A perturbed Rydberg atom

H. R. Sadeghpour
ITAMP, Harvard-Smithsonian Center for Astrophysics

“This book will amaze, baffle and delight ...” - Nature

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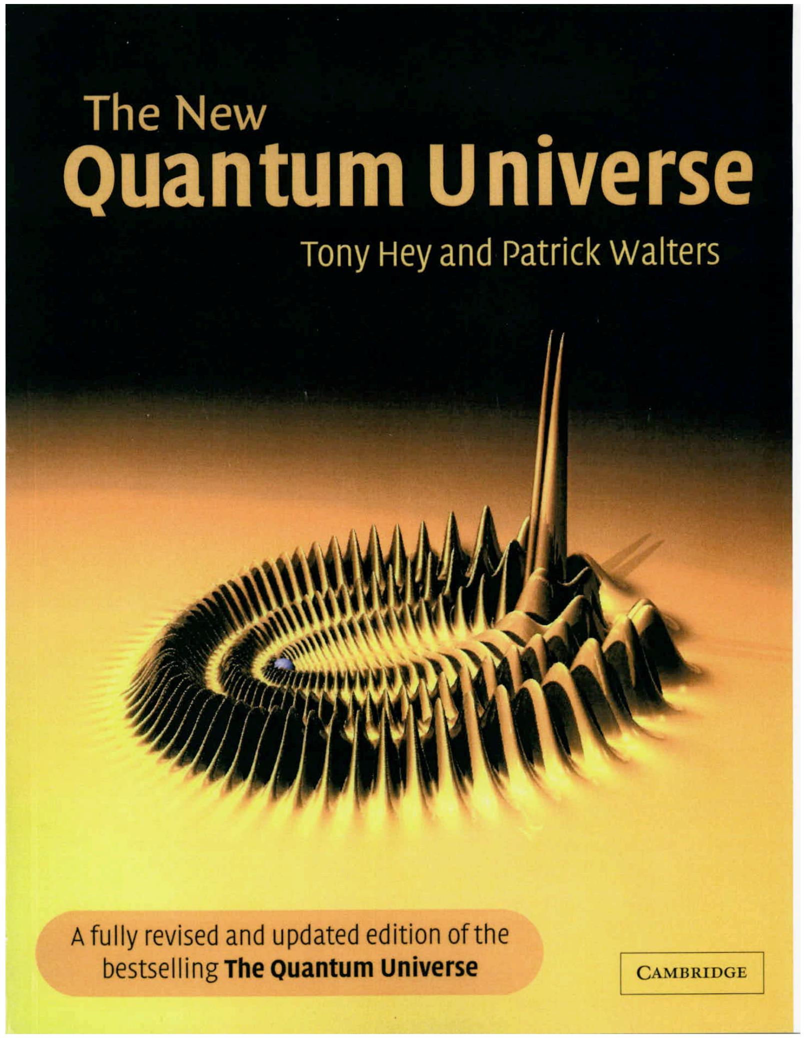

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strong (but) binary interactions ....

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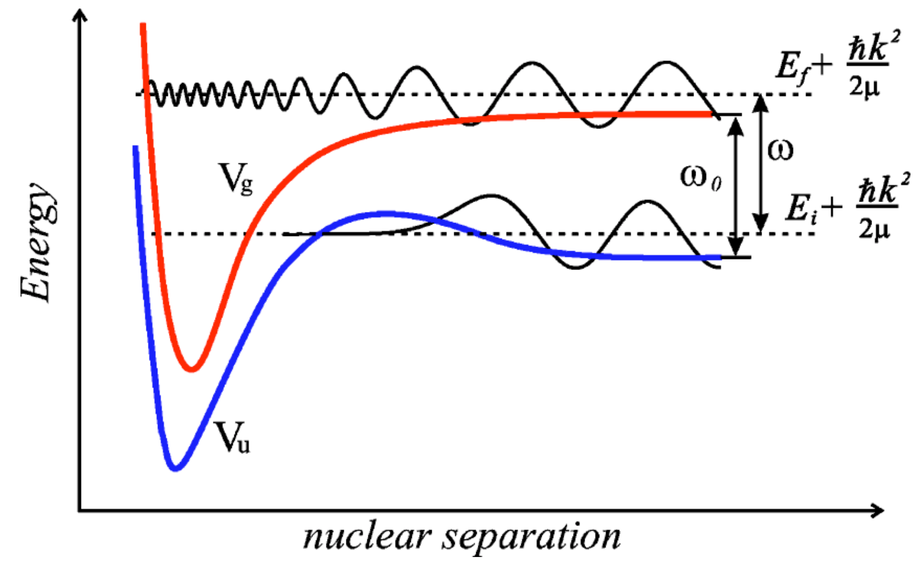
$$I(\omega) \sim \frac{|\langle \beta | e\mathbf{r} | \alpha \rangle|^2}{(\omega - \omega_0 - d)^2 + (\Gamma/2 + w)^2}$$

shift

width

$$\mathrm{w} - id \equiv \Delta_{\beta\alpha} = \hbar n \langle v \sigma_{\beta\alpha} \rangle = p \frac{\hbar \langle v \rangle}{k_B T} \langle \sigma_{\beta\alpha} \rangle$$



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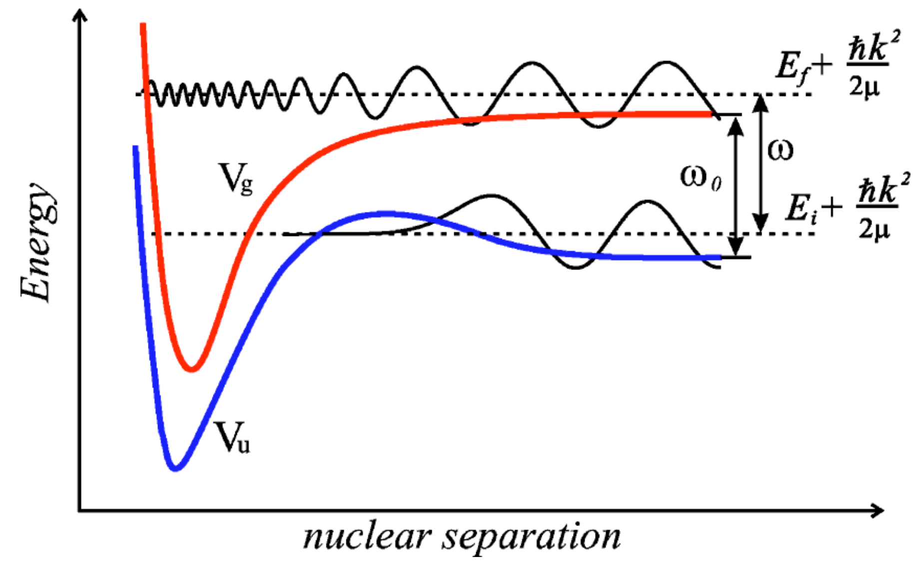
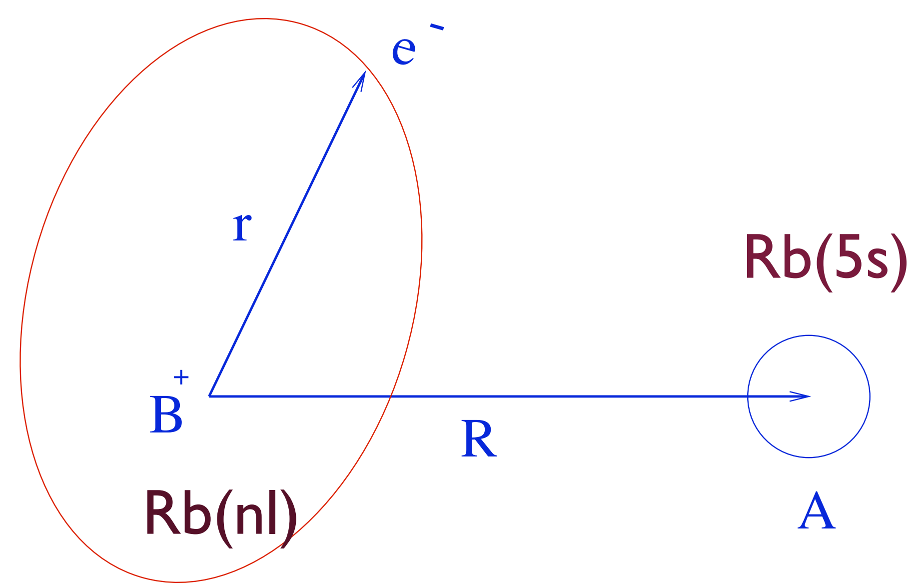


$$V(\mathbf{R}, \mathbf{r}) = V_{e-A}(\mathbf{R}, \mathbf{r}) + V_{pol}(\mathbf{R}, \mathbf{r})$$



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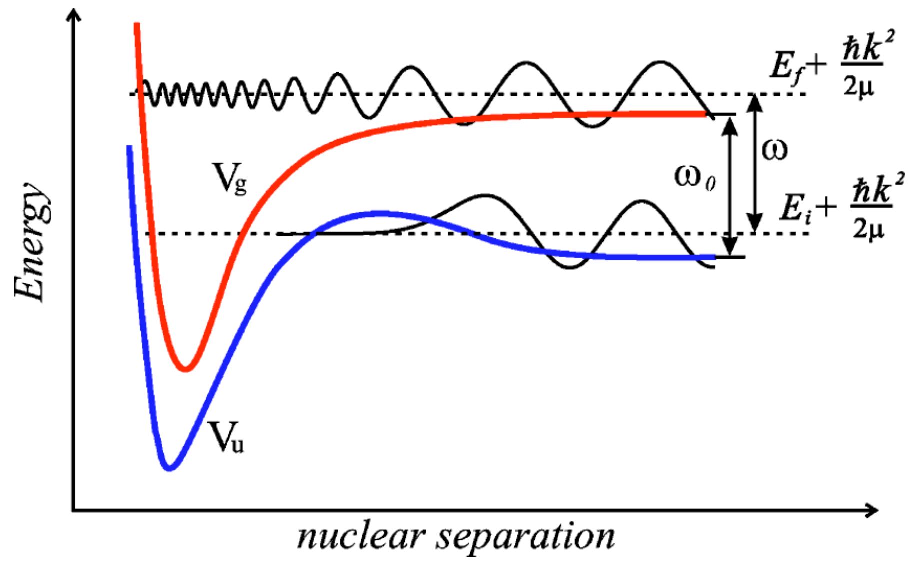

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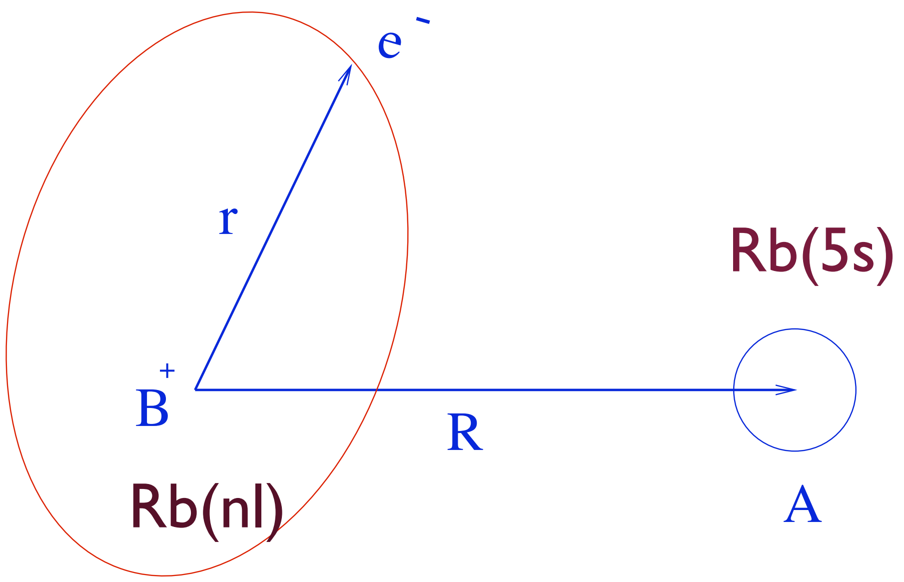


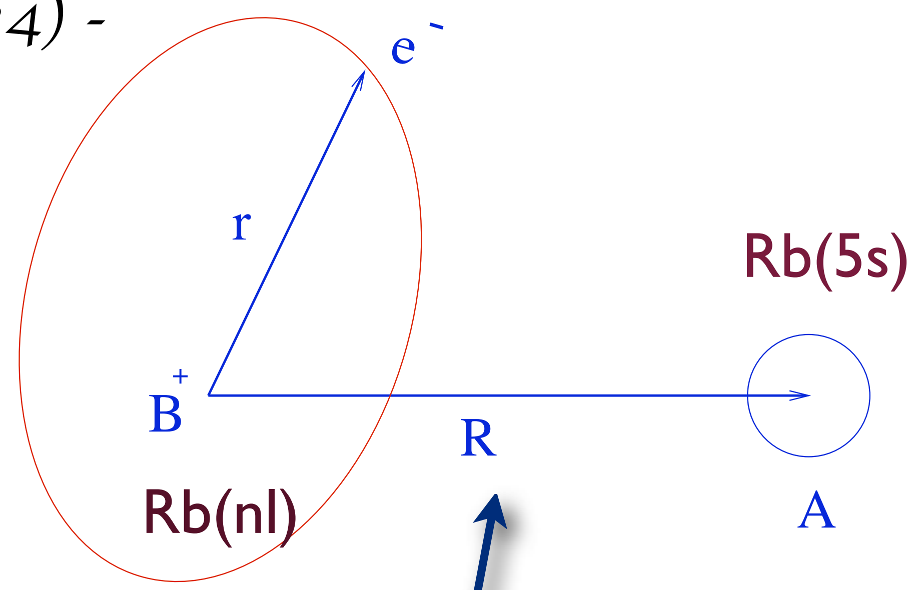
$$V_{\mathrm{pol}}(\boldsymbol{R}, \boldsymbol{r}) = -\frac{\alpha}{2R^4} + \alpha \frac{R^2 - (\boldsymbol{R} \cdot \boldsymbol{r})}{R^3 |\boldsymbol{R} - \boldsymbol{r}|^3} - \frac{\alpha}{2|\boldsymbol{R} - \boldsymbol{r}|^4}$$

$$V_{e-A}(\mathbf{R}, \mathbf{r}) = V_0 \delta(\mathbf{r} - \mathbf{R}) - \frac{\alpha_A}{2|\mathbf{r} - \mathbf{R}|^4}$$

Fermi pseudopotential

Fermi observed that how Rydberg lines shifted depended on the species.... species-dependent scattering length

Contact interaction (Nuovo Cimento 11, 157(1934) - pressure broadening and shift



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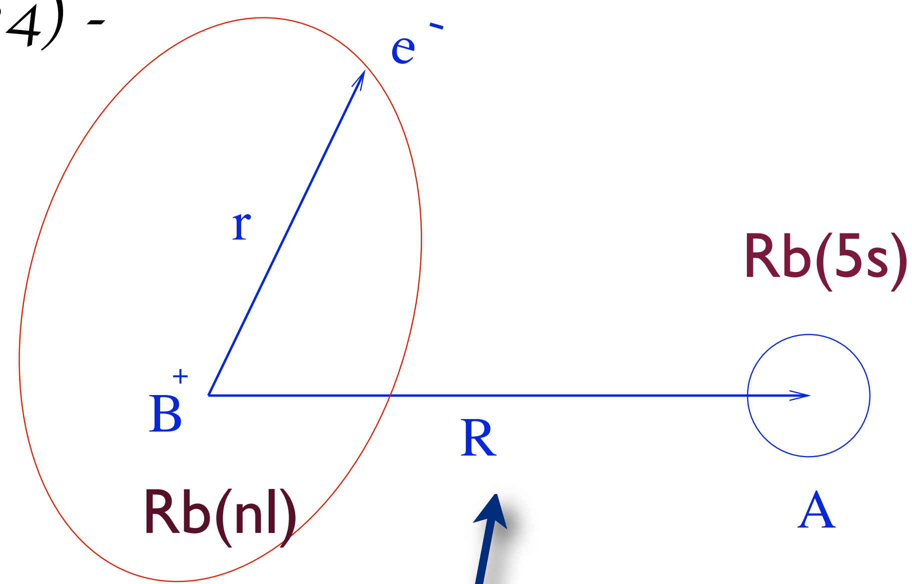

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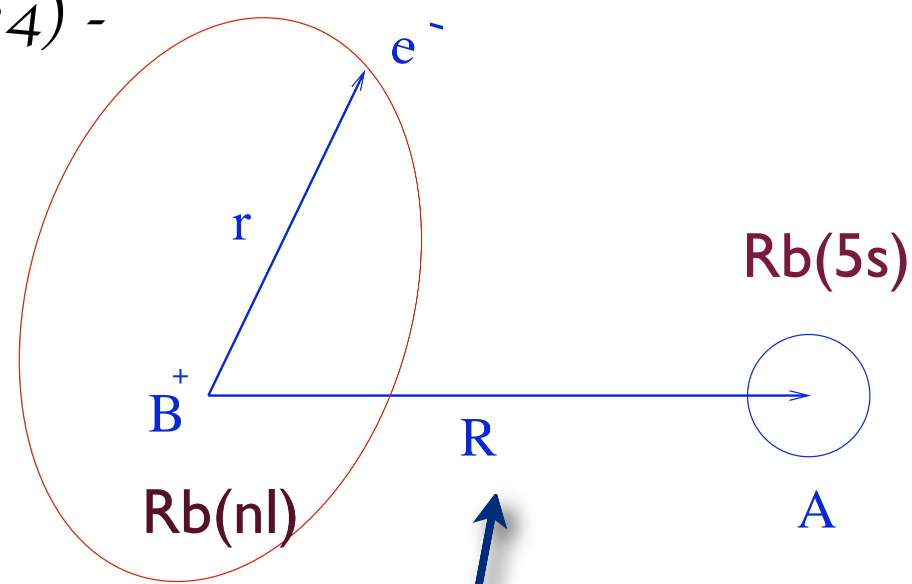

$$\tfrac{1}{2}k^2(R) = -\tfrac{1}{2n^2} + \tfrac{1}{R}$$

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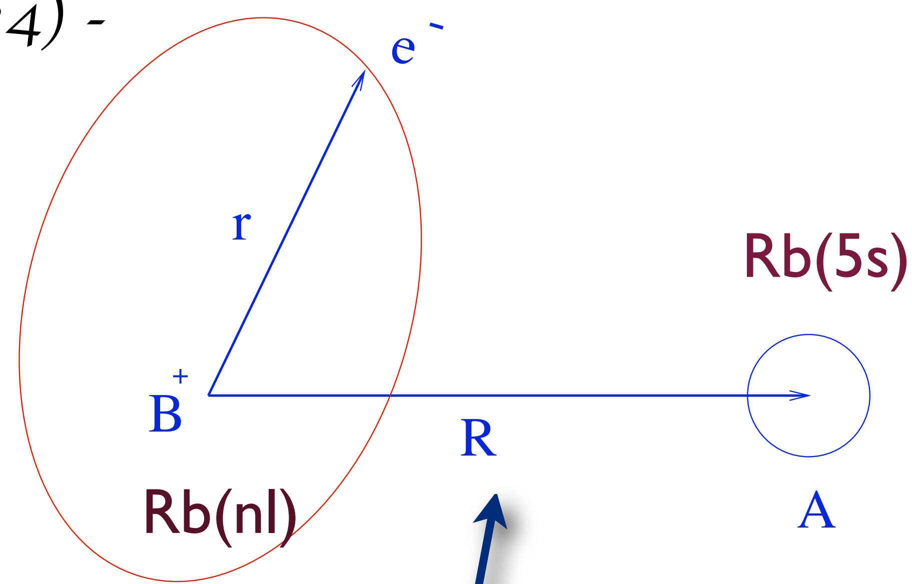

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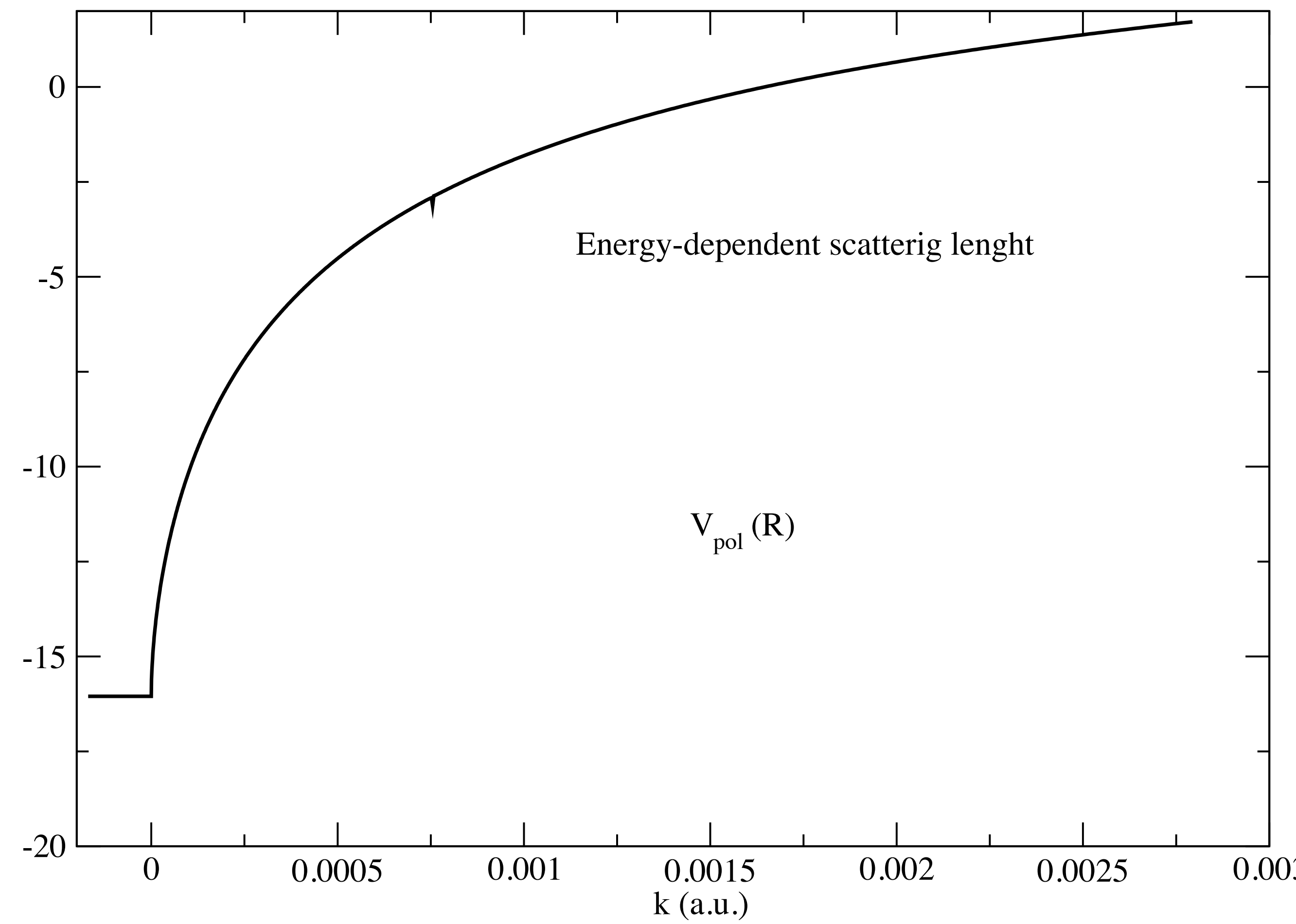
$$V_{pol}(R) = -\frac{\alpha_A}{2R^4}$$

$$a_T[k] = -\tan \delta_0^T(k)/k$$

zero-range e^- scattering leads to long-range molecular binding

Energy-dependent scattering length



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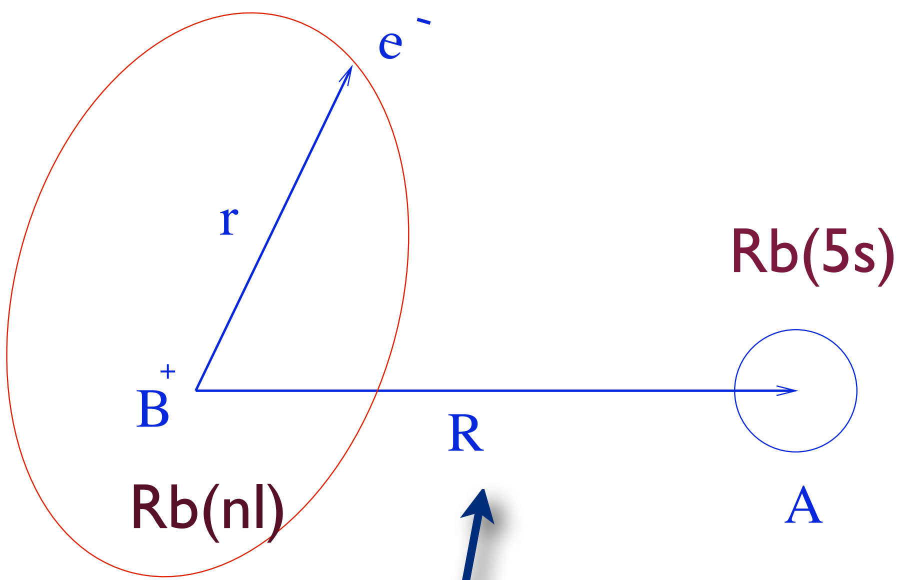

