Letters to the Editor

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Elastic Scattering of Gammas by Bound Electrons*

P. Greifinger, J. Levinger,† and F. Rohrlich‡
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York
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The cross section for elastic scattering of gammas by atoms, as measured by Moon, Storruste,[1] and Wilson[2] is due to the coherent combination of Thomson, Delbruck, and reasonance scattering by the nucleus, and Rayleigh scattering by the bound electrons.[3] In the present note we report on calculations of Rayleigh scattering of Co^{60} 1.332-Mev gammas by K electrons of Pb at an angle of 180°. Our results are compared with the form factor calculation of Bethe[4] which is based on Dirac wave functions for the K electrons.

Feynman's methods can be used to calculate the amplitude for Rayleigh scattering. In this note we assume that the electron is free in the intermediate state of the scattering process. It seems likely that the effects of binding in the intermediate state are appreciable.[5] However, our present result is one term in the complete expression to be calculated by the expansion of Brown and Woodward.[5]

The matrix element for 180° scattering is proportional to[6]

$$M=\int d^3p\bar{\psi}(\mathbf{p}+\mathbf{Q})\frac{i\boldsymbol{\gamma}\cdot\mathbf{p}+\gamma_4(m-\epsilon+\omega)-m+2i\gamma_xp_x}{p^2-\omega^2-2m(\omega-\epsilon)+\epsilon(2\omega-\epsilon)}\psi(\mathbf{p}-\mathbf{Q})+\int d^3p\bar{\psi}(\mathbf{p}+\mathbf{Q})\frac{i\boldsymbol{\gamma}\cdot\mathbf{p}+\gamma_4(m-\epsilon-\omega)-m+2i\gamma_xp_x}{p^2-\omega^2+2m(\omega+\epsilon)-\epsilon(2\omega+\epsilon)}\psi(\mathbf{p}-\mathbf{Q}),$$

where ω = gamma-ray energy; ϵ = electron binding energy; $\mathbf{Q}=\frac{1}{2}$ the momentum change of the photon; and ψ = Dirac Coulomb wave functions in momentum space. All momenta and energies are in units of $Z\alpha m$ $(c=1)$.

The first term represents the case where the photon is first absorbed and then emitted, while in the second term the order is reversed. The matrix element for scattering with change of polarization vanishes such that the above expression gives the amplitude for polarized as well as for unpolarized radiation.

The dispersive scattering amplitude M_d (principal parts of the integrals) was evaluated by a double numerical integration. The results are given in Table I relative to Bethe's form factor calculation, which is 0.022 for this case. In this table "large-large" represents the contribution to the matrix element by terms involving transitions between the large components for both initial and final wave functions. The other columns are labelled by the corresponding transitions.

Table I. Amplitudes for the 180° scattering of 1.332-Mev gammas by the K-shell of Pb.

	Form factor	(Dispersive) M_d	(Absorptive) M_a
Large-large	0.89	0.83	0.78
Small-small	0.11	−0.14	−0.12
Large-small	0	−0.16	−0.34
Sum	1.00	0.53	0.32

The scattering amplitude also has an absorptive term, M_a, due to the poles of the integrand which corresponds to real photoelectric absorption and re-emission. This term is also included in Table I.

We note that the dispersive scattering amplitude is about half Bethe's form factor, while the absorptive scattering amplitude is surprisingly large. As noted above, our results may be modified appreciably by binding effects in the intermediate state.

* Supported in part by the ONR.
† Now at Louisiana State University, Baton Rouge, Louisiana.
‡ Now at Princeton University, Princeton, New Jersey.
1 P. B. Moon, Proc. Phys. Soc. (London) **A63**, 1189 (1950); A. Storruste, Proc. Phys. Soc. (London) **A63**, 1197 (1950).
2 R. R. Wilson, Phys. Rev. **82**, 295 (1951).
3 See J. S. Levinger, Phys. Rev. **87**, 656 (1952), for references to calculations of these processes.
4 H. A. Bethe (private communication). The formula is quoted in reference 3.
5 G. E. Brown and J. B. Woodward (private communication).
6 See reference 3, Appendix A, for derivation.

