events, we find a mean life for the $2\pi$ decays for particles two-thirds of which must initially have been $\bar{\theta}^0$'s. The value is $(0.8 \pm 0.3) \times 10^{-10}$ sec, indicating that the $\bar{\theta}^0$ can indeed decay by the $\theta_1^0$ mode.

A determination of the $\theta_2^0$ mean life has also been made, using the events which initially were predominantly $\theta^0$'s. Since the total number and the energy spectrum of the $\theta_2^0$'s ought to be the same as those of the $\theta_1^0$'s, one can calculate the total time the $\theta_2^0$'s spend in the visible region of the chamber from the total potential time for the $\theta_1^0$'s, for which the location and momentum spectra are known. However, a correction must be made for the number of $\theta_2^0$'s eliminated by nuclear interactions[4] in the approximately 50 meters of path traversed in the chamber.

We have observed two definite $\theta_2^0$ decays, and in one of them both particles ($e^-$ and $\pi^+$) could be identified. There are three other events with large measurement errors which we cannot definitely exclude as possible $\theta_2^0$ decays. Allowing for this uncertainty, we find for a mean life

$$\tau(\theta_2^0) = (9_{-7}^{+6}) \times 10^{-8} \text{ sec.}$$

This result is in good agreement with the determination of Bardon *et al.*,[5] who used a very different method.

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* Supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

† Present address: Department of Physics, Rutgers University, New Brunswick, New Jersey.

‡ Now at the Tata Institute of Fundamental Research, Bombay, India.

[1] Blumenfeld, Boldt, Bridge, Caldwell, Leavitt, Pal, Rossi, and Willard (to be published).

[2] Eisler, Plano, Prodell, Samios, Schwartz, Steinberger, Bassi, Borelli, Puppi, Tanaka, Woloschek, Zobuli, Conversi, Franzini, Manelli, Santangelo, and Silvestrini, Nevis Cyclotron Laboratories Report No. 69, 1958 (unpublished).

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

[4] A discussion of these nuclear interactions is given in the following Letter [E. Boldt *et al.*, Phys. Rev. Lett. 1, 150 (1958)]. It is important to note that the time spent by $\theta_2^0$'s in the chamber can be calculated also from the number of $\bar{\theta}^0$ interactions seen. The $\theta_2^0$ mean life obtained in this way is in good agreement with that determined by using the $\theta_1^0$'s to find the $\theta_2^0$ potential time. This internal consistency gives further evidence that the events described in the following Letter are indeed caused by $\bar{\theta}_2^0$ interactions.

[5] Bardon, Chinowsky, Fuchs, Lande, and Lederman, Nevis Cyclotron Laboratories Report No. 61, 1958 (unpublished). This determination involved measuring $\theta_2^0$ decays at two different distances from a target and normalizing the measurements by counting neutron stars in the cloud chamber gas.

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## $\theta_1^0$ - $\theta_2^0$ MASS DIFFERENCE*

Elihu Boldt,† David O. Caldwell, and Yash Pal‡
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received July 30, 1958)

We have observed directly the change with time of the nature of the neutral particle produced in association with the $\Lambda_0$ hyperon. The "particle", initially the $\theta^0$, is observed to interact with matter to produce another hyperon only when at some distance from its origin, and never when close to that origin. This observation is a direct confirmation of the particle-mixture theory for the $\theta^0$ meson of Gell-Mann and Pais,[1] and when quantitatively interpreted in terms of that theory, yields an estimate of the mass difference between the $\theta_1^0$ (short-lived) and $\theta_2^0$ (long-lived) components of the $\theta^0$.

During an investigation of the properties of heavy unstable particles produced by $\pi^-$ mesons of 1.5-Bev median energy in the iron plates of a large multiplate cloud chamber,[2] we have observed twelve cases of hyperon production by neutral particles. A scan for interactions caused by high-energy neutrons from the accelerator, the Brookhaven Cosmotron, showed that such neutrons could not have been the source of these hyperons. Neutrons from $\pi^-$ interactions in the chamber also could not have contributed. Since a $\pi^-$-produced $\Lambda^0$ which scatters would appear to come from a neutral origin, this effect also was taken into account.

