"Fundamentals of Rydberg Atoms and Molecules »
Workshop "YEA" (Young Excited Atomix)

Properties and dynamics of a cold sample of Rydberg atoms

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COHERENCE School
and YEA meeting
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Cold Rydberg atoms / Ultracold plasmas

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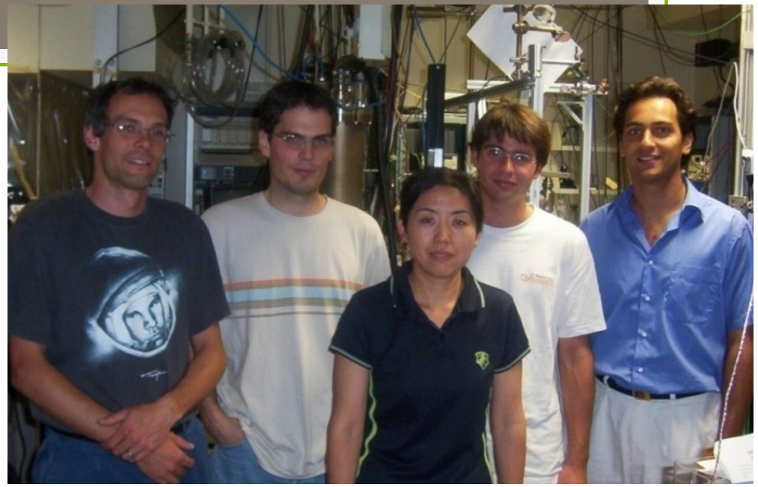


Collaborations:

On few-body effects with Phil F. Gould, Univ of Connecticut and Jianming Zhao, Univ of Shanxi

On dipole blockade with the group of Ennio Arimondo, Univ of Pisa

On ultracold plasmas with Thomas F. Gallagher, Univ of Virginia and Ducan Tate, Colby College

On collective excitation of a pair of atoms in the dipole blockade regime with Philippe Grangier, Antoine Browaeys et al., Institut d'Optique

LAC 80 ans 1927-2007

UNIVERSITE PARIS-SUD XI

Institut Francilien de Recherche sur les Atomes Froids IFRAF

La Grenouille qui se veut faire aussi grosse que le Boeuf

Une grenouille vit un boeuf
Qui lui sembla de belle taille.
Elle, qui n'était pas grosse en tout comme un oeuf,
Envieuse, s'étend, et s'enfle, et se travaille,
Pour égaler l'animal en grosseur,
Disant : « Regardez bien, ma soeur ;
Est-ce assez ? dites-moi ; n' y suis-je point encore ?
- Nenni. - M' y voici donc ? - Point du tout. - M' y voilà ?
- Vous n'en approchez point. » La chétive pécore
S'enfla si bien qu'elle creva.
Le monde est plein de gens qui ne sont pas plus sages :
Tout bourgeois veut bâtir comme les grands seigneurs,
Tout petit prince a des ambassadeurs,
Tout marquis veut avoir des pages.

Jean de Lafontaine (1621 – 1695)

