shift to the blue under infra-red stimulation. The large decrease in stimulation between 0.003 and 0.01 percent Cu may be attributed to the large decrease in the number of effective blue-emitting centers (caused by an increase in the relative number of green-emitting centers and hence an increase in the rate of the process by which holes are transferred from blue-emitting to green-emitting centers) as shown by spectral curves.[4]

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† This work was done under contract between ONR and RCA.
[1] G. F. J. Garlick and D. E. Mason, J. Electrochem. Soc. **96**, 90 (1949).
[2] E. F. Daly, Proc. Roy. Soc. **196**, 554 (1949).
[3] Proportions are given in weight percent.
[4] Full discussion of the preparation and luminescence characteristics of these phosphors is included in a paper by the author, R. H. Bube, Phys. Rev. **80**, 657 (1950).
[5] G. F. J. Garlick and A. F. Gibson, J. Opt. Soc. Am. **39**, 935 (1949).

Further Remarks on the Absorption of π^--Mesons in Hydrogen*

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PANOFSKY, Aamodt, and York[1] have measured the γ-ray spectrum arising from the absorption of π^--mesons in hydrogen. As a result, it now appears fairly certain that the two processes hypothesized in an earlier paper,[2] namely: $\pi^-+P\rightarrow N+\gamma$ (radiative absorption) and $\pi^-+P\rightarrow N+\pi^0$ (mesic absorption) actually take place in nature.[3] Apart from the sensitive method which is furnished for the determination of the π^0-mass, the ratio of the mesic to radiative absorption probability determines the strength of the π^0-nucleon coupling. It is interesting to calculate[4] values of the π^0 coupling constant for various possible combinations of π^-- and π^0-fields and couplings.[5] The results are given in Table I. Column 1 contains expressions for the radiative absorption probability from the K-shell, while the remaining columns list expressions for the mesic absorption probability[6] and the values of the π^0-coupling constant (in units of $1/\hbar c$) which follow from the observed equality of radiative and mesic absorption.[7] The quantities g_P and g_N are the π^0-coupling constants with proton and neutron, respectively.

TABLE I. Absorption probabilities per sec.*

Radiative	Mesic		
$S(S)$	$S(S)-S(S)$	$S(S)-PS(PS)$	$S(S)-PS(PV)$
$2e^2\Gamma^2\delta^2$	$4\beta(\Delta g)^2$	$\beta^3\delta^2(\Delta g)^2$	$4\beta^3(\Delta g)^2$
	$(\Delta g)^2=0.008$	$(\Delta g)^2=27$	$(\Delta g)^2=0.15$
$PS(PS)$	$PS(PS)-S(S)$	$PS(PS)-PS(PS)$	$PS(PS)-PS(PV)$
$2e^2\delta^2$	$\frac{\beta^3}{4}\delta^4(\Delta g)^2$	$\beta\delta^2(\bar{g})^2$	$\beta\delta^2(\Delta g)^2$
	$(\Delta g)^2=210$	$(\bar{g})^2=0.06$	$(\Delta g)^2=0.06$
$PS(PV)$	$PS(PV)-S(S)$	$PS(PV)-PS(PS)$	$PS(PV)-PS(PV)$
$8e^2$	$\beta^3\delta^2(\Delta g)^2$	$\beta\delta^2(\Delta g)^2$	$\beta\delta^2(\bar{g})^2$
	$(\Delta g)^2=210$	$(\Delta g)^2=11$	$(\bar{g})^2=11$
$V(V)$	$V(V)-S(S)$	$V(V)-PS(PS)$	$V(V)-PS(PV)$
$(2/3)e^2$	$(4/3)\beta^3\delta^2 g_P^2$	$\beta\delta^2(\Delta g)^2$	$\beta\delta^2(\bar{g})^2$
	$g_P^2=13$	$(\Delta g)^2=0.93$	$(\bar{g})^2=0.93$
$PV(PV)$	$PV(PV)-S(S)$	$PV(PV)-PS(PS)$	$PV(PV)-PS(PV)$
$(2/3)e^2$	$4\beta(\Delta g)^2$	$\frac{\beta^3\delta^2}{3}[(\Delta g)^2+2(\bar{g})^2]$	$\frac{4\beta^3}{3}[(\Delta g)^2+2(\bar{g})^2]$
	$(\Delta g)^2=0.005$	$[(\Delta g)^2+2(\bar{g})^2=52$	$[(\Delta g)^2+2(\bar{g})^2]=0.3$

