Observation of 1.5% Parity-Nonconserving γ-Ray Asymmetry*

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The angular distribution of the 501-keV γ radiation from low-temperature polarized ^{180m}Hf was found to exhibit a very large parity-nonconserving forward-backward asymmetry. At a polarization of 71%, the measured asymmetry is $-(1.49\pm0.25)$%. This asymmetry corresponds to an $\tilde{E}2/M2$ mixing ratio of magnitude 0.038 ± 0.007 in fairly good agreement with circular-polarization experiments. We also deduce the $E3/M2$ mixing ratio to be $+6.0\pm0.5$, agreeing with angular-correlation measurements.

A parity-nonconserving interaction between nucleons is generally described by the current-current theory of weak interactions of Feynman and Gell-Mann.[1] This interaction is the order of 10^{-7} of the parity-conserving strong interaction, and generally leads only to very small experimental effects.[2] The present investigation, however, demonstrates that the unusual structure of ^{180}Hf results in a 1.5% forward-backward γ-ray asymmetry at our temperature and implies a somewhat larger effect at sufficiently low temperatures.

The level scheme of ^{180}Hf is shown in Fig. 1. A parity-nonconserving nucleon-nucleon interaction would permit admixing of the 1142- and 1085-keV levels. The 501-keV transition would then be expected to have some irregular $\tilde{E}2$ radiation admixed with its regular $M2$, $E3$ character. According to Michel's single-particle approximation,[3] one would not expect significant $\tilde{E}2$ if $M2$ is appreciable. Even though the 501-keV radiation is 97% $E3$ and only 3% $M2$ in intensity,[4] the parity mixing should still be relatively small. However, all the radiation components of the 501-keV transition are severely retarded because of the extreme K forbiddenness ($\Delta K=8$). Thus it is conceivable that the irregular $\tilde{E}2$ radiation might be significantly enhanced relative to the regular $M2$, $E3$ radiation. Because the regular radiation is primarily $E3$, one would expect that the γ-ray asymmetry effect, which is sensitive to $E3$-$\tilde{E}2$ (as well as $M2$-$\tilde{E}2$) mixing, would be significantly larger than the circular-polarization effect which only measures the $M2$-$\tilde{E}2$ mixing.

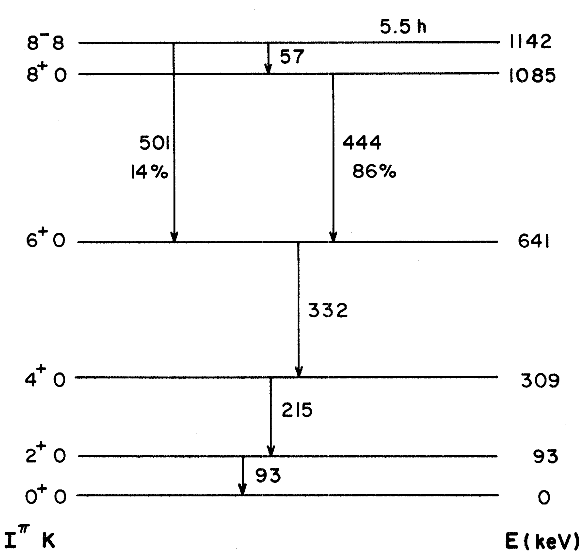

FIG. 1. Decay scheme of ^{180}Hf.

The angular distribution of γ radiation from polarized nuclei is described by[5]

$$W(\theta)=\sum_k B_k U_k A_k Q_k P_k(\cos\theta). \quad (1)$$

The A_k are characteristic of the radiation being observed, the U_k describe depolarizing effects of preceding radiations (since there are none for the 501-keV isomeric transition, $U_k=1$), and the B_k are a measure of the initial polarization. The Q_k are finite solid-angle correction factors and the P_k are Legendre polynomials. The normalization is such that $W(\theta)=1$ for unpolarized nuclei.

