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Magnetised Positronium

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Abstract. Magnetised positronium is formed by impacting low energy positrons onto a gas covered target immersed in a magnetic field (B $\geq$ 1T). The resulting weakly bound positronium atoms subsequently travel some distance in an arrangement of Penning-type traps whereupon they can be field ionised. The remnant positrons are accumulated and then detected by forced annihilation on the target. The production efficiency of the magnetised atoms has been measured for different species of gases, gas layer thickness and the strength of the magnetic field. The positronium loss as a function of the distance travelled has been measured and is shown to be caused by the magnetron drift of the positronium atom.

1. Introduction

Several years ago Estrada *et al*. [1] observed that, when bombarding a target consisting of a gas covered surface with low energy positrons in a 5.3 T magnetic field, a small fraction of the positrons formed magnetised positronium. The maximum yield per incoming positron was found to be 2×10^{-3}, as measured by field ionisation in a Penning trap located about 6 cm from the target. More recently, Jelenković *et al*. [2], who used a similar technique to load a trap to study sympathetic cooling of positrons using laser-cooled beryllium ions, found a maximum yield (6×10^{-7}) around three orders of magnitude lower than Estrada's results. Although not yet explained, this dramatic discrepancy could be caused by the different targets used in the two experiments. The target surface in Estrada's work consisted of a repeatedly annealed tungsten crystal held at cryogenic temperatures which was covered by a layer of gas resulting from direct condensation onto the surface of residual gas species from their vacuum chamber following their cryogenic cool down procedure. They showed that when the gas was removed the yield plummeted. On the other hand, Jelenković *et al*. used an annealed room temperature copper target in a baked UHV system.

Both experiments showed that magnetised, and therefore loosely bound, positronium can be transported over some distance. Thus, such positronium atoms could possibly be used to form antihydrogen by exploiting a charge exchange process with an antiproton [3, 4, 5, 6]. This, and the fact that the role of gas on the target is not yet properly understood, prompted the research reported here.

In this paper we present the results of magnetised positronium studies using a number of gases and target coverages as a function of the magnetic field, the maximum electric field used for ionisation and the distance travelled before ionisation.

2. Experimental Details

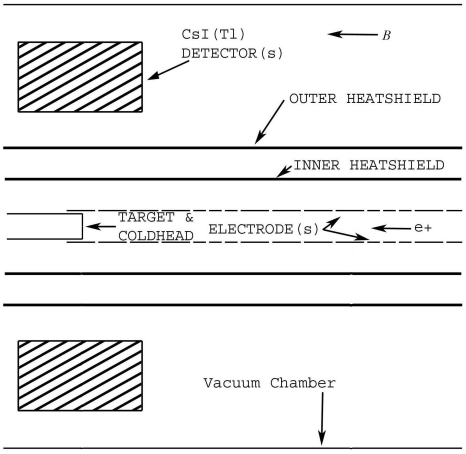

Figure 1. Schematic diagram of the target area.

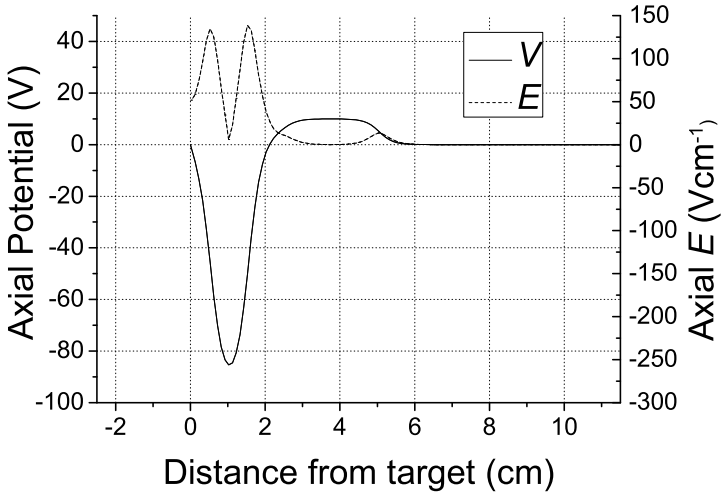

Figure 2. Typical electrical potential on axis (V) and the magnitude of the electric field E as calculated using Simion^{TM}.

