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A POSITRONIUM BEAM AND POSITRONIUM REFLECTION FROM LiF

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INTRODUCTION

At the Brookhaven National Laboratory we have constructed a positronium (Ps) beam by transmitting monoenergetic, low energy positrons through a gas cell containing either Ar or He which provide an electron to form positronium. A description of the positron beam and of the Ps formation mechanisms are found in these Proceedings (see M. Weber, et al. and B. L. Brown). The positrons were obtained by magnetically deflecting positrons in the straight section of the positron beamline (see Fig. 1) into a beamline which contained the gas cell and a Ps detection chamber. By having two beamlines we are able to switch from an experiment which uses positrons (a study of the angular correlation of annihilating radiation--ACAR) to one which uses Ps atoms without breaking vacuum, nor moving equipment. This, however, put a constraint on the placement of the Ps beamline because it could not interrupt the annihilation gamma ray in its long flight from the target chamber to a gamma ray position imaging detector (Anger camera). At present this constraint has resulted in a degradation of the positron beam intensity and energy resolution in the Ps beamline. Efforts are presently underway to eliminate this problem.

Very preliminary information has been obtained on the characteristics of the Ps beamline and on the reflection of Ps from a LiF crystal.

Characteristics of the positron beam

(a) The intensity of the positron beam is approximately 8×10^6 e^+/sec. This is a reduction of more than an order of magnitude from its intensity in the straight section.

(b) The energy resolution (energy width between 90% and 10% of the intensity) is 20% at a positron energy of 200 eV, 4% at a positron energy of 120 eV 2.8% at a positron energy of 18 eV (see Fig. 2 and Fig. 3).

It is felt that both (a) and (b) can be improved by increasing the radius of curvature of the positron trajectory at the beam splitter shown in Fig. 1.

Characteristics of the Ps beam

A channeltron was placed 3 cm from the gas cell and a 3"x3" NaI detector was placed 6 cm above the channeltron and perpendicular to the positronium beam which exits from the gas cell. The potential on the gas cell was varied from 170 V to 200 V, and the positrons had an energy of 200 eV before entering the cell. Voltages were placed on grids near the exit of the gas cell and on the channeltron to prevent positrons and electrons from reaching the channeltron. In Fig. 4 the coincidence rate between the channeltron and NaI detector is shown as a function of the potential on the gas cell with Ar gas in the cell at a pressure of $5x10^{-4}$ torr (gas on) and with no gas in the cell (gas off). In Fig. 5 the coincidence rate is shown as a function of the potential on the gas cell when Ar gas at a pressure of $5x10^{-4}$ torr was in the cell. The diamond shaped points along zero coincidence counts are the rates when the positron beam was turned off in the block house, and the crosses are when 200 eV positrons entered the gas cell. It should be noted that the data

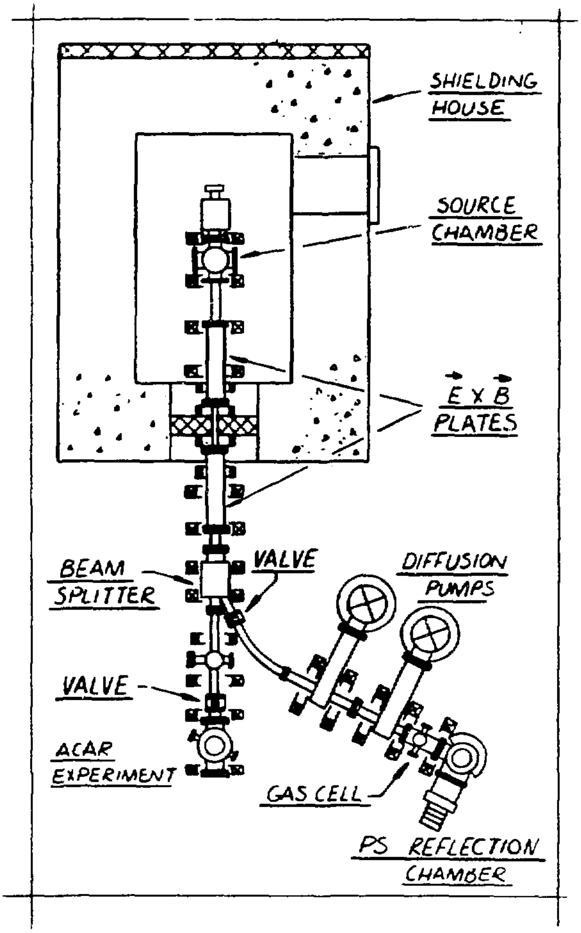

Fig. 1 Positron and positronium beamline.

