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Measurement of positron polarization in the unique second forbidden transition of ^{22}Na

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The polarization of positrons in the $3^+ \to 0^+$ unique second forbidden decay of ^{22}Na has been measured relative to the allowed decay of ^{68}Ga with the result $P_L = \beta(1.00 \pm 0.05)$. This is the first measurement of P_L in a unique second forbidden decay and the third such determination in any unique decay. The method employed our newly introduced positron polarization comparator. The implications of this measurement, the possibility of its improvement, and extension of the technique to the unique first forbidden β^+ decay of ^{84}Rb are discussed.

[RADIOACTIVITY Measured positron polarization in the unique, second forbidden transition of ^{22}Na.]

Unique forbidden β transitions are theoretically characterized in leading order by a single dominant axial vector matrix element, as in the case of allowed Gamow-Teller β decay. In principle, their study can similarly provide information on modifications to the standard $(V-A)$ description induced by the presence of the strong interaction, as well as specific aspects of nuclear structure including many-body effects and exchange processes.[1] The induced corrections are of particular interest, since the magnitudes of the weak magnetism, induced pseudoscalar, and induced tensor coupling constants (g_M, g_P, and g_T, respectively) are predicted by the conserved vector current (CVC), partially-conserved axial current (PCAC), and G-parity invariance hypotheses.

In practice, however, the experimental results from unique decay are inconsistent with one another and with theory. While deviations of decay observables such as spectral shape, β longitudinal polarization (P_L), and $\beta\gamma$ correlations from leading order predictions are anticipated to be about 10^{-3}, spectral shape deviations of the form $(1+aE)$, where E is the β energy and $|a|$ is of order several percent per MeV, are generally observed in unique first forbidden ($\Delta J = 2$, $\Delta\pi = \text{yes}$) decay.[2–4] Theoretical model-dependent analyses of these deviations in ^{42}K, ^{86}Rb, ^{90}Sr, and ^{90}Y which includes both higher order nuclear structure and induced effects under the assumption of CVC, were unable to reproduce the experimental results without the inclusion of large g_P and/or g_T contributions in disagreement with results from allowed transitions, $0^- \to 0^+$ transitions, and μ capture.[2–5] Spectral shape analysis alone, however, is insufficient in providing useful information regarding the induced contributions, since these deviations can in general be reproduced to within experimental uncertainties by suitable, model independent, variation of the matrix elements. Accurate measurements of the β polarization and/or $\beta\gamma$ directional correlation are additionally required, since the former is effectively independent of both nuclear structure and g_T, while the latter is independent of g_P. In particular, the close correlation between the spectral shape factor and β polarization suggests that any large shape deviations should also appear in similar magnitude as deviations (δ) of the polarization from v/c: $P_L = (v/c)(1+\delta)$.

There have been only two previous β polarization measurements in strictly unique forbidden decay, of which the result[6] in ^{142}Pr yielded the anomalously large deviation of

$$\delta = (-6.6 \pm 1.5) \times 10^{-2} .$$

The theoretical analysis of this decay, including both higher order nuclear structure and induced corrections as well as variations of the lepton wave functions over the nuclear volume, was unable to simultaneously reproduce both spectral and polarization deviations without introducing $g_P = 38 \pm 9$.[7] This result is in severe disagreement with the PCAC prediction[1] of $g_p \simeq 6 \times 10^{-2}$, and is also in conflict with results which are in agreement with PCAC obtained both from a model-dependent analysis[8] of ^{16}N and recent μ capture measurements in H and ^{12}C.[9] A polarization measurement in ^{90}Y yielded no deviation at the level of 3%. Since subsequent analysis of this decay was able to reproduce both spectral and polarization data by model-independent variation of the nuclear structure parameters without including induced effects,[10] no anomalous behavior is suggested. Although a measurement in ^{86}Rb yielded a large deviation of

$$\delta = (-6 \pm 2) \times 10^{-2} ,$$

this result is here discounted since the experiment failed to separate the contribution of the competing nonunique transition, which could, as in the case of *RaE*, yield a large δ due presumably to matrix element cancellations.[11] As evident, a careful reinvestigation of these results, together with accurate new experimental studies of unique decay properties, is necessary in order to resolve these discrepancies. Herein we report the measurement to an accuracy of 5% of P_L in the unique forbidden decay of ^{22}Na. This constitutes the first such measurement in a unique second forbidden ($\Delta J = 3$, $\Delta\pi = 0$) transition, and only the third polarization determination in any unique decay. The immediate and future implications of this measurement will be thoroughly discussed in the conclusions.

