Measurement of the Σ^0-Λ Transition Magnetic Moment

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The Σ^0-Λ transition magnetic moment has been measured to be $|\mu(\Sigma^0\text{-}\Lambda)| = 1.59 \pm 0.05 \pm 0.07$ nuclear magnetons. The Σ^0 lifetime is $\tau(\Sigma^0) = (0.76 \pm 0.05 \pm 0.07) \times 10^{-19}$ sec. The uncertainties are statistical and systematic, respectively.

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Static moments of hyperons, measured by spin precession in a magnetic field[1] or transitions in exotic atoms,[2] provide insight into hadron structure and agree qualitatively with a nonrelativistic, s-wave, broken-SU(6) quark model.[3] The moment for baryon B is the matrix element $\mu_B = \langle B|H_{M1}|B\rangle$, where H_{M1} is the magnetic dipole Hamiltonian. The Primakoff effect[4,5] allows determination of the off-diagonal element $\mu_{\Sigma\Lambda} = \langle \Sigma^0|H_{M1}|\Lambda\rangle$ from the cross section for $\Lambda \to \Sigma^0$ in the nuclear Coulomb field. By T invariance, $|\mu_{\Sigma\Lambda}|^2$ is proportional to the width for $\Sigma^0 \to \Lambda\gamma$ or the inverse lifetime, since competing processes are negligible. The differential cross section is[6,7]

$$d\sigma/dq_t^2 = (\mu_{\Sigma\Lambda}/\mu_N)^2 (98 \text{ mb}) (Z/82)^2 (p_\Lambda^2/m_\Lambda^4)(q_l q_t/q^2)^2 F^2(q^2), \tag{1}$$

where Z is the atomic number of the target, p_Λ is the Λ momentum, $q_l = (m_\Sigma^2 - m_\Lambda^2)/2p_\Lambda$ and $q_t = p_\Lambda \sin\theta_{\Sigma\Lambda}$ are the longitudinal and transverse momentum transfers, $q^2 = q_l^2 + q_t^2$, m_Λ and m_Σ are Λ and Σ^0 masses, and $F(q^2) \approx 1$ is a form factor which includes nuclear and atomic electron charge distributions and nuclear absorption. The cross section is concentrated at small q_t, i.e., at $q_t = q_l$ (~ 1 MeV/c for $p_\Lambda = 200$ GeV/c), in contrast to strongly produced Σ^0 with $\langle q_t\rangle \approx 300$ MeV/c. This sharp forward peaking and the Z^2 dependence are distinctive features of Σ^0 produced this way.

Since the resolving power in q_t for the experiment described here is ~ 30 MeV/c, only the total cross section can be measured. Models for $F(q^2)$ needed to integrate Eq. (1) yield results that vary little from a black sphere model.[6] In the present analysis, we use a complete optical model including nuclear absorption of incoming and outgoing hyperons and orbital electron screening.[8]

In this experiment we determined the number of Σ^0 produced in various materials by a Λ beam, separated Coulomb-produced Σ^0 from strongly produced Σ^0, and, by normalizing to the incident Λ flux, computed the cross section, from which the transition moment and Σ^0 lifetime were calculated.

The experiment was done in the Fermilab Proton Center beam line.[9,10] A 400-GeV proton beam was steered onto a 1-mm^2 × 46-mm-long lead target at the entrance to a 7.3-m-long neutral-beam channel with a 3.5-T vertical field. The limiting aperture was a 2-mm-diam hole in tungsten. Four uranium converters in this hole, each three radiation lengths ($3L_r$) thick, halved the ratio of γ to Λ in the beam and softened the γ-energy spectrum.

The neutral beam ($\langle p_\Lambda\rangle \approx 200$ GeV/c) was incident on one of seven secondary or Primakoff (PK) targets (Table I). The reaction sought was $\Lambda + Z \to \Sigma^0 + Z$, and the subsequent decay $\Sigma^0 \to \Lambda\gamma$, in which the nucleus remains nearly at rest and no charged particles emerge. A counter surrounded the target to veto reactions with charged particles.

