Spin Polarization of Low-Energy Positron Beams

P. W. Zitzewitz,[a] J. C. Van House, A. Rich, and D. W. Gidley
Department of Physics, University of Michigan, Ann Arbor, Michigan 48109
(Received 28 June 1979)

It is discovered that the 1-eV positrons formed on an MgO-coated moderator with use of positrons from a ^{58}Co source are polarized with degree of polarization $P = 0.22^{+0.04}_{-0.02}$. Improved design could increase P to 0.40 with a flux of 10^5–10^6/sec. Applications of this discovery are discussed.

When high-energy positrons from a radioactive source are incident on a variety of solids (called moderators) up to one in 3×10^4 may emerge with energies of about 1 eV.[1] Monoenergetic beams ($0.1 < \Delta E < 1$ eV) of these "slow" positrons have been used in several experiments including the first observation of the $n=2$ state of positronium and the measurement of its fine structure,[2] the measurement of the vacuum decay rate of orthopositronium,[3] the production of positronium and positrons from clean metal surfaces,[4] and numerous studies of positron scattering in gases.[1] In this Letter we report the discovery that the slow positrons emitted from our particular moderator are polarized! The polarization of the beam is determined to be $P = 0.22^{+0.04}_{-0.02}$. Applications of this discovery will be discussed at the end of the paper.

The apparatus, shown in Fig. 1, consists of a slow-positron–beam generator, a Wien filter (spin rotator), and a polarimeter. Slow positrons are generated with a 150-mCi ^{58}Co β source. From the $V-A$ theory the source positrons have helicity $h=v/c$, which, after averaging over the energy spectrum, yields an average helicity of 0.65. The positrons are incident over a 2π solid angle onto a cylindrically symmetric moderator consisting of a 0.2-mg/cm^2 gold foil coated with 4 mg/cm^2 of MgO smoke followed by a MgO-coated tungsten grid. Approximately 1 in 10^5 source positrons are converted to slow positrons which are electrostatically focused into an axially polarized beam and then bent through an angle of 90°. This transversely polarized beam enters the Wien filter where the spin of the undeflected positrons is rotated through a selected rotation angle.

The basic theory and design of the positron polarimeter has been described in detail by Gerber *et al.*[5] Our version consists of a 9-in. electromagnet, a positron detector (start signal), an annihilation γ-ray detector (stop signal), and a conventional time-to-amplitude converter-multichannel analyzer (TAC-MCA) timing system.

A new and essential feature of this slow-positron polarimeter is the use of a chevron electron multiplier array (CEMA) (Galileo Electro-Optics 3025) as both the detector of low-energy positrons in a high magnetic field and the positronium formation surface. The beam enters along the axis of the 6.3-kG magnetic field through a hole in one of the pole pieces and strikes the surface of the CEMA. These 500-eV positrons generate secondary electrons which form a start pulse for the TAC. About 10% of the incident positrons capture an electron and form orthopositronium which leaves the CEMA surface and enters the surrounding vacuum chamber. The subsequent annihilation γ rays (stop signal) are detected in a 5-cm×33-cm-diam Pilot-B plastic scintillator coupled to four RCA 8850 photomultipliers. The lifetime of each positron event is directly measured and recorded with use of the TAC-MCA system.

The operation of the polarimeter is based on the fact that in a magnetic field the $m=0$ sub-

