Fission of Ag and Br in Nuclear Emulsion by 1.0–3.0-Bev Protons*

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(Received December 15, 1961)

A study was made of the fission stars produced in low sensitivity nuclear emulsions by 1.0–3.0 Bev protons. These events are characterized by two densely ionizing tracks in approximately opposite directions. The fractions of the inelastic cross section of Ag and Br leading to fission at 1.0, 2.0, and 3.0 Bev are 0.03, 0.06, and 0.11, respectively. Symmetric fission is most probable: in 41% of the events the ratio of track lengths is 1.0–1.5; in 27% the ratio is 1.5–2.0. The fission fragment velocity distribution (mean of 0.044c) was derived from the range distribution (mean of 9 μ). The average angle between the fission fragments deviates from π by 42°, indicating that the center-of-mass system is moving at a mean velocity of 0.016c approximately along the line bisecting the angle between the fragments. From a study of the energy spectrum of the alpha particles and of their angular distribution with respect to the fission fragments it appears that about 75% of the alphas are emitted prior to fission and about 25% simultaneously with fission.

INTRODUCTION

THERE is little information in the literature on the fission of intermediate weight elements by high-energy particles. Three radiochemical studies have been reported on the fission of silver with protons of a few hundred Mev. Kurchatov *et al.*[1] used 480-Mev protons and determined a fission cross section of roughly 0.1 mb. Kofstad[2] estimated a cross section of 0.01 to 0.10 mb at 340 Mev. In the recent investigation of Rind,[3] fission cross sections of 0.015, 0.060, and 0.250 mb were reported at 156, 286, and 380 Mev, respectively. Lavrukhina *et al.*[4], studied the radioactive products from antimony irradiated by 660-Mev protons. They report a fission cross section of 0.25 mb. In a nuclear emulsion study of silver and bromine fission, Shamov[5] found a cross section of 0.32±0.1 mb which was independent of proton beam energy between 300 and 660 Mev. This result is in sharp contrast with the rapid increase in cross section with energy reported by Rind.[3]

In the present investigation, the fission of Ag and Br in nuclear emulsion has been studied at 1.0, 2.0, and 3.0 Bev. Data are presented on the fission cross section, on the degree of fission asymmetry, on the velocity distribution of fission fragments, and on the angular correlation of the fission fragments to each other. The alpha particles and light fragments associated with fission events have also been studied and their production in fission and in nonfission events have been compared.

EXPERIMENTAL

As reported previously,[6,7] 200-μ Ilford D.1 nuclear emulsions were exposed to 1.0-, 2.0-, and 3.0-Bev protons at the Cosmotron. The plates were relatively insensitive so that only alpha particles and heavier fragments were recorded. Among the stars produced, those which were characteristic of fission events were selected for measurement and analysis. The criteria used in this selection were the dense ionization of each track and the appearance of a taper toward the end of the range. Calibration plates containing tracks of nitrogen ions were used to determine the minimum ionization acceptable for this group. Since only those fragments with $Z \geq 7$ ($A \geq 14$) were classified as fission fragments, events in which the ratio of track ranges exceeded 5 were not accepted. The more symmetric fission events, with ratios of track ranges ≤ 2, are referred to as group III_{sym}; the less symmetric events, with ratios of track ranges between 2 and 5, are referred to as group III_{asy}. About 400 fission events were studied at each of the three bombarding energies. Except where specifically mentioned, the results reported below are for the III_{sym} fissions, although no significant differences in the results were found for the III_{asy} group. The ranges and angles in space were measured for all of the observed particles.

RESULTS AND DISCUSSION

It was found[7] that fission (III_{sym} and III_{asy}) accounts for 3%, 6%, and 11% of the total inelastic cross section of Ag and Br at 1.0, 2.0, and 3.0 Bev, respectively. Ternary fission, with production of three fragments of comparable mass, was observed with a frequency of about 0.02 of binary fission. The fission cross section increases slightly faster from 1.0 to 2.0 Bev than does the calculated[8] mean excitation energy in this interval (Figs. 1 and 2, reference 7).

* Research performed under the auspices of the U. S. Atomic Energy Commission.