A spectrometer (Fig. 1) detected charged particles from Λ decay giving a resolution $\sigma = 2.1$ MeV at the Λ mass. The photon was detected by a lead-glass array with resolutions $\sigma_E/E = 0.01 + 0.11[E/(1 \text{ GeV})]^{-1/2}$ and $\sigma_x = \sigma_y = 1.5$ cm in energy and position. Selected

TABLE I. Cross-section analysis for Primakoff production of Σ^0.

No.	Target Z	L/L_r	$q_t^2 < 0.004$ GeV^2 $N(\Sigma^0)$	$N(\Sigma^0_{\mathrm{str}})$[a]	g_{tgt}[b]	All q_t^2 $N(\Sigma^0_{\mathrm{PK}})$[c]	$10^{-7}N(\Lambda')/f$[d]	σ_{PK} (mb)
1	. . .	. . .	9 ± 41	6	0.0	. . .	1.255	. . .
2	4	0.032	53 ± 33	6	0.26	15 ± 10	0.965	0.068 ± 0.048
3	4	0.151	53 ± 36	20	0.64	24 ± 27	1.046	0.023 ± 0.025
4	50	0.574	266 ± 60	18	0.93	271 ± 66	3.044	2.65 ± 0.64
5	50	0.999	621 ± 65	36	0.96	701 ± 73	3.993	3.48 ± 0.36
6	82	0.147	64 ± 44	8	0.76	49 ± 39	1.453	8.17 ± 6.45
7	82	1.002	887 ± 76	36	0.97	968 ± 86	5.044	9.22 ± 0.82

[a]Statistical uncertainty ± 2 on strongly produced Σ^0.
[b]g_{tgt} = (target L_r)/(total L_r).
[c]Corrected upward by ~ 17% (target dependent) for q_t^2 resolution.
[d]Approximately 1.2% uncertainty. Typically, $f = \frac{1}{512}$.

events consisted solely of one Λ and one γ.[9]

The Λ trigger required no charged particles entering or leaving the PK target, one positive and one negative particle through the spectrometer, and a signal from the scintillator, P, on the positive side. The Σ trigger required a γ in the lead glass: no signal from S_7 and S_{7a} to veto charged particles, $\gtrsim 0.4$ GeV deposited in the first glass segment, and $\gtrsim 2.5$ GeV in the second segment. (Off-line cuts raised these to 1 and 5 GeV.) A modified trigger, $\Lambda' = \Lambda \cdot (\bar{S}_7 + \bar{S}_{7a})$, included all veto requirements of the Σ trigger. All Σ triggers and a known fraction of Λ and Λ' triggers (typically $\frac{1}{512}$) were recorded.

Assumption of a Λ-γ vertex in the PK target allowed reconstruction of the Λ-γ invariant mass, q_t, and other quantities. Narrow structure at the Σ^0 mass and $q_t^2 \approx 0$ exists, consistent with experimental resolution, e.g., for target 7 in Fig. 2. The $\Lambda\gamma$ background, to be subtracted from the Σ^0 mass peak, had two major components: (1) noninteracting beam Λ's paired with an accidental γ; and (2) $\Xi \to \Lambda\pi^0$, $\pi^0 \to 2\gamma$, with one γ undetected. A sample of events of type (1) came from Monte Carlo (MC)-simulated beam Λ's paired with single-γ's lead-glass data. Type (2) events were simulated by MC methods, with the observed momentum spectrum of $\Xi^0 \to \Lambda\pi^0$ with both γ's detected. To avoid cutting the data at the Σ^0 peak, a MC-generated Σ^0 event was included. These three distributions were fitted to the data in a three-dimensional space of nearly independent variables: q_t^2; r^2, the square of the distance between production target and the projected position of the daughter Λ; and $M(\Lambda\gamma)$. Each background source had a distinctive distribution in this space. With proper normalization, their sum accounted for most of the background. Since the Σ^0 peak had little weight in the fit, the method gave only a reliable

