Meson Reactions in Hydrogen and Deuterium*

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1. INTRODUCTION

IN June, 1947, at the Shelter Island Conference on Theoretical Physics, the contradiction between the large production cross section for mesons in the high atmosphere and their subsequent extremely weak nuclear interaction at low altitudes were subjected to a careful and searching scrutiny. Conversi, Pancini, and Piccioni[1] had already performed their classic experiment on the absorption of slow negative mesons in matter of low atomic number and Fermi, Teller, and Weisskopf[2] had shown that the observed decay of the negative mesons implied a meson interaction with nuclei weaker by a factor of 10^{12} or more than that previously assumed. Many suggestions[3] were offered to explain the apparent lack of reversibility between emission and absorption of mesons and the two-meson hypothesis put forward by the author[4] as a way out of the difficulties seemed but another "shot in the dark." However, before the Shelter Island meeting was many weeks old, the first two-meson photographs obtained by Powell and his collaborators[5] reached the U. S. and provided the initial evidence in favor of the two-meson theory. Since then many experiments have confirmed the idea that the heavier or π-mesons are strongly coupled to nucleons whereas the lighter or μ-mesons are the decay products of π-mesons and experience weak interactions with nucleons. We shall not enter into a discussion of these experiments here but it is useful to point out that all these experiments imply that π-mesons should react vigorously with the nuclei of hydrogen and deuterium whereas μ-meson reactions with these two lightest nuclei should be quite unobservable. Hence, when we speak of meson reactions in hydrogen and deuterium, we mean π-meson reactions.

It was clear at the outset that a great deal of fundamental information about the π meson-nucleon interaction and the properties of the π-meson would be derived from studies of π-meson reactions in hydrogen and deuterium. It was evident that meson reactions with hydrogen and deuterium would not require knowledge of the complexities of nuclear structure; indeed, reactions with heavier nuclei would probably reveal more about nuclear constitution than about the properties of mesons. It was also obvious that experiments with hydrogen and deuterium would have to await the development of artificial sources of π-mesons because of the small intensities of π-mesons in the cosmic radiation. It was not immediately evident that the deuteron was in certain ways—because of the operation of the Pauli exclusion principle—a more interesting object of investigation than the proton. Nor was it clear at the beginning that investigation of the reactions of charged π-mesons with protons and deuterons would yield some very important information concerning the neutral π-meson. Fortunately, nature has been kind and, by endowing the neutral π-meson with appreciably smaller mass than the charged π-meson, has permitted some very important conclusions regarding the π^0 meson to be drawn from the slow π^- meson experiments in hydrogen and deuterium recently carried out at Berkeley.[6]

We propose to spell out the sort of information which has already been obtained from the Berkeley experiments with the slow π^- meson reactions in hydrogen and deuterium and to indicate the additional insight into the properties of π-mesons which can reasonably be expected to result from experiments on the fast π^- and π^+ meson reactions in the same substances. Whenever we present the quantitative results of theoretical calculations, it must be understood that these results are deduced on the basis of a perturbation treatment of the π meson-nucleon interaction (i.e., the so-called "weak coupling" approximation). We fully realize the inadequacies of such a treatment; however, we shall present the weak coupling results since, in most of the crucial cases, the qualitative features of the theoretical predictions do not depend on the validity of the perturbation method but follow rather from general selection rules based on the angular momentum and parity of the π meson fields. In other cases, the quantitative differences are so striking that the qualitative effects would probably persist in a correct theory; in this connection it is interesting to note that where strong coupling calculations exist, the results are in qualitative agreement with the weak coupling results. In order to avoid any misunderstanding, we shall point out in each instance the measure of generality which attaches to a particular numerical prediction.

* This article contains the expanded contents of an invited paper delivered at the New York meeting of the American Physical Society, February, 1951.

[1] Conversi, Pancini, and Piccioni, Phys. Rev. **68**, 232 (1946).

[2] Fermi, Teller, and Weisskopf, Phys. Rev. **71**, 314 (1947).

[3] See, e.g., V. F. Weisskopf, Phys. Rev. **72**, 510 (1947).

[4] See R. E. Marshak and H. Bethe, Phys. Rev. **72**, 506 (1947); a two-meson theory was proposed independently by S. Sakata and T. Inoue (Prog. Theor. Phys. **1**, 143 (1946)) in order to explain the low scattering cross section and the difficulties with Yukawa's scheme of nuclear beta-decay. However, since neither phenomenon is as glaringly contradictory as the observed μ^- decay in light elements, Sakata and Inoue predicted much too short a lifetime for $\pi-\mu$ decay, namely, 10^{-21} sec instead of 10^{-8} sec.

[5] Lattes, Muirhead, Occhialini, and Powell, Nature **159**, 694 (1947).

[6] Panofsky, Aamodt, Hadley, and Phillips, Phys. Rev. **80**, 94 (1950); see also Aamodt, Hadley, and Panofsky, Phys. Rev. **80**, 282 (1950).

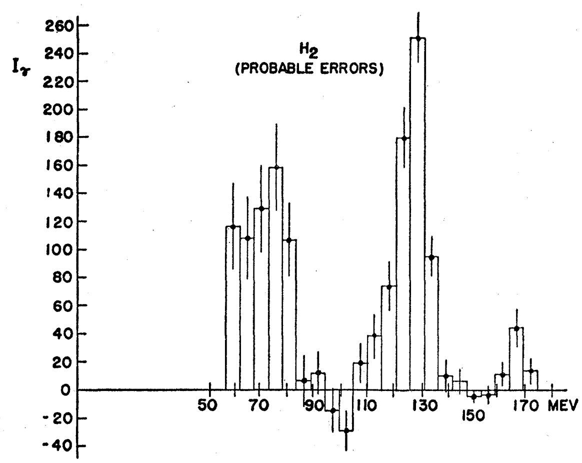

FIG. 1. Gamma-spectrum from π^-+P.

2. SLOW MESON REACTIONS IN HYDROGEN

Let us turn first to a consideration of the slow meson reactions in hydrogen. Tomonaga and Araki[7] were the first to point out the importance of the coulomb field of the nucleus for the behavior of slow mesons. Their argument was intended to apply to μ-mesons but the fact that the slowing down and atomic capture of slow mesons depend essentially on the charge and mass of the meson implies that it is also valid for π-mesons. Tomonaga and Araki's argument was that the repulsion of a slow positive meson by the positively charged nucleus would prevent it from approaching the nucleus and compel it to wander around in matter until it decays. On the other hand, the electric attraction for a slow negative meson would enable the latter to approach very closely to a nucleus and allow it to undergo nuclear absorption. Fermi and Teller[8] analyzed the problem further and showed that most negative mesons, starting with energies of several Mev, end up in K "orbits" about nuclei like carbon and iron in times of the order of 10^{-13} sec—times extremely short compared to the decay time of either the μ- or π-meson. It was still necessary to prove that the time for slowing down and atomic capture in hydrogen is also much shorter than the decay time of the π-meson; this demonstration was provided by Wightman.[9] Consequently, slow meson reactions will only involve π^- mesons and will take place predominantly[10] from the K shell of the mesic-hydrogen atom (or at least from s-states).

