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AN EXPERIMENT TO MEASURE THE RADIATIVE LIFETIME OF THE 2P STATE OF POSITRONIUM

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An experiment intended to measure the radiative lifetime of the 2P state of positronium, by monitoring the Lyman-α transition photon in coincidence with a signal indicating Ps formation, is described.

1. Introduction

Positronium, Ps, is the bound state of a positron and an electron, the properties of which should be described to high order by QED. The persisting discrepancy between theory and experiment for the lifetime against annihilation of the 1^3S_1 state [1] provides strong motivation for further tests on this purely leptonic system.

Ps, with a reduced mass of $m_e/2$, has Bohr orbits twice and binding energies half of those of hydrogen. Thus, the corresponding radiative lifetimes are expected to be approximately twice those of H. For the 2P to 1S transition, which results in the emission of a Lyman-α photon at 243 nm, the radiative lifetime ($\tau_{\text{Ly-}\alpha}$) is given to the lowest order in α, the fine structure constant, by

$$\tau_{\text{Ly-}\alpha} = 64\ \text{h}/(5\pi\alpha^3 R_\infty) = 3.187\ \text{nsec},$$

where R_∞ is the Rydberg energy in Joules.

2. Production of excited positronium (Ps^*)

The re-emission of positrons from the surfaces of various metals into which they have been implanted and then subsequently thermalised is well known [2]. The requirement for this process to occur is that the work function for positrons should be negative. In some cases, the positron may capture an electron to form positronium as it leaves the surface. Since positronium cannot exist within the bulk of a metal, this e^+ emission channel is characterised by the so-called positronium formation potential $\varepsilon(\text{Ps})$, which is given by

$$\varepsilon(\text{Ps}) = \phi(e^+) + \phi(e^-) - R_\infty/2,$$

where $R_\infty/2$ is the ground state ($n = 1$) Ps binding energy in vacuum ($\equiv 6.8$ eV) and $\phi(e^{\pm})$ are the positron/electron work functions. ε(Ps) has been found to be negative for all metals investigated, including those for which $\phi(e^+)$ is positive. However, for states for which $n > 1$, the Ps binding energy, which scales as $1/n^2$, is not sufficient to ensure that the formation potential for that state is negative. Therefore, the production of excited positronium Ps^* by positrons which have thermalised and diffused back to the surface of the material is not allowed.

It is also known that positrons implanted into materials with energies of a few hundred electron-volts or less can be backscattered and re-emerge from the surface with a kinetic energy in excess of that expected from work function considerations. Ps may also be formed by these so-called epithermal positrons [3] and due to the extra kinetic energy available, may be in an excited state. The first observation of Ps^* in 1975 [4] utilised this technique.

Energetic Ps is also observed by backscattering from insulators, e.g. MgO and SiO_2 [5]. Here, Ps formation not only occurs at the surface but also in the bulk, although for Ps^* to be emitted into vacuum, however, production must occur close to the surface. The yield of 2^3P Ps, produced in backscatter from MgO, relative to 1^3S_1, is estimated to be $\sim 10^{-2}$, based upon measurements of the microwave-induced $2^3S_1 - 1^3S_1$ transition [6] and assuming that the Ps^* on formation is equally distributed in all $n = 2$ states. For the purposes of the present experiment, MgO is the preferred positronium converter, for together with its $n = 2$ formation properties, it has a high secondary electron yield which may be used to give a timing signal.

Other work on Ps^* includes its formation by positron collisions with gases [7], accurate determinations of the $2^3P_J - 2^3S_1$ fine structure intervals [8], and the first attempts at measuring $n = 2$ radiative lifetimes [9].

3. The apparatus

The apparatus consists of an electrostatically guided positron beam of approximately $2 \times 10^2\ e^+s^{-1}$, variable in energy within a 50–1000 eV range. The typical energy spread of the beam is 3 eV. The beam is focused through a 15 mm aperture and onto vanes smoked with magnesium oxide. This region is enclosed by a glass sphere internally coated with a highly reflective aluminium surface (fig. 1). A photomultiplier tube is located at 90° to the beam axis and views the interaction region through a 20 mm diameter aperture.