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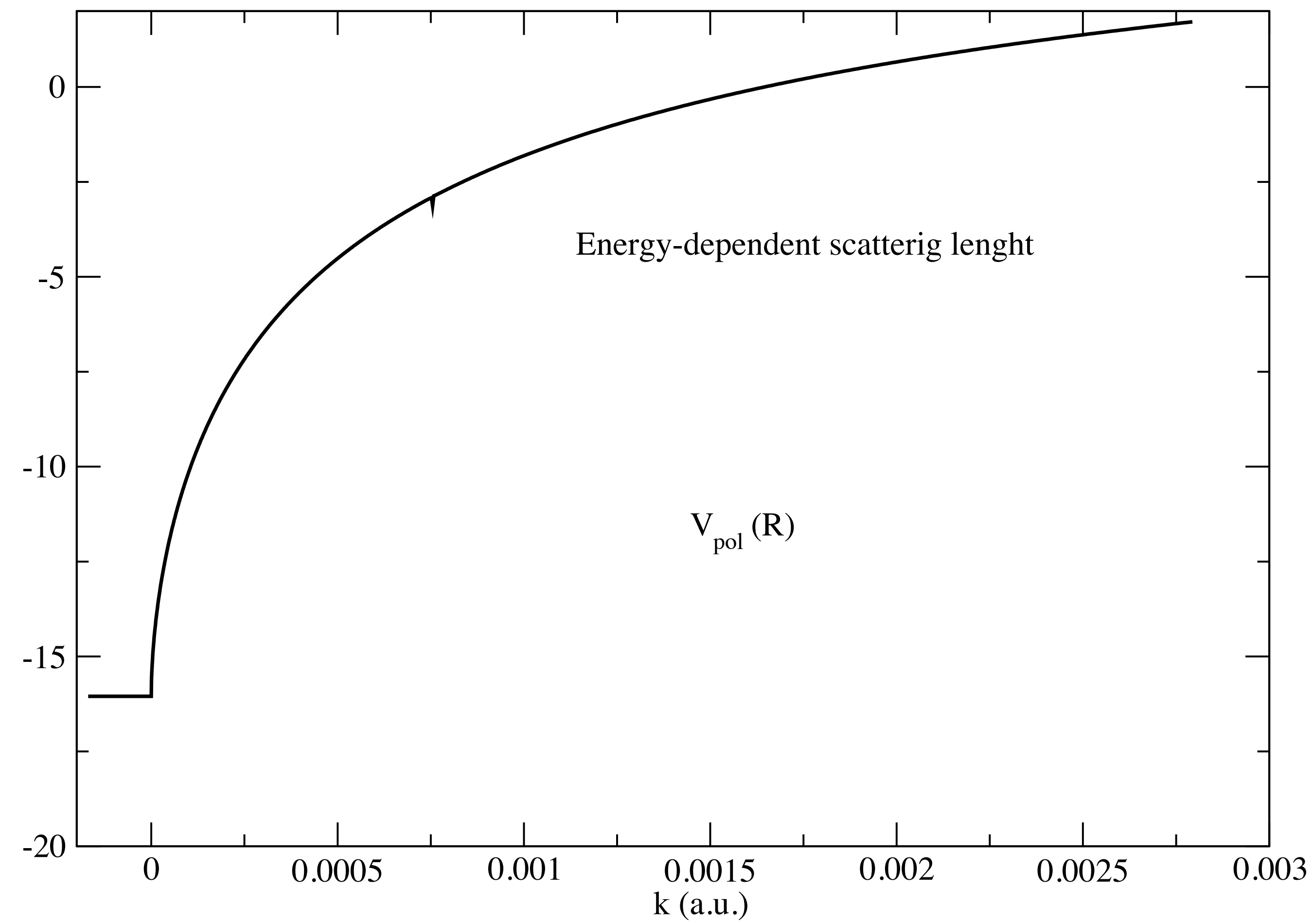
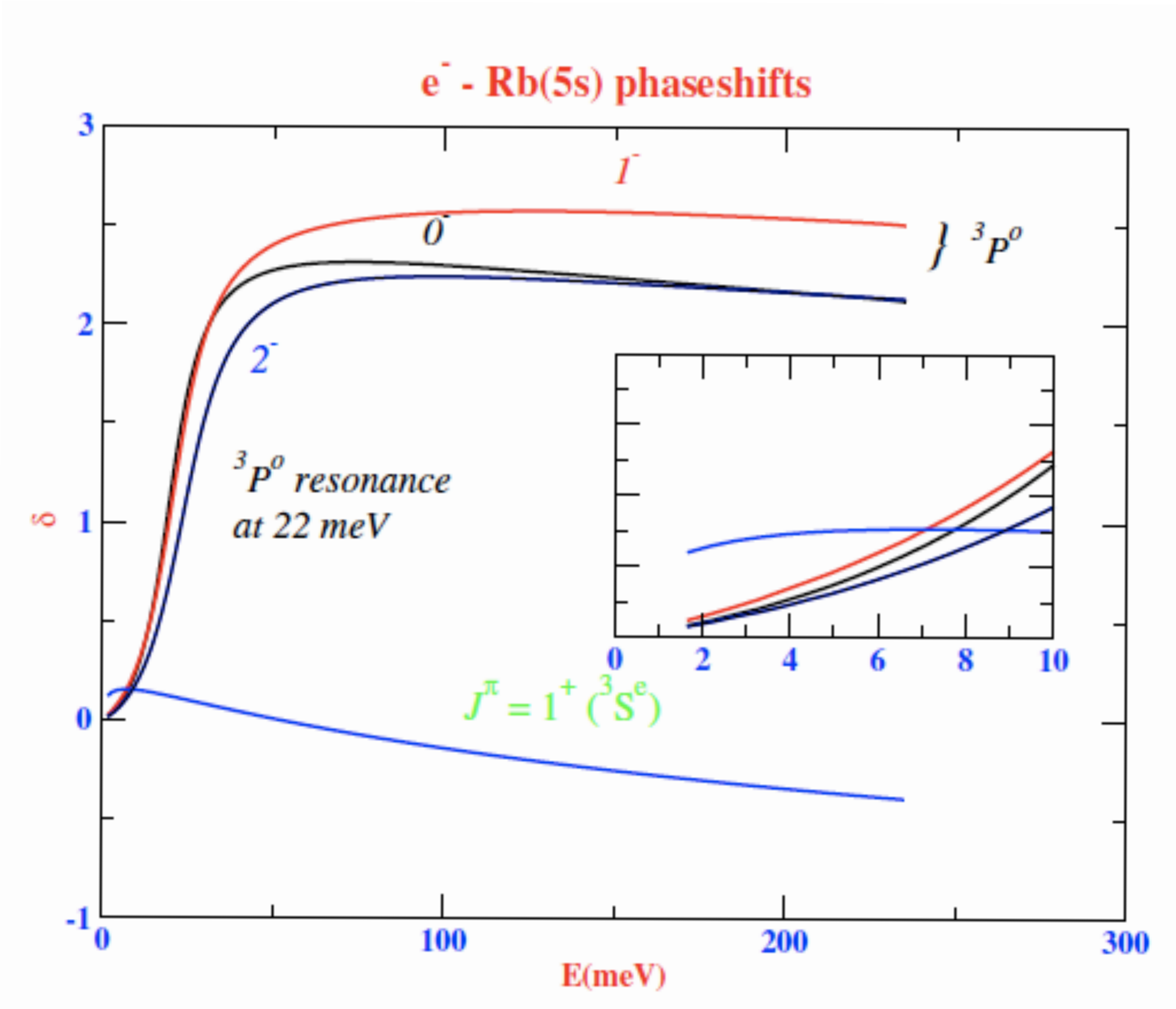


scattering phase shifts



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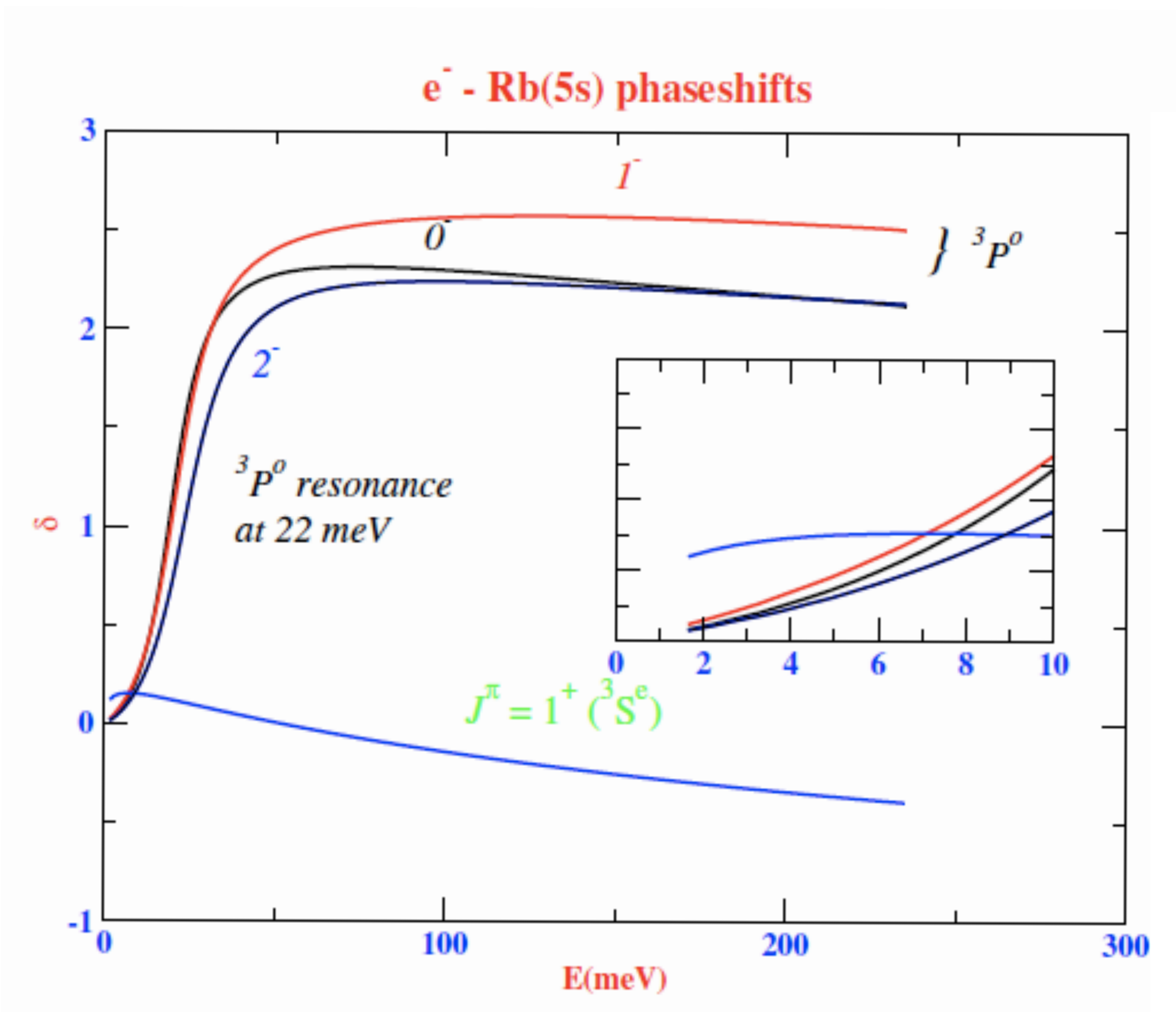

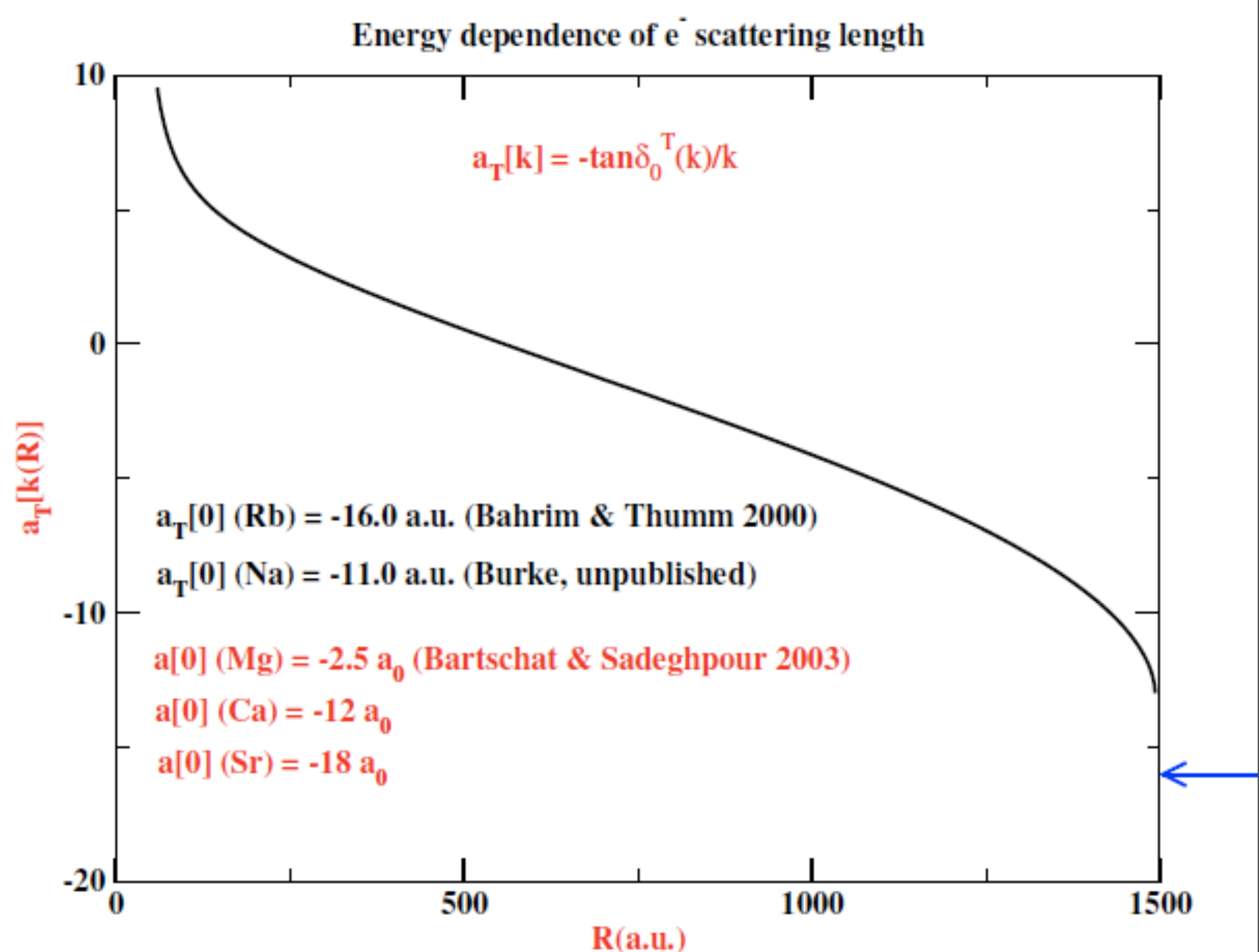

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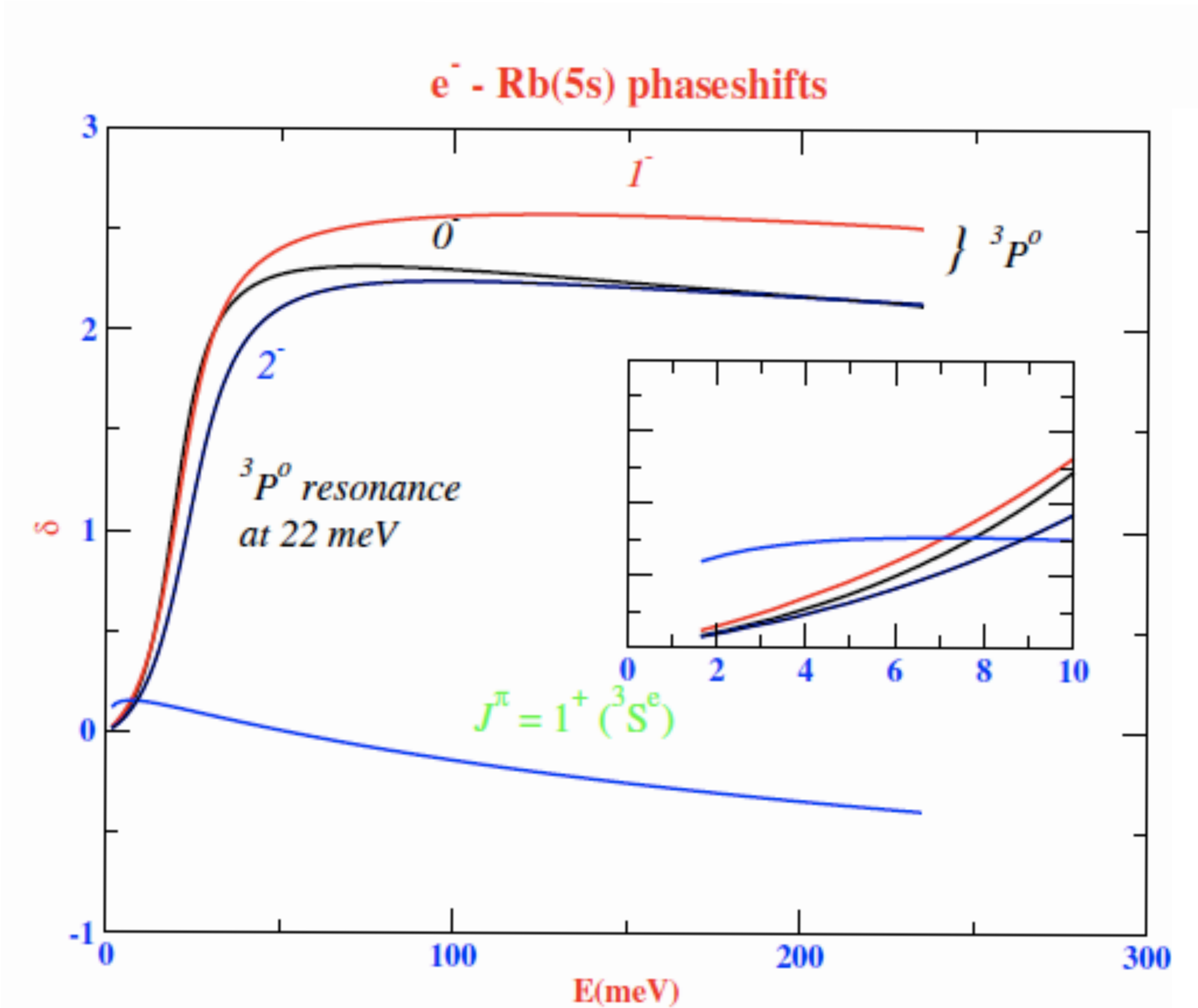

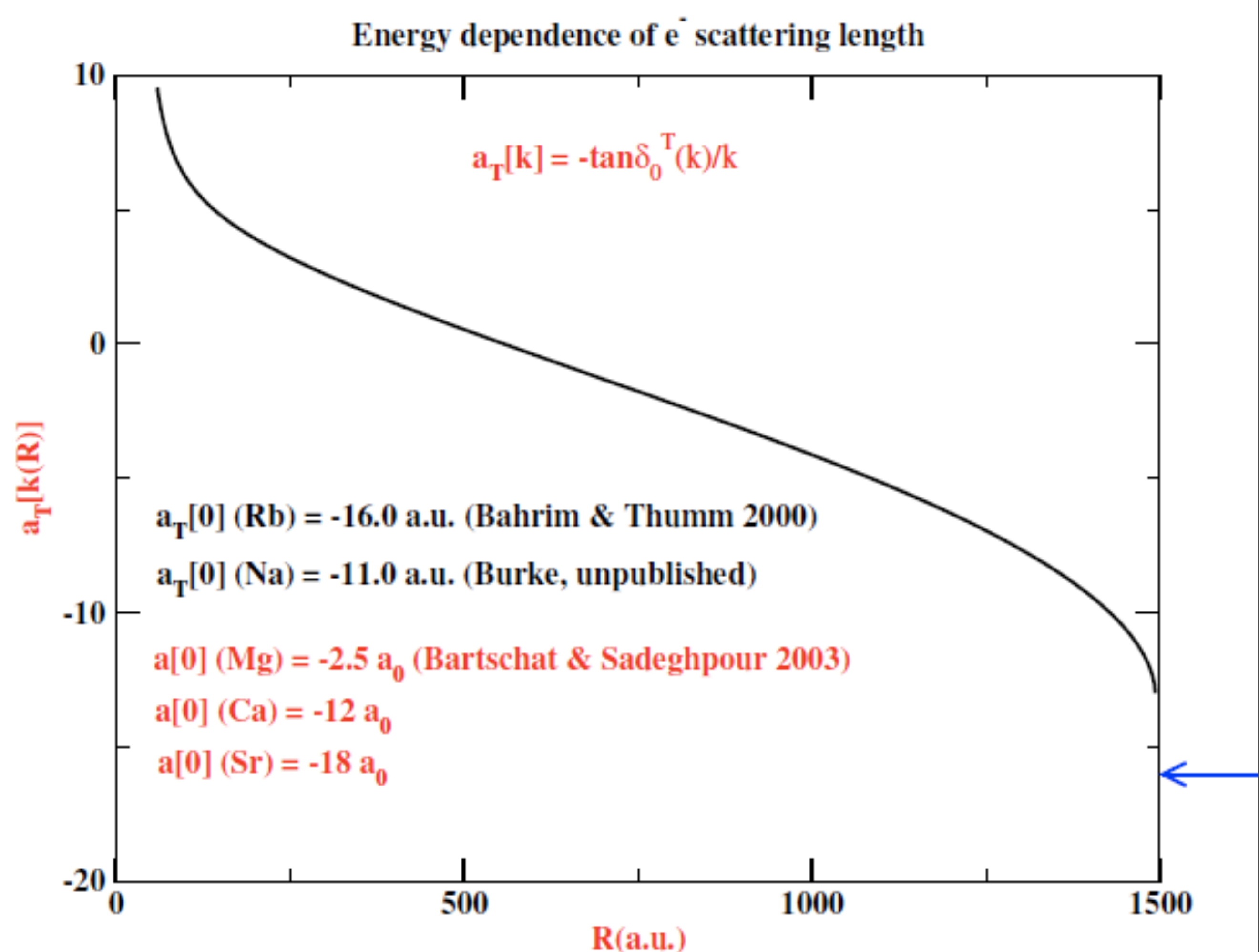

Alkali metals in ^3S_e: scattering length --- all negative; form molecular Rydberg levels

$$V_{e^- - A}(\mathbf{r}, \mathbf{R}) = V_0 \delta(\mathbf{r} - \mathbf{R})$$

Alkali metals in ^1S_e: scattering length --- all positive; a_T (Rb) = 0.2 a_0

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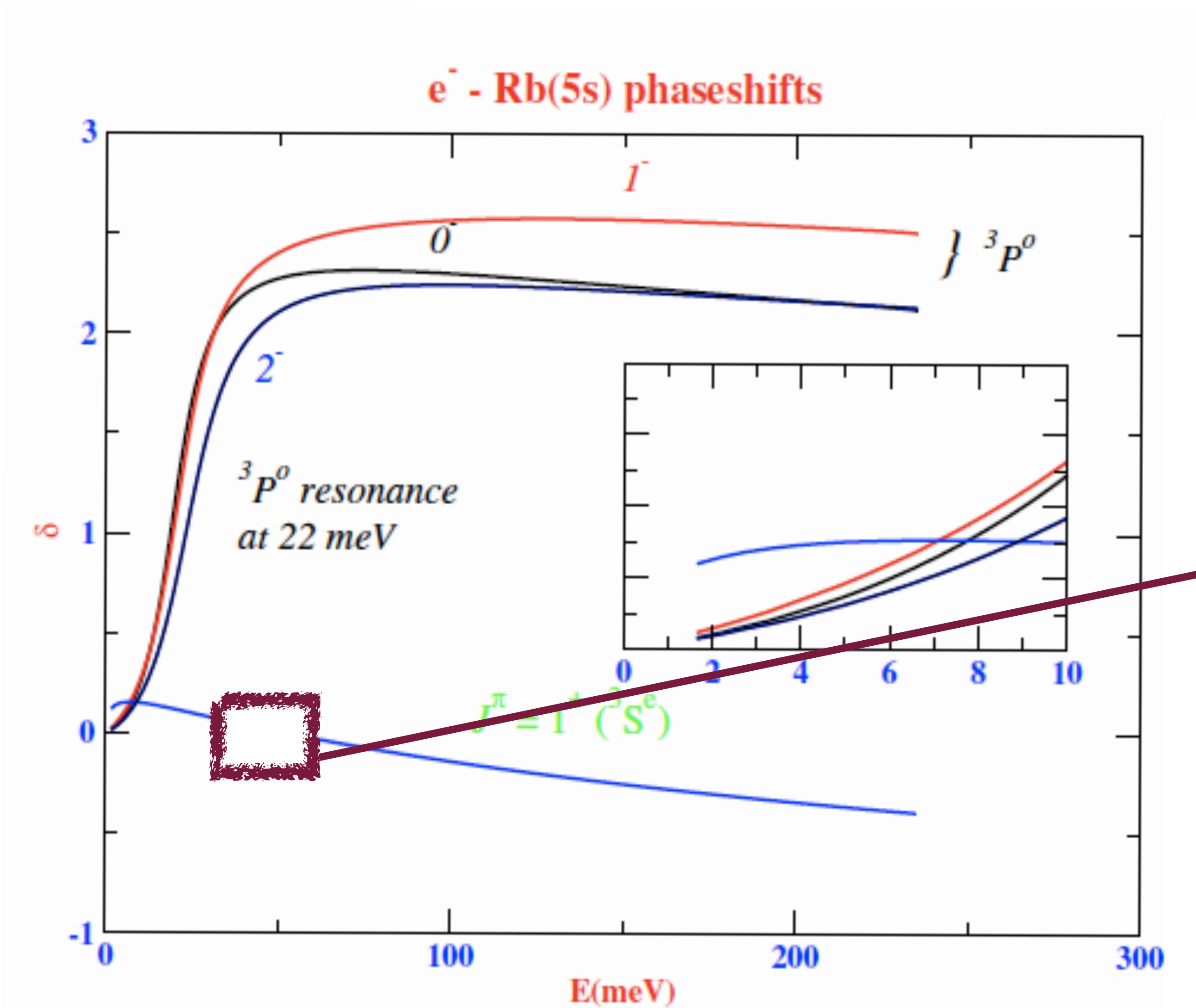

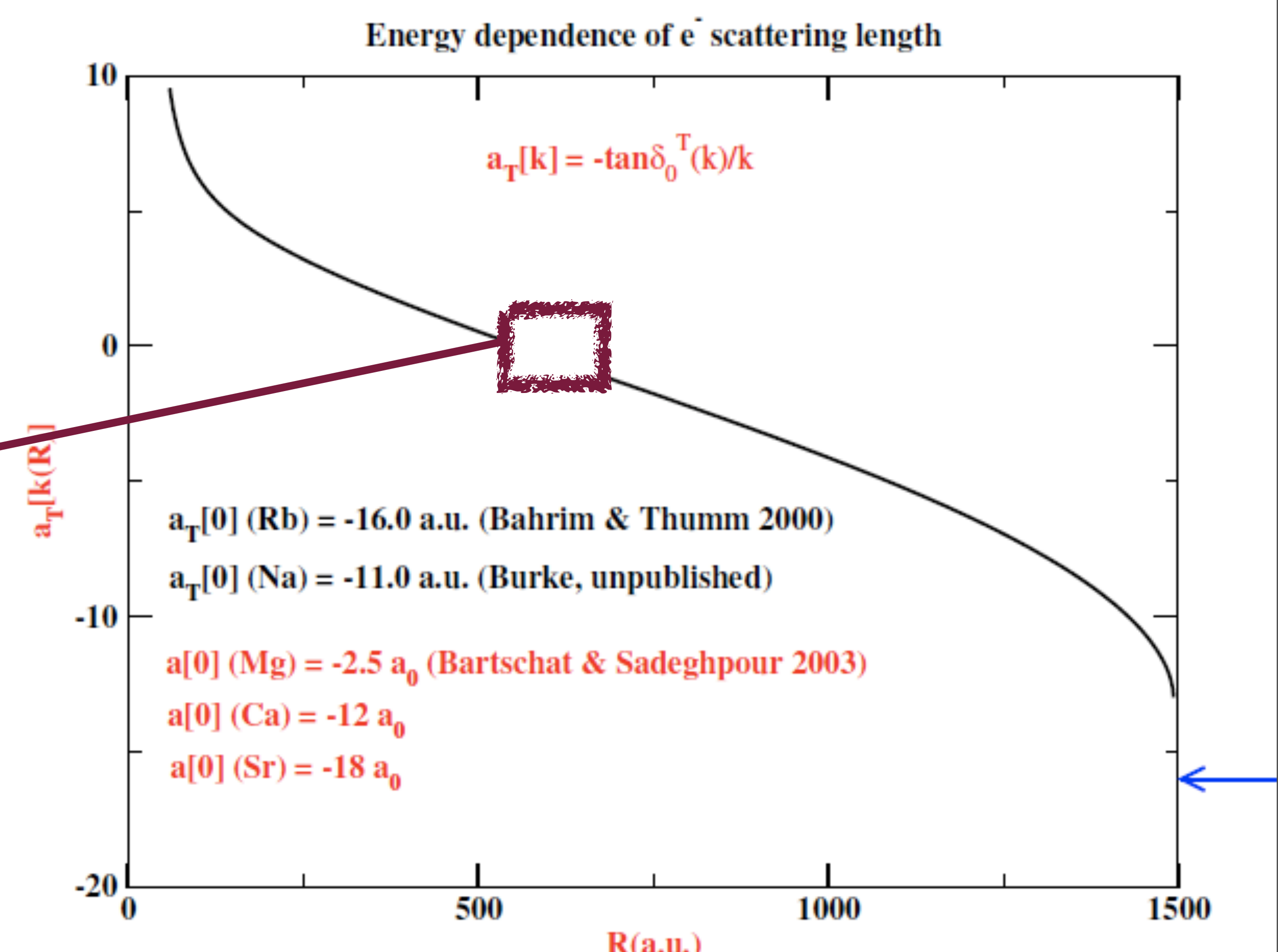

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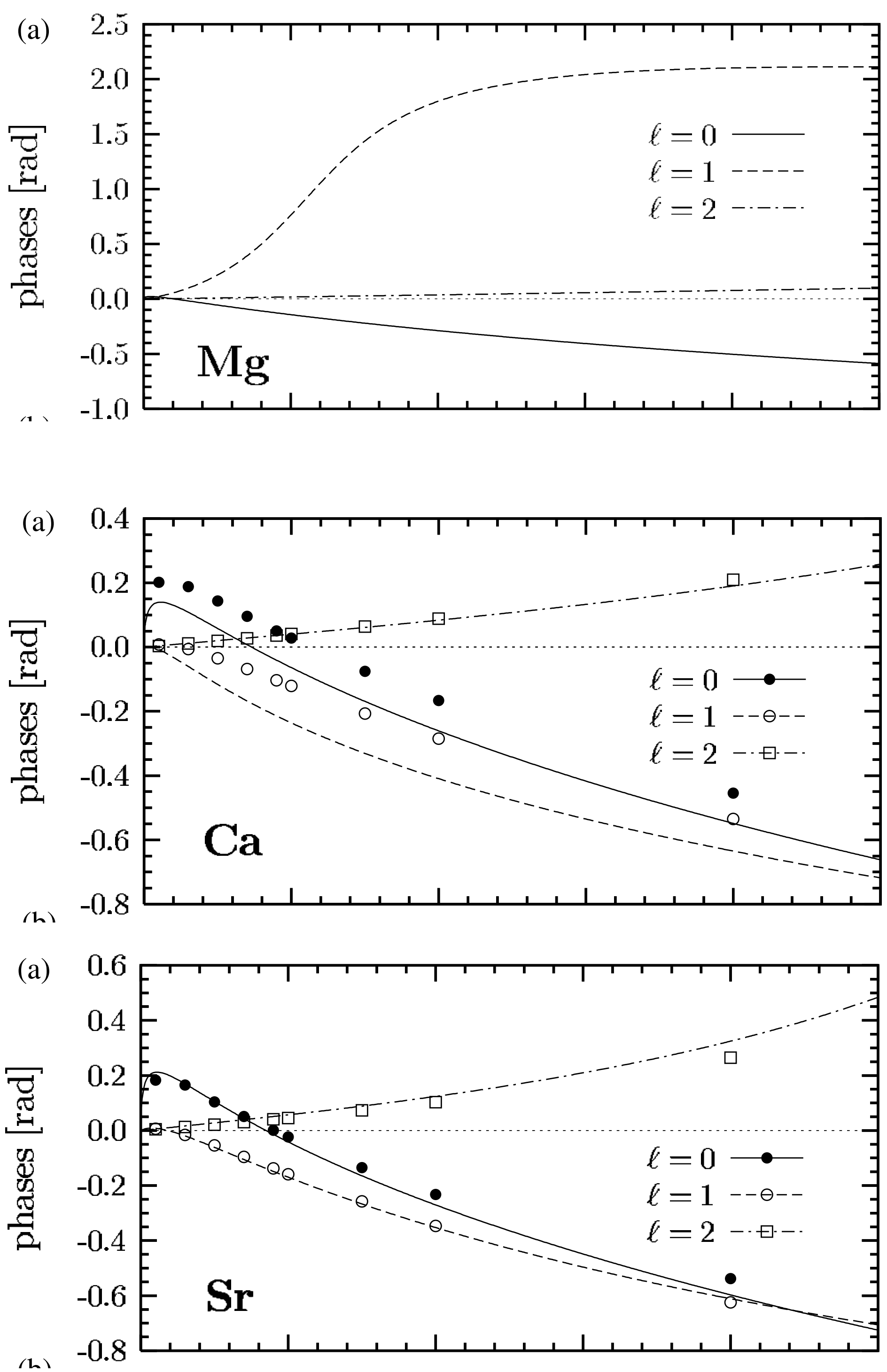
e^- - Alkaline-earth (^{1}Se) elastic phase shift



