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α-PARTICLES EMITTED BY HEAVY EMULSION NUCLEI IN EMULSIONS BOMBARDED BY HIGH-ENERGY PROTONS

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An investigation has been made of the energy spectra of α-particles emitted by heavy nuclei in emulsions bombarded by protons with energies of 360, 560, and 660 Mev, assuming different excitation energies for these nuclei. The calculated evaporation spectrum is found to be in satisfactory agreement with experiment in the α-particle range up to 14 Mev without requiring any reduction of the Coulomb barrier as proposed by Le Couteur. By subtracting the calculated evaporation spectrum from the experimental spectrum the energy distribution for the cascade α-particles and the relative number of such particles which appear in one disintegration event at the three experimental energies cited above have been obtained.

INTRODUCTION

THE α-particles emitted in the disintegration of nuclei in emulsions bombarded by high-energy nucleons have been studied by many investigators.[1–14] However, most of these studies have been carried out with non-monoenergetic fast-particle sources (cosmic rays); thus there is a high degree of uncertainty in the interpretation of the results. In addition, the methods used for distinguishing between stars due to heavy nuclei and light nuclei are not always effective. Finally, in most cases the investigators did not have at their disposal a sufficient number of events to ensure good statistics for studying the α-particle energy spectra at different excitation energies.

In a number of papers[1,3–5,12–14] it has been noted that among the α-particles emitted from silver and bromine nuclei there is an anomolously large (from the point of view of nuclear evaporation theory) number of slow α-particles. Le Couter[15] and Fujimoto and Yamaguchi,[16] on the basis of an idea suggested by

Begge concerning the thermal vibrations of the nuclear fluid, have assumed that the appearance of these so-called "sub-barrier" particles is due to the significant reduction of the potential barrier in strongly excited nuclei. Certain other investigators, however, have found this interpretation to be inadequate. Thus Perkins[3] has advanced the hypothesis that at high excitation energies nuclei emit fragments which are unstable and decay into α-particles in flight. Süssmann,[17] developing this hypothesis further, has proposed that the assumed excitation in these nuclei can lead either to particle evaporation or to fission and subsequent evaporation, both modes being equally probable. Thus, according to Süssmann the appearance of α-particles with energies significantly below the Coulomb barrier of the original nucleus can be explained, firstly, by the lower barrier in the daughter nuclei and, secondly, by the Doppler effect (evaporation of particles from a moving fragment).

In the work discussed above it has also been noted that in the energy distributions of both α-particles and protons emitted from the emulsion nuclei, there is a long "tail" in the high energy region. This "tail" cannot be accounted for by evaporation theory because the particle angular distribution in the high-energy region is anisotropic — the motion of these particles is peaked in the direction of the bombarding-nucleon beam. In Ref. 18, in which stars exhibiting a recoil-nucleus track were studied, 40 — 50 percent of all the α-particles emitted by silver and bromine nuclei in stars induced by 460 and 660 Mev protons were assigned to the cascade stage of the disintegration process in the nucleus. This conclusion was reached on the basis of a comparison of the observed number of α-particles in these stars with the number of particles expected from evaporation theory.

In the present work, which is essentially an extension of the work carried out in Ref. 18, a detailed study has been made of the energy distribution of α-particles from stars produced in heavy emulsions by high energy protons. Several α-energy spectra have been considered; each of these corresponds to a definite range for the nuclear excitation energy. An attempt has been made to interpret the "sub-barrier" α-particles from the point of view of ordinary evaporation theory and to obtain information on the number of cascade α-particles and their energy distribution.

EXPERIMENT AND EXPERIMENTAL DATA

The work was carried out with fine-grained P-9 nuclear emulsions having a sensitivity of 30 Mev for protons.[18] The plates were irradiated by placing them in the proton beam of the synchrocyclotron of the Joint Institute for Nuclear Research. The beam direction was parallel to the plane of the emulsion. The bombarding-proton energies were 360, 560 and 660 Mev. The protons with energies below 660 Mev were obtained by degrading the beam in graphite blocks.

In the measurements we chose stars exhibiting recoil tracks; these are produced, for the most part, by heavy nuclei in the emulsion. On the basis of the available data,[19,20] the number of stars exhibiting a recoil track, associated with light nuclei in the emulsion, is less than 10 percent of the total number of stars exhibiting recoil tracks. Obvious cases of "light" disintegration were rejected even when accompanied by a dense track of length less than 10μ so that the actual admixture of "light" stars was less than 1 percent in the cases chosen for measurement.

