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Precision measurement of positron polarization in ^{68}Ga decay based on the use of a new positron polarimeter*

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We report a new measurement of positron polarization ($\vec{P}$) in ^{68}Ga decay. Using a new polarimeter the asymmetry (A) in the decay of positronium in a magnetic field was measured to 5%. When combined with a calculation of the positron depolarization on stopping in MgO powder the overall uncertainty in P is 11%. The most precise prior determination of P was to 12% accuracy. An eventual precision of 1% in A and 0.1% in comparisons of asymmetries from different sources is anticipated. In addition to the ^{68}Ga work we point out the possible use of the polarimeter in a number of new measurements including a determination of e^+ polarization in μ^+ and nuclear decay and in a $g-2$ experiment.

Accurate and efficient measurement of positron polarization $\vec{P}=\langle\vec{\sigma}\rangle$ and helicity $(h=\langle\vec{\sigma}\cdot\vec{p}\rangle/|\vec{p}|$ is important in a number of current experiments as well as in tests of the $V-A$ theory of weak interactions. We have developed a positron polarimeter which is at least eight times as efficient as prior instruments and allows a *comparison* of the polarization of positrons of equal momenta but from different nuclei (or from the low-energy tail of the μ^+-positron distribution) to an accuracy of up to 0.1% (3% for positrons from μ^+ decay). Absolute measurements of the polarization of positrons from a single source are now limited only by uncertainty in the calculation of depolarization for positrons stopping in the polarimeter. The polarimeter may also be used to determine the value of P at various energies relative to its value at a fixed upper energy—say 0.5 MeV—to accuracies of order (1–3)%. The above accuracies generally represent an improvement of better than an order of magnitude over past positron polarimetry measurements. The experiments which this new level of precision opens up for investigation will be mentioned in the last section. Before describing the new polarimeter and its use in the ^{68}Ga measurement we present a brief review of related prior instruments.

In 1959, Telegdi[1] and Lundby[2] suggested that if positronium (Ps) were formed by polarized positrons in a magnetic field $\vec{B}$, the quantity $\vec{P}\cdot\vec{B}$ could be determined from the time spectrum of the decay of the $^3S_1(m=0)$ state of Ps. Appropriate variation of θ ($\theta\equiv\cos^{-1}\hat{P}\cdot\hat{B}$) would then give $|\vec{P}|$. Discussions of the effect, first verified by Dick, Feuvrais, Madansky, and Telegdi,[3] have appeared in a number of papers.[3-6] A fraction f_p ($f_p\sim\frac{1}{4}$ to $\frac{1}{2}$) of positrons incident on a target form Ps, and the remainder annihilate directly at a rate Λ_D ($\Lambda_D \sim 10^{10}$ to 10^{12} in solids). The spin eigenstates of $n=1$ Ps for zero field in vacuum are ($\uparrow$ or $\downarrow$ indicates e^- spin; $\Uparrow$ or $\Downarrow$ indicates e^+ spin)

$$\Psi_T(\pm 1)=\uparrow\Uparrow \text{ or } \downarrow\Downarrow,\quad \Psi_T(0)=(\uparrow\Downarrow+\downarrow\Uparrow)/\sqrt{2}\,,\qquad \Psi_S=(\uparrow\Downarrow-\downarrow\Uparrow)/\sqrt{2}\,. \tag{1}$$

The lifetimes are $\tau_T=\Lambda_T^{-1}=138$ nsec and $\tau_S=\Lambda_S^{-1}=0.13$ nsec. With $\vec{B}$ on, $\Psi_T(\pm 1)$ and τ_T are unperturbed, while $\Psi_T(0)$ and Ψ_S and their respective lifetimes become approximately

$$\Psi'_{T,S}(0)=(1+Y^2)^{-1/2}[\Psi_{T,S}(0)\pm Y\Psi_{S,T}]\,, \tag{2a}$$

$$\Lambda'_{T,S}=(\tau'_{T,S})^{-1}=(1+Y^2)^{-1}(\Lambda_{T,S}+Y^2\Lambda_{S,T})\,, \tag{2b}$$