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a[0] (Ca) = -12 a_0

a[0] (Sr) = -18 a_0

R-matrix calculations

Bartschat + Sadeghpour (2003)

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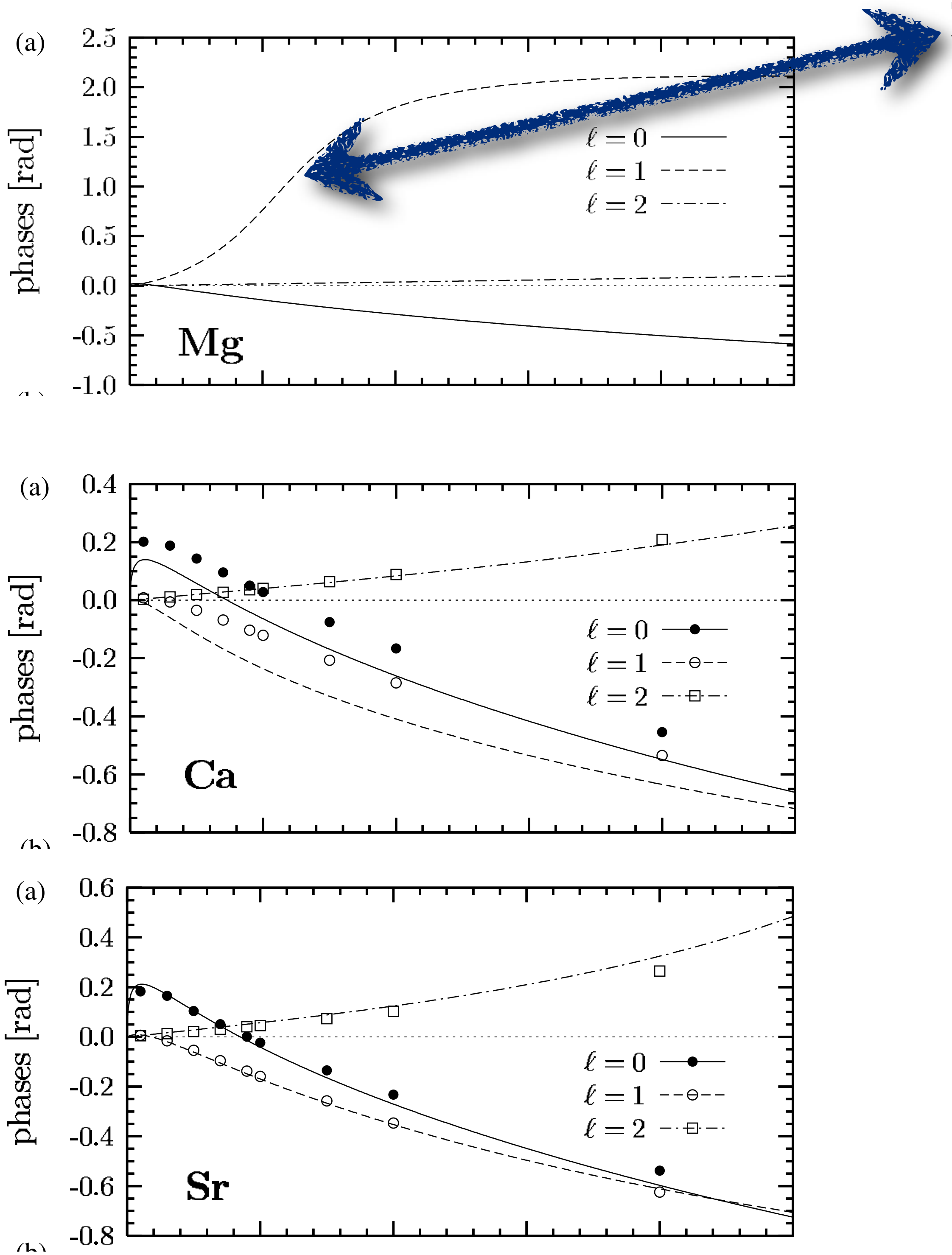

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s-wave e^- scattering $^3\Sigma$

p-wave e^- scattering $^3\Sigma$ $^3\Pi$

Born-Oppenheimer Rydberg molecular potentials

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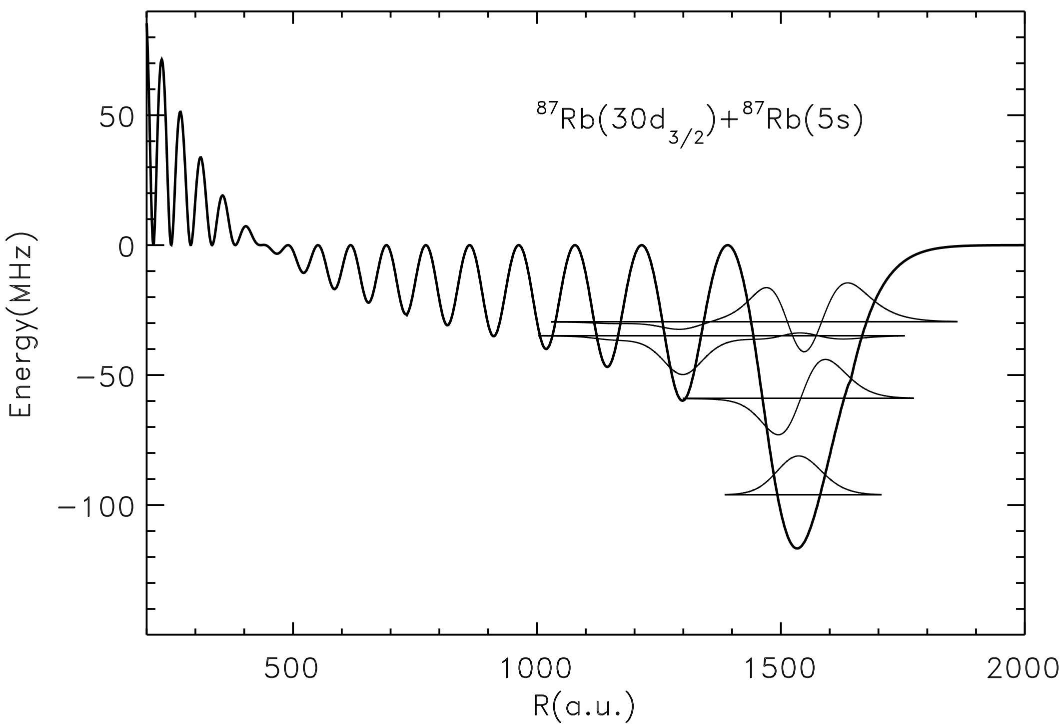

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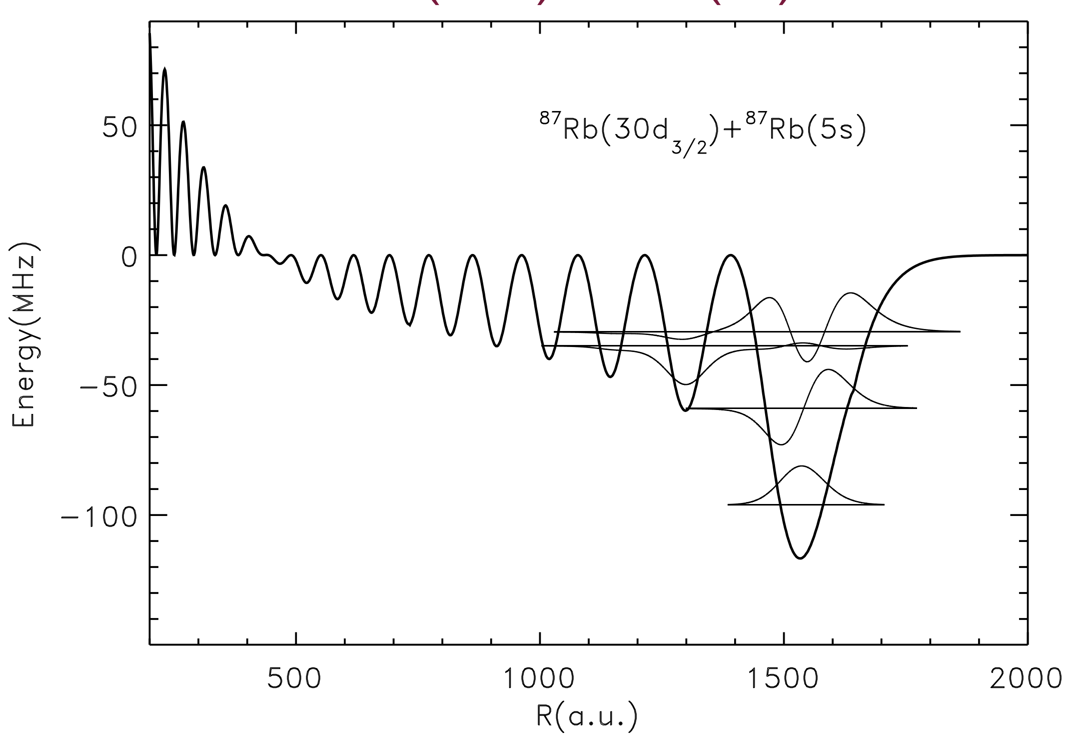

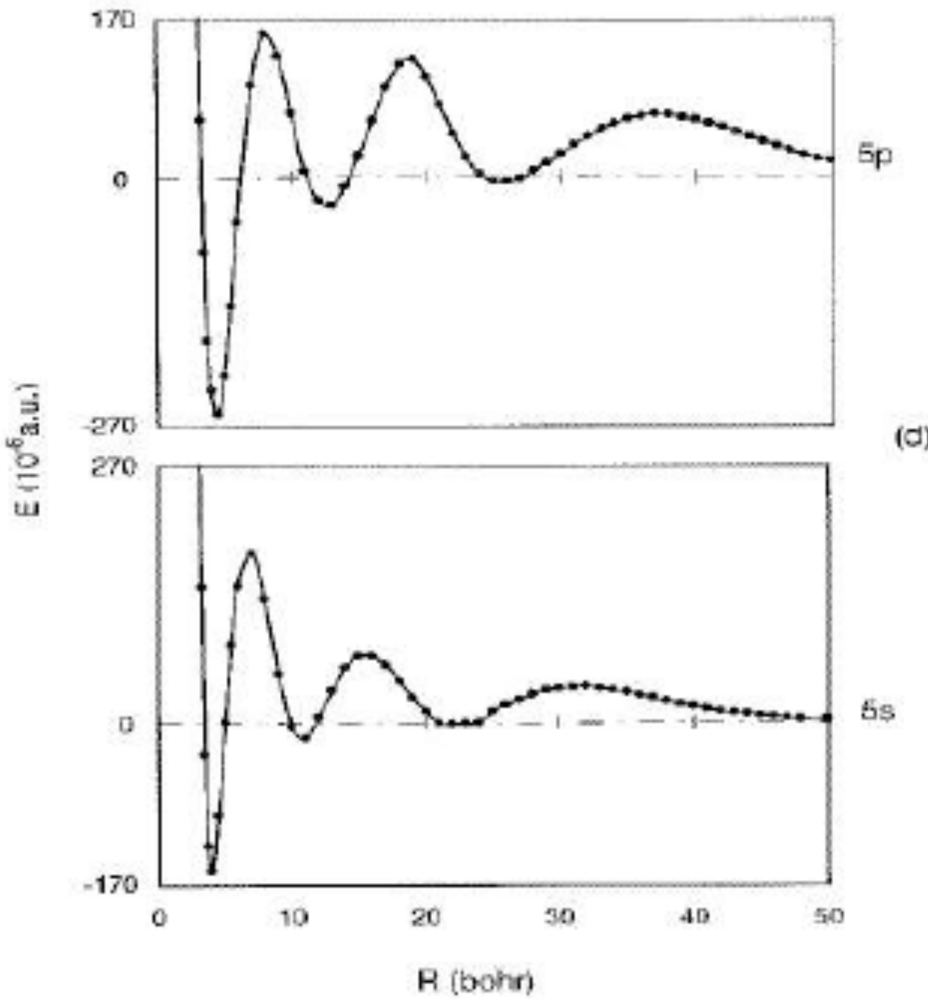

LiHe potentials - Jeung PRA 1999

undulations in BO potentials

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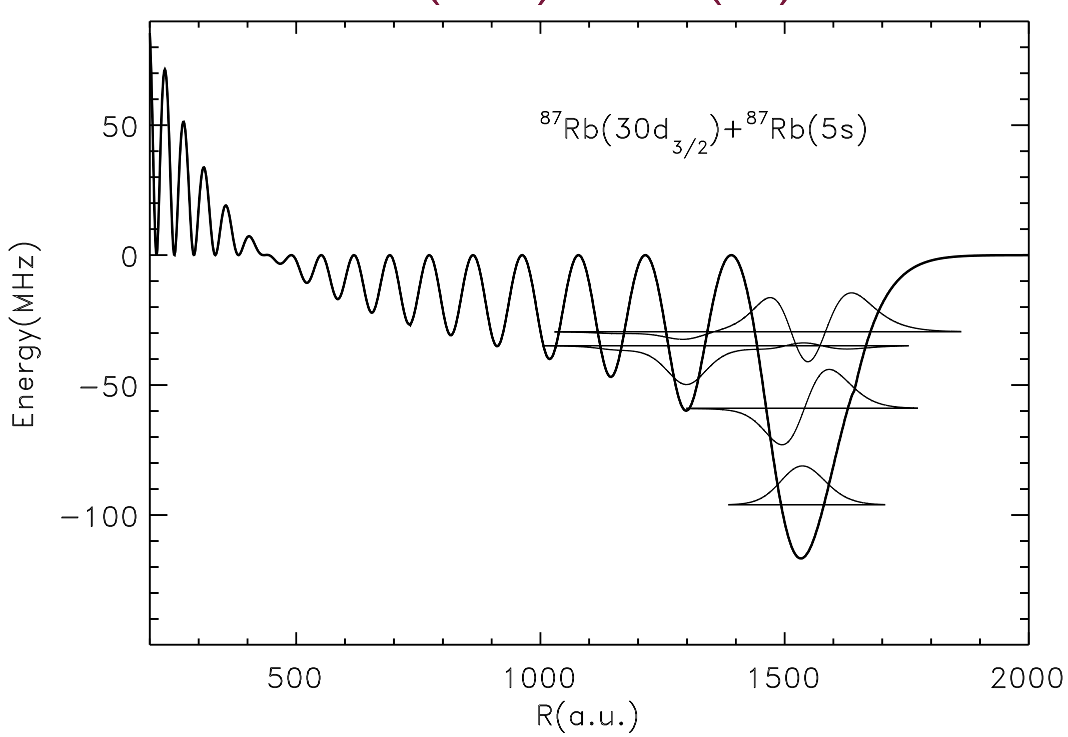

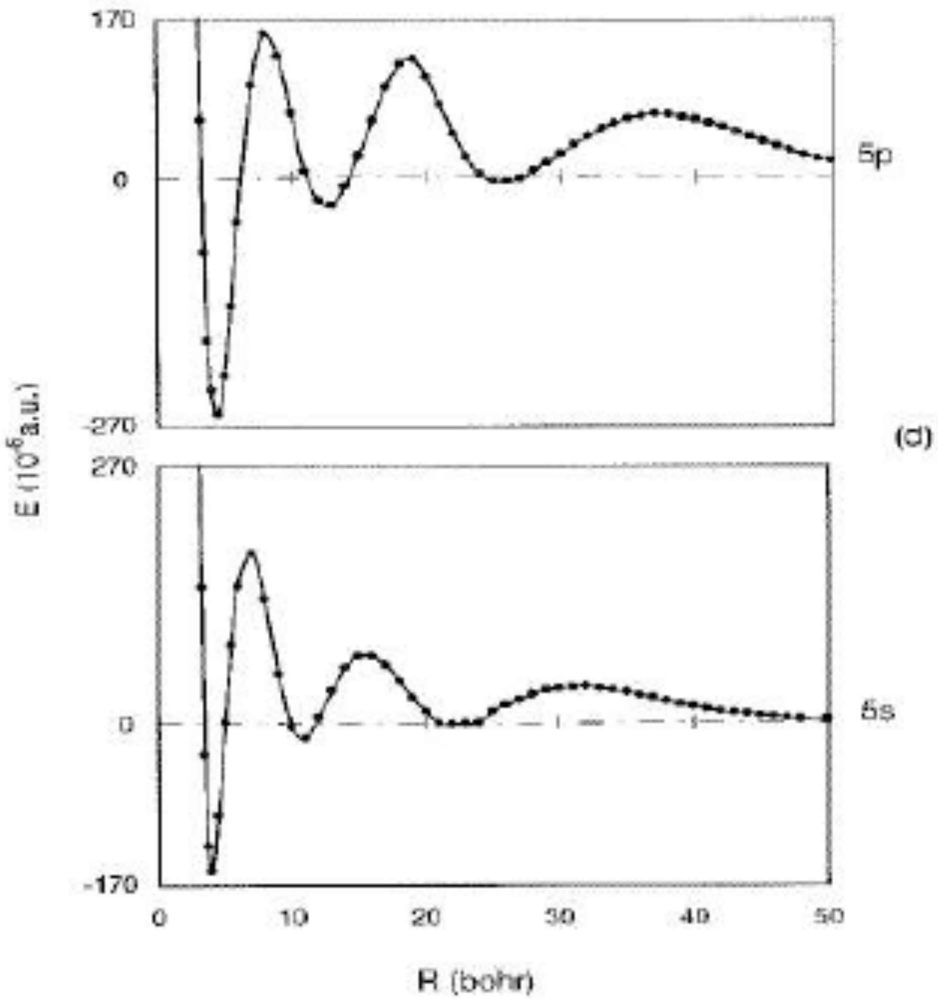

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Experimental Verification of Minima in Excited Long-Range Rydberg States of Rb_2

Chris H. Greene,[1] Edward L. Hamilton,[2] Heather Crowell,[3] Cedomil Vadla,[4] and Kay Niemax[5]
[1]*Department of Physics and JILA, University of Colorado, Boulder, Colorado 80309-0440, USA*
[2]*Department of Chemistry, Northwestern University, Evanston, Illinois 60208-3113, USA*
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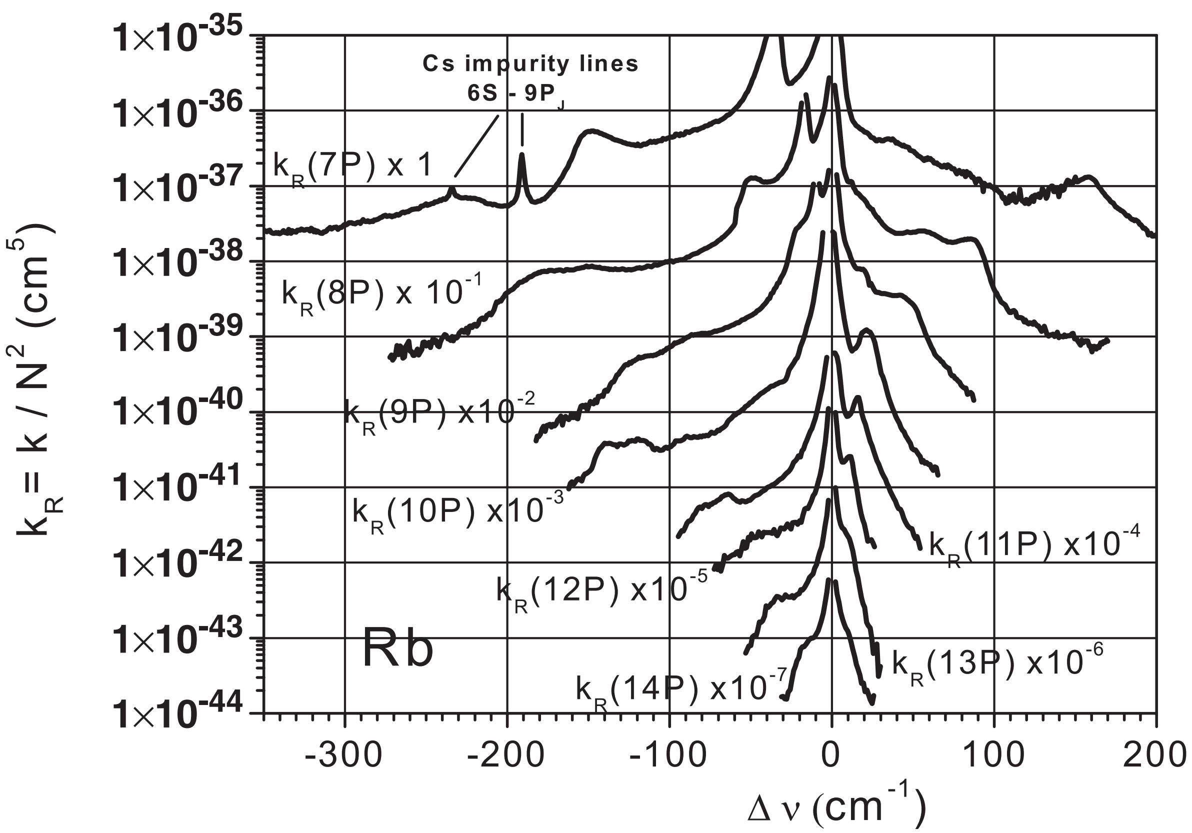
[4]*Institute of Physics, Bijenicka 46, 10000 Zagreb, Croatia*
[5]*ISAS-Institute for Analytical Sciences at the University of Dortmund, Bunsen-Kirchhoff-Str. 11, D-44139, Dortmund, Germany*
(Received 1 September 2006; published 8 December 2006)

Recent theoretical studies with alkali atoms A^* excited to high Rydberg states predicted the existence of ultra-long-range molecular bound states. Such excited dimers have large electric dipole moments which, in combination with their long radiative lifetimes, make them excellent candidates for manipulation in applications. This Letter reports on experimental investigations of the self-broadening of Rb principal series lines, which revealed multiple satellites in the line wings. The positions of the satellites agree quantitatively with theoretically predicted minima in the excited long-range Rydberg states of Rb_2.



Wednesday, September 15, 2010

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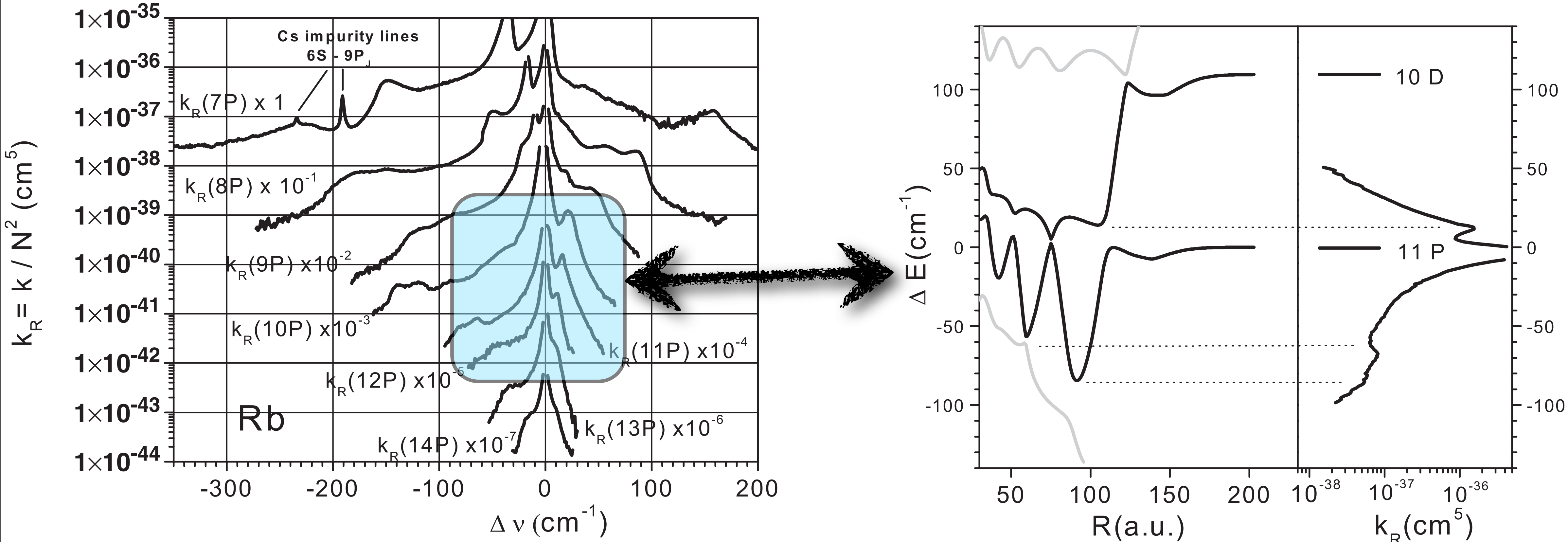

Beyond s-wave ...

$$< k_f|V(\mathbf{r}-\mathbf{R})|k_i >= -\frac{2\pi}{k}\sum_l (2l+1) tan(\delta_l) P_l(k_i \cdot k_f)$$

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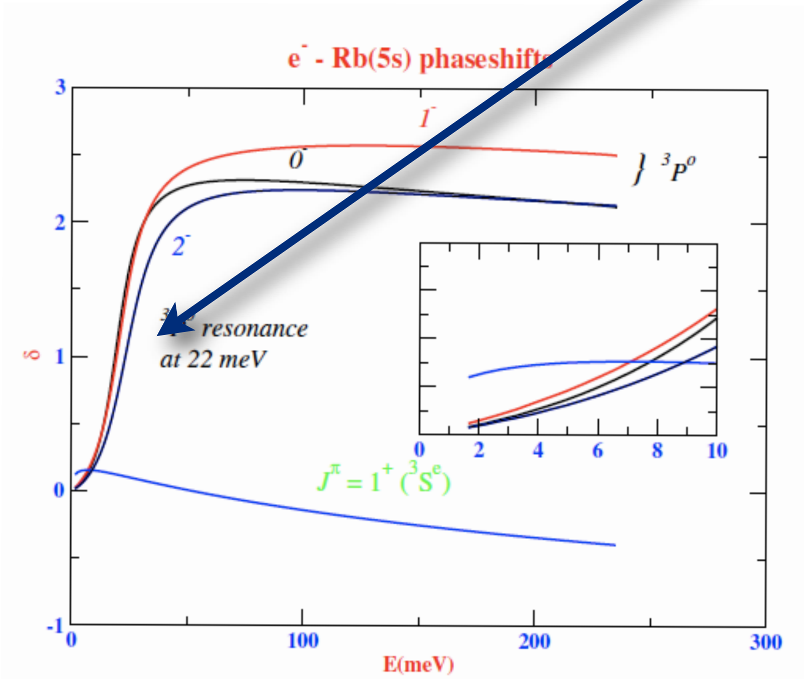
$$\langle\Psi_1|V_p|\Psi_2\rangle = -\frac{6\pi\tan\delta_1^T}{k^3(R)}\vec{\nabla}\Psi_1(\vec{R})\cdot\vec{\nabla}'\Psi_2(\vec{R})$$



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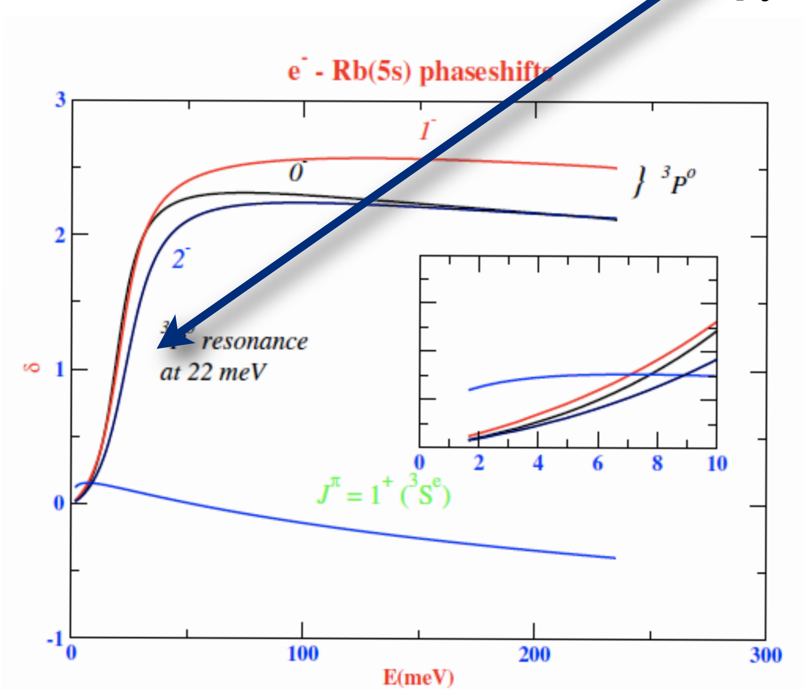

... creates two molecular classes: one which maximizes gradient perp to R, and one which maximizes gradient para to R

Weibin .... numerical tour-de-force

Exotic molecules?

