Realization of Laser Cooling of Positronium

Laser cooling of positronium in one dimension has been successfully demonstrated. A sequence of optical pulses at 243 nm, with rapidly varying central frequencies, was employed to achieve chirp cooling of positronium. A segment of the velocity distribution initially at 600 K was effectively cooled using a 100 ns-long pulse train, resulting in a narrowed Doppler distribution corresponding to an effective temperature of approximately 1 K. This demonstration represents a significant advancement toward precision spectroscopy of purely leptonic two-body atoms, enabling rigorous tests of quantum electrodynamics and paving the way for the realization of a quantum many-body system comprising antimatter.

Positronium (Ps) is a bound state of an electron and its antiparticle, the positron. Both the electron and the positron are elementary particles classified as leptons. In contrast, an ordinary atom consists of a nucleus made up of protons and neutrons, which are composite particles composed of quarks, with electrons bound to them. Therefore, positronium, being composed of only these two fundamental particles, represents the simplest atomic structure. By precisely measuring the energy states of Ps using laser technology and comparing the results with theoretical calculations based on quantum electrodynamics, it is anticipated that we can evaluate potential discrepancies in the standard model's description of electromagnetic interactions as well as test the fundamental symmetries between particles and antiparticles that underlie theoretical assumptions.

Experimental challenges arise because the motion of atoms can lead to decreased measurement precision and systematic shifts in observed values in laser spectroscopy. Therefore, it is essential to minimize the motion of positronium and maintain it as close to zero velocity as possible. However, due to the extremely lightweight nature of positronium, its translational motion can reach speeds of approximately 70 km/s at 300 K, highlighting the significance of effective deceleration and cooling techniques as critical issues in experimental research.

The laser beam consists of many photons that share identical properties, including frequency and propagation direction. When the frequency of light is brought close to the atomic transition frequency, atoms can absorb the photons from the laser. Photons possess a small amount of momentum. When an atom absorbs a photon, it experiences a recoil in the direction of the laser beam equal to the momentum of the photon. Consequently, if atoms absorb a laser light that opposes their motion, they will be slightly decelerated.

An atom that has absorbed a photon becomes excited and subsequently returns to its original state by emitting a photon (spontaneous emission process). During this emission, the atom experiences another recoil, but the direction of photon emission is random for each event. As a result, when the processes of laser beam absorption and spontaneous emission repeat, the recoil induced by the former accumulates, whereas the recoil from the latter averages out to zero. This leads to a net deceleration of the atoms. This principle underpins laser cooling, which has enabled the cooling of atoms from room temperature to near absolute zero on a millisecond timescale, thus creating a significant field of research on cold atoms and molecules.

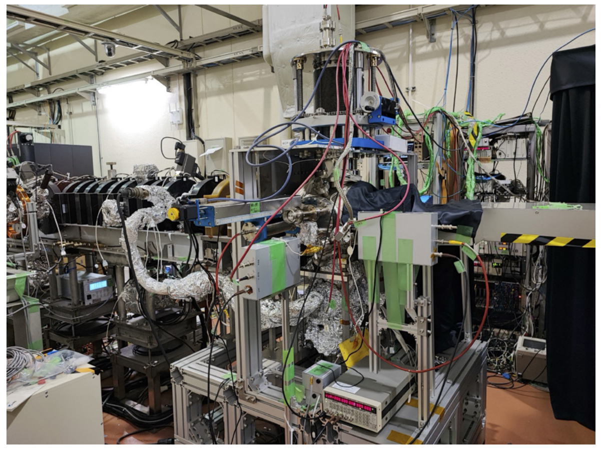

Figure 1: Experimental setup including the beamline and experimental station used in the study. The positron beam from the SPF-B1 beamline is transported and focused within the vacuum chamber, where it irradiates the materials for positronium generation. A laser booth is positioned on the right side of the image, allowing multiple laser beams to be introduced into the chamber.

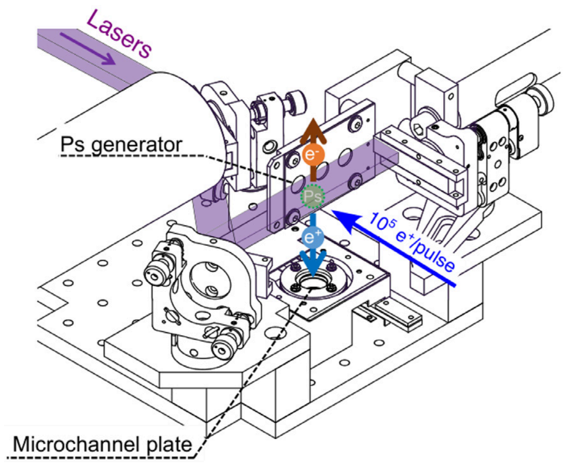

Figure 2: Configuration in the experimental station. A positron bunch is injected into silica aerogel, leading to the emission of positronium into the vacuum. A counter-propagating cooling laser beam is directed parallel to the surface of the aerogel for a duration of 100 ns. Finally, a probe laser pulse is irradiated to measure the velocity distribution, detecting positrons generated in a photoionization process as the excitation signal.