where $Y=X/[1+(1+X^2)^{1/2}]$ and $X=4\mu_0B/(E_T-E_S)=B/36$ kG. Terms of order $[\hbar\Lambda_S/(E_T-E_S)]^2\approx 10^{-4}$ have been neglected in Eqs. (2a) and (2b). The accuracy obtained is more than sufficient for our purposes. Note that for 5 kG$<B<$20 kG, $\Lambda'_S\simeq\Lambda_S$ and $\Lambda'_T\simeq Y^2(1+Y^2)^{-1}\Lambda_s$. In materials, processes such as electron pickoff (P) and spin exchange (E) "quench" the Ps so that Λ_T is replaced by $\Lambda_T(m)=\Lambda_T+\Lambda_P+\Lambda_E+\cdots$, and similarly for $\Lambda_S(m)$ and $\Lambda'_S(m)$.

The fraction $df(t)$ of the annihilations in the time interval t to $t+dt$ after the positrons have stopped in the material is

$$\begin{aligned} df(t)/dt &= \Lambda_D(1-f_p)\exp(-\Lambda_D t) \\ &+\tfrac{1}{2}f_P\big[\Lambda_T(m)\exp[-\Lambda_T(m)t]+\tfrac{1}{2}\{\Lambda'_T(m)\exp[-\Lambda'_T(m)t]+\Lambda'_S(m)\exp[-\Lambda'_S(m)t] \\ &+P\epsilon\cos\theta(-\Lambda'_T(m)\exp[-\Lambda'_T(m)t]+\Lambda'_S(m)\exp[-\Lambda'_S(m)t])\}\big]\,, \end{aligned} \tag{3}$$

where $\epsilon \equiv X/(1+X^2)^{1/2}$. This relation may be derived by noting that, for example, incoming spin-down positrons form the Ps states $\uparrow\downarrow$ and $\downarrow\downarrow$, where for $\theta=0$ the state $\uparrow\downarrow$ may be expanded as

$$\left(\frac{1+\epsilon}{2}\right)^{1/2}\Psi_T' \exp\left[\frac{-iE_T'}{\hbar}-\frac{\Lambda_T'(m)}{2}\right]t+\left(\frac{1-\epsilon}{2}\right)^{1/2}\Psi_S' \exp\left[\frac{-iE_S'}{\hbar}-\frac{\Lambda_S'(m)}{2}\right]t.$$

The symbols E_S' and E_T' refer to the field-perturbed singlet and triplet energy levels. The polarization-dependent term in Eq. (3) results from decay probabilities proportional to $(\uparrow\downarrow)(\uparrow\downarrow)^*$, generalized to the case $P<1$ and $\theta\neq 0$.

The experimentally measured asymmetry $A(t)$ is defined as

$$A\equiv\frac{2\left[\frac{df}{dt}(\theta)-\frac{df}{dt}(\theta+\pi)\right]}{\frac{df}{dt}(\theta)+\frac{df}{dt}(\theta+\pi)}. \tag{4}$$

The asymmetry can be observed by reversal of either $\vec{B}$ or $\vec{P}$. For t large enough such that $\Lambda_S'(m)\exp[-\Lambda_S'(m)t]\ll 1$ and $\Lambda_D(m)\exp[-\Lambda_D(m)t]\ll 1$, this becomes

$$A(t)\simeq\frac{2P\epsilon\cos\theta}{1+2\frac{\Lambda_T(m)}{\Lambda_T'(m)}\exp\{[\Lambda_T'(m)-\Lambda_T(m)]t\}}. \tag{5}$$

