Calculations of antihydrogen loss from collisions with H and He

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ALPHA

Antihydrogen collisions

- Nuclear annihilation

$$\bar{\mathrm{H}} + \mathrm{A} \rightarrow \pi^+ + \pi^- + \pi^0 + e^+ + Ne^-$$

- Electron-positron annihilation

$$\bar{\mathrm{H}} + \mathrm{A} \rightarrow \bar{p} + Z + 2\gamma/3\gamma$$

- Rearrangement processes

$$\bar{\mathrm{H}} + \mathrm{A} \rightarrow [Z\,\bar{p}\,(N-1)e^-] + \mathrm{Ps}$$

$$\bar{\mathrm{H}} + \mathrm{A} \rightarrow [Z\,\bar{p}\,Ne^-] + e^+$$

- Formation of molecule

$$\bar{\mathrm{H}} + \mathrm{A} \rightarrow [\bar{\mathrm{H}}\mathrm{A}] + \gamma$$

- Elastic scattering

The low-energy cross sections are characterised by the complex scattering length $a = \alpha - i\beta$.

Elastic scattering: $\sigma^{\mathrm{el}} = 4\pi(\alpha^2 + \beta^2)$
Inelastic processes: $\sigma^{\mathrm{inel}} = 4\pi\beta/k_i$

Inelastic processes always dominate below a certain collision energy. This energy sets the lower limit for sympathetic cooling of antihydrogen.

The scattering-length approximation is valid up to energies ~10^{-6} a.u. or temperatures ~1 Kelvin.

In this energy range only s-wave scattering contributes.

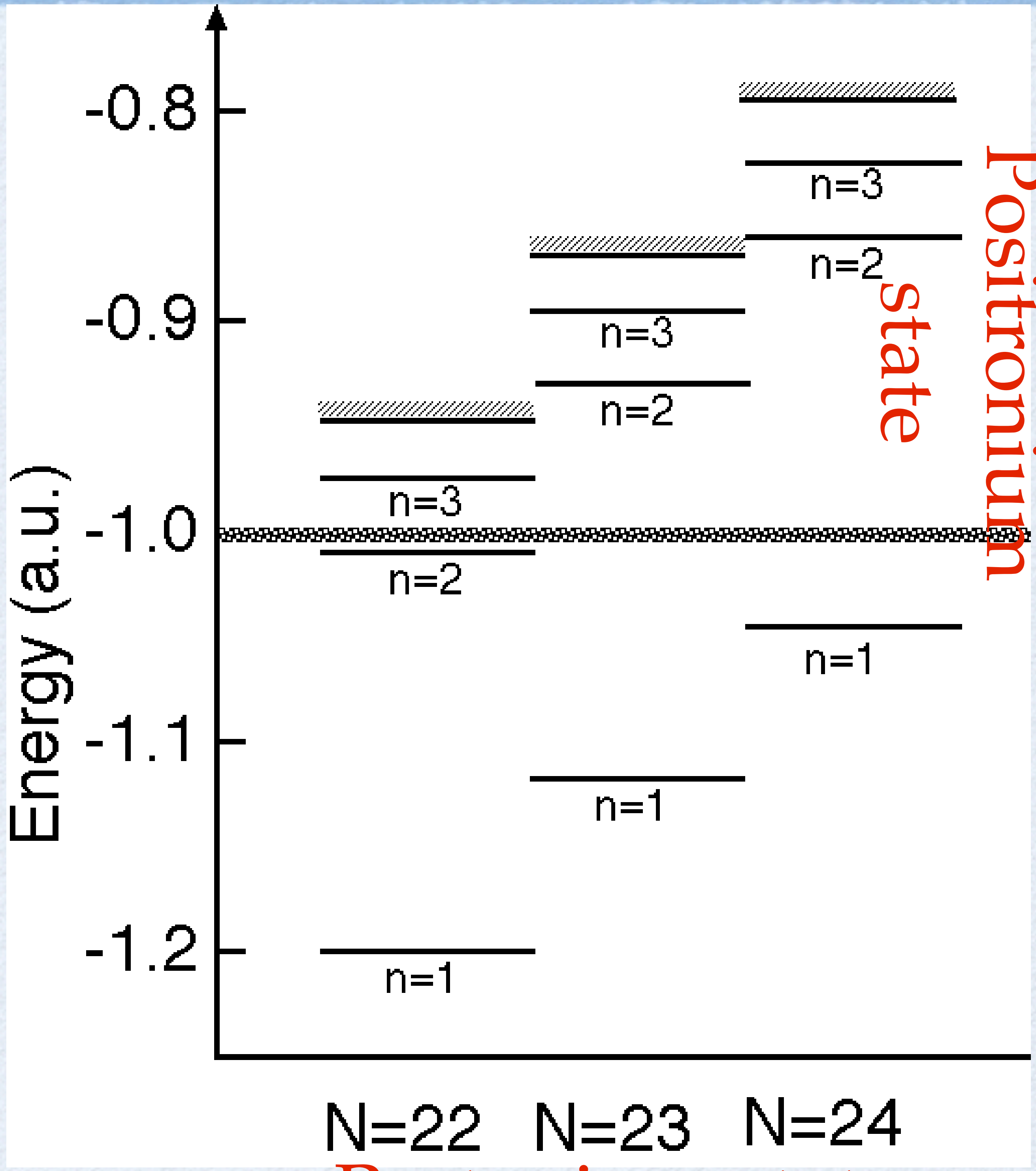
Rearrangement for H-$\overline{\text{H}}$

