to great difficulty in achieving optimum tuning. The problem is greatest at the highest masses since more charge states are present and they are more closely spaced in Q/A. To alleviate the problem, a tracer tuning technique was developed.

A light, partially stripped ion is chosen which is very closely matched in Q/A to the heavy ion desired (generally to better than 0.2 percent). Since charge states for light ions are widely separated in Q/A, it is straightforward to isolate the desired charge state and tune it through the transfer line and Bevatron acceleration process. Because of Q/A matching, this tuning will also serve for the heavier ion; all that is required is that the heavy-ion beam position and velocity at the top of the transfer line be matched to those of the tracer.

In operation, the technique has worked exceptionally well. For xenon beams (Ne^{7+} tracer), close to theoretical transmission through to the experimental target is achieved with no adjustments of any transfer line or Bevatron parameters, and the final success with uranium was achieved by tuning with a tracer, after two unsuccessful attempts without it.

For the 11 May attempt to accelerate uranium, a tracer of Fe^{16+} was selected for the U^{68+} ions expected from the stripper; N^{4+} ions could have been used, but an iron source was operating at the time and was most convenient. While the Bevatron operators were tuning the Fe^{16+} ions from one injector down the transfer line and through the Bevatron, the SuperHILAC operators worked at peaking the Abel uranium beam. On completion of the tracer tuning, the beam was switched from iron to uranium while we watched a scintillator signal from the external beam line at the Bevatron. As the energy matching was done, by slowly varying the last SuperHILAC tank parameters, the scaler counts slowly grew from 10 per spill on up through 100 to finally more than 1000.

At this point beam characterization studies were performed, with the emulsion and CR-39 exposures discussed in the following reports (*9, 10*) forming the final verification of the ionic species as uranium.

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Characteristics of the Ionization Tracks and Interactions of Uranium-238 Nuclei in Emulsion

Abstract. *The acceleration and extraction of uranium-238 nuclei by the Bevalac have been confirmed by their visual detection in nuclear research emulsion. A preliminary result for the collision mean free path for stopping uranium-238 (energy ≤ 115 million electron volts per nucleon) is 3.1 ± 0.6 centimeters. Qualitative characteristics of the observed uranium-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 by 3 inch, 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 MeV per nucleon.

Both exposures were successful. The uranium ions entered the edges of the emulsions, parallel to the emulsion surfaces. With maximum track densities of