The tracks formed by α-particles were distinguished from tracks due to other charged particles by visual means; the scanners received preliminary training. The reliability of this method of identification was checked by control observations of individual tracks as in Ref. 21.

The α-particle energy was determined from the length of those tracks which remained in the emulsion layer, using the range-energy relation given in Ref. 22. The emulsion shrinkage factor was taken as 2.5. The correction for α-particles with energies below 12 Mev which escaped from the emulsion was computed assuming an isotropic particle distribution. To correct for high-energy α-particles, a measurement of the angular distribution with respect to the beam was carried out in the plane of the field of view. Expressing this distribution in the form $a + b\cos^2\theta$ it is possible to compute the corrections for the isotropic and anisotropic parts of the distribution separately for the forward and backward hemispheres. The corrections for the $\cos^2\theta$ distribution were determined from the expression:

$$\frac{N_0}{N} = \frac{2d\sqrt{d^2 + R^2}}{2d^2 + R^2 - R\sqrt{R^2 + d^2}},$$

where N_0 is the total number of tracks with range greater than R, N is the observed number of tracks, and d is the thickness of the emulsion.

Using the true geometric correction we obtain the "mean star" value of the isotropic and anisotropic correction coefficient. Although the actual angular distribution differs from the projected distribution obtained in the present work this fact is not of importance because corrections to the track yields are small for short-range particles and the high-energy distribution is approximately the same as the spatial distribution.

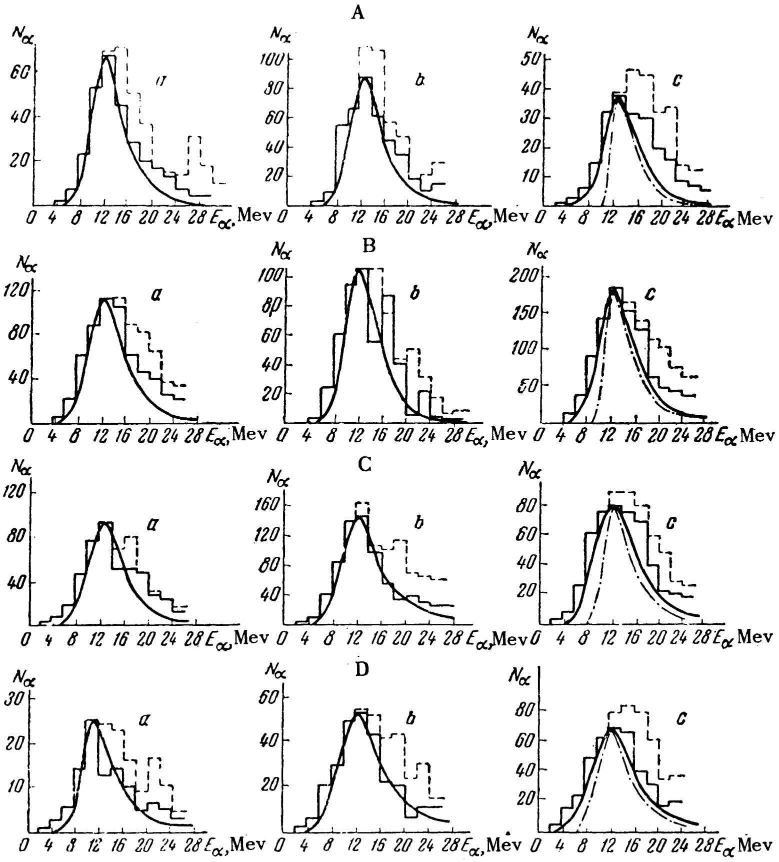

FIG. 1. α-particle energy spectra in Ag and Br stars corresponding to the following initial excitation energies of the nucleus U: A — 0 — 50 Mev; B — 50 — 100 Mev; C — 100 — 150 Mev; D — 150 — 200 Mev. The bombarding-proton energies are as follows: a — 360 Mev; b — 560 Mev; c — 660 Mev; the solid line indicates the "back" spectrum; the dashed line the "front" spectrum and the dot-dash line is the calculated spectrum.

All the recorded α-particles were assigned to groups corresponding to a given excitation energy range for the nucleus. Using the relations given in Ref. 18, which establish the connection between the number of prongs in a star and the mean excitation energy of the nucleus, these groups were taken as shown in Table I.

