Measurement of the Magnetic Moment of the Λ^0 Hyperon*

W. Kernan,† T. B. Novey, and S. D. Warshaw
High Energy Physics Division, Argonne National Laboratory,‡ Argonne, Illinois

and

A. Wattenberg
Department of Physics, University of Illinois, Urbana, Illinois§
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A measurement of the magnetic moment of the Λ^0 hyperon has been done by the spin precession technique in a 200-kG pulsed magnetic field. The result is that $\mu_\Lambda = 0.0 \pm 0.6$ nuclear magneton.

Early in 1961 experiments were performed by two groups at the Brookhaven Cosmotron using a jointly designed π meson beam in an attempt to measure the magnetic moment of the Λ^0.

For our measurements, polarized Λ^0 produced in the reaction $\pi^- p^+ \to \Lambda^0 + K^0$ were allowed to pass through a 200-kG pulsed magnetic field directed parallel or antiparallel to the Λ^0 momentum. The up-down asymmetry of the non-parity-conserving $\Lambda^0 \to p^+ + \pi^-$ was detected in a diffusion cloud chamber, and the orientation of the plane of decay used as an indicator for the precession of the magnetic moment vector of the Λ^0.[1] The results of the measurement indicate a small or zero magnetic moment.

The experimental arrangement is shown in Fig. 1. The incident beam of negative pions at 1.18 GeV/c ($\pm 3\%$) momentum is allowed to strike a small LiH target (2.5-cm diam, 3.5-cm long) close to the entrance of a pulsed field solenoid, labeled PM in the figure (precession magnet). The beam was carefully collimated and all but a small fraction passed clear of PM. Those Λ's formed in the target that had a direction that corresponded to the aperture of the magnet (2-cm diam by 7-cm long), $25 \pm 5°$, passed through parallel (or antiparallel) to the field of PM. The axis of the solenoid was horizontal. The decay of the hyperons into $\pi^- + p^+$ was observed in a small diffusion cloud chamber fitted with a pulsed analyzing field of 15 kG. Details about these two magnets are given elsewhere.[2]

It is well known[3] that the Λ decay is described by the correlation

$$dn \sim (1 + A\cos\theta)d\omega, \qquad (1)$$

where θ is the angle between the direction of the decay pion and the spin of the Λ^0 in the rest system of the Λ^0 and $d\omega = \sin\theta d\theta d\phi$. A has been measured[3] in this energy region and found to be ≈ 0.6.

If the Λ has a magnetic moment and passes through a magnetic field, the direction of polarization will be precessed; the precession can be observed as a rotation (through an angle ψ_0) of the distribution of the decay planes. For this purpose it is desirable to rewrite the distribution (1) in terms of ψ, the azimuthal angle in a plane perpendicular to the direction of motion of the Λ, and thus, the dihedral angle between the decay plane and the plane determined by the Λ^0 spin and momentum. The corresponding polar angle χ is the angle between the direction of the decay π in the laboratory and the direction of motion of the Λ.

By vector algebra[4] expression (1) becomes

$$dn \sim [1 + A\sin\chi\cos\psi]\sin\chi d\chi d\psi. \qquad (2)$$

If the distribution is precessed through an angle ψ_0, expression (2) becomes

$$dn \sim [1 + A\sin\chi\cos(\psi - \psi_0)]\sin\chi d\chi d\psi, \qquad (3)$$

where

$$\psi_0 = g\mu_0 Bl/\hbar pc = \omega_0(\mu_\Lambda/\mu_0)(Bl/2pcs), \qquad (4)$$

where p is the laboratory momentum of the Λ^0 in units

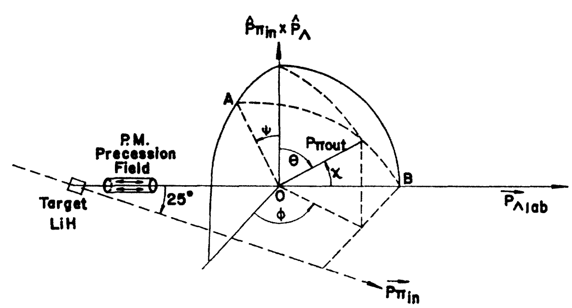

Fig. 1. Basic geometry and angles for measurement of the precession. PM is the precession magnet. $P_{\pi\text{in}}$ is the direction of the incoming pions. $P_{\Lambda\text{lab}}$ is the direction of the produced Λ that passes through the precession magnet. $P_{\pi\text{out}}$ is the direction of the π meson from the decay of the Λ.

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† Now at the New York University, New York, New York.

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[1] M. Goldhaber, Phys. Rev. **101**, 1828 (1956).

[2] R. L. Kuskowski, T. B. Novey, and S. D. Warshaw, Rev. Sci. Instr. **32**, 674 (1961).

[3] For example, F. Crawford, Jr., M. Cresti, M. Good, *et al.*, Phys. Rev. **108**, 1102 (1957); F. Eisler, R. Plano, A. Prodell, *et al.*, *ibid.* **108**, 1353 (1957).

