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(Talk given at Research Progress Meeting on August 11, 1960)

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ABSTRACT

Double scattering of antiprotons of the momentum of 1.65 Bev/c in the 72-in. hydrogen bubble chamber has been studied experimentally. A method for the simultaneous determination of the antiproton polarization and the antiproton magnetic moment was proposed and applied in the analysis of 300 double-scattering events. An average polarization of 0.48 ± .09 was obtained in the angular region from 6 to 25 deg. The value of the antiproton magnetic moment was measured to be $\mu_{\bar{p}} = -1.9 \pm 1.4$ nuclear magnetons.

EXPERIMENT ON DOUBLE SCATTERING OF ANTIPROTONS IN HYDROGEN*

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This is the report on a measurement which was a part of the 72-in. bubble chamber antiproton experiment of the Alvarez group. The group members and other participants at various stages of the experiment included J. Button, P. Eberhard, G. Kalbfleisch, J. Lannutti, G. Lynch, A. McMullen, L. Stevenson, C. Rindfleisch, and N. Xuong.

INTRODUCTION

There have been no direct observations on the spin properties and the magnetic moments of antinucleons.

An attempt to detect the polarization of antiprotons produced in the Bevatron, by examining the asymmetry of antiprotons scattered in carbon, has given an inconclusive result.[1] In that measurement 970-Mev/c antiprotons were produced on a Be target at 5 deg in the laboratory (169° cm). For antiprotons scattered within 45 deg, the asymmetries obtained were:

$e_{\text{right-left}} = 0.12 \pm .17$ $\qquad$ $e_{\text{up-down}} = 0.18 \pm .15.$

Since e equals P_1P_2, it could not be determined whether the absence of asymmetries in a measurement of this kind was due to the real absence of polarization of the antiproton beam, P_1, or to the lack of analyzing power in carbon scattering, P_2.

We are reporting on a measurement with 960-Mev (1.65-Bev/c) antiprotons in which both the first and the second scattering are identical processes (except for a small energy difference). This makes $P_1 \cong P_2$ and reduces the experiment to measureing of only one observable quantity, $e = P^2$. However, such an experiment determines the magnitude but not the sign of the polarization, since we have $P = \pm\ e^{1/2}$.

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*This work was done under the auspices of the U.S. Atomic Energy Commission.

[1]Lewis E. Agnew, Antiproton Interactions in Hydrogen and Carbon below 200 Mev (Thesis) UCRL-8785, July 23, 1959.

The importance of measuring the antiproton polarization is threefold. First, the general theoretical importance is that it introduces spin-orbit interaction into the nucleon-antinucleon problem. If we write the scattering amplitude, a, as a sum of the central and the spin-flip scattering, $a = f + g$, the polarization is $P = \mathrm{Re}\, f\, g^*$ so that (with certain assumptions on f and g), experimental knowledge of P can determine the relative sign of the two types of interactions. Even if the actual sign of P is not known, the conclusions on the sign of the spin-orbit force can be drawn in some cases. In the region of small angles the coulomb scattering is dominant, f becomes $f_{coulomb}$, and the behavior of the P vs θ distribution is strongly influenced by the sign of the interference of the spin-orbit coupling with the coulomb scattering. That is, if the polarization changes sign at an angle where the coulomb amplitude is approximately equal to the nuclear amplitude, one can conclude that the spin-orbit force has the sign opposite to that of the coulomb force. A qualitative argument on this effect in nucleon-nucleus scattering, first given by Cassels,[2] has later been confirmed by the more refined calculations of Sternheimer.[3] If the sign of P does not change, no definite conclusions can be drawn unless a detailed shape of P vs θ is experimentally known at small angles. Of course, for a complete anlaysis of the problem, the phase difference, cos α, between f and g could be important, and a triple-scattering experiment would be needed. Second, if we learned how to produce polarized antiproton beams, we could study the spin dependence in reactions of the type $\bar{p}p \rightarrow \Lambda\bar{\Lambda}$ or $\Sigma\bar{\Sigma}$. Third, it is of practical importance in that polarization of the antiproton would make it possible to measure its magnetic moment.

The theory of antiproton polarization has not existed prior to this experiment. On the basis of qualitative arguments, we believed that $\bar{p}p$ could produce an appreciable polarization. The main feature of the theory of $\bar{p}p$ interaction of Chew and Ball is that the absorption is strongly spin dependent.[4] Some spin states are very attractive and lead almost entirely to annihilation (reflection R=0); other spin states are repulsive and lead entirely to elastic scattering (R=1). The theory has been worked out only up to about 300 Mev, but it is

[2] J. Cassels, Proceedings of the Fifth Annual Rochester Conference on High-Energy Physics, 1955. (Interscience Publishing Co., New York, 1955), p. 158.

[3] R. Sternheimer, Phys. Rev. 112, 1789 (1959).

