Fission of U, Bi, Au, and Ag Induced by 29-GeV ^{14}N Ions*

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The binary fission cross sections measured with mica track detectors are threefold larger than with protons of 29 GeV. Ternary events are ~1% of binary. With U, Bi, and Au there is little preference for emission of fragments into the forward hemisphere. There is no indication of interactions which involve large momentum transfers to heavy target nuclei from 29-GeV ^{14}N ions. However, with Ag targets there is evidence of significant momentum transfer.

Beams of ^{14}N ions have been accelerated to high energies at the Lawrence Berkeley Laboratory Bevatron (2.6 GeV/amu)[1] and at the Princeton Particle Accelerator (0.53 GeV/amu).[2] All previous heavy-ion accelerators produced beams with kinetic energies ≤ 10 MeV/amu. Thus it is now possible to study interactions between heavy ions and complex nuclei not only at energies far above the Coulomb barrier but also in the region well above the pion production threshold. One way to investigate nuclear interactions induced by these projectiles is to study a specific, presumably well-understood, nuclear reaction and compare the results with previous work done with other particles. Thus, we have measured the binary and ternary fission cross sections of U, Bi, Au, and Ag irradiated with 29-GeV ^{14}N ions by means of the mica track-detector technique. The cross sections for production of single, unpaired tracks in both the forward and backward directions have also been determined. Comparisons of these results are made with similar results from experiments with protons,[3] antiprotons,[4] pions,[4] and ≤ 10 MeV/amu heavy ions[5] as incident particles.

Details of the mica track-detector technique, with which we measure only fragments with $Z > 14$ and kinetic energy > 8 MeV, have been described previously.[4] Evaporated films of UF_4, Bi, Au, and Ag (20, 130, 160, and 250 $\mu g/cm^2$, respectively) were sandwiched between 0.1-mm-thick sheets of mica. Twelve such sandwiches were stacked and vacuum sealed in Mylar. Three stacks in tandem, ~1 g/cm^2 total thickness, were irradiated at the Bevatron for 12 h with an external beam of 29-GeV ^{14}N ions having an intensity of about 1.5×10^4 particles/sec in a spot size 5 mm in diameter. The beam intensity was monitored continuously with a plastic scintillation counter ~1 m downstream from the target. In addition, 100-μm Ilford G.5 pellicle emulsions were exposed for short times (2–3 beam pulses) periodically during the run to calibrate the counter. The number and distribution of ^{14}N beam tracks in the emulsion were determined by scanning at a magnification of 1500, and comparisons were made between the total number of tracks measured in the emulsion and the numbers of events recorded by the counter during the emulsion exposure. The four ratios obtained at full beam intensity (emulsion tracks)/(counter events) were 1.10, 1.14, 1.29, and 2.26. Two similar ratios obtained at reduced beam intensity ($\frac{1}{5}$) were 0.98 and 1.19. Thus it appears that during some portion of the irradiation the scintillation counter lost a significant fraction of the beam particles because of pileup. A mean ratio of 1.4 ± 0.3 was calculated for the entire run by averaging the ratios obtained at the beginning and end of each counting period weighted by the counts recorded by the scintillator during the same period. The total number of ^{14}N particles recorded by the counter and corrected for this ratio was $(7.1\pm1.5)\times10^8$.

Before disassembly, alignment holes were drilled through the corners of the mica stacks. The target layers, of known areas, were then dissolved off the mica and their thicknesses determined by chemical analysis. After they were etched in 48% HF for 90 min at room temperature, adjacent pieces of mica were realigned and mounted for microscopic examination at 150×. Scanning (in duplicate) was for binary and ternary events (fission) and for single tracks with projected length ≥ 4 μm. The detection efficiencies were 99% for fission events and 89% for the unpaired tracks.

Results of the measurements are presented in Tables I–III and compared with similar data obtained from proton, antiproton, and pion irradiations.[3,4] The ^{14}N-induced fission cross sections are based on ~600 binary events each for U, Bi, and Au targets, and 67 events for Ag. The numbers of observed ternary events were as follows:

U, 4; Bi, 5; Au, 7; Ag, none. No corrections were applied for impurities in the beam (~5%) or for the effects of secondary particles produced in the stack. However, these effects are certainly small compared to the uncertainty in beam intensity. The estimated errors are ±25% in the binary fission cross section and ±30% in the single track results.

Inspection of Table I shows that ^{14}N-induced fission cross sections are about 3 times as large as cross sections for fission induced by protons of the same total kinetic energy (29 GeV) and about twice as large as those for protons with the same kinetic energy per nucleon (2 GeV). It should be noted that for each target 1.73-GeV anitprotons and 29-GeV ^{14}N ions give about the same fission cross section. For both these projectiles the total interaction cross sections are substantially larger than for protons or pions. For high-energy protons, the total interaction cross section of U has been measured as 1900 mb,[6] and for 29-GeV ^{14}N ions the total geometric cross section can be estimated by taking as a radius for each nucleus that value for which the nuclear density falls to $\frac{1}{10}$ that of the maximum. From Hofstadter's electron scattering data,[7] these radii are 7.8 and 3.5 fm for U and N and the geometric cross section is then ≈4 b. Thus from our measurements $\sigma_f/\sigma(\text{geom}) \cong 0.5$, the same as the ratio for 2-GeV protons.

In addition, we note the interesting fact that within experimental error the fission cross section of U is the same for ^{14}N ions of 0.14 GeV[5] and 29 GeV. At the lower energy, Viola and Sikkeland[5] measured $\sigma_f(U) = 2100$ mb, in good agreement with the total reaction cross section obtained from optical-model calculations.

