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SMR 1302 - 14

WINTER SCHOOL ON LASER SPECTROSCOPY AND APPLICATIONS

19 February - 2 March 2001

Cold Collisions Studied by

High Resolution Molecular Beam Spectroscopy

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These are preliminary lecture notes, intended only for distribution to participants.

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Cold collisions studied by high resolution molecular beam spectroscopy

or

Preparation and Spectroscopy of Atomic Pairs in Molecular Beams

Eberhard Tiemann

University Hannover, Institute of Quantum Optics

- Studying the case of alkali dimers to compare it with results from atomic traps
- Preparation of molecular states with ultra low binding energy
- Theoretical model for molecular levels close to the asymptote
- Scattering length and collision resonances
- Tuning the collisions by fields

cold collisions
photoassociation

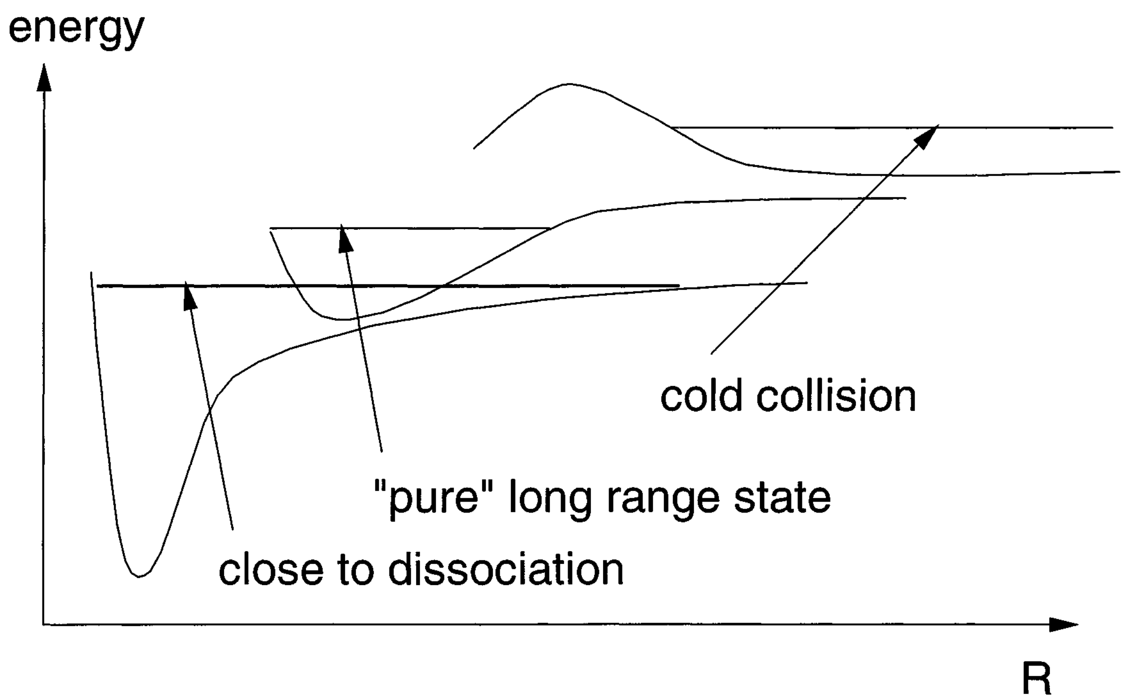
bound molecules
atomic pairs

low kinetic energy of relative motion
for long observation time

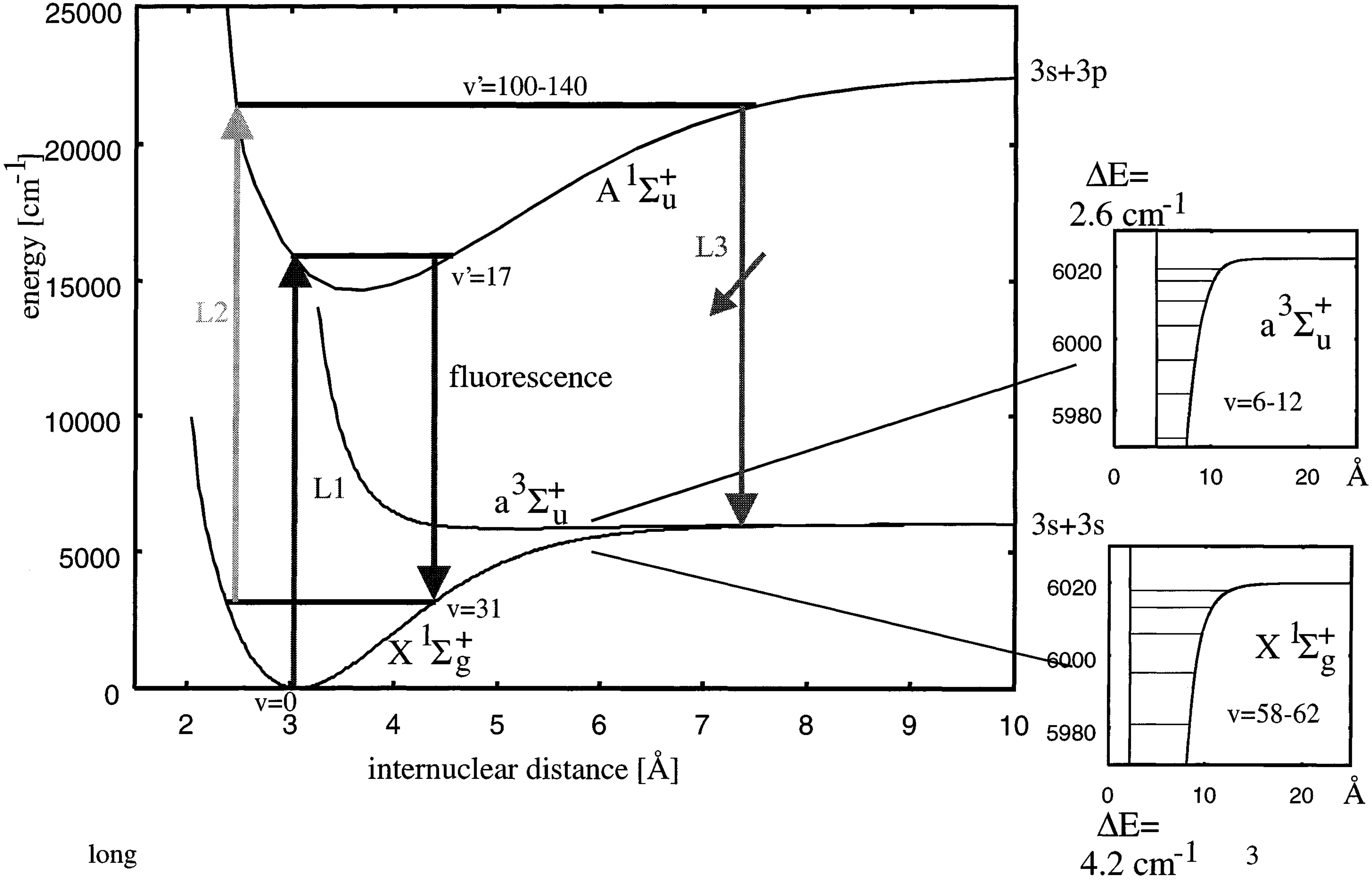
thermal ensemble
little restriction

quantum state
strong restriction

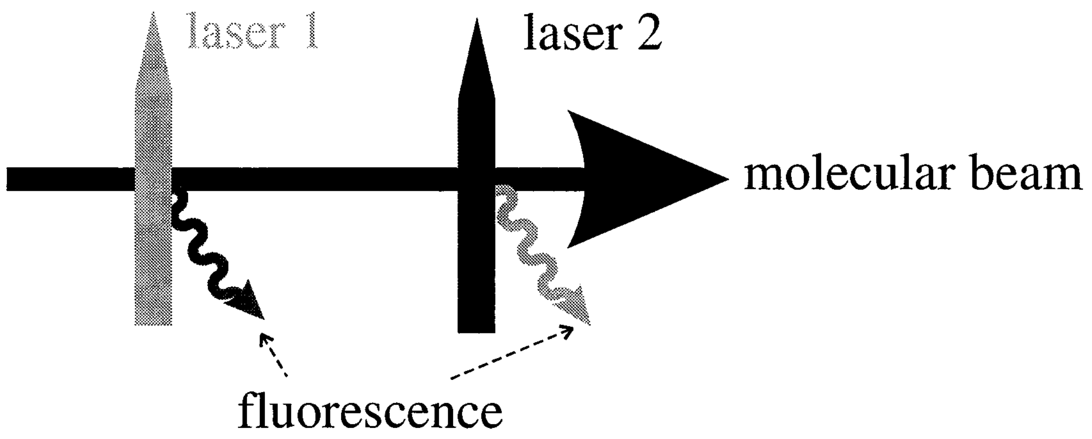
by selection rules



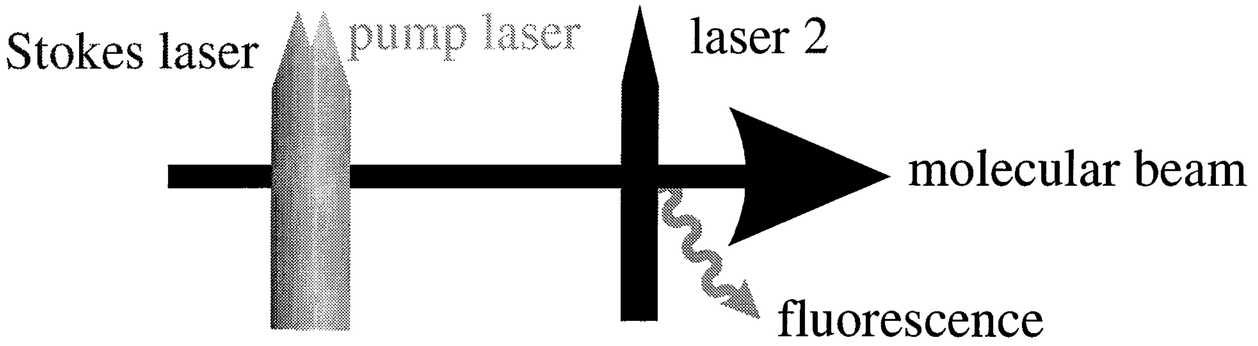
Preparation of molecular states with large internuclear distance