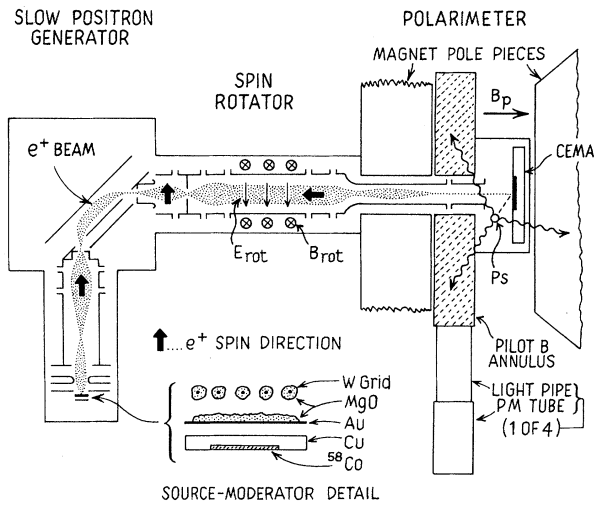

FIG. 1. The apparatus used to generate the slow-positron beam and to measure its polarization. The crossed fields, E_{rot} and B_{rot}, form a Wien filter spin rotator.

states of singlet and triplet positronium are mixed to form two field-perturbed states. Not only does magnetic mixing increase the decay rate λ' of the perturbed ($m=0$) triplet state but it also renders the fraction of positronium which decays from this state dependent on the quantity $\vec{P}\cdot\vec{B}$ (see Ref. 5). For times sufficiently beyond the prompt peak of free annihilation and singlet decays the time spectrum of triplet positronium decay is

$$dN(t)/dt = \tfrac{1}{4}N[2\lambda e^{-\lambda t} + (1-\epsilon P\cos\theta)\lambda' e^{-\lambda' t}]. \quad (1)$$

Here N is the total number of positronium atoms formed, λ is the magnetically unperturbed ($m=\pm 1$) decay rate including all quenching mechanisms ($\lambda^{-1}=132$ nsec), and θ is the angle between $\vec{P}$ and $\vec{B}$. The parameter ϵ is given by $\epsilon = x/(1+x^2)^{1/2}$, where $x=0.0276B$ for B in kilogauss. At 6.3 kG, $(\lambda')^{-1}=15$ nsec and $\epsilon=0.171$. Thus decays from the perturbed ($m=0$) state can be distinguished from decays from the magnetically unperturbed ($m=\pm 1$) states by their shorter lifetime. By measuring changes in the intensity of the $m=0$ component relative to the intensity of the unperturbed component when the positron spin direction or the magnetic field direction is varied, the quantity ϵP can be determined.

The relative intensity of the perturbed $m=0$ component is measured by accumulating counts in two separate time windows in the background-corrected lifetime spectrum. The inner window, from $t_1=11$ nsec to $t_2=33$ nsec, is composed primarily (55%) of decays from the $m=0$ state. The normalization window, from $t_3=72$ nsec to $t_4=548$ nsec, is 99% composed of unperturbed decays. The ratio of counts in the inner window to counts in the normalization window is proportional to the relative $m=0$ intensity. This ratio, R, is shown in Fig. 2 as a function of θ_c, the angle between $\vec{P}$ and the polarimeter field, $\vec{B}_p$ (see Fig. 1). We *calculate* θ_c from the measured fields within the spin rotator. The observed sinusoidal variation of R in θ_c, as expected from Eq. (1), conclusively demonstrates that the positron beam is polarized.

The data in Fig. 2 were fitted to the four-parameter function

$$R = \bar{R}[1 \pm C\cos(\theta+\varphi)], \quad (2)$$

where the $-(+)$ sign was used for B_p (B_{ap}) and $\bar{R}$ is the ratio that would be obtained for an unpolarized beam. The fitted value of θ agreed with θ_c within the calculated uncertainty of 10%. The phase angle, φ, accounts for the rotation of $\vec{P}$ due to transverse fringing fields of the polarimeter magnet. The fitted amplitude, C, is related to P by $C=f\epsilon P$, where f is the fraction of events in the inner time window due to decays from the $m=0$ state. This fraction ($f=0.55$) was determined from a separate run with $B=0$ [$f=1-R(B=0)/\bar{R}$] and, independently, from a fit of the lifetime spectrum to Eq. (1). The measured values of P are $P=0.192\pm0.014$ for B_p and $P=0.173\pm0.013$ for B_{ap}. In addition, four systematic checks, three involving different beam focusing conditions and one with a polarimeter field of 4.45 kG, yielded values for P of 0.182 ± 0.012, 0.162 ± 0.019, 0.180 ± 0.014, and 0.160 ± 0.016. The weighted average of all six values is $P=0.177\pm0.006$ ($\chi^2=3.2$).

