opposite to that shown by the positrons from the μ^+ in (3). The confirmation of these predictions would have paramount importance with respect to a unified classification of the known fundamental particles.

[1] T. Nakano and K. Nishijima, Progr. Theoret. Phys. Japan **10**, 581 (1953).
[2] M. Gell-Mann, Phys. Rev. **92**, 833 (1953).
[3] R. G. Sachs, Phys. Rev. **99**, 1573 (1955).
[4] *The Proceedings of the Sixth Annual Rochester Conference on High-Energy Physics, 1956* (Interscience Publishers, Inc., New York, 1956).
[5] Wu, Ambler, Hayward, Hoppes, and Hudson, Phys. Rev. **105**, 1413 (1957).
[6] Garwin, Lederman, and Weinrich, Phys. Rev. **105**, 1415 (1957).
[7] J. I. Friedman and V. L. Telegdi, Phys. Rev. **105**, 1681 (1957).
[8] Coffin, Garwin, Lederman, Weinrich, and Berley, Bull. Am. Phys. Soc. Ser. II, **2**, 204 (1957).
[9] C. S. Wu, Bull. Am. Phys. Soc. Ser. II, **2**, 206 (1957).
[10] T. D. Lee and C. N. Yang, Phys. Rev. **104**, 254 (1956).
[11] T. D. Lee and C. N. Yang, Phys. Rev. **105**, 1671 (1957).

Nuclear Quadrupole Moment Ratio of Re^{185} and Re^{187}†

S. L. Segel and R. G. Barnes
Institute for Atomic Research and Department of Physics, Iowa State College, Ames, Iowa
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THE pure nuclear quadrupole resonance spectrum of the natural rhenium isotopes Re^{185} and Re^{187} has been detected in rhenium pentacarbonyl, $Re_2(CO)_{10}$. Two resonances have been observed for each isotope, corresponding to the $\pm\frac{5}{2}\leftrightarrow\pm\frac{3}{2}$ and $\pm\frac{3}{2}\leftrightarrow\pm\frac{1}{2}$ transitions for spin $I=\frac{5}{2}$. The observed frequencies are listed in Table I.

Since both isotopes have the same spin, the ratio of the nuclear quadrupole moments is given directly by the ratio of the frequencies belonging to the same transition. The mean value of the two ratios is $Q(Re^{185})/Q(Re^{187})=1.056\pm0.005$. This is almost exactly the average of the values 1.085 and 1.020 obtained by Schüler and Korsching[1] from measurements on the hfs of the atomic $^8P_{7/2}$ and $^8P_{5/2}$ levels, respectively. All of the resonances are broad and weak (total sample was only 500 mg), and this factor limits the accuracy attainable in the frequency measurements. The $\pm\frac{3}{2}\leftrightarrow\pm\frac{1}{2}$ transitions were at the limit of observability with oscilloscopic presentation using a super-regenerative spectrometer; the $\pm\frac{5}{2}\leftrightarrow\pm\frac{3}{2}$ transitions were only found with the aid of a lock-in detector and integrating circuit.

TABLE I. Nuclear quadrupole resonance frequencies in Mc/sec of rhenium isotopes in $Re_2(CO)_{10}$ at room temperature.

Transition	$\nu(Re^{185})$	$\nu(Re^{187})$	$\nu(Re^{185})/\nu(Re^{187})$
$\pm\frac{3}{2}\leftrightarrow\pm\frac{1}{2}$	28.836±0.030	27.191±0.030	1.060±0.003
$\pm\frac{5}{2}\leftrightarrow\pm\frac{3}{2}$	39.650±0.080	37.730±0.080	1.051±0.006

In most compounds formed by transition metals the metal atom occupies a position of such high symmetry that a quadrupole coupling is precluded. In the dinuclear and polynuclear metal carbonyls,[2,3] however, one of the six bonds may differ at least in ionic character from the other five. For example, in $Re_2(CO)_{10}$ each metal atom is octahedrally coordinated by five carbonyl groups and the other metal atom.[4] Even a small electric field gradient can lead to a significant coupling energy since most of the transition metals appear to have fairly large quadrupole moments. Thus, one might hope to find pure quadrupole resonances in appropriate compounds of iridium, ruthenium, and molybdenum, for example. Although the details of the chemical bonding in such compounds are probably not sufficiently well known to permit an accurate determination of the quadrupole moments themselves, the moment ratios of the isotopes can be unambiguously evaluated.

