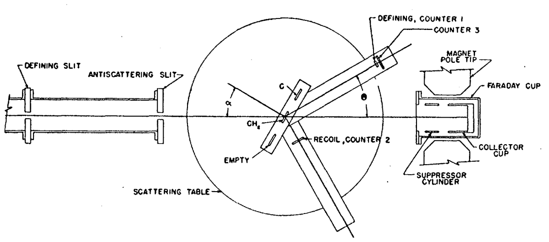

FIG. 1. Experimental equipment.

and a Faraday cup to measure the incident proton flux. The angular distribution from 90° to 40° in the center-of-mass system was observed at 95 Mev. The cross section at 90° for lower energies was obtained by degrading the beam with lithium hydride absorbers.

The experimental arrangement is shown in Fig. 1. To detect both of the protons as in the method of Wilson and Creutz[1] two arms whose angles could be accurately adjusted were mounted on the circular scattering platform. Fastened to the arms were supports for the detectors consisting of stilbene crystals mounted on 1P21 photomultiplier tubes. The pulses from the photomultipliers were fed into diode bridge coincidence circuits.[2] Coincidences between the defining counter 1 and counter 3 directly behind the defining counter as well as coincidences between the defining counter and the recoil counter 2 were obtained from the diode bridge coincidence circuits. These could then be mixed in a slow coincidence circuit to obtain threefold coincidences. At the lower energies the protons did not have sufficient energy to pass through the defining counter, and only twofold coincidences between the defining and recoil counters were measured. Throughout the experiment suitable checks on efficiency and accidentals were performed. Also, to eliminate any effects due to polarization of protons in the beam or misalignment of the scattering table, the defining counter was placed alternately on the right and left side of the beam.

The targets employed in this phase of the experiment were two thicknesses of polyethylene with carbon targets of approximately equal stopping power. At 90° in the center-of-mass system the cross section was also checked with a polystyrene target. Because of the low incident beam intensity it was necessary to use a geometry in which genuine coincidences from carbon could not be neglected, and this contribution to the coincidence rate in the polyethylene was therefore suitably subtracted. With the thickness of targets necessary to obtain reasonable counting rates it was impossible to detect both protons corresponding to angles smaller than 40° in the center-of-mass system. It is hoped that this region as well as the angles up to 90° will be investigated soon with liquid hydrogen targets.

The number of protons in the beam was measured with a Faraday cup. The energy of the incident particles was determined by finding the fraction of particles penetrating known amounts of aluminum. In this way it was found that the full width at half-maximum was 2 Mev at the full energy of 95 Mev and increased to a width of 4.8 Mev at a mean energy of 41 Mev. The total charge collected on the Faraday cup was measured using a Brown vibrating reed electrometer modified to operate with a specially constructed capacitor mounted in the Faraday cup vacuum system. It was found that the charge collected on the cup was independent of parameters of the cup system such as electrical and magnetic suppression of secondaries as well as distance of the front foil and other geometrical considerations.

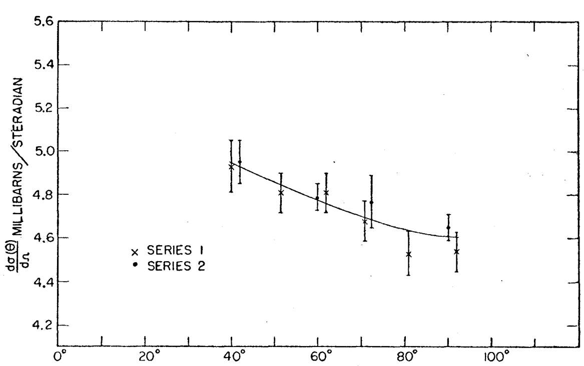

FIG. 2. Angular distribution at 95 Mev—counting statistics only.

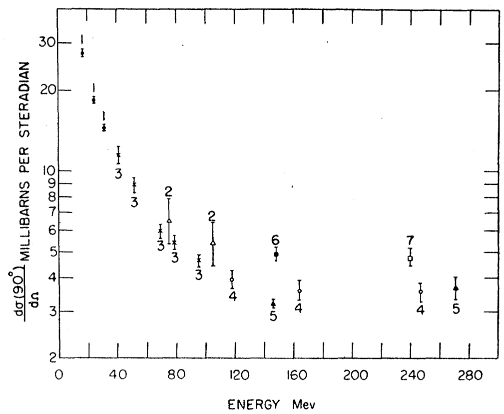

FIG. 3. Cross sections at 90° center-of-mass. 1. Berkeley, reference 7; 2. Harvard, reference 6; 3. Harvard, present data; 4. Berkeley, reference 3; 5. Chicago, reference 8; 6. Harwell, reference 5; 7. Rochester, reference 4.

