This work is being continued in the direction of increasing the path length (and also the time spent) between exciting and detecting coils, with a view to possibly obtaining narrower resonant responses.

The author wishes to thank Professor R. H. Dicke for frequent advice during the course of the work.

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[2] George Benedek, "An Experiment to Determine With High Precision the Average Value of a Magnetic Field Over an Extended Path in Space," Harvard University, June 4th, 1952 (unpublished).

Experiments with High-Energy Polarized Protons*

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THERE have been recent reports[1,2] on high-energy polarized proton beams and their scattering properties. We also have been scattering protons in the Berkeley cyclotron and investigating their polarization by double-scattering experiments and we wish to give at this time a progress report because the data so far collected appear of interest.

The beam is polarized by scattering on target A of beryllium or carbon (Fig. 1) and is deflected by a steering magnet into the shielded experimental area (cave).

The angle of scattering Ψ in a horizontal plane and at target A varies between 17° and 20° in different experiments. The energy

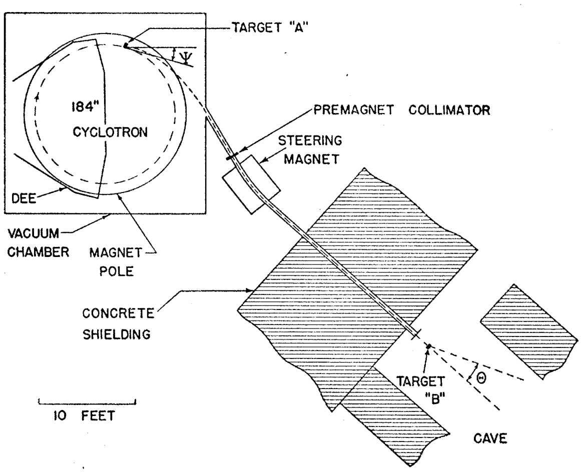

FIG. 1. Plan view of the experimental arrangement showing the angles Ψ and Θ at the first and second targets. The angle Φ, measuring rotation of the apparatus in the cave around the beam, is equal to zero for the configuration shown.

E_0 of the primary beam is 340 Mev. The scattered beam follows an orbit as drawn in Fig. 1 and its energy is approximately $E=E_0\cos^2\Psi$ as if it underwent an elastic scattering on a free nucleon. E is measured by a range determination.

The following experiments show that the beam between targets A and B is polarized: A second scatterer B, in the cave, scatters the beam by an angle Θ. To completely define the direction of the scattered beam we need also an angle Φ between the plane of the incident and scattered beam and the horizontal plane in which Ψ has been measured. For a given Θ the scattered intensity I is a function of Φ and we call

$$e(\Theta)=[I(\Phi=0°)-I(\Phi=180°)]/[I(\Phi=0°)+I(\Phi=180°)].$$

By the use of targets A and B of carbon, measured values of I at $\Theta=15°$ are found to be as follows: $I(\Phi=0°)=134.1\pm4.0$, $I(\Phi=90°)=101.8\pm3.7$, $I(\Phi=180°)=59.3\pm4.3$, $I(\Phi=270°)=104.7\pm3.3$, from which $e=0.39\pm0.04$; and $[I(\Phi=90°)-T(\Phi=270°)]/[I(\Phi=90°)+I(\Phi=270°)]=0.01\pm0.02$, which is a satisfactory check indicating that the polarization is a real effect.

When liquid hydrogen was used as scatterer B, we found that $e(\vartheta)$, where ϑ is the scattering angle in the c.m. system, is given by the curve of Fig. 2. It will be noticed that e(90° c.m.) is consistent

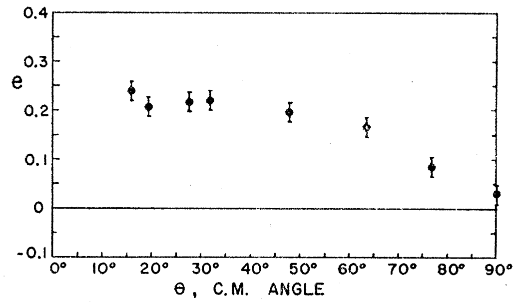

FIG. 2. The asymmetry parameter e plotted as a function of the center-of-mass scattering angle ϑ for proton-proton scattering at target B. The errors shown include only counting statistics.

with zero as it should be for reasons of symmetry. These checks and an accurate study of the alignment, geometry, and counter properties, which we do not now report, have convinced us that the polarization effect is real. Furthermore we have checked that the external beam extracted in the ordinary way shows no asymmetry with either hydrogen or carbon as target B. (This confirms the fact that our p-p scattering experiments[3] were not influenced by polarization effects.)

