New Method for Precision Positron Polarimetry: First Results and Future Applications

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A new instrument capable of precisely comparing the polarization of positrons from the decay of different nuclei is described. The decays of ^{22}Na and ^{68}Ga have been compared to 1% accuracy with a first-generation instrument. Systematic studies indicate that an eventual accuracy of 4×10^{-4} can be reached, allowing improved limits to be set on parity-symmetric formulations of the weak interactions.

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We report the first successful measurements obtained by using the prototype of a new instrument, the "positron polarization comparator" (PPC), which compares the polarization of positrons with equal energy from two sources. Specifically, we have compared the longitudinal polarization (P_L) of positrons from the decay of ^{22}Na and ^{68}Ga to an accuracy of 1%. In allowed nuclear β decay, $P_L = |\langle\vec{\sigma}\cdot\hat{v}\rangle| = |\vec{\beta}|(1+\chi)$, where $|\vec{\beta}| = |\vec{v}|/c$ with $\vec{v}$ the velocity of the particle and $\vec{\sigma}$ the Pauli spin matrix. The quantity χ is expected to be of order $\pm10^{-2}$ to $\pm10^{-4}$ as a result of nuclear-recoil-order effects as well as more exotic weak-interaction phenomena associated for example with the proposed right-handed currents resulting from parity-symmetric formulations of the weak interactions[1,2] or from the possible presence of scalar and tensor charged weak currents.[3,4]

Previous polarization measurements have achieved an accuracy of order 10^{-2} with electrons[5] and only 10^{-1} with positrons.[6] Moreover, certain features of the weak current are not accessible by measurements of electron β decay, since superallowed pure Fermi decay, in which the recoil corrections are minimal, occurs exclusively through positron emission. The comparison technique described in this article reduces all major systematic uncertainties associated with absolute polarization measurements to negligible levels. This feature, plus the high statistical efficiency of the polarimeter,[6,7] is expected to allow polarization comparisons with an accuracy of 4×10^{-4} or better in future versions of the PPC.

The PPC (Fig. 1) consists of a magnetic β-ray spectrometer, which momentum selects positrons from one of two interchangeable sources, coupled to a high-efficiency polarimeter. Positrons enter the polarimeter magnet through a hole in the pole piece, pass through a 0.25-mm Pilot-B scintillator detector (start signal), and stop in a target of compressed MgO powder, where approximately 25% form positronium (Ps). The subsequent annihilation γ rays are detected in a large γ scintillator (stop signal). The lifetime of each event is directly measured by a time-to-amplitude converter–multichannel analyzer system.

The singlet and $m=0$ triplet substates of Ps $[\psi_S, \psi_T(0)]$ have lifetimes in field-free MgO of $\lambda_S^{-1}=0.1$ nsec and $\lambda_T^{-1}=135$ nsec (in vacuum $\lambda_T^{-1}=142$ nsec). In the polarimeter magnetic field B, these states are admixed to form two field-perturbed states, ψ_S' and ψ_T'. The magnetic mixing increases the decay rate (λ_T') of ψ_T' $[(\lambda_T')^{-1}$

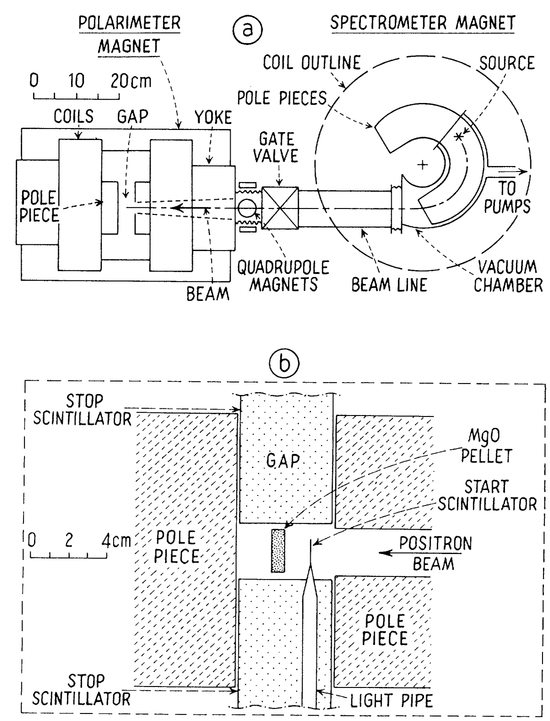

FIG. 1. (a) Diagram of the spectrometer-polarimeter system (PPC) and (b) detail of the polarimeter.

