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Antiproton- and Pion-Induced Fission at 2.5 GeV/c†

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Mica track detectors were used to measure the fission cross sections of U, Bi, and Au irradiated with 2.5-GeV/c antiprotons and negative pions. The binary-fission results in mb are: U, 2170 ± 330 for $\bar{p}$ and 1090 ± 160 for π^-; Bi, 293 ± 60 for $\bar{p}$ and 191 ± 40 for π^-; Au, 210 ± 40 for $\bar{p}$ and 107 ± 20 for π^-. The π^- cross sections are about the same as for protons but the $\bar{p}$ cross sections are higher by about a factor of 2. Approximate ternary-fission results in mb are: U, 8 for $\bar{p}$ and 4 for π^-; Bi, 6 for $\bar{p}$ and 1.5 for π^-; Au, 6 for $\bar{p}$ and 2 for π^-. Ternary fission induced by antiprotons appears to be about an order of magnitude more probable than that induced by protons of the same momentum. The results are discussed relative to the large annihilation cross section of antiprotons.

INTRODUCTION

When antiprotons interact with complex nuclei large excitation energies are deposited[1] because of the high probability of annihilation. At 2.5 GeV/c the antinucleon-nucleon annihilation cross section σ_{anh} is about $\frac{1}{2}$ of the total cross section.[2-4] At lower momenta σ_{anh} is an even larger fraction of the total. In a complex nucleus an antiproton cannot survive more than 2–3 collisions without being annihilated. About five pions are produced[2] and some of these are reabsorbed[5,6] in the nucleus with deposition of considerable excitation energy. Only a few reports have appeared[1,7,8] which give experimental information on the product nuclei resulting from such reactions. This is mainly because high-purity antiproton beams have been available only at very low intensity (~100 $\bar{p}$/sec).

In this paper we report the cross sections of antiproton- and π^--induced fission measured with mica track detectors. The results are compared with previous data[9-12] on high-energy proton-induced fission of U, Bi, and Au. No previous report on antiproton-induced fission has been found in the literature. Fission induced by pions up to 300 MeV has been studied to a small extent.[13,14]

EXPERIMENTAL

The experimental method is similar to that used previously[9] but several changes were made. The mica was cleaved to a thickness of 0.1 mm and cut into 51 × 19-mm rectangles. Clear pieces were selected, annealed at 550°C for 14 h, and pre-etched for 5 h in 27 N HF at 23°C. Target layers of Au, Bi, and UF_4 were evaporated onto separate pieces of mica in thicknesses of ~300 μg/cm^2. These were stacked as shown in Fig. 1. The stacks were vacuum sealed between sheets of 0.1-mm heat-sealable Mylar and thus all the layers were pressed tightly together by atmospheric pressure.

Two stacks, spaced 10 cm apart, were irradiated simultaneously in the medium-energy separated beam[8] slightly upstream from the 30-in. bubble chamber at the Alternating Gradient Synchrotron (AGS). The purity of the antiproton beam was about 99% with respect to charged particles; neutral particles were shown[8] to be <3%. The muon and electron contamination in the π^- beam was estimated as ≤2%. Each beam had a spread of about 1 cm vertically full width at half maximum and 4.5 cm horizontally. The intensity was monitored with a counter telescope consisting of two thin plastic detectors. Since only about 80 antiprotons per sec were available, it was necessary to irradiate the targets in this beam for about 20 days. The negative-pion beam intensity was ~2.5 × 10^4 per sec so that a 15-h irradiation was adequate. The counter telescope was calibrated several times during each run with 100-μ-thick Ilford G.5 pellicle emulsions,[15] placed adjacent to the targets. The incident particles entered normal to the surface and registered plunging tracks in the emulsion. By careful scanning, accurate profiles of the beam were obtained. The shape of the beam remained nearly constant during the run but its position drifted up and down by a few mm. This position drifted up and down by a few mm. This effect was small but it was taken into account when the number of incident projectiles (Table I) was calculated by numerical integration over the target area.

