# Fission of Uranium Nuclei in Flight at Relativistic Energies

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The charge, mass, and energy spectra of clean binary-fission events of $^{238}U$ projectiles at energies up to 1 GeV/nucleon are presented. The inelastic interaction cross section and the cross section for the production of binary fission (50% of all interactions) are found to be constant over the entire energy range.

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The various studies of the fission of uranium nuclei carried out so far are mostly limited to those where the uranium nuclei are at rest. Recently, Bevalac at Lawrence Berkeley Laboratory was upgraded to provide beams of ions as heavy as uranium up to 960 MeV/nucleon. This enabled us to study the fission of uranium nuclei at relativistic energies in nuclear emulsion and, as far as we know, this is the first discussion of mass, charge, energy, and angular distributions of fragments produced in the fissioning of the accelerated uranium beam from the Bevalac.

We exposed two small stacks, one dozen each of Ilford G-5 pellicles of sizes 4×8 and 4×5 in.[2], and of 600 $\mu$m thickness to the $^{238}U$ beam with a flux density of $10^3$ particles/cm$^2$. The beam was parallel to the surface of the emulsion and its energy was measured by a bending magnet after its extraction from the Bevalac and passage through a thin foil to ensure that uranium ions were fully stripped of their electrons. The beam entered the emulsion with $Z=92$ at $E=956$ MeV/nucleon.[1] Primary tracks were picked up at the entering edge of the pelliciles and were followed in the emulsion by along-the-track method under 1500× magnification on the digitized microscopes until they either interacted or stopped in the stack. A total length of 32.8 m was followed yielding 894 interactions. The inelastic interaction mean free path (mfp) averaged over the entire energy range was found to be $(3.67 \pm 0.12)$ cm corresponding to $\sigma_T = (3449 \pm 115)$ mb. This value compares favorably with the geometrical cross section (3508 mb) calculated from the modified Bradt and Peters formula[2]:

$$\sigma_{BT} = \pi r_0^2 [(A_B^{1/3} + A_T^{1/3}) - b_0(A_B^{-1/3} + A_T^{-1/3})]^2, \qquad (1)$$

where $r_0 = 1.36$ fm and $b_0 = 1.3$. For $A_T$, we used the composition of G-5 emulsion as given by Barkas.[3] This formula gives reasonable cross-section values for other relativistic heavy-ion beams.[2] We looked at each interaction under 1500× magnification and found that 50.9% of all interactions consisted of fissionlike fragments $(\sigma_F = 1755 \pm 82$ mb). They were characterized by the emission of two heavy projectile fragments of comparable masses and charges.[4] We subdivided these events into three categories, as shown in Fig. 1(a): (i) fission type $F_0$ (20%), consisting of only two fragments and no other charged particles or target fragmentation tracks $(N_h = 0)$; (ii) fission type $F_1$ (8%), consisting of two major fragments along with one or more light projectile fragments ($p$, $d$, $t$, and $\alpha$) but no target fragments $(N_h = 0)$; and (iii) fission type $F_2$ (23%), consisting of two major fragments along with target fragments $(N_h \geq 1)$ with or without light projectile fragments ($p$, $d$, $t$, and $\alpha$).

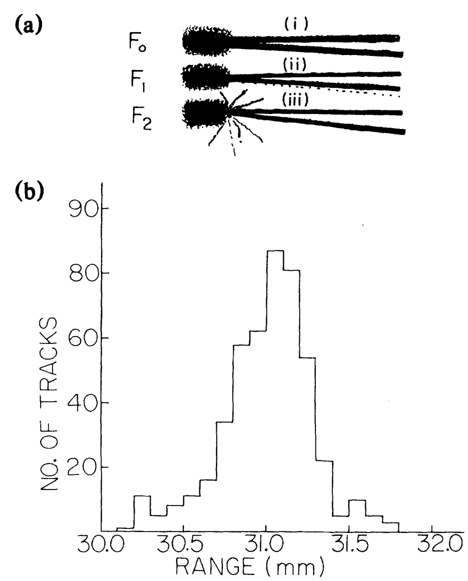


FIG. 1. (a) Drawings of different types of fission events: (i) $F_0$, (ii) $F_1$, and (iii) $F_2$. (b) Range distribution for stopping $^{238}U$ tracks.

