Associated Production of $\Xi^-$ with Two $\theta^0$ Particles*

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(Received July 11, 1955)

A cosmic-ray event is described in which a negative cascade particle and two neutral heavy mesons appear to be produced in a single nuclear interaction above a cloud chamber. It is suggested that this event may be an example of the associated production of a $\Xi^-$ particle with two $\theta^0$ particles according to the scheme of Gell-Mann.

Experimental information concerning the associated production of unstable heavy particles was first obtained by Shutt and his collaborators at Brookhaven. Using a hydrogen diffusion chamber in the 1.37-Bev $\Xi^-$ beam, these researchers have found that neutral or charged hyperons may be produced with neutral or charged $K$-mesons.

Recent data have shown that associated production occurs to some extent in cloud chambers triggered on penetrating showers and in nuclear emulsions exposed to cosmic rays. Here again the evidence is that hyperons are produced associated with heavy mesons.

In the 48-inch magnet cloud chambers operating in Pasadena (Fig. 1), we have obtained a photograph showing four $V$ events (Fig. 2), all connected with a single penetrating shower origin. This event is produced by a primary particle of $>4$ Bev/c momentum and unknown sign of charge which enters from above and behind chamber 2. Only 6 mm above the top inside wall of chamber 3 the primary makes a high-energy nuclear interaction which produces the penetrating shower containing the four $V$-particles, all of which decay in chamber 3. There are no other tracks besides the primary in chambers 1 and 2, and all of the tracks in chambers 3 and 4 appear to result from the single interaction at the top of chamber 3.

In Fig. 3, the various decays are shown in an isometric projection of the tangents to the pertinent tracks at their decay points. All decay secondaries pass through the front of the apparatus except for FH and IK which travel down through chamber 4.

There are three $V^0$ decays, FGH, CDE, and IJK. The planes of both FGH and IJK pass through the origin within experimental error, the angles of noncoplanarity for O with respect to FGH and IJK being $2.8\pm 1.4^\circ$ and $0.5\pm 1.4^\circ$ respectively. Moreover, the

\[ \theta^0 \rightarrow \pi^+ + \pi^- + Q(\pi, \pi), \]

FGH gives

\[ Q(\pi, \pi) = 240 \pm 60 \text{ Mev} \]

from the measured momenta of the secondaries. The momentum of the positive secondary of IJK cannot be determined directly, but by assuming two-body decay and momentum balance we obtain from the momentum of the negative secondary

\[ Q(\pi, \pi) = 270 \pm 70 \text{ Mev}. \]

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Therefore, $FGH$ and $IJK$ are quite consistent with normal $\theta$ decay where $Q(\pi, \pi) = 214$ Mev.

The third $V^0$ decay, $CDE$, cannot be identified directly from the characteristics of its secondary tracks. However, the established coplanarity of this decay plane with the decay point of the $V^-$ particle suggests strongly that it is the secondary of the well-known $\Xi^-$ decay,

$$\Xi^- \rightarrow \Lambda^0 + \pi^- + Q(\Lambda^0, \pi),$$

and is thus a $\Lambda^0$ particle. The $Q(\Lambda^0, \pi)$ for the assumed $\Xi^-$ decay can be computed from the roughly measured momentum of the negative secondary, $AB$, and the geometry of the event. The result is

$$Q(\Lambda^0, \pi) = 95^{+100}_{-90} \text{ Mev},$$

which is consistent with previously measured values of $\sim 66$ Mev.

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Fig. 2. Cloud-chamber photograph of a penetrating shower which includes two $\theta$ decays ($FG - FH$ and $IJ - IK$) and one $\Xi^{-}$ decay ($OAB$) with its secondary $\Lambda^0$ ($CD - CE$).

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Table I. Basic data.

<table>
<thead>
<tr>
<th>Track</th>
<th>Charge</th>
<th>Measured momentum Mev/c</th>
<th>Estimated ionization times minimum</th>
<th>Estimated mass from ionization or momentum in mμ</th>
<th>l</th>
<th></th>
<th>m</th>
<th></th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>PO</td>
<td>?</td>
<td>&gt;4000</td>
<td>&lt;2</td>
<td>...</td>
<td>-0.0625</td>
<td>-0.0951</td>
<td>+0.2764</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OA</td>
<td>-</td>
<td>&gt;200</td>
<td>&lt;2</td>
<td>...</td>
<td>-0.0756</td>
<td>-0.0979</td>
<td>+0.2773</td>
<td></td>
<td></td>
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<tr>
<td>OP</td>
<td>0</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>-0.3889</td>
<td>-0.9160</td>
<td>-0.0994</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OI</td>
<td>0</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>0.0211</td>
<td>-0.9612</td>
<td>+0.2748</td>
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<td></td>
</tr>
<tr>
<td>AB</td>
<td>-</td>
<td>500±500</td>
<td>&lt;2</td>
<td>&lt;2000</td>
<td>+0.1489</td>
<td>-0.9165</td>
<td>+0.3714</td>
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<td></td>
</tr>
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<td>...</td>
<td>...</td>
<td>...</td>
<td>-0.1380</td>
<td>-0.9680</td>
<td>+0.2091</td>
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<tr>
<td>CD</td>
<td>-</td>
<td>&gt;180</td>
<td>&lt;2</td>
<td>...</td>
<td>-0.2222</td>
<td>-0.8716</td>
<td>+0.4368</td>
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<td></td>
</tr>
<tr>
<td>CE</td>
<td>+</td>
<td>&gt;180</td>
<td>&lt;2</td>
<td>...</td>
<td>-0.1116</td>
<td>-0.9835</td>
<td>+0.1282</td>
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<td></td>
</tr>
<tr>
<td>PG</td>
<td>0</td>
<td>520±150</td>
<td>&lt;2</td>
<td>&lt;1500</td>
<td>-0.5056</td>
<td>-0.7684</td>
<td>+0.3924</td>
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<td></td>
</tr>
<tr>
<td>FH</td>
<td>0</td>
<td>920±220</td>
<td>&lt;2</td>
<td>&lt;2800</td>
<td>-0.1992</td>
<td>-0.9759</td>
<td>-0.0895</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IJ</td>
<td>-</td>
<td>&gt;640</td>
<td>...</td>
<td>...</td>
<td>+0.0671</td>
<td>-0.9083</td>
<td>+0.4131</td>
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<td></td>
</tr>
<tr>
<td>IK</td>
<td>+</td>
<td>475±110</td>
<td>&lt;2</td>
<td>&lt;1500</td>
<td>-0.2139</td>
<td>-0.9696</td>
<td>-0.1190</td>
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</tbody>
</table>

