Positron Annihilation in a Simulated Low-Density Galactic Environment

B. L. Brown, M. Leventhal, A. P. Mills, Jr., and D. W. Gidley
AT&T Bell Laboratories, Murray Hill, New Jersey 07974
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A low-energy positron beam is used to study the behavior of positrons in low-density ($\approx 10^{-3}$ Torr) H_2 and He. Positronium is formed in flight and the collision-free Doppler-broadened singlet annihilation linewidth in H_2 is found to be 6.4 ± 0.1 keV in agreement with the calculations of Bussard, Ramaty, and Drachman. The measured fraction of positrons surviving below the positronium threshold is larger than predicted. We conclude that the neutral interstellar environment cannot be ruled out as a galactic annihilation site.

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Since the discovery of the narrow 511-keV positron annihilation line coming from the direction of the galactic center,[1,2] there has been speculation about the nature (density, temperature, degree of ionization of gas, etc.) of the medium where the positrons annihilate and about how the medium affects the observed linewidth and positronium (Ps) fraction. With the experiment presented here we investigate the problem by directly simulating, with a minor extrapolation, the possible astrophysical situation of very-high-energy ($>>1$ keV) positrons slowing down via ionization and excitation collisions with interstellar gas, eventually forming Ps below ≈ 200 eV with a few positrons surviving below the Ps formation threshold energy. The Doppler profile of the annihilation line is sensitive to the Ps formation cross section as a function of energy, while the fraction of positrons surviving below the Ps threshold is sensitive to the ratio of the ionization and excitation cross sections to the Ps formation cross section. In previous theoretical work discussing the galactic-center positron annihilation,[3] the relevant cross sections had not been experimentally verified. Although measurements have more recently been made of the total collision cross section[4] and Ps formation cross section[5] for positrons in H_2, which agree with the estimates used in previous theoretical work, the ionization and excitation cross sections have not been measured.

In this Letter we report the behavior of positrons in neutral low-density H_2 and He, using a low-energy positron beam. We inject positrons of a specific energy (10 eV to 1.3 keV) into a differentially pumped target gas region with a typical pressure of 10^{-4} to 10^{-2} Torr, and Ps is formed (both singlet and triplet) in the gas chamber in flight via the charge-exchange interaction. The singlet Ps formed has a lifetime much less than the mean collision time of Ps and a gas atom or molecule, and the experiment thus simulates the interstellar vacuum as far as the Ps 511-keV annihilation is concerned. The width of the Doppler-broadened Ps annihilation line is measured with a Ge(Li) detector and compared to the width of the astrophysical line. This is the first experiment to measure the Doppler-broadened spectrum of collision-free singlet Ps in a gas. The measured fraction of the positrons surviving below the Ps formation threshold, which can affect the width of the astrophysical line, is reported here. The Ps formation threshold energy, the lower limit of the Ore gap, is defined as $E_{th} = E_I - E_{Ps}$, where E_I is the ionization energy of the ground state of the gas and E_{Ps} is the Ps binding energy ≈ 6.8 eV.

A 100-mCi ^{58}Co source was used in conjunction with a tungsten (111) moderator, followed by an $\vec{E} \times \vec{B}$ filter, to produce low-energy positrons which are magnetically guided (150 G) to the target gas region (refer to Fig. 1). The bias on the moderator (and source) was changed to produce different incident beam energies E_0 from 10 eV to 1.3 keV, with a typical measured axial energy spread of $\Delta E \approx 20$ eV in the high-field (10^3 G) regions 1–3. The spread in total energy of the positrons is measured to be about 3 eV, due to the W(111) moderator. The high field in the gas target region 2 is designed to slow the positron diffusion in the radial direction as discussed below. The entire length of the beam is differentially pumped so that a typical pressure for the source region is 10^{-9} Torr with the target gas region at 10^{-3} Torr. The target gas is leaked continuously into the center of region 2 with a Varian leak valve and the pressure is measured with a McLeod-type Hg manometer (5% absolute accuracy). A 5-cm-thick lead collimator with a 2.5-cm-diam hole along the central beam axis is used to reduce greatly the Ge(Li) detector sensitivity to annihilations produced by triplet Ps collisions with the walls of the gas chamber. A full detector view of the central axis is afforded when the detector is about 70 cm from region 1. Grids in regions 1 and