Table I shows the percentages and the production cross sections for these events. It is interesting to note from Table I that the relative yield of the singly charged particles ($p$, $d$, or $t$) along with fission fragments, in events with $N_h = 0$, is larger by at least one order of magnitude than the corresponding yield obtained for fission at rest.[5] We would also like to report the observation of one event that can be considered as ternary fission of a $^{238}$U nucleus, the rough estimate of charges being 10, 35, and 47. Apart from these events, we have also observed events with both target and projectile fragmentations (37.6%), events with only projectile fragmentation ($N_h = 0$, i.e., no excitation of the target) (5.0%), events with only target fragmentation ($N_h \geq 1$) (2.0%), and events with central collision (4.5%).

In order to identify the $F_0$ fission fragments, we first checked the validity of the theoretical range-energy relation for heavy ions in emulsion. The residual range $R$ of a heavy ion with velocity $\beta$ is given by the general relation[5]

$$R(\beta) = MZ^{-2}[\lambda(\beta) + B_Z(\beta)], \tag{2}$$

where $M$ and $Z$ are the mass and charge of the particle in units of the proton mass and charge and $\lambda(\beta)$ is the experimental range of protons with velocity $\beta$ in G-5 emulsion as given by Barkas.[3,6] The function $B_Z(\beta)$, corrected for extension in the range of an ion owing to charge pickup at low velocities, can be written as[3]

$$\begin{aligned} B_Z(\beta) &= 1.525\times 10^{-3}\beta Z^{5/3} \text{ cm if } \beta \leq \tfrac{2}{137}, \\ B_Z(\beta) &= 2.233\times 10^{-5} Z^{8/3} \text{ cm if } \beta > \tfrac{2}{137}. \end{aligned} \tag{3}$$

These formulas were applied to the cases of $^{238}_{92}$U at 956 MeV/nucleon, $^{84}_{36}$Kr at 1.52 GeV/nucleon, and $^{197}_{79}$Au at 998 MeV/nucleon. The calculated ranges are 31.25, 129.8, and 36.20 mm for the three heavy ions, respectively. While following the primary $^{238}$U tracks, we observed 457 beam tracks that stopped in the stack. Because the beam was very flat, more than 80% of these tracks stopped in the same pellicle. The ranges of these tracks were measured using the digitized microscopes to within $\pm 5$ $\mu$m in the entire range. The range distribution of these 457, $^{238}$U primary stopping tracks is shown in Fig. 1(b). This distribution is found to have a peak value of 31.15 mm which compares very well with the calculated value of 31.25 mm as stated above. We have recently exposed a stack of G-5 emulsion to a beam of $^{84}_{36}$Kr at 1.52 GeV/nucleon. A preliminary investigation of the ranges of stopping Kr primary beam tracks in the stack shows a peak value of 130.7 mm which, again, agrees very well with the calculated value of 129.8 mm as mentioned above. For the $^{197}_{79}$Au, we compared our calculated value of 36.2 mm with the experimentally measured range distribution which shows a peak at 36.4 mm in emulsion.[7] As is evident, the agreement is, again, quite good. It is therefore concluded that the calculation of heavy-ion ranges in emulsion in the concerned energy range, according to the formulae outlined above, is perfectly valid. We have used these formulae to plot the range-momentum curves of ions of various charges and masses.

TABLE I. Cross section for different fissioning fragments.

| | Type | % | (mb) |
|---|---|---|---|
| $F_0$ | $N_h = 0$ | 20 | $690 \pm 52$ |
| $F_1$ | $F_0 + 1\alpha$ | 3 | $100 \pm 20$ |
| | $F_0 + 1(p, d, \text{ or } t)$ | 3 | $96 \pm 20$ |
| | $F_0 + > 1(p, d, t, \text{ or } \alpha)^{a}$ | 2 | $75 \pm 25$ |
| $F_2$ | $N_h \geq 1$ | 23 | $794 \pm 58$ |

[a]It includes more than one light charged particle.

In order to analyze the $F_0$ events, we primarily considered those events where both fission fragments stopped in the stack. A large majority of these fragments stopped in the same pellicle. We also considered those $F_0$ events where one of the two fission fragments stopped in the emulsion while the other interacted. The angles of all the fragments were measured very accurately as the emulsion has the highest spatial resolution. We checked the coplanarity of these clean events and considered them as pure two-body processes to which the laws of conservation of momentum in the laboratory system are applicable. A knowledge of the $^{238}$U projectile's momentum at the scission point and the production angles of the fragments enabled us to uniquely determine the momenta of the fragments in the laboratory system. The momentum and the measured range of a fragment identifies the fragment completely from the momentum-range curves. The results of all these calculations, in the form of charge and mass spectra of those $F_0$ events where both fragments stopped in the emulsion, are shown in Figs. 2(a) and 2(b).