Positrons originating from a 0.67 GBq ^{22}Na source were moderated using solid neon, resulting in a beam of $\sim 1 \times 10^6$ e^+s^{-1} [7]. These positrons were accelerated to an energy of about 100 eV, and were magnetically guided into an electrode array and implanted into a biased, gold plated, target (see figure 1). The target and electrodes were immersed in a high magnetic field (which could be varied in the range 1-5 T) and were able to reach cryogenic temperatures. To that effect the electrodes were in thermal contact with the inner heat shield (see figure 1) which was connected to, together with the electrically isolated (using sapphire) target, the second stage of a SHI-Cryogenics SRDK-408E cold head. The lowest temperatures reached were 6.7 K on top of the inner heatshield and 3.2 K on the second stage of the cold head as measured by calibrated CERNOX sensors.

Weakly bound positronium atoms, formed at the surface of the target, were ionised by an electric field similar to that shown in figure 2. The resultant free positron was then trapped in the potential well. After a certain "load time" the incoming beam was blocked and the positrons dumped back onto the target. The subsequent gamma rays were detected by the two in-situ CsI detectors shown in figure 1. Throughout this paper we will use the observable R, which is the ratio of the number of trapped positrons, obtained by field ionisation of the positronium atoms, per incoming positron per second.

3. Results and Discussion

Positronium can be said to be in a magnetised state by applying insights gained by Glinsky and O'Neil [8] (and used in our earlier work [9]) into the properties of the so-called guiding centre atoms. In that work a guiding centre atom is a weakly bound ion-electron pair immersed in a strong magnetic field. The pair exhibit three separate motions which can be described by three characteristic frequencies: the cyclotron motion with frequency $\omega_c = eB/m$, the axial motion, caused by the inter-particle potential, with a frequency $\omega_z = (e^2/(4\pi\epsilon_0 m r_{ee}^3))^{1/2}$ and the drift with a frequency $\omega_d = e/(8\pi\epsilon_0 B r_{ee}^3) = \omega_z^2/(2\omega_c)$. Here e and m are the electronic charge and electron/positron mass, respectively, r_{ee} is the distance between the positron and electron and B is the magnitude of the magnetic field. The pair is defined to be magnetised when

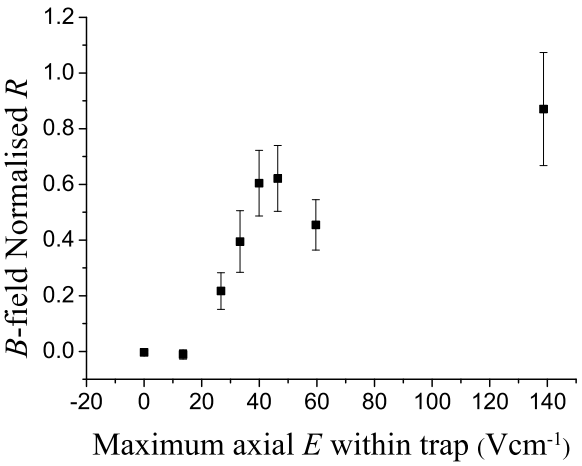

Figure 3. R as a function of the maximum ionisation field ("original measurements"). The ionisation well was 1 cm away from the target and the load time was 2000 s. The data are a weighted average for B = 1, 3 and 5 T, where the weighting was derived from figure 6.

