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Nuclear Collisions of Uranium Nuclei up to ~1 GeV/Nucleon

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Summary

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 at the LBL Bevalac. 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.

[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.]

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On September 25, 1982, the Lawrence Berkeley Laboratory Bevalac accelerated for the first time uranium ions of charge 68+ to a nominal kinetic energy of 956 MeV/nucleon.

As soon as acceleration was achieved, we exposed several packets of Ilford G-5 nuclear emulsions to the uranium beam, viz.: a) two packets of 12 glass-backed pellicles, 50 microns thick, b) two packets of 12 glass-backed pellicles, 200 microns thick, and c) two stacks of 600-micron 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.

After traversing the 0.5 mm Al exit window of the vacuum tank, ~30 cm of air and ~10 mg/cm^2 of plastic tape, the uranium ions were essentially stripped of their electrons and entered the emulsions at $Z = 92$.

The results reported here represent a first, exploratory, scan of the glass-backed emulsions, of size 2.5 x 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 ~960 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) x magnification until they either interacted with nuclei in the composition of the emulsion or left the pellicle. The uranium tracks (also visible by naked eye, see Fig. 1) were identified by their characteristic delta-ray halo, as well as by the large frequency of binary fissions (see Fig. 2a 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 analysis of these interactions constitutes the basic topic of this report.

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 3 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[1] and to a value of 3.6 cm expected from geometrical cross-section considerations.[2]

As a preliminary classification of the nuclear events induced by uraniuum nuclei and detectable under our experimental conditions,[3] we distinguish

1) Fission-like 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. 2a), unaccompanied by any charged particle tracks, and "dirty" fissions (Fig. 2b), where light projectile and/or target fragments are present.

2) Events with jet-like structure, having no target-related fragments, i.e., $N_h = 0$ (Fig. 2c and 2d).

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

Table I shows the percentages of events in the different subclasses, along with the actual numbers of events observed. As can be seen, ~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; however, there appears to be a trend (at a 2-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. 2f. 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

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

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.

Measurements of the angular distributions of fragments from the different event topologies are in progress and will be reported separately.

We are very indebted to the Bevalac crew for help in the successful exposure and to R. Gimpel, M. Heckman, and H. Yee for help in the scanning of the events. We give special credit to Howel Pugh, Scientific Director of the Bevalac, for his active interest and encouragement in this work.

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References and Footnotes

1. H.H. Heckman, Y.J. Karant, and E.M. Friedlander, Science 217, 1137 (1982).
2. H.H. Heckman, D.E. Greiner, P.J. Lindstrom, and H. Shwe, Phys. Rev. C17, 1735 (1978).
3. Uranium-proton elastic Coulomb interactions would lead to recoil protons having ranges <10 microns, hardly observable in the large delta-ray background; Coulomb-induced binary fissions have been calculated to contribute to, at most, ~3% of the inelastic reaction cross section.

Table I: Event Topologies

	FISSION-LIKE		JETS	STARS
	Clean	Dirty	$N_h = 0$	$N_h \geq 1$
1) Percent	19 ± 1	33 ± 1	12 ± 1	36 ± 2
2) Number	113	200	74	215

Table II: Energy Dependence of Event Rates

<E>/A	MFP	Event rates (number/meter)		
(GeV)	(cm)	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	3.7 ± 0.3	5.7 ± 1.0	8.4 ± 1.3	1.5 ± 0.4
0.1*	3.1 ± 0.6	7.5 ± 2.8	6.4 ± 2.6	0.9 ± 0.5

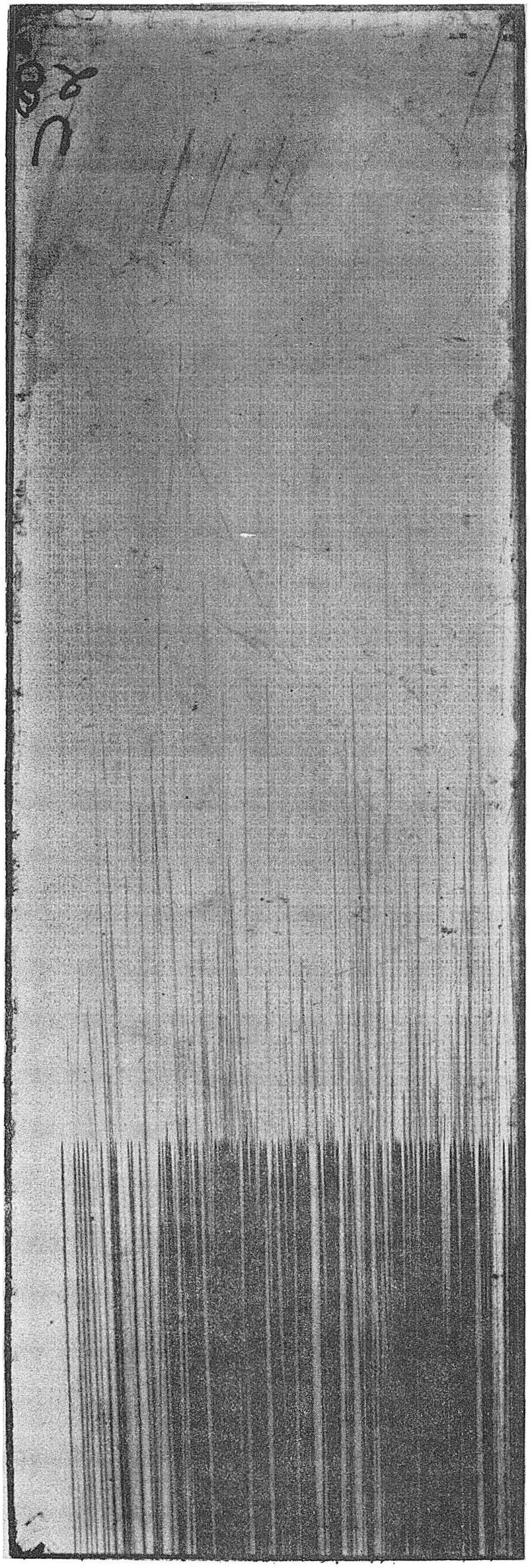
*Data from Ref. 1 included for comparison.