[4] J.S. Ball and G. F. Chew, Phys. Rev. 109, 1385 (1958).

suggestive. One can believe that the relative importance of some spin states will change in going to 1 Bev; but there is no reason to believe that the general qualitative feature--spin-selective absorption--will disappear. For example, for P wave interaction, only three out of eight possible spin-isospin states take part in the elastic scattering (R= 1): $^1P_1^1$, $^1P_0^3$, $^3P_1^1$. The first and third mean $\uparrow\downarrow$ (no polarization); the second, $\uparrow\downarrow\downarrow$ (polarization). Thus we have

$$\frac{\text{No.}\uparrow - \text{No.}\downarrow}{\text{No.}\uparrow + \text{No.}\downarrow} = \frac{1-2}{3} = -\frac{1}{3} = -33\%.$$

At our energy, we have $\ell_{max} = 4$, so the D, F, and G waves participate as well. This is only an illustrative example, but it suggests that it is not altogether hopeless to look for $\bar{p}$ polarization.

In general, intensity presents the main problem in double-scattering experiments: the single scattering yield for a reasonable target thickness and geometry in any non-bubble-chamber experiments is about 10^{-3}. Hence, for double scattering, it is about 10^{-6}. However, use of the volume of hydrogen in the dual role of scatterer and detector affords two unique features: (1) an attendant large available solid angle and (2) a high (practically infinite) angular resolution. The mean free path for an elastic $\bar{p}p$ scattering is about six lengths of the 72-in. bubble chamber so that the double-scattering yield is $\frac{1}{6} \cdot \frac{1}{6} = (36)^{-1} \sim 10^{-2}$. (The actual practical figure is 0.6×10^{-2}.)

Before presenting the experimental data, we list some relations relevant to double-scattering experiments which we shall use. For right-left asymmetry we have

$$e_0 = \frac{RR + LL - RL - LR}{RR + LL + RL + LR} = \frac{A - B}{A + B}. \quad (1)$$

This equation is correct when two scattering planes are exactly parallel (or antiparallel). In general, we have

$$e = e_0 \left| \cos \Phi \right| , \quad (2)$$

where Φ is the angle between the first and second scattering planes. Relation (2) is a useful check to see if an asymmetry found is a genuine effect; the asymmetry should be a straight line when plotted against $\left| \cos \Phi \right|$. In addition since we have

$$e = P^2, \quad (3)$$

we also have

$$P^2 = P_0^2 \left| \cos \Phi \right| . \quad (2')$$

To obtain the polarization we first compute the angle $\overline{\Phi}$ for each event. If e behaves like Eq. (2), we weigh each event with its $\cos \overline{\Phi}$ and evaluate the asymmetry, e, according to

$$e = \frac{A - B}{A + B} = \frac{\sum^{A+B} \cos \overline{\Phi}}{\sum^{A+B} \cos^2 \overline{\Phi}} , \tag{4}$$

which is a combination of Eqs. (1) and (2). Finally, P is obtained by using Eq. (3).

The fractional error in asymmetry is

$$\frac{\partial e}{e} = \frac{1 - e^2}{2e} \left(\frac{1}{A} + \frac{1}{B} + \frac{2}{\sqrt{AB}} \right)^{1/2} , \tag{5}$$

while in polarization it is

$$\frac{\partial P}{P} = \frac{1}{2} \frac{\partial e}{e} , \tag{6}$$

i.e. the statistics of, for example, 100 double scatterings are comparable to statistics of about 400 single events except for the small cross term $2/\sqrt{AB}$.

Another way to represent the polarization is by the likelihood function

$$L(P) = \prod_{k}^{A+B} (1 + P^2 \vec{n}_1 \cdot \vec{n}_2) , \tag{7}$$

where $\cos \overline{\Phi}_k = \vec{n}_1 \cdot \vec{n}_2$. We shall use the likelihood-function method in addition to Eq. (4), particularly in the part of this work dealing with the magnetic moment of the antiproton.

EXPERIMENTAL DATA

The separated 1.64 ± .20 Bev/c (960 Mev) antiproton beam has been described elsewhere.[5] An integrated flux of 4.6×10^4 antiprotons entered the 72-in. bubble chamber during the exposure. The statistics of the sample of events related to this measurement are:

[5] J. Button, P. Eberhard, G.R. Kalbfleisch, J. Lannutti, G.R. Lynch, B.C. Maglić, M.L. Stevenson, N. Xuong, The Reaction $\overline{p}+p \rightarrow \overline{\Lambda} + \Lambda$, UCRL-9347, August 10, 1960.

(1) Number of (2-prong) → (2-prong) events 900
(2) Rejected on scanning tables as inelastic, unmeasurable, outside the central zone of the chamber, or due to π-mesons (δ-rays > 1.7cm) 276
(3) Recoil-proton rescatters....................................159
(4) Number of 2p → 2p events measured; (1)-(2)-(3)..............465
(5) Rejected as noncoplanar, KICK-rejects, pc too low (below 1.60 Bev/c), and angles too large (>25 deg)..................172
(6) Total identified as $p\bar{p}$, elastic, double-scattering events above 1.60 Bev/c and in the angular region 3 to 25 deg.......293

The upper limit of 25 deg to the scattering angle corresponds to 54 deg in the center-of-mass and to a momentum loss larger than 200 Mev/c (energy loss ~160 Mev).

