ANGULAR DISTRIBUTIONS OF MULTIPLY CHARGED PARTICLES PRODUCED BY 75–350 MeV PROTONS

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The angular distributions of secondary multiply-charged particles and fast protons are measured relative to incident beams of 76-, 100-, 200-, and 350-MeV protons. The experimental angular distributions of fast protons relative to the beam, the correlations between fast protons and multiply charged particles, and the dependences of these correlations on the emission angle and beam energy are compared with the conventional Monte Carlo calculation of the intranuclear cascade and with the quasi-elastic ejection calculation. The comparison indicates that for 70–100-MeV protons the multiply charged particles are produced through quasi-elastic scattering of the bombarding protons on instantaneous nuclear substructures. An indication is obtained that the intranuclear momentum distribution of multiply-charged particles is Gaussian.

INTRODUCTION

In order to ascertain the production mechanism of multiply charged particles from interactions between high-energy nucleons and nuclei, it is most important to investigate the angular correlations between the different reaction products. Multiply charged particles could theoretically be produced in any process occurring when high-energy nucleons interact with nuclei (if the existence of short-lived aggregates in the nucleus is postulated[1]), i.e., in cascades, evaporation, fission, or fragmentation.[1)] The angular distributions provide the most sensitive means of testing different production mechanisms of multiply charged particles. Indeed, in the evaporation theory changes of parameters can lead to total cross sections that are relatively several times greater or smaller. The same applies, although to a lesser degree, to the energy spectra of ejected particles,[2] but the angular distribution determines the applicability of evaporation theory almost unambiguously. For the present problem it has been shown[3] that evaporation theory cannot account for the large angular asymmetry of multiply charged particles relative to the incident proton beam. Mainly on the basis of this experimental result it has been shown that multiply charged particles cannot be produced by asymmetric fission.[4] Finally, from the angular distributions in emulsion stars involving fragments it has been concluded[5] that no new fragmentation process is required to account for multiply charged particles with Z = 3 – 7. The investigation of angular distributions has also led to the hypothesis that multiply charged particles might be produced in a nuclear cascade involving the quasi-elastic ejection of instantaneous nuclear substructures.[3,6] It is therefore especially interesting to make a more detailed study of different angular relations associated with the production of multiply charged particles, for comparison with a recent calculation based on the cascade model.[1]

EXPERIMENTAL PROCEDURE

A proton beam extracted from the synchrocyclotron of the Joint Institute for Nuclear Research irradiated P-9(ch) emulsions on plates making a 7° angle with the beam. The 76-, 100-, 200-, and 350-MeV protons had been slowed down in copper and polyethylene blocks. A deflecting magnet and a collimator system excluded higher-energy protons and background neutrons from the beam.

The energies of particles impinging on the photo-

1)The term "fragmentation" has different meanings in the Soviet and foreign literatures. In our literature fragmentation means the emission of multiply charged particles (fragments) occurring when high-energy nucleons interact with nuclei, independently of the process involved. In the American literature fragmentation is a definite process associated with the production and absorption of mesons in the nucleus, as a result of which nucleon-nucleon bonds are broken and both nucleon aggregates and a large number of individual nucleons are produced.

graphic plates were determined by measuring the proton ranges in the retarding material for $E_p = 100$, 200, and 350 MeV and by an additional measurement of the grain density in a calibration plate for $E_p = 76$ MeV. In order to measure proton energies in the calibration plate bearing a PR emulsion, which is sensitive to relativistic particles, we plotted the relation between grain density and ionization loss (Fig. 1), obtaining a straight line through the experimental points by means of least squares.[7] On the basis of this straight line the measured grain densities on primary particle tracks indicated the energy losses and therefore the proton energies. The minimum bombarding proton energy was 76 ± 8 MeV.

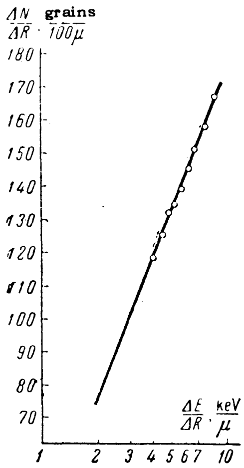

FIG. 1. Grain density versus ionization loss.

In scanning we selected stars containing dense tapered tracks of fragments with $Z \geq 3$, length $l \geq 15$, and dip angle $< 35°$. We thus selected multiply charged particles having energies of at least 1—2 MeV per nucleon. We also selected emission events of two α particles forming angles smaller than 3°, which were identified with the $_4Be^8$ nucleus. It must be noted that this stringent angular criterion may have considerably reduced the yield of these fragments,[8] since only the ground state of $_4Be^8$ was taken into account.