Since the binding energy of the π^- meson in the K shell of hydrogen is only 3 kev, the question we must ask ourselves is what will happen when a π^- meson of essentially zero kinetic energy and zero orbital angular momentum is absorbed by a proton. Let us suppose a π^- meson is absorbed by a proton: then energy and momentum conservation require that at least one neutral particle is emitted in addition to the neutron. The simplest assumption to make is that only one neutral particle Q is emitted; we write:

$$\pi^- + P \rightarrow N + Q. \qquad (1)$$

Thus, if π^- is a fermion, Q has to be a fermion, e.g., a neutrino. On the other hand, if π^- is a boson, Q has to be a neutral boson, either a γ-ray or a neutral π^0 meson. The emission of a π^0 can only occur if the mass of π^- exceeds the mass of π^0 by an amount greater than 1.25 Mev, i.e., the mass difference between the neutron and proton. The latter two modes of decay can be represented by:

$$\pi^- + P \rightarrow N + \gamma \text{ (radiative absorption)}, \qquad (2)$$

$$\pi^- + P \rightarrow N + \pi^0 \text{ (mesic absorption)}. \qquad (3)$$

In the case of radiative absorption, the final products will be a neutron of about 10 Mev and a discrete γ-ray of about 130 Mev, the exact values depending on the mass of the π^- meson. If mesic absorption takes place, the final products will be a neutron of less than 1 Mev and a square pulse of γ-rays centered at about 70 Mev (since the π^0 meson decays into two γ-rays with an extremely short lifetime—less than 5.10^{-14} sec[11]), the width of the square pulse depending on the π^- and π^0 masses. In any case, the boson or fermion character of the π^- meson can be decided[12] by looking for γ-rays associated with reaction (2) or (3).

Panofsky, Aamodt, Hadley, and Phillips[6] have examined the γ-rays resulting from the absorption of slow π^- mesons in hydrogen. Their latest γ-ray spectrum is shown in Fig. 1. It is obvious that there is a γ-ray peak in the neighborhood of 130 Mev, thereby proving that radiative absorption takes place and demonstrating beyond any shadow of a doubt that the charged π-meson is a boson.[13] Figure 1 also exhibits a square pulse of γ-rays in the 70-Mev region, thus providing exceedingly strong evidence for mesic absorption.[14] Careful analysis of the γ-ray peak, in terms of the various contributions to the finite resolving power of the pair spectrometer used to measure the γ-ray energies, leads to an accurate determination of the π^- mass, namely, $m_{\pi^-} = 275.2 \pm 2.5 m_e$. In addition, analysis of the square pulse of γ-rays, which extends from 53.6 ± 2.8 Mev to 85 ± 2.8 Mev yields an equally accurate determination of the π^0 mass, namely, $m_{\pi^0} = 264.6 \pm 3.2 m_e$. The remarkably accurate determi-

[7] S. Tomonaga and G. Araki, Phys. Rev. **58**, 90 (1940).
[8] E. Fermi and E. Teller, Phys. Rev. **72**, 399 (1947).
[9] A. Wightman, private communication.
[10] S. Tamor (Phys. Rev. **82**, 38 (1951)) and Brueckner, Serber, and Watson (Phys. Rev. **81**, 575 (1951)) have shown that nuclear absorption from p-states is negligible compared to optical transitions from p to s-states.

[11] Carlson, Hooper, and King, Phil. Mag. **41**, 701 (1950).
[12] See R. E. Marshak and A. S. Wightman, Phys. Rev. **76**, 114 (1949).
[13] The large excitation energies observed in π^- stars in photographic emulsions already had provided strong evidence for the boson character of the charged π-meson (see W. B. Cheston and L. J. Goldfarb, Phys. Rev. **78**, 683 (1950)).
[14] To be absolutely sure that the 70-Mev γ-rays are due to π^0 mesons, a coincidence γ-ray experiment should be performed. *Note added in proof:* This experiment has been successfully carried out by A. Sachs and J. Steinberger [Phys. Rev. **82**, 973 (1951)].

nation of the π^0 mass is, of course, due to the doppler amplification of the small mass difference between π^- and π^0, of the order of 5 Mev, into a large energy spread for the γ-rays, of the order of 30 Mev. One more important piece of experimental information, of the greatest theoretical interest, is the relative probability of mesic to radiative absorption which turns out to be 0.94 ± 0.20.

What does the theory predict about the transition probabilities for radiative and mesic absorption from the K shell of the mesic-hydrogen atom? The probabilities will differ, of course, depending on the fields and nucleon couplings which are assumed to govern the charged and neutral mesons. Some idea of relative magnitudes, however, can be obtained immediately by inquiring, for each assumed field for π^- and π^0, into the angular momenta and parities of the γ-ray and π^0 meson which can be emitted. Table I lists the total angular momenta and parities of the meson-proton system[15] for the four possible fields for π^-, the lowest pole of the outgoing photon (*e.d.* = electric dipole, *m.d.* = magnetic dipole) (radiative absorption) and the angular momentum state of the outgoing π^0 meson (mesic absorption) for the two possible spin zero[16] fields. When cognizance is taken of the low kinetic energies of the π^0 meson (3–4 Mev) and of the recoil neutron ($\sim\frac{1}{2}$ Mev), it is evident that the mesic absorption probability decreases rapidly as the angular momentum of the outgoing π^0 increases. Consequently, Table I predicts that opposite parity for π^- and π^0 mesons will be much less favorable for mesic absorption than the same parity. For spin 1 π^- mesons, the qualification must be added that, for the same parity for π^- and π^0, mesic absorption is only probable for the $J=\frac{1}{2}$ substate of the meson-proton system; mesic absorption from the $J=\frac{3}{2}$ substate is greatly reduced and one would expect that at least $\frac{2}{3}$ of the π^- mesons (the statistical weight of the $J=\frac{3}{2}$ substate is 4 compared to 2 for the $J=\frac{1}{2}$ substate) would undergo radiative absorption unless the π^0 coupling constants are inordinately large.[17]

Before comparing with experiment, it is interesting to see to what extent weak coupling theory bears out the above qualitative predictions. Table II lists the transition probabilities for both radiative and mesic absorption of the π^- meson from the K shell of the mesic-hydrogen atom on the basis of weak coupling theory.[17] The transition probabilities are expressed in units of $\alpha^3(g^2/\hbar c)(\mu c/\hbar)=0.9\times10^{16}(g^2/\hbar c)$ sec^{-1} where α is the find structure constant, μ is the π^- mass, and g is the π^- coupling constant. The abbreviations used are $\delta=\mu/M$ (M is the nucleon mass), $\bar{g}=g_P+g_N$, $\Delta g=g_P-g_N$ (g_P and g_N are the π^0 coupling constants to the proton and neutron respectively), $\Gamma=4.71=$ difference between proton and neutron magnetic moments (in units of nuclear magneton), and $\beta=p_0/\mu_0c$ (p_0 and μ_0 are the recoil momentum and mass of the π^0, respectively).

