Diatomic systems containing antihydrogen

Vasily Sharipov

Leonti Labzowsky, Günter Plunien

V. A. Fock Institute, St. Petersburg State University, Russia
Technical University Dresden, Germany

Contents

- Motivation
- Current status of experiment
- Interaction between the antihydrogen atom ($\mathbf{\bar{H}}$) and an ordinary matter atom
- Quasibound states of the $\mathbf{H\bar{H}}$ and $\mathbf{He\bar{H}}$ systems
- Conclusions

Motivation

- Search for a CPT-violation via comparison of hydrogen and antihydrogen spectra
- Search for long-lived states of $\bar{\mathbf{H}}$ compounds with an ordinary atom

Existence of these states provides a possibility to store and transport the $\bar{\mathbf{H}}$ atoms

Current status of experiment

ATHENA (Amoretti *et al*., Nature **419**, 456 (2002))

ATRAP (Gabrielse *et al*., PRL **89,** 213401 (2002))

- Penning trap, ~10^3 at./hour
- External electric (~10^2 V/cm) and magnetic (~1 T) fields
- $\bar{\mathbf{H}}$ atoms were produced in Rydberg states (n=30-50)

ALPHA (Andresen *et al*., PRL **98,** 023402 (2007))

Hints

- All investigations consider the interaction of the $\bar{\mathbf{H}}$ atom in the ground state with ordinary matter systems (**H, He,** $\mathbf{H_2}$)
- The most accurate calculation employed

Explicitly Correlated Gaussian basis set

K. Strasburger, H. Chojnacki, and A. Sokolowska,
J. Phys. B **38**, 3091 (2005)

- An optical potential provides an adequate description of the $\mathbf{H\bar{H}}$ quasibound states

B. Zygelman, A. Saenz, P. Froelich, and S. Jonsell, PRA **69**, 042715 (2004)

Born-Oppenheimer approximation

$$\Psi(\mathbf{x},\mathbf{X}) = \Psi^{\mathrm{lep}}(\mathbf{x},R)\Phi^{\mathrm{nuc}}(\mathbf{X})$$

$$\Psi^{\mathrm{lep}}(\mathbf{x},R) = \Psi_{\Lambda}^{\mathrm{lep}}(\mathbf{r},R)\chi_{SM_S}^{\mathrm{lep}}(\boldsymbol{\sigma})$$

$$\mathbf{H}^{\mathrm{lep}}(R)\Psi_{\Lambda}^{\mathrm{lep}}(\mathbf{r},R) = \mathrm{V}_{\Lambda}^{\mathrm{lep}}(R)\Psi_{\Lambda}^{\mathrm{lep}}(\mathbf{r},R)$$

$$\mathbf{L}_{\mathbf{R}}\Psi_{\Lambda}^{\mathrm{lep}}(\mathbf{r},R) = \Lambda\Psi_{\Lambda}^{\mathrm{lep}}(\mathbf{r},R)$$

Explicitly Correlated Gaussians

$$\Psi_{\Lambda}^{\text{lep}}(\mathbf{r}, R) = \sum_{k=1}^{N} C_k \mathbf{P}\{G^{(k)}(\mathbf{r}, R) \cdot \eta_{\Lambda}^{(k)}(\mathbf{r}, R)\}$$

$$G^{(k)}(\mathbf{r}, R) = \exp\left(-\sum_{i>j}^{n} b_{ij}^{(k)} (\mathbf{r}_i - \mathbf{r}_j)^2 - \sum_{i=1}^{n} a_i^{(k)} (\mathbf{r}_i - \mathbf{R}_i^{(k)})^2 \right)$$

$$\eta_{\Lambda}^{(k)}(\mathbf{r}, R) = |\mathbf{v}^{(k)}|^{\Lambda} \, Y_{\Lambda\Lambda}(\mathbf{v}) \qquad \mathbf{v}^{(k)} = \sum_{i=1}^{n} u_i^{(k)} \mathbf{r}_i$$

