

The 4-body structure and scattering calculations for the antihydrogen - positronium system: aiding the experiments comparing matter and antimatter.

P. Froelich, T. Yamashita, Y. Kino, S. Jonsell, E. Hiyama



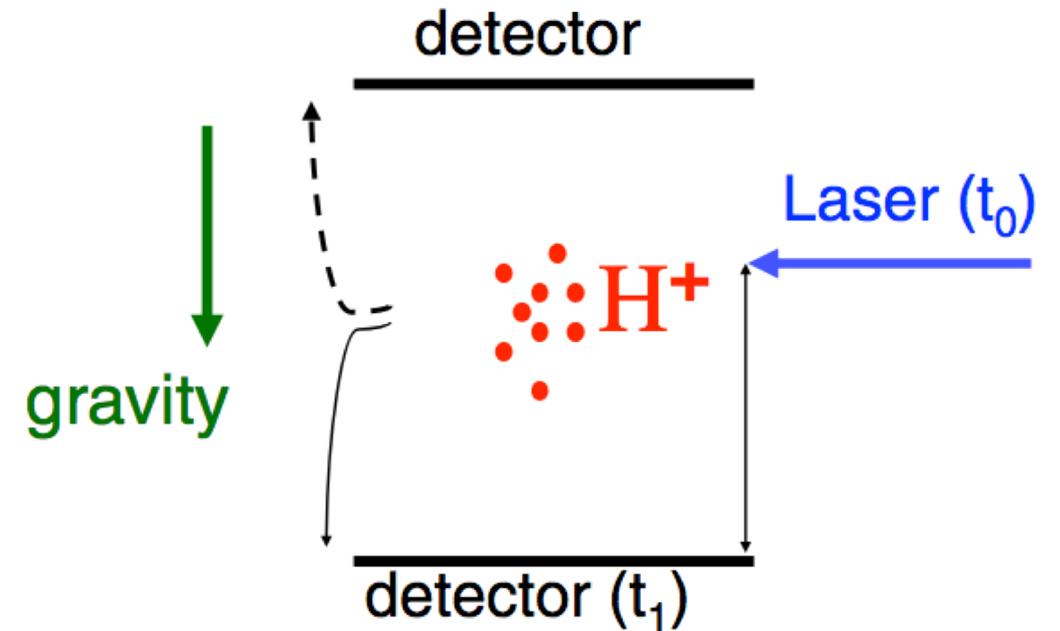
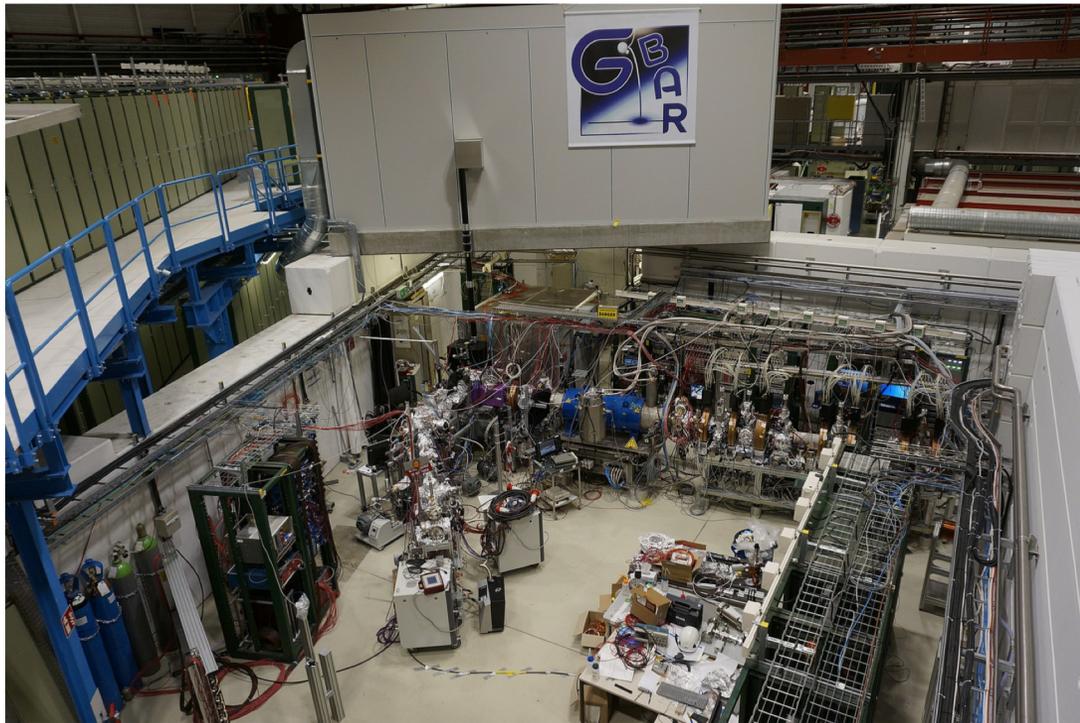
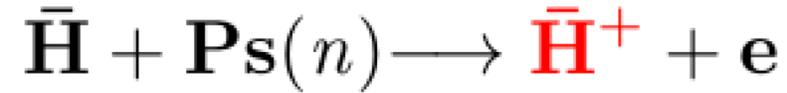
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- Basics of the 4-body treatment of antihydrogen-positronium collisions
- Calculation of the \bar{H}^+ formation in rearrangement collisions: $\bar{H} + Ps(n) \rightarrow e + \bar{H}^+$
- Calculation of the cross sections for all other coupled processes competing with \bar{H}^+ formation:
elastic scattering, excitation, deexcitation, polarization, depolarization
- Discussion of the near-threshold scattering in view of the Wigner laws
- Resonances in elastic and inelastic $\bar{H} + Ps$ scattering below the \bar{H}^+ threshold : energies, partial widths, total widths
- Binding energy and structure of $\bar{H}Ps$: analysis in terms of the 3-dimensional, angle-resolved probability densities
- Discussion of the accuracy. Unitarity of the S-matrix. Parity. Threshold laws. Scattering length. Binding energy.
- Impact on experiments at CERN.

