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Prospects for forward emitted positronium from nanoporous membranes at AEgIS

Benjamin Rienäcker,[a,*] S. Alfaro Campos,[b,c] M. Auzins,[d] M. Berghold,[e] B. Bergmann,[f] P. Burian,[f] R. S. Brusa,[g,h] A. Camper,[x] R. Caravita,[h] F. Castelli,[i,j] G. Cerchiari,[b,c] R. Ciuryło,[k] A. Chehaimi,[g,h] G. Consolati,[i,l] M. Doser,[m] K. Eliaszuk,[n] R. Ferguson,[g,h] M. Germann,[m] A. Giszczak,[n] L. T. Glöggler,[m] Ł. Graczykowski,[n] M. Grosbart,[m] F. Guatieri,[e,g,h] N. Gusakova,[m,o] F. Gustafsson,[m] S. Haider,[m] S. Huck,[m,p] C. Hugenschmidt,[e] M. A. Janik,[n] T. Januszek,[n] G. Kasprowicz,[q] K. Kempny,[n] G. Khatri,[m] Ł. Kłosowski,[k] G. Kornakov,[n] V. Krumins,[d,m] L. Lappo,[n] A. Linek,[k] S. Mariazzi,[g,h] P. Moskal,[r,s] M. Münster,[e] P. Pandey,[r,s] D. Pecak,[t] L. Penasa,[g,h] V. Petracek,[u] M. Piwiński,[k] S. Pospisil,[f] F. Prelz,[i] S. A. Rangwala,[v] T. Rauschendorfer,[m,w] B. S. Rawat,[a,y] V. Rodin,[a] O. M. Røhne,[a] H. Sandaker,[a] S. Sharma,[r,s] P. Smolyanskiy,[f] T. Sowiński,[t] D. Tefelski,[n] M. Volponi,[m] C. P. Welsch,[a,y] M. Zawada,[k] J. Zielinski,[n] N. Zurlo[z,aa] and (AEḡIS collaboration)

[a] *Department of Physics, University of Liverpool,*
Liverpool L69 3BX, UK

[b] *University of Siegen, Department of Physics,*
Walter-Flex-Strasse 3, 57072 Siegen

[c] *Institut für Experimentalphysik, Universität Innsbruck,*
Technikerstrasse 25/4, 6020 Innsbruck, Austria

[d] *University of Latvia, Department of Physics,*
Raina boulevard 19, LV-1586, Riga, Latvia

[e] *Heinz Maier Leibnitz Zentrum (MLZ), Technical University of Munich,*
Lichtenbergstraße 1, 85748, Garching, Germany

[f] *Institute of Experimental and Applied Physics, Czech Technical University in Prague,*
Husova 240/5, 110 00, Prague 1, Czech Republic

[g] *Department of Physics, University of Trento,*
via Sommarive 14, 38123 Povo, Trento, Italy

[h] *TIFPA/INFN Trento,*
via Sommarive 14, 38123 Povo, Trento, Italy

[i] *INFN Milano,*
via Celoria 16, 20133 Milano, Italy

[j] *Department of Physics "Aldo Pontremoli", University of Milano,*
via Celoria 16, 20133 Milano, Italy

[k] *Institute of Physics, Faculty of Physics, Astronomy, and Informatics,*
Nicolaus Copernicus University in Toruń, Grudziadzka 5, 87-100 Toruń, Poland

