Resonant dipole-dipole interaction of Rydberg atoms for quantum information

I.I.Beterov, M. Saffman, D.B.Tretyakov, V.M.Entin, E.A.Yakshina, G.N.Hamzina, S.Bergamini, E.A.Kuznetsova, C.Andreeva and I.I.Ryabtsev

Rzhanov Institute of Semiconductor Physics SB RAS, Novosibirsk, Russia
Novosibirsk State University, 630090 Novosibirsk, Russia
Novosibirsk State Technical University, 630073 Novosibirsk, Russia
Open University, Milton Keynes, UK
University Wisconsin-Madison, USA

Collaborators

Novosibirsk State University
*THE REAL SCIENCE

Novosibirsk team
Rzhanov Institute of Semiconductor Physics SB RAS
Novosibirsk State University

Igor I. Ryabtsev (PI)
Ilya I. Beterov
Denis B. Tretyakov
Vasily M. Entin
Elena A. Yakshina

Open University, UK

The Open University

Silvia Bergamini

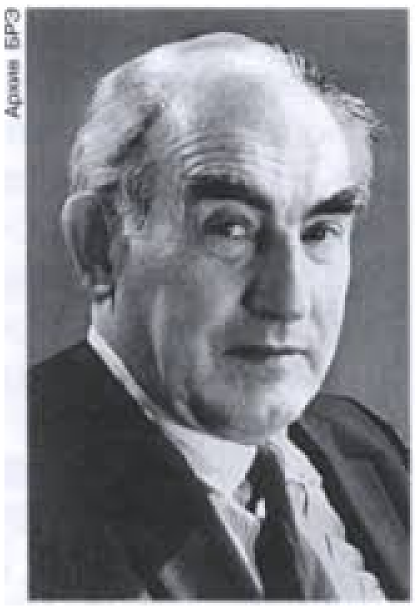
University Wisconsin-Madison, USA

Mark Saffman

Institute of Applied Physics RAS

Elena A. Kuznetsova

Vitaly Ginzburg



ON SUPERCONDUCTIVITY AND SUPERFLUIDITY

Nobel Lecture, December 8, 2003

by

VITALY L. GINZBURG

P. N. Lebedev Physics Institute, Russian Academy of Sciences, Moscow, Russia.

30 most important problems in physics

6. Second-order and related phase transitions. Some examples of such transitions. Cooling (in particular, laser cooling) to superlow temperatures. Bose–Einstein condensation in gases.

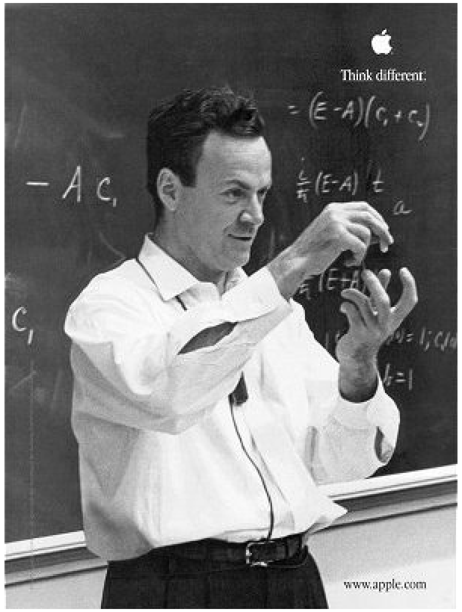
in [2]. The 'great problems' are, first, the increase in entropy, time irreversibility, and the 'time arrow'. Second is the problem of interpretation of nonrelativistic quantum mechanics and the possibility of learning something new even in the field of its applicability (I personally doubt this possibility but believe that one's eyes should remain open). And third is the question of live-

Pioneers of quantum computing

Yuri Manin

"Computable and Uncomputable", 1980
You need quantum automat to model quantum systems like DNA!

Richard Feynman



"Simulating Physics with computers", "Quantum mechanical computers", 1981

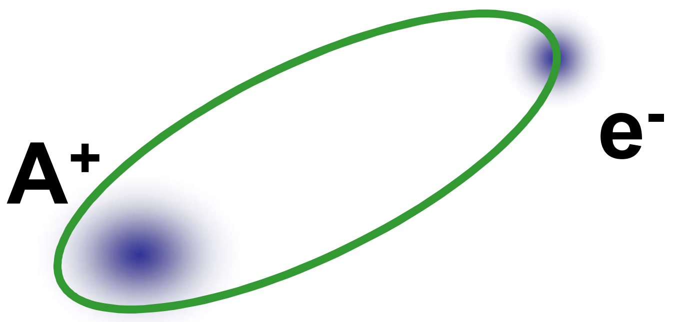
Outline

Quantum information with Rydberg atoms

CZ gate using adiabatic passage of Förster resonances

Rydberg experiment in Novosibirsk

What is a Rydberg atom?



Rydberg atom: n>>1

Rydberg formula (1888):

$$E_n = -\frac{Ry}{n^{*2}}$$

Johannes Rydberg

$$Ry_{Rb} = 109736.60672249\ \text{cm}^{-1}$$

Properties of Rydberg atoms

Hydrogen-like wavefunctions

Small binding energy $\sim n^{-2}$ (100 cm^{-1} at n=100)

Large radiative lifetimes $\sim n^{3}$ (1 ms at n=100)

Large orbital radius $\sim n^{2}$ (0.5 um at n=100)

Transition frequency $\sim n^{-3}$ (10 GHz at n=100)

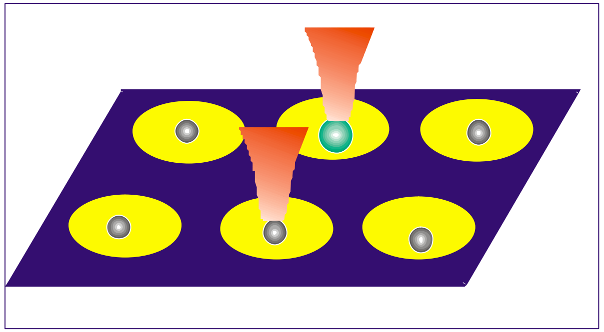
Polarizability $\sim n^{7}$

T.F.Gallagher “Rydberg atoms”

Motivation: quantum register with neutral atoms

Possible implementation of a quantum register:

Array of individually addressed traps loaded by single atoms (Madison, Palaiseau)



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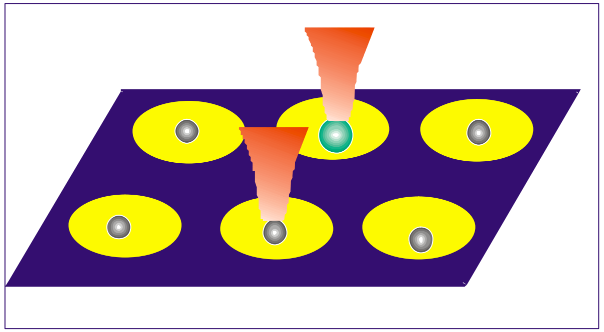