Throughout this work we assumed that the initial antiproton beam was unpolarized. Our numerical conclusions will have to be modified if this assumption turns out to be incorrect. At present, measurement of the single-scattering events, now in progress, has set an upper limit of 20% to the initial polarization.

RESULTS ON POLARIZATION

We have first plotted the angular distribution of all single-scattering events, including those above 25 deg. This plot is shown in Fig. 1 together with the data of Armenteros et al. obtained at the same energy.[6] It is interesting to note that 1 to 2% of the antiprotons scatter in the backward hemisphere. The solid curve was calculated using the phenomenological optical model of Greider and Glassgold.[7] The dashed curve is obtained with the exact black-sphere model and is drawn only where two solutions are substantially different. To obtain the polarization, the angle Φ between the two scattering planes was computed for each event by using fitted values for azimuthal and dip angles. The distribution of cos Φ is shown in Fig. 2. The polarization, P, obtained from these events is shown in Figs. 3 and 4. To evaluate P more accurately we used Eq. (4).

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[6] R. Armenteros, C. A. Coombes B. Cork, G. L. Lambertson, and W. A. Wenzel, Antiproton-Proton Cross Sections at 1.0, 1.25, and 2.0 Bev, UCRL-8851, March 21, 1960.

[7] K. Greider and A. Glassgold, Annals of Physics 10, 100 (1960).

A sample of 197 events in the region 6 deg $< \Theta <$ 24 deg gave an average asymmetry $e = +0.21 \pm .06$ and the polarization

$$P = \pm 0.46 \pm .09. \quad (8)$$

A sample of 99 events in which one scatter occurred in the region 3 deg $< \Theta <$ 6 deg yielded $e = -0.024 \pm .11$ which gives

$$P = \mp 0.04 \pm .19 \quad (9)$$

as an average P between 3 and 6 deg.

THE MAGNETIC MOMENT OF THE ANTIPROTON

The 72-in. bubble chamber has a vertical magnetic field of 18 Kgauss. Since the spin-polarization vector $\vec{P}$ is parallel to the magnetic moment, $\vec{\mu} = g\vec{S} = (g/2)\,\vec{n}_1$, where $\vec{n}_1$ is the unit vector normal to the scattering plane, the μ of the antiprotons will be subjected to a precession between the two scatterings. Those antiprotons that first scatter in the horizontal plane will have $\vec{\mu} \,||\, \vec{B}$, and the μ precession will not change the direction of $\vec{\mu}$. On the other hand, those antiprotons which first scatter in the vertical plane will have $\vec{\mu} \perp \vec{B}$, and the direction of μ will be subjected to a maximal rotation about $\vec{B}$. This is equivalent to an apparent depolarization before the second scattering, which will result in a decrease of the asymmetry in those events that scattered both times in the vertical plane. The net result is a difference between the right-left asymmetry e_{RL} and the up-down asymmetry e_{UD}. It can be shown that $e_{UD}/e_{RL} \cong \cos\delta$, where δ is the angle between $\vec{\mu}$ and the particle momentum just before the second scattering. It is well-nown that the angle δ is proportional to the deflection in the magnetic field ϕ,

$$\delta = \gamma\,(\mu - 1)\,\phi. \quad (10)^*$$

In our bubble chamber the deflection is $\overline{\phi} = 7.5$ deg. With $\gamma = 2$ and $\mu = +2.78$, we have $\overline{\delta} = 27$ deg.

To account for all intermediate cases between "right-left" and "up-down" we use the likelihood function,

$$L(P) = \prod_k^N \left(1 + P^2\,\vec{n}_1 \cdot \vec{n}_2\right) = \prod_k^N \left(1 + P^2 \cos \underline{\phi}_k\right), \quad (11)$$

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*We consider the relative sign of μ and the charge q i.e., in the above relation μ was assumed to have the same sign as q.

