Laboratory Simulation of Direct Positron Annihilation in a Neutral-Hydrogen Galactic Environment

B. L. Brown and M. Leventhal
AT&T Bell Laboratories, Murray Hill, New Jersey 07974
(Received 19 June 1986)

The linewidth for thermalized positrons directly annihilating with bound electrons in low-density molecular hydrogen gas has been found to be 1.56 ±0.09 keV, by use of a Ge detector with a low-energy pulsed positron beam. This linewidth measurement together with previous experimental results makes it possible to determine precisely the composite spectrum due to positrons annihilating in a neutral-hydrogen galactic medium.

PACS numbers: 95.30.Cq, 78.70.Bj

Observers using gamma-ray telescopes in the late 1970's detected a 511-keV line originating from the direction of the galactic center.[1,2] The line has been universally interpreted as a positron annihilation line.[3] Since the line is not gravitationally redshifted, it is generally assumed that the positrons are annihilating in a gaseous interstellar environment.[4] A previous laboratory simulation of a neutral-hydrogen annihilation medium has shown that most positrons slowing down from high energies (>keV) will form positronium (Ps) at relatively low energies, ≈10–100 eV, and annihilate in flight.[5,6] A small fraction drop below the Ps formation threshold and directly annihilate with bound electrons giving rise to an extremely sharp line which can dominate the composite linewidth. In this paper we present the first experimental determination of the direct annihilation linewidth in gaseous H_2. Previous annihilation studies were done in H_2 liquid[7] and in dense gases other than H_2.[8] Our results were obtained by use of a pulsed positron beam with a gas pressure of ≈10 mTorr and are in reasonable agreement with theoretical predictions.[9] We are now able properly to construct the composite annihilation spectrum[10] based completely on experimental results. In the near future observations with gamma-ray telescopes are planned in which large parts of the sky will be surveyed with an array of high-energy resolution Ge gamma-ray detectors.[11] The detailed understanding of the annihilation spectrum for a neutral medium presented here will undoubtedly be helpful in the interpretation of positron lines detected in such a future search.

The slow positron beam used for the experiment is obtained from a ^{58}Co source with a W(110) moderator followed by an $\mathbf{E}\times\mathbf{B}$ filter.[5] Positron beam energies of 0.5 to 19.5 eV (width of 0.2 eV) were used for the measurements presented here. Several stages of differential pumping separate the source region from the gas-target region. A detail of the target chamber is shown in Fig. 1. The positrons enter at an energy E_0 which was typically below the threshold energy for Ps production (below the Ore gap) which is 8.6 eV for H_2. After undergoing a collision, positrons are trapped in the target region by the biased cylinder and baffle in region 3 and the biased plate in region 1, if their longitudinal energy goes below the potential barrier set up in region 3 (typically $E_0 - 1.5$ eV). Positrons thus trapped can directly annihilate either with bound electrons in H_2 or on the walls. Positrons can be temporarily trapped by elastic collisions in the gas cell since the change in direction suffered in such collisions can drop the longitudinal energy below the barrier in region 3. There is a fractional energy loss during each elastic collision of $2m/M$, where m is the positron mass and M is the H_2 mass. The positrons also can lose energy by inelastic collisions below the Ps

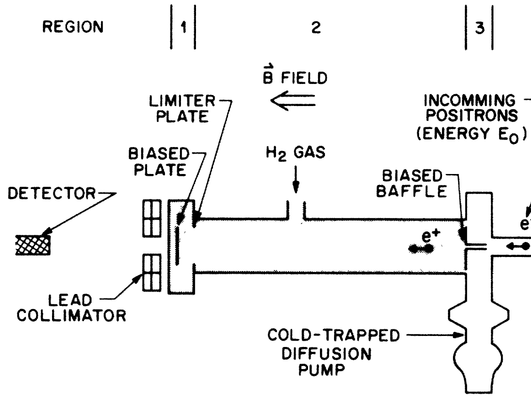

FIG. 1. Gas cell used to trap positrons and observe the direct annihilation of positrons with bound atomic electrons in H_2. The positrons are trapped principally by undergoing vibrational collisions with the hydrogen molecules. The longitudinal magnetic field and potential barriers in regions 1 and 3 create a bottle for positrons which lose sufficient energy in region 2.