Energy conservation limits which Ps and Pn states can be formed.

$$\mathcal{E}_{1s}^{\text{H}} + \mathcal{E}_{1s}^{\bar{\text{H}}} + \varepsilon_i = \mathcal{E}_{N}^{\text{Pn}} + \mathcal{E}_{n}^{\text{Ps}} + \varepsilon_f$$

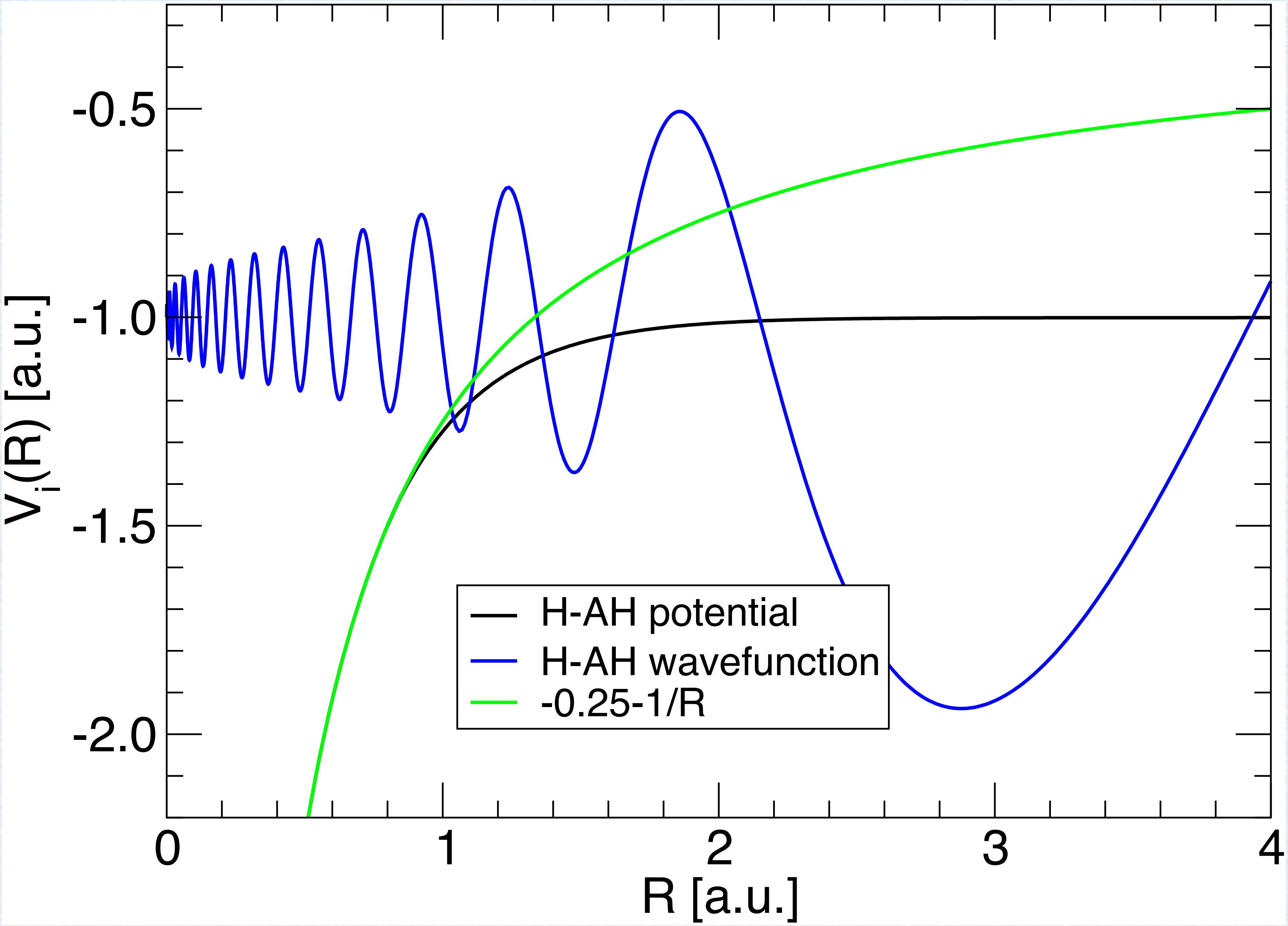
The highest allowed Pn state is $N = 24$.

Excited states of Ps require $N \leq 22$.



Protonium state

Hydrogen-antihydrogen potential

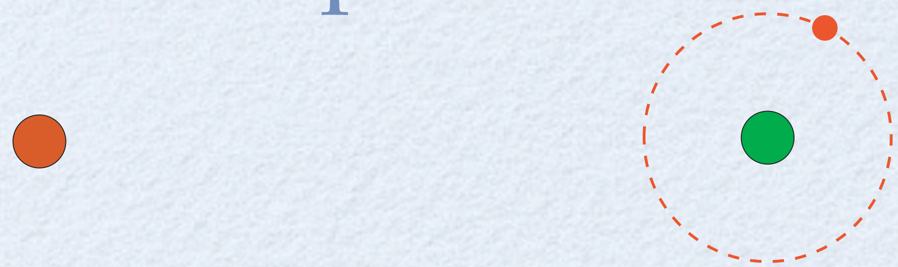


At the critical distance $R_c \lesssim 0.744$ a.u.the potential joins the continuum. (Strasburger, J.Phys. B35, L435 (2002))

Critical Distance

Consider a proton scattering on antihydrogen:

- At large internuclear distances the positron is bound to the antiproton.



