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Angular dependence of positronium formation in molecular hydrogen

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We report measurements of the angular distribution of positronium formed by charge exchange of monoenergetic positrons in molecular hydrogen for various incident positron energies. These data are compared with recent calculations of Ps formation in H_2 . The implications of these results for the formation and potential utility of energetic positronium beams are discussed.

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Since the first observation of positronium (Ps) more than 40 years ago [1], many studies have been carried out on its properties and formation in various media [2,3]. As a result of that work and the further development of monoenergetic positron beams in the past decade [3], it is now possible to construct Ps beams with tunable energies. Because the Ps atom can be considered as a neutral particle with a mass that is three orders of magnitude smaller than the hydrogen atom, its interaction with various forms of matter, ranging from electrons and protons to atoms, molecules, solid surfaces, and plasmas, can provide important information about the target medium. For example, we have proposed a method to study transport in fusion plasmas using the positron as an electron-mass test particle [4]. In this scheme, the positrons are injected into the plasma as neutral Ps atoms. As another example of the utility of Ps beams, recent research has shown that monoenergetic Ps beams can potentially be a useful probe of solid surfaces [5]. The efficient creation and the characterization of Ps beams are essential to these applications.

While some effort has been made to measure the Ps energy distribution and to identify the states of Ps atoms formed by charge exchange in gases [6], the resulting angular distribution of the Ps atoms has not been systematically studied [7]. This information is not only important for Ps-scattering studies but also relates directly to the intensity of the Ps beam in a given solid angle (i.e., the brightness of the Ps beam).

Several methods of producing energetic positronium atoms have been explored [5,8,9]. Of these, the one most highly developed is that using charge exchange between incident positrons and gas atoms or molecules [5,9]. In this paper, we report measurements of the angular distribution of Ps formed in a gas cell containing molecular hydrogen. Hydrogen gas was chosen as the medium for charge exchange for two reasons. It is suitable for the application as a fusion-plasma diagnostic, since typical tokamak plasmas are composed of hydrogen. Consequently, plasma contamination problems are avoided. In

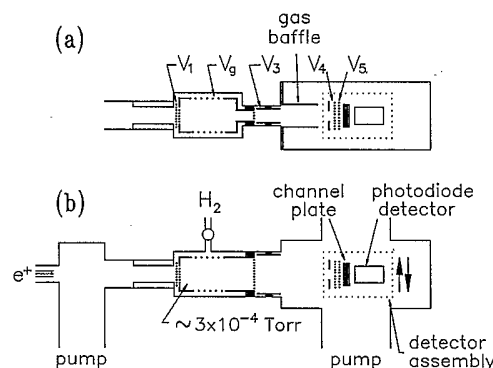


FIG. 1. Schematic diagram of the experiment: (a) top view showing the beam-switching grid V_1 , gas-cell electrode V_g , repelling electrode V_3 , and the retarding grids V_4 and V_5 ; (b) side view showing the structure of the gas cell and detector.

addition, molecular hydrogen is the simplest molecule from the point of view of electronic structure. Thus, measurement of Ps formation in H_2 can also provide information with which to test theoretical models of Ps formation in positron collisions with atoms and molecules.

The experimental apparatus is shown in Fig. 1. Monoenergetic positrons with energies of 42.0 ± 0.7 eV are guided magnetically into a gas cell which has an effective length of 16.5 cm. Hydrogen gas is admitted to the gas cell by a leak valve. Differential pumping of the cell is accomplished by restriction of the gas flow at both ends of the cell and by the addition of a gas baffle at the exit of the cell. Positrons incident upon the gas cell are switched on and off by changing the voltage, V_1 , on the grid in front of the gas cell, from 0 to +60 V. The energy of positrons entering the cell is determined by the voltage applied to the electrode, V_g . The electrode V_3 immediately after the gas cell is used to prevent positrons and positive ions from entering the region where the Ps atoms are detected. At the exit to the gas cell, the repelling electrode V_3 and the baffle restrict the aperture in the horizontal direction only, with no restriction in the vertical direction, in order to facilitate measurement of the angular distribution of the Ps.