=10 nsec at 8 kG]. It also renders the fraction of Ps which is formed in this state dependent on the quantity $P_D B\cos\theta$ (see Ref. 6), where $P_D = \eta P_L$ is the polarization of positrons after stopping in the target ($1-\eta$ is the stopping depolarization) and θ is the angle between $\vec{B}$ and $\vec{P}_D$. When $\vec{B}$ is reversed ($\theta \to \theta+\pi$) the asymmetry A in the ψ_T' formation rates $(r_T')^+$ and $(r_T')^-$ is given by

$$A = \frac{2[(r_T')^+ - (r_T')^-]}{(r_T')^+ + (r_T')^-} = 2\epsilon P_D \cos\theta. \qquad (1)$$

Here $\epsilon = x/(1+x^2)^{1/2}$, $x = 4\mu_B B/(E_T - E_S) \approx 0.0276 \times B(\mathrm{kG})$, and $E_T - E_S$ is the ψ_S-ψ_T energy splitting. We detect this asymmetry by observing the decay of the Ps states during a time interval 13.5 to 38 nsec after Ps formation, selected to minimize statistical and systematic uncertainties. The fraction f of the incoming beam which contributes to the asymmetry is approximately 3×10^{-3} in the present apparatus (Ps formation fraction is 0.25, perturbed triplet fraction is 0.25, γ-ray detection efficiency is 0.2, and fraction of ψ_T' decays in the time interval is 0.25). The observed asymmetry is 9.6% diluted from $2\epsilon P_D = 24\%$ (at the present field of 8 kG) by $\psi_T(m = \pm 1)$ decays and background events. The figure of merit, fA^2, for our polarimeter is equal to that of the best Mott analyzer[5] for electrons, and a straightforward redesign of the instrument for higher fields and better time resolution can result in an order of magnitude improvement.

The primary systematic effect limiting absolute polarization measurements using this technique is the depolarization [calculated[8] to be (20 ±10)% in the present experiment] as the positrons slow down in the target. In the comparison technique, however, the fractional depolarization is expected to be exactly equal for equal-energy positrons from the two sources, so that the fractional difference in polarization can be found from the asymmetries measured for sources 1 and 2:

$$\frac{\Delta P}{P} = \frac{P_L(1)/\eta - P_L(2)/\eta}{P_L(1)/\eta} = \frac{\Delta A}{A}. \qquad (2)$$

The primary systematic errors (Table I) in the present comparison measurement are due to depolarization in the different source foils (presently a 2.3×10^{-3} contribution) and to particles initially above the beam energy which reach the polarimeter after scattering in the spectrometer. Contamination of the beam by particles depolarized in large-angle scattering is different for sources with different end-point energies and the present result represents essentially a "worst-case" comparison inasmuch as the end-point energies differ by a factor of 3. As shown below, the near equality of the end-point energies of the transitions to be compared in the next experiment will reduce all systematic errors associated with scattering in the spectrometer to negligible levels.

TABLE I. Systematic errors for the present (^{22}Na-^{68}Ga) experiment and the expected errors for the planned (^{30}P-^{26}Al^m) comparison.