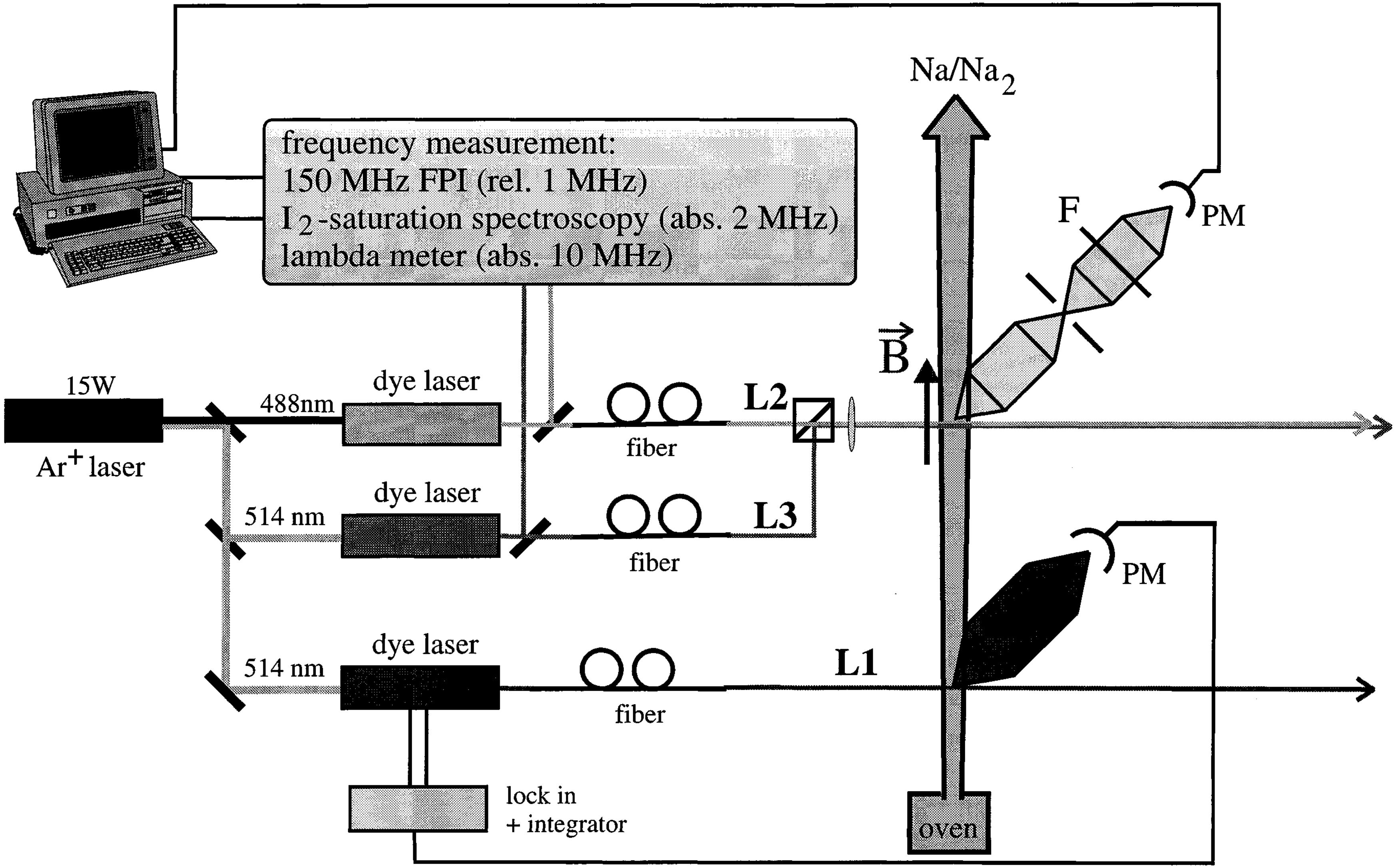
Franck-Condon pumping

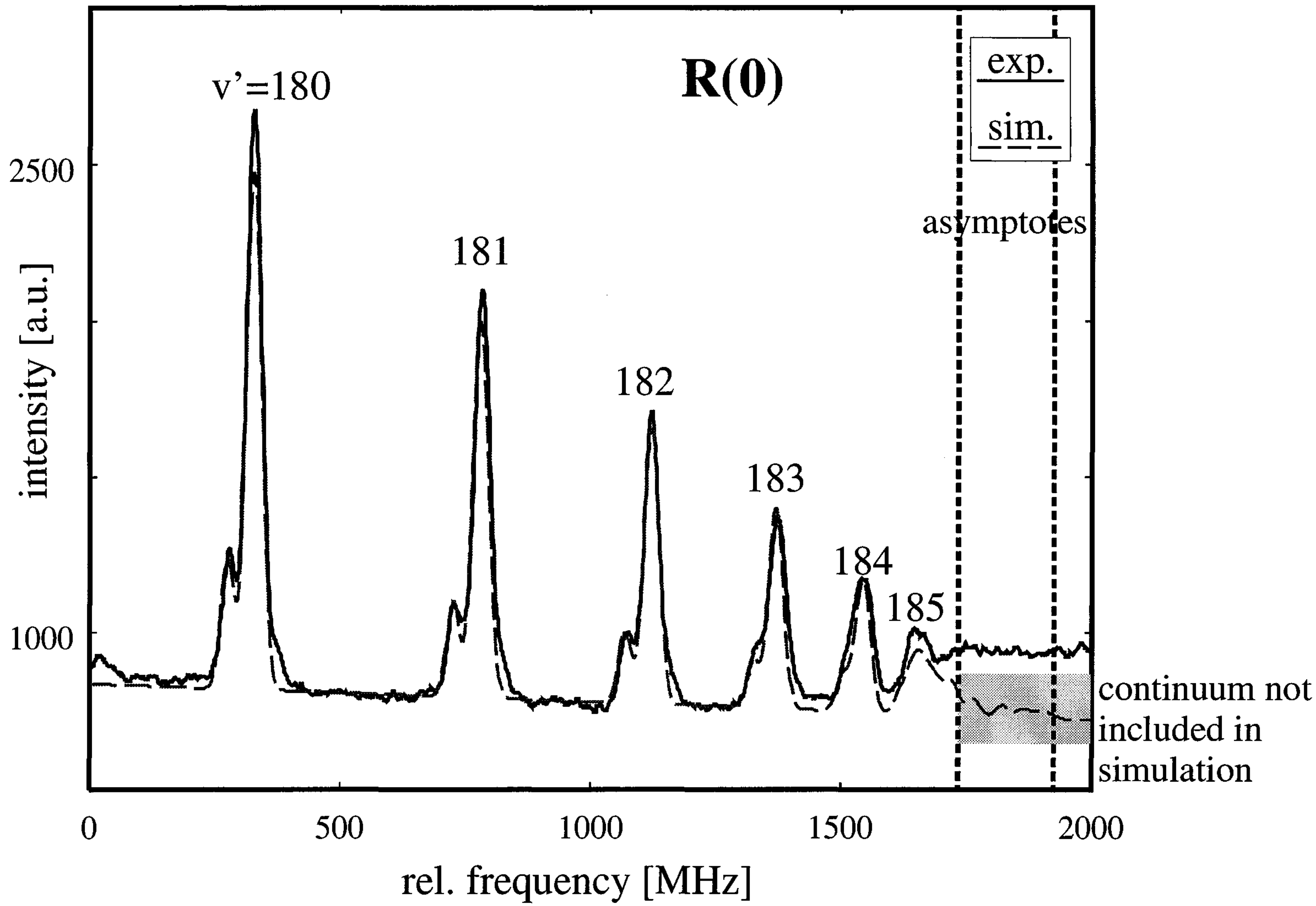


STIRAP



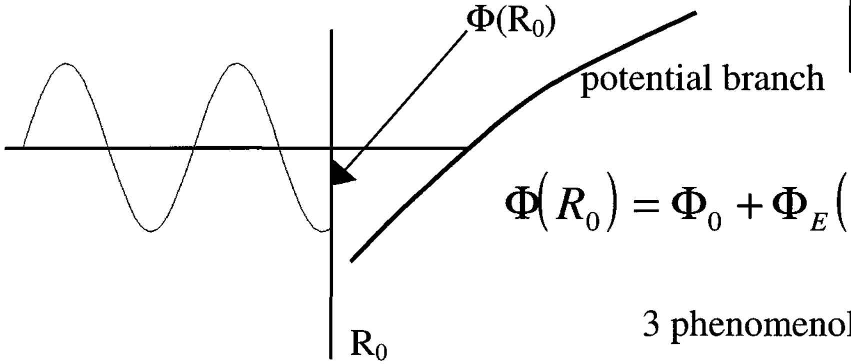
Experimental setup





R(0)
exp.
sim.
v'=180
181
182
183
184
185
asymptotes
continuum not
included in
simulation
intensity [a.u.]
2500
1000
0
500
1000
1500
2000
rel. frequency [MHz]

boundary condition for eigenstate replaced by phase at R_0



Moerdijk, Verhaar, Axelsson, Phys.Rev.A51,4852 (1995)

$$\Phi(R_0) = \Phi_0 + \Phi_E(D_e - E) + \Phi_J J(J+1) + \ldots$$

3 phenomenological parameters

$$U(R) = D_e - \frac{C_i}{R^i}$$

eigenstates are described by $\Phi(R_0)$, D_e *and* C_i

phase scattering length — at asymptotic energy — dispersion coefficient

reliable extrapolation by fitting spectroscopic observations

estimation of spectral intensities by the asymptotic wave function,
the inner part keeps its form

Dipole-dipole coupling of degenerated states

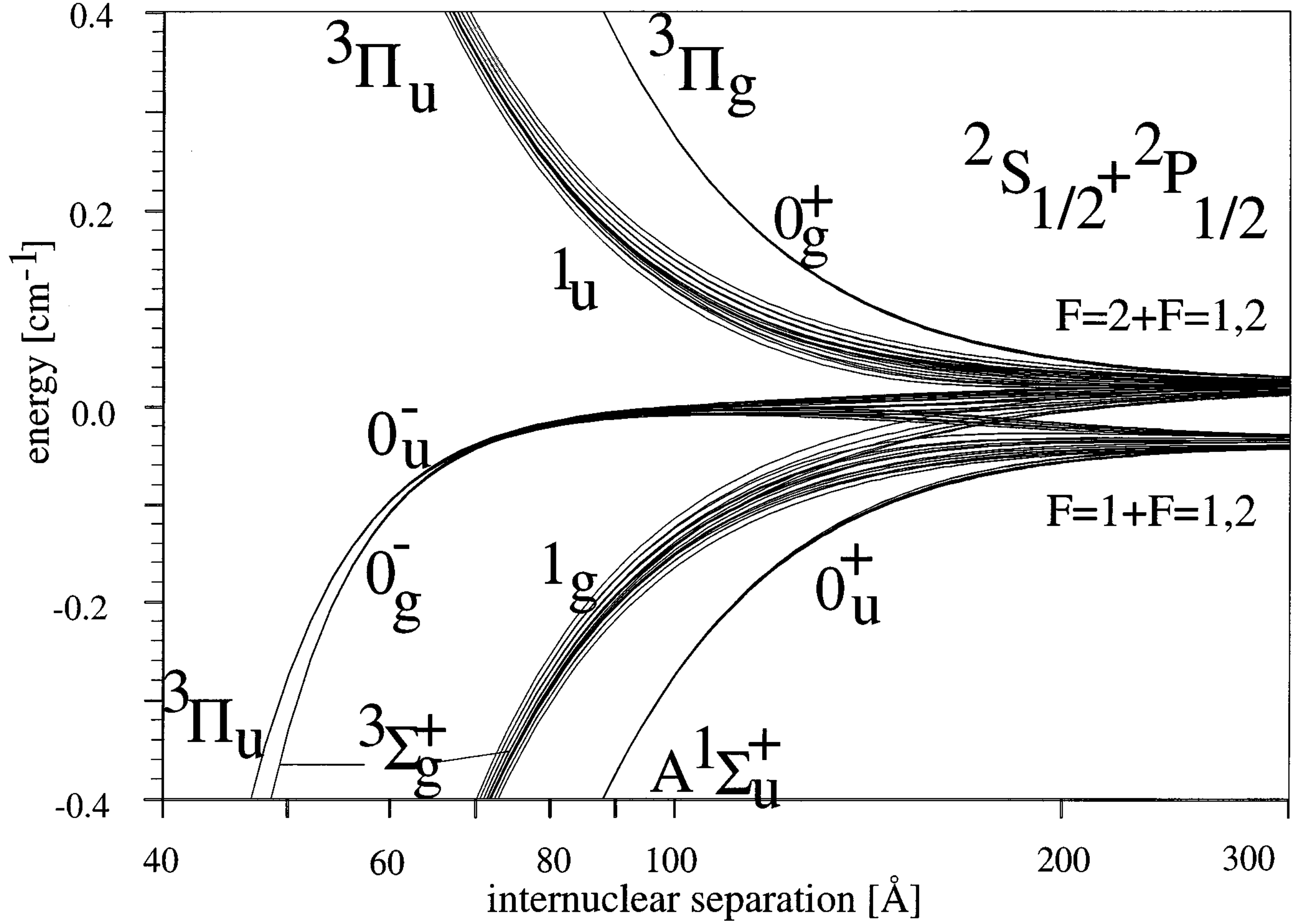
R between atom A and B $\longrightarrow$

pure electrostatic	with spin-orbit	with hyperfine interaction
$\|3s\rangle_A \|3p\rangle_B$	$\|{}^2S_{1/2}\rangle_A \|{}^2P_{1/2}\rangle_B$	$\|{}^2S_{1/2}IF\rangle_A \|{}^2P_{1/2}IF'\rangle_B$
$\pm$	$\pm$	$\pm$
$\|3s\rangle_B \|3p\rangle_A$	$\|{}^2S_{1/2}\rangle_B \|{}^2P_{1/2}\rangle_A$	$\|{}^2S_{1/2}IF\rangle_B \|{}^2P_{1/2}IF'\rangle_A$

atomic parameters:

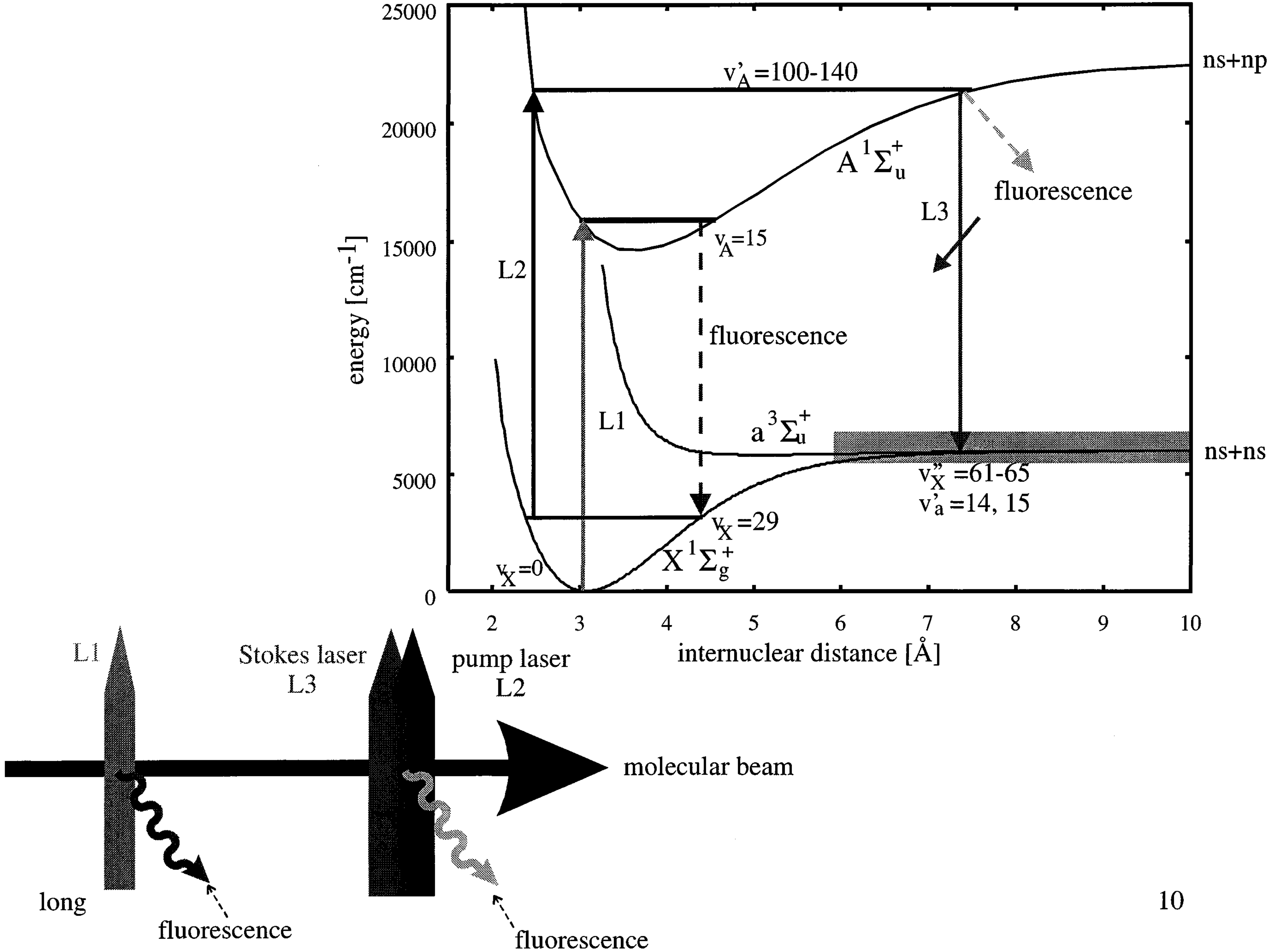
$C_3 \sim \|\langle 3s\|z\|3p\rangle\|^2$	C_3 , ζ_{nl}	C_3 , ζ_{nl} , a , b

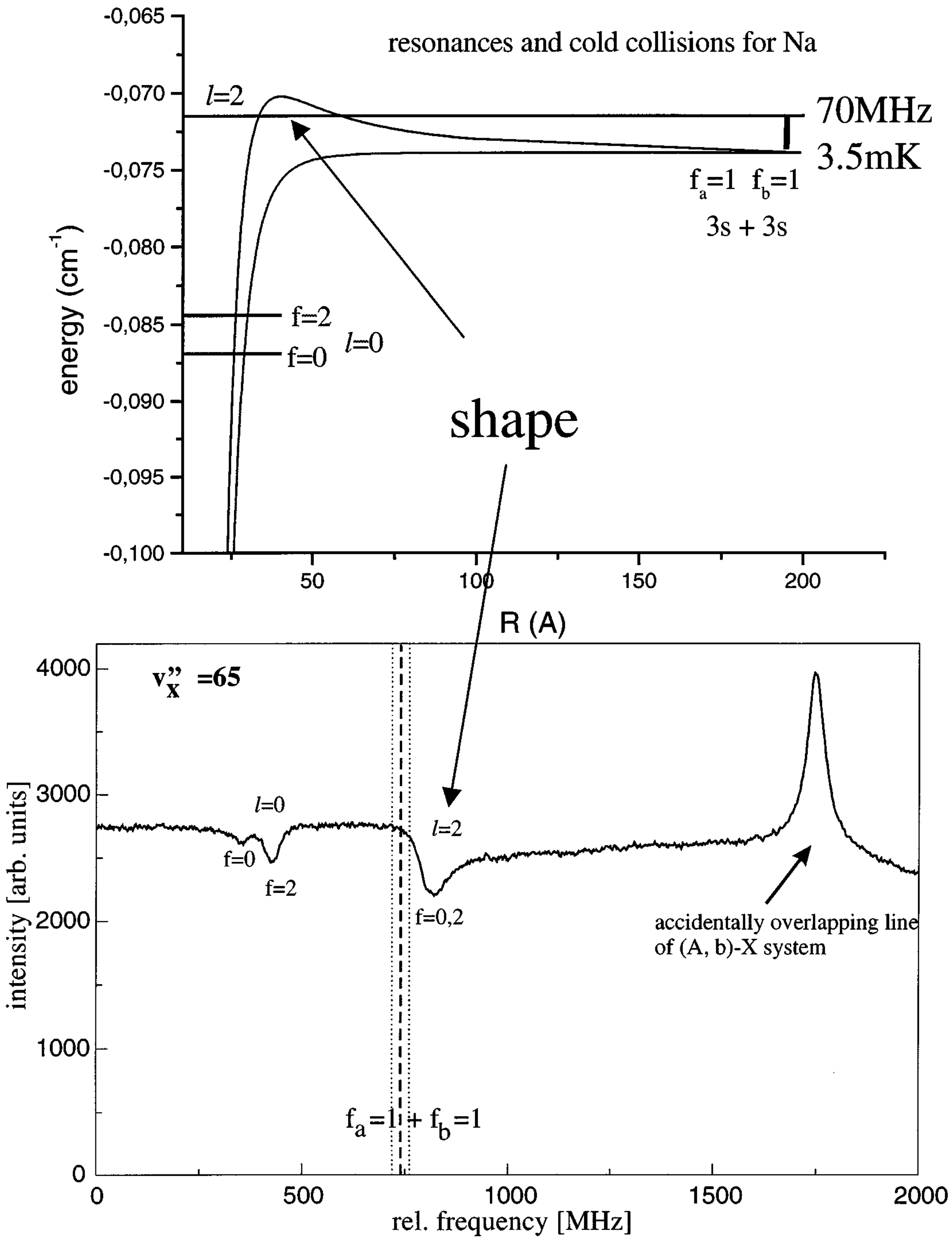
Asymptotic potential for alkali dimers



coupling: dipole-dipole interaction, spin-orbit interaction, hyperfine interaction