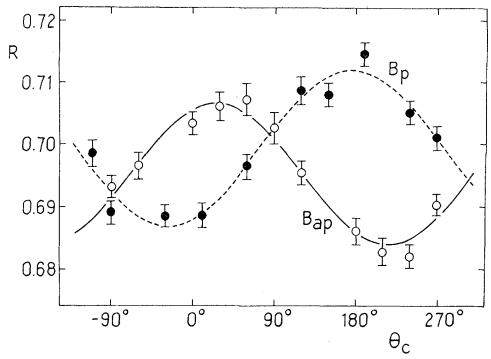

FIG. 2. The ratio of counts in the two time windows, R, is plotted vs the calculated angle, θ_c, between $\vec{P}$ and $\vec{B}_p$. Defining θ_c with respect to $\vec{B}_p$, the magnetic field parallel to the beam direction distinguishes the data acquired in the antiparallel field, $\vec{B}_{ap}$ from data acquired in $\vec{B}_p$. χ^2 per degree of freedom of the fit to Eq. (2) is 10.1/6 for B_p and 8.1/7 for B_{ap}.

The above result must be considered an absolute minimum value for the actual beam polarization for two reasons: Fringing fields of the polarimeter magnet can rotate the polarization vector in a plane perpendicular to the spin rotator plane, thus decreasing the component of $\vec{P}$ along the axis by as much as 15%; and depolarization due to the polarimeter magnetic field gradient is determined to be (20 ± 10)% by measuring the transfer of beam momentum from axial to cyclotron motion using the lens system. Therefore the most probable value for the polarization of the beam is $P=0.22^{+0.04}_{-0.02}$. The error shown is associated with the systematic effects discussed above.

The above value of P should then be compared with the estimated polarization, P_β, of positrons stopping in the moderator. The ^{58}Co source is

electroplated onto a 0.013-mm Cu foil (see Fig. 1) which is in contact with the moderator. The Cu foil, in eliminating positrons below 100 keV, limits the original helicity of any transmitted positrons to the range $0.53 < h < 0.85$. Averaging over energy ($100 < E < 470$ keV) and angle (2π steradians), and accounting for systematic errors in the calculation due to backscattering, yields an initial source polarization of 0.34 ± 0.07. Depolarization will occur on slowing down from source emission energies of several hundred keV to the eV or near thermal range. Extrapolating the calculations of Bouchiat and Lévy-Leblond[6] from plastic to Cu and MgO (according to their approximate prescription) we estimate this depolarization to be $(15 \pm 5)\%$. In addition we assume that the approximately 1 nsec lifetime of positrons in MgO indicates that significant spin relaxation is unlikely.[7] Thus the polarization of the source positrons slowing down in the moderator is estimated to be $P_\beta = 0.29 \pm 0.06$.[8] We conclude that a slow-positron beam polarization of 0.40 should be achievable by mounting a ^{58}Co source on a thin, low-Z foil and by limiting the positron-emission angle subtended by the moderator to π steradians. In addition, our depolarization calculations in MgO indicate that the use of higher-energy β sources will not increase the polarization of the beam.