* The absorption probabilities per sec. are given in units of $\alpha^3\cdot g^2,/\hbar c(\mu c^2/\hbar)\cdot(1/\hbar c)$, $\alpha=e^2/\hbar c$, g is the π^--coupling constant, μ is the π^-- mass $\Gamma=4.71$ =difference between proton and neutron magnetic moments (in units of the nuclear magneton), $\delta=\mu/M$, $\beta=p_0/\mu_0 c$, $\Delta g=g_P-g_N$, $\bar{g}=g_P+g_N$; in the first column, $PS(PV)$ means the absorption of a PS π^- with PV coupling; in column 3, for example, $PS(PV)-PS(PS)$ means the absorption of a PS π^- with PV coupling and the emission of a PS π^0 with PS coupling, etc.

Examination of Table I permits us to discard some of the theories when proper account is taken of other π-meson experiments; e.g., the upper limit of $5\cdot10^{-14}$ sec. on the lifetime[8] of π^0, the photon production[9] of $\pi^\pm$, π^0, etc. Since the very recent experiment on the π^--absorption in deuterium definitely excludes the scalar and vector fields for the charged π-meson,[9a] we shall pursue this analysis here only to the extent of pointing out that Table I provides evidence against a scalar field for π^0: the extremely large π^0-coupling constants predicted by combining a PS field for π^- with a S field for π^0 contradicts the assumption of weak coupling, whereas the extremely small π^0-coupling constants predicted by combining PV for π^- and S for π^0 leads to too long a lifetime for π^0-decay. Thus, the only consistent weak coupling theory which is possible is a PS field for π^0 and a PS or PV field for $\pi^\pm$. In order to decide between the PS and PV fields for the charged π-meson, it is necessary to invoke some other experiment; e.g. Brueckner[9] has concluded that the leveling off with energy of the cross section for photon production of π^+ is evidence for the PS field.

Even if we assume that both the charged and neutral π-mesons are pseudoscalar, neither the hydrogen nor the deuterium experiment fixes the nature of the coupling of the PS π-meson to the nucleon. In principle, a linear combination of PS and PV couplings is possible; the ratio, R, of the mesic to radiative absorption probabilities in hydrogen would then become (g_P, g_N, g, now refer to PS coupling while f, f_P, f_N refer to PV coupling):

$$R=\frac{\beta[g(\bar{g}+\Delta f)+f(\Delta g+\bar{f})]^2/\hbar c}{2\alpha(g-2/\delta f)^2}. \quad (1)$$

Equation (1) contains the dominant terms in an expansion in powers of δ; however, if a particular choice of g_P and g_N leads to a cancellation in the mesic absorption probability, the next term in δ has to be considered. For example, in the pure $PS(PS)-PS(PS)$ theory, R vanishes when $g_P=-g_N$; to the next order[10] in δ, $R=(\beta\delta^2/8\alpha)(\Delta g)^2/\hbar c$ so that the choice $g_P=-g_N$ leads to $g_P^2/\hbar c=g_N^2/\hbar c=2\alpha/\beta\delta^2=2.8$ (see Table I). A promising method for deciding between PS and PV coupling is to study the energy dependence of ordinary and charge exchange π-meson scattering by nucleons. PS coupling leads to a decreasing cross section with energy whereas PV coupling yields a rapidly increasing cross section.[11] For the meson energies produced by present accelerators (up to 150 Mev, say) the reaction of the meson field should not seriously modify the qualitative predictions of weak coupling theory.[12]

We are greatly indebted to Professor Panofsky for keeping us closely informed of experimental developments.

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[1] Panofsky, Aamodt, and York, Phys. Rev. **78**, 825 (1950).
[2] R. Marshak and A. Wightman, Phys. Rev. **76**, 114 (1949); see also B. Bruno, Ark. f. Fysik 1, No. 2 (1949).
[3] A complete demonstration of the latter process would consist, of course, in measuring the two "low" energy γ-rays in coincidence.
[4] We use weak coupling theory; however, strong coupling theory yields similar results for some of the theories, according to a private communication from C. N. Yang.
[5] We have omitted the derivative couplings for the scalar, vector, and pseudovector theories since they do not lead to any essentially new results. Only spin zero theories are considered for π^0 since π^0 decays into two γ-rays.
[6] The $S(S)-S(S)$ expression given in Table I agrees with that given in reference 2 whereas the $PS(PS)-PS(PS)$ expression (Eq. (11)) is δ^2 times smaller. It is *not* true that the equivalence theorem holds for mesic absorption; as a matter of fact, the $PS(PS)-PS(PS)$ and $PS(PV)-PS(PV)$ expressions are *identical*. It is precisely this breakdown of the equivalence theorem for mesic absorption (in contrast to radiative absorption) which makes the hydrogen experiment so interesting and is responsible for some of the surprising numbers listed in Table I.
[7] Panofsky, Aamodt, and Hadley, private communication; $\beta\equiv p_0/\mu_0 c$ =0.23 was used where μ_0 and p_0 are the π^0-mass and momentum respectively.
[8] A. Carlson, J. Hooper, and D. King, Phil. Mag. **41**, 701 (1950).
[9] J. Steinberger and A. Bishop, Phys. Rev. **78**, 494 (1950). Steinberger, Panofsky, and Stellar, Phys. Rev. **78**, 802 (1950). K. Brueckner, Phys. Rev. **79**, 641 (1950).