After the irradiations the target stacks were placed in a standard jig and five 1-mm-diam holes were drilled through the mica near the corners. The target layer on each piece of mica was dissolved off with acid and its mass determined by chemical analysis (Table I). Etching was performed by immersion of the mica in 27 N HF at

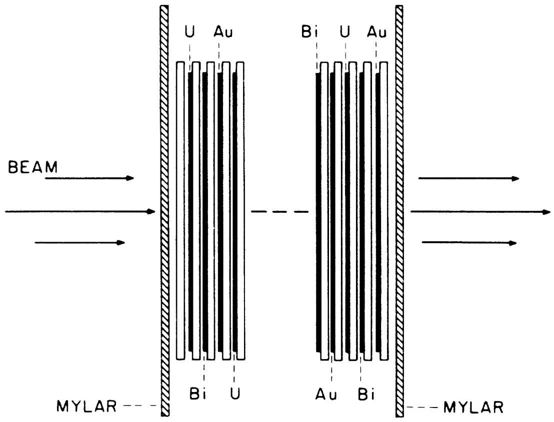

FIG. 1. Stack of targets on mica, 51×19 mm. Each target, ~0.3 mg/cm^2 thick, was evaporated onto a piece of mica 0.1 mm thick. Five layers of each target (total of 15) were vacuum sealed between two sheets of 0.1-mm Mylar.

room temperature for 90 min. Then two adjacent pieces of mica, one over the other, were brought into alignment with pins, and mounted on a Lucite slide that had five holes pre-drilled exactly as in the target stack. No spacer was placed between the two micas (as was done previously[9]), and thus both etched tracks of a matched pair, at the two inner mica surfaces, could be seen in the microscope simultaneously. With the normal magnification of 150× one track was in focus while the other one was slightly out of focus. Etched tracks at the outer two mica surfaces were completely out of focus, and thus did not interfere with the scanning.

The fission-track densities obtained in these pion and antiproton irradiations were much lower than those obtained previously[9] in the proton irradiations. Thus it became easier to distinguish correlated pairs of tracks from chance pairs of single tracks. However, due to the lower track density it was necessary to scan larger areas of mica. This was done by scanning directly with the microscope rather than by means of photomicrography, as was done earlier,[9] because direct scanning is more efficient at low track densities. The rate of scanning was increased by use of the relatively low magnification of 150×. However it was necessary to etch the tracks to a larger diameter than before: 90 min in HF instead of 30. A few pieces of mica were scanned first after a 30-min etch and then rescanned after an additional etch of 60 min. By slight adjustment of the scanning criteria the numbers of fission events counted remained the same, within an uncertainty of ±5%. Each piece of mica was scanned at least twice; the detection efficiency for fission events was >90% in nearly every case. For the unpaired tracks the efficiencies were ~80% for U targets and ~70% for Bi and Au targets.

On the basis of the test experiments reported previously[8,9] it was assumed that effects of the following are negligible: (1) beam impurities such as neutral particles or muons; (2) secondary particles produced by the beam in the target stack; and (3) events originating in the mica rather than in the target layer.

RESULTS

The numbers of events obtained from the mica scanning are listed in Table I. Corrections were made for detection efficiency and for those true binary events (5%) which record as singles when the fragments enter the mica near grazing incidence.[9] Cross sections were calculated from the expression $\sigma = F/NP$, where F is events/cm^2, N is target atoms/cm^2, and P is incident projectiles/cm^2.

The binary-fission cross sections are listed in Table II, where they are compared with the corresponding values for proton-induced fission.[9] Overall experimental uncertainties were estimated by considering the statistical errors and the errors involved in the scanning of emulsions and mica (e.g., events which failed to record or events which were incorrectly identified). These uncertainties are ±15% for U targets and ±20% for Bi and Au targets. With protons as projectiles[9] the uncertainties were ±10 and ±15%, respectively.

TABLE I. Irradiation and scanning data: interaction of 2.5-GeV/c antiprotons and negative pions with U, Bi, and Au. Events are recorded as tracks in mica.

Beam target	1.33×10^8 Antiprotons U	Bi	Au	1.47×10^9 Pions U	Bi	Au
No. of target layers	5	6	8	2	4	6
Target atoms/cm^2 (units of 10^{18})	3.80	6.77	9.95	1.59	3.26	5.10
Area scanned (cm^2)	33.6	40.3	53.8	13.4	26.9	40.3
Binary-fission events	1095	265	279	2547	917	804
Ternary-fission events	4	5	7	9	7	14
Single, unpaired events	740	71	126	457	202	241

TABLE II. Fission of U, Bi, and Au by antiprotons, negative pions, and protons: cross sections and cross-section ratios. The estimated experimental uncertainties are ±15% for U, ±20% for Bi and Au.