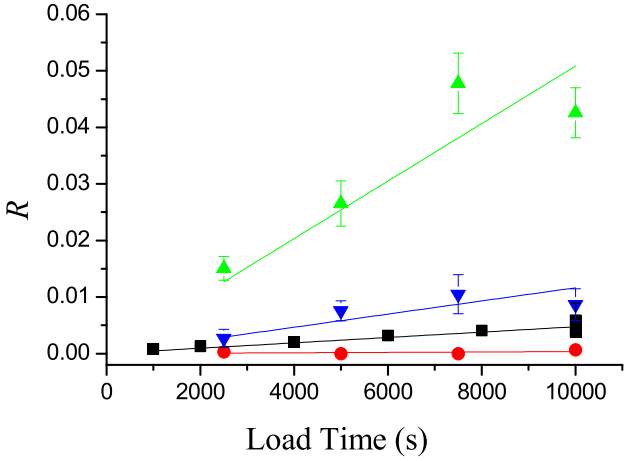

Figure 4. R as a function of the load time for ionisation wells at z = 1 cm (▲), 2 cm (▼), 3 cm (■), 8.5 cm (●). The data were taken under conditions in which the field used for ionisation was E = 139 V cm^{-1} and at B = 5 T. The lines represent linear fits to the data points.

$\omega_c >> \omega_z >> \omega_d$ which can be translated to the condition $\omega_c >> \omega_z/2$. Reworking leads to a condition for the inter-particle distance as,

$$r_{ee} >> \left(\frac{m}{16\pi\epsilon_0 B^2}\right)^{1/3}. \quad (1)$$

For magnetic fields between 5 and 1 T the above condition becomes $r_{ee} >> 0.04 - 0.13$ μm.

An initial experiment, using a clean target surface (i.e. no gas deposited on it), established that the value of R was zero. Only after inserting nitrogen for extended periods via an upstream buffer gas accumulator device [7] whilst maintaining the target and electrodes at $\sim$ 6 K, was the Rydberg positronium signal observed. No optimisation of this process took place. In the discussion that follows results obtained in this manner are called "original". Subsequently, the experimental apparatus was altered in such a way that gas could be admitted into the chamber in a controlled manner. Typically, a certain gas pressure was maintained for a specific time while the system was cooled down from just above the atmospheric condensation temperature of the gas to about 4.5 K. By varying the pressure of a particular gas the target was exposed to a larger amount of gas and, therefore, likely a higher coverage on the target was formed. It has been assumed that this coverage is proportional to the product of the pressure and the exposure time. However, it is unlikely that the coverage of the various gas species is the same for a given pressure × exposure time.

Figure 3 shows the effect of the maximum axial ionisation field on R. This parameter is essentially zero until about 20 Vcm^{-1}, then rises up to about 40 Vcm^{-1}, after which it stays approximately constant. The magnitude of the self electric field at the positron or electron is given by $e/(4\pi\epsilon_0 r_{ee}^2)$. When equating this to the maximum ionisation field we derive values of r_{ee} between 0.5 – 0.8 μm, indicating that the positronium atoms were just in the magnetised regime.

Figure 4 shows that R increases linearly with time indicating that the lifetime of the positrons in the trap is much in excess of 10000 seconds which is our maximum load time. The fitted

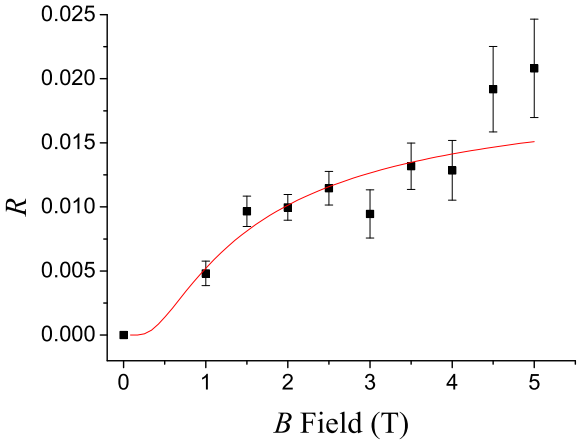

Figure 5. Gradient of the lines in figure 4 as a function of the distance from the target. The solid line is a fit of the functional form $R_t = Ae^{-z/z_c}$ (see text).

