MULTI-CHARGED PARTICLES EMITTED IN DISINTEGRATION OF CARBON NUCLEI BY 660-Mev PROTONS

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Multi-charged particles ejected from a thin polystyrene film bombarded with 660-Mev protons and possessing ranges larger than 20μ were investigated by means of nuclear emulsions. The effective cross section for production of these particles and their angular and energy distribution have been obtained. Measurements of the thickness of tracks produced by the fragments were used to determine the charge of particles with ranges above 40μ in the emulsion.

RECENT experiments[1,2] on the disintegration of various nuclei by high energy particles have shown that multi-charged particles called fragments (Li, Be, B and other nuclei) are emitted in such processes with a cross section of the order of several millibarns. Experiments making use of photographic plates and magnetic and radiochemical analyses have yielded some understanding of this process. Unfortunately very little experimental data is presently available and it is difficult to interpret it in terms of a single hypothesis. Photoemulsion techniques may yield valuable information on the process of fragmentation as it permits one to observe the elementary interaction of a fast nucleon with a nucleus. However, nuclear emulsion targets suffer from the disadvantage that the disintegration of heavy (Ag and Br) as well as light nuclei (C, O, N) are registered in the emulsion stack, and it may not always be possible to decide with sufficient certainty whether an observed event belongs to one or the other nuclear group. Various criteria are used to identify the nuclear target (in the above sense). Lazhkin and Perfilov,[1] for example, assume that a star containing fragments and produced by a high-energy proton is due to the disintegration of Ag and Br nuclei if it contains a nuclear recoil track (the maximum length of which is 9 or 10μ) or if the sum of the observed charges in the star exceeds 8e. In reference 3 this criterion is supplemented by the requirement that a star without nuclear recoil track contain at least one α particle or a proton track of low energy (less than 8 and 4 Mev respectively) to be classified as a disintegration of a light emulsion nucleus. It is evident that this method of selection is not quite exact and it is desirable to carry out some controlled experiment in order to check the reliability of the assumed criteria and to refine earlier experimental results.

In our work we studied multi-charged particles ejected by carbon nuclei bombarded by 660-Mev protons. A 20μ polystyrene film mounted on a photographic plate served as target. Fragments emitted from the film were registered in an emulsion stack. Such a method definitely guarantees an exact identification of the disintegrated nucleus but it does not allow observation of the complete picture of the inelastic interaction of a proton with a nucleus leading to the ejection of a fragment. Nonetheless it is possible to obtain valuable data on this process and thus supplement available facts.

We used an emulsion of type P-9, which is sensitive to protons of energy up to 30 Mev; it is very fine grained and permits one to separate easily the tracks of fragments (charge > 3) from those of α particles over a range of approximately 10μ.[1]

Irradiation by the external proton beam of the synchrocyclotron of the Joint Institute for Nuclear Research was carried out in darkness without protective black paper, in order to minimize background tracks from particles not originating in the polystyrene film. The bombarding beam was passed through a collimating system, and its direction was defined to within $\sim 2°$. The distance between the back edge of the last collimator and the plates was over 2 m. The plates were singly exposed every time. Irradiation took place for three positions of the emulsion plane with respect to the beam direction: (1) parallel, (2) perpendicular, (3) at an angle of 30°. Such a choice of geometry was dictated by the need for minimizing the uncertainty in the measurement of the range of multi-charged par-