Incoming positrons are incident on the earthed MgO vanes and liberate a number of secondary electrons, some of which are scattered towards the channel plate electron multiplier arrays (CEMA), where they experience an accelerating potential and are detected (fig. 2). It is estimated that this process occurs in less than 1 nsec, with approximately 30% of the beam being detected. Of the incident positrons, $\sim 10^{-2} - 10^{-3}$ form Ps^*, the 2P component which comprises all but 4/16 of the $n = 2$ state de-excites, and the Lyman-α photon is detected in coincidence

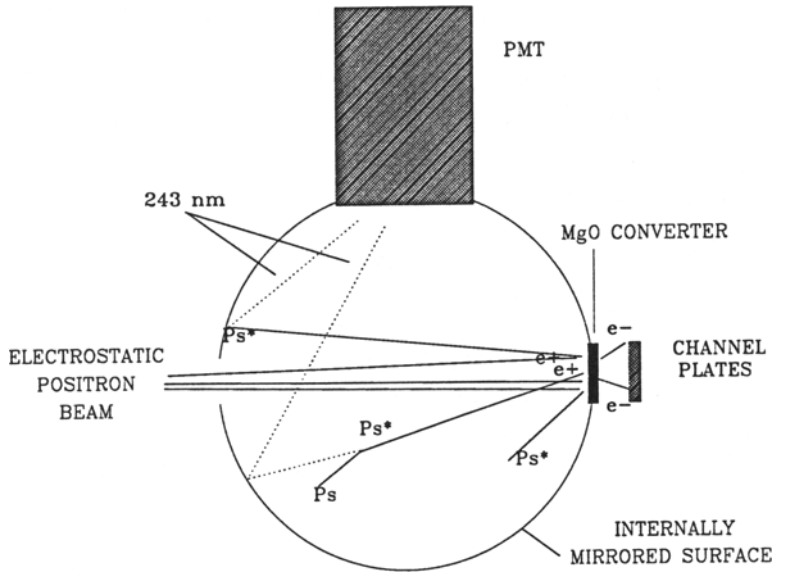

Fig. 1. The interaction region.

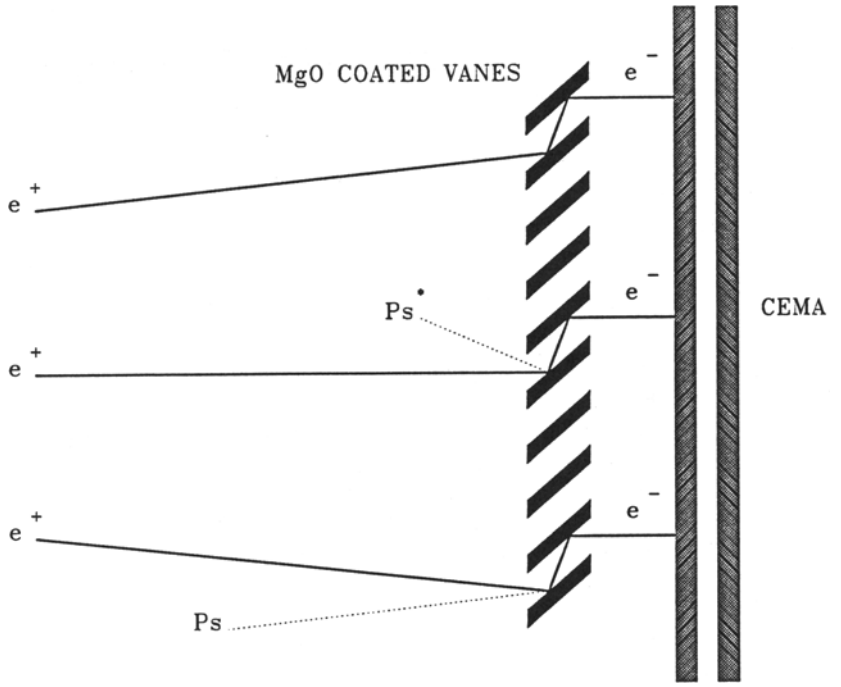

Fig. 2. The Ps converter.

with the positron arrival at the converter. A lifetime spectrum is thus produced, from which $\tau_{Ly\text{-}\alpha}$ may be determined.

With a lifetime against annihilation of approximately 1 nsec, the 2^1P component contribution to the Lyman-α signal is expected to be less than 10%.

4. Results and discussion

Spectra have been observed for several incident positron energies and all exhibit similar features. Here, the spectra for one beam energy, 120 eV, will be described.

To ensure that the spectra obtained were truly due to positronium events and not caused by excitation of any residual gas atoms by positron impact, the experiment was repeated using electrons for which the excitation cross sections are of similar magnitude. The resulting spectra were found to contain only random coincidences.

