Energy and Angular Distributions of Alpha Particles from Reactions of High-Energy Protons with Ag and Br Nuclei*

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An investigation has been made of the energy and angular distributions of α particles emitted from silver and bromine nuclei in Ilford *D*-1 (200 μ) nuclear emulsions, during bombardments in the Brookhaven Cosmotron with 1.0-, 2.0-, and 3.0-Bev protons. The α energies studied were in the interval from 0–50 Mev with particular emphasis placed on the low-energy region. An attempt has been made to correct the observed spectra for the center-of-mass motion of the emitting nucleus and then to compare these spectra with those calculated from nuclear evaporation theory. Two sets of center-of-mass transformations were made. In one case the beam direction was considered to be that of the moving system, and in the second case the direction of the observed recoil was considered to be that of the moving system. Good agreement was obtained with the theoretical spectra throughout the energy region studied. An apparent excess of low-energy α particles in the uncorrected spectra was removed by assuming that the emitting nucleus moves in the observed direction of the recoil at $0.015c$ at 1.0 Bev and $0.02c$ at 2.0 Bev. These velocities were consistent with the measured lengths of the observed recoil nuclei. Both the angular distributions of the recoil fragments and of the α particles were consistent with random emission from this moving system. It seems likely, therefore, that one can, at the same time, explain the observed angular distributions and the low-energy α particles by isotropic evaporation from a moving system.

INTRODUCTION

DURING the past ten years discrepancies have been reported in the literature between the observed alpha spectra produced by high-energy incident nucleons, and those calculated from nuclear evaporation theory. In studying the events produced by high-energy cosmic rays, Harding, Lattimore, and Perkins[1] have observed that large numbers of α particles ($\sim$40%) are ejected with kinetic energies well below what is generally assumed to be the Coulomb barrier for heavy nuclei in emulsions. Le Couteur[2] and Fujimoto and Yamaguchi[3] have proposed an explanation, based on an idea of Bagge's, that at high excitation the appearance of these low-energy particles may be due to an increase in the effective nuclear radius and therefore a substantial reduction of the potential barrier. It has been suggested by Perkins[4] that the origin of these slow particles may be the ejection of unstable fragments which then decay by α emission in flight. It has further been proposed by Süssmann[5] that at high excitation energies fission may occur with the subsequent evaporation from these fragments.

In the present investigation a study has been made of the α energy distributions from proton bombardments at 1.0, 2.0, and 3.0 Bev, and particular emphasis has been placed on the low-energy region of these spectra. In addition studies have been made of the angular distributions of the recoil nuclei relative to the direction of the incident beam; of the α particles relative to the beam, and of the α particles relative to the recoiling nuclei. An average velocity was assumed for the emitting nuclei at each bombarding energy. The energies and angles of the particles in the center of mass of this system were then calculated. This was done in two ways: (1) by the use of the measured angles between the α particles and the incident beam and (2) by the use of the measured angles between the α particles and the recoil direction of the parent nuclei. In the first case the direction of the moving system was considered to be the same as that of the beam direction. In the second case the direction of the moving system was considered to be the same as the observed recoil direction.

EXPERIMENTAL

Ilford *D*-1 (200 μ) nuclear emulsion plates were exposed in the internal proton beam of the Brookhaven Cosmotron at 1.0-, 2.0-, and 3.0-Bev energies. A copper block and aluminum shutter were placed in the machine in such a way as to prevent lower energy protons from entering the emulsions. The plates were placed at an angle of 10° to the beam and lowered $\frac{3}{4}$ inch below the median plane. In this manner a gradient of beam intensity was established along both the length and the width of the plate and an optimum scanning area could easily be located.

The *D*-1 plates were selected for this work because it was felt that with them the maximum discrimination could be obtained for α particles and other multi-charged fragments. Tracks with charges of $Z=2$ and $Z=6$ may easily be blob counted and calibrated with known heavy ions. In the present investigation the α

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

[1] Harding, Lattimore, and Perkins, Proc. Roy. Soc. (London) **A196**, 325 (1949).

[2] K. J. Le Couteur, Proc. Phys. Soc. (London) **A63**, 259 (1950).

[3] Y. Fujimoto and Y. Yamaguchi, Progr. Theoret. Phys. (Kyoto) **5**, 76 (1950).

[4] D. H. Perkins, Phil. Mag. **41**, 138 (1950).

[5] C. Süssmann, Z. Naturforsch. **8a**, 404 (1953).

tracks were identified by blob count curves obtained from 40-Mev α particles accelerated by the Brookhaven Cyclotron, and by the use of similar curves of the heavier Li^8 "hammer" tracks produced from the nuclear disintegrations in the plates being scanned.

In the identification of α particles by means of blob counting, a compensating effect was observed between tracks flat in the emulsion and those with considerable dip. In the flat tracks all blobs were visible and distinct, whereas in the steeper tracks all of the blobs were no longer distinct, and the count therefore decreased. Although the true length of the steep tracks was somewhat greater than the observed length, the number of blobs, per unit projected length, remained nearly constant. This effect was confirmed by exposing plates to cyclotron α particles at dip angles of 20°, 40°, and 60°. It was felt that α particles could be reliably identified and accepted with dip angles up to 50° in the undeveloped emulsion. For heavier charged particles, however, the maximum acceptable dip angle would decrease as the charge of the particles increased.

Another feature of the Ilford *D*-1 plates is that they can be developed in such a way as to render them completely insensitive to singly charged particles. This insensitivity was confirmed by exposing the plates to 10-Mev protons at the Brookhaven Cyclotron.

Since light elements (C, N, and O) are also present in emulsions, the criteria for the selection of events taking place in heavy nuclei (Ag and Br) required that the recoil fragment in each case be heavier than carbon and that at least one α particle be present. If the recoil was short and therefore questionable then the sum of the charges of the other prongs was used. Since singly charged particles cannot be detected these events do not represent the total number of interactions produced by the Bev protons but rather the total number of interactions where at least one α particle was emitted.

The geometrical efficiency for observation of tracks was calculated as a function of angle in the emulsion, depth in the emulsion, and the length of track. This was used to make the correction for the number of tracks not measurable because of excessive dip or because of failure to end in the emulsion. This correction therefore did not assume an isotropic distribution about the beam direction.