The detector assembly consists of an aperture 2.5 cm in diameter that defines the detection solid angle, two grids (labeled V_4 and V_5 in Fig. 1) that are used to repel charged particles, and a chevron microchannel plate (MCP) and a CsI photodiode, which are used for coincidence measurements. The characteristics of both detectors are unaffected by the magnetic field. The detector assembly can be moved vertically through the positronium beam. The detector is located 17.5 cm from the exit of the gas cell.

Coincidence of counts in the MCP and the photodiode is used to detect the Ps and to differentiate from scattered particles and annihilations not taking place at the detector surface. The photodiode and MCP signals are used as the start and stop pulses for a time-to-amplitude converter, and the output is sent to a multichannel analyzer (MCA). A typical coincidence spectrum is shown in Fig. 2. Counts between channels 200 and 850 were included in the peak. To eliminate the accidental coincidences, the

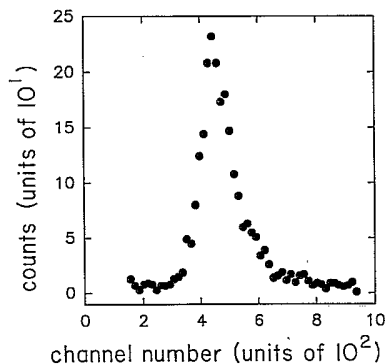


FIG. 2. Spectrum of coincidence counts as a function of time delay between the photodiode and the microchannel-plate signals. Each channel corresponds to a delay of 19.5 ns, and the data shown were binned in 15-channel increments.

average per-channel count in the region of the MCA spectrum between 900 and 950 is subtracted from each channel before summation of the total counts under the peak.

Immediately before and after each Ps run, the positron beam intensity was measured using the same set of detectors, with the gas-cell electrode potential (V_g) at the same setting as that for the corresponding Ps formation measurements. These data were taken for both beam-on ($V_1=0$) and beam-off ($V_1=60$ V) conditions. All other electrodes grounded ($V_3=V_4=V_5=0$). The beam-off data were subtracted from the beam-on data, and the resulting positron beam intensity was used as a normalization factor to obtain the absolute Ps formation fraction.

For the Ps formation measurements, the hydrogen pressure was maintained at $\sim 3 \times 10^{-4}$ Torr. The voltages applied to the repelling electrodes to stop any residual positrons and other charged particles from reaching the detector were $V_3=120$ V, $V_4=-120$ V, and $V_5=300$ V. Positronium formation was measured at different detector positions to determine the angular distribution of the Ps, and the experiment was repeated for various incident positron energies. Some positronium formation also occurred in the region before the gas cell. In addition, a small number of high-energy positrons reached the detector. In order to remove these effects and that of the natural background from the data, coincidence measurements were taken for both positron beam-on and beam-off conditions for each detector position (typically 20 min each). The beam-off counts were then subtracted from the beam-on counts. The results were then normalized by the incident positron beam intensity to obtain the ab-

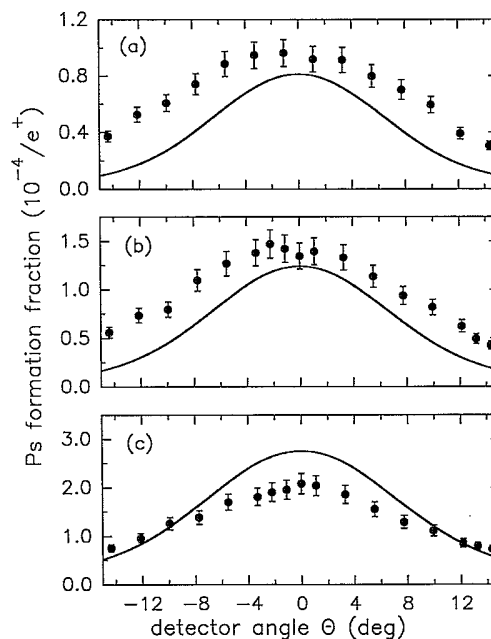


FIG. 3. The positronium formation fraction as a function of detector angle θ for positron energies of (a) 100 eV, (b) 80 eV, and (c) 50 eV. The angle θ is defined as that between the incident positron beam direction and the line between the center of the gas cell and the center of the detector aperture. The experimental values (solid circles) are compared with the theoretical predictions (solid lines) from Ref. [10].

solute Ps formation fraction.