threshold.[12] The inelastic processes in H_2 include excitation of the vibrational (minimum energy loss 0.55 eV) or rotational modes (minimum loss ≈ 0.01 eV). The threshold for direct impact dissociation of H_2 occurs at about 9 eV and it is not a factor in trapping below the Ps threshold. Vibrational excitation is the most significant mechanism for trapping in view of the expected energy loss and of recent cross-section calculations.[13] By use of a technique of measuring the number of positrons which survive after a given delay time[6] the trapping efficiency was found to be 28% at 10 mTorr and 35% at 30 mTorr.

To minimize the effect of wall annihilations, a 5-cm-thick lead shield was used with a 2.5-cm-diam collimation hole to shadow the walls effectively from the detector. In addition, an annular limiting plate was placed behind the collimator so that positrons diffusing radially would annihilate in a shielded area, never reaching the walls. Cu material was used for the biased plate in region 1, the limiting plate, the baffle in region 3, and all the baffles along the differentially pumped beam line. This was done to produce an instrumental annihilation line of uniform width which could be separated from the direct annihilation linewidth in the data analysis. The remainder of the apparatus is stainless steel, which has nearly the same annihilation width as Cu although it is not as Gaussian in shape.

The beam was pulsed on for 1 ms and off for 1 ms. The intrinsic Ge detector (1.08-keV FWHM resolution at 511 keV) was enabled only during the off cycle, after an initial delay of 100 μs. The pulsing eliminated the background from the prompt annihilation of the injected positrons on the baffles; the delay allowed time for the positrons nearly to thermalize before the detector was enabled. Again by use of the survival-fraction technique the $1/e$ measured lifetime of positrons in the apparatus, τ_m, was found to be ≈ 13 ms at a pressure of 10 mTorr. The measured lifetime decreased at higher pressures. From lifetime measurements in H_2 the number of effective electrons $Z_{\rm eff}$ is reported[14] to be 14.7, which corresponds to an annihilation lifetime of 260 μs Torr. At a pressure of 10 mTorr the direct annihilation lifetime, τ_a, is thus 26 ms. The chamber confinement time, τ_c, is surmised to be ≈ 26 ms with use of the relation $\tau_c = (\tau_a \tau_m)/(\tau_a - \tau_m)$. With this confinement time we would expect a significant amount of direct annihilation in the gas. The positron thermalization time in H_2 has been measured to be 3.3 ns amagat ($=2.5$ μs Torr) at relatively high gas densities.[15] This corresponds to 250 μs at 10 mTorr. This thermalization rate is thus two orders of magnitude faster than the direct annihilation rate given above, and we expect the positrons to be thermalized before directly annihilating.

A note to avoid possible confusion is in order here. The direct annihilation of positrons with atomic electrons is sometimes referred to as free annihilation (cf. Ref. 15). We wish to reserve the term free annihilation to refer to the annihilation of positrons with free (unbound) electrons (cf. Ref. 4).

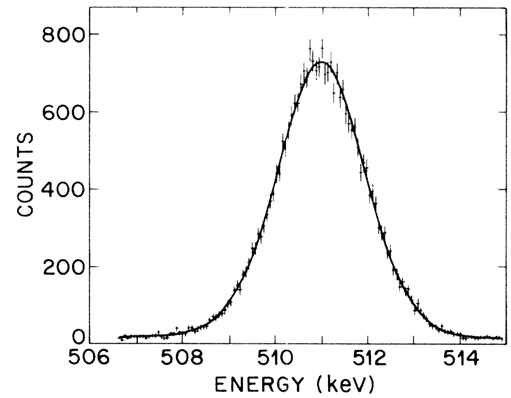

FIG. 2. Direct annihilation data obtained with a high-resolution Ge detector. The solid line shows fit to the data with use of the model described in the text. The pressure for this 5-d run was 15 mTorr.