Coherent excitation scheme to the cold collision regime

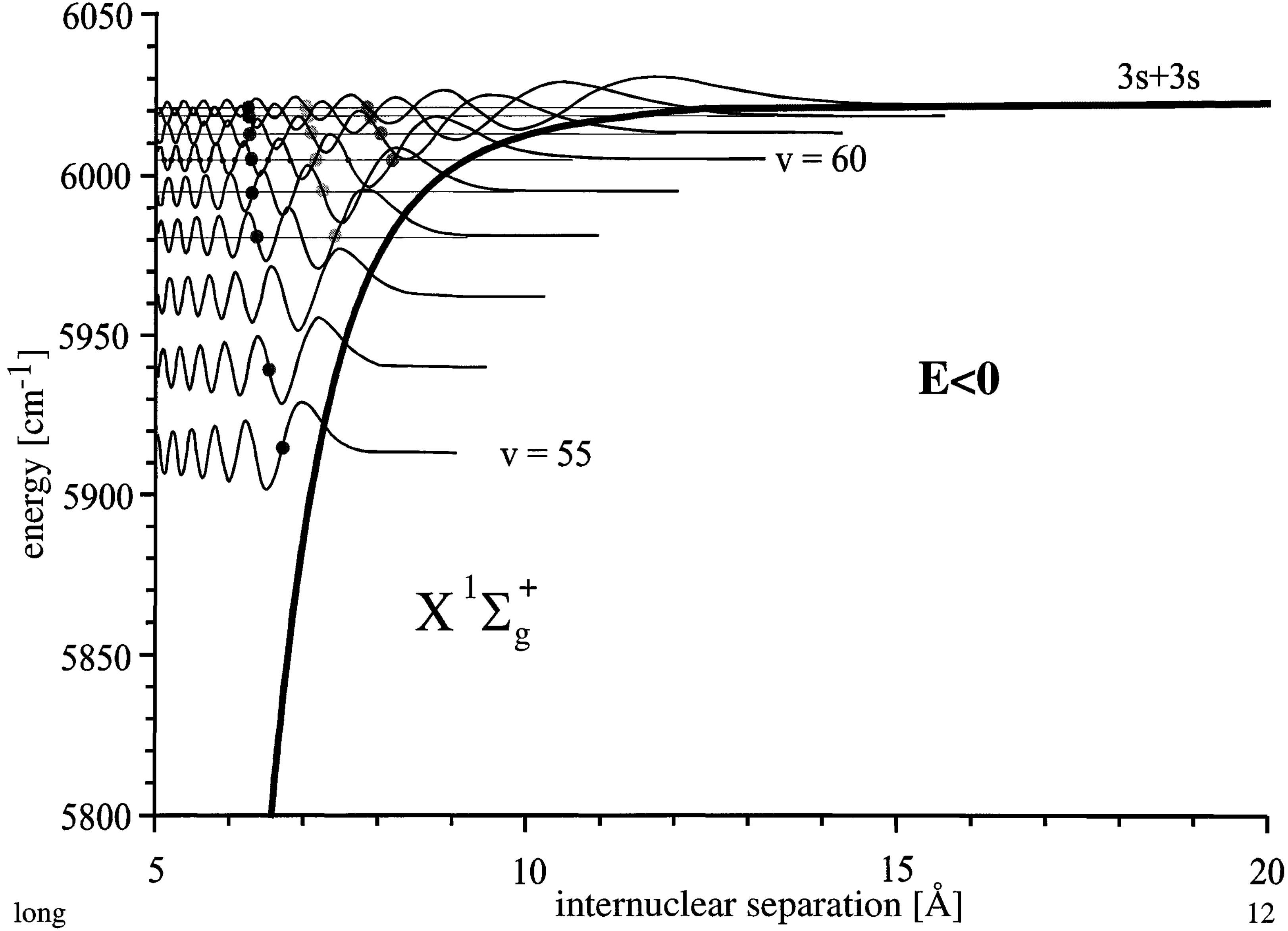


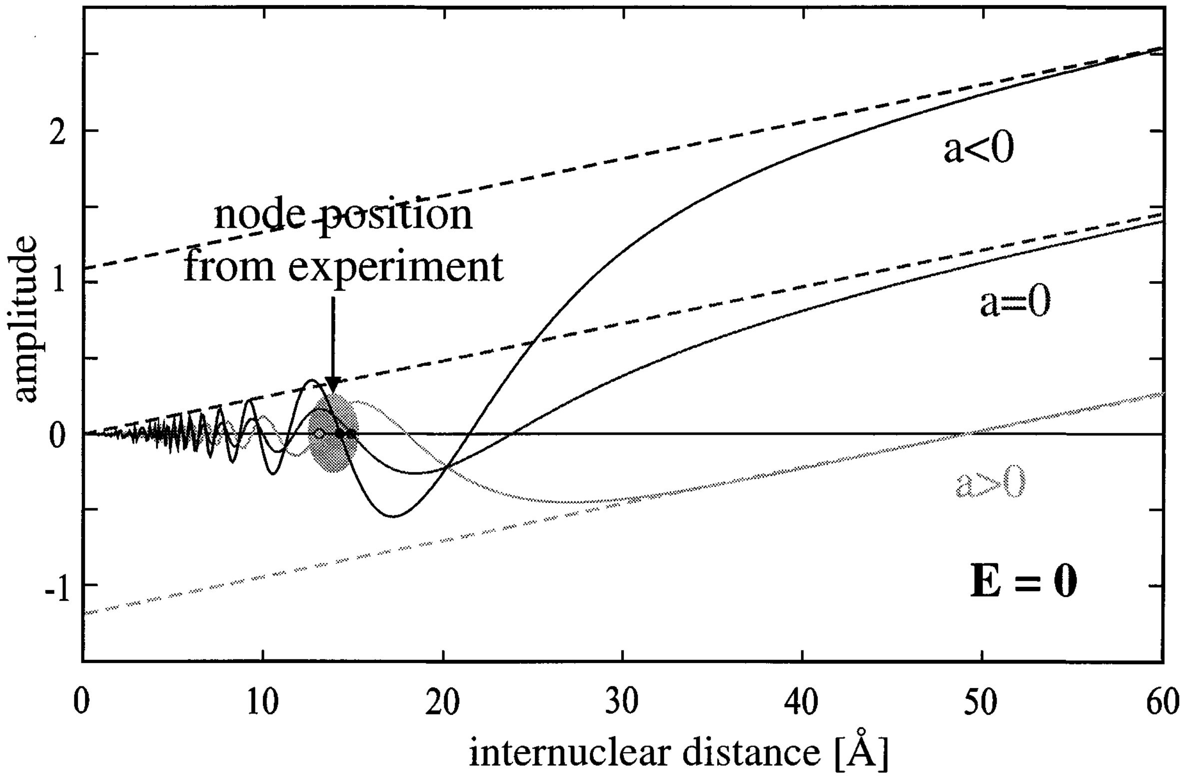


resonances and cold collisions for Na
l=2
70MHz
3.5mK
f_a=1 f_b=1
3s + 3s
f=2
f=0
l=0
energy (cm-1)
R (A)
shape
v"x =65
l=0
l=2
f=0
f=2
f=0,2
accidentally overlapping line
of (A, b)-X system
intensity [arb. units]
f_a=1 + f_b=1
rel. frequency [MHz]

long

from bound levels to scattering length

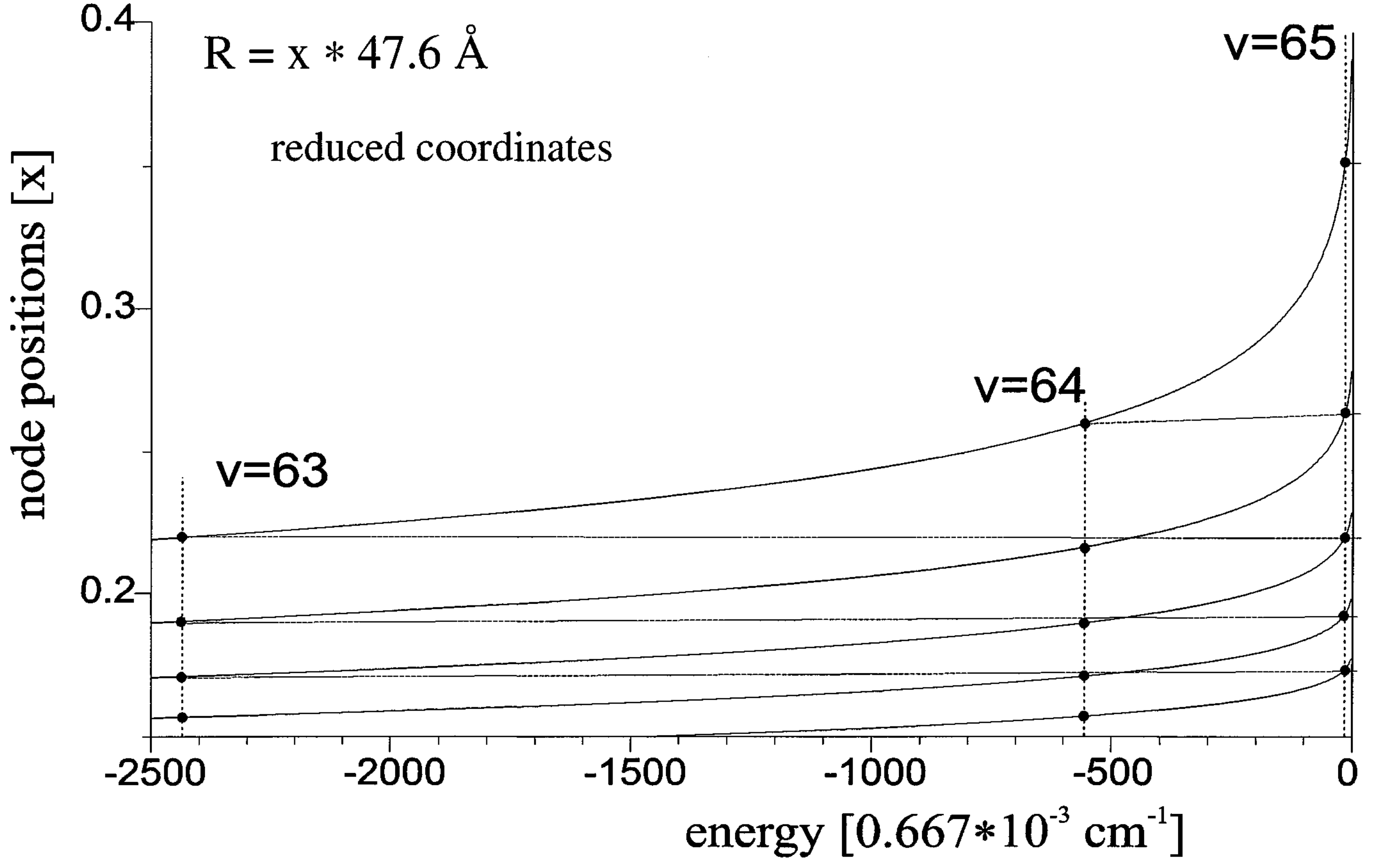




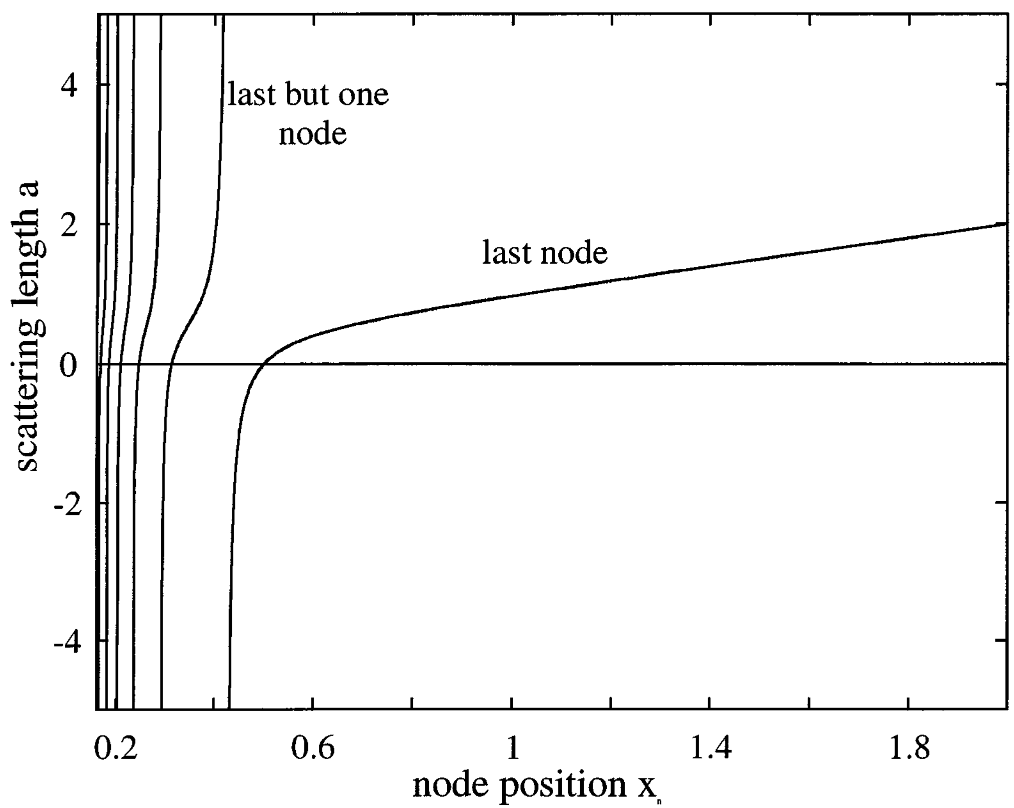
amplitude
2
1
0
-1
node position
from experiment
a<0
a=0
a>0
E = 0
0
10
20
30
40
50
60
internuclear distance [Å]

long

Graphical extrapolation to node positions for energy zero



A. Crubellier, O. Dulieu, F. Masnou-Seeuws, M. Elbs, H.Knöckel, E. Tiemann
Eur. Phys. J. D **6**, 211 (1999)



$$a = \frac{\Gamma\left(\frac{p-3}{p-2}\right)}{(p-2)^{2/(p-2)}\,\Gamma\left(\frac{p-1}{p-2}\right)} \frac{J_{-\frac{1}{p-2}}\left(\frac{2}{(p-2)x_n^{(p-2)/2}}\right)}{J_{\frac{1}{p-2}}\left(\frac{2}{(p-2)x_n^{(p-2)/2}}\right)}$$