The topics outlined above and in the following slides will be presented in form of a survey, and/or discussed separately in more depth with interested participants.

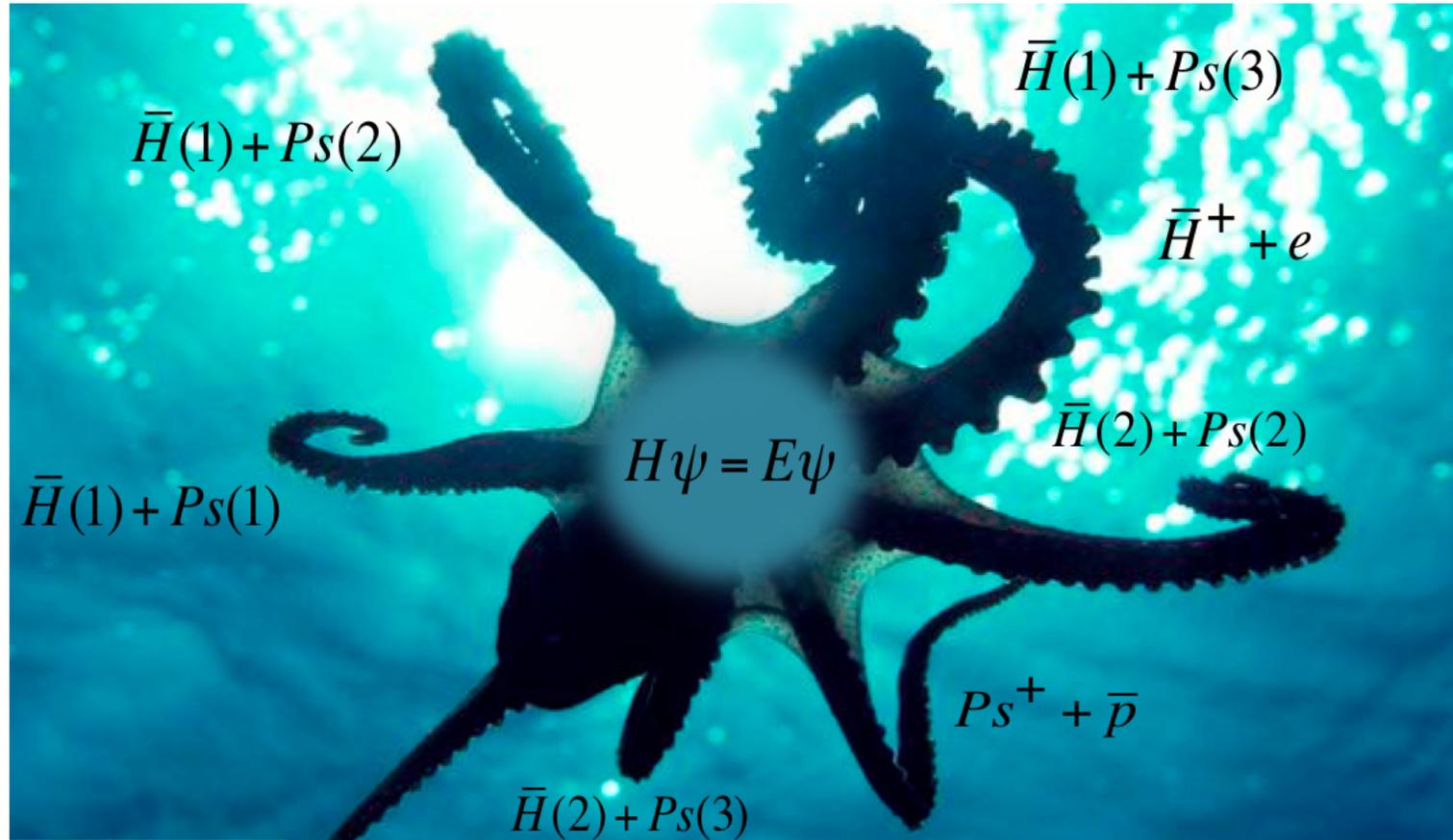
Formation rates of \bar{H}^+ in low energy $\bar{H} + Ps(n)$ collisions

