Disintegration of Silver and Bromine Nuclei by High Energy Protons

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We have studied the interaction with heavy nuclei in emulsion of protons with energies 130, 460 and 660 mev. By observing the tracks of recoil nuclei in stars formed as a result of this interaction, we have determined the average number of cascade protons and alpha-particles in stars with different numbers of prongs. The relation between the number of "black" prongs and the mean excitation energy of the nucleus was established for all three energies of the bombarding protons. The distribution of nuclei according to excitation energy was found. The experimentally observed energy spectrum of the protons differs somewhat from an evaporation spectrum.

INTRODUCTION

It is well known that the process of disintegration of nuclei by fast particles is made up of two stages: cascade and evaporation. The occurrence of the second stage is caused by the fact that as a result of the passage of the primary particle through the nucleus, and the consequent development of a cascade of successive collisions of nucleons, the nucleus is left in an excited state; the excitation energy is usually only a part, small or large, of the initial kinetic energy of the bombarding particle. The excitation energy is one of the most important characteristics of the interaction process. There are several papers in which this quantity has been calculated for different cases of interaction.[1–3] The experimental determination of the excitation energy, for example in work done by radiochemical analysis of the disintegration products, is extremely inexact and is rather in the nature of an estimate. In particular cases estimates have been based on theoretical relations, which in their turn require experimental verification. Lock et al.[4], in studying the interaction of 950 mev protons with nuclei in emulsion, determined the mean excitation energy of the nucleus from the average number of charged particles accompanying each disintegration. In their work they used the relation between the number of charged particles evaporated and the excitation energy, as calculated by Le Couteur.[5] From observations of stars produced in emulsion by high energy cosmic ray particles, Bernardini and co-workers[1] showed that an excitation energy of 35 mev in Ag and Br corresponds on the average to the evaporation of one charged particle (whereas this number is ~ 0.3 according to Ref. 5). The computation of the cascade stage carried out by these authors,[1] as well as the results of their experiments with 400 mev protons, confirm the correctness of the relation they give between number of particles and excitation energy. Stars produced by 450 mev protons were also studied in Reference 6. The authors of this paper came to the conclusion that Le Couteur's curve does not agree with their experimental data, while the relation given in Ref. 1 is in very close agreement.

It would be interesting also to find the distribution function for the nuclear excitation energy. This distribution was computed in the paper of Bernardini et al.,[1] but there are no experimental data on this point.

While the study of fast cascade particles emerging upon disintegration of nuclei by high energy nucleons has been covered in many papers, by using nuclear emulsions, similar investigations of the "black" component of knock-on particles is made difficult by the presence of the evaporation particles. Estimates of the fraction of cascade protons with energy below 30 mev were made[7,8] by observing the angular anisotropy of black tracks in stars on heavy nuclei in emulsion. It comprises 25–30% of the total number of prongs. The Monte Carlo method[1] gives a very similar result. In all these investigations, it was assumed that the "black" cascade particles consist only of protons and of neutrons, (which are not observable in experiments with plates), though there are experimental indications that alpha-particles are present.

The present investigation is devoted to the questions raised above. The method used in this work was described by us in an earlier paper.[9,*] The analysis of tracks of recoil nuclei in stars, on which this method is based, has also been developed by Harding[10] and Grilli and Vitale.[11] In both of these

*The results published in Ref. 9 should be regarded as preliminary, and for purposes of illustration.

papers, it was assumed that the nucleus which produces the recoil track is moving with a velocity whose magnitude and direction are determined by the sum of two independent velocities: 1) the velocity given to the nucleus as a result of the passage of the primary particle which loses part of its kinetic energy in traversing the nucleus (we call this component the transfer velocity), and 2) the velocity acquired by the nucleus during the succeeding evaporation of particles. A similar model of the formation of recoil tracks is also the basis of our method, with the difference that the first component of the momentum of the nucleus is assumed to be equal in magnitude and direction to the change in momentum of the primary particle, which after colliding with the nucleus preserves its initial direction of motion, while the decrease in kinetic energy of the bombarding particle is assumed to be equal to the excitation energy of the nucleus.

