OBSERVATION OF PARTICLES OF CHARGE $Z > 2$ IN DISINTEGRATIONS PRODUCED IN PHOTOGRAPHIC EMULSIONS BY HIGH-ENERGY NEUTRONS

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Experimental data are given on the observation of particles of charge $Z > 2$ in disintegrations produced in nuclear emulsion by high-energy neutrons. The neutrons had a broad energy distribution with a maximum in the 395 Mev region. Measurements have been made of the cross-section for the emission of heavy particles, their angular and energy distributions, and their charge distribution.

THE emission of heavy particles in nuclear interactions has been studied in many experiments both with cosmic rays and with artificially-accelerated particles.[1-6]. A considerable portion of the evidence concerning such heavy particles has been obtained from observations of the disintegration of nuclei in emulsions. Notwithstanding the known deficiencies of the photographic technique, it has been established by this method that the emission of heavy particles, especially those with high energies, occurs by a mechanism different from that connected with evaporation from an excited nucleus.

We present in this paper experimental data on particles with $Z > 2$, obtained from observations on nuclear disintegrations ("stars") produced by high energy neutrons in photographic emulsions.

A total of 10,037 stars were registered. The prongs of these stars included 19 hammer tracks, 16 pairs of α particles differing by very small angles, 2 emissions of 3 α particles within a narrow cone, 4 tracks of Be^8 decomposing in flight, 1 case of the emission of B^9 decomposing in flight, and 23 tracks of particles with $Z > 2$.

CONDITIONS OF THE EXPERIMENT AND THE METHOD OF CHARGE DETERMINATION

Photographic plates having emulsions of high sensitivity, 200 μ thick, were placed in a collimated neutron beam produced by 480 Mev protons bombarding a Be target. The energy distribution of the neutrons in the beam has been investigated in special experiments and has been reported previously.[7] The spectrum covers a large energy region and has a maximum in the region of 395 Mev. The scanning of the plates was carried out with a microscope having a magnification of 1350 ×.

The following were recorded: (1) all stars with more than 2 prongs, except those having centers at the surface of the glass or emulsion and those having a fast particle moving in the same direction as the neutron beam; (2) all single tracks that begin and end in the emulsion; (3) 2-prong stars (a) whose prongs make an angle less than 90° and (b) whose prongs differ in grain density.

The charge of the majority of particles was determined from the appearance of the disintegration (hammer tracks, pairs of α particles, etc.). In the remaining cases the charge Z was determined from measurements of the thinning-down length, L, using the relation $L = cZ^2$ (Ref. 8). The value $c = 0.8$ was found by counting the δ-electrons and measuring the length L of one of the fragments. It should be pointed out that this is not a very accurate way of determining charge and depends on the validity of the relation $L \sim Z^2$ and $c = $ constant for all the charges measured. However, over the narrow range of Z values studied here, there are apparently no significant deviations from these relations. [This method yielded values $Z = 4$ (5 tracks) and $Z = 5$ and 6, (13 tracks).]

The magnitude of L was measured with an ocular micrometer at a total magnification of 2025. The thickness of the track was measured over 2.26 μ of its length. Another method was also used for the determination of L in the cases of stars lying in the plane of the emulsion. For these tracks the variation of the thickness with length was taken from photometric measurements of the tracks. The two methods give commensurate results.

STAR CHARACTERISTICS

The table shows the principal characteristics of the stars formed by 390 Mev neutrons in emulsions. The prong distribution is based on the measurement of a thousand stars. The average number of prongs per star is 3.8. From the table it is evident that the distribution by prongs of stars with heavy particles ($Z > 2$) is similar to the distribution of stars without such particles.

