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Characterization of a transmission positron/positronium converter for antihydrogen production

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ABSTRACT

In this work a characterization study of forward emission from a thin, meso-structured silica positron/positronium (Ps) converter following implantation of positrons in light of possible antihydrogen

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production is presented. The target consisted of a ~1 μm thick ultraporous silica film e-gun evaporated onto a 20 nm carbon foil. The Ps formation and emission was studied via Single Shot Positron Annihilation Lifetime Spectroscopy measurements after implantation of pulses with $3-4\cdot10^7$ positrons and 10 ns temporal width. The forward emission of implanted positrons and secondary electrons was investigated with a micro-channel plate – phosphor screen assembly, connected either to a CCD camera for imaging of the impinging particles, or to a fast photomultiplier tube to extract information about their time of flight. The maximum Ps formation fraction was estimated to be ~10%. At least 10% of the positrons implanted with an energy of 3.3 keV are forward-emitted with a scattering angle smaller than 50° and maximum kinetic energy of 1.2 keV. At least 0.1–0.2 secondary electrons per implanted positron were also found to be forward-emitted with a kinetic energy of a few eV. The possible application of this kind of positron/positronium converter for antihydrogen production is discussed.

1. Introduction

Positronium (Ps) [1,2] is a purely leptonic, bound state of an electron and its antiparticle, the positron (e^+). It lends itself to a range of fields as a key testing ground; for studies of QED [3], astrophysics [4], and the characterization of porous materials [5]. Ps can exist in two states: the singlet state, parapositronium (p-Ps, total spin 0, formation probability 1/4) or in the triplet state, orthopositronium (o-Ps, total spin 1, formation probability 3/4). In vacuum, p-Ps predominantly decays into 2 γ-rays with a mean lifetime of 125 ps, while o-Ps decays into 3 γ-rays with a mean lifetime of 142 ns.

Many experiments require the availability of a large amount of cold o-Ps, including antihydrogen beam production for gravitational measurements [6–8], gravitational experiments on o-Ps [9,10], Bose–Einstein condensation of o-Ps [11], and the production of di-positronium molecules [12].

Ps can be obtained by implanting positrons with an energy of a few keV into solids [13,14]. In case of metals and semiconductors, Ps can only be formed by thermal and epithermal positrons reaching the surface [15]. In insulators, on the other hand, Ps can form in the bulk, diffuse to the surface and be emitted into vacuum, or be trapped in a nano-sized pore. If the nanoporosities are connected to the surface, however, o-Ps can move along the pores losing a fraction of its energy by collisions with the walls and reach the vacuum. In silica o-Ps is formed with an energy of 1–3 eV [16] and can escape into vacuum with an energy distribution ranging from a fraction of eV to thermal energy, depending on the length of its path and the structure of the nanoporosities. The lifetime of a fraction of o-Ps is shortened in the nanoporosities by pick-off annihilation, in which the positron of the o-Ps annihilates with an electron of the walls of the pores into 2 γ-rays. Porous silica has proved to be a good choice for converting positrons into cold positronium due to the large Ps yield in the bulk and on the porous surface, combined with the relatively efficient cooling of o-Ps by collisions with the walls of the pores [17–19].

Until now, most experiments have focused on o-Ps formation in reflection geometry, i.e. o-Ps emitted from the same surface into which positrons are implanted [20,21]. Recently, thin mesostructured silica film targets have been developed in order to obtain Ps in transmission geometry, i.e. o-Ps emitted from the opposite side of the target with respect to the positron implantation [22–24].

The transmission geometry holds great promise in all experiments where o-Ps has to be transported, like tests of the gravitational free-fall of o-Ps [10] or charge exchange production of cold antihydrogen (in which o-Ps atoms excited to Rydberg levels – to enhance the cross section of the reaction – interact with an antiproton plasma) [7]. Although transmission targets are not yet competitive with reflection targets in terms of Ps production and cooling efficiency, they offer potential advantages. In the case of antihydrogen production, the reaction efficiency would benefit from an enhancement of the geometrical overlap between antiprotons and o-Ps, granted by transmission e^+/Ps converters with respect to reflection targets [7]. A possible scheme would be the following: after filling antiprotons into a Penning-Malmberg trap, a transmission e^+/Ps converter would be mechanically moved from outside the electrode stack and inserted upstream, in the proximity of the first electrode of the trap. Subsequently, a positron pulse would be implanted in the target, and forward-emitted o-Ps would react with the antiproton plasma after excitation to Rydberg states [25,26]. A transmission target can be placed closer to the antiproton cloud with respect to a reflection target, providing a greater geometrical overlap between antiprotons and o-Ps.

Unfortunately, Ps is not the only species forward-emitted by the converter. Due to its limited thickness, a fraction of positrons are expected to cross the target after partial thermalization. Moreover, secondary electrons are produced by e^+ interaction with the material and possibly emitted by the target [27,28]. The presence of charged particles emitted in the direction of the antiprotons could pose a problem for the stability of the plasma; it could heat up by interaction with positrons and electrons [29]. This, in turn, could affect the charge exchange reaction and the characteristics of the produced antihydrogen [6].

In this work, we have characterized a transmission e^+/Ps converter for its possible application in antihydrogen production. Three different techniques were used to investigate the Ps yield and the forward emission of charged particles. First, the Ps emission was studied via Single Shot Positron Annihilation Lifetime Spectroscopy (SSPALS) measurements. SSPALS is a measurement of the time distribution of annihilation gamma rays resulting from implantation of an intense positron bunch [30]. Secondly, the forward emission of positrons and electrons was investigated with a micro-channel plate (MCP) – phosphor screen assembly connected to a charge-coupled device (CCD) camera for imaging of impinging particles. Thirdly, the same MCP – phosphor screen assembly was coupled to a fast photomultiplier tube (PMT) to extract information about the time of flight. A strategy to avoid interaction between charged particles and the antiproton plasma in future antihydrogen production is suggested.

2. Experimental setup

In the present experiment, bunches containing up to $3-4\cdot10^7$ positrons (estimated using a calibrated CsI detector coupled to photodiodes [31]) were implanted in the transmission e^+/Ps converter. Positron bunches were produced using the AEgIS positron system located at the Antiproton Decelerator (AD) ring at CERN. The system is described in detail elsewhere [31,32]. Briefly, positrons emitted by a 50 mCi ^{22}Na source were moderated by a solid Ne film [33] and prepared by a Surko-style trap [34] and accumu-