N - number of basis functions

n - number of light particles

Optical potential

$$\Psi(\mathbf{x},\mathbf{X}) = \mathrm{F}(\mathbf{X})\left|a\right\rangle + \sum_{\mathbf{k}} f_{\mathbf{k}}(\mathbf{X})\left|\mathbf{k}\right\rangle$$

$$\left(-\frac{1}{2\mu}\Delta_{\mathbf{R}} + \mathrm{V}_{\Lambda}^{\mathrm{lep}}(R) - \frac{Z}{R}\right)\mathrm{F}(\mathbf{R}) +$$

$$+\int d\mathbf{R}'\,\mathrm{V}_{\mathrm{opt}}(\mathbf{R},\mathbf{R}';E)\,\mathrm{F}(\mathbf{R}') = E\,\mathrm{F}(\mathbf{R})$$

Perturbation theory in V_{opt} : zero-order approximation

$$\left(-\frac{1}{2\mu}\Delta_{\mathbf{R}} + \mathrm{V}_{\Lambda}^{\mathrm{lep}}(R) - \frac{Z}{R} \right) \Phi^{\mathrm{nuc}}(\mathbf{X}) = E\Phi^{\mathrm{nuc}}(\mathbf{X})$$

$$\Phi^{\mathrm{nuc}}(\mathbf{X}) = \frac{1}{R}\chi_{\Lambda nl}(R)\,\mathrm{Y}_{lm}(\mathbf{R})\cdot\beta(\sigma_{\mathrm{nuc}})$$

$$\frac{d^2\chi_{\Lambda nl}(R)}{dR^2} + \left(\mu(E_{\Lambda nl} - E_{\Lambda}(R)) - \frac{l(l+1)}{R^2} \right)\chi_{\Lambda nl}(R) = 0$$

Annihilation of leptons

$$\Gamma^{\text{lep}} = A_{2\gamma}^{\text{lep}} \left\langle \Psi(\mathbf{x},\mathbf{X}) \,|\, {\sum_{i,j}}' \delta(\mathbf{r}_i - \mathbf{r}_j)(1 - \mathbf{S}_{ij}) \,|\, \Psi(\mathbf{x},\mathbf{X}) \right\rangle +$$

$$+ A_{3\gamma}^{\text{lep}} \left\langle \Psi(\mathbf{x},\mathbf{X}) \,|\, {\sum_{i,j}}' \delta(\mathbf{r}_i - \mathbf{r}_j)\mathbf{S}_{ij} \,|\, \Psi(\mathbf{x},\mathbf{X}) \right\rangle$$

$$P_{\Lambda}^{2\gamma,3\gamma}(R) = \left\langle \Psi_{\Lambda}^{\text{lep}}(R) \,|\, \sum_{i,j}^{2\gamma,3\gamma} \delta(\mathbf{r}_i - \mathbf{r}_j) \,|\, \Psi_{\Lambda}^{\text{lep}}(R) \right\rangle$$

$$\Gamma_{\Lambda\text{nl}}^{\text{lep}} = \Gamma_{2\gamma}^{\text{lep}} + \Gamma_{3\gamma}^{\text{lep}} = \int_{R_c}^{\infty} |\,\chi_{\Lambda\text{nl}}(\mathrm{R})|^2 \,[P_{\Lambda}^{2\gamma}(R) + P_{\Lambda}^{3\gamma}(R)]\,dR$$

Nuclear annihilation

$$\Gamma^{\text{nuc}} = A^{\text{nuc}} \left\langle \Psi(\mathbf{x}, \mathbf{X}) \,|\, \delta(\mathbf{R}) \,|\, \Psi(\mathbf{x}, \mathbf{X}) \right\rangle$$

$$\Gamma^{\text{nuc}} = A^{\text{nuc}} \left| \frac{\chi_{\Lambda nl}(R)}{R} \right|^{2}_{R \to 0}$$

Annihilation constant A^{nuc} have to be taken from experiment of nucleus - antiproton scattering