The criteria for the selection of the tracks were: 1. Angle of dip was ≦50° in the undeveloped emulsion; 2. The tracks were emitted from Ag or Br nuclei; and 3. The tracks ended in the emulsion. The detection of α tracks with energies up to 50 Mev was reliable.

The following data are based on 365, 287, and 271 stars at 1.0, 2.0, and 3.0 Bev, respectively. The data of Figs. 6, 14, and 15, however, are derived from measurements on 699 stars at 1.0 Bev and 637 stars at 2.0 Bev.

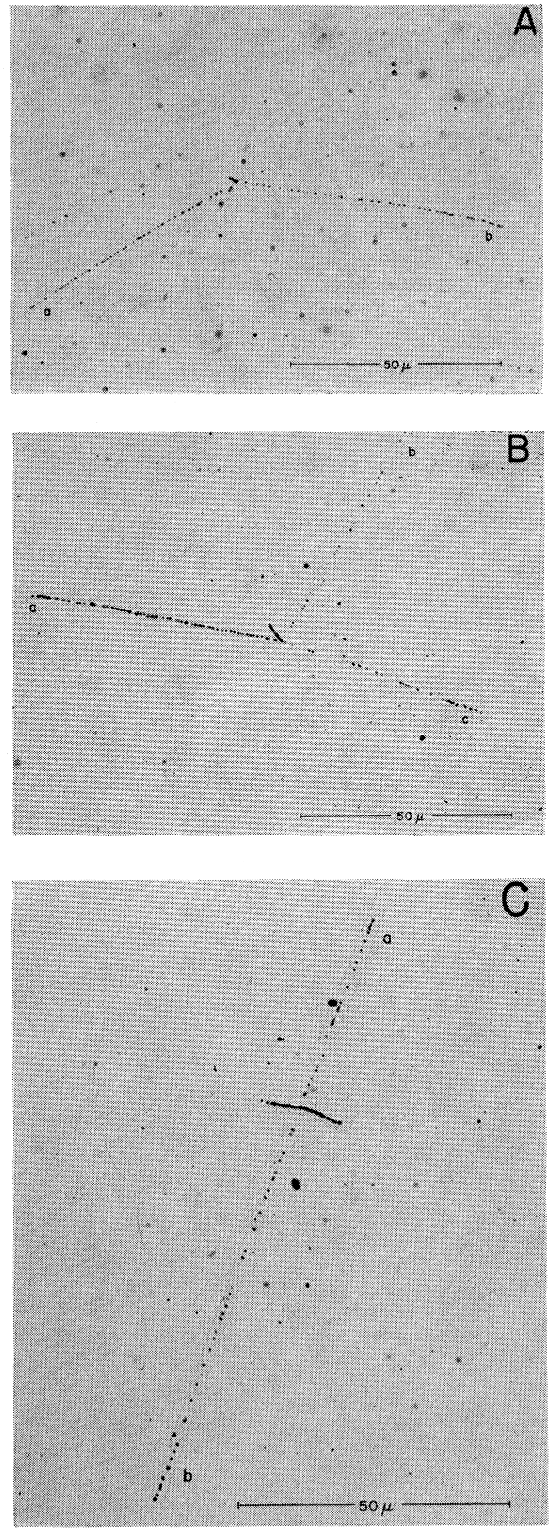

FIG. 1. (A) Group I event—Recoil with two α particles (*a*) and (*b*). (B) Group II event—Recoil with 3 tracks: (a) carbon; (*b*) particle leaving emulsion; and (*c*) α particle. (C) Group III event—Two heavily ionizing fragments with 2 α particles (*a*) and (*b*).

RESULTS AND DISCUSSION

Events in which multicharged fragments are emitted can be classified in three groups. Group I events [Fig. 1(A)] are characterized by a recoiling nucleus and one or more α particles. In Group II events [Fig. 1(B)] fragments of charge $(2<Z\leqslant 6)$ appear in addition to the recoil and α particles. In Group III events [Fig. 1(C)] there appear two short, heavily ionizing tracks which may be fission fragments,[6] in addition to α particles and sometimes fragments of charge $(2<Z\leqslant 6)$. These heavy tracks could neither be blob counted nor gap counted and therefore the fragments could not be identified. The angle and direction of the recoiling nucleus cannot be studied in the case of Group III events since there is no one obvious recoil. Most of the present discussion, therefore, will be based only on α particles appearing in Group I and Group II events.

The average number of α particles per observed event as a function of bombarding energy is shown in Fig. 2 as a solid line. Since only those events having at least one α particle were accepted, it was necessary to correct to the total number of interactions produced by the Bev protons. The corrections were made from Monte Carlo calculations[7–9] and the number of α

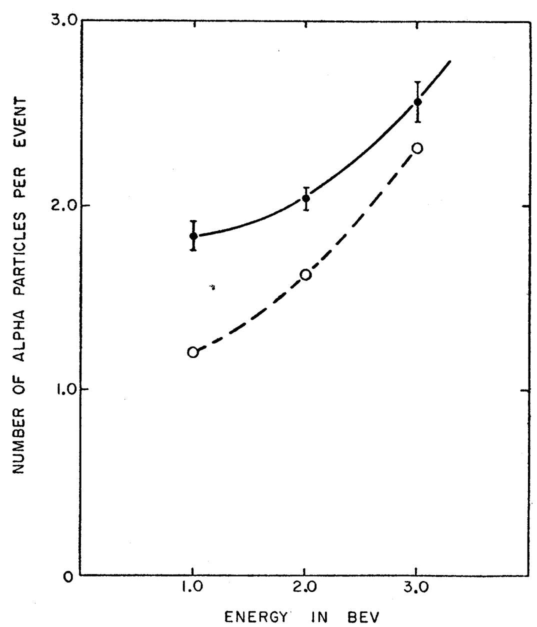

FIG. 2. The solid line shows the average number of α particles found in events having at least one α particle. The dotted line shows the number of α particles per proton interaction as a function of bombarding energy.

[6] C. F. Denisenko and N. A. Perfilov, Phys. Rev. **109**, 1770 (1958).