TABLE I. π^- absorption in hydrogen.

π^- field	Initial state	Pole of γ-ray	Ang. mom. of π^0: Scalar	Ang. mom. of π^0: Pseudo-scalar
Scalar	$J=\frac{1}{2},+$	*m.d.*	*s*	*p*
Pseudoscalar	$J=\frac{1}{2},-$	*e.d.*	*p*	*s*
Vector	$J=\frac{1}{2},-$	*e.d.*	*p*	*s*
	$J=\frac{3}{2},-$	*e.d.*	*p*	*d*
Pseudovector	$J=\frac{1}{2},+$	*m.d.*	*s*	*p*
	$J=\frac{3}{2},+$	*m.d.*	*d*	*p*

In the first column of Table II, $S(S)$ means the absorption of an S π^- meson with S coupling leading to the emission of a γ-ray, etc.; in the remaining columns the first designation, e.g., $PS(PS)$, refers to the absorbed π^- meson and the second, e.g., $S(S)$, refers to the emitted π^0 meson. For reasons which will become apparent later, we list the values of the π^0 coupling constants, obtained by using the experimental numbers for P_γ/P_{π^0} and β, namely, 0.94 and 0.23, respectively, even when they belie the basic assumption of weak coupling theory.

Examination of Table II reveals mostly expected but also some strange results. For example, the ratio of $PS(PS)$ to the $PS(PV)$ radiative probability is $\delta^2/4$, as would be expected from the equivalence theorem. Similarly, the ratio of the $PS(PS)-S(S)$ to the $PS(PV)-S(S)$ mesic probability is $\delta^2/4$. The fact that, in these examples, the equivalence theorem holds for both radiative and mesic absorption explains the identical values shown for the scalar π^0 coupling constants. The ridiculously large and meaningless values for the scalar coupling constants, which are listed in Table II are merely a manifestation of the enormous drop in the probability for mesic absorption when opposite parity is assumed for spin 0 π^- and π^0 mesons (see Table I). A similar effect is exhibited for the $S(S)-PS(PS)$ and $S(S)-PS(PV)$ theories. If both π^- and π^0 possess spin 0, the fact that the same parity leads to reasonable values of the π^0 coupling constant whereas opposite parity leads to completely unreasonable ones, is probably to be taken as support for the same parity. If spin 1 is assumed for the π^- meson, the two widelv disparate

[15] We shall refer to the mesic-hydrogen atom in its ground state (K shell) as the meson-proton system.

[16] If we exclude spins greater than 1 for elementary particles, the two γ-decay of the π^0 requires spin 0.

[17] This table is taken from Marshak, Tamor, and Wightman, Phys. Rev. **80**, 766 (1950); the entry for the $PS(PV)-S(S)$ mesic transition was incorrectly transcribed in that paper and is now corrected. The mesic entries for the $V(V)-PS(PS)$, $V(V)-PS(PV)$, and $PV(PV)-S(S)$ theories are also changed: the transition probabilities are multiplied by a factor of 3, the π^0 coupling constants are reduced by the same factor and all entries refer to the $J=\frac{1}{2}$ substate of the meson-proton system. The $J=\frac{3}{2}$ substate leads to much smaller transition probabilities (by at least a factor 10^3) and to correspondingly much larger π^0 coupling constants. Of course, comparison with experiment yields only one coupling constant (see subsequently) determined by weighting the two substates according to their statistical weights; the breakdown is emphasized because each substate acts as an independent system and leads to π^0's of different angular momenta (see Table I).

TABLE II. Absorption probabilities per sec in hydrogen.

Radiative	Mesic		
$S(S)$ $2e^2\Gamma^2\delta^2$	$S(S)-S(S)$ $4\beta(\Delta g)^2$ $(\Delta g)^2=0.008$	$S(S)-PS(PS)$ $\beta^3\delta^2(\Delta g)^2$ $(\Delta g)^2=27$	$S(S)-PS(PV)$ $4\beta^3(\Delta g)^2$ $(\Delta g)^2=0.15$
$PS(PS)$ $2e^2\delta^2$	$PS(PS)-S(S)$ $\frac{\beta^3}{4}\delta^4(\Delta g)^2$ $(\Delta g)^2=210$	$PS(PS)-PS(PS)$ $\beta\delta^2(\bar{g})^2$ $(\bar{g})^2=0.06$	$PS(PS)-PS(PV)$ $\beta\delta^2(\Delta g)^2$ $(\Delta g)^2=0.06$
$PS(PV)$ $8e^2$	$PS(PV)-S(S)$ $4\beta^3\delta^2 g_p{}^2$ $(2g_p)^2=210$	$PS(PV)-PS(PS)$ $\beta\delta^2(\Delta g)^2$ $(\Delta g)^2=11$	$PS(PV)-PS(PV)$ $\beta\delta^2(\bar{g})^2$ $(\bar{g})^2=11$
$V(V)$ $(2/3)e^2$	$V(V)-S(S)$ $(4/3)\beta^3\delta^2 g_p{}^2$ $(2g_p)^2=52$	$V(V)-PS(PS)$ $\left.\begin{matrix}3\beta\delta^2(\Delta g)^2\\(\Delta g)^2=0.3\end{matrix}\right\}J=\frac{1}{2}$	$V(V)-PS(PV)$ $\left.\begin{matrix}3\beta\delta^2(\bar{g})^2\\(\bar{g})^2=0.3\end{matrix}\right\}J=\frac{1}{2}$
$PV(PV)$ $(2/3)e^2$	$PV(PV)-S(S)$ $\left.\begin{matrix}12\beta(\Delta g)^2\\(\Delta g)^2=0.002\end{matrix}\right\}J=\frac{1}{2}$	$PV(PV)-PS(PS)$ $\frac{\beta^3\delta^2}{3}[(\Delta g)^2+2(\bar{g})^2]$ $[(\Delta g)^2+2(\bar{g})^2]=52$	$PV(PV)-PS(PV)$ $\frac{4\beta^3}{3}[(\Delta g)^2+2(\bar{g})^2]$ $[(\Delta g)^2+2(\bar{g})^2]=0.3$

values for the π^0 coupling constant required for the $V(V)-PS(PS)$, $V(V)-PS(PV)$, and $PV(PV)-S(S)$ theories, corresponding to the $J=\frac{1}{2}$ and $J=\frac{3}{2}$ substates, must be regarded as evidence against the same parity for π^0 since the experimental ratio of 0.94 for P_γ to $P_{\pi 0}$ can only be matched by choosing, in each case, the large and unreasonable value for the π^0 coupling constant.