[1] B. V. Kurchatov, V. N. Mekhedov, N. I. Borisova, M. Ya. Kuznetsova, L. N. Kurchatova, and L. V. Chistyakov, *Proceedings of the Conference of the Academy of Sciences of the U.S.S.R. on the Peaceful Uses of Atomic Energy, Moscow, July, 1955* (Akademiia Nauk, S.S.S.R., Moscow, 1955) translation by Consultants Bureau, New York: Atomic Energy Commission Report TR-2435, 1956, p. 111.

[2] P. K. Kofstad, University of California Radiation Laboratory Report UCRL-2265, June 1953 (unpublished).

[3] K. W. Rind, thesis, Columbia University, New York, July, 1961 (unpublished).

[4] A. K. Lavrukhina, E. E. Rakovskii, Su Hong-Kuei, and S. Khoinatskii, Zhur. Eksp. i Teoret. Fiz. **40**, 409 (1961). [translation: Soviet Phys.-JETP **13**, 280 (1961)].

[5] V. P. Shamov, Zhur. Eksp. i Teoret. Fiz. **35**, 316 (1958) [translation: Soviet Phys.-JETP **8**, 219 (1959)].

[6] E. W. Baker, S. Katcoff, and C. P. Baker, Phys. Rev. **117**, 1352 (1960).

[7] E. W. Baker and S. Katcoff, Phys. Rev. **123**, 641 (1961).

[8] N. Metropolis, R. Bivins, M. Storm, A. Turkevich, J. M. Miller, and G. Friedlander, Phys. Rev. **110**, 204 (1958).

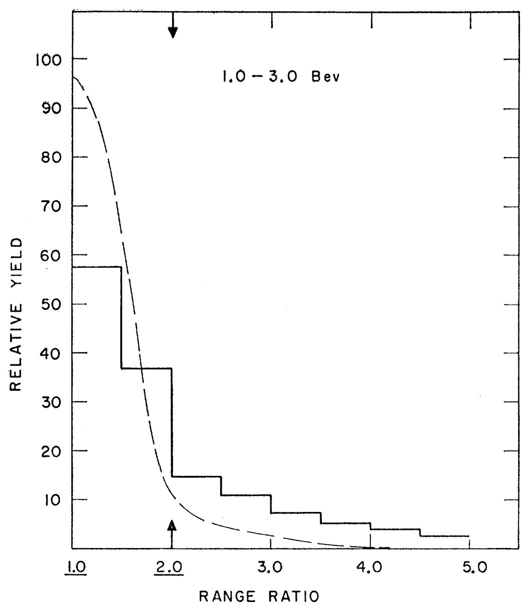

FIG. 1. Distribution of fission fragment length ratios. The calculated dashed curve is explained in the text.

The ratio of the fission fragment lengths l_L/l_H shows a distribution which does not depend on incident proton energy. The combined data from the three energies are plotted in Fig. 1 as the solid histogram. Although the distribution is broad it may be seen that about two thirds of the fission events fall within group III_{sym} and

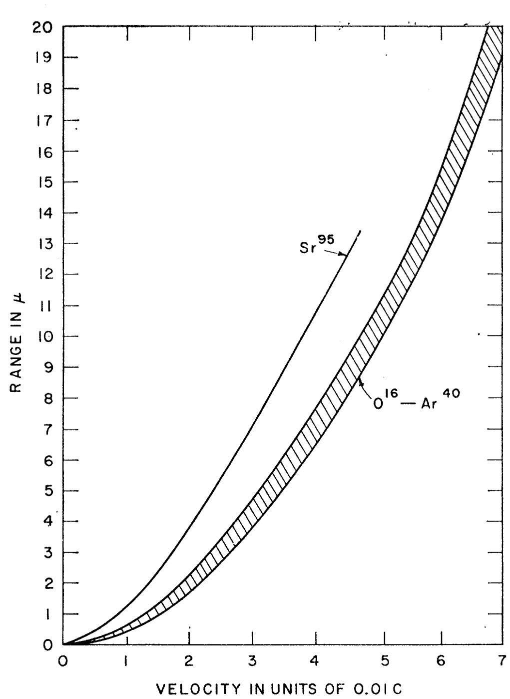

FIG. 2. Range vs velocity for various heavy ions in nuclear emulsion (references 10–13).