- In the limit of zero internuclear separation the positron is unbound.

- At some intermediate distance the dipole created by the proton and antiproton ceases to bind the positron. This is the critical internuclear distance.

Systems without critical distance

The system of a ground-state atom colliding with ground-state antihydrogen does not posses a critical distance if the atom before it in the periodic table is able to bind positronium.

Systems without critical distance:

Alkalis	Alkaline earths	Inert gases	other
no	Be, Mg, Ca	He, Ne, Ar, Kr, Xe	N, F, Zn

(J. Mitroy et al., J. Phys. B 35, R81 (2002))

These atoms are likely to have smaller rearrangement cross sections.

Rearrangement for H-$\overline{\text{H}}$

Low-energy limit for formation of Ps(1s) with angular momentum $l = 0$, $\sigma^{\text{rearr}} \sqrt{\varepsilon_i}$.

Pn state	pl. w. (1)	Kohn (2)	Optical (3)	DWBA (4)
24	0,038	0,21	0,32	0,15
23	0,022	0,45	0,48	0,24
22	0,016	0,01	0,14	0,002
21	0,009		0,10	0,02
20	0,006		0,04	0,001
19	0,003		0,03	0,003

(1) P. K. Sinha and A. S. Ghosh, J. Phys. B 35, L281 (2002)
(2) E.A.G. Armour and C.W. Chamberlain, J. Phys. B 35, L489 (2002)
(3) B. Zygelman et al. PRA 69, 042715 (2004)
(4) S. Jonsell et al., J. Phys. B 37, 1195 (2004)

Strong nuclear force

- The nucleus and anti-nucleus are attracted by the Coulombic interaction.
- At short distances (~1fm) the strong nuclear force dominates.
- The strong force causes both annihilation and a change in the elastic cross section.

Strong force scattering lengths

For hydrogen:

$$a_{sf} = 0.84 - 0.70i \text{ fm}$$

Determined from the shift and width of the 1S state of protonium.

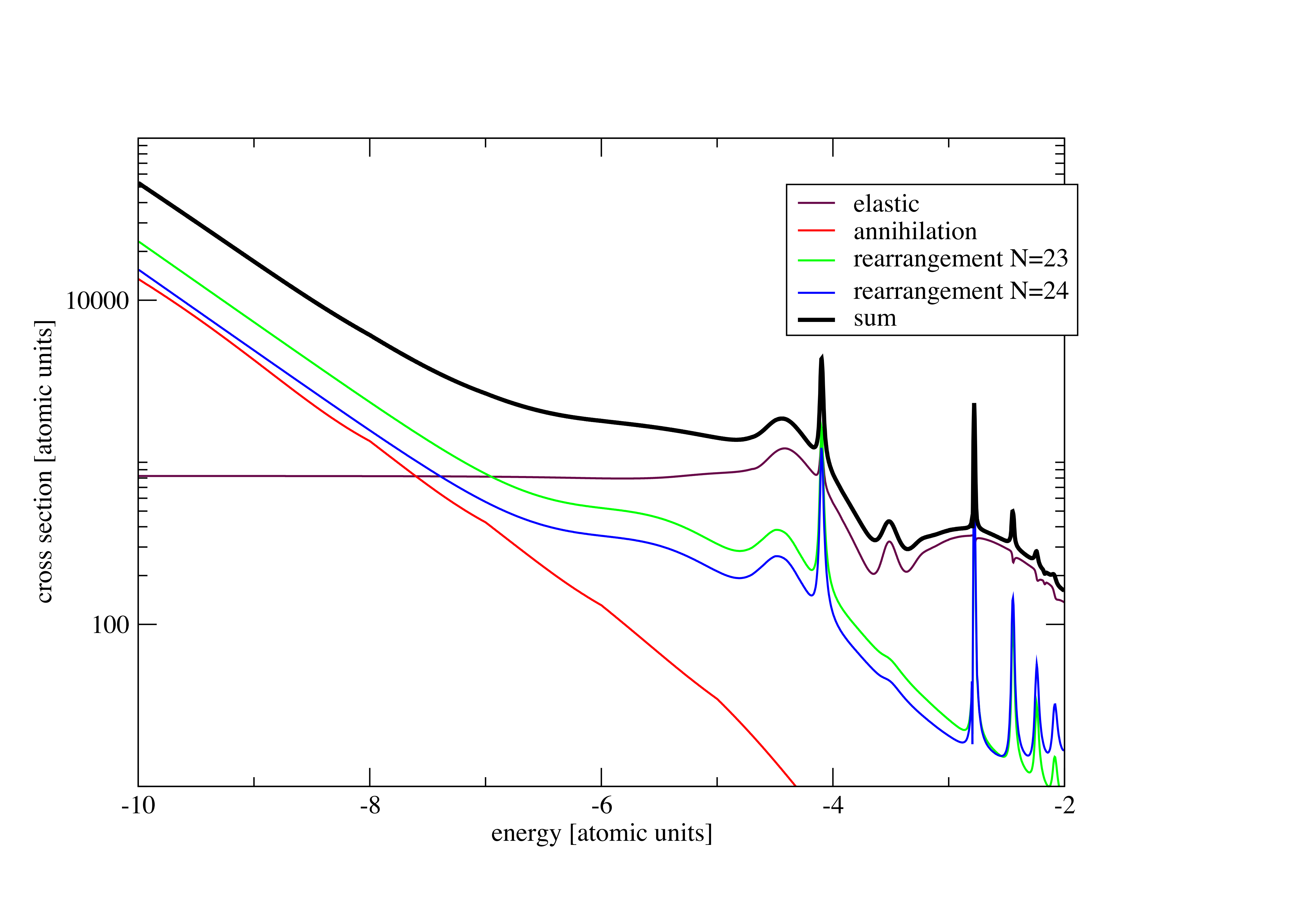
For helium:

$$a_{sf} = 1.85 - 0.63i \text{ fm}$$

Determined from low-energy annihilation data and the shift and width of the 2P state of protonium (Gal, Nucl. Phys. A699, 300c (2002)).

