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Measuring positron–atom binding energies through laser-assisted photorecombination

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Abstract. Described here is a proposed experiment to use laser-assisted photorecombination of positrons from a trap-based beam and metal atoms in the gas phase to measure positron–atom binding energies. Signal rates are estimated, based in part upon experience studying resonant annihilation spectra using a trap-based positron beam.

While positrons are important in many areas of science and technology including materials science, medicine and astrophysics, there are a number of open, fundamental questions regarding positron interactions with ordinary matter. One such topic is positron binding to atoms and molecules. There are accurate theoretical calculations of positron binding to atoms [1]. However, the predictions of these theories have not been tested experimentally due to the difficulty in forming positron–atom bound states in two-body collisions. In contrast, there have been extensive experimental studies of positron binding to molecules. Positron–molecule collisions can lead to positron capture in vibrational Feshbach resonances, and the signatures of these resonances in the annihilation spectra have been used to measure positron–molecule binding energies [2, 3]. By way of further contrast, calculations of such binding energies in the positron–molecule case have proven to be much more difficult than for atoms [4, 5].

The goal of this paper is the development of a method to study positron–atom bound states using laser-assisted photorecombination, which should lead to enhanced annihilation.

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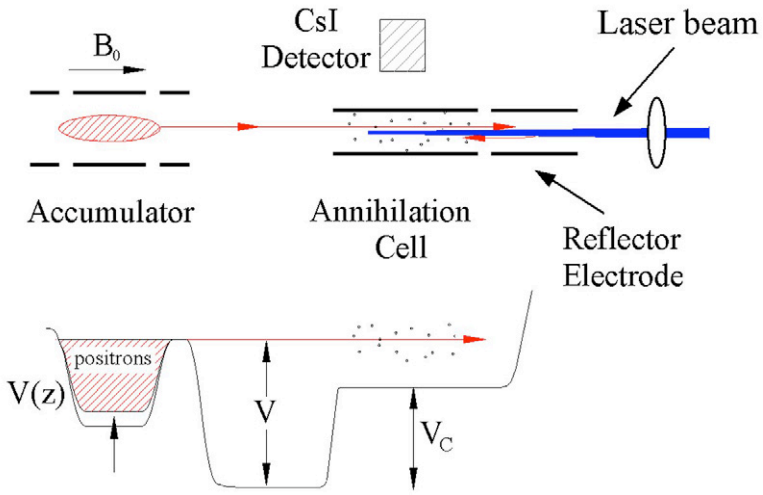

Figure 1. Schematic diagram of the experimental arrangement (top), and the corresponding electrical potential profile along the magnetic axis (bottom).

A process similar to this has been proposed to form antihydrogen atoms from positron and antiproton plasmas [6] and negative ions [7]. With regard to the present application, other possible experimental approaches to measuring positron–atom binding energies are discussed in [8–10].

The envisioned experimental arrangement is shown schematically in figure 1. Except for the inclusion of a laser beam, it is similar to that used previously to measure positron–molecule binding energies. Pulses of positrons with a small thermal energy spread $\Delta\varepsilon$ (e.g. $\sim$40 meV full-width at half-maximum (FWHM)) from a buffer-gas positron accumulator are passed through a cell containing the test gas, in this case a 'hot cell' at elevated temperature to provide sufficient atomic number density n_a. The variable electrical potential of the annihilation cell is used to set the positron energy. A pulsed laser beam with tunable photon energy $\hbar\omega$ is introduced collinearly with the positron beam. The laser and positron beams are arranged so as to have maximum overlap in the region of view of a CsI detector that is used to measure single 511 keV gamma rays from two-quantum positron–atom annihilation. The detector is gated to monitor annihilation events only when both the positron and laser pulses are present.

The condition for a photo-enhanced signal is

$$\hbar\omega = \varepsilon + \varepsilon_b, \tag{1}$$

where ε is the total kinetic energy of the positrons in the gas cell, and ε_b is the positron–atom binding energy. Knowing $\hbar\omega$ and tuning ε to this resonance condition thus provides a method for measuring ε_b.