Systematic	$\frac{P(\mathrm{Na})-P(\mathrm{Ga})}{P(\mathrm{Ga})}$ ($\times 10^3$)	$\frac{P(\mathrm{P})-P(\mathrm{Al})}{P(\mathrm{Al})}$ ($\times 10^3$)
Spectrometer:		
Source depolarization	2.3 ± 2.3	0.0 ± 0.20
Source alignment	0.0 ± 0.6	0.0 ± 0.02
Source holder	4.5 ± 2.0	0.09 ± 0.04
First slit	0.7 ± 0.9	0.01 ± 0.02
Vacuum chamber	2.1 ± 1.2	0.04 ± 0.02
Shield	2.0 ± 3.1	0.04 ± 0.06
Back scattering	0.2 ± 0.6	0.01 ± 0.01
Shield leakage	− 0.5 ± 0.5	− 0.01 ± 0.01
Polarimeter:		
Deflection	0.0 ± 1.0	0.00 ± 0.05
Time shifts	0.0 ± 1.5	0.00 ± 0.05
Dead time	0.0 ± 2.0	0.00 ± 0.05
Temperature drifts	0.0 ± 0.8	0.00 ± 0.05
2-nsec component	0.0 ± 2.0	0.00 ± 0.05
Count rate	0.0 ± 0.4	0.00 ± 0.05
Net	11.3 ± 5.8	0.18 ± 0.25

We have compared the polarization of positrons from the allowed decays of ^{22}Na and ^{68}Ga in order to evaluate the prototype instrument. These sources were chosen primarily for convenience as easily obtainable, long-lived laboratory sources. The polarization of positrons from allowed decay is given to first order in recoil (an accuracy sufficient for our purposes) by[9]

$$P_L = \beta\left(1 + \frac{c}{a^2+c^2}\frac{m_e^2}{3ME}(-2c+2b+d)\right)^{-1}. \qquad (3)$$

Here E and m_e are the total energy and mass of the positron; a, b, c, and d represent the Fermi, weak-magnetism, Gamow-Teller, and induced tensor form factors, respectively; and $M = \frac{1}{2}(M_1 + M_2)$ is the average of the parent and daughter nuclear masses. With $a=0$ and the approximations[9] $b \sim d \sim 4Ac$, we estimate the polarization of ^{68}Ga positrons at 350 keV to be $P_L(\mathrm{Ga})_{\mathrm{theor}} = \beta(0.9987 \pm 0.0013)$ while $P_L(\mathrm{Na})_{\mathrm{theor}}$ has recently[10,11] been calculated to be $P_L(\mathrm{Na}) = \beta(1.009 \pm 0.002)$, so that $\{[P_L(\mathrm{Na}) - P_L(\mathrm{Ga})]/P_L(\mathrm{Ga})\}_{\mathrm{theor}}$

$=0.0102 \pm 0.0025$. The result of our preliminary comparison measurement is $\{[P_L(\mathrm{Na}) - P_L(\mathrm{Ga})]/P_L(\mathrm{Ga})\}_{\mathrm{expt}} = 0.004 \pm 0.011$. The agreement of $(\Delta P/P)_{\mathrm{expt}}$ and $(\Delta P/P)_{\mathrm{theor}}$ leads us to conclude that the PPC functions correctly at the 10^{-2} level of precision.[12]

In order to reduce the above errors to the 10^{-4} level, we plan, in the next stage of our work, to compare P_L from the decays of ^{30}P (pure Gamow-Teller, $E_0 = 3.24$ MeV) and $^{26}\mathrm{Al}^m$ (pure Fermi, $E_0 = 3.21$ MeV), using an accelerator to activate the source foils. The 1% difference between $E_0(^{30}\mathrm{P})$ and $E_0(^{26}\mathrm{Al}^m)$ leads to an expected error of 10^{-4} due to differences in the number of particles which reach the polarimeter after scattering in the spectrometer. The uncertainty due to differences in source-foil depolarization will be reduced to 2×10^{-4} by the use of thin, low-Z foils (2 mg/cm^2 each of ^{26}Mg and ^{30}Si). Other systematic errors have been predicted on the basis of the present experiment and are listed in Table I. The planned factor of 40 increase in transmission of the spectrometer plus an increase in the polarimeter field to 13 kG to optimize the polarization asymmetry are expected to improve the statistical efficiency of the PPC by a factor of 300 relative to the present experiment. The combined uncertainty from statistics and all systematic effects is expected to be below 4×10^{-4}, more than an order of magnitude improvement over any previous technique using electrons or positrons. The recoil corrections to $^{26}\mathrm{Al}^m$ and ^{30}P, estimated by assuming conserved vector current and using single-particle matrix elements[13] in the impulse approximation, result in a predicted polarization difference of $(6\pm6)\times10^{-4}$. This estimate of the error includes uncertainties in the matrix elements as well as those due to the impulse approximation itself.[14] When this uncertainty is combined with the expected experimental error of 4×10^{-4}, the overall accuracy for this test would be 7×10^{-4}.