We wish to acknowledge the loan of the sample of rhenium pentacarbonyl from Dr. L. F. Dahl of this Laboratory. A discussion of the significance of these observations for understanding the bond properties of rhenium pentacarbonyl will appear elsewhere.

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[1] H. Schüler and H. Korsching, Z. Physik **105**, 168 (1937).
[2] J. C. Bailar, *Chemistry of the Coordination Compounds* (Reinhold Publishers, New York, 1956).
[3] J. W. Cable and R. K. Sheline, Chem. Revs. **56**, 1 (1956).
[4] Dahl, Ishishi, and Rundle, J. Chem. Phys. (to be published).

Radiative Corrections to the Asymmetry Parameter of Low-Energy Positrons in Muon Decay*

Toichiro Kinoshita and Alberto Sirlin
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York
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THE distribution of decay positrons from a polarized positive muon, integrated over the entire energy spectrum, is peaked backward with respect to the muon momentum.[1] On the basis of this, the two-component neutrino theory[2] predicts that the positron distribution should be peaked forward in the low-energy region. Simple calculation shows that the asymmetry parameter can be as large as 0.26 when the spectrum is integrated from 0 to 10 Mev. However, preliminary experimental results[3] indicate that the angular distribution of positrons is almost isotropic in this energy range.

The purpose of this note is to report on the radiative correction to the asymmetry of low-energy positrons of μ^+ decay in the two-component neutrino theory. As was discussed before,[4] the radiative correction is quite large at the lower end of the decay spectrum. Furthermore, it tends to reduce the asymmetry there because some of the low-energy positrons correspond to higher energy ones of the uncorrected spectrum where the backward emission is favored. Thus the radiative correction will be an important factor in reducing the discrepancy of theory and experiment.

The decay spectrum of a positive muon in the two-component neutrino theory is given by

$$dN \sim \left[3-2x+\frac{\alpha}{2\pi}f(x)-\xi\cos\theta\left(1-2x+\frac{\alpha}{2\pi}h(x)\right)+6\zeta\frac{m}{\mu}\left(\frac{1-x}{x}\right)\right]x^2dxd\Omega, \quad (1)$$

if one retains a term of order $m/\mu=1/206.9$ from the uncorrected spectrum and includes radiative corrections to order α. The muon is assumed to be at rest with its spin completely polarized. The parameter x is the positron momentum measured in units of $\mu/2$; θ is the angle between the positron momentum and the direction of muon spin; and ξ and ζ are defined by

$$\xi=\frac{2\,\mathrm{Re}(g_V^*g_A)}{|g_V|^2+|g_A|^2},\quad \zeta=\frac{|g_A|^2-|g_V|^2}{|g_V|^2+|g_A|^2}. \quad (2)$$

The functions $f(x)$ and $h(x)$ represent radiative corrections to the isotropic and $\cos\theta$ terms. Their explicit forms and numerical values are given in reference 4.

The observed angular distribution of the decay positron is usually expressed as $1+a(x)\cos\theta$. The theoretical asymmetry parameter may be written as

$$a_r(x,\xi,\zeta)=\frac{\xi}{3}\left(\frac{-2x^3+3x^4+(\alpha/2\pi)[H(0)-H(x)]}{2x^3-x^4+(\alpha/2\pi)[F(0)-F(x)]+\zeta(m/\mu)(6x^2-4x^3)}\right), \quad (3)$$

derived by integrating Eq. (1) over x from 0 to x. $F(x)$ and $H(x)$ are obtained from $f(x)$ and $h(x)$ by integration and are given in reference 4.

