Measurement of the Magnetic Moment of the Antiproton*†

J. D. Fox
Brookhaven National Laboratory, Upton, New York 11973

and

P. D. Barnes, R. A. Eisenstein, W. C. Lam,‡ J. Miller, and R. B. Sutton
Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213

and

D. A. Jenkins and R. J. Powers
Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061

and

M. Eckhause, J. R. Kane, B. L. Roberts, M. E. Vislay, and R. E. Welsh
College of William and Mary, Williamsburg, Virginia 23185

and

A. R. Kunselman
University of Wyoming, Laramie, Wyoming 82070
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We have measured fine-structure splittings in atoms formed by antiprotons with both lead and uranium. Since the fine structure is produced by an interaction between the magnetic moment of the antiproton and the Coulomb field of the nucleus, a value for the magnetic moment can be derived from the observed splitting. We find a magnetic moment of -2.83 ± 0.10 nuclear magnetons which agrees with the TCP prediction.

Although the antiproton is a stable particle, it has a short lifetime in matter, which hinders measurement of its magnetic moment. The only other measured property of the $\bar{p}$, its mass, was determined in order to verify the identity of the particle when it was discovered.[1] If the TCP theorem is true, both the masses and magnetic-moment magnitudes of the proton and antiproton must be equal and the magnetic moments must have opposite signs. We have determined the $\bar{p}$ magnetic moment by measuring the fine-structure splitting of x rays emitted in atomic transitions of $\bar{p}$'s. X rays from $\bar{p}$ atoms have been observed at CERN in a measurement of the $\bar{p}$ mass, but the fine-structure splitting was not resolved.[2]

The magnetic moment can be written as

$$\mu=(g_0+g_1)\mu_N,$$

where μ_N is a nuclear magneton, $g_0=1$ for the proton and -1 for the $\bar{p}$, and g_1 is the anomalous part of the magnetic moment, equal to 1.79 for the proton. Then the fine-structure splitting of an atomic level is given by[3]

$$\Delta E=(g_0+2g_1)\frac{(\alpha Z)^4}{2n^3}\frac{m}{l(l+1)}, \qquad (1)$$

where Z is the nuclear charge, m is the reduced mass of the $\bar{p}$-nucleus system, and n and l are the principal and orbital angular-momentum quantum numbers, respectively, of the atomic level. Therefore, a measurement of the fine-structure splitting gives the magnitude and sign of g_1, the anomalous part of the magnetic moment, which can be compared to the proton's g_1.

The experiment was performed at the alternating gradient synchrotron of the Brookhaven National Laboratory. A beam of $\bar{p}$'s was formed by placing a 3-in. copper target in the 30-GeV external proton beam. The $\bar{p}$'s, produced at an angle of $10\frac{1}{2}°$ with a momentum of 750 MeV/c, passed through a magnet system with a solid-angle acceptance of 2.6 msr. The beam was separated and stopped in an x-ray target 15 m from the production target.[4] The $\bar{p}$ beam intensity was 1150 per pulse of 10^{12} protons on the production target, with a $\pi^-/\bar{p}$ ratio of 75. Of these, 340 per pulse stopped in a 5-g/cm^2 thick target.

Six counters were used to identify a stopping $\bar{p}$. Counters 1–4 were made from plastic scintillator, and a Cherenkov counter C was made from Lucite for counting pions. Two pulses were taken from counter 3—an anode pulse (3_a) for logic and a dynode pulse (3_d) for energy discrimination. Since $\bar{p}$'s stopping in the target should lose more

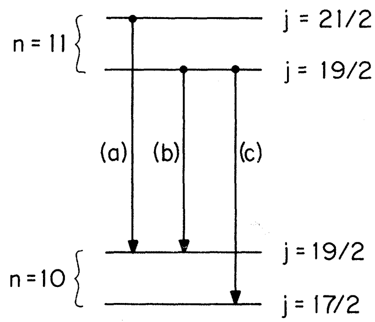

FIG. 1. Atomic-level diagram for the 11-10 transition. Arrows indicate allowed transitions. The intensity ratio $a:b:c=209:1:189$, assuming the levels are statistically populated.

energy in counter 3 than pions which pass through the target, the discrimination threshold on pulse 3_d was set high to count only $\bar{p}$'s. Also, a time-of-flight signal Z was derived from a counter placed about 8 m upstream. The signature for a stopping $\bar{p}$ was $123_a3_d4\,\bar{C}Z$ count.