EXPERIMENTAL ARRANGEMENT

In our work we used plates with fine-grained emulsion type P–9, prepared in N. A. Perfilov's laboratory, and also plates with NIKFI type K emulsion, on which parallel experiments were done. The emulsion layer was 150 microns in thickness. The emulsion recorded protons with energies up to 30–35 mev, as was established by observing π–μ decay. In the experiment at 140 mev, the NIKFI emulsion was sensitive out to 100 mev. The irradiation was carried out in external, collimated beams of protons, with energy 140, 460, and 660 mev, at the synchrocyclotron of the Institute for Nuclear Problems of the Academy of Sciences of the USSR. The 140 mev protons were obtained by slowing down faster protons in a copper block. When the energy loss in the emulsion layer is included, the effective energy of these protons is set at 130 mev. The beam was incident parallel to the plane of the emulsion within 5°. The number of background stars, as determined from control plates exposed simultaneously but outside the beam, did not exceed 2%. The angles were measured to 1°, the track lengths to 0.3 microns. All the measurements were made under maximum magnification (100 × 20 × 1.5). The small grain size of P–9 emulsion makes it especially valuable for measuring recoil tracks, as was confirmed by comparison data from parallel experiments on K and P–9 emulsions.

The velocities of the recoil nuclei were determined from the range-velocity curves[12] for light fission fragments from uranium, where the conversion coefficient from range in air to range in emulsion was taken as 1760. We selected for measurements those stars which contained recoil tracks which did not deviate by more than 30 ° from the plane of observation. Only the projection of the track length on this plane was measured. If a star contained alpha-particle tracks shorter than 40 microns while the total number of prongs was less than 6, it was discarded as very probably being the result of disintegration of light nuclei in the emulsion.

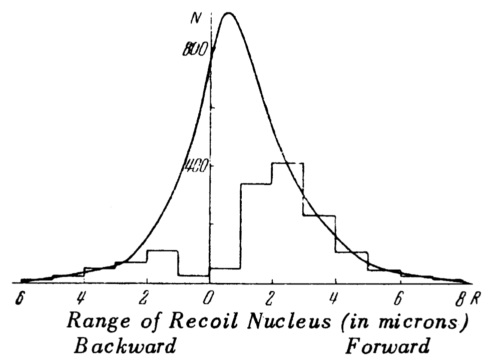

FIG. 1. Distribution of stars according to range of recoil nuclei; "backward" and "forward" refer to direction relative to the bombarding beam. The solid curve is drawn including unobservable cases.

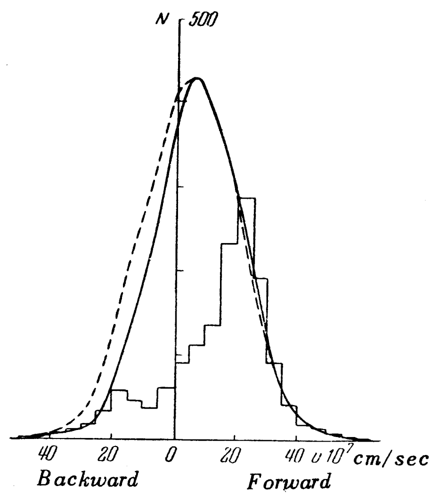

FIG. 2. Distribution of nuclei according to recoil velocity component v. The solid curve is the distribution corrected for unobservable cases, the dashed curve was calculated from formula (2) of the present paper.

EXPERIMENTAL DATA

Figure 1 shows the distribution in range of recoil nuclei, for incident proton energies of 460 and

660 mev (1483) cases). The curve is drawn taking into account cases which are missed because of low velocity of the recoil nucleus (cf. below). Figures 2 and 3 show the distribution of x and y components of the velocity—v and w.* Both these curves are drawn including the correction for unobservable cases. This correction was obtained from the assumption that the true distribution of w is Gaussian. The points for $v = \pm 15 \times 10^7$ cm sec in Fig. 2 were corrected correspondingly. For the points $v = \pm 5 \times 10^7$ cm/sec, the correction was made so that the total number of cases was twice as great as that observed, since the number of stars from Ag and Br which contain recoil tracks is about 50% of all disintegrations of those nuclei. The range correction was made similarly, using the relation between R, v and w.

