Possible Parity and Time-Reversal Experiments using the Mössbauer Effect*

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In the successive transition of the beta and gamma decays, the excited and ground states of the daughter nucleus are effectively polarized, when the satellites of the Mössbauer effect are separately observed. Using this nuclear polarization, we design various experiments to detect parity nonconservation and time-reversal invariance in beta decay. These experiments involve the measurement of the coincidence counting rate of beta rays and satellites of the Mössbauer effect. The resulting improvement in accuracy will make possible, for example, the precision measurement of the asymmetry of beta-ray angular distributions.

MANY experiments have been performed in the last several years to verify Lee and Yang's theory of parity nonconservation in beta decay.[1] These experiments are characterized by measurement of[2] (1) beta-ray angular distributions from polarized nuclei, (2) circular polarizations of gamma rays in coincidence with the preceding beta rays, and (3) longitudinal polarizations of the beta particles. The measurements involve low-temperature techniques, the use of an analyzer of the circular polarization of the gamma ray, or Mott or Møller scattering. Such requirements necessarily introduce limited accuracy in the experimental data. The above three experiments are measurements of the pseudoscalar quantities under reflection (P). A similar consideration has been made for time-reversal (T) invariance.[3]

In this paper, we will show a fourth possibility for testing parity nonconservation and time-reversal invariance in beta decay, by using the Mössbauer effect.[4] In the proposal experiments, the Mössbauer effect is adopted merely as a technique to polarize the daughter nucleus. As is shown later, the degree of the nuclear polarization is known unambiguously. Besides, this nuclear polarization is achieved at room temperature, if the Mössbauer effect takes place at all. The resulting improvement in accuracy will make possible, for example, the precision measurement of the energy dependence of the asymmetry of beta-ray angular distributions (that is, the precise value of C_i/C_i', the higher order corrections due to the assumption of a conserved vector current,[5,6] etc.).

Consider a nuclear cascade transition, $j(\beta)j_1(\gamma)j_2$, where the hyperfine structure is the nuclear Zeeman effect caused by an external magnetic field H. The gamma ray, which is to be resonantly scattered or absorbed, is fixed in direction. The beta ray is observed in coincidence with one of the Mössbauer satellites. In this geometry, the beta ray angular distribution has an asymmetry with respect to the direction of H. The reason for expecting the asymmetry is as follows: If we observe only one Mössbauer satellite corresponding to the gamma decay of the (j_1,m_1) state to the (j_2,m_2) state, no other magnetic substates of j_1 except m_1 contribute to the cascade transition. Therefore, the j_1 state is effectively polarized with a degree of polarization m_1/j_1, as far as this cascade transition is concerned. Next, if the polarized j_1 state emits the beta particle and decays into the unoriented j state, the beta ray angular distribution is, of course, asymmetric. As is well known, the angular distribution of the original process, $j\rightarrow j_1$, is the same as that of the reversed process, $j_1\rightarrow j$, except for a sign. After the above consideration, one can derive without calculation the first and second lines of Eq. (1) below from the published formula.[7]

The relative intensity of the beta ray in coincidence with a Mössbauer satellite, $m_1\rightarrow m_2$, is given by

$$\begin{aligned}W(\theta,\theta_1)&\\=\Big[&\sum_{n,L\leq L'}(-)^{j-m_1}(j_1j_1m_1-m_1|n0)\\&\times W(j_1j_1LL',nj)b_{LL'}^{(n)}(2j_1+1)P_n(\cos\theta)\Big]\\&\times\Big\{\sum_{n_1,L_1,L_1'}(-)^{m_2-m_1+n_1+1}(\tau)^{n_1}\\&\times[(2L_1+1)(2L_1'+1)]^{\frac{1}{2}}(L_1L_1'1-1|n_10)\\&\times(j_2\|L_1\|j_1)(j_2\|L_1'\|j_1)\\&\times(L_1L_1'm_2-m_1m_1-m_2|n_10)\\&\times(j_1L_1m_1m_2-m_1|j_2m_2)\\&\qquad\times(j_1L_1'm_1m_2-m_1|j_2m_2)P_{n_1}(\cos\theta_1)\Big\}.\quad(1)\end{aligned}$$

$\tau=1$ (-1) for the right (left) circularly polarized gamma ray.

If the circular polarization of the gamma ray is not

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[1] T. D. Lee and C. N. Yang, Phys. Rev. **104**, 254 (1956).

[2] For example, see C. S. Wu, in *Proceedings of the Rehovoth Conference on Nuclear Structure*, edited by H. J. Lipkin (North-Holland Publishing Company, Amsterdam, 1958), p. 346.

[3] For example, see M. Morita and R. S. Morita, Phys. Rev. **110**, 461 (1958).

[4] R. L. Mössbauer, Z. Physik **151**, 124 (1958); Z. Naturforsch. **149**, 212 (1959).

[5] M. Gell-Mann, Phys. Rev. **111**, 362 (1958).

[6] M. Morita, Phys. Rev. **113**, 1584 (1959); Nuclear Phys. **14**, 106 (1959/60).