[7] Metroplis, Bivins, Storm, Miller, Friedlander, and Turkevich, Phys. Rev. **110**, 204 (1958).

[8] Dostrovsky, Rabinowitz, and Bivins, Phys. Rev. **111**, 1659 (1958).

[9] J. Hudis and J. M. Miller, Phys. Rev. **112**, 1322 (1958).

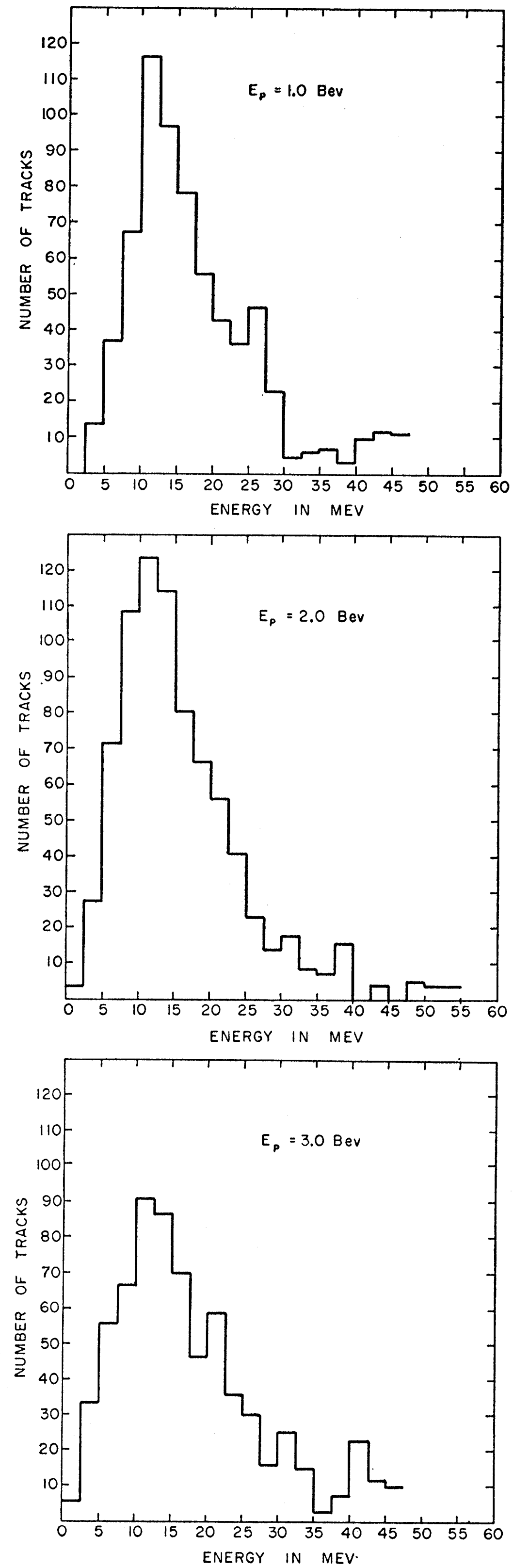

FIG. 3. α spectrum from Group I, II, and III events at 1.0 Bev, at 2.0 Bev, and at 3.0 Bev.

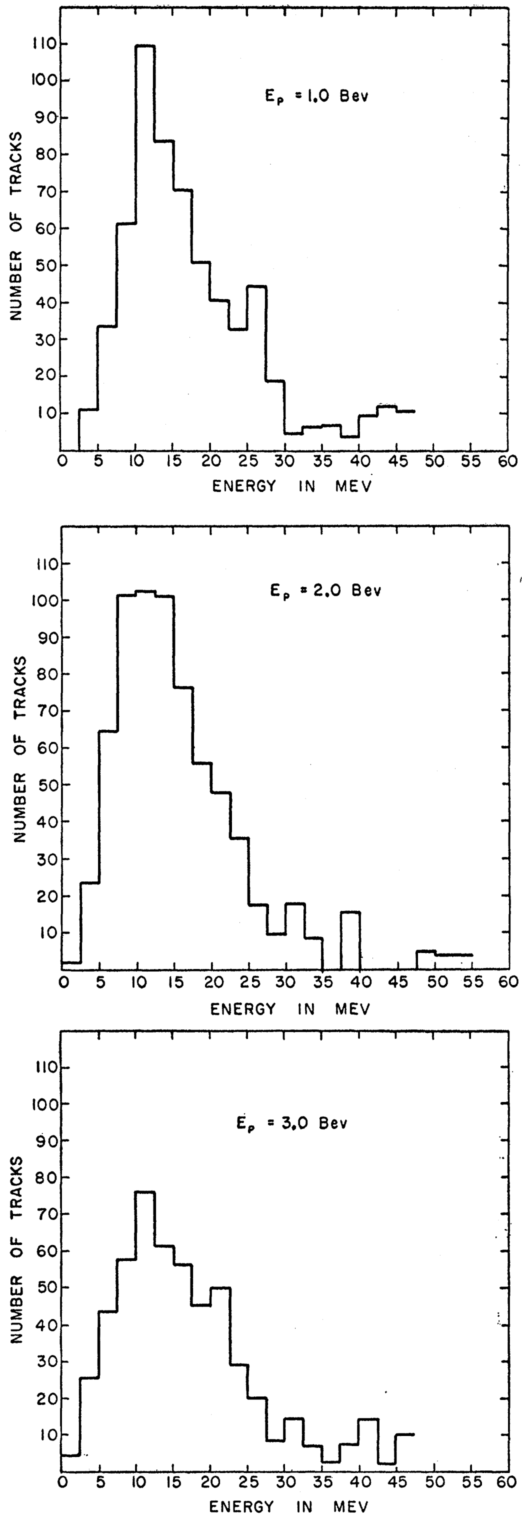

FIG. 4. α spectrum from Group I and Group II events at 1.0 Bev, at 2.0 Bev, and at 3.0 Bev.