TABLE I

Proton energy, Mev	360		560		660	
Excitation energy of nucleus, Mev	Number of prongs	Number of α-particles	Number of prongs	Number of α-particles	Number of prongs	Number of α-particles
0—50	1—2	366**	1—2	272	1—2	379
50—100	3—4	753	3—4	683	3—5	1551
100—150	5—6	570	5—7	980	6—7	867
150—200*	7 or more	314	8 or more	403	8 or more	777

* For stars due to 660-Mev protons the upper limit for the excitation energy is approximately 250 Mev.
** The statistics in each group have been taken arbitrarily.

In Fig. 1 are shown the energy spectra for α-particles emitted by silver and bromine nuclei in the forward ("front" spectrum) and rear ("back" spectrum) hemispheres corresponding to various proton energies. The difference in the "front" and "back" spectra is small at α-particle energies below 12 Mev and is explained by the imparted motion of the evaporating nucleus. When the appropriate corrections are introduced (cf. Ref. 18) the "front" and "back" spectra become almost identical in the energy region up to 12 — 14 Mev and overlap in the figure; however, the difference in the high-energy spectra remains.

In order to compare the present data with the results obtained by Deutsch[10] a plot has been made of the energy distribution of α-particles emitted by silver and bromine nuclei at small angles (below 30°) to the 360-Mev proton beam (Fig. 2). The small difference in the energy spectra is apparently due to the fact that stars due to silver nuclei were considered in Deutsch's work whereas in the present work a considerable fraction of the events occur in the lighter bromine nucleus.

EVAPORATION SPECTRUM AND CASCADE PARTICLES

As a rule, in work on stars in heavy-emulsion nuclei the excitation energy has been determined for an average nucleus of mass 94 and charge 41. Our calculations of the evaporation spectra were carried out separately for the Ag^{108}_{47} and Br^{80}_{35} nuclei.

In Ref. 18 the excitation energy was determined for the mean imparted velocity of a target nucleus with A = 94, obtained as the difference of the velocity components of the recoil nucleus in the direction of the beam and perpendicular to it. This imparted velocity implies a certain loss of energy and momentum for the primary proton which, by hypothesis, moves through the nucleus without changing its direction. It is further assumed that the energy loss of the proton is equal to the excitation energy of the nucleus plus the binding energy of the particles emitted in the cascade stage of the process.

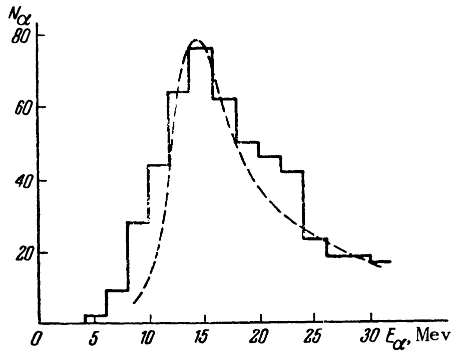

FIG. 2. Energy spectrum of α-particles emitted by heavy-emulsion nuclei at angles smaller than 30° with respect to a beam of 360-Mev protons. The dashed curve refers to results reported by Deutsch.[10]

TABLE II

Proton energy, Mev	360	660
α-particle energy, Mev	Percentage of the α-particles emitted in the forward direction	
12–15	53±6*	54±7
15–25	61±6	59±5
>25	90±21	74±12

*The statistical errors in the experiment are shown.

In the present work we have modified this approach to calculating the excitation energy of the nucleus. Assuming that the velocity imparted to the nucleus obtained in Ref. 18 corresponds to that of a bromine nucleus (since these are determined from the range-energy curve for a light fragment of uranium fission) and that in the same length of recoil track the velocities of the silver nuclei are smaller by 5 percent, we have calculated the excitation energy separately for Ag and Br for a given number of prongs in a star. The initial temperature of the excited nucleus is then determined from the expression:

$$T = \sqrt{(12.5/A)\,U}.$$

We have assumed further that a nucleus excited to an energy U undergoes thermal expansion; this effect leads to some reduction of the potential barrier. This thermal expansion is characterized by the function:[23]

$$R = R_0(1 + 0.008\,T^2),$$

where $R_0 = [1.4(A - 4)^{1/3} + 1.2] \times 10^{-13}$ cm.

The α-particle Coulomb barriers for silver and bromine are determined by the expression

$$V = 2(Z - 2)\,e^2/R,$$

where the symbols A and Z in the formulas written above are to be understood as the mass and charge of the original nucleus, taking into account the emission of several nucleons as a result of the cascade process.[18] As particle evaporation proceeds the nuclear temperature is reduced; at the same time the charge and mass are reduced and these quantities affect the value of V. Calculation shows that with a given initial excitation energy the height of the barrier remains constant throughout the entire evaporation process.