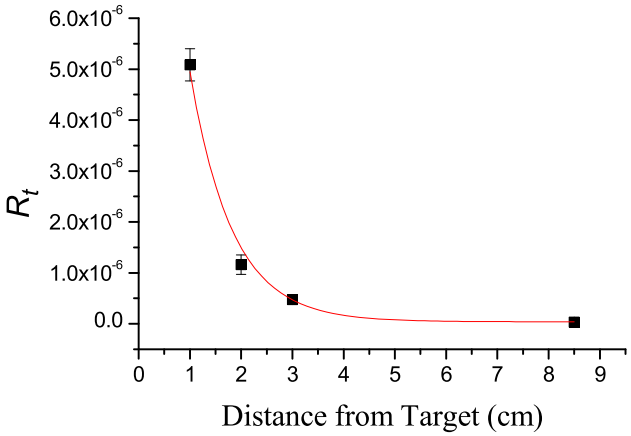

Figure 6. R as a function of B. The ionisation well is at $z = 1$ cm from the target and the maximum $E \sim 38$ Vcm^{-1}. The solid line is a fit of the form $R = Ae^{-D/B}$.

slopes in figure 4, which give the time normalised R, R_t, are plotted as a function of the distance travelled by the positronium from the target to its position of field ionisation (see figure 5). The solid line is a fit given by $R_t = Ae^{-z/z_c}$ with the amplitude, A, and the critical distance, z_c, being free parameters.

The exponential decrease of R_t can be explained by realising that magnetised positronium will have a transverse (magnetron) drift speed, v_d, brought about by the $\mathbf{E} \times \mathbf{B}$ drift, where the relevant electric field is that between the positron and the electron. A positronium atom at a position z will have travelled for a time $t = z/\langle v_{Ps} \rangle$, where $\langle v_{Ps} \rangle$ is the average axial positronium speed and will have moved a transverse distance $r = v_d t = v_d z/\langle v_{Ps} \rangle$. So, $z_c = r_c \langle v_{Ps} \rangle / v_d$, where r_c is the critical radius and is defined by the electrode geometry. This radius should be smaller than, or equal to, the inner trap electrode radius, $r_{el} = 5$mm. Using $v_d = \omega_d r_{ee}$ we derive that $z_c \lesssim \langle v_{Ps} \rangle r_{el} B r_{ee}^2/720$ m, where r_{ee} is given in μm. The fitted line in figure 5 gives a value for $z_c \approx 8$ mm. Therefore, $\langle v_{Ps} \rangle r_{ee}^2 \gtrsim 280$ ms$^{-1}(\mu$m$)^2$, which leads to a positronium temperature lower than the 3.2 K target temperature when assuming the values of r_{ee} derived above. The data points in figure 5 can also be fitted with the function Az^n, resulting in a value of $n = -2.0 \pm 0.3$ indicating isotropic emission of the positronium atoms. However, this is inconsistent with the conclusion derived above that the positronium is magnetised.

In figure 6 R is plotted as a function of the magnetic field for a well at 1 cm distance and a maximum ionisation field of about 38 V cm^{-1}. Combining the expression above for z_c and the function for R used in figure 5 we can show that $R = Ae^{-D/B}$, where A and D are constants. The fitted line in figure 6 together with the above mentioned value for r_{el} gives a value for $\langle v_{Ps} \rangle r_{ee}^2 \sim 1.3 \times 10^3$ ms$^{-1}(\mu$m$)^2$, which is not inconsistent with the conclusion derived from figure 5.