Scattering lengths are spin-averaged values.

H-Hbar cross sections



The He-$\overline{\mathrm{H}}$ system is simpler since there is no critical distance.

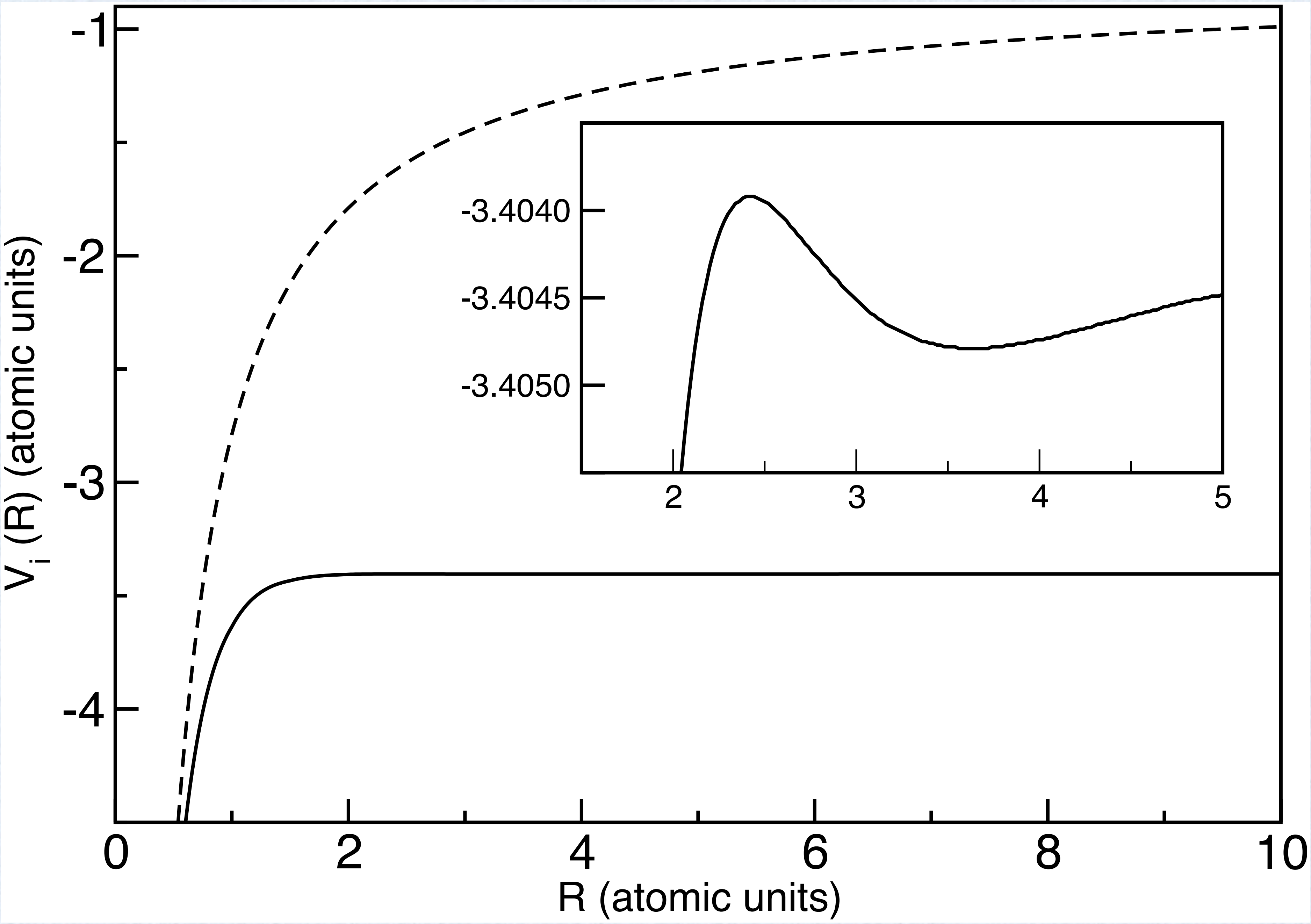
Rearrangement channels:

- $\bar{\mathrm{H}}(1s) + \mathrm{He}(1s^2) \rightarrow (\mathrm{He}^+\bar{p})_{v,J=0} + \mathrm{Ps}(1s)$
  dominating channel is $v = 35$
  with low-energy cross section $\sigma = 0.142/\sqrt{\varepsilon_i}$

- $\bar{\mathrm{H}}(1s) + \mathrm{He}(1s^2) \rightarrow (\mathrm{He}\bar{p})_{v,J=0} + e^+$
  smaller cross sections, $\sigma_{v=33} = 2.77 \times 10^{-4}/\sqrt{\varepsilon_i}$
  $\sigma_{v=32} = 2.96 \times 10^{-4}/\sqrt{\varepsilon_i}$

