CASCADE α-PARTICLES IN STARS PRODUCED BY 360 and 660 Mev PROTONS

V. I. OSTROUMOV, N. A. PERFILOV, and R. A. FILOV

Radium Institute, Academy of Sciences, U.S.S.R.

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Stars containing tracks of α particles with energies above 30 Mev were studied in nuclear emulsions irradiated by 360 and 660 Mev protons. The effective cross section for production of these stars, the angular distribution of fast α particles, and the relative probability of their emission from light and heavy emulsion nuclei were determined. A similarity was found between the emission of cascade α particles and of fragments from nuclei as a result of bombardment with protons, which seems to indicate that both processes have an identical mechanism.

INTRODUCTION

In a series of experiments on the interaction of high-energy protons with nuclei of emulsion, it was found that α particles are emitted in stars with an energy and angular distribution which contradicts the assumption that we are dealing with an evaporation process.[1,2] The energy spectrum of these particles has a long tail in the high-energy region. The direction of emission of α particles is correlated with the direction of the primary protons. The majority of them are emitted in the forward direction, and the degree of anisotropy increases with increasing kinetic energy of the α particles. As is well known, a similar picture is valid for nucleons ejected from the nucleus during the cascade stage of the nuclear interaction with the primary proton. The appearance of fast α particles is therefore also connected with the development of the nuclear cascade in the nucleus, although the mechanism of the transfer of considerable kinetic energy to a complex consisting of our nucleons is unclear.

Even heavier particles, called fragments, are observed in nuclear disintegrations, the cross sections of these events being smaller by approximately one order of magnitude.[3-6] At present, there are no well-founded ideas about the fragmentation process which could explain all experimental facts. It is reasonable to assume that the process of emission of all multi-charged particles (among them α particles) is basically similar. There are no special reasons to believe that the emission of a He nucleus in the cascade process has different causes and is connected with a basically different mechanism, than the emission, let us say, of a Li and Be nucleus. The study of inelastic interactions between high-energy nucleons with nuclei, which give rise to cascade α particles, will therefore be helpful for the study of the fragmentation mechanism, and has, of course, its own intrinsic interest. Experiments with α particles can be carried out in better conditions, and their results can be interpreted more exclusively, than experiments on the study of fragments since, in the latter case, the observed variety of particles, the identification of which is not always possible, makes it difficult to reduce the experimental data.

In the present work, we studied stars in a nuclear emulsion containing tracks of fast α particles. The results of observations were, whenever possible, compared with the corresponding data on fragments given in reference 5.

EXPERIMENTAL METHOD

Fine-grain nuclear emulsion P-9, sensitive to protons in the energy range 30 — 40 Mev, was used in the experiment. The emulsions were irradiated, using the Joint Institute for Nuclear Research synchrocyclotron, by the collimated external proton beam incident perpendicularly to the surface of the emulsion. The energy of the protons was 660 and 360 Mev. The lower energy value was obtained by slowing the protons down in a copper absorber.

Stars containing tracks of α particles with energy higher than 30 Mev were noted in scanning the emulsion. Only those cases where the particles stopped in the emulsion and where the inclination of their tracks with respect to the plane of emulsion was not larger than 7° (in undeveloped emulsion) were selected for further analysis. The visual selection of such tracks did not cause any difficulties, since the type of emulsions chosen had good discriminating power for singly- and doubly-charged particles. However, our data contained a certain number of tracks of fast Li nuclei which could not be easily distinguished from the tracks of α particles. Checking 70 randomly-chosen tracks of particles with charge larger than unity over the length of $300\,\mu$ by the method of counting the number of intervals of the ocular scale obscured by grain,[7] it was found that the admixture of triply charged particles in our experiment amounted to less than 15%. The energy of α particles was determined from the track length using the range energy curves for protons.[8] The transition coefficient from the range in air to the range in emulsion was taken as 2000.

In the observed stars, we measured the angle between the projection of the track of a fast α particle on the emulsion plane and the direction of the bombarding beam. Since the chosen tracks have a small inclination to that plane, such a procedure gives the angular distribution of cascade α-particles per unit solid angle accurately enough. Necessary corrections for the finite thickness of the chosen spherical zone were applied.