Surprisingly enough, opposite parity cannot be excluded for spin 1 π^- and spin 0 π^0 because both substates ($J=\frac{1}{2}$ and $J=\frac{3}{2}$) of the π^- meson-proton system lead to p-states for the π^0 and while the π^0 emission is depressed, the π^0 coupling constants turn out not to be unreasonable. Some unexpected results are also to be found in the fact that the ratios of the $PS(PS)-PS(PS)$ to the $PS(PS)-PS(PV)$ and of the $PS(PV)-PS(PS)$ to the $PS(PV)-PS(PV)$ mesic probabilities are unity except for the changes in relative signs of g_P and g_N. This strange result is due to a breakdown of the equivalence theorem when the pseudoscalar field is assumed for both π^- and π^0 and yields a much larger relative mesic probability for PS coupling as compared to PV coupling. When this effect is combined with the operation of the equivalence theorem for the radiative probability, we obtain the surprising inversion of the magtudes of $PS(PS)$ and $PS(PV)$ coupling constants shown in Table II when the same coupling is assumed for both π^- and π^0; for different couplings (and the same pseudoscalar field), the values of the coupling constants are inverted back and so are the relative signs of g_P and g_N. It should also be noted that in the $PS(PS)-PS(PS)$ and $PS(PV)-PS(PV)$ cases, equal magnitudes and opposite signs for g_P and g_N would require much larger values for the π^0 coupling constants. The pseudoscalar numbers have no particular quantitative significance; however, if the pseudoscalar field governs both the π^- and π^0 mesons, then the striking disagreement of the pure coupling (i.e., $PS(PS)-PS(PS)$ and $PS(PV)-PS(PV)$) numbers with those obtained from other processes may be indicative of opposite neutral mesic charges for the proton and neutron or of the need of a linear combination of PS and PV coupling.

3. SLOW MESON REACTIONS IN DEUTERIUM

The two competing slow π^- meson reactions observed to take place in hydrogen both give rise to high energy γ-rays, the measurement of whose energies and intensities has led to several important deductions. Recent experiments[6] on the absorption of slow π^- mesons in deuterium have significantly extended our knowledge of the properties of the charged and neutral π-mesons. We shall see that these important additions to our knowledge have been made possible chiefly by the fact that nucleons obey the Pauli exclusion principle.

The slowing down and capture mechanism for π^- mesons is essentially identical in deuterium and hydrogen. Hence, the problem for deuterium, as for hydrogen, is to predict the reactions which will take place from the K shell of the mesic-deuterium system. In contrast to hydrogen, the requirements of energy and momentum conservation do not require the absorption of π^- mesons in deuterium to be accompanied by the emission of γ-rays or π^0 mesons. It is now possible for the rest energy of the π^- meson to be completely converted into the kinetic energies (≈ 70 Mev apiece) of the two final neutrons in accordance with the reaction scheme: $\pi^-+D\rightarrow N+N$ (we shall term this process neutron absorption). As a matter of fact, since the electromagnetic reaction is inherently weak and the 5-Mev mass difference between the π^- and π^0 mesons barely allows the mesic absorption to take place (the $\pi^- - \pi^0$ mass difference must be larger than the sum of the deuteron binding energy and the neutron-proton mass difference, namely, 3.5 Mev) one would expect neutron absorption to be the dominant reaction. It turns out, however, that when the Pauli principle is combined with parity and angular momentum considerations, this conclusion is strongly modified for some of the possible π^- meson fields. For some fields, the reaction $\pi^- + D \rightarrow N + N + \gamma$ (radiative absorption-involving the emission of two slow neutrons and a high energy γ-ray) acquires a transition probability comparable to or even greater than that of neutron absorption and the possibility of competition from the reaction $\pi^- + D \rightarrow N + N + \pi^0$ (mesic absorption-involving the emission of two slow neutrons and a π^0 meson) throws light on the relative parities of the π^- and π^0 mesons.

Just as in hydrogen, slow π^- mesons moving through deuterium are quickly slowed down and captured into K shells of zero orbital angular momentum before they have the opportunity to decay. Once the π^- meson is in the K shell of the mesic-deuterium atom, the total angular momentum and parity of the meson-deuteron system (just as the meson-proton system—see reference 15) depends on the intrinsic spin and parity of the π^- meson. Thus, suppose the π^- meson possesses spin 0 and even parity (scalar); then since the deuteron has total angular momentum 1 and even parity, the meson-deuteron system would also possess $J=1$ and even parity. Similarly, a π^- meson with spin 0 and odd parity (pseudoscalar) would lead to $J=1$ and odd parity for the meson-deuteron system. On the other hand, if the π^- meson were to possess spin 1, there would be three possible values for the total angular momentum of the meson-deuteron system, namely, $J=0, 1, 2$. The parity of the meson-deuteron system would be odd or even depending on whether the π^- meson were vector or pseudovector. We have already stated that spins greater than 1 are not considered for reasons of simplicity although this point can be settled by one of the fast meson reactions in deuterium (see subsequently). Now, if neutron absorption is to take place, the two final neutrons, by the Pauli principle, must be in a $^1S_0$, $^3P_{0,1,2}$, $^1D_2$, $\cdots$ state. Consequently, a scalar π^- meson in the K shell of the mesic-deuterium atom cannot undergo neutron absorption at all.[18] Also, neutron absorption cannot take place for pseudovector π^- mesons in the $J=1$ substate of the meson-deuteron system. No such selection rules operate for pseudoscalar and vector mesons. There are also selection rules for radiative and mesic absorption but not absolute ones as in the case of neutron absorption. Table III lists the total angular momenta and parities of the meson-deuteron system for the four fields, the states of the two neutron system for which neutron absorption transitions are possible, the lowest two neutron states for which radiative absorption takes place and finally the lowest two neutron states for which mesic absorption is allowed assuming that the outgoing π^0 meson is first a scalar and then pseudoscalar. In the radiative column of Table III we have indicated the character of the outgoing electromagnetic radiation (*e.d.*, *m.d.* as before (see Table I), *e.q.*= electric quadripole) and in the mesic columns the angular momentum state of the outgoing π^0 meson. These selection rules have been discussed briefly by Tamor and Marshak[19] and some of them are presented in detail in forthcoming papers by Tamor[10] and by Brueckner, Serber, and Watson.[10]

We see from Table III that the absorption of a π^- meson from the K shell of a mesic-deuterium atom is strongly affected by the requirements of the exclusion principle applied to the final two neutrons. These effects of the exclusion principle derive from simple properties of the angular momentum and parity and thus the chief qualitative conclusions can be drawn from a comparison of Tables I and III without having recourse to the questionable weak coupling meson theory. By the same token, the use of weak coupling theory should, as in the case of hydrogen, confirm the correctness of the selection rules and provide quantitative estimates of some interest. Tamor[10] performed the weak coupling calculations and has found the transition probabilities for the three competing reactions assuming, in turn, the four possible fields for the π^- meson. His treatment of the three processes was phenomenological so that the relative probabilities of neutron and radiative absorption are independent of any detailed theory of nuclear forces and of the strength of the π^- meson-nucleon coupling. Such a treatment is possible because in the case of neutron absorption the two final neutrons have such high energies that the plane wave approximation can be used whereas in the case of radiative absorption the two final neutrons are so slow that only the low energy parameters (i.e., the effective range and scattering length) enter. Tamor's mesic absorption predictions appear to require knowledge of the strength of the π^0 nucleon coupling but

TABLE III. Slow π^- absorption in deuterium.