Pseudoscalar Interaction in the Theory of Beta-Decay*

T. Ahrens,† E. Feenberg, and H. Primakoff
Washington University, St. Louis, Missouri
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In the theory of beta-decay an approximation to the matrix element is customarily obtained by evaluating the radial part of the lepton wave functions at the boundary of the nucleus. The application of this procedure in the usual manner to the pseudoscalar interaction yields incomplete results. This can be seen by reducing the relativistic pseudoscalar matrix element $(f|Q\beta\gamma_5L|i)$ to a partially nonrelativistic form:

$$(f|Q\beta\gamma_5L|i)=i(f|Q\boldsymbol{\sigma}\cdot(\boldsymbol{\nabla}L)|i)/2M+(f|Q\beta\gamma_5|i)L_{\mathrm{at}\ \rho}. \quad (1)$$

In Eq. (1) natural units are employed; f and i stand for final and initial nuclear states; Q converts a neutron into a proton; L is the lepton covariant $\psi_e{}^*\beta\gamma_5\psi_\nu$, $\boldsymbol{\sigma}$ operates on a nucleon spin variable; $M=1836$ is the mass of the transformed nucleon. The conventional procedure overlooks the term in $\boldsymbol{\sigma}\cdot(\boldsymbol{\nabla}L)$,[1] in which one evaluates the radial part of the lepton wave functions at the nuclear boundary after the gradient operation has been performed on them. The correct procedure yields, for the pseudoscalar correction factor in the case $\Delta I=0$, (yes) the following expression to the lowest order in ρ:

$$C_{1P0}=(2p^2F\rho^2)^{-1}(G_P/2M)^2\left|\int\boldsymbol{\sigma}\cdot\boldsymbol{\kappa}\right|^2\times[(g_0'+\Gamma g_0)^2+(f_{-2}'+\Gamma f_{-2})^2]. \quad (2)$$

Here $\Gamma=\alpha(\Lambda Z)^2/2A^{\frac{1}{3}}$, Λ is a factor in the neighborhood of unity,[2] and the prime denotes the derivative with respect to ρ; the other symbols have their usual meaning.[3] The relative importance of the primed and unprimed coefficients in Eq. (2) can be seen from the estimate

$$|g_0'/\Gamma g_0|\cong(\alpha Z)^2/2\Gamma\rho=2/\Lambda^2. \quad (3)$$

Thus the two terms in the right-hand member of Eq. (1) make about the same contribution to the transition probability. The ratio of the pseudoscalar to the tensor transition probability for $\Delta I=0$, (yes) is then approximately given, for not too small Z, by the expression

$$(G_P/G_T)^2[(1-\tfrac{1}{2}\Lambda^2)Z/1836A^{\frac{1}{3}}]^2, \quad (4)$$

which is sensitive to Λ. Equation (4) shows that (G_P/G_T) must be about $1836A^{\frac{1}{3}}/Z$ in order that the pseudoscalar interaction should contribute appreciably to $\Delta I=0$, (yes) transitions. According to Petschek and Marshak[4] the RaE decay involves this type of transition. On the other hand, an even larger value of (G_P/G_T), namely about 1836, is necessary to introduce considerable deviations to the otherwise expected and experimentally observed allowed shape of the neutron decay spectrum.[1] A more complete and detailed report on the pseudoscalar interaction, worked out to a higher order of approximation, and including $\Delta I=0$, 2 (yes) as well as no parity change transitions with their cross terms, energy dependence, and plane wave approximations will soon be submitted for publication.

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† AEC predoctoral fellow.

[1] In the pseudoscalar treatment of the neutron decay the $\boldsymbol{\sigma}\cdot(\boldsymbol{\nabla}L)$ term gives the same energy correction to the allowed spectrum as the rigorous relativistic matrix element, while the second term gives no contribution. The rigorous matrix element has been worked out in a paper by Yamaguchi, Umezawa, Takebe, and Koiani to appear soon; reference to previous work on the neutron decay is given there.