[7] M. Morita and R. S. Morita, Phys. Rev. **109**, 2048 (1958).

measured, the n_1 is even. The θ and θ_1 are emission angles of the beta and gamma rays with respect to the spin j_1. They are given by $\mathbf{J}_1\cdot\mathbf{p}=\cos\theta$ and $\mathbf{J}_1\cdot\mathbf{k}=\cos\theta_1$. $\mathbf{J}_1$, $\mathbf{p}$, and $\mathbf{k}$ are unit vectors in the directions of the nuclear spin j_1, and of the momenta of the beta ray and gamma ray, respectively. The $b_{LL'}{}^{(n)}$'s are the beta-ray parameters and are given elsewhere.[8] The other symbols are of common use. It should be noticed that Eq. (1) has no $\mathbf{p}\cdot\mathbf{k}$ term, although it is the coincidence counting rate of the beta and gamma ray. This fact follows because only one satellite, $m_1\rightarrow m_2$, is taken into account. Therefore, the time-reversal experiment is impossible in this case.

On the contrary, when the absorption line consists of more than two (but not all) Mössbauer satellites with different value of (m_1-m_2), the coincidence counting rate of the beta ray and the absorption line involves the interference between satellites. Then, experiments for testing time-reversal invariance in beta decay can be designed.

In general, parity nonconservation and time-reversal invariance experiments in beta decay involve measuring pseudoscalars under P and/or T, such as

$$(\mathbf{J}_1\cdot[\mathbf{p}\times\mathbf{k}])^a(\mathbf{J}_1\cdot\mathbf{k})^b(\mathbf{J}_1\cdot\mathbf{p})^c(\mathbf{p}\cdot\mathbf{k})^d,$$

or

$$(\text{the same form of the above})\times(\text{Coulomb term } \alpha Z), \quad (2)$$

with appropriately chosen powers a, b, c, and d. A complete study has been done for all these powers in the case of beta decay from oriented nuclei.[3] Changing $\mathbf{J}$ (the unit vector of the direction of the spin j) by $\mathbf{J}_1$ does not alter the discussion. We do not repeat it here. In the Appendix, an explicit formula is given for the measurement of $\mathbf{J}_1\cdot\mathbf{p}$.

The ratio of the probability of recoiless gamma decays in the solid to that of gamma decays in the free nucleus is given by the Debye-Waller factor,

$$\exp\left\{-3\frac{(\hbar K)^2}{Mk\Theta_D}\left[\frac{1}{4}+\left(\frac{T}{\Theta_D}\right)^2\int_0^{\Theta_D/T}\frac{x}{e^x-1}dx\right]\right\}. \quad (3)$$

Here, k, T, Θ_D, K, and M are the Boltzmann constant, the experimental temperature, the Debye temperature, the wave number of the gamma ray, and the mass of the parent nucleus, respectively. This factor was once studied for the elastic scattering cross section of neutrons by a crystal lattice.[9] One may argue that the smallness of the factor at room temperature limits the present proposal experiments. However, low temperature could be used to increase its value without affecting the polarization of beta-active nuclei. For example, the value in the square brackets of Eq. (3) is 1.03, 0.27, and 0.25 at $T=\Theta_D$, $(\Theta_D/10)$, and 0°K, respectively.[10] At $T=(\Theta_D/10)$, which is achieved easily in experiments, the Debye-Waller factor is almost a maximum, while the polarization of the parent nucleus is practically zero.

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APPENDIX

An explicit form of Eq. (1) is given in the case of the V-A allowed transitions with $C_i=C_i'$. The dependence on θ_1, which is the angle between directions of the gamma-ray momentum and the spin j_1, is dropped from the formula, since the gamma ray is fixed in direction. In order to make the intensity of the beta ray in coincidence with the Mössbauer satellite a maximum, an appropriate value of θ_1 is found for each decay scheme, by analyzing the third to eighth lines of Eq. (1). The relative intensity of the beta ray is given as a function of θ, which is the emission angle of beta ray with respect to the spin j_1, as follows.

$$W(\theta)=1+A\frac{v}{c}\frac{m_1}{j_1}\cos\theta,$$

$$A=\left[\pm\lambda_{jj_1}\left|C_A\int\boldsymbol{\sigma}\right|^2 -2\delta_{jj_1}\left(\frac{j_1}{j_1+1}\right)^{\frac{1}{2}}\mathrm{Re}\left(C_A{}^*C_V\int\boldsymbol{\sigma}^*\int 1\right)\right] \times\left[\left|C_A\int\boldsymbol{\sigma}\right|^2+\left|C_V\int 1\right|^2\right]^{-1},$$

and

$$\begin{aligned}\lambda_{jj_1}&=1 && \text{for} \quad j=j_1-1\rightarrow j_1\\ &=1/(j_1+1) && \text{for} \quad j=j_1\rightarrow j_1\\ &=-j_1/(j_1+1) && \text{for} \quad j=j_1+1\rightarrow j_1.\end{aligned}$$

Here the upper (lower) sign is for β^- (β^+).

[8] These parameters are given by M. Morita and R. S. Morita, Phys. Rev. **107**, 1316 (1957), for the allowed transition, and in reference 7 for the first forbidden transition. They are also given in reference 6, where various higher order corrections are taken into account.

[9] W. E. Lamb, Phys. Rev. **55**, 190 (1939). L. S. Kothari and K. S. Singwi, in *Solid-State Physics*, edited by F. Seitz and D. Turnbull (Academic Press, New York, 1959), Vol. 8, p. 109.

[10] For numerical values of the integral in the Debye-Waller factor, see C. Zener, Phys. Rev. **49**, 122 (1936); and R. G. Ringo, *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, Germany, 1957), Vol. 32, p. 552.