

The Spin of the Pion via the Reaction $\pi^+ + d \rightleftharpoons p + p$

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It is possible to determine the spin of the pion by comparing the forward and backward rates of the reaction $\pi^+ + d \rightleftharpoons p + p$. The backward rate has been measured in Berkeley. We have measured the forward rate. Comparison of the two results shows the spin to be zero. In the light of other recent experimental results the meson is then pseudoscalar.

DURING the past few years there has accumulated an increasing amount of evidence that the pion is pseudoscalar. This consists chiefly of the following:

(a) The pion has integral spin. This follows from star formation in the capture of π^- mesons in photographic emulsions, as well as from angular momentum conservation in such reactions as $p + p \rightarrow \pi^+ + d$; $p + h\nu \rightarrow \pi^+ + n$.

(b) The neutral pion does not have spin one, since it decays into two γ -rays and such a transition is forbidden for systems with angular momentum \hbar .¹

(c) Because of their similar masses and their similar nuclear production cross sections, as well as from the evidence on charge independence of nuclear forces, it is likely that neutral and charged mesons have the same transformation properties, so that charged pions also cannot have spin one.

(d) The pion is not scalar. This follows from the experiment on the capture of stopped negative pions in deuterium,² as well as the results on the production of pions, both charged and uncharged, by γ -rays.³ Both experiments give best theoretical agreement in the pseudoscalar meson theory. It has therefore appeared quite probable that the pion is pseudoscalar; but the evidence, especially against a spin of two or greater, is poor.

It has been pointed out by Cheston and Marshak⁴ that the reaction $\pi^+ + d \rightleftharpoons p + p$ lends itself to a determination of the spin of the pion. The forward and backward reactions are related by a detailed balancing argument, if one assumes initially unpolarized particles, so that

$$\frac{d\sigma(\rightarrow)}{d\Omega} / \frac{d\sigma(\leftarrow)}{d\Omega} = \frac{4}{3} \frac{p^2}{q^2(2s+1)},$$

where s is the spin of the meson, and p, q , are the momenta of the proton and meson in the center-of-mass system. The cross sections, of course, are also in the center-of-mass system. The argument is rigorous, independent of meson theory, and in this rests its chief contribution. The reaction $p + p \rightarrow \pi^+ + d$ has been measured by Cartwright, Richman, Whitehead, and Wilcox⁵ for 340-Mev protons, corresponding to a meson energy of 21 Mev in the center-of-mass system. We present here results on the inverse reaction.

The experimental arrangement is shown in Fig. 1. The Nevis cyclotron delivers a beam of approximately 20 positive mesons per square centimeter per second outside the concrete shielding. These are produced when the 380-Mev protons strike an internal Be target. The mesons are magnetically analyzed in the fringing field of the cyclotron, and by a small magnet outside the shielding. The energy resolution is ± 4 Mev at 75 Mev and the composition of the beam is 90 percent π^+ , and 10 percent μ^+ mesons.⁶ The beam is defined by the

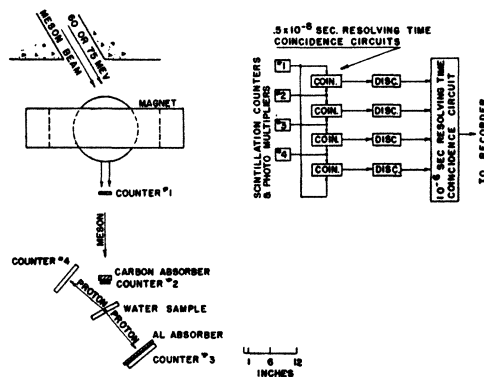


FIG. 1. Arrangement of the beam collimation, water sample, and detectors. Block diagram of circuits.

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¹ Steinberger, Panofsky, and Steller, *Phys. Rev.* **78**, 802 (1950); C. N. Yang, *Phys. Rev.* **77**, 242 (1950).

² Panofsky, Aamodt, and Hadley, *Phys. Rev.* **82**, 97 (1951); Brueckner, Serber, and Watson, *Phys. Rev.* **81**, 575 (1951).

³ Bishop, Steinberger, and Cook, *Phys. Rev.* **80**, 291 (1950).

⁴ R. E. Marshak, *Phys. Rev.* **82**, 313 (1951); W. B. Cheston, to be published.

