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PRECISION MEASUREMENT OF THE g FACTOR OF THE FREE POSITRON*

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We report a new measurement of the positron g factor. Our result is five times more accurate than the best previous value for this quantity. It shows that the positron and electron g factors are identical to within one part per million.

We have just completed a precision measurement of the positron g factor. With the g factor written in terms of the anomaly a, as $g=2(1+a)$, our result is $a(e^+)_E=(11\,602\pm11)\times10^{-7}$. This is five times more accurate than the best previous positron determination.[1] The corresponding value of g agrees, at the 1-ppm level, with both the theoretical (T) value[2] and the previously measured experimental (E) value[3] for the free electron. In terms of a, $a(e^+)_T=a(e^-)_T=0.5(\alpha/\pi)-0.328\,48(\alpha/\pi)^2+1.6(\alpha/\pi)^3=(1\,159\,660\pm2)\times10^{-9}$ and $a(e^-)_E=(1\,159\,549\pm30)\times10^{-9}$. The error in a_T is due only to error in α which we take as $\alpha^{-1}=137.0361\pm0.000\,26$. Possible error in the coefficient of $(\alpha/\pi)^3$ is not considered here.

The basic experimental technique is the same as that used in the last Michigan experiment, hereafter $g(e^+)_I$. A group of positrons from a Co^{58} source is confined in a magnetic mirror trap. After a measured length of time the particles are ejected from the trap into a polarimeter. On emission from the Co^{58} source, the positron "beam" is already polarized parallel to its "average" velocity, $\langle\vec{V}\rangle$, with polarization $\vec{P}=\langle\vec{V}\rangle/c$. While in the field the beam undergoes cyclotron orbital motion at angular frequency ω_C. Simultaneously $\vec{P}$ precesses at an angular frequency ω_S. Since these two frequencies are slightly different, $\vec{P}$ rotates about $\vec{v}$ at the beat or difference frequency $\omega_D=\omega_S-\omega_C$. If we neglect certain small corrections (to be discussed later), we may write

$$a=(m_0c/eB)\omega_D. \tag{1}$$

To determine a we must measure ω_D and B. The constant $(e/m_0c)_{e^+}$ is known to sufficient accuracy.

One detects ω_D by the use of a polarimeter, a polarimeter being any device which has a linear response to the projection of $\vec{P}$ onto a fixed direction, $\hat{h}$, in the laboratory frame. If the beam always enters the polarimeter in exactly the same direction, independent of trapping time, this projection differs by only a constant phase angle from $\vec{P}\cdot\vec{v}/v$. It is proportional to $\cos(\omega_DT+\varphi)$. Here T is the time the particles are trapped in the field and φ is a phase constant. In order to obtain ω_D we measure the output of the polarimeter as a function of T. The data are then fitted by a sinusoid from which ω_D may be in-

ferred.

The polarimeter is similar to that used in $g(e^+)_I$. On ejection from the well, positrons are made to stop in a plastic scintillator situated in a 10-kG magnetic field $\vec{B}_P$. This field defines the fixed direction $\hat{h}$, i.e., $\vec{B}_P = \hat{h}B_P$. Roughly half of the entering positrons from positronium, Ps. A fast-coincidence circuit counts the number of Ps atoms which decay during a given time interval Δt. This number can be expressed theoretically as the sum of several exponential decay terms.[1,4] Two of the terms are proportional to $\vec{P}\cdot\hat{h}$, i.e., to $\vec{P}\cdot\vec{v}/v$. Thus the output (N) of the fast-coincidence circuit may be written as $N = A + B\cos(\omega_D T + \varphi)$, where A and B are constants which depend on $\vec{B}_P$, $\vec{P}$, singlet and triplet Ps lifetimes, etc.

Figure 1 is a schematic diagram of the experiment. A solenoid (11 ft long × 2 ft in diameter) is used to produce the trap field of 262 G. The four Co^{58} sources, each with an initial activity of 200 mCi, are placed in a collimator. It is designed so that all positrons must enter the trapping region on a helical trajectory with a radius (r) of 7.6 ± 0.4 cm. The radius and field establish the particle energy at 273 ± 21 keV, corresponding to $|\vec{P}| = 0.76 \pm 0.02$.

