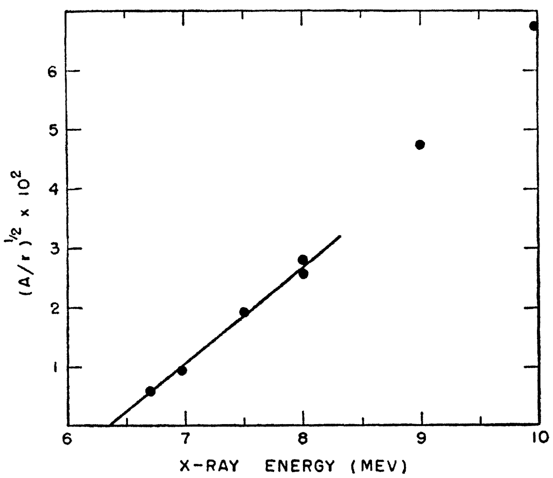

FIG. 1.

to 10 Mev. The bombarded thorium was chemically purified to remove fission products and thorium daughters. Uniform 25-mg samples of ThO_2 were prepared for counting by igniting painted layers of an organic thorium solution. The Th^{231} activity was measured with a thin window Amperex Geiger tube. The samples were covered with an aluminum absorber (7 mg/cm²) to stop alpha-particles. Purified, unirradiated ThO_2 samples (25 mg) gave a counting rate of 3 count/min over background (16 count/min) with this arrangement. Growth of the Th^{228} daughters amounted to 1 count/min three hours after purification. Observed Th^{231} activities ranged from 2 to 60 count/min. The activities decayed with the correct half-life of about 26 hours. The x-ray beam intensity was monitored with a Victoreen integrating roentgen meter.

The square root of the total Th^{231} activity produced in each bombardment divided by the total roentgens registered by the Victoreen meter, i.e., $(A/r)^{\frac{1}{2}}$, appeared to be a linear function of bombardment energy within experimental error up to 8 Mev. The data are given in Fig. 1. Extrapolation by the method of least squares gives a threshold of 6.35±0.04 Mev for the $Th^{232}(\gamma, n)Th^{231}$ reaction. This value is in fair agreement with 6.1±0.2 Mev obtained indirectly by the method of neutron detection.[3]

* This work was supported in part by the joint program of the AEC and ONR.
[1] Huizenga, Magnusson, Simpson, and Winslow, Phys. Rev. **79**, 908 (1950); J. A. Harvey, Phys. Rev. **81**, 353 (1951); Kinsey, Bartholomew, and Walker, Phys. Rev. **82**, 380 (1951).
[2] Huizenga, Magnusson, Fields, Studier, and Duffield, Phys. Rev. **82**, 561 (1951).
[3] R. W. Parsons and C. H. Collie, Proc. Phys. Soc. (London) **A63**, 839 (1950).

Theory of Dibaric Particles

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IN a series of seminars on the self-energy of the vector meson, J. Schwinger found it convenient to introduce as a mathematical artifice a system of spin 1 whose properties were intermediate between those of the vector meson and those of the electron. It is the purpose of this note to discuss the possible physical significance of this system.

A study was made of a quantum-mechanical system postulated to obey the equation of motion

$$(p_\mu\beta_\mu - ik)\psi = 0,$$

where β_μ was formed from the fusion of two Dirac-like matrices

$$\beta_\mu = \tfrac{1}{2}(\gamma_\mu^{(1)} + \gamma_\mu^{(2)})$$

obeying the commutation rules

$$\gamma_\mu^{(i)}\gamma_\nu^{(i)} + \gamma_\nu^{(i)}\gamma_\mu^{(i)} = 2\lambda^{(i)}\delta_{\mu\nu},$$
$$\gamma_\mu^{(1)}\gamma_\nu^{(2)} - \gamma_\nu^{(2)}\gamma_\mu^{(1)} = 0,$$

where $\lambda^{(1)} + \lambda^{(2)} = 2$. Such a system may be interpreted physically as a pair of strongly coupled spin $\frac{1}{2}$ particles of different mass.

The β's are represented as 16×16 matrices using a fusion representation developed by de Broglie.[1] The present theory is intermediate between that of Kemmer[2] (in which $\lambda^{(1)} = \lambda^{(2)} = 1$) and that of Dirac (in which $\lambda^{(1)} = 2$, $\lambda^{(2)} = 0$), but because of the occurrence of discontinuities does not include either of these extreme cases.

The system was found to have the following properties:

(1) It could exist in either of two mass states, with masses

$$m = (k/c)[2/(1\pm\lambda)]^{\frac{1}{2}}, \quad \lambda \equiv (\lambda^{(1)}\lambda^{(2)})^{\frac{1}{2}},$$

from which it is evident that the phenomenon of dibarism is peculiar to this intermediate case and would occur in neither the Kemmer case ($\lambda = 1$) nor the Dirac case ($\lambda = 0$).