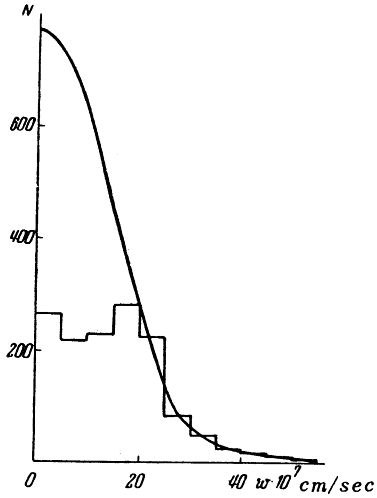

FIG. 3. Distribution of nuclei according to velocity component w. The solid curve is a Gaussian distribution.

The measured values of velocity for stars with different numbers of prongs, and also the velocity of transferred motion of target nuclei calculated from the tracks, $u = v^+ - w$, are shown in Fig.4. The spread in the individual values for each point is extremely large, and very good statistics are necessary for obtaining more or less smooth curves. For this reason, the experimental points on the graphs are taken as an average for two successive values of the prong number n. In some experiments, the values of w were measured separately in two directions— "up" and "down" with respect to the bombarding beam. The average values obtained were equal within the limits of statistical accuracy, as was to be expected, since evaporation is an isotropic process.

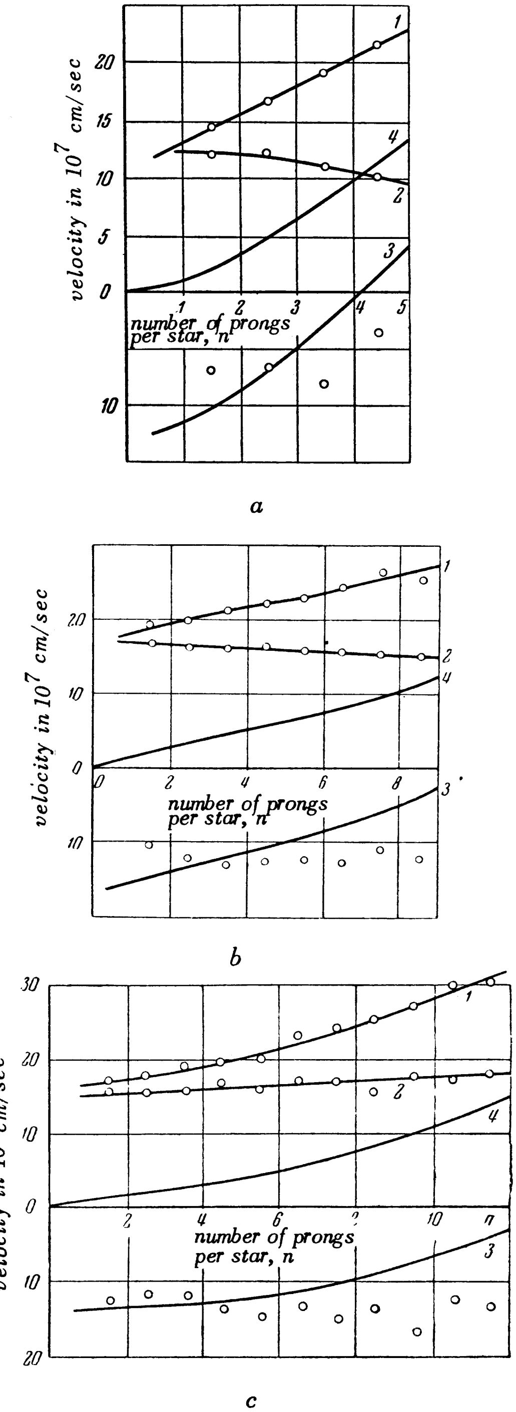

FIG. 4. Average values of the "forward" component of velocity: 1— v^+, 2—w; 3—"Backward" component of velocity v^-; 4—transfer velocity u as a function of prong number, for stars formed by protons with energy: a) 130, b) 460, c) 660 mev.

*Here and throughout the paper we shall stick to the notation used in Ref. 9, where the x-axis is taken along the direction of the incident protons.

