Title
INTERACTIONS OF 380-MEV ALPHA PARTICLES IN NUCLEAR TRACK EMULSION

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A study has been made of stars produced by 380-Mev alpha particles in Ilford G. 5 emulsion. The mean free path for star production is $18.4 \pm 0.9$ cm. The number of prongs per star varies from one to eight. The average number of prongs per star is 3.3. The striking feature of these stars is stripping, or splitting of the incident alpha particle. This is evident in the large number of two-prong stars in which both prongs emerge with high energy at small angles to the beam direction; in the presence of one-prong stars, in which the single prong is a fast proton or deuteron emerging in nearly the forward direction; and in the very narrow angular distribution of the fast prongs.

The star prongs have been divided into two groups, one group consisting almost entirely of cascade prongs, and the other consisting predominantly of evaporation prongs. The properties of the two groups of prongs are examined. It is found that the excitation produced by alpha particles is similar to that produced by protons of the same energy, but the cascade differs in important respects.

By observing the stars with prongs of energy lower than is necessary to escape the barrier of a heavy nucleus, one can identify 27 percent of the stars as originating in light nuclei. This places a lower limit on the number of events occurring in the gelatin.
INTERACTIONS OF 380-MEV ALPHA PARTICLES IN NUCLEAR TRACK EMULSION
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I. INTRODUCTION; STAR-PRODUCTION PROCESSES

The interaction between a nucleon or light nucleus of a few hundred Mev energy and a complex nucleus is generally believed to proceed in two steps known as the cascade and the evaporation processes. The initial stage lasts probably less than 5x10^-22 second, and consists of nucleon-nucleon collisions violent enough so that one or both colliding nucleons are projected from the nucleus, generally in the forward hemisphere. This may be complicated by the escaping nucleons' "picking up" other nucleons in traversing the distance to the edge of the nucleus. There appears also to be the possibility of a collision between a nucleon and a group of nucleons existing as an instantaneous substructure in the nucleus.

After the initial stage of the disintegration is over, the nucleus will often still contain energy of excitation sufficient for the evaporation process to take place. This consists of the slow emission of both charged and uncharged particles from the nucleus. The amount of the excitation should depend on the bombarding energy, and probably also on the bombarding particle.

Alpha-particle stars might be expected to resemble somewhat those produced by protons of the same energy. Throughout this paper, the study of Bernardini et al. on stars formed by protons of 350 to 400 Mev will be compared with the results reported here. Some striking differences are observed, which arise from the fact that in the cascade stage of the reaction an important process occurs in the alpha-particle stars that is not found with protons. It was observed by W. H. Barkas that often the alpha particle strips or breaks into fragments, thus contributing another component to the cascade. This observation suggested that the alpha-particle stars merited a detailed investigation, both to study this effect and to observe other aspects of the high-energy disintegration process.

The mean free path in emulsion for nuclear interactions of the alpha particle is expected to be less than that of a proton of the same energy. The following considerations tend to this conclusion: (a) The greater size of the
alpha particle and the possibility of electrostatic disintegration of the alpha particle should increase the interaction cross section above that observed for protons. (b) The light elements, which are partially transparent to a proton at 350 to 400 Mev, must not be appreciably so for a 380-Mev alpha particle, which consists of four nucleons, each of nominal energy 95 Mev. The probability of an interaction is raised both by the number of particles and by the fact that the nucleon-nucleon cross sections are larger at 95 Mev than at higher energies. In addition, the finite size of the alpha particle adds relatively more to the geometric cross section of the light elements than to heavy elements, so that stars from light elements should be found with greater abundance, both relative to silver bromide stars and in absolute number among alpha stars than among proton stars.

The interactions of fast alpha particles with the nuclei in photographic emulsions were first studied by the late Eugene Gardner, who exposed Eastman NTA plates to beams of alpha particles accelerated by the 184-inch cyclotron to 50, 95, 130, 170, and 210 Mev. Gardner had envisioned extending the study to 380-Mev alpha particles, and intended using electron-sensitive emulsions, because the fast prongs were not visible in the NTA emulsion. The work reported here was carried out in much the way Gardner had anticipated.

