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Development of a Position-Sensitive Detector for Positronium Inertial Sensing Measurements

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In the last twenty years, both free fall and interferometry/deflectometry experiments have been proposed for the measurement of the gravitational acceleration on positronium, which is a purely leptonic matter–antimatter atom formed by an electron and its antiparticle (positron). Among the several challenges posed by these experiments is the development of position-sensitive detectors to measure the deflection of positronium in the Earth's gravitational field. In this work, we describe our recent progress in the development of position-sensitive detectors. Two different detection schemes are considered. The first is based on Ps ionization in a strong homogeneous magnetic field and imaging of the freed positron with a microchannel plate. The second scheme is based on scanning the positronium atom distribution on a plane by moving the slit or a material grating with sub-nm accuracy, and counting the atoms crossing the obstacle and those annihilating on it. The possibility of reaching a spatial resolution of around 15 μm using the former detection scheme is shown, and preliminary steps towards the development of a detector following the latter scheme (with potential position sensitivity in the sub-nm range) are described.

topics: positronium, antimatter, spatial-sensitive detector

1. Introduction

The observed predominance of matter over antimatter in the universe is one of the great mysteries in modern physics [1]. The mechanisms leading to this asymmetry are not fully understood, either from a theoretical or experimental point of view. This triggered several experiments to verify if the origin of the asymmetry could come from violations of the CPT symmetry (i.e., charge conjugation, parity transformation, time reversal symmetry), see for instance [2–5], or weak equivalent principle (WEP). The possibility of WEP violation is currently explored at CERN by three experiments, aiming to perform tests of free fall and deflectometry/interferometry on antihydrogen (AEgIS [6], ALPHA [7] and GBAR [8]). One more experiment (BASE [9]) examines the charge-to-mass ratio of antiprotons by measuring their cyclotron frequency in a strong magnetic field.

These experiments use hadronic systems where around 99% of the mass comes from the binding energy, while only around 1% is the mass of antiquarks (see for example [10]). In this picture, it may be interesting to use leptonic systems such as positronium (Ps) [11–15] where 50% of the mass is given by the antiparticle, or muonium [16, 17] (bound state of an antimuon and an electron) where the mass given by the antiparticle is around 99.5% total mass.

Both the free fall [11, 12] and deflectometry/interferometry experiments [13, 15] were proposed to measure the gravitational acceleration of Ps in the field of the earth. These proposed experiments would take advantage of the development of positronium detectors with position sensitivity ranging from a few μm down to a fraction of nm.

In the present work, we briefly summarize the spatial resolution requirements for Ps detection in the proposed inertial sensing experiments (Sect. 2). Next, we will discuss the development of two

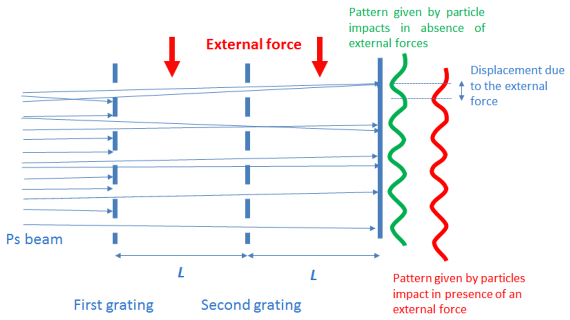

Fig. 1. Schematic of a deflectometry system with two material gratings. The fringe pattern formed by the Ps atoms at the exit of the device and its displacement due to the presence of an external force are sketched.

position-sensitive detectors. The first one is based on Ps ionization in a strong homogeneous magnetic field and imaging of freed positrons with a microchannel plate (MCP) (Sect. 3.1) [18]. The second detector case is based on scanning of the distribution of Ps atom on a plane by using a slit or material grating moved with sub-nm accuracy and by counting positronium crossing an obstacle and those annihilating on it (Sect. 3.2) [15]. Recent progress in the development of such detection schemes will be illustrated.

