Laser cooling system of ortho-positronium


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Abstract

We have studied laser cooling (Doppler cooling) of ortho-positronium to achieve Bose–Einstein condensation of positronium atoms. We have been developing a long-pulse laser with the wavelength of 243 nm, a bunched slow positron beam to realize the proposed experiment and a Monte Carlo simulation program for theoretical understanding. The Monte Carlo analysis clarified that we were able to obtain 7% of ortho-positronium atoms which were cooled down to 1 K and confined within a small volume without using a trap system. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

A positronium (Ps) atom is a bound state of an electron (e⁻) and a positron (e⁺), so that Ps is the lightest atom whose mass \( m = 1.02 \text{ MeV}/c^2 \). The Ps atoms have two spin states distinguished by their lifetimes: para-Ps (p-Ps), the spin singlet state, dominantly decays into two \( \gamma \)-rays with a lifetime of 0.125 ns, while ortho-Ps (o-Ps), the spin triplet state, dominantly decays into three \( \gamma \)-rays with a lifetime of 142 ns. The light mass and short lifetime cause the specific features of Ps Bose–Einstein Condensation (PsBEC) [1,2] and its cooling process.

As is well known, phase transition from the normal state to BEC one occurs for a high phase-space density \( \rho \geq 2.612 \). The quantity \( \rho \) is given to be

\[
\rho = n \lambda_D^3,
\]

where \( n \) is an atomic density and \( \lambda_D = h/\sqrt{2\pi mk_B T} \) is the de Broglie wavelength at a temperature \( T \). The de Broglie wavelength \( \lambda_D \) of Ps is much larger than that of normal atoms because of its small mass. Therefore, Ps-BEC occurs with much higher temperature compared with other atoms at the given atomic density. For example, the PsBEC can be achieved at \( T = 1 \) K for the atomic density of \( 1.8 \times 10^{16} \text{ cm}^{-3} \), while the BEC of hydrogen requires \( T = 1 \) mK at the same density [3]. Fig. 1 shows critical densities \( n_c = 2.612/\lambda_D^3 \) as a function of a temperature for Ps, H and Rb. However, the shorter lifetime of Ps requires the rapid cooling of...
the same order as the Ps lifetime. As a first step towards the goal of achieving the PsBEC, we have been planning a laser cooling of o-Ps and developing an experimental apparatus. Using a Monte Carlo simulation, we have been persisting to study realistic aspects of cooling process, in which we utilize an ultraviolet, long pulse, and wide linewidth laser to cool o-Ps to 1 K [4].

The laser cooling of o-Ps is theoretically predicted by utilizing the 1S–2P transition whose energy interval is 5.1 eV corresponding to the wavelength of 243 nm. As a lifetime of the spontaneous transition from the 2P to 1S is 3.2 ns, it is difficult to cool p-Ps by the Doppler cooling due to the extremely short lifetime (0.125 ns). As for o-Ps, half of o-Ps atoms occupies the 2P state if the intensity of the cooling laser is high enough. Thus, spontaneous emission occurs every 6.4 ns, which is two times longer than the lifetime of the spontaneous transition from the 2P state, and the o-Ps lifetime is doubled i.e. \( \tau_d = 284 \) ns, because the direct decay time (100 \( \mu \)s) from the 2P state is extremely longer than that from the 1S state. A characteristic feature of the laser cooling of o-Ps is that the recoil energy is large owing to the small Ps mass, and the one photon recoil limit (0.6 K) is higher than the Doppler limit of 7.5 mK. A cloud of Ps atoms produced at a room temperature, in which each atom typically has a thermal energy of 39 meV, is cooled down to the one photon recoil limit in 50 cycles of the 1S–2P stimulated absorption and the 2S–1P spontaneous emission. Therefore, the total cooling time is estimated to be \( 6.4 \times 50 \approx 3.3 \times 10^2 \) ns, which is comparable with the doubled lifetime of o-Ps, \( \tau_d = 284 \) ns in a sufficiently intense laser light.

2. Experimental apparatus

We have been developing an experimental apparatus of the laser cooling system which consists of an \( e^- \)-beam generator, a beam bunching system and an ultraviolet laser. The \( e^- \)-beam generator TOPPS (Tokyo metropolitan university Polarized Positron System) [5], illustrated in Fig. 2, consists of a 100 mCi \( ^{22} \)Na RI source, a transmission moderator (6 \( \mu \)m poly-crystal tungsten), and a magnetic beam transport system. The initial positrons produced from \( \beta^- \)-decays, which have a wide energy spread with the maximum energy of 546 keV, are injected on the moderator and extracted as a monochromatic beam with the intensity of about \( 10^5 \) s\(^{-1}\). The continuous beam is supplied to the beam bunching system in order to synchronize the timing of beam arrival with the laser pulse whose repetition rate is 25 Hz. A basic idea of the beam bunching system is shown in Fig. 3 [6]. The positrons are trapped in an electrostatic potential well and then extracted as a pulsed beam by opening the potential gate. The positrons are confined longitudinally by the electric potential and radially by the axial magnetic field. In order for the positrons to be trapped, they have to lose their kinetic energy in the potential well. A variety of energy-loss mechanisms, such as inelastic collisions with gas molecules, have been proposed and applied by other groups till now. Here, we use a new mechanism adopting a transverse magnetic field as shown in Fig. 3. This apparatus can be smaller in size and lower in cost compared with other systems because of its simple structure. A positron passing the transverse magnetic field \( B_T \) changes its momentum
direction and thus loses the longitudinal component of kinetic energy, so that it cannot pass the potential gate at the entrance again. A prototype of the beam bunching system has been tested using an electron beam with the energy of 200 eV. Here, the electric potential at the entrance (exit) gate is set to 198 V (202 V), the axial magnetic field $B_L$ is 80 G, and the transverse field $B_T$ is 5 G. The trapped positrons are extracted by lowering the exit gate potential down to 192 V for 100 ns. Fig. 4 shows that the number of electrons in the 100-ns pulse is enhanced while the trapping system is not working. It should be noted that the enhancement is not large enough because the exit potential gate is open by 8 V and only about 8% of the trapped electrons are expected to be extracted. A Monte Carlo simulation shows 90% of positrons can be trapped for 50 μs by optimizing the electric potential shape and thus the bunched beam of about 200 positrons per bunch with the time spread of 10 ns can be formed from the continuous beam of $10^5$ positrons/s.