The absolute intensity of the polarized beam entering the cave was approximately 2×10^5 protons per second over an area of 5 cm².

In order to use the polarized beam for quantitative measurements we would like to know its degree of polarization $P=(F_+-F_-)/(F_++F_-)$, where $F_\pm$ is the intensity of the protons with spin up or down, respectively. If the scatterings in targets A and B were elastic, and the targets were of the same material, and if Θ equals Ψ, then P equals $\sqrt{e}$ at least approximately. (We neglect the degradation of energy.) At present we have no completely satisfactory way of knowing the degree of polarization of the beam.

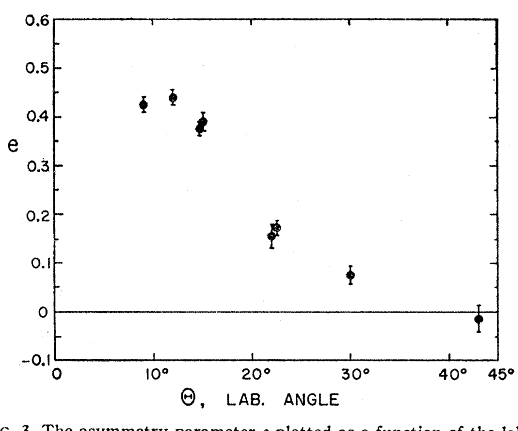

FIG. 3. The asymmetry parameter e plotted as a function of the laboratory angle Θ for scattering from a carbon target at position B. Different absorbers were used in the counter telescope at different angles as outlined in the text. The errors shown indicate counting statistical errors.

A curve with targets A and B of carbon is given in Fig. 3. This curve is obtained with an absorber in the telescope which would cut off protons with an energy smaller than $\frac{3}{4}$ of the energy $E\cos^2\Theta$ which would obtain in an elastic nucleon-nucleon scattering. It shows that at 30° the polarization is sufficiently small to have escaped Marshall, Nedzel, and Marshall.

Since in the case of carbon a large part of the scattering might be inelastic, especially at large Θ, it is important to investigate e not only as a function of Θ but also of the energy of the protons detected. We have started this investigation by taking measurements with various energy cutoff values by inserting various absorber thicknesses in our counter telescope at $\Theta=15°$ and 9°. In each case the lowest energy group of scattered protons (0 to 210 Mev) shows no observable asymmetry. For $\Theta=15°$ the intermediate energy group (210 to 280 Mev, quasielastic scattering) gives large asymmetry with $e=0.37\pm0.04$, and the elastically scattered protons (290 Mev) indicate $e=0.45\pm0.04$. For $\Theta=9°$, the elastically scattered protons show $e=0.43\pm0.02$.

If the beam polarization P were known, we could determine the polarization in scattering by hydrogen P_H from the relation $e_H=P\,P_H$. If we tentatively assume that $e_C=P^2$ (even though the carbon scattering is not elastic) then we obtain from the data for $\Psi=\Theta=20°$ the result $P=0.5$, and $P_H=2e_H$. This allows a provisional interpretation of the data of Fig. 2. Quite aside from the absolute value of P_H, its angular distribution is given in Fig. 2 and this indicates a more complex dependence than the $\sin(2\vartheta)$ dependence obtained by considering only s and p waves.

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

[1] Oxley, Cartwright, Rouvina, Baskir, Klein, Ring, and Skillman, Phys. Rev. 91, 419 (1953).

[2] Marshall, Nedzel, and Marshall, Phys. Rev. 93, 927 (1954). Chicago meeting.

[3] Chamberlain, Segrè, and Wiegand, Phys. Rev. 83, 923 (1951).

Polarization by p-p Collision at 310 Mev*

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The discovery of polarized protons at 240 Mev by Oxley and co-workers[1] led us to look for similar phenomena at 320 to 430 Mev. For angles and energies consistent with quasi-free nucleon scattering inside the beryllium nucleus from 25° to 35°, we have reported an unsuccessful search.[2] We are grateful to Segrè for telling us of preliminary results at Berkeley indicating production of a polarized 340-Mev proton beam by small-angle scattering from carbon. Following this lead, we have obtained a polarized proton beam of about 310 Mev by scattering of 322-Mev average energy protons at 14° to the right from a beryllium target inside the cyclotron. The polarization has been demonstrated by a