Proton-induced fission of U, very probable at low excitation energy, shows a decrease in cross section as E_p increases from 1 to 30 GeV.[4]

TABLE I. Binary fission cross sections (in millibarns) of U, Bi, Au, and Ag induced by high-energy ^{14}N ions, protons, antiprotons, and negative pions.

Projectile	Kinetic energy (GeV)	Cross section U	Bi	Au	Ag
^{14}N	29	2170	320	230	8
p	2.0[a]	1050	165	76	<5
p	29[a]	670	105	63	<6
$\bar{p}$	1.73[b]	2520[c]	293	210	⋯
π^-	2.36[b]	1090	191	107	⋯

[a]Ref. 3. [b]Ref. 4. [c]Ref. 11.

Monte Carlo calculations[8] show that low-energy excitations are produced by high-energy protons mainly in peripheral collisions. This would make it seem that, in reactions with very energetic projectiles, fission of U would tend to result primarily from peripheral collisions and spallation primarily from collisions at smaller impact parameters.

At energies >2 GeV/nucleon, pion production and reabsorption is probable, and central collisions of 29-GeV ^{14}N ions with nuclei must lead, in general, to complex nucleonic cascades and high deposition energies. For U target nuclei this is expected to lead in large part to nonfission events. Thus, although $\sigma_f(U)$ is the same for 140-MeV and 29-GeV ^{14}N ions, the reactions which lead to fission are probably very different in these two cases: compound-nucleus-type reactions in the former and peripheral reactions in the latter.

As with U, the ratios $\sigma_f/\sigma(\text{geom})$ for Bi and Au are about the same for 29-GeV ^{14}N ions and 2-GeV protons. However, it is also known that the probability for fission increases with increasing angular momentum,[9] and thus one would expect higher fission cross sections with heavy ions than with protons because of the larger amounts of angular momentum transferred, especially in peripheral collisions.

In addition, for targets like Bi and Au the probability for fission is very dependent on the values of Z^2/A of the nuclei left after the nucleonic cascade. Although emulsion studies of very energetic heavy ions in cosmic rays[10] indicate that the nucleonic cascades initiated by heavy ions are, on the average, more complex than those produced by protons of comparable energy, we have no way of comparing the distributions in Z and A of the cascade nuclei in the two cases. We cannot estimate the relative importance of this effect.

For an appreciable fraction of the fission events, both tracks were observed in the same piece of mica: either forward (downstream) or backward (upstream). The pairs forward minus the pairs backward for the various targets were as follows: U, 3%; Bi, 4%; Au, 3%; and Ag, 16%. The small excess forward in the case of the three heavy targets indicates that only a very small fraction of the ^{14}N projectile momentum could have been transferred to the fission fragments.

Table II shows that fission into three fragments of roughly comparable mass amounts to about 1% of binary fission for ^{14}N projectiles. This is con-

TABLE II. Ratio of ternary to binary fission, given in percent, for targets of U, Bi, and Au irradiated by various high-energy projectiles.

Projectile	Kinetic energy (GeV)	Ratio U	Ratio Bi	Ratio Au
^{14}N	29	~0.7	~0.7	~1.4
p	2–3[a]	0.11	0.16	0.22
p	29[a]	0.06	0.03	0.13
$\bar{p}$	1.73[b]	0.3[c]	2	3
π^-	2.36[b]	0.4	0.8	2

[a]Ref. 3. [b]Ref. 4. [c]Ref. 11.

siderably greater than for proton beams[3] but about the same as for antiproton and pion beams.[4]

Finally, Table III shows approximate cross sections for production in mica of single, unpaired tracks ≥ 4 μm projected length. With one exception, the ^{14}N beam gives much higher values for all the targets than do the other beams. If the increase were due to large nuclear fragments being knocked out of the target nuclei by the incident ^{14}N ions, one would expect to see the tracks predominantly forward. In fact, the forward hemisphere to backward hemisphere ratios are, for U, 0.8 ± 0.2; Bi, 1.1 ± 0.2; Au, 1.0 ± 0.2; and Ag, 1.9 ± 0.3. Thus from data on both binary and single track events there is no evidence for large momentum transfers from the incoming very energetic heavy ions to heavy target nuclei nor to portions of the target nuclei. If such processes occur, they must have small cross sections. The larger single-track cross sections are probably due to the emission of substantially more cascade particles.[10] Thus a greater fraction of the spallation residues have energies above the recording threshold in mica (~15 MeV).

In the case of Ag targets there is a substantial excess of tracks in the forward hemisphere, from both binary and unpaired events (above). This observation indicates appreciable momentum transfer to medium weight targets, and it appears that initial interactions at small impact parameters are required to produce fission fragments and unpaired fragments of sufficient mass and energy to register acceptable tracks.

TABLE III. Approximate cross sections (in millibarns) for production in mica of single unpaired tracks originating in various targets irradiated by high-energy ^{14}N ions, protons, antiprotons, and negative pions.

Projectile	Kinetic energy (GeV)	Cross section U	Cross section Bi	Cross section Au	Cross section Ag
^{14}N	29	740	470	520	150
p	2.0[a]	270	73	55	38
p	29[a]	300	140	140	49
$\bar{p}$	1.73[b]	810[c]	80	95	...
π^-	2.36[b]	200	42	32	...

[a]Ref. 3. [b]Ref. 4. [c]Ref. 11.

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