diamonds (◇), radiochemical data, Ref. 1.

[17] E. Hyde, *The Nuclear Properties of the Heavy Elements* (Prentice-Hall, Inc., Englewood Cliffs, N.J., 1964), Vol. III, pp. 401–485.

The origin of the single unpaired tracks can be sought in two types of processes: (a) asymmetric fission where one of the partners is below recording threshold and (b) spallation where the residue is of sufficiently high kinetic energy to give an acceptable track. That the first mechanism plays an important role is indicated by the fact that the unpaired fragment cross sections for U are much larger than for Bi or Au, especially at the lower beam energies (Fig. 6).

It is possible to estimate the contribution of high-energy spallation processes to the observed cross section for single tracks from U irradiated with 2–3-GeV protons. Pate and Poskanzer[18] found values of 3–4 mb per mass number in the 220–230 mass region and Crespo *et al.*[19] estimated ∼3 mb as the spallation contribution at mass 131 and ∼0.6 mb at mass 103. From these data one can assume that $\sigma_{\text{spall}}(A)\lesssim 3$ mb per mass number between $A=230$ and $A=130$ and decreases to ∼0.6 mb at $A\sim 100$. In addition, the energy spectra of Tb^{149} produced from gold[20] and Ba^{131} from uranium[19] have been measured. The fraction $f(A)$ of recoiling spallation products which have energies >15 MeV (the approximate cutoff value for single tracks in this experiment)

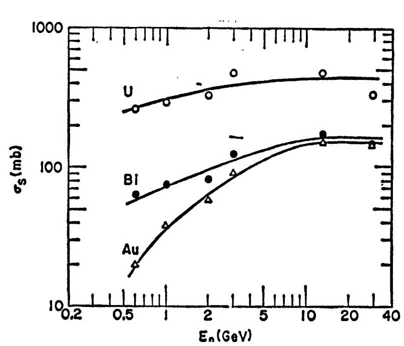

FIG. 6. Cross sections for production of unpaired tracks in mica track detectors 0.6–29 GeV.

[18] B. D. Pate and A. M. Poskanzer, Phys. Rev. **123**, 647 (1961).
[19] V. P. Crespo, J. B. Cumming, and A. M. Poskanzer, Phys. Rev. **174**, 1455 (1968).
[20] V. P. Crespo, J. B. Cumming, and J. M. Alexander (private communication).

can be calculated from the results of Crespo *et al.*[19] These figures are rather small: $\sim 1\frac{1}{2}\%$ of the Tb^{149} nuclei produced from Au and $\sim 17\%$ of the spallation produced Ba^{131} from U. Assuming that the shapes of the momentum spectra of spallation products are nearly independent of target and product nuclei but depend only on ΔA, the mass difference between the two, one can evaluate $f(A)$ as a function of ΔA. A calculation in which $\sigma_{\text{spall}}(A)$ is multiplied by $f(A)$ for values of A between 100 and 200 yields $\sim$50 mb for the cross section of spallation residues which would have been recorded as single tracks in mica. The observed cross section at 3 GeV is 417 mb (Table II). Thus for energies at least up to 3 GeV the single tracks from U must be due mainly to binary fission events in which one partner was below recording threshold in mica. At 13 and 29 GeV, the contribution of spallation to the single tracks from U is probably more important, because apparently the total spallation cross section is larger, while the fission cross section is smaller.

From Bi and Au targets there are even fewer data available to aid in the interpretation of the σ_s results. However, it is known that the fission cross sections for these elements (Table I) are factors of 6 to 20 lower than for U, whereas the total inelastic cross sections differ by only 20%. Thus spallation reactions must account for most of the total cross section for Bi and Au. For these elements as targets, most of the single tracks in mica are probably from spallation products with kinetic energies >15 MeV. If the 50-mb figure for σ_s(U) due to high-energy spallation residues is taken at face value, then $\sim$2.5% of the inelastic cross section of U results in such products. It is reasonable to assume that the same fraction or more of the inelastic cross section of Bi and Au lead to similar products. On the basis of this argument, one would expect at least $\sim$45 mb for σ_s(Bi) and σ_s(Au) due to spallation products. This figure is close to the measured values of σ_s(Au) at 2 and 3 GeV (55 and 86 mb) and only about a factor of 2 below the σ_s(Bi) figures (73 and 113 mb).

At the very highest beam energies the distinction between fission reactions and spallation reactions becomes blurred. The term "spallation" has been used in general to describe a reaction in which many nucleons or small aggregates of nucleons (e.g., α particles) have been emitted. However, at high energies there is an increased probability that fragments heavier than α particles are emitted during the deexcitation process. The mass of these fragments may extend up to as high as mass 50 for heavy-element targets and their cross sections rise about a factor of 2 or 3 between 3 and 29 GeV. One has reached the situation where any distinction between asymmetric fission and fragment emission may be a purely semantic one. Events of this type contribute to the unpaired tracks seen in mica detectors when the mass of the fragment is ≥ 30 or when the energy of the spallation residue is ≥ 15 MeV. There is a small probability that both fragments will record, and such events are indistinguishable from fission. Their frequency should increase with the bombarding energy. Indeed, the lack of a marked decrease in the observed σ_f for Au at 13 and 29 GeV may be due to appreciable contribution from these highly asymmetric events.

The ternary fission cross sections of U, Bi, and Au in the range 2.0–29 GeV are roughly 0.1% of their binary fission cross sections. At 0.6 GeV, $\sigma_t/\sigma_f \leqq 0.01\%$. The data of Table IV suggest that there may be a moderate decrease in σ_t/σ_f between 3 and 29 GeV but the small number of events make this uncertain. Brandt *et al.*[8] measured the ratio of ternary to binary fission of U at 18 GeV with mica detectors and found a value of $1:(760\pm 150)$, which is consistent with the results given here. Thus, ternary fission into fragments of roughly comparable mass is a rare process even at very high energies. Debeauvais *et al.*,[9] who used plastic detectors, found that ternary fission of U at 18 GeV amounts to about 2% of binary fission but one of the three fragments was very likely of mass 20–30.

The data from irradiation of Ag targets. (Table V) fail to show correlated pairs of tracks in mica; upper limits of 5 mb are set in the range 2.0–13 GeV. Nuclear emulsion data[21] at 2–3 GeV give cross sections of $\sim$40 mb for events which show two dense tracks in roughly opposite directions. However, most of these tracks were ascribed[21] to fragments of mass 15–35, and therefore the probability is low that both of them will record in mica. It is probable that one of the two will record. The total single unpaired track cross sections increase from 3 mb at 0.6 GeV to 50 mb at 29 GeV. The forward/backward ratio decreases from 3.7 at 1.0 GeV to 1.6 at 29 GeV.

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[21] S. Katcoff, Phys. Rev. **164**, 1367 (1967).