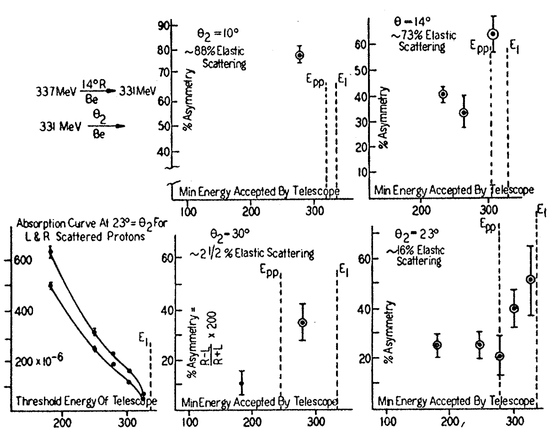

FIG. 1. Dependence of polarization of beryllium-scattered protons on scattering angle θ_2 and on energy of scattered protons. E_1 is the energy of protons incident on the second beryllium target. E_{pp} is the energy a proton would have if scattered by a free nucleon. The high absorption curve at $23°=\theta_2$ is for right-scattered protons, the lower for left. The percent elastic scattering is estimated by using the elastic scattering cross sections measured by Moyer *et al.* (see reference 4) at 340 Mev.

second scattering on a beryllium target outside the cyclotron giving asymmetries as high as 80 percent. The polarization increases as shown in Fig. 1 with thickness of absorber as if the main polarized component were the elastic scattering. We estimate a rough value of the amount of polarization of the beam as $(\frac{1}{2}\text{ asymmetry})^{\frac{1}{2}}$ (see definitions in reference 1), where the asymmetry is measured at 14° excluding the nucleon-scattered component, these conditions being true for both first and second scatterings. Our beam therefore is believed to be ~60 percent polarized.

Liquid hydrogen was substituted for the second beryllium target, and the asymmetry of scattering was measured as shown in Fig. 2. The polarization due to hydrogen, P_H, is obtained from the data of Fig. 2 according to the relation $0.6\,P_H=\frac{1}{2}$ asymmetry. A phase shift analysis indicates that the asymmetric part of the p-p scattering should vary as $\sin\theta\cos\theta$, where θ is the barycentric angle if only ^3P states act, but if ^3P and ^3F states both are impor-

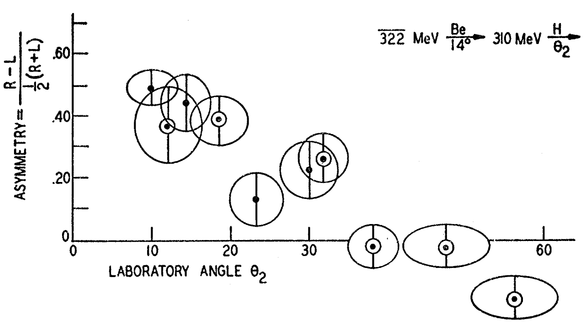

FIG. 2. Asymmetry produced by second scattering from liquid hydrogen of estimated 60 percent polarized 310-Mev proton beam.

tant, the asymmetry should vary as $\sin\theta\cos\theta(a+b\cos^2\theta+c\cos^4\theta)$. The singlet states do not give asymmetric terms. The data of Fig. 2 indicate large values of b and c and a small value of a. We are investigating the effect of this result on the phase shifts.

The values of p-p differential scattering cross section previously reported by us[3] were for a beam scattered first to the right at a small angle and scattered externally always to the left. The evidence of Fig. 1 is that a similar beam at 310 Mev is polarized. The evidence of Fig. 2 is that cross sections measured to the left will be lower than the cross sections for a nonpolarized beam. Consequently our cross sections at 420 Mev may have been low at small angles. This point is under further investigation.

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[1] Oxley, Cartwright, Rouvina, Baskir, Klein, Ring, and Skillman, Phys. Rev. 91, 419 (1953).

[2] Marshall, Nedzel, and Marshall, Phys. Rev. 93, 927 (1954).

[3] Marshall, Marshall, and Nedzel, Phys. Rev. 93, 927 (1954).

[4] Richardson, Ball, Leith, and Moyer, Phys. Rev. 86, 29 (1952).

Energy Spectrum of Negative Pions Produced in Beryllium by 2.3-Bev Protons*

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The study of pion production by nucleon-nucleon and nucleon-nucleus collisions is of considerable basic interest, and a number of experiments have been performed[1] both at comparatively low-incident nucleon energies (up to 440 Mev) with particles produced by particle accelerators and at extremely relativistic energies with cosmic-ray particles. The existing experimental data have shed considerable light on the nature of the π meson and its interaction with nucleons. Since the Brookhaven Cosmotron produces protons of energies up to about 2.3 Bev and