Instead, these twelve cases are consistent with the neutral particle, originally of positive strangeness, having acquired in time some negative-strangeness component and interacting as $\bar{\theta}^0 + n \rightarrow Y + \pi$. In five of the cases, a charged $\pi$ is directly identified as one of the interaction products and, in another case, a shower indicates a $\pi^0$ was produced. Seven of the interactions yield $\Lambda^0$'s, while five give $\Sigma^\pm$. Correcting for losses in the plates and for the neutral mode of decay of the $\Lambda^0$, the resulting ratio of $\Sigma^\pm$ to $\Lambda^0$ is 1.3. If one assumes charge independence to find the portion of $\Lambda^0$'s which were originally

$\Sigma^0$'s, then the $\Sigma/\Lambda$ ratio in the $\bar{\theta}^0$ interactions is 5.6.

The number of these $\bar{\theta}^0$ interactions depends on the mass difference, $\Delta m$, between the $\theta_1^0$ and $\theta_2^0$ constituents of the $\theta^0$, according to particle-mixture theory.[1] The intensity of the $\bar{\theta}^0$ component at a time $t$ after the production of a $\theta^0$ is given by

$$I = \tfrac{1}{4}[\exp(-t/T_1) + \exp(-t/T_2) - 2\exp(-t/T_1 - t/T_2)\cos(m\Delta m t/E\hbar)],$$

where $T_1$ and $T_2$ are the lifetimes of $\theta_1^0$ and $\theta_2^0$ in the laboratory system, and $E$ is the total energy of $\theta_1^0$ of mass $m$. Because of the oscillatory term, the number of interactions, for a given $\Delta m$, depends on the time taken by the particle to reach the first, and to a lesser extent the second, plate after that in which it was produced.

From the 120 $\theta_1^0 \to \pi^+ + \pi^-$ decays seen, we have determined the number, spatial distribution, and momentum distribution of the $\theta^0$'s produced. Using this information and the particle-mixture theory,[1] we have calculated[3] the expected number of $\bar{\theta}^0$ interactions in various plates of the chamber for different values of $\Delta m = k\hbar/\tau_1$, where $\tau_1$ is the proper lifetime of $\theta_1^0$. The result is shown in Fig. 1 in which the observed numbers, corrected for invisible modes of interaction, are also given. Distances are determined to the most likely, nearest, and farthest possible $\pi^-$ interactions which could have produced the $\theta^0$. In $\frac{1}{3}$ of the cases[4] the correct $\pi^-$ interaction is marked by an associated hyperon.

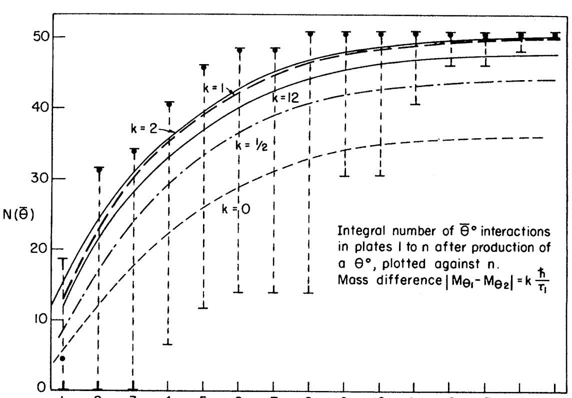


FIG. 1. Integral number of $\bar{\theta}^0$ interactions in plates 1 to $n$ after the plate in which the $\theta^0$ was produced vs $n$, for various values of the $\theta_1^0 - \theta_2^0$ mass difference in units of $\hbar/\tau_1$. The most likely values of the corrected observations are shown as solid circles, with flags giving minimum and maximum values based on the uncertainty as to which $\pi^-$ interaction was the $\theta^0$ origin. The statistical errors are not shown.

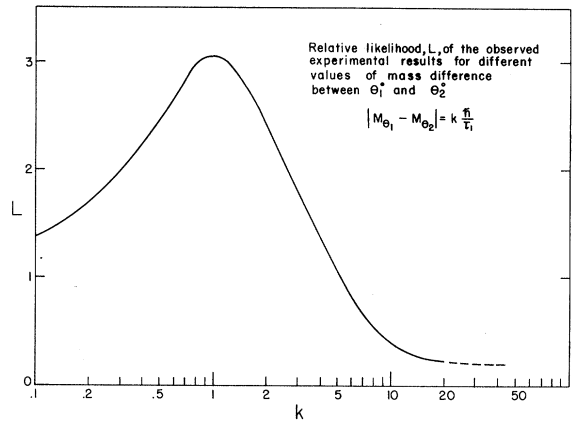


FIG. 2. Relative likelihood, $L$, of the observed experimental results for different values of the mass difference between the $\theta_1^0$ and $\theta_2^0$, in units of $\hbar/\tau_1$, where $\tau_1$ is the $\theta_1^0$ lifetime.

