Associated Production of Σ^0 and $\theta_2{}^0$; Mass of the Σ^0*

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An event in which $\theta_2{}^0$ and Σ^0 production and decay are both observed, is described. This event yields a mass value for the Σ^0 and demonstrates the associated production of the $\theta_2{}^0$. Additional events yielding mass values of the Σ^0 are reported.

DURING the course of studying the production and decay of strange particles in a liquid hydrogen bubble chamber, we have observed a most unusual event. This event, an example of the reaction $\pi^-+p\rightarrow\Sigma^0+\theta^0$, has two features of exceptional interest.

(A) The θ^0 produced in this reaction is observed to decay via the *long-lived* $\theta_2{}^0$ decay mode first predicted by Pais and Gell-Mann.[1]

(B) The Σ^0 undergoes the decay $\Lambda^0+e^++e^-$, permitting an accurate measurement of the mass of the Σ^0 hyperon.

The above event occurred in a chamber 12 in. in diameter and 6 in. deep, filled with liquid hydrogen at a density of 0.06 g/cm³. The chamber was in a magnetic field of 13.1 kilogauss. The exposure was to a 950-Mev π^- beam at the Brookhaven National Laboratory Cosmotron.

Figure 1 is a photograph of the event. A π^- meson interacts at point A. Leaving the point of interaction are an electron and positron. Originating at point B and pointing to A is a V particle which is identified as a Λ^0 decay. Reconstruction in space of the Σ^0 decay permits us to predict the *vector* momentum of the θ^0 which was produced in the primary reaction. Upon examining the projected line of flight of the θ^0, we do indeed find a V at C. Both prongs of the V are on one side of the direction of flight so that it is clear that this V cannot arise from a two-particle decay. Furthermore, the elapsed time from production to decay is 10^{-9} second in the θ^0 rest frame. This is *ten* times the lifetime of the ordinary $\theta_1{}^0$, which decays into two pions. Measurement of the decay angles and momenta establish the decay mode as being consistent with either

$$\theta_2{}^0\rightarrow\pi^\pm+\mu^\mp+\nu,\quad\text{or}\quad\theta_2{}^0\rightarrow\pi^\pm+e^\mp+\nu.$$

Previously reported experiments[2,3] have established the existence of a neutral particle with a mass approximating that of the $\theta_1{}^0$, with three-particle decay modes including those mentioned above, and a lifetime of $\sim10^{-7}$ second. In these aspects this particle fits the picture of the $\theta_2{}^0$ drawn by Pais and Gell-Mann.[1] Furthermore, it has been shown[4] that approximately one-half of the θ^0's produced in association with conventional hyperons can reasonably be accounted for only if one assumes a long-lived decay mode with a lifetime $\geq3\times10^{-8}$ second. The event described herein is the first reported case where this long-lived decay mode is actually observed in association with a hyperon. As such, it provides one of the last remaining links in the verification of the theory of Pais and Gell-Mann. This is the only three-body θ^0 decay observed by us. In the same photographs we have seen 450 Λ^0 production events, with an average *potential* θ^0 *decay time* in the chamber of 5.5×10^{-10} sec in the θ^0 rest system. If one-half of the θ^0's decay in the three-particle modes with long lifetime ($\theta_2{}^0$), our single observation corresponds

Table I. Comparison of measured angles with angles expected for associated production and decay of Σ^0 and $\theta_2{}^0$.

Angle	Measured angle (degrees)	Expected angle[a] (degrees)
$\pi_{in}{}^--\theta^0$	31.0±1.0	30.8
$\pi_{in}{}^--\Lambda^0$	5.2±1.0[b]	5.4
$\pi_{in}{}^--e^+$	54.7±1.5	54.7
$\pi_{in}{}^--e^-$	61.5±1.0	61.5
Σ^0 (projected)	9.0±1.0	9.2
π^--p	62.5±4	61.5
Λ^0-p	6.9±0.4[c]	6.5
$\Lambda^0-\pi^-$	55.6±3.0[c]	55.0
θ^0-L^+	54.5±1.0	
θ^0-L^-	29.6±1.5	
L^+-L^-	61.3±1.5	

[a] Chosen so as to make consistent fit with known beam momentum of 1090 Mev/c.
[b] From measurements on π^- and p.
[c] Determined from total opening angle and measured moments.

Table II. Comparison of measured and expected momenta of decay products.