Our discovery that the slow positrons which leave the MgO surface are polarized suggests their use in a number of new applications which include the following ones:

(a) *Polarized low-energy positron diffraction (PLEPD).*—Recent work[9-11] in polarized low-energy electron diffraction (PLEED) has demonstrated that PLEED complements LEED in investigations of crystal structure, with PLEED being more sensitive to certain surface parameters. The substitution of PLEPD for PLEED in the experiments described in Refs. 9 and 10, or LEPD for LEED,[12] should provide a strong consistency check on LEED models of crystal structure since the sign of the charge is reversed and exchange terms in the Hamiltonian are eliminated when positrons are used. For magnetized substances, calculations and a recent experiment[13] indicate that the exchange interaction can produce significant polarization. A direct comparison of PLEED with PLEPD would provide an important consistency check on isolation of the exchange terms.

Polarized slow-positron beams, comparable in both intensity and polarization to the polarized electron beams used in Ref. 10, could be obtained with ^{58}Co sources of 1–2 Ci. Measurements similar to Ref. 9 could also be made to comparable accuracy with approximately the same running times.

(b) *Interaction of polarized positrons with optically active molecules.*—Polarized electrons and positrons have been used in numerous experiments to investigate the hypothesis that the origin of biomolecular optical activity might be linked to the polarization of β particles from radionuclides.[14] Recently a large observed effect involving asymmetric formation of triplet positronium in L vs D amino acids[15] was interpreted as possibly being due to positron helicity. This interpretation was shown to be invalid[16] for the positrons of high initial energy used since, as a result of velocity randomization, the residual helicity at positronium formation energies (~ 10 eV) should be negligible. In addition, the effect was not reproducible.[17] We are now undertaking an experiment (see Ref. 16) to search for this effect but at greatly improved accuracy using our polarized positron beam whose low energy should minimize the loss of positron helicity prior to positronium formation.

(c) *Polarization measurements as a probe of slow positron emission.*—The slow-positron–emission process from MgO-coated moderators is not well understood. One emission theory suggests that some fraction of the slow positrons result from field ionization of excited-state positronium at the MgO surface.[1,18] However, dissociation of positronium would lead to 50% depolarization of the positrons emitted due to the fine and hyperfine interactions. Further studies of depolarization and backscattering in the source and moderator should allow quantitative limits to be set on this fraction.

We thank G. W. Ford, D. E. Newman, M. A. Skalsey, and E. Sweetman for helpful discussions, and A. Nudelfuden and K. D'Orazio for contributions to early phases of this work. The financial support of the National Science Foundation (Contract No. PHY77-28139), the National Aeronautics and Space Administration (Contract No. NSG7452), the Research Corporation, the Institute of Science and Technology, Rackham Graduate School, and the Dearborn Campus Grants Committee of The University of Michigan is gratefully acknowledged.

---

[a] Permanent address: Department of Natural Sciencess, University of Michigan–Dearborn, Dearborn,

Mich. 48128.

[1]See the review article by S. Berko, K. F. Canter, and A. P. Mills, Jr., in *Progress in Atomic Spectroscopy*, edited by W. Hanle and H. Kleinpoppen (Plenum, New York, 1979), Part B, p. 1427.

[2]A. P. Mills, Jr., S. Berko, and K. F. Canter, Phys. Rev. Lett. 34, 1541 (1975), and references therein.

[3]D. W. Gidley and P. W. Zitzewitz, Phys. Lett. 69A, 96 (1978), and references therein.

[4]A. P. Mills, Jr., P. M. Platzman, and B. L. Brown, Phys. Rev. Lett. 41, 1076 (1978), A. P. Mills, Jr., Phys. Rev. Lett. 41, 1828 (1978); K. G. Lynn, Phys. Rev. Lett. 43, 391, 803(E) (1979).

[5]G. Gerber, D. Newman, A. Rich, and E. Sweetman, Phys. Rev. D 15, 1189 (1977).

[6]C. Bouchiat and J. M. Lévy-Leblond, Nuovo Cimento 33, 193 (1964).

[7]Since the slow positrons emitted from MgO are polarized and the polarization can be accurately measured, we suggest that a calculation of positron spin relaxation in MgO is now of interest. The only existing information on the polarization of positrons thermalized in solids has been carried out for positrons annihilating in ferromagnetic materials [see S. Wakoh and Y. Kubo, J. Magn. Magn. Mater. 5, 202 (1977), for recent results and prior references]. The polarization in these cases can, however, be estimated only crudely.