Knowledge of the value of u enables us to determine the excitation energy for each type of star from the formula:

$$U+Q = E_0 - [\sqrt{(p_0 - Mu)^2 c^2 - m^2c^4} - mc^2], \quad (1)$$

where U is the excitation energy, Q is the sum of the binding energies of the ejected particles, M and u are the mass and velocity of the nucleus, m, E_0 and p_0 are the mass, energy and momentum of the impinging proton. In this way we find the dependence of n $(U+Q)$, the number of prongs per star, on the quantity $U+Q$. In order to determine the number of ejected particles, and consequently the value of Q, one can proceed as follows: upon setting some value for the number of charged particles evaporated, n_{evap}, we determine the numbers of alpha-particles and protons evaporated from the theoretical dependence of $(\alpha/p)_{evap}$ on n_{evap}[13] Knowing from the experiment the average number of α-particles and protons in a given type of star and subtracting from the total number of a particular particle the number of evaporation particles, we determine the composition of the charged prompt component. Data concerning the number of fast protons (with energies greater than 30 mev) were obtained from observations on electron-sensitive plates (cf. Table I). We compare the value of U found from (1) with the magnitude of the initial excitation energy necessary for evaporating the given number of particles n_{evap}. If the value of U from formula (1) does not agree with the value of the excitation energy obtained from the theoretical curve of n_{evap} (U), the computation is repeated for a new value of n_{evap}. The ratio of the numbers of cascade neutrons and protons was taken in accordance with Ref. 2 (a check for the case of 460 mev protons showed that n (U) obtained by the method just described changes only slightly if the numbers of neutrons and protons are taken to be equal). In Fig. 5 we show the dependence of the number of black tracks per star on the excitation energy, for all three energies of the bombarding particles.

EXCITATION ENERGY

The curves n (U) enable us to construct the distribution of cases of interaction of fast protons with Ag and Br nuclei according to excitation energy of these nuclei. For this purpose it is necessary to know the prong distribution of stars produced in the emulsion. Disintegrations which are not accompanied by emergence of charged particles of low energy, as well as a considerable number of the one– and two–pronged stars, cannot be counted even in relativistic emulsions, when one is making an area search. Therefore, the experimental data on prong distribution of stars produced by 460 and 660 mev protons were corrected for unobservable cases, in accordance with the data of Bernardini et al.[1] The prong distribution of stars from 130 mev protons was taken as the average of the data of Refs. 3 and 7. The effect of star formation on light nuclei in the emulsion was taken into account by using the results of experiments with high energy neutrons.[8] In Table II we give the prong distributions of stars as obtained from observations of disintegrations in electron-sensitive plates and corrected in the manner just described. For comparison we also give the distribution of stars with more than two prongs, as found in P–9 emulsion and assigned in accordance with our criterion to disintegrations of Ag and Br.

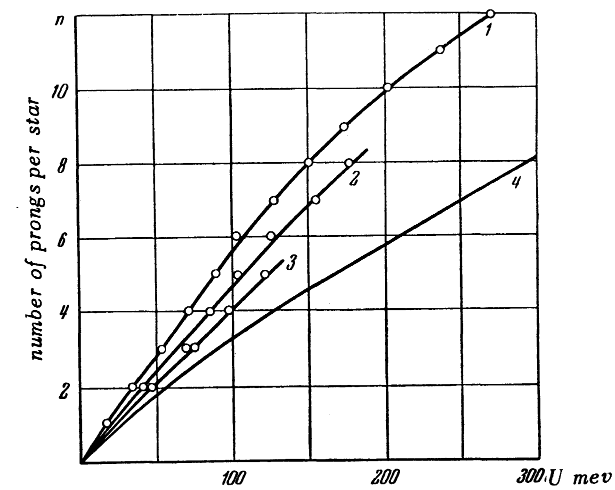

FIG. 5. Relation between number of black prongs per star and excitation energy of Ag and Br nuclei, for proton energies: *1*—660 mev, *2*—460 mev, *3*—130 mev, *4*—theoretical evaporation curve (Ref. 13).

Figure 6 shows the distributions of nuclei according to initial excitation energy, constructed from the data of Fig. 5 and Table II. The distribution found for the case of disintegration by 460 mev protons is in good agreement with the results of computation.[1]

TABLE I

Average Number of Fast Protons (E > 30 mev) in stars from Ag and Br

Number of black tracks, n	Energy of incident protons, mev		
	130	460	660
—	0	—	2,1
1	0.76	1,31	1,57
2	0.40	1.08	1.34
3	0.33	1,02	1.21
4	0.27	0,96	1,13
5	0.20	0.78	1.05
6	—	0.66	0,96
7	—	0.49	0,84
8	—	0,40	0,72
9	—	0,27	0,63
10	—	—	0.50
11	—	—	0.33
12	—	—	0.12
average	0.40	0,97	1,13