A typical example of our data at 15 mTorr is shown in Fig. 2. A nonlinear least-squares fit was made with the following components: (1) two Gaussian curves of the same line center for the instrumental line and the direct annihilation line (one Gaussian has a fixed width of 2.52 keV which is characteristic of the Cu instrumental line); (2) a step function below 511 keV for triplet Ps that could be formed on the chamber walls and be present in the instrumental background and for the Ge detector response; and (3) a measured constant room background with the beam completely off. This background is subtracted from the data. A χ^2/ν of 109.3/123 was obtained for this five-parameter fit. The data runs were typically 5 d long in part because of the weak ≈ 30-mCi ^{58}Co source that was used. The data were taken in 1-d intervals and then added together (after adjustment of the gain if necessary) before fitting. No statistically significant changes in the resulting linewidth were found by variation of the gas pressure or the incoming positron energy. Pressures of 5 to 200 mTorr and positron energies of $E_0 = 4.5$, 7.5, and 19.5 eV were tried. The relative amount of instrumental line in the result did vary with pressure. The lower pressures produced a lower overall counting rate with a higher instrumental fraction, which is not surprising since the direct annihilation lifetime is longer at lower pressures. The linewidth for a beam energy of 19.5 eV (above the Ps formation threshold) would not be expected to vary from the linewidth for lower-energy runs if the positrons are nearly thermal before the detector is enabled. The direct annihilation width did show a significant correlation with the width chosen in the data analysis for the Cu line. The correlation was ≈ 2 to 1 at a gas pressure of 45 mTorr, meaning that a change of $+0.2$ keV in the Cu linewidth would produce a change of $+0.1$ keV in the direct annihilation width. At a pressure of 10–15 mTorr the correlation was ≈ 1 to 1. Another systematic error was due to the slightly non-Gaussian form of the Cu line. This is taken into account in the final result by construction of an artificial spectrum consisting of the measured instrumental line plus a Gaussian direct annihilation line of appropriate intensity. The artificial spectra were then fitted by use of the model described above and our final results were adjusted accordingly. The measurement of the Cu instrumental linewidth was made with low-energy positrons, $E_0 = 0.5$ eV, impinging on the Cu plate in region 3. The width was found to be 2.52 ± 0.03 keV.

The final result is given for three high-quality runs, one at a pressure of 45 mTorr and two at a pressure of 15 mTorr. The runs yielded a direct annihilation width of 1.56 ± 0.09 keV where the error is given as the sum of the statistical error (0.04 keV) and the suspected systematic error (0.05 keV). The reason for not including more data is that our systematic uncertainties have begun to outweigh the statistical uncertainty in the final result. Our result is in good agreement with a calculation made by Darewych using a one-state approximation. His work, using a simple positron wave function, implies a rather Gaussian shape with a linewidth of 1.6 keV FWHM. The same calculation, incidentally, gives a value of $Z_{\mathrm{eff}} = 1.9$ in poor agreement with the measured value of 14.7 (Ref. 14). Darewych notes that electron-positron correlation effects are not included in his calculation and that this is the reason for the discrepancy. Although current theory indicates that H_2 fails to bind positrons by a small amount,[16] it is conceivable that direct annihilation occurs in a weakly bound state, giving rise to a high Z_{eff}. If this were the case, it would still not alter the predicted annihilation width appreciably.[17] Our results also agree with the linewidth for direct annihilation in liquid H_2, obtained with reasonable accuracy from the angular correlation spectrum in Ref. 7.