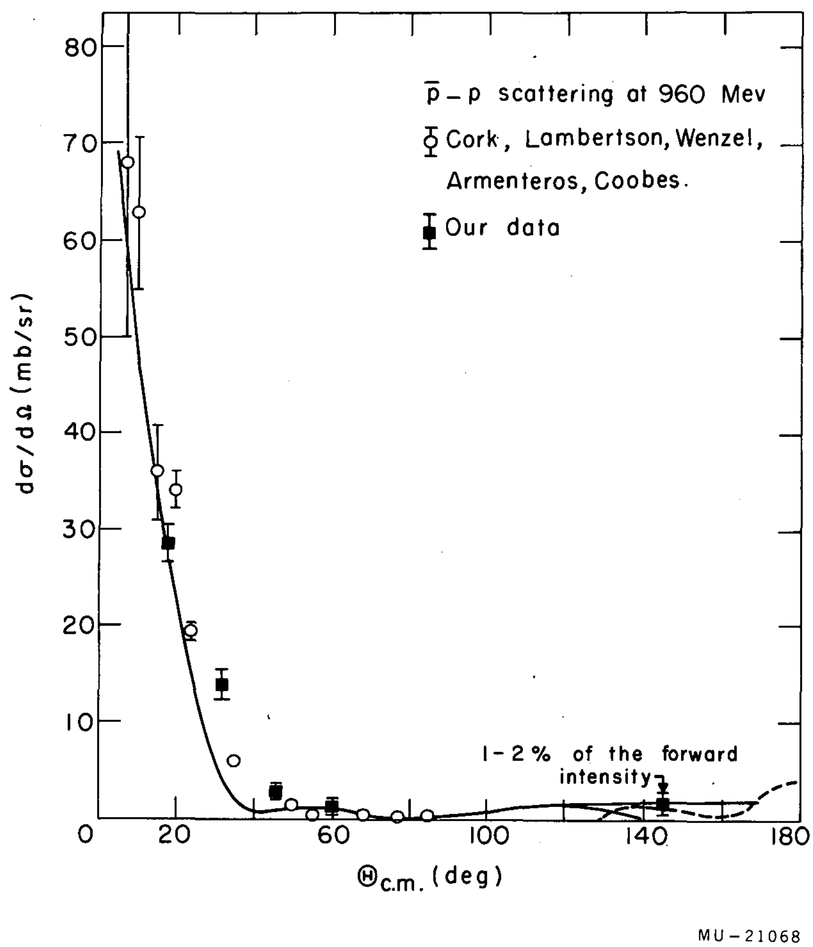

Fig. 1. Angular distribution of elastically scattered antiprotons in hydrogen at 900 Mev. The solid line was calculated using the phenomenological optical model of Greider and Glassgold. The dashed curve is obtained with the black-sphere model and is drawn only where the two solutions are substantially different.

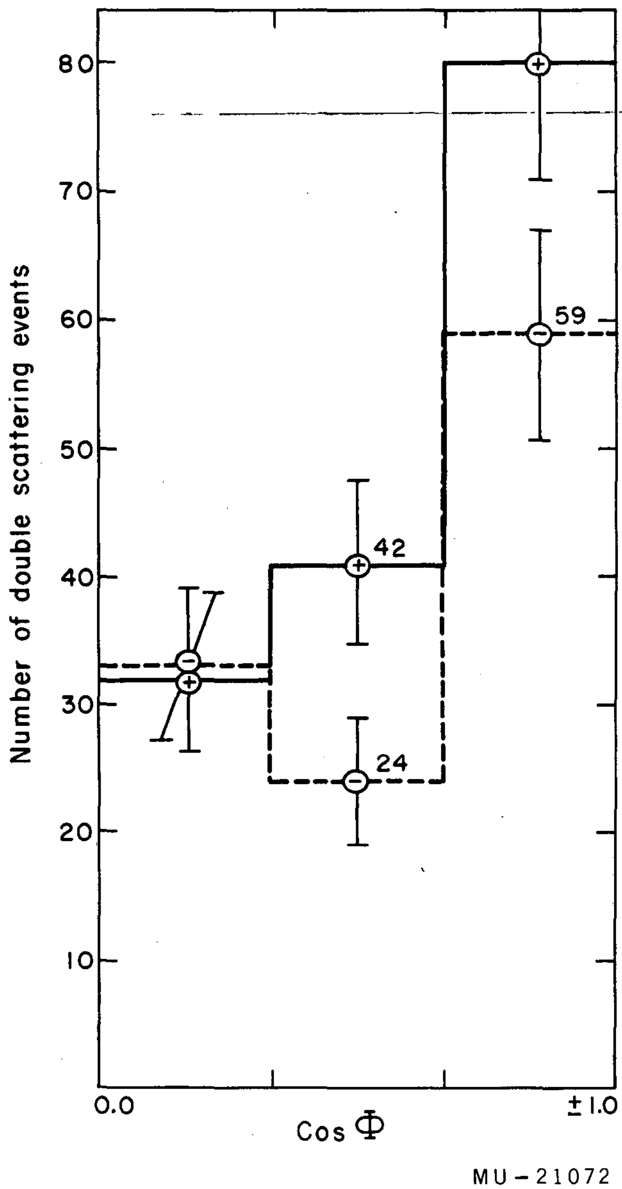

Fig. 2. Number of double-scattering events *vs* cos Φ. In this diagram, + and - refer to the sign of cos Φ.

