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Nuclear collisions of uranium nuclei up to ~ 1 GeV/nucleon

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We report observations of inelastic interactions of uranium nuclei with energies up to ~ 1 GeV/nucleon in nuclear emulsions exposed on the occasion of the first successful acceleration of relativistic uranium ions. About one-half of the interactions lead to binary fission. With increasing primary energy, the relative frequency of violent nuclear interactions increases at the expense of binary fissions. Also reported is a range measurement of uranium nuclei in emulsion at 0.945 GeV/nucleon.

NUCLEAR REACTIONS Emulsion exp., ^{238}U at $E/A \leq 1$ GeV/nucleon. Energy dependences of mean free path length and frequencies of event topologies. Range measurements.

On the occasion of the first acceleration of uranium ions of charge +68 to a nominal energy of 0.957 GeV/nucleon at the Lawrence Berkeley Laboratory, we exposed several packets of Ilford G-5 emulsions to the extracted uranium beam. The emulsion detectors consisted of (a) two packets of 12 glass-backed pellicles, 50 μm thick, (b) two packets of 12 glass-backed pellicles, 200 μm thick, and (c) two stacks of 600-μm-thick stripped emulsion pellicles of 20 pellicles each. In all cases the incident flux was ~ 1000 beam nuclei per cm^2 at the entrance edge of the stacks.

The acceleration of uranium involved the sequential acceleration and extraction of $^{56}Fe^{+16}$ and $^{238}U^{+68}$ beams under identical accelerator-operating conditions. The rigidity of the beams was nominally 5.75 GV, corresponding to beam energies equal to 0.9570 GeV/nucleon and 0.9577 GeV/nucleon for the ^{238}U and ^{56}Fe nuclei, respectively. After traversing the 0.5-mm Al exit window of the vacuum tank, and ~ 24 mg/cm^2 of air and ~ 10 mg/cm^2 of plastic tape, the beam nuclei entered the emulsions and, in the case of the emulsion stacks, were brought to rest. The ranges of the Fe and U were measured and compared with those calculated by appropriately scaling the empirically measured proton range-energy relation[1] and the range extension due to charge neutralization.[2] Whereas the observed mean range of the Fe beam nuclei agrees to within < 1% of the calculated range (for emulsion density = 3.815 g/cm^2), the range of the uranium nuclei (3.082 ± 0.003 cm at $E_{\rm inc}$ = 0.9455 GeV/nucleon) is found to differ from the calculated value, relative to that calculated for Fe, by an amount −5.15 ± 0.14%. This means that the range of ~ 0.95A-GeV uranium ions is shortened by a substantial amount, indicative of enhanced rates of energy loss for U relative to Fe over the same range of velocities. Such a deviation in the range of the uranium nuclei is far outside any systematic error, e.g., in the beam energy, emulsion density, charge-state distributions, etc., that could affect the measurement and, hence, represents a significant deviation from the Z^2 charge dependence of the Bethe-Block stopping power theory.[3]

The following results represent a first, exploratory, scan of the glass-backed emulsions, of size 2.5 × 7.5 cm^2. The beam entered the plates normal to the 7.5-cm edge and parallel to the surface of the emulsions. The alignment of the emulsions with the beam was sufficiently accurate to allow a large fraction of beam nuclei to traverse the entire 2.5-cm width of one emulsion plate. Energy loss by ionization is such (at $Z \approx 92$) that uranium nuclei entering the emulsions at ~ 950 MeV/nucleon would emerge from the 2.5-cm-wide emulsion with a residual kinetic energy of ~ 350 MeV/nucleon or, equivalently, with a residual range of ~ 6 mm of emulsion.

All resolvable uranium tracks entering the edge of the pellicles were followed under (200–500) × magnification until they either interacted with nuclei in the composition of the emulsion or left the pellicle. The uranium tracks were identified by their characteristic delta-ray halo, as well as by the large frequency of binary fissions [see Fig. 1(a) and Table I, below].