- $\bar{\mathrm{H}}(1s) + \mathrm{He}(1s^2) \rightarrow (\alpha\bar{p})_{v,J=0} + \mathrm{Ps}^-$
  in progress (not likely to be large)

Helium-anithydrogen potential

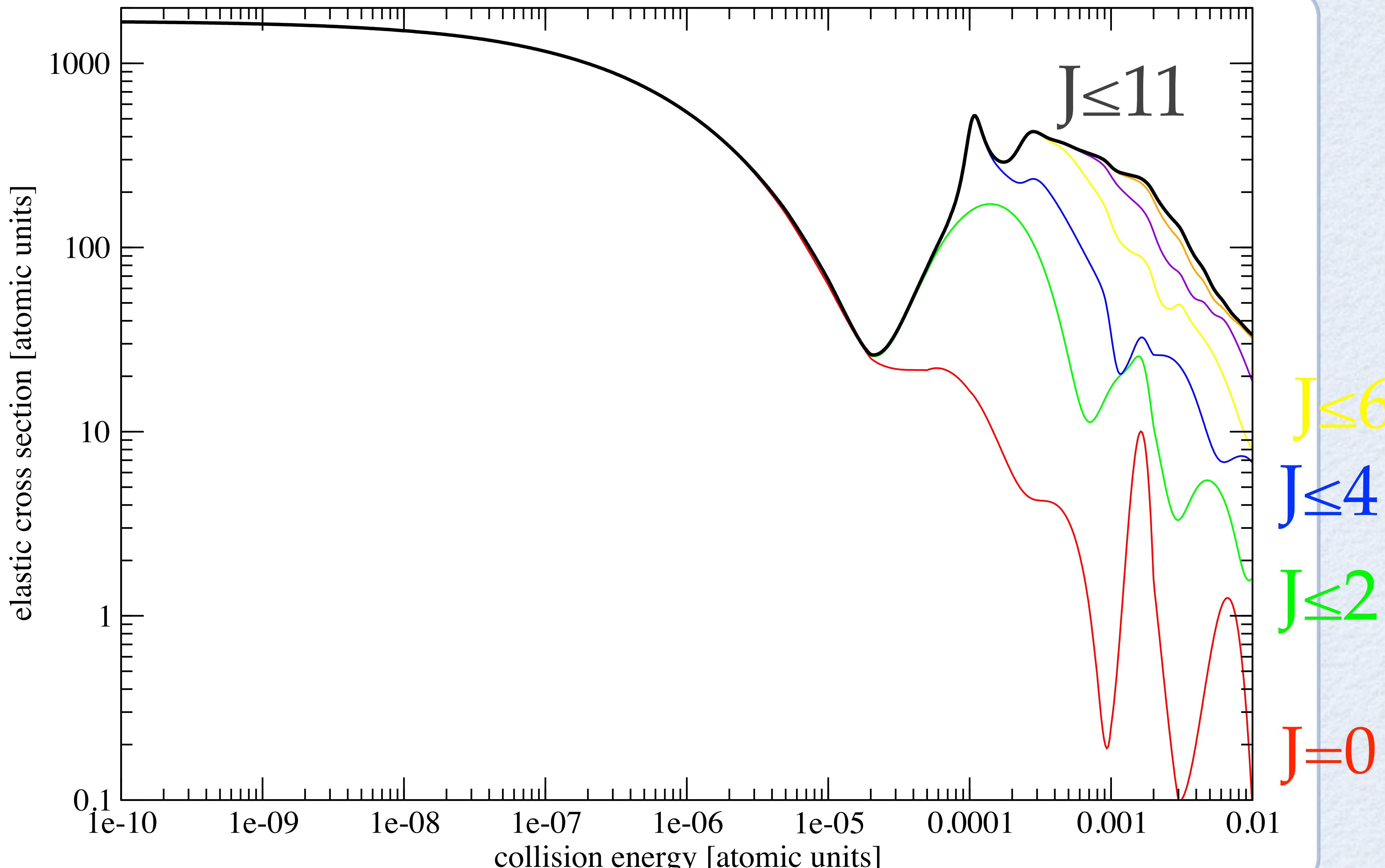


No critical distance

Barrier (height 3.2×10^{-4} a.u.)

Potential by K. Strasburger (Phys. Rev. Lett. 88, 163201 (2002))