		Final states			
				Mesic absorption	
π-meson theory	Initial state	Neutron absorption	Radiative absorption	π^0 scalar	π^0 pseudo-scalar
Scalar	$J=1(+)$	none	$^1S_0$ (*m.d.*)	$^3P_{0,1,2}(p)$	$^1S_0(p)$
Pseudo-scalar	$J=1(-)$	$^3P_1$	$^1S_0$ (*e.d.*)	$^1S_0(p)$	$^3P_{0,1,2}(p)$
Vector	$J=0(-)$	$^3P_0$	$^3P_1$ (*m.d.*)	$^3P_0(s)$	$^1S_0(S)$
	$=1(-)$	$^3P_1$	$^3P_{0,1,2}$ (*m.d.*)	$^3P_1(s)$	$^3P_{0,1,2}(p)$
	$=2(-)$	$^3P_2$, $^3F_2$	$^3P_{1,2}$ (*m.d.*)	$^3P_2(s)$	none
Pseudo-vector	$J=0(+)$	$^1S_0$	$^3P_1$ (*e.d.*)	$^1S_0(s)$	$^3P_0(s)$
	$=1(+)$	none	$^1S_0$ (*m.d.*)	$^3P_{0,1,2}(p)$	$^1S_0(p)$
	$=2(+)$	$^1D_2$	$^1S_0$ (*e.q.*)	none	$^3P_2(s)$

[18] Dr. A. Wightman (private communication) has shown that this absolute selection rule is rigorous and also holds in a relativistic treatment.

[19] S. Tamor and R. E. Marshak, Phys. Rev. **80**, 766 (1950); see also B. Ferreti, Report on Intern. Conf. on Fundamental Particles, Cambridge, 1946, p. 75.

TABLE IV. Neutron and radiative absorption probabilities in deuterium.

π^- meson theory	$S(S)$	$PS(PS)$	$PS(PV)$	$V(V)$	$PV(PV)$
Neutron	0	$2.7\cdot10^{-3}$	0.25	0.12 ($J=0, 1, 2$)	$2.5(J=0)$ $0(J=1)$ $0.05(J=2)$
Radiative	0.012	$6.6\cdot10^{-4}$	0.12	$2.2\cdot10^{-3}$ ($J=0, 1, 2$)	$1.4\cdot10^{-2}(J=0)$ $2.0\cdot10^{-2}(J=1)$ $1.3\cdot10^{-2}(J=2)$
Ratio	0	4.1	2.1	55	2

actually even this arbitrariness is removed by making use of the hydrogen absorption experiment. That is to say, the known ratio of radiative to mesic absorption in hydrogen can, because of the weak binding of the deuteron, be employed in a semi-empirical fashion, (using the π^0 coupling constants in Table II as numbers in a "ledger," so to speak) to predict the relative intensities of these two modes of absorption in deuterium. Thus, as an example, consider the absorption of a pseudoscalar π^- and the emission of a pseudoscalar π^0: in hydrogen, the radiative absorption process is electric dipole whereas the mesic absorption yields an $s-\pi^0$ meson (see Table I). In deuterium, the radiative absorption is again electric dipole; however, the mesic absorption involves a transition to a $^3P_0$ state for the two neutrons and a p-state for the π^0 meson. It is clear that the ratio:

$$\left(\frac{P_{\pi^0}}{P_\gamma}\right)_D \Big/ \left(\frac{P_{\pi^0}}{P_\gamma}\right)_H \ll 1$$

and inserting numbers leads to an estimated π^0: γ-ratio in deuterium in agreement with the weak coupling prediction (see Table IV).

Table IV lists the theoretical probabilities for neutron and radiative absorption in deuterium for the four types of fields using direct coupling in all cases except for the pseudoscalar field where the results are given for both direct and derivative coupling. The numbers are listed in units of 0.9×10^{16} $g^2/\hbar c$ sec^{-1} where $g^2/\hbar c$ is the

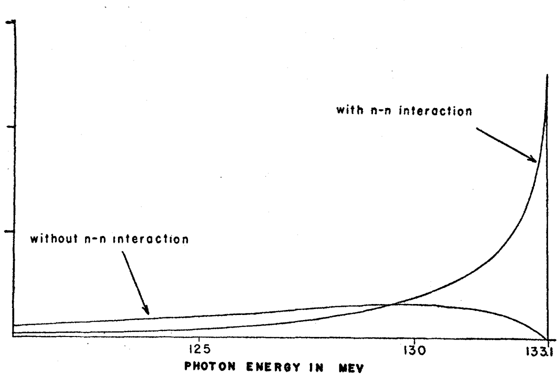

FIG. 2. Theoretical gamma-spectrum from $\pi^- + D \rightarrow N + N + \gamma$.

dimensionless π^- meson-nucleon coupling constant. The ratios of neutron to radiative absorption predicted by the various theories are also listed.[19a] It is interesting to note that the ratios for the $PS(PS)$ and $PS(PV)$ theories are different because of the breakdown of the equivalence theorem for neutron absorption. Dyson[20] has shown that the equivalence theorem breaks down when the interaction between the two nucleons contains a charge exchange part; as a consequence, the $PS(PS)$ ratio actually depends upon the assumed nucleon-nucleon interaction potential-in contrast to the $PS(PV)$ theory. While neutron absorption implies the emission of two high energy neutrons of roughly 70 Mev apiece, radiative absorption leads to two slow neutrons plus a continuous γ-ray spectrum sharply peaked in the neighborhood of 130 Mev. The sharp peaking is due to the nuclear interaction of the two slow neutrons in the final S-state, which greatly enhances the probability for the emission of high energy γ-rays. Figure 2 shows the theoretically predicted γ-ray spectra for the pseudoscalar π^- meson assuming that the $N-N$ interaction is absent and that it is the same as the $P-P$; the half-

TABLE V. Mesic absorption in deuterium (in units of $g^2/\hbar c\times0.9\times10^{16}$ sec^{-1}).

$S(S)-S(S)$ 5.5×10^{-7}	$S(S)-PS(PS)$ or $PS(PV)$ 1×10^{-3}
$PS(PS)-S(S)$ 4.5×10^{-5}	$PS(PS)-PS(PS)$ or $PS(PV)$ 2.5×10^{-8}
$PS(PV)-S(S)$ 8×10^{-3}	$PS(PV)-PS(PS)$ or $PS(PV)$ 4×10^{-6}
$V(V)-S(S)$ $3\times10^{-3}(J=0,1,2)$	$V(V)-PS(PS)$ or $PS(PV)$ >30 $(J=0)$
$PV(PV)-S(S)$ >30 $(J=0)$	$PV(PV)-PS(PS)$ or $PS(PV)$ 2×10^{-3} $(J=1)$

width at maximum in the latter case is less than 2 Mev. The shapes of the γ-ray spectra arising from the scalar and pseudovector fields for the π^- mesons would be almost indistinguishable from the pseudoscalar shape.