A total of 22.8 m of U track were scanned for interactions. Detectable interactions (charge change and/or target fragment emission) were collected throughout the full width of the pellicles (2.5 cm), hence throughout the interval of kinetic energy mentioned above. In particular, 13.1 m of track belonged to the region where the kinetic energy of the uranium nuclei exceeded 800 MeV/nucleon. Over the whole energy range 603 interactions were observed; the

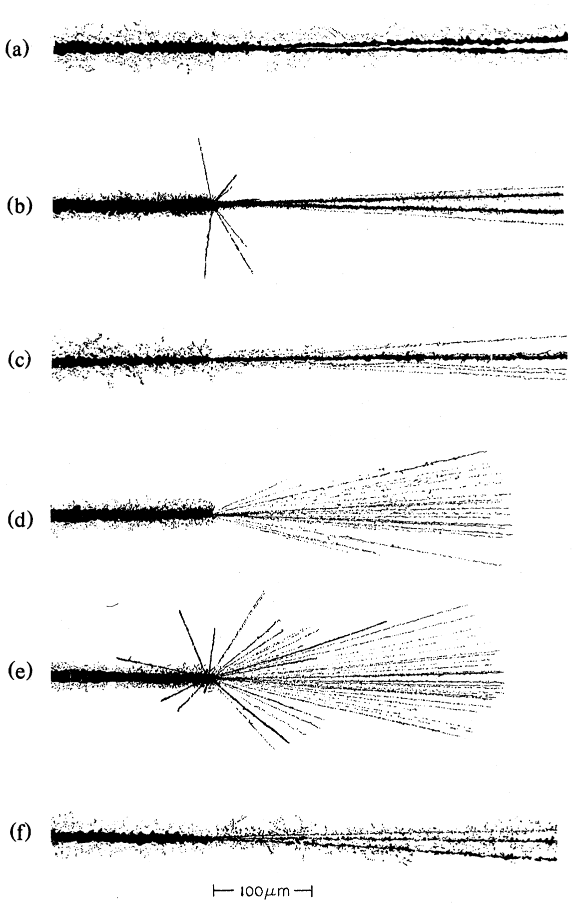

FIG. 1. Microprojection drawings of ~0.9 GeV/nucleon uranium interactions in nuclear emulsion. (a) "Clean" fission. (b) "Dirty" fission (with both target and additional projectile fragments). (c) $N_h=0$ event with one heavy projectile fragment. (d) $N_h=0$ event with only light projectile fragments. (e) "Star" induced in a (Ag-Br) target nucleus. (f) "Ternary" fission.

analysis of these interactions constitutes the basic topic of this Communication.

The energy range was divided into four regions having comparable populations of events with mean energies close to 900, 800, 700, and 500 MeV/nucleon, respectively.

The inelastic reaction mean free path (MFP) averaged over the whole energy range was obtained and found to be 3.78 ±0.15 cm. No significant variation of the MFP with energy was observed (see Table II); the χ^2 for consistency with a single mean is 4.0 with three degrees of freedom.

The observed value of the MFP is to be compared to the value of 3.1 ±0.6 cm measured in our earlier investigation of uranium interactions at ~100 MeV/nucleon[4] and to a value of 3.6 cm expected from geometrical cross-section considerations.[5]

As a preliminary classification of the nuclear events induced by uranium nuclei and detectable under our experimental conditions,[6] we distinguish:

(1) Fissionlike events, characterized by the emission of two heavy projectile fragments of comparable charges (as estimated from their track widths and delta-ray densities). These can be subdivided into "clean" fissions [Fig. 1(a)], unaccompanied by any charged particle tracks, and "dirty" fissions [Fig. 1(b)], where light projectile and/or target fragments are present.

(2) Events with jetlike structure, having no target-related fragments, i.e., $N_h=0$ [Figs. 1(c) and 1(d)].

(3) "Star-like" events characterized by visible target fragments, i.e., $N_h \geq 1$ [Fig. 1(e)]. Events of classes (2) and (3) are either composed only of light projectile fragments [Fig. 1(d)] or include one heavy projectile fragment, comparable in Z to fission fragments or heavier [Fig. 1(c)].