The absolute Ps fraction as a function of the angular position of the detector relative to the incident beam is shown in Fig. 3 for positron energies of 50, 80, and 100 eV. The size of the vertical error bars is predominantly due to the uncertainty of the H_2 pressure in the gas cell. Due to the close proximity of the detector to the gas cell, which has a finite extent along the beam direction, a given detector angle θ corresponds to a relatively large spread in scattering angles. For example, $\theta=8^\circ$ includes contributions from angles between 6° and 11.7° from Ps generated at the entrance and exit of the gas cell, respectively. Due to in-flight decay of the positronium, these angles are not all weighted equally.

In order to compare our measurements with the theoretical predictions, we have taken into account the effects of finite angular spread of the positron beam, finite extent of the Ps formation region, finite detector size, and in-flight decay of the Ps using the following procedure. The solid curves in Fig. 3 are calculated using theoretical predictions [10] for the differential cross sections for Ps formation in the $1S$, $2S$, and $2P$ states, the annihilation lifetimes of these states, and our experimental geometry. These calculations assume a circular positron beam, 1.5 cm in diameter, having a Gaussian angular distribution with $\sigma=1.5^\circ$.

Theory and experiment are in reasonable agreement; however, there are some systematic differences. Table I shows the ratios of the observed and predicted Ps fraction in the forward direction and the ratios of the observed and predicted angular full widths at half maximum (FWHM). These data have been taken directly from the data and curves in Fig. 3. The measured widths are larger than those predicted for all three values of incident positron energies studied. The measured peak values of the Ps formation efficiency are smaller than the calculation at 50 eV, but larger at 80 and 100 eV. Comparison between previous measurements [11] of the total Ps formation cross section in H_2 and the calculations of Ref. [10] shows similar results, in that the experimental value is smaller than the calculation at positron energies around 50 eV and larger at energies of 80 and 100 eV.

Both the recent calculation of Ref. [10] and earlier work [12] were done using the first Born approximation. The work of Ref. [10] eliminated all additional approximations employed in the earlier work, thereby improving the accuracy of the theoretical predictions. In the energy range from 50 to 150 eV, however, the first Born approximation may not be entirely adequate to describe the charge-exchange process, and treatments including higher-order Born approximations may be necessary. Since the accuracy of the calculations also hinges on the molecular wave function employed, the calculations may also be improved as more accurate molecular wave functions become available. Both of these factors may con-

TABLE I. The ratio R_p of the measured peak value of the positronium formation fraction to that predicted theoretically, and the ratio R_w of the corresponding width (FWHM) for different values of incident positron energy E .

E (eV)	R_p	R_w
50.0	0.76	1.22
80.0	1.17	1.37
100.0	1.23	1.39

tribute to the observed differences between the experimental measurements and the theoretical predictions [13].

In the analysis of our experimental results, the same detection efficiency was assumed for positrons and positronium in both the ground and excited states. However, to our knowledge, no systematic studies of the mechanisms of Ps detection have been carried out, and we cannot rule out the possibility that the detection efficiencies for the positrons and Ps atoms are different. We have also assumed that the detection efficiency is constant over the surface of the channelplate. Due to the fact that the detector aperture is placed 2 cm in front of the channel plate, different regions of the channel plate are illuminated at different angular positions. Consequently, such nonuniformities in detection efficiency could lead to asymmetries in the measured angular distribution as a function of θ . This could explain the slight asymmetries evident in the data shown in Fig. 3.

The measured angular distributions of the Ps shown in Fig. 3 provide a guide to the design of Ps beams, particularly with regard to predicting beam strength and brightness. For applications such as Ps-surface scattering and diffraction, which require beams with small angular divergence, the data suggest that beam collimation will be required. For applications such as the fusion-plasma diagnostic, which permit a relatively large beam size and angular divergence [4], the angular distributions of Ps shown in Fig. 3 are adequate. At energies greater than about 50 eV, the measurements indicate a somewhat larger beam strength than that predicted theoretically. These results should be useful as a guide to refined theoretical approaches to Ps formation in gases.

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