The experimentally verified composite annihilation spectrum for positrons in a neutral H_2 medium is shown in Fig. 3. This spectrum consists of a *p*-Ps (singlet) annihilation component of width of 6.4 keV (Ref. 3), a direct annihilation fraction of 10.3% (Ref. 4), and a direct-annihilation-component width of 1.56 keV. The *o*-Ps (triplet) is also included with the proper Doppler broadening. This consists of the experimentally verified[18] curve, originally derived by Ore and Powell, convolved with a 6.4-keV-wide Gaussian distribution. (The *o*- and *p*-Ps have the same Doppler-broadening profiles.) The composite line for H_2 has a FWHM of 2.2 keV, but the reader should be

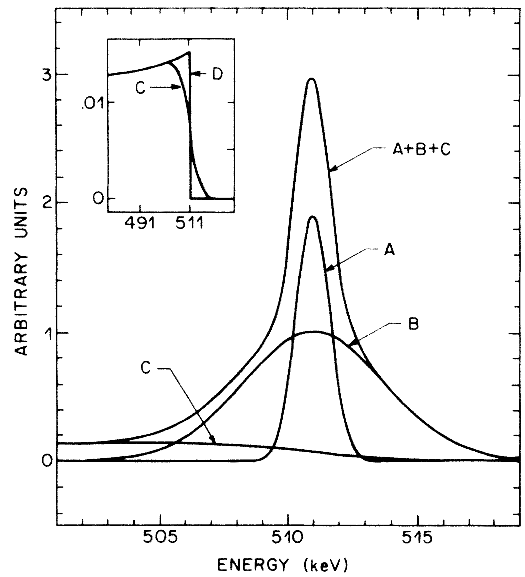

FIG. 3. Composite spectrum for positron annihilation in a neutral H_2 medium using previous experimental results together with those presented here. The curve A is the direct annihilation line, B is the *p*-Ps line, C is the *o*-Ps line, and the inset shows the *o*-Ps line without Doppler broadening, D. The sum $A + B + C$ represents the shape expected for H_2 with no instrumental rounding. The results for H_2 and the expected shape for atomic H are virtually indistinguishable. A neutral-H spectrum (see text) has been fitted directly to the data obtained from the direction of the galactic center in Ref. 10 and it was shown that neutral hydrogen cannot be ruled out as an annihilation medium.

cautioned that the width of this non-Gaussian line cannot be directly compared to the limits set by a Gaussian fit to the galactic data.[10]. The respective parameters that are predicted for neutral atomic H are 6.4 keV (Refs. 4 and 5), 9% (Ref. 10), and 1.3 keV (Ref. 19). The corresponding composite spectrum for neutral H has a FWHM of 1.9 keV and it is almost identical to the H_2 spectrum. Distinguishing between the atomic and molecular hydrogen annihilation spectra is virtually impossible from an experimental standpoint, especially after the addition of the detector resolution. The predicted spectrum for neutral H has been fitted directly to the data obtained from the direction of the galactic center and it was shown that neutral hydrogen cannot be ruled out as an annihilation medium.[10] The same conclusion holds for our experimentally verified spectrum in H_2.

While a large number of molecular hydrogen clouds are known to exist near the galactic center,[20] we would like to stress that other media also seem reasonable. Models involving a time-varying neutral medium,[19] a partially ionized region,[4] or a region where dust plays a major role[21] cannot be ruled out at this time. In fact, where there is a clearly varying signal intensity from the galactic center,[2] all three models may come into play at various times. Future observations of the galactic center and of large unexplored areas of the sky may help us to distinguish specific annihilation media more clearly.

The authors would like to thank R. J. Drachman, J. W. Darewych, D. W. Gidley, A. P. Mills, Jr., P. M. Platzman, and W. H. Zurek for informative discussions.

[1]M. Leventhal, C. J. MacCallum, and P. D. Stang, Astrophys. J. **225**, L11 (1978).

[2]G. R. Riegler, J. C. Ling, W. A. Mahoney, W. A. Wheaton, J. B. Willett, A. S. Jacobsen, and T. Prince, Astrophys. J. **248**, L13 (1981).