We calculate the accurate scattering cross sections for production of antihydrogen ions in antihydrogen - positronium rearrangement collisions:



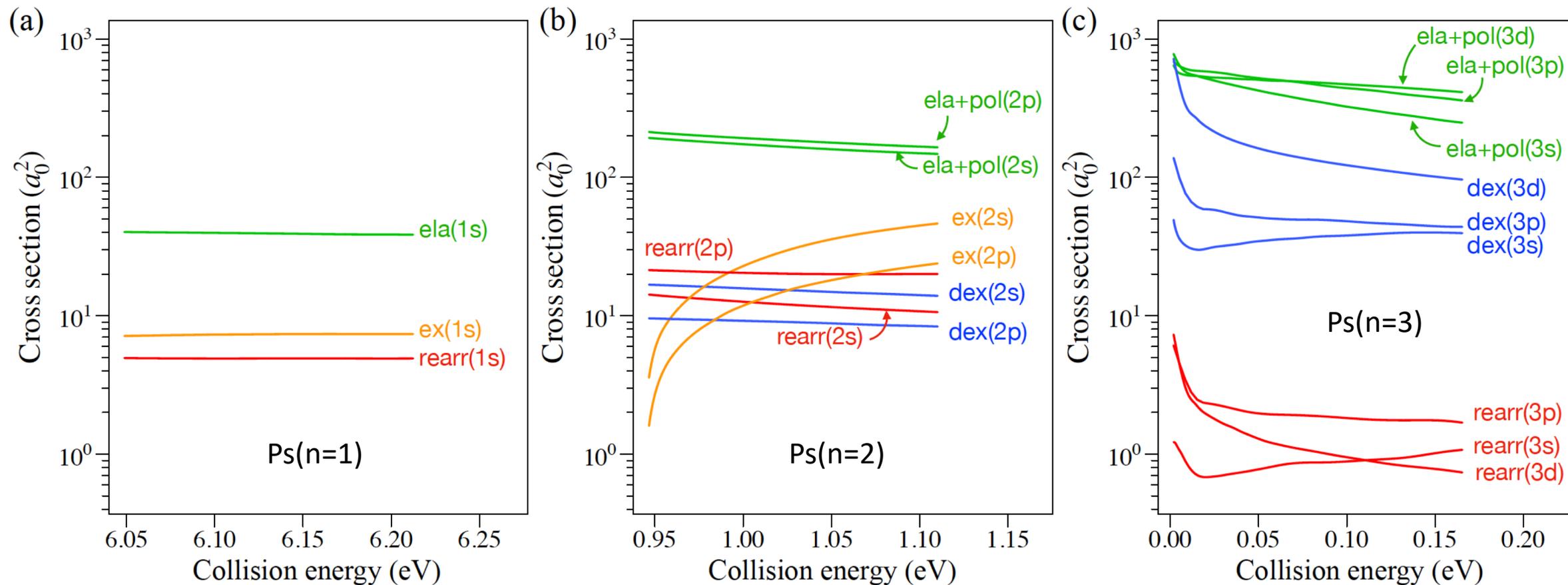
\bar{H}^+ ions are to be used in the GBAR experiment at CERN as a source of ultracold \bar{H} atoms for ballistic and interferometric tests of the gravitational interaction between matter and antimatter

