Disintegration of Light Nuclei by $\sigma$-Meson Capture

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$\sigma$-stars in photographic plates are classified into those originated from heavy and light nuclei. The branching ratio of disintegration modes, the $\alpha:p$ ratio, and the energy distribution of emitted particles are measured for light stars. Following characteristic features of light stars are ascertained; 1) the large prong number, 2) the large $\alpha:p$ ratio, 3) the low kinetic energy of emitted particles, and 4) the frequent emission of heavy fragments. The disintegration of $C^9$ into two $\alpha$-particles and a proton are studied in detail, and the possible emission of $Be^8$ nuclei is discussed. It turns out to be the main disintegration mode, that the rest energy of $\sigma$-meson is primarily shared among only a few member of nucleons and the residual part remains in a similar to the excited levels appeared in low energy reactions.

§ 1. Introduction

Since the discovery of two mesons, many authors have investigated the $\sigma$-stars in detail. Through the works of Perkins¹) and Menon, Muirhead and Rochat²), we know that the general features of stars from heavy nuclei can satisfactorily be understood by the evaporation theory. While, for $\sigma$-stars from light nuclei, our knowledge is left rather obscure.

We have observed 93 light stars out of total 200 $\alpha$-stars in Eastman NTA emulsion, which was supplied by the Radiation Laboratory of Berkeley. The branching ratio for various disintegration modes, and the energy distribution of emitted particles were measured. The emission of $Be^8$ nuclei is examined for ten favourable cases among carbon stars and for further nine examples found in another plate, Ilford C2. A possible interpretation will be given, referring to experimental data on other reactions of light nuclei.

§ 2. Classification of $\sigma$-stars

Various methods for the identification of light and heavy stars were proposed by Perkins³) and Heidemann and Leprince-Ringuet⁴) and others. Here, we adopt similar criteria as were used by Menon, Muirhead and Rochat⁵). They are;

1) If it is accompanied by a slow electron, it is a heavy star.
2) If it has a blob, it is a heavy star.
3) If it has a recoil track longer than $3\mu$ or two or more short tracks, it is a light star.
4) If it has a particle of sufficiently low energy (proton of \( \lesssim 4 \) MeV and \( \alpha \)-particle of \( \lesssim 9 \) MeV), it is a light star.

5) If the total charge of a star is definitely \( \leq 4e \), it is a heavy star.

Out of total 200 \( \sigma \)-stars with any prong, we were able to identify 93 stars as light and 78 as heavy. Though remaining 29 stars were left undetermined, a considerable part of them could be heavy stars on account of their \( \alpha: \beta \) ratio.

We define the tracks longer than 5\( \mu \) as prongs, and their prong number distributions are shown in the following table. This distribution is in agreement with that obtained by other authors.

<table>
<thead>
<tr>
<th>No. of prongs</th>
<th>Light stars</th>
<th>Heavy stars</th>
<th>Undetermined</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18</td>
<td>50</td>
<td>12</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>20</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>14</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>total</td>
<td>93</td>
<td>78</td>
<td>29</td>
</tr>
</tbody>
</table>

\[
\text{percentage: } 46.5 \pm 5.8 \% \quad 39.0 \pm 5.8 \% \quad 14.5 \pm 4.9 \%
\]

\[\text{No. of prongs: } 80 \quad 56 \quad 43 \quad 19 \quad 2 \quad 200\]

\[
\text{percentage: } 40.0 \pm 5.8 \% \quad 28.0 \pm 4.8 \% \quad 21.5 \pm 4.3 \% \quad 9.5 \pm 2.8 \% \quad 1.0 \pm 0.6 \%
\]

§ 3. Some characters of light stars

Tracks longer than 10\( \mu \) are identified by inspection as protons (including deuterons and tritons), \( \alpha \)-particles and heavy fragments, whereas some vertical tracks are left undeter-

<table>
<thead>
<tr>
<th>Disintegration Mode</th>
<th>Certain</th>
<th>Number of stars</th>
<th>Total</th>
<th>Percentage</th>
</tr>
</thead>
</table>
| 1\( \rho \)        | 2       | 0               | 2     | 2.2 \( \pm 4.3 \) \%  
| 2                  | 17      | 0               | 17    | 18.3 \( \pm 7.4 \) \%  
| 3                  | 10      | 1               | 11    | 11.8 \( \pm 6.9 \) \%  
| 4                  | 12      | 0               | 12    | 12.9 \( \pm 7.0 \) \%  
| 5                  | 9       | 6               | 15    | 16.1 \( \pm 7.2 \) \%  
| 6                  | 4       | 5               | 9     | 9.7 \( \pm 6.2 \) \%   
| 7                  | 0       | 7               | 7     | 7.5 \( \pm 6.0 \) \%   
| 8                  | 3       | 4               | 7     | 7.5 \( \pm 6.0 \) \%   
| 9                  | 3       | 3               | 6     | 6.5 \( \pm 3.7 \) \%   
| 10                 | 1       | 0               | 1     | 1.1 \( \pm 0.5 \) \%   
| Undetermined       |         |                 | 6     |             |
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mined. Among tracks shorter than 10$\mu$ they are attributed to heavy fragments, as far as the conservation of charge compells it. Other short tracks are tentatively assigned as "probable" $\alpha$'s.

