Present status of the low energy linac-based slow positron beam and positronium spectrometer in Saclay

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Abstract. A new slow positron beamline featuring a large acceptance positronium lifetime spectrometer has been constructed and tested at the linac-based slow positron source at IRFU CEA Saclay, France. The new instrument will be used in the development of a dense positronium target cloud for the GBAR experiment. The GBAR project aims at precise measurement of the gravitational acceleration of antihydrogen in the gravitational field of the Earth. Beyond application in fundamental science, the positron spectrometer will be used in materials research, for testing thin porous films and layers by means of positronium annihilation. The slow positron beamline is being used as a test bench to develop further instrumentation for positron annihilation spectroscopy (Ps time-of-flight, pulsed positron beam). The positron source is built on a low energy linear electron accelerator (linac). The 4.3 MeV electron energy used is well below the photoneutron threshold, making the source a genuine on-off device, without remaining radioactivity. The spectrometer features large BGO (Bismuth Germanate) scintillator detectors, with sufficiently large acceptance to detect all ortho-positronium annihilation lifetime components (annihilation in vacuum and in nanopores).

1. Introduction

One of the fundamental questions of today’s physics is the action of gravity upon antimatter. A difference between the free fall of matter and antimatter in the gravitational field of Earth would signal a violation of the Weak Equivalence Principle. The GBAR experiment [1], recently accepted at CERN, proposes a scheme for a direct measurement of the gravitational acceleration of the simplest antimatter atom, the antihydrogen, with 1% precision. The distinctive feature of the experimental scheme is that the extreme low energy (10 \(\mu\)K) that is needed for the precise determination of the gravitational constant is reached through cooling of positively charged antihydrogen atoms, which are then neutralized by photodetachment prior to the free fall measurement. The production of the ions require a positronium (Ps) cloud with unprecedented density (\(10^{15}\) Ps/cm\(^3\)) as target for the antiproton beam provided by the Antiproton Decelerator facility at CERN. A high field Penning-Malmberg trap accumulates the particles from an intense slow positron source and ejects them in an intense pulse
after typically 110 s. Positronium will be generated by the e\(^+\) pulse, hitting a positron-positronium converter target.

An experimental facility (Figure 1) has been built at CEA-IRFU (Saclay, France) to test and develop the key constituents of the experimental setup, needed for the production of the dense positronium cloud. The facility consists of a linac-based slow positron generator, a high field (5 T) positron trap (a contribution from RIKEN, Japan) and a large acceptance positronium lifetime spectrometer. The spectrometer is being used in the development of the positron-positronium converter. In addition to the application in the GBAR experiment, the spectrometer will be used in positron annihilation studies of nanoporous oxide films and layers.

2. The slow positron generator
A linac based slow positron generator does not produce any radioactive contamination in the structural elements below 10 MeV electron energy. The fact that the positron source does not contain any radioactive parts in its "off" state makes it an attractive alternative to positron sources based on radioactive isotopes. Such sources can be deployed in laboratories where there is no infrastructure for the use of radioactive isotopes. The slow positron generator at IRFU [2] is based on a linac of 4.3 MeV electron energy, which is well below the photoneutron threshold of all structural materials. The accelerator produces electron bunches with an effective length of 2.5 µs at 200 Hz repetition rate and 140 mA peak current. The electron beam is incident on a water cooled tungsten target and generate positrons by pair production. The setup at CEA-IRFU contains a magnetic selector, which separates the positrons emitted from the target from the electron flow. This feature will allow the use of solid neon moderator in a later phase of development. In the present working setup, a positron moderator is placed directly behind the electron target. The positron moderator is formed by a stack of thin tungsten meshes, annealed by Joule heating in a separate vacuum chamber. Possibility of in-situ heating will be added in a later phase of the project. We found optimum positron production at 12 mesh layers. Work is underway to improve the positron yield with an optimized moderator structure. At present, a sustained positron rate of 2x10^6 e\(^+\)/s is available.
3. The slow positron transport beamline
Positrons are adiabatically transported in 8 mT magnetic field, generated by solenoids wound around the vacuum tube. A positron pulse stretcher is inserted into the beamline at the exit point of the concrete bunker of the biological shield. The function of the pulse stretcher is to form a quasi-continuous beam from the 2.5 µs pulses generated by the linac. It is a low-field Penning-Malmberg trap, which consists of three electrodes. The second electrode is 4 m long, in order to accommodate the entire slow positron pulse. The other two electrodes open and close the trap, synchronized with the linac pulses. A static beam switch, based on a rotatable coil, feeds the beam into two beamlines. One line is reserved for the high field (5 T) Penning-Malmberg positron trap, used to develop the technology to trap up to $2 \times 10^{10}$ positrons for the GBAR experiment. The second beamline feeds a large acceptance positronium lifetime spectrometer, used in the development of the positron-positronium converter for the GBAR project and for materials science studies.