n =200 000 ! Very sentitive to any perturbation

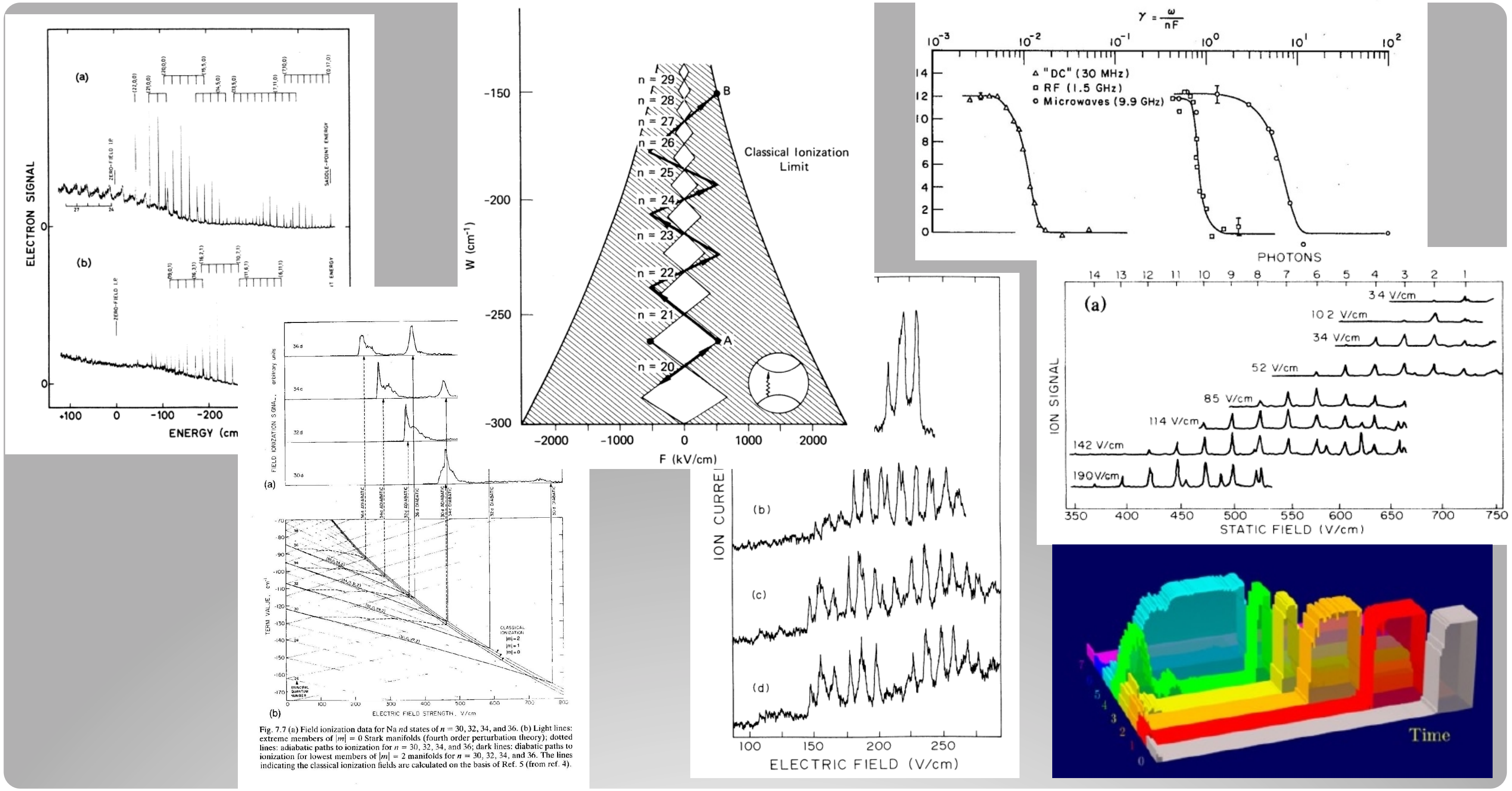


Fig. 7.7 (a) Field ionization data for Na nd states of n = 30, 32, 34, and 36. (b) Light lines: extreme members of |m| = 0 Stark manifolds (fourth order perturbation theory); dotted lines: adiabatic paths to ionization for n = 30, 32, 34, and 36; dark lines: diabatic paths to ionization for lowest members of |m| = 2 manifolds for n = 30, 32, 34, and 36. The lines indicating the classical ionization fields are calculated on the basis of Ref. 5 (from ref. 4).

Rydberg atoms versus electric field

Behaviors of Rydberg atoms in electric field? From static field to quantum field

Stark spectroscopy, photoionization of H, electric field ionization, microwave ionization, multiphoton transitions, microwave assisted collisions, Rydberg atoms in cavity

WHY **Co**ld Rydberg atoms? **Co**llective effects

The atoms are cold and Rydberg

Cooperativity, **co**herence, **co**rrelation

Due to

Interaction, **int**erference, **int**rication (entanglement)

Main properties of a cold Rydberg gas

- Cold: frozen gas
- Rydberg: Strongly interacting
- Long-range forces: Penning ionization

- Consequence: at the frontier of solid state physics and plasmas physics

Dipole – dipole interaction

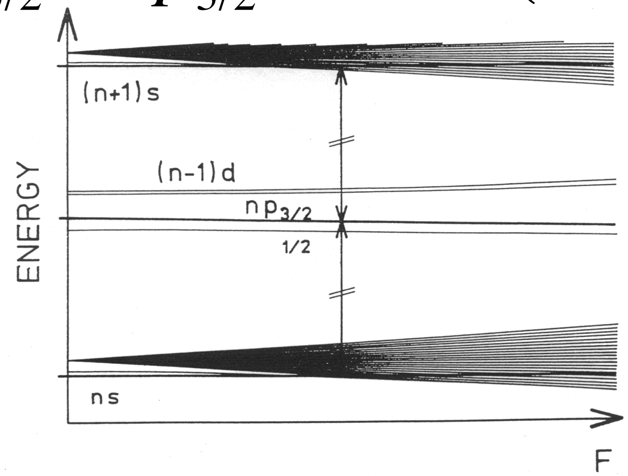
Förster resonances

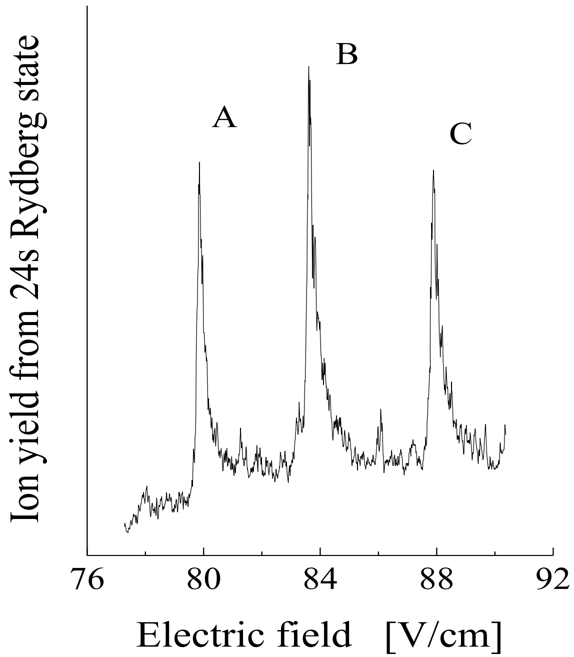
Förster dipole-dipole resonances (exchange of internal energy)