Following an approach similar to that used to describe photodisintegration of the deuteron (i.e. assuming a zero-range-potential wave function of the positron–atom bound state and a plane-wave description of the incident positron) [11], the differential cross-section for positron–atom recombination accompanied by the spontaneous emission of a photon of a given polarization is

$$\frac{d\sigma_r}{d\Omega} = 2\alpha^3 a_0^2 \frac{\sqrt{\varepsilon_b \varepsilon}}{\varepsilon_b + \varepsilon} \cos^2\theta, \tag{2}$$

where $\alpha \approx 1/137$ is the fine-structure constant, a_0 is the Bohr radius, θ is the angle between the positron momentum and the photon polarization vector and $d\Omega$ is the element of the solid angle into which the photon is emitted. The presence of a quasi-monochromatic light field of intensity I will enhance the recombination cross-section $d\sigma_r/d\Omega$ in the solid angle $d\Omega$ in which photons are present. The enhanced, total *stimulated recombination* cross-section is

$$\sigma_{sr} = \left\langle \frac{d\sigma_r}{d\Omega} \right\rangle \xi, \tag{3}$$

where the cross-section of equation (2) has been averaged over θ (see below), and the dimensionless enhancement factor ξ is [7, 11]

$$\xi = \frac{8\pi^3 c^2 I}{\omega^3} f(\hbar\omega - \varepsilon_b), \tag{4}$$

with $f(\varepsilon)$ the positron energy distribution function normalized as $\int f(\varepsilon)\, d\varepsilon = 1$. Equation (4) assumes that the laser bandwidth is much smaller than the positron energy spread, which is characterized by $f(\varepsilon) \sim 1/\Delta\varepsilon$. Equations (2)–(4) agree to within a numerical factor with those developed in [7] where the theory was used to describe laser-stimulated photorecombination of electrons with molecules to produce dipole-bound anions.

In order to estimate the expected signal level, specification of further details of the experimental setup is required. We assume that the positron beam consists of pulses of duration τ_p, containing N_p positrons with velocity v, energy ε and total energy spread $\Delta\varepsilon$. They are magnetically guided through the cell at a frequency ν_p. A rotating electric field in the buffer-gas positron accumulator will be used to compress the positrons radially to a transverse radial extent r_p in the gas cell, which will be in a magnetic field of 0.08 T.

The gamma ray detector is assumed to monitor annihilation over a length L_D of the coincident laser and positron beams. The efficiency of the detector, including the collection solid angle, is η_D. The laser pulses with total energy E per pulse are assumed to have a time duration $\tau_l \ll \tau_p$.

The rate of photo-induced bound state formation per positron is

$$\Gamma = n_a \sigma_{sr} v, \tag{5}$$

where n_a is the atomic number density. If the positron pulses are long in spatial extent compared with L_D, i.e. $L_D \ll v\tau_p$, the number of positrons in view of the detector (and available for bound-state formation) will be $N_p L_D / v\tau_p$. It is assumed that all positrons in bound states annihilate in a time of a few nanoseconds in two gamma events and hence these gamma rays are available for detection. With these assumptions, the rate at which either of the two annihilation gamma rays will be detected when both the laser and positron beams are present is

$$\widetilde{S} = n_a \sigma_{sr} \left(2\eta_D N_p \frac{L_D}{\tau_p} \right). \tag{6}$$

This rate is maintained only during the time τ_l that the laser pulse is on; thus the average number of detected counts per single laser pulse will be $\bar{N}_c = \tilde{S}\tau_l$, which can be a fraction of a count per pulse. Taking into account the positron pulse rate ν_p, the overall expected signal rate will be

$$S = 2 n_a \sigma_{sr} \eta_D N_p L_D \nu_p \frac{\tau_l}{\tau_p}. \tag{7}$$

Due to the fact that $\sigma_{sr} \propto \xi$, and for laser pulses of fixed energy, $\xi \propto 1/\tau_l$; the signal rate S is independent of the laser pulse duration τ_l.