The decay of ^{22}Na comprises primarily an allowed $3^+ \to 2^+$ pure Gamow-Teller transition ($\log ft = 7.4$) followed by a $2^+ \to 0^+$ γ transition to the ^{22}Ne ground state (1.275 MeV γ). The unique ($3^+ \to 0^+$) ground state to ground state transition of ^{22}Na comprises 0.05% of the total decay, with $\log ft = 13$ which is normal for decays for this degree of forbiddenness and suggests no reduction of the leading order matrix element. The single measurement of the spectral shape[12] is in agreement with a normal unique second forbidden distribution, although the uncertainty is sufficiently large to permit deviations in the polarization of up to 15% at the 90% confidence level. The technique used to determine the positron polarization has been described previously,[13] and relies on positronium formation in an 8 kG magnetic field $\vec{B}$ which mixes the singlet and $m=0$ triplet positronium states. The relative formation rates of the perturbed $m=0$ states (r_S', r_T') are sensitive to the quantity $\vec{P}_D \cdot \vec{B}$, yielding an asymmetry in formation rate for each $m=0$ state upon reversal $(+ \rightarrow -)$ of the magnetic field given by

$$A = \frac{(r_T')^+ - (r_T')^-}{(r_T')^+ + (r_T')^-} = \epsilon P_D \cos\theta \; , \qquad (1)$$

where P_D is the polarization of positrons after stopping in the target, $\epsilon = x/(1+x^2)^{1/2}$, $x \approx 0.0276B$ (kG), and θ is the angle between $\vec{B}$ and $\vec{P}_D$. The depolarization on stopping is given by $(1-\eta)$, such that $P_D = \eta P_L$. The formation asymmetry is detected by observing the decay spectrum of positronium, since the respective states are distinguishable by their differing lifetimes.

The primary systematic limitation to the determination of absolute polarization in this system is the depolarization experienced by the positrons as they slow down from beta decay energies of several hundred keV to positronium formation energies (≈ 10 eV).[13] The effect of the stopping depolarization is eliminated by a relative measurement on equal-energy positrons selected by a β spectrometer from two sources,

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

The system [which we call the positron polarization comparator (PPC)] consists of a magnetic sector β-ray spectrometer (momentum resolution of 3%) which focuses positrons from one of two interchangeable sources into the polarimeter. In this measurement, the polarization of ^{22}Na positrons was compared to a "normalizing" source of positrons from the allowed decay of ^{68}Ga, where the deviation from $P_L = \beta$ is calculated to be of order 10^{-3}.[14] This technique introduces new systematic effects (see Table I), but at a level much lower than those associated with absolute measurements. These systematics include differential scattering from various exposed surfaces, effects due to the differential positioning of the two sources, and the shielding of the source not in use. Most of the polarimeter-related systematics (time shifts, dead time and background corrections, cable properties, and count rate dependent effects) are associated with the timing electronics, and the analysis is standard.[13] "Windup" is the effective depolarization of the positrons when entering the polarimeter due to their deflection into helical trajectories by the magnetic field gradient. The 2 nsec component appears in the lifetime decay spectrum and is due to positronium formed in the plastic start detector.

TABLE I. A summary of systematic errors.

Systematic	Effect $(\times 10^{-2})$ $\frac{\Delta P}{P}$ (Ga-Na)
Spectrometer	
Source depolarization	$+1.5 \pm 1.5$
Source alignment	0.0 ± 0.2
Scattering-associated effects:	
source holder,	
first slit,	
vacuum chamber, shield,	
back scattering	-0.2 ± 0.1
Shield leakage	0.0 ± 0.1
Polarimeter	
Entrance "windup"	0.0 ± 0.1
Time shifts	0.0 ± 0.5
Dead time, background	0.0 ± 0.2
Temperature of cable	0.0 ± 0.2
2 nsec component	0.0 ± 0.5
Count rate	0.0 ± 0.5
Net effect	$+1.3 \pm 1.8$

The largest systematic effect in this polarization comparison is due to depolarization in the sources. The ^{68}Ga positrons are emitted from a ^{68}GeCu$_3$ source of ≈ 150 μCi intensity.[15] The alloy is electroplated onto 0.45 mg/cm^2 nickel foil which is sandwiched between ≈ 50 μg/cm^2 layers of VYNS film.[16] Total source thickness is estimated to be 4 ± 2 mg/cm^2, resulting in 0.0035 ± 0.0035 average depolarization.[17] The ^{22}Na source of 50 mCi intensity is deposited on a backing of beryllium and covered with a 2.3 mg/cm^2 titanium window. The average source depolarization is 0.018 ± 0.015 and results primarily from the effects of multiple small angle scatterings in the window and source material, as well as from large angle single scatterings in the beryllium backing.