[9a] S. Tamor and R. E. Marshak, following letter.
[10] See Aidzu, Fujimoto, Fukuda, Hayakawa, Takayanagi, Takada, and Yamaguchi, Prog. Theor. Phys. (to be published).
[11] See Ashkin, Simon, and Marshak, Prog. Theor. Phys. (to be published); it is found that as the meson energy increases from 0 to $2\mu c^2$, the $PS(PS)$ scattering cross section decreases by a factor of 1.7 while the $PS(PV)$ cross section increases by a factor of 675.
[12] As is well known, strong coupling theory for PV coupling leads to the same rapid increase of cross section with energy.

On the Absorption of π^--Mesons in Deuterium*

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SOME work on the absorption of π^--mesons by deuterons has already been published.[1,2] These papers do not consider the three possible modes of mesic disintegration of the deuteron. The π^--absorption may not only lead to the emission of two high energy neutrons (neutron absorption) but in analogy with the absorption in hydrogen,[3] absorption may also be accompanied by the emission of a γ-ray (radiative absorption) or a neutral meson (mesic absorption). A phenomenological treatment of these processes enables one to calculate the relative probabilities of neutron and radiative absorption independently of any detailed theory of nuclear forces and of the strength of the π^--meson-nucleon coupling; in fact, the ratio depends primarily upon the spin and parity of the π^--meson. The mesic absorption predictions depend to some extent on the π^0-nucleon coupling; even this arbitrariness is eliminated by making use of the hydrogen absorption experiment.

Wightman has shown[4] that most π^--mesons have moderation times down to the K shell of the mesic deuterium atom which are short compared to the lifetime for π–μ-decay. The neutron absorption of a π^--meson from the K shell is strongly affected by the requirements of the exclusion principle applied to the final two-neutron system. Thus, since the ground state of the deuteron is $^3S_1+^3D_1$ and the interaction of scalar mesons (with scalar coupling[5]) with nucleons does not lead to a spin flip, absorption of scalar mesons from states of even L are forbidden by parity conservation and the exclusion principle. Instead, absorption of a scalar meson will be accompanied by the emission of a photon in spite of the fact that the electromagnetic interaction is inherently weak. The other theories are also affected by the selection rules but in different ways.

The neutron and radiative absorption probabilities are listed in Table I, as is the ratio of the two. N is a normalization factor for the radial wave function of the deuteron and $\phi(0)$ is the amplitude of the meson wave function at the origin. We see that in view of the widely different theoretical predictions, the search for γ-rays from the absorption of π^--mesons in deuterium should yield fairly decisive information concerning the nature of the charged π-meson. The detection of appreciable numbers of γ-rays would exclude the vector charged π-meson. Furthermore, most scalar mesons which reach the K shell (absorption from the L shell is discussed below), should give rise to γ-rays in contrast to the other theories.

It should be mentioned that the distortion of the final state wave function by the neutron-neutron interaction (taken equal to the proton-proton interaction) affects the spectral distribution of the γ-rays. If one ignores this interaction, the γ-spectrum has a peak near 130 Mev and a width of about 12 Mev. The interaction sharpens the peak to a width of about 2 Mev and shifts the maximum to 134 Mev (assuming 140 Mev for the π^--mass); however, the total transition probability is affected only slightly.

The emission of a neutral meson is also possible if the $\pi^- - \pi^0$-mass difference exceeds[6] 3.55 Mev. Experiments at Berkeley indicate a mass difference of about 5 to 6 Mev. Using this mass difference and the coupling constants for π^0 obtained from the absorption in hydrogen[7] we can determine the competition from mesic absorption. For π^--mesons of spin 1, mesic absorption may be comparable to or even larger than radiative absorption, but both are dominated by neutron absorption. Assuming spin zero for π^- we find that mesic absorption is very improbable (down by a factor 10^4 compared to radiative absorption) for the same parity of π^- and π^0 because of the operation of the exclusion principle; for opposite parity, mesic absorption can compete with radiative absorption.