- Experimentally introduced by T.F. Gallagher (P.R.L. 40, 1362 (1981), in Rydberg-Rydberg collisions
- Case of Cs $np_{3/2}$ (n < 42)

$$np_{3/2} + np_{3/2} \rightarrow ns + (n+1)s$$

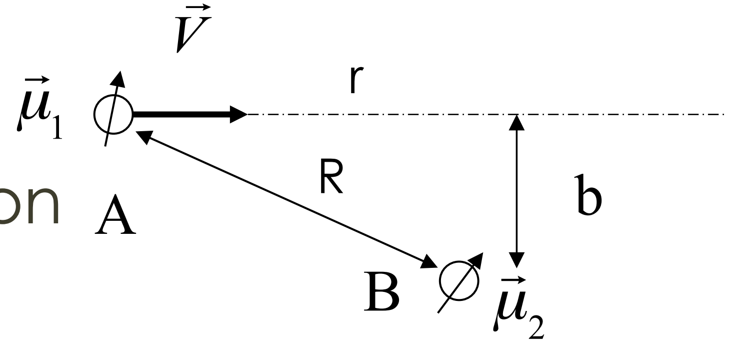
$m_1 + m_2$
A 1/2 + 1/2
B 1/2 + 3/2
C 3/2 + 3/2





Dipole-dipole collisions

- Atomic beam
- Dipole-dipole interaction



$$W = \frac{\vec{\mu}_A.\vec{\mu}_B}{R^3} - 3\frac{\left(\vec{\mu}_A.\vec{R}\right)\left(\vec{\mu}_B.\vec{R}\right)}{R^5}$$

$$W = \frac{\mu_A\mu_B\left(1-3\cos^2\theta\right)}{R^3} = \frac{\mu_A\mu_B\left(-2r^2+b^2\right)}{\left(r^2+b^2\right)^{5/2}}$$

$$\mu_A = \langle ns|er|np\rangle \quad \text{and} \quad \mu_A = \langle (n+1)s|er|np\rangle$$

Collision time and impact parameter

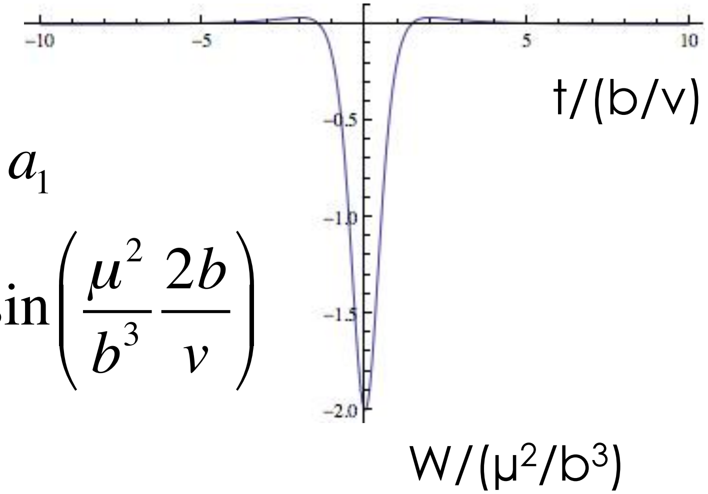
$$\left|\psi(t)\right\rangle = a_1(t)\left|pp\right\rangle + a_2(t)\left|ss\right\rangle$$

$$i\dot{a}_1 = W(t)a_2 \quad \text{and} \quad i\dot{a}_2 = \delta a_2 + W(t)a_1$$

$$\delta = 0: \quad a_2 = -i\sin\left(\int_{-\infty}^{\infty} W(t')dt'\right) = i\sin\left(\frac{\mu^2}{b^3}\frac{2b}{v}\right)$$

$$\sigma = \pi\int_0^{\infty}\sin\left(\frac{2\mu^2}{vb^2}\right)2b\,db = \frac{\pi^2\mu^2}{v}$$

$$b_0 \approx \sqrt{\frac{\mu_A\mu_B}{v}} \quad \text{and} \quad \tau_0 = \frac{2b_0}{v} \approx \frac{\sqrt{\mu_A\mu_B}}{v^{3/2}}$$