This measurement would dramatically improve present limits on the admixture of non-$(V-A)$ currents in the weak interactions.[1-4] Scalar couplings, limited to 0.6% by previous experiments, are predicted by gauge theories to occur at the 10^{-4} to 10^{-5} level. Tensor couplings are not permitted in renormalizable gauge theory, and have been experimentally limited to 2%. The planned Fermi-Gamow-Teller comparison would reduce these limits to 10^{-3}, an order of magnitude improvement.

Of even greater immediate interest, however, are the improved limits which this work could set on left-right symmetric theories of the weak interactions.[1,2] Such theories imply the existence of right-handed charged weak currents mediated by a right-handed gauge boson. The physical bosons would exist as a combination of the pure $V\pm A$ states with mixing angle ζ, and would have different masses as a result of spontaneous symmetry breaking.[15] Current model-independent experimental limits[5,16] constrain the mass ratio δ of the right- to left-handed W bosons, $\delta = M(W_R)/M(W_L)$, to be 2.8 or greater and the allowed range of ζ to be $|\zeta| \leq 0.07$ (Fig. 2; 3σ limits), while planned measurements[17] of the muon asymmetry parameter ξ would set a lower limit of 5 on δ at $\zeta = 0$. The limits that would be set by our experiment at the expected accuracy of 7×10^{-4} are shown as dashed lines in Fig. 2. For the range $0.01 \leq |\zeta| \leq 0.07$, our results would set new lower limits of 5.8 to 13 on δ.

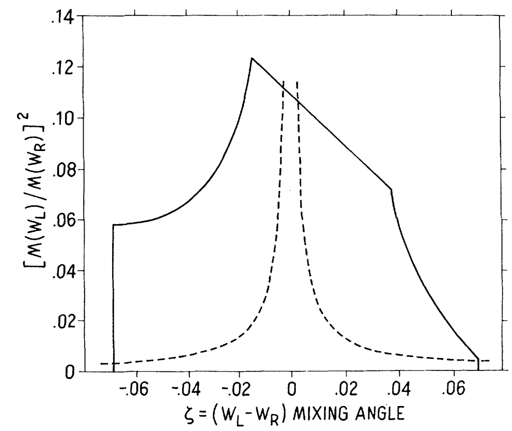

FIG. 2. Present 3σ limits (solid lines) on the mass ratio of right- to left-handed W bosons and the mixing angles ζ, calculated from the experimental results of Refs. 5 and 16, using the parametrization of Refs. 1 and 2. Expected 3σ limits from the proposed Fermi-Gamow-Teller polarization comparison (dashed lines) are shown.

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Production of High-Transverse-Energy Events in *pp* Collisions at 400 GeV/*c*

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High-transverse-energy events produced in *pp* collisions at 400 GeV/*c* were studied using the large-acceptance Fermilab multiparticle spectrometer. The cross sections for such interactions exhibit an exponential dependence on transverse energy with values of the slope increasing with the decreasing azimuthal acceptance of the trigger. The majority of events selected with full azimuthal acceptance are nonplanar; hence they do not show jet-like event structure. The fraction of planar events is small and remains constant as a function of transverse energy.

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The hadronic production of high-transverse-momentum (high-p_t) secondaries is expected to result from the hard collision of hadronic constituents rather than from a collision between hadrons as a whole.[1] Such production may be considered as being due to the scattering and

