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Weakly bound positron–electron pairs in a strong magnetic field

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Abstract
Weakly bound positron–electron pairs have been created in vacuum following low energy positron bombardment of a surface held at a temperature close to 4 K. The pairs, which behave as magnetized positronium atoms in the strong (>1 T) magnetic fields used in this experiment, were detected following their field ionization using an arrangement of Penning traps. Yields, which at highest are around 5×10^{-6} per incident positron, are presented and compared with previous work. Measurements of the behaviour of the yield as the distance from the production target to the ionization well was varied are presented and discussed, as are results taken for a fixed well at different magnetic fields. Both data sets were found to be consistent with a model in which the positronium moves across the magnetic field lines with a constant drift speed.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

It has been known for many years that bombarding a surface with low energy positrons can lead to the emission of positronium atoms into vacuum [1, 2]. It was in this manner that excited state positronium was unambiguously identified for the first time [3] and laser spectroscopic studies of positronium were achieved [4–6]. More recently, during experiments aimed at loading high magnetic field (typically 5–6 T) Penning traps with positrons, a new phenomenon was discovered [7, 8]. It was found that the main effect responsible for trapping was the ionization of weakly bound electron–positron pairs (which had been emitted from a surface following positron bombardment) using the electric fields inherent to the Penning traps. The magnitude of the stripping electric field (typically 10's of V cm^{-1}) provided an estimate of the separation, r_{ee}, of the pair, which could be compared to their Larmor radii, r_L, in the Penning trap magnetic field. It was found that $r_{ee} \gg r_L$ such that the pair could be construed as being bound as magnetized positronium atoms by the strong magnetic field.

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These observations have prompted the present study. Although it was unambiguous that field ionization of positronium was responsible for the trapping (Estrada *et al* [7] demonstrated this by showing that electrons could be trapped with equal efficiency to the positrons by reversing the electrical potentials on their trap electrodes), the mechanism by which the pair became bound sufficiently tightly along the axis of the magnetic field to prevent their separation was not clear. Furthermore, in [7], the ionization well was located around 6 cm from the target, suggesting that the atoms had been transported as a magnetized pair along the magnetic field, presumably with high efficiency. One could thus imagine transporting positronium along magnetic fields to facilitate its interaction with other species. Interactions of loosely bound (sometimes called Rydberg) states with charged particles usually proceed with large, typically geometric, cross sections. Thus, for instance, interactions of high-lying states of positronium atoms can be an efficient source of antihydrogen if the excited species interact with a source of antiprotons [9–11].

Although the two studies to date [7, 8] agree that correlated electron–positron pairs, or magnetized positronium, can be produced in vacuum, the yields from the two experiments differed by around three orders of magnitude.

Simplifying somewhat, Estrada *et al* [7] found that the efficiency of magnetized positronium production was around 10^{-6} in their system, assuming irradiation of the surface of their target with positrons direct from a ^{22}Na source. By contrast, Jelenković *et al* [8] found a result closer to 10^{-9}. The possible influence of differences in the two experimental arrangements was highlighted in [8], and will be discussed as appropriate below.

The two studies [7, 8] are also of interest in that they have provided an interesting new two-body system in a unique environment which might challenge theory. Indeed, the existence of long-lived states of positronium in crossed electric and magnetic fields of laboratory strength has been established from calculation [12, 13]. Furthermore, the similar two-body physics seems to be relevant in the formation of weakly bound antihydrogen atoms in Penning trap systems [14, 15]. Here, the recombining positrons and antiprotons are thought to form in magnetized states, sometimes referred to as guiding centre atoms [16–18]. These entities will be discussed where relevant to the present investigation in section 3.

In this report, we present studies of the ionization well yield (which is equivalent to the efficiency of production of magnetized positronium) by varying: (i) the strength of the axial magnetic field in the range 1–5 T; (ii) the strength of the stripping electric field and (iii) the distance of the ionization well trap from the positronium production target. We discuss these, together with a number of other observations concerning the behaviour of the well yield, in the context of the previous work [7, 8] in section 3. The following section describes our experimental set-up and procedures.