2. Proposed free fall and deflectometry/interferometry experiments with positronium

In 2002, A.P. Mills and M. Leventhal [11] examined the possibility of detecting the free fall of thermal Ps, excited with a laser to the circular Rydberg state with the principal quantum number n and the azimuthal quantum number $l = n - 1$. The experimental scheme studied consisted in allowing the Ps beam to travel a few meters in the horizontal direction, focusing it with an electrostatic mirror [19] and finally allowing it to travel a few more meters to converge to a 1 μm spot on the position-sensitive detector. The expected deflection of the spot (given in [μm]) due to gravity acceleration, g, is

$$\Delta x = \frac{1}{2}\, gT^2 = 24.8\, q^2 \left(\frac{n}{25}\right)^{10.47}, \tag{1}$$

where T is the traveling time, q is the number of lifetimes of Ps in the state with the principal quantum number n. If Ps in $n = 25$ is employed and $q = 1.5$ lifetimes is used, the deflection to be resolved is of the order of 50 μm.

In another work in 2002, M. Oberthaler [13] investigated the possibility of measuring the gravitational acceleration of positronium in the metastable 2^3S level using an interferometer realized with standing light waves. The possibility of using deflectometer with material gratings was also explored [15]. The experimental scheme is the same in both cases. The beam of Ps at the metastable 2^3S level crosses two gratings placed at the distance L. A fringe pattern is thus formed on the plane at the distance L from the second grating (see sketch relative to material gratings in Fig. 1).

In the presence of an external force with corresponding acceleration a, the pattern shows a displacement Δx

$$\Delta x = at^2, \tag{2}$$

where t is the interrogation time (i.e., the time spent to travel between the two gratings). The minimum measurable acceleration, $a_{\min}$, is [13, 15]

$$a_{\min} = \frac{d}{2\pi\sqrt{N}\, Vt^2} \tag{3}$$

where d is the pitch of the gratings, V is the fringe visibility, t denotes the already introduced interrogation time, and N is the number of the Ps atoms detected. For particles with infinite lifetime, N and t are independent. Consequently, the minimum measurable acceleration, $a_{\min}$, can be reduced simply by increasing the interrogation time. For probes with finite lifetime such as Ps in the 2^3S state, this is no longer true. Indeed, N scales like

$$N = N_0 T \exp\left(-\frac{2t}{\tau}\right), \tag{4}$$

where N_0 is the number of particles entering the interferometer/deflectometer, T is the transparency of the gratings, and τ is the lifetime of the probe. By combining (3) and (4), it results that the minimum measurable acceleration is no longer a monotonous function decreasing with the increase of t, but it shows a minimum. For Ps in the 2^3S state (lifetime of 1.142 μs), the minimum is at $t \sim 2$ μs [13, 15]. The presence of an optimal value for the interrogation time fixes the displacement Δx that must be resolved to measure the given acceleration (see (2)). For the measurement of $a = g$, Δx is of the order of 0.3 nm [15].

3. Development of a position-sensitive detector for positronium

3.1. Ps ionization in a homogeneous magnetic field

Recent work has demonstrated the possibility to develop a position-sensitive detector for slow Ps based on positronium photo-ionization in a homogeneous 1 T magnetic field and photo-positron imaging with MCP — a phosphor screen assembly placed with its face perpendicular to the magnetic field [18]. Due to the presence of the magnetic field, the photo-positron travels along the field lines keeping the memory of the position of the original Ps. The diameter of the cyclotron orbit of the photo-positron in a 1 T magnetic field is expected to be < 3 μm. A spatial resolution of around 90 μm has been demonstrated for Ps using the described detection scheme [18].