In disintegrations yielding multiply charged particles we discriminated tracks belonging to protons having energies above 15—20 MeV for $E_p = 76$ MeV, and above 20 MeV for other incident proton energies. These protons, which we shall call "fast," were identified both visually and by means of grain counts. The energy threshold for fast protons was based on a kinematical calculation,[1] where it was shown that recoil proton energy following a collision with a multiply charged particle in the nucleus is usually above 20 MeV.

In stars with multiply charged particles we measured the space angles between the proton beam direction and all prongs, as well as the space angles of all other particles relative to the multiply charged particles; a special MIGÉ-1 microscope was used for this purpose. A VUM-1 computer was used to calculate track lengths, direction cosines, and space angles; more than 10,000 angles were measured and calculated.

At each proton energy all observed stars were divided into three groups. The first group included all stars having a recoil-nucleus track, or a combined particle charge greater than 9; these events were considered disintegrations of heavy emulsion nuclei. The second group contained stars having the track of at least one α particle with < 9 MeV or of a proton with < 4 MeV. These events, having particles with energies below the potential barrier for heavy nuclei, were considered disintegrations of light nuclei. The third group contained disintegrations not assigned to either of the other groups. The group of light-nucleus disintegrations could possibly have included some heavy nuclei (for example, due to the appreciable probability of subbarrier proton evaporation from heavy nuclei) or, on the other hand, the heavy-nucleus group could have included some light nuclei. However, calculations[6] show the approximate equality of these transitions; therefore the groups of heavy and light nuclei actually do indicate the relative numbers of disintegrations of light and heavy emulsion nuclei.

In cases when it was necessary to obtain a complete separation of disintegrations into groups of light and heavy nuclei, as, for example, in determining the emission anisotropy of multiply charged particles, we analyzed the disintegrations assigned to the mixed group, dividing them statistically according to the prong distribution of stars by the method described in [6].

RESULTS AND DISCUSSION

1. The most characteristic feature of the angular distribution of multiply charged particles relative to the initial beam is its anisotropy, represented by considerable forward peaking. Table I gives the anisotropy measurements (forward to backward ratios) for the disintegrations of light and heavy emulsion nuclei at the four bombarding energies. The anisotropy is seen to diminish with increasing proton energy, and it is always greater for light nuclei than for heavy nuclei. This is confirmed by the angular distributions of multiply charged particles shown in Fig. 2.

The marked peaking of multiply charged parti-

Table I

Target nuclei	Beam energy, MeV			
	76	100	200	350
C, N, O	72 : 1	34 : 1	15 : 1	12 : 1
Ag, Br	33 : 1	(6.3±1.6) : 1	(3.9±0.7) : 1	(3.0±0.6) : 1

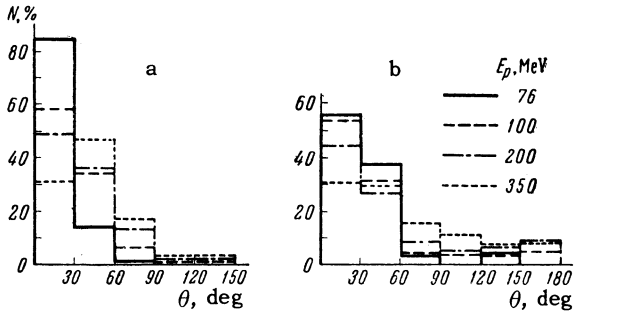

FIG. 2. Angular distributions of multiply charged particles relative to proton beam. a – light nuclei; b – heavy nuclei. Ordinates are percentages of particles per unit solid angle.

cles in the proton beam direction indicates a relationship between fragment emission and a fast cascade process. Indeed, we can omit any attempt to describe this effect by means of any statistical theory such as the evaporation theory, since it is difficult on the basis of the latter to understand the dependence of anisotropy on proton energy even if we should be able to attribute the large anisotropy at any single proton energy to the transfer of incident momentum. Indeed, with increasing beam energy the momentum transfer effect is enhanced and the energy dependence of anisotropy for a statistical process would be the opposite of that observed experimentally.

2. The peaking of fragments in the beam direction is obviously consistent with the quasi-elastic ejection of multiply charged particles, assuming some probability that instantaneous substructures exist in nuclei.[1] In that case, if the investigated multiply-charged particles result from the quasi-elastic scattering of cascade nucleons on nuclear substructures, i.e., if nucleon-multiparticle collisions occur within the nucleus in addition to nucleon-nucleon collisions we can expect that the properties of disintegrations yielding fragments will differ from those of ordinary disintegrations not yielding fragments, which are described very well by the nucleon-nucleon collision model.