Table V lists the theoretical predictions for the probabilities of mesic absorption for the various possible combinations of fields for the π^- and π^0 mesons. The mesic absorption probabilities are based on a $\pi^- - \pi^0$ mass difference of 4.75 Mev and the π^0 coupling constants to which they are proportional are taken from Table II. Tables IV and V show quite clearly that the relative probabilities for the three competing slow π^- meson reactions in deuterium depend strongly upon the assumed spins and parities of the π^- and π^0 mesons, in agreement with the selection rules indicated by Tables I and III. The theoretical predictions can therefore be summed up as follows: if the π^- meson possesses spin 0 and even parity (scalar), no neutron absorption

[19a] *Note added in proof:* Our numbers disagree with some of those in Table I of a recent paper by Ogawa, Yamada, and Nagahara [Prog. Theor. Phys. 6, 227 (1951)] because of their failure to take account of selection rules.

[20] F. J. Dyson, Phys. Rev. 73, 929 (1948).

should take place and the vast majority of π^- mesons should undergo radiative absorption. If the π^0 meson is also scalar, mesic absorption should be negligible whereas if π^0 is pseudoscalar, about 10 percent of the π^- mesons should give rise to π^0's. If the π^- meson possesses spin 0 and odd parity (pseudoscalar), neutron and radiative absorption should compete on roughly comparable terms; if π^0 has the same parity (pseudoscalar), mesic absorption should again be extremely improbable whereas the emission of a π^0 of opposite parity (scalar) should again be about 1/10 as probable as the radiative absorption. For a spin 1 π^- meson, the relative probabilities for the three modes of absorption depend on the particular substate ($J=0$, 1, or 2) of the meson-deuteron system from which the transition takes place. Since each substate behaves, as far as the processes in question are concerned, as an independent system, the predicted ratios of neutron to radiative and radiative to mesic absorption must be weighted according to the statistical weight, $(2J+1)$, of each substate.[21] Carrying out this weighting procedure, it can be shown by use of Tables IV and V that for a vector π^- meson (spin 1 and odd parity), neutron absorption should be much more probable (by a factor of 100) than radiative[22] absorption. On the other hand, if the π^- meson possesses spin 1 and even parity (pseudovector), the ratio of neutron to radiative absorption should be 2 to 1 (determined by the statistical weights of the $J=0$, 1, 2 substates of the meson-deuteron system). Some competition from π^0 emission should result (of the order of 10 percent), regardless of the parties of π^0 and π^-.

What is the experimental situation? Panofsky, Aamodt, Hadley, and Phillips[6] have looked for γ-rays from the absorption of π^- mesons in deuterium. Using the same apparatus as for the hydrogen absorption experiment, they have observed the γ-ray spectrum given in Fig. 3. The conspicuous features of this spectrum are the peak in the neighborhood of 130 Mev (corresponding to radiative absorption) and the absence of γ-rays in the middle energy region (corresponding to mesic absorption). No direct measurement of the neutron absorption probability has been made but instead has been inferred from the γ-ray experiment by comparing the intensity of the high energy peak with the similar peak in the hydrogen absorption experiment. In addition, a direct comparison of the middle energy γ-rays has been made by sending the slow π^- mesons first into high

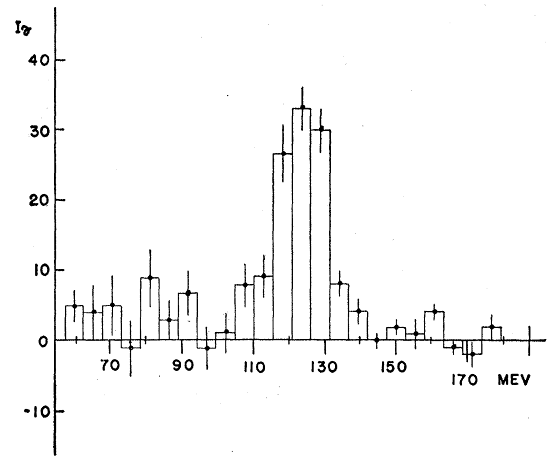

FIG. 3. Gamma-spectrum from π^-+D.

pressure hydrogen gas and then into high pressure deuterium gas. The respective numbers of counts are shown in Table VI. The observation that about $\frac{1}{3}$ of the π^- mesons yields 130-Mev γ-rays enables us to conclude immediately that the scalar and vector fields are excluded for the charged π-meson. Both the pseudoscalar and pseudovector fields for the charged π-meson are, in view of the theoretical and experimental uncertainties, consistent with the data. If the π^- meson is pseudoscalar, the absence of γ-rays in the middle energy region is some evidence against mesic absorption and for a pseudoscalar π^0 meson although this evidence is not conclusive because of the experimental error. If the π^- meson is pseudovector, nothing more definite can be said about the π^0 field on the basis of the deuterium absorption experiment. Careful analysis of the shape of the γ-ray peak further leads to the conclusion that the di-neutron cannot be bound by more than 200 kev.[23]

4. FAST MESON REACTIONS IN HYDROGEN AND DEUTERIUM

We have discussed in considerable detail the slow π^- meson reactions in hydrogen and deuterium. This has been done for two reasons: the existence of fairly accurate experimental data and the possibility of drawing important conclusions concerning the charged and neutral π-mesons on the basis of very general properties of the meson field. When we come to the fast meson reactions in hydrogen and deuterium, the less certain

TABLE VI. Experimental data on π^- absorption in hydrogen and deuterium.

Type of absorption	Hydrogen	Deuterium
Mesic	$0.45\ \pm0.09c/m$	$-0.007\pm0.020c/m$
Radiative	$0.470\pm0.046c/m$	$0.275\pm0.034c/m$
Neutron	···	$0.65\ \pm0.11c/m$

[21] This point was taken into account by S. Tamor (reference 10) for neutron and radiative absorption for the PV theory but not for the other possibilities; we consider the breakdown for all three modes of absorption for both the V and PV theories. We are indebted to Mr. Cheston for assistance with these computations.

[22] At first sight, it seems that radiative absorption should compete favorably with neutron absorption from the $J=1$ substate since the same initial and final neutron states are involved as in the pseudoscalar theory (see Table III). However, while the V and PS neutron absorption probabilities are indeed comparable, the radiative absorption probability turns out to be much lower for a vector π^- meson (compared to a pseudoscalar π^-) because of the character of its coupling to the electromagnetic field.

[23] K. Watson and R. Stuart, Phys. Rev. 82, 738 (1951).