[2] T. Ahrens and E. Feenberg, Phys. Rev. **86**, 64 (1952); D. L. Pursey, Phil. Mag. **42**, 1193 (1951); these references give

$$\int \gamma_5=(i\Lambda\alpha Z/2\rho)\int \boldsymbol{\sigma}\cdot\kappa$$

and in the same manner it can be shown that

$$2M\int \beta\gamma_5=(\Lambda\alpha Z/2\rho)\int \gamma_5.$$

[3] E. J. Konopinski and G. E. Uhlenbeck, Phys. Rev. **60**, 308 (1941).

[4] A. G. Petschek and R. E. Marshak, Phys. Rev. **85**, 698 (1952).

The Spin and Magnetic Moment of V^{50}

A. Hitchcock*
Institute of Nuclear Studies, University of Chicago, Chicago, Illinois
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In the $j-j$ spin orbit coupling model, V^{50}, with 23 protons and 27 neutrons, has 3 protons in the $1f\ 7/2$ shell and 7 neutrons in the $1f\ 7/2$ shell. There are 42 different states available to such a configuration, with spins ranging from 0 to 11. The interaction energy of these states has been calculated. It is found that, for very short range forces, the 4 lowest states have spins 6, 4, 3, and 5, respectively. The energy of these 4 states and of the lowest state of spin 7 has further been calculated for the following forms of an extended range interaction with convenient corresponding radial wave functions:

$$V(\mathbf{r}_{12})=\delta(\mathbf{r}_{12})P,\text{—radial wave function } R_f(r) \text{ irrelevant.} \quad (1)$$

This case is denoted by δ in the table, for a δ-function potential.

$$V(r_{12})=V_0\,[\exp(-\alpha r_{12})/r_{12}]P, \quad (2)$$

where

$$V_0=89\times10^{-13}\text{ Mev cm},\quad \alpha=0.858\times10^{13}\text{ cm}^{-1}.^1$$
$$R_f=N_f r^3\exp(-\beta r),\quad \beta_1=0.6435\times10^{13}\text{ cm}^{-1},$$
$$\beta_2=1.2122\times10^{13}\text{ cm}^{-1}.$$

These cases are denoted by $Y1$ and $Y2$ respectively in Table I, for Yukawa potential.

$$V(r_{12})=V_0[\exp(-\alpha r_{12}^2)]P,\quad V_0=42\text{ Mev},$$
$$\alpha=0.317\times10^{-26}\text{ cm}^{-2}.^1\quad R_f=N_f'r^3\exp(-\beta r^2),\quad (3)$$
$$\beta=0.1089\times10^{+26}\text{ cm}^{-2}.$$

This is denoted by G in the table, for Gaussian potential.

In each case the following forms of the exchange operator P were considered:

(a) $P=(0.8M+0.2H)$, called MH in the table.

(b) $P=(0.3W+0.4M+0.1B+0.1H)$, called Se in the table (Serber mixture).

(c) $P=(0.5W+0.3M-0.3B+0.5H)$, called Sy in the table ("Symmetric" mixture), where W, M, B, and H denote the usual Wigner, Majorana, Bartlett, and Heisenberg exchange operators.

Comparison of wave functions indicates that the region of physical interest corresponds to that between the cases $Y1$ and $Y2$, and probably to the region $0.65<\beta\times10^{-13}<0.75$ for the Yukawa potential.

For the Gaussian potential the region of interest corresponds to $0.08<\beta\times10^{-26}<0.14$. As the table shows, the ground state is in all cases of extended range, one of spin 5. The effect of the Coulomb force, which is not included in the given results, is not great enough to affect this result. The values in the table are subject to a maximum error estimated in the column ME.

The transition to the ground state of either Cr^{50} or Ti^{50} is, therefore, on Gamow-Teller rules, 4th forbidden, corresponding to a half-life of 10^{11} years at least, which is adequate to explain the occurrence of the isotope in nature.

The gyromagnetic ratio of the calculated lowest state has also been obtained, and is shown in the table as "g." This should be compared with the experimental value of 0.557.[2] The calculated value is subject to an estimated maximum error of 3 percent.