(2) The spin angular momentum operator had eigenvalues 0, $\pm\hbar$; we note that the particle is a boson.

(3) The magnetic moment was similar to that of the Kemmer particle, except for an additional term (which vanished for spin eigenstates) of value

$$\pm(ehc/2k)(\lambda^{(1)} \pm \lambda^{(2)});$$

there thus appear nonzero spin magnetic moments for states of zero spin, as might be expected from the fact that one is adding magnetic moments of particles of different masses.

(4) Transitions from the heavier (mass $(n+\Delta n)$ electron masses) to the lighter (mass n electron masses) state accompanied by gamma-emission were investigated. The lifetime of the heavier state, approximately

$$(9\times 10^{-17}/n)(n/\Delta n)^3 \text{ sec},$$

proved too short to measure except for very small mass difference.

(5) Coulomb scattering, with and without change of mass, was also investigated; the cross section for the latter case reduced to the Rutherford formula as would be expected.

In its relativistic form, the theory was found to be unrealistic, because of the existence of negative energy states which, since the particle is a boson, cannot be filled up arbitrarily. These negative energy solutions may be accounted for by the binding energy associated with the fusion of the two spin $\frac{1}{2}$ particles. It would therefore seem that the theory discussed above is meaningful only in the nonrelativistic limit.

The author would like to express her thanks to Professor Herman Feshbach for suggesting the problem and for many stimulating discussions.

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[1] L. de Broglie, Actualités sci. et ind. **181** (1934); **411** (1936)
[2] N. Kemmer, Proc. Roy. Soc. (London) **A173**, 91 (1939).

Note on the Relativistic Formula for Photoelectric Absorption

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RECURRING references[1] in the literature to the relativistic photoeffect formula

$$\frac{\phi_K}{\phi_0} \cong \frac{3}{2}\frac{Z^5}{137^4}\frac{\mu}{k}\exp[-\pi\alpha + 2\alpha^2(1-\log\alpha)] \qquad (1)$$

contain comments which indicate that the degree of validity of this formula is not generally understood. The notation of Eq. (1) is Heitler's.[2]

The derivation of this formula, published in 1934,[3] was originally criticized by Hulme *et al.*[4] It appears to have escaped attention, however, that Hulme's criticism was removed in a rigorous treatment of the problem for the high energy limit in 1936.[5] Heitler in particular requotes the same criticism in the second edition of reference 2 in 1945. Current practice, on the other hand, appears to follow the pattern of quoting the criticism stated by Heitler, and then of using the formula anyway because it fits the data so well.

It is hoped that the present letter will suffice to establish recognition of the rigorous treatment on which Eq. (1) is based.

[1] E.g., W. Heitler, *The Quantum Theory of Radiation* (Clarendon Press, Oxford, 1945), second edition; Bishop, Collie, Halban, Hedgran, Siegbahn, du Toit, and Wilson, Phys. Rev. **70**, 113 (1950).
[2] See W. Heitler, reference 1, p. 126.
[3] H. Hall, Phys. Rev. **45**, 620 (1934).
[4] Hulme, McDougall, Buckingham, and Fowler, Proc. Roy. Soc. (London) **139**, 131 (1935).
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New Aspects of the Pseudoscalar Meson Theory*

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We wish to demonstrate here a canonical transformation on the hamiltonian describing the interaction of a neutral pseudoscalar meson field with a single nucleon through pseudoscalar coupling, which has the property that it reveals the equivalence theorem between pseudoscalar and pseudovector coupling in a new light and at the same time reduces the hamiltonian to a form in which it may be amenable to strong-coupling treatment.

The hamiltonian with which we begin is

$$H=\beta M+\boldsymbol{\alpha}\cdot\mathbf{p}+ig\beta\gamma^5\varphi_0+H_\mu,\quad H_\mu=\tfrac{1}{2}\int\{\pi^2+(\nabla\varphi)^2+\mu^2\varphi^2\}d\mathbf{x},\quad (1)$$

where all symbols have their usual meaning, units are chosen so that $\hbar$ and c are unity, and the subscript 0 represents the evaluation of the corresponding meson field quantity at the nucleon position. Under the canonical transformation

$$H\rightarrow H'=e^{iS}He^{-iS}$$

with

$$S=\tfrac{1}{2}\gamma^5\tan^{-1}\{g\varphi_0/M\}\quad (2)$$

the hamiltonian takes the form

$$H'=\beta M[1+g^2\varphi_0^2/M]^{\frac{1}{2}}+\boldsymbol{\alpha}\cdot\mathbf{p}+H_\mu+\frac{g}{4M}\left\{\frac{1}{1+g^2\varphi_0^2/M^2}[\boldsymbol{\sigma}\cdot\nabla\varphi_0-\gamma^5\pi_0]+[\boldsymbol{\sigma}\cdot\nabla\varphi_0-\gamma^5\pi_0]\frac{1}{1+g^2\varphi_0^2/M^2}\right\}+\frac{g^2}{8M^2}\int\left[\frac{\delta(\mathbf{x}-\mathbf{x}_0)}{1+g^2\varphi_0^2/M^2}\right]^2d\mathbf{x}.\quad (3)$$