Single-qubit gates:

Raman laser pulses D. Yavuz et al., PRL 96, 063001 (2006)

Microwave transitions T. Xia et al. PRL 114, 100503 (2015)

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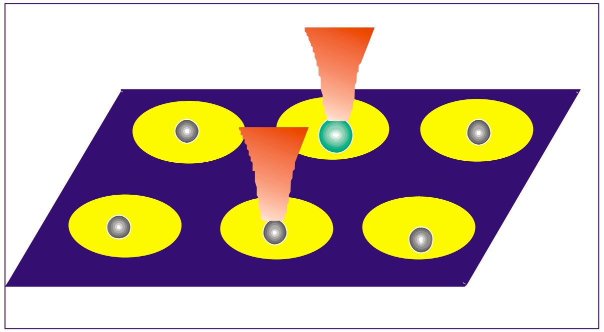


Single-qubit gates:

Raman laser pulses D. Yavuz et al., PRL 96, 063001 (2006)

Microwave transitions T. Xia et al. PRL 114, 100503 (2015)

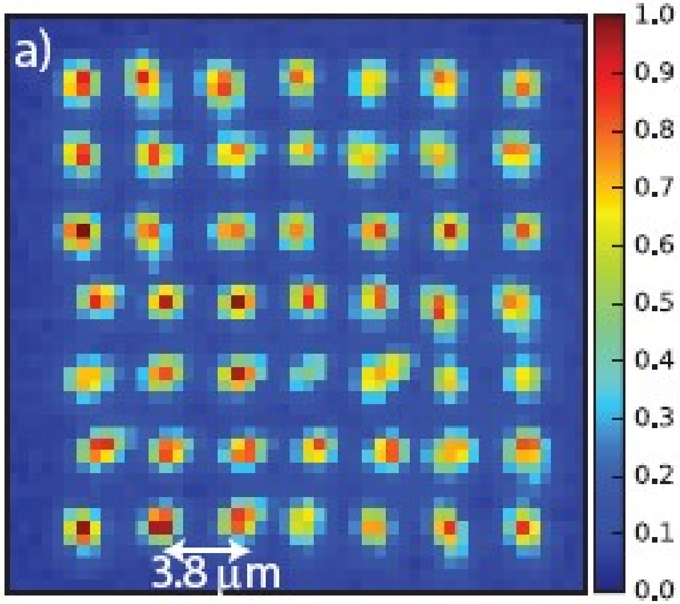
Two-qubit gates:

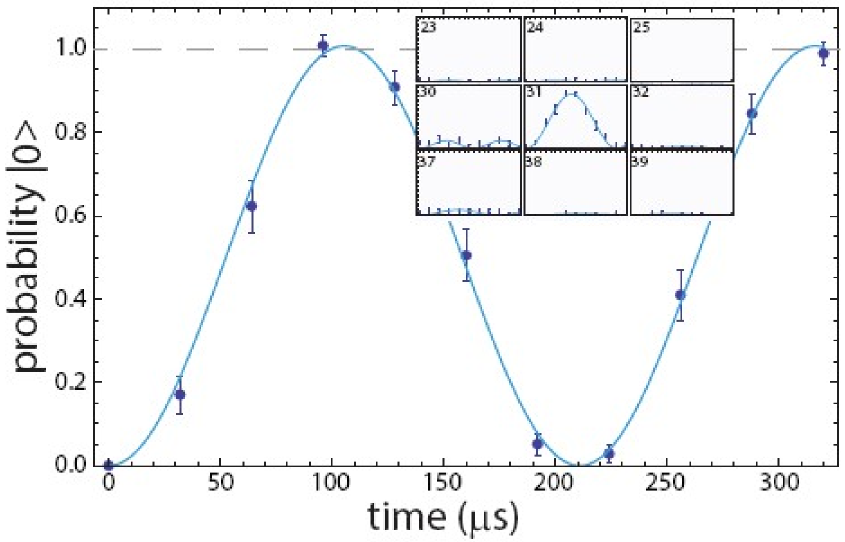
Rydberg blockade L. Isehhower et al., PRL 104, 010503 (2010)

Interaction gates D.Jaksch et al., PRL 85, 2208 (2000); S. Ravets et al., Nature Physics 10, 914 (2014)

Quantum register with Rydberg atoms

Up to 49 qubits in University Wisconsin-Madison!





T.Xia et al., PRL 11, 100503 (2015)

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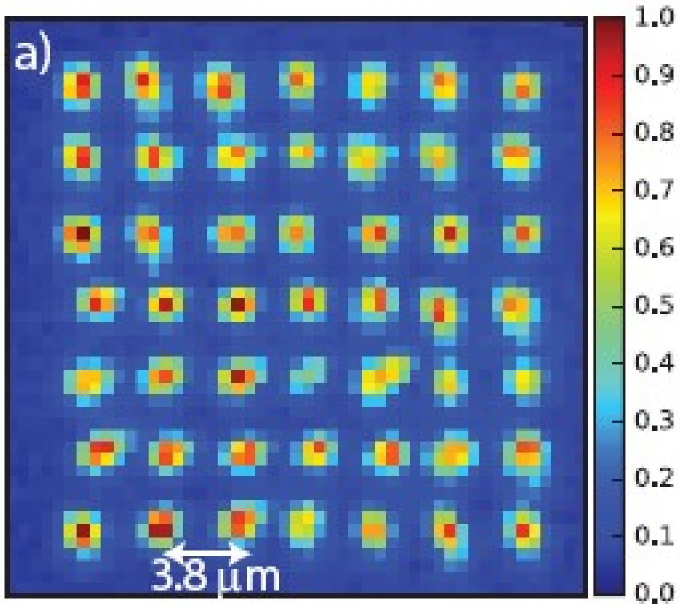
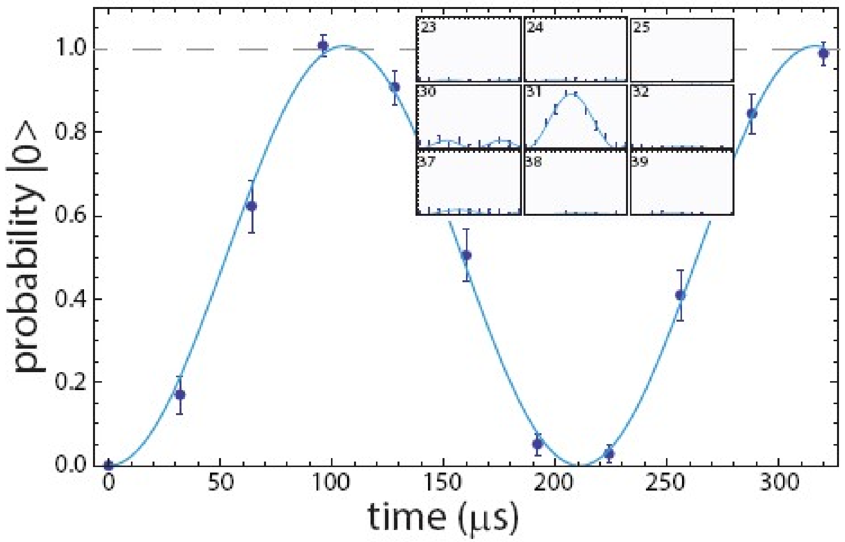
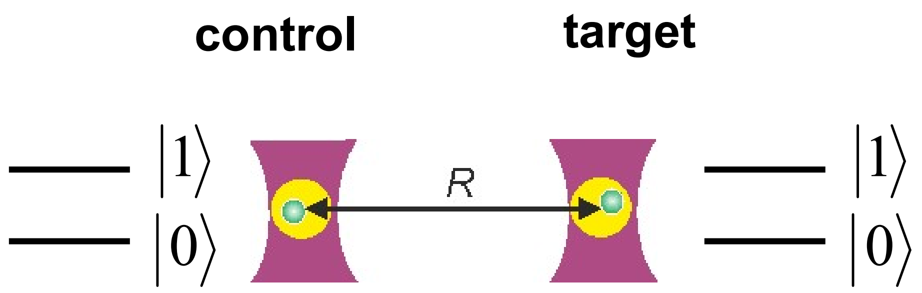