The energy spectrum of the evaporated α-particles is given by the expression

$$N(E)\,dE = \Phi(E/T^2)\exp(-E/T)\,dE,$$

where $\Phi = \exp[-2g\gamma(E/V)]$ is the quantum-mechanical penetrability of the Coulomb barrier for α-particles given by Bethe,[25] $\gamma(E/V)$ is a tabulated function,[24] $g = (2MZze^2R)^{1/2}/\hbar$ and z is the charge of the α-particle.

Since the emission of each particle results in a noticeable "cooling" of the nucleus, the process in which the excitation energy is dissipated must be divided into a number of stages, each of which is characterized by its own value of T. The energy spectrum which characterized the α-particle evaporation process for a given nucleus is actually the sum of the energy distributions calculated for each cooling stage. A step-by-step calculation of the evaporation process was carried out as by Shamov[26] but with these differences: firstly, in Ref. 26 a stronger, functional dependence V(T) was assumed; secondly, in our case the values of the relative probability of emission of various particles from Ref. 27 were used whereas Shamov based his work on the analysis given by Le Couter.[15] The summation of the individual-stage spectra is carried out taking account of the number of emitted α-particles in each stage. The partial α-spectra obtained in this manner for Ag and Br nuclei are then added, after being normalized. The probability of α-particle emission by a nucleus characterized by temperature T can be given in the form

$$\psi = \sigma w \gamma .$$

Here σ is the cross section for an inelastic interaction between the proton and nucleus, w(T) is the probability that a nucleus is excited to a temperature T in such an interaction, γ(Z, T) is the probability of α-particle emission by a nucleus of mass A and charge Z at temperature T. Assuming that Ag and Br contents are the same in the emulsion, the intensity ratio of the α-spectra for these nuclei is given by:

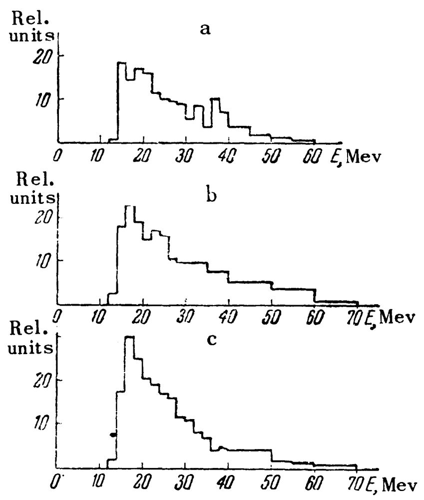

FIG. 3. Energy spectra for cascade α-particles emitted from Ag and Br nuclei at the following proton energies: a — 360 Mev; b — 560 Mev; c — 660 Mev.

TABLE III

Proton energy, Mev	360			560			660			460*	660*
Excitation energy of the nucleus, Mev	Forward	Backward	Total	Forward	Backward	Total	Forward	Backward	Total	Total	Total
0—50**	56***	19	39	47	21	37	80	42	66	67	80
50—100	45	17	33	42	18	31	52	22	39	50	52
100—150	43	16	30	43	10	29	49	29	40	33	38
150—200	60	13	40	40	9	27	47	16	35	29	40
Mean	52	18	36	45	18	34	66	33	53	39	50

*Taken from the data of Ref. 18.
**Here and in all other cases the values of the excitation energy are for an "average" nucleus.
***The relative errors shown in Table III are approximately 15-20 percent.

$$\frac{N_1}{N_2} = \left(\frac{A_1}{A_2}\right)^{2/3} \cdot \frac{w_1}{w_2} \cdot \frac{\gamma_1}{\gamma_2}$$

(the subscripts 1 and 2 refer to Ag and Br respectively).

It would seem that no great error is introduced by assuming $w_1 = w_2$. From Ref. 27 [Eq. (24)].

$$\frac{\gamma_1}{\gamma_2} = \frac{\sigma_1}{\sigma_2} \exp\left\{-\frac{1}{T}\left[(V_1 - V_2) + (p_1' - p_2') + (Q_1 - Q_2)\right]\right\}, \quad (p' = p - V).$$

The quantities p′ and Q do not differ greatly for Ag and Br. It may be assumed that they are equal. In general an exact calculation of these quantities is not possible since the masses and binding energies of the nuclei formed in the cascade process are not known. Thus,

$$N_1/N_2 = (A_1/A_2)^{4/3} \exp\left[(V_1 - V_2)/T\right].$$

The dependence of α-particle emission probability on the barrier V is taken into account by the factor Φ. Hence the total α-spectrum for stars in heavy nuclei may be obtained approximately if we add the partial spectra for Ag and Br, multiplying the first by 1.5. In Fig. 1 are shown the α-spectra (solid smooth curves) which result from these calculations. The experimental and theoretical distributions are normalized at the maximum. The discrepancy in the position of the maxima in these two distributions is less than 1 Mev.