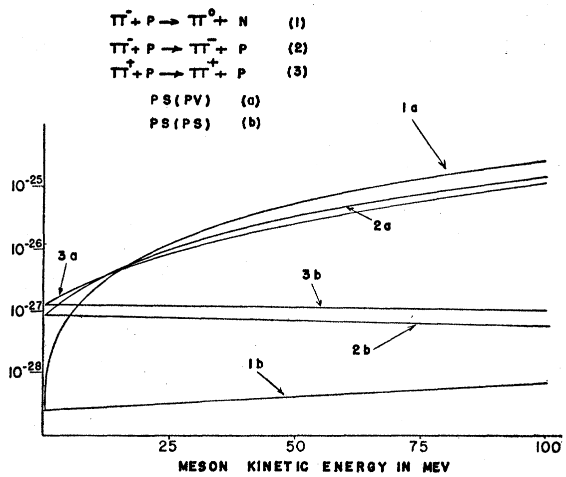

FIG. 4. Theorerical scattering cross sections

$$\left(\text{units } \frac{g^2}{\hbar c}\frac{g_P^2}{\hbar c}\,(1),\ \frac{g^4}{\hbar^2 c^2}\,(2),\,(3)\right).$$

features of meson field theory enter and hence our discussion will be much briefer.

We have seen that the slow π-meson reactions in hydrogen and deuterium necessarily involve only the negative variety and that the reactions take place from the K shell of the appropriate mesic atom. On the contrary, the fast meson reactions[24] which we consider involve π-mesons of both signs of charge and take place directly from the continuum. For fast mesons, it is no longer true that selection rules operate to produce large probabilities for the inherently weak γ-ray reactions and it is reasonable to restrict ourselves to those reactions which do not lead to the emission of γ-rays. In the case of hydrogen, this means restricting ourselves to the ordinary and charge-exchange scattering reactions, namely:

(1) $\pi^- + P \rightarrow N + \pi^0$ (charge-exchange scattering)
(2) $\pi^- + P \rightarrow P + \pi^-$ (ordinary scattering)
(3) $\pi^+ + P \rightarrow P + \pi^+$ (ordinary scattering).

In the case of deuterium, the reactions which remain are:

(1) $\pi^+ + D \rightarrow P + P$ (absorption)
(2) $\pi^+ + D \rightarrow D + \pi^+$ (ordinary elastic scattering)
(3) $\pi^+ + D \rightarrow P + N + \pi^+$ (ordinary inelastic scattering)
(4) $\pi^+ + D \rightarrow P + P + \pi^0$ (charge exchange inelastic scattering).

We have only recorded the π^+ reactions for deuterium because there is a one-to-one correspondence between the π^- and π^+ reactions if P is changed into N and conversely; also, from an experimental point of view, the π^+ reaction (1) is much easier to measure than the corresponding π^- reaction. For the purposes of the present discussion, we shall only consider the three reactions in hydrogen assuming spin 0 for the charged π meson and reaction (1) in deuterium.

Rigorous weak coupling expressions for the three scattering reactions in hydrogen have been calculated by several authors[25] for the spin zero theories. Assuming spin 0, we know that the π^- meson cannot be scalar and probably the same is true for the π^0 meson; hence we only give the results of the pseudoscalar calculations. Figure 4 shows the variation of total scattering cross section with energy from 0 to 100 Mev for reactions (1) to (3) for both pseudoscalar and pseudovector coupling; the cross sections are divided by the corresponding coupling constants. The cross sections for the ordinary scattering reactions (2) and (3) differ only slightly from each other both as regards absolute value and variation with energy; that they differ at all is due to the fact that in (2) the emission of the final meson follows the absorption of the initial meson whereas the converse is true for (3). The cross sections for the charge exchange reaction depend very sensitively on the relative signs of the π^0 meson coupling to the proton and neutron; if the two coupling constants have the same sign, the predicted cross sections are very similar to those for reactions (2) and (3) and are not plotted in Fig. 4. The curves which are given are those corresponding to opposite sign of the proton and neutron π^0 coupling constants ("symmetrical" theory) and differ greatly from the curves for reactions (2) and (3); the $PS(PS)$ curve for reaction (1) has the same shape as the $PS(PS)$ curves for (2) and (3) but is reduced by a factor of 50 whereas the $PS(PV)$ curve for reaction (1) starts out much lower than the $PS(PV)$ curves for (2) and (3) but becomes almost identical with the latter two above 15 Mev. It is interesting to note that the zero energy cross sections (Thomson limit) are identical for PS and PV coupling for equal coupling constants and that the charge-exchange reaction (1) in the Thomson limit can be derived immediately from our previous calculation for the transition probability of π^- mesic absorption from the K shell of the mesic-hydrogen atom (see Table II) by replacing the reciprocal volume of the meson-proton system by the number of protons per cm^3.

The striking features of the curves for all three scattering reactions in hydrogen are the almost constant cross section as a function of energy predicted by the $PS(PS)$ theory in contrast to the rapidly increasing cross section predicted by the $PS(PV)$ theory. The fact that the $PS(PV)$ strong coupling[26] theory leads to the same rapid increase with energy as the weak coupling theory underlines the characteristic behavior

[24] When we speak of fast mesons, we refer to mesons which can be produced artificially, say in the energy region 5 to 100 Mev (we restrict ourselves to energies greater than 5 Mev so that the coulomb field of the proton and deuteron can be neglected).

[25] See Ashkin, Simon, and Marshak, Prog. Theor. Phys. **5**, 634 (1950); see also M. Jean and J. Prentki, Compt. rend. **230**, 365 (1950). The curves in Fig. 4 were computed by T. Auerbach.

[26] W. Pauli, *Meson Theory* (Interscience Publishers, Inc., New York, 1947).

of a derivative type coupling. There are some equally striking differences predicted by the $PS(PS)$ and $PS(PV)$ theories for the angular distribution of the scattered mesons (see reference 25) but we shall not enter into their discussion here. These differences should provide the means for distinguishing between direct and derivative coupling for pseudoscalar charged π-mesons provided the pseudoscalar character of the charged π-field is fixed by other experiments. Experiments on the charge-exchange scattering should help to decide whether the π^0 mesic charges of the proton and neutron are equal or opposite in sign. If the charged π meson turned out to possess spin 1, similar considerations would apply.

Scattering experiments on heavy nuclei carried out thus far with artificially produced π-mesons by Bernardini *et al.*[27] and by Bradner and Rankin[28] have not led to any data which can be compared directly with the one-nucleon theory. The large cross section (close to geometrical) which has been observed in the energy region 30 to 100 Mev and the large probability for slow mesons emerging in inelastic scattering which has been found perhaps favor the $PS(PV)$ theory although it is necessary to perform scattering experiments with pure hydrogen before drawing any firm conclusions.