T.Xia et al., PRL 11, 100503 (2015)

Problem: low fidelity of two-qubit quantum gates!

Two-qubit gate



CZ

$$|00\rangle \to |00\rangle$$
$$|01\rangle \to |01\rangle$$
$$|10\rangle \to |10\rangle$$
$$|11\rangle \to -|11\rangle$$

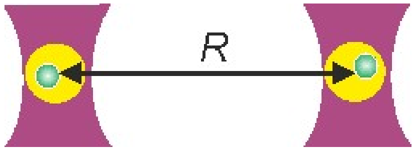
$$CZ = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

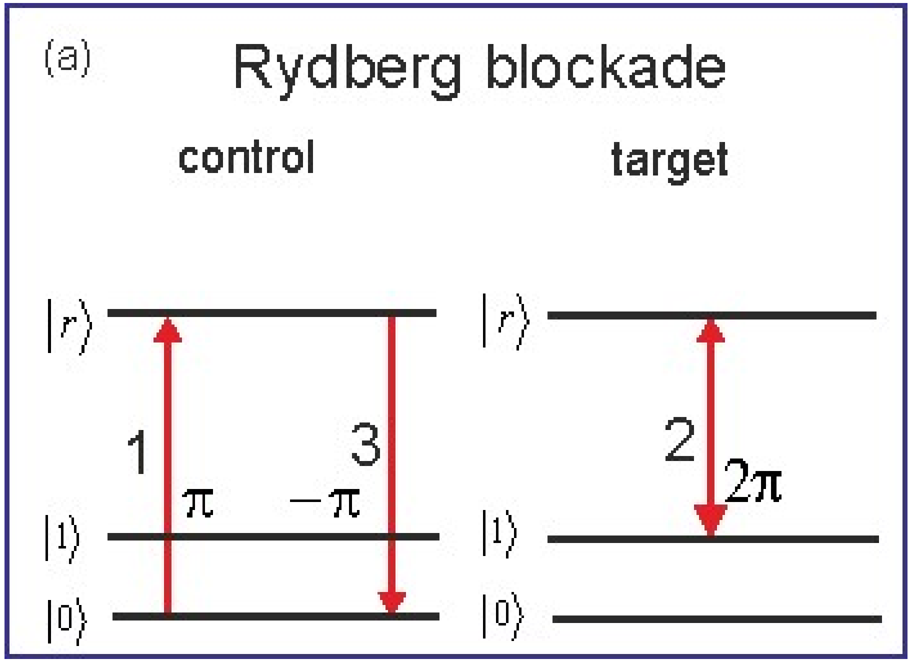
CNOT

$$|00\rangle \to |00\rangle$$
$$|01\rangle \to |01\rangle$$
$$|10\rangle \to |11\rangle$$
$$|11\rangle \to |10\rangle$$

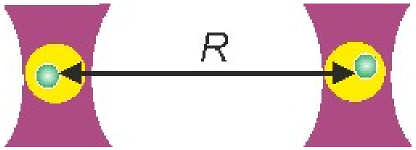
$$CNOT = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

