UCRL-10949

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Contract No. W-7405-eng-48

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This report describes the use of a target containing polarized protons in a particle-scattering experiment.[1] Positive pions of 246-MeV kinetic energy were scattered from the polarized protons. The parameter P that was measured is equivalent to that determined by analyzing the recoil-proton polarization in scattering from an unpolarized target. It has been measured to a higher accuracy than heretofore achieved in pion-proton scattering, at an energy and at angles inconvenient for double-scattering techniques.

The target material was a 26-g, roughly one-inch-cube sample of crystalline lanthanum magnesium double nitrate: $La_2Mg_3(NO_3)_{12} \cdot 24H_2O$, grown from a solution in which 1% of the lanthanum is replaced by even isotopes of neodymium. The hydrogen nuclei in the water of hydration are polarized by a method developed at Saclay[2,3] and at Berkeley.[4,5] During this experiment, the average proton polarization was 22%. At various times a polarization of 27% was achieved for periods of more than 2 hr. The hydrogen constitutes only 3% of the weight of the crystal. In this experiment it was shown that by use of the kinematics of two-body scattering from a free particle at rest, the true hydrogen events can be separated satisfactorily from the background.

The sample is maintained in a microwave cavity at a temperature of 1.2 to 1.5°K by bathing it in superfluid helium, and in a magnetic field of 9100 G. Under these conditions the neodymium ions act similarly to single unpaired electrons whose spins are about 60% polarized. Microwave power is applied at the proper frequency (near 35 kMc in this case) and in sufficient intensity to saturate the "forbidden" transition in which the neodymium polarization is transferred to the protons. Spin-lattice relaxation processes are such that the neodymium ions return promptly to the thermal-equilibrium polarization and are thus available to polarize many protons. The proton polarization relaxes slowly with a time constant of 10 to 20 min when the microwaves are turned off. Either sign of proton polarization can be obtained by proper choice of which "forbidden" transition is saturated. The change from one to the other is effected by a 0.3% change in microwave frequency, or in magnetic field.

The target polarization is measured by detecting the nuclear magnetic resonance (NMR) signal from the hydrogen nuclei with a Q-meter detection system. The size of the NMR signal when the protons are highly polarized is compared to the signal size at thermal equilibrium (microwaves turned off), for which the polarization can be calculated easily. At $1.2^{\circ}$K and 9100 G, the proton thermal-equilibrium polarization is 0.075%. When microwaves are applied, signal sizes become typically 200 to 400 times larger. Because of the large sample size and high polarization obtained, the NMR signal is not exactly proportional to the polarization. Corrections have been applied to take account of the nonlinearity due to $\Delta Q/Q$ being appreciably large (0.1); a change of Q due to a temperature change when microwaves are turned on (10% change); and a considerable change in shape of the proton NMR signal when the polarization is large. It is estimated that the average absolute polarization of the sample is known to within $\pm$ 15% of itself.

Two methods were used to discriminate between background events and the scattering from polarized protons:

1. When the recoil proton had sufficient energy to escape from the target, coincidence between this proton and the scattered pion was required. Counters (about 2 by 1-1/2 in. at 4 ft from the target) were placed at five fixed angles to detect recoil protons. All five were separately in coincidence with a common

counter which overlapped them all (to reduce chance coincidences) and with the pion counter. The pion counter (4-1/2 by 4-1/2 in. at 22 in. from the target) was mounted on a circular rail and could be moved to the position appropriate for hydrogen-event coincidences with each of the proton counters. Figure 1 shows the relative counting rate in one of the five coincidence channels when the pion counter was placed at various angles to the beam, while the proton counter remained fixed. At the position of the pion counter which satisfies two-body kinematics, the hydrogen events give a peak that is about one and one-half times background. This ratio depends on instrumental parameters such as beam momentum spread, target size, multiple scattering in the target, and detector geometry.

As a check on this background, a dummy target was substituted for the polarized sample. This dummy was made up of elements like those in the crystal, in the same proportions, but not containing hydrogen. The counting rate, as a function of pion-counter angle, with the dummy target is also indicated in Fig. 1.