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[*] Speaker

[l] *Department of Aerospace Science and Technology, Politecnico di Milano,*
via La Masa 34, 20156 Milano, Italy
[m] *Physics Department, CERN,*
1211 Geneva 23, Switzerland
[n] *Warsaw University of Technology, Faculty of Physics,*
ul. Koszykowa 75, 00-662, Warsaw, Poland
[o] *Department of Physics, NTNU, Norwegian University of Science and Technology,*
Trondheim, Norway
[p] *Institute for Experimental Physics,*
Universität Hamburg, 22607, Hamburg, Germany
[q] *Warsaw University of Technology, Faculty of Electronics and Information Technology,*
ul. Nowowiejska 15/19, 00-665 Warsaw, Poland
[r] *Marian Smoluchowski Institute of Physics,*
Jagiellonian University, Kraków, Poland
[s] *Centre for Theranostics,*
Jagiellonian University, Kraków, Poland
[t] *Institute of Physics, Polish Academy of Sciences,*
Aleja Lotnikow 32/46, PL-02668 Warsaw, Poland
[u] *Czech Technical University, Prague,*
Brehová 7, 11519 Prague 1, Czech Republic
[v] *Raman Research Institute,*
C. V. Raman Avenue, Sadashivanagar, Bangalore 560080, India
[w] *Felix Bloch Institute for Solid State Physics,*
Universität Leipzig, 04103 Leipzig, Germany
[x] *Department of Physics, University of Oslo,*
Sem Sælandsvei 24, 0371 Oslo, Norway
[y] *The Cockcroft Institute,*
Daresbury, Warrington WA4 4AD, UK
[z] *INFN Pavia,*
via Bassi 6, 27100 Pavia, Italy
[aa] *Department of Civil, Environmental, Architectural Engineering and Mathematics, University of Brescia,*
via Branze 43, 25123 Brescia, Italy

E-mail: `b.rienaecker@cern.ch`

Antihydrogen formation at AEgIS at CERN leverages charge exchange between Rydberg positronium (Ps*) and antiprotons, with cross-sections scaling with the Ps principal quantum number n^4 and inversely with relative velocity v^{-2}. However, the motional Stark effect and velocity mismatch between Ps and antiprotons impose stringent constraints, limiting efficiency. Advances in transmission positronium converters mitigate self-ionization losses and improve velocity alignment, promising a significant boost in antihydrogen yield. This work evaluates formation cross-sections, Ps velocity profiles, and the integration of advanced transmission Ps converters for precision gravitational studies.

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1. Introduction

Antihydrogen ($\bar{\mathrm{H}}$) formation through charge exchange between Rydberg-positronium (Ps*), the highly-excited bound state of an electron and a positron, and antiprotons lies at the heart of AEgIS' (Antimatter Experiment: gravity, Interferometry, Spectroscopy) effort to create a directed antihydrogen beam for precision studies of antimatter gravity at CERN. The formation cross-section $\sigma_{\bar{\mathrm{H}}}$ for this reaction strongly depends on the principal quantum number n of Ps and the relative velocity v of the interacting species, scaling as n^4 and in the range of low velocities as v^{-2} [1]. As a consequence, the directive is to excite Ps to high Rydberg-levels and match the velocities of the excited Ps fraction and antiprotons.

Two effects put strict limits on this basic principle. The first is a 1T magnetic field ($\vec{B} = [0, 0, B_z]$) in the antihydrogen formation region of AEgIS. This leads to self-induced electric fields by the $\vec{v} \times \vec{B}$ motional Stark effect for those Ps atoms that move under an angle to the B-field. As positronium is in highly excited Rydberg states, the induced Stark-shifts can be sufficient to ionize an increasing fraction of the Rydberg-Ps atoms as n goes up. The second effect is the large difference in velocities of Ps and antiprotons. At 1 eV kinetic energy, for example, the antiprotons are moderately slow ($v = 10^4\,\mathrm{m\,s^{-1}}$) due to their larger masses, whereas positronium still has $v = 10^5 - 10^6\,\mathrm{m\,s^{-1}}$, with a very broad Doppler profile. The high velocities not only reduce the cross-section per se, but also put more stringent limits on the Rydberg-level due to the self-ionization.

1.1 Self-Ionization Threshold

The Stark effect induces self-ionization in Rydberg-Ps when the motional electric field $|\vec{E}_{\mathrm{mot}}|$ surpasses the ionization threshold E_{min} as derived in Ref. [2]:

$$\vec{E}_{\mathrm{mot}} = \vec{v} \times \vec{B}, \quad E_{\mathrm{min}} = \frac{e}{16\pi\epsilon_0 a_0{}^2} \cdot \frac{1}{9n^4},$$

where e is the elementary charge, ϵ_0 is the permittivity of free space, and a_0 is the Bohr radius. Ps atoms with velocities $v_\rho^2 = v_x^2 + v_y^2 > v_{\mathrm{lim}} = E_{\mathrm{min}}/B$ exceed the ionization threshold and dissociate. This can be described by a single angle θ, thanks to the rotational symmetry of the Ps emission cone along the target normal, which in turn is aligned with the magnetic field. If the speed of Ps $v_{\mathrm{Ps}} < v_{\mathrm{lim}}$, this angle is unconstrained. Otherwise, $\theta = \arccos(\frac{v_{\mathrm{lim}}}{v_{\mathrm{Ps}}})$.