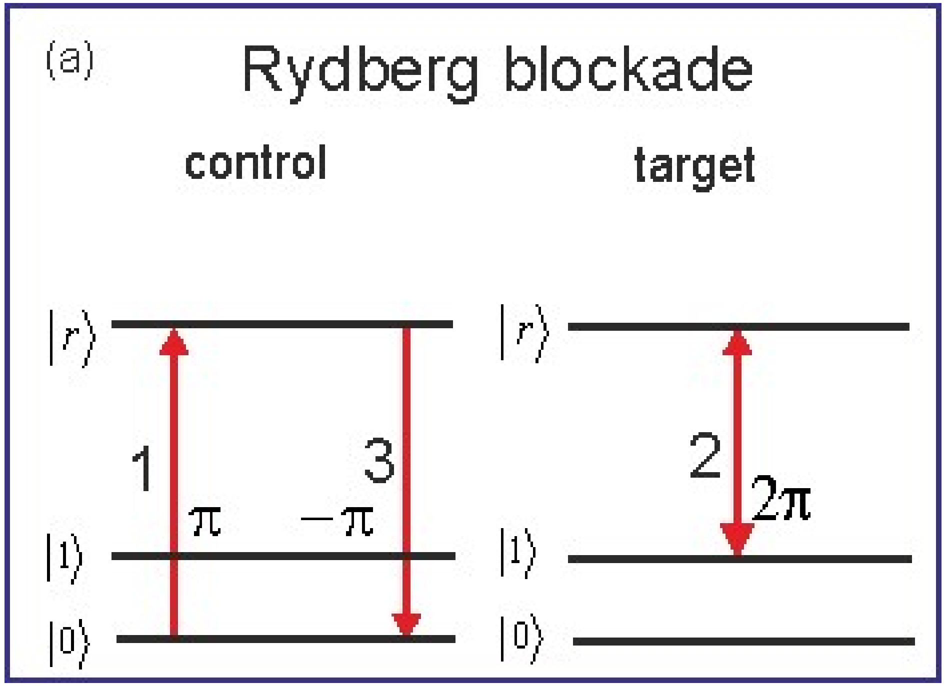
CZ gate with Rydberg atoms

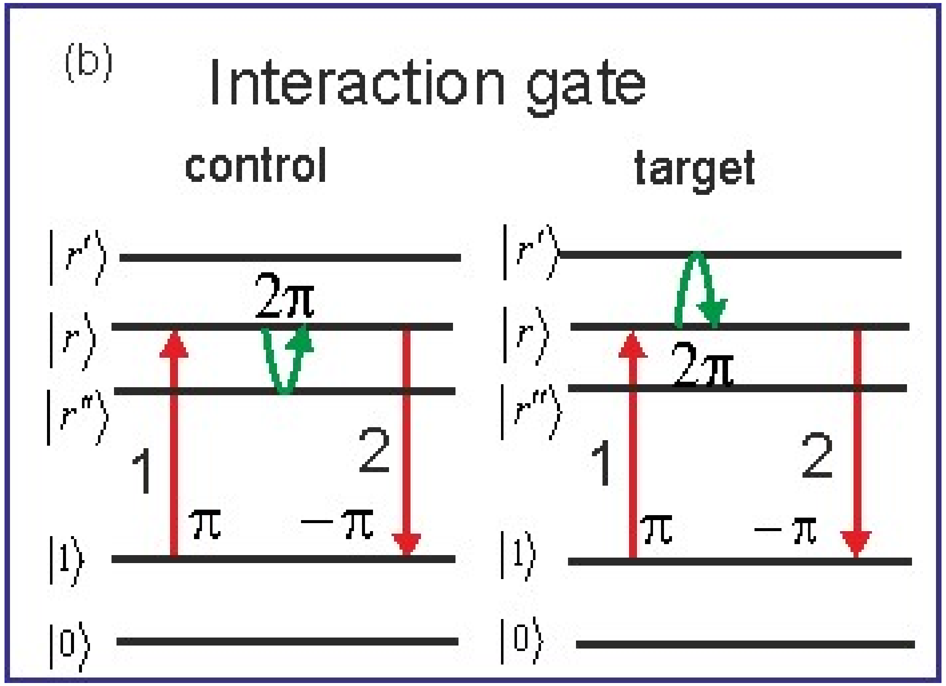




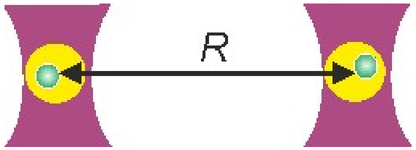
CZ gate with Rydberg atoms

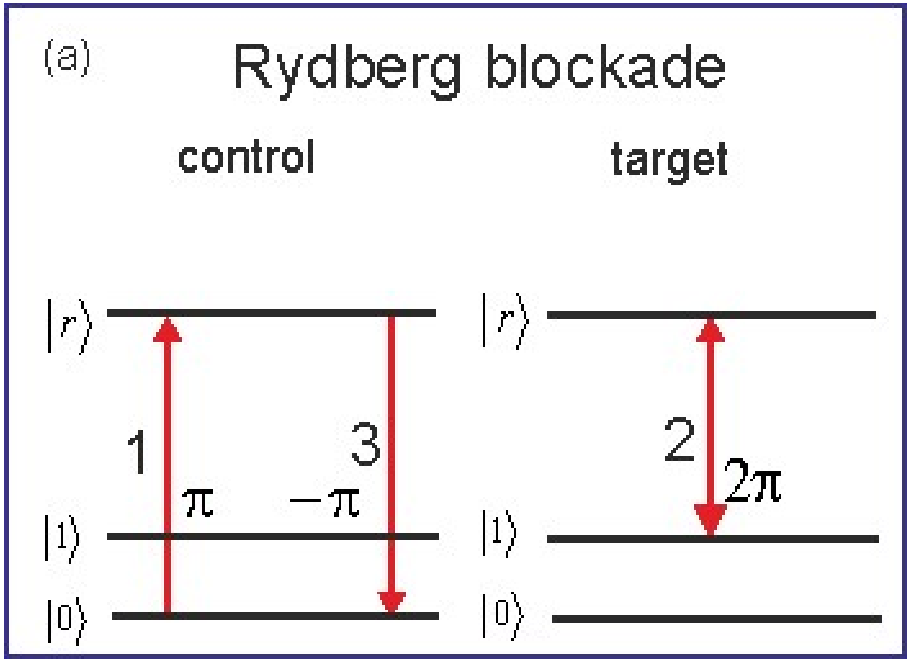


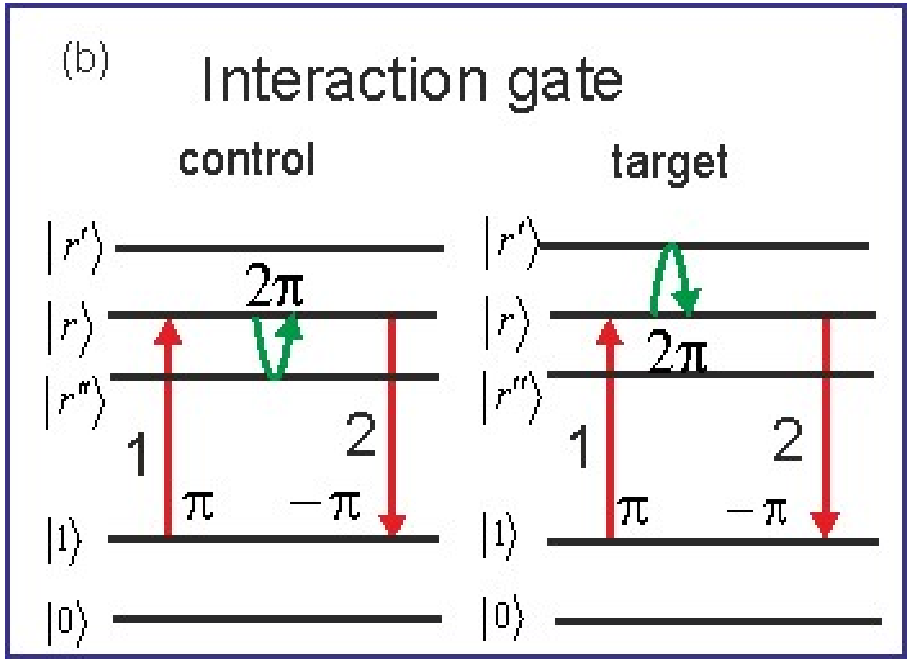




CZ gate with Rydberg atoms



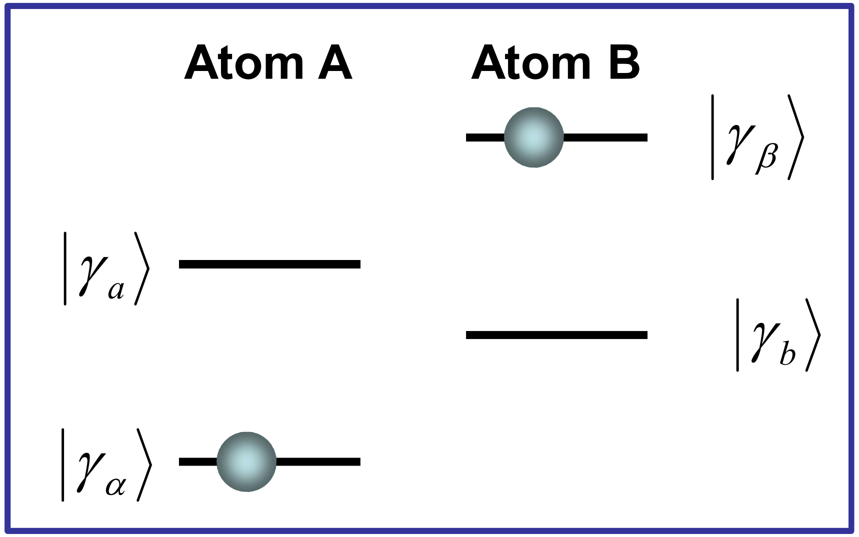




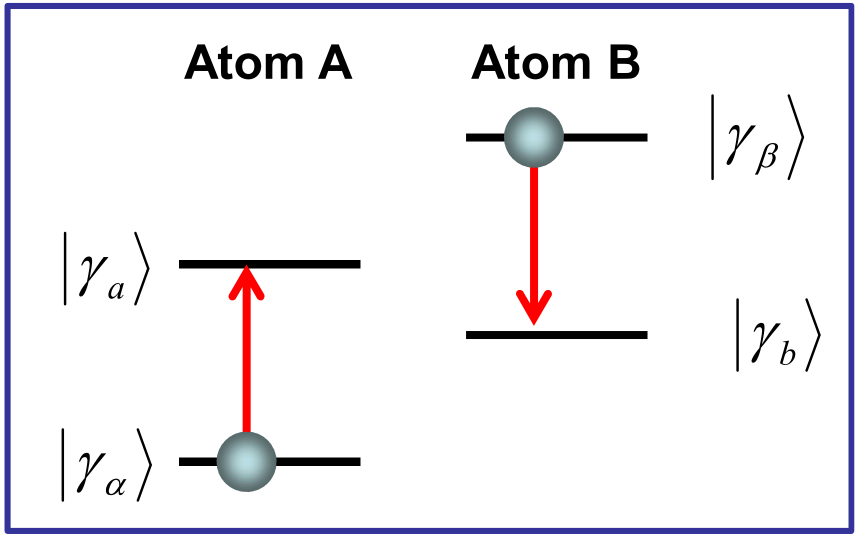
Advantage: Insensitive to fluctuations of interaction energy
Disadvantage: Requires strong interaction

Advantage: Weak interaction energy