2. At smaller scattering angles, the energy and the angle of the scattered pion alone were used to distinguish the elastic scattering on hydrogen. This method is inferior to the two-particle coincidence technique, especially since there is no coplanarity requirement, but it still serves to identify the hydrogen events. A range telescope was set up to detect pions scattered at a given angle which traversed a given thickness of copper. Figure 2 is a differential range curve, showing the number of particles that penetrated a variable thickness of copper but did not register in the veto counter behind an additional 11 $g/cm^2$.

The slight rise in counting rate in the vicinity of 60 $g/cm^2$ variable moderator is attributed to mesons elastically scattered on hydrogen. This is the expected range of these mesons. The asymmetry was measured at the point on the range curve where the fraction of hydrogen events was largest, as indicated in Fig. 2. The range curve with dummy target substituted is also shown in Fig. 2 and gives a quantitative estimate of this fraction.

In both Figs. 1 and 2, the slight rise in counting rate from the dummy target at the points where the hydrogen events are expected to occur is attributed to scattering from the hydrogen in the mylar He container and in the mylar window of the vacuum can which surrounded the target. This explanation is supported by data taken with the target completely removed.

The parameter P was measured at five angles by using the pion-proton coincidence method, and at two angles by using the pion range telescope. Counts were taken alternately with each sign of the target polarization. The "up" direction is defined as $(\vec{p}_\pi)_{incident} \times (\vec{p}_\pi)_{final}$. The effect observed is then

$$\epsilon = \frac{N(up) - N(down)}{N(up) + N(down)},$$

where N(up) and N(down) refer to the counting rates when the target polarization is in the up(down) direction. The numerator can arise only from scattering from the polarized protons. It carries a considerable statistical error, since the effect observed was generally only a few per cent. The systematic errors in measuring the polarization or determining what fractions of events were background are small compared to the statistical errors in this experiment.

The parameter P may be calculated from the data as

$$P = \frac{\epsilon}{\text{target polarization}} \times \frac{\text{No. total counts}}{\text{No. hydrogen events}}.$$

Table I gives the pertinent data and results, which are plotted in Fig. 3.

The curve in Fig. 3 is the parameter P calculated from a set of phase shifts extrapolated to our energy from the SPD Fermi I set obtained by Rogers et. al. at 310 MeV.[6] In the extrapolation, simple $\eta^{2\ell+1}$ behavior was assumed for all phase shifts except $P_{33}$, which was assumed to have a Chew-Low-type energy behavior.[7] This curve contains no Coulomb corrections; it was calculated from a set of purely nuclear phase shifts.

Additional pion range curves were taken at even smaller angles to determine the limitations of this method. When the recoil takes off as much as 35 MeV, the pion differential-range curve still shows the hydrogen-elastic peak resolved from the peak at its upper end due to coherent scattering on nuclei. With the background subtraction based on dummy-target data, one can separate the hydrogen events when the recoil energy is as little as 20 MeV.

In conclusion, we may say that the polarized target technique can now be applied to measure the P parameter at all energies in the $\pi$-p (and K-p) systems, and hopefully settle phase-shift ambiguities and spin-parity assignments. The double- and triple-scattering parameters in proton-proton scattering are also now more easily measured. The polarized target also makes possible the direct measurement of the relative intrinsic parities of strange particles,[8] and of the spin-rotation parameters[9] in systems like pion + proton, which are not accessible without this technique.

Since completion of this experiment we have achieved polarizations above 50%, using a microwave generator of 70 kMc, and a magnetic field of 19,000 G.

We wish to acknowledge the help of Messrs. J. Arens, F. Betz, B. Dieterle, H. Dost, and W. Troka in setting up and running this experiment. We are indebted to Mr. Roger Hill for his interest and for his estimate of the polarization to be expected at 250 MeV. Finally, we acknowledge the work of the crew of the 184-inch cyclotron and of the many other workers at the Lawrence Radiation Laboratory, without whose support this project could not have been carried out.

## FOOTNOTES AND REFERENCES

* This research supported by the U. S. Atomic Energy Commission.

