double counting.

We do not know yet whether this equivalence is a very general feature of strong interactions. But we might mention one additional example, $K^{\pm}p$. Assume for the moment that the Pomeranchon is a special case with $\alpha_P(t)\equiv 1$, and that for purposes of describing $K^{\pm}p$ we can lump together all odd-signature meson trajectories (ρ, ω, φ) into one trajectory X, and all even signature trajectories (A_2, f, f') into Y. We further assume that X and Y are exchange degenerate.[9] If we now partial-wave analyze the Regge amplitudes, we find that the Pomeranchon does not generate resonance circles because it is purely imaginary. The meson signature factor in K^+p factor is real, $(+1-e^{-i\pi\alpha})_X-(-1-e^{-i\pi\alpha})_Y=2$, and we cannot obtain resonances. On the other hand, for K^-p the phase of the Regge amplitude rotates, $(+1-e^{-i\pi\alpha})_X+(-1-e^{-i\pi\alpha})_Y=-2e^{-i\pi\alpha}$, the imaginary part has zeros at $\alpha=0, -1, -2, \cdots$, and the real part has zeros at $\alpha=\cdots, +\frac{1}{2}, -\frac{1}{2}, -\frac{3}{2}, \cdots$. Therefore we expect that resonances will be generated in K^-p.

The argument in the opposite direction is well known.[9] No resonances in K^+p (and pp, KK) means that there are only direct forces, but no exchange forces, in $K\bar{K}\to p\bar{p}$ (and $p\bar{p}\to p\bar{p}$, $K\bar{K}\to K\bar{K}$). Therefore (ρ, ω, φ) are "exchange degenerate" with (A_2, f, f'), and the total cross sections in K^+p and K^+n must be constant and equal.

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TEST OF TIME-REVERSAL INVARIANCE USING THE MÖSSBAUER TRANSMISSION OF THE 73-keV TRANSITION IN Ir^{193} †

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The real and imaginary parts of the $E2$-$M1$ mixing ratio of the 73-keV transition in Ir^{193} have been determined in an arrangement that requires no correction for Faraday rotation. The values $\mathrm{Re}\delta=+0.556\pm0.010$ and $\mathrm{Im}\delta=(+0.6\pm2.1)\times10^{-3}$ result in a phase angle between $E2$ and $M1$ of $\eta=(+1.1\pm3.8)\times10^{-3}$, thus showing no evidence for T nonconservation.

The CP nonconservation observed in the K_2^0 decay[1] led Bernstein, Feinberg, and Lee[2] to conjecture that T invariance is violated in the electromagnetic interaction of hadrons. As a result of such a violation, nuclear matrix elements would contain an admixture of a T-odd amplitude. Under favorable conditions, the fractional admixture could be as large as 10^{-3} to 10^{-2} and lead to effects observable in interference terms, $\langle f|L|i\rangle\langle f|L'|i\rangle^*+\mathrm{c.c.}$, of mixed gamma transitions. If T invariance holds, the ratio of reduced matrix elements is real[3]; a complex mixing ratio indicates failure of T invariance.[4] Experiments so far have been done on $E2$-$M1$ mixed transitions where we write for the ratio of reduced matrix elements[5]

$$\delta=\langle f\|E2\|i\rangle/\langle f\|M1\|i\rangle=|\delta|e^{i\eta}.$$

A deviation of the phase angle η from 0 or π indicates violation of T invariance. We have performed a measurement of δ for the 73-keV $\frac{1}{2}^+\to\frac{3}{2}^+$ transition in Ir^{193} using the Mössbauer effect in a geometry that requires no correction for Faraday rotation. Our result, $\mathrm{Re}\delta=+0.556\pm0.010$, $\mathrm{Im}\delta=(+0.6\pm2.1)\times10^{-3}$, $\eta=(+1.1$

$\pm 3.8)\times 10^{-3}$, shows no evidence for T nonconservation, in agreement with Kistner's Mössbauer experiment.[6]

Jacobsohn and Henley[7] and Stichel[8] have shown that for a mixed gamma transition the polarization distribution contains a term linear in $2|\delta|\sin\eta$ of the form

$$(\hat{k}\cdot\hat{J}\times\hat{\epsilon})(\hat{k}\cdot\hat{J})(\hat{\epsilon}\cdot\hat{J})\propto \mathrm{Im}Y_3{}^2,$$