Figure Captions

Fig. 1. Contact print of a 600 μm emulsion pellicle exposed to the 0.96-GeV/nucleon uranium beam. The uranium tracks are visible by the naked eye, as is the clean-cut, 3.1 cm range of the monokinetic beam. Tracks of fission and other heavy projectile fragments can also be seen, extending to much longer ranges.

Fig. 2. Micro-projection 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.



XBB 831-592

Fig. 1

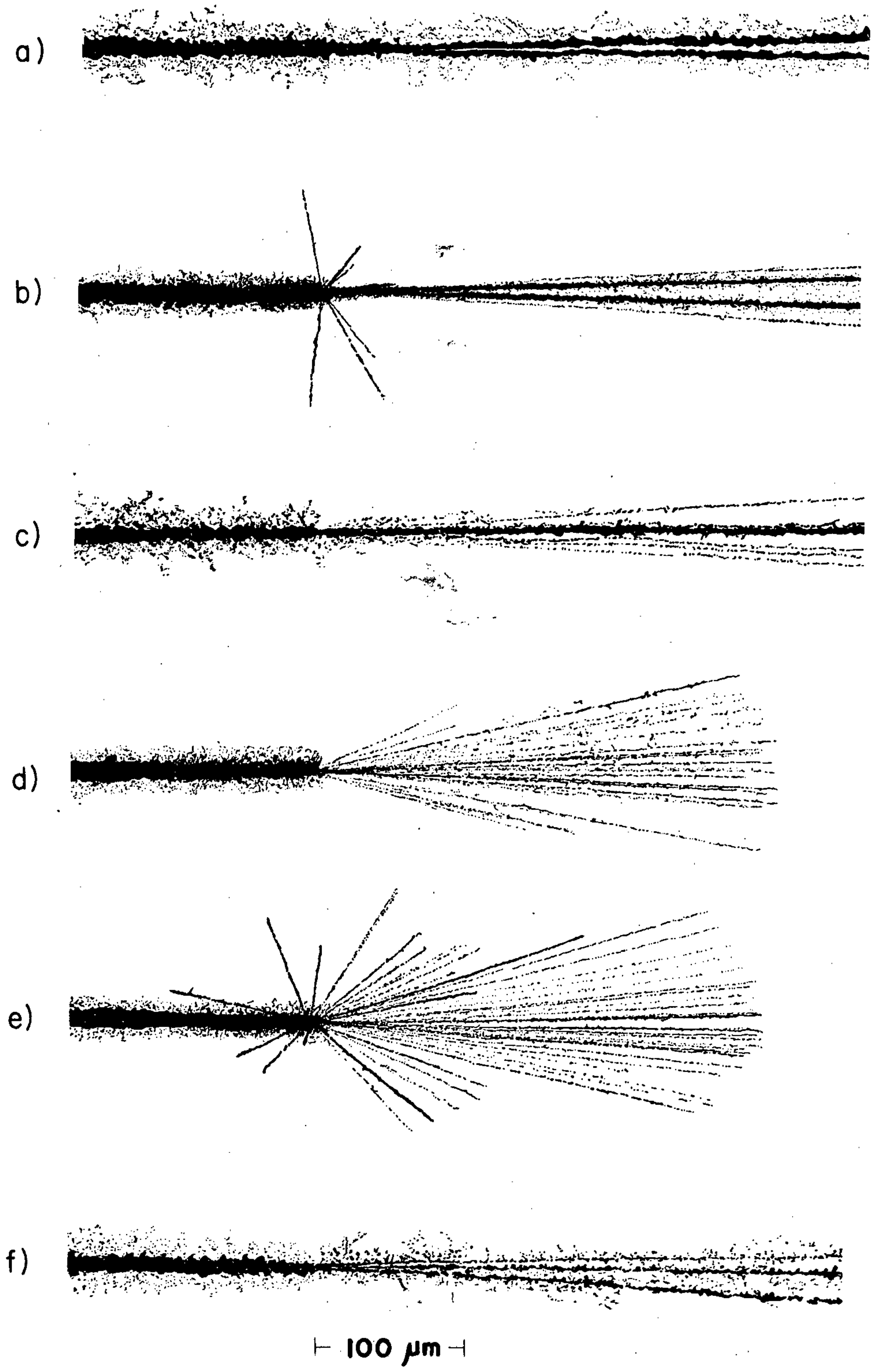


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Fig. 2

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