Track	Measured momentum (Mev/c)	Expected momentum (Mev/c)
p	717 ±30	740
π^-	105 ±10	103
e^-	95.4± 6.0	95.4
e^-	8.6± 0.5	8.6
L^+	195 ±10	...
L^-	80 ±12	...

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[1] A. Pais and M. Gell-Mann, Phys. Rev. **97**, 1387 (1955).

[2] Lande, Booth, Impeduglia, Lederman, and Chinowsky, Phys. Rev. **103**, 1901 (1956).

[3] Fry, Schneps, and Swami, Phys. Rev. **103**, 1904 (1956).

[4] Eisler, Plano, Samios, Schwartz, and Steinberger, Nuovo cimento **5**, 1700 (1957).

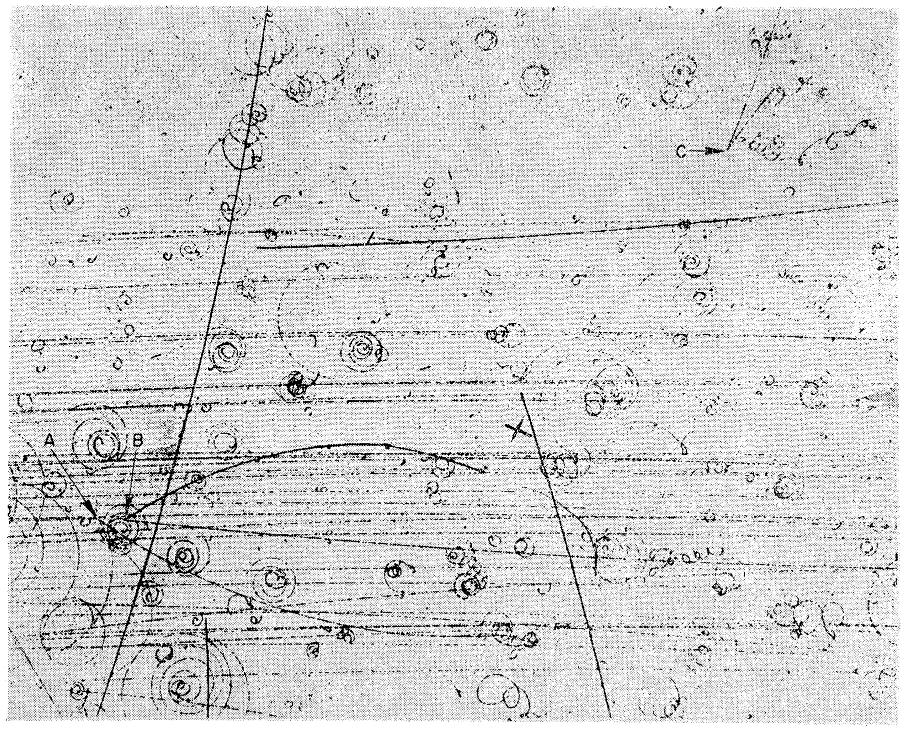

FIG. 1. Σ^0 and $\theta_2{}^0$ associated production and decay observed in a liquid hydrogen bubble chamber.

to a lifetime of $225\times5.5\times10^{-10}=1.2\times10^{-7}$ sec. This is quite in line with the lifetime of $(0.8\pm0.4)\times10^{-7}$ sec reported by Bardon *et al.*[5]

Details of the angle and momentum measurements of the complete event are given in Tables I and II. The π^- from the Λ^0 decays in flight at point D and its secondary μ^- stops in the glass. The electron from the μ^- decay re-enters the chamber. The momentum of the π^- is established from the range and emission angle of the secondary μ^-. All other momenta are obtained from curvature measurements.

Using the momenta of the Λ^0, e^+, and e^- and the angles between each of them and the projected Σ^0, we compute the Q of the reaction $\Sigma^0\rightarrow\Lambda^0+\gamma$. The Λ^0 momentum used was adjusted to provide the best fit to the known incoming-beam momentum (1090 ± 15 Mev/c). We obtain

$$Q=80\pm5 \text{ Mev}.$$

The error is due primarily to multiple scattering and secondarily to error in dip-angle measurement on the electron tracks.

TABLE III. Tabulation of Σ^0 decay Q values.

Event	Q (Mev)
1	70 ± 10
2	75 ± 12
3	82 ± 15
4	72 ± 12
5	82 ± 13
6	73 ± 16
7	76 ± 17

[5] Bardon, Chinowsky, Fuchs, Lande, and Lederman, Bull. Am. Phys. Soc. Ser. II, **3**, 24 (1958).

