Title
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Abstract

Confirmation of the acceleration and extraction of ^{238}U nuclei by the Bevalac has been obtained by their visual detection in nuclear research emulsion. A preliminary result for the collision mean free path for stopping ^{238}U, $E \leq 115$ AMeV, is $\lambda = 3.1 \pm 0.6$ cm. Qualitative characteristics of the observed ^{238}U-nucleus collisions are also described.

An integral part of the first successful acceleration and extraction of ^{238}U nuclei at the Bevalac was the exposure of nuclear research emulsion detectors to obtain visual confirmation of the acceleration of uranium nuclei. Two exposures of emulsion-detector packets containing 1" x 3", glass-backed 50 and 200 μm-thick Ilford G-5 emulsions were made immediately after beam monitors indicated the presence of extracted ^{238}U nuclei. The energy of the ^{238}U ions was, from the machine parameters, estimated to be 147.7 AMeV.

Both exposures were successful. The uranium ions entered the edges of the emulsions, parallel to the emulsion surfaces. With maximum track densities of ~10^4 cm^{-2}, up to ~20 stopping tracks were observed per mm along the leading edges of the 200 μm-thick emulsions. Within one hour after their exposure, the 50 μm plates had been developed, and the spectacular tracks of ^{238}U were seen, first by the naked eye, Fig. 1a, and then in detail under the microscope. The identification of the tracks as being due to uranium was immediately evident by the predominance of collisions involving binary fission of the uranium projectile.

A more systematic examination of the thicker (200 μm) emulsions has led to an independent estimate of the energy of accelerated uranium, their interaction mean free path in emulsion, and a qualitative description of the most dominant characteristics of the observed inelastic uranium collisions with emulsion target nuclei (80% by weight AgBr).

The immediate impression one has when observing the track of a stopping ^{238}U ion is the immense number of δ rays (energetic, knock-on electrons) it produces and the dramatic narrowing of the ionization track as it loses energy in coming to rest. This is illustrated in Fig. 1b, which is a photomicrograph of a uranium ion that entered the top surface of the emulsion at grazing incidence (a few ions did so) and came to rest after traveling a distance of about 1.5 mm. The characteristic tapering of the stopping track (left to right) is attributable to two effects: a) the decrease in the maximum δ-ray energies, hence ranges, produced by the ion as its velocity decreases in coming to rest; this tapering is a well-known effect and is observed for all stopping ions, $Z \geqslant 3$, in electron-sensitive emulsions,[1,2] and b) the diminution of the net charge of the ion due to the capture of electrons as its velocity decreases, an effect that compounds the tapering of the uranium track.

The mean range of the noninteracting U ions observed in the emulsion detectors was $R = 1.50 \pm 0.01$ mm, the error being estimated from the dispersion of the ranges obtained in eight different emulsion plates. Before entering the emulsions, the uranium beam traversed a 136 mg/cm^2 thick Al window, ~62 mg/cm^2 of air and ~10 mg/cm^2 of paper.

The calculated energy of stopping ^{238}U ions for this sequence of materials, based on the range-energy relations of Barkas and Berger[3] and Heckman, et al.[1], as formulated by Benton and Henke[4] is 149.5 ± ~3 MeV/amu, where the error includes estimates of variations in the thickness of the combination of Al + air + paper absorbers and systematic uncertaintites in extrapolating the range-energy relation of heavy ions to the high energies and charges of the U ions. That the observed track ranges of the extracted beam from the Bevalac were in very good agreement with those predicted for the 147.7 MeV/amu ^{238}U beam was vital to the confirmation that a uranium beam was accelerated.

