EXPERIMENTAL DETERMINATION OF THE Λ SPIN*

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Lee and Yang have recently proposed a method of determining the Λ spin.[1] In this Letter we apply their method to a sample of 614 decays of the type

$$\Lambda \rightarrow \pi^- + p. \qquad (1)$$

The Λ's were produced in our 10-inch liquid hydrogen bubble chamber via the reaction

$$\pi^- + p \rightarrow K^0 + \Lambda, \qquad (2)$$

by incident pions of momenta 1.23 Bev/c (184 events), 1.12 Bev/c (253 events), 1.09 Bev/c (53 events), 1.03 Bev/c (94 events), and 0.95 Bev/c (30 events).

The beauty of the Lee-Yang method is that it makes possible an absolute determination of the Λ spin without assumptions other than that angular momentum is conserved in the Λ decay.[2] This can be contrasted with the method of Adair,[3] in which details of the production reaction (2) must be considered in order to reach a conclusion about the Λ spin. In particular, assumptions must be made as to the final orbital-angular-momentum states present in the $K^0+\Lambda$ system. Similarly, assumptions must be made about the K^0 spin, and a selection of the data made accordingly; the lower the assumed K^0 spin, the more data one can use. For instance, Eisler et al.[4] have applied the Adair analysis to their associated production data and have concluded that the Λ spin is $\frac{1}{2}$, provided that the K^0 spin is zero, and provided that only S, P, and D waves are important in the $K^0+\Lambda$ system.

The disadvantage of the Lee-Yang method is that a very large amount of data is needed in order to achieve conclusive results.[5]

The Lee-Yang method depends for its success upon the very large up-down asymmetry found[6-8] in the parity-nonconserving decay (1) of Λ's produced in reaction (2). In principle, one starts with any collection of Λ's, chooses a quantization direction in any way that is independent of the decay (1), and then examines the decay distribution $W(\xi)d\xi$, where ξ denotes the cosine of the angle between the (negative) decay pion and the quantization direction—all in the Λ rest frame. For a Λ spin J, $W(\xi)$ is in general a polynomial with powers up to and including ξ^{2J}. One might suppose that a given experimental ξ distribution could always be more easily fitted to large spin J than to small spin, since then more coefficients are available for "curve fitting." However, angular-momentum conservation severely constrains the coefficients. In fact, a very large up-down decay asymmetry cannot be achieved with a large spin. (This can be understood qualitatively through the observation that, classically, the disintegration of a system of high spin tends to yield fragments moving in the equatorial plane rather than towards the poles.)

The constraints on the shape of $W(\xi)$ can be summarized through the Lee-Yang test functions $T_{J,M}(\xi)$, all of which satisfy the inequality

$$\langle T_{J,M}\rangle \leq 1, \qquad (3)$$

where the bracket denotes averaging over the decay distribution $W(\xi)$, and where $M=J, J-1, \ldots, -J$.

For spin $J=\frac{1}{2}$, the decay distribution is

$$W(\xi)d\xi = \tfrac{1}{2}\, d\xi(1+a\xi). \qquad (4)$$

The test functions are $T_{1/2,\pm 1/2} = \pm 3\xi$, so that one has $\langle T_{1/2,\pm 1/2}\rangle = \pm a$, and the Lee-Yang inequality (3) reduces to $-1 \leq a \leq 1$.

For Λ spin $J=\frac{3}{2}$, the decay distribution is a cubic in ξ. The four test functions are

$$T_{3/2,3/2} = 9P_1(\xi) + 5P_2(\xi) - (7/3)P_3(\xi), \qquad (5)$$

$$T_{3/2,1/2} = 3P_1(\xi) - 5P_2(\xi) + 7P_3(\xi), \qquad (6)$$

and $T_{3/2,-3/2}$ and $T_{3/2,-1/2}$, which are obtained by substituting $-\xi$ for ξ in Eqs. (5) and (6). The $P_k(\xi)$ are Legendre polynomials. Similar test functions are constructed for spin $\frac{5}{2}$, $\frac{7}{2}$, etc.

To illustrate the method, suppose the Λ spin were really $\frac{1}{2}$, and that we had a decay sample with the maximum possible asymmetry, that is with $a=1$. Then we would find (with enough data so that statistical fluctuations were negligible) $\langle T_{3/2,\pm 3/2}\rangle = \pm 3a = \pm 3$, and $\langle T_{3/2,\pm 1/2}\rangle = \pm a = \pm 1$. The first of these fails to satisfy the inequality (3), and spin $\frac{3}{2}$ would thereby be ruled out. The other three spin-$\frac{3}{2}$ test functions satisfy the inequality and yield no information. We notice that a sample of spin-$\frac{1}{2}$ Λ's having $|a| \leq \frac{1}{3}$ would satisfy all four of the spin-$\frac{3}{2}$ Lee-Yang inequalities, and therefore would be useless for application of the method.