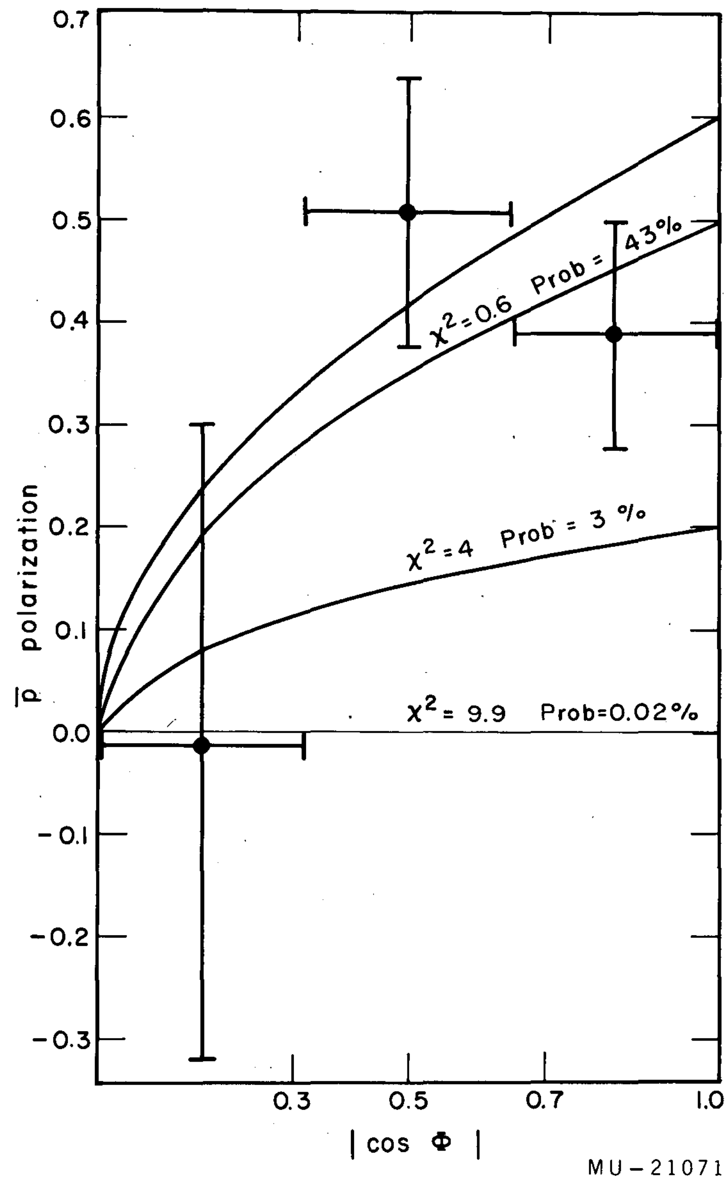

Fig. 3. Polarization vs cos Φ.

