Sensitivity of β-γ circular polarization measurements of a possible right-handed current presence in the weak interaction

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The description of β-γ circular polarization correlations in the allowed decay of unoriented nuclei is extended to include possible right-handed currents within a parity symmetric model of weak interactions assuming manifest symmetry and essentially massless Dirac neutrinos. The result is of sensitivity generally equal to that of β polarization and asymmetry determinations. Present experiments are, however, insufficiently precise to permit the extraction of new information on their existence.

Measurements of the β-γ (circular polarization) correlation ($\tilde{A}$) in the weak decay of unoriented nuclei provides, as a natural consequence of angular momentum conservation, information essentially equivalent to that obtained from the asymmetry parameter (A) in the decay of oriented parent nuclei. In past years, both measurements have been extensively used to complement each other in determining Fermi matrix elements, isospin impurity coefficients, and effective Coulomb matrix elements in allowed isospin-forbidden transitions, as well as spins and multipole mixing ratios of transitions in daughter nuclei.[1,2]

More recently, measurement of A in ^{19}Ne decay has been used[3] to extract limits on alternative, parity-symmetric (PS) extensions of standard electroweak theory based on $SU(2)_L \times SU(2)_R \times U(1)$. Such models, discussed extensively in recent literature,[4] are characterized by a second, predominantly right-handed boson (W_2) which arises from a mixing of the chiral gauge fields via the Higgs mechanism. Within this picture, charged current interactions are parametrized in terms of a mixing angle (ζ) and a mass ratio $\delta \equiv (m_1/m_2)^2$, where $m_1(m_2)$ is the mass of the predominantly left- (right-) handed gauge boson. Present limits on (ζ, δ), derived from nuclear β decay only,[3,5,6] are shown in Fig. 1 and suggest $(\zeta, \delta) < (0.04, 0.07)$ corresponding to $m_2 > 300$ GeV in the limit $\zeta = 0$. These limits are extracted from analyses assuming a manifest parity symmetry and light Dirac neutrinos. Although models accommodating heavy right-handed Majorana neutrinos[7] would kinematically preclude the sensitivity of any low energy experiment to PS effects beyond the extent to which $\zeta \neq 0$, there is no compelling evidence for either choice at present and several alternative scenarios have recently been suggested which leave the question open.[8] More restrictive limits have been obtained from analyses of both leptonic and nonleptonic processes under essentially identical assumptions.[9] These limits are, however, subject to some concerns regarding model dependency, and their equivalence with those derived from semileptonic processes cannot be *a priori* assumed, since the weak vertex couplings may differ.

Since all analyses to date imply that direct experimental tests of PS theory are well beyond the immediate capabilities of present-day accelerators,[10] an increased motivation for the improvement of indirect experiments naturally arises. Further precision determinations of both the β asymmetry parameter in ^{19}Ne decay and the β longitudinal polarization (P_L) are currently in progress.[11] As a generally greater number of nuclear β decays with subsequent γ transitions are available, and measurements of $\tilde{A}$ do not require the use of nuclear orientation techniques, an examination of the extent to which β-γ (CP) measurements might again be useful is suggested.

Considerations are restricted to allowed ($\Delta J = 0, \pm 1$; $\Delta\Pi = 0$) transitions of the general form $J(\beta)J'(\gamma)J''$. Cal-