Table II gives data on the angular distribution of fast protons in disintegrations with multiply-charged particles (first line); these data pertain to the disintegrations of both heavy and light nuclei for 100- and 200-MeV beams. This table also gives data[9] on the angular distribution of fast protons in ordinary disintegrations of emulsion nuclei (second line) and Monte Carlo calculations (for 140-MeV protons) taking only nucleon-nucleon collisions into account. It can be seen that our present results disagree sharply with the experimental and calculated results (which are in good agreement with each other) for ordinary disintegrations mainly because of a large contribution at angles > 120°.

It is thus indicated that in disintegrations with fragments cascades do not develop through nucleon-nucleon collisions alone; the great contribution of large proton scattering angles is evidence of collisions between nucleons and nuclear substructures.

3. When incident nucleons or those produced in cascades are scattered on instantaneous substructures, a correlation should exist between multiply charged particles emerging from the nuclei and the scattered protons. We investigated this correlation in all disintegrations yielding fragments. Figure 3 shows the distribution of angles between the directions of fragments and fast protons; a strong correlation is indicated for obtuse angles. There is little change in the distri-

Table II

Angle, deg	0–20	20–40	40–60	60–70	80–100	100–120	>120
Experimental no. of protons, present work	6	22	23	21	11	11	23
Experimental no. of protons from [9]	22	46	27	11	3	5	3
Calculated no. of protons from [9]	22	41	26	20	4	2	2

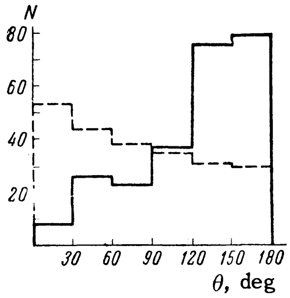

FIG. 3. Distribution of angles between fragments and fast protons. Solid line – experiment at E_p = 200 MeV; dashed line – calculated distribution (obtained by random trials). N is the number of particles per unit solid angle.

bution at other beam energies. In order to test whether this correlation results from an accidental resemblance between the angular distributions of multiply charged particles and fast protons, this possible random correlation was calculated by statistical trials. Figure 3 shows that the experimental correlation was not accidental. The obtained correlation can be compared with the calculation[1] of the angular distribution of multiply charged particles produced in the quasi-elastic scattering of incident protons on nuclear substructures.

Figure 4a shows the calculations for the ejection of Li^7 and Be^9 at 30° by 70-MeV protons (solid line) and the experimental observations of fragments with charges 3 and 4 at angles 20—40° produced by 76-MeV protons (dashed line). Pearson's test indicated very good agreement of the experimental and calculated results ($\chi^2 = 6.8$). A comparison between experiment and the calculation for 100-MeV protons gives considerably less satisfactory compatibility ($\chi^2 = 9.8$); at 200 MeV there is a complete absence of agreement ($\chi^2 \geq 50$). This result is obviously associated with the fact that at high energies multiply charged particles are not ejected by primary protons but by nucleons produced in cascades, whereas the calculation was performed for ejection by a directly incident nucleon; an effective energy therefore exists for fragment ejection.

Indeed, it has previously been suggested[3] on the basis of the identical fragment range distributions for different proton energies that in multiply charged particle production an effective energy range of incident protons exists within which fragment production is most probable. It is reasonable to assume that this region extends from the threshold of multiply charged particle production (~ 50 MeV) to 100 MeV. This is possibly associated with the greater agreement between the wavelengths of incident particles and the linear dimensions of ejected fragments. The probability of multiply charged particle ejection will then be a decreasing function of incident particle energy; this is confirmed by the foregoing comparison between calculations and experiments with 70-, 100-, and 200-MeV protons.

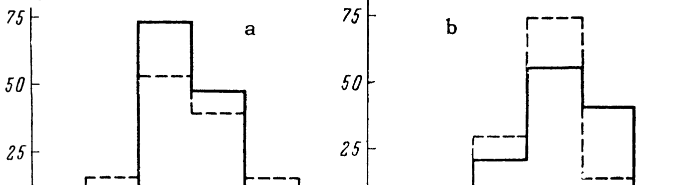

FIG. 4. Comparison of experimental (dashed line) and calculated (solid line) correlation angles (Ψ is the angle between the directions of fast proton and fragment emission) for different fragment emission angles. a – θ = 20–40°; b – θ = 0–20°.