4. The large acceptance ortho-positronium lifetime spectrometer
Lifetime spectrometers used routinely in positron annihilation spectroscopy can detect intensity and length of lifetime components up to a few nanoseconds. The presence of long-living ortho-positronium (o-Ps) in a system, however, makes the reliable analysis of the spectra difficult. One problem is the difference between the energy distribution of photons created in two gamma annihilation processes dominant at short lifetime components and those of three-gamma annihilation events of ortho-positronium. Correct evaluation of the spectra is possible only by using a correction factor, determined experimentally or by Monte-Carlo simulation. Measurement of positron annihilation lifetime spectra in the presence of long ortho-positronium components in a slow positron beam poses another problem. In highly porous samples, where a significant fraction of ortho-positronium escapes from the sample, the spectrum will be distorted by the difference between the detection efficiency of annihilation events in the sample and those of the escaping positronium. This is the case in all samples suitable for use as positron-positronium converter in the GBAR experiment. To tackle this problem, we have developed a special device, a large acceptance ortho-positronium lifetime spectrometer, in a collaboration between IRFU and ETH Zurich (Switzerland) [3]. A similar spectrometer has been implemented and tested (Figure 2) on the CEA-IRFU slow positron beamline described in the present paper. The spectrometer uses secondary electrons, ejected by the impinging positrons, as start signal (detected by a micro-channel plate detector) and one of the annihilation gamma photons as stop signal. Two large (55 mm
diameter, 200 mm long) BGO (bismuth germanate) scintillation detectors are used for gamma detection with large acceptance. The lifetime spectrometer uses the quasi-continuous slow positron beam provided by the positron pulse stretcher, with a collimator of variable diameter to limit the beam diameter on the sample. The positron energy is set by the potential of the sample holder.

5. Development of positron-positronium converter for GBAR and study of nanoporous silica

Positron lifetime studies using the large acceptance ortho-positronium spectrometer have shown that nanoporous silica with high porosity is a promising candidate as the basis of the positron-positronium converter for GBAR [4]. Our time-of-flight studies [5] as well as laser-based measurements [6] confirmed that the energy of the reemitted o-Ps remains under 50 meV, a value that is satisfactory for the GBAR target construction. We analyzed nanoporous silica films with larger pore size (32-75 nm) to understand better the underlying physical processes and find ways to optimize pore size and density for the GBAR positron-positronium converter [7]. Our studies have also confirmed that the positron method can contribute to the better understanding of the pore properties of nanoporous silica and can serve as a basis of quality control devices for low-κ dielectrics used in microelectronics.

6. Summary and outlook

We constructed a low energy linear linac-based slow positron generator and an associated beamline at CEA-IRFU. The installation serves as a test bench for the various technologies needed to create a high density ortho-positronium cloud, essential for the formation of antihydrogen ions in the GBAR experiment. One beamline of the two feeds positrons into a high field trap, the second one provides a quasi-continuous flux of slow positrons for a large acceptance positronium lifetime spectrometer. Extension of the second beamline with other detection methods and construction of a new sample chamber is planned to extend the capability of the spectrometer to study of a wider range of materials.

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