1.2 Ps velocity distribution

The velocity profile $G(v_{\mathrm{Ps}})$ of Ps is modeled using a 3D Gaussian, i.e. a Maxwell-Boltzmann distribution:

$$G(v_{\mathrm{Ps}}) = \frac{1}{\sqrt{2\pi\sigma_v^2}} \exp\left(-\frac{v_{\mathrm{Ps}}^2}{2\sigma_v^2}\right) v_{\mathrm{Ps}}^2 \cdot 2\pi\cos(\theta),$$

where σ_v is the 1D velocity spread of the Ps cloud. The angular correlation accounts for ionizing trajectories perpendicular to the magnetic field, causing a deviation from the normal distribution with speed $v_{\mathrm{Ps}}^2 = v_x^2 + v_y^2 + v_z^2$. This deviation manifests in a reduction of the fast tail of the velocity distribution as can be seen in Fig. 1. Note that there are still components present faster than the threshold, which comes from summing all three components of v_x, v_y, v_z – and only the v_x and v_y are required to be slower than v_{lim}, but not v_z.

1.3 Cross-section dependence on velocity

The charge-exchange cross-section for antihydrogen formation is modeled in Ref. [1] as:

$$\sigma_{\bar{\mathrm{H}}}(n, v) = \left(\frac{s_1}{k^2} + s_2\right) n^4,$$

where $k = 2nv/v_{\mathrm{au}}$ and v is the relative speed between a Rydberg-Ps atom and an antiproton. Since Ps typically is much faster than the antiprotons, this v can often be substituted by the speed of Ps v_{Ps} and

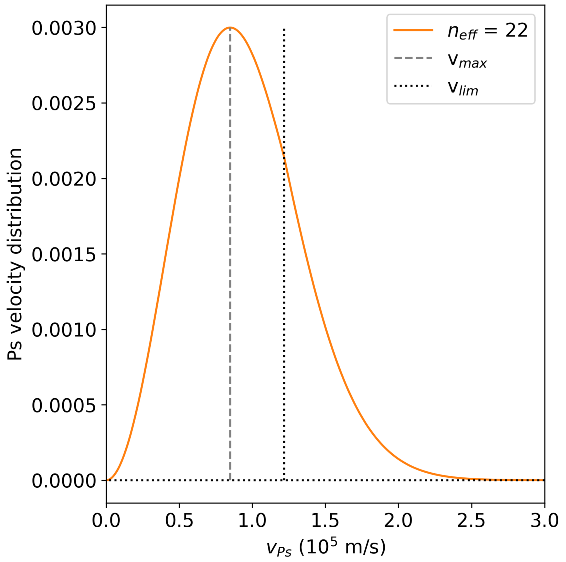

Figure 1: Ps velocity distribution for Ps in the $n_{\mathrm{eff}} = 22$ manifold with the converter target's normal aligned with the magnetic field B. Due to self-ionization effects, the distribution decreases faster beyond the threshold velocity v_{lim}.

the antiprotons are considered static. This is not generally true and needs to be adjusted as the model and aspired precision requires it. The atomic unit of velocity is $v_{\mathrm{au}} = 2.188 \cdot 10^6\,\mathrm{m\,s^{-1}}$ and the fit parameters $s_1 = 1.32 \cdot 10^{-16}$, $s_2 = 1.12 \cdot 10^{-15}$ were found numerically. At larger k the cross-section diminishes rapidly due to velocity mismatch between Ps and antiprotons. The complex dependency of the cross-section on n and v_{Ps} is shown in Fig. 2, bottom. It becomes clear that at lowest Ps speed and highest Rydberg levels the normal ground state cross-section can be boosted by almost seven orders of magnitude. Of course, the self-ionization in magnetic fields, the broad Ps velocity spread and the requirement of dense particle clouds during antihydrogen formation severely limit the resulting formation efficiency again.