⁵ Cartwright, Richman, Whitehead, and Wilcox, *Phys. Rev.* **81**, 652 (1951); V. Peterson, *Phys. Rev.* **79**, 407 (1950); C. Richman and M. H. Whitehead, to be published. We are most indebted to Professors Richman and Wilcox, Mr. Cartwright, and Miss Whitehead for the privilege of quoting as yet unpublished results, and in particular, the fine meson spectrum shown in Fig. 5.

⁶ The beam is analyzed in the following way: Heavy particles and electrons are detected in a measurement of the velocity distribution of the beam particles by means of a time of flight measurement. The mesons have velocities $\sim 0.7c$, the electrons which penetrate the counters have the velocity of light, and heavy particles have smaller velocities. The μ -mesons are measured at the end of their range by means of the delayed coincidences of their electron decay product. This is only possible in the π^- beam, since π^+ mesons at the end of their range are not captured but produce μ^+ mesons and interfere. We have assumed that, since the μ -mesons in the beam are the result of the decay in flight of the π -meson and since π^- and π^+ mesons have at least approximately the same lifetime [Lederman, Booth, Byfield, and Kessler,

crystal scintillation counters 1 and 2, and the energy reduced in the carbon absorber. The liquid scintillation counters 3 and 4 are set with respect to the water sample so that protons emitted 180° apart in the center-of-mass system of the meson and deuteron will be detected.⁷ The water sample is 2.5 g/cm^2 thick. The aluminum absorber in front of counter No. 3 is thin enough to transmit the protons emitted in the meson absorption under study, but stops scattered protons or deuterons. The difference in counting rate using heavy water and light water targets is entirely due to the reaction $\pi^+ + d \rightarrow p + p$. It is in principle quite easy to check that this is so. In actuality, the counting rate is small and only a limited number of checks have been made, to wit: (1) Plateau. In the beginning of each experiment the counters are placed so that the meson beam penetrates all four, and the voltages (amplification) of the phototubes adjusted so that mesons are detected with full efficiency. But the proton pulses in counters 3 and 4 should be larger by a factor two or three than the

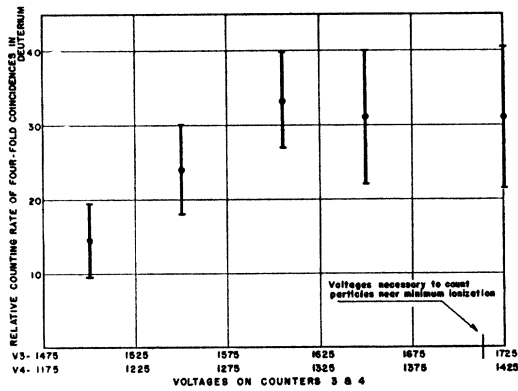


FIG. 2. Counting rate of fourfold events after subtraction, as a function of phototube voltage (amplification) in the proton detection counters 3 and 4.

meson pulses. Figure 2 shows that the pulses responsible for the subtracted fourfold coincidences are large. The D_2O-H_2O difference is counted with full efficiency at voltages 100 volts (i.e., a factor of two in gain) below those necessary to count mesons. (2) When counters 3 and 4 were moved out of line to angles improper for the detection of protons with 180° c.m. angular correlation, no events were observed within statistical accuracy.

Figure 3 shows the energy dependence of the reaction at 45° in the c.m. system. It is sufficiently flat that errors due to energy spread of the meson beam and finite target thickness are small.

Phys. Rev. 83, 686 (1951)], the μ -contamination is independent of charge.

⁷ The center-of-mass transformation is small, approximately $0.05c$. The correlation angles in the laboratory system do not differ from 180° by more than 15° . Angular distribution measurements are easier in this reaction than in the inverse, where the large center-of-mass transformation results in a large variation of experimental conditions with angle.

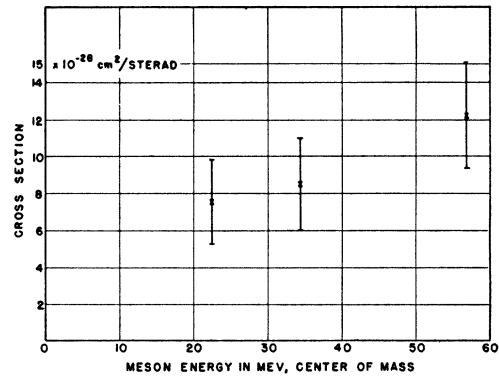


FIG. 3. Differential cross section for the emission of a proton at 45° (and one at 135°) to the meson beam in the c.m. system.