Table 1. Assumed parameters for measuring positron–atom binding energies by photorecombination and monitoring subsequent, prompt annihilation.

Positrons		
Pulse strength	N_p	1×10^5
Pulse rate	ν_p (Hz)	3
Pulse duration	τ_p (μs)	1.5
Beam radius	r_p(mm)	1.5
Total positron energy	ε (eV)	0.25
Perpendicular energy spread	kT (eV)	0.025
Total beam energy spread	$\Delta\varepsilon$ (eV)	0.040
Laser		
Photon energy	$\hbar\omega$ (eV)	0.35
Pulse energy	E (mJ)	10
Pulse duration	τ_l (ns)	3.0
Beam radius	r (mm)	1.5
Intensity	I (MW cm^{-2})	47
Detector		
Length of view	L_D (cm)	12
Detection efficiency	η_D	0.03
Atoms		
Pressure	P (μtorr)	35
Atomic density	n_a (cm^{-3})	7×10^{11}
Binding energy (Zn)	ε_b (eV)	0.1
Cross-sections (for Zn)		
Photorecombination	$\langle d\sigma_r/d\Omega\rangle$ (cm^{2}sr^{-1})	4.9×10^{-25}
Enhancement factor	ξ	1.1×10^7
Stimulated recombination	σ_{sr} (cm^2)	5.4×10^{-18}
Expected signal rate	S (s^{-1})	1.6×10^{-3}

Assumed values of the experimental parameters are given in table 1. Most parameters, except those of the laser, are similar to those used in positron–molecule resonant annihilation experiments [3]. To evaluate $\langle d\sigma_r/d\Omega\rangle$ in equation (3), the spread in positron energies perpendicular to the magnetic field is assumed to be a Maxwellian distribution with a temperature kT [3], resulting in $\langle d\sigma_r/d\Omega\rangle = (d\sigma_r/d\Omega)_{max}\, kT/2\varepsilon$ where $(d\sigma_r/d\Omega)_{max}$ is the maximum cross-section value from equation (2) (i.e. at $\cos\theta = 1$). One difference in the positron part of this experiment, as compared with the positron–molecule binding energy measurements, is that a rotating electric field will be used to compress the beam pulses radially by a factor of $\sim$2.5, from a radius of $\sim$7.5 to 3 mm. Based on the experience with buffer-gas traps and positron compression using rotating electric fields, the assumption of this degree of radial compression is probably conservative [12].

The assumed laser parameters are based on the specifications of a LaserVision optical parametric oscillator/optical parametric amplifier pumped by a Continuum Surelite EX Nd:YAG laser. It is capable of 12 mJ pulses at a 10 Hz rate for photon energies in the range

from 0.35 eV (used below) to 0.8 eV. The estimates made here include an additional assumed 20% power loss due to imperfect optical elements.

As an example of a specific experiment, we consider the signal expected for zinc (Zn) atoms with a predicted binding energy $\varepsilon_b = 0.10\,\text{eV}$ [1] and an estimated vapor pressure of $\sim 3.5 \times 10^{-5}$ torr at 235 °C [13]. In this case, the positron energy at resonance is expected to be $\varepsilon = 0.25\,\text{eV}$. Using the values in table 1, the expected signal rate is $S = 0.0016\,\text{s}^{-1}$. Thus, resolving the resonant enhancement with 10 points in energy at 50 counts per point at the peak, the expected time for a spectrum will be $\sim 3 \times 10^5$ s, or ~3.5 days. In the positron–molecule binding measurements, it has been possible to work with similar and even smaller signal rates.