Disadvantage: Sensitive to fluctuations of interatomic distance

Förster resonance in Rydberg atoms



Förster resonance in Rydberg atoms



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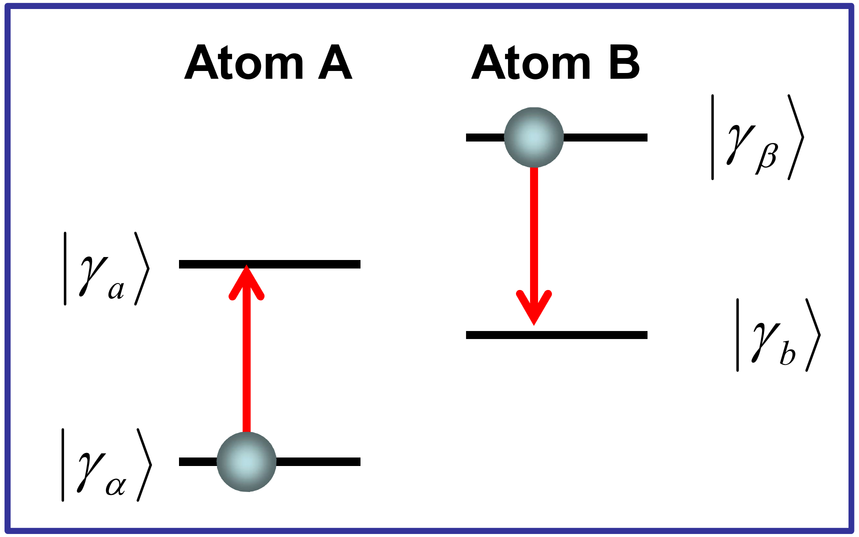
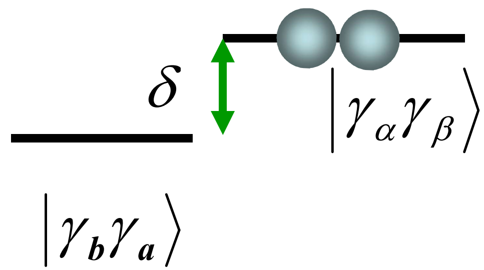
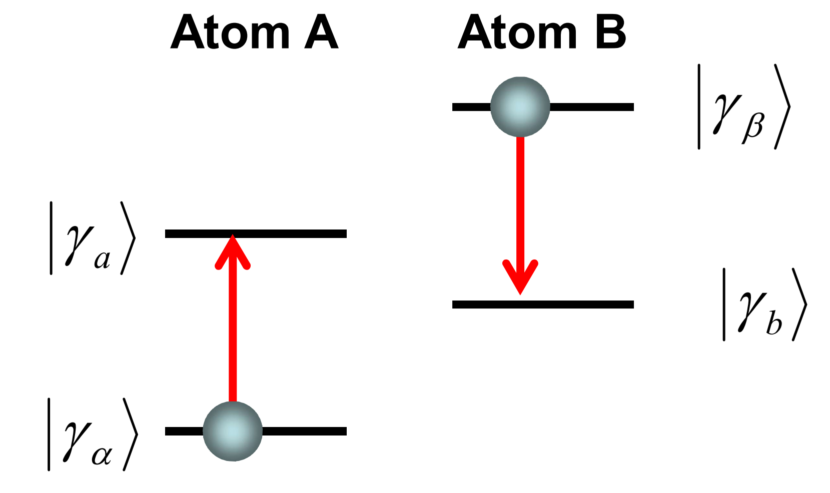


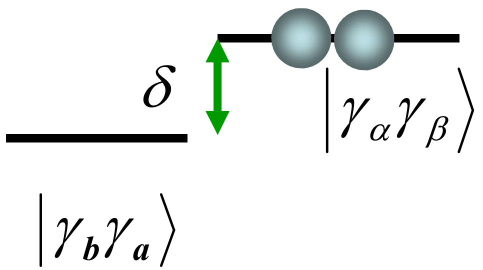


Detuning from the Förster resonance

$$\hbar\delta = \left(\boldsymbol{E}_\alpha - \boldsymbol{E}_a\right) + \left(\boldsymbol{E}_\beta - \boldsymbol{E}_b\right)$$