Formation of a positronium (**Ps**)

$$\left(-\frac{1}{2\mu}\Delta_{\mathbf{R}} + \mathrm{V}_{\Lambda}^{\mathrm{lep}}(R) - \frac{Z}{R}\right)\mathrm{F}(\mathbf{R},t) +$$

$$+\int d\mathbf{R}'\,\mathrm{V}_{\mathrm{opt}}(\mathbf{R},\mathbf{R}')\,\mathrm{F}(\mathbf{R}',t) = i\frac{\partial}{\partial t}\mathrm{F}(\mathbf{R},t)$$

$$\mathrm{F}(\mathbf{R},t) = e^{-iEt-\Gamma t/2}\Phi_{\Lambda nlm}^{\mathrm{nuc}}(\mathbf{R})$$

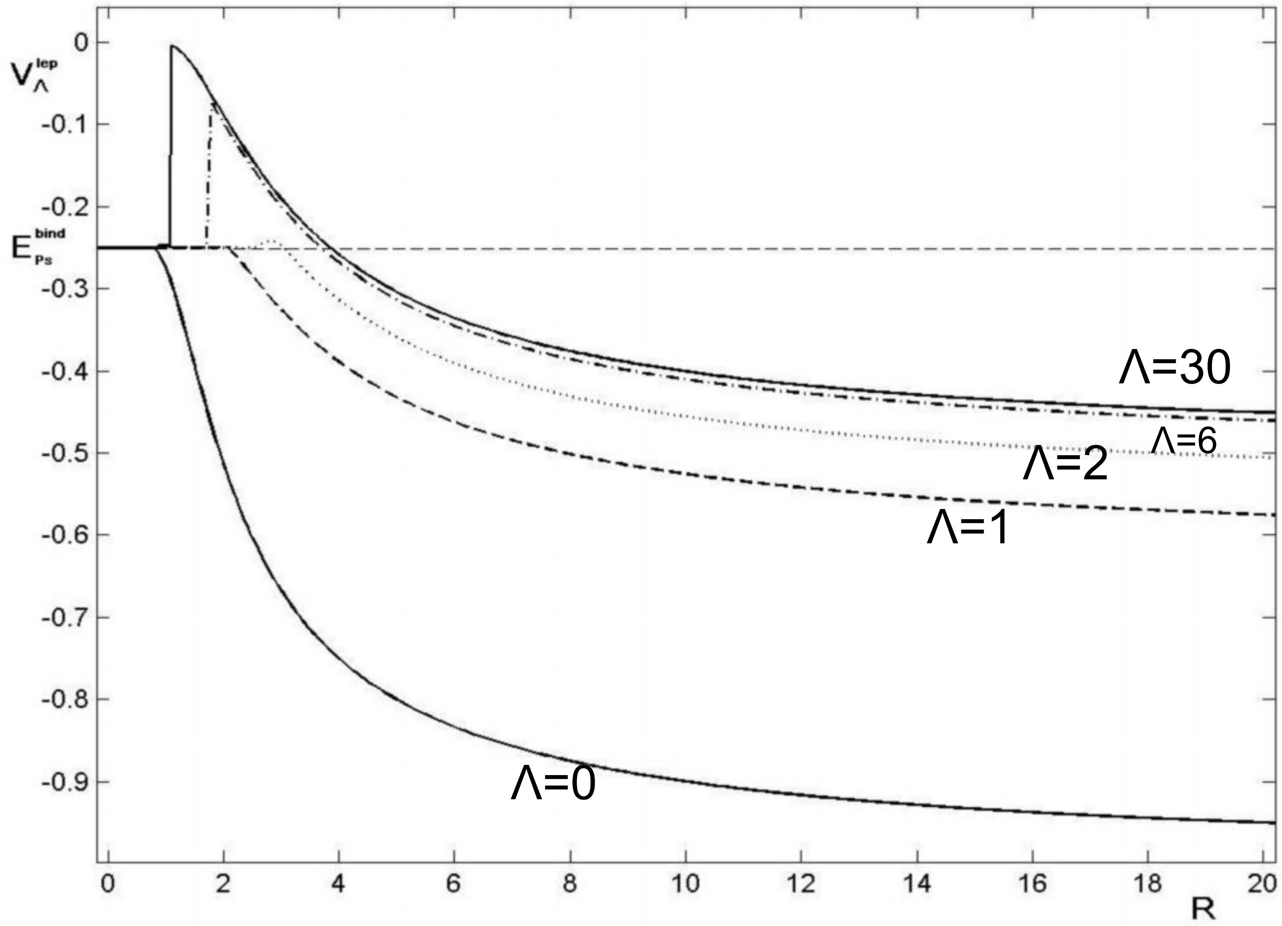
$$\Gamma_{\Lambda nlm}^{\mathrm{Ps}} = -2\iint d\mathbf{R}d\mathbf{R}'(\Phi_{\Lambda nlm}^{\mathrm{nuc}}(\mathbf{R}))^{*}\,\mathrm{Im}(\mathrm{V}_{\mathrm{opt}}(\mathbf{R},\mathbf{R}'))\Phi_{\Lambda nlm}^{\mathrm{nuc}}(\mathbf{R}')$$

