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A New Limit on the Electric Dipole Moment of the Λ Hyperon

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ABSTRACT

The electric dipole moment has been measured to be $d_\Lambda = (-3.0 \pm 7.4) \times 10^{-17}$ e - cm.

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Searches for electric dipole moments of elementary particles have been going on for years. The observation of a non-zero edm of an elementary particle implies the simultaneous breakdown of P and CP symmetries.[1] But since these symmetries are known to be violated, it is not unreasonable to expect edm's to exist at some very tiny level. For the baryons a dimensional argument estimates the edm as $e\langle r\rangle G\, m_p^2 \eta$, where e is the elementary charge, $\langle r\rangle$ is the particle size, $G\, m_p^2 = 10^{-5}$ is the weak coupling constant in dimensionless form, and η characterizes the CP violation. Taking $\langle r\rangle \sim 10^{-13}$cm and $\eta \sim 10^{-3}$ gives an edm $\sim 10^{-21}$e - cm. Specific models usually lead to estimates smaller than this, anywhere in the 10^{-23} - 10^{-30} range.[2]

Previous experimental work has included searches for an edm of the electron,[3] the muon,[4] the proton,[5] the Λ hyperon,[6] and an increasingly precise series of experimental limits on the edm of the neutron.[2] The most accurate electron and proton results were obtained from measurements on neutral atoms or molecules, where the acceleration of the charged particle in an external electric field could be avoided. Slow transversely polarized neutrons travelled through a region with parallel E and B fields to search for a shift in the Larmor frequency caused by a $\vec{d}\cdot\vec{E}$ interaction. The muon and Λ measurements employed a different technique. Both were by-products of measurements of the magnetic dipole moment of the particle, and exploited the fact that a particle moving in a transverse magnetic field is subject to an electric field in its rest frame.

The data used here were obtained in the experiment which yielded the precise measurement of the Λ magnetic dipole moment.[7] Details of the experimental apparatus and the analysis of the Λ spin direction based on measured asymmetries in the decay $\Lambda \rightarrow p\pi^-$ are discussed in Reference 7 and 8. The magnetic dipole moment μ_Λ was obtained from the precession angle ϕ of the Λ spin after passing through a known uniform magnetic field region. The initial configuration of vectors is shown in Figure 1a. The spin is initially perpendicular both to the magnetic field and the hyperon velocity. As the particle travels through the magnetic field, the spin precesses due to the torque $\vec{\mu}_\Lambda \times \vec{B}$ as shown in Figure 1b.

In the Λ rest frame an effective electric field $\vec{E}^* = \gamma\frac{\vec{v}}{c} \times \vec{B}$ appears, where $\gamma = E_\Lambda/m_\Lambda c^2$. Let $\vec{d}_\Lambda$ be the electric dipole moment. Then in the notation of Reference 6, the equation of motion of the spin in the Λ rest frame is

$$\frac{d\vec{S}}{d\tau} = \vec{\mu}_\Lambda \times \vec{B}^* + \vec{d}_\Lambda \times \vec{E}^*, \qquad (1)$$

where $\vec{B}^*$ and $\vec{E}^*$ are rest frame fields, and τ is the proper time. As shown in Figure 1, the laboratory vectors were: $\vec{B} = (0, -B, 0)$; $\vec{v} = (0, 0, v)$; $\vec{S}(0) = (-S_0, 0, 0)$; $\vec{E} = (0, 0, 0)$. Then

$\vec{B}^* = (0, -\gamma B, 0)$, and $\vec{E}^* = (\frac{\gamma v B}{c}, 0, 0)$. Defining the dimensionless constants μ and d via the relations $\vec{\mu}_\Lambda = \frac{\mu e}{m_p c}\vec{S}$ and $\vec{d}_\Lambda = \frac{de}{m_p c}\vec{S}$ where m_p is the proton mass, then gives the following equations of motion for the components of $\vec{S}$

$$\frac{dS_x}{dt} = \frac{\mu e B}{m_p c} S_z \qquad (2)$$

$$\frac{dS_y}{dt} = (\frac{v}{c})\frac{deB}{m_p c} S_z \qquad (3)$$

$$\frac{dS_z}{dt} = -\frac{eB}{m_p c}\,[\mu S_x + (\frac{v}{c}) d S_y]. \qquad (4)$$

Here t is the laboratory time and B is the laboratory magnetic field. The electric dipole moment d enters in Equations 3 and 4. The magnetic moment creates a component S_Z, not present at t = 0, which couples through the edm to the electric field along $\hat{x}$ to cause a precession in the yz plane. This precession creates a component S_y, not otherwise present in the experiment. Equations 2-4 are solved exactly in Reference 6, but for the purpose of this analysis the part proportional to d in Equation 4 can be ignored. Integration then gives

$$S_y(t) = (\frac{v}{c})\frac{d}{\mu}\, S_o(\cos \omega t - 1), \qquad (5)$$

where $\omega = \mu eB/m_p c$, and ωt is the angle ϕ shown in Figure 1b.

