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Effect of Time Reversal Non-Invariance on Nuclear γ-Decay Observables*

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ABSTRACT

Some criteria are proposed which should allow greatly increased sensitivity of nuclear γ-decay studies to possible time reversal violation (TRV). While the nature of TRV is not known at this time, general arguments show that strongly hindered γ-transitions would greatly magnify any TRV effects, regardless of the source of TRV. Hindrance can be a more significant criterion in choosing nuclei for investigation than that previously employed - namely multipole mixing ratios near unity. Some promising nuclear transitions are indicated.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

Since the observation of spatial symmetry (parity) violation,[1] the question of time reversal symmetry violation has been examined in numerous calculations and experiments.[2] The possibility of time reversal violation in nuclear interactions was suggested by the observation of CP (charge conjugation and parity) violation in the decay of the long-lived neutral K meson,[3] which implies T (time reversal) violation if CPT conservation is taken as valid.

In low-energy nuclear physics the approach has been based on the fact[4] that in a mixed multipole γ-transition (with multipolarities L and L', where, for example, L = M1 and L' = E2) time reversal invariance requires that the relative phase of the reduced matrix elements between states 1 and 2 must be 0 or 180°; that is, $\langle 2 \| L' \| 1 \rangle / \langle 2 \| L \| 1 \rangle = |\delta| e^{i\eta}$, with $\eta = 0$ or π. A small TRV gives rise to a small deviation of η from 0 or π ; thus the mixing ratio becomes complex. All attempts in the past have been made to measure η by choosing $\delta \sim 1$ for greatest sensitivity. However, the approach emphasized here affords considerably more sensitivity to TRV in nucleon-nucleon interactions than has been previously utilized.

While the existence and the mechanism of TRV are a matter of speculation at this time, TRV would necessarily appear as a time-odd nucleon-nucleon interaction and possibly as a TRV electromagnetic transition operator as well. In the first case we have a nuclear hamiltonian $H = H_e + H_o$ where H_e is the main part which is even (invariant) with respect to the time reversal operator T, and H_o is the time-odd part; i.e. $T^{-1} H_e T = H_e$ and $T^{-1} H_o T = -H_o$. In the second case, TRV effects may also arise if the transition operator L has an

even and odd part, $L = L_e + iL_o$.[5,6] (The i has been taken out of the operator to show explicitly the time reversal violating phase.) We now consider separately the effect of these two cases on the experimental observables.

First, if $H = H_e + H_o$ the mth state of the complete hamiltonian in terms of eigenstates $|n_e\rangle$ of the main H_e part is in first order perturbation theory

$$|m\rangle = |m_e\rangle + \Sigma_n \frac{\langle n_e|H_o|m_e\rangle}{E_m - E_n} |n_e\rangle \tag{1}$$

where the summation includes all states $|n_e\rangle$ of the same spin and parity as the state $|m\rangle$. Since $\langle n_e|H_o|m_e\rangle$ is purely imaginary we can rewrite this equation

$$|m\rangle = |m_e\rangle + i\varepsilon_m|m_o\rangle \tag{2}$$

where ε_m is the amplitude of the out-of-phase part of the wave function (of the order of H_o/H_e) which reflects TRV.

The interference between L and L′ gives rise to TRV observables, $\mathcal{O}$, in experiments. This is generally written as

$$\mathcal{O} = |\delta|\sin\eta/(1 + |\delta|^2) = \mathrm{Im}(\langle 2||L||1\rangle\langle 2||L'||1\rangle^*) \times \left[|\langle 2||L||1\rangle|^2 + |\langle 2||L'||1\rangle|^2\right]^{-1} \tag{3}$$

or to first order in ε_1 and ε_2

$$\mathcal{O} = \frac{\left[\begin{array}{l} \langle 2_e \| L' \| 1_e \rangle \, [\varepsilon_1 \langle 2_e \| L \| 1_o \rangle - \varepsilon_2 \langle 2_o \| L \| 1_e \rangle] \\ \quad - \langle 2_e \| L \| 1_e \rangle \, [\varepsilon_1 \langle 2_e \| L' \| 1_o \rangle - \varepsilon_2 \langle 2_o \| L' \| 1_e \rangle] \end{array}\right]}{|\langle 2_e \| L \| 1_e \rangle|^2 + |\langle 2_e \| L' \| 1_e \rangle|^2} \tag{4}$$

In the second case (that is if TRV is dominated by TRV in the electromagnetic transition operators, i.e. in photon-nuclear coupling) we have

$$\langle 2 \| L \| 1 \rangle = \langle 2 \| L_e \| 1 \rangle + i \langle 2 \| L_o \| 1 \rangle \tag{5}$$

with $\langle 2 \| L_e \| 1 \rangle$ and $\langle 2 \| L_o \| 1 \rangle$ real.