The emission of prompt neutrons may introduce only a negligibly small error in the distributions.[8] Considering the worst case where the three neutrons may be emitted in the beam direction carrying maximum longitudinal momentum per nucleon

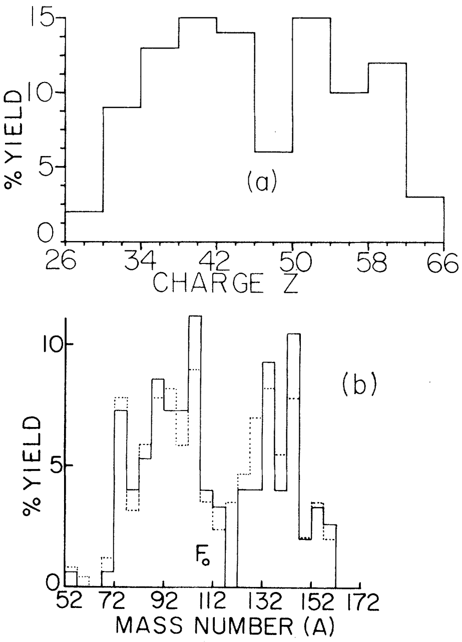


FIG. 2. (a) Charge distribution and (b) mass distribution of $F_0$ fragments with *both* fission fragments stopping in emulsion; dotted lines, with one stopping fragment.

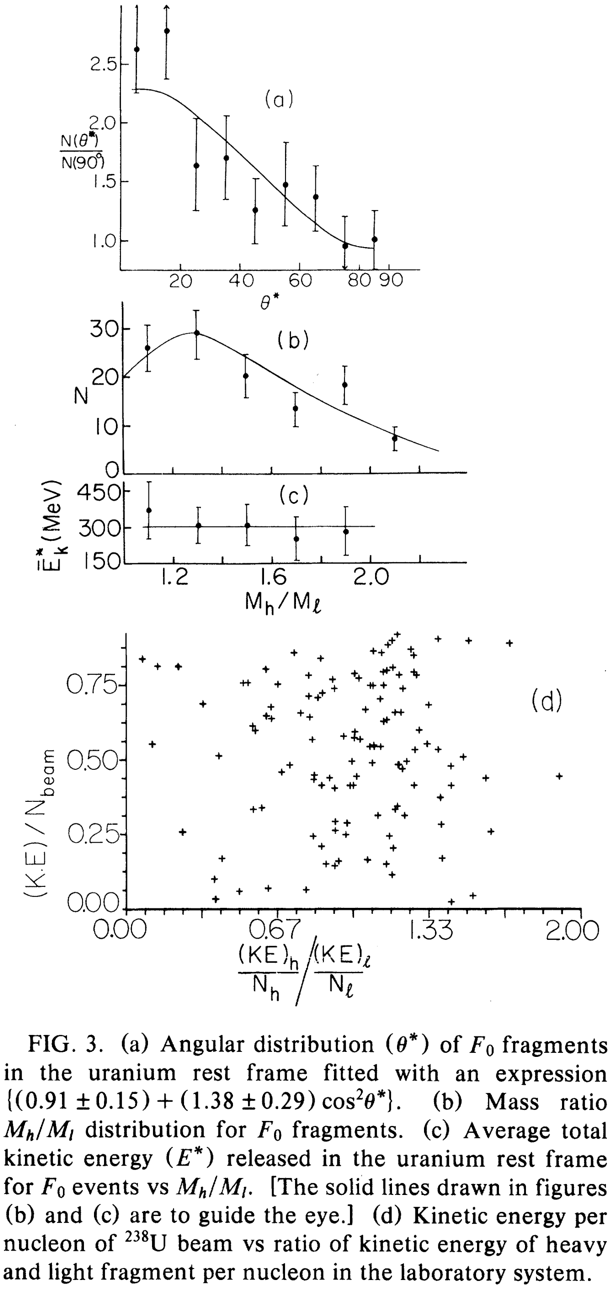


FIG. 3. (a) Angular distribution ($\theta^*$) of $F_0$ fragments in the uranium rest frame fitted with an expression $\{(0.91 \pm 0.15) + (1.38 \pm 0.29) \cos^2\theta^*\}$. (b) Mass ratio $M_h/M_l$ distribution for $F_0$ fragments. (c) Average total kinetic energy ($E^*$) released in the uranium rest frame for $F_0$ events vs $M_h/M_l$. [The solid lines drawn in figures (b) and (c) are to guide the eye.] (d) Kinetic energy per nucleon of $^{238}$U beam vs ratio of kinetic energy of heavy and light fragment per nucleon in the laboratory system.