Rb(5s)+Rb(ns) ; $\mu_s = 3.13$

Rb(5s)+Rb(np$_{1/2,3/2}$); $\mu_p = 1.67$

Rb(5s)+Rb(nd$_{3/2,5/2}$); $\mu_d = 1.35$

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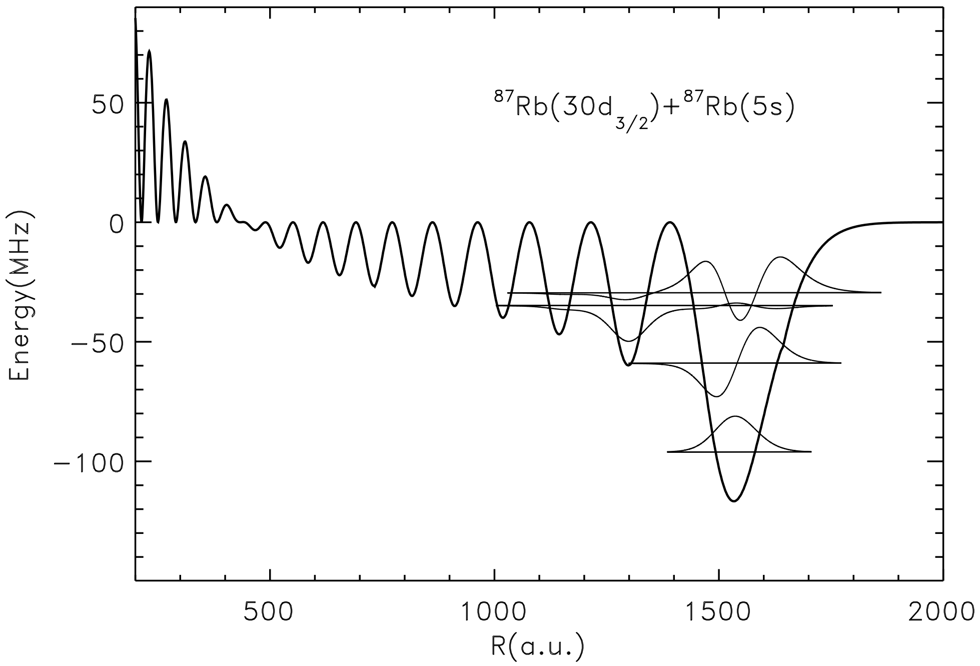

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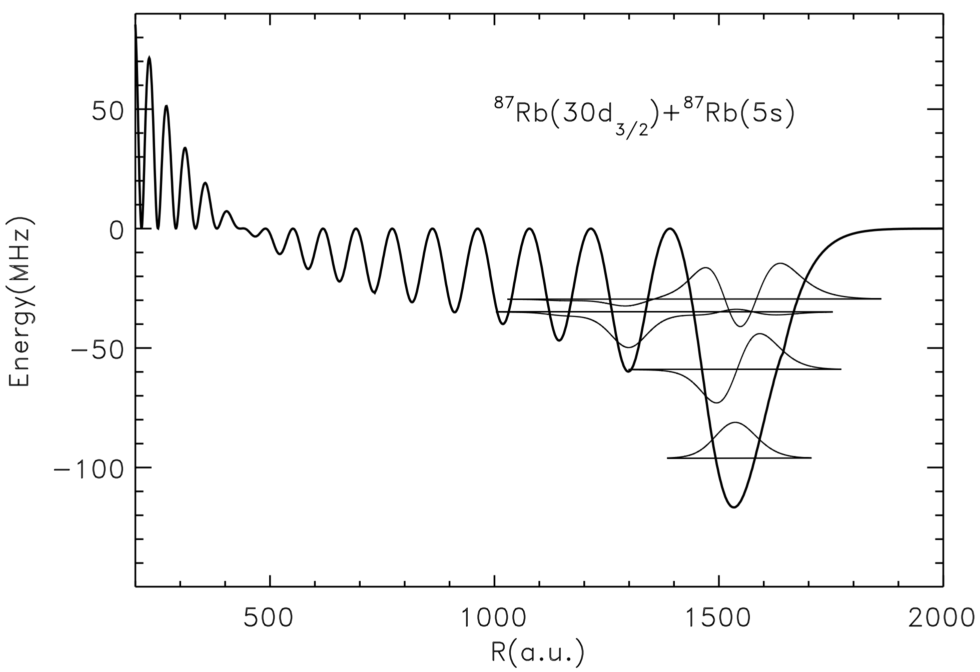

Rb(5s)+Rb(nl>2); $\mu_d \sim 0$

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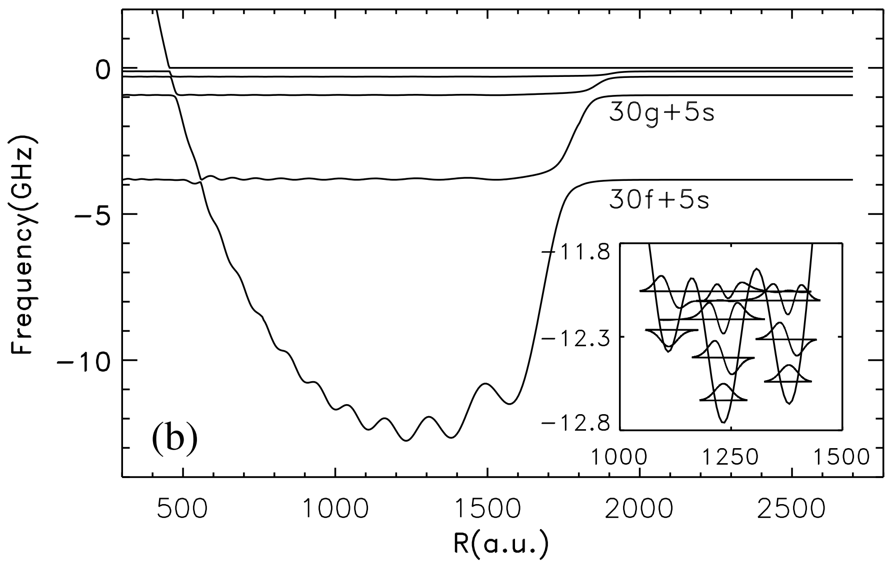

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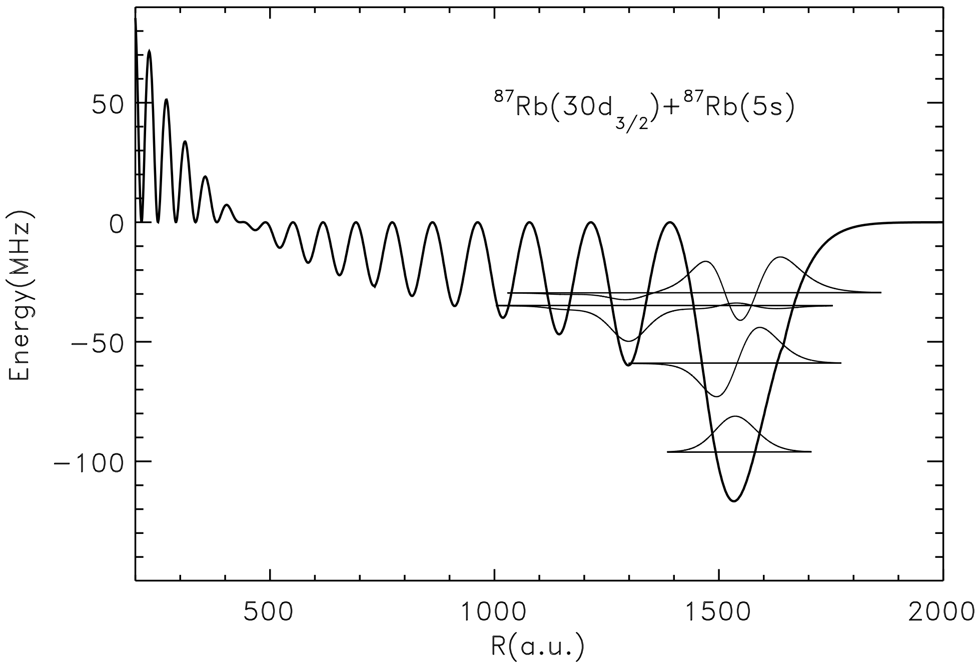

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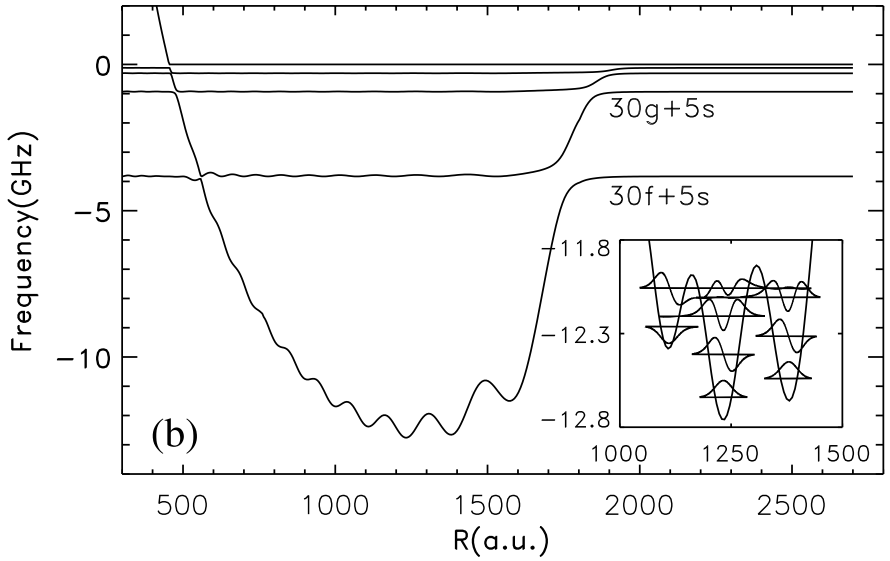

s-wave

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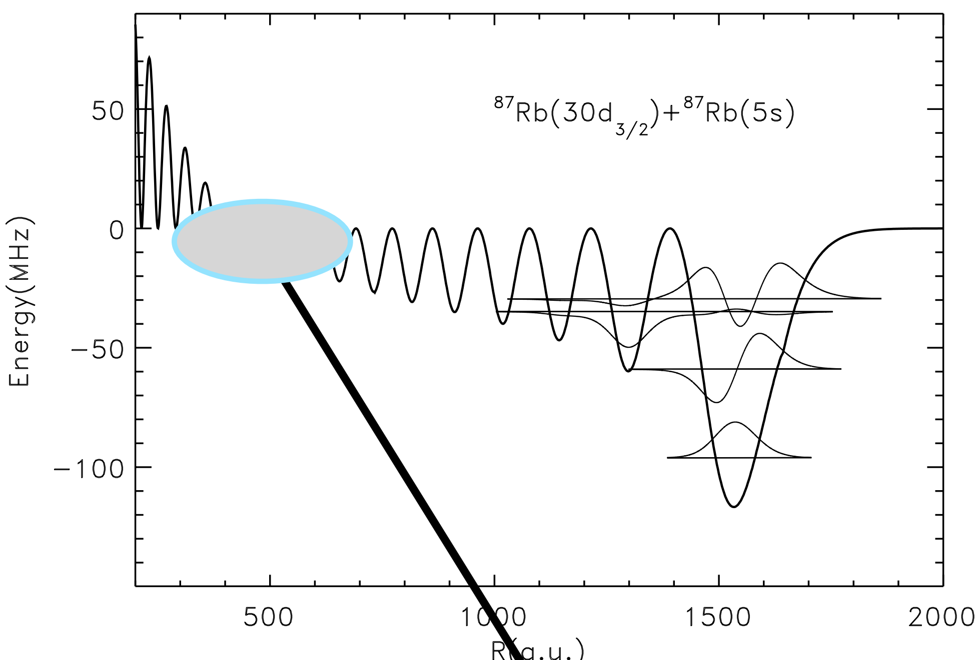
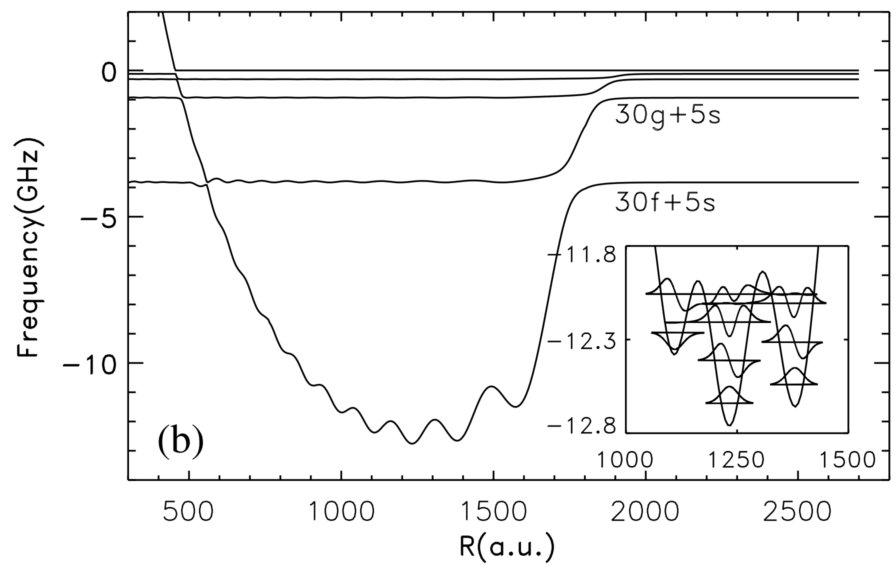
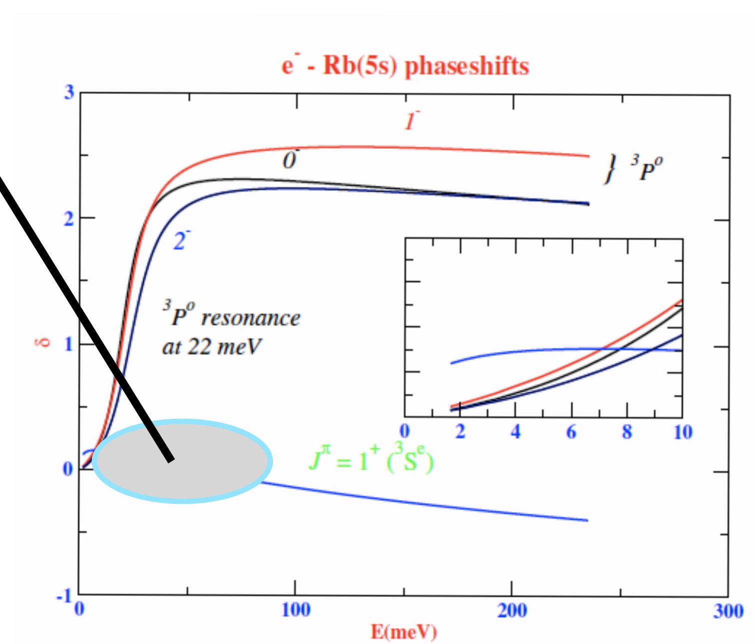




s-wave



Exotic molecules?

Rb(5s)+Rb(ns) ; $\mu_s = 3.13$

Rb(5s)+Rb(np1/2,3/2); $\mu_p = 1.67$

Rb(5s)+Rb(nd3/2,5/2); $\mu_d = 1.35$

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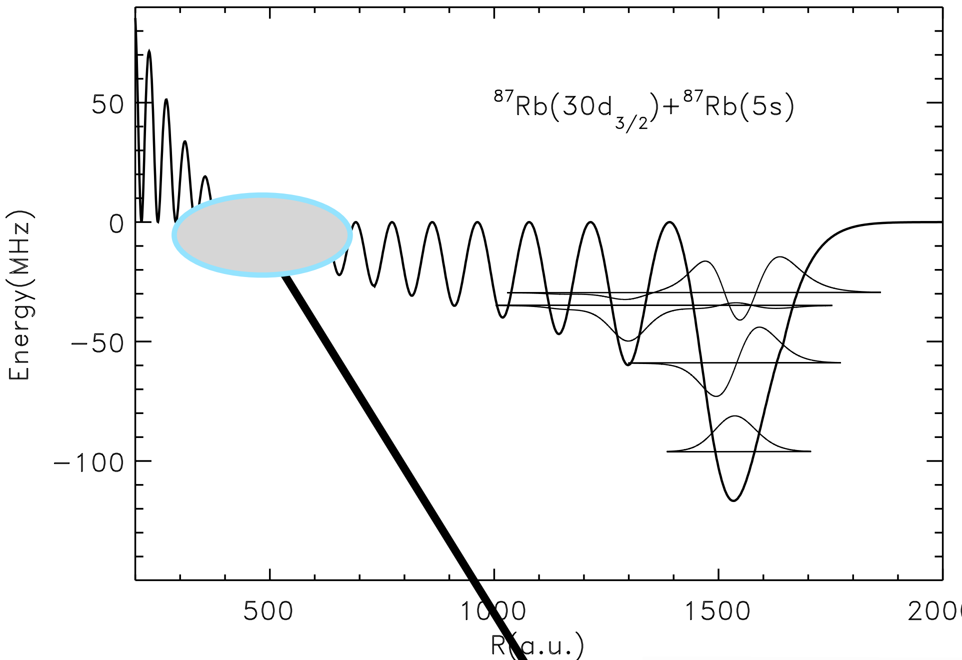
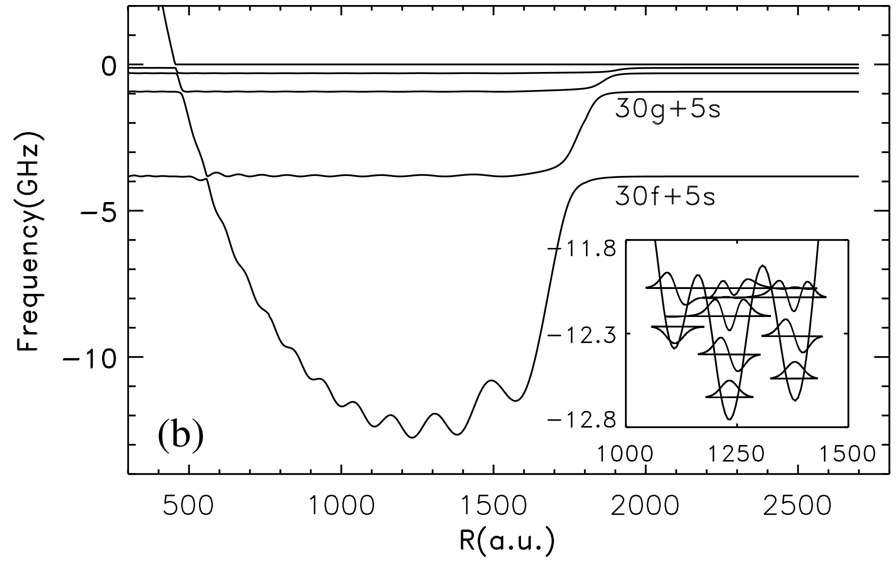
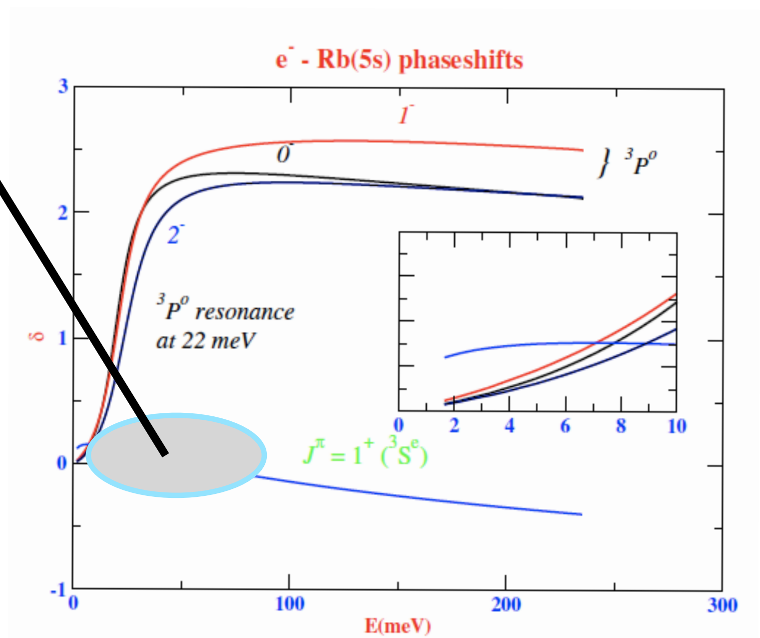


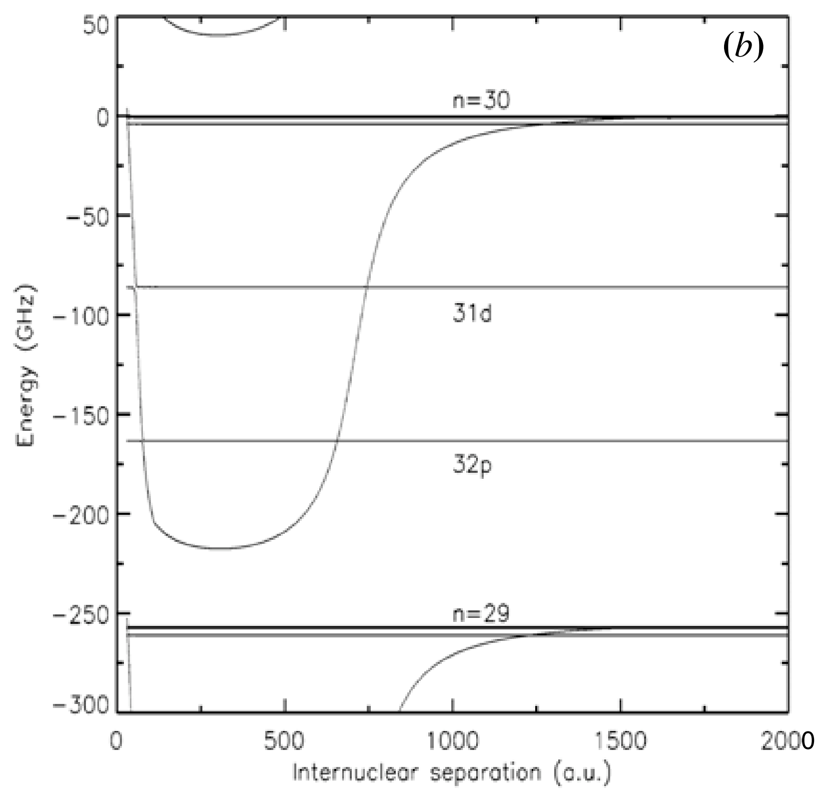


s-wave

$$\langle\Psi_1|V_p|\Psi_2\rangle = -\frac{6\pi\tan\delta_1^T}{k^3(R)}\vec{\nabla}\Psi_1(\vec{R})\cdot\vec{\nabla}'\Psi_2(\vec{R})$$

p-wave





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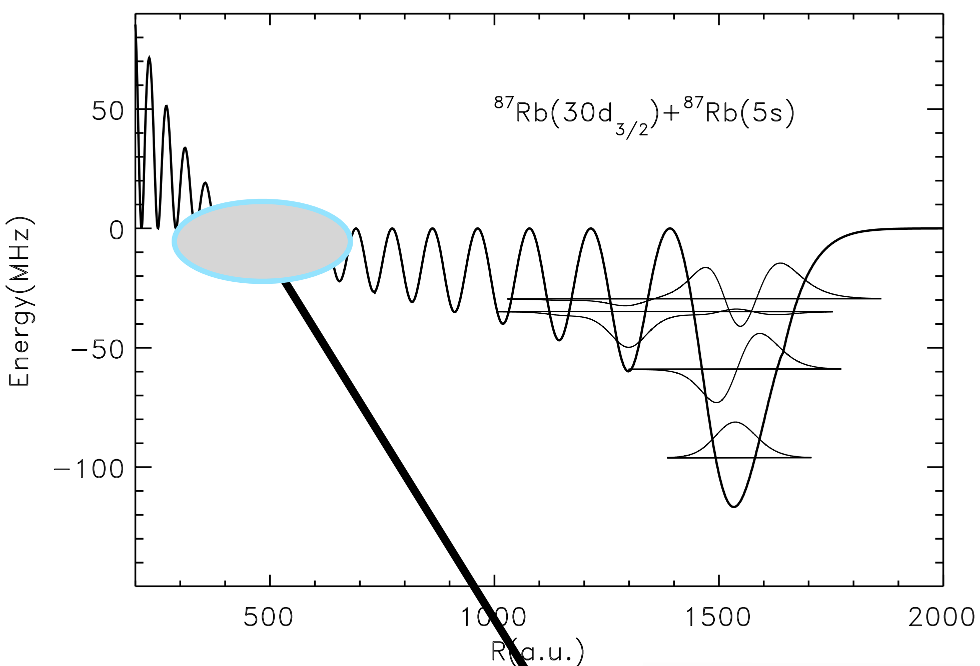

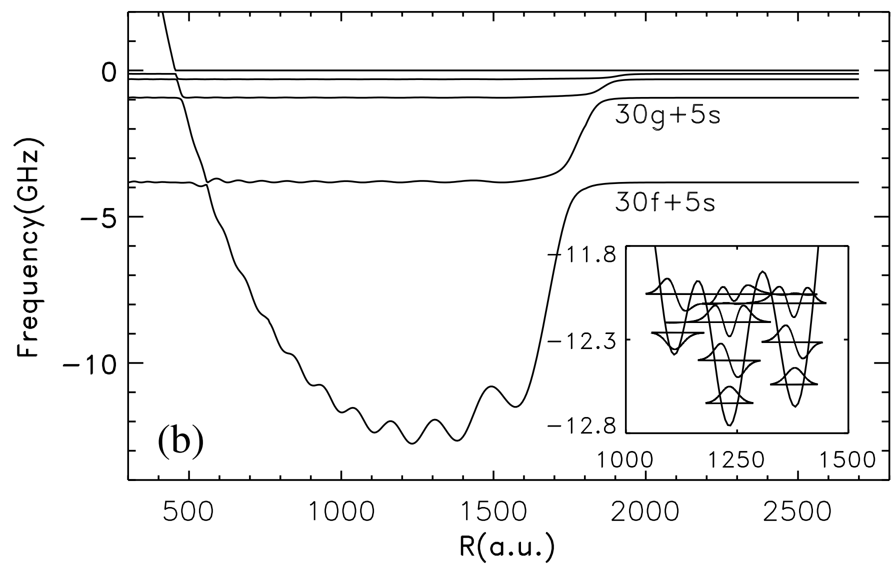

s-wave

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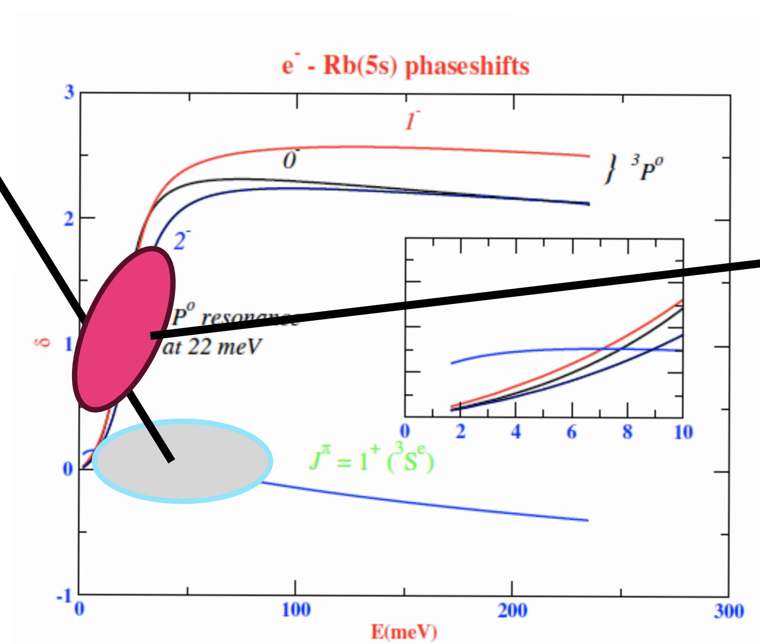
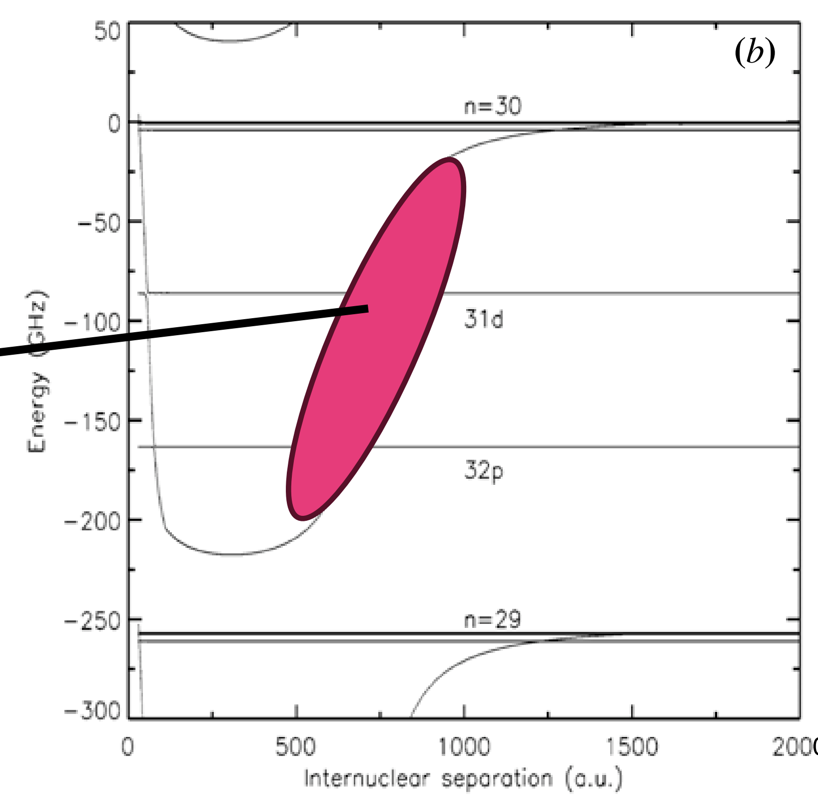