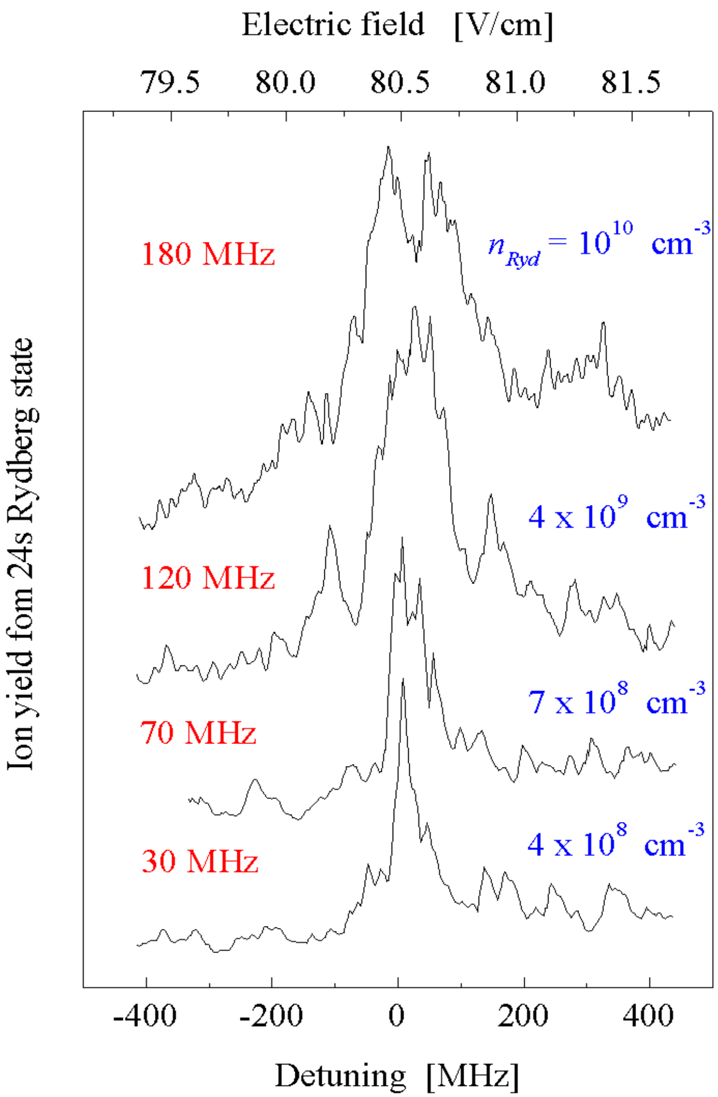


- Very large impact parameter ~1 μm for *n=20 and* v=300 m/s
- Collision time ~10 ns

Slow collisions and frozen Rydberg gas approximation

- The width of the resonance is the inverse of the collision time and becomes narrower for slow collisions
- For cold atoms v ~ 0.1 m/s, the impact parameter is ~ 50 µm (comparable to the volume size) and the collision time ~ 1 ms (larger than the Rydberg lifetime)
- No motion (at least when the experiment starts < 1µs) ; the atoms move their size 100nm
- The atoms interact altogether
- **FROZEN RYDBERG GAS approximation**
- What about collective effects: many-body effects?

Dipole-dipole interactions in a frozen Rydberg gaz



$$23p_{3/2}(|m_j| = 1/2) + 23p_{3/2}(|m_j| = 1/2)$$

$$\rightarrow 23s + 24s$$

Population Transfer ~ 10-15 %

Interaction between the closest neighbors leads to a too small width: $W_{typ} \approx \frac{\mu_1\mu_2}{\bar{R}_{AB}^3} < 1.5$ MHz

The frozen Rydberg gas cannot be explained in the framework of two-body effects

- Many-body effects in a frozen Rydberg, I. .Mourachko, D. Comparat, F . de Tomasi,, A. Fioretti, P. Nosbaum, V. Akulin et P. Pillet, Phys. Rev. Lett., 80, 253 (1998)

- Resonant dipole-dipole energy transfer in a nearly frozen Rydberg gas, W.R. Anderson, J.R. Veale, and T.F. Gallagher, Phys. Rev. Lett., 80, 249 (1998)

Many-body effects

Interplay with a two-body effect and many-body phenomena

Elementary processes:

I - Resonant transfer of internal energy

$Cs_A\ [np_{3/2}] + Cs_B\ [np_{3/2}]$

$\rightarrow Cs_A\ [ns] + Cs_B\ [(n+1)s]$

(resonant for a given electric field)