II. MEASUREMENT OF MEAN FREE PATH

For this study a 400-micron Ilford G.5 plate was exposed in the external 380-Mev alpha-particle beam. In the area scanned, the linear density of alpha-particle tracks was \((2.92 \pm 0.036) \times 10^3\) per cm. The plates were exposed so that the alpha particles entered the plate with a dip angle of only 1.5°. The length of alpha-particle track was therefore \(2.92 \times 10^3\) cm per cm². By area scanning, one can find a mean free path upon dividing this length by the number of stars found per square centimeter. A total of 1250 stars was found by area scanning with a 53x oil-immersion objective and 5x oculars. This number of stars was corrected for the loss of efficiency in finding one, two, and three-prong stars. Beam-particle tracks were followed in order to find stars, and it was determined from a sample of 70 stars that the area scanning was only 50 percent efficient for one-prong stars; 82 percent efficient for two-prong stars, and 92 percent efficient for three-prong stars. No larger stars were missed in the scanning. The over-all efficiency was 90 percent. No examples were found in this study of interactions in which no charged particles
were emitted from the collision. By close examination of events under high magnification, a number of neutron-induced stars were eliminated as well as a number of cases in which crossing and stopping tracks merely appeared to be stars when seen under low power. The corrected mean free path was $18.4 \pm 0.9$ cm. Elastic scattering events are not included in this figure. Gardner's value of 96 cm at 210 Mev is surely too high, probably in part because his insensitive emulsions did not record energetic protons. Consequently he was unable to recognize stars that consisted entirely of cascade protons. The mean free path can be calculated if one assumes that the alpha-particle radius is to be added to the nuclear radius to obtain an effective geometrical cross section. Putting the nuclear radius equal to $r_0 A^{1/3}$, one obtains agreement with the measured mean free path if $r_0$ is $1.23 \times 10^{-13}$ cm. This appears reasonable.

III. CHARACTERISTICS OF STARS AND PRONGS

A. Total Prong Spectrum

An initial classification of each star of a group of 281 studied under high magnification (97x oil objectives and 10x ocular) was made on the basis of the total number of prongs present. Following Hodgson, a prong of less than 4 microns was not counted as a genuine prong, unless the presence of other short prongs showed that the star originated in a light nucleus. (See section IV.) In the frequency distribution shown as curve a in Fig. 1, the correction for scanning efficiency mentioned above has been applied. The average number of prongs per star is 3.3. No slow mesons were observed, nor were any "hammer tracks" of Li$^8$, B$^8$, or Li$^9$ seen.

B. Analysis of Prongs

The prongs of the stars in the area selected for intensive study were examined to determine their mode of emission. The criteria used to separate the cascade from the evaporation prongs are the result of work by Bailey, who has found that when silver is bombarded with alpha particles the evaporation protons emitted in the forward hemisphere with energy greater than 22 Mev constitute less than five percent of the protons emitted. He finds similarly that in the backward hemisphere, evaporation protons with energy greater than 20 Mev are present with an abundance of less than 0.2 percent. Singly charged particles, emitted either forward or backward, with grain densities lower than those corresponding to the energy limits quoted above, were classified as cascade
particles. Only eight were found in the backward hemisphere. Particles heavier than protons were also classified as cascade particles if their energies could be shown to be higher than limits similarly used for protons. A considerable number of cascade particles are not identified by this procedure, but 82 percent of the stars show at least one cascade particle and 21.8 percent consist entirely of cascade prongs. Figure 2B shows the angular distribution (projected onto the plane of the emulsion) of 427 identified cascade prongs. The peaking forward is very pronounced: the ratio of the number of prongs in the forward hemisphere to the number in the backward hemisphere is $419/8$, and three-fourths of the prongs are emitted within $30^\circ$ of the forward direction. The distribution is considerably more peaked than that found for gray and sparse black prongs in the proton stars studied by Bernardini et al., and indicates an important contribution to the cascade from the fragmentation of the alpha particle.

Figure 2A shows the angular distribution of "black prongs." The ratio of the number of prongs in the forward hemisphere to those in the backward hemisphere is 2.4:1. If the black prongs were all emitted by evaporation, their angular distribution would be isotropic in the rest frame of the emitting nucleus. Any forward excess observed in the evaporation spectrum would be due to the velocity of the parent nucleus in the laboratory system. This cannot account for the large excess of black prongs in the forward direction. Unfortunately, the separation criteria allow inclusion among the black prongs of low-energy cascade protons and of heavier cascade particles, whose higher ionization makes them impossible to identify if they remain in the emulsion only a short distance.