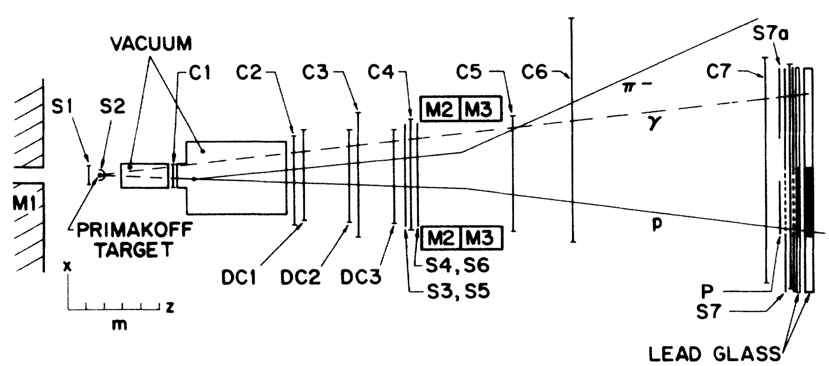

FIG. 1. Plan view of the apparatus showing $\Sigma^0 \to \Lambda\gamma$ and $\Lambda \to p\pi^-$. S_1 and S_2 are incident-beam and target-surrounding veto scintillators. C_1–C_7 are multiwire proportional chambers. DC_1–DC_3 are drift chambers. M_2 and M_3 are dipole magnets with combined bending power of 1.57 GeV/c. P is scintillator in the expected proton position before the lead glass. The glass intercepted γ's which passed through M_2–M_3 and was segmented along $\hat{z}$: ~ $3L_r$ followed by ~ $12L_r$. The latter was stacked bricklike in six rows of blocks, each 10×10 cm^2. A 4-block-wide hole in the midplane passed daughter protons. Hodoscope S_{7a} detected charged tracks, mainly π^-, entering the glass. A lead-scintillator sandwich, S_3–S_6, in combination with C_4 detected and eliminated events with γ's outside M_2's aperture. A 1.7-L_r lead sheet, preceded by veto S_7, assisted the early initiation of the γ shower.

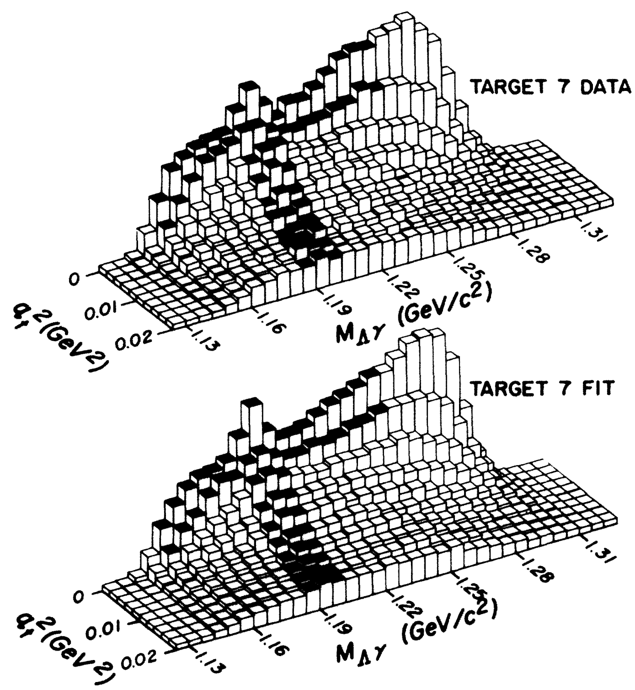

FIG. 2. Two-dimensional histograms of data and fit described in the text for target 7 (Pb) vs q_t^2 and the invariant mass $M_{\Lambda\gamma}$. The bands of shaded bins cross where the Primakoff events are expected.

