

Status report on the setup for the decay rate measurement of the negative positronium ion

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Abstract. The negative positronium ion Ps^- is a bound system consisting of two electrons and a positron. Its three constituents are point-like and stable leptonic particles with equivalent mass, which are only subjected to the electroweak and the gravitational force. Hence Ps^- represents an ideal object to study the quantum mechanics of three-body systems.

We present a status report on a new measurement setup, which was used to perform several high precision lifetime measurements at the NEPOMUC facility. The combined results of systematic test measurements are discussed and an outlook to future measurements as well as preliminary results of the most recent beam time will be given.

1. Introduction

The Ps^- apparatus, which was used in the present study was designed by Frank Fleischer in Heidelberg to produce Ps^- and to measure its decay rate [1]. It was successfully applied to measure the Ps^- decay rate in 2006 with unprecedented accuracy [2]. Since a low intensity positron source was used the measurement was limited by statistics. Therefore, the setup was slightly modified and transferred to the NEPOMUC facility in Munich in order to increase statistics. However, first experiments at NEPOMUC showed systematic deviations of the measured value for the decay rate compared to previous measurements. After the installation of the remoderator, which decreased the primary beam energy from ≈ 1000 eV to about 20 eV, further systematic examinations revealed an unexpected dependence of the measured decay rate on the energy of the incident positron beam. The technical details of the advanced Ps^- setup, that allowed us to eliminate this dependence are presented.

2. Experimental Setup

The beam-foil technique first presented by A. Mills was applied to produce Ps^- [3]. The principle of this measurement can be described as follows: Ps^- are produced and drifted with a certain energy over a variable decay gap. The intensity I of the surviving Ps^- ions is measured as a function of the gap width d : $I \propto e^{-\mu \cdot d}$. Hence we get the decay constant μ , which can be converted into the decay rate Γ as described below. The high-intensity positron beam provided

by the NEPOMUC facility is directed onto a DLC foil¹ with an incident positron energy of 750 – 1200 eV. The positron subsequently picks up two electrons to create Ps^- . After the first electron is captured the emerging positronium can acquire an additional electron by inelastic scattering with a carbon atom. This is possible if the impact energy is insufficient to ionize the carbon atom but suffices to lift one of the outer shell electrons into the bound state of Ps^- (for a more detailed discussion see [1] or [4]). Therefore, the starting energy E_0 of the Ps^- ions is limited by the binding energy for the second electron, which is calculated to $E_b = 0.326675$ eV [5]. This could be confirmed by previous experiments where E_0 was found to be < 0.3 eV [1].

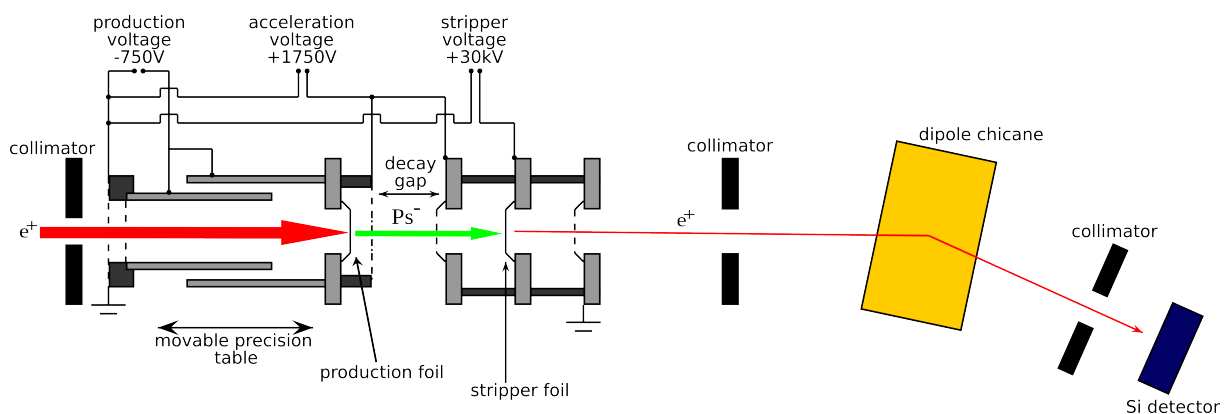


Figure 1. Schematics of the Ps^- setup. From left to right: Production and acceleration device, field-free decay gap and tandem-like stripping and detection unit.

The produced Ps^- ions are accelerated by an electric field between the production foil and a fine-meshed grid to their final energy of $(U_{\text{accel}} - U_{\text{prod}})e = 2500$ eV. Passing the acceleration grid the Ps^- ions enter the field-free decay volume which is terminated by a second fine-meshed grid. This field free decay volume represents the major difference to previous experiments, where the Ps^- acceleration took place over the whole decay gap. The variable distance between these two grids defines the length of the decay gap which can be adjusted by a high precision linear positioning stage.

The surviving Ps^- ions are accelerated towards a second DLC foil, to which a voltage of $U_{\text{strip}} = +30$ kV is applied. When the Ps^- ions impinge on the foil, the two electrons are stripped off and the remaining positron is again accelerated towards a grounded grid. At the exit of this tandem-accelerator-like setup the positrons have an energy of 40 keV and are magnetically guided towards a silicon particle detector. In order to increase the signal-to-noise ratio a chicane is mounted in front of the detector, which can only be passed by positrons with the right energy of 40 keV. Secondary electrons and ions are deflected and cannot reach the detector. This allowed us to increase the signal-to-noise ratio by a factor of 2 compared to the setup without the dipole. Consequently, a 40 keV positron signal in the detector serves as a fingerprint for a surviving Ps^- ion. The count rate of the surviving Ps^- ions is measured for a set of different gap distances in order to determine the decay constant μ .