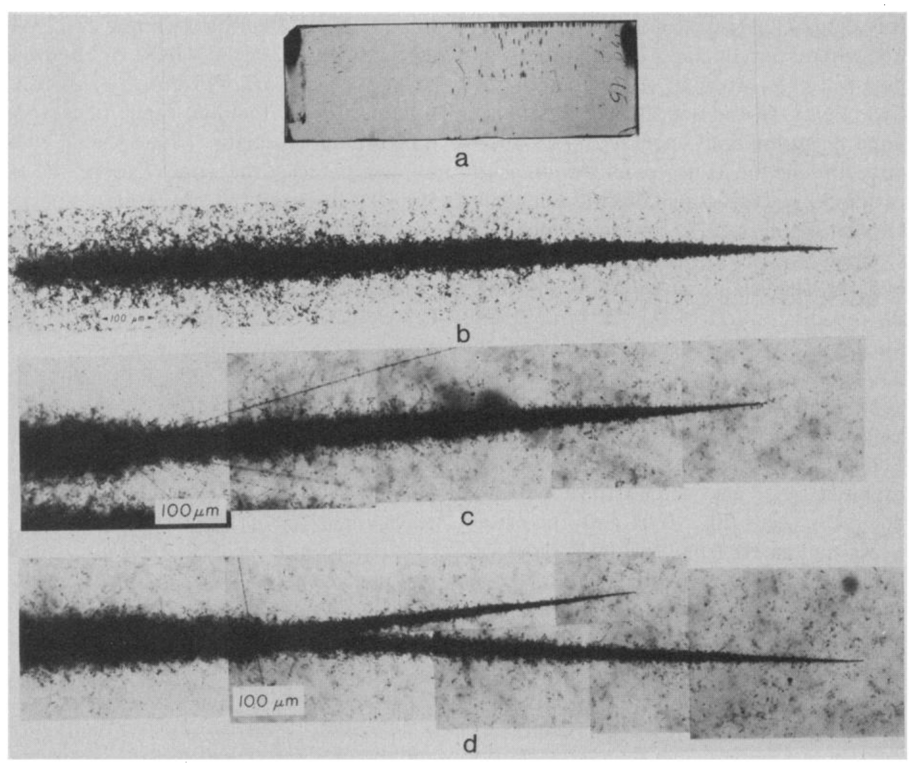

Fig. 1. (a) Contact print of a 1 by 3 inch, 200-μm emulsion plate exposed to ^{238}U ions at 115 MeV per nucleon. The tracks of the ions, 1.5 mm in length, are visible to the naked eye and are seen to enter the upper leading edge of the emulsion and at grazing incidence to the surface of the emulsion. (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) Interaction leading to the fragmentation of the uranium nucleus, where both heavy (one) and light projectile fragments are produced. (d) Example of a collision leading to binary fission of the uranium projectile.

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$\sim 10^4$ cm^{-2}, up to $\sim$ 20 stopping tracks were observed per millimeter along the leading edges of the 200-μm-thick emulsions. Within 1 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. That the tracks were due to uranium was immediately evident from 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 ions, 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 percent 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: (i) 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 of atomic number $Z \geqslant 3$ in electron-sensitive emulsions (*1, 2*), and (ii) 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 uranium ions observed in the emulsion detectors was 1.50 ± 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 an Al window, 136 mg/cm^2 thick; air, $\sim$ 62 mg/cm^2; and paper, $\sim$ 10 mg/cm^2.

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 $149.5 \pm \sim 3$ MeV/amu, where the error includes estimates of variations in the thickness of the combination of Al, air, and paper absorbers and systematic uncertainties in extrapolating the range-energy relation of heavy ions to the high energies and charges of the uranium ions. That the observed track ranges of the extracted beam from the Bevalac were in very good agreement with those predicted for the ^{238}U beam at 147.7 MeV/amu was vital to the confirmation that a uranium beam was accelerated.

Table 1. Characteristics of uranium interactions ($E \leqslant 115$ MeV per nucleon) and number of interactions per 0.5-mm range interval. In the first column, *n*H refers to the number of heavy fragments (fission fragments and heavier), and L indicates the emission of lighter projectile or target fragments.

Type	Abundance (%)	Number in range interval (mm)		
		1.5 to 1.0	1.0 to 0.5	0.5 to 0.0 (ending)
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

This result indicates that the range-energy relation in emulsion (*1*) (based on measurements of nuclei with atomic mass number $A \leqslant 40$ and energy $E \leqslant 10$ MeV per nucleon) is valid for uranium ions at $E \leqslant 150$ MeV per nucleon. 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 uranium ion at entry into the emulsion, where its residual range is 1.50 mm, are computed to be ≈ 115 MeV per nucleon and 88, respectively. Although the track appears to decrease in dE/dx as it approaches its end, the rate of energy loss actually increases 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/μm—that is, a rate of 300 GeV/cm. At a residual range of 100 μm, the uranium ion has a kinetic energy of about 10 MeV per nucleon and an effective charge $Z^* \approx 54$.

Measurements of the mean free path 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 pathlength of interacting and noninteracting ^{238}U ions, the interaction mean free path is $\lambda = 3.1 \pm 0.6$ cm in the interval $0 \leqslant E \leqslant 115$ MeV per nucleon. This value is compatible with that calculated for the mean free path of ^{238}U in emulsion, assuming geometric nuclear sizes (*5*), that is, $\lambda_{calc} = 3.6$ cm.

Table 1 gives the relative frequencies of several classifications of uranium interactions that were observed and the range interval in which they occurred. To illustrate two of the classifications as defined in Table 1, 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 $E \leqslant 115$ MeV per nucleon are apparent from the data in Table 1. These are:

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

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

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

4) Although the number (three) of L-only events is small, they all occur within the highest bin of residual range corresponding to $86 \geqslant E \geqslant 115$ MeV per nucleon, 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 observations above will be carried out as soon as these uranium beams become available.

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