In order to analyze previous polarimeters employing positronium formation in plastic scintillators, we take as typical values 10 kG $<B<$ 20 kG and $\Lambda_P\simeq 5\times 10^8$ nsec^{-1}. Then $\Lambda_T'(m)\simeq(1.3$ to $3)\Lambda_T(m)\simeq(1.3$ to $3)\Lambda_P$ and $A_{\max}(t)\simeq(\frac{3}{4}$ to $1)P\epsilon\cos\theta$. Additionally, if $\tau_R\simeq 1$ to 2 nsec (as in previous devices), $A(t)\simeq A_{\max}\simeq(\frac{1}{3}$ to $\frac{1}{2})P\epsilon\cos\theta$ for 2 to 6 nsec after $t=0$, i.e., resolving-time effects reduce A by $\frac{1}{4}$ to $\frac{1}{2}$. At a field which optimizes the response, about 15 kG, and for a typical beam ensemble average of $\langle P\cos\theta\rangle$ of about 0.5, $A_{\max}$ is about 0.07 to 0.10. The efficiency, i.e., the fraction of incident positrons which contribute to determining A, is about 10% since about 40% of the positrons form Ps and about 30% of these decay at times greater than about $2\tau_R$. Systematic errors of at least 10% in converting A to $|\vec{P}|$ result from uncertainty in $\Lambda_T(m)$ and t. Alternative methods[7] previously used for determining positron helicity were characterized by efficiencies of 10^{-4} or less, asymmetrizes of order 10^{-1}, and systematic errors of at least 3%. The increased efficiency of the Ps polarimeter made it useful in tests of the $V-A$ theory of weak interactions in nuclear and μ^+ decay,[3,6,8] in studies of the depolarization of stopped positrons,[5] and in a positron $g-2$ experiment.[6]

In our improved version of the polarimeter, Ps is formed in a 0.3-g/cm^3 sample of MgO powder,[9] rather than in plastic scintillator. The lifetime of the $\Psi_T(\pm 1)$ states in powder is 138 nsec (as opposed to about 2 nsec in plastic), while the magnetically quenched $\Psi_T'(0)$ lifetime is 2.2 to 6.6 nsec for 10 kG $<B<$ 20 kG. This lifetime difference allows clean separation of the $\Psi_T'(0)$ state from the $\Psi_T(\pm 1)$ state thereby increasing the asymmetry by up to a factor of 3. Equation (5) then becomes $A\simeq 2\epsilon|\vec{P}|\cos\theta$ if $\tau_R\lesssim t\lesssim\tau_T/5$. A further improvement is obtained by resolving Ψ_T' from the Ψ_S' and direct annihilation time components. In previous work these fast components mixed into the delayed component, reducing the asymmetry[3-6] by at least a factor of 2 below the values predicted from Eq. (5). Since the Ps formation efficiency in MgO is 50% of that in scintillator the total statistical power of our polarimeter is 8 to 18 times greater than any yet achieved, i.e., only $\frac{1}{8}$ to $\frac{1}{18}$ as many positrons are needed for a specified uncertainty in A. In addition, and of more importance, the separation of states by virtue of their different decay times should permit an eventual absolute accuracy of better than 1% in the determination of A.

The apparatus which demonstrates the feasibility of the new technique (Fig. 1) uses positrons produced by a 20-μC source of ^{68}Ga. To determine the decay spectrum, the signal from the β scintillator (pilot B) is used as the start ($t=0$) signal and the large γ scintillator (Naton 136) gives the stop signal. The MgO powder target was evacuated to 10^{-2} Torr in order to eliminate oxygen-induced spin-exchange quenching. We were limited to 2.9

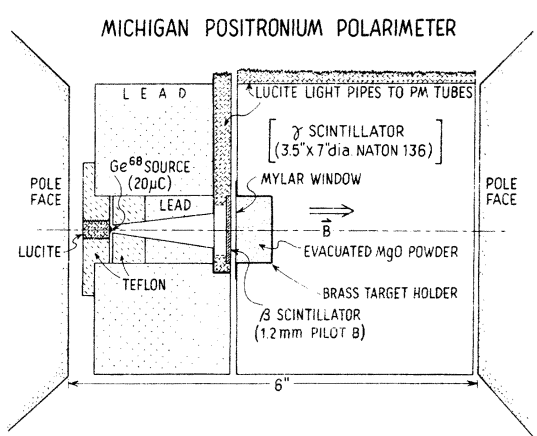

FIG. 1. Polarimeter apparatus, shown in cross section, has cylindrical symmetry. Positrons from ^{68}Ge-^{68}Ga source form positronium in the MgO target, and decays are detected by the γ scintillator.