where $\hat{k}$, $\hat{J}$, and $\hat{\epsilon}$ are unit vectors along the wave vector $\vec{k}$ of the gamma rays, the nuclear spin $\vec{J}$, and the plane of linear polarization $\hat{\epsilon}$, respectively, with $\hat{\epsilon}\cdot\hat{k}=0$. Such a term can be measured directly in a Mössbauer transmission experiment provided that the source and absorber exhibit a resolved Zeeman spectrum due to magnetic fields $\vec{H}_S$ and $\vec{H}_a$ of specified directions. These requirements are met for the 73.8-keV transition of Ir^{193} if the source nuclei, i.e., the 32-h parent isotope Os^{193}, and the absorber nuclei, Ir^{193} with a natural abundance of 61.5 %, are embedded in iron and are placed in an externally applied field. To maximize the $\sin\eta$ term in the beam emitted by the source, we put $\hat{H}_S$ and, therefore, $\hat{J}$ at a polar angle of $\theta = 54°44'$ with respect to $\hat{k}$ $(\hat{H}_S\cdot\hat{k}=3^{-1/2})$; and an azimuthal angle $\Phi=\pm 45°$ with respect to $\hat{\epsilon}$. We further put $\vec{H}_a$ perpendicular to $\hat{k}$ so that $\hat{H}_a$ defines the plane of linear polarization $\hat{\epsilon}$. The experimental arrangement corresponding to this choice of directions of $\hat{k}$, $\hat{J}$, and $\hat{\epsilon}$ is shown in Fig. 1. The intensity I transmitted through the absorber can be written as

$$I = 1 - I_0 - I_1\cos 2\Phi - I_2\sin 2\Phi.$$

Here the intensity off resonance, which includes background as well as recoilless and nonrecoilless radiation, is normalized to unity. The last three terms represent the recoilless absorption. They depend on the nuclear parameters, the internal fields, the angles $(\hat{H}_S,\hat{k}) = \theta$ and $(\hat{H}_a,\hat{k})=\theta_a$, the recoilless fraction f, the number n of Ir^{193} atoms per unit area in the absorber, and the Doppler shift. In general, each term I_i contains an absorptive and a dispersive part, and if $\theta_a \neq 90°$ the dispersive parts of I_1 and I_2 will give rise to a nuclear Faraday rotation.[6,9] For $\theta_a = 90°$, as in our geometry, no Faraday rotation occurs. Even for finite solid angle, centered about $\theta_a = 90°$, the Faraday rotation can be neglected.

Keeping only terms up to first order in the small quantity η, we have

$$I_0 = I_0{}^{\mathrm{e}} + 2|\delta|\eta I_0{}^{\mathrm{o}};\quad I_1 = I_1{}^{\mathrm{e}} + 2|\delta|\eta I_1{}^{\mathrm{o}};$$

$$I_2 = 2|\delta|\eta I_2{}^{\mathrm{o}} + I_2{}^{\mathrm{e}}.$$

Here the superscript e (o) denotes even (odd) functions of Doppler shift. Figure 2 shows a plot of the three dominant terms $I_0' = \alpha\cdot I_0{}^{\mathrm{e}}$, $I_1' = \alpha\cdot I_1{}^{\mathrm{e}}$, and $I_2' = \alpha\cdot 2|\delta|I_2{}^{\mathrm{o}}$ as a function of v, the velocity of the source with respect to the fixed absorber, calculated for the geometry of Fig. 1. The constant $\alpha = 4.17$ is the experimental ratio of the total number of counts to the number of 73.8-keV counts accepted. The parameters used in calculating the spectra of Fig. 2 were $E_\gamma = 73.8$ keV, $g_{3/2} = 0.1055$,[10] $g_{1/2} = 0.9408$, $\delta = 0.556$, $H = 1.437$ MG, $\Gamma_{\mathrm{eff}} = 10^{-7}$ eV, $\sigma_0 = 3.2\times 10^{-20}$ cm^2, $n = 7.8\times 10^{20}$ cm^{-2}, and $f = 0.5$. The ratio $g_{1/2}/g_{3/2} = 8.92\pm 0.05$,[11] the internal field H, the mixing ratio δ,[11] and the effective linewidth $\Gamma_{\mathrm{eff}} = 1.5\times\Gamma_{\mathrm{nat}}$, Γ_{nat}

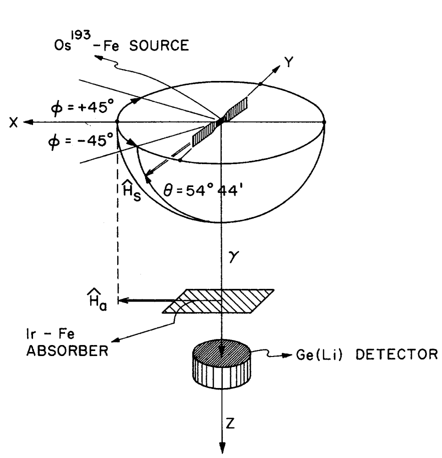

FIG. 1. Geometry used in the time-reversal test.