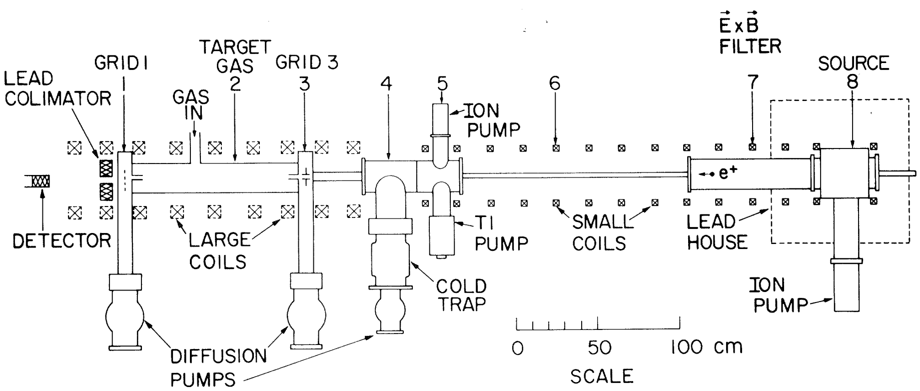

FIG. 1. Experimental apparatus showing small- and large-coil regions for 150 G and 1 kG fields, respectively. Positrons are produced in region 8 and travel through differentially pumped regions to the gas target region 2.

3 are biased to trap a positron if it makes a single inelastic collision with a gas atom or molecule. Grid 1 in region 1 is a fine mesh, set at a reflecting potential for positrons (typically $V_1 = E_0 + 40$ V); grid 3 in region 3 is a cylindrical tube 1.7 cm i.d. × 3.8 cm (typically $V_3 = E_0 - 20$ V). A tube is used for grid 3 to prevent direct annihilation of positrons on a grid mesh. Cu baffles were used to enhance the differential pumping between beam sections: regions 1-2 and 2-3, a 1.7-cm-i.d. × 4.5-cm tube; region 3-4, a 1-cm-i.d. × 12-cm tube; and region 4-5, a 1.1-cm-diam hole. Typical pressures in regions 1 and 3 are 30 times less than that of region 2, reducing the possibility of Ps formation during the turnaround.

A Ge(Li) detector [1.5-keV full width at half maximum (FWHM) resolution at ≈ 511 keV] is used to obtain the gamma-ray spectra shown in Fig. 2; all linewidths quoted have the detector resolution taken out. A good least-squares fit to the data is obtained with two Gaussian functions centered at 511-keV energy, a constant function below 511 keV (to simulate the triplet Ps continuum), and a constant background all folded with the measured detector resolution. Specifically, six fitting parameters were used: one for the central location of both Gaussians, one for each Gaussian width, one for each Gaussian intensity, and one for the triplet constant function. A chi square per degree of freedom of $\chi^2/\nu = 176/135$ (134/135) was obtained for the $E_0 = 524$ eV (243 eV) data shown in Fig. 2. The fit was unacceptable when a single Gaussian or single Lorentzian was used in place of the double Gaussian. The wider (6–9 keV) of the two Gaussians is taken to be the Doppler-broadened singlet Ps line because in the absence of gas in region 2 it disappears along with the triplet continuum and it has an intensity consistent with the measured surviving