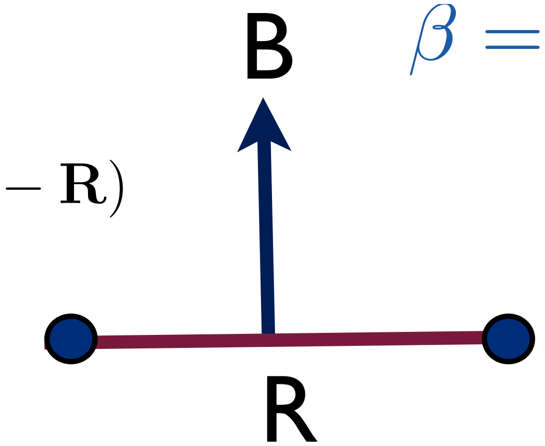


$$H \;=\; \frac{1}{2}\mathbf{p}^2 + V(\mathbf{r}) + \frac{1}{2}\mathbf{B}\cdot\mathbf{L} + \frac{1}{8}\left[\mathbf{B}\times\mathbf{r}\right]^2 + 2\pi A_T[k(R)]\delta(\mathbf{r}-\mathbf{R})$$

Lesanovsky et al. (2005)

Magnetized trilobites

$\beta = 0$



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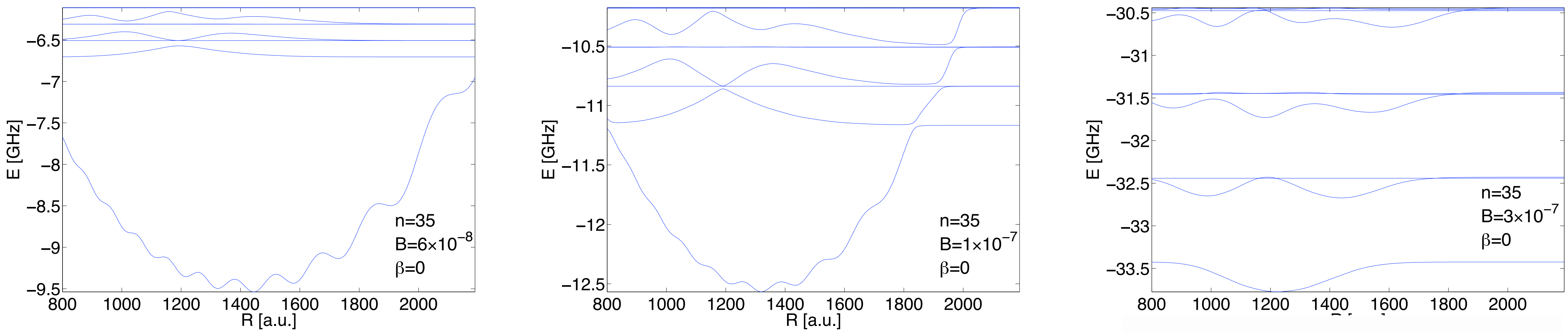
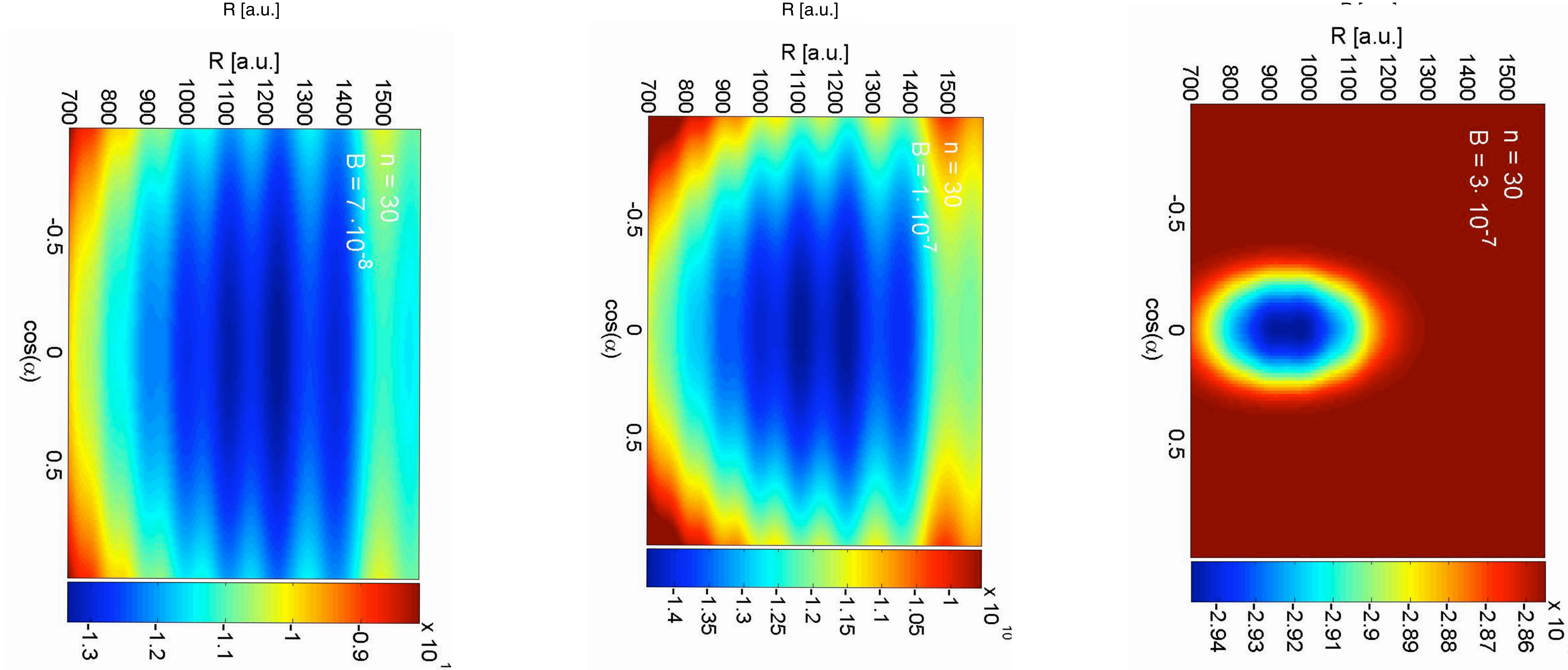
$$\beta = \frac{\pi}{2} - \cos^{-1}[\hat{B}\cdot\hat{R}]$$

Lesanovsky et al. (2005)



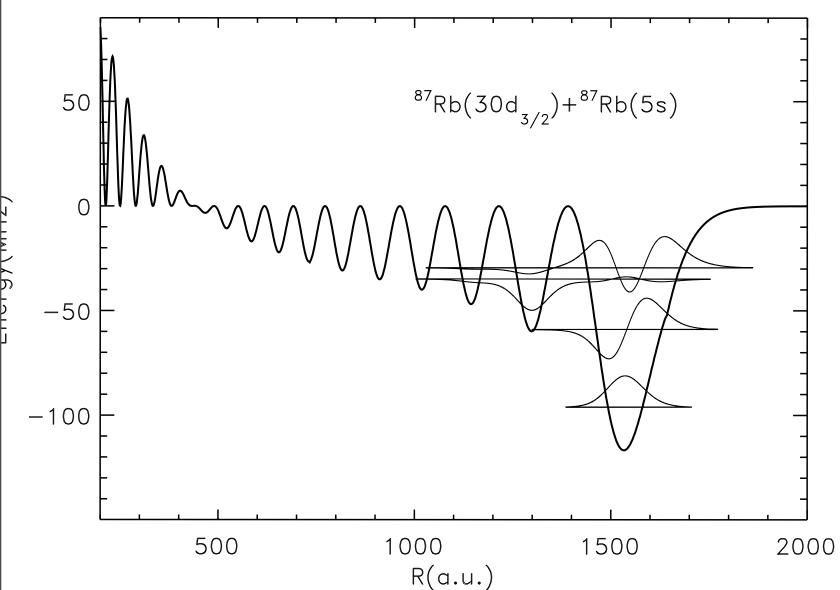


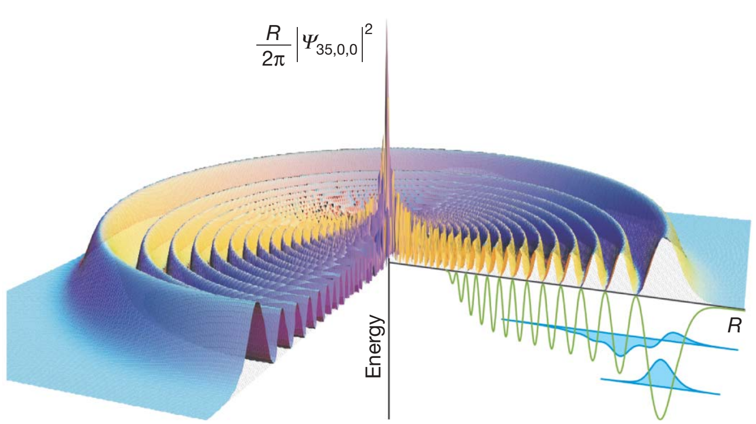
Three cases:

Three cases:

a case of ....

no dipole... well!





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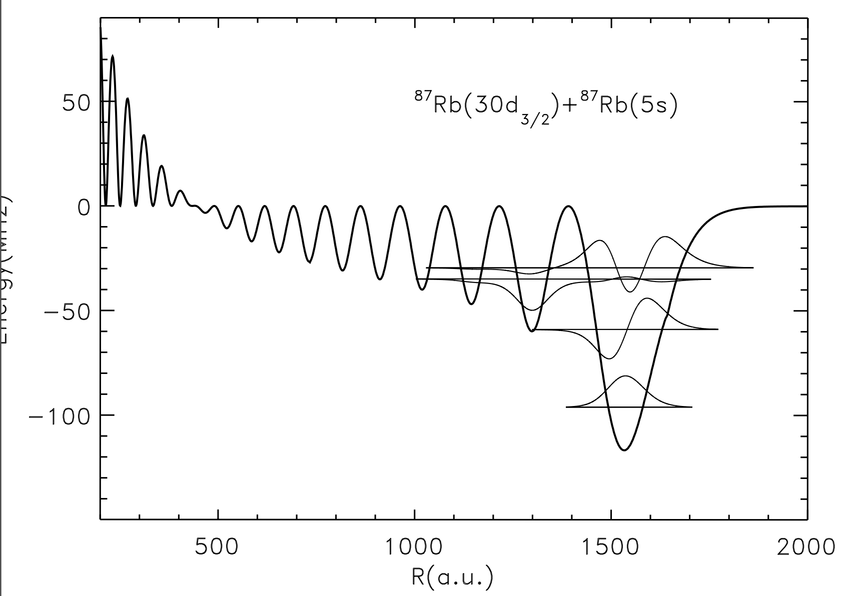
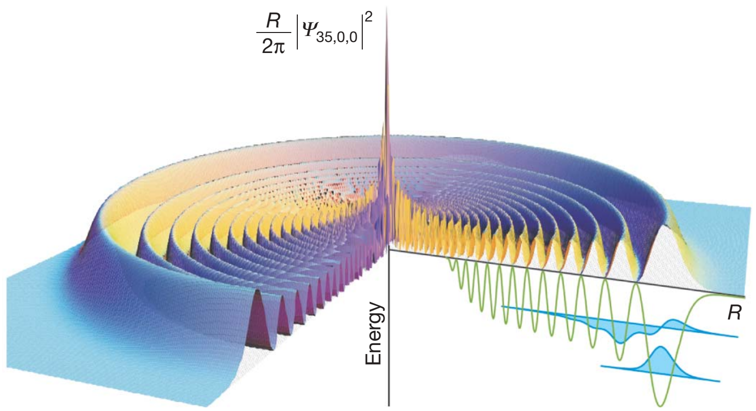
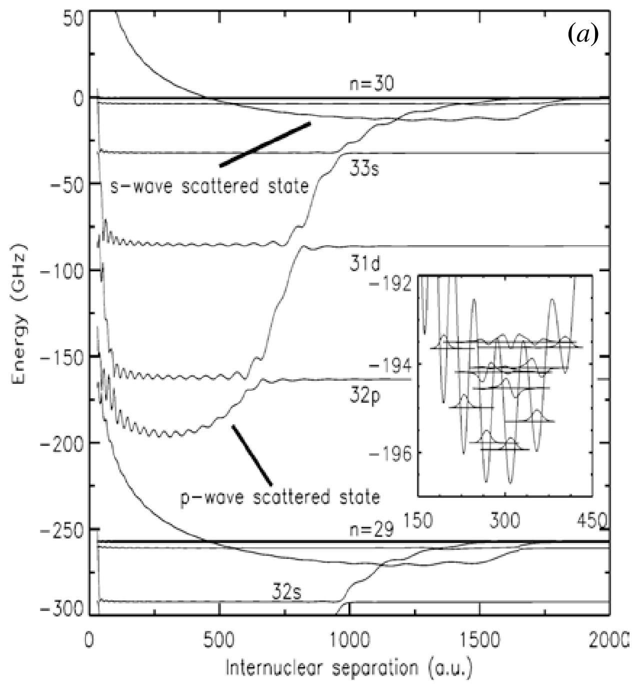
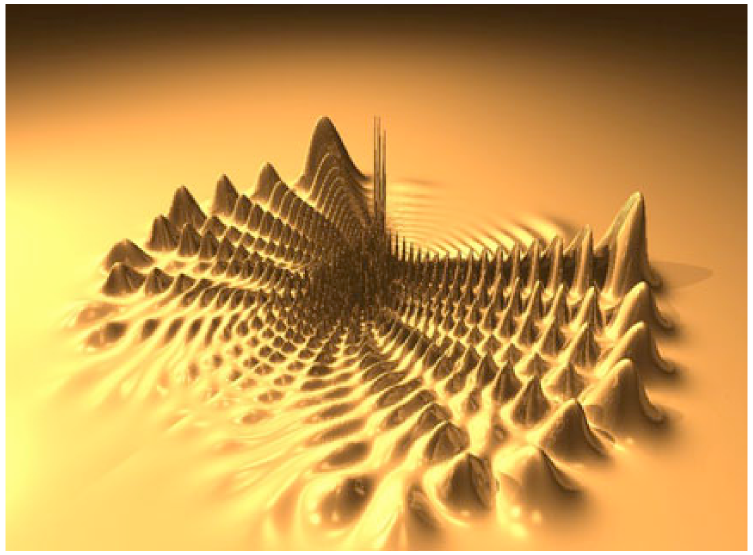




... a case of butterflies!

large dipole





Three cases:

a case of ....

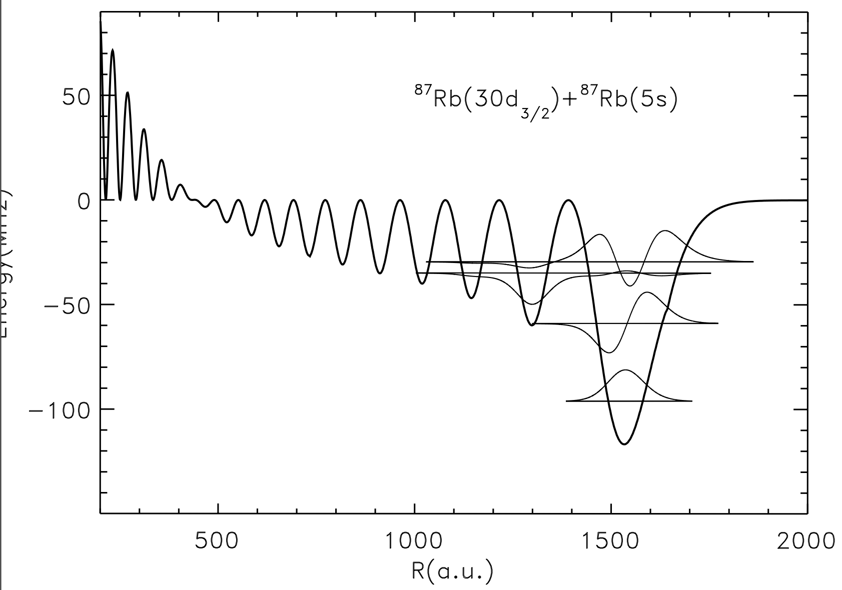
no dipole... well!

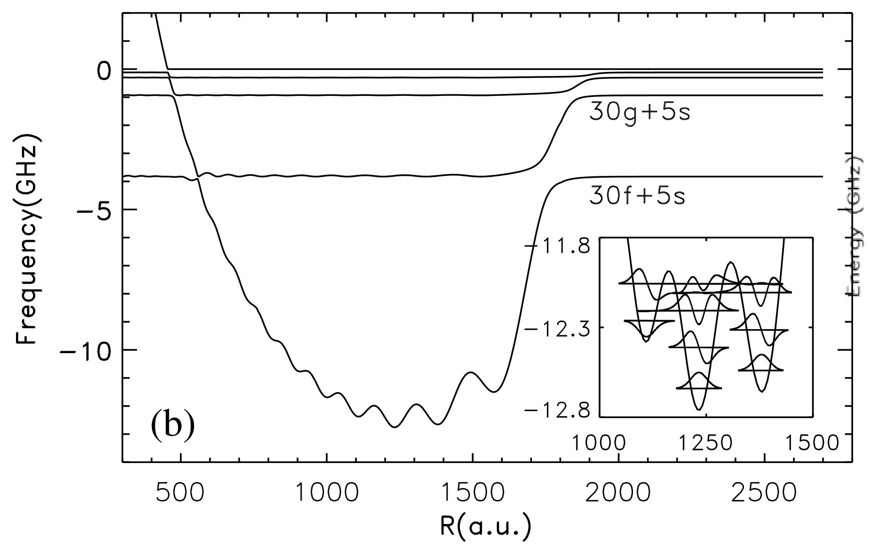
... and a case of trilobites!

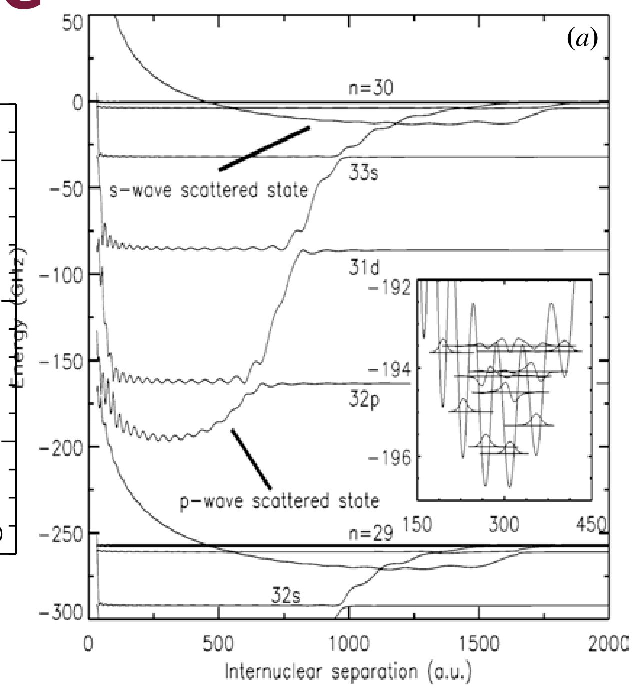
and even larger dipole

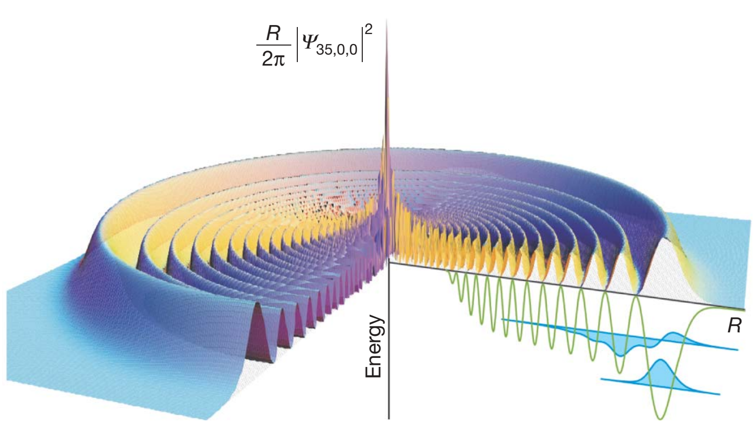
... a case of butterflies!

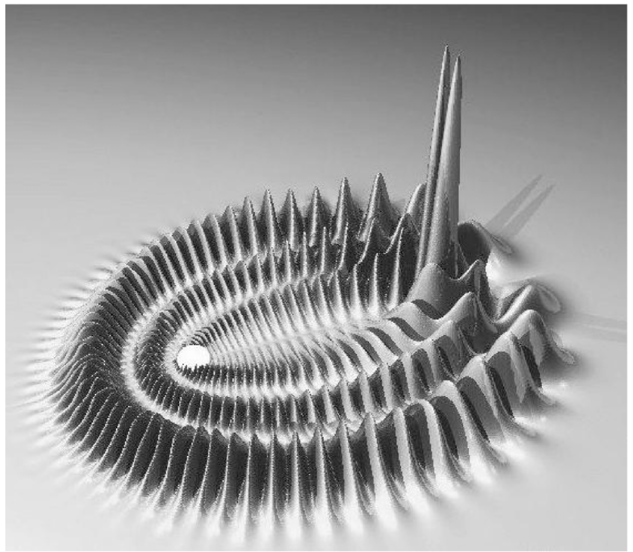
large dipole

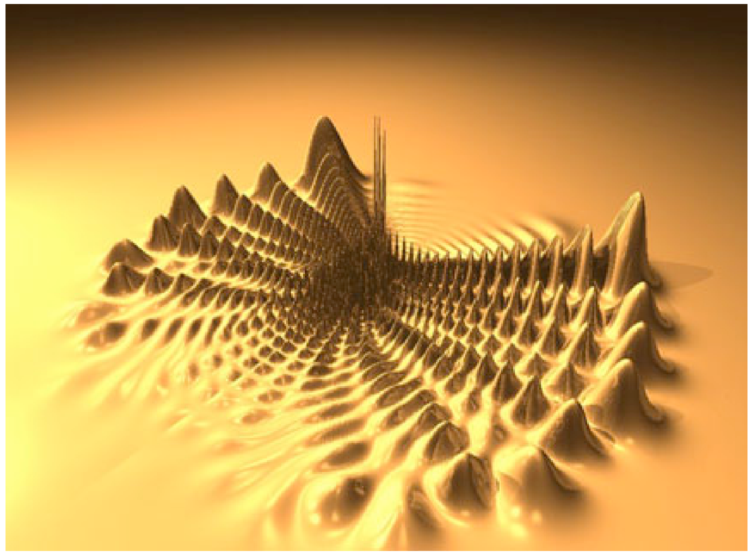






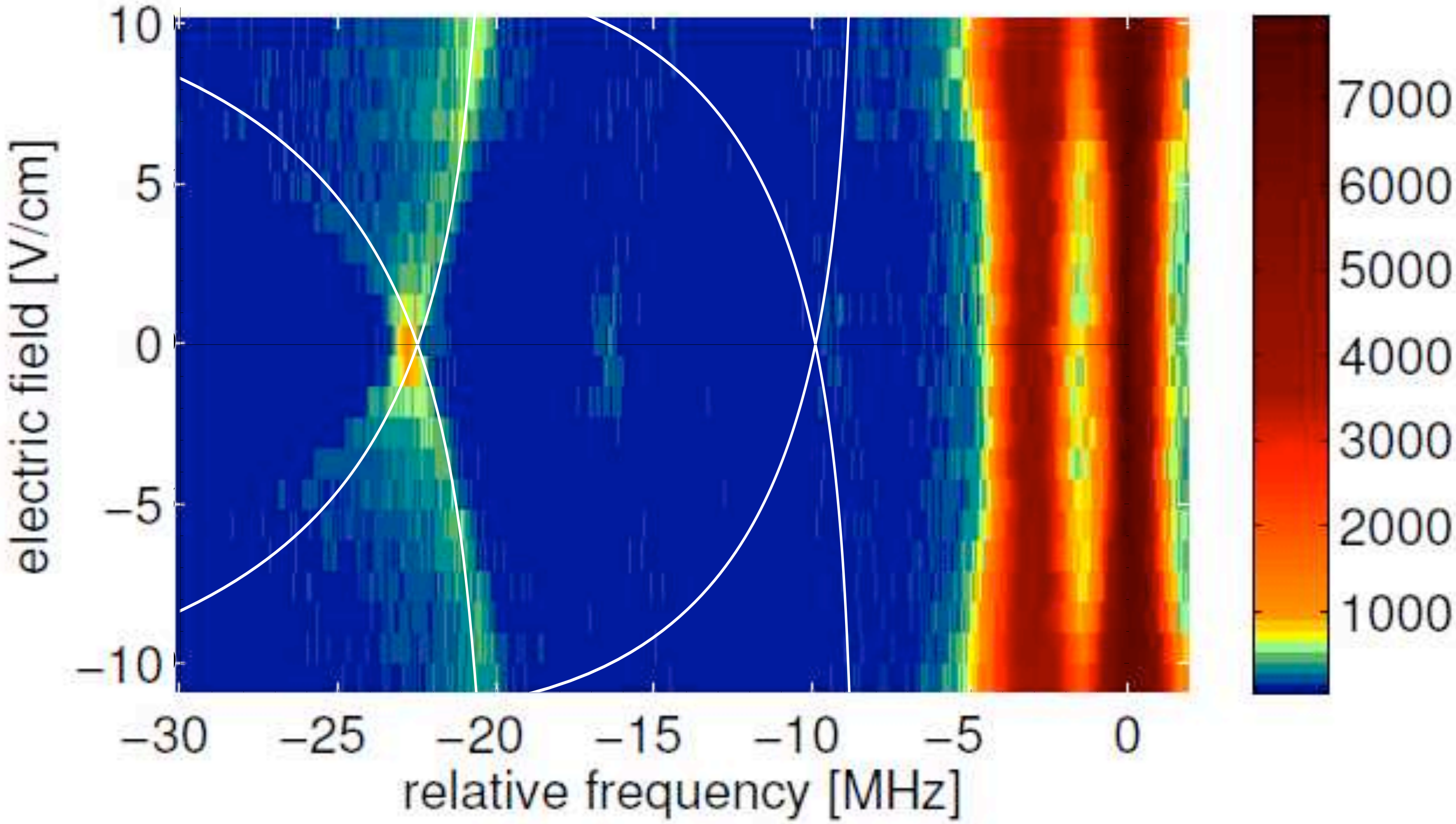




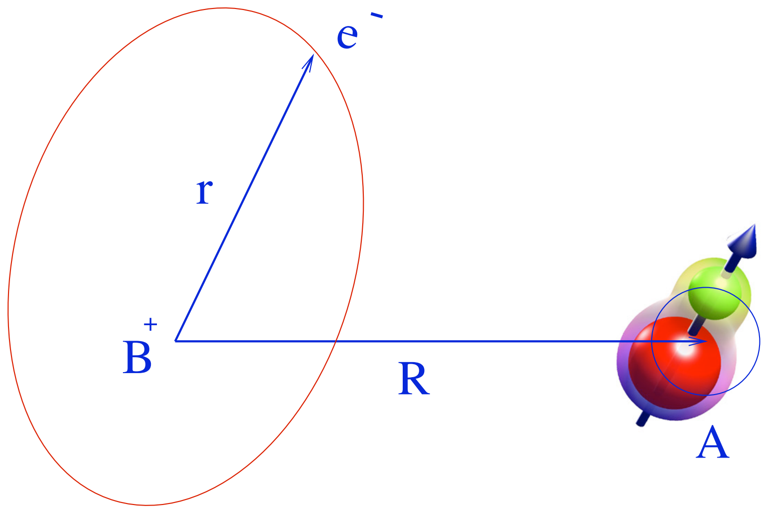


Stark-spectrum

substracting atomic Stark-shift



Switching gear ...



... no longer short range
scattering length picture does not hold

e⁻ - dipole interaction:

$$\lambda(\lambda+1)/R^2 = (a-1/4)/R^2$$

$a > a_c = 0.639\ \mathrm{a.u.}$ = 1.63 D .... Fermi-Teller dipole

... e⁻ - binds to dipole (supercritical dipole) ... negative ion forms

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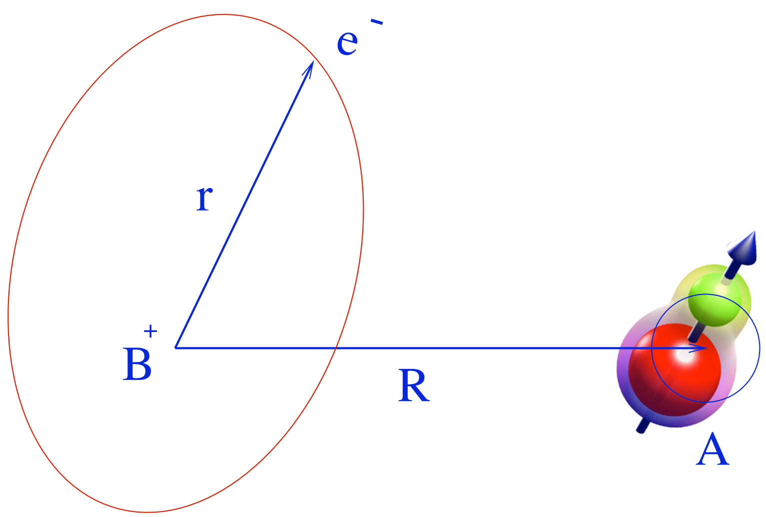

Seth Rittenhouse... (last week)

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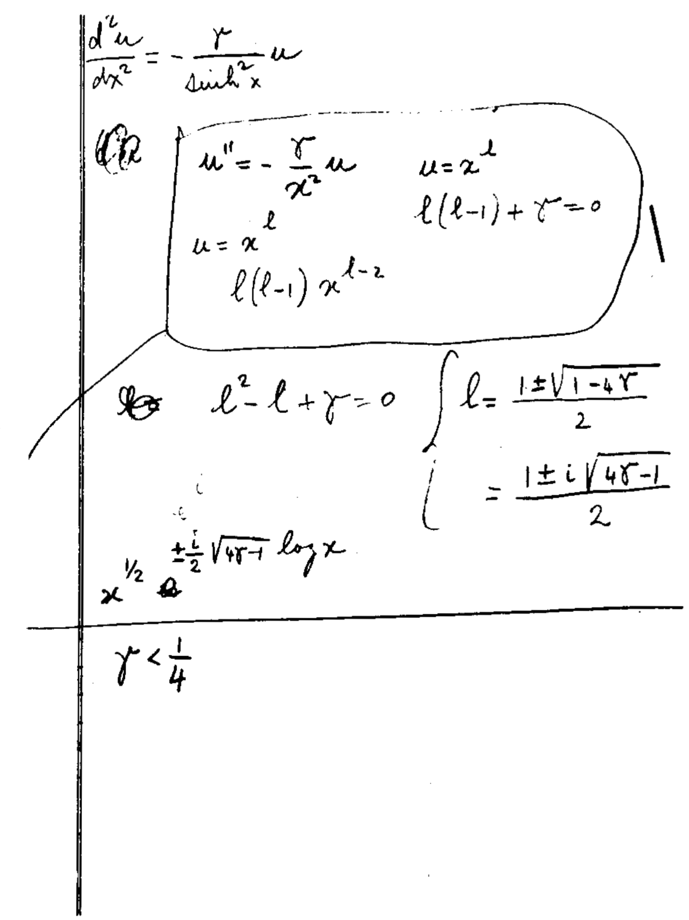

Fig. 5. Condition on modified separation constant $\gamma = -\alpha - \epsilon$ for zero-energy solution. Notebook 100 (D12), p. 297.