2. Experimental details

The positron beamline used for the present investigation is, in essential detail, identical to that described previously elsewhere [19]. A (∼18 mCi; 0.67 GBq) ^{22}Na source and a solid neon moderator (e.g. [20]) provide a quasi-mono-energetic positron beam of $\sim 1 \times 10^6\,e^+s^{-1}$ at a kinetic energy of ∼100 eV. This beam is radially confined by magnetic fields of up to 500 G and transported ∼5.2 m through a two-stage buffer gas accumulator (which is not in operation for the studies reported here) to the cryogenic, high magnetic field region ($|\mathbf{B}| \leqslant 5T$). This region is partially illustrated schematically in figure 1(a) and contains four main pieces of apparatus; an electrode array, a target, two CsI(Tl) detectors and a SHI-Cryogenics SRDK-408E 3.2 K closed cycle helium cold head. The electrode array is a flexible Penning trap system comprising 35 electrodes of 1 cm inner diameter that can be biased individually to facilitate a variety of experimental configurations. Of present interest is the ability to establish harmonic wells at various distances, z (1 cm $\leqslant z <$ 31 cm) from the target by appropriately biasing three or more consecutive electrodes as required. Four sector segmented electrodes of 0.5 cm length are situated 4 cm and 9.5 cm from the target, each flanked by additional 0.5 cm electrodes, compared to the 1 cm length of the remaining 29 electrodes. In the present studies the sectors were held at the same fixed potential, as appropriate for a given well.

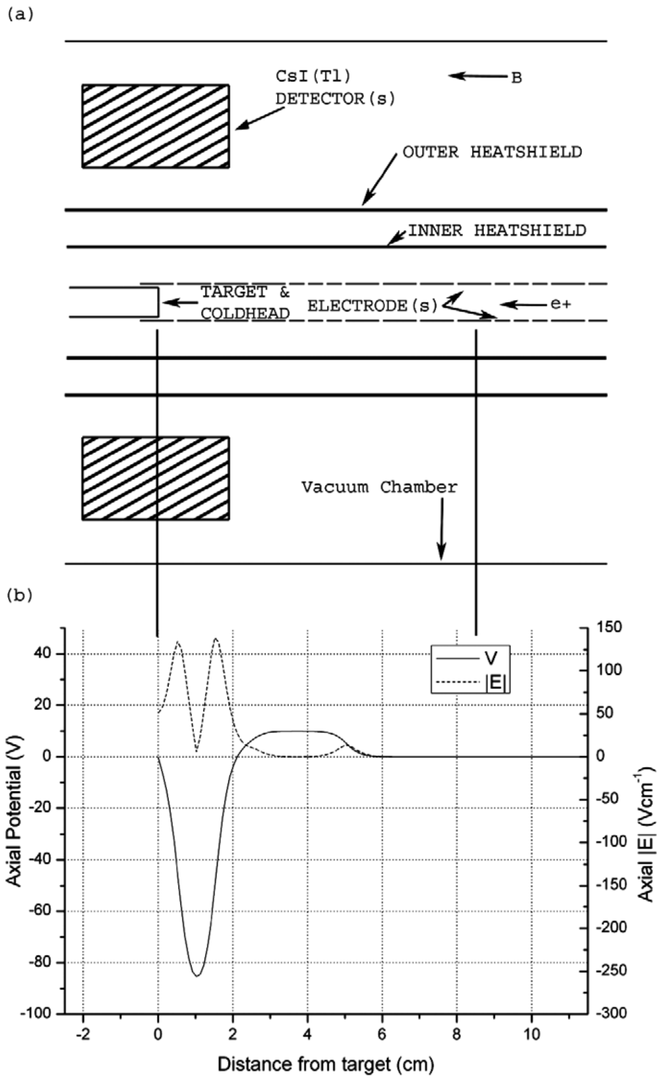

Figure 1. (a) Schematic illustration of the target area of the apparatus. (b) The on-axis electric potential (V) and electric field magnitude ($|\mathbf{E}|$) for the 1 cm well. These were derived using the SIMION™ programme. The other well positions used in the investigations have a similar profile for V and $|\mathbf{E}|$.