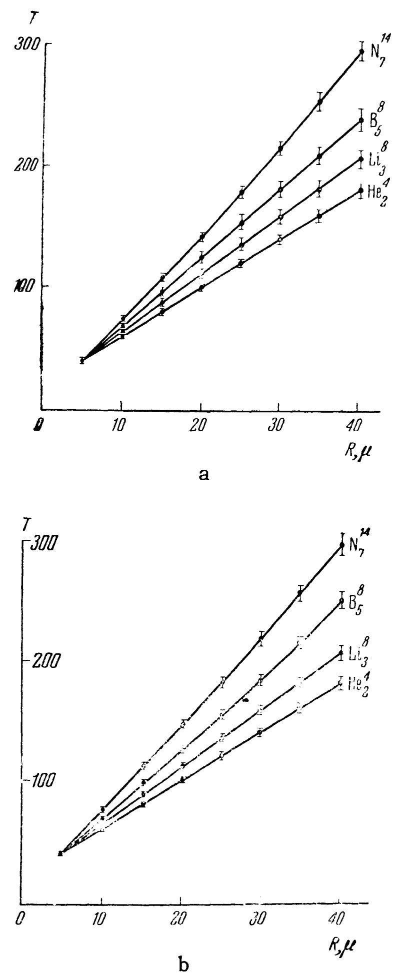

FIG. 1. a) Dependence of the interval thickness of the track upon the range of particles of various charges inclined at 30° to the emulsion. The statistical spread of individual events is indicated; b) same as in (a) for an inclination of 30 to 60°.

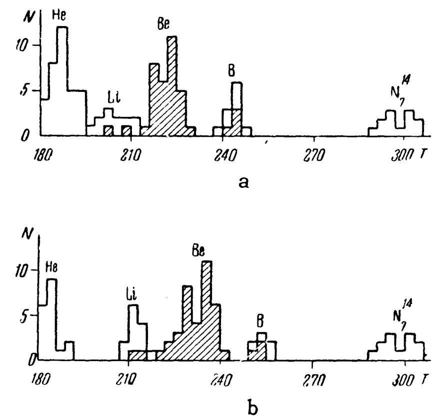

FIG. 2. a) Distribution of tracks belonging to particles of different charges over the integral thickness for a range of 40 μ. Angle of inclination up to 30°. The shaded distribution was obtained from measurements of tracks coming from the film; b) same as in (a) for an inclination of 30 to 60°.

ticles, arising from the finite width of the film.

In examining the plates, we recorded the dense tracks formed by heavy particles which entered the surface of the emulsion at an angle no greater than 60° (for undeveloped emulsion) and stopped within the sensitive layer. The angular distribution of these particles with respect to the beam was obtained in the usual manner, i.e., from measurements of the vertical and horizontal components and angles projected on the emulsion surface. The shrinkage factor of the emulsion was taken as 2.6 ± 0.1. In computing the range, account was taken of particle retardation in the film and it was assumed that the point of departure of the particles lie in the middle plane of the film. The stopping power of polystyrene was computed from the atomic stopping power of carbon and hydrogen.

The charge of the particles was obtained as follows: the track thickness was measured with an eyepiece micrometer at intervals equally spaced along the track length, starting from the end.[4] The integrated thickness (i.e., the sum of the thicknesses up to that point) was then plotted as a function of track length. These curves were found to differ considerably for particles of different charges. To construct an absolute independent calibration, we have used α-particle tracks and hammer tracks of Li_3^8 and B_5^8 found in the same emulsion. In addition, we used plates of the same type of emulsion* irradiated by a current of N_7^{14} ions. To minimize errors due to different inclinations of the tracks with respect to the emulsion surface, measurements were compared only for tracks having approximately the same inclination. Figure 1 presents the results of measurements of control tracks of two groups: one includes tracks at an angle of inclination of no more than 30° (in the undeveloped emulsion), and the other from 30° to 60°.† Figure 2 shows the distribution of individual cases according to interval thickness at a range of 40 μ. In particular, it is seen from this figure that the hammer tracks are sharply divided into two groups which we have identified as Li_3^8 and B_5^8.

Of the total number of 302 tracks found for multi-charged particles coming from the film, 204 were used in the final measurements. The rest were rejected because their inclination exceeded 60°. In addition to these, there were also observed 8 cases of emission into one direction of two α particles of about equal energy which may be considered as due to the decay-in-flight

*These plates were kindly obtained for us by O. V. Lozhkin.
†The tracks of the nitrogen ions were inclined at 30°.

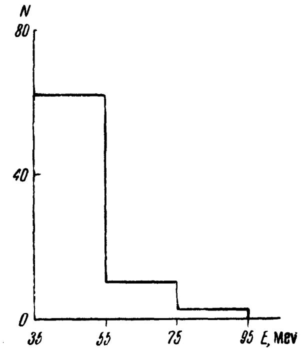

FIG. 3. Energy spectrum of fragments having a range > 40.