The bunched beam thus produced is to be injected into a cooling chamber, which is under development, and strikes a metal target in it to generate Ps atoms. Most of Ps generated on the target have kinetic energy of a few eV corresponding to the Ps work function but a portion of Ps are expected to have the thermal energy ($\sim 39$ meV) [7], and can be effectively utilized for the laser cooling experiment.

The laser system for $o$-Ps cooling experiments, illustrated in Fig. 5, consists of a Cr:LiSAF ($Cr^{3+}$-doped LiSrAlF$_6$) laser to create a laser light with
Fig. 4. Number of electrons measured at the exit of the bunching system. The kinetic energy of electrons is 200 eV, the electric potential of the entrance (exit) gate is 198 eV (202 eV), and the axial and transverse magnetic fields are 80 and 5 G, respectively. Solid (dashed) line is in the case of the trap turned on (off). The exit potential is lowered down to 192 eV for 220 ns. About 8% of trapped electrons are extracted while the exit gate is open.

Fig. 5. Schematic view of the cooling laser system.

the wavelength of 972 nm, a second-harmonic generator (SHG) and a fourth-harmonic generator (FHG) that provides the required wavelength of 243 nm corresponding to the energy interval of the 1S–2P states. This system is specially designed to produce laser lights having a long pulse and wide linewidth; the former is required by the cooling time ( ~ 3.3 × 10^2 ns) and the latter by compensation of the Doppler shift due to thermal motion of Ps atoms at the room temperature. The Cr:LiSAF crystal was chosen because it has the long lifetime (67 µs) of the excited state. The pulse width and linewidth of the 972 nm light from the Cr:LiSAF have been measured to be 250 ns (FWHM) and 1.2 nm (FWHM), respectively, and the energy is 10 mJ/pulse with a repetition of 25 Hz. Consequently, the wavelength modulators, the SHG and the FHG consisting of six BBO (β-Ba borate) crystals can be aligned independently to adjust the intensity and linewidth of the laser light. This structure is to keep the wide linewidth of the laser light after conversion from 972 to 486 nm (243 nm) by the SHG (FHG). Thus, the modulation by the SHG changes the pulse width into 187 ns, the linewidth into 500 pm and the energy into 2.5 mJ/pulse. Finally, the FHG provides the 243 nm laser light with the pulse width of 160 ns, the linewidth of 140 pm and the energy of 60 µJ/pulse.

3. Monte Carlo simulation

To estimate properties relating to the cooling process, we have developed a Monte Carlo simulation, in which realistic experimental conditions, such as the o-Ps lifetime, o-Ps and laser photon distributions, detuning, etc. have been taken into account. The 1S–2P transition rate of Ps in a laser field is given as

\[ P = \int \frac{\Omega^2 \Gamma}{(\omega_0 - k \cdot v - \omega)^2 + \Gamma^2} d\omega, \]

where \( \omega_0 \) is the resonance of the 1S–2P, \( k \) the wave number vector, \( v \) the velocity vector of Ps, and \( \omega \) the laser frequency. The quantity \( \Omega \) is a Rabbi frequency defined as \( \Omega = \mu E / h \), where \( E \) is the laser field and \( \mu \) is a dipole moment of the 1S–2P transition whose magnitude is \( 1.263 \times 10^{-29} \) Cm. Generally, the quantity \( E \) is given as a function of the position \( x, y, z \), the time \( t \), and the frequency \( \omega \) in the laser light. The quantity \( \Gamma \) stands for...
a relaxation constant which is assumed to be important only for the spontaneous emission from the 2P state, i.e. $\Gamma = 2\pi/3.2 \times 10^{-9}$ s$^{-1}$. In the simulation, it is assumed that the cooling lasers irradiate onto the Ps cloud along $\pm x$, $\pm y$, $\pm z$ directions and the intensity of each laser light is 10 µJ, which is $\frac{1}{2}$ of our laser intensity. The spatial volume of the Ps cloud at time $t = 0$ is determined from reasonable assumptions of the radius (0.75 mm in 1σ) and the bunch length (2.5 ns in 1σ) of the $e^+$-beam at the target. The initial energies of each Ps are assumed to be the thermal energies with the Maxwell Boltzmann distribution at the room temperature (300 K). Then the velocity and energy state of each Ps are calculated using Eq. (2) for every 0.05 ns step.

A cooling effect is clearly demonstrated in Fig. 6, where the large enhancement emerges around the original production point of Ps when the laser is switched on (Fig. 6(a)) whereas only the broad distribution is seen when the laser is not applied (Fig. 6(b)). It should be noted that 44% of initial $\alpha$-Ps is contained in Fig. 6(a) whereas only 21% is available in Fig. 6(b). The Monte Carlo simulation has also shown that about 7% of $\alpha$-Ps atoms initially produced are cooled down to 1 K within 220 ns, that is consistent with the calculation given in Section 1.

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