II - **Migration of the reaction products**

$Cs_C\ [np_{3/2}] + Cs_A\ [ns] \rightarrow Cs_C\ [ns] + Cs_A\ [np_{3/2}]$

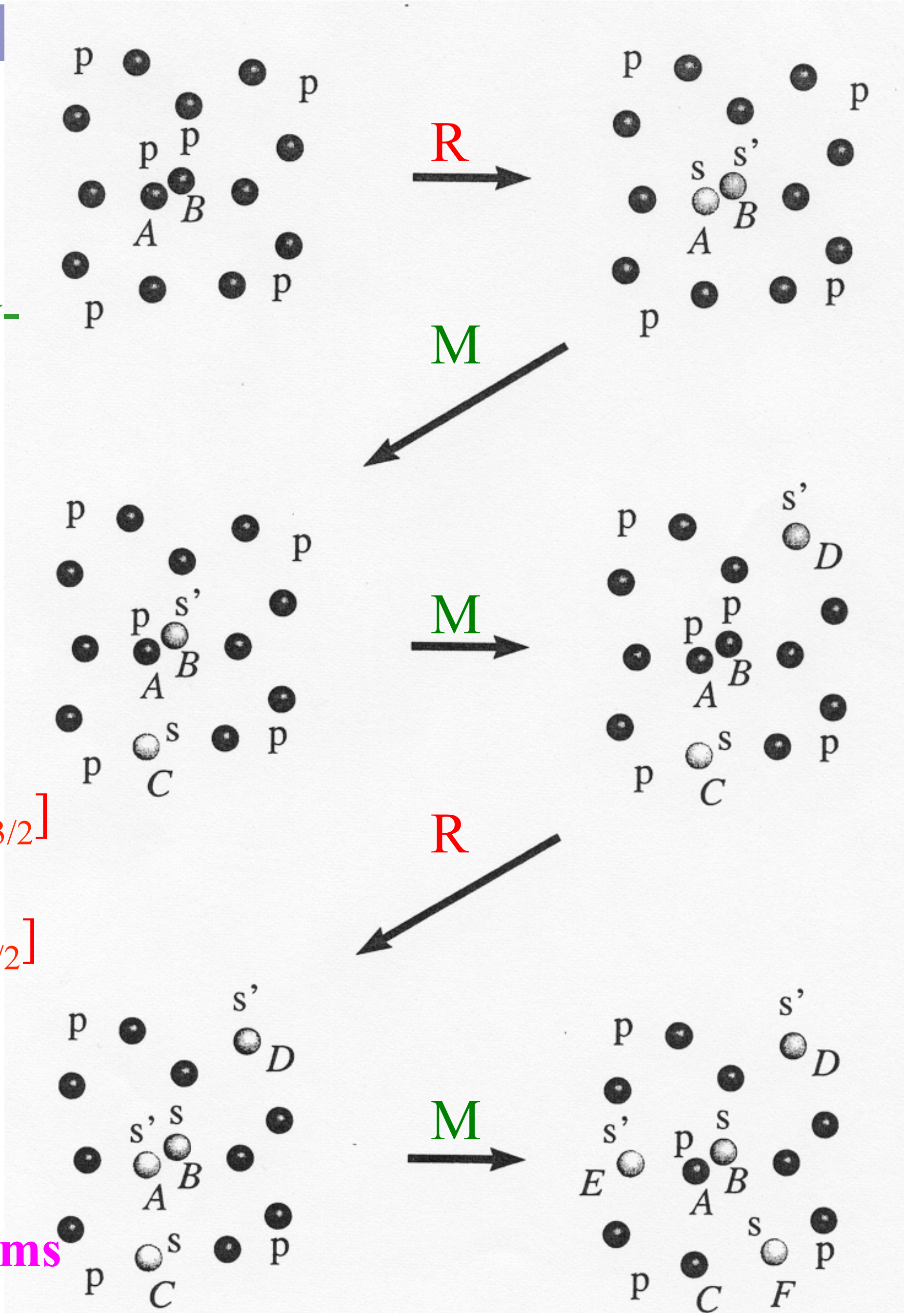
$Cs_D\ [np_{3/2}] + Cs_B\ [(n+1)s]$

$\rightarrow Cs_D\ [(n+1)s] + Cs_B\ [np_{3/2}]$

(no sensitive to the electric field)

Mourachko et al., PRA 70, 031401 (2004)

Importance of the "fluctuations"
in the Rydberg density of pairs of close atoms



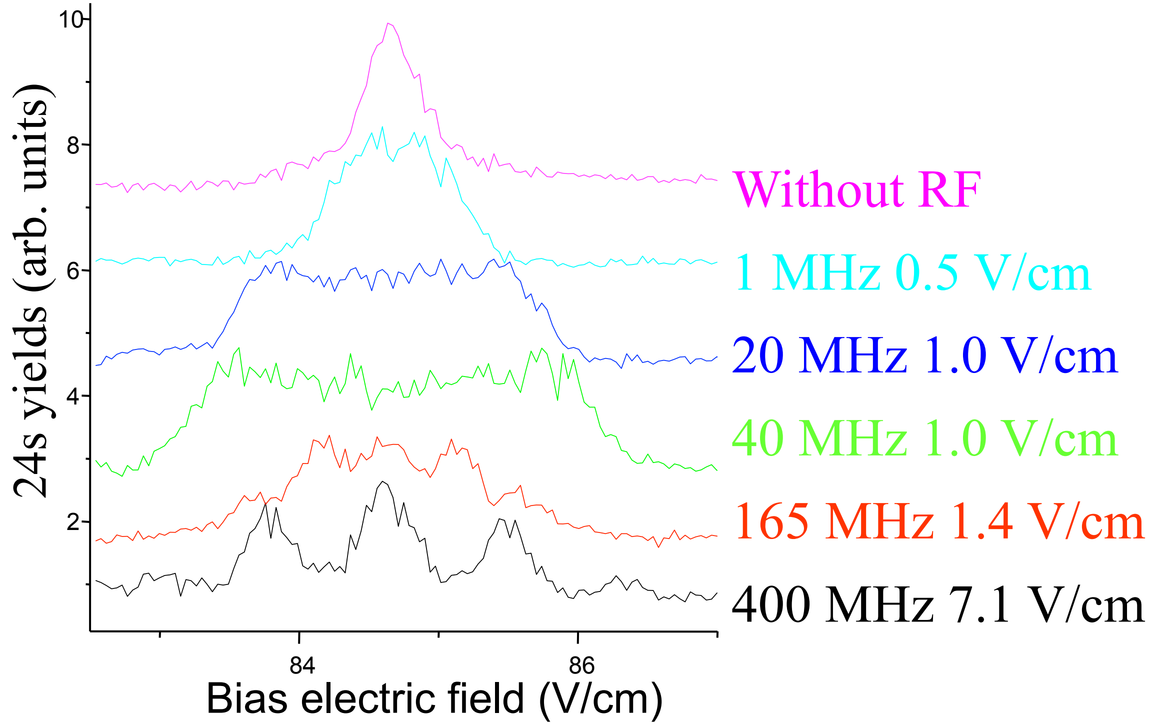
Dipole – dipole interaction assisted by microwave

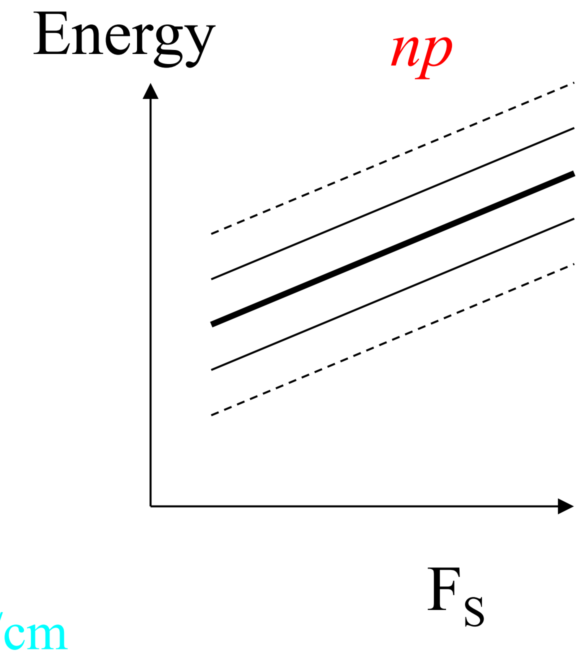
Förster resonances

Frozen Ryddberg gas:
Dipole-dipole interaction assisted by microwave frequency

$F = F_S + F_{RF}\cos(\omega t)$

- Low frequency ($\omega << \Gamma$) broaden lineshape
- High frequency ($\omega >> \Gamma$) sidebands