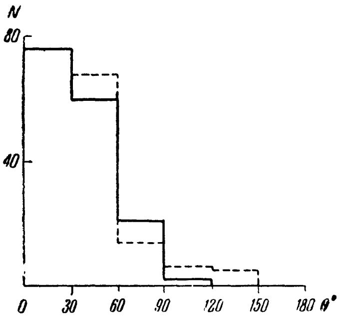

FIG. 4. Angular distribution of fragments relative to the proton beam (per unit solid angle). The dotted lines correspond to the distribution obtained in reference 1.

of the B_4^8 nucleus. These cases are not included in our experimental results.

The charge was determined for 80 tracks of length greater than $40\,\mu$. The results of this measurement are shown as the shaded portion of Fig. 2. The energy of every fragment identified by its track was determined from the energy-range relation for multi-charged ion introduced in reference 5. Figure 3 presents the energy spectrum of fragments having range greater than $40\,\mu$, and consisting mainly of Be nuclei (69 of 80 tracks are due to fragments having $Z = 40$). The angular distribution of multi-charged particles with respect to the direction of bombarding protons is given in Fig. 4. It does not vary noticeably for different kinetic energies of the emitted fragments. The angular distribution and energy spectrum were computed taking proper account of slowing down and absorption of particles in the polystyrene film. The method for computing corrections in track losses is given in the appendix.

The effective cross section for fragmentation of carbon nuclei by 660 Mev protons was also estimated. A repeated search for multi-charged particles in the same plate was carried out to verify scanning effectiveness and revealed that about 5% of the tracks are lost during scanning. This scanning effectiveness remained practically the same for plates exposed to different intensity flux. Background of isolated fragment tracks not formed in the carbon carrying film was measured by scanning control plates exposed under identical conditions though without the film. The background accounted for less than 10%. The proton flux was determined from the number of stars formed with emulsion nuclei in the same plate. The cross section for star formation was taken as equal to 1060 millibarns.[6] In so doing, account was taken of the lesser effectiveness of star counting for stars with small number of rays. The computation of omissions of stars with few rays was carried out according to the data of Bernardini et al.[7] The cross section for fragmentation of carbon nuclei was found to be 1.4 ± 0.5 millibarns. The uncertainty includes statistical error and uncertainty in flux measurement. This cross section corresponds to ejection of multi-charged particles having range greater than $20\,\mu$ and charge greater than 3. The effective cross section for emission of Li_3^8 nuclei (for $E > 10$ Mev) equals $(5 \pm 2) \times 10^{-29}\ cm^2$.

The present experimental results are in satisfactory agreement with the results of Lozhkin and Perfilov.[1] We can therefore assert that the identification of stars with fragments by the presence of nuclear recoil tracks assumed in reference 1 is a good approximation and does not lead to serious errors, at least for disintegration of nuclei by protons of 600 to 700 Mev energy.

To obtain the total yield curve for all the particles emitted from light nuclei during the cascade stage of a disintegration process, we have made use of the data of Serebrennikov[8] who analyzed stars produced by 660-Mev protons in C, O, N nuclei in a gelatin emulsion. Figure 5 shows, on a semi-logarithmic scale, points calculated from the data of reference 8 and of the present investi-

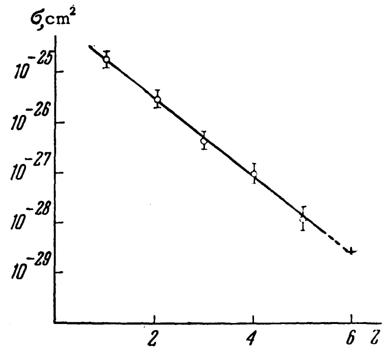

FIG. 5. Cross section for ejection of cascade particles from carbon nuclei for an incident-proton energy of 660 Mev. The particle charge is plotted along the abscissa; the effective cross section is plotted along the ordinate on a semi-logarithmic scale. The points for Z = 1 to 3 were obtained from reference 8. The cross indicates the value of the cross section for ejection of carbon nuclei, obtained by extrapolation of the experimental straight line.