The average excitation energy can be determined from : 1) the distribution given in Fig. 6; 2) from the transfer velocity u averaged over all stars, using formula 1); 3) from the average number of

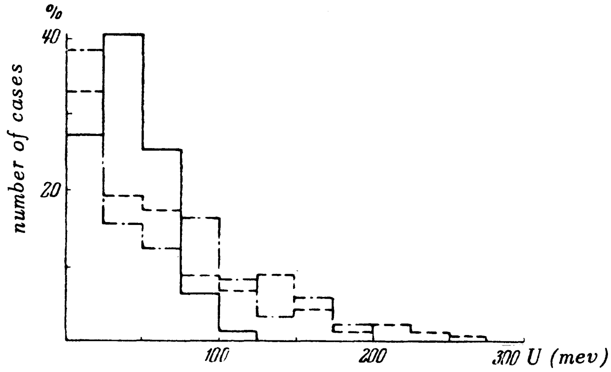

FIG. 6. Distribution of Ag and Br nuclei according to excitation energy from bombardment by protons of energy: 130, solid curve; 460, dash curve; 660 mev, dot—dash curve.

charged evaporation particles, obtained by transforming the curve n $(U + Q)$ to a curve of $n(U)$. All three methods lead to an average value of the excitation energy which is equal, for the case of $E_0 = 130$, $E_0 = 460$ and $E_0 = 660$ mev respectively,

TABLE II.

Prong distribution of stars in Ag and Br

number of black prongs, n	$E_0 = 130$ mev calc. all stars %	$E_0 = 130$ mev calc. stars with $n \geq 1$ %	$E_0 = 130$ mev exp. stars with $n \geq 1$ %	$E_0 = 460$ mev calc. all stars %	$E_0 = 460$ mev calc. stars with $n \geq 3$ %	$E_0 = 460$ mev exp. stars with $n \geq 3$ %	$E_0 = 660$ mev calc. all stars %	$E_0 = 660$ mev calc. stars with $n \geq 3$ %	$E_0 = 660$ mev exp. stars with $n \geq 3$ %
0	3,1	—	—	20	—	—	17,5	—	—
1	24,4	25.2	18.3	18,7	—	—	15,3	—	—
2	40.6	41.7	37.3	15.5	—	—	13,5	—	—
3	25,1	25.9	31.3	11.7	25,7	27.8	11.3	20.9	16.4
4	5.6	5.8	9.6	11.7	25.7	25,2	10,0	18,5	21.6
5	1,2	1.4	3.5	9.1	19,9	20.7	8,5	15.7	22,2
6	—	—	—	6,1	13,4	13,2	7.3	13.5	16,4
7	—	—	—	4.5	9.8	8,4	6,2	11.5	10,1
8	—	—	—	1,9	4.1	3,2	4,6	8,5	7,2
9	—	—	—	0.6	1.4	1.5	3,1	5,7	3,3
10	—	—	—	—	—	—	2,0	3,7	2,0
11	—	—	—	—	—	—	0,7	1.3	0,7
12	—	—	—	—	—	—	0,4	0.7	0,2

to 48 ± 1, 52 ± 4, 58 ± 4 mev. It is obvious that these methods are interdependent, so the errors shown enable one merely to judge the accuracy of computation within the limits of the method used.

On the basis of the data of our experiment, we constructed a curve of nuclear yield from disintegration of silver and bromine by 460 mev protons (Fig. 7). On this same graph are plotted the experimental points obtained in Reference 14 from radiochemical analysis of the products from bombardment of silver by protons of this same energy. It is apparent that the results of the two papers are in agreement. A certain shift of the points is probably caused by the fact that in the experiment with emulsion the average charge of the target nuclei is somewhat less, and consequently the probability of emergence of charged particles is somewhat greater than in the experiment with pure silver.