[8]To show that P depends on P_β the source foil was reserved so that positrons with opposite spin would backscatter into the moderator. The decrease in P to 0.103 $\pm$ 0.015 is in good agreement with the calculated change in P_β for a backscattering coefficient of 0.3.

[9]G. C. Wang, B. I. Dunlap, R. J. Celotta, and D. T. Pierce, Phys. Rev. Lett. 42, 1349 (1979); W. N. Unertl, R. J. Celotta, and D. T. Pierce, in *Electron Diffraction 1927–1977*, edited by P. J. Dobson, J. B. Pendry, and C. J. Humphreys, The Institute of Physics Conference Series No. 41 (The Institute of Physics, Bristol and London, 1978), p. 287.

[10]J. Kirschner and R. Feder, Phys. Rev. Lett. 42, 1008 (1979).

[11]M. Kalisvaart, M. R. O'Neill, T. W. Riddle, F. B. Dunning, and G. K. Walter, Phys. Rev. B 17, 1570 (1978).

[12]LEPD has been considered by J. Oliva, Ph.D. thesis, University of California, San Diego, 1979 (unpublished).

[13]L. A. Vredevoe and R. E. DeWames, Phys. Rev. 176, 684 (1968); R. Feder, Phys. Status Solidi (b) 58, K137 (1973); R. J. Celotta, D. T. Pierce, G.-C. Wang, S. D. Bader, and G. P. Felcher, Phys. Rev. Lett. 43, 728 (1979).

[14]The most recent experiment to show an effect with polarized electrons was reported by W. A. Bonner, M. A. Van Dort, and M. R. Yearian, Nature (London), 258, 419 (1975); however, this effect could not be reproduced—see G. K. Walters, Bull. Am. Phys. Soc. 24, 653 (1979).

[15]A. S. Garay, L. Keszthelyi, I. Demeter, and P. Hrasko, Nature (London) 250, 332 (1974), and Chem. Phys. Lett. 23, 549 (1973).

[16]A. Rich, Nature (London) 264, 482 (1976).

[17]W. Brandt and T. Chiba, Phys. Lett. 57A, 395 (1976).

[18]T. C. Griffith, G. R. Heyland, K. S. Lines, and T. R. Twomey, Phys. Lett. 69A, 169 (1978).

Cluster Phenomena and the Displacive to Order-Disorder Crossover

Alastair D. Bruce,[a] T. Schneider, and E. Stoll
IBM Zurich Research Laboratory, S-8803 Rüschlikon ZH, Switzerland
(Received 2 August 1979)

Renormalization-Group methods are used to calculate the critical distribution functions for large *groups* of ordering coordinates in two- and three-dimensional systems undergoing structural phase transitions. In two dimensions the distribution function shows clear evidence of well-defined clusters of precursor order, and cluster walls: The asymptotic collective behavior is *always* that of an order-disorder rather than a displacive system. In three dimensions the order-disorder component of the asympototic behavior is markedly weaker.

Systems undergoing structural phase transitions (SPT's) have traditionally been subdivided into two categories: "displacive" and "order-disorder." In the weakly anharmonic displacive limit the wells of the anharmonic local potential (an essential ingredient of any SPT) are shallow on the scale of the critical thermal energy; phonon-based approximation schemes appear qualitatively viable[1] and yield (for $T > T_c$) a *single*–time-scale behavior for the soft collective coordinate; quasiharmonic motion about the high-symmetry sites is implied. In the strongly anharmonic order-disorder limit, the local potential is deep and pseudospin methods are appropriate[2]; the behavior of the soft coordinate reflects the existence of the *two* different time scales associated with the two components (interwell hopping and in-well oscillation) manifestly present in the