The angular distribution obtained at 95 Mev is shown in Fig 2; counting statistics only are shown. When possible systematic errors are included, the reliability of the ratio of the cross sections at 90° and 40° is estimated to be 4 percent. In Fig. 3, the cross sections at 90° in the center-of-mass system are compared to results previously reported.[3–8] The estimated errors for the absolute cross section listed by the authors are shown except in the Chicago results where only a preliminary estimate is available.

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† Society of Fellows.
‡ National Science Foundation Predoctoral Fellow.

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Polarization by *p-p* Collision at 439 Mev*

H. G. DE CARVALHO, E. HEIBERG, J. MARSHALL, AND L. MARSHALL
Institute for Nuclear Studies, The University of Chicago, Chicago, Illinois
(Received April 30, 1954)

PREVIOUS measurements of asymmetry of *p-p* scattering for polarized protons of 340[1] and 310[2] Mev indicate that at these energies triplet states of angular momentum greater than 1 have become important in *p-p* collisions. This is made evident by the fact that the asymmetry of scattering varies as $\sin\theta\cos\theta$ if only ^3P states act, but at 310 and 340 Mev it is fitted by $\sin\theta\cos\theta(a+b\cos^2\theta+c\cos^4\theta+\cdots)$ where b and c are probably larger than a. Terms other than the first can arise only by interference in triplet states of angular momentum greater than 1.

We report here a measurement of asymmetry of *p-p* scattering with 439-Mev polarized protons, from which we hoped to learn more about the additional triplet angular momentum states acting. We used an external proton beam of fifty percent polarized protons of 439±6 Mev, produced when protons of 435-Mev average energy (in the 450-Mev equilibrium orbit of the cyclotron) were scattered at 14° to the right from a beryllium target in the cyclotron. An estimate of the degree of polarization of the beam was obtained by measuring the asymmetry of second scattering from a beryllium target in the experimental area. The scattering was measured at 14°, excluding the nucleon-scattered component by filtration of the scattered protons through $5\frac{3}{4}$ inches of copper. (The mean range of the 439-Mev incident beam was $6\frac{1}{8}$ inches of copper). We assumed the first and second events to be similar in nature, and estimated the polarization of the beam as $(\frac{1}{2}\text{ asymmetry})^{\frac{1}{2}}$ = fifty percent polarized.

Next the asymmetry of scattering of the 439-Mev beam from liquid hydrogen was measured and found to be as shown in Fig. 1.

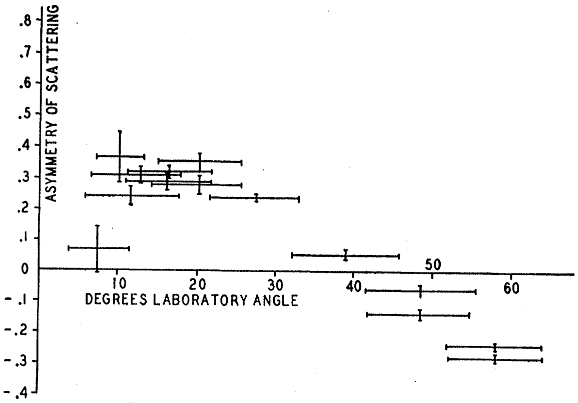

FIG. 1. Asymmetry of scattering [defined as $(R-L)/\frac{1}{2}(R+L)$] from liquid hydrogen for 439-Mev 50-percent-polarized protons, shown plotted against laboratory angle. A best curve through the data crosses the axis at 43°, as it should, owing to the relativistic nature of the protons. For the above data, the polarization P_H is equal to the asymmetry.

The horizontal dimensions of the data represent geometrical width of the counters, and the vertical dimensions are the statistical counting errors. For laboratory angles greater than 26°, the two scattered protons were measured in coincidence with each other (and with the incident proton) in order to exclude meson production events. At smaller angles such a coincidence measurement is no longer useful because it can be triggered by an event in which a meson enters one counter and a proton enters the counter on the other side of the beam. At angles of 8° or less, the situation becomes even more ambiguous in that events may be recorded in which a meson enters one counter while a deuteron enters the other counter.