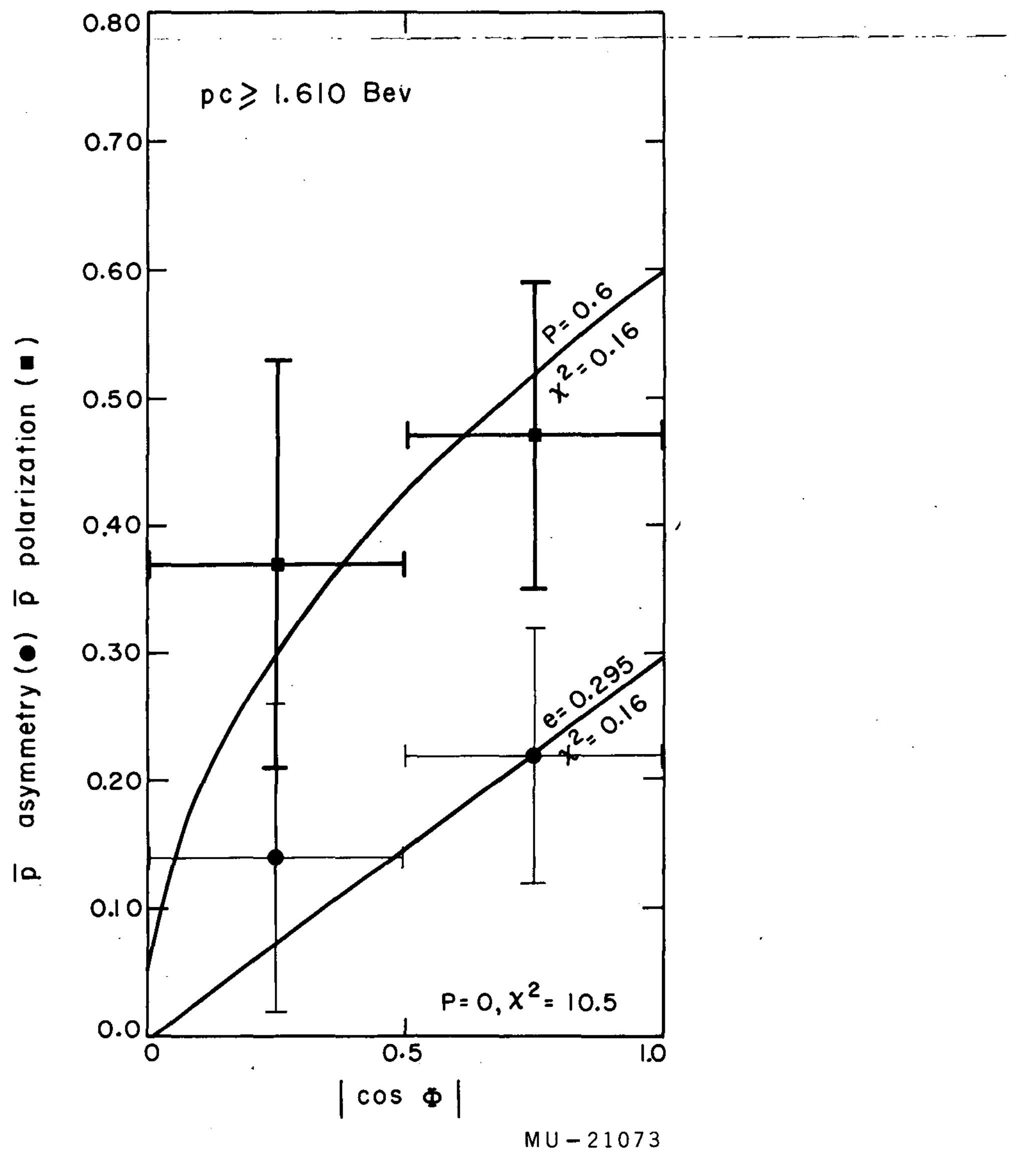

Fig. 4. Polarization and asymmetry vs cos Φ for events pc $\geq$ 1.61 Bev.

where K is k the index number of the event, and N is the total number of events. Clearly, the spin direction right after the first scattering $\vec{n}_1$ will change before it reaches second scattering $\vec{n}_1 \rightarrow \vec{n}'_1$. It can be shown that an element of the modified likelihood function becomes

$$Z_{ijk} = 1 + P^2 \vec{n}'_1 \cdot \vec{n}_2 = 1 + \frac{P_i^2}{(\sin\Theta_1 \operatorname{Sin}\Theta_2)} \Big[(\alpha_1\alpha_2 + \beta_1\beta_2) \cos\delta_i - (\beta_1\alpha_2 - \alpha_1\beta_2) \sin\delta_j + \gamma_1\gamma_2 \Big] , \tag{12}$$

where α_1, β_1, γ_1, and α_2, β_2, γ_2 are geometrical parameters for the first and second scattering, respectively, and Θ_1 and Θ_2 are scattering angles. For example, the parameter α_1 is

$$\alpha_1 = y_{11}Z_{12} - y_{12}Z_{11} = \cos\lambda_{11} \sin\phi_{11} \sin\lambda_{12} - \cos\lambda_{12} \sin\phi_{12} \sin\lambda_{11}.$$

From each event we feed its nine measured parameters (eight angles and one momentum) into Eq. (12). Then 34 values of P_i^2 in the range -1 to +1 are given for each value μ_j and 17 values of μ_j in the range -6 to +6 nm are given for each value P_i. This makes a total of 34 $\times$ 17 = 578 values of Z_{ij} for each event k. In practice, we reduced the number of Z_{ij} to 181 for each event, since we narrowed the range of P_i by an iteration procedure. For the next event, say event No. 2, another 181 Z_j are computed. Then each of these 181 Z_{ij}'s from event No. 1 are multiplied by the corresponding Z_{ij} of event 2, etc. The likelihood function so obtained,

$$L(P_i, \mu_j) = \prod_{k=1}^{N} Z_{ijk} , \tag{13}$$

represents a surface in three dimensions. By inserting a range of values P_i and μ_j into it, we seek those values for which the surface has a maximum, and so determine the polarization and the magnetic moment of the antiproton simultaneously.

A program called PAP was written to handle this analysis on the IBM 704 computor. The final product of 200 events is shown in Fig. 5. We see that the maximum is at P=0.51, μ= -1.9. Figures 6 and 7 represent two perpendicular cuts through the maximum. We have fed several sets of random numbers (each simulating 200 double scatterings) into the likelihood function and have convinced ourselves that the peak is not an analytic property of