The Ps^- vacuum decay rate Γ can hence be calculated from the measured decay constant μ :

$$\Gamma = \mu\beta\gamma c \quad (1)$$

¹ Diamond Like Carbon

with

$$\beta = \sqrt{1 - \frac{1}{\left(1 + \frac{(U_{\text{accel}} - U_{\text{prod}})e + E_0}{3m_e c^2}\right)^2}} \quad , \quad (2)$$

the Lorentz factor $\gamma = (1 - \beta^2)^{-\frac{1}{2}}$, e the electron charge and m_e the electron mass.

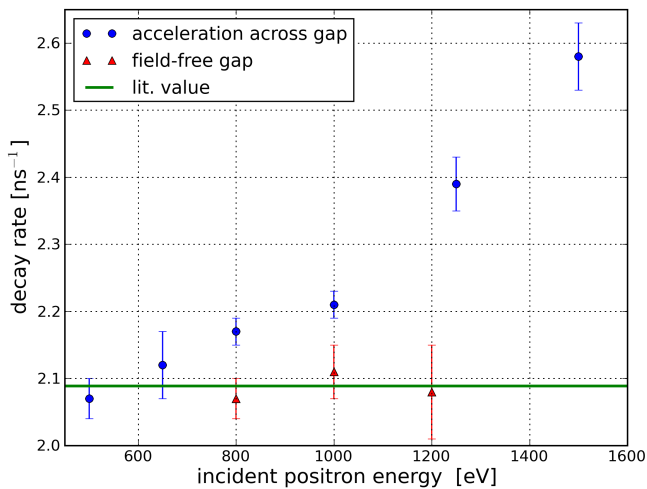


Figure 2. Dependence of the measured decay rate on the incident positron energy E (energy due to production voltage plus primary beam energy): values obtained with field-free decay gap are indicated by Δ , values obtained with Ps^- acceleration over the decay gap are indicated by \circ .

3. Results

First measurements revealed an increase of the decay rate with the incident positron energy (see Fig.2). Using the setup with the field-free decay gap we were able to eliminate this dependence, as can be seen in Fig. 2. The results of a previous measurement of the Ps^- decay rate Γ performed by Fleischer in Heidelberg could be confirmed within the error bounds. In two days of beam time at the NEPOMUC facility we were able to measure the decay rate with an accuracy of 1.1% [8] to:

$$\Gamma = 2.083(23) \text{ ns}^{-1}$$

This value is in good agreement with recent theoretical calculations for the decay rate of $\Gamma_{\text{Th}} = 2.087963(12) \text{ ns}^{-1}$ [7] as well as with the value obtained in Heidelberg $\Gamma_{\text{Exp}} = 2.089(15) \text{ ns}^{-1}$ [2]. It was shown that the new setup ensures a constant detection probability for the surviving Ps^- ions as well as a lower sensitivity to external perturbations such as stray magnetic fields, since all acceleration stages now operate at fixed positions in space and therefore with constant electric fields. This allows us also to resolve the problem with dependence of the measured value for the decay rate on the incident positron energy (see Fig. 2).

4. Discussion

The dependence of the measured decay rate on the incident positron beam energy is attributed to positrons which are transmitted through the production foil. The transmission probability itself, which depends on the positron energy, thickness and quality of the foil, is assumed to be constant. However, transmitted positrons are reflected in the acceleration² field and can

² This field is called "acceleration" field because it is used to accelerate the Ps^- ions. For positrons it acts as a retarding field.

be reflected back onto the production foil with a certain probability, where they contribute to the production of Ps^- . Therefore, the probability that a transmitted positron produces Ps^- is dependent on the reflection efficiency, which varies with the strength of the acceleration field.

While the transmission probability is constant throughout the measurement, the reflection efficiency and therefore the number of transmitted positrons, which are reflected back onto the foil, varies with the gap width. Hence the Ps^- production rate can change with the gap width, if the transmitted positrons have a significant contribution to the overall Ps^- production rate. Theoretical calculations and simulations [8] suggest that this effect has no significant contribution for incident positron energies below 800 eV and for short gap widths, which was both the case in previous measurements [4], [2]. However for higher energies the contribution of transmitted positrons to overall Ps^- production rate is clearly not neglectable.

However, this effect can be completely overcome by using a field-free decay gap, which allows to keep the acceleration field constant as shown above. As can be seen in Fig. 2 the measured decay rate is independent of the incident positron energy when the setup with the field free decay gap is used. Hence an error due to a varying Ps^- production rate with the gap distance is eliminated by the new setup.

5. Outlook

The preliminary evaluation of a recently completed beam time of about 10 days shows that with the increased statistics we are able to increase the accuracy for the decay rate measurement by a factor of 2-3 compared to previous measurements:

$$\Gamma = 2.0869(67) \text{ ns}^{-1}$$

This measurement was performed using the setup with the field-free decay gap, which we presented here. A complete discussion of the measurement and the data and error treatment is to be published [9].

Furthermore, an experiment for the Ps^- photo detachment and the production of a mono energetic ortho-positronium beam is already in preparation and will soon be operational.

6. Acknowledgement

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