1.4 Efficiency estimation

The formation efficiency of antihydrogen is determined by integrating the cross-section weighted by the Ps velocity distribution $G(v_{\mathrm{Ps}})$, neglecting the particle cloud densities during overlapping:

$$\eta_{\bar{\mathrm{H}}} = \int \sigma_{\bar{\mathrm{H}}}(n, v_{\mathrm{Ps}}) G(v_{\mathrm{Ps}}) dv_{\mathrm{Ps}}.$$

The result of this integration can be seen in Fig. 2, top. For each addressed Rydberg manifold n_{eff}, taking into account the self-ionization at that level for a Ps emission cone aligned with the 1T magnetic field, the formation efficiency is plotted, and together with the particle cloud densities it would denote the number of formed antihydrogen atoms. Hence, the higher this efficiency becomes, the more atoms can be expected.

In the current setup of AEgIS, with $n_{\mathrm{eff}} = 22$ and a velocity spread of $\sigma_{\mathrm{vPs}} = 60\,\mathrm{km\,s^{-1}}$, an increase of one order of magnitude with respect to the 2018/19 setup, with $n_{\mathrm{eff}} = 16$ and a velocity spread of $\sigma_v = 100\,\mathrm{km\,s^{-1}}$, can be achieved. A mild increase can still be expected for even higher Rydberg levels, but no dramatic improvement from thereon.

2. Transmission Ps converters

2.1 Current status of Ps formation at AEgIS

While significant progress has been made over the years in producing and manipulating cold positronium ($v < 10^5\,\mathrm{m\,s^{-1}}$) [3–5], traditional methods utilizing reflection geometry converters have inherent limitations.

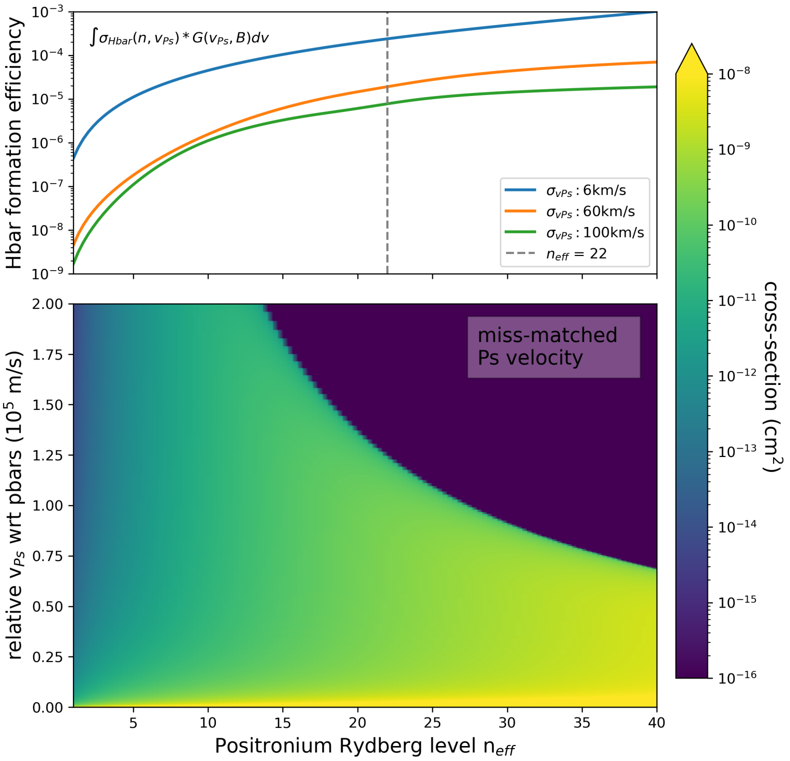

Figure 2: Bottom: Calculated $\bar{\text{H}}$ formation cross-section as a function of v_{Ps}. Regions of low v_{Ps} and high n yield maximum cross-section. Top: Integrated cross-section weighed with the velocity distribution of the Ps emission cone. The converter target normal is assumed to be aligned with the magnetic field and self-ionization effects are taken into account as well.