For the lower energy limit of recorded α particles (30 Mev), it could be confirmed that the majority of found tracks were not related to the process of evaporation of nuclei, which substantially simplifies the analysis of experimental results. For the estimate of the cross section for the production of α particles with energy larger than 30 Mev in nuclear interactions of fast protons, we measured the frequency of occurrence of such cases among all stars found in the emulsion. The cross section for star production for 360-Mev protons was taken from the work of Bernardini et al.,[9] and that for 660-Mev protons from the work of Grigor'ev and Solov'eva.[10]

EXPERIMENTAL RESULTS

All observed cases were divided into three groups. All stars having the track of the recoil nucleus were ascribed to the first group. We assumed that these represent the result of disintegration of heavy nuclei of the emulsion. For brevity, we shall call these cases H stars. To the second group belong stars without a visible track of the recoil nucleus, with total charge of emitted particles smaller than 8e, and which contained at least one track of an α-particle with energy smaller than 8 Mev, or of a proton with energy smaller than 4 Mev. These stars were assumed to represent events involving light nuclei (L-stars). Finally, the third group contains disintegration not

TABLE I

Proton energy, Mev	Group			Total stars	σ_T, mbn	σ_L, mbn
	I H stars	II L stars	III H and L stars			
360	397	68	203	668	85 ± 15	17 ± 6
660	363	77	160	600	120 ± 25	18 ± 6

falling within anyone of the two former groups. The number of stars in each of the three groups is given in Table I.

Observations of the disintegrations in the gelatine layer, produced by fast protons, indicate that the fraction of stars involving light nuclei showing a track of the residual nucleus is smaller than 20 – 25%.[11,12] If we assume that about 20% of all stars visible in the emulsion involve light nuclei, it is found that the admixture of L-stars in the first group is smaller than 10%. It is obvious that a certain number of stars involving Ag and Br nuclei is present in the second group. From the data of references 2 and 3, the fraction of H stars with less than seven prongs containing sub-barrier particles amounts to about 5 to 10% of the total number of heavy nuclei disintegration. All of these corrections therefore compensate roughly each other, and the intensities of the first and second group represents accurately enough the real relation of probabilities of appearance of L and H stars containing a fast α particle.

The number of L stars in the third group can be estimated by the following methods:

(1) From the angular distribution of fast α particles. We shall assume that the distribution is identical for all L stars of the second and third groups. Such an assumption is not correct for H stars, since, the presence or absence of the visible track of the recoil nucleus may be due to a change of direction of the emission of a fast particle.

To determine the fraction k of α particles emitted in the forward direction in H stars of the third group, we plotted the dependence k(R) for H stars of the first group (R is the length of the recoil nucleus track). Extrapolation of this plot to the value R = 0 gives the value of K for H stars of the third group. The fraction of L stars in this group will then be equal to

$$x = (k_0 - k_T) / (k_L - k_T), \qquad (1)$$

where the indices O, L, and H refer correspondingly to the stars of the third, second, and first groups.

(2) From the multiplicity distribution of stars. The multiplicity distribution of stars of the third

TABLE II

Proton energy, Mev	x, %				Average x
	Method				
	1	2	3	4	
360	31	34	54	—	(40±10)%
660	15	16	11	17	(15± 3)%

group represents a mixture of two distributions (for L and H stars), having statistical weights equal to x and 1 − x respectively. The value of x is formed by simple calculation under the assumption that the multiplicity of L and H stars is independent of the above criterion of dividing the stars into groups.

(3) Form the value of the ratio α/p of the number of doubly-charged particles to the number of singly-charged particles in L and H stars. In writing this expression, it is also assumed that the value of α/p is similar to that in stars produced on nuclei of one type (L and H), independently of the number of the group. It is easy to obtain the formula for x:

$$x=\frac{[(\alpha/p)_0-(\alpha/p)_T]\,[1+(\alpha/p)_L]\,n_T}{[(\alpha/p)_L-(\alpha/p)_0]\,[1+(\alpha/p)_T]\,n_L} \tag{2}$$

where n is the mean multiplicity of a star, and where the indices O, L, T, have the same sense as in Eq. (1).