** On leave from Centre d'Etudes Nucleaires, Saclay, France.

1. A separate article is being prepared to describe the operation of this target.

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Table I. Data and results. The parameter P in $\pi^+$-p elastic scattering at 246 MeV.

| $\theta_{c.m.}$ | Method of discrimination | Raw asymmetry $\epsilon$ | Average target polarization | Fraction hydrogen counts | P |
|---|---|---|---|---|---|
| 69° | range telescope | 0.0163 ± 0.0068 | 0.248 | 0.221 | 0.297 ± 0.145 |
| 82° | range telescope | 0.0149 ± 0.0071 | 0.222 | 0.193 | 0.364 ± 0.125 |
| | | 0.0182 ± 0.0046 | 0.269 | 0.179 | |
| 108° | π-p coincidence | 0.0241 ± 0.0061 | 0.198 | 0.577 | 0.211 ± 0.075 |
| 118° | π-p coincidence | -0.0031 ± 0.0066 | 0.212 | 0.449 | -0.033 ± 0.071 |
| 128° | π-p coincidence | 0.0036 ± 0.0074 | 0.194 | 0.593 | 0.031 ± 0.064 |
| 137° | π-p coincidence | -0.0067 ± 0.0061 | 0.300 | 0.523 | -0.064 ± 0.059 |
| 147° | π-p coincidence | -0.0155 ± 0.0068 | 0.219 | 0.489 | -0.145 ± 0.064 |

# FIGURE CAPTIONS

Fig. 1. Discrimination against background by $\pi$-p coincidences. Open circles show counting rate vs position of pion counter. Black circles show similar data for a dummy target containing no hydrogen.

Fig. 2. Discrimination against background, using range telescope. The solid curve (black circles) shows differential range distribution of pions emitted at a fixed laboratory angle. The dashed curve (open circles) shows similar data for a dummy target containing no hydrogen.

Fig. 3. The parameter P in $\pi^+p$ scattering at 246 MeV. The solid curve is explained in the text.