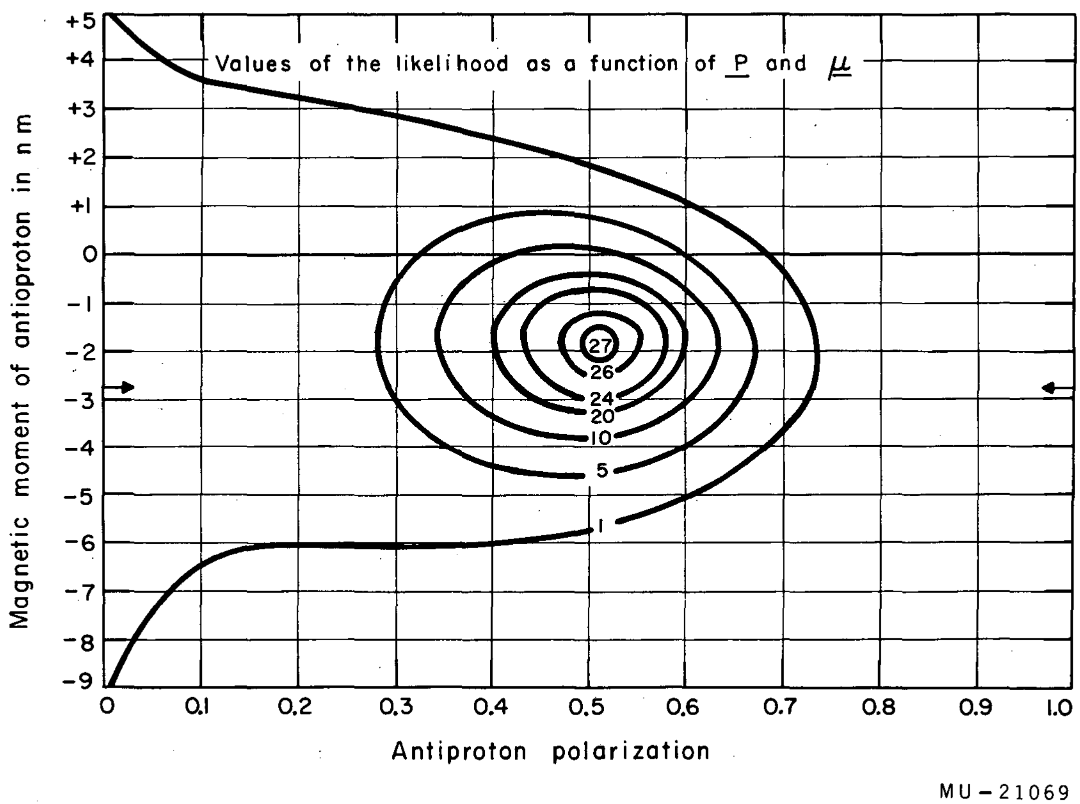

Fig. 5. Three-dimensional plot of L vs P and $\mu_{\bar{p}}$.

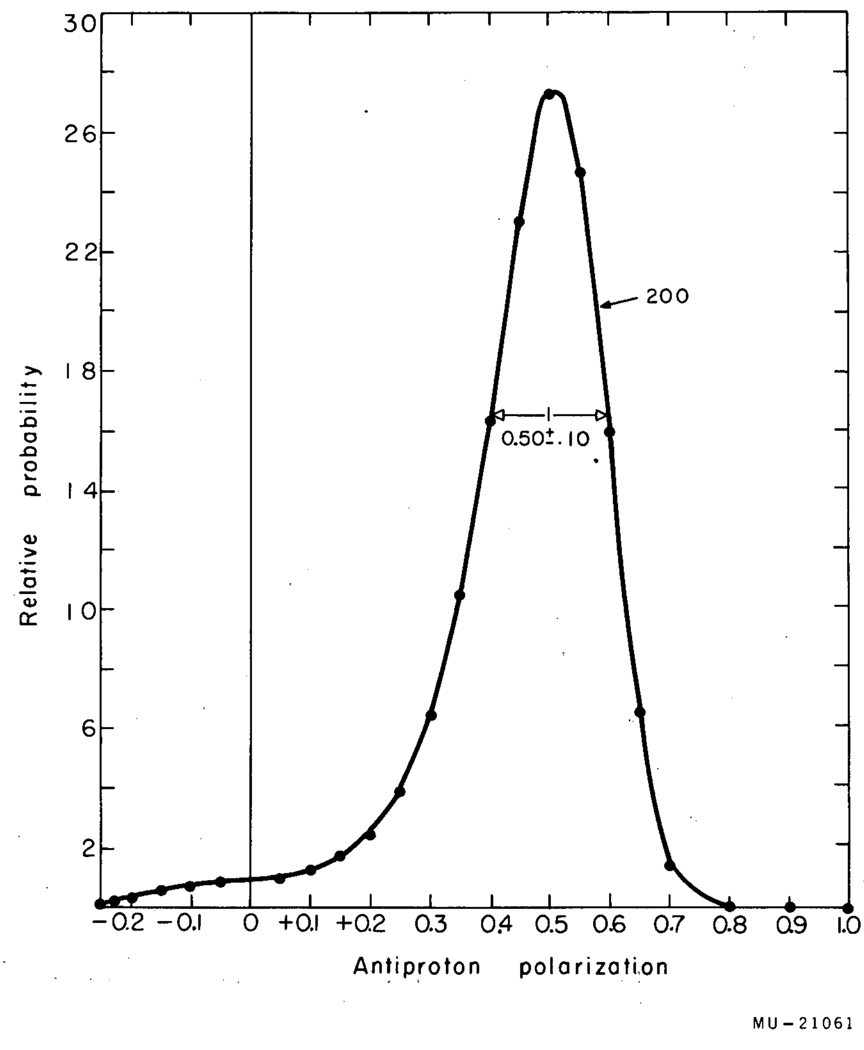

Fig. 6. Relative probability vs antiproton polarization.