In order to eliminate uncertainties introduced by meson production, the following measurements were made. The asymmetry of meson production at 58°±6.5° and 48.5°±8.5° was measured for the process $p+p\rightarrow\pi^++d$. For these measurements 4 counters were connected in quadruple coincidence, counters A and B forming a telescope in the incident beam, counter K extending from 3.1° to 13.8° laboratory angle, and counter C on the other side of the beam placed one time from 41.5° to 64.5° and in the next measurement from 40° to 57° laboratory angle. The quadruple coincidence ABCK then detected events in which a meson was produced at 58°±6.5° or at 48.5°±8.5° and accompanied by a deuteron. Under these conditions the deuteron goes forward approximately at 8°. This quadruple coincidence also detected approximately 78 percent of the "unbound" reaction $p+p\rightarrow\pi^++p+n$. The observed asymmetries asym $=\{[I(R)-I(L)]/\frac{1}{2}[I(R)+I(L)]\}$ were (+7.5±11) percent at 58° and (−21±12) percent at 48.5°. These laboratory angles respectively correspond to 98° and 85° in the barycentric system of meson and deuteron.

The asymmetry of meson production which arises from an interference between s and p angular momentum states of the pion-nucleon system, varies to a first approximation[3] as $\sin\theta$, and hence is maximal in the region where we measured it. Because the asymmetry varies as $\sin\theta$, we can average these two values which are approximately equally removed from 90°, and obtain thereby the statistically more accurate value of (−7±8.5) percent asymmetry.

Although this number is not of high accuracy, still it suffices to demonstrate that at small angles one can measure the asymmetry of scattering of total charged particles and interpret it as asymmetry of scattered protons, with very little error introduced from asymmetry in meson production. The argument follows. The meson asymmetry measurement included also an absolute measurement of meson production cross section calculated from the average intensity scattered to right and to left. We found 0.143±0.010 mb/sterad at 100° barycentric angle and 0.125 ±0.008 mb/sterad at 85° barycentric angle.

The asymmetric part of the meson production has the value therefore of $0.07\times 0.134\sin\theta=0.01\sin\theta$ mb/sterad. The asymmetric part of the proton cross section from 10−25° is ~4 mb/sterad×forty percent = 1.60 mb/sterad. At 25° it follows that $0.01\sin 25°/1.60$ or less than one percent of the asymmetry is due to meson production. At smaller angles the meson contribution is smaller.

This amount of ambiguity we considered negligible, and we proceeded to measure the asymmetries below 25° using a telescope of two counters to catch the scattered particles in coincidence with a telescope of two counters in the incident beam, with the resulting asymmetries shown in Fig. 1. The polarization of hydrogen is calculated from the relation $P_H=\frac{1}{2}(\text{asym}/0.50)$ where 0.50 represents polarization of the incident beam. In this case it follows that P_H = asymmetry.

The results of this experiment seem to be little different from those of 340[1] and 310[2] Mev. There seems to be little tendency for higher angular momentum states to increase their contribution. In fact if there is any difference at all, the angular distribution is more nearly $\sin\theta\cos\theta$ (triplet p interaction) than it was at the lower energy.

Assuming an angular dependence of $0.2+\cos^2\theta$ for the bound and unbound meson production, and assuming the bound meson production cross section $(p+p\rightarrow d+\pi^+)$ to be 1.0 mb,[4] we compute a value of 3.75±0.24 mb for the unbound reaction. Let the total meson production cross section be written as $\sigma(p+p\rightarrow\pi^++\text{nucleons})=\sigma_{10}(\pi^++d)+\sigma_{10}(\pi^++p+n)+\sigma_{11}(\pi^0+p+p)$. Then the branching ratio is defined[4] as $[\sigma_{10}(\pi^++p+n)\div\sigma_{10}(\pi^++n+p)+\sigma_{10}(\pi^++d)]$. We use 0.22 mb for σ_{11} and compute for the branching ratio the value of 3.5.

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Polarization of Elastically Scattered Nucleons from Nuclei in the Born Approximation*

WARREN HECKROTTE
Radiation Laboratory, Department of Physics, University of California, Berkeley, California
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RECENT experiments on the polarization of high-energy nucleons elastically scattered from nuclei[1] have led to the interpretation of these results in terms of an effective spin-orbit nuclear potential[2] in addition to the usual central nuclear potential used to explain[3] the total and experimental cross sections of the high-energy nuclear scattering. A small spin-orbit potential is sufficient to account for the large polarization observed.

At these high energies (~300 Mev) and at least for lighter nuclei, it has been pointed out that the Born approximation or