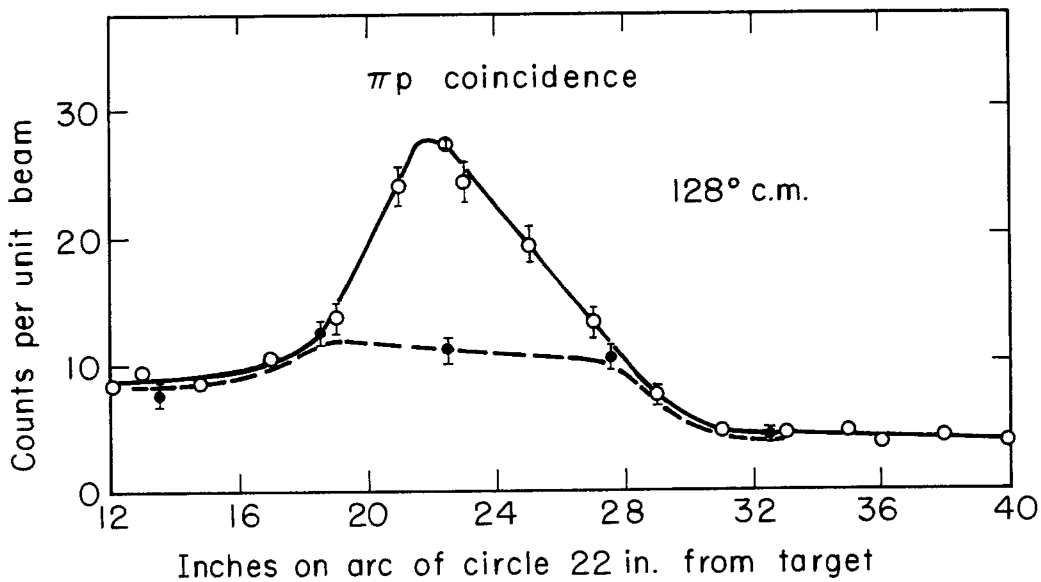


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Fig. 1

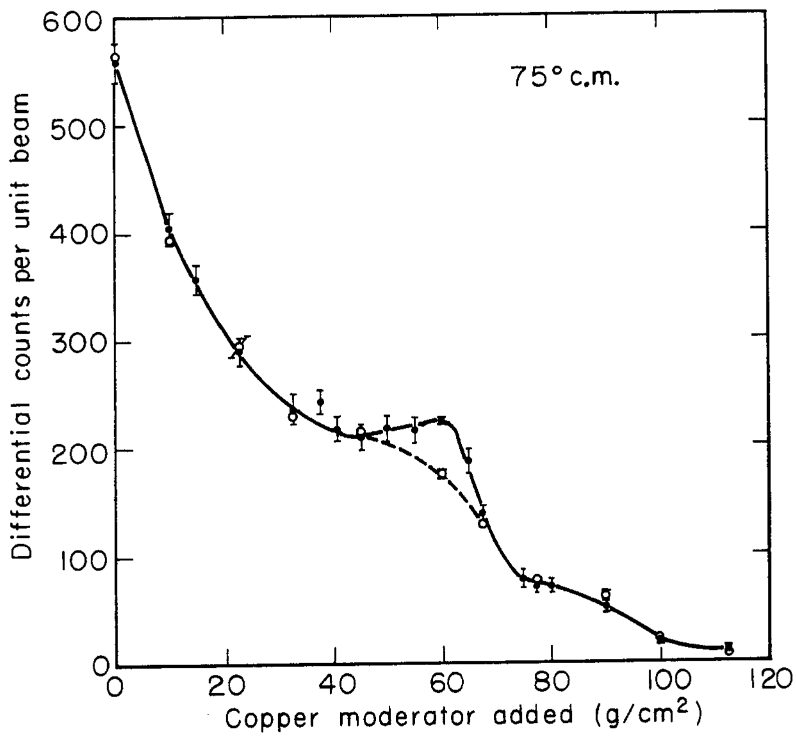


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Fig. 2

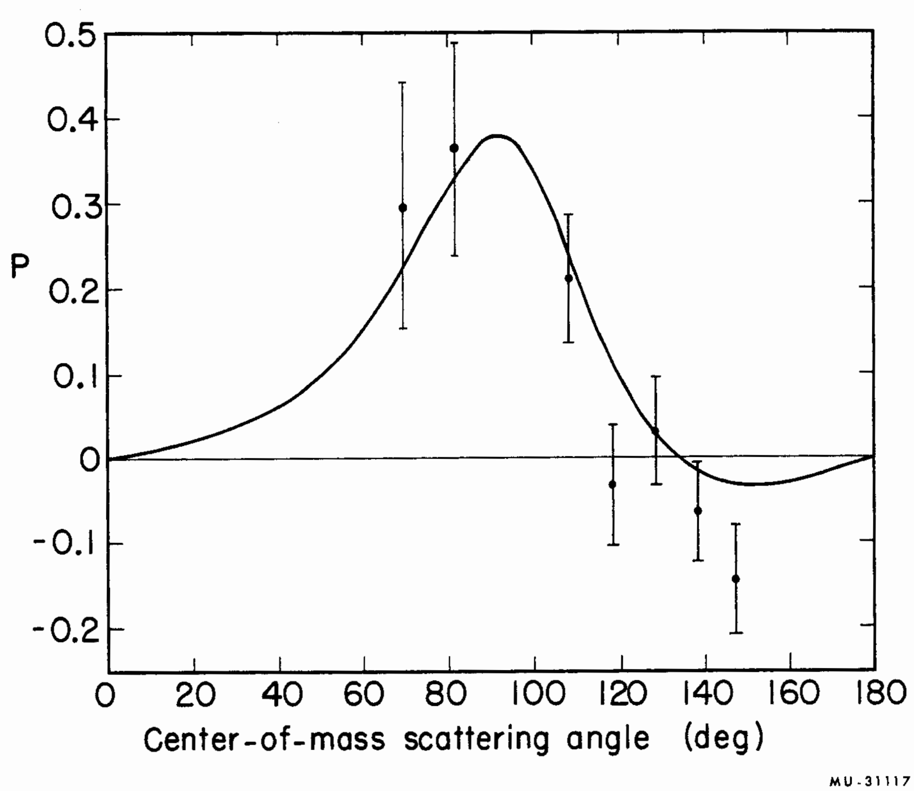
0.5
0.4
0.3
P
0.2
0.1
0
-0.1
-0.2
0
20
40
60
80
100
120
140
160
180
Center-of-mass scattering angle (deg)
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Fig. 3