Study of Ortho-Positronium Laser Cooling

K.Wada, T.Asonuma, T.Hirose, H.Iijima, M.Irako, K.Kadoya, T.Kumita, B.Matsumoto,
N.N.Mondal, H.Yabu
Department of Physics, Tokyo Metropolitan University,
1-1 Minami-Ohsawa, Hachioji, Tokyo 192-0397, Japan

K.Kobayashi
Sumitomo Heavy Industries USA Inc.,
666 Fifth Avenue, 10th floor New York, N.Y. 10103-1999, U.S.A.
c/o Aculight Corporation, 11805 North Creek Parkway South, Suite 113 Bothell, WA 98011, USA

M.Kajita
Communications Research Laboratory,
4-2-1 Nukui-Kitamachi, Koganei, Tokyo 184-8795, Japan

We have been investigating so far Bose-Einstein Condensation (BEC) of ortho-positronium (o-Ps) using an ultraviolet laser, by which 1s-2p transitions of o-Ps are induced. As the first step toward achievement of BEC, we have been studying laser cooling of o-Ps. As a result of a three-dimensional Monte Calro simulation, we clarify that o-Ps atoms with thermal energy (300 K) are cooled down to 1K using the laser with a wavelength of 243.02 nm corresponding to the energy interval of the 1s-2p states, i.e. 5.1 eV. In order to conduct proof-of-principle experiments, we have constructed a laser cooling facility which consists of a slow positron beam generator and a laser system with Cr:LiSAF (972 nm). The laser light of the 243 nm wavelength is obtained using the second and fourth harmonic generators. A bunched positron beam generated with a positron accumulator is injected on an Au target to produce thermal o-Ps with a thermal energy, which plays a significant role for BEC of o-Ps. We measured a production rate of thermal o-Ps as a function of the target temperature. We report the present status of laser cooling experiments as well as theoretical indications to the laser cooling clarified in the Monte Calro simulation.

PACS: 03.75.F; 32.80.P; 36.10.D; 52.55.L

Introduction

A posironium (Ps) atom is a bound state of an electron and positron, so that Ps is the lightest atom whose mass is 1/918 of a hydrogen atom. The Ps atoms have two spin state distinguished by their lifetimes: para-Ps, the spin singlet state, dominantly decays into two γ-rays with a lifetime of 0.125ns, while ortho-Ps, the spin triplet state, dominantly decays into three γ-ray s with a lifetime of 142ns.

The laser cooling of o-Ps is theoretically predicted by Liang *et al*. utilizing the 1S-2P transition whose energy interval is 5.1eV corresponding to the wave length of 243nm[1]. As a lifetime of the spontaneous transition from the 2P to 1S is 3.2nsec, it is difficult to cool p-Ps by the Doppler cooling due to its extremely short lifetime (0.125ns). As for o-Ps, spontaneous emission occurs every 6.4ns, which is two times longer than the lifetime of the spontaneous transition from the 2P state if intensity of the cooling laser is high enough, and the o-Ps lifetime is doubled i.e. τ_d=284ns, because the direct decay time (100μs) from the 2P state is extremely longer than that from the 1S state, and existence probability of o-Ps in each state is divided evenly between the 1S and the 2P state, i.e. 50%. A characteristic feature of the laser cooling of o-Ps is that the recoil energy is large owing to the small Ps mass, and photon recoil limit (0.6K) is higher than the Doppler limit of 7.5mK.

There are two kinds of production processes of the o-Ps on metal surface[2,3], namely thermal Ps and work function Ps. The thermal Ps energy obeys a Maxwell Boltzmann distribution, so that the typical energy is 39meV at the room temperature. On the other hand, the work function Ps has the energy about a few eV corresponding to the negative work function for metal. Thermal Ps atoms at the room temperature of 300K are cooled down to 1K in 32 cycles of the 1S-2P stimulated absorption and the 2S-1P spontaneous emission. The total cooling time is estimated to be 6.4×32~200ns, which is comparable with the

