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# New Bunched Positron Beam at the AntiMatter Laboratory in Trento: Planned Quantum Experiments with Positronium

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At the AntiMatter Laboratory in Trento, a new setup to produce intense bunches of positrons with a time duration of 2.5 ns and positron kinetic energy from 0.5 to 15 keV is under commissioning. The apparatus is designed for carrying out two main fundamental quantum experiments, i.e., the study of entanglement of three positronium annihilation gammas and the measurements of accelerations of positronium (including gravitational acceleration). In addition to the bunched beam, production of positronium in vacuum and its excitation in long-lived states will be necessary. Based on the acquired know-how of the AntiMatter Laboratory, the design of the experiments will be described.

topics: positronium, positron beams, entanglements, inertial sensing

## 1. Introduction

The production of clouds of positronium (Ps) in vacuum has opened the route for the realization of precise spectroscopy measurements and new experiments with this exotic atom composed of an electron and a positron. These experiments are carried out with the ortho-Ps, the triplet state of Ps, that annihilates in vacuum with a mean lifetime of 142 ns. Its lifetime can be further extended in the microsecond range by laser excitation to metastable $2^3S$ state or Rydberg states [1]. The production and the study of Ps in a vacuum is possible thanks to two techniques, one introduced by C.M. Surko [2] and the other by A.P. Mills [3]. Surko has developed a buffer gas trap (usually known as Surko trap) that allows the cooling, storage, and dumping of positron packets. Mills has introduced the Ps manipulation with lasers and the SSPALS (single-shot positron annihilation lifetime spectroscopy) technique for the analysis of the annihilation of many Ps atoms in a microsecond time. Here, we will present a novel apparatus, located at the AntiMatter Laboratory (AML) in Trento, based on a buffer gas trap with a pre-bunching and bunching system, with characteristics suited for the realization of two fundamental experiments. Moreover, we briefly recall the knowledge we have acquired in the past years on Ps formation and Ps manipulations, concerning the building blocks that complete the apparatus and allow the realization of these new experiments.

## 2. AntiMatter Laboratory

The AntiMatter Laboratory (AML) located at the Department of Physics of the University of Trento started working with positrons in the 1980s [4], and since 1998, it has been equipped with a fully electrostatic continuous positron beam (named SURF from SURFace) [5] (see Fig. 1). The positron energy in this apparatus is tunable from a few eV to up to 30 keV, and the experiments are carried out in a versatile vacuum chamber. The positrons from a $^{22}$Na source are moderated by a 1-micron monocrystalline W film conditioned up to 2000°C. The beam is used for basic and applied studies in solids using Doppler broadening spectroscopy (DBS), $2\gamma/(3\gamma)$ ratio measurements, and time-of-flight (ToF) Ps measurements. At present, a many-positron bunched beam based on a solid gas moderator coupled to a $^{22}$Na radioactive source and a gas buffer trap is under test. The solid gas moderators produce an intense ($1.5\times10^5$ $e^+$/(s mCi)) continuous positron beam that, through a switch, can be sent to the Surko cooling trap or to a re-moderator for a possible future single-positron bunched micro-beam for PALS (positron annihilation lifetime spectroscopy).

Since 2010, AML researchers have also been strongly involved in the AEgIS (Antimatter Experiment: Gravity, Interferometry, Spectroscopy) at CERN, an international experiment, the primary goal of which is the study of the free fall of a pulsed

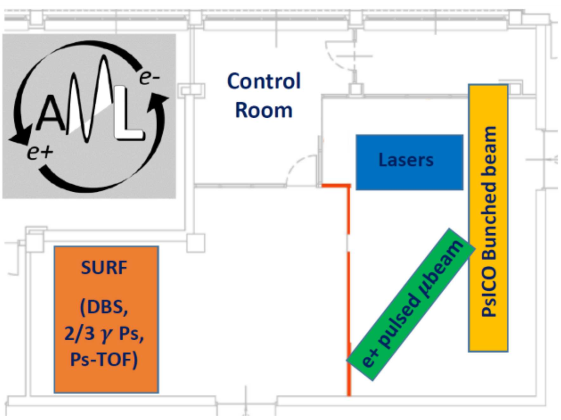

Fig. 1. AntiMatter Laboratory with the location of the SURF continuous positron beam and the bunched positron beam for fundamental experiments with Ps.

antihydrogen beam through a moiré deflectometer. Antihydrogen is formed by charge exchange between antiprotons and Ps atoms excited into Rydberg state [6]. In 2012, the AML group set up the "positronium experimental chamber" at CERN, which allows the AEgIS collaboration to conduct research on Ps laser manipulation in parallel to the main experiment [7, 8].