If the injection cylinder is pulsed 600 V positive, any particle which happens to cross the gap between the injection and ejection cylinders will lose axial momentum. Some will lose enough to cause reflection at the right-hand magnetic hill, which is also a potential hill of 1040 eV/G depth for axial motion. If the pulse can be removed before the reflected positron recrosses the gap, net momentum is lost and the particle is trapped. To eject we pulse the left-hand ejection cylinder positive. Positrons then leave the vacuum section via a small Mylar window and enter the stopping scintillator, Naton 136. Here their arrival is detected by an RCA 8575 photomultiplier; the positronium decay γ is detected by Naton 136 and an RCA 4522 photomultiplier. The 10-kG field required for efficient working of the polarimeter is generated by a small pulsed coil positioned concentrically about the stipping scintillator. The coil is pulsed on for 1.5 μsec when particles are ejected; otherwise it is off.

The use of a pulsed coil marks the principal difference between this experiment and $g(e^+)_I$. In $g(e^+)_I$ positrons were extracted from the solenoid and brought to a dc polarimeter magnet. Fringe fields from the magnet caused severe drifting of the trapped beam. In fact, there was no usable intensity beyond a 30-μsec trapping time. This corresponded to only 8 cycles of ω_D. Limited trapping capability was one of the principal restrictions on the ultimate precision of $g(e^+)_I$. In the new arrangement, trapping times of over 150 μsec, corresponding to 80 cycles of ω_D, are feasible. This increase in the number of cycles that we are now able to record accounts for our improved accuracy.

Figure 2 shows the normalized output of the polarimeter as a function of trapping time. The two curves, run 1 and run 2, are least-squares fits to the eight points which determine each segment. The expected χ^2 for each run was 4.35, as compared with the experimental value of 7.43 for run 1 and 2.15 for run 2.

In order to determine $\tau_D = 2\pi/\omega_D$ we first obtain the zero-phase points T_1 and T_2. Since T_1

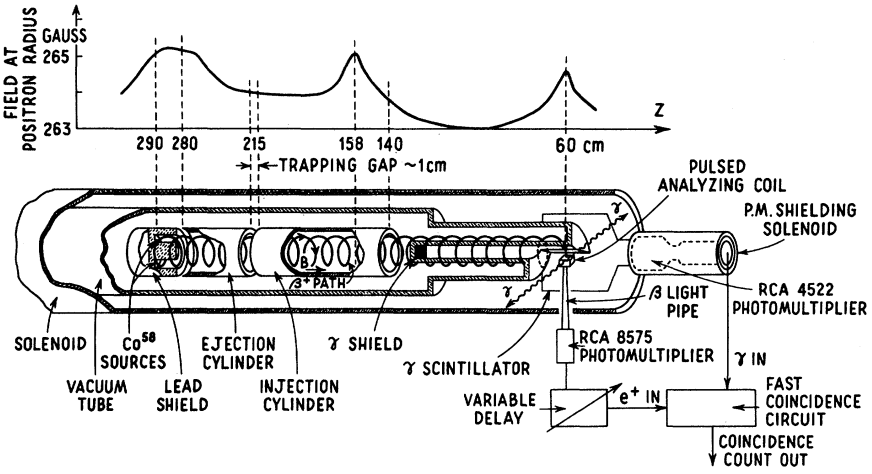

FIG. 1. A schematic diagram of the positron g-factor experiment.