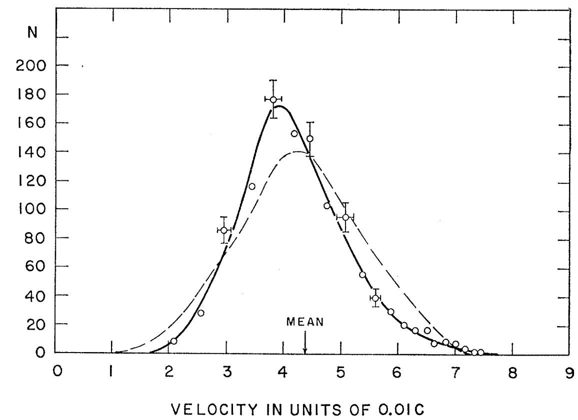

FIG. 3. The fission fragment velocity distribution, group III_{sym} (solid curve). See text for explanation of dashed curve.

that the remainder are in group III_{asy}. The dashed curve, derived from a calculation to be described below, shows the distribution of range ratios produced in laboratory coordinates by fission which is perfectly symmetric in the moving system. Thus the distribution of mass ratios is considerably narrower than would appear from the observed distribution of range ratios. From estimates of the number of nucleons knocked out in the initial cascade,[8] of the most probable deposition energy,[8] and of the approximate number of nucleons evaporated,[9] one finds that the most probable fission events yield products in the neighborhood of mass 35. Most fission products are likely to be in the region from sodium to vanadium.

The mean range of the fission fragments is about 9 μ compared to 3.5 μ for recoils from nonfission events (Fig. 7 of reference 7). (Shamov[5] has reported a mean fission fragment range in nucelar emulsion of about 15 μ. The reason for the discrepancy with our result is not clear.) From the observed distribution in range of the fission fragments (Fig. 8 of reference 7), it is possible to derive a fairly accurate velocity distribution for the III_{sym} fragments. The transformation from range to velocity was performed by means of the range versus velocity relations of Heckman *et al.*,[10] which are nearly independent of fragment mass in the region from O^{16} to Ar^{40} (Fig. 2). The fission fragment velocity distribution is shown in Fig. 3, solid curve. The mean velocity is $0.044c$, a value which may be compared with that expected from the mutual repulsion of two nuclei produced in a symmetric fission. For example, two Ca^{40} nuclei would have velocities of $0.042c$ if $r_0=1.3\times10^{-13}$ cm. In addition to the Coulomb repulsion velocity there are additional components resulting from momentum transferred by the incident proton and from evaporation of particles. The observed width of the velocity distribution can be accounted for by these effects and by the

[9] I. Dostrovsky, Z. Fraenkel, and R. Bivins, Phys. Rev. **111**, 1659 (1958).
[10] H. H. Heckman, B. L. Perkins, W. G. Simon, F. M. Smith, and W. H. Barkas, Phys. Rev. **117**, 544 (1960).

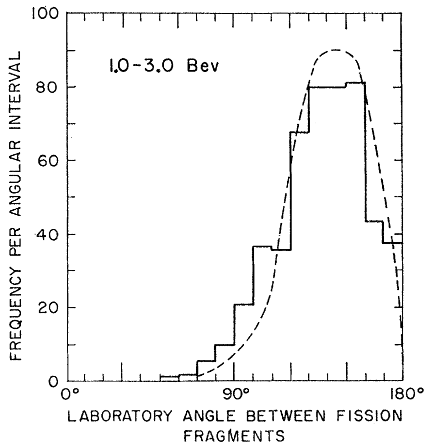

FIG. 4. Distribution of angles between the fission fragments. Dashed curve explained in text.

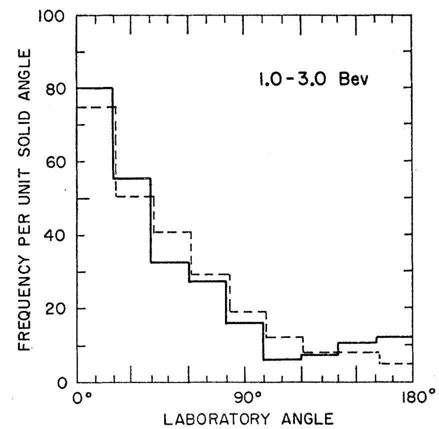

FIG. 5. Angular distribution to the beam of the line bisecting the angle between the fission fragments (solid histogram). The dashed histogram shows the angular distribution of recoils in nonfission events.

distribution of fission fragment masses, as discussed below.