Rearrangement scattering and structure calculations for $\bar{H} + Ps(n)$



The $\bar{H} + Ps(n)$ collision may result in very many outcomes. We may have elastic scattering, excitation of positronium, excitation of antihydrogen, formation of antihydrogen ion, formation of positronium ion, ... We present the cross sections for all these processes, obtained from the rigorous ab initio, four-body, multi-channel scattering calculation. We address the relevance of the rearrangement collisions resulting in \bar{H}^+ ions for the ongoing matter-antimatter experiments at CERN. We also discuss the binding and resonant structure of the $\bar{H}Ps$ system, particularly its atomcule character.

Rearrangement scattering in $\bar{H} + Ps(n)$ collisions. \bar{H}^+ formation and competing processes.

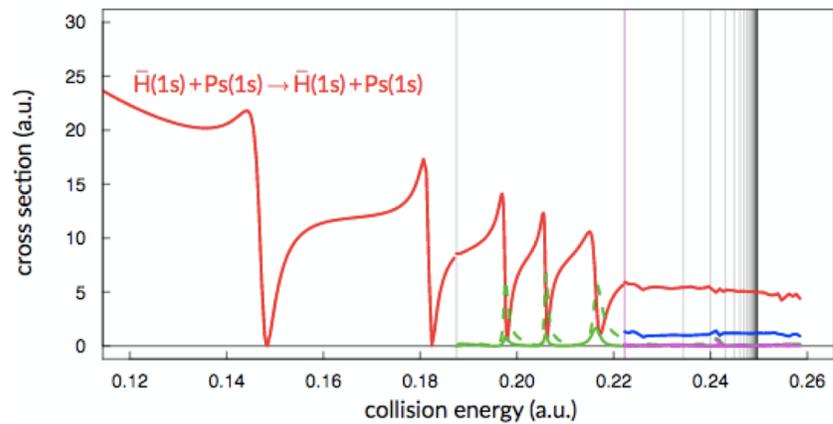
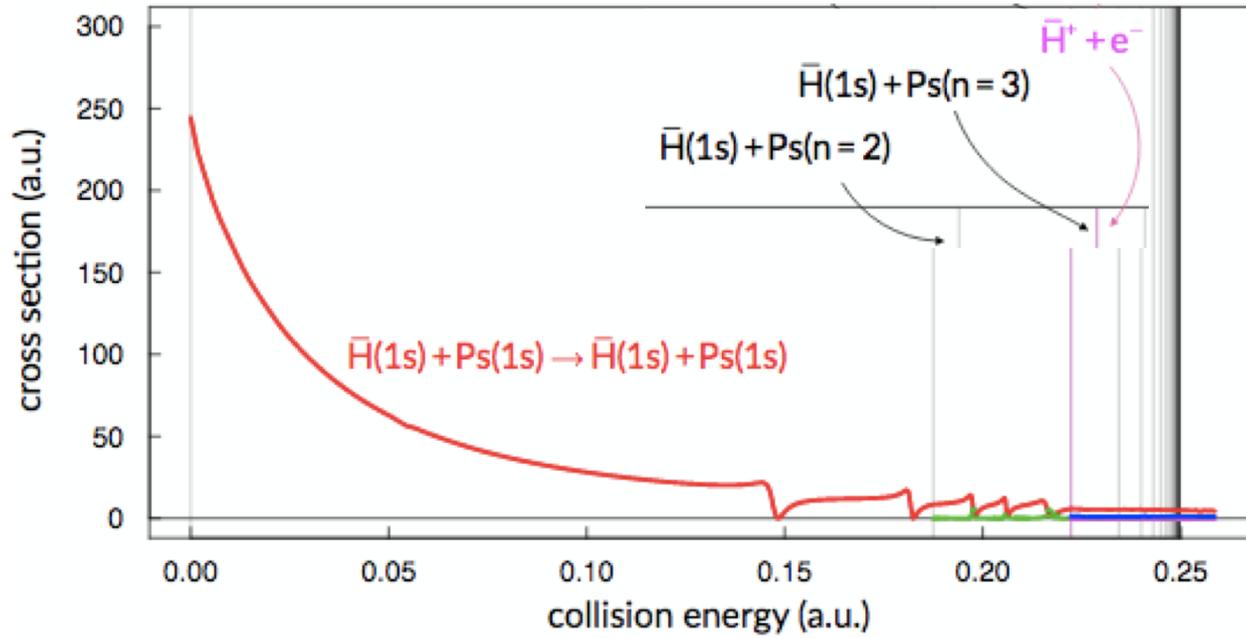


