Positronium surface-scanning microscopy (O-possum II)

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ABSTRACT

We report on progress made towards the development of the first anti-atom beam optics with a source of positronium atoms shaped through interaction with a laser. Ultraviolet laser pulses with 24 ns duration were used to repeatedly address positronium atoms on the 1S→2P transition, with the goal of demonstrating antimatter laser pushing. The process was studied experimentally and numerically as a function of the detuning from resonance. Laser developments towards significantly longer pulses with larger spectral bandwidth needed for laser cooling of positronium atoms were pursued in parallel.

Keywords: positronium; laser; ultraviolet; cooling.

1. INTRODUCTION

Atomic microscopy requires the ability to produce and manipulate a low-divergence beam of atoms and to focus it on the surface to be scanned. One way to create optical elements for an atomic microscope is to use laser pulses to push the atoms by acting on their internal states. To date, the neutral beams that have been used to carry out microscopy have relied on massive atomic systems, whose interaction with the surface to be scanned cannot be neglected; electron microscopy on the other hand has the drawback of the sensitivity of the probe to external electric and magnetic fields.

- Positronium (o-Ps), the bound state of a positron with an electron, ideally combines the benefits of the lightweight electrons with those of a neutral atomic system, but, because it is formed as a hemispherically emitted burst at a velocity corresponding to approximately 1000 K, it can not yet be used for (anti)atomic imaging. Building beam optics for such a divergent beam of o-Ps, requires establishing laser-cooling of the o-Ps atoms in the plane parallel to the surface of the membrane in which they are formed, thus reducing their transverse momentum, and thus the beam's divergence.

- Laser-cooling Ps is highly challenging due to the very short lifetime of o-Ps of 142 ns, which entails that the duration of the cooling laser pulse must not exceed 150 ns. The short lifetime of the 2P state (3ns) on which cooling on the 1S→2P transition relies allows a small number of cooling transitions to occur, sufficient nonetheless given the very small mass of positronium.

- In this project, we proceed on several fronts to address this challenge: in parallel to adapting a 243 nm alexandrite-based laser to produce the commensurate 100-ns long laser pulses, we also developed, modified and characterized a further existing laser system to provide 24-ns long laser pulses at 243 nm with 50GHz bandwidth and 800 μJ per pulse for first proof-of-principle measurements. We studied the positronium laser-pushing process both experimentally and numerically (via Monte-Carlo simulation-based approaches) as a function of the detuning from resonance of the 1S→2P transition. We used Single Shot Positronium Annihilation Lifetime Spectroscopy [1] to probe the population of positronium excited in the 2P level by photoionization. For the simulations, we extended a code based on a kinetic Monte Carlo approach to solve rate equations, scattering and dipole forces for several electronic levels including the annihilation channel [2].

2. STATE OF THE ART

Laser manipulation of neutral atomic species is used in many different applications as in laser cooling to reach Bose-Einstein condensation or in atomic interferometers to test the validity of the weak equivalence principle and is foreseen to be used in gravitational waves detection. While a number of atoms such as Sodium, Rubidium, or Strontium are nowadays routinely laser cooled, other species are much more challenging to manipulate with lasers. In the case of positronium, several challenges have to be addressed. One of them is the need for a powerful ultraviolet laser. Another difficulty is the small number of atoms that can be produced in a given amount of time and the short lifetime of positronium (142 ns in the ortho ground state) which limits the time window to scatter photons of the atoms. The initial temperature of positronium is yet another challenge. As for simulating the process, the traditional model of optical molasses does not apply because of the short lifetime (3 ns) of the positronium 2P excited state, which prevents coherences to establish during the excitation process. The use of kinetic Monte Carlo approaches to model the interaction between the cloud of atoms and the electric field is well established [2] but it has to be tuned to the laser-positronium system. Different mechanisms and techniques for laser cooling of alkaline atoms have been developed over the years, including using broad and narrow band lasers, continuous waves and pulsed lasers, frequency combs, laser spectrum with a dark line, frequency chirp, spatial shaping of electric and magnetic fields and more. These different situations can be modelled with the kinetic Monte Carlo approach to optimize the cooling scheme and help design the most efficient laser for positronium cooling. To date, neither laser cooling nor laser pushing of positronium have been demonstrated.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

The O-possum II project was initiated to demonstrate the feasibility of using ultraviolet laser pulses as focusing optics for positronium atoms. In order to start with the lowest possible initial temperature and demonstrate the strongest effect as possible, positronium was generated in a home-made nanochannel converter [3]. Since the initial temperature of the cloud is still noticeably larger than what is usually observed for manipulation of alkaline atoms and the time available for laser manipulation is limited by the annihilation of positronium, we chose to develop a broadband approach in which all components of the velocity distribution are addressed simultaneously. Two laser systems were developed in parallel. The first system that was implemented for interaction with positronium is based on a dye cavity composed of an oscillator and an amplifier, pumped with the third harmonic of a Nd:YAG pulsed laser. Thanks to a stretching cavity, 24 ns pulses at 243nm with 450μJ (after stretching) could be generated. The other system based on an alexandrite cavity can produce 100ns pulses with several milli Joules per pulse at 243nm. The dye laser has about 50 GHz bandwidth while the alexandrite laser has 200 GHz spectral width, which allows to address the entire Doppler profile of the positronium cloud. Those specifications are not found anywhere in the literature. In particular, long pulse laser systems are rather rare, even if this is a very promising approach to production of powerful ultraviolet light through up conversion.