Data for the distribution of angles observed between the two fission fragments have been combined for the three bombarding energies and are shown by the histogram of Fig. 4. The mean angles are 140°, 137°, and 136° at 1.0, 2.0, and 3.0 Bev, respectively. The average angle between fission fragments for the III_{asy} group is 138° for the three combined bombarding energies. Deviation from 180° results from the fact that the fission takes place in a moving system. The mean velocity of this system is found to be 0.016*c* by assuming that the direction of its motion is along the line bisecting the 138° mean angle between the two fission fragments, each of which has an average laboratory velocity of 0.044*c*. The mean fragment velocity in the moving system is then 0.041*c*. The choice of the "fission bisector" as the approximate direction of motion seems equivalent to the choice of the recoil direction for nonfission events.[6] The angular distribution for the "bisectors" with respect to the beam is shown by the solid histogram of Fig. 5, while that for the nonfission recoils is shown by the dashed histogram.

The data shown in Figs. 1, 3, and 4 are compared with a calculation based on the following model. Consider the nucleus, struck by a high energy proton, to emit cascade and evaporation particles until it is reduced to an intermediate nucleus in the region of mass 70. This intermediate nucleus, which is assumed to have the velocity distribution given by the recoil ranges in nonfission events, then undergoes symmetric fission isotropically. The nonfission events selected were those produced by 2.0-Bev protons in which light fragments ($2<Z\leq 6$) are emitted (Fig. 8 of reference 7); the velocities of these recoil nuclei were estimated from their ranges and from the range and velocity data given in the literature[11–13] for uranium fission fragments. The velocity of the fission fragments in the system of the intermediate nucleus was taken as 0.041*c*. Thus, for each center-of-mass velocity, a distribution function was derived for the laboratory angle between the fission fragments, and another distribution function was derived for the laboratory velocity of the fission fragments. These distributions were then appropriately weighted according to the recoil range distribution and then combined to give the dashed curves of Figs. 1, 3, and 4. From Fig. 4 it may be seen that the calculated angular distribution is in good agreement with the observed one. The calculated velocity distribution (Fig. 3) is slightly broader than the observed distribution, although one might have expected it to be slightly narrower, since exactly symmetric fission was assumed in the calculation. This apparent deviation may be accounted for by the manner in which the III_{sym} events were selected. As shown by the dashed curve of Fig. 1, range ratios exceeding 2 can sometimes result even from purely symmetric fission; since ratios above 2 were rejected from the III_{sym} group, the observed velocity distribution is made somewhat narrower. Thus it has been shown how center-of-mass motion affects the fission fragment range ratios, their velocity distribution, and the distribution of angles between them.

The alpha spectrum from fission events as observed in the laboratory system is shown by the solid histogram of Fig. 6(c). The solid histogram of Fig. 6(d) shows the alpha spectrum for the same fission events in the center-of-mass system. For comparison, the corresponding alpha spectra from nonfission events are shown in Fig. 6(a) and (b). The dashed histograms represent a spectrum derived from Monte Carlo evaporation calculations.[8,9,14] The transformations were made assuming the direction of the moving system to be along the path of

[11] L. Vigneron, Compt. rend. **231**, 1473 (1950).
[12] R. B. Leachman and H. W. Schmitt, Phys. Rev. **96**, 1366 (1954).
[13] J. M. Alexander and M. F. Gazdik, Phys. Rev. **120**, 874 (1960)
[14] J. Hudis and J. M. Miller, Phys. Rev. **112**, 1322 (1958).

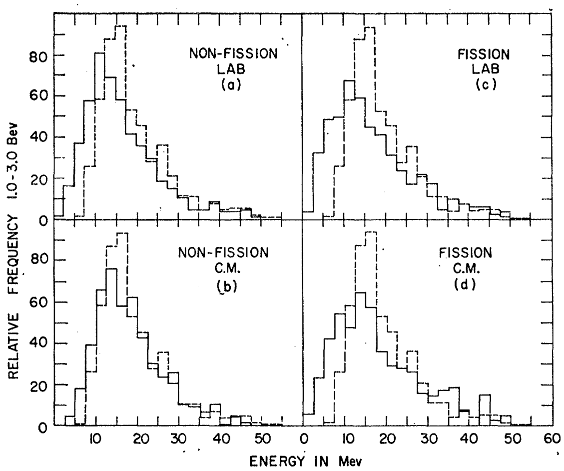

FIG. 6. Alpha-particle spectra from fission events (c and d) and from nonfission events (a and b). The dashed histograms show the same calculated evaporation spectrum in each quadrant of the figure.