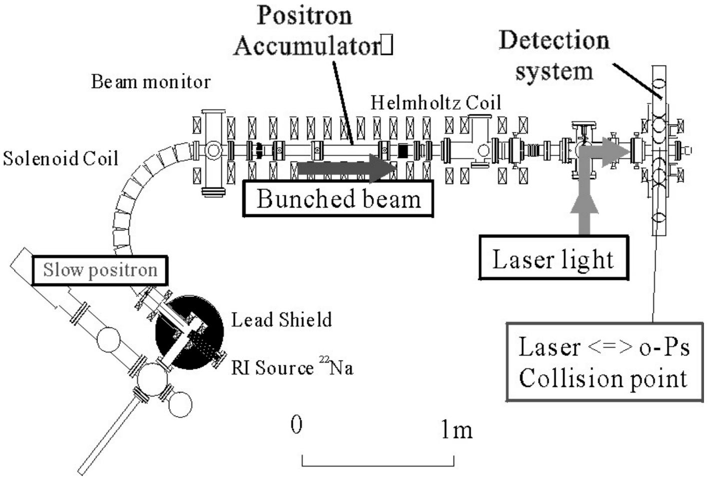

Fig.1 Schematic view of the e$^+$-beam line

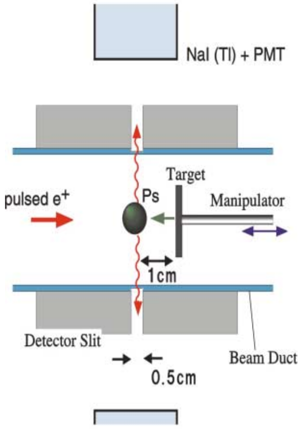

Fig.3 Schematic view of the TOF measurement system.

doubled lifetime of o-Ps, τ_d =284ns in a sufficiently intense laser light.

In order to construct a cooling apparatus, and study various properties of the cooling process, we developed a three-dimensional Monte Carlo simulation code[4]. The simulation which incorporated various parameters of laser beam and positronium distributions expected in the current cooling apparatus, revealed that about 7% of o-Ps initially produced are cooled down to 1K.

Experimental apparatus

We have developed an experimental apparatus of the laser cooling system, which consists of an e$^+$ beam generator and a laser facility[5]. The beam generator illustrated in Fig.1 consists of a RI source and a beam bunching system. Positrons emitted from the 100mCi ^{22}Na impinge on the mesh type W-moderator. The monoenergetic positron beam thus generated are guided into a positron accumulator through magnetic beam transport system. Then positron beam is bunched with the positron accumulator for the synchronization with a laser pulse, and injected on a target to produce the Ps atoms[6]. This pulsed beam has a pulse width of 24nsec with the intensity of 5.0×10^2 e$^+$/sec at 100kHz operation. The laser light is also irradiated to the target in a cooling chamber through a quartz window which seals the vacuum from air. The Laser system for o-Ps cooling experiments, illustrated in Fig.2, consists of a Cr:LiSAF laser system to create a laser light with the wavelength of 972nm, a second harmonic generator and a forth harmonic generator , which the harmonic provides the required wavelength of 243nm utilizing two BBO crystals in the each generator.

This laser pulse has a long time duration of 280nsec which is longer than o-Ps lifetime, and the energy of 40 J/pulse, and is produced with the repetition rate of 25Hz, and the linewidth of 40pm which is consistent with the required line width for the compensation of the initial Doppler broadening of o-Ps. To confirm the laser cooling process, we observes the o-Ps velocity. Using a time-of-flight method, the decay distance and the decay time of o-Ps are measured[7]. Fig.3 shows the TOF measurement system which consists of a cylindrical-shape lead collimator with a gap size of 5mm and the γ-ray detector. The typical distance from the target to the gap is *l* = 1cm. Decay γ-rays going through the gap are measured by 10 peaces of NaI scintillation counters. The target

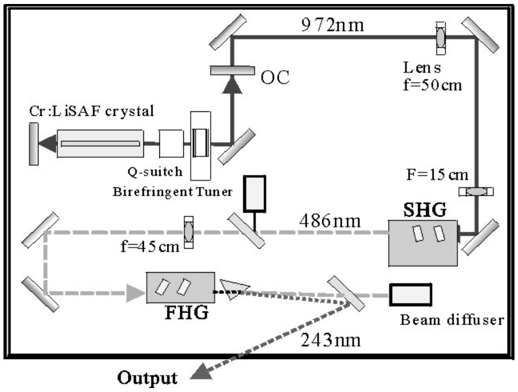

Fig.2 Schematic view of the cooling laser system

temperature can be controlled from 300K to 1000K, and its position is changed by a manipulator.