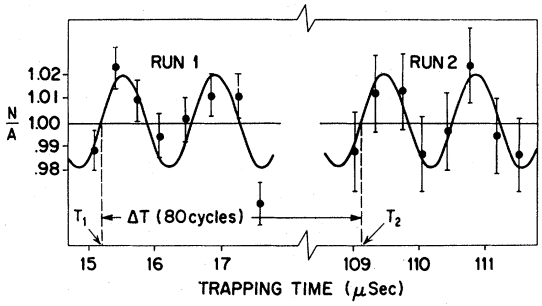

FIG. 2. The best-fit curves $N/A = 1 + (B/A)\cos(\omega_D T + \varphi)$ to the normalized data for runs 1 and 2. The value of A is about 7200 counts for run 1 and 3400 counts for run 2.

and T_2 are separated by exactly 80 cycles (see below), we have $\tau_D = \Delta T/80 = 94.036/80 = 1.1754$ μsec. Here ΔT refers to $T_2 - T_1$.

Error in ΔT is primarily due to statistical uncertainty in phase. The standard deviation $\sigma(\varphi)$ in the phase of the curves was computed using the method of maximum likelihood.[5] Since data were taken at approximately 90° intervals, the error matrix is diagonal and yields a simple analytic solution for the phase error. Specifically, $\sigma(\varphi) \simeq B\sqrt{2}/AN_T^{1/2}$ where N_T is the total number of counts in the record. The results for runs 1 and 2 are $\sigma_1 = 16°$ (0.053 μsec) and $\sigma_2 = 22°$ (0.072 μsec). As a further check, we plotted the value of the likelihood function versus phase φ, using best-fit values for baseline and frequency. The resulting curves are very nearly Gaussian, with half-widths at half-maximum of 15° and 21°. Finally, we broke the data for runs 1 and 2 into 13 and 10 separate groups, respectively, and fitted a cosine to each group. The standard deviation for the mean $\bar{\varphi}$ of the phases is given by the usual equation,

$$s^2(\varphi) = [n(n-1)]^{-1} \sum_{I=1}^{n} (\varphi_I - \bar{\varphi})^2.$$

This calculation yielded $s(\varphi_1) = 16°$ and $s(\varphi_2) = 18°$. Since all the methods give essentially identical phase error, we will use the result of the error matrix. Statistical error in τ_D is then

$$\delta\tau_D = [(0.052)^2 + (0.072)^2]^{1/2}/80 = 0.0011 \ \mu\text{sec}$$

so

$$\tau_D = 1.1754(1 \pm 940 \text{ ppm}) \ \mu\text{sec}.$$

Systematic errors in ΔT associated with time measurement and control are negligible.

The above discussion assumes knowledge of the true number of cycles in ΔT. To minimize the probability of a miscount, we took data for another eight-point curve about midway in trapping time between T_1 and T_2. This reduced the chance of a one-cycle error to about one in a thousand. Discussion of this and other fine points in the statistical analsis will appear in forthcoming articles.

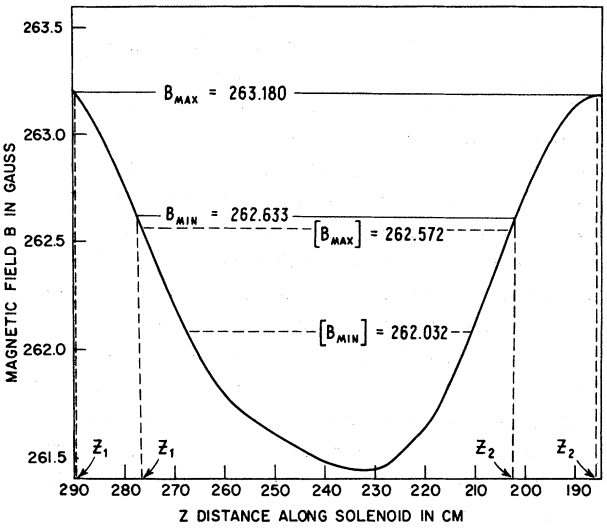

FIG. 3. The magnetic field in the trapping region at $r = 7.6$ cm.