(4) In the experiment with 660-Mev protons it was possible to estimate the fraction of L stars containing tracks of low-energy particles from the ratio to the total number of stars involving C, O, and N nuclei, and making use of the observations of Serebnikov, who studied stars in a layer of gelatine.[12] The fraction of light L stars with sub-barrier particles is probably not changed markedly in the case of the emission of an α particle with energy > 30 Mev.

Results of the calculations of the fraction of L stars in the third group, as obtained by each of the three methods, are given in Table II.

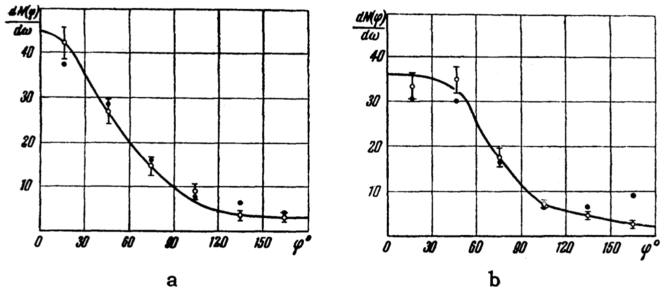

FIG. 1. Angular distribution of α particles with E > 30 Mev, calculated per unit solid angle (H nuclei) a – for 660-Mev protons, b – for 360-Mev protons. Black dots – data of reference 5.

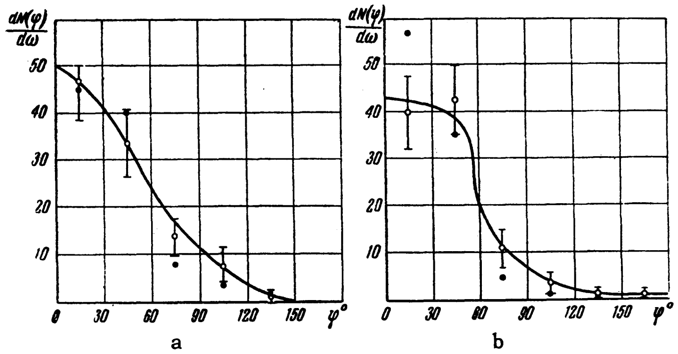

FIG. 2. Same as Fig. 1 for L nuclei.

Knowing the values of x, it is possible to distribute all stars of the third group statistically among the L and H groups, and to determine the relative cross sections for the production of fast α particles on heavy and light nuclei of the emulsion.

The cross section for the production of stars containing α particles are given in Table I (last two columns), calculated as averages of our data and the data of reference 2. The given errors include the errors in the determination of x and the error in the identification of stars according to the tracks of the recoil nuclei, assumed to be equal to 10%.

Apart from stars with one fast α particle (in the following we shall call them α stars, while the cases with emission of a fragment will be called f stars), five cases with two tracks of α particles of more than 30 Mev, satisfying the assumed criterion of selection, were found for 660-Mev incident protons, and four such cases for 360-Mev protons. If we assume the total star production cross section on T nuclei to be equal to unity, then the cross sections for the production of α and 2α stars relative to it equal 0.11 and 0.008 respectively. Among α stars, cases are found in which a track of the fragment may be observed (αf stars). In the course of the experiment, 28 and 15 such stars were found for proton energies of 660 and 360 Mev, respectively. Two stars of the type 2αf were found with the 660-Mev proton beam. Consequently,

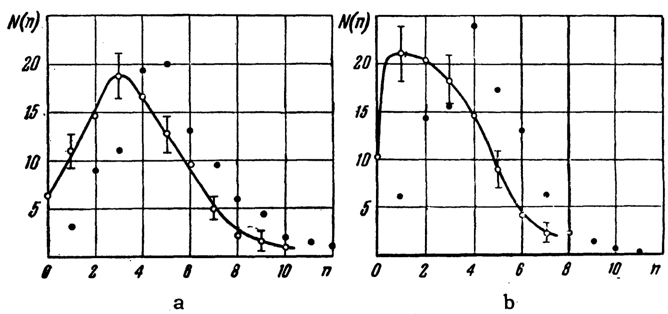

FIG. 3. Multiplicity distribution of α stars (H nuclei): a – for 660-Mev protons, b – for 360-Mev protons. Black dots – the same for f stars (data of reference 5).