If it is assumed that the calculated curves yield the proper energy spectra for α-particles which result from evaporation and that the excess of "evaporated" particles with energies above 14 Mev is due to the cascade process, we can obtain the spectrum of the cascade α-particles as the difference between the experimental and theoretical distributions (Fig. 3). The shape of the ejected α-particle spectra is the same in the "forward" and "backward" directions with the one difference that the "forward" spectrum contains a considerably larger number of particles with energies greater than 30 Mev. In Table III is shown the relative number of cascade α-particles for stars characterized by various excitation energies.

It is further assumed that the "back" spectrum is completely due to the evaporation component, it turns out that about 20 percent of the total number of α-particles are a result of the cascade process (cf. Table II, in which the relative number of α-particles with energies greater than 12 Mev emitted in the "forward" direction is shown).

DISCUSSION OF THE RESULTS

As is to be expected, the spectra for α-particles emitted in the backward direction are found to be in good agreement with evaporation theory. The discrepancy between the evaporated and experimental distribution in the region of low α-particle energy is due partially to the admixture of stars from light nuclei. This slow-particle excess (approximately 5 — 6 percent for all groups of stars) may be explained by the fact that emission takes place in a moving nucleus which has acquired a considerable velocity as a result of prior evaporation of particles. If this assumption is correct, there should be a definite angular correlation between the recoil nucleus and the low-energy α-particle. In Fig. 4 is shown the distribution of α-particles with energies below 10 Mev as a function of the angle formed by motion of these particles and the direction of motion of the recoil nucleus (in projection). It is apparent that there is a considerable concentration of these particles in the direction opposite to the motion of the residual nucleus.

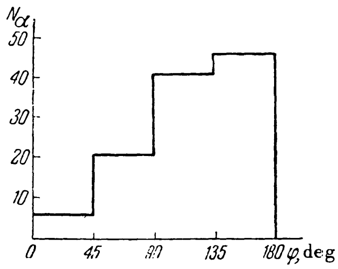

FIG. 4. Angular distribution (in projection) of α-particles with energies less than 10 Mev with respect to the recoil track.

Thus "sub-barrier" α-particles can be considered in terms of ordinary evaporation theory without assuming that fission occurs or that there is a considerable reduction in the Coulomb barrier in excited nuclei. It should be noted that even if one assumes a Coulomb barrier reduction, following Le Couter, taking $V = V_0/(1 + U/200)$ (V_0 is the normal height of the nuclear barrier and U is the excitation energy in Mev), it is impossible to obtain reasonable agreement between the theoretical spectrum and the observed spectrum if the usual calculation for an "average" nucleus at "average" temperature is used. In Fig. 1c are shown evaporation spectra (dot-dash lines) computed as by Le Couter for a nucleus with $A = 94$, but with cooling taken into account (calculations based on an "average" temperature would lead to a still greater deviation between the curves and experimental data). The fission model is also unable to furnish any additional interpretations of the experimental facts, for example, the sharp anisotropy in the recoil tracks (approximately 50 percent of these are at angles smaller than 30° with respect to the beam), the low number "sub-barrier" α-particles in the small-angle region with respect to the recoil track and so on.

In the last two columns of Table III are shown data on the number of cascade α-particles obtained in Ref. 18 obtained by comparing the observed number of α-particles with the number to be expected from evaporation theory. When account is taken of the experimental uncertainties and the approximations used in the theory one would expect the results of these two papers to be in agreement.

It would be of interest to verify the suggestion that elastic interactions between the incoming proton and the α-aggregates are responsible for the high-energy α-particles. Sörenson,[9] who has analyzed the fast α-particles in cosmic stars, concludes that the correlation between the energy and emission angle of these particles cannot be explained by elastic collisions. The analysis of α-particles with energies higher than 25 Mev carried out by us corroborates this result. However, account should be taken of the fact that the proton does not collide with a free α-particle; it is necessary to introduce appropriate corrections for effects which are due to the existence of a potential well. Under these conditions the absence of a direct relationship between the emission angle of fast α-particles and energy may still not be a sufficient basis for rejecting the notion of an elastic interaction between the primary proton and a nucleon complex inside the nucleus.

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