For the simulation, the program modelling the interaction between the laser and the atoms takes into account the linear or quadratic Stark and Zeeman effects, the transitions lines (dipole transitions, photo-detachment or photoionization cross sections), the initial temperature of the cloud of atoms, the magnetic fields and all parameters relevant to the laser pulse (e.g. waist size and position, polarisation, power, linewidth, wavelength). When running, the program calculates at time t all absorption and emission rates. Then a kinetic Monte Carlo algorithm gives the exact time $t+dt$ for an event (absorption or emission), compares this time to a typical external motion time, and then evolves it in motion and event. This versatile program is very complete and can model precisely the laser interaction with positronium including its decay by annihilation.

4. PROJECT RESULTS

The results obtained in the frame of the O-possum II project are threefold. First, two laser systems were developed in the ultraviolet range. One system is intended for a proof of principle experiment while the second one is foreseen for an optimized setup. Both lasers are quite unique in this wavelength range for their pulse duration, energy per pulse, bandwidth and tunability. In order to characterize and monitor the laser bandwidth, we developed a Fabry-Pérot interferometer working in the ultra-violet range. In particular, we used an ultra-violet enhanced coating on a CMOS sensor to acquire the ring systems in which the laser bandwidth is encoded. Fig. 1 shows the ring system obtained for the 243nm pulse generated with the dye laser. From this ring pattern, we determined that the laser bandwidth was 50 GHz (sigma), which can consequently address a significant fraction of the Doppler profile of the positronium cloud. The second laser is alexandrite based and has been developed in collaboration with the company Berilialaser.

Secondly, a code to simulate the laser atom interaction in view of shaping the positronium cloud was developed. The optimization of this Monte Carlo-based numerical experiment and its fine-tuning to the case of positronium allowed us to conclude that the laser systems we developed should allow for efficient laser manipulation of positronium. It will also be used to test different manipulation schemes, including frequency chirping and spectral shaping. Note that it has been developed with free source software and is available on demand. In Fig. 2, we present the result of the simulation for a laser bandwidth (FWHM) of 50GHz and a 24 ns long 243nm pulse. This illustrates the ability to shape the velocity distribution over time, which opens the way to laser focusing of positronium.

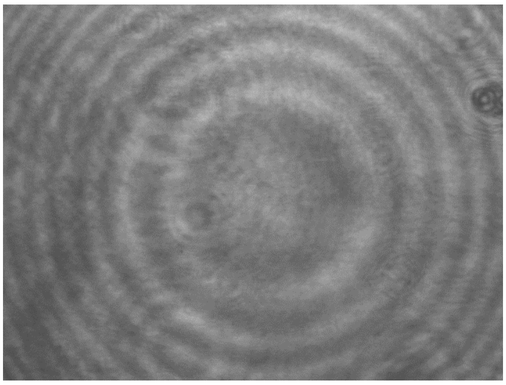

Fig. 1. Ring system revealing the bandwidth of the 243nm dye laser system. A Fabry-Pérot interferometer was developed for this purpose.

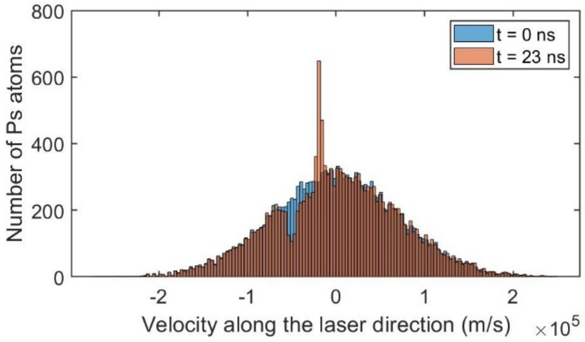

Fig. 2. Velocity distribution of positronium atoms before (t=0ns) and after (t=23ns) interaction with a 243nm laser pulse of 50GHz bandwidth detuned by 5 cm^{-1} with respect to resonance as simulated by the Monte Carlo approach for 16000 atoms.

Finally, first tests were performed with the dye laser, demonstrating our ability to excite, detect and characterize positronium in the 2P state with the dye laser. Fig. 3 shows a Doppler measurement of the transverse velocity distribution with the 243nm laser.

5. FUTURE PROJECT VISION

The initial proof-of-principle effort is still ongoing, and is expected to be completed on the time scale of a further year, with full use of the 100 ns pulse length dedicated alexandrite laser. With that system, transverse cooling of Ps can be investigated in detail, and the next steps envisaged. Of critical importance will be optimal matching of the parameters of the cooling laser to the (transverse) velocity of the cooled Ps while cooling is taking place. This can be achieved by e.g. dynamically chirping the laser peak wavelength throughout the 100 ns pulse duration, to be followed by subsequent o-Ps beam optical manipulations relying on micro-structured devices leading to a focused spot.