Scattering cross sections above the $\bar{H} + e$ threshold for $Ps(n=1)$, $Ps(n=2)$ and $Ps(n=3)$.

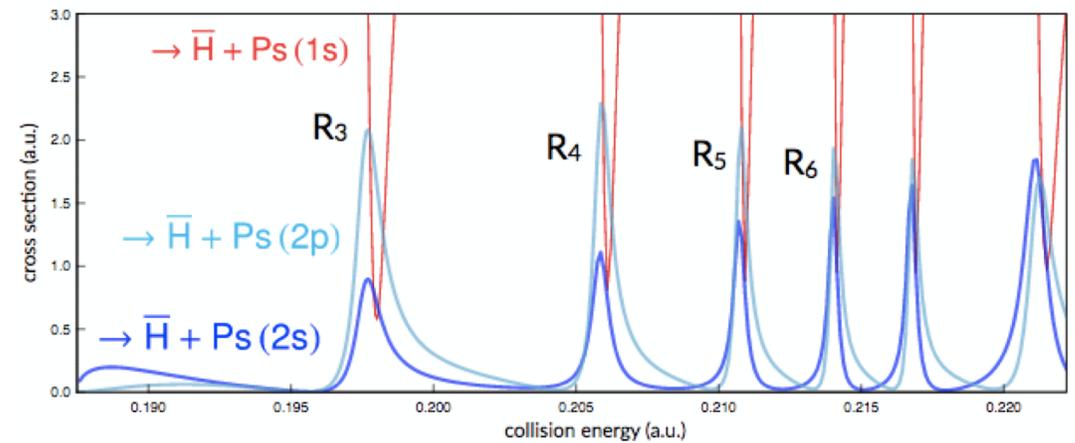
Red: \bar{H}^+ formation, green: elastic scattering, polarization/depolarization of Ps , orange: excitation of Ps , blue: deexcitation of Ps . Spin weighting included.

Early gbar estimation for $Ps(3d)$: $300 a_0^2$.