$$x_n = \left(\frac{\hbar^2}{2\mu C_p}\right)^{1/(p-2)} R_n$$

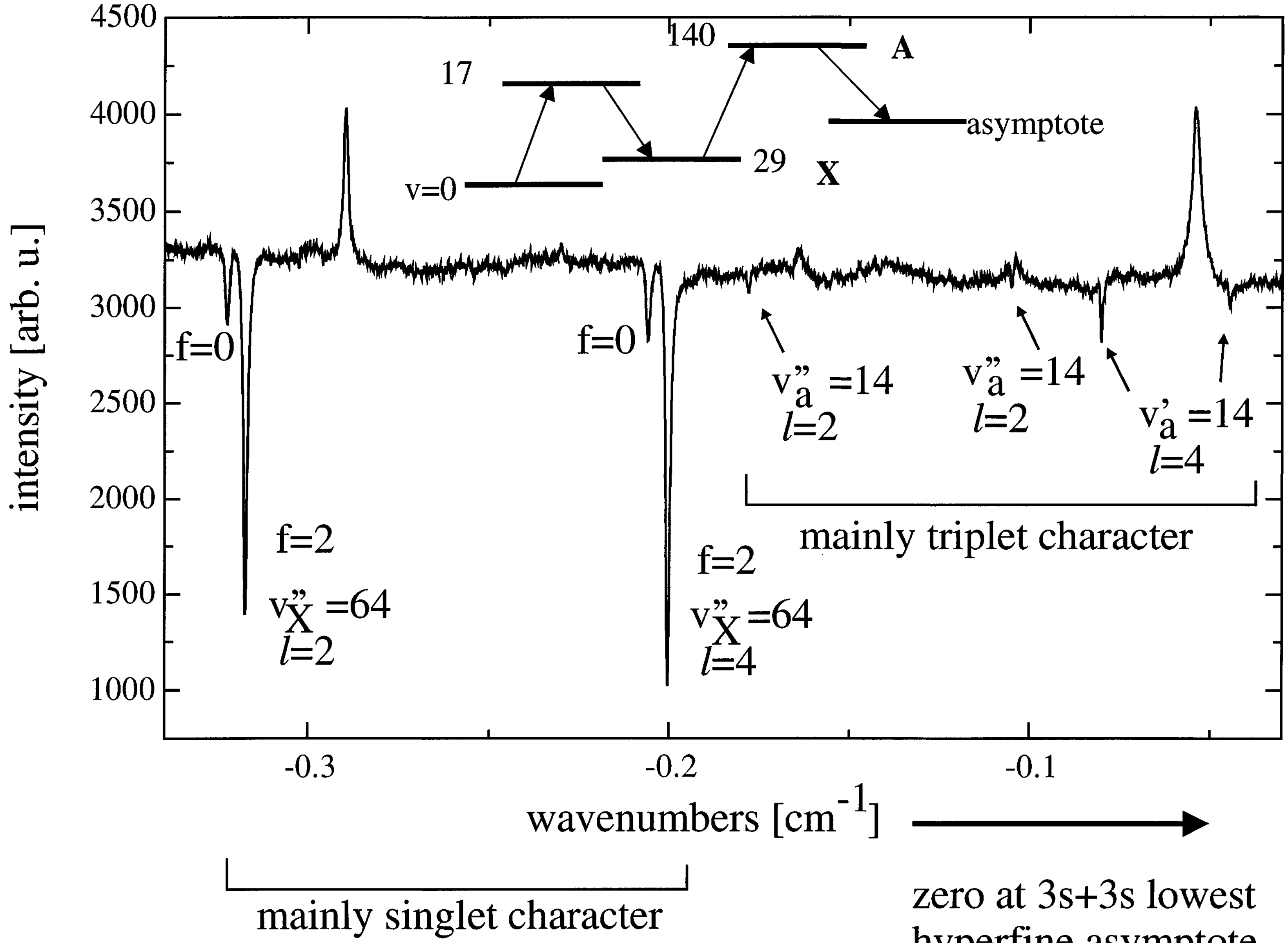
results for the scattering lengths at the asymptote 1+1:

$$a_1(f=2) \triangleq a_{1,-1} = 55.1\ (1.6)\ a_0$$
$$a_1(f=0) = 50.0\ (1.6)\ a_0$$

Compare:

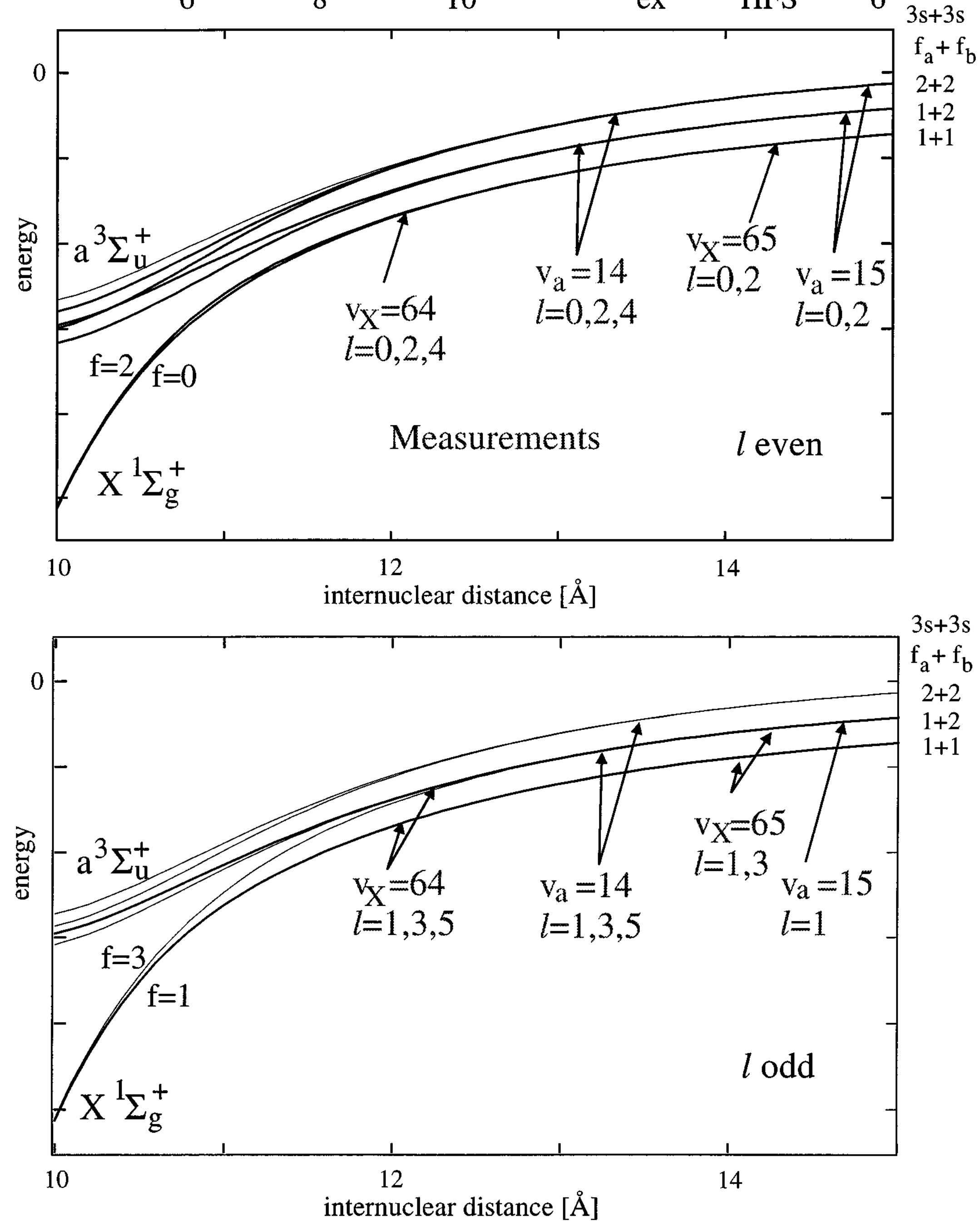
$a_{1,-1}$=52(5) a_0 (NIST , 1996, intensity pattern in photo association)
$a_{1,-1}$=92(25) a_0 (MIT, 1995, scattering cross section in cold collisions)