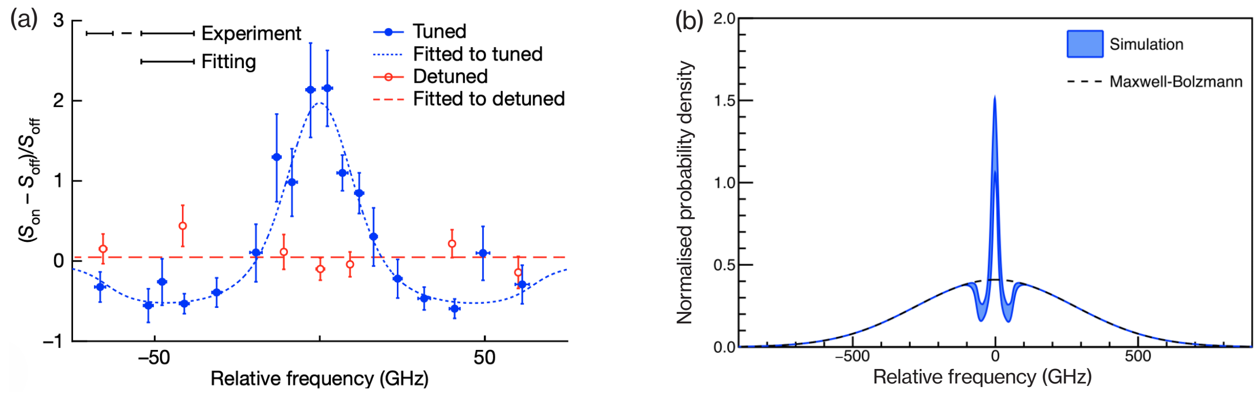

Figure 3: (a) Changes in the Doppler profile of ortho-Ps at 127 ns after generation, comparing the case with a cooling laser beam applied (S_{on}) for 100 ns and the case without it (S_{off}). (solid circles) The optical frequency of the cooling laser is tuned to enhance the zero-velocity component. The width of the peak corresponds to a temperature of approximately 1 K. (open circles) The optical frequency of the cooling laser is significantly detuned. (b) (solid line) Doppler profile obtained from first-principles simulations reproducing the experiment. The dashed line represents the theoretical Doppler profile at a temperature of 600 K without cooling. [3].

In principle, Ps should also be amenable to laser cooling; however, this has not been realized for many years. The processes of photon absorption and spontaneous emission must occur repeatedly within the limited ortho-Ps lifetime of 142 ns. Furthermore, due to the low mass of positronium, the recoil velocity from a single cooling cycle is substantial, reaching up to 1.5 km/s. When accounting for the Doppler effect, the laser frequency must change by roughly 6 GHz to enable further photon absorption after each cooling cycle. However, there has been no control method capable of changing the light frequency so significantly in such a brief period, making it challenging to maintain the cooling cycle. In this study, a cooling method based on the sequential illumination of light pulses was proposed, in contrast to the traditionally used laser light for laser cooling. A chirped light pulse train with a wavelength of 243 nm was prepared [1, 2], enabling very fast chirp cooling of Ps via the 1S-2P transition.

In the Slow Positron Facility (SPF) at the Institute of Materials Structure Science, experiments have been conducted three times a year (Fig. 1). A laser developed at the University of Tokyo for cooling purposes was transported to the facility to facilitate concentrated preparations and data acquisition during the experimental periods. Following the injection of the positron bunch into the Ps generation material (silica aerogel), a cooling pulse sequence was synchronized with the release of Ps into a vacuum, targeting Ps at approximately 600 K. By reflecting the laser beam coaxially, one-dimensional cooling was induced over a duration of 100 nanoseconds. Subsequently, another pulsed laser was employed to assess the velocity distribution of the cooled Ps using a method known as Doppler spectroscopy (Fig. 2). Figure 3 presents the measured change in the distribution near zero velocity within the velocity distribution at 600 K. The decrease in the values on the vertical axis indicates that as the optical frequency was swept, the Ps was sequentially decelerated from high speeds to low speeds, resulting in a reduction in the number of Ps within that velocity range. Conversely, the increase in values near the center indicates a concentration of Ps affected by the cooling effect around zero velocity. The result marks for the first time that Ps can be effectively cooled by laser light to approximately 1 K [3].

REFERENCES

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BEAMLINE

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