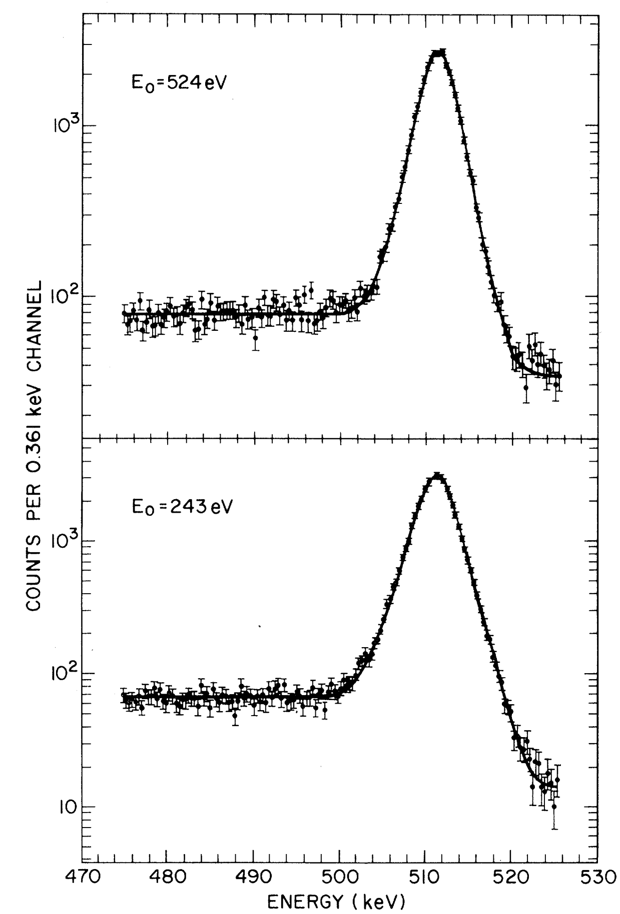

FIG. 2. Typical spectra obtained with positrons in H_2. The solid line represents a least-squares fit using two Gaussian functions (one wide for Ps singlet annihilation, and one narrow for baffle annihilation) and a constant function (for Ps triplet annihilation). The ratio of narrow to wide intensities is 1.2 to 1 for the upper spectrum and 1.1 to 1 for the lower spectrum. The FWHM for the wide line at $E_0 = 524$ eV is 7.0 keV and for $E_0 = 243$ eV it is 7.8 keV.

fraction discussed below. There is some magnetic quenching of the $m=0$ triplet state of Ps: 18% is estimated to annihilate into two photons with a lifetime of about 120 nsec.[6] With geometry considered this contributes at most 10% to the wide-line intensity, but it has the same Doppler-broadened characteristics as the singlet contribution and thus is inconsequential. The width of the narrow line was found consistently to be near 3 keV. We found that positrons impinging directly on a Cu plate produced a 2.9 ± 0.1-keV-FWHM line. The positrons can reach the Cu baffles by drifting off the central axis through diffusion. Typical radial diffusion distances r are estimated to be $(\overline{r^2})^{1/2} \approx 0.2$ cm for positrons going from energy 1 keV down to 20 eV in a field of 1 kG. For positrons going from just below the Ore gap in H_2 down to thermal energies, we estimate $(\overline{r^2})^{1/2} = 0.7$ cm with a thermalization time of ≈ 100 ms. In addition to diffusion, positrons may drift off axis and hit a Cu baffle because of an $\vec{E}\times\vec{B}$ drift produced by a radial $\vec{E}\times\vec{B}$ component (in cylindrical coordinates) in the turnaround grid regions 1 and 3. For example with our grid placement, a θ component of 0.1% in either field in the grid region gives an estimated confinement time of ≈ 1 ms for positrons below the Ore gap. The positrons, if they do not hit a Cu baffle, will directly annihilate after $\approx (6\times 10^{-14} n_g)^{-1}$ sec, where n_g is the density of the gas (in inverse cubic centimeters), or $\frac{1}{3}$ s at 1.4×10^{-3} Torr.[7] At this time the positron would be at thermal equilibrium. Direct annihilation with electrons in the gas should produce a narrow annihilation line (≈ 1.3-keV FWHM).[8] The confinement time was measured to be ≈ 1 ms by means of a gated beam technique, and thus it is likely that most positrons below the Ore gap hit Cu baffles in our apparatus.