Unpublished LAC data

Many-body and few-body processes

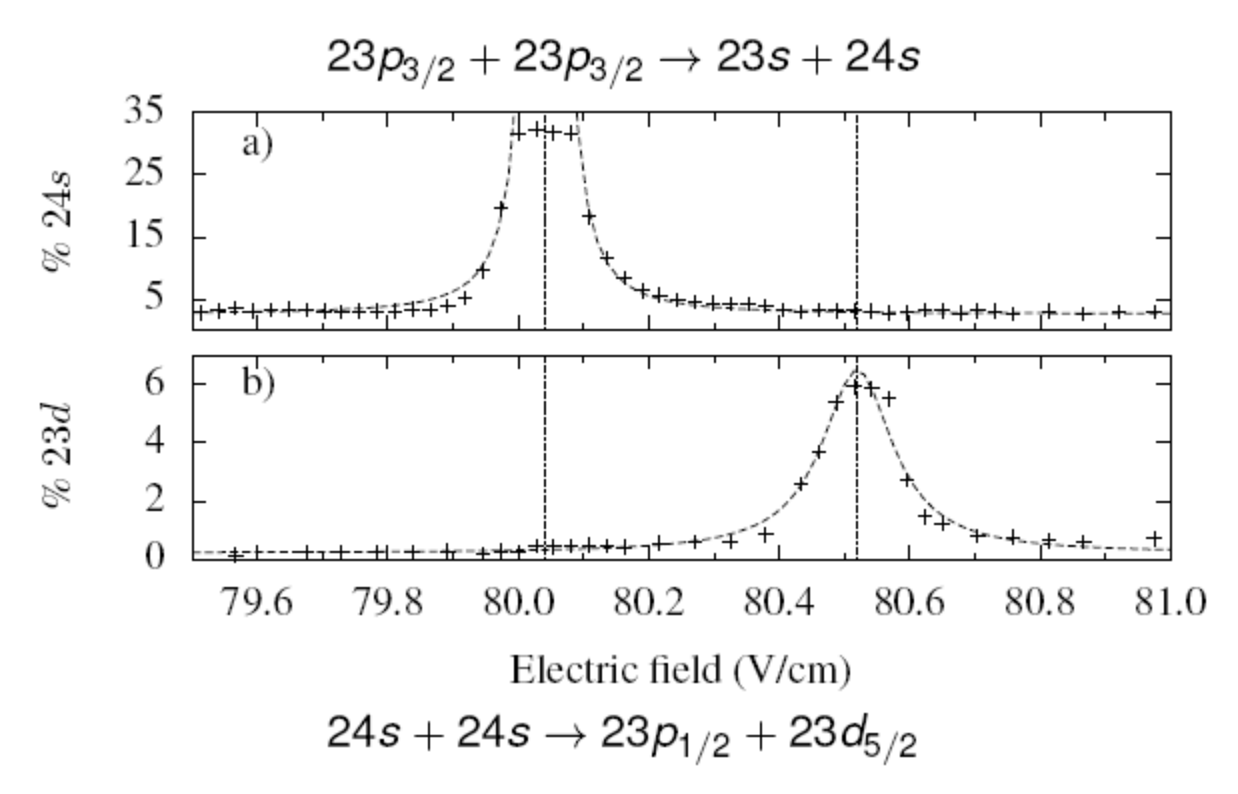
Four-body resonance

J. H. Gurian, P. Cheinet, P. Huillery, Y. Bruneau, A. Fioretti,
J. Zhao*, P. L. Gould**, D. Comparat, P. Pillet

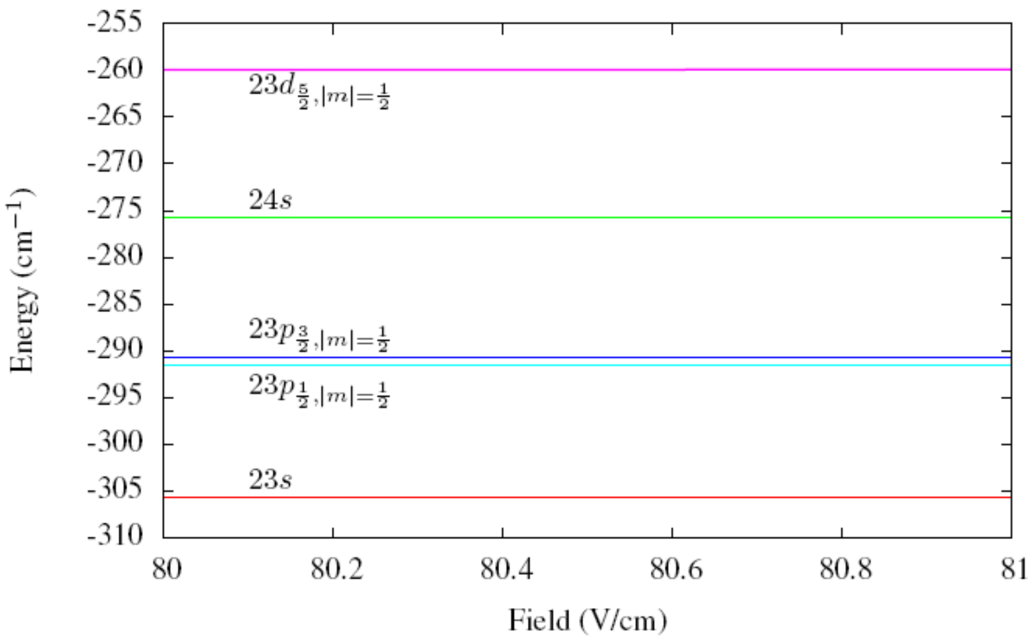
Phys.Rev.Lett. 108, 023005 (2012)