the recoil for the nonfission events and along the line bisecting the angle between the two fragments for the fission events. As shown previously,[6] the proportion of low energy alpha particles, below 10 Mev, from nonfission events is considerably reduced when a suitable center-of-mass transformation is made; and the observed spectrum is in good agreement with the calculated distribution based on evaporation theory. In the fission events, however, the proportion of low energy

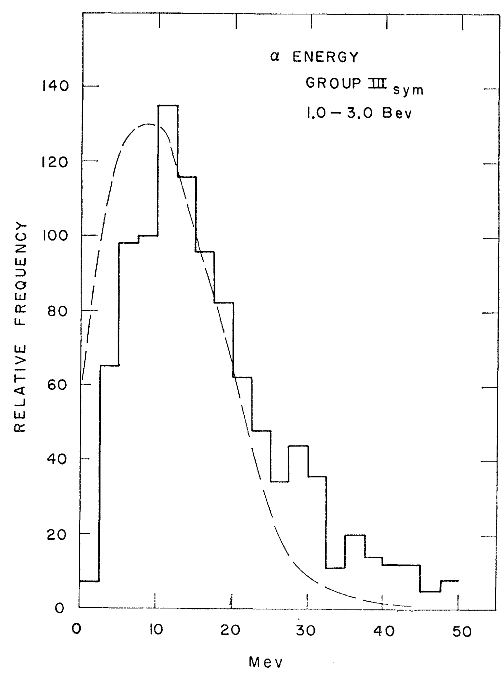

FIG. 7. Observed alpha spectrum from fission events (histogram) compared with spectrum in the laboratory system calculated (dashed curve) for alpha particles evaporated from moving fission fragments.

alpha particles is substantial even after making the transformation. Although the higher energy alpha particles may also be explained by an evaporation process, as in the nonfission events, the excess of low energy particles in the center-of-mass system is not consistent with evaporation from a nuclues whose Coulomb barrier is near that of Ag or Br. One must, therefore, postulate some additional, though not necessarily large, contribution from another mechanism.

In order to determine the possible mechanisms causing the shift to lower alpha energies in the fission events, both evaporation from the fission fragments and simultaneous emission have been considered. A calculation has been made to determine the expected distributions in energy and angle for the case in which the alpha particles are evaporated from the fission fragments.[15] It was assumed that the particles are emitted isotropically from fragments moving at $0.04c$ and that the alpha spectrum in the moving system has the shape characteristic of nonfission events but with the Coulomb barrier reduced to one-half that of the intermediate excited nucleus. Figure 7 shows the comparison in the laboratory system between the calculated energy distribution (dotted curve) and the observed distribution (solid histogram). Alpha particles emitted simultaneously with the act of fission,[16] would also be expected to show an energy distribution somewhat similar to the calculated one of Fig. 7. The observed distribution does not show as great a downward shift in energy and therefore indicates that the majority of alpha particles are not emitted via either of these mechanisms.

Additional information on these two mechanisms can be obtained from a study of the angular distribution of the alpha particles with respect to the fission fragments.

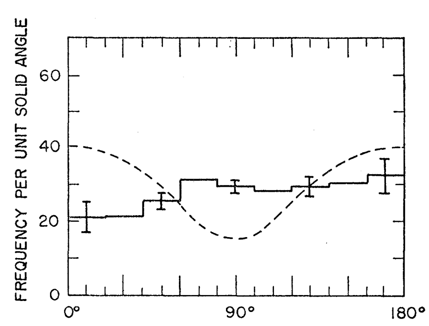

FIG. 8. Angular distribution of alpha particles to the fission fragments (histogram) compared to the distribution expected for alpha particles emitted from moving fission fragments (dashed curve).

[15] A study of neutron evaporation from moving uranium fission fragments has been made by J. S. Fraser, Phys. Rev. **88**, 536 (1952).

[16] Studies of the energy spectrum and angular distribution of alpha particles emitted simultaneously with the fission fragments in thermal uranium fission have been made by several authors: C. B. Fulmer and B. L. Cohen, Phys. Rev. **108**, 370 (1957); N. A. Perfilov and Z. I. Solov'eva, Zhur. Eksp. i Teoret. Fiz. **37**, 1157 (1959) [translation: Soviet Phys.-JETP **10**, 824 (1960)].