The target was an electrically isolated, gold-plated copper cylinder (whose planar face was used as the target) which, along with the electrode array (via the inner heatshield), was in thermal contact with the cold head. The temperature of the apparatus was measured by CERNOX™ sensors and displayed on a Lakeshore 331 temperature controller. Typical temperatures recorded by the sensors were 3.2 K (on the second stage of the cold head) and 6.7 K (on the external surface of the inner heatshield at $z \approx 35$ cm).

The CsI(Tl) detectors were positioned close to the inner wall of the vacuum chamber, approximately 4.85 cm off axis on either side of, and adjacent to, the target as shown in figure 1(a). They consisted of a 2.0 cm diameter, 2.5 cm long CsI(Tl) scintillator, a Si PIN 1.0 cm × 1.0 cm photodiode and a vacuum-compatible charge-sensitive preamplifier. The fraction of the total solid angle covered by the detectors for gamma rays emitted following positron annihilation at the target was $\epsilon_\Omega \sim 3.4\%$.

A typical experiment began with the establishment of a static ionization well (figure 1(b)) with the slow positron beam initially prevented from reaching the target by applying a retarding potential near the electrode array entrance for a few seconds (so that initial experimental conditions were quiescent). The retarding potential was then removed and with the positron beam incident upon the target the 'load time' was initiated and continued for a variable period ($\leqslant$ 10 000 s). A short ($\leqslant$ 10 s) 'hold time' followed where the incident positrons were once again prevented from reaching the target (as detailed above) before the well was emptied such that trapped positrons were ejected (or 'dumped') by raising the applied potential of the well base and the three outermost adjacent electrodes to a few volts with respect to the target. This results in the trapped positrons being directed towards the target where annihilation occurs. We refer to this sequence as the trap 'Load, Hold and Dump' cycle. The details of the cycle varied according to the requirements of a particular investigation but all were driven by custom-written LabView™ code which set the voltage and timing sequences of output hardware.

The rise time of the CsI(Tl) detector is slow compared to the arrival and resulting detection of the annihilation photons such that the recorded signal of the CsI(Tl) output is directly proportional to the number of ejected positrons from the trap. Thus, the number of trapped positrons N_{e^+} can be inferred from the height, P_T, of the stored oscilloscope traces as

$$N_{e^+} = \frac{P_T}{G\varepsilon_T S_{e^+}}, \quad (1)$$

where G is the gain of the amplifiers used to process the CsI(Tl) signals, ε_T is the total detection efficiency and S_{e^+} is the average CsI(Tl) signal associated with a single positron–electron annihilation event.

In order to obtain S_{e^+}, a succession of annihilation events was recorded with a calibrated multi-channel analyser. The mean output voltage of the CsI(Tl) detectors corresponding to the 511 keV positron–electron annihilation peak was used as S_{e^+}. ε_T is the product of ε_Ω, ε_A (experimentally determined 511 keV γ-ray attenuation factor of the electrodes and heatshields) and ε_I (supplied intrinsic scintillator efficiency) which gives $\varepsilon_T \approx 0.17\%$.

Throughout the 'Load, Hold and Dump' cycle the incident positron intensity, I_{e^+}, was monitored, which enabled the normalized ratio, R, of N_{e^+} per incident slow positron per second to be calculated as

$$R = \frac{N_{e^+}}{I_{e^+}}. \quad (2)$$

3. Results and Discussion

In this section absolute yields of trapped positrons, R, are presented, following the method described in section 2. First, we make the general comment that, following the initial preparation, pump down and cooling of the electrode and target system shown in figure 1, no trapped positrons could be registered above detector noise. The signal was finally detected following admission of nitrogen gas for prolonged periods into our upstream two-stage buffer gas accumulator. No optimization of this procedure took place, which occurred over a ~3 day period where the pressure was raised to $\sim 10^{-9}$ mbar in the experimental region for $\lesssim 40\%$ of the time whilst the beamline was used for other experiments.