## 3. Building blocks for the planned experiments

### 3.1. Positron/positronium converters

For precise experiments with Ps, it is necessary to produce and emit Ps into the vacuum, with high efficiency and at the lowest achievable temperature. Ordered and tunable in diameter and length nanochannels in silicon, after proper oxidation in air, have been demonstrated to be very efficient in out-diffusing Ps into vacuum [9]. Ps are formed at the internal surfaces of oxidized nanochannels with an energy between 1–3 eV, then out-diffuse into the vacuum, partially losing kinetic energy by collisional cooling with the walls of the channels. Up to 40% (25%) of implanted positrons at energy of 1 keV (7 keV) are emitted into the vacuum as Ps. Fraction of very cold Ps atoms can be obtained by tuning the positron implantation energy, the dimension of the nanochannels to avoid quantum confinement [10], and the temperature of the converter [11, 12]. Although the longitudinal Ps emission velocity can be measured by the ToF technique [11, 12], the faster and more precise method is to characterize the Ps emission velocity by measuring the Doppler broadening of a transition line shape (for example, $1^3S$–$2^3P$) [13]. With an opportune choice of the cited above parameters, it was found that a fraction of the thermalized Ps at the sample temperature (i.e., room temperature (RT) and cryogenic temperature) was emitted [11–13]. The energy distribution of the out-diffused Ps from the nanochanneled structure was studied using the Monte Carlo method [14]. The simulation showed that the distribution measured by ToF can be fairly well approximated by two superimposed Maxwellian beam distributions.

### 3.2. Laser manipulation of positronium in vacuum

In 2002, Oberthaler [15] proposed the use of metastable $2^3S$ state for a measurement of gravity on Ps. One of the motivations for the choice of the $2^3S$ state with a lifetime of 1140 ns, as opposed to the longer-living Rydberg states, was its low electrical polarizability (six orders of magnitude smaller than Ps in $n = 15$ state). The first observation of the optical excitation from $1^3S$ to $2^3S$ was obtained by Chu and Mills [16] using two-photon excitation.

More than thirty years passed before single-photon techniques were successfully applied to the $2^3S$ production. Two different paths were used. Alonso et al. [17] used a single-photon excitation in the presence of an electric field for Stark mixing the $1^3S$–$2^3P$ sublevels. The adiabatic switching of the electric field allowed the formation of $2^3S$ metastable Ps ($\sim 6.2\%$ of the formed Ps). In the AEgIS collaboration, the population of the $2^3S$ state was obtained by spontaneous radiative decay from the Ps excited from the ground level to the $3^3P$ state. In the absence of magnetic and electric fields, the branching ratio of this process is theoretically evaluated to be 12% [18].

After showing the possibility of obtaining $2^3S$ from spontaneous emission, a beam of $2^3S$ metastable state was successively obtained by shooting the laser to excite the $1^3S$–$3^3P$ transition at different increasing retarding times from the positron implantation into the nanochanneled $e^+$/Ps converter, exciting a fraction of Ps population that has spent more time in the collisional cooling process before out-diffusing into the vacuum. Ps velocity was tuned from $1\times10^5$ to $7\times10^4$ m/s with an efficiency of 1–1.5% with respect to the formed Ps in vacuum. A branching ratio of $9.7\pm2.7\%$ of the $3^3P$–$3^3S$ spontaneous emission was obtained without the presence of electric fields [19]. Successively, the natural branching ratio of spontaneous emission was relatively increased by $\sim 3$ times by stimulating the $3^3P$–$2^3S$ transition with a 1312.2 nm broadband infrared (IR) laser [20]. Recently, the AEgIS collaboration has demonstrated the possibility of one-dimensional Doppler cooling of Ps with a broadband alexandrite laser (70 ns long 243 nm pulse) in a magnetic and electric field-free environment. For the cooling process, the $1^3S$–$2^3S$ transition was

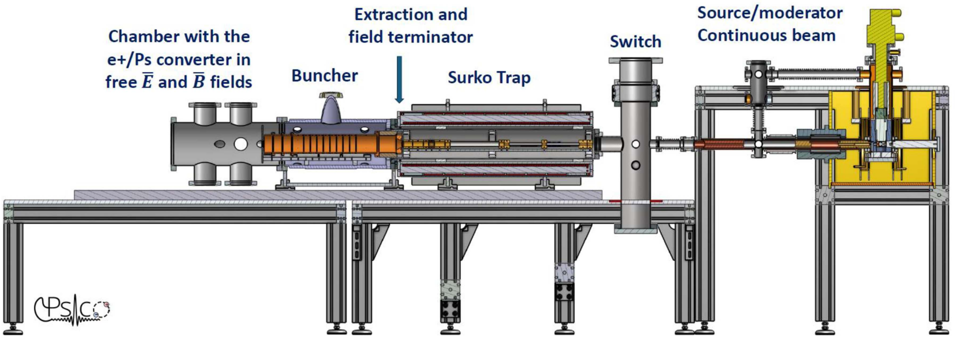

Fig. 2. Sketch of the apparatus. The different sections described in the text are indicated.