shown in Fig. 5 is in agreement with the experimental results of L. S. Fornari, et al.[1] Their ratio of the Ps formation cross section, Q_{Ps}, in argon at 20 eV and 10 eV is

$$\frac{Q_{Ps}(20\ \text{eV})}{Q_{Ps}(10\ \text{eV})} = 1.9 \pm 0.3$$

This ratio obtained from the data in Fig. 5 is

$$\frac{\text{coincidence counts at 20 eV}}{\text{coincidence counts at 10 eV}} = 1.6 \pm 0.2$$

It is observed in both figures that Ps is not detected until the positron has an energy 200 eV - 184 eV ≈ 16 eV. The positron must have an energy greater than 8.9 eV to form Ps in Ar, and when it is formed it has a binding energy of 6.8 eV. It appears that the channeltron is not

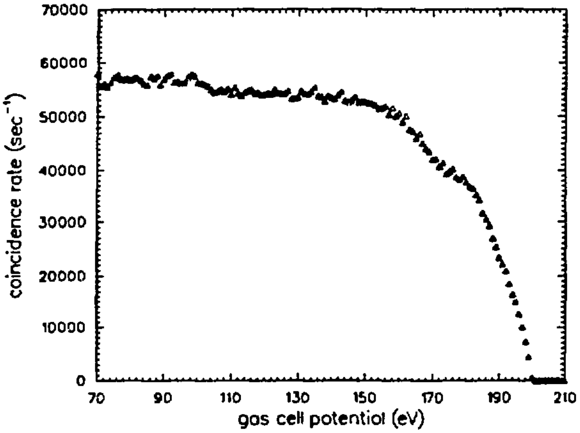

Fig. 2 Coincidence rate between a channeltron placed 3 cm from the gas cell and a 3"x3" NaI detector placed 6 cm from the channeltron and perpendicular to the positron beam exiting the gas cell. The gas cell is devoid of gas and its potential is varied from 70 to 210 volts. The positrons had an energy of 200 eV upon entering the empty gas cell.

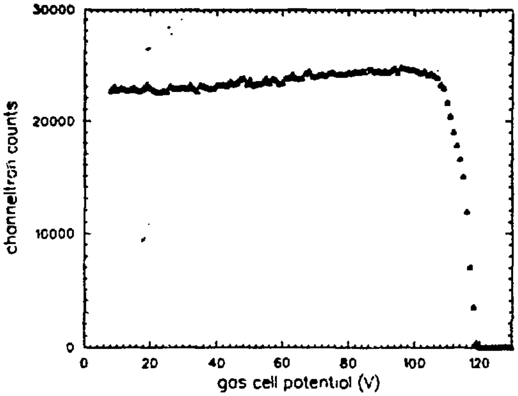

Fig. 3 A measurement similar to Fig. 2 except the positrons had an energy of 120 eV upon entering the empty gas cell.

sensitive to Ps unless the Ps energy is great enough to dissociate it. Thus Ps is not detected if the energy of the positron entering the gas cell is below 9 eV + 8.9 eV ≈ 15.7 eV. It should be noted that in Figs. 2 and 3 the energy resolution shown is the transverse energy spread mainly due to magnetically deflecting positrons into the positronium beamline. The total energy spread will be narrower. This is indicated by the sharp increase in positronium formation as a function of energy shown in Figs. 4 and 5. Of course this results in a reduction of Ps emanating from the gas cell.

The rate of Ps atoms in the Ps beam emerging from the gas cell is estimated to be several thousand per second.