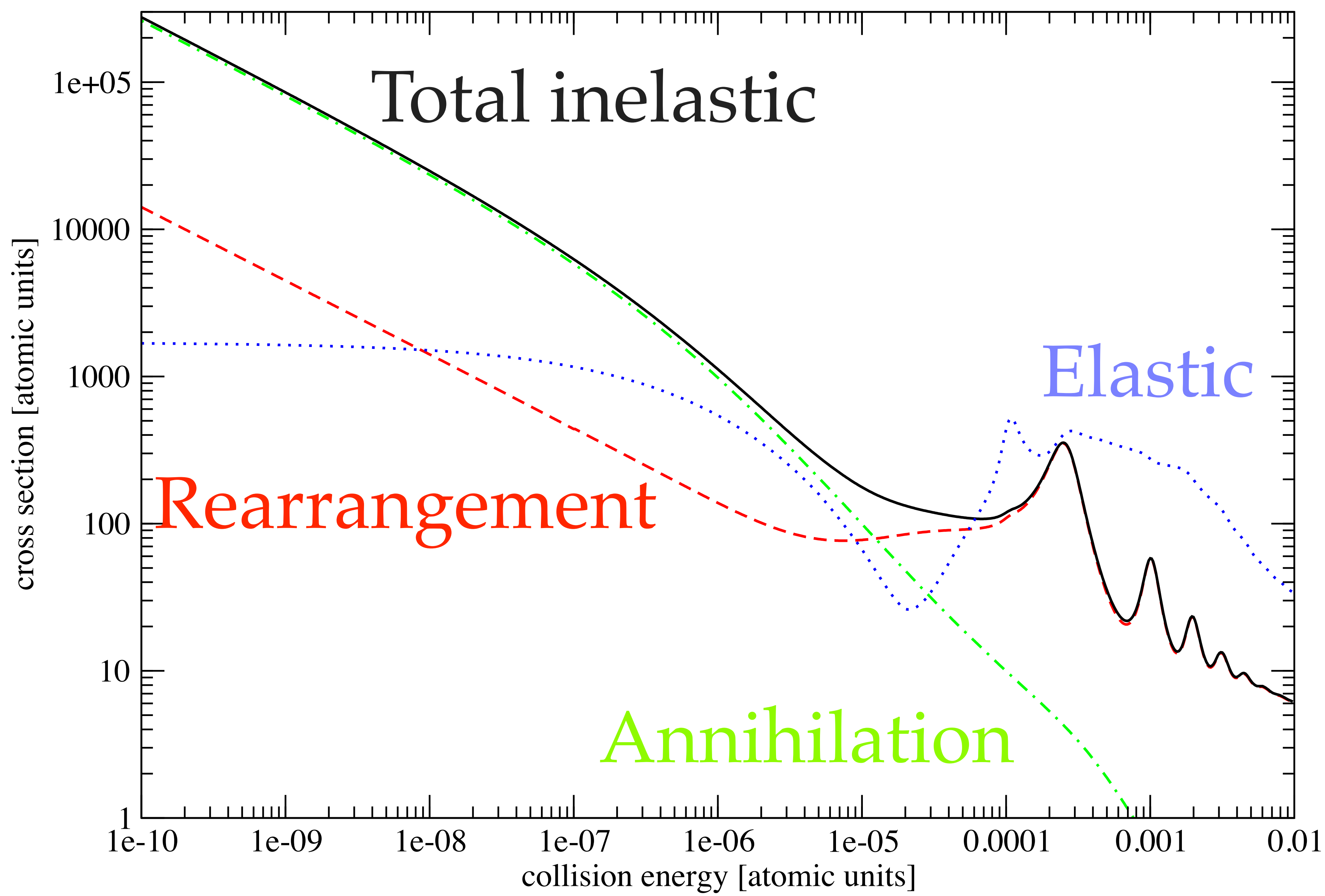
Elastic cross section, partial waves



Resonant enhancement around $E_r = 1.04 \times 10^{-4} \approx 30$ K.

Minimum around $E = 2 \times 10^{-5} \approx 6$ K.

