

Production of long-lived positronium states via laser excitation to 3^3P level

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Abstract. The 3^3P state of positronium is an intermediate level suitable for producing long-lived positronium states. On one hand, it can be used in a two-step laser excitation scheme from the ground state to Rydberg levels. On the other hand, excitation of positronium to 3^3P level is a simple pathway for producing metastable 2^3S positronium atoms by spontaneous radiative decay. In this work, experiments showing the production of such long-lived levels, using the 3^3P state as intermediate state, are presented. The characteristics of the two long-lived levels, in view of experiments of deflectometry/interferometry with positronium, are discussed.

INTRODUCTION

Positronium (Ps) is a leptonic system particularly interesting for tests of QED [1-3], experiments of Ps-Ps interaction [4-7], production of electron-positron (e^+) plasmas [8] and creation of Bose-Einstein condensed Ps [9]. All these experiments could take advantage from Ps excitation to long-lived states. Moreover, long-lived Ps has a central role in several proposed studies of matter-antimatter interactions. Indeed, Rydberg Ps has been identified as a promising intermediate system for production of antihydrogen to be used for experiments of gravitational acceleration [10, 11]. Alternatively, Ps, excited to long-lived states, has been proposed as candidate for direct measurements of free-fall in the gravitational field of the Earth [12, 13]. Rydberg Ps is usually produced via two-step laser excitation using 2^3P as intermediate level [14]. The 3^3P level constitutes an interesting alternative offering the possibility to reach, in an easy way, also the long-lived 2^3S level.

In the present work we describe experiments of long-lived Ps production involving laser excitation of a dense cloud of Ps to the 3^3P level. Ps laser excitation from the ground state to the Rydberg levels, via $n=3$, and production of Ps in the metastable level 2^3S via spontaneous decay from the 3^3P , previously populated, are presented. The characteristics of the two long-lived states are compared and their suitability for experiments of deflectometry/interferometry is discussed.

EXPERIMENTAL

The 3^3P energy level can be reached by Ps via single photon transition from the ground state 1^3S (see sketch in Fig.1). In the present experiments, an intense bunch of e^+ is prepared with the AEgIS positron system (see Ref.[15] for details) and implanted in a e^+ /Ps converter [16, 17]. A fraction of the formed Ps is emitted into the vacuum as a dense cloud of Ps in the 1^3S level.

The $1^3S \rightarrow 3^3P$ transition was obtained with an UV laser pulse set at the resonance wavelength $\lambda_{UV} = (205.045 \pm 0.005) \text{ nm}$ (energy $> 60 \text{ } \mu\text{J}$ and FWHM of its spot $\sim 3.0\text{-}3.5 \text{ mm}$). The laser setup is described in detail elsewhere [18]. Simultaneously with the UV pulse, the system allows to shoot an intense IR laser pulse at 1064 nm

able to selectively photoionize Ps in the 3^3P state (see Fig.1). In alternative, a second IR pulse with wavelengths in the range 1650-1720 nm suitable for exciting Ps Rydberg levels can replace the photoionization pulse [19].

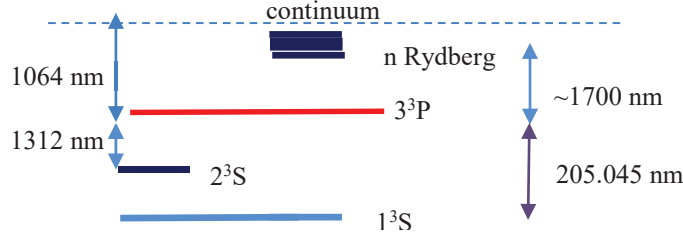


FIGURE 1. Sketch of the relevant energy levels of a Ps atom accessible after 3^3P excitation.

A 20x25x25-mm $PbWO_4$ scintillator, coupled to a Hamamatsu R11265-100 photomultiplier tube (PMT) and digitized by a HD4096 Teledyne LeCroy oscilloscope, was placed 40mm above the e^+ /Ps converter and used to record the time distribution of gamma rays emitted by e^+ and Ps annihilations (Single-Shot Positron Annihilation Lifetime Spectroscopy spectrum, SSPALS). SSPALS spectra were acquired and analyzed, with the procedure described in Ref. [19, 20], with the goal to study the changes in the Ps population induced by the interaction with lasers.