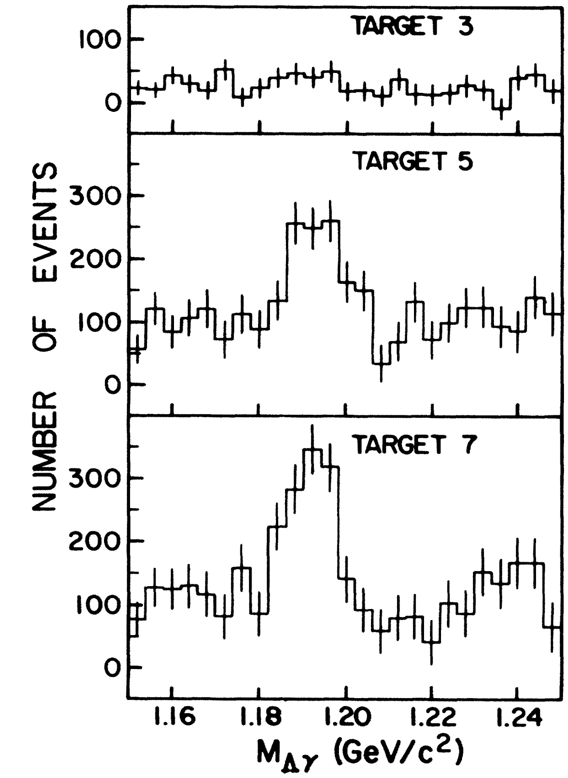

FIG. 3. Histograms of the invariant mass $M_{\Lambda\gamma}$ for targets 3 (Be), 5 (Sn), and 7 (Pb) for $q_t^2 < 0.004$ GeV^2 after subtraction of the fitted non-Σ^0 background.

estimate for the dominant backgrounds, not the Σ^0 yield.

Background subtraction was done in two steps. First, the fit described above was done over a broad kinematic range, and normalized non-Σ^0 distributions subtracted from the data to yield the distributions shown in Fig. 3 which display the Σ^0 signal and residual background. For $q_t^2 < 0.004$ GeV^2 the wings of the $M(\Lambda\gamma)$ distribution outside the Σ^0 mass region were fitted by a polynomial for the second step of the subtraction. Column 4 of Table I lists the number of events in the mass peak above this baseline.

Strongly produced Σ^0 were obtained from the data at $q_t^2 > 0.1$ where they showed a mass peak, proportional in strength to target absorption length, with small ($\sim 20\%$) background, and free of any forward-peaked component. These Σ^0's were consistent with a distribution $\exp(-10q_t^2)$.[11] This was used to estimate, by MC fits, the contribution of strongly produced Σ^0 to the low-q_t^2 mass peak [$N(\Sigma^0_{\rm str})$ in Table I].

The possibility of sharply peaked, strong, coherent production of Σ^0 from the entire nucleus was considered by Dydak *et al.*[12] and ruled negligible at ~ 15 GeV/c from Z^2 and q_t^2 dependence. Even if such a process accounted for their entire uranium cross section, on extrapolation to lead at 200 GeV/c with the assumption of ρ ($\Delta I = 1$) Regge exchange,[13] it would account for $< 7\%$ of our cross sections. We assume it negligible.

The number of Σ^0 was corrected for material near the PK target (S_1, S_2, air, and a vacuum window) by the factor $g_{\rm tgt}$ in Table I, and was raised by 17% to correct for events lost to the $q_t^2 < 0.004$ GeV^2 cut. The cross section is

$$\sigma = \frac{A}{G\rho A_0 L}\frac{fN(\Sigma^0_{\rm PK})}{N(\Lambda')\epsilon_1\epsilon_2\epsilon_3\epsilon_4}. \qquad (2)$$

A, L, and ρ are the atomic weight, length, and density of the target, and A_0 is Avogadro's number. $N(\Sigma^0_{\rm PK})$ is the number of Coulomb-produced Σ^0, and $N(\Lambda')/f$ (Table I) is the number of reconstructed Λ from the Λ' trigger corrected for the fraction, f, recorded. $G = (1-e^{-u})/u$ corrects for veto of Λ-γ events by S_2 from $\gamma \rightarrow e^+e^-$ in the target, where $u = 7L/9L_r$. Use of $N(\Lambda')$ for normalization cancels acceptances and efficiencies except those involving a photon, viz. ϵ_1 is the geometric acceptance for γ, equal to 0.495 ± 0.004; ϵ_2 is the software acceptance for a Σ^0 after it passed all the Λ' cuts, equal to 0.50 ± 0.01; ϵ_3 is the correction for veto of single-γ events by S_7 because of backscatter from showers initiated in the lead converter, equal to