Data were taken at six different precession angles $\phi = \pm 153°$, $\pm 119°$, and $\pm 102°$. The sign was changed by reversing the magnetic field. Equation 5 does not depend on the sign of ϕ, however, because, although the electric field $\vec{E}^*$ reverses, the precession sense due to μ_Λ also reverses, leaving the effect due to the edm invariant. Half of the data were taken with the initial spin S_o as shown in Figure 1a, along $-\hat{x}$, and half with it along $+\hat{x}$ to reverse the asymmetry in the $\Lambda \to p\pi^-$ decay in space caused by the Λ polarization, while leaving asymmetries caused by the apparatus the same. The signal was $S_y = (S_{y+} - S_{y-})/2$, while the sum $(S_{y+} + S_{y-})/2$ was called the "bias". The Λ momenta were between 60 GeV/c and 250 GeV/c, for which v/c = 1 to better than 0.02%.

The results are summarized in Table I. Note that the instrumental biases are all small, and are removed by the subtraction technique. The data at each precession angle $\pm\phi$ have been averaged over all hyperon momenta. The weighted average of the dipole moment ratio is $d/\mu = +.0048 \pm .0116$, or an electric dipole moment not larger than $\sim 1\%$ of the magnetic dipole moment. The definition $d_\Lambda = de\bar{\lambda}/2m_p c$ together with the proton Compton wavelength $\bar{\lambda}_p = \hbar/m_p c = 2.10 \times 10^{-14}$ cm and $\mu_\Lambda = -0.6138 \pm .0047$[7] gives

$$d_\Lambda = (-3.0 \pm 7.4) \times 10^{-17} \text{e-cm}.$$

This represents a number about two orders of magnitude smaller than the previous result.[6]

This analysis was stimulated by a summary talk given by Pakvasa,[9] in which it was noted that the edm of the Λ might be several hundred times larger than that of the neutron. In the quark model both μ_Λ and d_Λ depend only on the s quark, and the s and d quark edm's might be very different. Ansel'm and Dyakonov[10] find that the s quark edm is larger than the d quark edm by a factor $m_s \cos^2\theta_c/m_d$, where θ_c is the Cabibbo angle. This factor is about 550 if current quark masses are used. In that case a value $d_\Lambda \sim -1 \times 10^{-22}$e-cm is predicted. The precision of the result reported here falls short of testing this expectation by about six orders of magnitude.

Can measurements in polarized Λ beams approach the required precision? Certainly not easily. The present experiment involved the reconstruction of some $3 \times 10^6 \Lambda \to p\pi-$ decays. It would be difficult to reconstruct many more, although it might be possible for fast computation on-line to measure the y asymmetry without complete analysis, which might gain a factor of 10 or so. There may be a region of phase space in the production reaction where S_0, the initial Λ polarization, is appreciably larger than .085. A factor of two there is equivalent to a factor of four in statistics. The maximum value of $|\cos\omega t - 1|$ in Equation 5 is two, nearly the value in this experiment. Neither a longer magnetic field nor a larger value of $\gamma = E_\Lambda/m_\Lambda c^2$ helps. At first it might seem that it would be more sensitive to put the initial spin and the magnetic field parallel rather than perpendicular, but because of the coupled motion equations this is not so. Equation 5 is as sensitive a relation between a polarization component and d as is possible to obtain. Thus it is difficult to see how this technique could do better than $\sim 10^{-18}$ e-cm.

This experiment was performed in the Meson Laboratory at Fermilab, and the Laboratory staff played a crucial role in its success. We wish to thank our other colleagues in the hyperon group who helped during the running and analysis of the original experiment. The work was supported in part by the U.S. Department of Energy and the National Science Foundation.

Table I

Observed polarization component S_y for various precession angles ϕ. ΔS_y is the statistical error common to S and the bias. The ratio d/μ is calculated from Equation 5 using the polarization S_o = .085 from Reference 8.

Events	ϕ	S_y	Bias	ΔS_y	d/μ	$\Delta d/\mu$
1,582,725	±153°	-.0023	-.016	.0023	-.0144	.014
895,496	±119°	+.0065	-.026	.0032	+.0500	.024
788,934	±102°	+.0023	-.019	.0032	+.0230	.032