The odd-k terms are nonvanishing for directional distributions only if parity is not conserved in the γ decay. We observe these parity-nonconserving terms by comparing the radiation intensities at 0° and 180°. At the temperatures at which we operate, the $k=5$ and $k=6$ terms can be safely neglected and the asymmetry $\mathfrak{A}$ becomes

$$\mathfrak{A}=\frac{W(0)-W(180)}{\overline{W}} \cong \frac{2B_1A_1Q_1+2B_3A_3Q_3}{1+B_2A_2Q_2+B_4A_4Q_4}, \quad (2)$$

where the direction is with respect to the applied field. The expression for A_1 is

$$A_1 = \frac{2F_1(2268)\langle M2\rangle\langle\tilde{E}2\rangle + 2F_1(2368)\langle E3\rangle\langle\tilde{E}2\rangle}{\langle E3\rangle^2 + \langle M2\rangle^2 + \langle\tilde{E}2\rangle^2}, \tag{3}$$

where the F coefficients are defined in Ref. 5. A_3 is similar, with the F_1's being replaced by F_3's.

To achieve polarizations sufficient to yield a measurable value of $\mathcal{A}$ it is necessary to cool the ^{180m}Hf to temperatures comparable with the hyperfine energy splitting $\mu H/I$. To achieve a large hyperfine field H at the Hf nucleus of moment μ and spin I, we use the alloy $(Hf_{0.1}Zr_{0.9})Fe_2$; and to achieve a low temperature, we use our ^{3}He-^{4}He dilution refrigerator, capable of 14 mK in the absence of a heat load.

The sources were made by arc melting natural hafnium, zirconium, and iron, annealing at 950°C for 16 h, and sanding a disk to 0.625 cm diam and 0.050 cm thickness. The alloy was shown by x-ray analysis to be a single-phase cubic structure, and it turned out to be a ferromagnet at room temperature. The source was activated in the Los Alamos Omega West reactor, receiving a total integrated flux of 2×10^{16} neutrons/cm^2.

The experimental apparatus is described in detail elsewhere.[6] Basically, the cold Hf nuclei were polarized using an external field of 2500 G. The field was produced by two pairs of perpendicularly oriented Helmholtz pairs, and it was periodically rotated smoothly among the 0, 90, and 180° counting angles. The γ-ray detection was achieved with two stationary 40 cm^3 Ge(Li) detectors, placed on either side of the source and connected to a pair of multichannel analyzers.

From the angular distribution of the pure $E2$ 444-keV transition (see Fig. 1), we determined that we had 71% nuclear polarization, and we deduced each B_k. (The sign of B_1 and B_3 is determined by the sign of μH.) We used a ^{54}Mn γ-ray thermometer to measure the temperature to be 21 mK, and thus determined the magnitude of the hyperfine energy of the ^{180m}Hf nucleus to be 7.9 mK. The A_k for the 501-keV transition are functions of its mixing ratio $\delta = \langle E3\rangle/\langle M2\rangle$. Knowing B_k and comparing $W(90)$ with $W(0)$, we found that $\delta = +6.0 \pm 0.5$, in agreement with angular-correlation measurements.[4] Also from the $W(90)$, $W(0)$ comparison we found the denominator of Eq. (2) to be 0.71.

If ϵ is the ratio $\langle\tilde{E}\rangle/\langle M2\rangle$, then we can calculate $B_1A_1Q_1 = 0.160\epsilon$ and $B_3A_3Q_3 = -0.019\epsilon$ at 71% polarization. Thus, Eq. (2) becomes

$$\mathcal{A} = \pm 0.397\epsilon. \tag{4}$$

In the case of circular polarization

$$P = 2\epsilon(1+\delta^2)^{-1} = 0.054\epsilon. \tag{5}$$

Our measured value of the asymmetry is

$$\mathcal{A} = -(1.49 \pm 0.25)\%. \tag{6}$$

This value is an average of 75 15-min counting periods during the course of two experimental runs. The counting angle was alternated between 0° and 180° with an occasional 90° measurement. A calculation of statistical variances showed consistency in our data. Examination of the background above the 501-keV peak shows no significant asymmetry from bremsstrahlung. The 444-keV ^{180}Hf γ ray also showed no forward-backward asymmetry. Our apparatus has been extensively tested with other isotopes and shown to produce no spurious asymmetries to better than one part in 10^4.