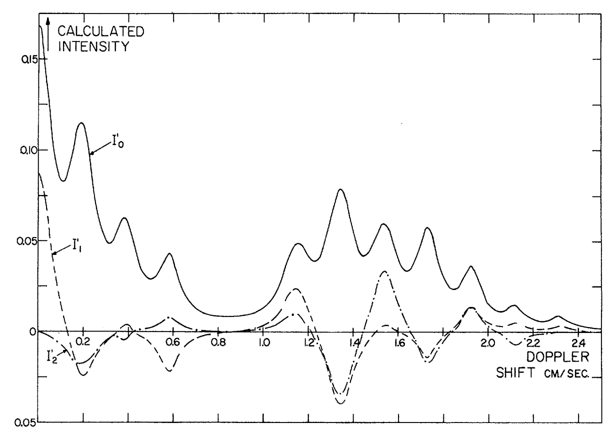

FIG. 2. The three dominant terms $I_0' = \alpha I_0{}^{\mathrm{e}}$, $I_1' = \alpha I_1{}^{\mathrm{e}}$, and $I_2' = \alpha\times 2|\delta|I_2{}^0$ as a function of Doppler velocity v calculated for the geometry of Fig. 1.

$=\hbar/\tau$, were adjusted to fit the experimental data. The phase angle η was determined from a measurement of the transmitted intensity $I(v,\Phi)$ at v equal to +1.54 and −1.54 cm/sec and Φ equal to +45° and −45°. At this particular velocity I_1 is small, and a small deviation $\Delta\Phi$ from $\Phi=\pm45°$ leads to a negligible asymmetry in the count rate due to $\Delta\Phi$.

Sources and absorbers were prepared from arc-melted alloys of iron with 4 at.% Os^{192} enriched to 98% and 10 at.% Ir of natural abundance, respectively. From the Os alloy a number of 3.5-mm×3.5-mm×1-mm samples were made which were neutron irradiated and then spot-welded to two Armco pole pieces and annealed. The absorber measured 1.5 mm×20 mm×28 mm. Two permanent magnets with pole pieces of soft iron produced the fields $\vec{H}_s$ and $\vec{H}_a$. A Li-drifted Ge detector was used to observe the gamma rays; the resolution of the system was 1.35-keV full width at half-maximum at 122 keV. With this detector the 73.8-keV gamma line is not resolved from the K_β x rays of Ir at 73.5 and 75.6 keV. The optimum ratio of 73.8-keV gamma rays to background within the window was $1/\alpha=0.24$. To measure the degree of polarization of the source and absorber, spectra were taken at $\theta=90°$, $\Phi=0°$ and 90°. The sum and the difference of the two spectra are displayed in Fig. 3. Comparison with the calculated spectra shows that the polarization-dependent $\cos2\Phi$ term is 75% of its maximum value. To correct for the incomplete polarization, we multiply in the following the polarization-dependent terms by a correction factor $\beta=0.75$.

For the time-reversal test a mechanical drive was used to move the source at a constant velocity with respect to the absorber. With a useful displacement of ±3 mm the change in solid angle was ±0.07%. The counts were gated by photocells measuring the displacement. The difference $2\epsilon_v$ in count rate between the up and down strokes was less than 10^{-4} both at room temperature and at 4°K.

The angle Φ was set by a photocell-controlled motor with an accuracy of ±0.2°. Ideally, for a given Doppler shift, the difference in count rate between +45° and −45° is proportional to the small number η. In practice, however, the effective solid angle is a function of the angle Φ because of a slight misalignment in the axis of rotation of the source assembly and the inherent asymmetry in the mass distribution. The nonuniformity of the detector and its imperfect alignment are a further source of asymmetry. To average out the effect of the latter the detector was rotated periodically. The average difference $2\epsilon_\Phi$ in count rate between +45° and −45° was $2\epsilon_\Phi=-5.2\times10^{-3}$. Test measurements of the count rate as a function of angle for zero Doppler shift showed that to first order the correct $\cos2\Phi$ dependence of the term I_1 is obtained if the count rate at helium temperature is divided by the count rate at room temperature.