TABLE I. Absorption probabilities per second from $1S$ state in units of $(N/3)\cdot(g^2/\hbar c)\cdot(\hbar/\mu c)^2\cdot\phi(0)^2\cdot c=0.91\cdot10^{16}\cdot g^2/\hbar c$ sec.$^{-1}$. $S(S)$ means scalar mesons with scalar coupling, etc.

Meson theory	$S(S)$	$PS(PS)$	$PS(PV)$	$V(V)$	$PV(PV)$[d]
Neutron[a]	0[b]	$2.7\cdot10^{-3}$[c]	0.25	0.12	2.5 $(J=0)$ 0 $(J=1)$ 0.15 $(J=2)$
Radiative	0.012	$6.6\cdot10^{-4}$	0.12	$2.2\cdot10^{-3}$	$2.0\cdot10^{-2}$ $(J=1)$ $2.4\cdot10^{-3}$ $(J=0,\ 2)$
Ratio	0	4.1	2.1	55	2

[a] These probabilities were obtained using the deuteron wave functions determined from the Hulthén potential; a change in the shape of the potential would not affect the ratios by more than a factor of 1.5.
[b] The zero result holds in the phenomenological approximation; a relativistic calculation leads to a transition probability of about $3\cdot10^{-4}$ (i.e., three percent of the radiative probability assuming that the latter receives contributions from the anomalous magnetic moments of proton and neutron).
[c] The neutron absorption for the $PS(PS)$ theory is about twice as great as the equivalence theorem would predict owing to the charge exchange in the nucleon-nucleon interaction [F. J. Dyson, Phys. Rev. **73**, 929 (1948)]. The calculation was done using the Berkeley potential [R. S. Christian and E. W. Hart, Phys. Rev. **77**, 441 (1950)].
[d] The ratio given here is not the ratio of the transition probabilities, but depends on the relative populations of the three states ($J=0$, 1, 2) of the meson-deuteron system. If the three states are populated according to their statistical weights, the ratio is 2:1. We are indebted to Dr. K. Brueckner for calling our attention to this point.

If the π^--meson is absorbed from a state of odd L, the selection rules are changed. However, absorption from P states is slower by a factor of 30 than the radiative transition to lower states (for scalar mesons). One can expect that about 95 percent of the π^--mesons will be absorbed from the $1S$ state.

While this letter was in preparation, Professor Panofsky very kindly informed us of the results of his experiment with Aamodt and Hadley on the π^--absorption in deuterium. Their observations are that about $\frac{1}{3}$ of the π^--mesons yield 130-Mev γ-rays while "low" energy γ-rays are absent. We believe that since the theory is phenomenological and is really quite insensitive to the more subtle properties of meson fields, it is difficult to escape the conclusion that the scalar and vector fields for the charged π-meson[8] are excluded by the results. There is further slight evidence that a pure $PS(PS)$ theory for the charged π-meson is ruled out. If the charge π-meson is pseudoscular, the absence of π^0 argues for equal parity[7] for π^0 and $\pi^{\pm}$.

A detailed paper will be published shortly by one of us (S.T.).
We are indebted to Dr. Wightman for several helpful conversations.

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[1] B. Ferretti, Report on the International Conference on Low Temperatures and Fundamental Particles, Cambridge (1946), p. 75.
[2] C. Marty and J. Prentki, J. de phys. et rad. **10**, 156 (1949).
[3] R. E. Marshak and A. Wightman, Phys. Rev. **76**, 114 (1949) and preceding letter.
[4] A. Wightman, private communication.
[5] Scalar mesons with vector coupling do not lead to any essentially new results; actually, none of the derivative couplings lead to any qualitatively different results except possibly for the pseudoscalar theory (see Table I).
[6] Obtained from the deuteron binding energy of 2.24 Mev and the neutron-proton mass difference of 1.31 Mev [R. Bell and L. Elliot, Phys. Rev. **74**, 1552 (1948)].
[7] Marshak, Tamor, and Wightman, preceding letter.
[8] This conclusion is in agreement with the one drawn from the angular distribution of photon-produced π^+-mesons [K. Brueckner, Phys. Rev. **79**, 641 (1950)].