For values of $k > 1$, for which this analysis becomes insensitive to $k$, the period of oscillation becomes sufficiently short so that there is an appreciable probability for $\bar{\theta}^0$ interaction in the same plate in which the $\theta^0$ was produced. We calculated the number of such apparent two-hyperon productions to be expected as a function of $k$, and used the fact that none has been seen by us or by the Columbia and Princeton cloud chamber groups.[5] Combining this result with that given above for the number of $\bar{\theta}^0$ events seen, we calculate a relative likelihood function for these experimental results as a function of $k$, and this is shown in Fig. 2.

We find the most likely value of the $\theta_1^0 - \theta_2^0$ mass difference to be about $\hbar/\tau_1$. Although the statistical accuracy of this result is poor, the experiment does demonstrate a straightforward method for measuring $\Delta m$.[6] More importantly, these results, combined with those reported in the previous Letter,[7] provide strong support for the essential features of the particle-mixture theory.

We would like to express our appreciation to Professor Bruno Rossi for his continued interest and encouragement in this work, and to Dr. Herbert S. Bridge, who was responsible for the construction and operation of the chamber. We wish to thank also Dr. H. Blumenfeld, Dr. C. E.

Leavitt, and Dr. D. Willard for their help in the chamber operation.

*Supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

†Present address: Department of Physics, Rutgers University, New Brunswick, New Jersey.

‡Now at the Tata Institute of Fundamental Research, Bombay, India.

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

[2] Blumenfeld, Boldt, Bridge, Caldwell, Leavitt, Pal, Rossi, and Willard (to be published).

[3] The calculation assumes (a) that all the matter in the plates is concentrated at their centers, in order that $\theta_1^0$ and $\theta_2^0$ decays can be treated separately from $\theta^0$ and $\bar{\theta}^0$ interactions; (b) that the plates (1/2-in. iron) are thin enough so that $\theta_1^0$ regeneration can be neglected; (c) that the relative phase difference between $\theta^0$ and $\bar{\theta}^0$ components in passing through matter is small; and (d) that $\tau_1 = 1\times10^{-10}$ sec, $\tau_2 = 7\times10^{-8}$ sec, and the mean free paths in iron for interactions which would eliminate $\theta^0$'s and $\theta^0$'s from observation are 1000 and 100 g/cm$^2$, respectively. Calculations indicate that errors arising from these assumptions are unimportant compared to the statistical errors.

[4] We calculate that we should see such a hyperon 38% of the time, and therefore this consistency tends to confirm that our events are indeed $\bar{\theta}^0$ interactions.

[5] We wish to thank Dr. Henry Blumenfeld and Dr. Theodore Bowen for supplying the necessary information.

[6] A similar method has been suggested independently by W. F. Fry and R. G. Sachs, Phys. Rev. 109, 2212 (1958).

[7] Boldt, Caldwell, and Pal, preceding Letter [Phys. Rev. Lett. 1, 148 (1958)].

## ERRATA

### ORIENTATION OF RUBIDIUM ATOMS BY SPIN EXCHANGE WITH OPTICALLY PUMPED SODIUM ATOMS. R. Novick and H. E. Peters [Phys. Rev. Lett. 1, 54 (1958)].

The following footnotes were omitted:

[4]E. M. Purcell and G. B. Field, Astrophys. J. 124, 542 (1958).

[5]G. Herzberg, Molecular Spectra and Molecular Structure (D. Van Nostrand Company, Inc., New York, 1955). The equilibrium radius of NaRb was estimated, from Morse's rule and from a consideration of covalent radii, to be $3.6\times10^{-8}$ cm.

### SPIN EXCHANGE IN SUPERCONDUCTORS. B. T. Matthias, H. Suhl and E. Corenzwit [Phys. Rev. Lett. 1, 92 (1958)].

Reference 3 should be omitted and replaced by a footnote after the paragraph that ends: "...; this occurs in the pure metal at low temperature or under pressure." The footnote should read:

C. Herring has suggested that the exchange interaction of the solute atoms with the spins of the conduction electrons should lower the energy of the normal state more than that of the superconducting state. This mechanism seems to account for the observed features qualitatively, and also gives the right order of magnitude of the effect.