More recently, MCP with a TimePix3 detector in place of a phosphorous screen has been tested with a continuous positron beam [20]. The TimePix3

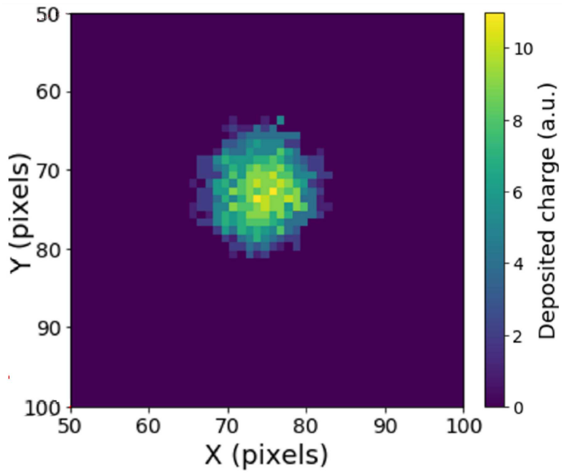

Fig. 2. Example of charge deposition on TimePix3 given by an electron cloud generated by the impact of a single positron on MCP.

detector is formed by a matrix of 256 × 256 pixels of 55 × 55 μm^2 and has a time resolution < 15 ns [21]. Thanks to these characteristics, it allows for imaging of the electron cloud emerging from the MCP channels, generated by the impact of a single positron. An example of such a cloud image is shown in Fig. 2.

By using the pixel-per-pixel absolute charge deposit, the centroid of the distribution can be extracted with the sub-pixel size spatial resolution. A spatial resolution on the impact position of the positron of around 12 μm was demonstrated [20]. The detection efficiency for a positron impinging MCP has been estimated to be up to 41% [20]. When using such a MCP+TimePix3 detector for imaging photo-positrons generated by Ps photo-ionization in a 1 T field, the spatial resolution on Ps is expected to be smaller than 15 μm (12 μm of spatial resolution on the impact position of the positron convoluted with the diameter of the photo-positron cyclotron orbit, < 3 μm). The reported spatial resolution is limited mainly by the characteristics of the employed MCP (in the present case, the channel diameter of 10 μm and the inter-channel distance of around 12 μm). The use of commercially available MCPs with channels of around 3 μm is expected to further improve the spatial resolution down to a few micrometers.

3.2. Scan of the Ps distribution with sub-nm accuracy

In order to reach a spatial resolution smaller than a few micrometers, a different detection scheme has been proposed. It consists in scanning the distribution of Ps atoms on the plane by using a slit or a material grating [22] moved with sub-nm accuracy [23]. The positron annihilating on the obstacles and the one crossing it can then be counted as a function of the slit/grating position, and the Ps distribution on the plane can be reconstructed (see Fig. 6 in [15]). In this detection scheme, the spatial resolution is given by the accuracy of the positioning of the obstacle. Commercial single-axis linear piezo nano-positioning systems guarantee sub-nm accuracy (see for instance [24]), making it feasible to resolve shifts in the positronium distribution on the plane down to less than 1 nm.

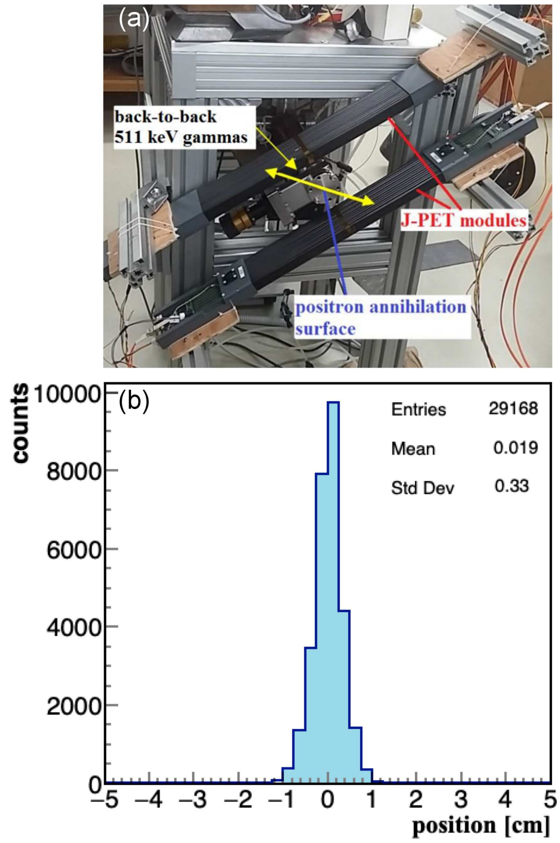

Fig. 3. (a) Picture of two J-PET modules and their position with respect to the positron annihilation plane. An example of back-to-back 511 keV gammas is also sketched. (b) Spatial distribution of positron annihilations on a plane as detected by two J-PET modules. The standard deviation of the distribution (~ 0.3 cm) is reported.