The ratio of the number of prongs in the distribution of Fig. 2A to that in Fig. 2B is an upper limit for the ratio of the number of prongs emitted by evaporation to the number emitted by cascade. This ratio is $1.57 \pm 0.10$ black prongs per identifiable cascade prong.

The frequency distribution of the number of black prongs per star as a function of the number of cascade prongs per star is shown in Fig. 3. Figure 3A shows the prong spectrum of stars with no identifiable cascade prongs. Figures 3B, C, and D show the black prong spectra for stars with one, two, and three cascade prongs, respectively. Not shown in these figures is a single star with no black prongs but with four cascade prongs. Figure 3 illustrates the decrease in the cutoff number of black prongs, from 8, through 7, 5, and 4,
to zero for stars with one, two, three, and four cascade prongs respectively. This shows clearly the decrease in energy left available in the nucleus for the evaporation process as more of the original alpha-particle energy is carried away by cascade prongs. This agrees with the result of Bernardini et al.\(^1\) that the average energy transfer to the nucleus per black prong is 35 to 50 Mev.

Figure 3C reveals a striking difference between stars formed by alpha particles and stars formed by nucleons. This is the large number of stars consisting entirely of two cascade prongs. These appear to be disintegrations of the alpha particle, but in 30 percent of these stars, one of the prongs was a fast, heavy fragment, the charge of which often appeared to exceed two.

Another difference between alpha stars and proton stars is found in the angular distribution of the cascade prongs. As shown in Fig. 2A, 63 percent of the cascade particles are emitted within 20° of the beam direction, whereas under proton bombardment only 31 percent are found in this interval. Part of this effect must be attributed to the stripping of the alpha particle. It must also be remembered, however, that the alpha particle is moving so slowly that only protons ejected well forward in nucleon-nucleon collisions are likely to be energetic enough to be classified as cascade particles.

IV. INTERACTIONS IN LIGHT NUCLEI

A lower limit on the number of stars that result from interactions with the light nuclei in the emulsion can be computed by noting the stars that have prongs of energy too low to escape the potential barrier of a silver or bromine nucleus. The ranges corresponding to these energies are 40 microns for alpha particles and 150 microns for protons. These criteria (which have been applied by many authors) have been confirmed recently by Bailey,\(^5\) who has measured the emission spectra of charged particles from pure-element targets. At least one such low-energy prong has been observed in 27 percent of the stars analyzed. One may compute the fraction of stars to be expected in the carbon, nitrogen, and oxygen of the emulsion by using the same assumptions as employed in calculating the mean free path. Such a calculation indicates that 37 percent of the stars are from light elements. This is a reasonable agreement, since it is hardly to be expected that all the light-element stars contain short prongs.

The frequency distribution of the total number of prongs per star for the identified light-element stars is shown as curve B in Fig. 1. The average
number of prongs per star is 4.4. This indicates that when an alpha particle disintegrates a light nucleus usually nothing remains but hydrogen and helium isotopes. The distribution of the number of black prongs for the stars from light nuclei is shown in Fig. 4. The average number of black prongs per star is 3.23.

These results differ in two ways from those for proton stars. Bernardini et al. found that the stars formed in the gelatin were predominantly "small." (They define a "small star" as a star with fewer than 5 black prongs.) In addition they found that only a few of the total number of large stars occurred in light nuclei. In this study about 15 percent of the light-element stars have five or more black prongs, and at least two thirds of all such stars originate in the gelatin.

The angular distribution of the prongs with energy above 22 Mev from light nuclei is shown in Fig. 5B. Figure 5A shows the angular distribution of the black prongs from the identified light nuclei. The distribution in Fig. 5A is more isotropic than the angular distribution of black prongs from all the stars. The ratio of the number of prongs emitted in the forward hemisphere to those emitted in the backward hemisphere is 2.04.

One must remember that these stars are probably not completely typical of all light-element stars. The separation criterion employed favors recognition of stars with a large number of prongs and stars with prongs emitted in the backward hemisphere. One can see that if the excitation energy imparted to the nucleus is divided among many emitted particles, the chance of finding a low-energy prong is greatly increased. Hence stars with many prongs will more often reveal their origin from a light element. Stars with prongs emitted in the backward hemisphere will have the prong velocity in the laboratory system reduced by the center-of-mass motion of the emitting nucleus. These prongs will appear less energetic in the emulsion and facilitate recognition of their parent nucleus, while particles emitted in the forward hemisphere will appear more energetic in the laboratory system and mask their origin.