Antiprotons were stopped in both natural Pb and U^{238} targets, and x rays were observed from the subsequent cascade through the atomic levels. The x rays were detected with a 50-cm^3 Li-drifted Ge detector (Princeton Gamma-Tech) which had a resolution (full width at half-maximum) of 0.9 keV at 122 keV. The data were stored in a 4096-channel pulse-height analyzer (Kicksort, model 711 A), and the gain of the detection system was stabilized on γ-ray lines from ^{152}Eu and ^{137}Cs. The transitions with largest intensity were between atomic levels with $n=l+1$. The highest energy transition observed in lead was the $n=10$ to $n=9$ transition; but this transition is close in energy to the 13-11 transition which could obscure a measurement of the fine-structure splitting, so the 10-9 transition was not used in our analysis. Since the $\bar{p}$ is captured by the nucleus from the $n=9$ level, the 9-8 transition and other higher-energy transitions were not observed. Therefore, the 11-10 transition was chosen for a fine-structure analysis.

Figure 1 shows the x rays which can be observed for transitions between the $n=11$ and $n=10$ levels. Only two lines are seen because the $n=11$, $j=\frac{19}{2}$ to $n=10$, $j=\frac{19}{2}$ x ray is very weak in intensity; thus the observed splitting is equal to the difference of the splittings in the $n=10$ and $n=11$ levels. The data for this transition are shown in Fig. 2. The positions of the centroids were determined by fitting Gaussian peaks to the data, and the best-fit peaks are shown. For the two lines observed, the expected intensity ratio of the low- to high-energy peaks is 1.11, whereas we measure 1.29 ± 0.17 for uranium. Since the lines in lead were not well resolved, we constrained the areas of the two peaks to equal the expected ratio of 1.11. The separation of the peaks in lead was determined to be 7.80 ± 0.65 channels, and, with our gain of 0.154 keV/channel, we obtain a fine-structure splitting of 1.20 $\pm$ 0.01 keV. For uranium we derived a splitting of 1.91 ± 0.09 keV. The errors are due to the statistical uncertainty of the data, and equal to 1 standard deviation.

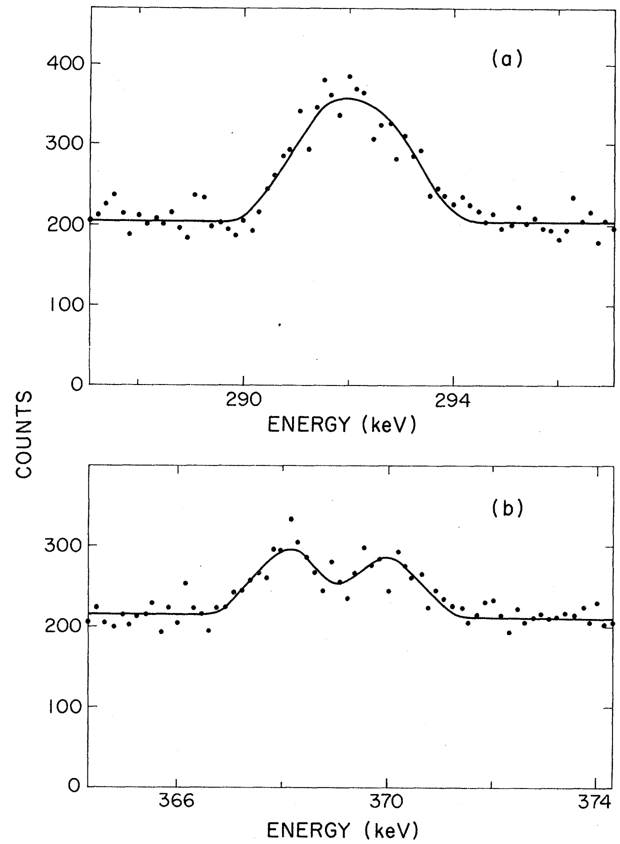

FIG. 2. $n=11$ to $n=10$ transition in (a) lead and (b) uranium. The lead data represent the results of 32×10^6 stopping $\bar{p}$'s, and the uranium data 36×10^6 stopping $\bar{p}$'s. The curve shows the results of fitting two Gaussians to the data.