In order to count both the Ps atoms annihilating on the obstacle and those crossing it, the proposed strategy is to introduce a stopper behind obstacle and count the 2γ radiation at 511 keV generated by the Ps annihilations on the two elements. A counting detector is then required to distinguish between annihilations on the slit/grating and those on the stopper.

Preliminary tests were performed to verify if the modular detection units of the J-PET tomograph could be suitable as counting detectors for the application described. The J-PET tomograph is based on plastic scintillator detectors developed for cost-effective total-body PET imaging [25–29] and positron imaging [30–34]. Two

J-PET units (each consisting of 13 plastic scintillators of $50 \times 2.4 \times 0.6$ cm^3 and read out by silicon photomultipliers located at both ends of the strip) were placed parallel and 20 cm apart, at a distance of around 10 cm from the plane in which a magnetically transported continuous positron beam was implanted [35] (see picture in Fig. 3a). Two units detected back-to-back gammas at 511 keV generated by positron annihilation. The impact position of each 511 keV gamma on the plastic scintillators was determined from the difference in the time of arrival of the light signals to both ends of the strips. By measuring the hit positions and the hit times of both 511 keV gamma rays, one can estimate the position of the positron annihilation event [30–34]. The positron annihilations occur on a plane corresponding to the position of 0 cm in Fig. 3b.

The determined spatial distribution shows a standard deviation of around 0.3 cm. This means that the detection system formed by two J-PET modules is able to distinguish the annihilations occurring on two planes separated by about one centimetre. This makes them a promising candidate as counting detectors for scanning the Ps distribution. Indeed, they would be able to distinguish between the Ps annihilations occurring on the slit/grating and the one on the stopper without the need to introduce a large distance between the two elements, which would result in loss of counts due to the Ps self-annihilation. Assuming the use of Ps in the 2^3S state with a velocity of 10^5 m/s, the number of self-annihilations on the distance of 1 cm between the grating/slit and the stopper would be around 8%.

The efficiency of reconstruction of positron annihilation distribution achievable with two J-PET units is still under investigation. The study of a multilayer configuration with more than two J-PET units is also planned to verify if a better spatial resolution is reached (in order to further reduce the number of the Ps self-annihilations between grating/slit and stopper) and to optimize reconstruction efficiency.

4. Conclusion

In this work, we describe the recent improvements in the development of a position-sensitive detector for slow Ps, suitable for free fall and inertial sensing measurements. Two experimental schemes were considered. The first one is based on ionization of Ps in a homogeneous magnetic field and photo-positrons imaging with MCP. The second scheme consists of scanning the Ps distribution on the plane by using a slit or a grating moved with sub-nm accuracy and counting the positron crossing the obstacle and those annihilating on it.

The spatial resolution currently achievable using the Ps ionization and imaging of the produced photo-positron is of the order of 15 μm when the TimePix3 detector is coupled to MCP. This spatial resolution already matches the requirements of proposed free fall experiments on Rydberg Ps, which aim to resolve a deflection of the order 50 μm [11]. Even if the considered detection scheme requires the use of a strong magnetic field, it should not affect the free fall measurement proposed in [11]. Indeed, the required field is in the same direction of the velocity of Rydberg Ps. Consequently, the self-ionizations caused by the motional Stark effects are expected to be negligible [36, 37].

Interferometry/deflectometry measurements of the gravitational acceleration of Ps in the 2^3S level would require a detector with a position-sensitive resolution in the sub-nm range. This can be obtained by scanning the distribution of the Ps atoms on the plane by moving the slit/grating with sub-nm accuracy and by counting the Ps crossing the obstacle and those annihilating on it. Preliminary tests of the two J-PET modules have shown that they are promising candidates as a counting detector for this application.

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