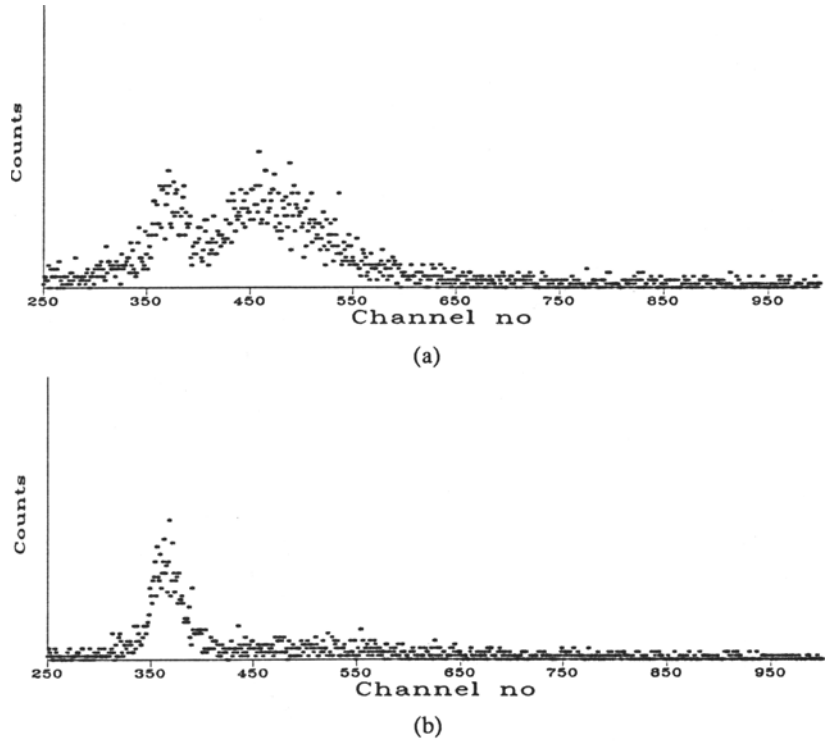

Fig. 3. (a) and (b).

The photomultiplier tube is sensitive over the 120–300 nm range, and for photons of 243 nm, has a quantum efficiency of 10%. Nevertheless, the detection

of some higher energy photons, such as γ-rays, would still be expected but with a very much reduced efficiency. The full lifetime spectrum (fig. 3(a)) therefore consists of a number of components. In the early time peak, prompt positron annihilation, para-positronium decays, and any Lyman-α events from the 2P state contribute. There is also an ortho-positronium, o-Ps, component, which gives a lifetime somewhat shorter than the accepted 142 nsec in vacuum, but which may be accounted for by the o-Ps that leaves the field of view and that which quenches at the walls. Superimposed on this o-Ps tail is another broad peak centred around the 13 nsec. That this peak is not due to γ-rays directly detected by the PMT is readily shown by the comparison of fig. 3(a) with spectra (fig. 3(b)), which was taken with a slide of glass, opaque to wave lengths below 300 nm, placed in front of the photocathode. If we assume that the appearance of this peak is in some way related to a collision of a Ps atom with the walls of the sphere, and that the average distance travelled by an atom is ~3 cm, then we arrive at an energy of 30 eV.

If this epithermal Ps were simply annihilating at the walls, then a peak at 13 nsec would also be expected in spectrum (b), and whilst there is a suggestion of a hump at later times, it does not appear to peak at the same point. At 13 nsec, most of the 2P Ps should have decayed; we therefore suggest that this delayed component could be due to the long-lived metastable 2S Ps, which undergoes de-excitation on collision with the walls. This requires that the probability of de-excitation is greater than that for break-up.

Although the 2S state composes only 4/16 of the $n = 2$Ps, it appears that the geometry of the present experiment may lead to a greater detection efficiency for the metastable 2^3S atoms. This is probably due to where the atoms de-excite. For all 2P Ps decays close to the converter, for which the reflectivity of the UV photons is lower, any geometrical dependence in photon detection could also strongly affect this signal. The metastable atoms, however, decay at all points on the sphere, even at the window of the PMT itself, and therefore may have a greater chance of being detected.

5. Conclusion

In principle, this experiment may be used to measure the 2P radiative lifetime: the method of Ps^* production and timing gives the efficiency and resolution close to those expected. However, it does seem that the present geometry introduces several problems. The detection probability for a given photon will depend on where the photon originates; also, the width of the delayed peak is not solely due to an energy distribution but is convoluted with distance travelled, which depends on the angle of emission and the size of the sphere.

We therefore intend to change the shape of the interaction region in an attempt to reduce any geometrical effects and to separate further the metastable component from the region in which we expect to find the 2P Ps.

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