A total of 12 sources were measured, each run lasting for two to three days. To keep the count rate approximately constant in spite of the 32-h half-life, the detector was moved closer to the absorber every 6 h, starting with an effective solid angle of $\Delta\Omega/(4\pi)=3\times10^{-4}$. At the same time the detector was rotated, thus changing the correction factor ϵ_Φ every 6 h. At a given angle, counts were accumulated for a total of 160 sec down and 160 sec up, then the source was rotated through 90° and an identical counting cycle was started. For each

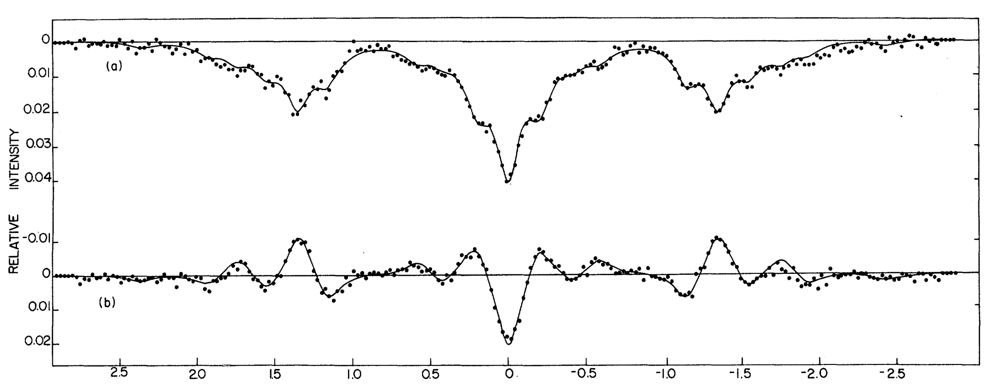

FIG. 3. Velocity spectra of (a) $2I_0$ and (b) $2I_1$ for $\theta=\theta_a=90°$ as obtained from the sum and difference, $I(\Phi=0°)\pm I(\Phi=90°)$, of two spectra taken at $\Phi=0°$ and $\Phi=90°$, respectively. The solid curves are the sum and difference of the computer fits to the individual spectra $I(\Phi=0°)$ and $I(\Phi=90°)$.

160-sec interval the number of counts $n(v, \Phi, t)$ was recorded and equivalent data points within the 6-h period were least-squares fitted to the function $n(v, \Phi, t) = N(v, \Phi)(1 + a_1 t + a_2 t^2)$. Whenever a data point out of a sequence of four differed by more than four standard deviations from this approximation, the whole quadruple of points was discarded. To allow for a small difference $2\epsilon_v$ in solid angle between the up and down strokes and $2\epsilon_\Phi$ between the angles +45° and −45°, the parameters $N(v, \Phi)$ were taken to be

$$N(++) = N(1+\epsilon_v)(1+\epsilon_\Phi)(1-I_0-\beta I_2),$$

$$N(+-) = N(1+\epsilon_v)(1-\epsilon_\Phi)(1-I_0+\beta I_2),$$

$$N(-+) = N(1-\epsilon_v)(1+\epsilon_\Phi)(1-I_0+\beta I_2),$$

$$N(--) = N(1-\epsilon_v)(1-\epsilon_\Phi)(1-I_0-\beta I_2).$$

Here we made the crucial but highly probable assumption that there is no first-order correction with the symmetry of the η term. The assumption that the corrections ϵ_v and ϵ_Φ are identical for resonant and nonresonant radiation is not essential in our analysis. Using the value $I_0 = 0.014$ at $v = 1.54$ cm/sec obtained from a measurement of the full Mössbauer spectrum and the calculated value $I_2'/I_0' = 0.56$, a typical term $N(v, \Phi)$ becomes $N(++) = 0.986N(1+\epsilon_v)(1+\epsilon_\Phi)(1-0.006\eta)$. If $\sigma(N)$ is the standard deviation of N, $\sigma(N) \gtrsim N^{1/2}$, the small parameters ϵ_v, ϵ_Φ, and 0.006η have a standard deviation $\sigma \approx \sigma(N)/(2N)$; the error on η is 1/0.006 ≈160 times larger. The parameters N, ϵ_v, ϵ_Φ, and η were determined for each 6-h period and, independently, for each quadruple of adjacent data points. The values of ϵ_v and η were normally distributed about their mean in either case. The values of ϵ_Φ, however, showed a normal distribution within a 6-h period only, since a change in position of the detector entails a change in ϵ_Φ. The parameters ϵ_v, ϵ_Φ, and η obtained from quadruples of adjacent data points were found to be statistically independent at a 10% level of significance within each 6-h period. The final result obtained was $\eta = 1.1\times10^{-3}$ with a standard deviation due to counting statistics of $\sigma = 3.8\times10^{-3}$ and a normalized χ^2 of 1.04. Systematic errors due to the combined effect of asymmetries in I_0 and a change in the effective polar angle θ between +45° and −45° are estimated to be smaller than 3×10^{-4}. We conclude that the admixture of a T-odd part in the transition amplitude is smaller than 4×10^{-3}.

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