Resonances in elastic and inelastic $\bar{H} + Ps$ scattering – gross view



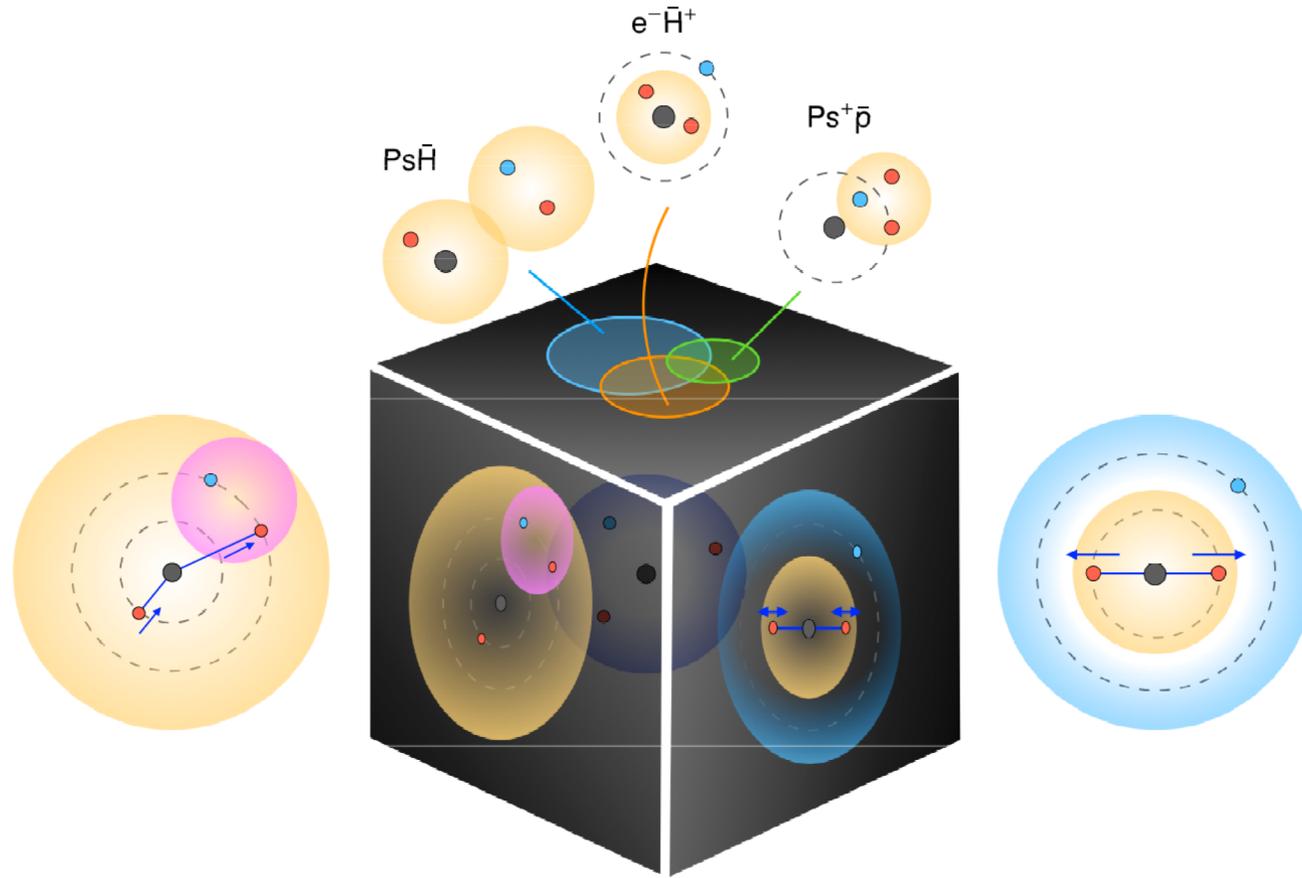
Magnification: resonances in elastic scattering



Magnification: resonances in inelastic scattering

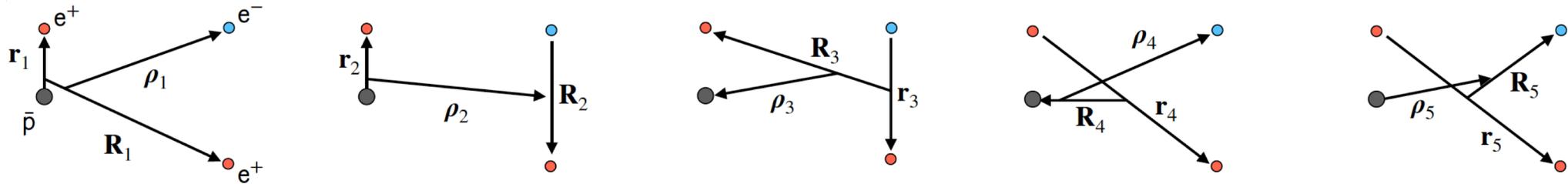
Four-body structure and binding in the $\bar{H}Ps$ system

The bound state of $\bar{H}Ps$ is a trichotomy of structures: atomic 68% (an electron bound to the \bar{H}^+ core), molecular 71% (binding of Ps to \bar{H}) and positronium ion binding to the \bar{p} 24%. These structures partially overlap.