Alpha particles produced in the act of fission tend to be emitted at right angles to the fission fragments.[16] On the other hand, those particles emitted from either of the fission fragments subsequent to fission would appear, in the laboratory system, to be forward with respect to the parent fragment and backward to the partner, thus giving rise to a strong forward-backward peaking.[15] The solid histogram of Fig. 8 shows the observed angular distribution of alpha particles relative to the fission fragments, and the dotted curve represents the distribution calculated for the emission of alpha particles from fragments as described earlier. The observed data show a nearly isotropic angular distribution rather than the 90° or the forward-backward peaking. Thus the observed distributions in angle, as well as in energy, indicate that neither simultaneous emission nor evaporation from fragments plays a major role in the emission of alpha particles. However, it is still necessary to account for the shift to lower alpha energies in fission events as compared to nonfission events.

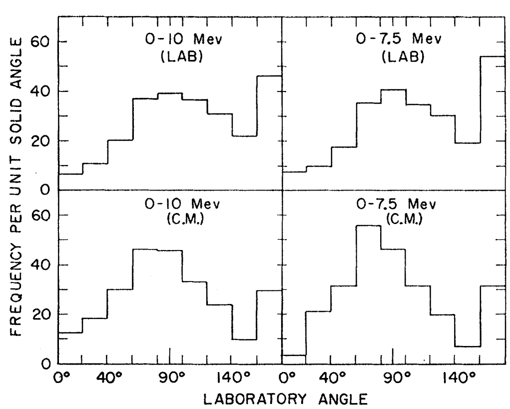

FIG. 9. Angular distribution of low-energy alpha particles to the fission fragments.

Since the discrepancy between the alpha spectra from nonfission and fission events lies in the low energy region, it is profitable to examine the angular distribution of these low energy particles with respect to the fission fragments. The histograms of Fig. 9 show these distributions for alpha particles whose laboratory energies fall in the 0–10 Mev region; also shown are distributions for the alpha particles whose center-of-mass energies fall in the same region. It may be seen that each of these low energy groups shows a broad peak about 90°. If these alpha particles are being emitted simultaneously with the fission process, the center-of-mass transformations, using the "bisector" as the direction of motion, are appropriate; and one should, therefore, expect to see a stronger correlation in the center-of-mass system than in the laboratory system. If, on the other hand, these alpha particles are being emitted primarily from the fission fragments, the transformations should have been made in the system of the fragments, and the choice of the "bisectors" would be in gross error, causing most, if not all, of the 90° correlation in the center-of-mass system to be lost. This would be particularly true as the angle between the fission fragments increases. The histograms of Fig. 9 indicate that these alpha particles do indeed originate from a system moving in the approximate direction of the "bisectors" and that they are being emitted simultaneously with the fission process. One effect which broadens these curves is the deviation from 180° of the angle between the fission fragments. The histograms of Fig. 10 are based on the same measurements as in Fig. 9 but include only those events in which the angles exceed 135°. The correlation about 90° becomes considerably sharper, particularly for those alpha particles shown in the center-of-mass distributions. This gives additional confirmation to the conclusions concerning the direction of the moving system and the time of emission of the low-energy alpha particles. The small excess of alpha particles in the backward direction for the laboratory system (Figs. 8–10) is a result of center-of-mass motion and is independent of the mechanism considered for the low-energy alpha particles.

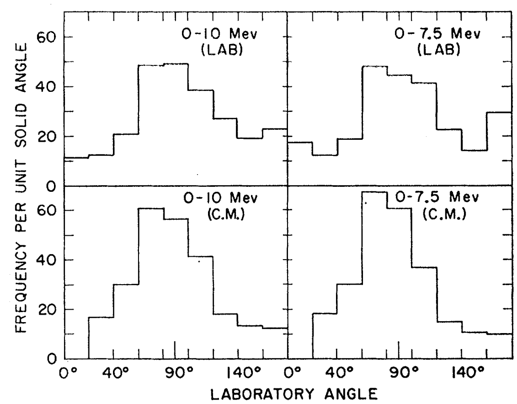

FIG. 10. Angular distribution of low-energy alpha particles to the fission fragments for those events where the angle between the fragments exceeds 135°.