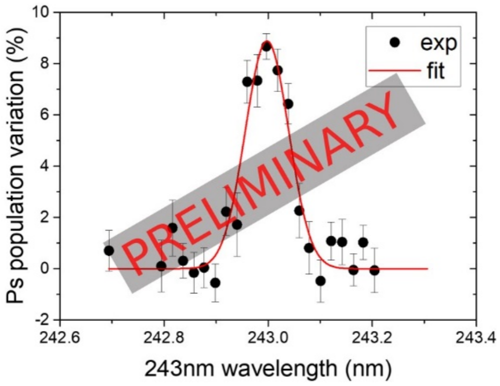

Fig. 3. Doppler scan of the positronium cloud produced in a nanochannel convertor target showing the initial transverse velocity distribution. Signal acquired by Single Shot Positronium Annihilation Lifetime Spectroscopy [1] using photoionization through the 2P level populated with the dye laser system.

5.1. Technology Scaling

Reaching TRL 4 with the existing system is within reach, which is however not expected to be sufficient to leverage further neutral beam technologies to the point where focusing of cooled o-Ps on a surface would be feasible (which would correspond to TRL 5 for the aimed-for technology). Input and expertise at TRL 3-4 from additional research groups will be needed for this, in particular in the fields of pulsed lasers and of ion-etched interferometric microstructures, but also in the area of spatially-sensitive o-Ps annihilation detection.

5.2. Project Synergies and Outreach

The existing consortium is thus growing by, in a first step, collaborating with a Norwegian laser expert group to develop the necessary ultra-fast chirping technologies, to be followed by a second ion-milling group at a slightly later stage. In parallel, collaboration with a group developing a (PET-like) detector capable of reconstructing the point of annihilation of o-Ps in 3D has been initiated. None of this expertise currently exist within the ATTRACT community.

As promising results on the proof-of-principle investigation were only possible at the very end of the ATTRACT phase 1, no public communication of the work beyond in the general context of communication on antimatter has taken place in 2019. Nonetheless, with public interest in antimatter unabated, as the prototype system produces first significant results, laser-cooling of positronium will feature much more prominently in our communication in the coming years.

5.3. Technology application and demonstration cases

Scientific research that goes beyond the state of the art requires improved techniques, improved diagnostics, and new tools. This project has the potential to provide a completely novel tool (non-destructive imaging via positronium) that has the potential to greatly expand the spectrum of what can be measured, including unperturbed and real-time distributions of electrons in active components. The techniques on which this tool is based are themselves of relevance, in particular with regards to in-pulse frequency chirping, which may allow improved optical data transmission; improved, tuneable and time-resolved, long duration (10x longer than fluorescence times) UV/C alexandrite-based lasers for deep UV absorption spectroscopy (e.g. of biomolecules [4]); and improved control of production of micron-scale micro-patterned devices (e.g. Fresnel zone plates).

5.4. Technology commercialization

Once TRL 5 is within reach, several of the developed technologies will be mature enough for a wider scientific client base. Two technologies in particular are of potential interest: first, the laser-cooled o-Ps beam itself, with scientific applications ranging from precision and fundamental science studies of o-Ps to tests of novel PET detector designs. And secondly, the within-pulse laser-chirping technology should provide a completely novel tool for enhanced (multi-frequency) data transmission with embedded error-correction potential. While some first scientific groups are already aware of the possibilities offered for their research by the first technology, discussions on commercialization of the second will be predicated on achieving at least TRL 3 in the second area.

5.5. Envisioned risks

Although several challenges in establishing the feasibility of forming a controlled beam of o-Ps have been successfully addressed, several further TRL 3 and 4 level challenges remain; establishing the requisite technology remains highly challenging.

5.6. Liaison with Student Teams and Socio-Economic Study

Our prior experience (crowd-sourcing and public science efforts on antimatter, high-school- and B.Sc.-level lectures) in involving and communicating with a broader audience, but also the topic itself (antimatter) and its overlap with quantum physics, lend themselves to close interaction in the future with student teams.

Specifically, the most experienced person of the current consortium is the natural contact point with external student teams (e.g. at universities or structures, such as ESADE, with whom contacts already exist) that would follow (by being included in regular discussions within the consortium) the developments, document (via interviews with e.g. the attendees of public lectures of the consortium members) the reception of the impact of the technological developments, and be involved in efforts to produce durable (e.g. via hosted blogs or hosted podcasts) informative and explanatory materials.

The incorporation in this material of data (such as is produced in interactions between the consortium members and this student team on the one hand, but also in interactions with potential industrial partners on the other) and documented by those performing an expert-driven socio-economic study of the ATTRACT initiative and ecosystem, should furthermore happen in “real time”. This will allow the general public to follow not only the advances (and set-backs) of the research and efforts to encourage its take-up by industry, but also to gain an appreciation of how this is part of a wider societal effort towards advanced technologies.

6. ACKNOWLEDGEMENT

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7. REFERENCES

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