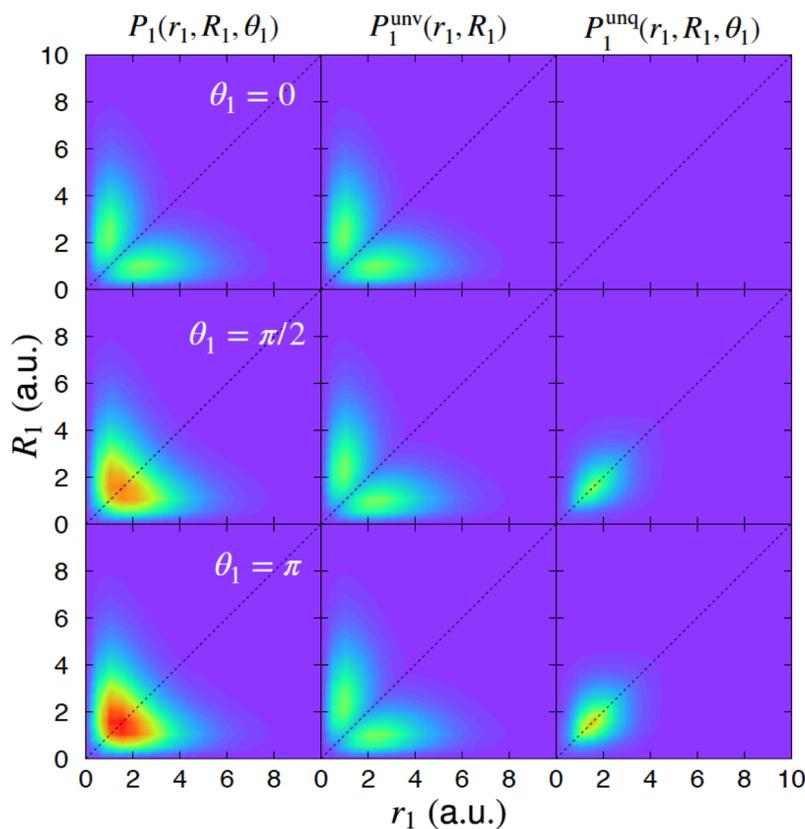


This trichotomy of structures in $\bar{H}Ps$ is demonstrated by probing the $\bar{H}Ps$ system with one, two and three dimensional, interparticle distances and angle dependent probability density functions.

Internal structure of $\bar{H}Ps$ from the 3-dimensional, angle resolved probability densities



Up: the 5 sets of Jacobi coordinates used to describe the wavefunction Ψ



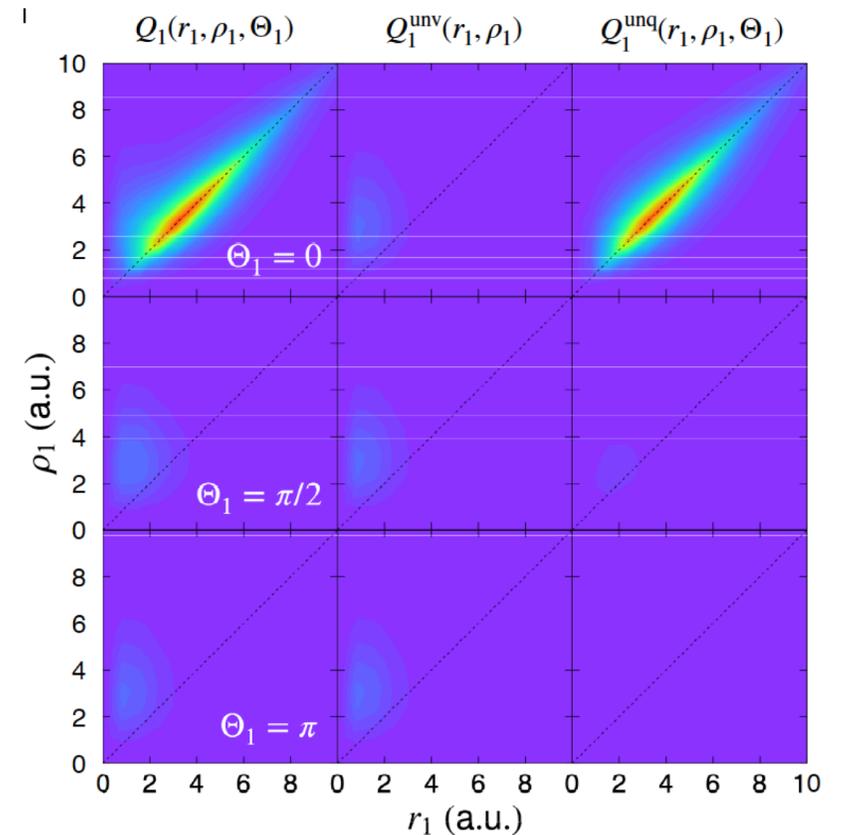
$$P_1(r_1, R_1; \theta_1) = N r_1^2 R_1^2 \int d\rho_1 d\hat{\tau}_1 \Psi^* \Psi$$

Left: emergence of the $e^+ - \bar{p} - e^+$ rotor structure and "unequal positron arm" structure in the \bar{H}^+ ionic core.