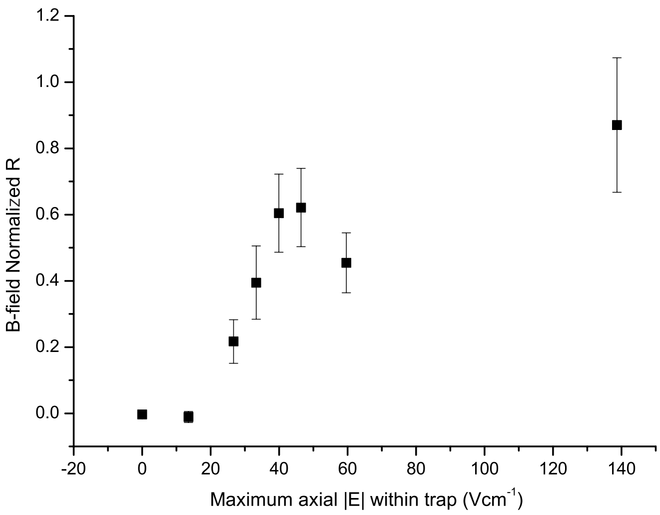

Figure 2. Normalized ionization well yield at various maximum electric fields. The data correspond to averaged data at $|\mathbf{B}| = 1, 3$ and 5 T and were taken for the well at $z = 1$ cm and for a load time of 2000 s. Note that a correction was applied to the measured R to allow for the observed variation of the yield with $|\mathbf{B}|$ (see figure 4 and accompanying discussion).

The effect of the gas is reminiscent of the observations of Estrada *et al* [7] who found that their trapped positron signal could essentially be eliminated when the adsorbates on their production target were removed using a pulsed laser. The adsorbates were naturally present as a result of the cooldown procedure in their fully cryogenic, closed system. Although their study, like this one, was not quantitative in terms of characterization, the role of what are presumably surface molecular impurities in forming the weakly bound positronium is confirmed here. One can speculate that the latter are formed within the molecular overlayer before liberation into vacuum. The existence of such states, which are analogous to Wannier excitons, has been postulated previously (see e.g. [21], where they were referred to as quasi-positronium) in the context of more conventional positron-condensed matter studies. The work of Jelenković *et al* [8] was carried out in a room temperature ultra-high vacuum system which had been baked as part of the preparation procedure. Thus, it was expected that the surface of the copper crystal which they used as a target was not significantly contaminated by the presence of adsorbed impurities. Indeed, the observed near three orders of magnitude difference between the trapped positron yields was attributed [8] to the presence, or lack, of surface adsorbates in the respective experiments.

Figure 2 shows our data for the ratio of the number of trapped positrons to the intensity of the incoming positron beam at various maximum electric fields. The latter quantity is the maximum axial field within a given trap configuration obtained by changing the voltage applied to the central electrode of a set of three used to establish the trap. It is

Table 1. Comparative summary of [7, 8] and the present work. The experimental parameters are the maximum axial |**E**|-field, maximum |**B**|-field, target temperature and distance of the ionization well from the target.

	Experimental parameters	Maximum yield per incident slow e^+	Inferred range of e^+–e^- separations (μm)
Estrada *et al* [7]	20 V cm^{-1}, 5.3 T, 4 K, 6 cm	2×10^{-3}	1–5
Jelenković *et al* [8]	30 V cm^{-1}, 6 T, 300 K, 1.5 cm	6×10^{-7}	1–5
Present work	140 V cm^{-1}, 5 T, 3.2 K, 1 cm	5×10^{-6}	0.5–0.8

notable (see figure 3) that the absolute positronium yields in the present experiment are of the order of 5×10^{-6} per incident 100 eV positron determined using the measured value of R and normalized for the load time.