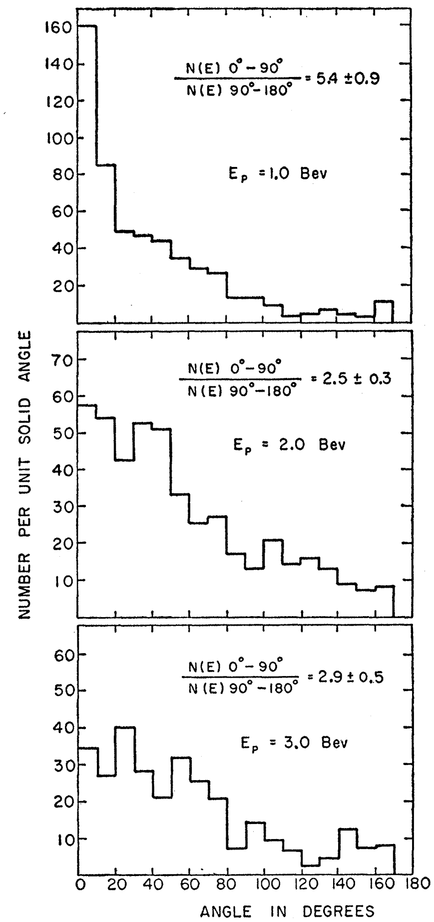

FIG. 5. Observed angular distribution of the recoil to the incident proton beam at 1.0, 2.0, and 3.0 Bev.

particles produced per proton interaction is represented in Fig. 2 by the broken curve.

The gross α spectra including Groups I, II, and III are shown at the three bombarding energies in Fig. 3. Figure 4 represents the spectra at each energy for only Group I and Group II. Within the statistics the two sets of spectra appear to be the same and both show a large number of low-energy or "sub-barrier" α particles, which number increases with increasing bombarding energy. It may also be seen from Fig. 4 that although possible fission events, Group III, have been omitted, the low-energy α particles persist.

Figure 5 shows the angular distribution of the recoiling nuclei relative to the beam in the energy region of 1.0-3.0 Bev. The strong correlation between the recoil and the beam, particularly at 1 Bev, indicates that after particle emission, the nucleus, on the average, still possesses a considerable amount of momentum imparted to it by the incident proton. Figure 6 shows the change in the forward to backward ratios of α particles as a function of their energy and again this result is not inconsistent with particle emission from

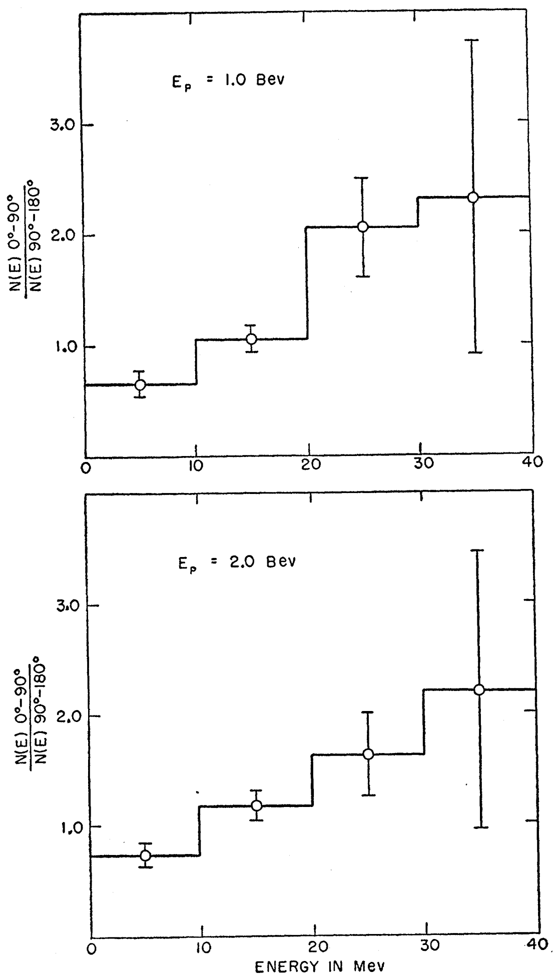

FIG. 6. The observed forward to backward ratios with respect to the beam, as a function of the α particle energy at 1.0 and 2.0 Bev.

TABLE I. Forward to backward ratios for group I and group II events.

	Forward to backward ratios of α particles relative to beam		
α Energy	1.0 Bev	2.0 Bev	3.0 Bev
0–10 Mev	0.65±0.10	0.69±0.11	0.59±0.12
10–50	1.34±0.12	1.42±0.17	1.24±0.18
0–50	1.15±0.09	1.15±0.09	1.04±0.11
	Forward to backward ratios of α particles relative to recoil		
α Energy	1.0 Bev	2.0 Bev	3.0 Bev
0–10 Mev	0.31±0.08	0.15±0.04	0.23±0.07
10–50	0.45±0.06	0.67±0.11	0.70±0.11
0–50	0.44±0.06	0.47±0.05	0.55±0.07
	Forward to backward ratios of recoils relative to beam		
	1.0 Bev	2.0 Bev	3.0 Bev
	5.4 ±0.9	2.5 ±0.3	2.9 ±0.5

a moving system.[10] Figure 7 shows the angular distribution of the α particles about the beam, which on the average is nearly isotropic. However, it is to be noted from Table I that the forward to backward ratios for α particles with energies between 10–50 Mev are greater than those for α particles in the energy region 0–10 Mev.

In each of the events where the recoil could be measured, the angles between the recoil and the α particles were determined. The energy and angular distributions of this group of events was found to be in good agreement with the total Group I and Group II data. The distribution in angle is shown in Fig. 8. The strong backward correlation between the α particles and the recoil suggests that an appreciable part of the recoil momentum is given to it by the emitted α particles. However, from Fig. 5 it may be seen that the recoil direction is by no means entirely determined by the emitted particles and that at the end of emission the recoil is still moving in the general direction of the incident proton.