From Eq. (1) we find $g_1=-1.83\pm0.19$ for Pb and -1.84 ± 0.11 for U, which can be combined to give an average of -1.83 ± 0.10. This result is in good agreement with the magnitude of the proton's anomalous moment of 1.79 but opposite in sign, as predicted by the TCP theorem.

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‡Present address: Brookhaven National Laboratory, Upton, N.Y. 11973.

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[4]For more details regarding the beam design, see J. D. Fox, BNL EP& S Division Technical Notes No. 7 and No. 20 (unpublished).

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FINAL-STATE INTERACTIONS IN NONLEPTONIC HYPERON DECAYS. J. H. Reid and N. N. Trofimenkoff [Phys. Rev. Lett. 27, 274 (1971)].

Equation (10) should be replaced by

$$Z(\alpha,\sigma)=[(M_\sigma+M_\alpha-M_\beta+M_\zeta)/2M_\sigma]\exp[\rho(-M_\alpha)-\rho(-M_\sigma)+i\delta_{1-}(M_\alpha)]+[(M_\sigma-M_\alpha+M_\beta-M_\zeta)/2M_\sigma]$$
$$\times\exp[\rho(-M_\alpha)-\rho(M_\sigma)+i\delta_{1-}(M_\alpha)].$$

Then the fit to the experimental decay amplitudes obtained with $\eta=0.625$, $D=-2.93\times10^{-5}$ MeV, and $F=3.87\times10^{-5}$ MeV is $A(\Lambda_-{}^0)=1.50$, $A(\Sigma_+{}^+)=-0.36$, $A(\Sigma_-{}^-)=1.87$, $A(\Xi_-{}^-)=-1.98$, $B(\Lambda_-{}^0)=11.1$, $B(\Sigma_+{}^+)=20.9$, $B(\Sigma_-{}^-)=-0.7$, and $B(\Xi_-{}^-)=3.9$, in units of 10^5 MeV$^{-1/2}$.

CALCULATION OF LOCAL EFFECTIVE FIELDS: OPTICAL SPECTRUM OF DIAMOND. J. A. Van Vechten and Richard M. Martin [Phys. Rev. Lett. 28, 446 (1972)].

The discussion around Eq. (7) should read as follows: The scattering efficiency is proportional to a factor $|\varphi(\vec{K})|^2$ in the notation of Freund and Levine,[16] which may be shown to be

$$\varphi(\vec{K})=\epsilon^{-1}{}_{\vec{K},0}\epsilon_{0,0}/(\epsilon_{0,0}-1). \tag{7}$$

In the present RPA calculation we find the largest φ to be $\varphi(111)\approx0.03$, nearly an order of magnitude smaller than the value of 0.28 estimated in Ref. 16 on the basis of a rigid-bond-charge model.

NEUTRON AND PROTON FORM FACTORS. C. L. Hammer and T. A. Weber [Phys. Rev. Lett. 28, 1675 (1972)].

A change in definition of the function $G_M(k^2)$ to include a factor of i was not made in Eqs. (15) and (16) of the published version. These equations should read, respectively,

$$S^p=-(2\pi)^{-2}ie^2\bar{u}_e(p_2)\gamma_\mu u_e(p_1)k^{-2}\bar{u}_p(p_4)\{\gamma_\mu[1-i\bar{f}_1{}^{p,M}(k^2)G_M(k^2)]$$
$$+\sigma_{\mu\nu}k_\nu[\mu_p/2m_p-i\bar{f}_2{}^{p,M}(k^2)G_M(k^2)]\}u_p(p_3)\delta(p_1+p_3-p_2-p_4), \tag{15}$$

$$G_M(k^2)=i(2\pi m^2)^{-1}\int_{\mathrm{c}}dm'\,\frac{(m/m')^4Z_1(m',m_1,m_1{}^*)}{(m'-m_1)(m'-m_1{}^*)}\,\frac{k^2+3m'^2\bar{f}_1{}^{\gamma,M}(k^2)}{k^2+m'^2-i\epsilon}. \tag{16}$$