Right: an electron follows one of the positrons to form Ps , leaving \bar{H} behind. The structure of $\bar{H}Ps$ molecule is emerging.

In addition, $e^+ - e - e^+$ tend to stay aligned, resulting in emergence of the Ps^+ structure (shown separately)

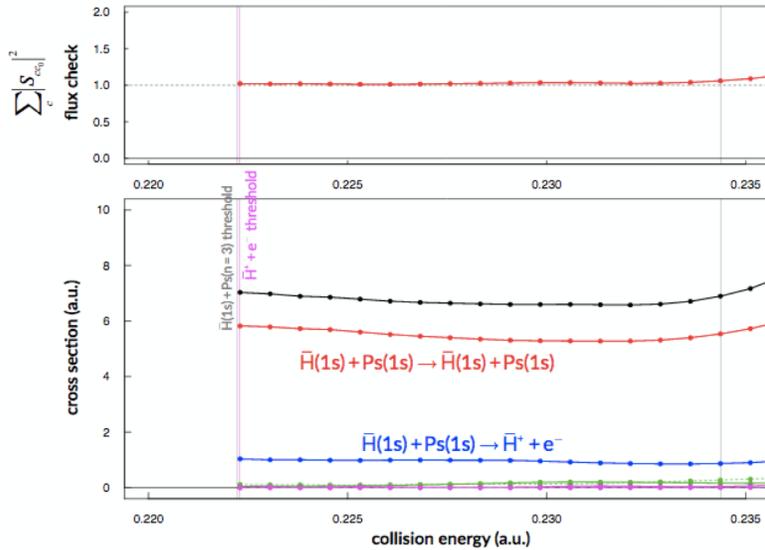
These structures coexist in the bound $\bar{H}Ps$ system.



$$Q_1(r_1, \rho_1; \Theta_1) = N r_1^2 \rho_1^2 \int d\mathbf{R}_1 d\hat{\tau}_1 \Psi^* \Psi$$

Discussion of the accuracy of the calculation

Unitarity and symmetry of the S-matrix: $\sum_{\beta} |S_{\beta\alpha}|^2 = 1$



Flux conservation: $\sum_{\beta} |S_{\beta\alpha}|^2 = 1 \pm 0.001$

0.6130	0.3736	0.3437	0.1393	0.0132	0.0739	0.0038	0.0190	0.0034	0.5735
0.3657	0.1603	0.4740	0.7019	0.0179	0.0218	0.0004	0.0350	0.0012	0.3311
0.3514	0.4886	0.2163	0.3667	0.0121	0.1374	0.0018	0.0228	0.0031	0.6722
0.1384	0.7040	0.3585	0.5177	0.0210	0.1003	0.0010	0.0256	0.0023	0.2788
0.0485	0.0149	0.0266	0.0173	1.0002	0.1765	0.0032	0.0773	0.0146	0.0121
0.1625	0.0430	0.1673	0.0969	0.1342	0.9921	0.0175	0.0583	0.0381	0.0620
0.0077	0.0024	0.0040	0.0032	0.0204	0.0304	0.9997	0.0157	0.0024	0.0060
0.0406	0.0482	0.0404	0.0437	0.0861	0.1783	0.0016	0.9997	0.0132	0.0207
0.0060	0.0011	0.0010	0.0015	0.0117	0.0020	0.0020	0.0102	0.9998	0.0030
0.5842	0.3299	0.6636	0.2743	0.0185	0.0750	0.0026	0.0150	0.0053	0.1712

Time-reversal symmetry: $S^T = S$

Binding energy of $\bar{H}Ps$
 $E_b = 0.027\,717\text{ a.u.} \pm 0.000\,0001\text{ a.u.}$

Scattering length for elastic scattering:

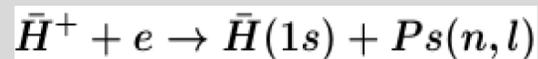
$$\lim_{k_i \rightarrow 0} \sigma^{elastic}(k_i) = 4\pi|a|^2$$

$$a = 4.291\text{ a.u.}$$

(lowest upper bound available today)

The calculated cross sections (colored lines) follow the general trend expected from the Wigner's threshold laws (grey shade)

Example: time-reversed process to \bar{H}^+ formation, i.e. Ps and \bar{H} formation in the rearrangement reaction:



$$\sigma^{reverse}(k_i \rightarrow 0) \propto k_i^{-2}$$