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3. B.V. Vasil'ev and E.V. Kolicheva, Soviet Physics JETP 47, 243 (1978). These authors quoted $d_e = (8.1\pm11.6) \times 10^{-23}$ e-cm based on detection of a small change in magnetic flux caused by the flip of μ_e when an electric field is applied to a sample. M.C. Weisskopf, et al., Phys. Rev. Lett. 21, 1645 (1968). These authors obtain $|d_e| < 3 \times 10^{-24}$ e-cm from a limit on the edm of the cesium atom in an atomic beam.
4. J. Bailey, et al., Journal of Physics G 3, 345 (1978). From the precise measurements of (g/2-1) these authors obtain $d\mu^+ = (8.6\pm4.5) \times 10^{-19}$ e-cm and $d\mu^- = (0.8\pm4.3) \times 10^{-19}$ e-cm.
5. G.E. Harrison, et al., Phys. Rev. Lett. 22, 1263 (1969). These authors quote an experimental limit on the proton edm from a molecular beam measurement: $|d_p| = (7\pm9) \times 10^{-21}$ e-cm. See also I.B. Khriplovich, Soviet Physics JETP 44, 25 (1976), who quotes $|d_p| < 5.5 \times 10^{-19}$ e-cm.
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9. S. Pakvasa, summary talk presented at the XX International Conference on High Energy Physics, held in Madison, Wisconsin, July, 1980 (to be published).
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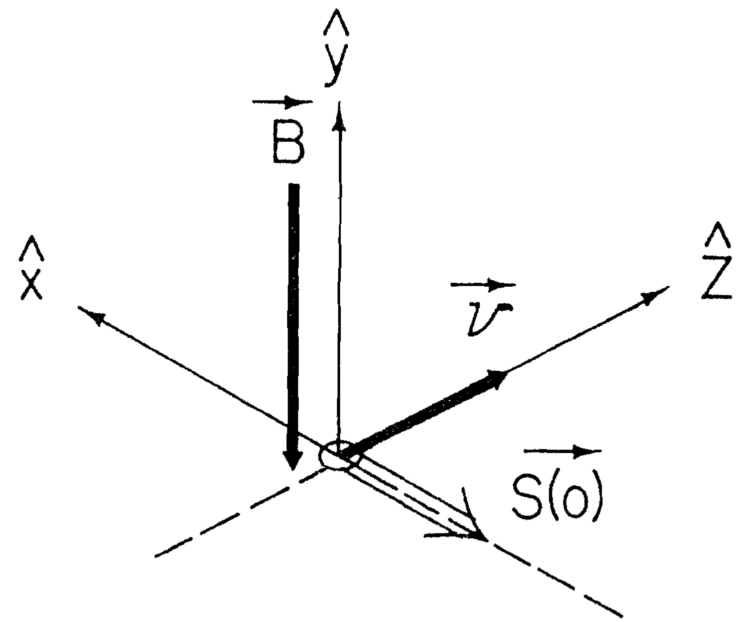
Figure Captions

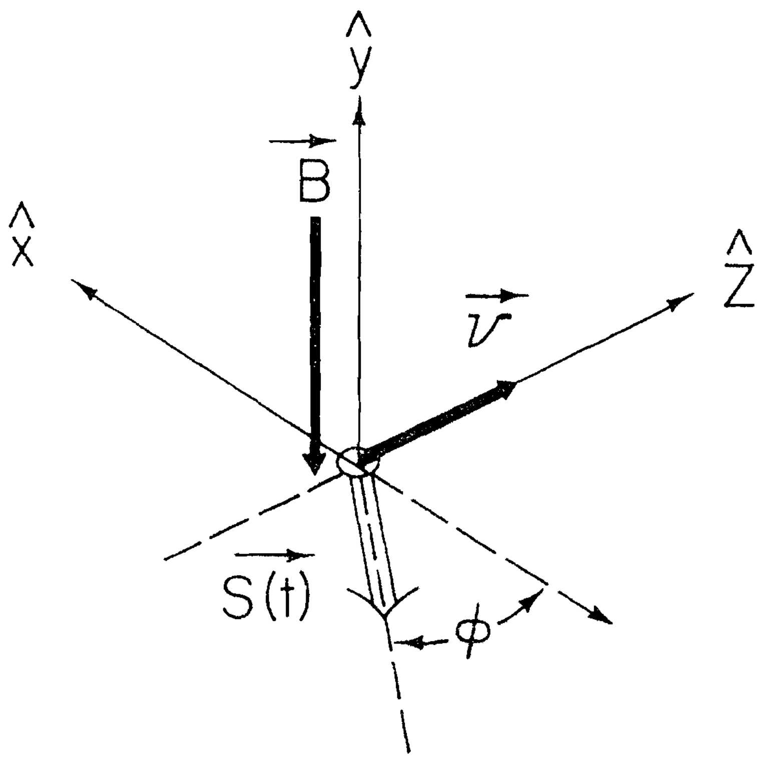
1a. Coordinate system for the description of the motion of the Λ hyperon in the external magnetic field $\vec{B}$. At time t = 0, the spin vector $\vec{S}(0)$ is perpendicular both to the velocity $\vec{v}$ and to $\vec{B}$.

1b. After a time t the negative magnetic moment has precessed the Λ spin in the direction shown by an angle ϕ. This creates a spin component along the z direction, which can couple through the edm to the effective electric field $\vec{E}^* = \gamma\frac{\vec{v}}{c} \times \vec{B}$ to cause a precession in the yz plane. This small yz motion is not shown.



$\hat{y}$
$\vec{B}$
$\hat{x}$
$\hat{Z}$
$\vec{\nu}$
$\vec{S}(o)$

(a)



$\hat{y}$
$\vec{B}$
$\hat{x}$
$\hat{Z}$
$\vec{\nu}$
$\vec{S}(t)$
ϕ

(b)