[4] One can obtain the desired relationships from the fivefold vector product:

$$\cos\theta = [\bar{\Lambda} \times (\bar{\pi}_{\text{out}} \times \Lambda)] \cdot [\bar{\pi}_{\text{in}} \times \bar{\Lambda}],$$

where Λ, $\bar{\pi}_{\text{out}}$, and $\bar{\pi}_{\text{in}}$ are unit vectors in the direction of motion of the Λ, decay π, and incoming π, respectively.

of $m_\Lambda c$, s is the Λ^0 spin, Bl is the magnetic field times the effective length of the field, and μ_0 is the proton magneton $e\hbar/2m_pc$; ω_0 is the proton cyclotron frequency.

Then inserting our measured[2] $Bl=1.42\times10^6$ G cm, we have

$$\psi_0=27.3\mu_\Lambda/p_\Lambda\mu_0 \text{ degrees,}$$

i.e., a rotation of 38° for a Λ^0 of momentum 700 MeV/c and a moment of one proton magneton.

TABLE I. Observed Λ^0 events.

Type[a]	Number of events	Number "straight"	PM_+	PM_-
Through	17	4	7	10
Through >0.85	3			3
Through <0.75	31	9		
Missed	38	12		
Total	89			

[a] "Through" means from the target completely through the aperture of the solenoid. "Missed" means the Λ moved through the copper or leads of the coil, but not through the strong field region. PM_+ means direction of precession field parallel to Λ direction.

During the experimental run, about 40 000 pictures were taken; these were triply scanned for V particles and the film analyzed by conventional means in order to identify Λ's. The production vertex (the incoming pion) is not visible in the pictures; therefore the identification depended strongly on the kinematic invariants of the Λ decay alone. Since the direction of each identified Λ was determined with rather good accuracy, a graphical construction was made to determine whether or not (1) the Λ^0 originated in the target and (2) the Λ^0 passed through the full aperture of the precession magnet. Some events (those for which the decay pion had too much dip angle for the 4–5 cm sensitive depth of the could chamber) proved to be not completely measurable on a Hermes. These were treated as Λ's if the momentum of the decay proton and the opening angle of the decay was consistent with the kinematic mass invariant of the Λ and are labeled "straight." Table I gives a resume of the data.

The measured lifetime for the sample of 20 "through" events was $2.7\pm1.0\times10^{-10}$ sec.

Since so few events have been detected, we must depend on a maximum-likelihood function for the extraction of ψ_0. The function is

$$L=\prod_i\{1+A\sin\chi_i\cos[\psi_i-(\psi_0\bar{p}/p_i)]\}, \qquad (5)$$

where $\bar{p}$ is the average momentum of the sample; $\bar{p}/p_i$ weights each event by the time it spends in the magnetic field. The factor $\sin\chi$ was retained to reduce a smearing of the distribution because of the kinematical forward folding in the laboratory and any possible bias that may have depended on the polar angle of the decay pion with respect to the Λ direction. The so-called "missed" Λ's of Table I gave a value of $A=0.7\pm0.3$, a value consistent with the accepted value (for a hydrogen target). We therefore have some measure of confidence that the experimental arrangements is capable of obtaining correctly the asymmetry in the Λ decay. During the run the polarity of the precession magnet was reversed periodically; the distribution of events in (PM_+) and (PM_-) is given in Table I. The likelihood function was computed with the sign of ψ_0 reversed for (PM_-).

Figure 2 shows the likelihood versus ψ_0 for the two groups of events; curve A is for the group of 20 passing through >85% of the field; curve B is for the group of 38 passing through <25% of the field.

Curve A is bell shaped, with a maximum at $\psi_0=0°$ and with one standard deviation equal to 16°. For this sample, the average momentum is 700 MeV/c. From the sample of twenty events, a simultaneous fit for both parameters A and ψ_0 gave $A=+1.1\pm0.4$ and $\mu=0\pm0.3$ nm. However, we consider that this error is a statistical fluctuation, especially since this value of A is not physically meaningful. Therefore, we have used the polarization value from the larger sample, $A=0.7\pm0.3$, to fit the sample of 20 events in the single variable ψ_0 to obtain an estimate of error $\Delta\mu=0.4$ nm. Furthermore, since the number of events is small we report a more pessimistic error of ±0.6 nm, which is the theoretically expected error for 20 events assuming $A=0.7$ with an error of 0.1 nm included for instrumental errors.[5]

Although the number of events is small, we believe that the systematic errors inherent in a measurement

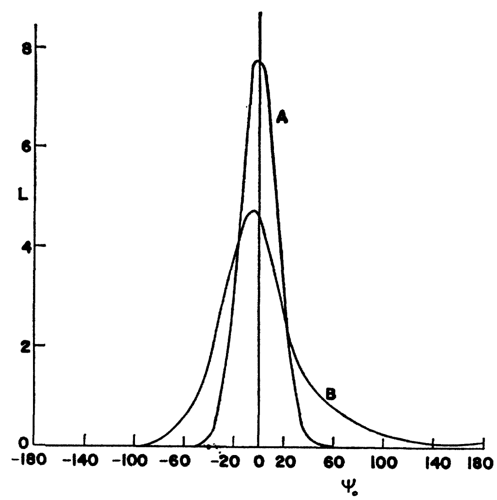

FIG. 2. Maximum likelihood distributions plotted as a function of the angle of precession. Thirty-eight degrees corresponds to one nuclear magneton. Curve B is the maximum likelihood plot for the events that "miss" passing through the precession magnet. Curve A is the maximum likelihood plot of the good events that passed through the precession magnet.