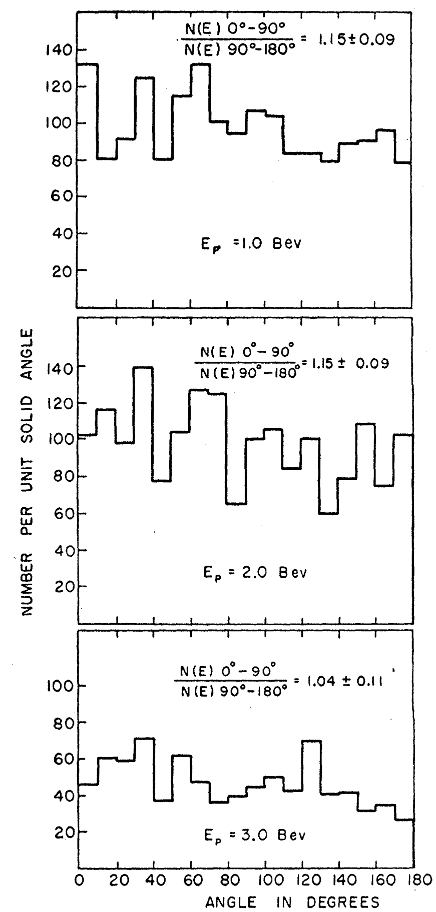

FIG. 7. The observed angular distribution to the beam of α particles at 1.0, 2.0, and 3.0 Bev.

[10] O. Skjeggestad and S. O. Sörensen, Phys. Rev. 113, 1115 (1959).

It was further observed, Figs. 9 and 10, that the low-energy α particles (0–10 Mev) were preferentially emitted in a direction opposite to the beam direction and predominantly in a direction opposite to the recoil.[11] If the nucleus is moving at the time of particle emission then the particles emitted in the direction opposite to the nuclear motion would appear to have less than their center-of-mass energy and those in the same direction would appear to have more. The particles most affected by this would be those of lowest energy, and those least affected would be those of highest energy.

In view of these observations, center-of-mass transformations were attempted both for a system moving in the beam direction and for a system moving in the observed recoil direction in order to determine whether such a correction could remove the anomaly of the very slow α particles. Since the exact kinematic situation at the time of each particle emission is not known, an average velocity of the moving system had to be assumed. A series of velocity values were tested and

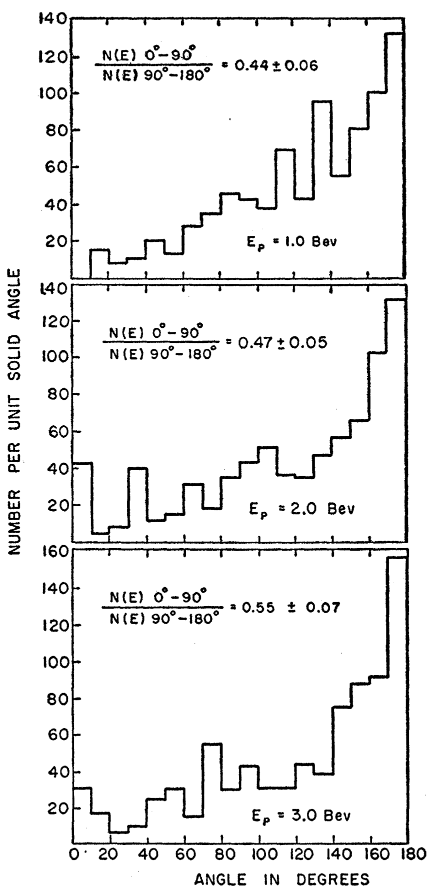

FIG. 8. The observed angular distribution to the recoil of α particles at 1.0, 2.0, and 3.0 Bev.

[11] P. A. Yaganov and V. I. Ostrovinov, J. Exptl. Theoret. Phys. U.S.S.R. 33, 1131 (1957) [translation: Soviet Physics JETP 6, 871 (1958)].

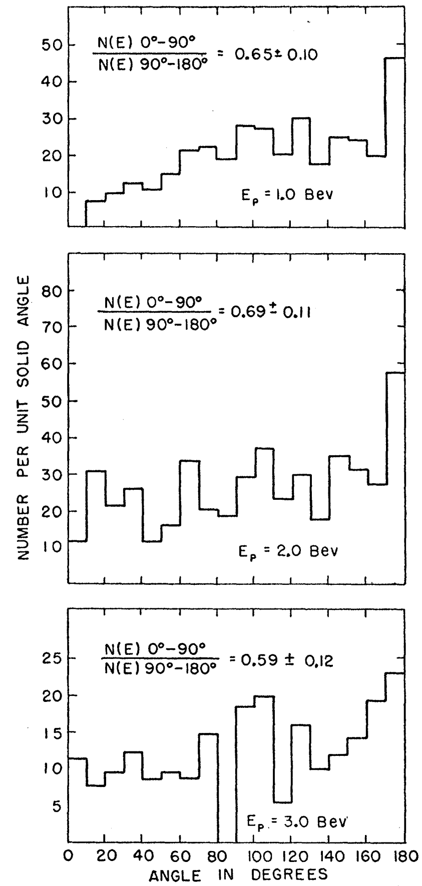

FIG. 9. The observed angular distribution of α's 0–10 Mev with respect to the beam.

the best agreement with the calculated evaporation spectra was found with $0.015c$ at 1.0 Bev and $0.020c$ at 2.0 and 3.0 Bev. In Figs. 11, 12, and 13 the solid lines show the energy spectra in all cases where the recoil could be measured, at 1.0, 2.0, and 3.0 Bev, respectively. The (a) spectra show the observed energy distributions in the laboratory system. The (b) spectra show the corrected energy distributions in the center-of-mass system calculated from the observed angle to the beam and a velocity of $0.015c$ at 1 Bev and a velocity of $0.020c$ at 2.0 and 3.0 Bev. The (c) spectra show the energy distributions in the center-of-mass system calculated from the observed angle to the recoil, and the same velocities as used in the (b) group. The dotted curves show the α spectra calculated from evaporation theory at 1.0 and 2.0 Bev. These curves were obtained from the combination of two Monte Carlo calculations, one on the knock-on phase of the nuclear reactions[7] and the other on the nuclear evaporation phase.[8] The methods used and the averaging procedures are described by Hudis and Miller[9] and were based on the combination of the two calculations. It may be noted that the Coulomb barriers and nuclear temperatures