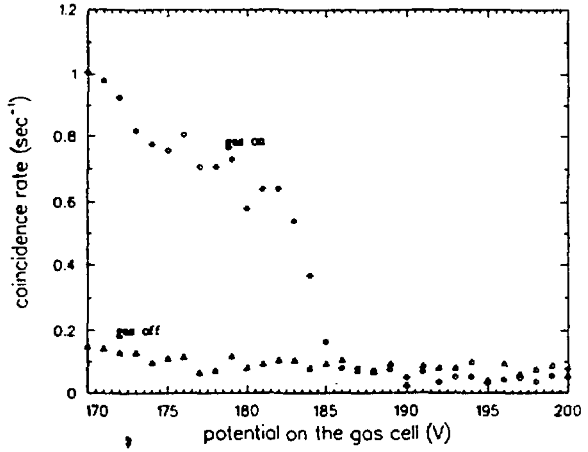

Fig. 4 The coincident rate between the channeltron and NaI detector vs. the potential on the gas cell with Ar gas in the cell at a pressure of $5x10^{-4}$ torr (gas on) and with no gas in the cell (gas off).

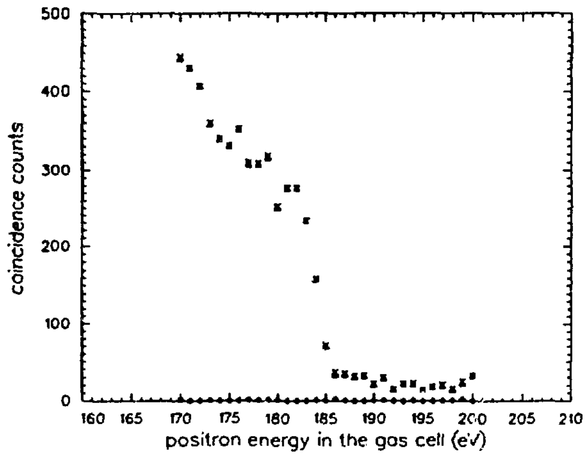

Fig. 5 The coincident rate vs the potential on the gas cell when Ar gas at a pressure of $5x10^{-4}$ torr is in the cell. The diamond shaped points along the zero counts are the rate when the positron beam is turned off in the block house, and the crosses are when 200 eV positrons enter the gas cell.

Reflection of Positronium

(a) A schematic diagram of the apparatus for measuring the reflection of Ps from LiF (100) is shown in Fig. 6. The crystal was cleaved in air by the supplier, and not treated in any way. Specular reflection of Ps by an angle $\theta = 45°$ from the crystal face to the Ps beam direction was measured by observing the annihilation of Ps on a stainless steel plate by two BGO ($Bi_4Ge_3O_{12}$) detectors in coincidence. The background was obtained by rotating the crystal to an angle $\theta = -20°$. The first very preliminary data of this experiment is shown in Fig. 7. We are presently pursuing systematic checks on the Ps beamline and our data acquisition system. It is apparent, however, that we are observing the reflection of Ps from LiF.

(b) We have constructed apparatus to measure the reflection coefficient of positronium from various crystalline surfaces. A diagram of the gas cell and the reflection chamber is shown in Fig. 8. The sample face can be rotated with respect to the direction of the Ps beam and a channeltron or channel plate located in the vacuum chamber can also be rotated about the same axis. Outside of the vacuum chamber are two BGO detectors, one

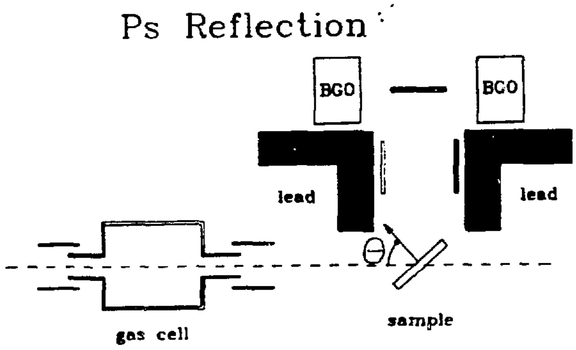

Fig. 6 Ps reflection apparatus utilized to obtain data given in Fig. 7.