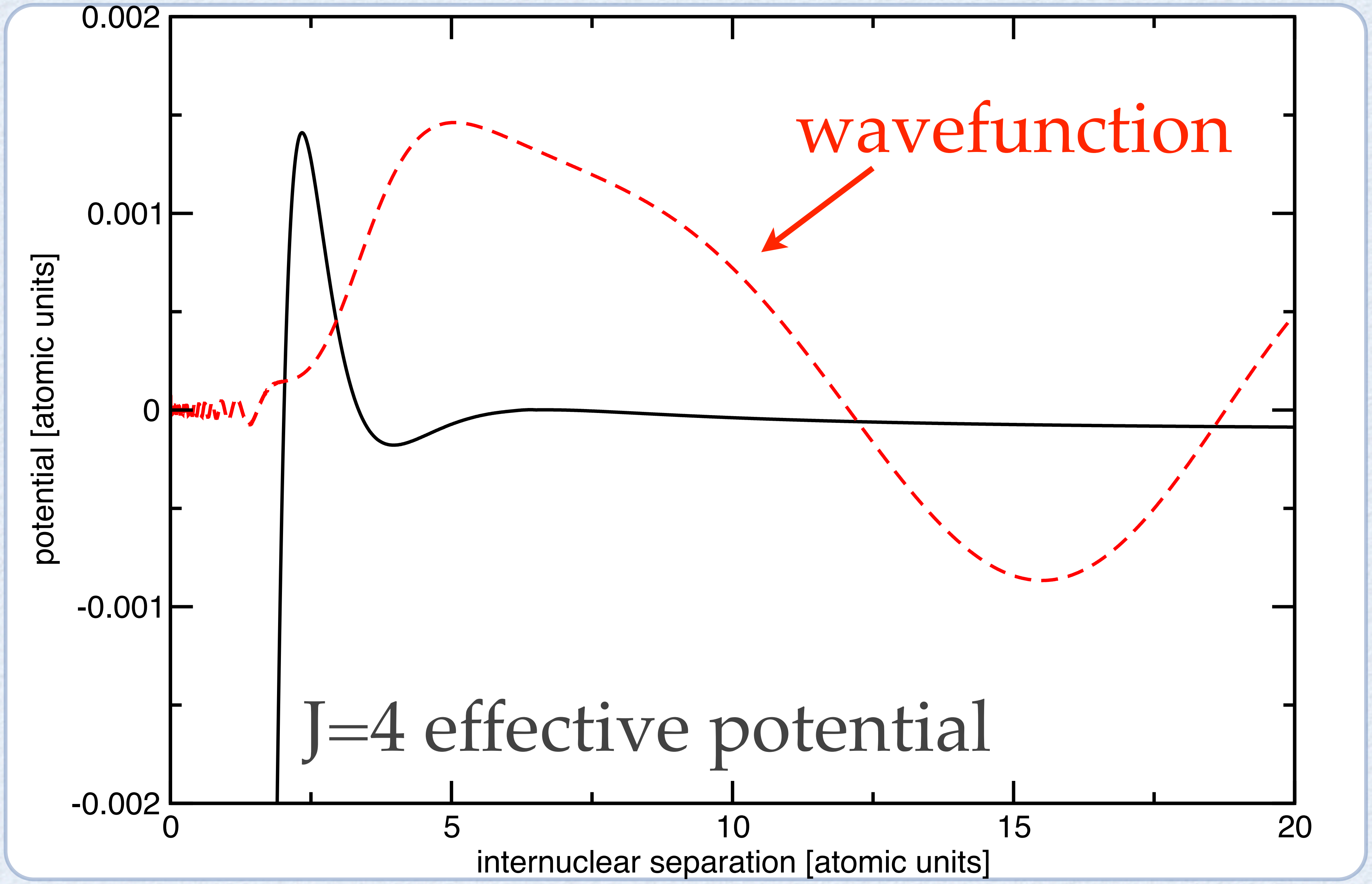
Helium-antihydrogen



Over $E = 6.1 \times 10^{-5} \approx 19$ K elastic loss dominates.

Elastic and inelastic comparable around $E = 2.5 \times 10^{-4} \approx 80$ K.

Weakly bound resonance in outer well



$E_r = 1.04 \times 10^{-4}$
$\Gamma = 3.40 \times 10^{-5}$

Only exists for J=4.
No enhancement in inner barrier.

Density of background gas

Can be estimated from the lifetime of antiprotons in the trap.

Langevin cross section: $\sigma = \pi\sqrt{\frac{2\alpha}{E}}$

α is the polarizability of the target (H/He/H_2)

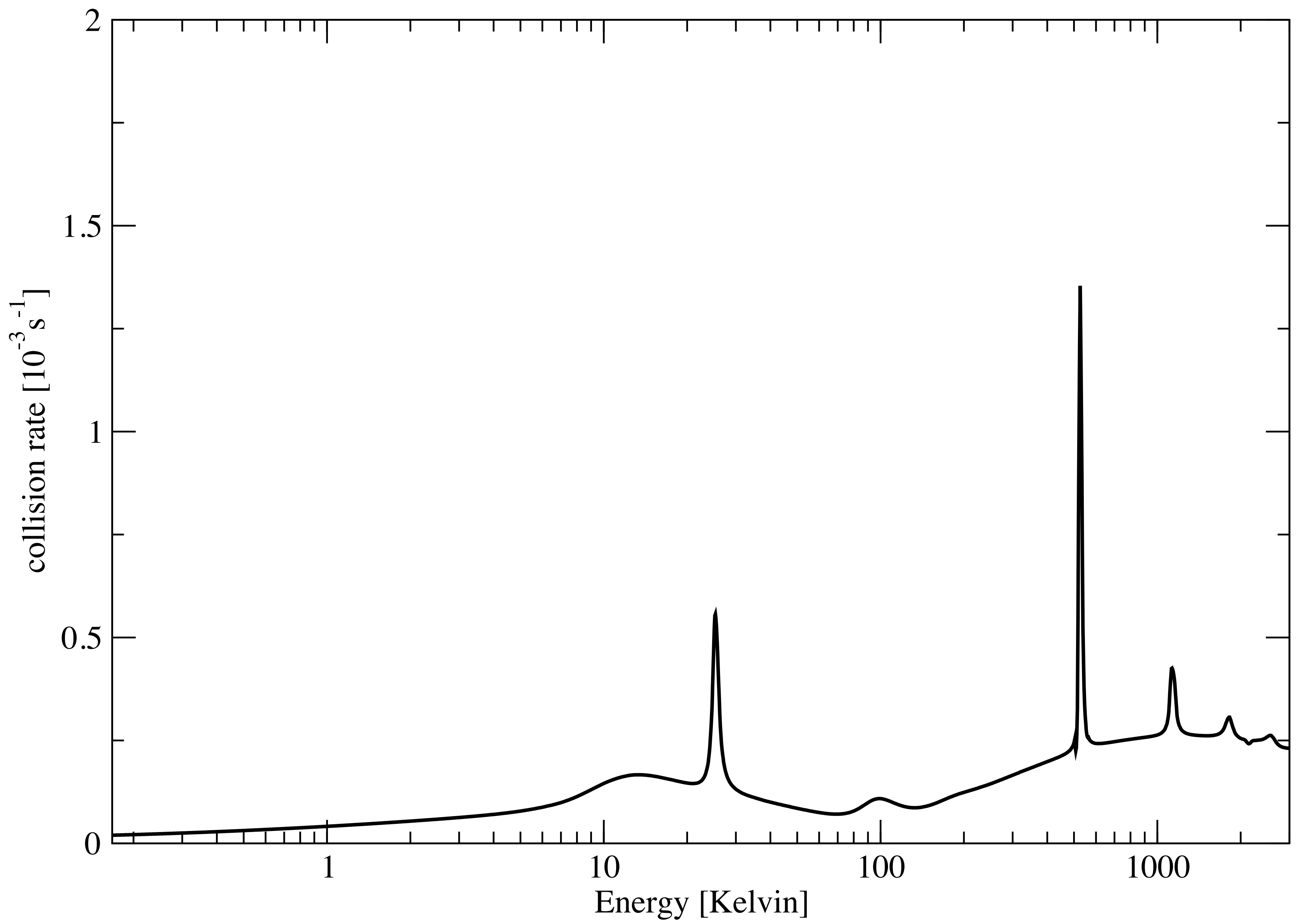
Long-range interaction $-\frac{\alpha}{2r^4}$