RESULTS AND DISCUSSION

$1^3S \rightarrow 3^3P$ excitation

In presence of Ps formation, SSPALS spectra present a prompt peak, given by the fast 2γ annihilations of e^+ implanted in the converter, and a tail that is dominated by the 3γ decay of 1^3S Ps emitted into vacuum (Fig. 2). When both UV and IR photoionization pulses are shot, a fraction of Ps is excited to 3^3P and immediately dissociated. The free e^+ are then quickly accelerated toward the last negative electrode of our setup where they annihilate [19]. This process decreases the Ps population decaying into 3γ . As photoionization has an efficiency close to 100% [19], the fraction of Ps excited to 3^3P can be directly evaluated by analyzing the relative reduction in the area below the SSPALS spectra when both lasers are shot with respect to the laser off measurement (Fig.2).

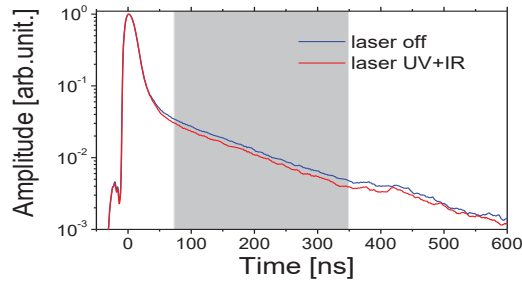


FIGURE 2. SSPALS spectra of Ps into vacuum with laser off (in blue) and UV+photoionization IR (in red) normalized to the prompt peak height. Each spectrum is the average of 700 single shots. The gray region indicates the window used for computing the S parameter (see text).

The fraction (S) of ionized Ps atoms was thus evaluated as $S = (f_{off} - f_{on}) / f_{on}$. Here f_{off} and f_{on} are the averages of the normalized areas f_{off-i} and f_{on-i} below the i -th SSPALS spectrum, calculated between 70 ns and 350 ns from the prompt peak, with both lasers off and on, respectively [19]. In the experimental condition of the measurements reported in Fig.2, an efficiency of 3^3P excitation $S = (13.8 \pm 0.4)\%$ was found, in agreement with the measurement of Ref.[19].

$3^3\text{P} \rightarrow \text{Rydberg}$ excitation

Excitation to Rydberg states was demonstrated by replacing the IR photoionization pulse with the second IR pulse with wavelength of ~ 1700 nm (Fig.1). Rydberg excitation increases the Ps lifetime (up to several μs) allowing a large number of atoms to reach the walls of the vacuum chamber. As a consequence, the SSPALS spectra show a decrease in the number of annihilations immediately after the laser shot and an increase at later times (Fig.3).

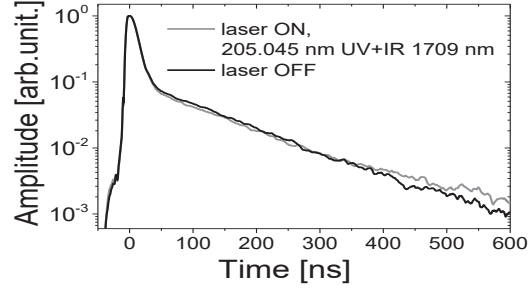


FIGURE 3. SSPALS spectra of Ps into vacuum with laser off (in black) and UV+ (1709 nm) IR (in gray) normalized to the prompt peak height. The 1709 nm wavelength corresponds to the excitation to $n=15$. Each spectrum is the average of 40 single shots.

The overall efficiency of the Rydberg excitation can be estimated by the relative reduction in the Ps signal in the same time window used for the photoionization experiment (see Fig.2). The $\sim 7.6\%$ found here, compared to the 13.8% overall photoionization efficiency, indicates that the $3^3\text{P} \rightarrow \text{Rydberg}$ excitation has an efficiency of the order of 50% [21].

$3^3\text{P} \rightarrow 2^3\text{S}$ transition

When only the UV pulse is shot, a fraction of Ps excited to 3^3P decays back to the 1^3S state while another fraction quenches to the rapidly annihilating 1^1S if a mixing magnetic field is present (25 mT in our e^+/Ps converter region [19]). A third fraction (around 10% of the 3^3P population [20]) decays radiatively to the metastable 2^3S level which has a lifetime of 1140 ns (in absence of electric fields). In presence of an electric field of few hundreds V/cm (like in our experimental chamber [19]), its lifetime is shortened to few hundreds of ns [20]. However, Ps atoms in this excited state constitute a longer-lived component that can be observed by means of SSPALS spectra. Fig.4 shows the amplitude distribution of the normalized areas $f_{\text{off-}i}$ and $f_{\text{on-}i}$ (UV off and on, respectively) between 70 and 350 ns (left panel) and in the range 350-500 ns (right panel). The figure reports the data of ~ 1800 shots with UV laser on and ~ 1800 with laser off. The data show a $(2.0 \pm 0.4)\%$ reduction of the annihilation rate in the *first region* (70-350 ns) which is ascribable to magnetic quenching. If this were the only phenomenon affecting the Ps lifetime, the same value of the S parameter would be observed also in the *second region* (350-500 ns), as quenching removes a fraction of the Ps immediately after the prompt peak but does not affect the lifetime of the remaining fraction. On the contrary, the experimental data show an S value of $(-0.9 \pm 0.7)\%$ in the *second region* which, subtracted to the S in the *first region*, gives an overall observed excess of $(2.9 \pm 0.8)\%$ consistent with the production of 2^3S Ps.