* Errors in measurement of direction cosines are less than ±0.015 for l and less than ±0.04 for n.
* These values are determined for chamber 3 from curvature measurements in chamber 4 with correction for the lead and brass in between.

Table II. Numerical results for the decays of Fig. 3. The values for αμ are computed for the four γ-particle decays, ABC, CDE, FGH, and IJK from angles only. The values for ασ are computed from momentum measurements alone. The angle θγ is the total included angle between decay secondaries. The values of Pμ sinθγ listed in the fourth column must be less than 118 Mev/c for A decay, which is not the case for FGH and IJK. ABC and CDE appear to be members of a cascade event and are therefore interpreted as Ξ- and Λ° decays respectively. The noncoplanarities, δ, with assumed origins are all zero within experimental error. The Q value for FGH was obtained from θγ and the momenta of the secondaries. The Q values in column 7 for both ABC and IJK were obtained from θγ, the momentum of one measurable secondary in each case, and the transverse momentum about their lines of flight. The Q values in column 8 were obtained from the cascade relationship between ABC and CDE as described in the text.

<table>
<thead>
<tr>
<th>Decay plane</th>
<th>αμ</th>
<th>ασ</th>
<th>θγ degrees</th>
<th>Pμ sinθγ Mev/c</th>
<th>Interpretation</th>
<th>Noncoplanarity angle degrees</th>
<th>Q values from momenta and geometry Mev</th>
<th>Q values from cascade geometry Mev</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABC</td>
<td>+0.5 ±0.1</td>
<td>...</td>
<td>19.2±1</td>
<td>100±160</td>
<td>Ξ- decay</td>
<td>...</td>
<td>95±100</td>
<td>76±15</td>
</tr>
<tr>
<td>CDE</td>
<td>+0.5 ±0.3</td>
<td>...</td>
<td>20.6±2</td>
<td>&gt;61</td>
<td>Λ° decay</td>
<td>0.2±1.0</td>
<td>...</td>
<td>32±10</td>
</tr>
<tr>
<td>FGH</td>
<td>-0.13±0.05</td>
<td>-0.29±0.26</td>
<td>35.4±1</td>
<td>535±125</td>
<td>θγ decay</td>
<td>2.8±4</td>
<td>240±60</td>
<td>...</td>
</tr>
<tr>
<td>IJK</td>
<td>-0.46±0.08</td>
<td>&lt; -0.05</td>
<td>35.2±2</td>
<td>&gt;370</td>
<td>θγ decay</td>
<td>0.5±1.4</td>
<td>270±70</td>
<td>...</td>
</tr>
</tbody>
</table>

* αμ = sin(θ_-θμ)/sin(θ_+θμ) for ABC, and ασ = sin(θ_-θσ)/sin(θ_+θσ) for CDE, FGH, and IJK.
* ασ = (P^2 - P^2)/P^2.

The momentum of the assumed Λ° can be obtained from transverse momentum balance with AB, but a more precise value can be obtained from the geometry of the Ξ- decay if we assume the decay scheme

Ξ-→Λ°+π^-+66 Mev.

From the derived momentum of the Λ°(792±50 Mev) and its decay geometry, we obtain for

Λ°→p+π^-+Q(ρ,π)

a Q(ρ,π) value of 32±10 Mev in agreement with the known value of 37 Mev. Conversely, if we assume that CDE is indeed a 37-Mev Λ° decay, we may calculate the momentum of the Λ° from geometrical factors only. From this new Λ° momentum and the geometry of the Ξ- event, we obtain

Q(Λ°,π) = 76±15 Mev,

in good agreement with the known value. Therefore, the decay dynamics are completely consistent with the interpretation that CDE is the secondary Λ° of a Ξ- event OAB.

Since there is evidence of only one nuclear interaction which could produce these unstable particles, it appears that the Ξ- was very probably produced in association with two θγ particles. Such a process is in direct agreement with the ideas presented by Gell-Mann.

ACKNOWLEDGMENTS

The authors wish to acknowledge the assistance of E. W. Cowan, G. H. Trilling, V. A. J. Van Lint, C. A. Rouse, and A. A. Strassenburg in the construction and operation of the apparatus which detected this event.

Fig. 2. Cloud-chamber photograph of a penetrating shower which includes two $\Theta^0$ decays ($FG-FH$ and $IJ-IK$) and one $\Xi^-$ decay ($OAB$) with its secondary $\Lambda^0$ ($CD-CE$).