$\mathbf{H\bar{H}}$ quasimolecule

- The states with Λ=0, 1, 2, 6 and 30 are considered
- Number of basis functions = 64
- Additional charge conjugation symmetry

V. Sharipov, L. Labzowsky, and G. Plunien,
PRL **97**, 103005 (2006)
V. Sharipov, L. Labzowsky, and G. Plunien,
PRA **73**, 052503 (2006)

$H\bar{H}$: leptonic potential



$\mathrm{H\bar{H}}$: decay rates

Small values of Λ (0, 1, 2)

$$\Gamma^{\mathrm{nuc}}_{\Lambda n00} \approx 3\cdot 10^{15} - 5\cdot 10^{13}\ \mathrm{Hz},\ \Gamma^{\mathrm{Ps}}_{\Lambda nlm} \approx 4\cdot 10^{14} - 7\cdot 10^{13}\ \mathrm{Hz},$$

$$\Gamma^{\mathrm{lep}}_{\Lambda nlm} \approx 4\cdot 10^{9} - 1\cdot 10^{8}\ \mathrm{Hz}; \qquad n = 20 - 41,\ l, m = 0, 1$$

Large values of Λ (6, 30)

$$\Gamma^{\mathrm{nuc}}_{\Lambda n00} \approx 4\cdot 10^{14} - 4\cdot 10^{13}\ \mathrm{Hz},\ \Gamma^{\mathrm{Ps}}_{\Lambda nlm} \approx 3\cdot 10^{13} - 4\cdot 10^{11}\ \mathrm{Hz},$$