Results

By injecting bunched e^+ beams on a heated Au metallic target, we observed decay distributions of o-Ps for the target temperature of 300K, 600K and 1000K. As seen in fig.4, the o-Ps production rate becomes larger as the Au-target temperature increases. Assuming that the work function o-Ps is independent of temperature, we can extract the thermal o-Ps contribution by subtracting the decay curve at 300K from that of 600K or 1000K. The broad peak appearing around 300nsec is due to beam reflections at the exit of the accumulator.

Fig.5 shows the production rate of thermal o-Ps denoted as R. As any signal of the thermal o-Ps production is not observed in the TOF measurement, it is concluded that R is negligibly small at 300K. Thus, it is reasonable to consider that the excess of the signals at 600K and 1000K over that at 300K is dominantly caused by the production of the thermal o-Ps. The normalized production rate at 1000K is obtained as 50% being equivalent to numbers of thermal o-Ps of 250/sec. As seen in fig.5 high target temperature is advantageous for laser cooling experiment.

The TOF distribution with the distance between the target and the gap of 1cm is observed at 1000K as shown in Fig.6. Using the TOF spectrum, we attempted to determine the temperature of o-Ps itself. We assume the Maxwell-Boltzmann distribution for the produced o-Ps which decays in the gap area. It is also taken into account that numbers of decaying o-Ps in the gap area depends on the velocity of o-Ps. Consequently the TOF spectrum is observed as,

$$S = \frac{S_0}{t}\exp\{-(\frac{S_1^2}{t^2}+\frac{t}{\tau_{o-Ps}})\}, \qquad (1)$$

where τ_{o-Ps} is the lifetime of o-Ps, and S_0 and S_1 are the fitting parameters. The quantity S_1 is given as a function of T:

$$S_1 = ml^2/2\pi k_B T, \qquad (2)$$

where k_B is Boltzmann constant. The o-Ps temperature T is thus obtained as 962K±189K, which is consistent of the target temperature of 1000K .

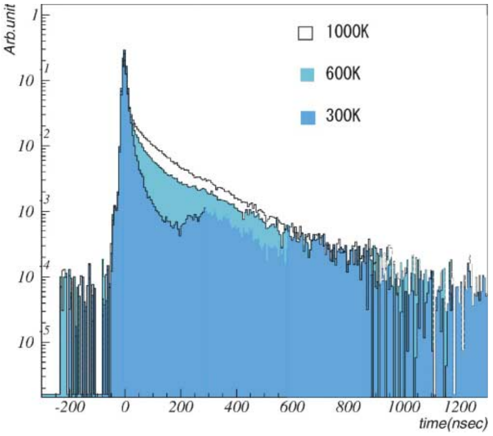

Fig.4 Decay curve of o-Ps produced on the Au target at the temperature of 300K, 600K and 1000K.