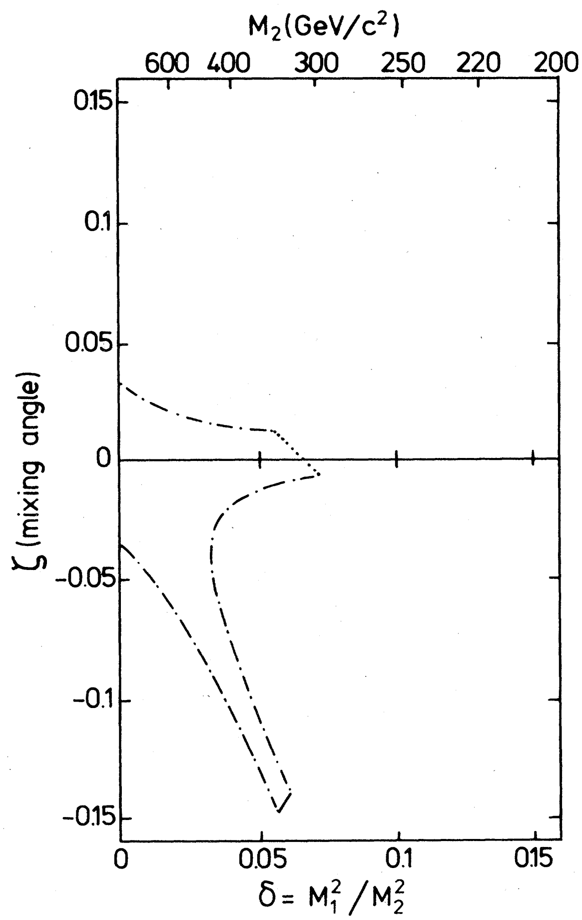

FIG. 1. Current experimental limits on (ζ, δ) derived from nuclear β decay experiments. Contours are obtained from Gamow-Teller β polarization (Ref. 5, dotted), ^{19}Ne β asymmetry parameter (Ref. 3, dot-dashed), and comparison of Gamow-Teller and Fermi β polarizations (Ref. 6, dark), and reflect single standard deviation uncertainties only.

culations assume the effective, manifestly parity-symmetric, semileptonic Lagrangian of Holstein and Triemann,[3]

$$L_{\rm sl}=\frac{g_{\rm sl}}{2}[(V_\mu^\dagger-\eta A_\mu^\dagger)l_\mu^- +(xV_\mu^\dagger+yA_\mu^\dagger)l_\mu^+] \ , \qquad (1)$$

where $l_\mu^\pm=\bar{e}(1\pm\gamma_5)\nu_e$, and $V_\mu(A_\mu)$ is the usual polar (axial) vector weak hadronic current. The validity of the conserved vector current hypothesis and time reversal invariance is assumed. Effects of finite neutrino mass are neglected, but may be introduced following Mursula.[8] Similarly, extensions to nonmanifest parity symmetry may be performed following Oka.[12]

The quantities x, y, and η are approximately related to ζ, δ by

$$x=\delta-\zeta,\ y=\delta+\zeta,\ \eta=1+2\zeta \ . \qquad (2)$$

For convenience, results are expanded in the general form

$$Y_{\rm PS}=Y_0\left[1+\sum_K \chi_K\right]\left[1+\sum_R a_R R\right] \ , \qquad (3)$$

where $R=\{\zeta^2,\delta^2,\zeta\delta\}$ and $Y_0(\chi_K)$ represents standard theory effects of leading (recoil) order. The PS coefficients $\{a_R\}$ are generally functions of nuclear structure and spin-dependent terms. Since $Y_{\rm PS}\approx Y_0$, an estimate of the PS sensitivity is then immediately obtained from $|a_R|$ and the relative uncertainty in measurement, R_σ.

To facilitate transparency, recoil order effects are herein further neglected, although a complete analysis of experiments performed to accuracies of order 10^{-3} requires their consideration.[13] A straightforward calculation then yields

$$\begin{aligned} a_{\zeta^2}&\cong\mp 2\frac{\Upsilon_{J'J''}\gamma_{J'J}c^2}{\tilde{A}_0(a^2+c^2)} \ ,\\ a_{\delta^2}&\cong -2 \ ,\\ a_{\zeta\delta}&\cong\mp\frac{2\Upsilon_{J'J''}\gamma_{J'J}c^2}{\tilde{A}_0(a^2+c^2)}-\frac{2(c^2-a^2)}{(c^2+a^2)} \ , \end{aligned} \qquad (4)$$

in which only terms in ζ,δ through lowest order are retained. Upper (lower) sign refers to $\beta^-(\beta^+)$ decay, and

$$\tilde{A}_0\cong\frac{\Upsilon_{J'J''(l)(J'+1)}}{a^2+c^2}\left[2\delta_{J'J}\left(\frac{J'}{J'+1}\right)^{1/2}ac\pm\frac{\gamma_{J'J}}{J'+1}c^2\right] \ , \qquad (5)$$

where $a(c)$ represents the dominant Fermi (Gamow-Teller) form factor in the elementary particle formalism of Holstein.[13] The spin dependent functions δ_{JJ}, γ_{JJ}, and $\Upsilon_{J'J''}(l)$ are defined in Ref. 13.

As is immediately obvious, $\tilde{A}_0$ is vanishing in pure vector $(c=0)$ decay. For pure axial vector $(a=0)$ transitions, Eq. (3) reduces to

$$\tilde{A}_{\rm PS}(\beta^+)\cong\tilde{A}_0(1-2\zeta^2-2\delta^2-4\zeta\delta) \qquad (6)$$

and is identical in structure to that of A and P_L to within their respective standard theory descriptions. Equal PS sensitivity is achieved for equal fractional experimental uncertainties, and the limiting contours in the (ζ,δ) plane are identical.