Förster resonance in Rydberg atoms

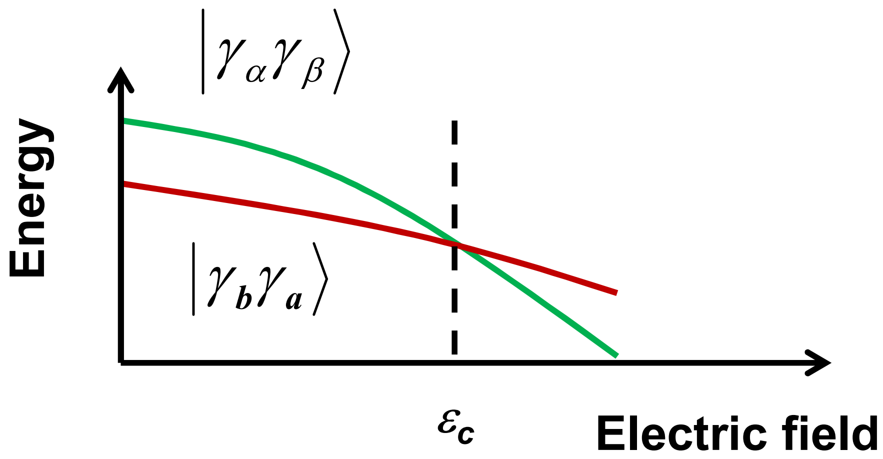




Detuning from the Förster resonance

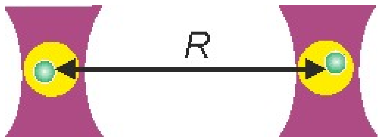
$$\hbar\delta = (E_\alpha - E_a) + (E_\beta - E_b)$$

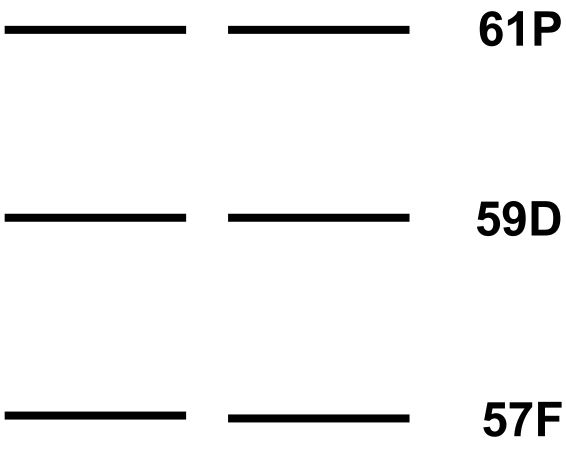
Stark tuning to the Förster resonance



Coherent coupling at Förster resonance

S. Ravets et al., Nature Physics 10, 914 (2014)





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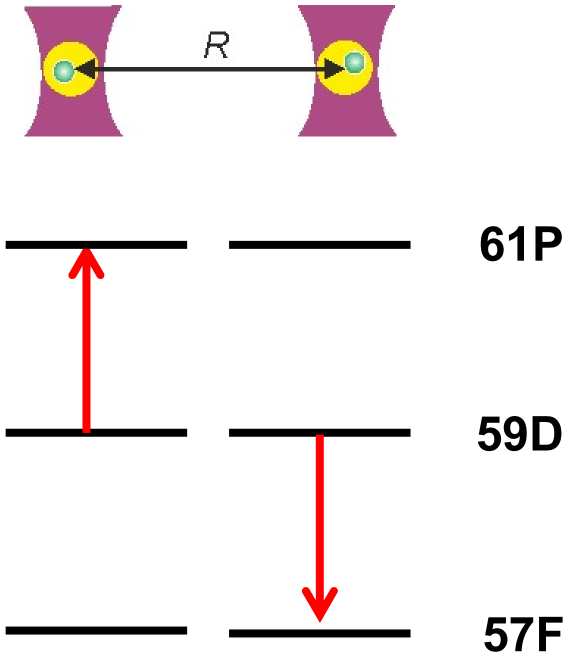

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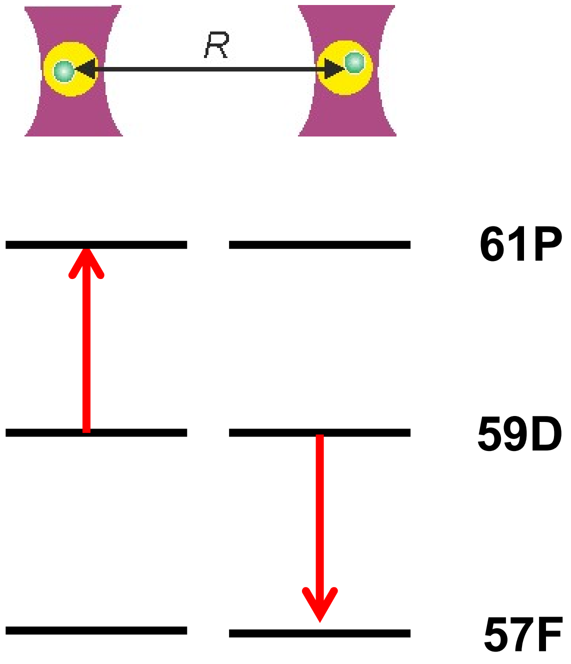

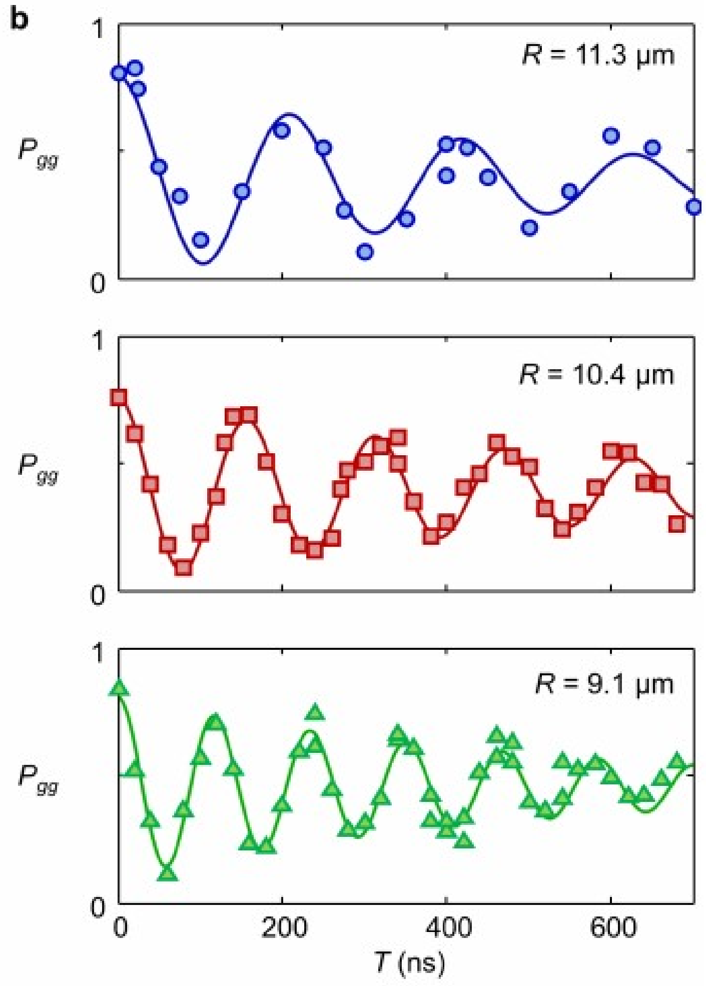

Key point

How to avoid the effect of fluctuation of the interatomic distance?