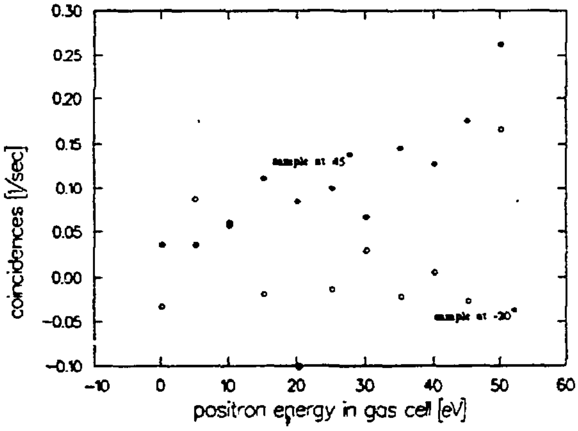

Fig. 7 Positronium reflection from LiF(100) at $\theta = 45°$ (solid circles) and coincidence rate at $\theta =$ [illegible] (open cirlces).

directly above and one directly below the channeltron or channel plate to detect the annihilation gamma rays. With this arrangement we have the option to require a threefold coincidence between the detectors to measure the rate of reflected Ps atoms.

Simultaneously with this effort to measure the reflection coefficient modifications of the apparatus are being made to increase the intensity of the Ps beam.

Purpose

The purpose of these measurements is to attempt to measure Ps diffraction (LEPSD) from crystalline surfaces. Ps diffraction is somewhat similar to He atom diffraction,[2] which is a powerful tool in surface structure determination because it is only sensitive to the outer surface layer. However, the savings in complexity in He atom diffraction by not having to treat multiple scattering from subsurface layers (as in the case of LEED) are somewhat mitigated by having to deal with long range forces that dominate in He diffraction. The 0.02 eV energy necessary for He atoms to have ≈1Å de Broglie wavelength results in the He atoms having classical turning radii far enough from the individual ion cores that the scattering is mainly due to the average potential presented by the surface. This requires an accurate treatment of the average potential for intensity analysis.[2] In order for Ps to have a ≈1Å wavelength, its energy must be on the order of ≈75 eV. At this energy, Ps atoms would be oblivious to the mean surface potential and only undergo elastic reflection in close encounters with the ion cores. Because of the large break-up probability of Ps, multiple scattering and other subsurface contributions to the elastically scattered Ps are expected to be negligible. Thus, Ps diffraction offers the possibility of being a novel and valuable probe.

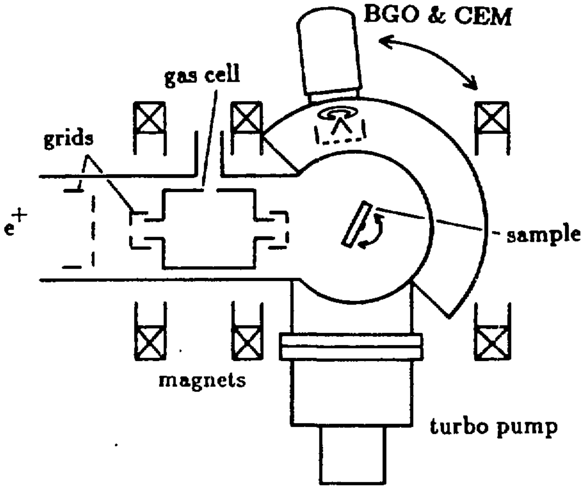

Fig. 8 Apparatus to measure reflected-diffracted Ps from various crystalline surfaces. The channeltron (CEM) is located inside the vacuum chamber and two BGO detectors, one directly above and one directly below the channeltron, to detect annihilation gamma rays are located outside the vacuum chamber. All three detectors can be rotated independently about an axis which is perpendicular to the Ps beam axis.

The degree to which Ps scatters only from the outer surface layer is determined mainly by the interstitial density of valence or conduction electrons of the material. Because of the low mass of weakly-bound electrons, and hence large recoil, elastic Ps-e^- collisions destroy the coherence of the scattered Ps and thus must be regarded as a source of attenuation of the diffracted Ps beam. Typical elastic cross sections in the 10 eV region for Ps-free e^- collisions are on the order of 10^{-15} cm^2.[3] Thus for solids having typical interstitial electron densities of $\approx 10^{23}$ cm^{-3},[3] a mean free path of ≈1Å for the Ps can be expected. Consequently, LEPSD from a solid surface would yield diffracted Ps intensities versus incident energy (i.e., "I(V)" curves) which would be dominated by the elastic scattering from only the outer layer atomic distribution. In the case of an ordered adsorbate overlayer, chemisorbed to a surface, however, the incident Ps could easily penetrate the relatively open spaces between the adsorbate atoms. This would lead to the interesting case of interference between Ps scattering from the adsorbate and from the outer surface with a high sensitivity to the structure of the adsorbate layer and outer surface.

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