This result indicates that the range-energy relation in emulsion[1] (based on measurements of nuclei $A \leqslant 40$ and $E \leqslant 10$ AMeV) is valid for U ions at energies $E \leqslant 150$ AMeV. We then can estimate the values of effective charge $Z^* \equiv [(dE/dx)/(dE/dx)_{Z=1}]^{1/2}$ as a function of the residual range of a stopping uranium nucleus, where the dE/dx's are evaluated at the same velocity, β. In Fig. 1b, for example, the kinetic energy and effective charge Z^* of the U ion at entry into the emulsion, where its residual range is 1.50 mm, are computed to be $\approx$ 115 MeV and 88, respectively. Although the track appears to <u>decrease</u> in dE/dx as it approaches its end, the rate of energy loss actually <u>increases</u> until the ion is only 100 μm from its stopping point, where it attains a maximum value of the calculated rate of energy loss $dE/dx)_{max} \sim 30$ MeV/micron, i.e., a rate of 300 GeV/cm! At a residual range of 100 μm, the U ion has a kinetic energy of about 10 AMeV and an effective charge $Z^* \approx 54$.

Measurements of the mean free path (mfp) for inelastic uranium-nucleus collisions and the qualitative features of these collisions gave further confirmation that we were dealing with energetic uranium nuclei. Based on 30 interactions in a total of 93.5 cm of path length of interacting and noninteracting ^{238}U ions, the interaction mfp is $\lambda = 3.1 \pm 0.6$ cm in the energy interval $0 \leqslant E \leqslant 115$ MeV. This value is compatible with that calculated for the mfp of ^{238}U in emulsion, assuming geometrical nuclear sizes[5], i.e., $\lambda_{calc} = 3.6$ cm.

Table I gives the relative frequencies of several classifications of uranium "stars" that were observed and the range interval in which they occurred. To illustrate two of the classifications as defined in Table I, we show in Fig. 1c an example of an event of the H + L type, where the uranium fragments to one heavy secondary accompanied by lighter fragments. Figure 1d is an event where the uranium undergoes binary fission, classified as a 2H event.

Several qualitative features of the uranium interactions in nuclear emulsion at energies $E \leqslant 115$ AMeV are apparent from the data given in Table I. These are

i) About 70% of the collisions involve binary fission of the uranium nucleus, with or without L-fragment emission.

ii) One-third of the events exhibit binary fission only. Such events would include both nuclear and Coulomb interactions.

iii) Two-thirds of the events exhibit L-fragment emission, a characteristic signature for a nuclear interaction.

iv) Although the number (3) of L-only events is small, they all occur within the highest bin of residual range corresponding to energies $86 \lesssim E \lesssim 115$ AMeV, suggesting an energy dependence for interactions leading to the "obliteration" of the incident uranium nucleus.

Further experiments on the interactions of ^{238}U nuclei in nuclear emulsions at the present and higher energies that will amplify and quantify the above observations will be carried out as soon as these uranium beams become available.

We appreciated the opportunity to work with the Bevalac staff and partake in their successful efforts to accelerate uranium nuclei. This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

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Table I. Characteristics of uranium interactions, $E \leq 115$ AMeV, and the number of interactions per 0.5 mm range interval.

Type*	Abundance	Number		
L	10 ± 5%	3	0	0
H+L	17 ± 6	1	3	1
2H+L	40 ± 7	5	5	2
2H	33 ± 7	2	4	4

1.5 1.0 0.5 0.0 (ending)

Residual Range

*nH refers to the number of heavy fragments, i.e., fission fragments and heavier; L indicates the emission of lighter projectile and/or target fragments.

Figure Captions

Fig. 1 a) Contact print of a 1" x 3", 200 μm emulsion plate exposed to 115 AMeV ^{238}U ions. The tracks of the ions, 1.5 mm in length, are visible to the naked eye and are seen to enter the upper leading edge of the emulsion and at grazing incidence to the surface of the emulsion.

b) Photomicrograph of the track of a stopping ^{238}U ion in emulsion. The ion enters from the left and has a range of 1.5 mm. A 100 μm scale is indicated.

c) An interaction leading to the fragmentation of the uranium nucleus, where both heavy (one) and light projectile fragments are produced.

d) An example of a collision leading to the binary fission of the uranium projectile.