[5] It should be pointed out that a 20-event experiment with a given length of a 200-kG magnetic field can, in fact, produce the same error in magnetic moment as a 140-event experiment with the same length of a 75-kG field; the error in the magnetic moment varies inversely as the magnetic field times the square root of the number of events, $\Delta\mu\propto1/B\sqrt{N}$.

of this kind are demonstrably small. In particular, the plane $\psi=0$ is known to better than $\pm 5°$ from the mechanical measurements and from the distribution of dihedral planes for those events which did *not* pass through the magnetic field (Fig. 2, curve B). The result obtained from the above events is in disagreement with that obtained in the other experimental run at the Cosmotron by Cool *et al.*[6] They obtained a result of -1.5 ± 0.5 nm. More accurate experiments are clearly indicated.

[6] R. L. Cool, E. W. Jenkins, T. F. Kycia, D. A. Hill, L. Marshall, and R. A. Schluter, Phys. Rev. **127**, 1952 (1962).

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Low-Energy Pion-Pion Scattering. II*

LOUIS A. P. BALÁZS
Lawrence Radiation Laboratory, University of California, Berkeley, California
(Received 23 August 1962)

A self-consistent calculation of low-energy π-π scattering is made in which, in addition to the usual P-wave resonance, an $I=0$, D-wave resonance is also retained. The only free parameter is the pion mass. The resulting resonances have masses of 685 and 892 MeV, respectively, and the half-width is about 160 MeV in each case. The procedure consists of combining the Chew-Mandelstam and generalized Ball-Wong techniques with self-consistency. An outline is also given of a possible generalization of such a procedure to an arbitrary S-matrix process.

INTRODUCTION

A METHOD for making calculations in the low-energy π-π problem was given in an earlier paper,[1] henceforth referred to as I. The nearby singularities were treated by the conventional Chew-Mandelstam approach,[2] while the more distant ones were taken into account by a generalization of the Ball-Wong technique.[3] These two techniques were then combined with the requirement of self-consistency. An approximate calculation was made in which we consistently neglected everything except the P wave. Such a calculation, in which the only free parameter is the pion mass, can give us a self-sustaining resonance.

Recently, however, it has been conjectured, on the basis of the Regge-pole hypothesis, that there is also present an $I=0$, D-wave resonance in the π-π problem, with a mass of about 1 BeV.[4] Such a resonance will be shown to arise even if we have only the P-wave resonance of I in the crossed channel, although the mass is then too small. However, a coupled P-D calculation, in which both the P- and D-wave resonances are consistently retained, gives masses roughly consistent with the expected values. These calculations, of course, are all made in the elastic approximation. To increase the accuracy of the calculation without adding phenomenological information would require some method for calculating inelastic processes. In the final section, a generalization of the method given in I to such processes is outlined.

THE P- AND D-WAVE RESONANCES

In I, the partial-wave amplitude for orbital angular momentum l and isotopic spin I was given by

$$A_{(l)I}(\nu)=N_l^I(\nu)/D_l^I(\nu), \tag{1}$$

with

$$D_l^I(\nu)=1-\frac{\nu-\nu_0}{\pi}\int_0^\infty d\nu'\left(\frac{\nu'}{\nu'+1}\right)^{1/2}\frac{R_l^I(\nu')N_l^I(\nu')}{(\nu'-\nu_0)(\nu'-\nu)}, \tag{2}$$

and

$$N_l^I(\nu)=A_{(l)I}(\nu_0)+\frac{\nu-\nu_0}{\pi}\int_{\nu_L}^{-1}d\nu'\frac{\mathrm{Im}A_{(l)I}(\nu')D_l^I(\nu')}{(\nu'-\nu_0)(\nu'-\nu)}+(\nu-\nu_0)\sum_{i=1}^{n}\frac{F_{(l)I}{}^i}{\omega_i+\nu}, \tag{3}$$

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[1] L. A. P. Balázs, Phys. Rev. **128**, 1939 (1962).
[2] G. F. Chew and S. Mandelstam, Phys. Rev. **119**, 467 (1960).
[3] J. S. Ball and D. Y. Wong, Phys. Rev. Letters **6**, 29 (1961).
[4] This is where the topmost $I=0$ Regge trajectory passes through Re$l=2$. See G. F. Chew and S. C. Frautschi, Phys. Rev. Letters **7**, 394 (1961); *ibid.* **8**, 41 (1962). (The author is indebted to Professor G. F. Chew for pointing out the possible importance of this resonance.)