Gives an energy-independent destruction rate, valid at energies ~ eV.

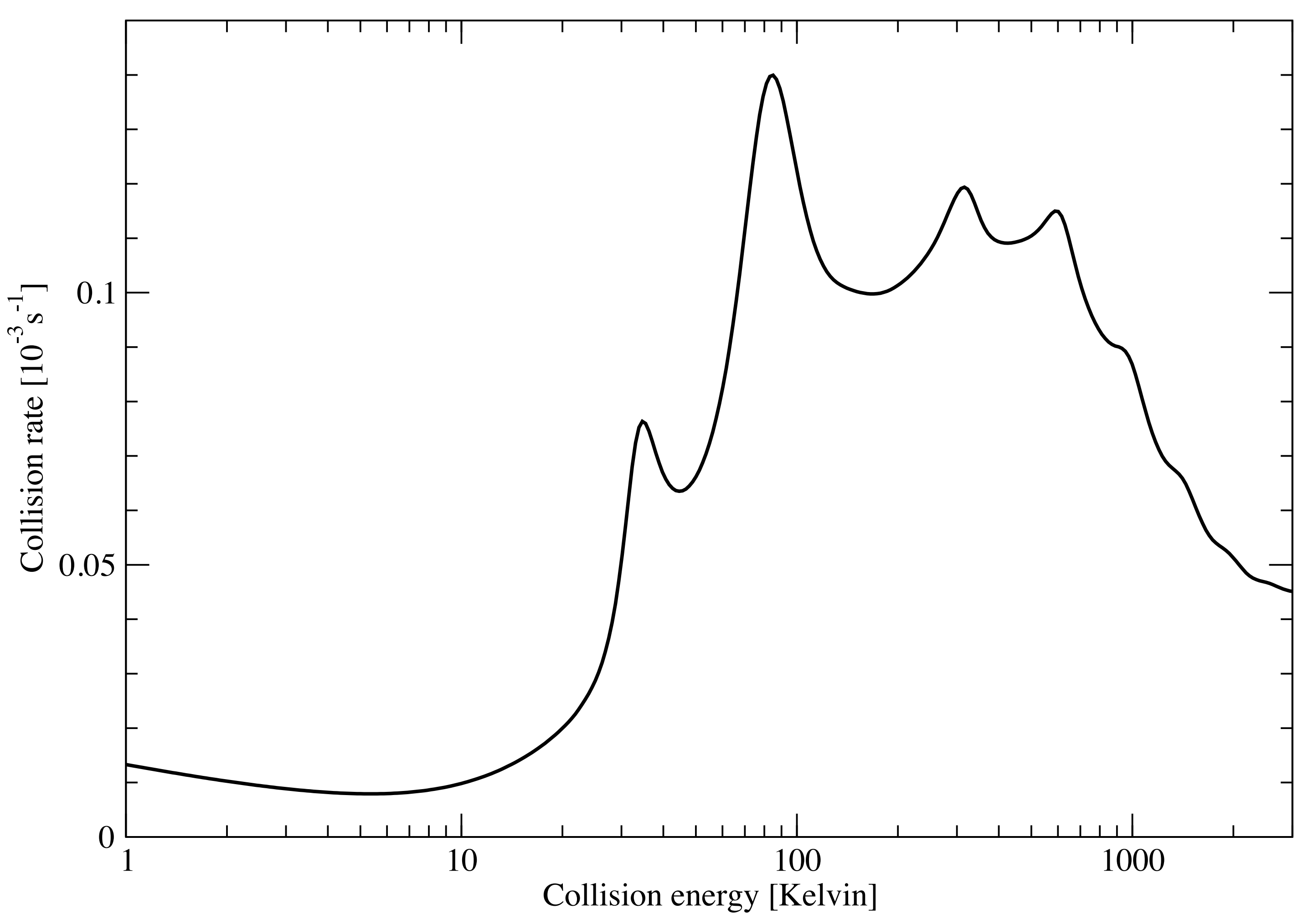
Measured antiproton lifetime $15000\text{ s} = n_p v\sigma$

Gives background gas density $5\times 10^{10}\text{ m}^{-3}$

Rate of collisions with H



Total collision rate with He



ALPHA cites >1000 s lifetime of trapped antihydrogen seems perfectly reasonable

Acknowledgements

- Hydrogen-antihydrogen:
  Alejandro Saenz (Berlin),
  Piotr Froelich (Uppsala),
  Bernard Zygelman (Nevada),
  Alex Dalgarno (Harvard).Text

- Helium-antihydrogen:
  Edward Armour (Nottingham)
  Martin Plummer (Daresbury)

- £££££: EPSRC, VR