Starting from our model of the formation of recoil tracks, the distribution function for the quantity v can be written as an integral:

$$F(v) = \int_{-\infty}^{\infty} P(w)\,\Phi(v-w)\,dw, \qquad (2)$$

where $\Phi(v-w) = \Phi(u)$ is the distribution of the velocity u, $P(w)$ the distribution for the velocity w. By solving (2) for $\Phi(u)$, one can, it is true, find the distribution of excitation energy, i.e., the curve of Fig. 6. We have limited ourselves to solving the inverse problem: from $\Phi(u)$ and $P(w)$ we calculated the function $F(v)$, a graph of which is shown as the dashed curve in Figure 2. The agreement of the results of the computation with the observed distribution is satisfactory for positive values v^+. For tracks directed opposite to the incident proton, the two curves differ somewhat. An attempt was made to obtain better agreement of the curves by changing the shape of the curve of $\Phi(u)$ in the region of low values of the argument, where it is determined least accurately. However, this attempt led to no significant improvement. Possibly the cause of this disagreement lies in the insufficient statistics for the corresponding cases.

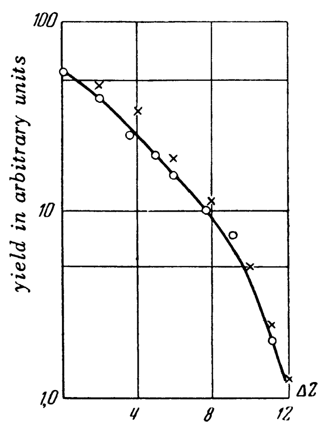

FIG. 7. Yield of nuclei with varying Z from bombardment of Ag and Br by 460 mev protons. The crosses are the results obtained in Ref. 14 and are adjusted to coincide with the present experiment at $\Delta Z = 0$. ($\Delta Z = Z_{in} - Z_{final}$).

PROTON ENERGY SPECTRUM

The energies of protons in the stars were measured from the length of tracks stopping in the emulsion, and the usual geometrical corrections for track yield were made, assuming that their angular distribution is isotropic. This assumption is not completely valid for protons with energy greater than 10 mev, but the observed anisotropy has an insignificant effect on the spectrum shape. The distinguishing of proton tracks from those of α-particles was done visually. This selection is more reliably done with fine-grained emulsion than with type K. The accuracy of selection was checked in a special experiment by a method proposed by Iu. I. Serebrennikov. Along an arbitrarily selected track, starting from its end, in a manner similar to grain-counting, the number of intervals of an ocular scale which were completely covered by developed grains was recorded. The processing of 90 tracks of length 80 μ, carried out by two independent observers, showed that the tracks of α-particles and protons begin to differ significantly after a length of 50 μ, and that visual distinction leads to negligible error (of the 90 tracks, three proton tracks were mistakenly attributed to α-particles).

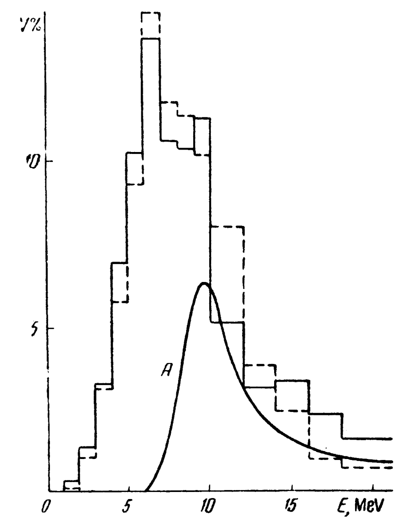

FIG. 8. Energy spectrum of protons emitted from Ag and Br nuclei bombarded by protons of energy: 660, solid line; 460 mev, dashed line. The first distribution was constructed from 6270 tracks, the second from 2500. Curve A shows the spectrum of "black" prompt protons averaged for both beam energies.

The energy spectra of protons (more precisely, singly charged particles) in stars produced by protons of energy 460 and 660 mev, are shown in Fig. 8. If in the first case the spectrum has a single peak due to protons from the evaporation process (and somewhat broadened by knock-on protons of low energy), in the stars from 660 mev protons there is apparently a second peak associated with direct ejection of a considerable number of protons with energy 8–10 mev. From the dependence of n (U) found in the present work it follows that with increasing excitation energy there is also an increase in the "black" component of directly ejected particles. This is confirmed by the graphs in Fig. 9, which show proton spectra for various initial excitation energies of the nucleus. For comparison, curves are shown for the theoretical evaporation spectra computed with the effect of nuclear cooling included. The difference between the experimental and evaporation spectra gives the energy distribution of prompt protons, whch is shown totaled for all stars in Fig. 8. The difference in shape of the observed and computed evaporation spectra in the energy region up to 4 mev (Fig. 9), can be attributed to inclusion of stars formed on light nuclei in the emulsion, and also to errors in track identification.