A) The classification of disintegration modes of 93 light stars are given in Table 2. $p$, $\alpha$ and $f$ denote proton, $\alpha$-particle and heavy fragment, respectively.

One can suppose that some "probable" $\alpha$'s are also heavy fragments. Therefore, an unobserved disintegration mode, such as $2f$ may be included in "probable" $1\alpha1f$, and $1\rho1\alpha1f$ in "probable" $1\rho2\alpha$, and so on. While we can show that there are few protons in "probable" $\alpha$'s, extrapolating the range distribution for protons.

B) The $\alpha$-$p$ ratio is found to be

$$\frac{\alpha}{p}=\frac{106}{103}=1.03 \pm 0.20,$$

including "probable" $\alpha$'s. We can in a less ambiguous way obtain the ratio of the number of $\alpha$-particles and heavy fragments to that of protons, i.e.,

$$\frac{(\alpha+f)}{p}=\frac{148}{103}=1.44 \pm 0.26.$$

These figures should be compared with the results of Menon, Muirhead and Rochat, who obtained $\frac{\alpha}{p}=263/271$ and $\frac{(\alpha+f)}{p}=1.55 \pm 0.20$.

C) The range distributions are obtained for stopped protons and $\alpha$-particles. We get their energy distributions, correcting for the fraction of escaping from the emulsion by geometrical considerations. They are shown in Fig. 1 and 2. The range distribution of heavy fragments are also shown in Fig. 3.

Fig. 1. Energy distribution of protons.

Fig. 2. Energy distribution of $\alpha$-particles. The broken line indicates the result excluding "probable" $\alpha$'s. The solid curve is an approximate analytic one, i.e.,

$$\sqrt{E} \exp\left(-\frac{E}{\epsilon}\right)$$

with $\epsilon=4.8$ Mev.

Fig. 3. Range distribution of heavy fragments.
§ 4. **Be⁸ emission from carbon star**

In some case such as $1\beta 2\alpha$ and $3\alpha$, we can make identification of the disintegration of particular nuclei. We examined in detail the disintegration of C¹⁸ nucleus into $1\beta 2\alpha$.

We picked up ten favorable cases, where emitted two $\alpha$-particles stop in emulsion. We can measure the range, i.e., the energy of two $\alpha$-particles and the angle between them. Now, we calculate the energies of the relative and the center of mass motion of them. Table 3 shows the results for ten cases.

**Table 3. 1$\beta 2\alpha$ Stars in NTA Emulsion.**

<table>
<thead>
<tr>
<th>Star No.</th>
<th>Energy of $\alpha$-particles (Mev)</th>
<th>Cosine of angle between them</th>
<th>Energy of center of mass motion (Mev)</th>
<th>Energy of relative motion (Mev)</th>
</tr>
</thead>
<tbody>
<tr>
<td>186</td>
<td>4.0</td>
<td>3.9</td>
<td>7.8</td>
<td>0.1</td>
</tr>
<tr>
<td>70</td>
<td>8.95</td>
<td>6.3</td>
<td>12.4</td>
<td>2.85</td>
</tr>
<tr>
<td>118</td>
<td>7.4</td>
<td>1.6*</td>
<td>6.0</td>
<td>2.95</td>
</tr>
<tr>
<td>115</td>
<td>5.7</td>
<td>1.4*</td>
<td>3.8</td>
<td>3.3</td>
</tr>
<tr>
<td>65</td>
<td>8.2</td>
<td>3.7</td>
<td>5.0</td>
<td>6.9</td>
</tr>
<tr>
<td>201</td>
<td>4.4</td>
<td>3.5</td>
<td>0.4</td>
<td>7.5</td>
</tr>
<tr>
<td>98</td>
<td>9.1</td>
<td>3.5</td>
<td>1.6</td>
<td>9.3</td>
</tr>
<tr>
<td>55</td>
<td>9.4</td>
<td>5.0</td>
<td>2.7</td>
<td>11.7</td>
</tr>
<tr>
<td>126</td>
<td>16.1</td>
<td>2.7</td>
<td>5.05</td>
<td>13.6</td>
</tr>
<tr>
<td>154</td>
<td>12.8</td>
<td>7.2</td>
<td>1.4</td>
<td>18.6</td>
</tr>
</tbody>
</table>

(* These are included in "probable" $\alpha$'s)

To obtain better statistics, we analyzed further nine $1\beta 2\alpha$ stars out of 200 $\alpha$-stars found in Ilford C2 emulsion, and the result is shown in Table 4.