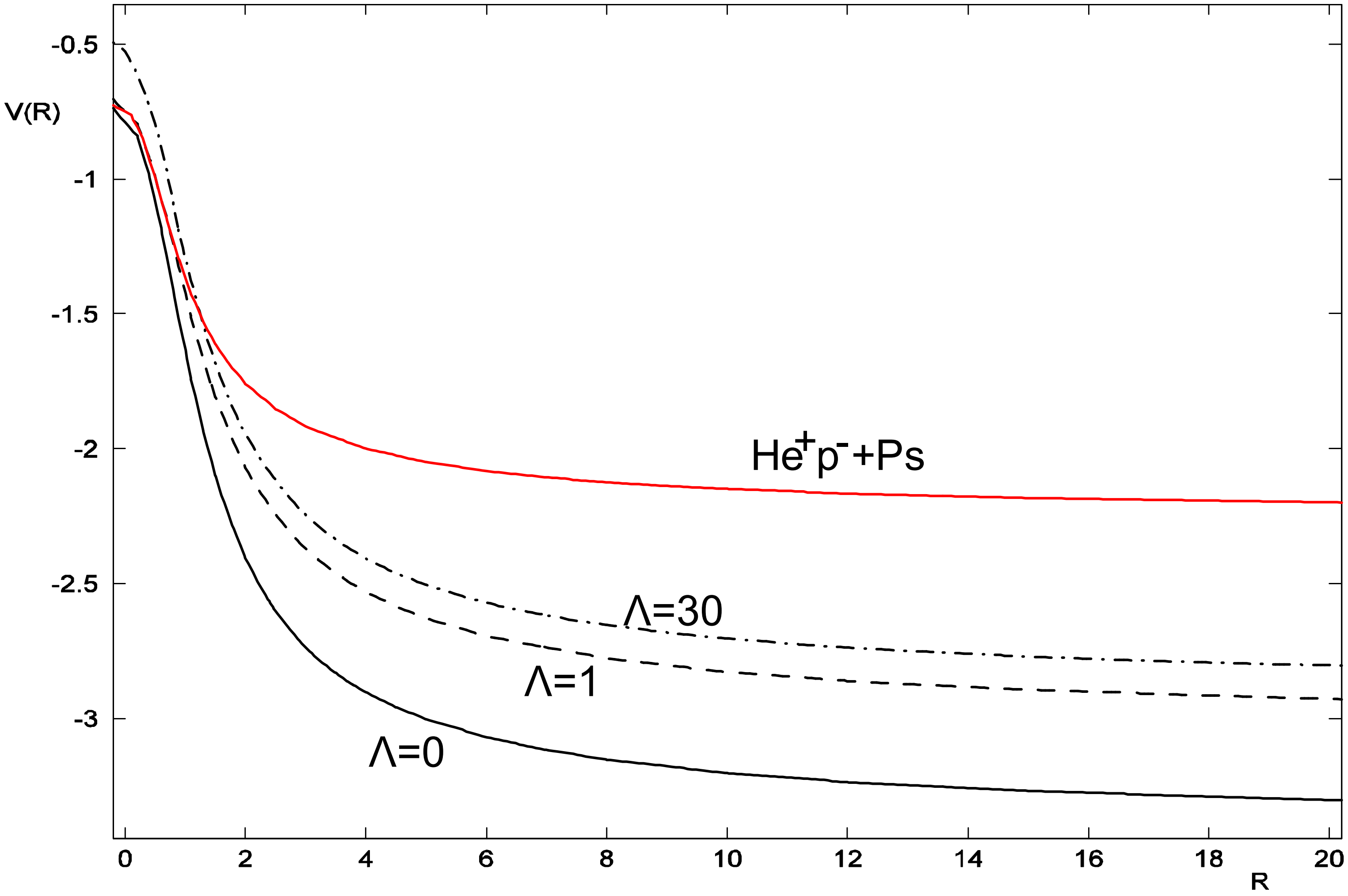
$$\Gamma^{\mathrm{lep}}\ \text{is negligible}; \qquad n = 40 - 32,\ l, m = 0, 1$$