Three stars were observed in which two heavily ionizing, very short prongs, i.e., range 1 to 3 microns, emerge at 180° to each other, appearing to be fission products of the residual nucleus after the emission of the other prongs. These events have been classified as occurring in light nuclei, since the excitation energy imparted to the nucleus is not great enough to cause fission of silver or bromine.
Blau, Oliver, and Smith have studied the stars formed by 300-Mev neutrons in emulsion, using laminated emulsions to study separately the stars formed in the light nuclei of the emulsion. For comparison, the results of these authors are listed below the results of this experiment in Table I. Their value for the mean number of prongs per star is $4.4 \pm 0.2$, but it should be noted that this average is the mean prong number for neutron stars of three or more prongs.

V. ONE-PRONG STARS

The one-prong stars fall into two groups. Most of them have as their only prong a fast singly charged particle, energetic enough to be well into the class of prongs designated by cosmic ray physicists as "grey". Such an event is shown in Fig. 6. An attempt was made to identify these particles by multiple scattering and opacity measurements. Only three of these were found with enough track length in the emulsion to justify such measurements. The results of the measurements were reconcilable with either protons or deuterons, but no definite identification could be made. In addition to this type of one-prong star, four one-prong stars were seen in which the single prong was a multiply charged heavy fragment.

VI. SCATTERING

In addition to the star-production process, the alpha particles can interact with nuclei and merely scatter, either elastically or inelastically. The inelastic scattering events that could be detected by a change of grain density in the primary constituted the one-prong stars. Deflections greater than $4^\circ$ in the emulsion plane were recorded. In Table II is given the distribution of these projected deflection angles for tracks that did not show any change of grain density after scattering.

It is a pleasure to thank Dr. Walter Barkas and L. Evan Bailey for their constant help and encouragement during the preparation of this paper.

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Table I

Frequency distribution of the number of prongs per star for identified light element stars.

<table>
<thead>
<tr>
<th>Number of Prongs</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent abundance in 380 Mev Alpha Stars</td>
<td>0</td>
<td>0</td>
<td>10.4</td>
<td>17.7</td>
<td>25.0</td>
<td>25.0</td>
<td>13.5</td>
<td>7.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Percent abundance in 300 Mev Neutron Stars</td>
<td>2</td>
<td>0</td>
<td>--</td>
<td>24</td>
<td>38</td>
<td>21</td>
<td>11</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>
Table II

Frequency distribution of the projection in the plane of the emulsion of the scattering angle in elastic alpha-nuclear scattering.

<table>
<thead>
<tr>
<th>Projected scattering angle</th>
<th>0-4°</th>
<th>4°</th>
<th>5°</th>
<th>6°</th>
<th>7°</th>
<th>8°</th>
<th>9°</th>
<th>10°</th>
<th>11°</th>
<th>12°</th>
<th>13°</th>
<th>14°</th>
<th>15°</th>
<th>16°</th>
<th>17°</th>
<th>18°</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of events</td>
<td>not measured</td>
<td>10</td>
<td>10</td>
<td>2</td>
<td>6</td>
<td>3</td>
<td>4</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>
LEGENDS FOR FIGURES

Fig. 1. Frequency distribution of the number of prongs per star. Curve A applies to all stars. Curve B to stars known to originate in light nuclei.

Fig. 2. Angular distribution of "black" (curve A) and cascade (curve B) prongs. $\theta$ is the projection on the plane of the emulsion of the prong angle with respect to the beam direction.

Fig. 3. Frequency distribution of the number of black prongs per star as a function of the number of cascade prongs in the star. Curve A is for stars with no cascade prongs; Curve B for stars with one cascade prong; Curve C, stars with two cascade prongs; Curve D, stars with three cascade prongs.

Fig. 4. Frequency distribution of the number of black prongs per star for interactions in the light nuclei of the emulsion.

Fig. 5. Angular distribution of the prongs from stars known to originate in light nuclei. Curve A is the distribution for black prongs. Curve B is the distribution for prongs with energy greater than 22 Mev. $\theta$ is the projection on the plane of the emulsion of the prong angle with respect to the beam direction.

Fig. 6. Photomicrograph of a one prong star produced by alpha stripping. Note the change in grain density at the star origin, which indicates that the prong is singly charged.
REFERENCES

Figure 1

A

B

Number of Stars

Number of Prongs

0 1 2 3 4 5 6 7 8