Since the magnetic field in the trap is, of necessity, not uniform, the time-average axial field $[B_z]$ seen by the positron must be computed. As B_z and B differ by less than 1 ppm in the trap, we will use B for B_z in what follows. Figure 3 is a plot of B versus axial distance in the well, z. The time-average field $[B]$ for a given positron is[6]

$$[B] = B(z_1) - \frac{\int_{z_1}^{z_2} \{B(z_1) - B(z)\}^{1/2} dz}{\int_{z_1}^{z_2} \{B(z_1) - B(z)\}^{-1/2} dz}, \qquad (2)$$

where z_1 and z_2 are the limits of axial travel, or axial amplitude, of the particle in the well.

Since $B(z_1)$ is not the same for all trapped particles, neither is $[B(z_1)]$. The range of $[B]$ values is ±1000 ppm. This uncertainty was reduced a factor of 5 as follows: Assume we know the amplitude distribution of the ensemble of particles. We then can write the ensemble average of $[B]$ as

$$\langle [B] \rangle = \int_{B_{\min}}^{B_{\max}} \rho(B_I)[B_I] dB_I. \qquad (3)$$

Here $\rho(B_I)$ is the normalized density of particles at the level B_I, $[B_I]$ is the time-average field for a particle at the amplitude B_I, and $B_{\min}$ and $B_{\max}$ are the minimum and maximum amplitudes of

the trapped particles. The distribution of particles in the well was obtained experimentally by studying the number of particles ejected from the well as a function of ejection pulse height. The result is a relatively smooth function peaking in the upper quarter of the well, and changing only negligibly with trapping time.

The ensemble average of B was determined to be $\langle[B]\rangle = 262.18(1 \pm 215 \text{ ppm})$ G. The above error is the square root of the sum of the squares of the probable errors introduced by NMR field regulation (75 ppm), NMR field mapping (30 ppm), and the ensemble averaging process (200 ppm). It is about $\frac{1}{5}$ of the statistical error in ω_D.

In order to calculate a, correction terms must be added to Eq. (1) to account for the finite axial velocity v_z of the beam in the well and for any time-average radial electric field $[E_r]$ experienced by the trapped beam. Specifically,[7]

$$a = \frac{m_0 c}{e}\frac{\langle[\omega_D]\rangle}{\langle[B]\rangle} + \frac{1}{2}a\frac{\langle[v_z^2]\rangle}{c^2} + \frac{1-\beta^2}{\beta}\frac{\langle[E_r]\rangle}{\langle[B_z]\rangle}. \quad (4)$$

The measured ω_D is automatically the double average $\langle[\omega_D]\rangle$.

For evaluation of the finite-pitch term we use[8]

$$[v_z^2] = \frac{v^2}{B(z_1)}\frac{\int_{z_1}^{z_2}\{B(z_1)-B(z)\}^{1/2}dz}{\int_{z_1}^{z_2}\{B(z_1)-B(z)\}^{-1/2}dz}. \quad (5)$$

The ensemble average of the $[v_z^2]$ is then calculated in a manner identical to the $[B_z]$ discussion. The result is $\frac{1}{2}a\langle[v_z^2/c^2]\rangle = (9.0 \pm 0.5)\times 10^{-7}$, where we have used $a = 0.001\,16$. In other words the "v_z" correction causes an error of only 50 ppm in the anomaly.

In stating the final value of a we have assumed that the $\langle[E_r]\rangle$ correction is negligible. This is reasonable in view of the fact that, as far as electric fields are concerned, the principal difference between e^+ and e^- work at our laboratory is the use of a radioactive source rather than an electron gun. The geometry, materials used in the vacuum sections, pumping technique, pressure, etc. are almost identical. In their e^- experiment Wilkinson and Crane[9] were able to measure a at several different values of B and from the data infer that $\langle[E_r]\rangle$ was about -0.003 V/cm. Low counting rates ruled out such a procedure in our work, but we note that a field of -0.003 V/cm would only result in a 20-ppm shift in $a(e^+)_E$.