dips show optimal transfer, according to resonance condition

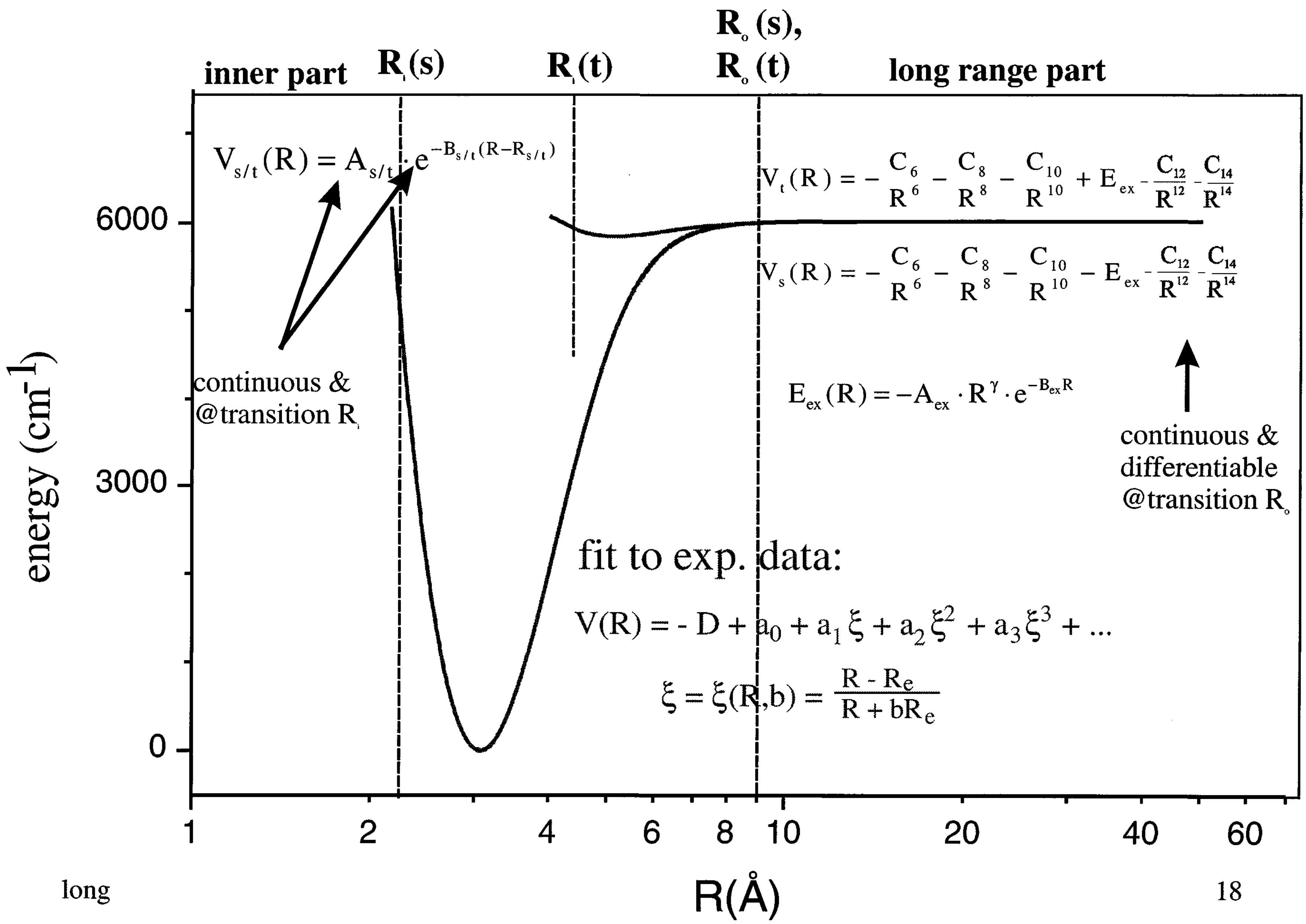


long

$$H = -C_6/R^6 - C_8/R^8 - C_{10}/R^{10} + H_{ex} + H_{HFS} + C_6/R^6$$



Construction of the adiabatic Na_2 ground state potentials



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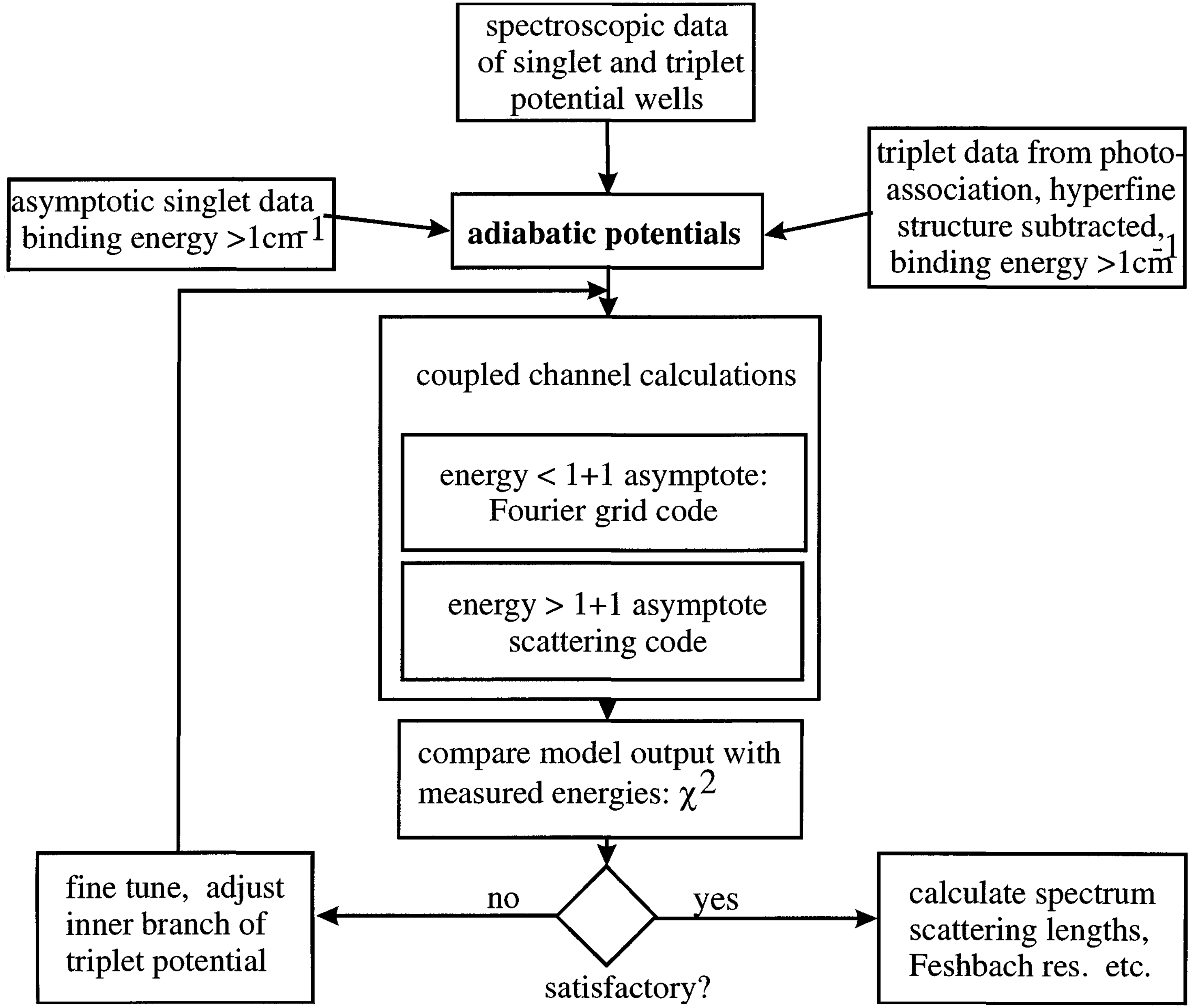