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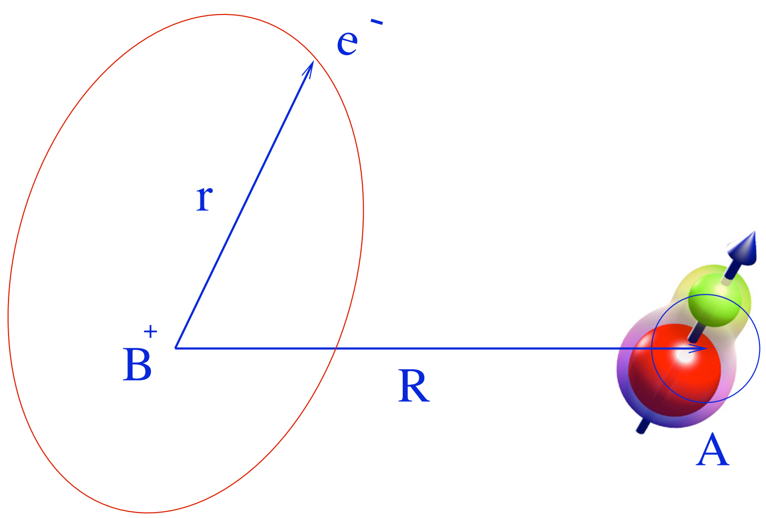

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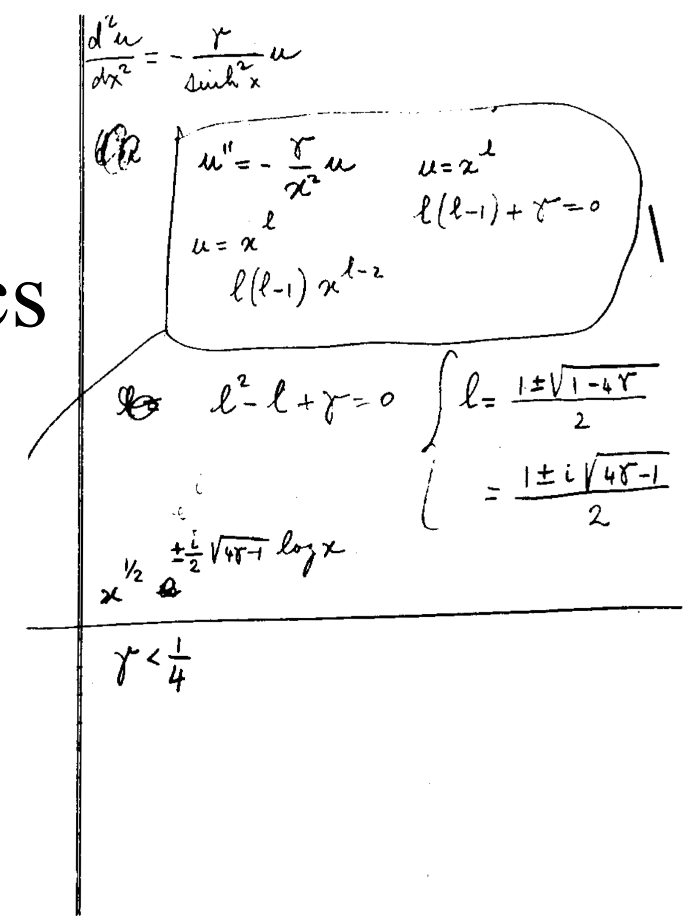
- longest range interaction in cold atom physics

- anisotropic interaction



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... Of dipole scattering and bound states

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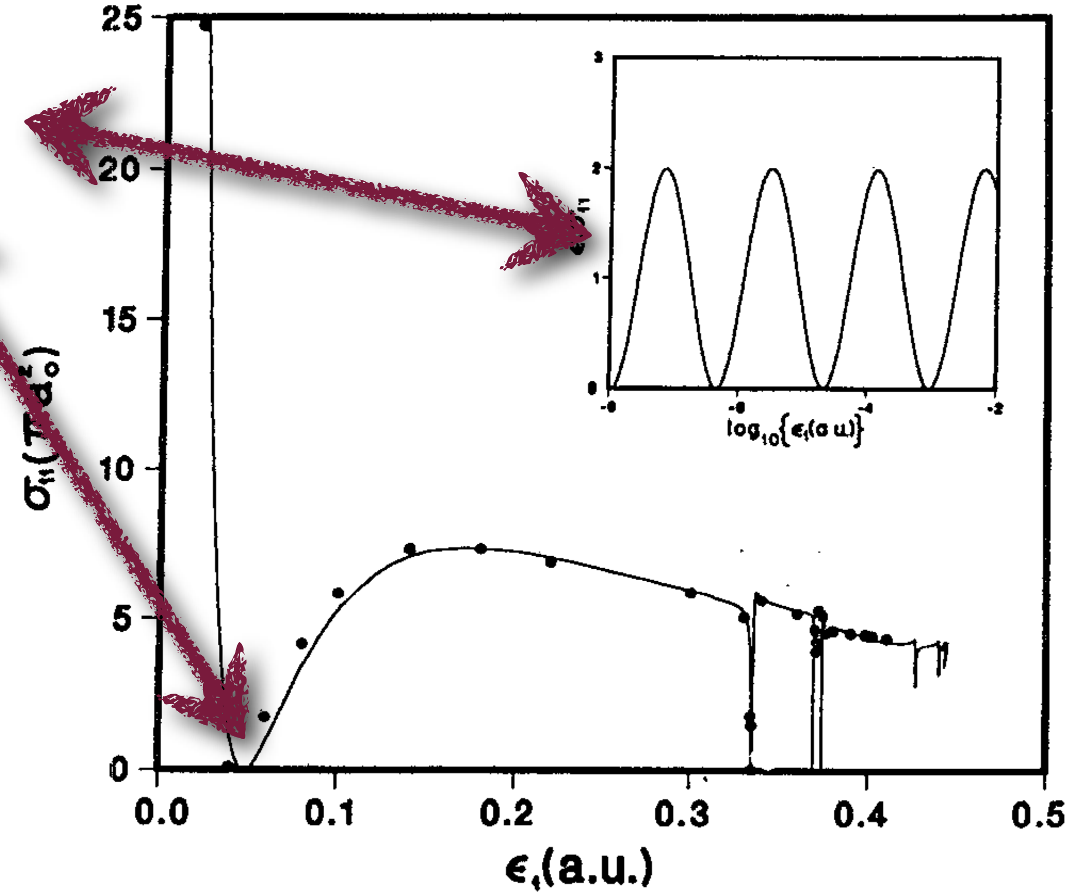
$\chi_\alpha=\arg[\Gamma(1-i\alpha_n)]$, $\alpha_n=(a_n-\frac{1}{4})^{1/2}$



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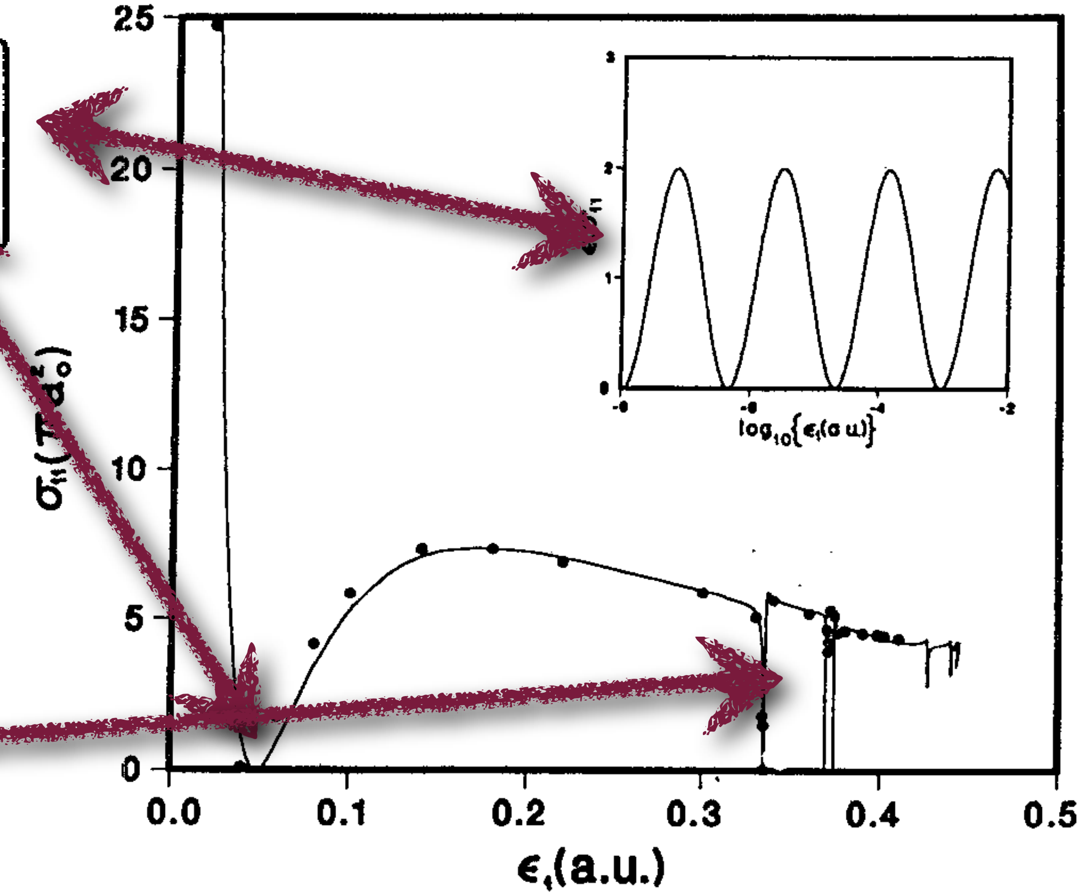
Exponential convergence of bound states

$$\epsilon^{(m)} = \epsilon^{(0)} exp(-2m\pi/\alpha)$$



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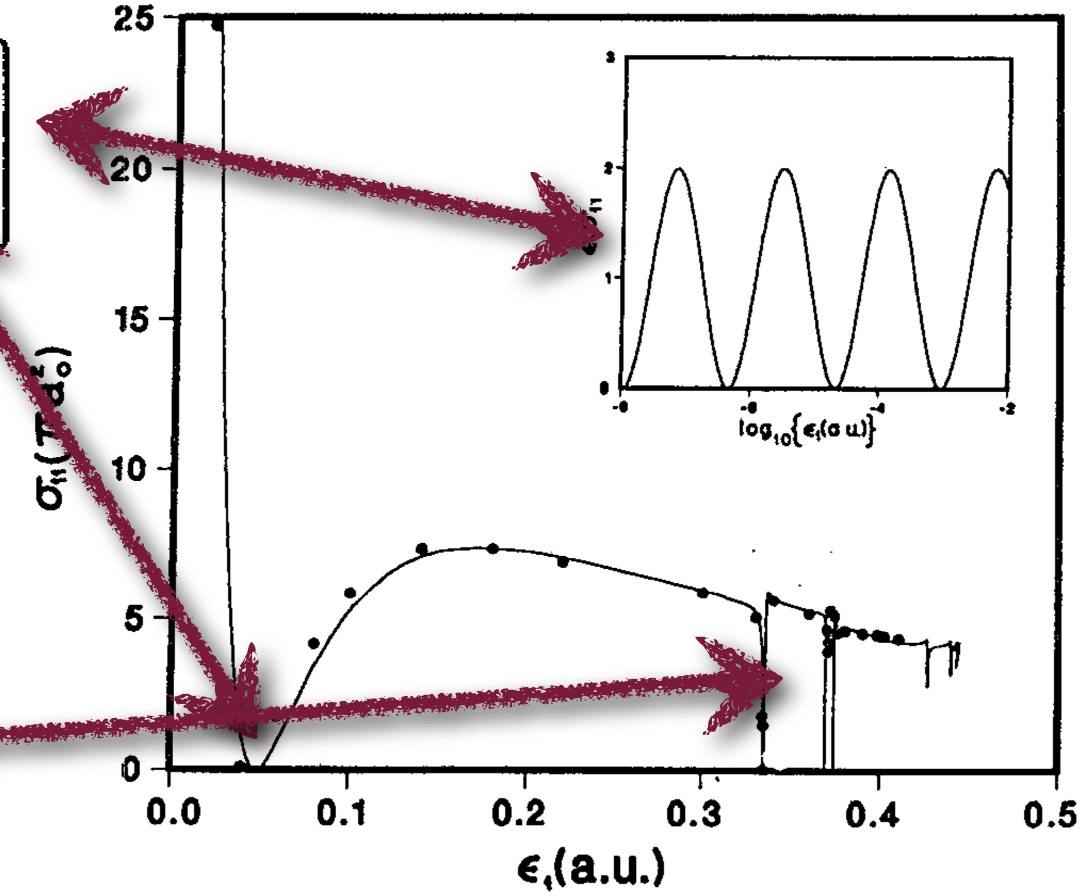

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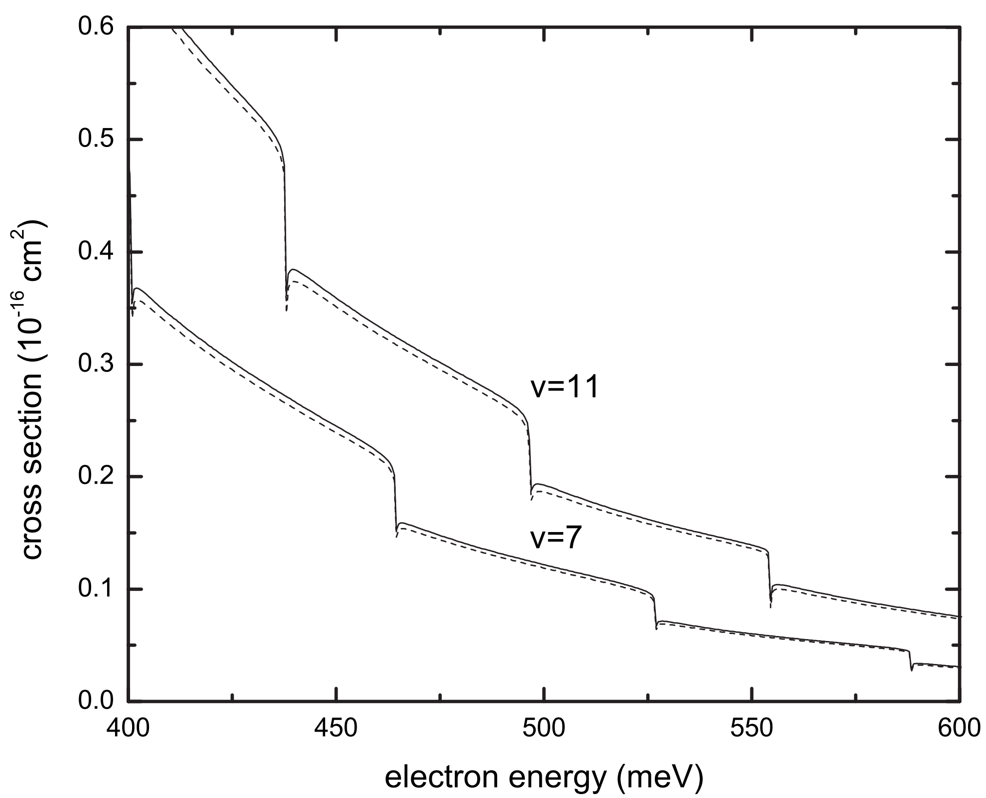
Dissociative electron attachment to CH3Br (Gallup + Fabrikant 2007)



... large two-body scattering length (no binding)

... Entirely different physics, but with the same long-range interaction... Efimov physics

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Universality of few-body physics .... large two-body interactions and few-body binding

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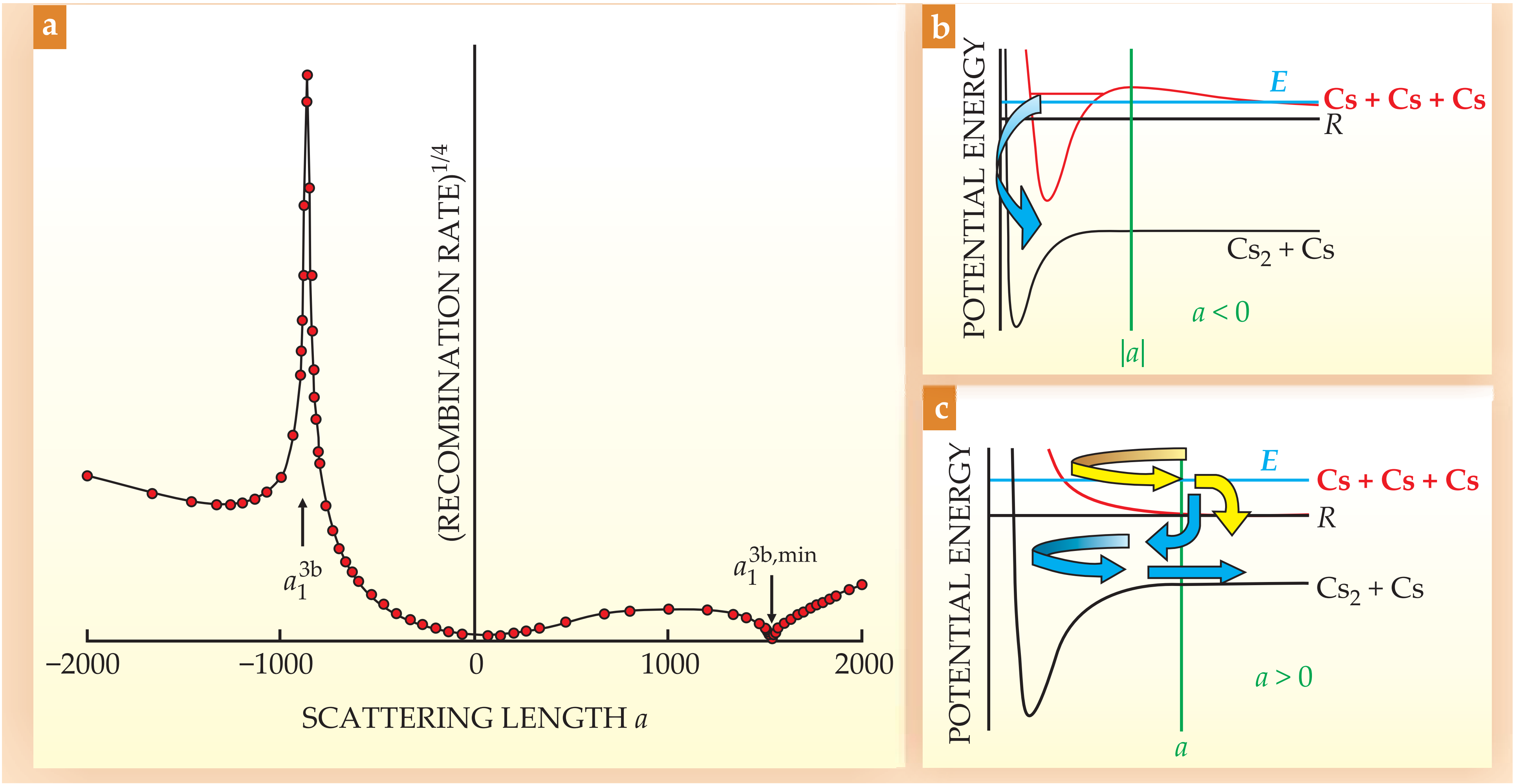
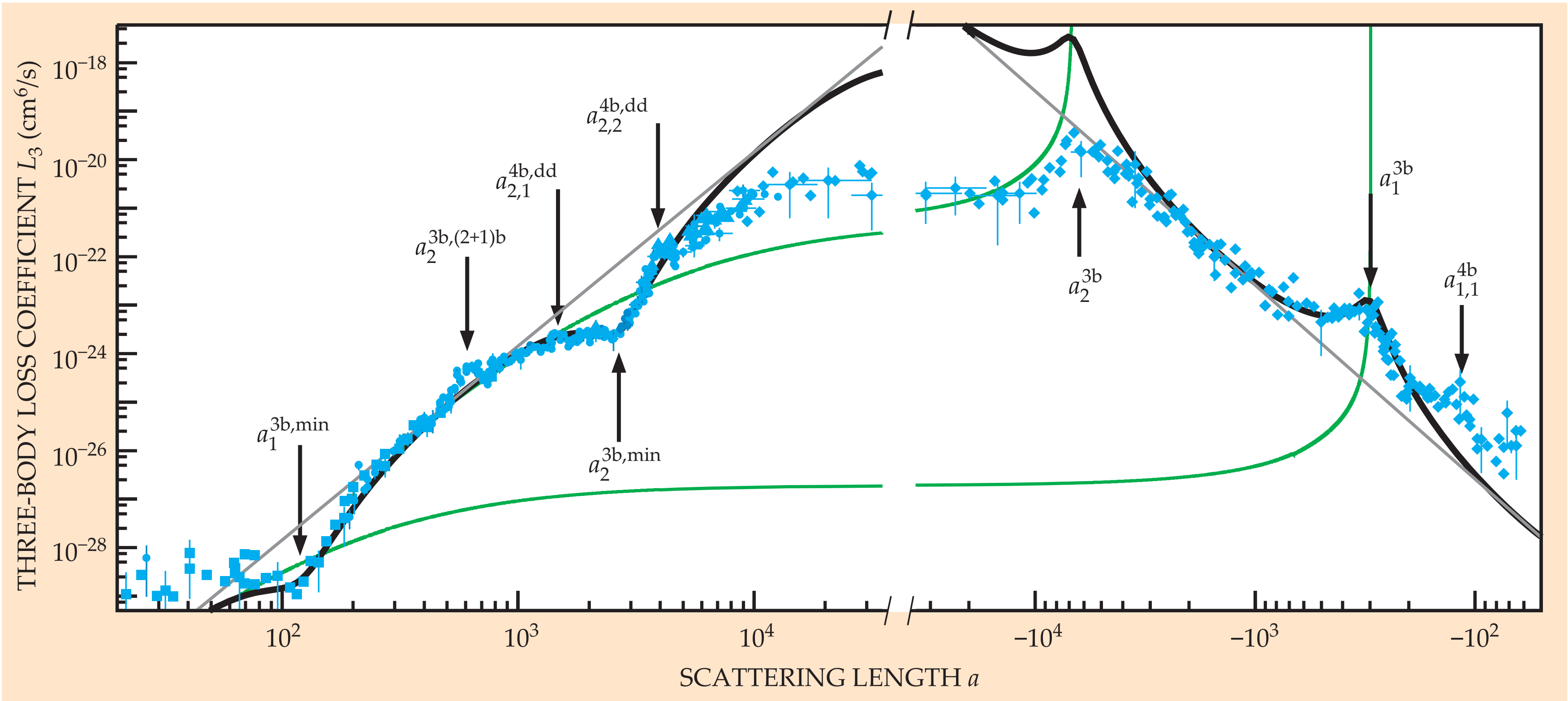
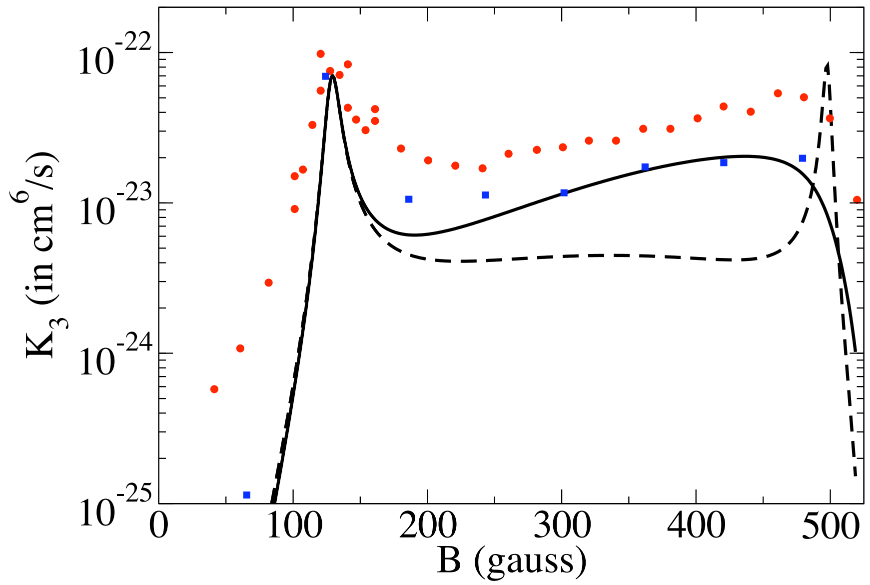
Greene, Nat. Phys. (2009) and Phys. Today (2010)



Hulet et al, Science (2009)



Rittenhouse (2010)



von Stecher et al. (2009)

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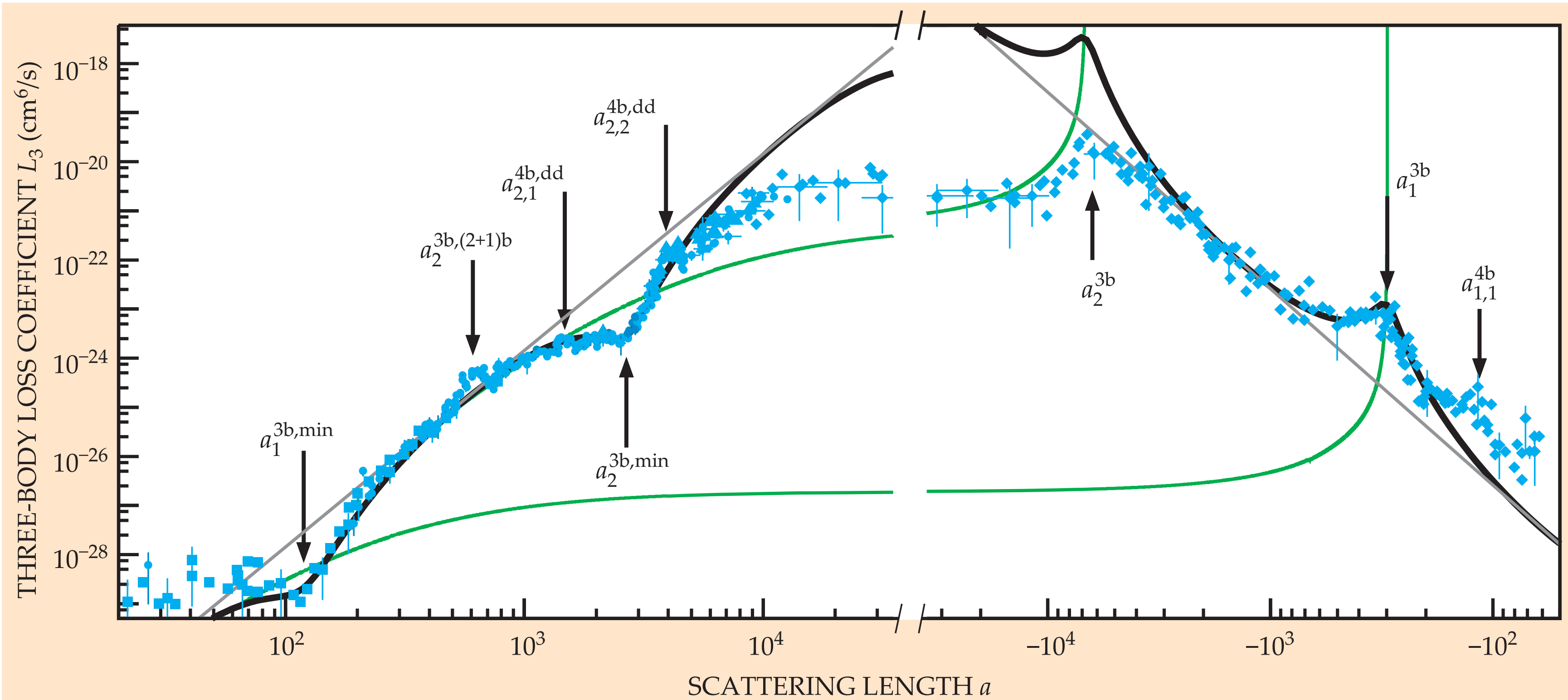