Outline

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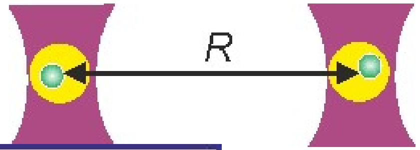
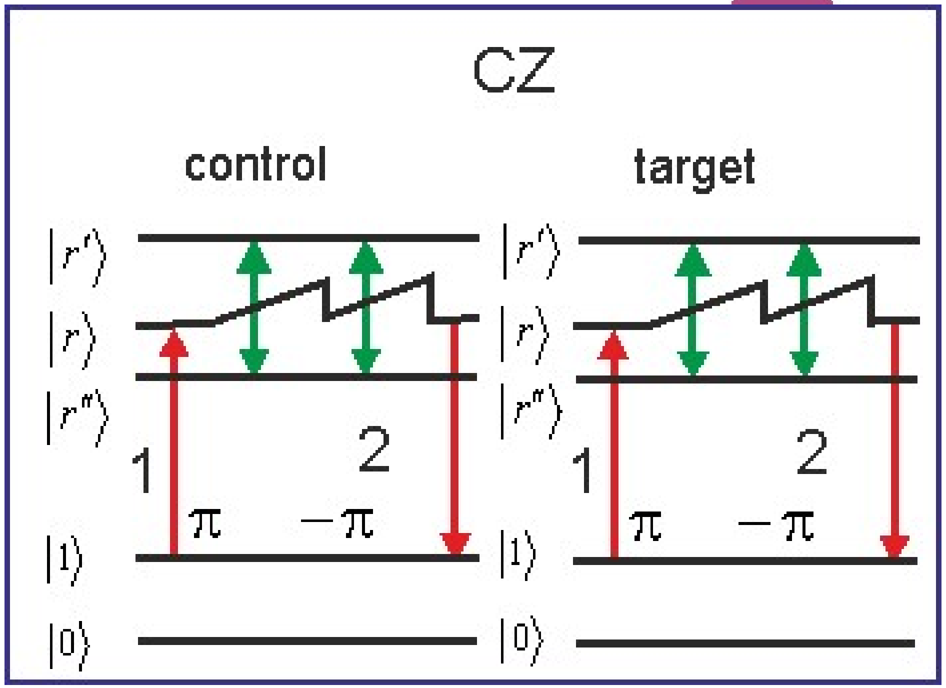
CZ gate using adiabatic passage of Förster resonances

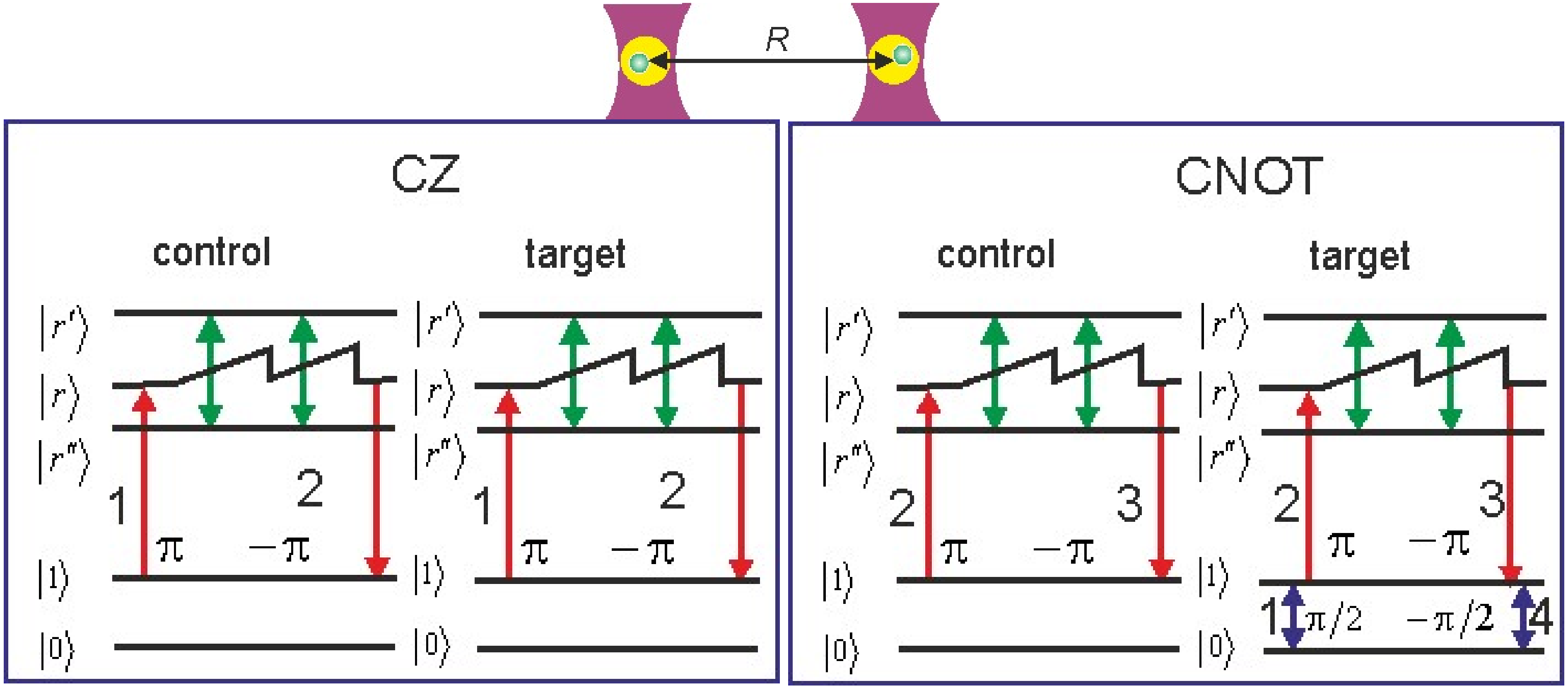
Rydberg experiment in Novosibirsk

CZ and CNOT with adiabatic passage





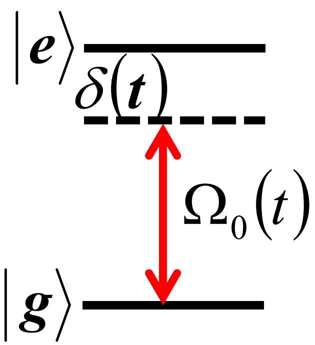
CZ and CNOT with adiabatic passage



Key point

What happens with the phase after double adiabatic passage?