0.75 ± 0.02; ϵ_4 is the glass trigger efficiency, equal to 0.88 ± 0.03. The cross sections are listed in Table I. Weighted averages for the three elements are $\sigma(\mathrm{Be}) = 0.033 \pm 0.022$ mb, $\sigma(\mathrm{Sn}) = 3.28 \pm 0.31$ mb, and $\sigma(\mathrm{Pb}) = 9.20 \pm 0.81$ mb, where the errors are statistical. These show the expected Z^2 dependence: $\sigma(Z)/Z^2 = 2.1 \pm 1.4$ μb for Be; 1.31 ± 0.13 μb for Sn; and 1.37 ± 0.12 μb for Pb. There is a 7% systematic uncertainty from the uncertainties of the ϵ's combined in quadrature. Uncertainties from background subtraction were estimated by comparison with a different procedure, viz., a polynomial fit, unconstrained by a physics model, to the mass distribution outside the Σ^0 peak for events with $q_t^2 < 0.004$ GeV^2. Results from the polynomial method differed from those of the method used by about 1σ, and, thus, raised the total systematic uncertainty to 10%.

Integration[8] of the bracketed part of Eq. (1) gave $(\mu_{\Sigma\Lambda}/\mu_N)^2$. Deviations from the impulse approximation $[F(q^2) = 1]$, primarily from nuclear absorption, were 1.4%, 9.2%, and 11.9% for Be, Sn, and Pb, respectively. The rms average for all targets is $|\mu(\Sigma^0\text{-}\Lambda)| = (1.59 \pm 0.05 \pm 0.07)\mu_N$. Since $\Sigma^0 \rightarrow \Lambda\gamma$ is $\sim 100\%$ of its total rate, the Σ^0 lifetime is given by

$$\left(\frac{\mu_{\Sigma\Lambda}}{\mu_N}\right)^2 = \frac{1}{\tau} \frac{8\hbar m_p^2 m_\Sigma^3}{\alpha(m_\Sigma^2 - m_\Lambda^2)^3} = \frac{1.92951 \times 10^{-19}\ \mathrm{sec}}{\tau}. \quad (3)$$

This yields $\tau = (0.76 \pm 0.05 \pm 0.07) \times 10^{-19}$ sec or, equivalently, a width $\Gamma = 8.6 \pm 0.6 \pm 0.8$ keV. In all cases the statistical uncertainty is quoted first. There is an additional uncertainty due to the Primakoff formalism itself estimated[8,14] to be $< 5\%$ for τ and Γ, and, thus, $< 2.5\%$ for μ.

The only previous measurement[12] is $|\mu(\Sigma^0\text{-}\Lambda)| = (1.82^{+0.25}_{-0.18})\mu_N$. This contains a numerical approximation[5,8] not compatible with present precision. We have recalculated[7,9] the moment from the directly measured cross sections in Ref. 12 to yield the revised result $|\mu(\Sigma^0\text{-}\Lambda)| = (1.72^{+0.17}_{-0.19})\mu_N$. The weighted average of our result and the recalculated result is $|\mu(\Sigma^0\text{-}\Lambda)| = (1.60 \pm 0.07)\mu_N$.

The naive quark model[3] [with exact or broken SU(6)] predicts that $\mu_{\Sigma\Lambda}$ depends only on the moments of the u and d quarks: $\mu_{\Sigma\Lambda} = (1/\sqrt{3})(\mu_d - \mu_u)$. One can substitute nucleon moments, $(\sqrt{3}/5) \times (\mu_n - \mu_p) = -1.63\mu_N$, or Σ moments,

$$\mu_{\Sigma\Lambda} = (\sqrt{3}/4)(\mu_{\Sigma^-} - \mu_{\Sigma^+}) = (-1.52 \pm 0.02)\mu_N$$

(Aguilar-Benitez *et al.*[15]). Both agree with the data within experimental uncertainties.

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