No. of Prongs	1	2	3	4	5	6	7	8	9	10
No. of stars, %	4.2	11.6	30.2	27.0	16.5	6.6	2.5	0.9	0.5	—
No. of stars with particles with Z>2, %	2	9	23	16	7	4	3	—	—	1
No. of stars with particles with Z>2, %	3.1	14.0	35.2	24.8	10.7	6.2	4.6	—	—	1.4

Li^8 EMISSION

Hammer tracks having an electron decay can be produced by either Li^8 or B^8 decaying according to the schemes:

$$Li^8 \rightarrow Be^{8*} + e^- + \nu; \quad B^8 \rightarrow Be^{8*} + e^+ + \nu$$
$$\quad \hookrightarrow 2He^4 \qquad\qquad\qquad \hookrightarrow 2He^4$$

Owing to its larger charge, the emission of B^8 is less probable than the emission of Li^8. For this reason all the hammer tracks with electrons were assigned to Li^8. Those tracks which were not accompanied by electrons were attributed to Be^8 decaying, after slowing down, into two α particles. Since the efficiency of observation for electron tracks under our conditions depends on their orientation in the emulsion, it may be that a portion of the tracks assigned to Be^8 really belong to Li^8 whose decay electrons were missed. However, the measured efficiency for observing electron tracks, carried out by observations of the decay process $\mu^+ \rightarrow e^+ \ldots$, gave a high value for the efficiency, around 90%.

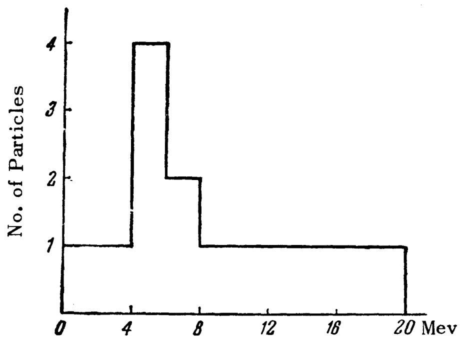

FIG. 1. Energy Distribution of Li^8

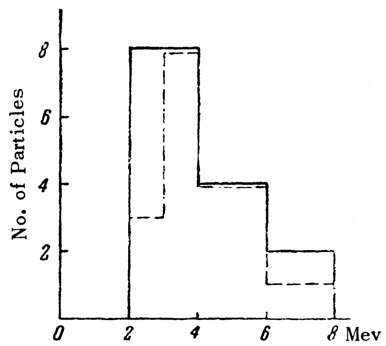

FIG. 2. Energy Distribution of α Particles. The dotted curve represents the data of Ref. 1

The kinetic energy of the Li nuclei was determined from a relation $R = f(E)$ for the emulsion, obtained from the range energy relation for α particles.[9] In this it was assumed* that $R(Li) = 8/9 \times R(\alpha)$.

The energy distribution of the Li^8 nuclei is shown in Fig. 1. From this it follows that Li^8 is most frequently emitted with an energy of ~ 5 Mev. Such a value for the most probable energy can be used as evidence that Li^8 in the majority of cases is emitted by light nuclei.[2] In support of this conclusion is also the fact that, with the exception of one case, all Li^8 nuclei observed are parts of stars having less than 5 prongs.

The energy spectrum of α particles found in the decay of Li^8 is shown in Fig. 2. The dotted curve is constructed from the data of Ref. 1. In spite of the relatively small number of cases found here, there is obviously agreement in the spectra. A similar agreement is also observed upon compariosn with the data of other authors.[9,11] The most probable energy of the α-particles is ~ 3 Mev and reflects the first excited state of Be^8 at 2.8 Mev.

In 14 out of 10,037 stars one of the prongs was found to be due to Li^8. The correction required to account for loss of Li^8 tracks from the emulsion is negligibly small, since all the tracks are much shorter than the emulsion thickness. Our value of the probability of the emission of Li^8 agrees satisfactorily with the value predicted by evaporation theory (~ 15 per 10^4 stars).[2]

*The energy of Li^8 obtained in this way agrees well with the value of the energy of Li as a function of its range, determined in the work of Ref. 10.

BERYLLIUM NUCLEI

It is known that the lifetime of a Be^8 nucleus in a ground state with even angular momentum is $\sim 10^{-16}$ sec. In this case the visible picture in a photographic plate will be 2 tracks of α particles coming out from the star center in the same direction. If the angular momentum of the Be^8 is large and odd and the emission of a γ-quantum requires a large change in angular momentum, the Be^8 lives a long time and stops in the emulsion prior to the radiation with subsequent decay into two α particles. In this case the emulsion shows a hammer track.