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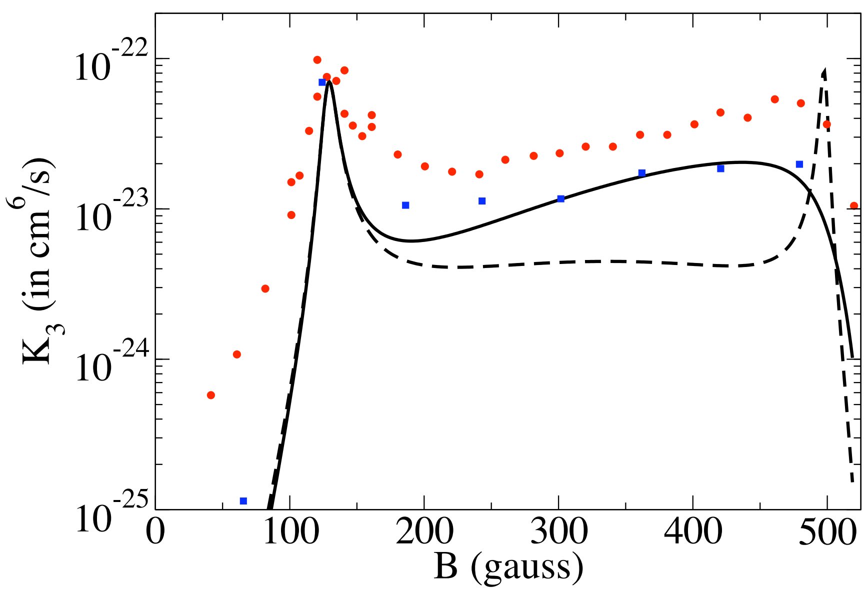

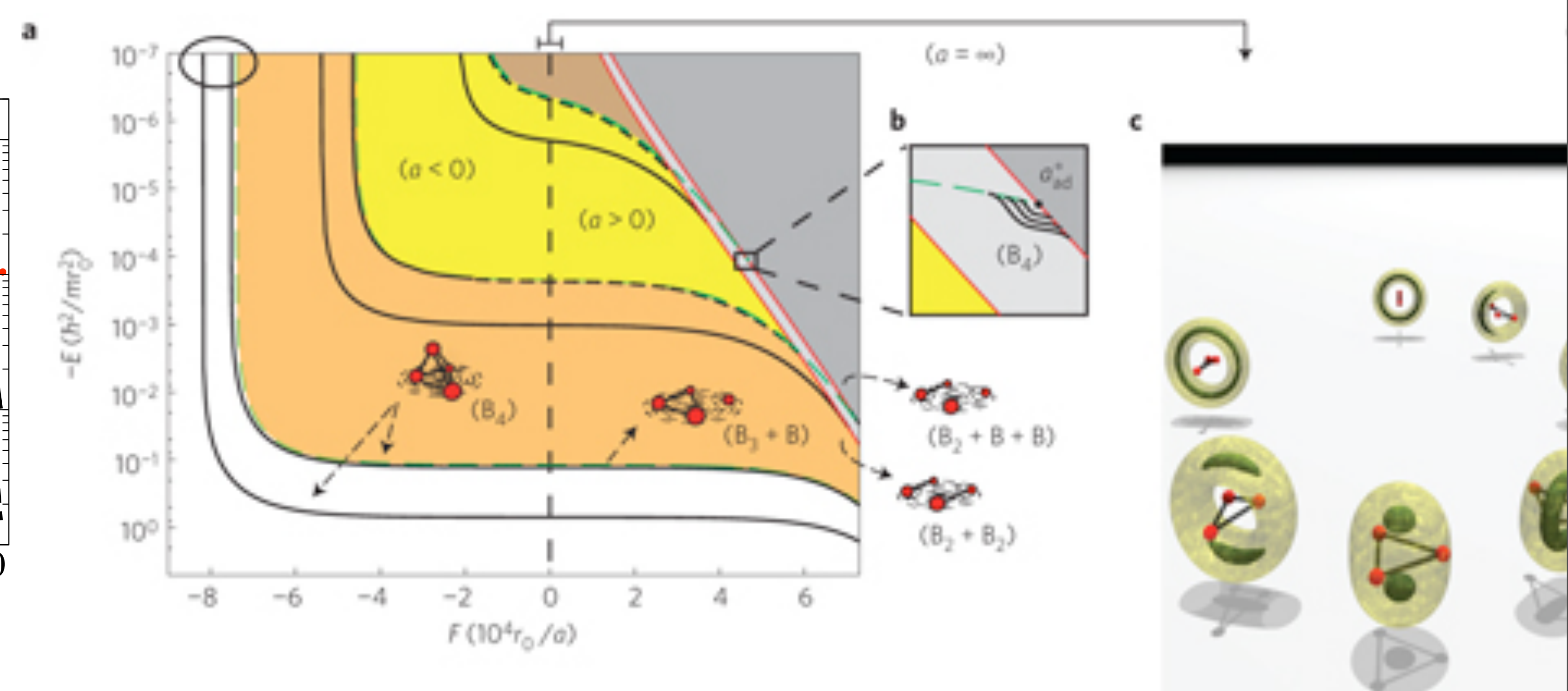

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$\Lambda - doublet$ molecules (OH, CH)

molecules with small rotational constants (KRb, RbCs)

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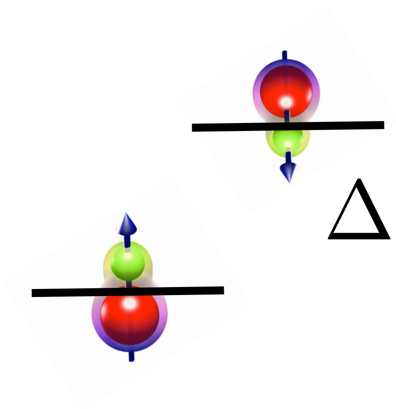
molecules with small rotational constants (KRb, RbCs)

two-level system

$$H_\Lambda = \begin{pmatrix} -Q & -\Delta/2 \\ -\Delta/2 & Q \end{pmatrix}$$



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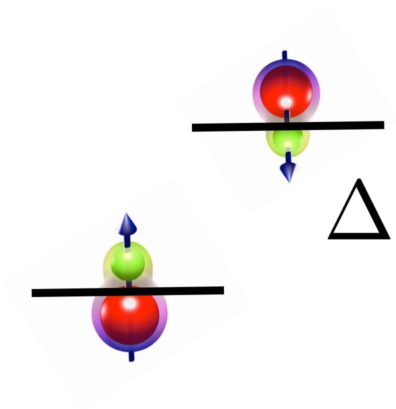
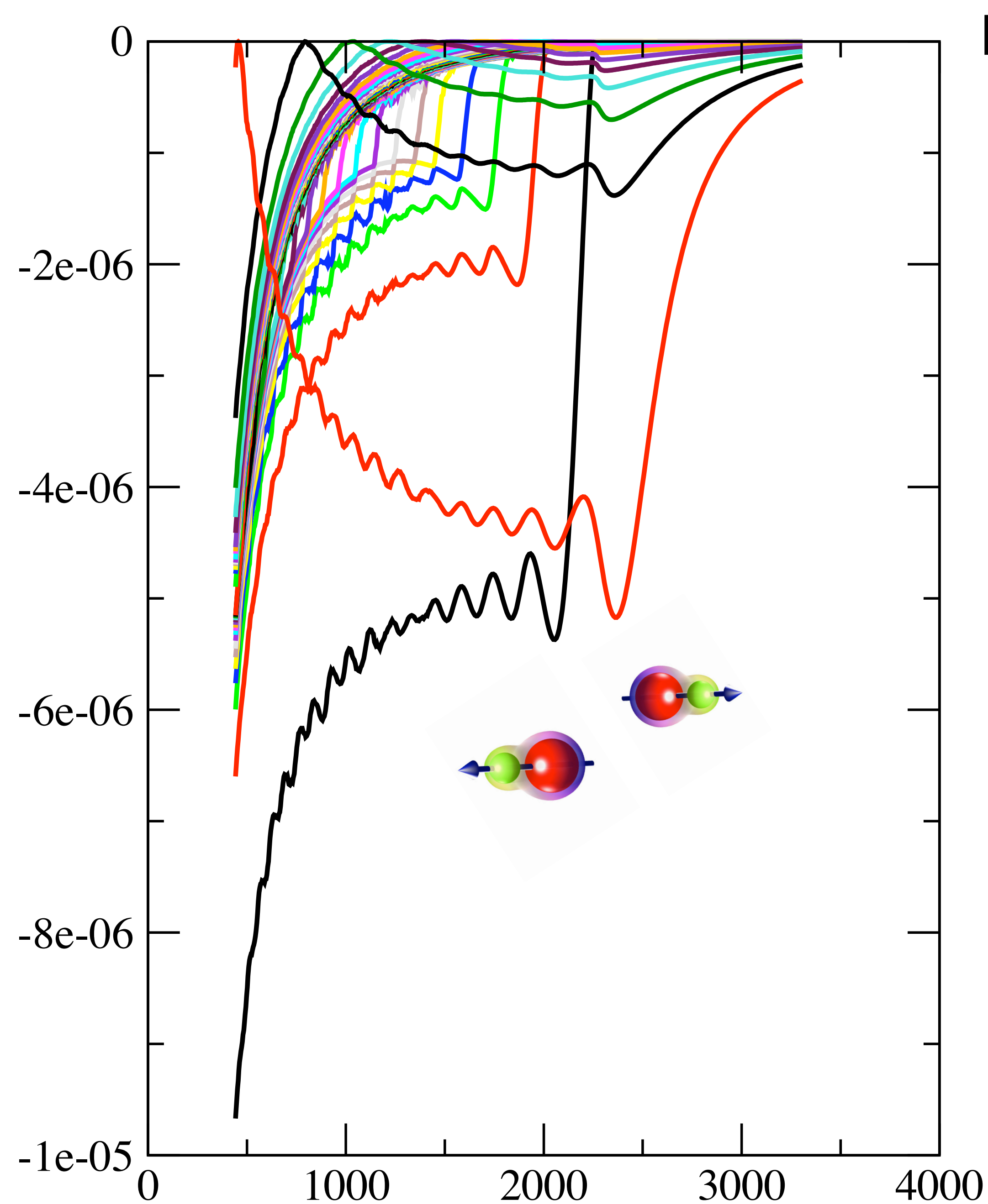
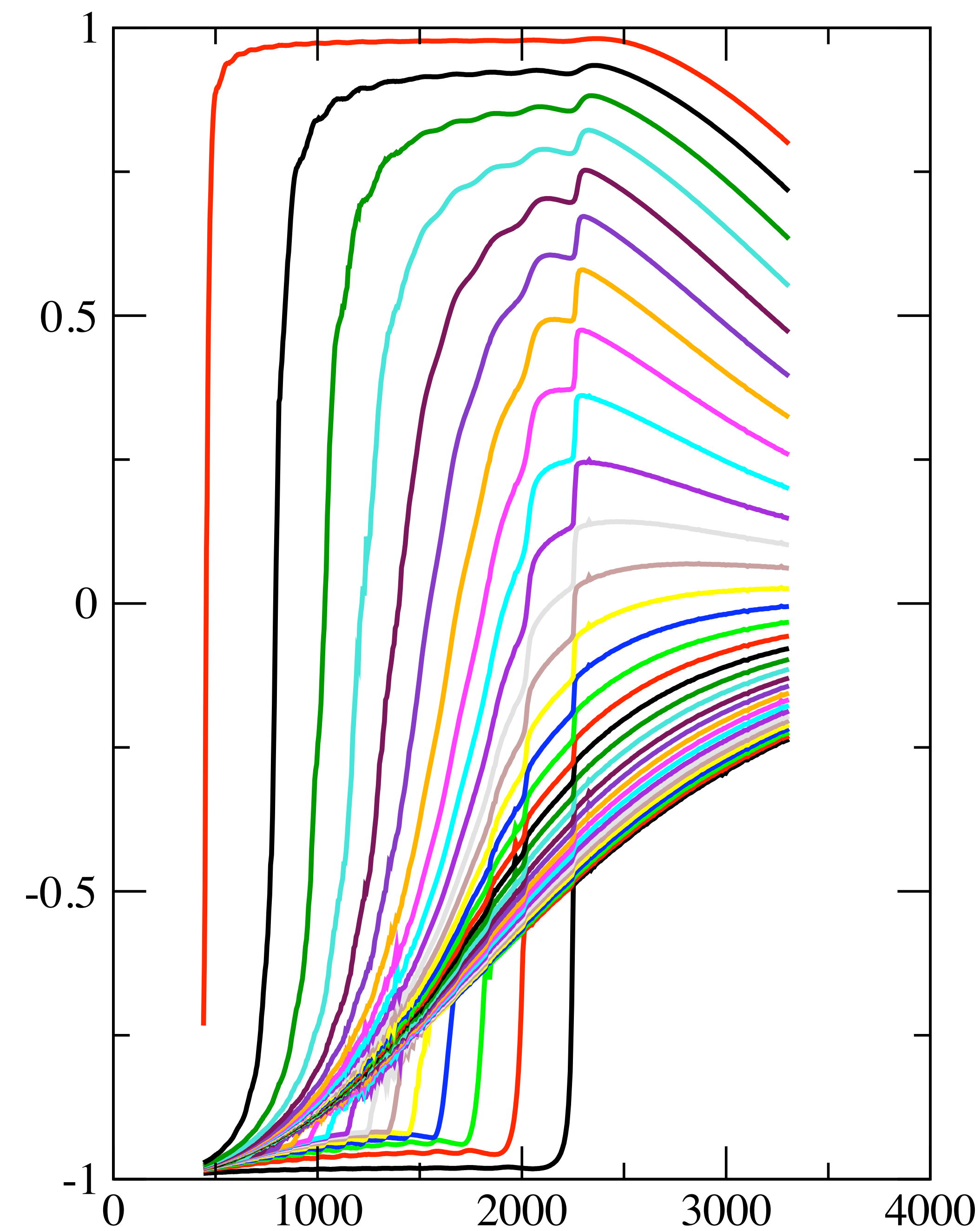


$$H_\Lambda = \begin{pmatrix} -Q & -\Delta/2 \\ -\Delta/2 & Q \end{pmatrix}$$

$$V_\lambda(R) = d\left[E_c - \sqrt{(E_\lambda(R) - \frac{1}{R^2})^2 + E_c^2}\right]$$



Rb(n=35)

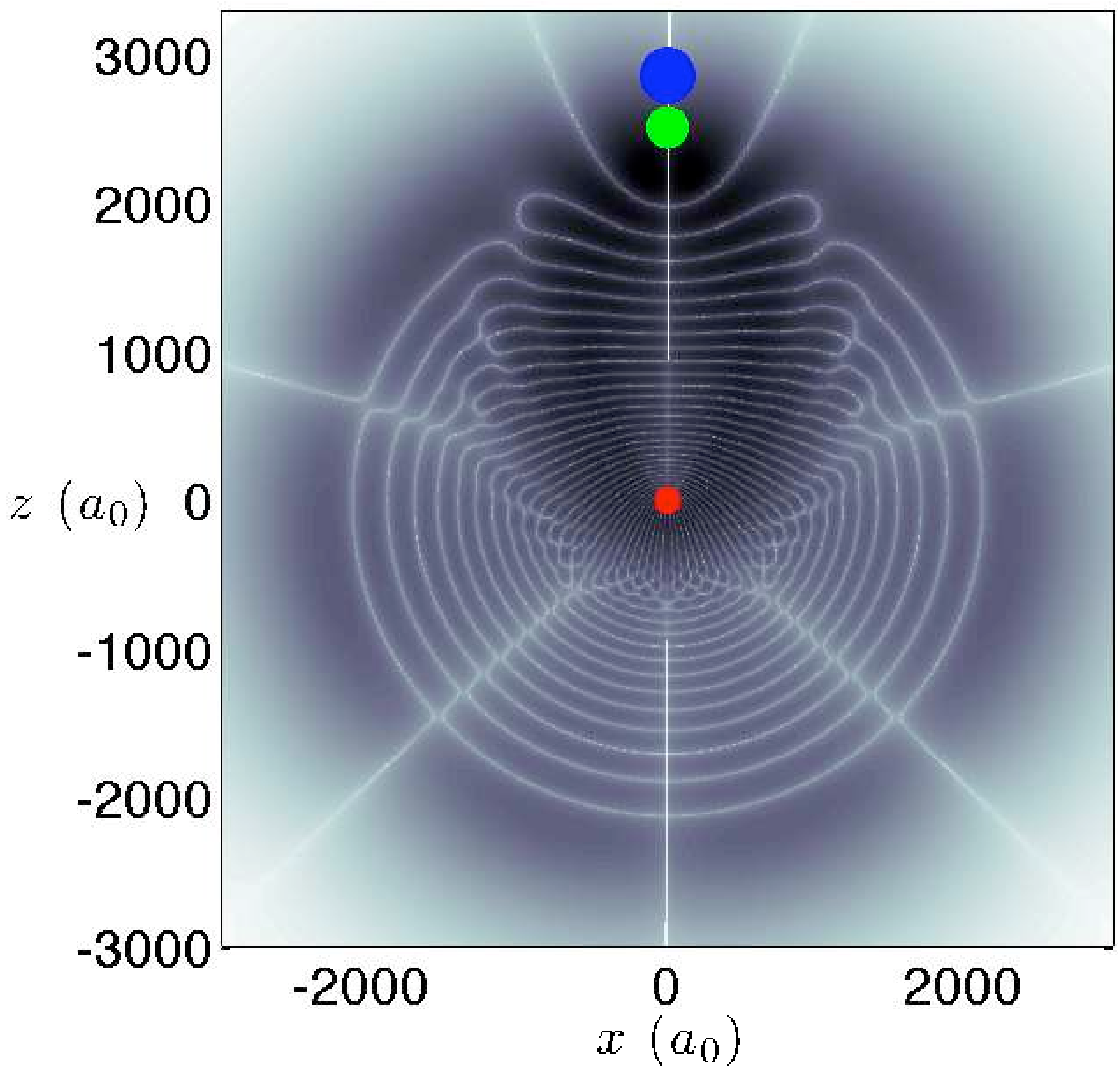


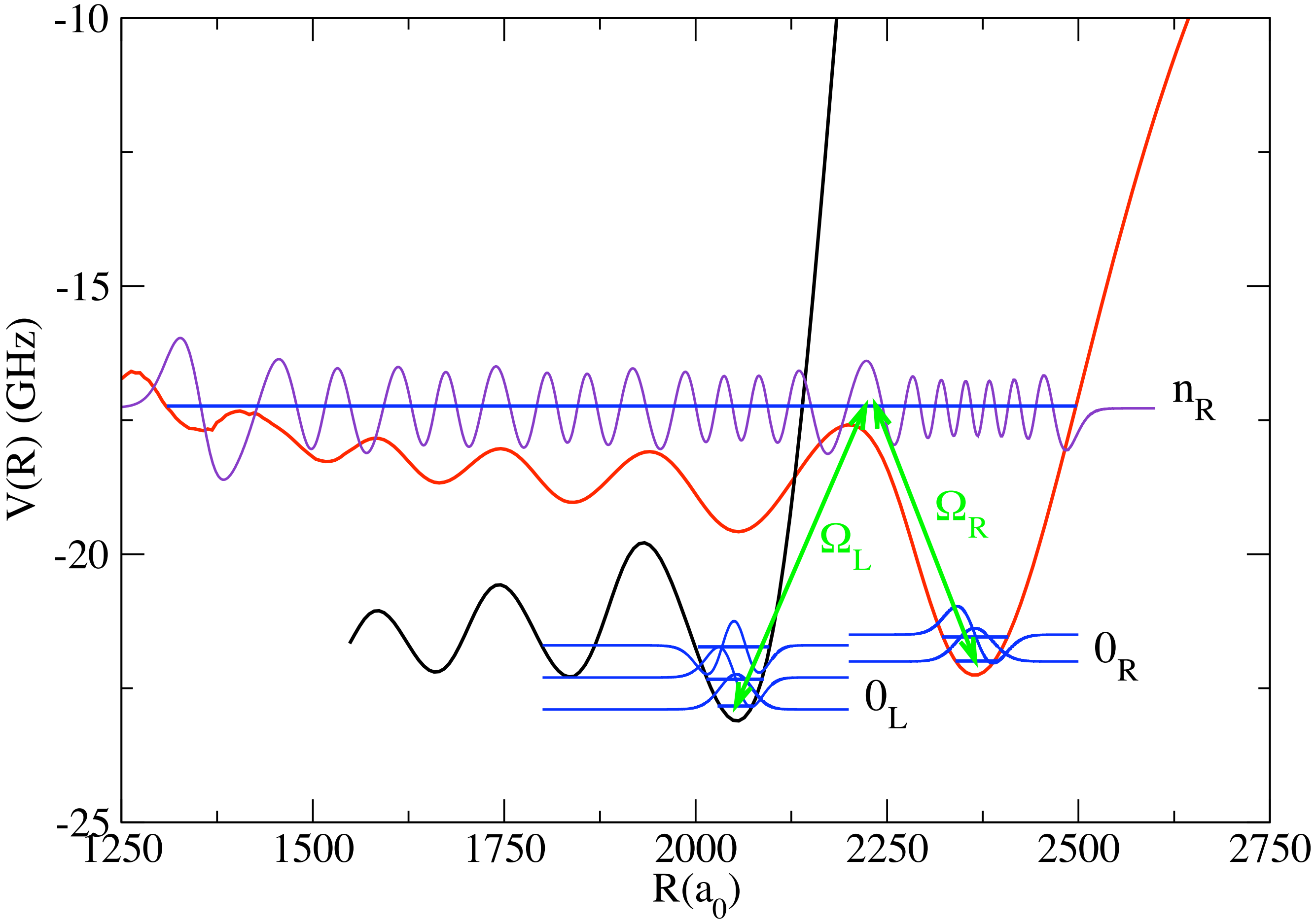
$E_c = 10^{-7} a.u. \sim 500 V/cm$

Rittenhouse & Sadeghpour, PRL 2010

non-adiabatic terms

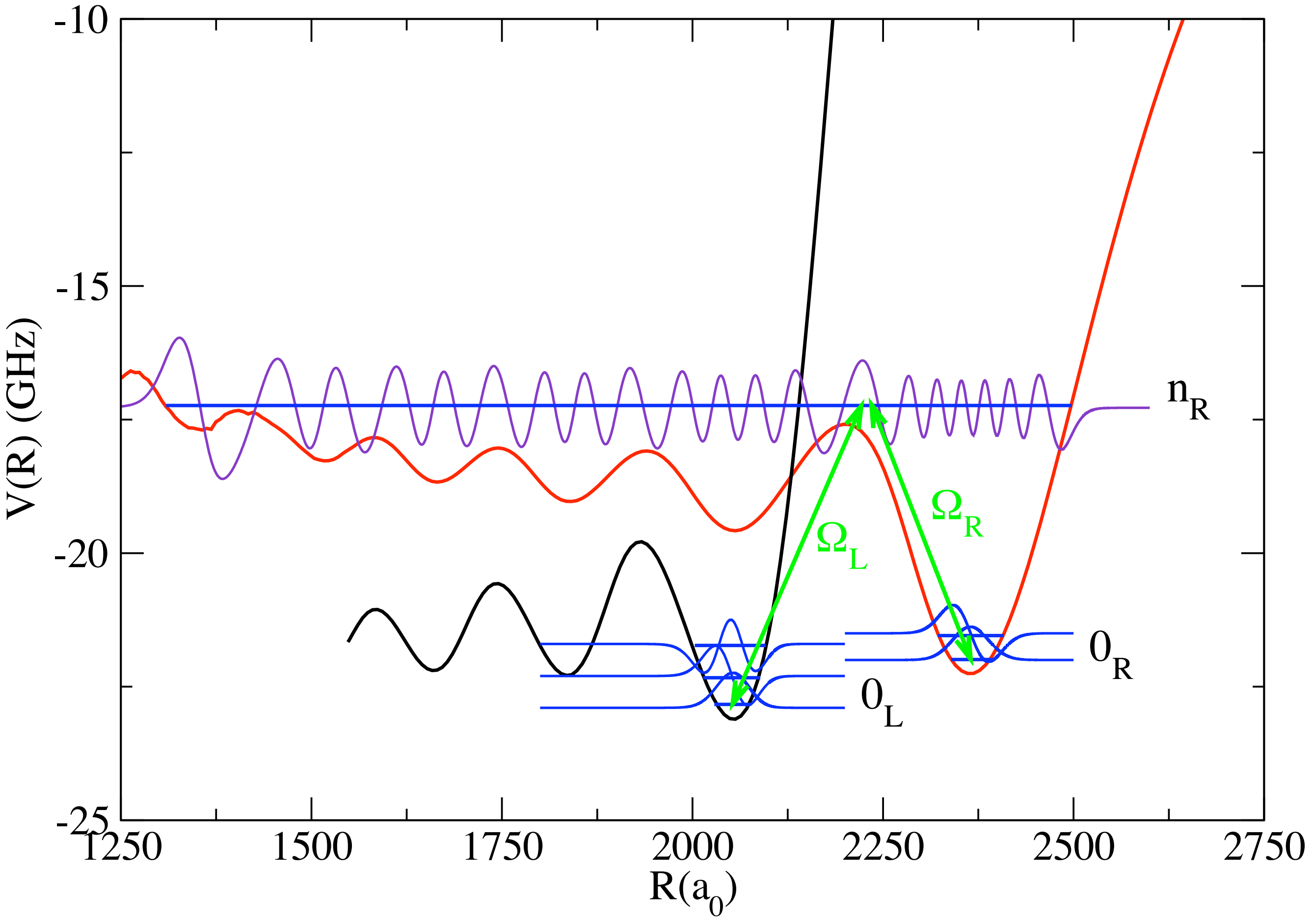
$$\langle \lambda_2 | \left| \frac{\partial}{\partial R} \lambda_1 (R) \right\rangle = \sum_{l,l'} \langle nl'm | \, |nlm\rangle \, a^{\lambda_2 *}_{nl'm}(R) \, a^{\lambda_1 '}_{nlm}(R)$$


3000
2000
1000
$z\ (a_0)$ 0
-1000
-2000
-3000
-2000
0
2000
$x\ (a_0)$



V(R) (GHz)
-10
-15
-20
-25
1250
1500
1750
2000
2250
2500
2750
R(a_0)
n_R
Ω_L
Ω_R
0_R
0_L