For mixed transitions, the relation between the interference and pure Gamow-Teller contributions in A and $\tilde{A}$ permits the possibility of enhanced PS coefficients. This is particularly evident in the case of the $\frac{1}{2}^+(\beta)\frac{1}{2}^+$ transition of ^{19}Ne, wherein the near equality of a and c form factors yields an extreme PS sensitivity of

$$A_{\rm PS}(^{19}{\rm Ne})\cong A_0(^{19}{\rm Ne})(1+24\zeta^2-2\delta^2+24\zeta\delta) \ . \qquad (7)$$

For the same decay, the sensitivity of the polarization measurement is virtually unchanged from Eq. (6), and $\tilde{A}$ is nonexistent.

A similar enhancement is encountered, for example, in the $4^+(\beta)4^+(\gamma)2^+$ decay of ^{56}Co, for which an $a/c=-0.091(5)$ yields

$$\tilde{A}_{\rm PS}(^{56}{\rm Co})\cong A_0(^{56}{\rm Co})(1-11\zeta^2-2\delta^2-13\zeta\delta) \ . \qquad (8)$$

Unfortunately, a/c is obtained[14] from $A(^{56}{\rm Co})$, which, although relatively insensitive to PS effects since $|a_R|\cong O(1)$, is more suspect than if obtained from external symmetry constraints and unpolarized decay measurements as in the case of ^{19}Ne. Estimates of the recoil order corrections are made difficult by the present uncertainties in *fpg* shell calculations. For isospin-hindered *sd*-shell decays in general, $a/c\leq 0.02$ yielding $\tilde{A}_0$ of order 10^{-1} and PS coefficients of order unity only.[2]

As suggested by their structural similarities, A and $\tilde{A}$ could in principle be used in combination. For example, in the pure Gamow-Teller decay of ^{60}Co,

$$\begin{aligned} \tilde{A}A^{-1}&\cong\tfrac{1}{3}(1+10\zeta^2+10\zeta\delta) \ ,\\ \tilde{A}A&\cong\tfrac{1}{3}(1-14\zeta^2-4\delta^2-18\zeta\delta) \ , \end{aligned} \qquad (9)$$

where in the first case the sensitivity to δ has been eliminated entirely.

The essential problem however lies with experiment. $\tilde{A}$ has only been generally determined[2] to order 5%. This primarily results from the small iron polarizability $(f=0.08)$ of Compton γ polarimeters, although systematic limitations due to multiple- and backscattering effects in sources additionally exist at the level of a few percent. Assuming the elimination of such effects through use of thin source techniques, the statistical limitations remain for which there appears no significant technological breakthrough in recent years. A twofold instrument, offering fourfold information with simultaneous reduction in systematic errors,[15] was developed some years ago, but does not appear to have been pursued to any significant extent.

In the case of ^{56}Co, the most precise determination of $\tilde{A}$ is by Pingot,[16] yielding $R_\sigma\cong 0.20$. This, however, suggests an $a/c=2\times10^{-3}$ in disagreement with asymmetry measurements[14] and in conflict with most measurements of $\tilde{A}$.[17] The most recent measurement of $\tilde{A}$ yields[18] $R_\sigma\cong 0.87$.

In contrast, absolute determinations of P_L are limited[19] to uncertainties of order 10^{-2}. Although a new technique in β^+ polarimetry[20] may soon permit relative measurements to better than 10^{-3}, a comparison (ΔP) of vector and axial-vector decay polarizations would yield only

$$\Delta P\cong 1+8\zeta\delta \ , \qquad (10)$$

which, while restricting the allowed area in (ζ,δ), yields no constraints on either parameter in the limit of the other being small. Measurement of A is generally limited to order 5% as a result of the currently low efficiency of nuclear polarization techniques. This has been reduced to $R_\sigma\cong 0.035$ by the Princeton group in the case of ^{19}Ne, who further suggest the possibility of achieving a two-to-four orders of magnitude increase in polarized beam statistics in the near future.[21]

Thus, within the context of current experimental considerations, the measurement of $A(^{19}Ne)$ is seen to provide the most sensitive restrictions on (ζ, δ) derivable from nuclear decay. In order to establish comparable sensitivity, measurements of $\tilde{A}$ would generally require relative accuracies of order 10^{-3} and precise knowledge of the standard theory effects. This possibility seems remote without significant improvement in the statistical efficiency of β-γ (CP) techniques. For this reason, such measurements appear to offer no immediate possibility of providing corroborative information on a right-handed current existence in nuclear β decay.

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