In view of the foregoing it is interesting to consider the dependence of anisotropy in heavy nuclei on proton energy, as in Table I, but separately for stars with small numbers (n = 1 — 3) and large numbers (n > 3) of prongs. In stars with small numbers of prongs the ejection of multiply charged particles occurred in the initial stage of the cascade or in the primary collision events. The small number of prongs is accordingly a good indication of a glancing collision, i.e., a collision between the incident proton and a nucleon aggregate at the edge of the nucleus, whereas the larger stars resulted from central collisions, with branched nuclear cascades, and fragments were ejected by secondary nucleons. If this is completely accurate the anisotropic angular distribution of fragments in few-pronged stars should be greater than in multipronged stars. The experimental anisotropies are 4.8 ± 0.9 and 2.4 ± 0.4, respectively. On the basis of these data (considering that the relative number of multipronged stars increases sharply with the beam energy) and from the foregoing comparison between the experimental and calculated angles, we conclude that for proton energies above 100 MeV multiply-charged particles are ejected mainly by secondary nucleons. At lower bombarding energies (at the effective energy) further analysis and comparison of experiment with calculations are required.

4. The calculation showed that the strongest angular dependence of the correlation is found in the shift of the most probable angles between multiply-charged particles and the incident protons when the angle of fragment emission is changed. Figure 4 shows the angular correlations for multiply-charged particles emitted at θ = 20 – 40° and 0 – 20° in the case of 76-MeV protons (the dashed line). With increasing fragment emission angle the distribution maximum is shifted towards less obtuse angles. A similar dependence is ob-

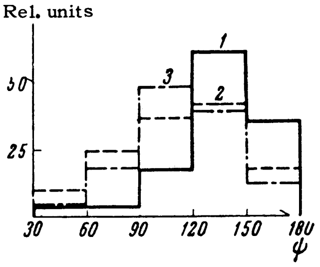

FIG. 5. Dependence of angular correlation on emission angle for 100-MeV protons. 1 – θ = 0–20°; 2 – θ = 20–40°; 3 – θ = 30–50°.

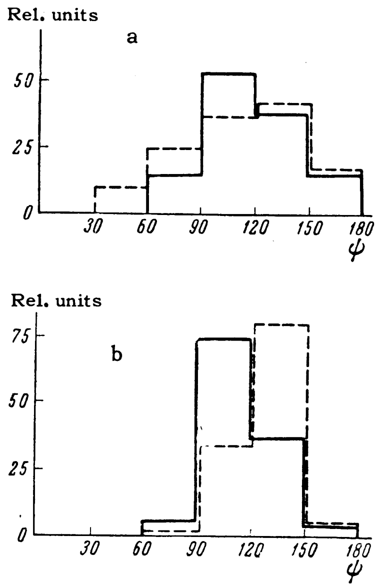

FIG. 6. Dependence of angular correlation on proton energy for different emission angles of multiply-charged particles. a – experimental, θ = 20–40°; b – calculated, θ = 30°. Solid lines, E_p = 76 MeV; dashed lines, E_p = 100 MeV.

served when angular correlations are calculated on the cascade model (Fig. 4).

With increasing incident proton energy a somewhat smaller shift of the correlation was calculated for changes in the fragment emission angle. Figure 5 shows the angular correlations for multiply charged particles emitted at 0—20°, 20—40°, and 30—50° in the case of 100-MeV protons; a comparison with Fig. 4 for 76-MeV protons confirms the calculated results. Whereas for E_p = 76 MeV when the average change of fragment emission angle is 20° the most probable angles undergo a large shift (~30°), for 100-MeV protons and a similar difference of emission angles the character of the correlation only becomes somewhat blurred and a 30° shift is observed only for a considerably greater difference in the emission angles of multiply-charged particles.

It is interesting to compare the experimental and calculated dependences of correlations on proton energy for different fragment emission angles. The calculation showed that the angular correlations are almost independent of proton energy for small emission angles; this was also observed experimentally (see Figs. 4 and 5 for θ = 0 – 20°). However, with an increase in the emission angles of multiply-charged particles the angular correlations depend on the beam energy, as shown in Fig. 6. The calculation is again seen to agree with experiment regarding the change in the character of the correlation.

The foregoing comparison of experiment with calculations shows that the observed angular correlations and their dependences on the beam energy, on the emission angle, and on both simultaneously agree with the calculation for the quasi-elastic ejection of multiply charged particles. It is difficult to believe that the agreement for such large changes of the parameters is accidental. Therefore we assume that for ~70 – 100 MeV protons multiply charged particles are produced through the quasi-elastic scattering of primary nucleons on instantaneous nuclear substructures.

5. It should be noted that the experimental results were compared with a calculation in which the momentum distribution of multiply charged particles within the nucleus was assumed to be Gaussian. It has previously been noted[1] that the angular correlations are as a general rule insensitive to the intranuclear momentum distribution of the particles, which is well determined from energy spectra. However, a tentative comparison of the experimental and calculated angular correlations indicates that intranuclear fragments have a Gaussian rather than a Fermi distribution (the values of χ^2 for 20—40° are 6.8 and 12.6 respectively); therefore a Gaussian distribution was assumed for the purpose of the comparison.

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