In this case

$$\mathcal{O} = \frac{\langle 2 \| L'_e \| 1 \rangle \langle 2 \| L_o \| 1 \rangle - \langle 2 \| L_e \| 1 \rangle \langle 2 \| L'_o \| 1 \rangle}{|\langle 2 \| L \| 1 \rangle|^2 + |\langle 2 \| L' \| 1 \rangle|^2} \tag{6}$$

to first order in L_o and L'_o .

In both cases, Eqs. (4) and (6), the "normal" (time-even) terms (for example $\langle 2_e \| L \| 1_e \rangle$ and $\langle 2 \| L_e \| 1 \rangle$)appear linearly in the numerator and quadratically in the denominator. Thus, in strongly hindered transitions where these terms are small, the effect of the small time-odd terms can be

magnified as long as they are not equally hindered. While little is known about the time-odd hamiltonians and operators, they are certainly different from the time-even hamiltonians and operators and have a different momentum dependence. In contrast to H_e, the biggest contribution to H_o is probably a three-body interaction.[6] Although L_e involves one-body operators, L_o is probably mainly a two-body operator.[6] Thus they are very unlikely to be similarly hindered.[7] The explicit time-reversal calculations of ref. 6 also suggest the advantage of a hindered transition in TRV studies, and hindrance due to isospin is predicted to enhance TRV effects in β - decay.[8]

It should be noted that there is no a priori advantage[9] to having $\delta \approx 1$; for instance if TRV appears primarily as $< 2||L_o||1 >$, there is no need whatsoever to have $< 2||L'||1 >$ comparable with $< 2||L||1 >$, i.e. $\delta \approx 1$ for small η.[10](In any event, choosing a case in which $\delta \approx 0.05$ loses an order of magnitude in the sensitivity of $\mathcal{O}$ to η relative to $\delta \approx 1$; however, if the former case is hindered by, say, 10^8, a net increase in sensitivity of perhaps 2-3 orders of magnitude may be obtained.) With less emphasis on the requirement that $\delta \approx 1$ the experimentalist's choice of transitions is increased considerably, allowing him to base his choice on other experimental considerations (for example, favorable branching ratios, convenient γ-ray energy, half lives, ease of polarization, etc.).

As can be seen from the form of Eq. (1), TRV effects associated with the elastic internucleon potential can be enhanced if state $|1>$ (or $|2>$) has a nearby state of the same spin and parity (H_o is taken as parity and spin conserving). From Eq. (4) it is clear that it is helpful if this level has a rapid transition to (from) state $|2>$ (or $|1>$), i.e. $< 2_e||L||1_o>$

(or $\langle 2_o \| L \| 1_e \rangle$) is large. Another situation occurs if the initial and final states $|1\rangle$ and $|2\rangle$ have the same spin; H_o will mix them directly, so that

$$|1\rangle = |1_e\rangle + i\varepsilon\, |2_e\rangle$$

$$|2\rangle = |2_e\rangle + i\varepsilon\, |1_e\rangle \tag{6}$$

Then Eq. 3 becomes:

$$\mathcal{O} = \varepsilon \frac{\left[\begin{array}{l} \langle 2_e \| L' \| 1_e \rangle (\langle 2_e \| L \| 2_e \rangle - \langle 1_e \| L \| 1_e \rangle) \\ - \langle 2_e \| L \| 1_e \rangle (\langle 2_e \| L' \| 2_e \rangle - \langle 1_e \| L' \| 1_e \rangle) \end{array}\right]}{|\langle 2_e \| L \| 1_e \rangle|^2 + |\langle 2_e \| L' \| 1_e \rangle|^2} \tag{7}$$

Since $\langle m_e \| L \| m_e \rangle$ are the static moments μ, Q, etc., it is helpful if $\mu_2 - \mu_1$, $Q_2 - Q_1$, etc., are large.

