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Precise Measurement of the Λ^0 Magnetic Moment

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The magnetic moment of the Λ^0 hyperon has been measured to be $\mu_\Lambda = (-0.6138 \pm 0.0047)\mu_N$.

Magnetic moments have played a major role in the development of our current understanding of the structure of matter. The Zeeman effect and the Stern-Gerlach experiments were crucial to modern ideas of angular momentum, spin, quantum mechanics, and atomic structure. Extraordinarily precise measurements of the magnetic moments of the electron and muon have supported the validity of quantum electrodynamics and established that these charged leptons behave as pointlike Dirac particles. The magnetic moments of the deuteron and other nuclei shed light on the structure of these composite systems. If the lessons of the past are any guide, precise measurements of baryon magnetic moments will provide us with strong constraints on models of hadronic structure, and important information about the nature of the constituents of hadrons.

The large anomalous moments for the neutron and proton have shown that these particles are not elementary. Their structure are related by unitary symmetry schemes which predict the ratio of their moments to 3% accuracy. Unitary symmetry also predicts the moments of the strange baryons. Previous measurements of the Λ^0 moment indicate that the symmetry is not exact, and that a symmetry-breaking parameter must be introduced into the theory.

In a simple s-wave quark model of the baryons, the nucleons contain only u and d quarks, and their moments can be used to calculate these quark moments. The magnetic moments of the other memebers of the baryon octet involve the strange quark. The lambda hyperon consists of u, d, and s quarks with the u and d quarks in a state with spin $J=0$. The spin and magnetic moment of the Λ^0 are identical to those of its s quark. Among the stable baryons, this property is unique. Thus, a precise measurement of the Λ^0 moment gives the s-quark moment directly. This, in turn, can be compared with the moment of the u quark to give the symmetry breaking. Further assumptions regarding the relationship between mass and magnetic moment allow calculations of quark masses which can be compared to those determined directly from hadron masses.

The observation that Λ^0's inclusively produced by 300-GeV protons are polarized has been reported.[1] This polarization offered an opportunity to measure the Λ^0 magnetic moment with unprecedented precision because of several advantages over earlier experiments. The large inclusive cross section and rapid data-acquisition techniques make it possible to obtain a large sample of polarized Λ^0's in a relatively short time. The high energy results in an average decay length of order 10 m. Conventional dc magnets over such distances give large precession angles. Finally, the Fermilab neutral hyperon spectrometer has high acceptance (greater than 70% averaged over momentum) which reduces systematic errors in measurements of the polarization vector. A measurement of the Λ^0 magnetic moment (to 9% uncertainty) was an intrinsic part of the original discovery of polarization. It was clear that a number of improvements could be made in a new experiment specifically designed to measure the moment.

The basic apparatus common to both measurements is illustrated in Fig. 1(a).[2] The coordinate system [Fig. 1(b)] has $\hat{Z}$ along the neutral beam direction. $\hat{Y}$ is vertical upwards, and $\hat{X} = \hat{Y} \times \hat{Z}$

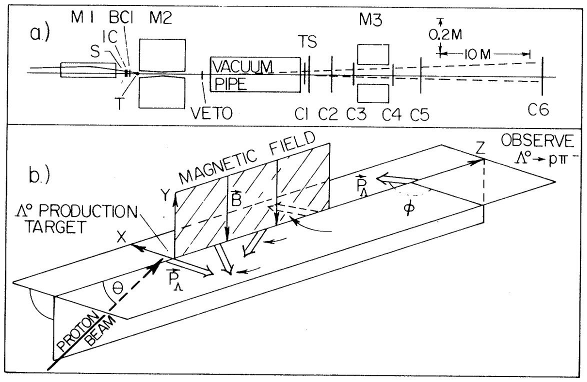

FIG. 1. (a) Elevation view of the apparatus. M1 was a vertical bending magnet used to vary the proton beam direction as it struck the Be target, T. S, IC, and BCI were proton beam detectors. M2 was the sweeper/precession magnet. The VETO scintillation counter defined the upstream boundary of the decay region. C_i were multiwire proportional chambers before and after the spectrometer magnet, M3. TS was a scintillation counter used for precise timing. (b) Schematic view of the coordinate system, production angle, polarization vector, and precession angle.