We can compare our value for the absolute positronium yield to those derived from the work of Estrada *et al* [7] and Jelenković *et al* [8]. The former quote a similar yield to that found here, but for trapped positrons per incident high energy positron. As they point out, their value would convert to around 0.2% for the incidence of low energy positrons if a typical fast–slow conversion yield of 10^{-3} for metal moderators was assumed. As pointed out in section 1, Jelenković *et al* [8] find yields around three orders of magnitude lower, and much closer to the figure found here. Specifically, their maximum quoted yield was 32 trapped positrons per hour for an incident flux of about 1.4×10^7 high energy positrons per second [22], resulting in a yield per fast positron of just over 6×10^{-10}. Using the fast–slow positron conversion quoted above of 10^{-3} results in a projected yield of 6×10^{-7} per incident slow positron, which is close to our value. We note here that Jelenković *et al* [8] employed a typical maximum stripping electric field of about 30 V cm^{-1}, and their trapping well was located around 1.5 cm from their production target. For comparison, Estrada *et al* [7] used maximum fields of about 20 V cm^{-1} with a trap, as noted in section 1, around 6 cm from their target. Some of the parameters and results from the experiments by Estrada *et al* [7] and Jelenković *et al* [8] are compared to the present work in table 1.

It is evident that the yields of Estrada *et al* [7] are much higher than those of Jelenković *et al* [8] and the present work, despite attempts to coat our target with molecular impurities to mimic the system employed in [7]. Furthermore, our yield of positrons resulting from positronium stripped by fields below 20 V cm^{-1} is negligible, whereas Estrada *et al* [7] find that their yield has saturated by this field. Currently we have no explanation of these observations. We note that Estrada *et al* [7] account for their upper limit for the stripping field by postulating that, at higher fields, their very weakly bound systems are being ionized before they reach the region in which they can be stored. A similar explanation is not readily applicable to our work.

In order to proceed with the discussion of the present experiment it is necessary to establish whether our data are consistent with magnetisation of the positronium. We will, in a similar fashion to O'Neil and co-workers [16–18], base our analysis on the behaviour of charged particles in Penning traps. In ideal Penning traps it is well established (see, e.g., [23–25]) that particles (here positrons/electrons) execute three separate harmonic motions, namely the cyclotron, axial and magnetron motions with respective angular frequencies, $\omega_c = e|\mathbf{B}|/m$, $\omega_z = \left(eV_0/mr_0^2\right)^{1/2}$ and $\omega_m = V_0/\left(2|\mathbf{B}|r_0^2\right)$. Here the magnetic field $|\mathbf{B}|$ is assumed to be directed along the z-axis, e and m are the electronic charge and mass and V_0 and r_0 are trap parameters associated with the depth and geometry of the trapping electrostatic well. For electrons and positrons in high $|\mathbf{B}|$-field Penning traps with typical trapping wells, it is easy to show that there is a frequency hierarchy such that

$$\omega_c \gg \omega_z \gg \omega_m. \tag{3}$$

As argued by O'Neil and co-workers, this hierarchy should also apply to magnetized, or guiding centre, atoms. The latter term was coined by Glinsky and O'Neil [16] to describe weakly bound electron–ion pairs in a strong magnetic field where the rapid cyclotron motion can be averaged out and the motion of the pair described by guiding centre drift theory. Therefore, we can replace V_0 by the Coulomb potential between the electron–positron pair and r_0 by their separation, r_{ee}. Thus, we find (substituting ω_m by its counterpart ω_d, the so-called drift frequency), with ω_c unchanged, $\omega_z = \left(e^2/\left(4\pi\epsilon_0 m r_{ee}^3\right)\right)^{1/2}$ and $\omega_d = e/\left(8\pi\epsilon_0|\mathbf{B}|r_{ee}^3\right)$. Noting that the three frequencies are related by $\omega_d = \omega_z^2/(2\omega_c)$ it can be seen that condition (3) simplifies to $\omega_c \gg \omega_z/2$, or equivalently,

$$r_{ee} \gg (m/(16\pi\epsilon_0|\mathbf{B}|^2))^{1/3}. \tag{4}$$

Numerically this results in the requirement that $r_{ee} \gg 0.13/(|\mathbf{B}|^{2/3})$ μm. Thus, it is necessary to extract a value for r_{ee} from our data to compare with (4).