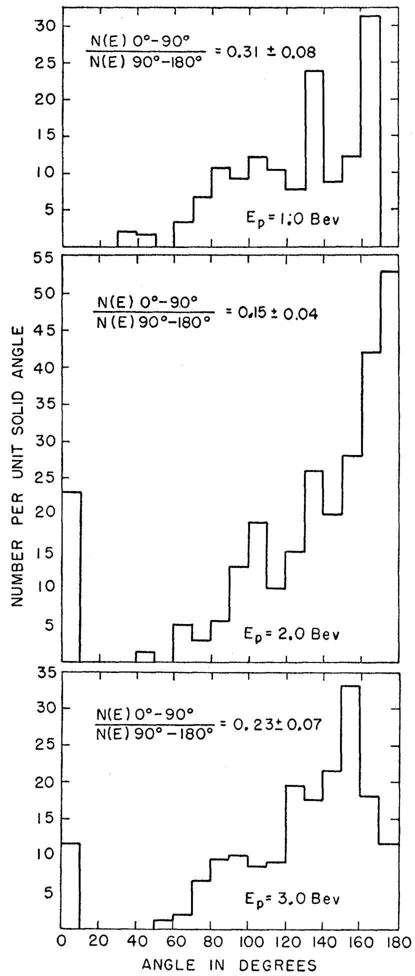

FIG. 10. The observed angular distribution of α's 0–10 Mev with respect to the recoil.

were recalculated for each step of the evaporation chain. The dotted curve in Fig. 12 was based on the calculated evaporation of He^3 and He^4 from silver irradiated with 2.0-Bev protons. It was assumed that the Ag and Br cross sections are equal and that the spectrum from Br is the same as that from Ag except for a downward shift on the energy scale by 3 Mev. The dotted curve in Fig. 11 was obtained from the same set of data using the proper weighting factors for 1.0-Bev protons.

It is seen that the best agreement with evaporation spectra can be found by assuming the observed direction of the recoil to be more nearly the direction of the moving system. It is possible that this agreement between the spectra may be fortuitous; however, the fact that there is a velocity of the center-of-mass system which largely eliminates the low-energy particles is much less likely to be fortuitous. If the α particles were really "sub-barrier" and emitted isotropically, no center-of-mass transformation could eliminate them. It must be concluded either that the slow particles are not "sub-barrier" but appear to be so only as a result of nuclear motion, or that these particles are emitted from a nearly stationary system with a preferred direction of emission.

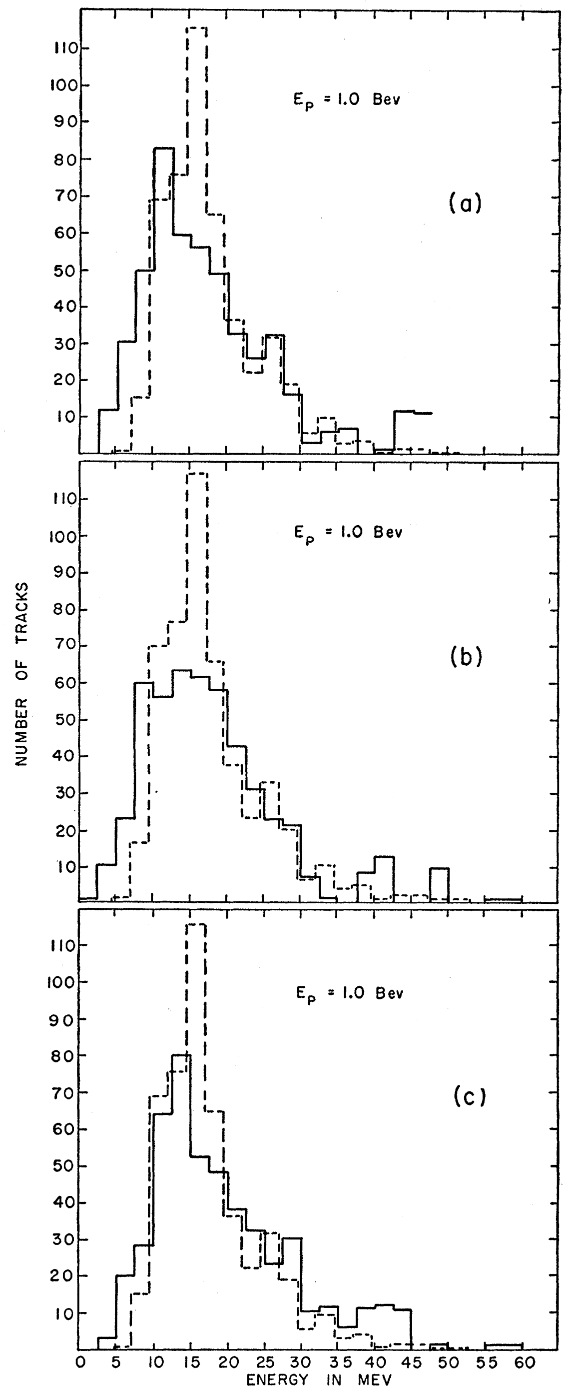

FIG. 11. Incident proton beam 1.0 Bev. (a) α spectrum in laboratory system, (b) α spectrum with center-of-mass velocity $=0.015c$, using angle to the beam, (c) α spectrum with center-of-mass velocity$=0.015c$, using the angle to the recoil. The dotted curves are the evaporation spectra based on Monte Carlo calculations for 1.0-Bev protons.

The velocities that have given the best agreement with nuclear evaporation theory are $0.015c$ and $0.02c$. Figure 14 shows the measured lengths of the recoiling nuclei at 2.0 Bev with the distribution peaking at 3.5 μ. From the range-velocity curve of Alexander and Gallagher[12] the average velocity of the residual nuclei was found to be $0.02c$ if one assumes an average mass number of 75.