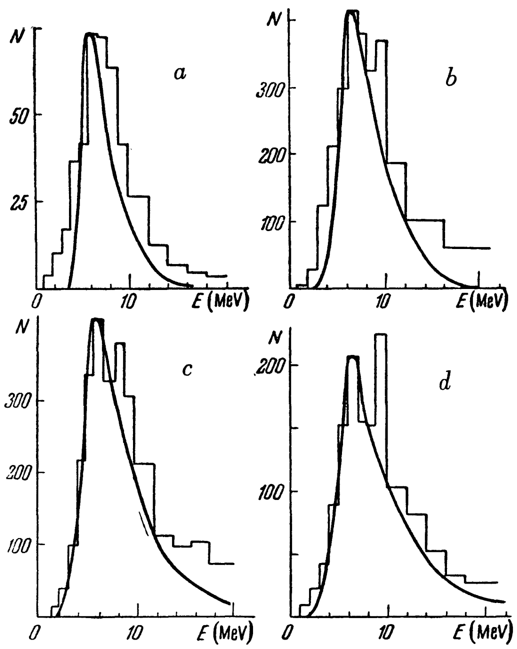

FIG. 9. Energy spectrum of protons for varying initial excitation energy of the nucleus. Computed evaporation spectra are shown for the following nuclear excitations: *a*) 0–50 mev (U_{av} = 25 mev); *b*) 50–100 mev (U_{av} = 75 mev); *c*) 100–150 mev (U_{av} = 125 mev); *d*) 150–200 mev (U_{av} = 175 mev).

A comparison which we have made of the spectra of protons emitted into the forward and backward hemispheres with respect to the beam shows that there is a small excess of particles of low energy (E < 7 mev) emitted backwards. This excess is quantitatively explained by the effect of the motion of the evaporating nucleus. On the other hand, in the high energy region where the direct ejection begins to have an effect, we observe an excess of protons emerging into the forward hemisphere.

KNOCK-ON COMPONENT

The presence of cascade particles of low energy is indicated by the appearance of angular anisotropy of the black tracks in the stars, the anisotropy being the same for protons and α-particles for all three energies of the incident protons in our experiment (56 ± 2% of the prongs are directed into the forward hemisphere).

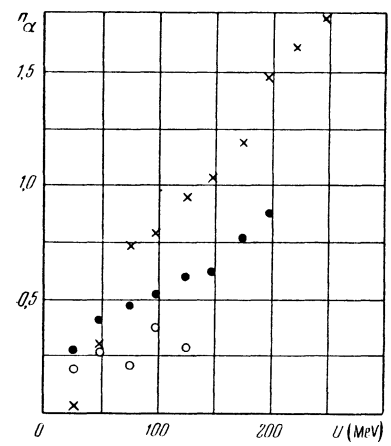

FIG. 10. Dependence of number of cascade α-particles on nuclear excitation energy. Crosses– E_0 = 660 mev; solid circles—E_0 = 460 mev; open circles—E_0 = 130 mev.

The fraction of knock-on particles can be determined from the overall observed anisotropy, by using the angular distribution data and computing by the Monte Carlo method. On the other hand, the average number of charged cascade particles can be found as the difference between the average number of prongs in a star and the number of evaporation particles corresponding to the given excitation energy. A third independent method for determining this quantity consists in observing the proton energy spectrum. As was pointed out above, one can separate the spectrum of cascade protons from the total spectrum observed in the experiment, and thus calculate the number of cascade particles. All three of these methods when applied to disintegrations by 460 and 660 mev protons lead to approximately the same result. Since there are no corresponding data in the literature concerning cascade α-partcles, the fraction of thelatter was determined only from computations of the n (U) curves, as indicated above. In Table III we present the data for the charged cascade component as obtained in thepresent experiment, and the results of computations in which the effect of α-particles was not included.

Figure 10 shows the relation between the number of cascade α-particles and the excitation energy of the residual nucleus, though the latter quantity should be regarded as a function of the total number of cascade particles.