used. The temperature of Ps was reduced from 380 to 170 K, increasing the fraction of Ps with $3.7 \times 10^4$ m/s by about 58% [21]. New and more precise spectroscopic measurements will be possible in the near future, thanks the cooling of Ps.

The experiments that we are planning, summarized in Sect. 5, are based on the use of the long-lived $2^3S$ metastable state and the Ps laser cooling.

## 4. Bunched positron beam

To produce Ps clouds of about $10^4$ atoms in a vacuum in a few ns, a bunched positron beam that delivers packets containing around $5 \times 10^4$ positrons in a couple of ns is necessary. In Fig. 2, a sketch of the apparatus for producing positron bunches at the AML is presented, and a photo of the apparatus is shown in Fig. 3. The biological shields allow the use of a 50 mCi $^{22}$Na source.

The first part of the apparatus consists of the source ($^{22}$Na)/moderator assembly for the formation of the continuous beam and a buffer gas trap [2] to cool and store positrons. Up to the electrodes for the storage of positron with an energy of 25 meV, the apparatus is similar to the positron beam line in the AEgIS experiment at CERN.

An improvement was introduced in the two sets of saddle coils necessary for the separation of the slow positrons from the fast ones coming from the radioactive source [22]. The moderator is a solid rare gas kept at cryogenic temperature. Ne, Ar, and Kr were deposited following the same procedure, and their efficiency was tested as a function of time (days), time-temperature of annealing, and operation temperature [23]. Ar showed the highest moderator/transport efficiency (measured $e^+$ versus emitted $e^+$ in $4\pi$ from the source) in the first two days ($> 1.5 \times 10^{-3}$), but then the efficiency progressively decreased, reaching $0.2 \times 10^{-3}$ after 8 days. Ne is more stable and maintains an efficiency of $> 1.2 \times 10^{-3}$ for 8 days. Kr efficiency, although very stable, is very low — $0.5 \times 10^{-3}$. Successively, the moderators must be regrown. After the velocity selector, the energy distribution of positrons slowed by Ne and Kr is $\sim 1.2$ eV, while the energy distribution from Ar is narrower, i.e., 0.2 eV. In the above range of efficiencies, we obtained a continuous beam of about (4–5) $\times 10^4$ $e^+$/(s mCi).

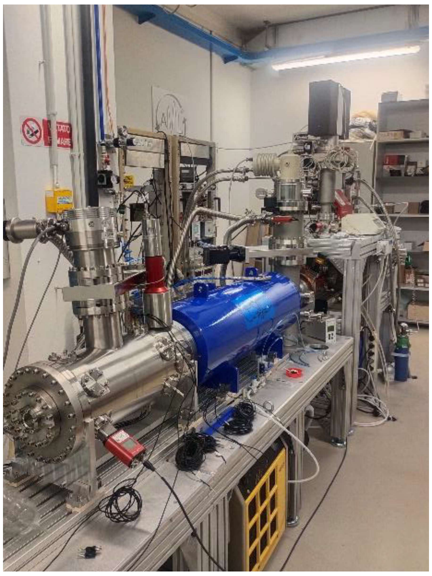

Fig. 3. Bunched positron beam at AML. Painted in blue is the magnet containing the buffer gas trap. It is followed by the chamber containing the main buncher.

The novelties of our apparatus start mainly with the extraction of the stored and compressed positrons in the $\sim 700$ Gauss Surko trap [24].

Positrons from the trapping electrodes are focused at sub eV energy and compressed in bunches of a few nanoseconds at the exit of the Surko trap through a similar parabolic voltage shape that produces a pre-bunching effect. The extraction of positrons from the high magnetic field is done in a non-adiabatic mode by closing the magnetic field lines with an iron field terminator and a high permeability spider. The magnetic field on the axis of the magnet falls abruptly from 700 to a few Gauss. Finally, positrons are extracted by the penetration field of a 5 kV lens and injected into the main buncher. The design of the buncher allows to compress positrons on the $e^+$/Ps converter with an energy from 0.5 to 15 kV in a spot of 2 mm FWHM (full width at half maximum) and a time spread of less than 2 ns [23]. After the buncher, there is a series of three electrodes acting as focusing lenses. The last one is held at ground potential, also functioning as a shield for the electric field. This configuration forms a region in which Ps can be formed and excited in the absence of magnetic and electric fields — a condition mandatory for the formation of a $2^3S$ beam and the Ps laser cooling [18, 21].