[3]M. Leventhal, Astrophys. J. **183**, L147 (1973).

[4]R. W. Bussard, R. Ramaty, and R. J. Drachman, Astrophys. J. **228**, 928 (1979).

[5]B. L. Brown, M. Leventhal, A. P. Mills, Jr., and D. W. Gidley, Phys. Rev. Lett. **53**, 2347 (1984).

[6]B. L. Brown, M. Leventhal, and A. P. Mills, Jr., Phys. Rev. A **33**, 2281 (1986).

[7]C. V. Briscoe, S. I. Choi, and A. T. Stewart, Phys. Rev. Lett. **20**, 493 (1968).

[8]F. L. Obenshain and L. A. Page, Phys. Rev. **125**, 573 (1962).

[9]J. W. Darewych, Can. J. Phys. **57**, 1027 (1979).

[10]B. L. Brown, Astrophys. J. **292**, L67 (1985).

[11]B. J. Teegarden, T. L. Cline, N. Gehrels, G. Porecca, J. Tueller, M. Leventhal, A. F. Huters, C. J. MacCallum, and P. D. Stang, in *Proceedings of the Nineteenth International Cosmic Ray Conference,* edited by F. C. Jones, J. Adams, and G. M. Mason, NASA Conference Publication 2376 (Goddard Space Flight Center, Greenbelt, MD, 1985), Vol. 3, p. 307.

[12]B. L. Brown, in *Positron Annihilation,* edited by P. C. Jain, R. M. Singru, and K. P. Gopinathan (World Scientific, Singapore, 1985), p. 362.

[13]S. Sur and A. S. Ghosh, in Ref. 12, p. 393. An earlier calculation was done by P. Baille and J. W. Darewych, J. Phys. (Paris), Lett. **35**, L243 (1974).

[14]P. G. Coleman, T. C. Griffith, G. R. Heyland, and T. L. Killeen, Appl. Phys. **3**, 271 (1974).

[15]M. Charlton, Rep. Prog. Phys. **48**, 737 (1985).

[16]D. M. Schrader and C. M. Wang, J. Phys. Chem. **80**, 2507 (1976).

[17]R. J. Drachman, private communication.

[18]C. Tianbao, T. Hsiaowei, and L. Yaoqing, in Ref. 12, p. 212.

[19]R. J. Drachman, in *Positron-Electron Pairs in Astrophysics,* edited by M. L. Burns, A. K. Harding, and R. Ramaty (American Institute of Physics, New York, 1983), p. 242.

[20]J. Bally, A. A. Stark, R. W. Wilson, and C. Henkel, Astrophys. J. Suppl. Ser. (to be published).

[21]W. H. Zurek, Astrophys. J. **289**, 603 (1985).

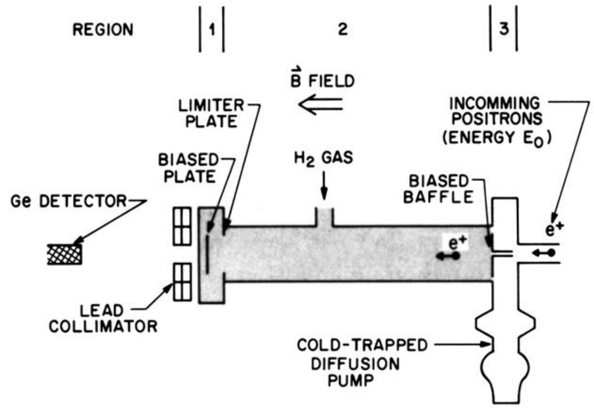

FIG. 1. Gas cell used to trap positrons and observe the direct annihilation of positrons with bound atomic electrons in H_2. The positrons are trapped principally by undergoing vibrational collisions with the hydrogen molecules. The longitudinal magnetic field and potential barriers in regions 1 and 3 create a bottle for positrons which lose sufficient energy in region 2.