Coherent control of molecular orientation



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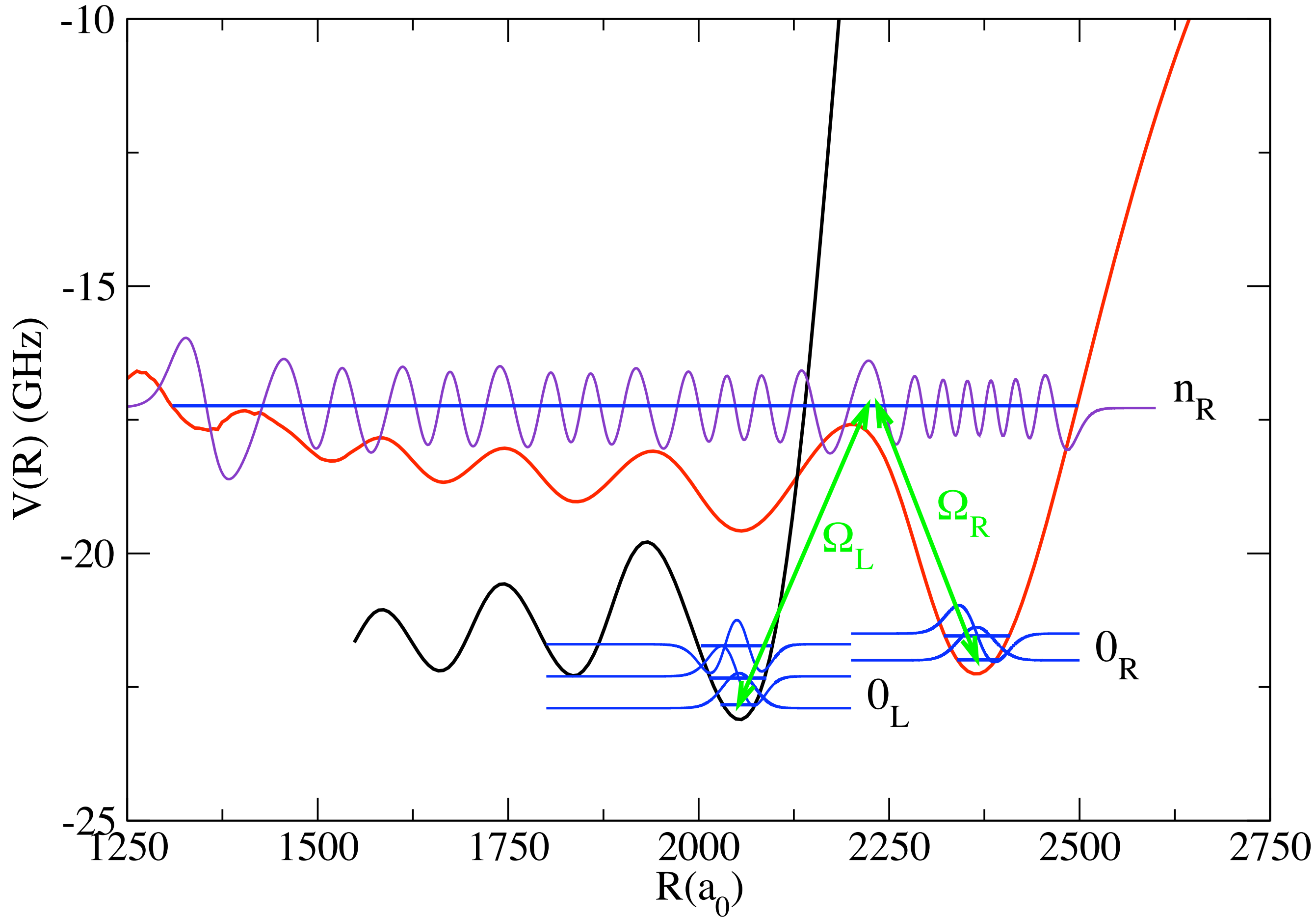
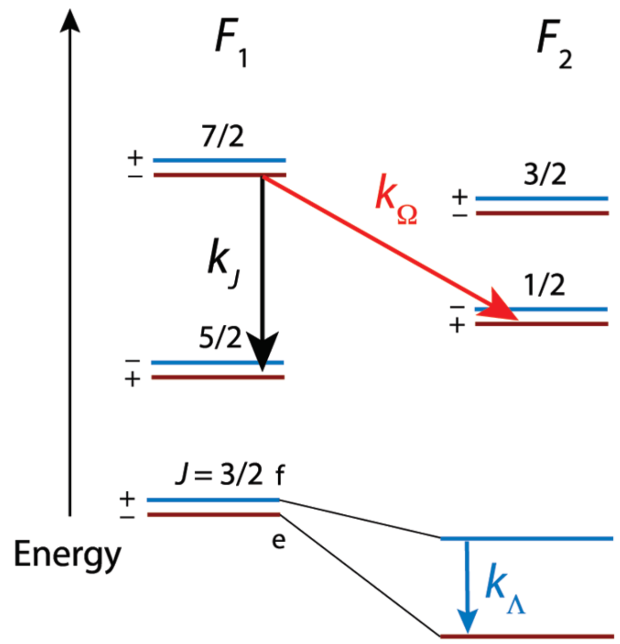
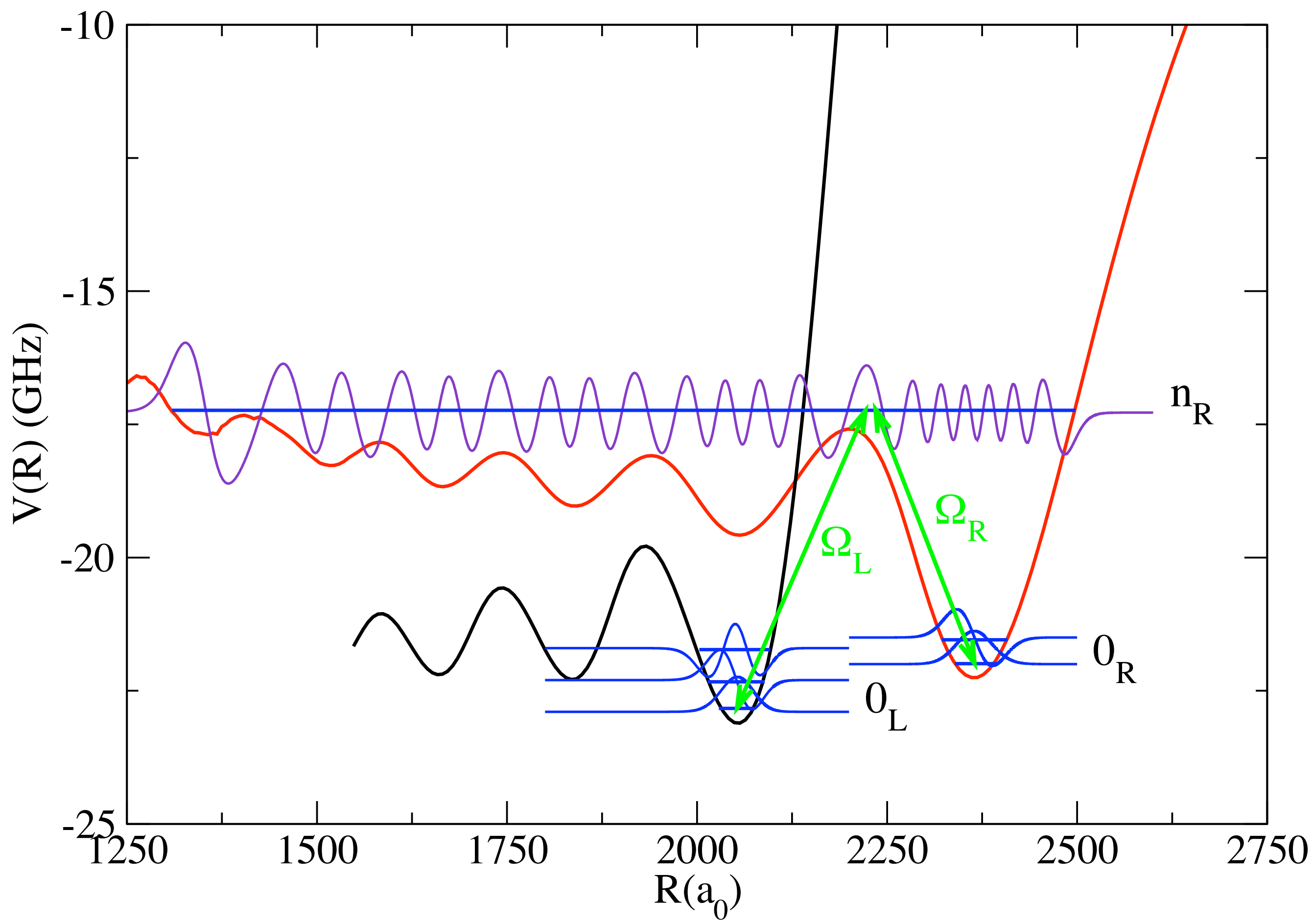
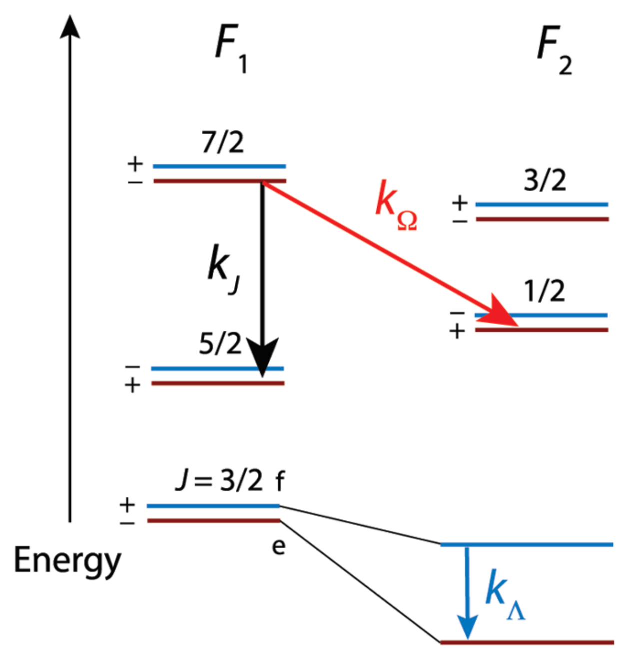




on-resonance coherent Raman transition

Coherent control of molecular orientation





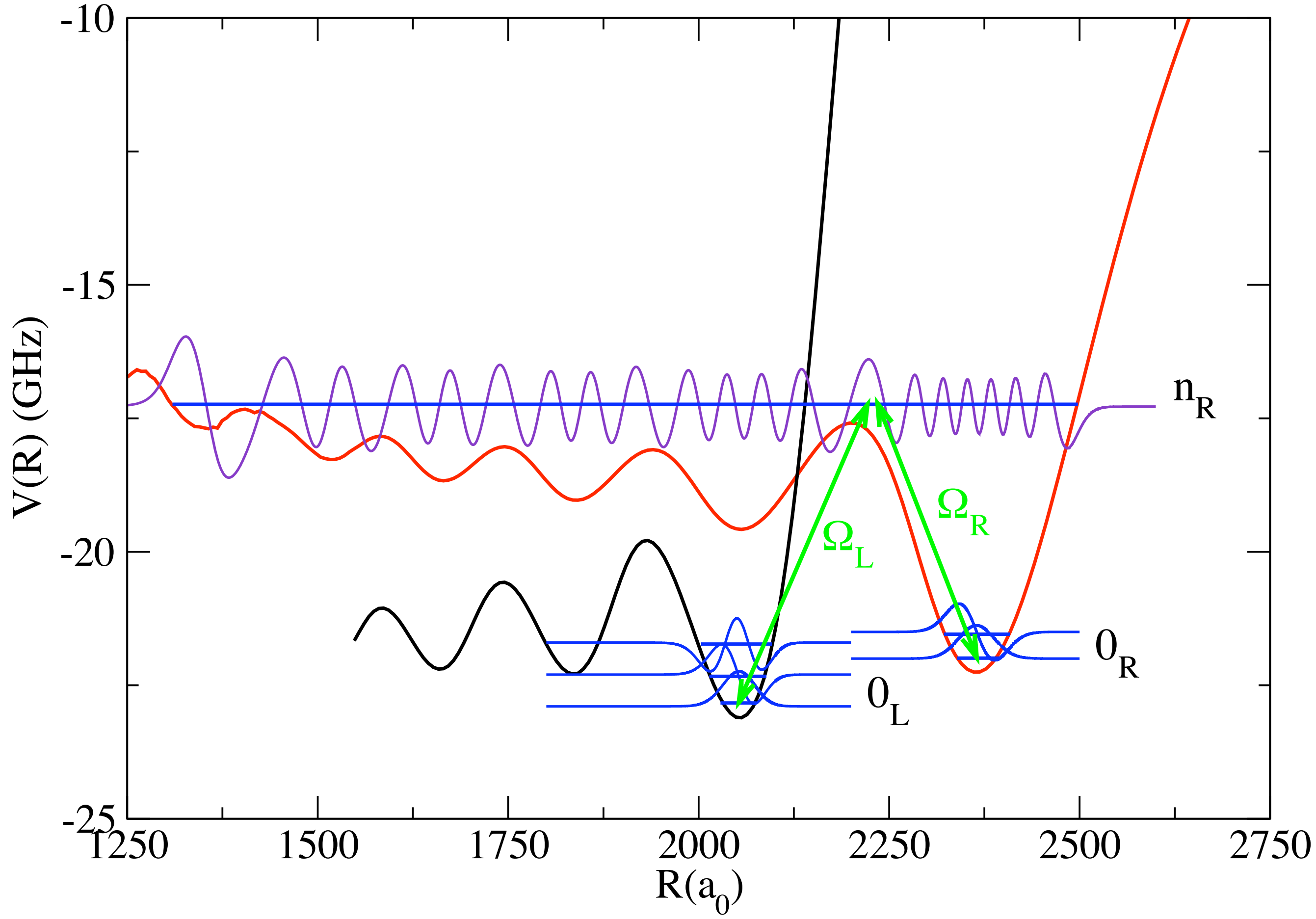
OH:

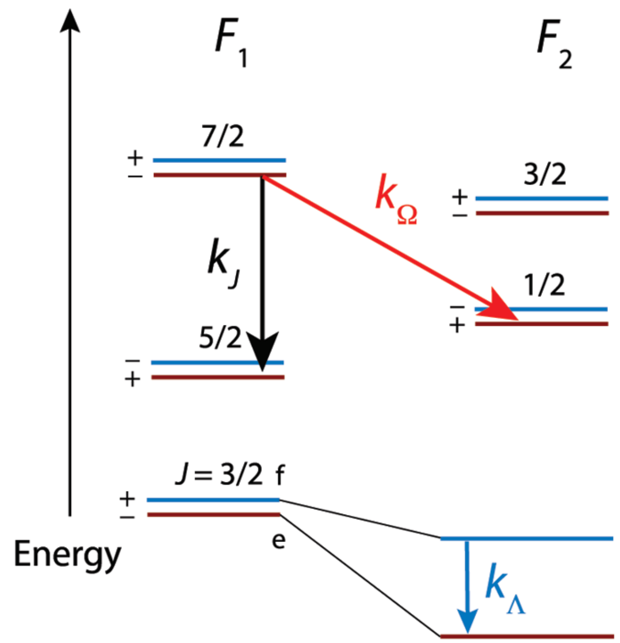
$$\Delta_\Lambda = 1.7 \text{ GHz}$$

$$d = 1.68D$$

on-resonance coherent Raman transition

Coherent control of molecular orientation



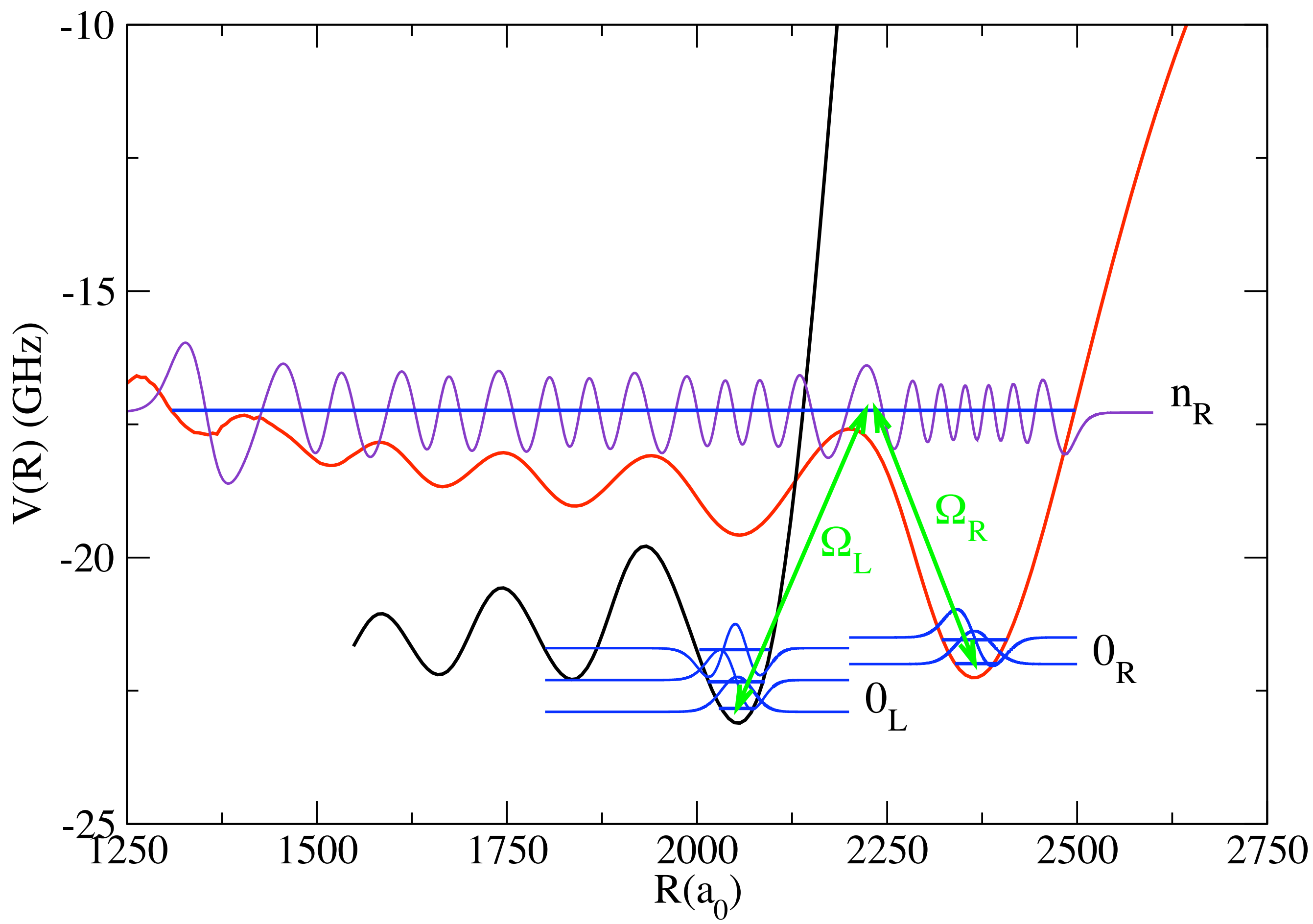


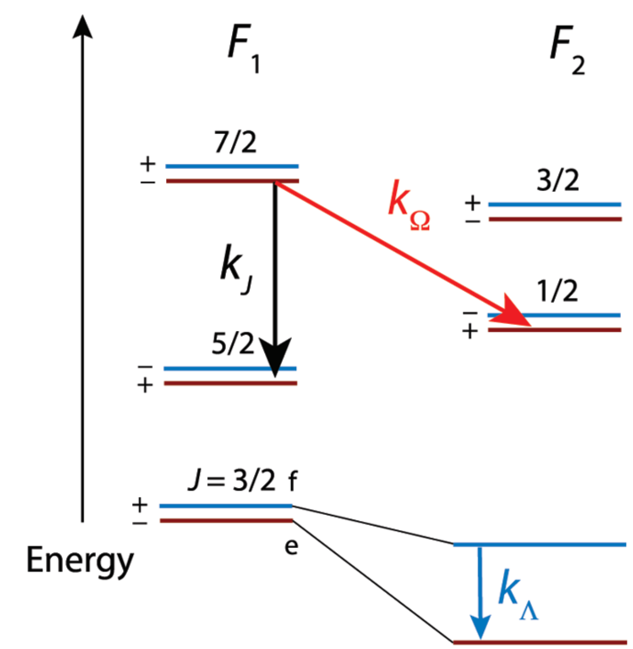
OH: $\Delta_\Lambda = 1.7$ GHz, $d = 1.68D$

CH: $\Delta_\Lambda = 3.03$ GHz, $d = 1.46D$

on-resonance coherent Raman transition

Coherent control of molecular orientation





OH: $\Delta_\Lambda = 1.7$ GHz

$d = 1.68D$

CH: $\Delta_\Lambda = 3.03$ GHz

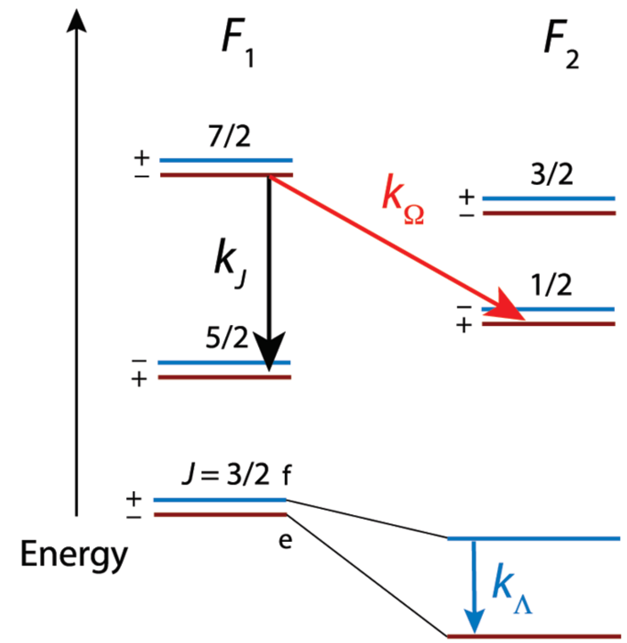
$d = 1.46D$

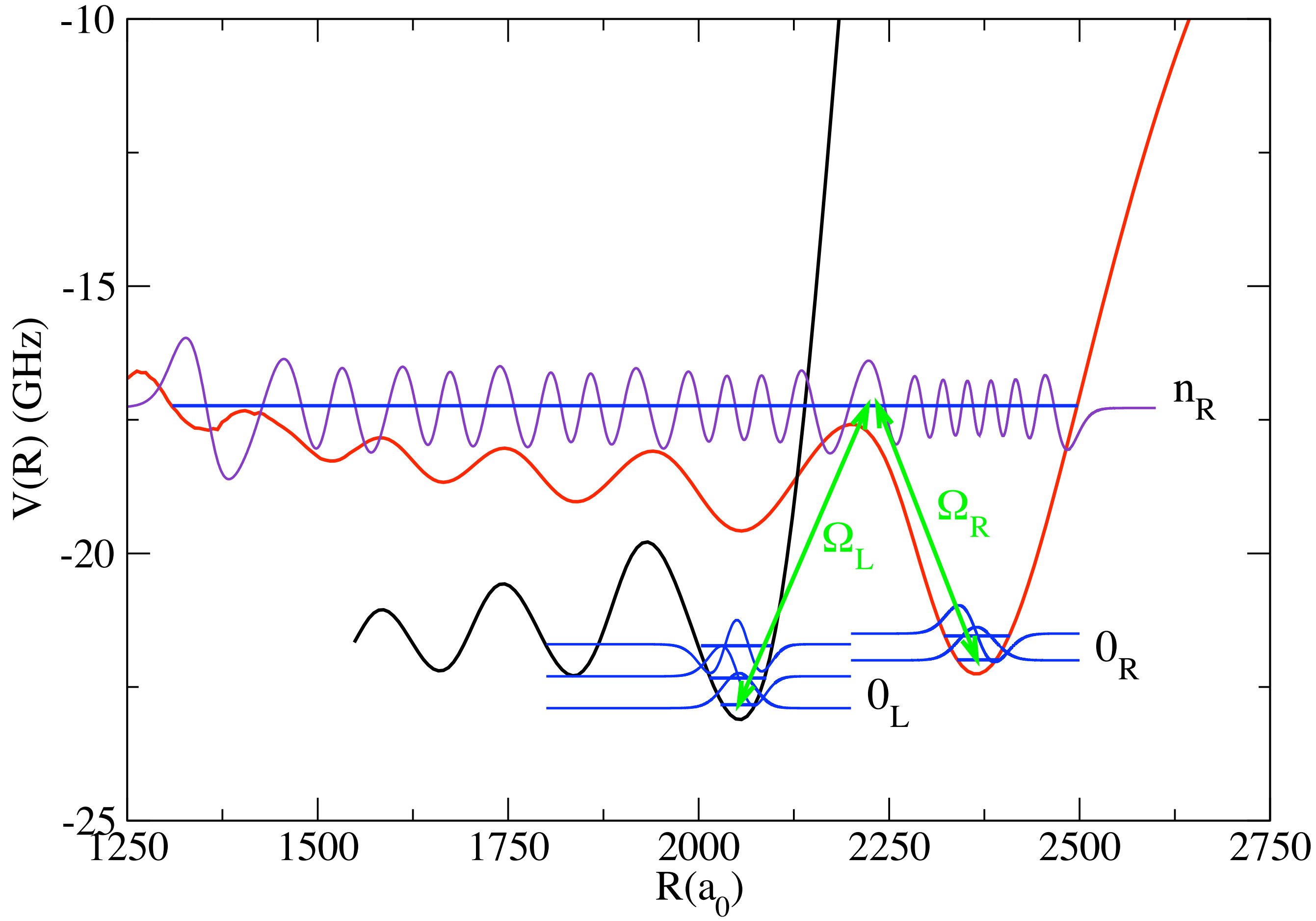
OD: $\Delta_\Lambda = 0.5$ GHz

$d = 1.60D$

on-resonance coherent Raman transition

Coherent control of molecular orientation





OH: $\Delta_\Lambda = 1.7$ GHz, $d = 1.68D$

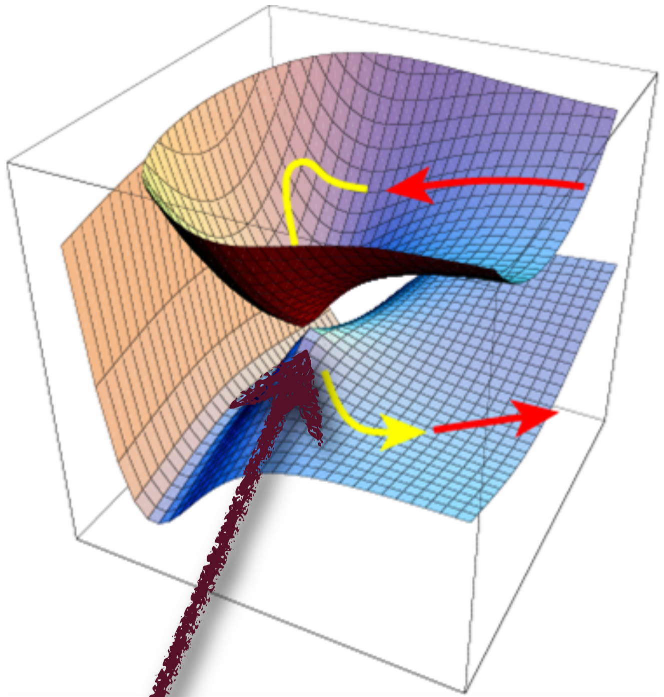
CH: $\Delta_\Lambda = 3.03$ GHz, $d = 1.46D$

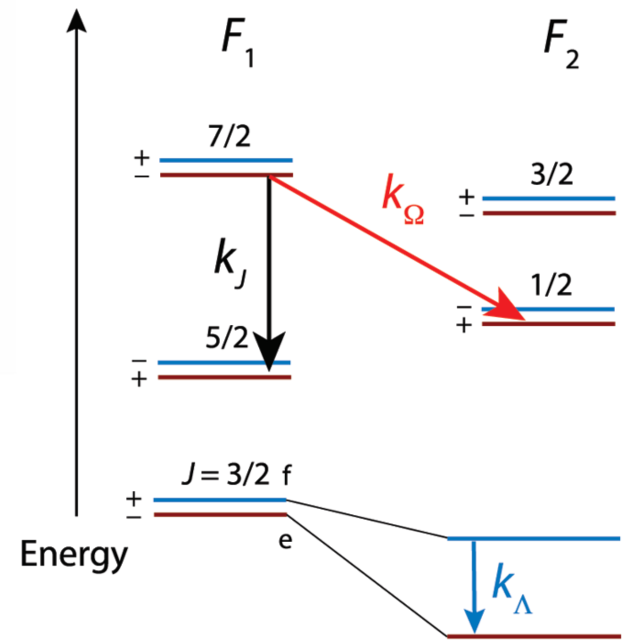
OD: $\Delta_\Lambda = 0.5$ GHz, $d = 1.60D$

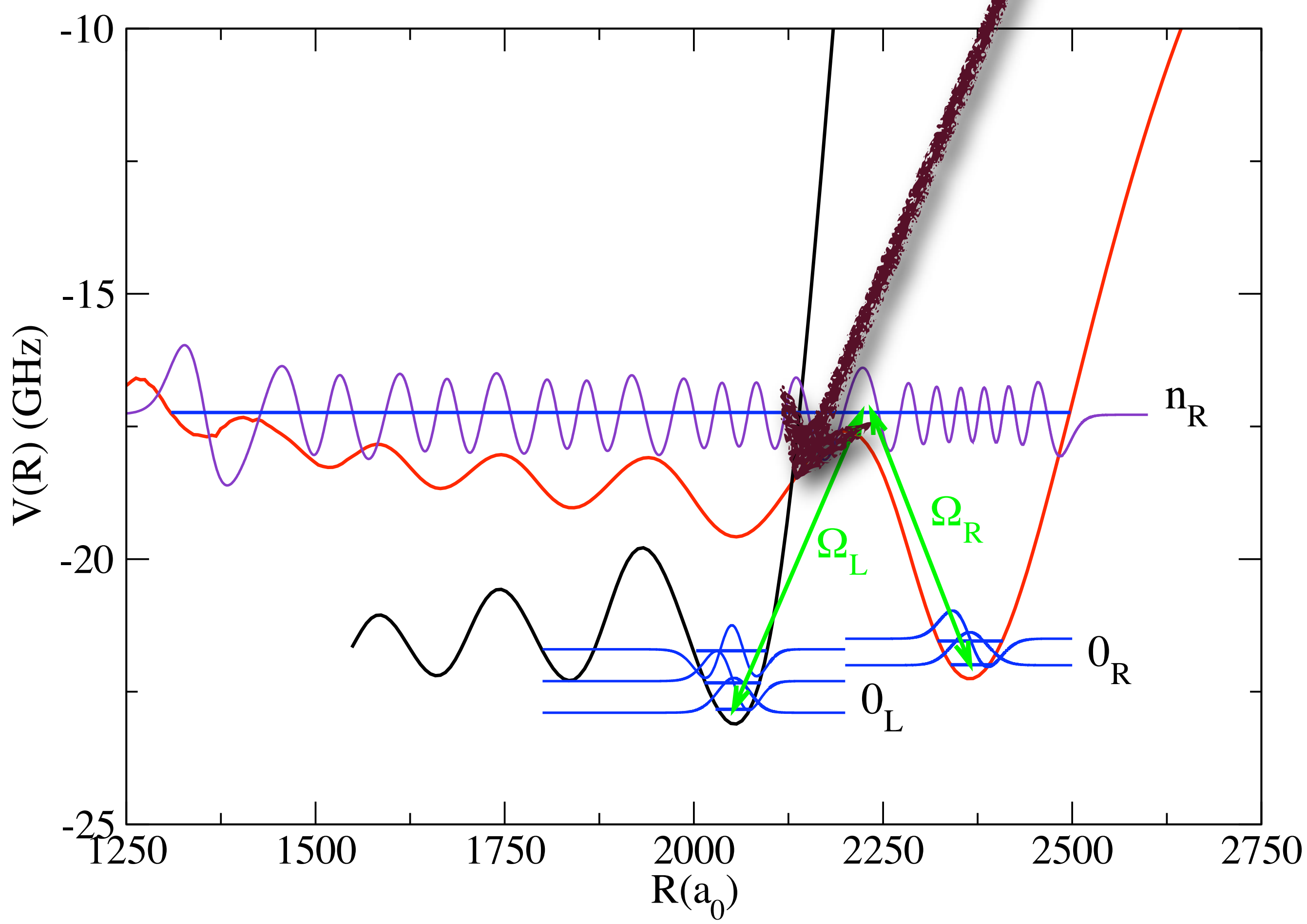
CD: $\Delta_\Lambda = 1.22$ GHz, $d = 1.46D$

on-resonance coherent Raman transition

Coherent control of molecular orientation







OH: $\Delta_\Lambda = 1.7$ GHz, $d = 1.68D$

CH: $\Delta_\Lambda = 3.03$ GHz, $d = 1.46D$

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CD: $\Delta_\Lambda = 1.22$ GHz, $d = 1.46D$

on-resonance coherent Raman transition

Higher angular momentum molecules are now accessible

Four-horsemen of chemical bonds: (ionic, covalent, hydrogen, and van der Waals)

... may now have company; ultralong Rydberg bond