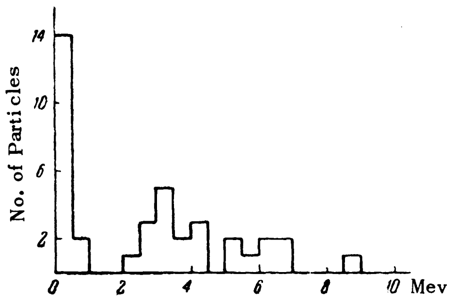

FIG. 3. Energy Distribution of α Particles from the Disintegration of Be^8

There were found 16 cases of the emission of two α particles within a narrow cone from the center of the star. The angle between such α particles was close to zero. The calculated probability of accidental occurrences that would lead to similar pairs of α particles is 5×10^{-4}. These pairs of α particles were attributed to decay of Be^8 which had not had time to leave a track in the emulsion. Knowing the energy of the α particles and the angle between them it is possible to find the energy of excitation ϵ of the Be^8 nucleus. The values of ϵ cluster about 85 kev, as expected from consideration of the mass defect of Be^8. Besides these 16 cases of α-particle pairs, there were found 5 hammer tracks attributable to the decay of Be^8 after stopping, and 4 cases of decay of Be^8 in flight. Evaluation of the lifetime of Be^8 based on measurements of the track lengths in these last four cases leads to $\tau = 10^{-12} - 10^{-13}$ sec.

Figure 3 shows the energy distribution of the α particles from the decay of Be^8. In the graph shows clearly the level corresponding to the ground state and that corresponding to a state of excitation of about 3 Mev. The distribution in the 4 — 7 Mev interval, in which there may be other excited states,[12,13,14] is less clearly defined. The absence here of detailed data concerning the highly excited states is due to the fact that, in these cases, the angle between the particles should be large and such pairs of α particles can thus be hidden among the α particles that have been emitted isotropically.*

PARTICLES WITH Z = 5 AND Z = 6

Sixteen cases were assigned to the general category of particles of charges 5 and 6. Thirteen had tracks with a sharply defined taper toward the end of the track. In two cases three α particles were observed to come out from the center of the star within a narrow angular cone. These could be considered as a disintegration of a carbon nucleus according to the scheme

$$C^{12} \rightarrow Be^{8*} + He^{8}$$
$$\quad\quad\quad \llcorner\!\rightarrow 2He^{4}$$

However, it is not possible to say definitely that a C^{12} nucleus is involved since the excitation of the C^{12} as measured by the α-particle ranges and by the angle between Be^8 and He^4 was smaller than the energy of the disintegration (7.4 Mev).

DISTRIBUTION BY CHARGES

We present below data on the distribution of the 65 particles by charges:

Z	3	4	5	6	6 — 9
Number of Particles	18	30	9	7	1

As in disintegrations produced by cosmic rays, the distribution shows a preponderance of particles with

*The question of the levels of Be^8 is still not settled. Some experiments confirm the presence in Be^8 of several excited states, others show only the known state at approximately 3 Mev.[15]

$Z = 4$. Out of 65 particles, 15 were β-active; 14 of these show hammer type tracks (Li^8), one particle with $Z = 5$ was possibly the B^9 nuclide emitting an electron.

DISTRIBUTION BY ENERGIES

The distribution according to energy, as determined for 63 particles, is shown in Fig. 4 (one α pair has not been included in this since the range of the α particles did not stay in the emulsion; a particle whose charge was not accurately determined has similarly been omitted). The Li energies were determined from the range vs. energy curve of Ref. 7. The energies of Be^8, in the cases where it was emitted in the form of two α particles, and the energies of C^{12} were measured as the sum of the energies of the α particles. In all other cases the energy was determined from the relation

$$E = 0.262\, M\, (R Z_{\mathrm{eff}}^2 / M)^{0.575}\ \mathrm{Mev},$$

which was obtained from the empirical relation

$$E = 0.262\, R^{0.575}\ \mathrm{Mev}$$

valid for protons.[16] Taking into account the fact that the average range of the particles being studied here is approximately equal to the tapering-down length and assuming that the nuclei lose their charge smoothly, the magnitude of Z_{eff} was taken as $Z/2$.*

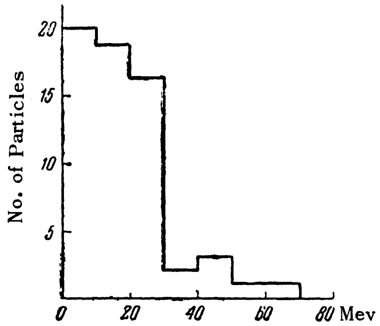

FIG. 4. Energy Distribution of Particles with $Z > 2$.