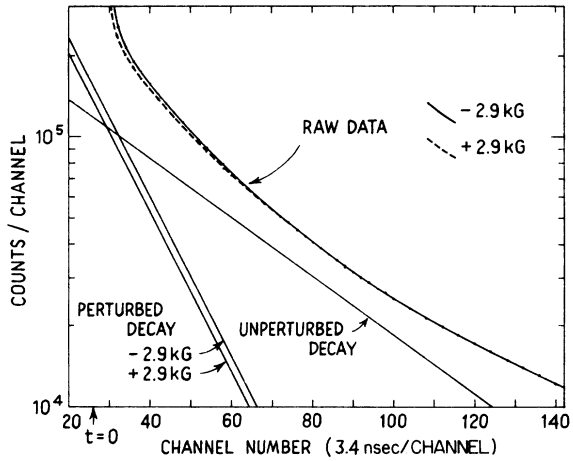

FIG. 2. Raw Ps decay data. The components were found by a computer fit. The asymmetry is given by the difference in count rates in early channels, labeled perturbed decay, when $\vec{B}$ is reversed.

kG by the small Varian magnet available, but higher fields will present no problem in future work.

The RCA 8575 signals were routed to an Ortec 467 time-to-amplitude converter and then to a Nuclear Data 1100 multichannel analyzer (MCA). The MCA drift was less than 1 nsec/day so that running times of 24 hours presented no drift or stability problem. The system time resolution was 3.1 nsec FWHM (full width at half maximum), sufficient to resolve Ψ_S', $\Psi_T'(0)$, and Ψ_T.

Lifetime curves are shown in Fig. 2. The value of τ_T, (138.0 ± 3.0) nsec, is in good agreement with recent measurements of τ_T in powders.[10] The measured values of τ_T' are (50.2 ± 1.3) nsec and (49.3 ± 1.3) nsec for $B = \pm 2.9$ kG, in good agreement with the calculated value of 50.1 nsec. The difference in the $\Psi_T'(0)$ intensities for opposing field directions is clearly resolved. The average of the $\Psi_T'(0)$ intensities was observed to be 5% lower than the expected value of half the $\Psi_T(\pm 1)$ intensity. This changes the 2 in the denominator of Eq. (5) to 2.1 and is consistent with a detection ratio for 2γ to 3γ events of 0.93.

A previously unreported component which appears to fit a (15 ± 5)-nsec lifetime was observed. This component had about $\frac{1}{10}$ as many counts as the field-perturbed state $\Psi_T'(0)$, and contributes less than 2% uncertainty to the final polarization.

The $V-A$ theory predicts[7] that positrons emitted by ^{68}Ga have helicity $h = v/c$. After averaging over angles and energies, this yields an expected beam polarization of 0.91 ± 0.01. The weighted average of depolarization over energies gives an estimated polarization of 0.70 ± 0.07 for the stopped positrons. This depolarization estimate is based on the calculations of Bouchiat and Lévy-Leblond.[11] Their results are for plastic and contain a number of unevaluated systematic uncertainties. In addition, we have extrapolated their results to MgO according to their approximate prescription. A reasonable error assignment in the depolarization has therefore been difficult, and a more precise calculation is needed to realize the full potentialities of even the prototype instrument.

Asymmetry data (Fig. 3) obtained with our apparatus yields $P\cos\theta = 0.58 \pm 0.03$. In view of the large systematic uncertainties in the depolarization calculation discussed above, we feel that this result is in agreement with the $V-A$ prediction. Data taken at lower fields showed proportionally

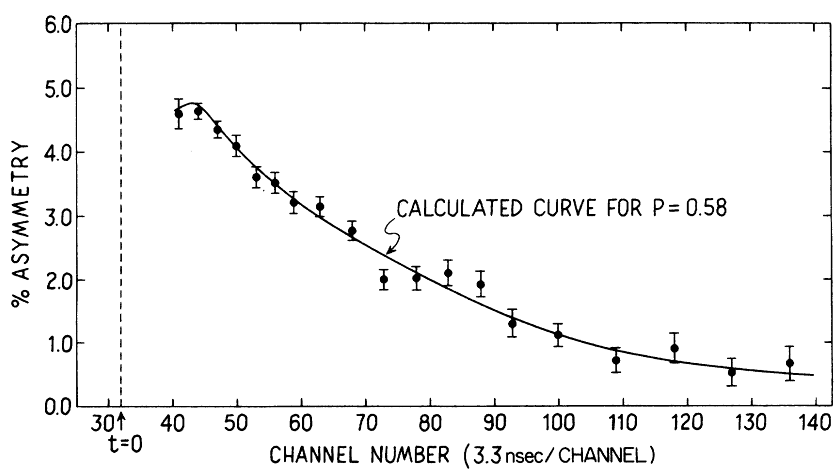

FIG. 3. Measured asymmetry at $B = 2.9$ kG. Statistical errors are shown.