	Projectile	Kinetic energy (GeV)	U	Bi	Au
Binary-fission cross sections, σ_f, (mb)	$\bar{p}$	1.73	2170	293	210
	π^-	2.36	1090	191	107
	p	1.7	1150 [a]	180 [a]	75 [a]
	p	2.4	1020 [a]	163 [a]	76 [a]
Cross-section ratios	$\bar{p}/\pi^-$	2	2.0	1.5	2.0
	$\bar{p}/p$	1.7	1.9	1.6	2.8
	π^-/p	2.4	1.1	1.2	1.4

[a] Data from Hudis and Katcoff, Ref. 9. Brandt *et al.* (Ref. 10) report for 2.9-GeV incident protons: U, 1070 ±160 mb; Bi, 227±33 mb; Au, 93±15 mb.

Inspection of Table II shows that π^--induced fission cross sections are about equal to, or slightly larger than, the corresponding proton-fission cross sections. However, the $\bar{p}$-induced-fission cross sections are higher by about a factor of 2.

Fission of U, Bi, and Au into three large fragments was found to be roughly 0.1–0.2% of binary fission when high-energy protons were used as projectiles.[9,12] Table III shows that the probabilities for ternary fission are 5- to 10-fold greater when the targets are irradiated with antiprotons or negative pions. The relative increase appears to be greater for Bi and Au than for U, and greater for antiprotons than for pions.

Table IV shows the cross sections σ_s for production of single, unpaired tracks ≥ 4-μ projected length. The uncertainty of identification and the scanning errors are considerably greater than for the binary and ternary events. Comparison of the results obtained with different projectiles should be made with care. Comparing the $\bar{p}$ and π^- results with each other is more reliable than the comparison of either with the proton results[9] because the latter were obtained by a somewhat different method (photographic instead of direct scanning). Thus it appears that for Bi or Au targets the ratio of single-track events to binary events, σ_s/σ_f, is roughly the same for antiproton irradiation as for negative-pion irradiation. However, for a U target this ratio is about 3.7-fold larger in $\bar{p}$ irradiations. The cross section for unpaired-track production from 1.73-GeV antiprotons interacting with U is surprisingly large: ~1460 mb. The single tracks cannot be attributed to a background of fossil-fission tracks, because most of these were annealed out before the irradiation and the remainder were pre-etched to very large diamond-shaped pits.

DISCUSSION

Very few measurements have been reported[16,17] on the absorption cross sections of antiprotons on nuclei. However, the following approximate values at 2.5 GeV/c have been derived from recent unpublished data[18]: Ag, 1500 mb; Au, 2200 mb; Bi, 2300 mb; U, 2500 mb. These cross sections are 32% greater than those of protons[19,20] or pions.[17] Thus if fission were the same fraction of the total interaction with each of these projectiles, we might expect a corresponding 32% increase in σ_f. Since the increase is considerably larger (Table II) other effects must be considered. One of these is the greater angular momentum delivered by the antiprotons because of the greater mean impact parameter. Heavy-ion experiments have shown that fission probability increases with angular momentum.[21]

The high probability of antiproton annihilation within the nucleus leads to very high nuclear excitation energies E^*. For example, when Ag and

TABLE III. Ternary fission induced by high-energy antiprotons, negative pions, and protons: cross sections and ratios to binary fission.

	Projectile	Kinetic energy (GeV)	U	Bi	Au
Ternary-fission cross sections, σ_t, (mb)	$\bar{p}$	1.73	8	6	6
	π^-	2.36	4	1.5	2
	p	2–3	1.1 [a]	0.3 [a]	0.16 [a]
Ratio, ternary to binary fission, σ_t/σ_f	$\bar{p}$	1.73	0.4%	2%	3%
	π^-	2.36	0.4%	0.8%	2%
	p	2–3	0.11%	0.16% [a]	0.22% [a]

[a] These results from 2- and 3-GeV proton irradiations (Hudis and Katcoff, Ref. 9) are based on 16 ternary events from U, 30 from Bi, and 34 from Au. Brandt *et al.* (Refs. 10 and 12) report for 18- and 23-GeV protons incident on U: 1.5 and 3.5 mb, respectively.