While there is no doubt that π-meson scattering experiments in hydrogen will yield some very important information about the π meson-nucleon interaction, it is possible that even the qualitative features of the theoretical predictions may not be significant because of the dependence of the calculations on the detailed properties of the meson field. When we come to the fast π^+ meson absorption reaction in deuterium, the story is much more promising. The first point to notice is that the absorption reaction: $\pi^+ + D \rightarrow P + P$ is the inverse of the reaction $P + P \rightarrow \pi^+ + D$ for which definite evidence has been obtained at Berkeley with 340-Mev protons. π^+ meson curves strongly peaked at the high energy end are known from the work of Cartwright *et al.*[29] and of Peterson[30] and imply that the reaction: $P + P \rightarrow \pi^+ + D$ competes seriously with the reaction $P + P \rightarrow \pi^+ + P + N$. The experimental cross section/sterad for the total π^+ production cross section is given in Table VII as a function of angle. It is likely that at least $\frac{1}{2}$ and possibly as much as $\frac{2}{3}$ of the π^+ mesons produced are associated with the formation of a real deuteron; thus, a total cross section of the order of 2×10^{-28} cm^2 for the reaction $P + P \rightarrow \pi^+ + D$ at 340 Mev is very likely. It is easy to show, by detailed balancing, that the total cross section for the π^+ mesic absorption reaction in deuterium is related to the π^+ production cross section by the equation:

TABLE VII. π^+ production in $P-P$ collisions at 340 Mev.

Lab. angle	0°	18°	30°	60°
$\sigma_{(\text{total})}$ (in units of 10^{-28} cm^2/sterad)	2.00	1.63	0.58	<0.17

$$\sigma_{\text{Abs}} = [2/3(2S+1)](p^2/k^2)\sigma_{\text{prod}}, \qquad \text{(I)}$$

where S is the spin of the π^+ meson, k is the momentum of the meson in the c.m. system and p is the momentum of the proton in the c.m. system. A π^+ meson energy of 22.7 Mev in the laboratory system corresponds to the incident proton energy of 340 Mev and should lead to an absorption cross section 18 times as large ($\approx 4\times 10^{-27}$ cm^2) as the production cross section if the π^+ spin is 0 and only 6 times as large if the spin is 1.[31] Table VIII, computed by Mr. Cheston, lists several characteristic proton and meson energies and the ratios of the absorption to the production cross section determined by Eq. (1) assuming $S=0$. Thus, measurement of the total absorption and production cross sections will provide a unique determination of the spin of the charged π meson independent of any details of meson theory. Mr. Cheston[32] has also carried out phenomenological calculations for the fast π^+ absorption in deuterium—similar to those of Tamor's for the slow π^- absorption—for the four types of meson fields. He restricted himself to π^+ meson energies in the range 5 to 100 Mev (less than 100 Mev so that the nucleons can be treated nonrelativistically) and finds that the total cross section is roughly constant for the spin 0 theories over the energy range considered whereas the spin 1 cross sections drop off by more than a factor 10. The scalar cross sections are down by a factor of 10 compared to the pseudoscalar but we already know that the charged π meson cannot be scalar. The angular distribution of the protons in the c.m. system is roughly isotropic for the spin 1 theories whereas the spin 0 theories exhibit forward maxima, slight for PS and very large for S. These effects can be understood in terms of approximate selection rules and are probably significant. Consequently, measurement of the proton angular dis-

TABLE VIII.

Proton kinetic energy (lab) in Mev	302	340	394	494
Meson kinetic energy (lab) in Mev	5	22.7	50	100
$\sigma_{\text{Abs}}/\sigma_{\text{Prod}}$ (spin 0 π^+)	95.4	18.0	8.9	5.1

[27] Bernardini, Booth, Lederman, and Tinlot, Phys. Rev. **80**, 924 (1950).

[28] H. Bradner and B. Rankin, Phys. Rev. **80**, 916 (1950).

[29] Cartwright, Richman, Whitehead, and Wilcox, Phys. Rev. **78**, 823 (1950).

[30] V. Peterson, Phys. Rev. **79**, 407 (1950).

[31] With sufficient accuracy, this experiment will determine the π^+ spin even if, to everyone's surprise, it were to be larger than 1; it should be recalled that the two γ-emission from π^0 would be consistent, for example, with spin 2.

[32] W. B. Cheston, Phys. Rev. (to be published).

tribution and the energy dependence of the total cross section for the reaction $\pi^+ + D \rightarrow P + P$ should help decide between the pseudoscalar and pseudovector fields for the charged π-meson. A little reflection shows that when the theoretical predictions for the absorption reaction in deuterium are combined with the detailed balancing Eq. (I), it follows that the cross section for the inverse reaction: $P + P \rightarrow \pi^+ + D$ should increase by a factor of 10–20 in the energy region 300 to 500 Mev for protons, for the spin 0 theories and stay roughly constant for the spin 1 theories; in the center-of-mass system, the π^+ angular distribution is identical with the proton angular distribution.

5. CONCLUSION

In conclusion, I should like to summarize what has been learned and what still remains to be learned from experiments on π-meson reactions in hydrogen and deuterium. From the two competing slow π^- reactions which have been observed in hydrogen, we have learned that the charged and neutral π-mesons are both bosons and that the π^0 meson possesses spin 0 (or a spin greater than 1). Measurement of the γ-ray energies and intensities have provided accurate values for the masses of both π^- and π^0 and have permitted tentative conclusions to be drawn regarding the odd parity of the π^0 meson and the nature of its coupling to the nucleons. No conclusions regarding the absolute magnitude of the π^0 coupling constants can be drawn with confidence until a better meson theory is in existence.

From the slow π^- absorption experiments in deuterium, we have learned that the charged π-meson has either spin 0 and odd parity (pseudoscalar) or spin 1 and even parity (pseudovector). There are also hints from the deuterium experiment that the π^0 is pseudoscalar; a reduction in the experimental error on the mesic absorption probability is needed to settle this point. A more accurate measurement of the shape of the γ-ray spectrum from deuterium will also permit a closer study of the neutron-neutron interaction. None of the above conclusions contradict the conclusions drawn from other experiments such as the photon production of charged and neutral π-mesons.[33]

The fast π-meson reactions in hydrogen and deuterium have still to be studied. The greatest immediate gain seems to lie in a measurement of the π^+ spin. If it turns out that the π^+ spin is 0, as it probably will,[34] this will permit the unequivocal deduction that both the charged and neutral π-mesons are pseudoscalar. The hydrogen scattering experiments should then help decide between pseudoscalar and pseudovector coupling for the charged π-meson and between the same and opposite sign of π^0 coupling to the proton and neutron. If we learn all this, we shall still be far from having a correct meson field theory of nuclear forces or of understanding the other phenomena in which virtual π-mesons are almost certainly involved, but we shall at last be on our way.

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[33] See K. Brueckner, Phys. Rev. **79**, 641 (1950) and M. F. Kaplon, Phys. Rev. **83**, 712 (1951).

[34] *Note added in proof:* Clark, Roberts, and Wilson [Phys. Rev. (to be published)] have recently measured the cross section for the reaction $\pi^+ + D \rightarrow P + P$ and have found the π^+ spin to be 0; a similar measurement has been carried out by Durbin, Loar, and Steinberger [Phys. Rev. (to be published)] with the same result.