Calculations have shown that the observed angular distributions of the recoil fragments (Fig. 5) are consistent with a mechanism in which particles are emitted isotropically from nuclei which have received a small forward component of velocity from the incident proton. This average forward component, v, can be estimated from the forward to backward ratio of the recoiling

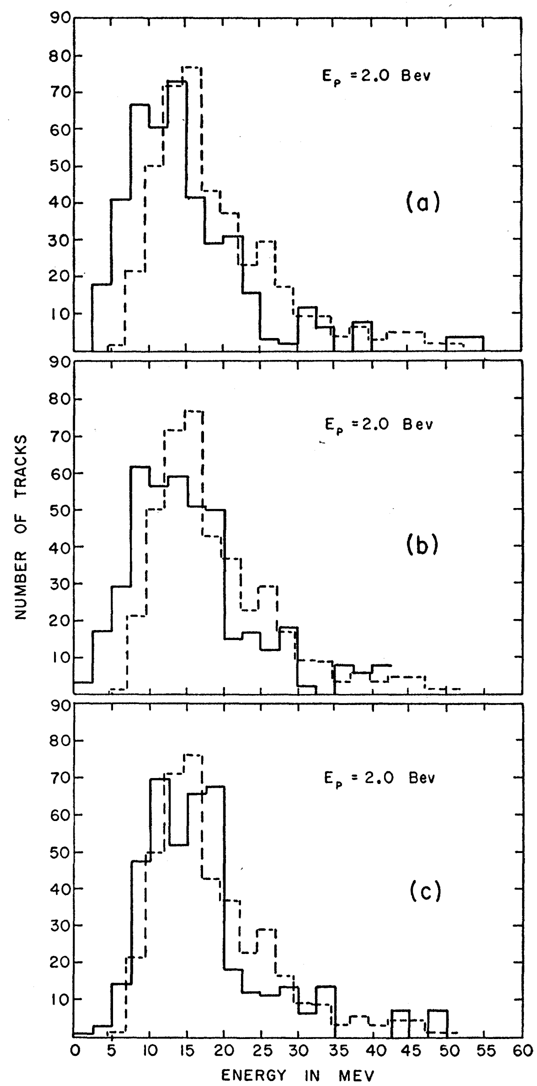

FIG. 12. Incident proton beam 2.0 Bev. (a) α spectrum in laboratory system, (b) α spectrum with center-of-mass velocity $=0.020c$, using angle to the beam, (c) α spectrum with center-of-mass velocity $=0.020c$, using the angle to the recoil. The dotted curves are the evaporation spectra based on Monte Carlo calculations for 2.0-Bev protons.

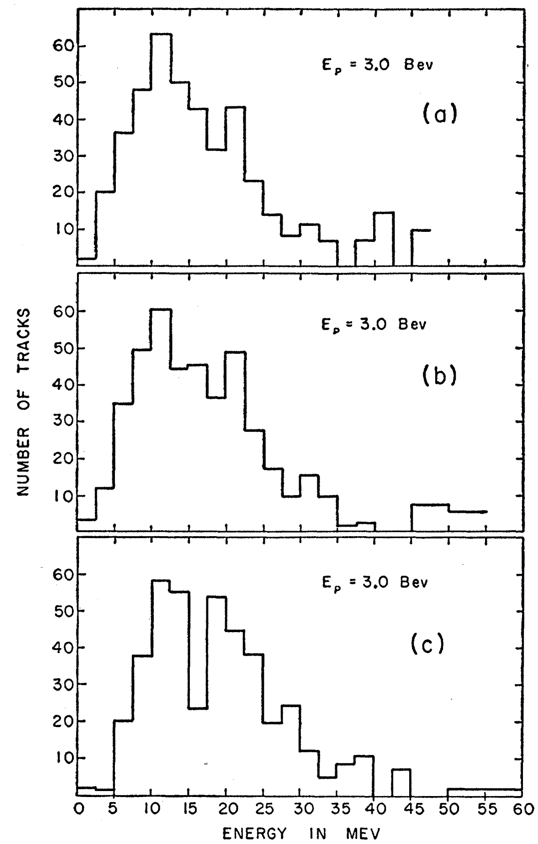

FIG. 13. Incident proton beam 3.0 Bev. (a) α spectrum in the laboratory system, (b) α spectrum with center-of-mass velocity $=0.020c$, using the angle to the beam, (c) α spectrum with center-of-mass velocity $=0.020c$, using the angle to the recoil.

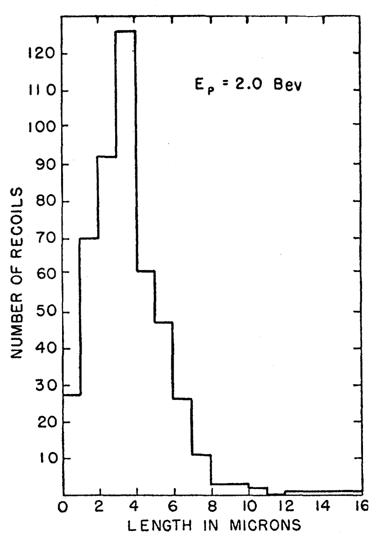

FIG. 14. Measured lengths of the recoil nuclei at 2.0 Bev.

[12] J. M. Alexander and M. F. Gallagher, University of California Radiation Laboratory Report UCRL-8618, November, 1958 (unpublished), p. 24.

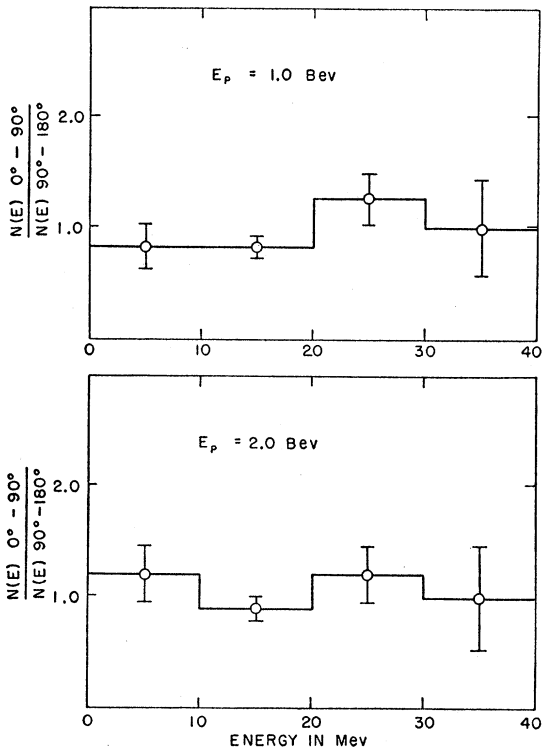

FIG. 15. The forward to backward ratios of the α particles with respect to the beam as a function of the α particle energy corrected to the system moving in the direction of the recoil at a velocity of $0.015c$ at 1 Bev and $0.02c$ at 2.0 Bev.