We now consider the way in which the sample of Λ decays is obtained. For the method to succeed, the preceding example shows that one needs a sample with a large asymmetry with respect to the quantization axis. On the other hand, in order to obtain an unbiased sample it is of primary importance not to select the Λ's or the quantization axis in a manner which involves "peeking" at the decay ξ values. With these considerations in mind, we naturally choose a priori a quantization axis perpendicular to the production plane of reaction (2), along $\vec{P}(\pi \text{ incident}) \times \vec{P}(\Lambda)$. We naturally exclude, a priori, from our sample any Λ's produced via $\pi^- + p \rightarrow K^0 + \Sigma^0$, $\Sigma^0 \rightarrow \gamma + \Lambda$. The question arises whether we should include the entire range of c.m. angles in the production reaction (2), or, as suggested by Lee and Yang,[1] include only a region centered at 90° (c.m.), where the polarization might be expected to be largest. We believe that it is very difficult to justify such a limitation, since in order to decide on the range of angles to be included one becomes involved either in a posteriori "peeking at the data," or in making implicit a priori assumptions as to the maximum angular complexity and thus as to the maximum number of partial waves involved in the $K^0 + \Lambda$ state. The former biases the distribution, and the latter spoils the beauty of the assumption-free Lee-Yang method. We therefore include the entire range of production angles. Similarly, the question arises whether we should include all incident-pion production energies, or only those in which the decay asymmetry appears to be largest. Since we have no a priori knowledge as to the energy dependence of the Λ polarization, we would be at the mercy of statistical fluctuations, with a consequent large chance for bias, if we excluded some datum because of its small observed up-down asymmetry. We therefore include, a priori, all production energies.

Finally we present the results. For each event, ξ is obtained from detailed dynamical analysis. Then $T_{3/2,3/2}(\xi)$ is calculated for each event, by using Eq. (5). Then (omitting the $\frac{3}{2}, \frac{3}{2}$ subscripts), $\langle T\rangle = (1/N)\sum T(\xi) \pm [(1/N)(\langle T^2\rangle - \langle T\rangle^2)]^{1/2}$, where $\langle T^2\rangle = (1/N)\sum T^2(\xi)$, and $N = 614$ is the total number of events. The other test functions are calculated analogously. Our 614 events yield

$$\langle T_{1/2,1/2}\rangle = 0.57 \pm 0.066,$$

$$\langle T_{3/2,3/2}\rangle = 1.77 \pm 0.244,$$

$$\langle T_{5/2,5/2}\rangle = 2.99 \pm 0.408.$$

Thus a Λ spin of $\frac{1}{2}$ easily satisfies the Lee-Yang inequality $\langle T_{J,M}\rangle \leq 1$, while spin $\frac{3}{2}$ fails to satisfy it by $(1.77-1)/(0.244) = 3.16$ standard deviations, and spin $\frac{5}{2}$ fails by 4.88 standard deviations.[9]

In addition to satisfying the spin-$\frac{1}{2}$ Lee-Yang inequality, $3\langle\xi\rangle \leq 1$, the ξ distribution must be linear [Eq. (4)], for spin $\frac{1}{2}$. Figure 1 shows a histogram of the experimental distribution. The straight line is a least-squares best fit and corresponds to the slope $a = 0.57$. Application of the χ^2 test to the fit yields $\chi^2 = 6.70$, with an "expected" value of 10 - 2 = 8. This corresponds to a χ^2 probability of 57% for a fit this bad or worse. The data thus fit a linear distribution (4) very well indeed.

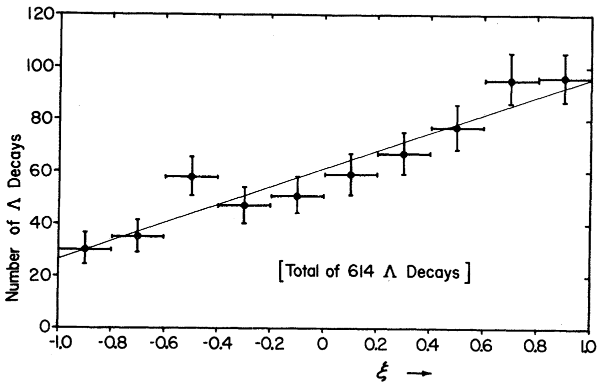

FIG. 1. "Up-down" distribution for $\Lambda \rightarrow \pi^- + p$.

Lastly, we have performed a control experiment, in order to search for possible hidden systematic errors in our determination of the Λ decay ξ distribution. Namely, we have determined, in exactly the same way as for the Λ's, the "ξ distribution" of a sample of 547 K^0 decays of the type $K^0 \rightarrow \pi^+ + \pi^-$. This sample includes substantially all our K^0 charged decays, from all production energies and from K^0's produced in association with Σ^0's as well as with Λ's. Figure 2 shows the results. As expected if there are

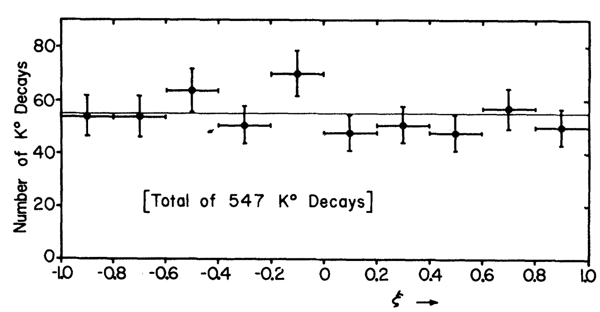

FIG. 2. Control experiment: up-down decay distribution for $K^0 \rightarrow \pi^- + \pi^+$.

indeed no biases, the ξ distribution is flat.[10]

We finally conclude, free from assumptions, that the Λ spin is $\frac{1}{2}$.