Hence we see that pseudoscalar coupling is equivalent to a nonlinear pseudovector coupling together with some additional non-spin-dependent nonlinear coupling terms.[1] It should be noted that the above transformation is exact to all orders in the coupling constant in contradistinction to other derived forms of the equivalence theorem.[2] The strong nonlinearity of the hamiltonian in the meson field is reminiscent of recent heuristic proposals by Heisenberg,[3] Finkelstein and Ruderman,[4] and Schiff,[5] and suggests the possibility that pseudoscalar meson coupling may provide the elements required for the explanation of nuclear force saturation and of the relative independence of one-particle motions in nuclei required by the nuclear shell model on a basis other than exchange forces.

The hamiltonian (3) is in a form such that the method of Foldy and Wouthuysen[6] may be applied to obtain the equivalent nonrelativistic hamiltonian. The result, disregarding all terms which vanish as the nucleon becomes infinitely heavy (after writing $g=fM$ and assuming f remains finite as $M\rightarrow\infty$), is

$$\mathcal{H}=M[1+f^2\varphi_0^2]^{\frac{1}{2}}-[\tfrac{1}{2}f\boldsymbol{\sigma}\cdot\nabla\varphi_0/(1+f^2\varphi_0^2)]+H_\mu+\frac{f^2}{8}\int\left[\frac{\delta(\mathbf{x}-\mathbf{x}_0)}{1+f^2\varphi_0^2}\right]^2d\mathbf{x}.\quad (4)$$

By the introduction of suitable source functions, it would appear possible to treat the hamiltonian (4) by the methods previously developed for strong coupling.

Similar treatments are possible for the charged pseudoscalar meson field with pseudoscalar coupling and for the second-quantized form of the Dirac field in both the Schrödinger and interaction representations. These, together with further investigations of the strong-coupling theory, will be presented in future publications.

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[1] The last term is of course strongly divergent. However, in the second-quantized form of the Dirac theory its analog is the more familiar "contact" term.
[2] See, for example, K. M. Case, Phys. Rev. **76**, 1 (1949).
[3] W. Heisenberg, Z. Naturforsch. **5a**, 151 (1950).
[4] R. Finkelstein and M. Ruderman, Phys. Rev. **81**, 655 (1951).
[5] L. I. Schiff, Phys. Rev. **80**, 137 (1950); Phys. Rev. **83**, 239 (1951).
[6] L. L. Foldy and S. A. Wouthuysen, Phys. Rev. **78**, 29 (1950).

Nuclear Spin of Actinium 227

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As part of a joint investigation of the actinium spectrum, interferometer exposures were made which yielded about 15 lines showing well-resolved hyperfine structure. The structure was in the form of flag patterns with either three or four components, with large degradation of spacing and intensity indicating a low nuclear spin. Since no more than four components were observed in spite of J values of at least 3 as shown by a term analysis, the number of levels in the split term is spin-limited, with $I=\frac{3}{2}$ for Ac^{227}, the isotope used. Evaluation of the nuclear magnetic dipole and electric quadrupole moments must await a more complete analysis of the spectrum, and will be reported later.

Erratum: A Self-Consistent Treatment of the Oxygen Dissociation Region in the Upper Atmosphere

[Phys. Rev. **83**, 109 (1951)]

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In Eq. (25) replace G_2 by G_2'.

In Appendix 1, replace the last two lines by "where G_1' is the statistical weight of two atoms in the ^3P state, and G_2' is 1 and is hence different from G_2."

In Appendix 4, Eq. (50) should be replaced by

$$B=\int_0^\infty\beta_v vF(v)dv=4.20\times10^{-21}T^{\frac{1}{2}}.\quad (50)$$

The value of B for $T=300°K$ is 7.25×10^{-20}. The equation for B' should be replaced by

$$B'=\int_0^\infty\beta_v' vF(v)dv=(G_1/G_1')(G_2'/G_2)(\nu_1^0/\nu_0)^2B\cong(1/24)B.$$

The above corrections do not affect any of the other results in the paper, since the correct expressions were used in calculating the results.

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