Collaborations with University of Shanxi*, University of Connecticut**

Two examples of two-body Förster resonances



4-body Förster resonance

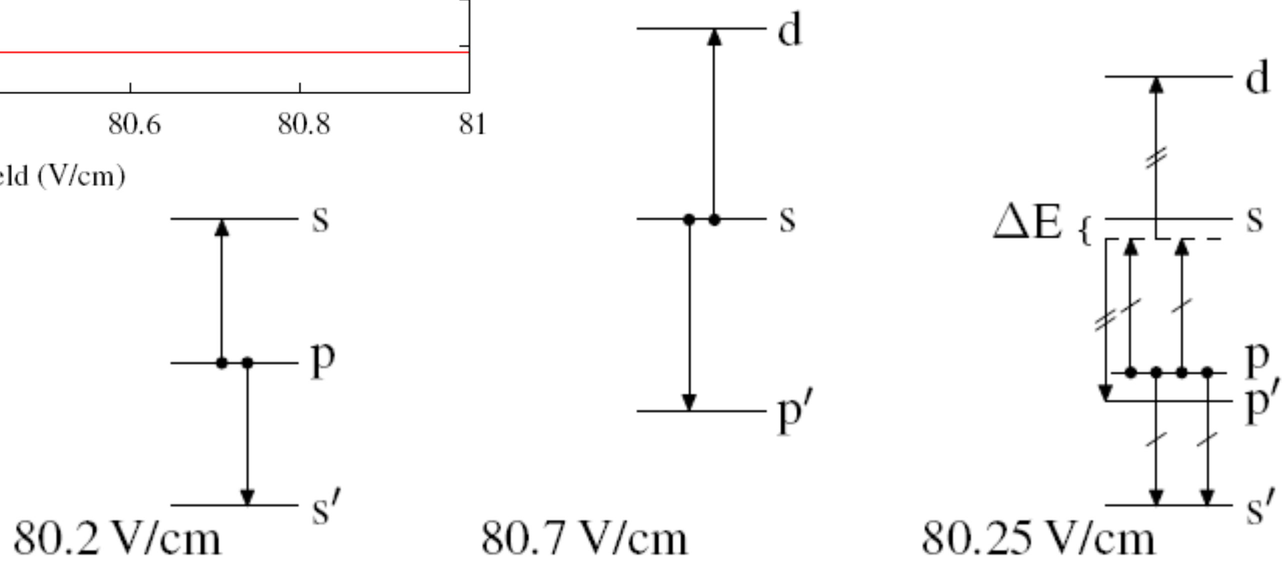


$23p_{3/2}+23p_{3/2} \rightarrow 23s+24s$

$24s+24s \rightarrow 23p_{1/2}+23d_{5/2}$

$4 \times 23p_{3/2} \rightarrow$

$2 \times 23s + 23p_{1/2}+23d_{5/2}$

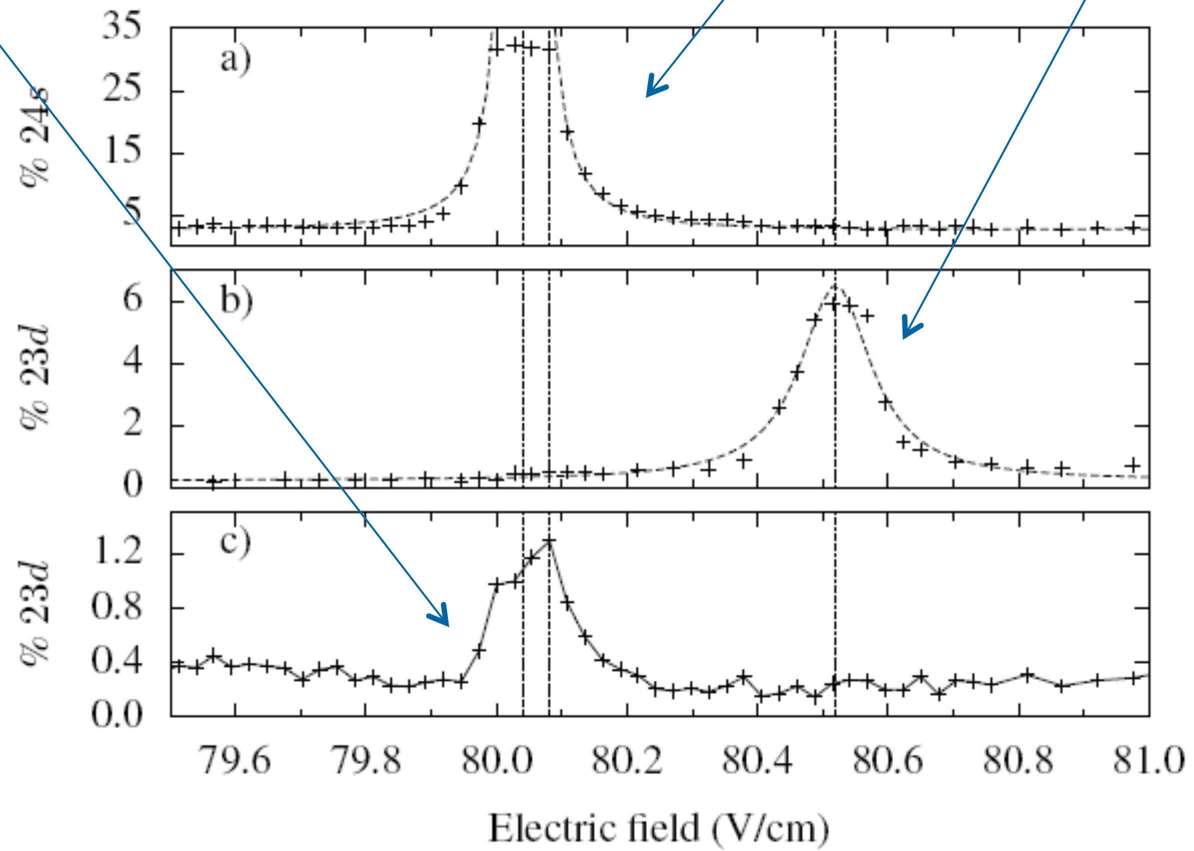


Four-body resonance

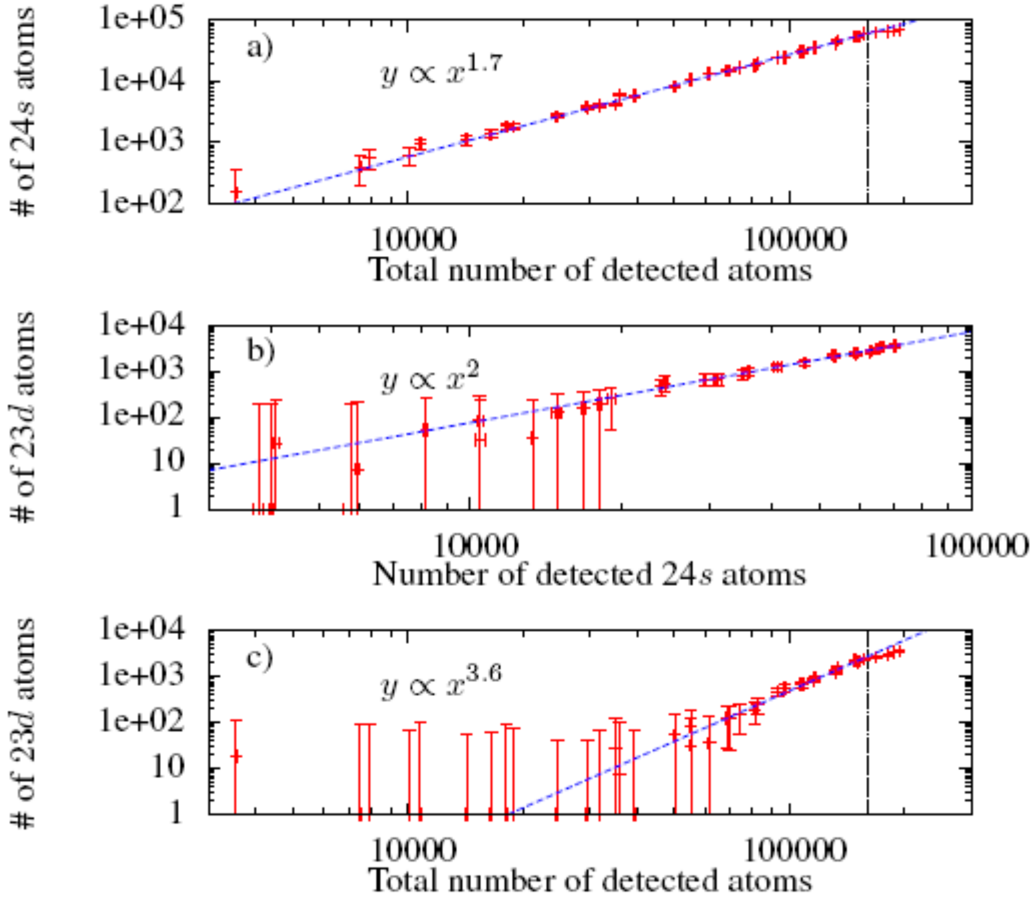
$23p_{3/2}+23p_{3/2} \rightarrow 23s+24s$

$24s+24s \rightarrow 23p_{1/2}+23d_{5/2}$

$4 \times 23p_{3/2} \rightarrow 2 \times 23s + 23p_{1/2}+23d_{5/2}$



Intensity behavior as $\sim N^4$



A-few-body interactions

- Difficult to characterize in a gas
- Difficult to discriminate 3, 4, 5… - body effects
- Observed when the two-body proccesses are saturated
- With cold Rydberg atoms we can have several signatures (transfer, resonance)
- Four-body resonance occurs here for low *n*
- Many configuarations may be more efficient can be studied, and four, six or eight-body Förster resonances could be demonstrated
- We create an entanglement of a few atoms