The great majority of the particles have energies less than the maximum electrostatic repulsion energy, which, for the particles considered, is about 30 Mev. Only very few particles are emitted with energies greater than this. Among these are four cases of the emission of Be^8 and one case of the emission of C^{12}. The analysis of the stars disclosed also very fast α particles having energies much higher than the Coulomb barrier of a heavy nucleus in the emulsion (30 α particles with energies greater than 60 Mev). Such α particles are easily distinguished from protons from the number of δ electrons in an equal region of the track. The α particle tracks had 5 — 7 δ electrons, the proton tracks 2 — 3 δ electrons. As has been shown earlier,[5,6] such cases of the emission of "higher than barrier" particles can hardly be explained as an evaporation from an excited nucleus. All the experimental data indicate that such particles arise in the primary interaction of the incident particle with the nucleus. However, the mechanism of their formation is still not clear.

ANGULAR DISTRIBUTION

From Fig. 5 it is evident that a considerable fraction of the heavy particles is emitted in the direction of motion of the incoming neutron. There are four times as many particles with $Z > 2$ in the forward hemisphere than in the backward one. An even greater anisotropy is observed for particles with $Z > 4$: out of 16 such particles, 15 go out into the forward hemisphere. Particles with one or two charges, however, have a significantly smaller anisotropy: only about twice as many of these are emitted in the forward hemisphere than in the backward one.

PRODUCTION CROSS-SECTIONS

The absolute cross-section for the emission of particles with charge $Z > 2$ was found, using the measured cross-section for star production, as determined in the same experiment. The number of neutrons passing through the photoemulsion during the time of irradiation was measured by counting the recoil protons with telescopes consisting of three proportional counters. The targets through which the neutron beam passed before impinging on the photographic plates were polyethlene and graphite. In order to determine the fraction in the beam of fast and slow neutrons of significantly different n–p scattering cross-sections, an absorber was placed before the third counter. This stopped the protons coming from neutrons having an energy less than 245 Mev.

*The energies calculated in these situations for the fragments agree satisfactorily with the values obtained for the same R, Z, and M in Ref. 8.

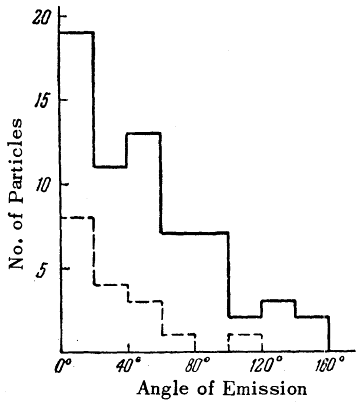

FIG. 5. Angular Distribution of Particles with Various Charges: Solid curve — Particles with $Z > 2$; dashed curve — Particles with $Z > 4$.

Using the values of the n–p scattering cross sections for the two energy groups, we found that a cross-section of $(0.43 \pm 0.2) \times 10^{-24}\,\mathrm{cm}^2$ for star production in the photographic plate for neutrons having the energy spectrum reported in Ref. 7. Using this value, the cross-section for the production of particles with $Z > 2$ was found to be $(2.8 \pm 1.4) \times 10^{-27}\,\mathrm{cm}^2$. The cross-sections for the emission Li^8 and Be^8 nuclei are $(0.8 \pm 0.4) \times 10^{-27}\,\mathrm{cm}^2$ and $(1.3 \pm 0.6) \times 10^{-27}\,\mathrm{cm}^2$ respectively.

The value of the cross section for the emission of Li^8 obtained here differs very little from the corresponding cross section found for the interaction of 340 Mev protons with carbon and nitrogen,[3] and from the cross section for the emission of Li^8 in the bombardment of the light nuclei of emulsion with 170 Mev protons.[1]

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