Polarization data were taken at positron energies of 800 and 1000 keV, well above the 546 keV end point energy of the allowed decay in ^{22}Na. The results of the two runs are

$$\Delta P/P = (P(\mathrm{Na}) - P(\mathrm{Ga}))/P(\mathrm{Ga})$$
$$= (-5 \pm 5) \times 10^{-2}$$

and $(+3 \pm 5) \times 10^{-2}$, respectively, or

$$(\Delta P/P)_{\mathrm{avg}} = (-1 \pm 5) \times 10^{-2} \; .$$

These are considered further systematic tests of the instrument and therefore the error is not reduced in the averaging. The results have been corrected for the presence of positron-emitting contaminants in the system, which contribute 4% of the positronium formed during the ^{22}Na measurement. Combining the polarization measurements with the systematic effects, the difference in polarization is

$$\left[\frac{\Delta P}{P} \right]^{\text{Na-Ga}} = (0 \pm 5) \times 10^{-2} \; . \qquad (3)$$

This result is a further demonstration of the high statistical efficiency of the new polarization measurement technique.[13] A previous measurement, in the nonunique second-forbidden decay of ^{137}Cs, with a branching ratio 100 times larger than ^{22}Na and the same 50 mCi source intensity, required eleven months of data acquisition using the method of Moller scattering.[18] The present measurement requires six weeks of data accumulation, and is four times as precise as the ^{137}Cs measurement, indicating that, as anticipated the actual overall efficiency of our PPC is 10^3—10^4 higher than that of Moller scattering.

Assuming the polarization of the ^{68}Ga "normalizer" to be

$$P_L = \beta(0.999 \pm 0.001)$$

(Ref. 14) the positron polarization of the unique second forbidden decay in ^{22}Na is then

$$P_L(^{22}\text{Na, forbidden}) = \beta(1.00 \pm 0.05) \ . \tag{4}$$

This measurement is consistent with $\delta = 0$ and suggests no large deviation as permitted by the shape factor measurement.

The contribution of g_P to δ in the case of unique second forbidden decay is given by[19]

$$\delta \simeq \frac{-g_P}{g_A} \left[\frac{9\alpha Z}{2MR} \right] \frac{(p_\nu^4 + p_e^2 p_\nu^2 + \frac{6}{7} p_e^4)}{3p_\nu^4 + 10 p_e^2 p_\nu^2 + 3p_e^4} (1 + a_0) \ , \tag{5}$$

with g_A the effective axial vector coupling constant, R the nuclear radius, Z the atomic number of the daughter nucleus, α the fine structure constant, and M the nucleon mass. The positron (neutrino) momentum is p_e (p_ν),

$$a_0 = \frac{8}{21\sqrt{3}} \frac{\langle r^4 Y_{34} \rangle}{R^2 \langle r^2 Y_{32} \rangle} \ ,$$

and the reduced nuclear matrix elements $\langle r^4 Y_{34} \rangle$ and $\langle r^2 Y_{32} \rangle$ are defined in the notation of Ref. 7. Assuming the anomalous value of $g_P/g_A = 30 \pm 7$ obtained from the ^{142}Pr analysis, and using the single particle matrix elements of Wildenthal[20] to estimate a_0, yields

$$\delta(^{22}\text{Na}) \simeq (-5.0 \pm 1.2) \times 10^{-2} \ .$$

This calculation should be considered as only a crude estimate of the effect on $\delta(^{22}\text{Na})$ implied by $\delta(^{142}\text{Pr})$, since a large g_P as the cause of the latter deviation is not established and the existence of a $\delta(^{22}\text{Na})$ larger than obtained from Eq. (5) is therefore not *a priori* precluded. Calculations similar to Eq. (5), in which only g_T is retained and the improbably large value[4] of

$$g_T = (1.3 \pm 0.5) \times 10^{-2}$$

assumed, yields $\delta \leq 1 \times 10^{-2}$, while the g_M contribution is of order 10^{-3}.

A value of

$$\delta = (-2.2 \pm 0.5) \times 10^{-2} \ ,$$

assuming only the anomalously large contribution of g_P above, is similarly calculated for the allowed decay of ^{22}Na, and was not observed in a previous measurement at the 2σ level.[13] As noted previously,[7] the experimental polarization study which included ^{142}Pr also reported[6]

$$\delta = (-4.0 \pm 1.5) \times 10^{-2}$$

in the allowed decay of ^{114}In, the theoretical analysis of which yields a value for g_P of similar magnitude to the ^{142}Pr result, but of opposite sign. While other independent polarization investigations exist in the case of ^{114}In, their accuracy is insufficient to either confirm or reject this deviation.[21]

Experience gained from the current ^{22}Na experiment suggests that a factor of 3—4 reduction in the uncertainty of the present result may be obtainable in future efforts which include both reduced differential source depolarization and an improved spectrometer to enhance the statistical efficiency. More significantly, these same improvements applied to a polarization measurement in the unique first forbidden β^+ decay of ^{84}Rb [for which

$$a = (-1.7 \pm 0.3) \times 10^{-2}$$

is observed,[22] and

$$\delta = (-4.7 \pm 1) \times 10^{-2}$$

is estimated using $g_P = 38 \pm 9$] suggests that an eventual accuracy of better than 0.5×10^{-2} in $\delta(^{84}\text{Rb})$ is feasible. This projected improvement over the current ^{22}Na result is due to a reduction in the statistical uncertainty which results from the 11% branching ratio of the ^{84}Rb decay. Measurements at this level of accuracy will serve as a definitive check on an anomalously large value of g_P as well as establish significant new limits on its existence in nuclear β decay.

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