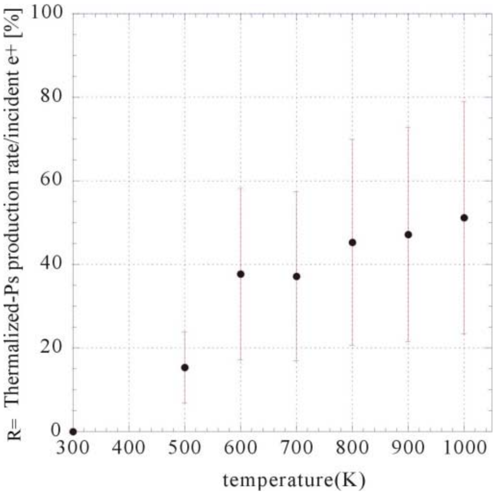

Fig.5 Production rate of thermal o-Ps

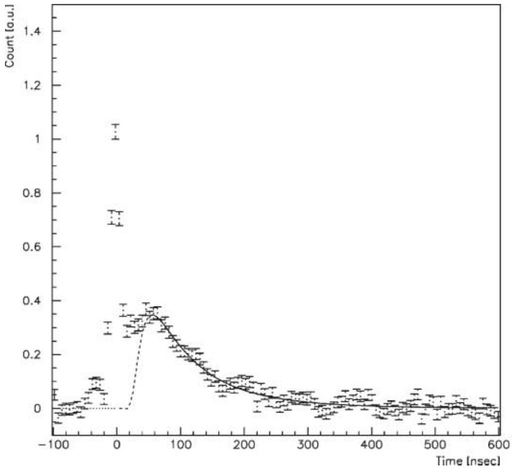

Fig.6 TOF spectrum at 1000K. A solid line shows a result of fitting of Eq.(1)

On the basis of the experimental results of thermal o-Ps measurement as well as the parameters of the laser system, a TOF spectrum expected in a future cooling experiment was studied using Monte Carlo simulation. Initial Ps atoms are assumed to have the thermal energy of 1000K. In addition, we adopt various parameters of the current laser system as the time duration of 160ns, the beam energy of 10 J, linewidth of 30pm and the beam radius of 5mm on the target. For compensation of the Doppler shift due to thermal motion of o-Ps, we optimized the detune of the peak wavelength to be 40pm.. Fig.7 shows that the tail of the TOF spectrum longer than ~200ns increases when the laser is turned on.

Conclusion

In summary, using the positron generator system we observed for the first time that the thermal o-Ps which is 50% of the initial positron was produced on the Au-target at 1000K. In addition, we measured the TOF and obtained the temperature of o-Ps of 962K±189K.

We are pursuing the improvement of the e+-beam intencity and the TOF resolution in order to reduce the time period of data taking. As for the laser system, final adjustment of the resonator is carried out to suppress a instability of the output wavelength. The laser cooling experiment will be executed in this autumn.

References

[1] E.P. Liang, C.D. Dermer, *Opt Common.* **65**, (1988) 419

[2] A.P. Mills, Jr., *Phys. Rev. Lett.* **41** (1978) 1828

[3] A.P. Mills Jr et al., *Phys. Rev. B* **44** (1991) 5791

[4] H.Iijima et al., *to be submitted to Jour. Jap. Phys. Soc.*

[5] H.Iijima et al., *Nucl. Inst. & Meth. Phys. Rep. A* **455** (2000) 104

[6] T.Kumita et al. *App. Surf. Sci*. **149** (1999) 16

[7] A.P. Mills Jr, Loren Pfeiffer, *Phys. Rev. B* **32** (1985) 53

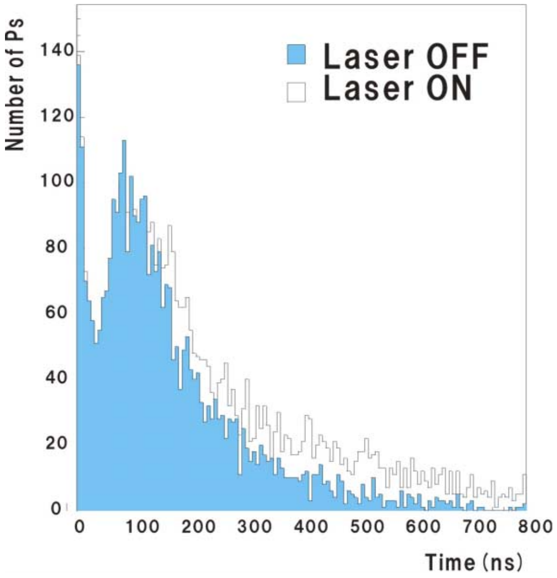

Fig.7 Result of the simulation for TOF measurement. Color part is when the laser is not applied, white part is when o-Ps is irradiated by laser light.