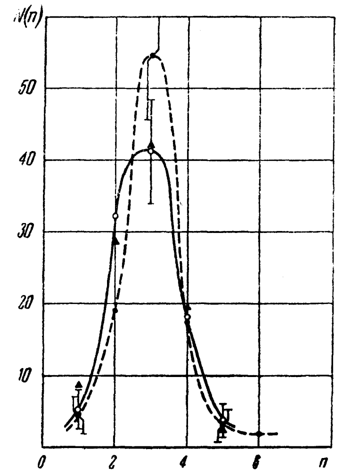

FIG. 4. Multiplicity distribution of α stars for L nuclei: solid curve – for 660-Mev protons, dashed curve – for 360-Mev protons. Triangles – multiplicity distribution of f stars for 660-Mev protons.

the ratio of the production cross sections for stars of the type α, αf, and α2f by 660-Mev protons is 1 : 0.04 : 0.003. The angular distribution of α particles is given in Figs. 1 and 2.

The multiplicity distribution of α-stars for H and L nuclei separately are given in Figs. 3 and 4. It is interesting to note that the mean multiplicity in α stars produced on H nuclei is apparently decreasing with increasing energy of the α particles (Table III).

For L stars, the mean multiplicity remains constant in all cases, and is equal to 2.8 ± 0.2 for 660-Mev protons, and to 3.0 ± 0.2 for 360-Mev protons (without the fast α particle).

Data on the relative emission probability of a fast α-particle from H and L nuclei for a different number of black prongs in the star are given in Figs. 5 and 6. This probability w_α is determined from the formula

$$w_\alpha(n) = \sigma_\alpha \alpha_n / \sigma_0, \quad (3)$$

where σ_α and σ_0 are the cross section for the production of α-stars and the total star production cross section respectively, and α_n is the

TABLE III. Multiplicity of α-stars

Proton energy, Mev	E_α, Mev: 30÷50	50÷80	>80	Total for α stars	Mean number of black prongs in normal H stars
360	2.6±0.1*	2.3±0.1	2.0±0.4	2.5±0.1	2.5±0.1
660	3.7±0.1	3.6±0.1	3.2±0.3	3.6±0.1	3.6±0.1

*The fast α particle is not counted among the black prongs.

fraction of α stars with the multiplicity n among all α stars. (Here and throughout, the fast α particle is not included in the number of tracks.) The values of α_n are taken from the graphs in Figs. 3 and 4, and the multiplicity distribution of normal stars is taken from reference 13 (H nuclei and 660-Mev protons), from reference 9 (360-Mev protons, H nuclei), reference 12 (660-Mev protons, L nuclei) and reference 11 (360-Mev protons, L nuclei). The errors shown in the figures correspond to statistical errors, and do not include the error in the determination of σ_α and σ_0.

DISCUSSION OF RESULTS

The data on α stars obtained in the course of the experiment were compared with the results of an investigation of the fragmentation process carried out in reference 5 for the same energies of bombarding protons. Such a comparison has meaning only under the condition that the observed α particles are not due to evaporation of the excited nuclei. Estimates based on the energy spectrum of α particles show that the number of evaporated particles among all those detected is not larger than 10%. The angular distribution of particles with energy > 30 Mev indicates also a small admixture of evaporated component.

With increasing proton energy, the effective cross section for the emission of fragments form H-nuclei increases sharply.[5] The cross section

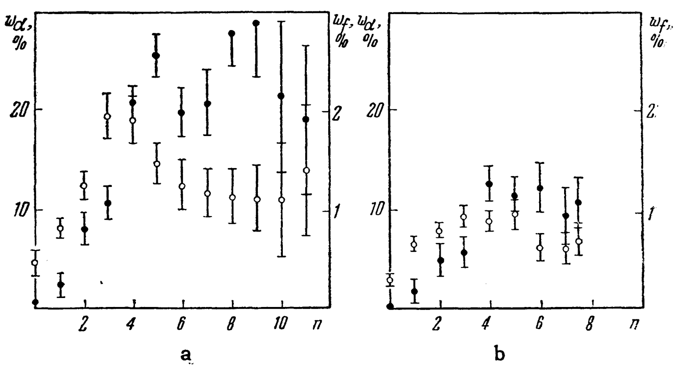

FIG. 5. The relative probability of emission of α particles (light circles) and fragments (filled circles) and the dependence on the number of prongs in the star (H nuclei) for a – 660-Mev and b – 360-Mev protons.