Thus, although the TRV part of H or $\langle \| L \| \rangle$ is expected to be small (10^{-3} if TRV occurs in electromagnetism[11] or in the medium strong interaction, 10^{-6} if it occurs in the weak interaction, and less than 10^{-9} if TRV occurs in a super-weak interaction[12]), all but the latter should be measurable in a properly selected nuclear decay experiment. The present experimental upper limit placed on the electric dipole moment on the neutron places a limit of 10^{-4} on the time and parity violation part of the internucleon potential.[13]

Some examples of promising transitions are:

1. The 501-keV transition in ^{180}Hf, where the E3/M2 (δ = 5.3)[7] transition is five-fold K forbidden and the M2 hindrance is 10.[14] Thus, an out-of-phase M2 (L_o) of 10^{-18} of the Weisskopf single particle intensity would give a measurable $\eta = \sqrt{10^{-18} \times 10^{14}} = 0.01$.

2. To investigate K-allowed transitions, the 282-keV (or 396-keV) transition in ^{175}Lu should be studied. The E1-hindrance is $10^7 (2 \times 10^6)$ and δ(M2/E1)[14] is near to - 0.1 .

3. The 922-keV transition in ^{184}W has δ(E3/E1)[15] = 0.24 and the E1-hindrance is 10^{11}. The E1 is four-fold K - forbidden.

All of these nuclei are readily polarized [7, 14, 15] using ultra-low temperature techniques.

The judicious selection of an appropriate nuclar γ-transition for investigation can greatly enhance the sensitivity of experimental observables to any small TRV effects which may be present. One should, in fact, be able to achieve a comparative enhancement of inherently small TRV effects beyond the 10^{-3} to 10^{-6} mock TRV effects expected[16] and considerably beyond the 10^{-3} present experimental upper limit on the size of the out-of-phase γ-transition matrix element.[17] The approach discussed in the present communication emphasizes the measurement of the size of this matrix element, rather than the amount by which it is out of phase.

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References

1. C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, Phys. Rev. 105, 1413 (1957).

2. See for instance the review by E. M. Henley, Ann. Rev. Nucl. Sci. 19, 367 (1969).

3. J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Letters 13, 138 (1964).

4. S. P. Lloyd, Phys. Rev. 81, 161 (1951).

5. The effect of TRV in quantum mechanics is discussed by A. Bohr and B. R. Mottelson, Nuclear Structure , V. I. (Benjamin, New York, 1969).

6. The possible natures of L_o and also H_o have been discussed by C. F. Clement and L. Heller, Phys. Rev. Letters 27, 545 (1971) and by C. F. Clement Annals of Phys. 75, 219 (1973).

7. Even in the case of nucleon-nucleon parity-nonconservating interactions analogous to H_o the small 10^{-7} parity-nonconserving part can be magnified to become a 10^{-2} effect; see for example K. S. Krane, C. E. Olsen, J. R. Sites, and W. A. Steyert, Phys. Rev. C, 4, 1906 (1971). Here the M2 hindrance is 10^{14} ($< 2\|M2\|1 >$ decreased by 10^{7}.) The perturbation approach used for parity nonconservation is similar to that used in arriving at equation 2.

8. A. Barroso and J. R. Blin-Stoyle, Phys. Letters, 45B, 178, (1973).

9. E. M. Henley and B. A. Jacobsohn, Phys. Rev. Letters 16, 706 (1966).

10. However decays to states with nuclear spin equal to zero prohibit any L and L′ mixing if parity and angular momentum are conserved.

11. J. Bernstein, G. Feinberg, and T. D. Lee, Phys. Rev. 139 , B1650 (1965).

12. Bruce McKellar, Proceedings of Third International Conference on High Energy Physics and Nuclear Structure, ed. by S. Devons, (Plenum Press, New York, 1970), p. 682.

13. D. J. Broadhurst, Phys. Rev. D, 5, 1228 (1972). See also a comprehensive recent review by R. Golub and J. M. Pendlebury, Contemp. Phys. 13, 519 (1972).

14. K. S. Krane, C. E. Olsen, and W. A. Steyert, Nuc. Phys. A197, 352 (1972).

15. K. S. Krane, C. E. Olsen, and W. A. Steyert, Phys. Rev. C7, 263 (1973).

16. See the lucid discussion of these problems in M. J. Holmes, W. D. Hamilton, and R. A. Fox, Nuc. Phys. A199, 401 (1973), and in Refs. 2 and 9.

17. Previous measurements of TRV effects have been most recently summarized by Holmes, et al., ref. 16. In most of these measurements, the M1-intensity is hindered by a factor 10^3 and the E2 is unhindered or enhanced. This M1-hindrance is just that necessary to overcome the tendency of M1 radiation to dominate over E2; i.e., the requirement $\delta \sim 1$ is equivalent to M1 hindrance $\sim 10^3$.

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