Installed out of the beam axis with an angle between the target's normal and the axis, such as it was done at AEgIS until 2019 [6], reflection converters suffered from self-ionization losses. At AEgIS, the target's normal angle against the beam axis was 30 degrees, and the overall overlap between the two particle species was rather low due to the physical distance of their sources - and ultimately the formation efficiency is also a function of the respective particle densities. Indeed, a systematic study conducted at AEgIS revealed that already at $n = 16$, about 25% of the Ps atoms were self-ionizing in the 1T-field [7] and no higher level could be chosen for the rather warm Ps cloud which had a peak velocity at $1.5 \cdot 10^5\ \text{m}\,\text{s}^{-1}$.

In the phase-II upgrade, a miniature 5×5 mm e^+/Ps-converter reflection target was installed on-axis inside the antihydrogen formation trap, in the center of a specially designed electrode that could be heated to remove frozen contaminants if needed. This change of geometry removed to first order the limitation of Ps self-ionization in AEgIS magnetic field bz aligning the target's normal with the beam axis, so that higher Rydberg levels up to $n = 22$ could be targeted. However, in this approach the centered reflection converter obstructs the downstream beam path, leading to annihilation losses of freshly formed antihydrogen, which has to pass the target in order to reach the upcoming moiré deflectometer for a gravity measurement. Furthermore, as the trajectory of Ps from the reflection target is facing upstream, the best antihydrogen formation efficiency for a gravity measurement is reached when the antiprotons are as static (cold) as possible. Formed antihydrogen atoms would thus expand in a 4π sphere, as the momentum is mainly defined by the heavier antiprotons'.

2.2 Prospects for transmission Ps converter targets at AEgIS

Recent advances in nanostructured materials, such as porous silicon membranes, have introduced the possibility of producing positronium in transmission geometry. This breakthrough, first demonstrated with efficiencies of up to 5% [8] and projected to exceed 20% [9], offers a promising avenue for enhancing antihydrogen yield. Transmission converters allow to form a Ps beam with downstream trajectories and thus overlap them with a still moving antiproton cloud. All formed antihydrogen atoms, which could be significantly more due to the matched velocities and the reduced self-ionization losses, will keep moving downstream and thus contribute to the gravity measurement. Techniques such as Doppler cooling of positronium [10, 11] opens further avenues for improved velocity distributions and beam collimation, and ultimately for novel experiments with cold and dense Ps beams.

By addressing the limitations of reflection converters and leveraging advances in transmission technology, AEgIS aims to achieve another major increase in antihydrogen beam intensity. This advancement will not only improve gravitational studies but could also serve as a critical resource for broader precision experiments with positronium such as studies into Bose-Einstein condensates and in-depth QED tests. Also tests of the Weak-Equivalence Principle via the gravitational red-shift of Ps could greatly benefit from this development [12–15].

Using the well-established technique of electrochemical etching with hydroflouric acid on doped silicon wafers at variable etching currents and times allows creating extremely thin nanoporous membranes in the range of few micrometer, matching the positron implantation profile at few keV kinetic energy and the necessary Ps diffusion length for thermalisation as demonstrated in [8]. Since these thin membranes are very fragile, a critical next step involves developing a modular membrane holder designed to operate inside and outside of AEgIS magnetic fields. This modularity minimizes risks associated with cryogenic stress and ensures reproducibility during experimental iterations. Cryogenic testing of these holders will evaluate their robustness under extreme conditions and refine installation procedures. Subsequent experiments will focus on achieving high Ps formation and excitation to Rydberg states around n= 30, projected to increase antihydrogen yield by more than an order of magnitude. Applying AEgIS technique of Ps Doppler cooling could further enhance beam quality, laying the groundwork for AEgIS' long-term goal of producing a highest-intensity antihydrogen beam.

The successful deployment of transmission converters will have a profound impact on antihydrogen studies. Enhanced beam quality reduces systematic uncertainties, providing a stable foundation for gravity measurements and symmetry tests. Moreover, these converters offer versatile applications across various positronium-based experiments, laying the ground for collaboration within the antimatter research community.

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