Returning to figure 2, the trapped positron yield is very small at fields below about 20 V cm^{-1} and rises thereafter to a plateau by about 50 V cm^{-1}. We can use these fields to estimate r_{ee}. Following [7] we can equate the magnitude of the externally applied electric field to the attractive Coulomb field of a pair of charges $|\mathbf{E}| = e/\left(4\pi\epsilon_0 r_{ee}^2\right) \sim 14\left(\mu\text{m}/r_{ee}^2\right)$ V cm^{-1} to obtain values of r_{ee} in the approximate range 0.5–0.8 μm. We note the electric field along the axis of the trap (i.e. parallel to **B**) is the only relevant electric field in this respect due to the strong radial confinement provided by the magnetic field. The data were taken at magnetic fields of 1, 3 and 5 T and, though the statistical fluctuations are large, there is no apparent difference in the trends of the ionized positron yield at each field. From (4) we require $r_{ee} \gg$ 0.04–0.13 μm, such that

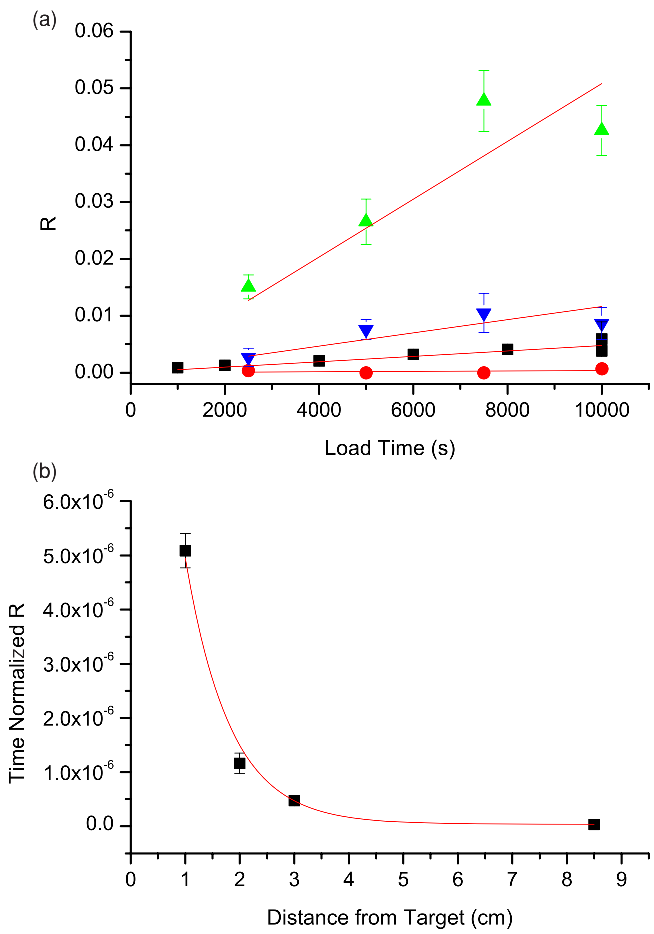

Figure 3. (a) Variation of R with trap load time for wells at $z =$ 1 cm (▲), 2 cm (▼), 3 cm (■) and 8.5 cm (●). The data were taken for a fixed maximum $|\mathbf{E}|$ of 139 V cm^{-1} and $|\mathbf{B}| = 5$ T. (b) Gradients of lines from (a) versus distance from the target. The fit is of the form $R = A\,\mathrm{e}^{-z/z_c}$; see text for details.

comparison with the extracted values of r_{ee} suggests that our low-field data are marginally in the magnetized regime. The data taken at 5 T fulfil the criterion for magnetized conditions. We also note here that values of r_{ee} one-half of those given above are found using the classical saddle point argument for the combined Coulomb–Stark potential normally applied to the non-magnetized case of Rydberg atoms; see e.g. [26].

Similarly, an estimate for the binding energies, E_b, of the positronium can be extracted as $E_b \sim 1.4/(\mu\mathrm{m}/r_{\mathrm{ee}})$ meV. This yields $E_b \sim 1.8$–2.8 meV, which is $\ll 6.8$ eV, the binding energy of ground-state positronium, such that a classical analysis of the kind presented here is justified.