gation. It is interesting to extend the straight line going through these points to a value of Z = 6. Such an extrapolation yields a cross section for the ejection of carbon nuclei with range greater than $40\,\mu$, equal to $\sim 3 \times 10^{-30}$ cm^2/sterad, and which may be considered as the elastic (or quasi-elastic) scattering cross section for protons against carbon nuclei in an angular interval of 60 to 180° in the laboratory system.* This value is not in disagreement with the results of reference 9, which gives $\sim 10^{-33}$ cm^2/sterad as the upper limit of the elastic scattering cross section of 660-Mev protons at an angle of $\sim 180°$.

The total cross section for ejection from C nuclei of multi-charged particles having $Z \geq 3$ and range $> 20\,\mu$ (which corresponds to a kinetic energy > 1 or 2 Mev per nucleon) is close to 4 mbn.

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APPENDIX

The transition from experimentally obtained values of angular or energetic distribution of fragments ejected from a layer of thickness a can be carried out as follows.

Assume that the particles are uniformly created throughout the film and are characterized by a distribution $N(\theta, R)$, where R is their range and θ the angle which their track froms with the bombarding beam (which is perpendicular to the surface of the emulsion). Then the number of fragments emitted into a unit solid angle, created within the layer $(t, t+dt)$ and having a range from ρ to $\rho + d\rho$ in emulsion at an ejection angle θ, will be

$$N\left(\theta, \rho + \frac{t}{\cos\theta}\right)\frac{dt}{a}\,d\rho, \qquad (1)$$

where we assume for simplicity that the stopping powers of the emulsion and the film are the same. (This limitation is easily removed by introducing into ρ a coefficient that accounts for the different stopping powers of polystyrene and the emulsion.) Integrating (1) with respect to t, we get

$$\frac{1}{a}\left[\int_0^a N\left(\theta, \rho + \frac{t}{\cos\theta}\right)dt\right]d\rho = n(\theta, \rho)\,d\rho; \qquad (2)$$

$n(\theta, \rho)$ is known from experiments on the angle and range distribution of particles in emulsion. The integral equation (2) may be solved by differentiation with respect to ρ:

$$\frac{\cos\theta}{a}\left[N\left(\theta, \rho + \frac{a}{\cos\theta}\right) - N(\theta, \rho)\right] = \frac{\partial n(\theta, \rho)}{\partial\rho}. \qquad (3)$$

*Not a single case of ejection of a sextuply-charged ion was recorded in our experiment.

We impose an obvious physical condition on the function $N(\theta, R)$: at sufficiently large values of R the function must reduce to zero.

Adding to (3) the system of equations

$$\frac{\cos\theta}{a}\left[N(\theta, \rho_{k+1}) - N(\theta, \rho_k)\right] = \frac{\partial n(\theta; \rho_k)}{\partial\rho}, \qquad (4)$$

where $\rho_k = \rho + ka/\cos\theta$ $(k = 0, 1, 2, \ldots)$, we obtain

$$N(\theta, \rho) = -\frac{a}{\cos\theta}\sum_{k=0}^{\infty}\frac{\partial n(\theta, \rho_k)}{\partial\rho}. \qquad (5)$$

The angular distribution of particles will have the following form

$$N(\theta) = \int_{R_{min}}^{R_{max}} N(\theta, R)\,dR = \frac{a}{\cos\theta}\sum_{k=0}^{\infty} n\left(\theta, \rho_{min} + k\frac{a}{\cos\theta}\right). \qquad (6)$$

R_{min} is here the minimum particle range that can be recorded within the photo emulsion, and R_{max} is the maximum range.

The energy spectrum of the particles is easily obtained from the range distribution of particles of a given charge. The latter in turn may be obtained from (5) by integrating over all angles θ from 0 to π. In practice the right-hand sides of (5) and (6) include only a finite number of terms based on the chosen condition at infinity (in R) for the function $N(\theta, R)$.

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