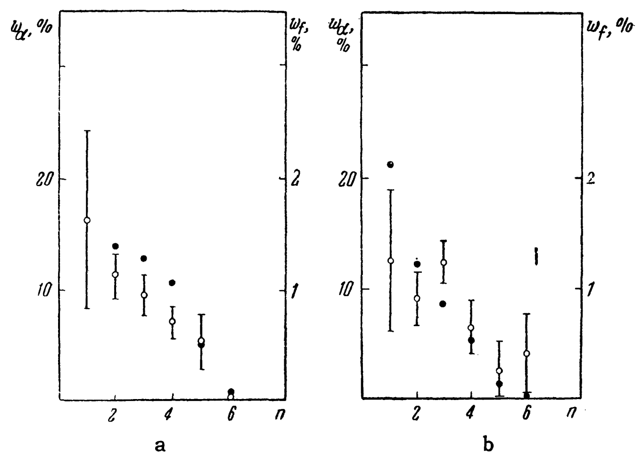

FIG. 6. Same as Fig. 5 for L nuclei.

for the emission of α particles increases less markedly, as can be seen from Table I. The cross section for fragment production on light nuclei does not vary with increasing energy of the beam, and this is the case also for the cross section for emission of fast α particles. Evidently, such difference in the energy dependence of the cross section for light and heavy nuclei is connected with different transparency of the nuclei for fast protons and with a different degree of development of the internal cascade process. It can be noted that the ratio of the cross section for the production of 1, 2, etc. fragments in α stars is approximately the same as that given in reference 5 for f stars, if we assume that the emission of a fast α particle is equivalent to the emission of a fragment.

The multiplicity distributions of α and f stars, similar to each other, are markedly different from the distribution of normal stars which do not contain tracks of a fast α particle or fragment. It can be seen from Figs. 5 and 6 that the relative probability of the production of an α particle on a H nucleus increases with increasing dimensions of the star, attaining a maximum and then falling off slowly. To a lesser extent, a similar behavior may be observed for the emission of fragments as well. An increase of the relative probability of the emission of α particles and fragments is due, we believe, to the increased number of collisions between nucleons in the cascade stage of the disintegration process, and to the increase in the number of the secondary nucleons responsible for the appearance of these multiply-charged particles. The fall-off in the curves $w_\alpha(n)$ and $w_f(n)$ for large n is due to the fact that, in a strongly developed cascade, colliding nucleons have, on the average, small energies which are not sufficient for imparting to the α particles or to the fragment the necessary energy. The relation between the energy of α-particles and the mean multiplicity in an α-star (Table II) indicates also that the more energetical α particles are emitted under the action of cascade nucleons of higher energies. The maximum of curve $w_\alpha(n)$ should therefore shift to the left with increasing energy of detected α particles. An experimental check showed that the shift of the curves $w_\alpha(n)$ constructed for α-particles of various energies really takes place. Data of reference 5 indicate that the mean multiplicity of f stars increases slightly if we consider events with emission of fragments having a long range. Such a conclusion should, however, yet be verified, since the observed variation of the mean multiplicity in f stars with varying range of the fragments lies within the limits of statistical fluctuations.

Special attention should be given to the practically identical angular distributions of α-particles and fragments in all four compared cases. Such a similarity is hardly due to chance, and the fact undoubtedly should be taken into account in considering any hypothesis proposed for the explanation of fragment emission. Observation also shows that the angular distribution of cascade α particles depends on their kinetic energy. In our experiment, the angular distribution of cascade α-particles with energy > 30 Mev was measured. It is probable, that in varying the energy limit, the angular characteristics of α particles will also change. The question therefore arises as to why the angular distribution of α-particles with energy > 30 Mev and of fragments with kinetic energy > 1 to 2 Mev per nucleon[5] are identical.