Using the data provided by the paper of Estrada *et al.*, where $r_{ee} \sim 2$ μm, $B = 5.3$ T and assuming a critical distance $z_c \sim 6$ mm (which is the distance between their target and ionisation well) and $r_{el} \sim 3.5$ mm a value for the mean positronium speed of about 600 ms^{-1} can be derived. This is comparable to the low positronium temperature found above with the caveat that the speed is dependent on the value of z_c, which was not explicitly given by Estrada *et al.*

Figure 7 shows the result of an investigation of the effect of target bias voltage on the value of R. Contrary to Estrada *et al.*, who obeserved a marked dependence of their Rydberg positronium yield on the applied voltage, our measured yield is essentially constant between -2 V and 1 V.

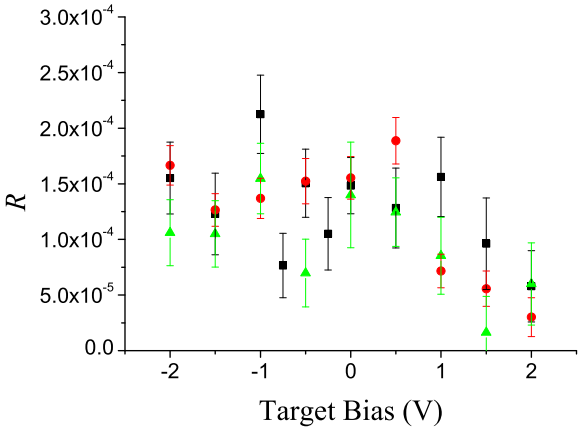

Figure 7. R as a function of the bias voltage on the target for O_2 (■), Ne (●), N_2 (▲). The ionisation well is at $z = 1$ cm.

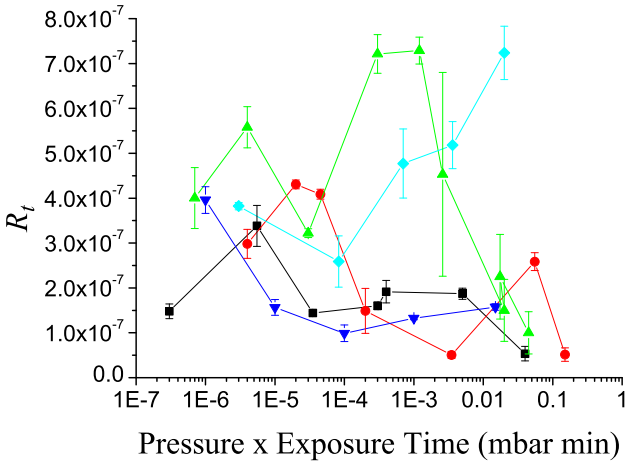

Figure 8. R_t as a function of the pressure times exposure time of the target for CO (■), N_2 (●), O_2 (▲), Ne (▼), dry air (◆). $|E| = 139$ V cm^{-1} and the ionisation well is at $z = 1$ cm.

It is also noticeable that, to within the uncertainties, the yield is species independent.

Figure 8 shows the effect on R as a function of the pressure × exposure time (see section 2) for a number of different gas species. It is clear that for each gas the yield depends on the amount of gas admitted. However, there are insufficient (properly calibrated) data to draw any firm conclusions.

4. Conclusions

Yields of R have been measured for a number of gas species as a function of B, distance from the target and the amount of admitted gas and have been found to be independent of gas species and much closer to the values found by Jelenković *et al*., rather then those of Estrada *et al*. The origin of these discrepancies probably lies in the differences in target surface properties. In order to resolve the large difference in yield more work with different types of target and gases is needed.

The behaviour of the yield versus distance from the target has been adequately explained by the $\mathbf{E} \times \mathbf{B}$ drift caused by the fact that the positronium is magnetised. The outcome of the analysis of this drift motion implies that the Rydberg positronium atoms are emitted from the target with relatively low axial speed.

There is an indication that the amount of gas deposited on the target influences the yield, but more work, with better characterised surface coverages, is needed.

5. Acknowledgements

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