We deduce a magnitude for ϵ of $0.038 + 0.007$. Circular-polarization measurements,[7] which determine $P = -(2.8 \pm 0.45)\times10^{-3}$, yield an ϵ of -0.052 ± 0.008 using our Eq. (5). (The negative value of ϵ implies a negative μ or H.) The conclusion from both types of measurement is that, in view of the weakness of the parity-nonconserving Hamiltonian, ϵ is quite large for the 501-keV ^{180m}Hf transition.

The amount of data on γ-ray parity mixing is still relatively small, but there is now at least one case in which large laboratory effects are observed. It is highly desirable, therefore, to continue making measurements on many isotopes using different experimental techniques, so that we may best exploit the close link between γ-ray parity admixture and the fundamental nucleon-nucleon interactions.

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Cross Section of Slow Neutrons on Parahydrogen*

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The total cross section for interaction of slow neutrons by parahydrogen has been measured to 0.1%. A pressure dependence has been found whose origin is obscure. By extrapolation to $p=0$, a value for the coherent scattering length of $(-3.707\pm 0.008)\times 10^{-13}$ cm is found, in agreement with the liquid-mirror result of $(-3.721\pm 0.004)\times 10^{-13}$ cm.

The interaction of neutrons and protons is one of the classical interactions of nuclear physics; by a comparison with the proton-proton interaction it yields the best available information on charge independence of nuclear forces.

Unlike the pp interaction, which always has isospin 1, the np interaction takes place in a mixture of isospin states $T=0$ and $T=1$. Because of the Pauli exclusion principle, the state $T=0$ (isospin singlet) is a triplet ordinary spin state at low energies, and $T=1$ is a singlet spin state. We clearly want to measure the interaction in each of these spin states. At low energies this can be accomplished using the properties of molecular hydrogen: Orthohydrogen is a triplet state of two protons and has the higher energy; parahydrogen is a singlet state of the two proton spins. At room temperature, where the energy difference is negligible compared with kT, hydrogen is three-fourths ortho and one-fourth para; at low temperatures, in equilibrium, it is almost all para [actually the ortho contribution is $(2S+1)\times(2J+1)\exp(-\epsilon/kT)\simeq 0.2\%$ at $T=20.4°K$].

In the limit of low neutron energies and very low temperatures, so that the parahydrogen is not excited to orthodydrogen and so that rotation or vibration is not excited, the cross section is given by

$$\sigma=\tfrac{16}{9}\pi f^2, \qquad (1)$$

$$f=\tfrac{1}{2}(3a_t+a_s). \qquad (2)$$

Since $a_s\simeq -3a_t$, this becomes a small quantity and the measurement is very sensitive. In practice, the movement of the target due to the temperature alters the measured cross section. A complete calculation yielding a more complex formula than Eq. (1) has been carried out by Hamermesh and Schwinger.[1] We used this more complex formula.

The last measurement of this quantity—and the only reliable one—is due to Squires and Stewart,[2] who used neutrons from a cyclotron and measured their energy by time of flight. Our measurement is an improvement by a factor of about 40. Slow neutrons from the high flux beam reactor at Brookhaven National Laboratory were made monochromatic by Bragg reflection from the basal plane of a graphite crystal. The energy may be varied by varying the scattering angle. The neutrons were brought back into a parallel-beam line by scattering from a second crystal.[3] The mosaic spreads of the crystals gave a rocking curve of 10 min of arc; this then allows neutrons over an energy range of about $\frac{1}{2}\%$ to be transmitted. The energy scale is known from x-ray measurements on graphite, and second- and higher-order reflections are suppressed by transmission through a filter of polycrystalline beryllium at 70°K.

The neutrons were collimated by $\frac{3}{8}$-in. holes in lithium-loaded plastic, and their attenuation was measured in an absorber 119.5 in. long of