TABLE IV. Cross sections σ_s for production of single, unpaired tracks, ratios of σ_s/σ_f, and total observed cross sections $\sigma_s+\sigma_f$. Proton data are from Ref. 9. Tracks are $\geq 4\mu$ in projected length.

	Projectile	Kinetic energy (GeV)	U	Bi	Au
Cross sections for single tracks, σ_s, (mb)	$\bar{p}$	1.73	1460	80	95
	π^-	2.36	200	42	32
	p	2.0	273	73	55
Ratios σ_s/σ_f	$\bar{p}$	1.73	0.67	0.27	0.45
	π^-	2.36	0.18	0.22	0.30
	p	2.0	0.25	0.43	0.73
Sums, $\sigma_s+\sigma_f$, (mb)	$\bar{p}$	1.73	3630	373	305
	π^-	2.36	1290	233	139
	p	2.0	1330	238	131

Br nuclei are irradiated with 3.7-GeV/c antiprotons,[1] E^* is roughly 1.5 times greater than obtained by irradiation with protons of the same momentum. In the previous proton-induced-fission experiments[9] it was found (above 1.7 GeV/c) that increasing excitation energies were correlated with *decreasing* fission cross sections. However, it was pointed out that the decrease in fission probability was related to lower Z^2/A values of the cascade product nuclei rather than directly to the higher E^* values. In the present case of antiproton irradiation the Z^2/A distribution of the cascade products cannot be predicted without detailed calculation. If antiprotons produce slightly shorter intranuclear cascades than protons or pions, this would yield higher Z^2/A values and contribute to the observed higher fission cross sections.

The single unpaired tracks in mica originating from Bi and Au irradiated by GeV protons were interpreted[9] as mostly high-energy spallation residues. From U targets most of the single tracks were related to asymmetric fission-type events in which one of the partners was below recording threshold. A similar interpretation appears appropriate for the single tracks observed here (Tables I and IV). However, the combined cross section $(\sigma_s+\sigma_f)$ for antiproton irradiation of U is 3600 ± 800 mb, which is greater than tne absorption cross section $\sigma_a=2500\pm250$ mb inferred from measurements made[18] on targets lighter than U. (The value of σ_f alone, 2170 mb, is 0.87 σ_a.) The disagreement is not appreciably outside experimental error; however the discrepancy appears more substantial if we consider those spallation residues which failed to record any acceptable tracks in the mica. These might contribute an additional few hundred mb to the total cross section. No explanation for the discrepancy is apparent but it would be useful to make direct measurements of σ_a on a U target.

Detailed studies of the nuclear product distributions from interaction of antiprotons with complex nuclei would contribute substantially to the understanding of all high-energy nuclear reactions. Beam intensities $\geq 10^4$ per sec and purity $\geq 90\%$ are needed for most spallation-type experiments even with low-level counting techniques.

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[1]S. Katcoff, Phys. Rev. 157, 1126 (1967).

[2]R. Armenteros and B. French, in *High Energy Physics*, edited by E. H. S. Burhop (Academic Press Inc., New York, 1969), Vol. IV, pp. 237–417.

[3]V. S. Barashenkov and V. M. Maltsev, Fortschr. Physik 9, 549 (1961).

[4]R. J. Abrams, R. L. Cool, G. Giacomelli, T. F. Kycia, B. A. Leontic, K. K. Li, and D. N. Michael, Phys. Rev. D 1, 1917 (1970).

[5]H. W. Bertini, Phys. Rev. 188, 1711 (1969).

[6]G. Giacomelli, P. Pini, and S. Stagni, CERN Report No. CERN/HERA 69-1, 1969 (unpublished).

[7]W. C. Bell, R. Brandt, K. F. Chackett, W. W.