**Table 4. 1$\beta 2\alpha$ Stars in C2 Emulsion.**

<table>
<thead>
<tr>
<th>Star No.</th>
<th>Energy of $\alpha$-particles (Mev)</th>
<th>Cosine of angle between them</th>
<th>Energy of center of mass motion (Mev)</th>
<th>Energy of relative motion (Mev)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1095</td>
<td>4.2</td>
<td>4.2</td>
<td>8.36</td>
<td>0.04</td>
</tr>
<tr>
<td>1073</td>
<td>6.0</td>
<td>0.8*</td>
<td>3.8</td>
<td>3.0</td>
</tr>
<tr>
<td>1087</td>
<td>2.5</td>
<td>2.3</td>
<td>0.6</td>
<td>4.2</td>
</tr>
<tr>
<td>1172</td>
<td>12.7</td>
<td>1.9*</td>
<td>7.7</td>
<td>6.9</td>
</tr>
<tr>
<td>1008</td>
<td>8.6</td>
<td>2.4</td>
<td>2.9</td>
<td>8.1</td>
</tr>
<tr>
<td>1096</td>
<td>10.2</td>
<td>0.8*</td>
<td>2.8</td>
<td>8.2</td>
</tr>
<tr>
<td>1040</td>
<td>8.7</td>
<td>1.9*</td>
<td>1.7</td>
<td>8.9</td>
</tr>
<tr>
<td>1075</td>
<td>9.0</td>
<td>4.4</td>
<td>0.7</td>
<td>12.7</td>
</tr>
<tr>
<td>1099</td>
<td>10.6</td>
<td>5.4</td>
<td>0.7</td>
<td>15.3</td>
</tr>
</tbody>
</table>

(* These are included in "probable" $\alpha$'s)

If one assumes that the two $\alpha$-particles are emitted in the form of unstable Be⁸ nuclei,
the energy of relative motion should be identified to a some known energy level of Be$^9$ nuclei. To see whether it be true or not, we made a possible correspondence, as shown in Fig. 4. We can find, in this figure, a well-known ground level and first excited one at 3 Mev.

![Distribution of energy of relative motion of two $\alpha$'s in carbon stars. The arrows indicate the known energy levels which disintegrate into two $\alpha$-particles].(Fig. 4)

Our measured values on the energy of relative motion have an error of at most 0.5 Mev in the most unfavourable cases, while only a few lowest excited energy levels of Be$^9$ nuclei are unambiguously established from experiments on artificial reactions. Therefore, the above assumption does not seem contradict with the experiments, especially in cases of the small energy of relative motion.

The energy of the center of mass motion should be compared with the kinetic energy of stable heavy fragments. The similarity of both energy distributions makes the assumption more plausible.

§ 5. Discussions

Light $\sigma$-stars have very different features from those of heavy ones. The remarkable points of the former case are;

1) Large prong number,
2) Large $\alpha$-$\beta$ ratio,
3) Low kinetic energy of emitted $\omega$-particles and protons,
4) Frequent emission of stable as well as unstable heavy fragments.

One may assume that most part of rest energy of $\omega$-meson is distributed among all nucleons and an equilibrium state is reached in some instance in the nucleus. This hypothesis, combining with the evaporation theory, can satisfactorily explain the main features of heavy $\sigma$-stars. But, when it is applied to light nuclei, we at once encounter serious difficulties. For example, the expected mean energy of emitted particles is much
smaller than the observed one. Therefore, we have to think that a $\sigma$-meson is absorbed by some small cluster of nucleons in nuclei, which Menon, Muirhead and Rochat named as "primary process". This primary process results in the emission of a few high energy nucleons, which easily escape from a nucleus due to its transparency. Then the rest part of the nucleus receives only a small disturbance, and it can be supposed to be similar to the excited states reached by low energy reactions.

The above consideration can schematically be understood in terms of the $\alpha$-particle model for light nuclei. In the case $^{12}$C, a $\sigma$-meson is absorbed by one $\alpha$-cluster in the nucleus, which is completely disrupted by this primary interaction. Due to this disturbance, the rest two $\alpha$-clusters are left behind in a state similar to an excited Be. Subsequently it disintegrates into two $\alpha$-particles or proton and Li, etc.

Menon, Muirhead and Rochat have found a few cases out of thousands stars, where the total rest energy seems to be completely disparted throughout the nucleus, though we have observed no such cases. Thus we may think that the aforesaid is the main disintegration mode of meson-absorbing nuclei.

It is regrettable that our knowledge on other high energy reactions of light nuclei is more obscure than this $\sigma$-star case. Gardner and Peterson observed the prong number distribution of stars induced by deuterons of $35\sim190$ Mev. We can suppose that these stars are mostly originated from light nuclei. They showed that the prong distribution does not vary with bombarding energy and is similar to that of light $\sigma$-stars.

Following our point of view, various high energy disintegration of light nuclei should have similar prong distribution, $\alpha$-$p$ ratio and energy distribution. The difference of kind of agent should appear only in primary interaction, i.e. in fast protons of stars.

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References
5) E. Gardner and V. Peterson, Phys. Rev. 75 (1949), 346.