lower asymmetries in agreement with our 2.9-kG data. Thus this test of the polarimeter constitutes a test to 11% accuracy of the $V-A$ prediction that $h=v/c$ over the energy range of positrons emitted from ^{68}Ga. The most precise previous test of $V-A$ for positrons was to an accuracy of 12% (Refs. 7 and 12). The 5% uncertainty in A comes from statistical uncertainty of 3% after 250 effective hours of running, and three possible errors of 2% due to systematic effects related to magnetic-field drift, variations in the 15-nsec lifetime component, and variations in the MCA linearity. All of these systematic effects can be reduced to 0.1% in future experiments. An rms average of the statistical and systematic errors has been taken in arriving at our estimated 5% uncertainty.

Insofar as the future possibilities of our instrument are concerned, we note that our maximum value of A (0.05) is comparable to asymmetries obtained by other groups using much higher fields. It should be straightforward to build polarimeters with fields of up to 15 kG which have six times the average asymmetry we observed and with possibly greater efficiency. With such polarimeters the following experiments become feasible:

(1) Tests of $V-A$ predictions in muon decay and in nuclear beta decay.[7,12] As noted above, uncertainty in estimating positron depolarization on stopping in MgO contributes an error of $\pm$ 7% in the absolute polarization of the ^{68}Ga spectrum. Larger depolarization uncertainties would be present for higher-energy positrons—e.g., those from μ^+ decay or from nuclei such as B^8 or Ne^{19}. However, the depolarization uncertainty can be avoided and the full power of our instrument brought to bear by comparing A for positrons from μ^+ decay, $A(e^+(\mu^+))$, with A for positrons of equal momenta from various radioactive sources $A(e^+(S))$ (with presumably equal depolarization). Preliminary calculations indicate that if we consider as an example only $e^+(\mu^+)$ with decay energies between 1 and 3 MeV we should be able to obtain $A(e^+\mu^+))$ with less than 5% error in several days of running at LAMPF. Conversion of $A(e^+(S))$ to $P(e^+(S))$ could be accomplished at the 5% level using Bhabha scattering,[12] thereby allowing an absolute measurement of $P(e^+(\mu^+))$ to better than 5%. Previous results for $P(e^+(\mu^+))$ attained an accuracy of at best $\pm$ 18%. The comparison method described above could be made to work for $e^+(\mu^+)$ above 5 MeV (where depolarization is severe) by accelerating positrons from nuclear decay to the energy of interest and then stopping the positrons, thereby providing a comparison asymmetry.[5]

Turning to comparisons of $A(e^+(\mu^+))$ in nuclear beta decay, we estimate that errors in the *ratio* of the asymmetries (hence polarizations) as low as 0.1% may be possible for positrons of the same momentum but from two different beta sources. Measurements of this precision may be sensitive to the effects of weak magnetism and second-class currents.[13]

(2) Measurement of the energy dependence of $P(e^+(S))$ for a given source using positrons in the energy range 100–500 keV, where total depolarization is thought to be less than 5%. Such measurements performed, for example, for e^- decay in ^{32}P (to an accuracy of $\pm$ 3% per energy point) were used to set limits on Fierz interference terms in the shape factor.[14] Measurements of comparable or better accuracy could now be performed for positron emitters.

(3) Quantitative verification of depolarization calculations.[5,11]

(4) Investigation (with Professor P. Zitzewitz) of the polarization of monoenergetic 1-eV backscattered positrons from certain metals.[15]

(5) A new positron $g-2$ experiment,[16] now in progress.

In conclusion, we have constructed a greatly improved positron polarimeter, used it in the most accurate test to date of the $V-A$ theory for positrons, and pointed out a number of new experiments which this instrument will make possible. We are now working on several of these experiments.

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