Figure 3(a) shows the trapped positron yield at various load times in wells located at different distances from the target; notably $z = 1$, 2, 3 and 8.5 cm. Note that the data at each distance are, within the statistical accuracy, adequately described by a straight line indicating that the lifetimes of the stored particles against annihilation, or any other loss mechanism, are very much in excess of our maximum load time of 10 000 s. This is to be expected in a high-field, cylindrically symmetric and cryogenic system such as the one employed for the present work. It was also found with positron plasmas deployed in similar circumstances by the ATHENA antihydrogen collaboration [27]. The gradients of the load curves are plotted in figure 3(b) and reveal that the yields are a strong function of z. The data were fit with an exponential function of the form $A\,\mathrm{e}^{-z/z_c}$, where A and z_c are constants.

Here we analyse the data in terms of a simple model in an effort to offer an explanation for the observed trends. The parameter z_c is interpreted as a critical distance along the axis beyond which the positronium cannot be ionized with the positron captured into a well. This is caused by the transverse magnetron drift, with drift speed, v_d. We note that the effect of the magnetron drift of weakly bound positronium was also apparent in simulations of antihydrogen production from antiproton–positronium interactions [28]. For a positronium flight time, t, the transverse distance moved is $r = v_d t$, and since $t = z/\langle v_{Ps}\rangle$, with $\langle v_{Ps}\rangle$ the average positronium speed along the axis, a critical radius r_c will be reached at $z_c = r_c\langle v_{Ps}\rangle/v_d$. The radius r_c will be determined by the geometry of the trap and will be less than r_{el}, the 5 mm inner radius of the trap electrodes. Using the expression for the drift frequency, we can compute an estimate for the drift speed as $v_d = \omega_d r_{\mathrm{ee}} = e\big/\big(8\pi\epsilon_0|\mathbf{B}|r_{\mathrm{ee}}^2\big) \sim 720\big/\big(|\mathbf{B}|r_{\mathrm{ee}}^2\big)$ ms^{-1} for r_{ee} in μm. Thus, $z_c \lesssim \langle v_{Ps}\rangle r_{el}|\mathbf{B}|r_{\mathrm{ee}}^2/720$ m.

From figure 3(b) the fitted value of z_c is ≈ 8 mm which, with $r_{el} = 5$ mm, yields $\langle v_{Ps}\rangle r_{\mathrm{ee}}^2 \geqslant 280$ ms$^{-1}(\mu\mathrm{m})^2$. Using our values for r_{ee} from above produces values of $\langle v_{Ps}\rangle$ lower than that characteristic of the 3.2 K temperature of the cold head. To achieve the latter requires $r_{\mathrm{ee}} \sim 0.15$ μm which, given the assumptions in our analysis and the sparsity of the data, is in tolerable accord with the finding presented earlier in this section. In any case, our data point to low axial positronium speeds, which seems to imply a different formation mechanism for the magnetized pairs compared to those normally assumed for positronium at, or near, surfaces [2, 29]. However, more data are needed before this discussion can be usefully taken forward.

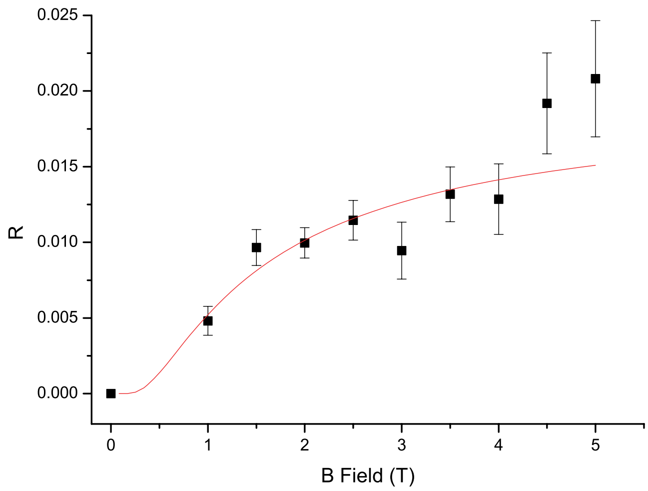

Figure 4. Variation of R with $|\mathbf{B}|$. These data were taken using the well at $z = 1$ cm and for a maximum electric field of 37.6 V cm^{-1}. The fit is of the form $R = A\,\mathrm{e}^{-D/|\mathbf{B}|}$; see text for details.