$\mathbf{He\bar{H}}$ quasi-molecule

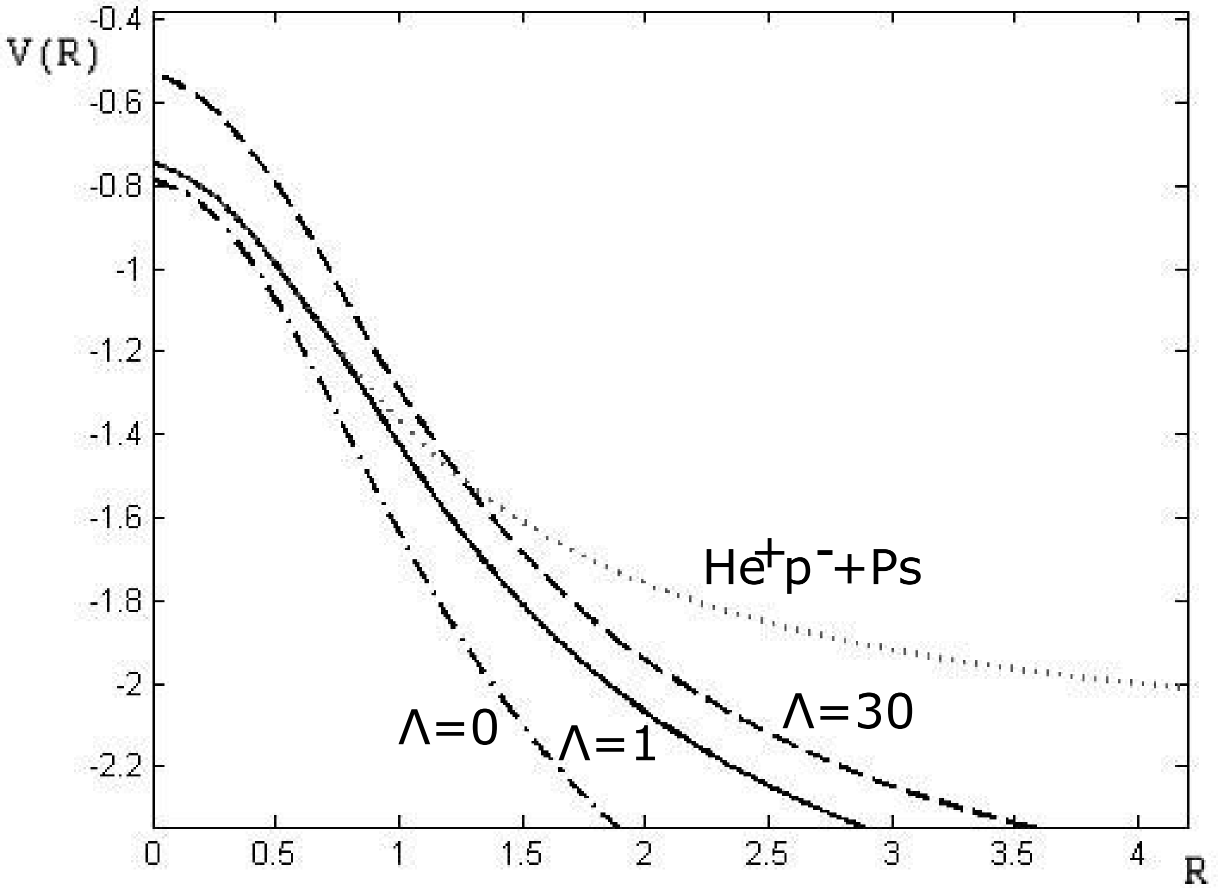
- The states with Λ=0, 1 and 30 are considered
- The number of basis functions = 300
- The critical internuclear distance is absent for the states with Λ=0 and 30

V. Sharipov, L. Labzowsky, and G. Plunien,
PRL **98**, 103001 (2007)

$He\bar{H}$: leptonic potential



$\mathbf{He\bar{H}}$: leptonic potential, the key region



He$\overline{\text{H}}$: decay rates

Λ=0

$$\Gamma^{\text{nuc}}_{\Lambda n00} \approx 1\cdot 10^{16} - 8\cdot 10^{13}\ \text{Hz}, \Gamma^{\text{Ps}}_{\Lambda nlm} \approx 6\cdot 10^{14} - 5\cdot 10^{12}\ \text{Hz},$$

$$\Gamma^{\text{lep}}_{\Lambda nlm} \approx 1\cdot 10^{10} - 4\cdot 10^{8}\ \text{Hz}; \qquad n = 42 - 38, l, m = 0, 1$$

Λ=30

$$l = 0\,(J = \Lambda) : \Gamma^{\text{nuc}}_{\Lambda n00} \approx 2\cdot 10^{15} - 4\cdot 10^{14}\ \text{Hz}$$

$$l \neq 0\,(J > \Lambda) : \text{metastable state}$$

Conclusions

- The decay rates for the various excited states of the **HH** and **HeH** systems were computed
- The decay rates for high Λ are about 10 times smaller than for small Λ
- There are metastable states in the **$\bar{\mathrm{H}}$eH** quasimolecule (high Λ and $l \neq 0$). Estimated lifetime of these states ~μsec
- **Ne$\bar{\mathrm{H}}$** system (core potential approach)