The results on the differential cross section at three angles are shown in Fig. 4. They are the combined results of three determinations, under conditions which varied somewhat. For instance, counters No. 3 and No. 4 were sometimes $4\frac{1}{2}$ in. and at other times 8 in. in diameter. The average meson energy in the target for the three runs was 28 Mev. The data are corrected for the geometrical efficiency of the detecting system which varied from 0.48 to 0.84, for the beam composition (90 percent π^+ , 10 percent μ^+), for the nuclear absorption of the mesons and the protons in the target (7 percent), and for an inefficiency of 8 percent in the circuits due to blocking.

The cross sections expected under the assumption of spins zero and one, on the basis of the results of Cartwright, Richman, Whitehead, and Wilcox, and of Peterson⁵ are also shown. The Berkeley group has measured the energy distribution of mesons produced in the bombardment of hydrogen by 340 Mev protons.

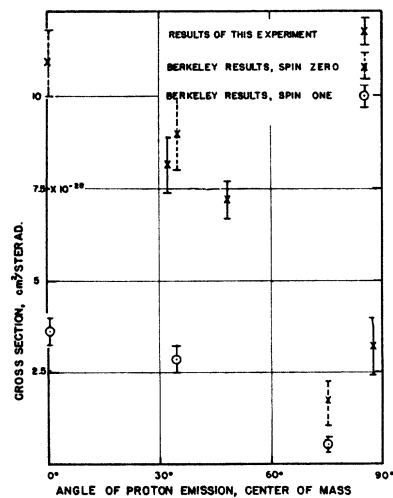


FIG. 4. Differential cross section of the reaction $\pi^+ + d \rightleftharpoons p + p$ at three angles of emission of the proton in the c.m. system. The average meson energy is 28 Mev in the c.m. system. The dotted points show the cross sections expected for spin one and spin zero pions on the basis of the Berkeley results (see reference 5).

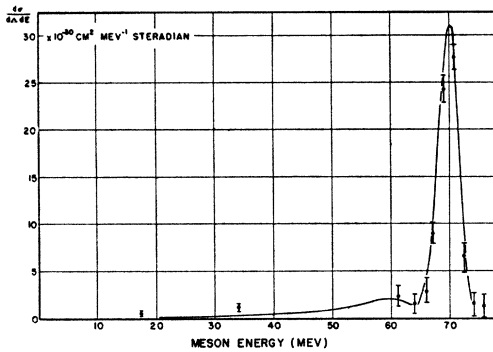


FIG. 5. The spectrum of mesons produced in the collision of 340 Mev protons in the forward direction. This experiment has been performed by Cartwright, Richman, Whitehead, and Wilcox (see reference 5).

(See Fig. 5.) This spectrum consists of a continuum due to the reaction $p+p \rightarrow \pi^+ + n + p$, and a sharp peak at an energy which exceeds the theoretical limit of the continuum and is due to the reaction $p+p \rightarrow \pi^+ + d$.⁸ The cross section is obtained by integrating the energy spectrum under the peak.

Comparison of the two results shows that the π^+ meson spin is zero, quite outside the possible limits of

⁸ The actual production of deuterons in coincidence with mesons has been observed by Crawford, Crowe, and Stevenson, *Phys. Rev.* **82**, 97 (1951).

error in the two experiments. Combining this result with those of Panofsky² and those on the photomeson production,³ the meson is very likely pseudoscalar.

It is necessary to point out that the same ratio of cross sections could be obtained also for non-zero spin mesons provided that pions were completely polarized both in the $p+\text{Be}$ and $p+p$ meson production reactions. Such polarization is theoretically possible, but only in the longitudinal mode, that is, in the mode with zero component of angular momentum along the propagation axis. This seems a rather remote possibility.

A similar experiment has been performed by D. L. Clark, A. Roberts, and R. Wilson, who have reached the same conclusions. We are indebted to them for a pre-publication copy of their results.

The experiment is being continued. The reaction is interesting also in other connections. As Bethe⁹ has pointed out, the angular distribution is quite perplexing. Furthermore, the energy dependence will shed some light on the momentum dependence of the meson nucleon interaction. We are therefore in the process of measuring the angular distribution at several energies.

We wish to acknowledge our indebtedness to the engineering staff of the Nevis Cyclotron Laboratory, especially Mr. Harrison Edwards and Mr. Julius Spiro.

⁹ H. A. Bethe, letter to R. E. Marshak with copies to C. Richman and J. Steinberger. We wish to express our thanks to Professor Bethe for this communication.