Figure 4 shows the trapped yield for the well at 1 cm, with a stripping field of around 38 V cm^{-1}, taken for various magnetic fields between 1 and 5 T. The fit is of the form $A\,\mathrm{e}^{-z/z_c}$, which, for a fixed z, but varying $|\mathbf{B}|$ gives $A\,\mathrm{e}^{-D/|\mathbf{B}|}$, with D a constant. The fit is shown in figure 4 and can be used to extract a value of $\langle v_{Ps}\rangle r_{\text{ee}}^2 \sim 1.3 \times 10^3$ ms$^{-1}(\mu\text{m})^2$ using the value for r_{el} given above. Again, the accord with other values extracted from this work is acceptable.

The analysis above can also be applied to the situation of Estrada *et al* [7]. Their typical r_{ee} is around 2 μm with $|\mathbf{B}| = 5.3$ T. Assuming that $z_c \sim 6 \times 10^{-2}$ m (the distance between their target and ionization well) and estimating their r_{el} to be 3.5 mm results in $\langle v_{Ps}\rangle \approx 600$ ms^{-1}. Although heavily reliant upon the value taken for z_c, which was not directly available from [7], this offers additional support for the low value of $\langle v_{Ps}\rangle$ extracted from our analysis.

Other functions can be found which provide consistent fits to the data shown in figure 3(b). For instance, the form Az^n, with A and n constants, yields $n = -(2.0 \pm 0.3)$ which suggests that the wells are populated according to simple solid angle considerations. However, this observation is inconsistent with the magnetization of the positronium, evidence of which was discussed above and which is also apparent from figure 4.

We have considered other mechanisms that might result in a decrease of trapped positrons with z. For the magnetized system there is no overlap between the electron and positron such that the self-annihilation rate is expected to be zero. Positrons would also be lost if the positronium atoms decayed to states that were non-magnetized and/or to states too deeply bound to be field ionized. Intuitively, we expect that radiative decay rates will be lower for the magnetized system than for the equivalent weakly bound Rydberg states. For positronium bound by ∼2–3 meV, radiative lifetimes will be in the ms regime, such that transitions are negligible for the projected flight times, which will be $< 10^{-4}$s to the ionization well most distant from the target. It is known from Rydberg atom physics that black-body radiation can also lead to transitions between levels [26]. The black-body energy density for the cryogenic temperatures of the trap is comprised of photons with frequencies overlapping both the energy splitting between levels equivalent to a principal quantum number of ∼50 and the quantum of energy in the cyclotron motion, $h\omega_c/2\pi$. However, given the low rates for black-body transitions [26], and that they mostly populate levels close to (above or below) the parent level, we can neglect their effect here.

4. Concluding remarks

Yields of magnetized positronium of around 5×10^{-6} per 100 eV positron incident upon a coated surface have been found. This yield is close to that of Jelenković and co-workers [8], but is around three orders of magnitude smaller than that found in similar conditions by Estrada *et al* [7]. Furthermore, binding energies of the positronium in the range 2–3 meV extracted from our field ionization data are about a factor of 2 larger than found elsewhere [7, 8]. Currently, we are unable to explain these differences. The behaviour of the yield versus distance from the production target and at various magnetic fields has been explained in terms of the magnetron drift of the electron–positron pair. We have found evidence that the magnetized pair have low (sub-thermal) axial speeds, though this conclusion must remain tentative. So far, we have been unable to shed further light on the detailed mechanism for the production of the magnetized atoms and further work is necessary in this respect.

Acknowledgments

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