ACCURACY OF THE METHOD

The internal consistency of the results obtained in the present work, as well as the agreement with corresponding data of other authors, permit us to conclude that the method proposed in Ref. 9, together with all the approximations, is admissible at least for the range of incident proton energies here considered, and is not associated with large errors. We have attempted to estimate the error in the determination of U which is caused by the recoil during ejection of secondary nucleons. By calculating the average angle of emergence of the cascade nucleons from their known angular distribution,[1] and assuming that on the average one nucleon is ejected from the nucleus into each of the energy groups (E < 30 mev; 30 < E < 100 mev, and E > 100 mev), we can determine the momentum imparted to the nucleus, and then from formula (1) find the average excitation energy U corresponding to this momentum Mu. On the other hand, U can be determined from the energy balance of the disintegration process. It was found that for a bombarding proton energy of 460 mev, the discrepancy between these two values of U was about 10%, reaching 50% for high excitation energies (~200 mev). However, for high excitation energies the actual error is in all probability smaller, because for a well-developed cascade the angular distribution of "black" prompt nucleons must approach isotropy, which leads to a decrease in the computational error. This is confirmed by the agreement of the maximum value of U (200 mev), as obtained from a Monte Carlo calculation,[1] with the value for the upper limit of U found in our experiment. We estimate the accuracy of the results obtained in the present work to be ~ 20%.

DISCUSSION OF RESULTS

As already pointed out earlier, there are a

TABLE III.

Incident proton energy, mev		130	460	660
		Number of particles per disintegration		
Cascade Protons	$E < 30$	0.25 (20% of all black protons)	0.57 (30% of all black protons)	0.84 (35% of all black protons)
	$E > 30$	0.49	0.95	1.03
	All cascade protons	0.74	1.52	1.87
Cascade α-particles		0.18 (27% of all α-particles)	0.25 (39% of all α-particles)	0.49 (50% of all α-particles)
Black knock-ons		0.43 (21% of all black prongs)	0.82 (32% of all black prongs)	1.33 (39% of all black prongs)
(α/p) in cascades		0.24	0.17	0.26
All charged knock-ons		0.92	1.77	2.36
Computed		1.19[3]	1.6[1]; 1.9[2]	2.2[2]

series of papers whose results do not agree with LeCouteur's evaporation theory. The data obtained in our experiment concerning the number of cascade particles, the magnitude of the excitation energy, etc., agree with computations by the Monte Carlo method, if we use Macke's thoretical curve.[13]

The appearance of a second maximum in the energy spectrum of protons from nuclear disintegrations by 660 mev protons appears, at first glance, quite unexpected. There is no indication of this in a single paper published up to the present time. However, one should consider that in these papers, as a rule, the spectrum was studied for all the nuclei in the emulsion lumped together, including the light nuclei, and sometimes even with undefined energy of the bombarding particles (as in experiments with cosmic rays). In addition, in certain experiments the statistics were poor, so that the authors had to take wide energy intervals in constructing a histogram, which led to a coalescence of the two peaks into a single one corresponding to evaporation protons. It is interesting to note that in work[4] done with protons of 950 mev energy, and free of the limitations just mentioned, a second maximum was obtained in the region of 8–10 mev which was even more intense than in our experiment. But the authors themselves[4] apparently regard the appearance of the second maximum as accidental and, wishing to obtain agreement with the experiment, draw the evaporation curve so that the average nuclear excitation turns out to be considerably greater than predicted by the Goldberger model.

The spectrum of cascade protons (Fig.8) agrees in shape with that calculated by the Monte Carlo method.[1–3] There is no good reason for doubting that the neutral component will have a similar spectrum, shifted toward lower energy because of the absence of a barrier. This means that for practical purposes, the spectra of cascade and evaporation neutrons will be even more indistinguishable than is the case for protons. It seems to us that this last point should be considered when interpreting experiments on the determination of the average nuclear excitation energy from the number of emerging neutrons.

In conclusion, the author expresses his deep gratitude to Prof. N. A. Perfilov for his constant interest in the work and for discussion of results, and to the administrative staff of the laboratory for assistance. The author is grateful to Prof. M. G. Meshcheriakov and Prof. V. P. Dzhelepov, as well as to his co-workers in the Institute for Nuclear Problems, N. P. Bogachev, E. L. Grigor'ev, B.S. Neganov and others, for the great cooperation they have provided him in carrying out the experiment.

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