In addition to the above, we have observed seven other events each giving a Q value for the Σ^0 decay. The latter events were observed in a propane chamber, 12 in. in diameter and 8 in. deep in a magnetic field of 13.4 kilogauss. The measured Q values are listed in Table III. Each of these events was characterized by an observed decay of the Λ^0 and the conversion in the liquid of the γ. The first three events have been described previously.[6] In the case of the last four events, the Q is obtained by making use of the Λ^0 momentum, the γ momentum, and the angle between the Λ^0 and the γ.

Combining all events, we obtain

$$Q=77.4\pm3.5 \text{ Mev}.$$

This Q value may be combined with the measurements on the $\Sigma^- - \Sigma^0$ mass difference.[7] The resulting Q value is $Q=75.1_{-2}^{+1.2}$ Mev. This gives a mass of the Σ^0: $M=1190.3_{-2}^{+1.2}$ Mev† using the latest value of the Λ^0 mass=1115.2 Mev.[8] For comparison, the most recent values of the Σ^+ and Σ^- masses are:

$$M_{\Sigma^+}=1189.5\pm0.3 \text{ Mev},^9$$
$$M_{\Sigma^-}=1196.5\pm0.4 \text{ Mev}.^9$$

[6] Plano, Samios, Schwartz, and Steinberger, Nuovo cimento **5**, 216 (1957).

[7] Alvarez, Bradner, Falk-Vairant, Gow, Rosenfeld, and Tripp, University of California Radiation Laboratory Report UCRL-3775 (unpublished).

[8] W. Barkas, *Venice Conference on Elementary Particles, September, 1957* (to be published).

[9] R. S. White, *Proceedings of the Seventh Annual Rochester Conference on High-Energy Nuclear Physics, April, 1957* (Interscience Publishers, Inc., New York, 1957), p. VIII-31.

† *Note added in proof.*—We would like to thank Professor A. Rosenfeld for pointing out an error in these values as given in our preprint.

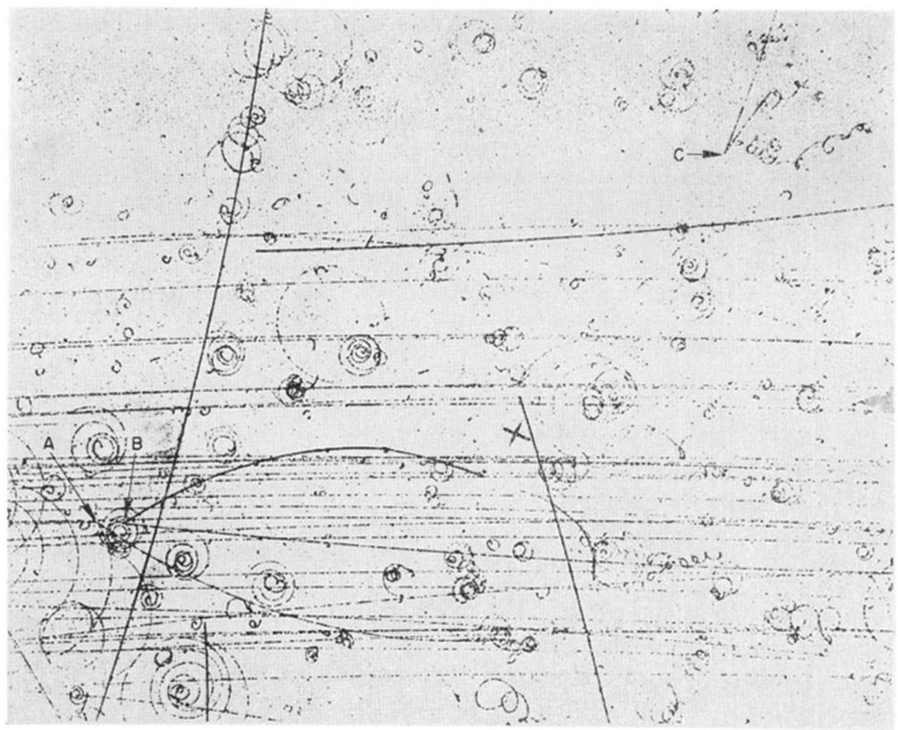

FIG. 1. Σ^0 and $\theta_2{}^0$ associated production and decay observed in a liquid hydrogen bubble chamber.