Table I shows the percentages of events in the different subclasses, along with the actual numbers of events observed. As can be seen, $\sim\frac{1}{2}$ of the events lead to binary fission. Of the 12% of events without target-related fragments, (7 ± 1)% lack a heavy projectile fragment and appear as narrow jets of, typically, ~15 projectile fragments of $Z>1$ accompanied by a wider shower of $Z=1$ tracks.

The energy dependence of two selected topologies, viz., clean fissions and stars with at least one target-related prong (i.e., $N_h \geq 1$) are given in Table II. The statistics gathered in this preliminary scan are still insufficient to allow definite conclusions; howev-

TABLE I. Event topologies.

	Fissionlike Clean	Fissionlike Dirty	Jets $N_h=0$	Stars $N_h \geq 1$
(1) Percent	19 ± 1	33 ± 1	12 ± 1	36 ± 2
(2) Number	113	200	74	215

TABLE II. Energy dependence of event rates.

$\langle E\rangle/A$ (GeV)	MFP (cm)	Event rates (number/meter) Clean fissions	Stars	Ratio
0.9	4.2 ± 0.3	3.9 ± 0.7	10.1 ± 1.1	2.6 ± 0.5
0.8	3.4 ± 0.3	5.5 ± 1.0	9.9 ± 1.4	1.8 ± 0.4
0.7	3.6 ± 0.3	5.3 ± 1.1	8.9 ± 1.5	1.7 ± 0.5
0.5	3.6 ± 0.3	5.7 ± 1.0	8.4 ± 1.3	1.5 ± 0.4
0.1[a]	3.1 ± 0.6	7.5 ± 2.8	6.4 ± 2.6	0.9 ± 0.5

[a] Data from Ref. 4 included for comparison.

er, there appears to be a trend (at a two standard deviation confidence level) for the frequency of clean binary fissions to decrease with energy, whereas the frequency of stars (mostly relatively "violent" collisions with the heavy Ag-Br component of the emulsion) appears to increase with energy (see the ratio of the event rates in the last column of Table II).

We also observed one event that can be ascribed to the ternary fission of a uranium nucleus into three fragments of comparable sizes, without any additional charged particle emission. This event is shown in Fig. 1(f). The charges of the fragments, roughly evaluated from delta-ray counts, are in the ratio of 1:3:2.5; using charge conservation, they are compatible with a ternary fission

$$92 \rightarrow 14+43+35 \quad .$$

Assuming approximate conservation of primary velocity (the event occurred at a location corresponding to ~ 900 MeV/nucleon) the emission angles of the three fragments are, within errors, compatible with momentum balance in the transverse plane.

The event in Fig. 1(e) is characteristic of the most violent U + Ag(Br) collision observed in emulsion and is representative of interactions involving the highest aggregate number of baryons partaking in nucleus-nucleus collisions observed to date. A particularly important aspect of the availability of high-energy uranium beams is that uranium-fragmentation reactions can now be examined in the projectile frame, enhancing and complementing the large body of information derived from traditional "target-frame" experiments where uranium nuclei are bombarded by various hadronic and heavy-ion beams.

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[1]W. H. Barkas, *Nuclear Research Emulsions* (Academic, New York, 1963), p. 438.

[2]H. H. Heckman, B. L. Perkins, W. G. Simon, F. M. Smith, and W. H. Barkas, Phys. Rev. 117, 544 (1960).

[3]S. P. Ahlen and G. Tarle, Phys. Rev. Lett. 50, 1110 (1983).

[4]H. H. Heckman, Y. J. Karant, and E. M. Friedlander, Science 217, 1137 (1982).

[5]H. H. Heckman, D. E. Greiner, P. J. Lindstrom, and H. Shwe, Phys. Rev. C 17, 1735 (1978).

[6]Uranium-proton elastic Coulomb interactions would lead to recoil protons having ranges $< 10\ \mu$m, hardly observable in the large delta-ray background; Coulomb-induced binary fissions have been calculated to contribute to, at most, $\sim 3\%$ of the inelastic reaction cross section.