The added presence of the Co^{58} sources has, nevertheless, been carefully considered, and rejected, as a possible new source of electric fields at the -0.003-V/cm level. For example, cross sections for ionization of residual gases by β and γ radiation from the source are several orders of magnitude too small to cause significant field production. Also, we find no reason to suspect charging of the collimator facing, or trapping cylinders by the sources. Here, in fact, an auxiliary experiment was performed based on the behavior of the untrapped beam as it traverses the well. The test was crude but did set an indirect upper limit of about 0.15 V/cm on $\langle[E_r]\rangle$. We have therefore shown experimentally that any shift in a due to $\langle[E_r]\rangle$ must be less than 1000 ppm. Finally, $\langle[E_r]\rangle$ due to beam space charge is completely negligible.

Several secondary effects have been considered and ruled out as significant sources of systematic error. Some of these are variation of the earth's field, changes in solenoid geometry with changes in room temperature, magnetic contamination of apparatus in the solenoid, and possible phase shifts in $\vec{P}$ not due to ω_D. In a neighboring laboratory the solenoid for a new electron g-factor experiment was turned on and off several times during our runs. Its fringe field has an effect of less than 30 ppm on B. Field maps over the whole volume of the trap showed that effects on $[B]$ from any possible drifting of the beam in the trap are insignificant. Uncertainties in c and $(e/m_0)_{e^+}$ are also negligible.[10]

We conclude that the positron and electron g factors are the same to 1 ppm. Since the μ^+ and μ^- g factors are equal to within 0.7 ppm,[11] any violation of TCP which manifests itself in a lepton-antilepton g-factor asymmetry is ruled out at the 1-ppm level.

It is a pleasure to acknowledge the informative advice and encouragement of Professor H. R. Crane during the entire duration of this experiment. We have also benefited from discussions with Professor G. W. Ford, Professor D. M. Dennison, Professor H. C. Girffin, and Mr. J. Wesley.

The mechanical apparatus was skillfully constructed by Mr. R. O. Roth. Much of the electronics was constructed and maintained by Mr. G. Yanik. The Co^{58} sources were fabricated by the Nuclear Science and Engineering Corporation.

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SELECTION RULES FOR DIFFRACTION DISSOCIATION*

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The concept that internal quantum numbers do not change in diffractive production is extended to the quantum numbers of the quark model. The resulting approximate selection rules are discussed and compared with the predictions of other models.

Diffraction-dissociation reactions are processes having approximately constant cross sections like elastic scattering. In Regge theory, they are the reactions which go by Pomeranchukon exchange. While we know that for a reaction such as $a+b \to c+b$ the internal quantum numbers B, S, I, G, etc., do not change from a to c, there has been some controversy about selection rules for changes of spin and parity. For example, Morrison[1] has given an empirical rule, $\Delta P = (-1)^{\Delta J}$, while Chou and Yang[2] have suggested that the production cross section vanishes in the forward direction unless the product of the intrinsic parities of all particles is positive. In the present paper we extend the idea that internal quantum numbers are conserved in diffraction dissociation and arrive at new rules for allowed production which agree with Morrison or Chou and Yang in some, but not all, cases. Corresponding with which these additional quantum numbers may be specified, we predict a hierarchy in strengths of diffraction production processes.

The rule that there is no change of B, S, I, and G is clearly indicated by experimental evidence[3] that cross sections for reactions involving the exchange of any of these quantum numbers fall rapidly at high energies. The preservation of internal quantum numbers also follows from popular theoretical picutres of diffraction dissociation: (i) If diffraction dissociation of a compound state results from elastic scattering of its components, then no internal quantum number changes. (ii) If the diffraction-dissociation amplitude is built up by unitarity from a coherent sum over intermediate states,

$$\mathrm{Im}A(ab \to cb) = \sum_n A^*(ab \to n)\rho_n A(n \to cb),$$

maximum coherence occurs when the quantum numbers of the final state are as close as possible to the quantum numbers of the initial state.

In specific models, states are characterized by further internal quantum numbers. Since internal quantum numbers should not change in diffraction dissociation, these models give rise to additional selection rules. However, such models are only approximate so one expects a hierarchy in diffractive production—some reac-