Neale, and H. L. Ravn, Z. Naturforsch. 21a, 1042 (1966).
[8]S. O. Thompson, L. Husain, and S. Katcoff, Phys. Rev. C 3, 1538 (1971).
[9]J. Hudis and S. Katcoff, Phys. Rev. 180, 1122 (1969).
[10]R. Brandt, F. Carbonara, E. Cieslak, H. Piekarz, J. Piekarz, and J. Zakrzewski, private communication.
[11]G. Remy, J. Ralarosy, R. Stein, M. Debeauvais, and J. Tripier, private communication.
[12]R. Brandt, E. Carbonara, E. Cieslak, I. Jarstorff, J. Piekarz, R. Rinzivillo, and J. Zakrzewski, J. Phys. (Paris) 31, 21 (1970).
[13]E. K. Hyde, *The Nuclear Properties of the Heavy Elements* (Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1964), Vol. III, pp. 481–485.
[14]B. Budick, S. C. Cheng, E. R. Macagno, A. M. Rushton, and C. S. Wu, Phys. Rev. Letters 24, 604 (1970).
[15]J. B. Cumming, G. Friedlander, and S. Katcoff, Phys. Rev. 125, 2078 (1962).
[16]L. E. Agnew, O. Chamberlain, D. V. Keller, R. Mermond, E. H. Rogers, H. M. Steiner, and C. Wiegand, Phys. Rev. 108, 1545 (1957).
[17]W. Galbraith, E. W. Jenkins, T. F. Kycia, B. A. Leontic, R. H. Phillips, A. L. Read, and R. Rubinstein, Brookhaven National Laboratory Report No. BNL-11598, 1967 (unpublished).
[18]R. J. Abrams, R. L. Cool, G. Giacomelli, T. F. Kycia, B. A. Leontic, K. K. Li, A. Lundby, D. N. Michael, and J. Teiger, private communication.
[19]T. Coor, D. A. Hill, W. F. Hornyak, L. W. Smith, and G. Snow, Phys. Rev. 98, 1369 (1955).
[20]G. Bellettini, G. Cocconi, A. N. Diddens, E. Lillethun, G. Matthiae, J. P. Scanlon, and A. M. Wetherell, Nucl. Phys. 79, 609 (1966).
[21]See Hyde, Ref. 13, pp. 380–387.

PHYSICAL REVIEW C VOLUME 4, NUMBER 1 JULY 1971

Effect of Pu^{240} Compound-Nucleus State on the Fission-Fragment Mass and Kinetic Energy Distributions*

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Fission-fragment mass and kinetic energy distributions have been obtained for fission of Pu^{239} induced by neutrons filtered through beryllium and by neutrons filtered through samarium. The beryllium filter enhances the contribution of the negative-energy resonance level to the fission cross section, and the samarium filter enhances the contribution of the 0.297-eV level. Surface-barrier detectors were used for the simultaneous measurement of both the fragment energies. Absolute fragment energies were calculated by using mass-dependent pulse-height energy relations.

The average total kinetic energy of the fragments produced in the fission induced by samarium-filtered neutrons was observed to be 0.75 ± 0.05 MeV greater than in the case of fission induced by beryllium-filtered neutrons. This result, when combined with the results of other experiments, implies $J = 0^+$ for the negative-energy level and $J = 1^+$ for the 0.297-eV level of Pu^{239}. The two mass distributions are similar except for a difference in the symmetric fission yield. This difference again implies the same spin assignments as above. The absolute average total kinetic energies were determined with somewhat less accuracy and are found to be 173.0 ± 1.5 and 173.7 ± 1.5 MeV for fissions induced by beryllium- and samarium-filtered neutrons, respectively, as directly measured, and 175.8 ± 1.5 and 176.5 ± 1.5 MeV, respectively, after correction for neutron emission.

INTRODUCTION

It is well accepted that the symmetric-to-asymmetric fission ratio varies with the excitation energy of the compound nucleus. It was suggested by Wheeler[1] that this ratio should also be different for the two possible spin states of the compound nucleus formed by the addition of a neutron to the nucleus. Experimental evidence of such a variation has been found in the cases of low-energy neutron-induced fission of U^{233}, U^{235}, and Pu^{239}. Radiochemical measurements of Regier *et al.*[2] indicate that this ratio is 5.3 times larger for one of the two spin states that can be formed by addition of a thermal neutron to the Pu^{239} nucleus. Walter, Neiler, and Schmitt (WNS)[3] have confirmed this large variation for Pu^{239} by double energy measurements of the fission fragments. However, they did not investigate the effect of the compound-nucleus state on the corresponding energy distributions. Melkonian and Mehta[4] have investigated the variation of average kinetic energy of one fragment in the resonance-neutron-induced fission of U^{235} and Pu^{239} and have found correlation between the average kinetic energy and the spin of the resonance level.