It is worthy of note that the experimental gyromagnetic ratio is within 0.2 percent of that which would be expected for any state ($J\neq0$) in which proton angular momentum and neutron angular momentum are separately constants of the motion, having eigenvalues $(7/2)\hbar$. This would be so in the spin 5 state if the proton-neutron force were some 10 times weaker, relative to the proton-proton force. For the state of spin 7 it is very nearly the case without such adjustment, but spin 7 is not in the competition for the ground state.

Finally it may be pointed out that the predicted spin does not agree with the rule of "parallel intrinsic spins" proposed by Scott[3] and in modified form by Nordheim.[4]

It is a pleasure to record that this work has been assisted by the University of Chicago, and by Trinity College, Cambridge.

Table I. Relative energy and gyroscopic ratio of g states of V^{50}. Energies are in Mev, except for case δ, where energies are in arbitrary units. A large positive energy means a tightly bound state. $E(7)$ = energy of state of spin 7, etc. ME is the estimated maximum error.

$V(r_{12})$	P	$E(7)$	$E(6)$[a]	$E(5)$[a]	$E(4)$	$E(3)$	ME	g[b]
δ	any	195	*230*	217	207	221	2	0.542
$Y1$	MH	−2.32	0.06	*0.15*	0.10	0.07	0.02	0.414
$Y1$	Se	−2.36	0.03	*0.09*	0.01	0.02	0.02	0.456
$Y1$	Sy	−2.26	0.05	*0.09*	0.05	0.05	0.02	0.450
$Y2$	MH	−17.62	10.69	*25.45*	19.30	14.70	0.20	0.419
$Y2$	Se	−11.52	3.14	*10.38*	5.99	5.45	0.10	0.440
$Y2$	Sy	−10.34	7.59	*13.63*	11.82	10.42	0.10	0.440
G	MH	−1.52	−1.22	*−0.49*	−2.03	−1.83	0.01	0.407
G	Se	−0.94	−0.25	*0.77*	−0.89	−0.77	0.01	0.421
G	Sy	−2.03	−1.12	*0.08*	−1.81	−1.51	0.01	0.420

[a] The lowest state for each interaction is italicized.
[b] Experimental value = 0.557.

* On leave from Cavendish Laboratory, Cambridge, England.

[1] These values are derived from those given by J. M. Blatt and J. D. Jackson, Phys. Rev. **76**, 18 (1950) and Revs. Modern Phys. **22**, 77 (1950).

[2] Walchi, Leysohn, and Scheitlen, Phys. Rev. **85**, 922 (1952).

[3] J. M. C. Scott "On the Spins of Odd-Odd Nuclei," privately circulated.

[4] L. N. Nordheim, Revs. Modern Phys. **23**, 322 (1951).

A Note on the ζ^0-Meson

M. F. Kaplon and D. M. Ritson
University of Rochester, Rochester, New York
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Danysz, Lock, and Yekutieli[1] have recently reported evidence for the existence of a new particle, the ζ^0-meson. From observations on the angular correlation of pairs of charged π-mesons emitted in showers characterized by $2\leqslant n_s\leqslant6$, they present evidence for the existence of an unstable particle with a lifetime less than 10^{-16} second which decays according to the scheme $\zeta^0\rightarrow\pi^++\pi^-+Q$; according to their data Q is several Mev. We have examined a different class of showers[2,3] characterized by a median charged multiplicity of the order of $\sim$20 particles with a median energy of $\sim5\times10^{12}$ ev in an effort to obtain evidence relating to this proposed new particle.

If we assume the existence of this particle decaying in its rest frame according to the above scheme, then if $Q\ll\mu$ ($\equiv$mass of π-meson), the maximum angular separation between the two mesons is given by $\theta_M=2(Q/\mu)^{\frac{1}{2}}/\gamma_0$, where γ_0 is the energy of the ζ^0-meson (in units of its rest mass) in the laboratory system. From the target diagrams of our showers we have determined the angular separation θ_s of pairs of shower particles (presumed π-mesons) in the diffuse part of the shower and the polar angle θ with respect to the shower axis of the line bisecting θ_s. We have