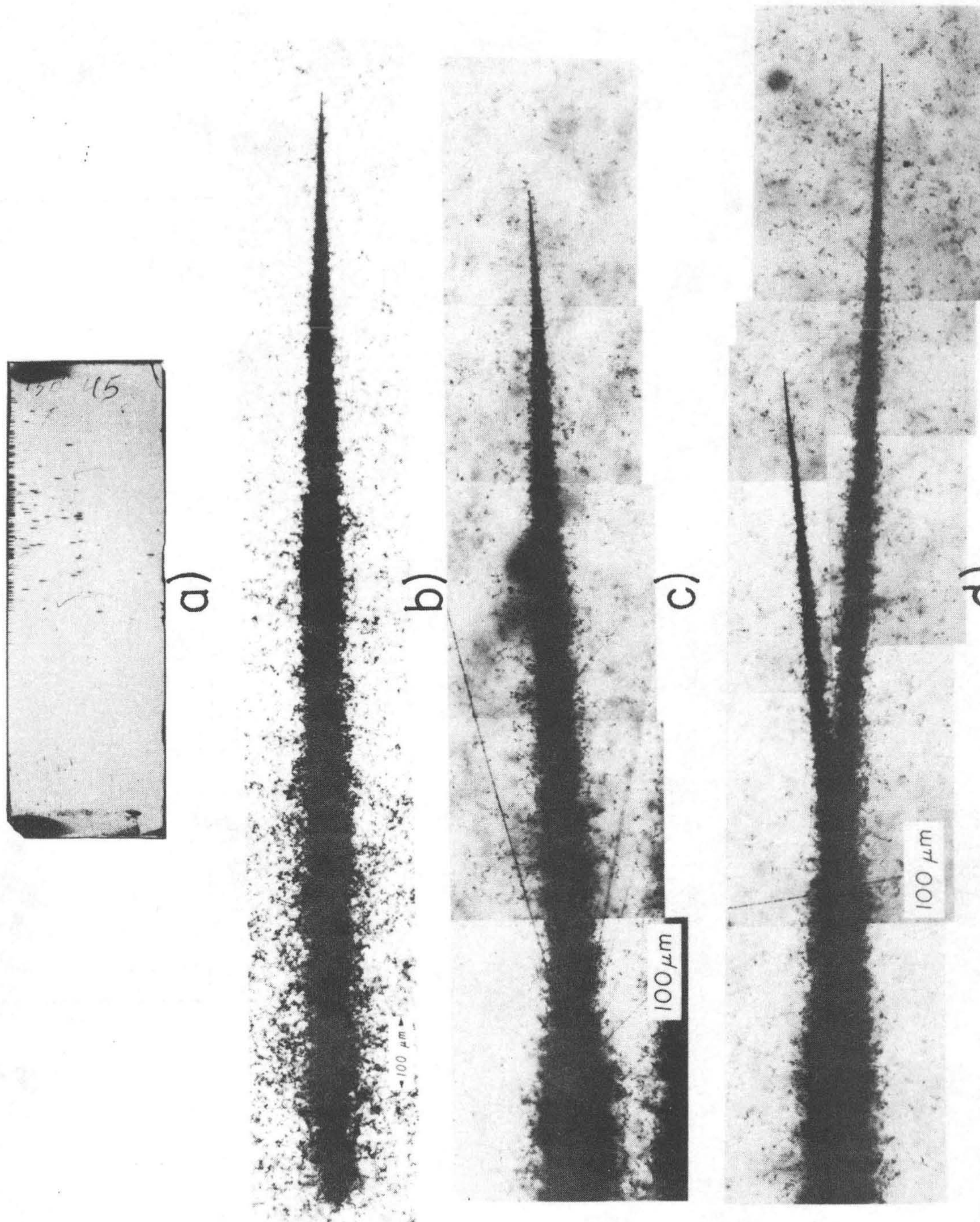

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Fig. 1

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