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[1]T. D. Lee and C. N. Yang, Phys. Rev. 109, 1755 (1958). An extension to include the polarization of the decay proton is discussed by Durand, Landovitz, and Leitner, Phys. Rev. 112, 273 (1958).

[2]The decay proton and pion spins are assumed to be 1/2 and zero. For a Λ spin of 1/2, the final state in decay (1) is an interfering mixture of states $S_{1/2}$ and $P_{1/2}$, for spin 3/2 a mixture of $P_{3/2}$ and $D_{3/2}$, etc.

[3]R. K. Adair, Phys. Rev. 100, 1540 (1955).

[4]F. Eisler et al., Nuovo cimento 7, 222 (1958).

[5]In the 1958 Annual International Conference on High-Energy Physics at CERN, edited by B. Ferretti (CERN, Geneva, 1958), we reported a Lee-Yang type analysis of 237 of our events at 1.12 Bev/c, plus a total of 162 events obtained by private communications from M. Schwartz and D. Glaser. The result was that the evidence against spin 3/2 was not conclusive.

[6]Crawford, Cresti, Good, Gottstein, Lyman, Solmitz, Stevenson, and Ticho, Phys. Rev. 108, 1102 (1957).

[7]Eisler, Plano, Prodell, Samios, Schwartz, Steinberger, Bassi, Borelli, Puppi, Tanaka, Woloschek, Zoboli, Conversi, Franzini, Mannelli, Santangelo, Silvestrini, Brown, Glaser, Graves, and Perl, Phys. Rev. 108, 1353 (1957).

[8]L. B. Leipuner and R. K. Adair, Phys. Rev. 109, 1358 (1958).

[9]Higher spins that 5/2 fail by an even larger margin. Also, as was expected from the illustrative example, the other spin-3/2 test functions do satisfy the Lee-Yang inequality, and therefore yield no information.

[10]Application of the χ^2 test to the horizontal straight line drawn through the experimental points yields $\chi^2 = 7.66$, where 10-1 = 9 is "expected." This corresponds to a χ^2 probability of 56%, and is thus a very good fit.

PHOTOGRAPHY OF COSMIC RAYS IN A LUMINESCENT CHAMBER*

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There is an increasing need in high-energy physics for a counter-controlled, high time-resolution device which records the tracks of particles. Such a device is the luminescent chamber,[1-4] in which the light from a charged particle passing through a scintillator is amplified in an image preserving manner and then photographically recorded. Chambers of useful size can be made using either a single scintillator crystal[1-4] or a bundle of scintillator filaments.[3] The major problem of obtaining sufficiently high light amplification had until now only been solved by Zavoisky and co-workers.[1,2] Unfortunately very little technical detail on this work has been available.

The authors have succeeded in consistently photographing minimum-ionizing cosmic rays in a sodium iodide crystal using available electronic and optical components. We believe that this is the first time that either cosmic rays or minimum-ionizing tracks have been recorded in a luminescent chamber. With modifications this apparatus can be used for luminescent chamber experiments in high-energy particle physics.

The system, Fig. 1, consists of three image-intensifier tubes, optically coupled to each other and to the crystal and film with refractive lenses. The total amplification of the system corresponds to about $2-8\times10^4$ photons falling on the film for each photon which strikes the first photocathode of the system. The first and third tubes are on continuously, and the second tube is pulsed on for one millisecond when a photomultiplier detects a cosmic ray passing through the crystal. The crystal is 3.8 cm in diameter and 1.9 cm thick. The lens viewing the crystal collects 0.5% of the light emitted by the particle.

Figure 2 shows a cosmic-ray track and also some image-tube background noise. Our optics would focus 530 quanta from each centimeter of minimum-ionizing track in the crystal onto the first image-tube cathode, releasing about 50 photoelectrons. This yields 150 photoelectrons from the entire track. In the photograph, the track is 3 cm long and 1 mm thick. This thick-

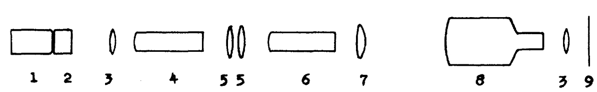

FIG. 1. Schematic sketch of the apparatus consisting of the following components: (1) photomultiplier; (2) 3.8-cm diameter by 1.9-cm thick NaI(Tl) crystal; (3) Erfle eyepiece lenses; (4) RCA C 73458A two-stage image tube; (5) American Optical eyepiece lenses; (6) RCA C 73458 two-stage image tube; (7) Kodak 110 mm, $f/0.75$ lens; (8) Westinghouse WX3897 one-stage image tube; (9) Kodak Royal X-Pan film.