One can attempt to explain this fact by assuming that the observed particles are emitted from the nucleus as a result of an elastic (quasi-elastic) collision of a fast nucleon with a nucleon complex.[14] We shall assume that nucleons of the same energies are responsible for the emission of α-particles and fragments (consequently the angular spread of these nucleons with respect to the direction of the beam is the same in both cases). The ratio of the kinetic energies of the particles emitted at the same angle to the beam will then be equal to

$$\varepsilon_f / \varepsilon_\alpha = 25 / [(M_f / m) + 1]^2, \qquad (\varepsilon_f = E_f/M_f, \quad \varepsilon_\alpha = E_\alpha/M_\alpha). \tag{4}$$

where M_α and M_f are the masses of α particles and fragments respectively, E_α and E_f their energy, and m the nucleonic mass.

In our experiment, the minimum value of ϵ_α is equal to 7.5 Mev. We have then for a particle with a mass $M_f = 9$ (Be nucleus), $\epsilon_f = 2$ Mev; for the B^{10} nucleus we have $\epsilon_f = 1.6$ Mev, etc. The values of the lower limit of the recorded multi-charged particles calculated according to formula (4) will be 1 to 2 Mev per nucleon, which corresponds to the conditions of the experiments of reference 5.

On the basis of the available experimental data, it is of course impossible to maintain that the mechanism of fragment production is essentially due to collisions. Keeping the hypothesis of elastic ejection of nucleon complexes from the nucleus, it should, for instance, be explained why there is no unique dependence of the energy of multi-charged particles on the angle of their emission. Alpha particles as well as fragments have a markedly smaller kinetic energy than they should possess at a given angle of their emission. The contribution of secondary nucleons does not remove the difficulty, since, in that case, the deviations would be spread uniformly both towards smaller and longer angles.

To determine the mechanism of emission of fragments and fast α particles, further work is necessary. In particular, it would be interesting to have data on the energy and angular distribution of fragments with a given charge, to find the connection between the emission of a multiply-charged particle and of a fast proton, etc. Analysis of the results of experiments of similar type, and comparison with the data on the emission of fast α particles, will make it possible to approach the solution of this problem.

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[1] H. Muirhead and W. G. Rosser, Phil. Mag. **46**, 658 (1955).

[2] P. A. Vaganov and V. I. Ostroumov, J. Exptl. Theoret. Phys. (U.S.S.R.) **33**, 1131 (1957), Soviet Phys. JETP **6**, 871 (1958).

[3] S. O. C. Sorensen, Phil. Mag. **42**, 188 (1951).

[4] D. Perkins, Proc. Roy. Soc. **203**, 399 (1950).

[5] O. V. Lozhkin and N. A. Perfilov, J. Exptl. Theoret. Phys. (U.S.S.R.) **31**, 913 (1956), Soviet Phys. JETP **4**, 790 (1957). O. V. Lozhkin, Dissertation, Radium Institute, Academy of Sciences, U.S.S.R. 1957.

[6] V. M. Sidorov and E. L. Grigoriev, J. Exptl. Theoret. Phys. (U.S.S.R.) **33**, 1179 (1957), Soviet Phys. JETP **6**, 906 (1959).

[7] Yu. I. Serebrennikov, Научно-информ. бюлл. Ленинградского политехнического ин-та (Sci. Info. Bull., Leningrad Polytech. Inst.) **12**, 85 (1957).

[8] E. Segrè (editor), Experimental Nuclear Physics, Vol. I, p. 156, N. Y., Wiley, 1953.

[9] Bernardini, Booth, and Lindenbaum, Phys. Rev. **88**, 1017 (1952).

[10] E. L. Grigor'ev, and L. I. Solov'eva, J. Exptl. Theoret. Phys. (U.S.S.R.) **31**, 932 (1956), Soviet Phys. JETP **4**, 801 (1957).

[11] Blau, Oliver, and Smith, Phys. Rev. **91**, 949 (1953).

[12] Yu. I. Serebrennikov, Научно-информ. бюлл. Ленинградского политехнического ин-та (Sci. Info. Bull., Leningrad Polytech. Inst.) **12**, 75 (1957).

[13] V. I. Ostroumov, J. Exptl. Theoret. Phys. (U.S.S.R.) **32**, 3 (1957), Soviet Phys. JETP **5**, 12 (1957).

[14] D. I. Blokhintsev, J. Exptl. Theoret. Phys. (U.S.S.R.) **33**, 1295 (1957), Soviet Phys. JETP **6**, 995 (1959).

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