As is easily seen, ζ satisfies the inequality

$$|\zeta|\leqq(1-\xi^2)^{\frac{1}{2}}. \quad (4)$$

Thus ζ must vanish if $|\xi|=1$. The available data[1,4] indicate that

$$|\xi|\gtrsim 0.76. \quad (5)$$

Equation (4) therefore implies

$$|\zeta|\lesssim 0.65. \quad (6)$$

Asymmetry parameters with and without radiative corrections are given in Table I. The second column, $a_0(x,-1,0)$, gives the maximum asymmetry that can be reached in the two-component theory when no radiative correction is included. The third column, $a_0(x,-0.76,\zeta)$, may be regarded as the lower limit of the asymmetry compatible with (5). The indicated uncertainty in $a_0(x,-0.76,\zeta)$ is obtained from (6). The fourth column, $a_r(x,-1,0)$, is the upper limit of the asymmetry when the radiative correction is included. Finally, $a_r(x,-0.76,\zeta)$ in column 5 gives the lower limit consistent with the two-component theory and the observed data at higher energies. The uncertainty in this quantity is again due to that of the ζ-term.

TABLE I. Asymmetry parameters for low-energy positrons in muon decay with and without radiative corrections.

x	$a_0(x,-1,0)$	$a_0(x,-0.76,\zeta)$	$a_r(x,-1,0)$	$a_r(x,-0.76,\zeta)$
0.1[a]	0.30	$0.23\pm0.02_3$	0.17	$0.13\pm0.00_9$
0.2	0.25_9	$0.19_7\pm0.01_0$	0.20_5	$0.15_6\pm0.00_6$
0.3	0.21_6	$0.16_4\pm0.00_5$	0.18_2	$0.13_8\pm0.00_4$
0.4	0.16_7	$0.12_7\pm0.00_3$	0.14_3	$0.10_9\pm0.00_2$
0.5	0.11_1	$0.08_4\pm0.00_2$	0.09_3	$0.07_0\pm0.00_1$
0.6	0.04_8	$0.03_6\pm0.00_0$	0.03_3	$0.02_5\pm0.00_0$
0.7	-0.02_6	$-0.01_9\pm0.00_0$	-0.03_8	$-0.02_9\pm0.00_0$

[a] The values of the asymmetry parameter for $x=0.1$ are calculated using the radiative correction in which the electron mass is not neglected. For $x\geqq0.2$, one can safely neglect the electron mass compared with its momentum.

The radiative correction reduces the asymmetry parameter by considerable amount in the low-energy part of the decay spectrum. However, it is not so large as to reverse its sign. If accurate measurement of the asymmetry reveals any discrepancy between experiment and our calculation, it might mean that either our radiative correction is not adequate or the two-component neutrino theory is not correct, at least in its simplest form. In view of the rather large radiative correction of the lowest order in the muon decay, it may not be entirely unthinkable that higher order corrections are appreciable. The effect of higher order radiative corrections is being studied.

Our considerations of course apply immediately to the μ^- decay if one simply changes the sign of the ξ term.

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[1] Garwin, Lederman, and Weinrich, Phys. Rev. **105** 1415 (1957); J. I. Friedman and V. L. Telegdi, Phys. Rev. **105**, 1681 (1957).
[2] T. D. Lee and C. N. Yang, Phys. Rev. **105**, 1671 (1957); A. Salam, Nuovo cimento **5**, 299 (1957); L. Landau, Nuclear Phys. **3**, 127 (1957).
[3] Pless, Brenner, Williams, Bizzarri, Hildebrand, Milburn, Ramsey, Shapiro, Strauch, Street, and Young, Bull. Am. Phys. Soc. Ser. II, **2**, 205 (1957).
[4] T. Kinoshita and A. Sirlin, Phys. Rev. **107**, 638 (1957), this issue.