Determination of potential function



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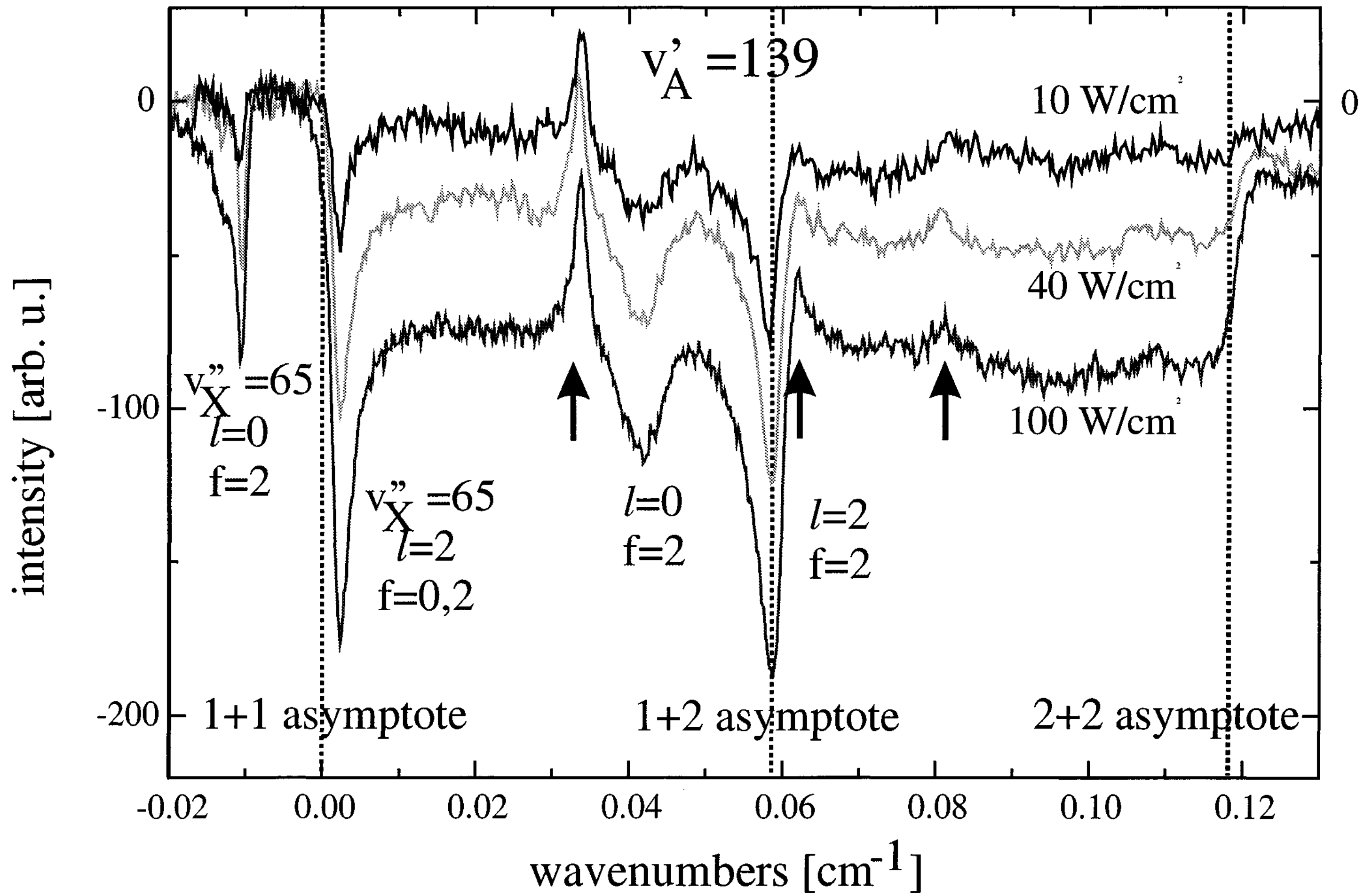
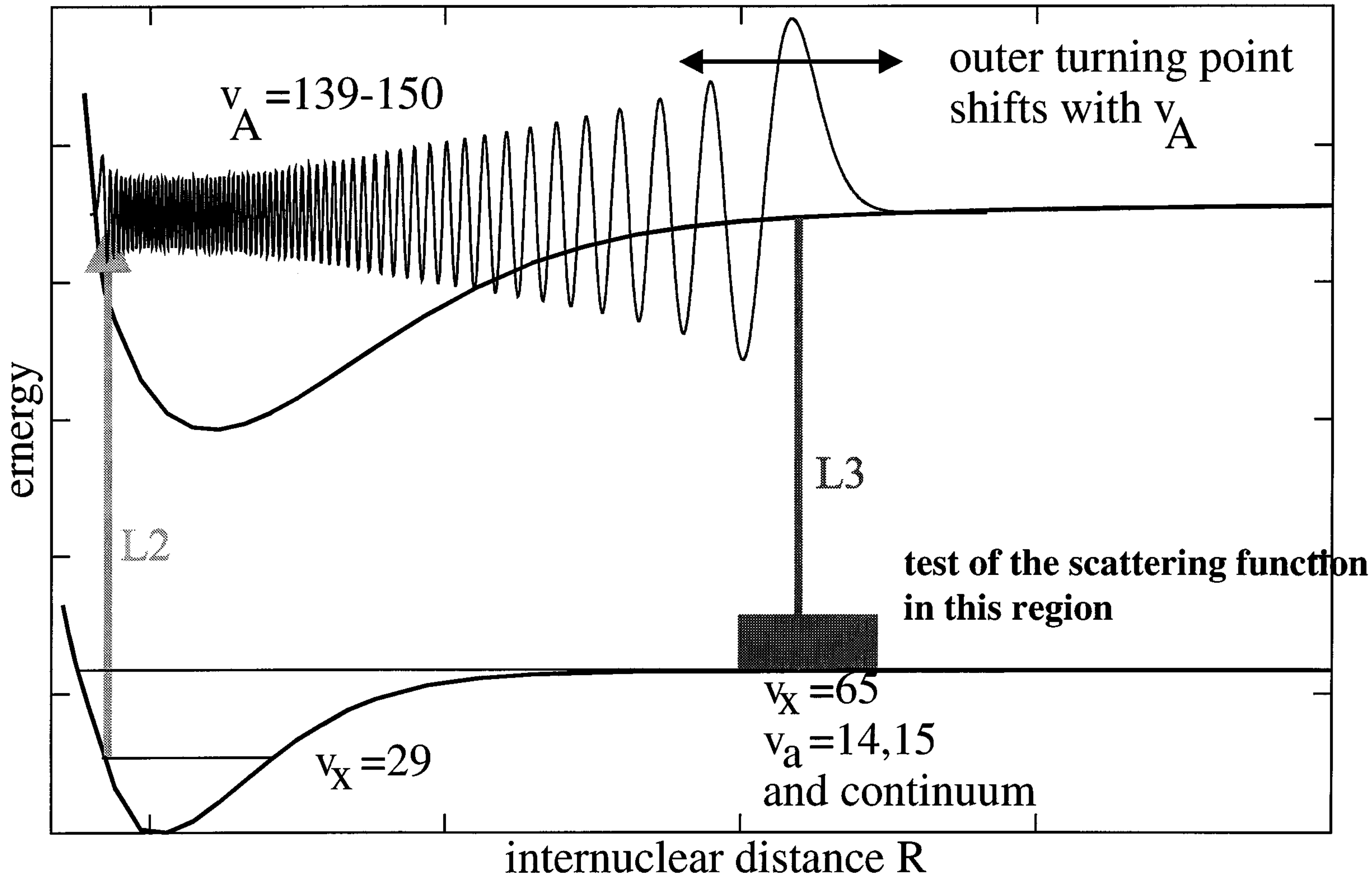
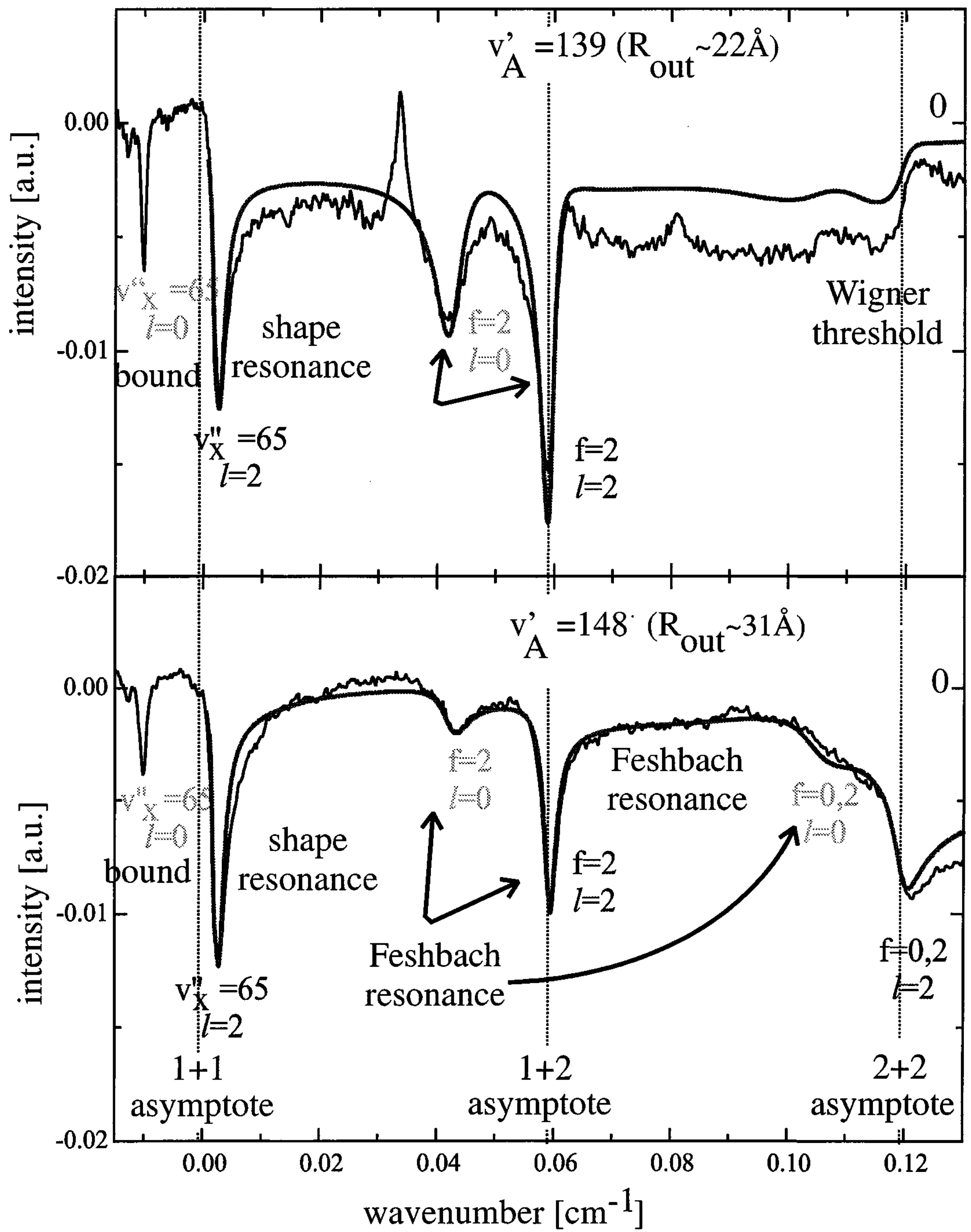
Power dependence of the transfer process to dissociating atom pairs