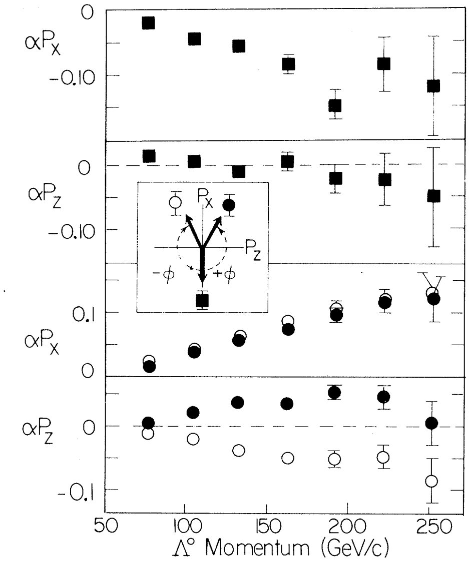

FIG. 2. X and Z components of the Λ^0 polarization vector with the precessing field off (solid squares), positive precession angle (solid circles), and negative precession angle (open circles). The polarization is along $-\hat{X}$ with the field off; rotates so that it has a large component along $+\hat{X}$ with the field on, independent of polarity; and acquires a Z component which reverses as the polarity, or precession sense, is reversed.

is horizontal. The incident proton beam was steered in the Y-Z plane onto the Be production target at each of several positive and negative angles relative to the Z axis. At the production target the polarization was in the parity-allowed direction, $-(\hat{k}_p \times \hat{k}_\Lambda)$, where $\hat{k}_p$ ($\hat{k}_\Lambda$) is the proton (Λ^0) momentum direction. The hyperon beam was defined by a brass collimator which constrained $\hat{k}_\Lambda$ to lie within a cone of 0.5 mrad half angle, centered on the Z axis.

A vertical magnetic field, applied along the entire 5.3 m length of the collimator, swept charged particles from the neutral beam, and precessed the Λ^0 spin in the horizontal plane through an angle $\varphi = (\mu_\Lambda c/\hbar\beta)\int B\,dL$, where $\int B\,dL$ is the integral of the field over the Λ^0 path, and μ_Λ is the Λ^0 magnetic moment. The numerical relation is $\varphi = (\mu_\Lambda/\mu_N)(18.30 \text{ deg/T m})\int B\,dL$, where μ_N is the nuclear magneton, $\mu_N = e\hbar/2M_p c = 3.152\,52 \times 10^{-14}$ MeV/T.[3] Above 60 GeV/c, $\beta = 1$ to better than 0.02%. Only Λ^0's which passed through the full length of the field and decayed within a well-defined volume were accepted. The proton and π^- from the charged decay mode were detected in a multiwire-proportional-chamber spectrometer of conventional design. Each of the three components of the polarization vector was obtained from the asymmetry of the decay-proton angular distribution in the Λ^0 rest frame.[4] The direction of this vector, measured for various known values of the magnetic field integral, yielded the magnetic moment.

Three major improvements increased the precision of the present measurement over the previous one. First, the sample of Λ^0's was increased by a factor of 10 to 3×10^6 with an average polarization of 8%. The Λ^0 sample and its polarization are described in more detail by Heller *et al.*[5] Second $\int B\,dL$ of the sweeping magnet was measured precisely by integrating numerically a field map obtained with a proton-resonance probe and a Hall probe. These values agreed well with flux-change measurements made with a long flip coil. The resonance probe remained in the field during the experiment to ensure precise setting of $\int B\,dL$ within the $\leq 0.1\%$ accuracy of the measurements. The third improvement involved bias cancellation. The earlier measurements[1] included periodic reversals of the sweeper magnetic field, which reversed the sign of the precession angle, and of the spectrometer magnetic field, which interchanged left and right in the downstream chambers. In the present experiment, the production angle, θ, was also reversed, thus reversing the Λ^0 spin direction in space. Data were taken at $\theta = 0$, $+7.2$, and -7.2 mrad.

The acceptance of the apparatus was well simulated by Monte Carlo calculations. However, small biases remained in the asymmetry measurements. These biases were independent of production angle and precession field integral, but they did depend on hyperon momentum. The biases were measured and eliminated by production-angle and magnetic-field reversals.

As a check on systematic errors, seven values of the field integral were used: 0, ±9.05, ±10.55, and ±13.64 T m. Thus, one can determine the change in the direction of polarization without any assumptions about its direction at the production target.

Figure 2 displays the precession in terms of the measured asymmetries, αP_x and αP_z, where $\alpha = 0.647 \pm 0.013$ is the asymmetry parameter.[6] The results can be understood in terms of the inset precession diagram.

The calculation of the magnetic moment was done by a least-squares technique, minimizing

$$\chi^2 = \sum_{ijk} (\pm \alpha P_i \cos\varphi_j \pm A_{xi} + B_{xi} - \alpha_{xijk})^2/\sigma_{xijk}^2 + (\pm \alpha P_i \sin\varphi_j \pm A_{zi} + B_{zi} - \alpha P_{zijk})^2/\sigma_{zijk}^2,$$

where P_{xijk} and P_{zijk} (σ_{xijk} and σ_{zijk}) are measured components (statistical uncertainties) of the polarization[2] for the seven momentum bins between 60 and 270 GeV/c ($i = 1-7$), the seven sweeper field settings ($j = 1-7$), and the four conditions of production angle sign and spectrometer polarity ($k = 1-4$). The parameters P_i represent the X components of the polarization vectors at the production target in the various momentum bins. An independent calculation established that the z components were zero. The values of P_i reverse sign with production angle. The precession angles, φ_j, measured relative to the initial polarization vector, were computed from the measured field integrals and the magnetic moment parameter through the relation noted above. The fit allowed for biases both symmetric and antisymmetric with respect to the spectrometer magnetic field. The bias parameters A_{xi} and A_{zi} reverse sign with spectrometer polarity. The bias parameters B_{xi} and B_{zi} do not. The results of the fit are presented in Table I. A single value of μ_Λ fits the data, with good χ^2, over a variety of precession angles, momentum bins, and bias conditions.