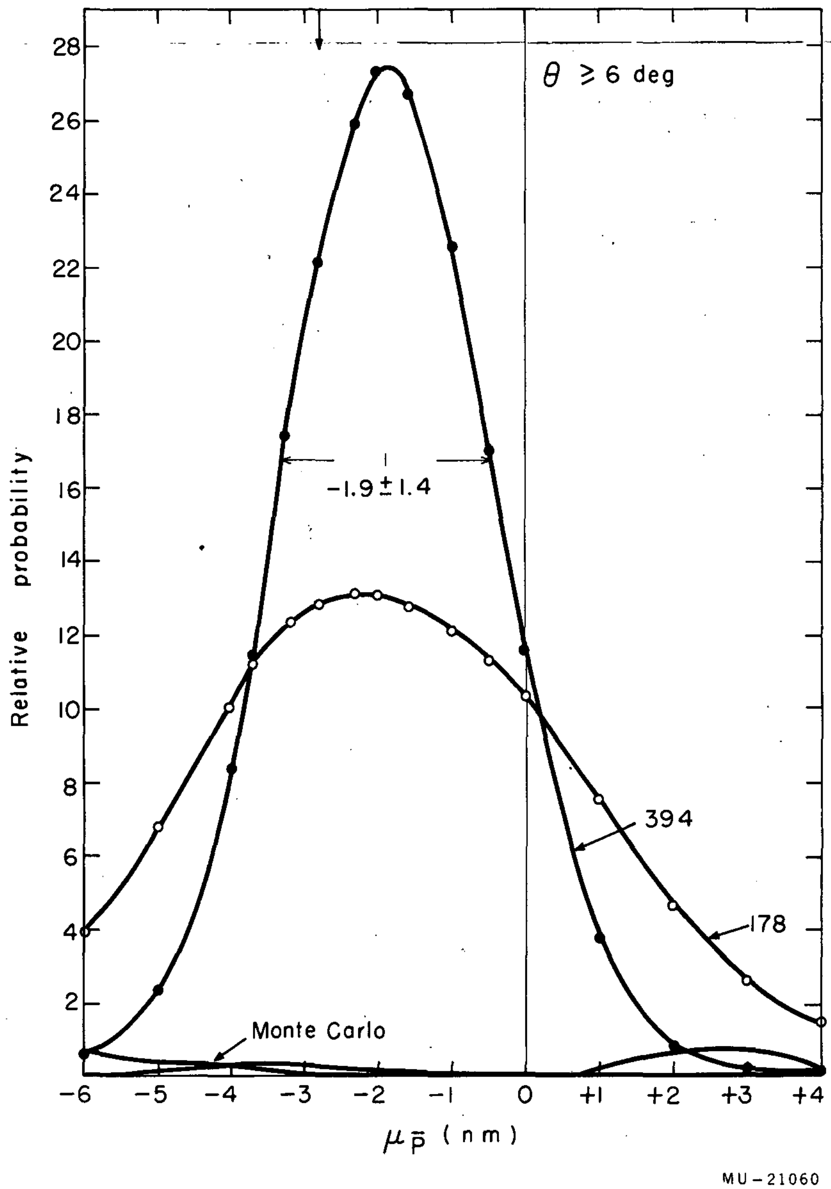

Fig. 7. Relative probability vs antiproton magnetic moment. The curves labeled "Monte Carlo" are obtained in three "experiments" with random numbers.

Eq. (12). We believe it reflects a real difference between e_{RL} and e_{UD}, which we can now ascribe only to the magnetic moment of the antiproton.

Our experimental results can be summarized as follows.

(1) Polarization. Average result of two methods [likelihood and Eq. (1)] :

$$P(6 - 25 \text{ deg}) = \pm\ 0.48 \pm .095$$
$$P(2 - 6 \text{ deg}) = \mp\ 0.04 \pm .20 \qquad (14)$$

(2) Magnetic moment:

$$\mu_{\bar{p}} = -\ 1.9 \pm 1.4 \text{ nm}. \qquad (15)$$

Our results can be interpreted as an evidence for the spin of the antiproton and for the sign of its magnetic moment.

On basis of charge conjugation the magnetic moment of antiparticles is expected to have an opposite sign to that of the corresponding particles. Our result [Eq. (15)] establishes the negative sign of the antiproton magnetic moment.

As for the spin properties of the antiproton, we believed we would be able to go a little further and draw some more specific conclusions than just the statement that the antiproton has a spin (of 1/2). Unfortunately, our experiment has not determined the sign or the shape of P vs θ in the angular region of coulomb scattering.