Saturation different between resonances and continuum

Stimulating to the continuum from different excited states

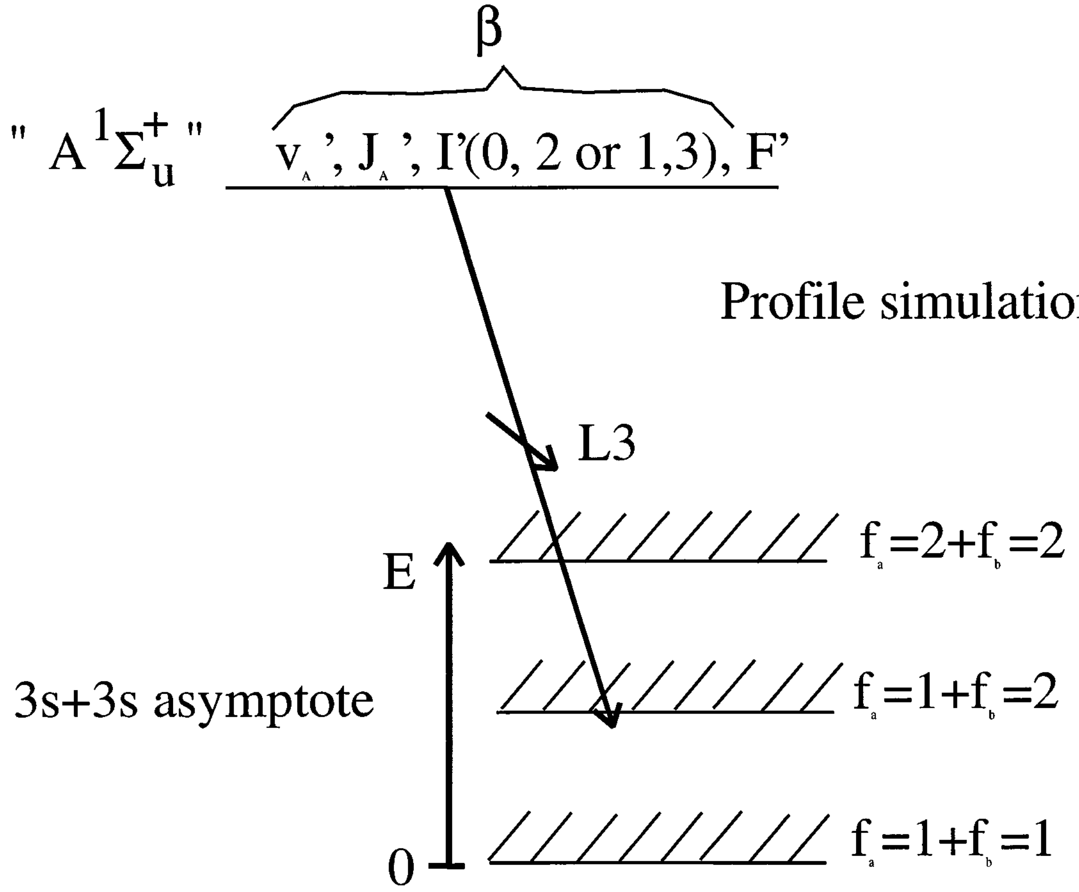




Comparison of
observed continuum structure
to
model calculation

long

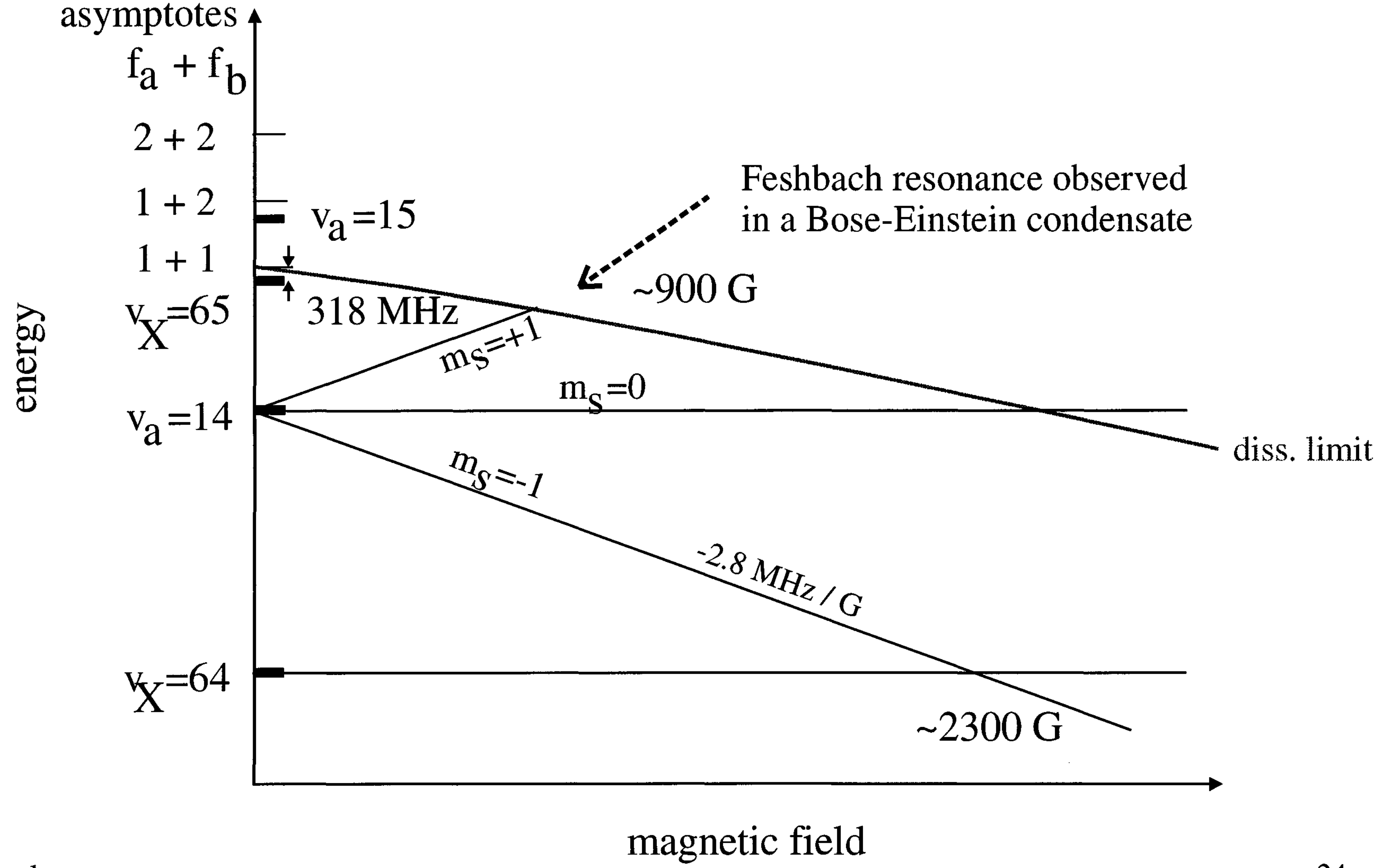
Profile simulation to the continuum



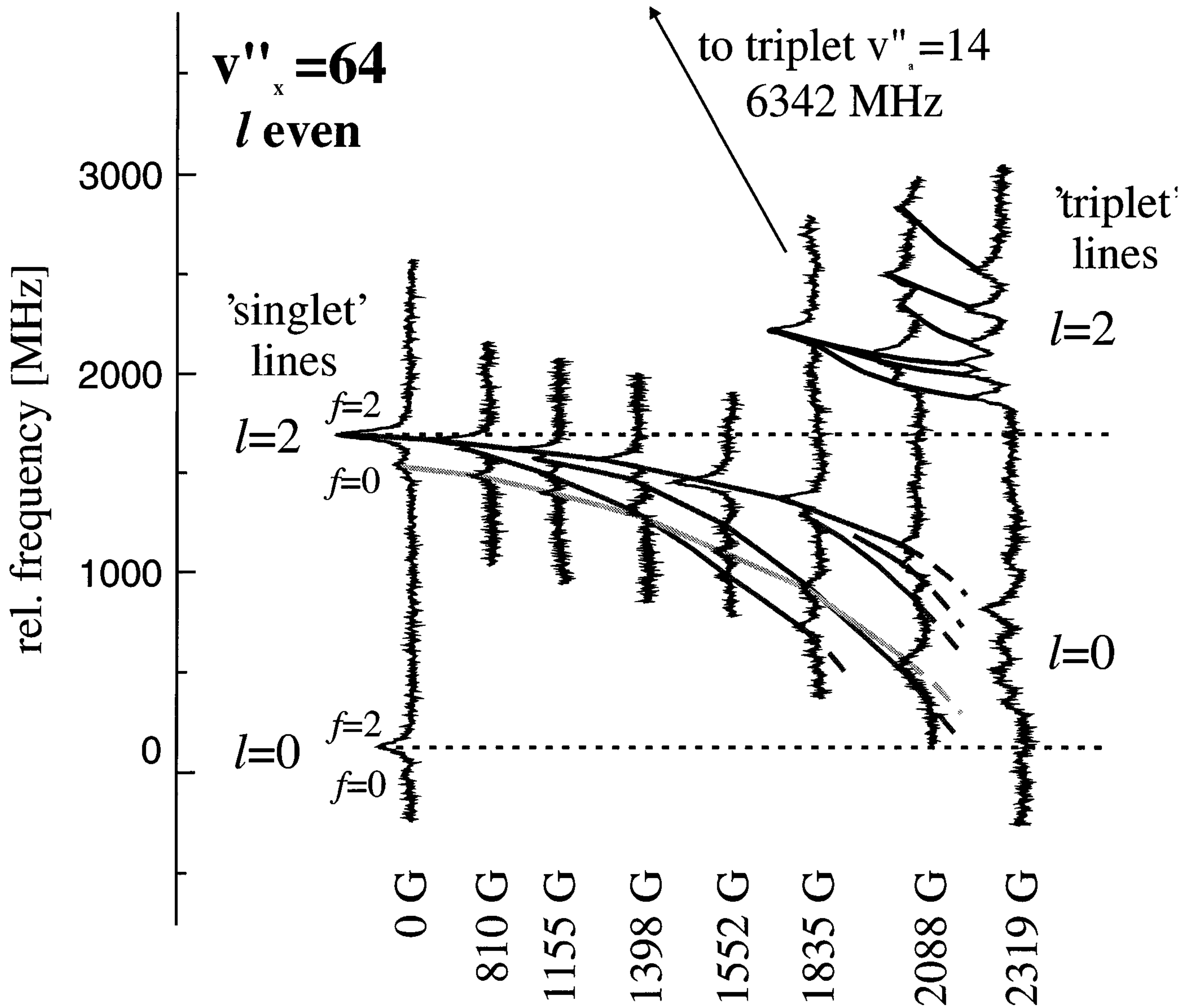
$$I_q(\omega_3) \propto \sum_{\beta F'M'} \frac{\gamma_{\beta F'}}{2\pi} \int_0^\infty dE \sum_{\alpha FM} \frac{\left|\left\langle \alpha E^{(-)} FM \; d_q \; A\beta F'M' \right\rangle\right|^2}{\left(E + \hbar\omega_3 - E_{\beta F'}\right)^2 + \left(\gamma_{\beta F'}/2\right)^2}$$

long initial final states

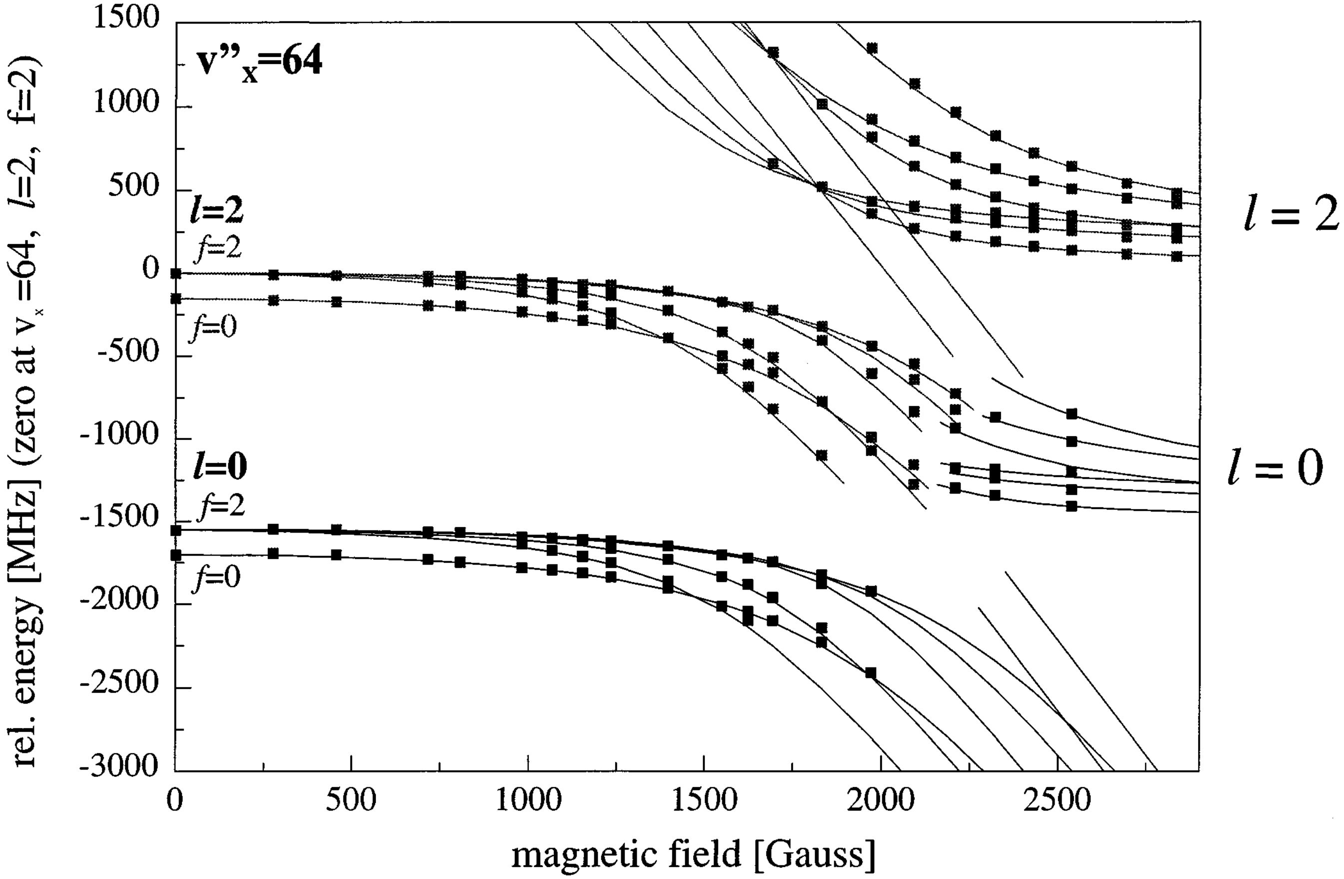
simplified scheme of the Zeeman effect at the asymptote 3s+3s



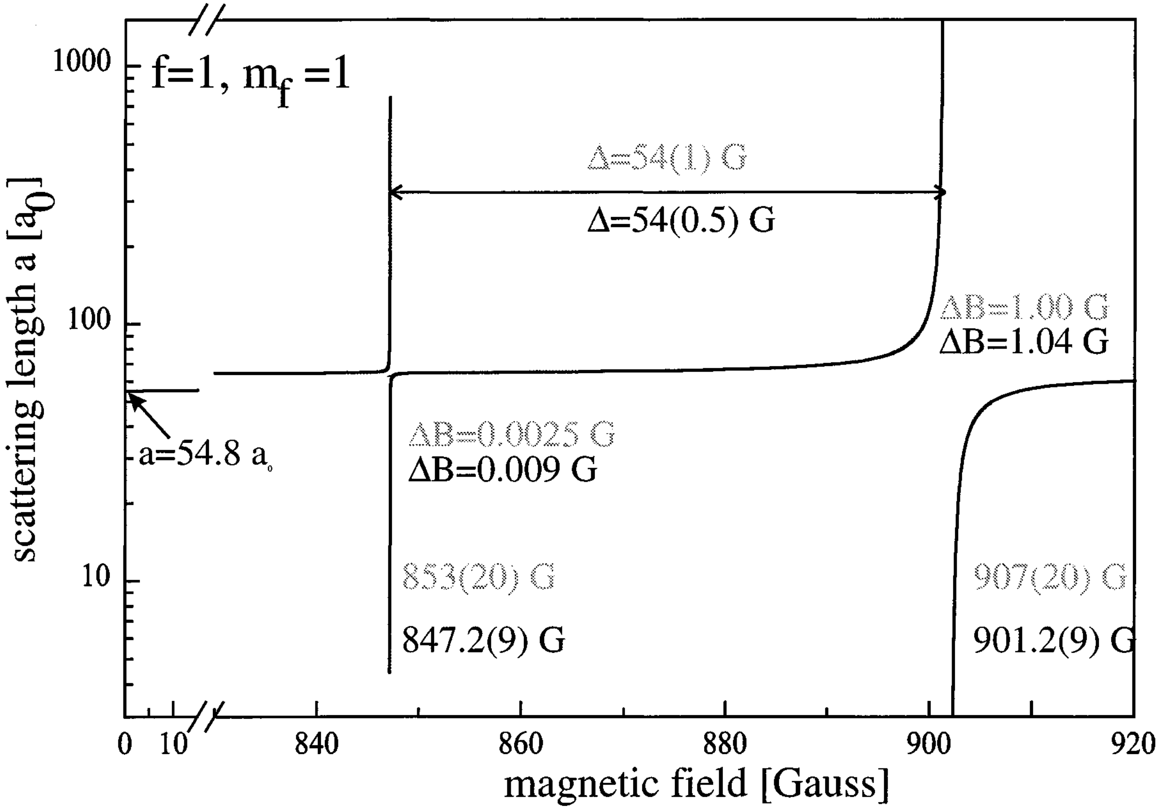
Avoided crossing by singlet triplet mixing



avoided crossing: theory and observation



Feshbach resonances at energy E=0



observed: S.Inouye,M.R.Andrews, J.Stenger, H.-J.Miesner, D.M.Stamper-Kurn, W. Ketterle, Nature 392, 151 (1998)

Conclusions

Precise determination of potential functions

Spectroscopic observation of cold collisions

Detailed study of collision resonances

Tuning resonances by magnetic fields

Future

Other molecular examples

Other tuning possibilities, tailoring of collisions

Production of cold molecules