nuclei by the following formula:

$$\frac{F}{B}=\frac{1+(v/V)}{1-(v/V)},$$

V is the average velocity in the moving system. From this we find the average forward component of the struck nucleus to be of the order of $0.007c$. Additional velocity is given to the nucleus by the perpendicular component and by the successive emission of particles and light fragments. The average velocities that have been chosen for the center-of-mass transformations, with respect to the recoil, appear to be reasonable ones. We can now conclude that most of the apparent low-energy α particles are not "sub-barrier" but appear to be so only as a result of nuclear motion.

If the energy distribution can be made consistent with nuclear evaporation theory by assuming emission of the α particles from a moving system, then one would expect to find forward to backward ratios which are also consistent with this model. The angle between the α particle and the observed recoil direction is likely to be somewhat larger than the actual angle between the α particle and the recoil direction before emission. This effect will be most pronounced when α particles are emitted at angles around 90° to the recoil nucleus. Although this is an insensitive region in the energy distribution it is the most sensitive region in determining the forward to backward ratios. For this reason the angular distribution is in somewhat greater error than the energy distribution and therefore more difficult to interpret. An attempt has been made, however, to try to determine the angular distributions in this moving system. Therefore the forward to backward ratios of the α particles with respect to the beam (Fig. 6) were recalculated and plotted as a function of the α particle energy corrected to the system moving in the direction of the recoil at a velocity of $0.015c$ at 1 Bev and $0.02c$ at 2.0 Bev. The results are shown in Fig. 15. The overall forward to backward ratios (0–40 Mev) are 0.939 ± 0.076 at 1.0 Bev and 0.995 ± 0.087 at 2.0 Bev. From both these results and the above mentioned calculations based on the angular distributions of the observed recoil fragments we are led to believe that within the statistical error the data are consistent with isotropic evaporation from a moving system, for α particles up to at least 40 Mev.

It seems likely that an energy dependent Coulomb barrier such as suggested by Le Couteur[2] $V=kV_0/(1+0.005E)$ may not be required for agreement between experimental and theoretical α spectra. It is clear, however, that more detailed type Monte Carlo calculations are needed where the directions, energies and masses of the recoil nucleus and of the emitted particles are taken into account at every step of the knock-on and the evaporation phases. Furthermore, a more accurate approximation[13] for quantum mechanical barrier penetration should be used. The present investigation and the recent work of Skjeggestad and Sörensen[10] show that at high energies it is important to take into account center-of-mass motion when considering the spectra and angular distributions of emitted particles. This factor is most significant in the low-energy region of the spectra.

ACKNOWLEDGMENTS

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[13] Dostrovsky, Fraenkel, and Friedlander, Phys. Rev. **116**, 683 (1959).

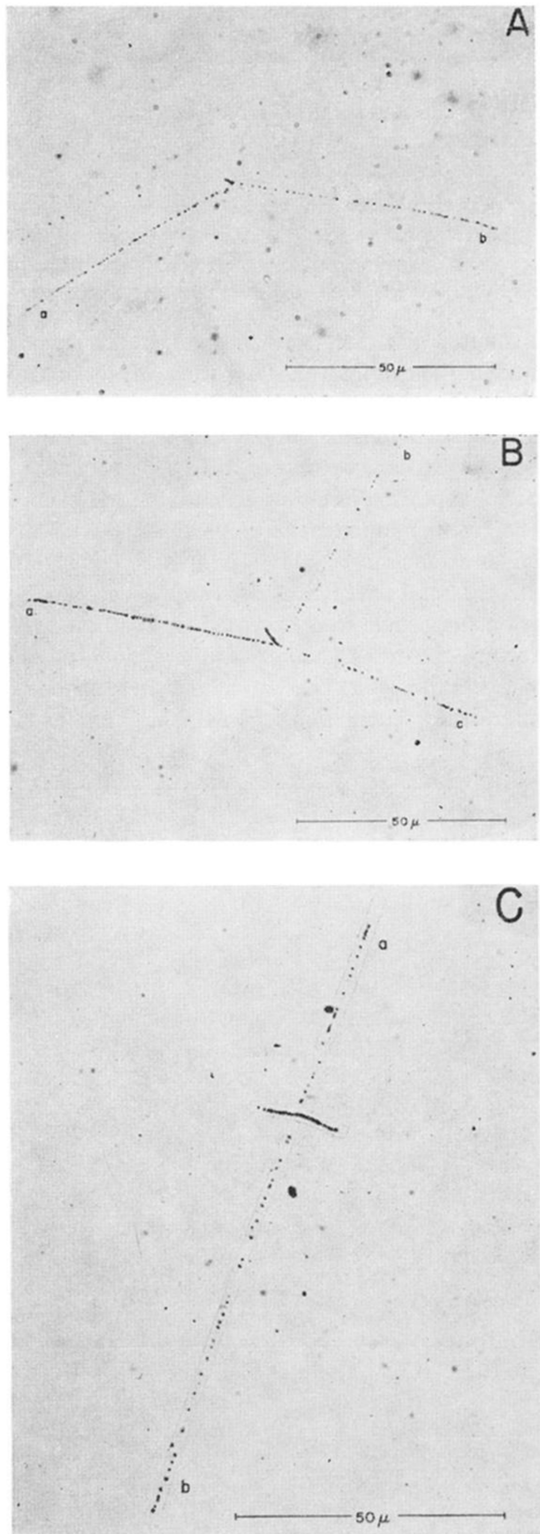

FIG. 1. (A) Group I event—Recoil with two α particles (*a*) and (*b*). (B) Group II event—Recoil with 3 tracks: (a) carbon; (*b*) particle leaving emulsion; and (*c*) α particle. (C) Group III event—Two heavily ionizing fragments with 2 α particles (*a*) and (*b*).