## 5. Quantum experiments design

The following two experiments are based on the production of bunches of Ps in the long-lived $2^3S$ metastable state. Taking into account the efficiency of the Surko trap [8] and of $1^3S$–$2^3P$ excitation and stimulated decay to $2^3S$, we estimate we will obtain about 35–70 Ps atoms in $2^3S$ state/(s mCi). The Surko trap will allow the production of about 6 bunches/s of a few ns durations.

### 5.1. Entanglements of the three gammas Ps annihilation

An $e^+$/Ps converter in reflection, tilted at 45° to the positron beam axis, will be used. After excitation, the Ps atoms in the $2^3S$ state will fly in an aluminum–quartz chamber to reduce the annihilation gammas absorption by the surrounding material. Theory [25, 26] predicts that the entanglement of the three gammas would depend on the angles between the gammas and the initial quantum state of Ps. Different entangled type states can be expected. The most notable are:

- the Greenberg–Horn–Zeilinger state

$$|\mathrm{GHZ}\rangle_{abc} = \frac{|RRR\rangle_{abc} + |LLL\rangle_{abc}}{\sqrt{2}}, \tag{1}$$

and

- the Dicke state

$$|\mathrm{W}\rangle_{abc} = \frac{|LLR\rangle_{abc} + |LRL\rangle_{abc} + |RLL\rangle_{abc}}{\sqrt{2}}, \tag{2}$$

where $L$ and $R$ represent, respectively, the left- and right-handed polarization of the three annihilation gamma rays.

Firstly, we will look at gammas emitted at angles of 120° and will prepare the $2^3S$ state in a magnetic quantum number $m = +1$ $(m = -1)$ by an opportune laser pulse polarized at $\sigma^+$ $[\sigma^-]$ for the transition $1^3S$–$3^3P$ and a second laser pulse polarized at $\sigma^-$ $[\sigma^+]$ to stimulate the transition $3^3P$–$2^3S$ [27]. The entanglement measurement requires the detection of the coincidence of the three gammas and the relative Compton scattered gammas in order to reconstruct the polarization of the three annihilation gammas [28, 29]. Thanks to the collaboration with the J-PET group of Jagiellonian University in Krakow, 3 pairs of modified-type J-PET (Jagiellonian Positron Emission Tomograph) plastic modules positioned at 120° will be employed. The first layer of detectors reveals the three annihilation gamma rays, while the second layer detects the Compton scattered rays [30].

### 5.2. Ps inertial sensing: Towards Ps free fall in Earth's gravitational field

For measuring forces on Ps, the Ps metastable beam will be produced in a linear configuration along the axis of the incoming positron bunches by using a thin film ($< 3.5$ $\mu$m) positron/Ps converter in a transmission geometry [31]. The produced Ps atoms, after being laser-cooled to decrease their angular divergence, will be excited in the $2^3S$ state and injected in a Mach–Zehnder interferometer [32]. Details of the measurement scheme can be found in [33]. The first two light gratings (365 nm periodicity) will be realized with standing waves of wavelength $\lambda = 730$ nm. This wavelength can be obtained with an alexandrite laser. The last grating will be a material grid that can be moved with nm precision on which the Ps atoms will annihilate. The measurement will be done by counting the annihilation events as a function of the grid displacement in a way that allows determining the deflection $\Delta y = at^2$ of Ps with respect to the horizontal position of an un-deflected beam. The time $t$ is the Ps time-of-flight between the grating distance $L$ ($\sim 20$ cm). To count the annihilations, a detector able to select the annihilations occurring on the grid plane is necessary. We have recently tested, in collaboration with the J-PET group, two J-PET slabs analyzing the two 511 keV gammas in the coincidence of positrons generated with a continuous positron beam and focused on a stopper. The annihilation position in the direction perpendicular to the plane was determined with a precision of $\sim 0.3$ cm [34].

## 6. Conclusions

At the AML in Trento we are setting-up a bunched positron beam for fundamental studies with Ps atoms produced in vacuum. The main characteristic and novelty of the apparatus have been reported and the first planned experiments, i.e., the measurement of the entanglement of the three Ps annihilation gammas and the acceleration of Ps under different forces, have been described.

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