To check for systematic effects in the data, over one hundred runs were made of several hours duration each, changing the magnetic field, the gas pressure, the baffle diameter and baffle bias, and the incoming positron beam energy. Only the beam energy produced a systematic effect in the linewidth of the wide Ps line as shown in Fig. 3. Since the positrons make a small number of collisions before forming Ps, the direction of the Ps formed is axially preferential in our apparatus. With this taken into account an approximate relationship between the width squared W^2 and the incident positron energy E_0 was derived:

$$W^2 \approx a + bE_0^{-3/2},$$

where a and b are related to moments of the distribution of Ps formation energies. This expression, valid for $E_0 > 200$ eV, was found by solving the diffusion equation in spherical coordinates, and then estimating that the rms angle of each scattering event is $\theta \approx (\Delta E/E)^{1/2}$. We find that the extrapolation to infinite beam energy yields a width of 6.4 ± 0.1 keV for H_2 and 7.7 ± 0.2 keV for He. The result for H_2 is in excellent agreement with the prediction made by Bussard, Ramaty, and Drachman[3] of 6.5 keV and it tends to support recent Ps formation-cross-section measurements.[5] According to Ref. 3 the Ps linewidth in neutral atomic H should be ≈ 6.5 keV, the same as for H_2. The reported galactic linewidth is $1.6^{+0.9}_{-1.6}$ keV,[2] considerably lower than our measurement.

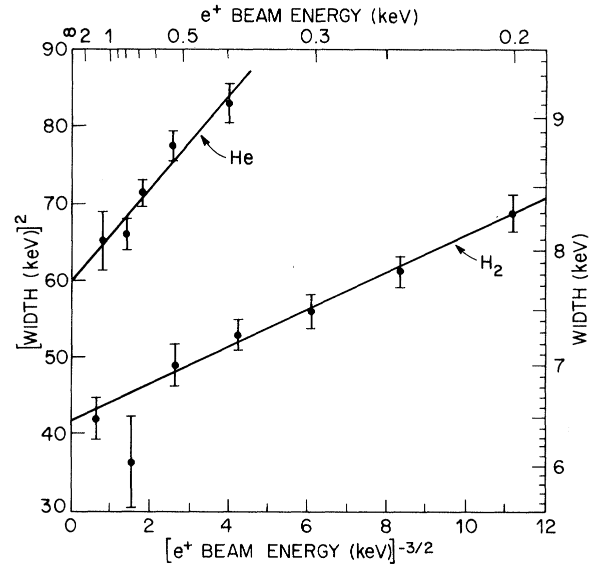

FIG. 3. Width of the wide positronium singlet annihilation in H_2 and He. The variation in width with incident positron beam energy, E_0, is due to preferentially directed Ps formation. The width extrapolated to infinite energy is 6.4 ± 0.1 keV for H_2 and 7.7 ± 0.2 keV for He. The data were taken at a pressure of 1.4×10^{-3} Torr in H_2 and 5×10^{-3} Torr in He.

We have measured the fraction of the positrons which survive below the Ps formation threshold energy (below the Ore gap) using a gated beam technique with a NaI detector (details to be presented elsewhere). The measured fraction of positrons surviving below the Ore gap is $(10.3 \pm 0.3)\%$ for H_2 and $(19.3 \pm 0.5)\%$ for He. The surviving fraction calculated by Bussard, Ramaty, and Drachman[3] for H_2 is 6.5% compared to our value of 10.3%. The surviving positrons, in a neutral interstellar environment, would directly annihilate and produce a narrow 1.3-keV-FWHM line.[8] When this contribution is added in proper proportion to the Gaussian singlet Ps contribution the resulting linewidth is quite narrow. With use of our experimental results and a folding in of the detector resolution, an annihilation spectrum for a neutral medium has been constructed and fitted directly to the HEAO-3 (High Energy Astronomical Observatory) galactic-center data of Ref. 2.[9] The fit obtained is good and therefore H cannot be eliminated as a possible annihilation medium.

In conclusion, we have measured the Doppler-broadened Ps linewidth and surviving positron fraction in low-density H_2 and He. Contrary to previous reports[3,8] we find that the galactic 511-keV gamma-ray line of width $1.6^{+0.9}_{-1.6}$ keV[2] could possibly be due to positrons promptly annihilating in a neutral diffuse interstellar environment. It is also still possible that galactic positrons are annihilating in a partially ionized gas, in dust grains,[10] or that they are impulsively injected into a neutral medium and only that small fraction surviving below the Ore gap has been observed.[8] Future astrophysical observations may provide better statistics on the 511-keV line shape and the possible triplet continuum, allowing a more detailed comparison with our simulation experiments.

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