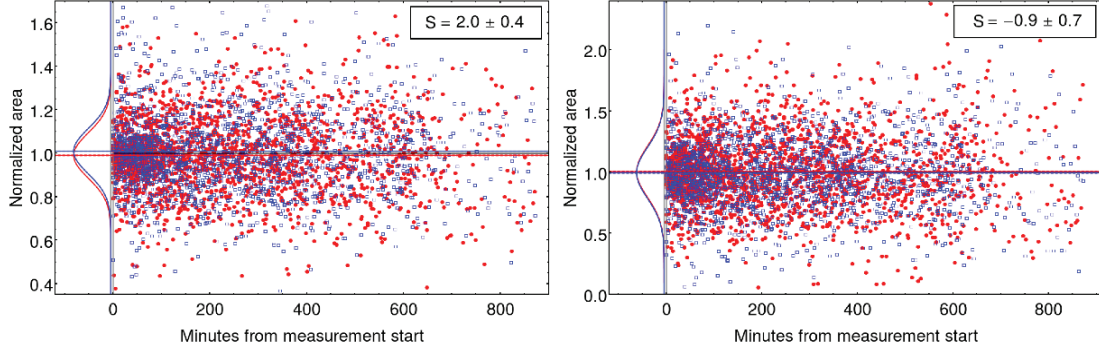


FIGURE 4. Amplitude distribution of the normalized areas f_{off-i} and f_{on-i} (UV off and on, respectively) in the *first region* (left panel) and in the *second region* (right panel). Full circles represent runs in which the UV laser has been shot, empty squares represent laser-off shots. The sideways Gaussian curves represent an estimate of the distribution of the f_{off-i} / f_{on-i} . In the inset the computed values of the S parameter are given (see text and Ref.[20] for details).

2³S vs. Rydberg for experiments of deflectometry/interferometry

With respect to the overall Ps emission, the present measurements suggest a production efficiency for Rydberg and 2³S production via 3³P level of ~7.6% and ~1.4% (13.8 % of n=3 excitation efficiency times ~10% of 3³P→2³S branching ratio), respectively. While 3³P→Rydberg excitation can be enhanced by a factor ~2 at most by an accurate optimization of the IR laser characteristics [14], 3³P→2³S transition efficiency could be significantly improved via stimulated emission. Preliminary calculations indicate the possibility to increase the efficiency of a factor ~4 following this path. However, in view of using long-lived Ps for experiments of deflectometry/interferometry, other parameters have to be taken into account. In particular, Rydberg levels have a much higher electrical polarizability ($6.67 \cdot 10^{-33} \text{ C m}^2 \text{ V}^{-1}$ for n = 15) with respect to 2³S ($3.82 \cdot 10^{-38} \text{ C m}^2 \text{ V}^{-1}$). On one hand, this high polarizability of Rydberg Ps allows to guide and focus it with electric field gradients [22] opening the path to the production of collimated beams. On the other hand, this high sensitivity of Rydberg Ps to external fields can make it unsuitable for interferometric measurements using matter gratings [23]. Moreover, the incoherent excitation process combined to spontaneous optical decay between high n-levels populates a large number of sublevels, making the control of the long-lived levels potentially more difficult.

CONCLUSIONS

The measurements reported in this work indicate the possibility to produce both Rydberg Ps and metastable 2³S Ps by using 3³P as intermediate level. While the Rydberg excitation efficiency following this scheme is at the moment ~5 times larger than 2³S production, the polarizability of 2³S is ~5 orders of magnitude lower than n=15. For measurements of interferometry, where long-lived states insensitive to electric field gradients are preferable, the low polarizability of 2³S level represents an unquestionable advantage with respect to Rydberg Ps. Further studies to make the 3³P→2³S production competitive with 3³P→Rydberg excitation also in term of efficiency are in progress.

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