gives us an error in the momentum determination of the fission fragments of the order of 1.3%. Also taking into account the possible error in the range given by Eq. (2) which can at the most be $\sim 1\%$, the resulting effect on the identification of the fragment is barely enough to shift the charge determination by one charge unit and the mass determination by two mass units. We therefore place an accuracy limit of $\pm 1$ charge unit and $\pm 2$ mass units in the distributions shown in Figs. 2(a) and 2(b). In Fig. 2(b) is also shown by the dotted line the mass distribution of those $F_0$ events where one fragment stopped while the other interacted. All these distributions are similar to those presented in the literature for the fission of uranium at rest.[8,9] In Fig. 3(a) is shown the angular distribution of $F_0$ fragments in the uranium rest frame ($\theta^*$) fitted with a simple anisotropic expression[8,9] of the form

$$\{(0.91 \pm 0.15) + (1.38 \pm 0.29) \cos^2\theta^*\}$$

with $\chi^2/\mathrm{DF} = 0.94$, which represents a good fit. In Fig. 3(b) is shown the mass ratio, $M_h$(heavy mass)/$M_l$(light mass), distribution for the symmetric and the asymmetric modes of $F_0$ events. In Fig. 3(c) is shown the average total kinetic energy produced for relativistic particles in the uranium rest frame. Both these distributions are approximately identical to the ones where the fissioning material is at rest.[8,9] Thus, the kinetic energy of the incident projectile $^{238}$U does not contribute significantly to the kinetic energy of the products. In Fig. 3(d) is shown the distribution of the ratio of the kinetic energy per nucleon in the laboratory system (LS) of heavy and light masses at different primary-beam energies (in LS), which seems to be independent of the primary energy. The analysis of the fission events of types $F_1$ and $F_2$ is being continued. The value of the asymmetry parameter

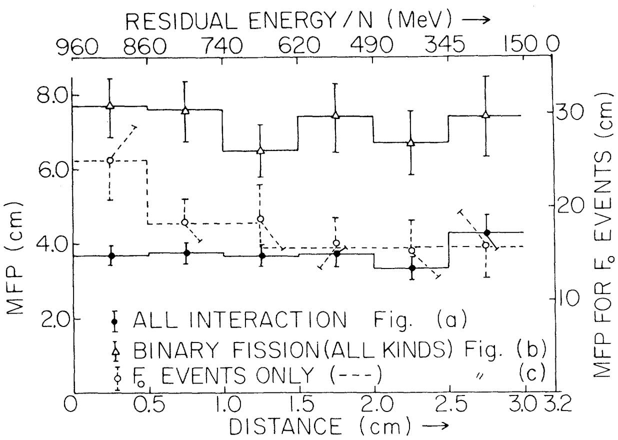


FIG. 4. Mean free path for (a) all interactions (closed circles); (b) all binary fission fragments for $F_0$, $F_1$, and $F_2$ events (triangles); (c) $F_0$ events alone (open circles).

$a = (\langle M_h \rangle - \langle M_l \rangle)^2 / M_0^2$ for $F_1 \simeq 0.018$ is almost half of that for $F_0$, which is 0.035.

We may also mention that the mfp of $^{238}$U for all interactions at different energy intervals is found to be constant, within the statistical errors, at all energies. The value, as stated above, is $3.67 \pm 0.12$ cm. Again, the mfp for the total fission process seems to be independent of energy. The average value of this mfp is $7.20 \pm 0.33$ cm. The two results are shown in Fig. 4 (closed circles and triangles). We find that the mfp for $F_0$ events is higher (by two standard deviations) at energy $E \geqslant 850$ MeV/nucleon where it is almost constant, as shown in Fig. 4 (open circles).

In conclusion, we find that the mass, charge, and angular distributions of fission fragments of $F_0$ events are quite similar to those for the $^{238}$U fission at rest. We also find that the inelastic-interaction cross section as well as the binary-fission production cross section of $^{238}$U nuclei are constant over the whole energy range up to 1 GeV/nucleon.

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