There will be a non-resonant background signal due to the so-called direct annihilation [3] on the zinc atoms. Annihilation rates are typically expressed as a dimensionless parameter, Z_{eff}, which is the expected rate normalized by that expected for annihilation on a gas of free electrons with a density equal to that of the neutral atom density. For Zn with an expected binding energy of 0.1 eV and at an incident positron energy of 0.25 eV, $Z_{\text{eff}} \sim 60$ [14]. In contrast, the effective annihilation rate when the laser is on is $Z_{\text{eff}} \sim 2.2 \times 10^4$.

In the relevant case of spatially overlapping positron and light beams in the viewing length of the detector, the signal will be inversely proportional to their overlap cross-sectional area. If either beam diameter is decreased to be less than the other, the signal will remain constant relative to the conditions where they are equal. Since the light beam can be focused easily to spot sizes less than ~3 mm in diameter, the limiting condition will be the diameter of the positron beam. Given previous experience in compressing plasmas with rotating electric fields, there is probably room for improvement here, although care must be taken, even at the assumed beam radius $r_p = 1.5$ mm, to avoid heating the trapped positrons and hence increasing the beam energy spread $\Delta\varepsilon$.

With an assumed 0.35 eV photon energy, bound states in the range $0.05 < \varepsilon_b < 0.3\,\text{eV}$ can be studied, with the upper limit constrained by the magnitude of the photon energy. The study of larger binding energies will require larger photon energies. In this case, as per equations (2), (3) and (7), and the average $\langle \cos^2\theta \rangle = kT/2\varepsilon$, the expected signal rate depends on photon energy as

$$S \propto \varepsilon_b^{1/2} \frac{(\hbar\omega - \varepsilon_b)^{-1/2}}{(\hbar\omega)^4}. \tag{8}$$

Thus, a larger value of $\hbar\omega$ will result in additional degradation of the signal, and using smaller $\hbar\omega$ (if a suitable laser could be found) will result in an increased signal. The signal rate S could also be enhanced by increasing $\langle \cos^2\theta \rangle$. Operating the annihilation cell at a larger magnetic field than that of the positron accumulator will lead to an increase in the positron perpendicular energy and hence could increase $\langle \cos^2\theta \rangle$.

As a (nontrivial) experimental detail, some means must be employed to carefully align the laser and positron beams to be coincident in the viewing region of the detector. Care must also be taken to prevent metal deposition on the optical elements in the vacuum system in the line of sight of the hot cell (i.e. a window or mirror). This could be accomplished by heating them to temperatures comparable to that in the hot cell. Another potential problem is ensuring uniformity of the electrical potential of the gas cell in the presence of evaporated metal atoms. While this would appear not to be a problem, we are not aware of experience with metal atoms in a hot cell at the tens of millivolts level.

The technique described here might also be used to measure positron–molecule binding energies as a complement to the present procedure of enhanced annihilation from vibrational

Feshbach resonances [3]. For some molecules, especially polar species, the positron bound state is not spherically symmetric. As a result, the dependence on laser polarization differs from that in equation (2). In particular, the cross-section does not vanish when the photon polarization is perpendicular to the incident positron momentum. Hence, the cross-section will not be suppressed by the $kT/2\varepsilon$ as it is for atoms, and stronger signals can be expected. The cross-section will also be enhanced for atomic and molecular species with p-wave-type bound states. In this case, radiative capture of incident s-wave positrons is allowed, which changes the energy dependence of the cross-section in equation (2) from $\sim\sqrt{\varepsilon}$ to $\sim 1/\sqrt{\varepsilon}$ at low energies. Finally, for atoms such as Zn and Mg, the p-wave positron has a shape resonance at low energies [15]. If the laser energy is such that the stimulated photorecombination occurs when the positron energy is near this resonance, the corresponding cross-section may be enhanced above the value given in equation (2). The magnitude of this enhancement will be inversely proportional to the energy width of the resonance.

To summarize, an experimental scenario is proposed that is capable of enabling the first measurements of positron–atom binding energies. If successful, this and related experiments can be expected to shed new light on the interaction of low-energy positrons with atomic and molecular systems.

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