The overall consistency of the data can be illustrated in other ways. In Fig. 3(a), the precession angle has been calculated for each of the field integrals. They are well represented by a straight line passing through the origin. In Fig. 3(b), the fit described above was performed separately for each momentum bin. The magnetic moment shows no dependence on momentum despite the strong momentum dependence of the biases given in Table I.

The criteria required to ensure a clean sample of Λ^0's involved relatively loose cuts. The moment was stable against a wide variation of cuts to better than 0.5 standard deviation. Backgrounds in the final sample were 0.5% K_s^0, 5% Λ^0's produced by neutrons in the collimator, and 0.1% Λ^0's from Ξ^0 decay. These effects changed the moment by less than 1 standard deviation.

Our result for the magnetic moment of the Λ^0 is $\mu_\Lambda = (-0.6138 \pm 0.0047)\mu_N$. This is to be compared with the average of all previous measurements,[1,7-13] $(-0.606 \pm 0.034)\mu_N$.

This number, together with the nucleon magnetic moments, can be used to calculate the mag-

TABLE I. Fit to Λ^0 precession: 392 data points, 36 parameters, $\chi^2 = 380$. $\mu_\Lambda = (-0.6138 \pm 0.0047)\mu_N$.

Momentum (GeV/c)	αP_i	A_{xi}	A_{zi}	B_{xi}	B_{zi}
77	−0.022 ± 0.002	0.024 ± 0.002	−0.003 ± 0.003	0.005 ± 0.002	−0.141 ± 0.003
105	−0.045 ± 0.002	0.019 ± 0.002	−0.009 ± 0.002	−0.001 ± 0.002	−0.043 ± 0.002
133	−0.067 ± 0.002	0.010 ± 0.002	−0.014 ± 0.002	−0.002 ± 0.002	−0.025 ± 0.002
163	−0.090 ± 0.003	0.014 ± 0.003	−0.020 ± 0.003	0.003 ± 0.003	−0.011 ± 0.003
192	−0.117 ± 0.005	0.007 ± 0.005	−0.024 ± 0.005	0.003 ± 0.005	−0.020 ± 0.005
222	−0.135 ± 0.009	−0.008 ± 0.009	−0.026 ± 0.009	−0.002 ± 0.009	0.004 ± 0.009
252	−0.144 ± 0.017	−0.015 ± 0.017	−0.028 ± 0.017	−0.049 ± 0.017	0.011 ± 0.017

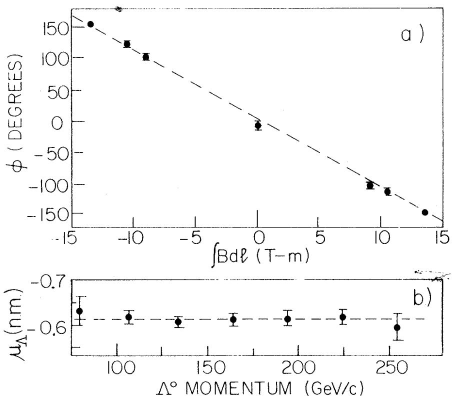

FIG. 3. (a) Plot of the measured precession angle vs the measured field integral. (b) Plot of the measured Λ^0 magnetic moment for each of seven momentum bins.

netic moments of the quarks, provided that some assumptions are made regarding the addition of quark moments to form the baryons. In the simplest S-wave broken SU(6) model, with $\mu_d = -\mu_u/2$, the value of μ_u can be calculated from either the proton or neutron moment. Taking $\mu_s = \mu_\Lambda$ and a simple average of the two results for μ_u, gives $\mu_u = 1.8875$, $\mu_d = -0.9438$, and $\mu_s = -0.6138$. Baryon moments constructed from these values agree quite well with those given in Table I of De Rújula *et al.*[14] Other predictions not listed there are $\mu(\Omega^-) = -1.8414$ and $\mu(\Sigma^0 \to \Lambda^0\gamma) = -1.6346$.[15]

The quark moments can be used to determine quark masses, if $g_q = 2$ is assumed, through the relation $M_q = (e_q \hbar)/(2\mu_q c)$.[16] The masses obtained in this way are $M_u = M_d = 0.331$ GeV/c^2 and $M_s = 0.510$ GeV/c^2. These values are in good agreement with the mass ratio[14] and difference[17] obtained from models of hadron mass splittings. This implies that the assumption $g_q = 2$ is reasonable, and that quarks may be pointlike Dirac particles.

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