The fraction of alpha particles emitted simultaneously with the fission process has been estimated as $\sim 25\%$. This can be only a rough estimate since the shape of the energy distribution of alpha particles emitted during the fission of Ag and Br is not well known. This fraction of particles could easily account for the excess of low-energy alpha particles observed in the fission events as compared with the nonfission events. It would also be consistent with the over-all angular distribution of alpha particles (0–50 Mev) with respect to the fission fragments (Fig. 8). No evidence has been found to support a mechanism in which alpha particles are emitted from the fragments after fission has taken place. It would follow, therefore, that about three-fourths of the alpha particles are evaporated prior to the fission of Ag and Br nuclei.

The angular distribution of the light fragments with

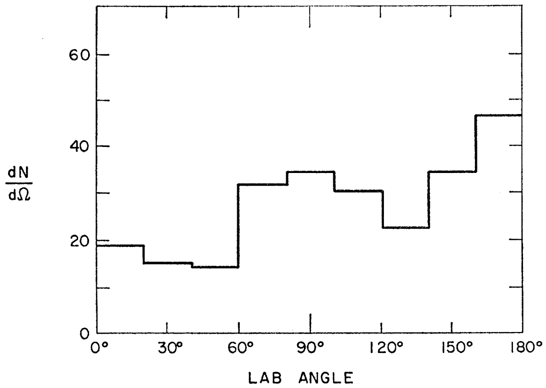

FIG. 11. Angular distribution of the light fragments with respect to the fission fragments.

respect to the fission fragments (Fig. 11) shows some peaking around 90°. The larger and variable mass of the light fragments makes the interpretation of these data somewhat uncertain. However, the results indicate a greater proportion of simultaneous emission of light fragments as compared with alpha particles.

CONCLUSION

Fission of medium weight elements differs from heavy element fission with respect to energetics. In heavy elements, the mass decreases by about 150 Mev, which is just about equal to the Coulomb energy and to the fragment kinetic energy. In the fission of medium weight elements the mass usually increases by 10–20 Mev. Since the Coulomb energy here is 40–50 Mev, there is a fission threshold of ~60 Mev.

The Monte Carlo nuclear cascade calculations[8] indicate that the mean excitation energy for all cascade products from the irradiation of Ru^{100} by 1.84-Bev protons is 270 Mev. Since the fission cross section increases very rapidly with energy,[3,7] it is reasonable to assume that the mean excitation energy is about 400 Mev for those cascade products which eventually undergo fission. Such high excitation may produce nuclear oscillations but it seems that these do not result in actual scission until the nucleus has had time to evaporate many particles. Since alpha particles are not observed to evaporate from the resulting fission fragments, and since the emission probability of alpha particles relative to nucleons seems to be almost independent of excitation energy[9,17] above 50 Mev, it is probable that, at most, only a few nucleons are emitted from the fission fragments.

An alpha particle or light fragment is frequently emitted simultaneously with the two heavy fragments. True ternary fission, in which three approximately equal fragments are produced, is very rare.

ACKNOWLEDGMENTS

We are greatly indebted to Mrs. Dorothea Hodgdon and Mrs. Doris Franck for scanning the emulsions and for assisting with the calculations.

[17] I. Dostrovsky, Z. Fraenkel, and G. Friedlander, Phys. Rev. **116**, 683 (1960), and G. Friedlander (private communication).

PHYSICAL REVIEW VOLUME 126, NUMBER 2 APRIL 15, 1962

Altitude Dependence of the Longitudinal Distribution of Atmospheric Čerenkov Radiation*

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The longitudinal distribution of the Čerenkov radiation generated by the electron component of extensive cosmic ray air showers interacting with the earth's atmosphere was measured at −46 m and 3801 m elevation. Although the two distributions are similar, a somewhat larger number of showers with small Čerenkov radiation thickness at 3801 m suggests that those showers contain substantial light contributions from elevations where electron scattering is small.

THE Čerenkov radiation associated with the electron component of extensive cosmic ray air showers is produced along that portion of the electron paths in the atmosphere during which the electron velocities exceed the phase velocity of light. The subsequent detection of this radiation can provide unique information concerning the history of the electrons. In general, the light arriving at the detector first will have been produced early in the shower development since Coulomb scattering of the electrons will delay their longitudinal progress relative to the Čerenkov photons.

Thus the time dependence of the incident Čerenkov

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