Adiabatic rapid passage



Hamiltonian:

$$\hat{\mathbf{H}}(t) = \frac{\hbar}{2}\begin{pmatrix} 0 & \Omega_0(t) \\ \Omega_0(t) & 2\delta(t) \end{pmatrix}$$

Schrödinger equation:

$$i\hbar\dot{\mathbf{c}} = \hat{\mathbf{H}}\mathbf{c}$$

Diagonalization:

$$\mathbf{T} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$

$$\hat{\mathbf{H}}_d(t) = \mathbf{T}\hat{\mathbf{H}}\mathbf{T}^{+} = \frac{\hbar}{2}\begin{pmatrix} \Omega_-(t) & 0 \\ 0 & \Omega_+(t) \end{pmatrix}$$

Mixing angle:

$$\tan 2\theta = \Omega_0(t)/\delta(t) \qquad \Omega_\pm(t) = \delta(t) \pm \sqrt{\Omega_0^2(t) + \delta^2(t)}$$

Dressed states:

$$\tilde{\mathbf{c}} = \mathbf{T}\mathbf{c}$$

$$|I\rangle = \cos\theta|e\rangle - \sin\theta|g\rangle \qquad |II\rangle = \sin\theta|e\rangle + \cos\theta|g\rangle \qquad i\hbar\dot{\tilde{\mathbf{c}}} = \mathbf{T}\hat{\mathbf{H}}\mathbf{T}^{+}\tilde{\mathbf{c}} - i\hbar\mathbf{T}\dot{\mathbf{T}}^{+}\tilde{\mathbf{c}}$$

Adiabatic approximation:

$$i\hbar\dot{\tilde{\mathbf{c}}} = \hat{\mathbf{H}}_d\tilde{\mathbf{c}}$$

$$\tilde{c}_1(t) = \tilde{c}_1(0)\exp\left[-\frac{i}{2}\int_0^t \Omega_-(t)dt\right] \qquad \tilde{c}_2(t) = \tilde{c}_2(0)\exp\left[-\frac{i}{2}\int_0^t \Omega_+(t)dt\right]$$

Double adiabatic passage

Mixing angle:

$$\tan 2\theta = \frac{\Omega_0(t)}{\delta(t)}$$

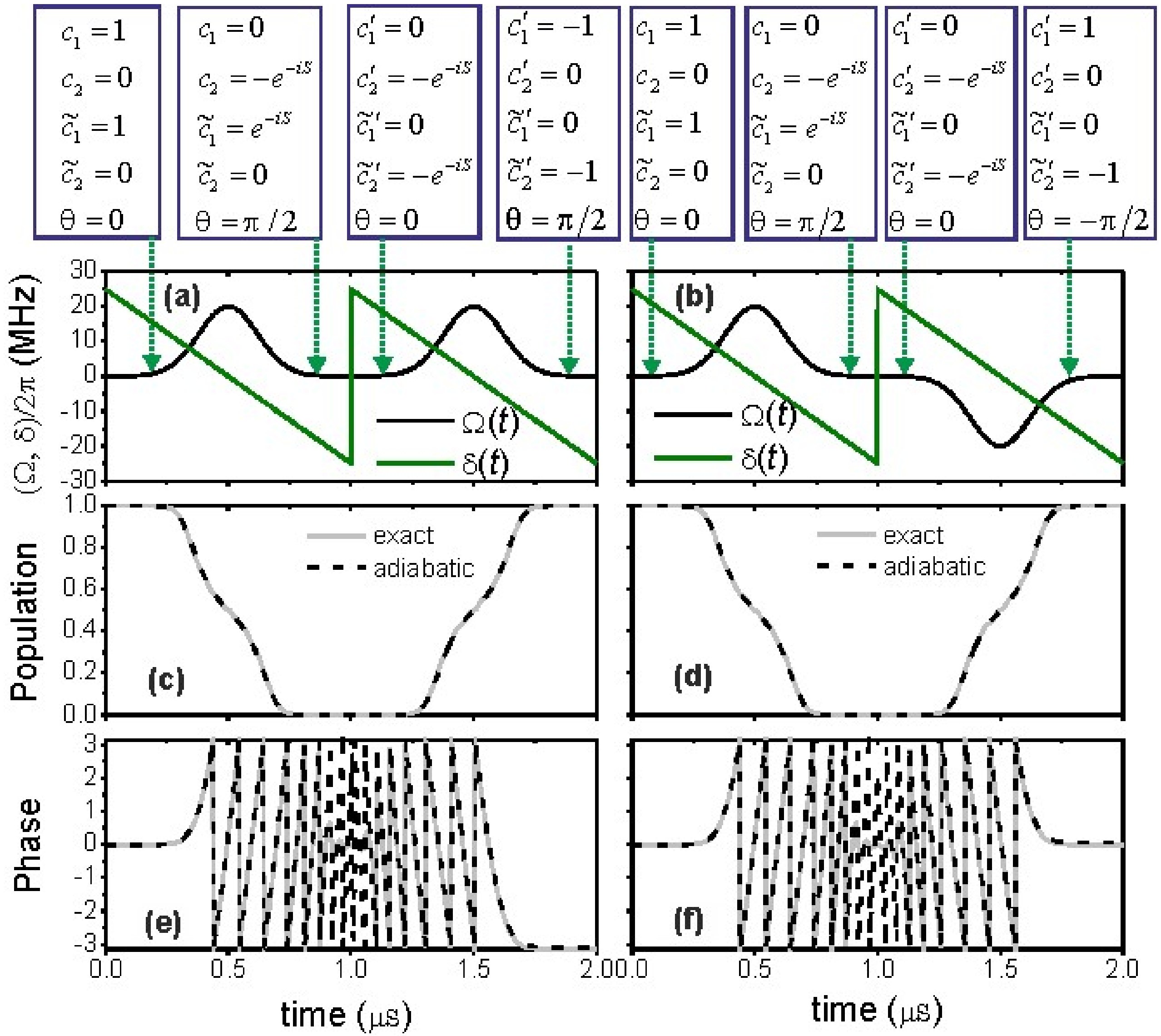
Dressed states:

$$|I\rangle = \cos\theta|e\rangle - \sin\theta|g\rangle$$

$$|II\rangle = \sin\theta|e\rangle + \cos\theta|g\rangle$$

$$\Omega_{\pm}(t) = \delta(t) \pm \sqrt{\Omega_0^2(t) + \delta^2(t)}$$

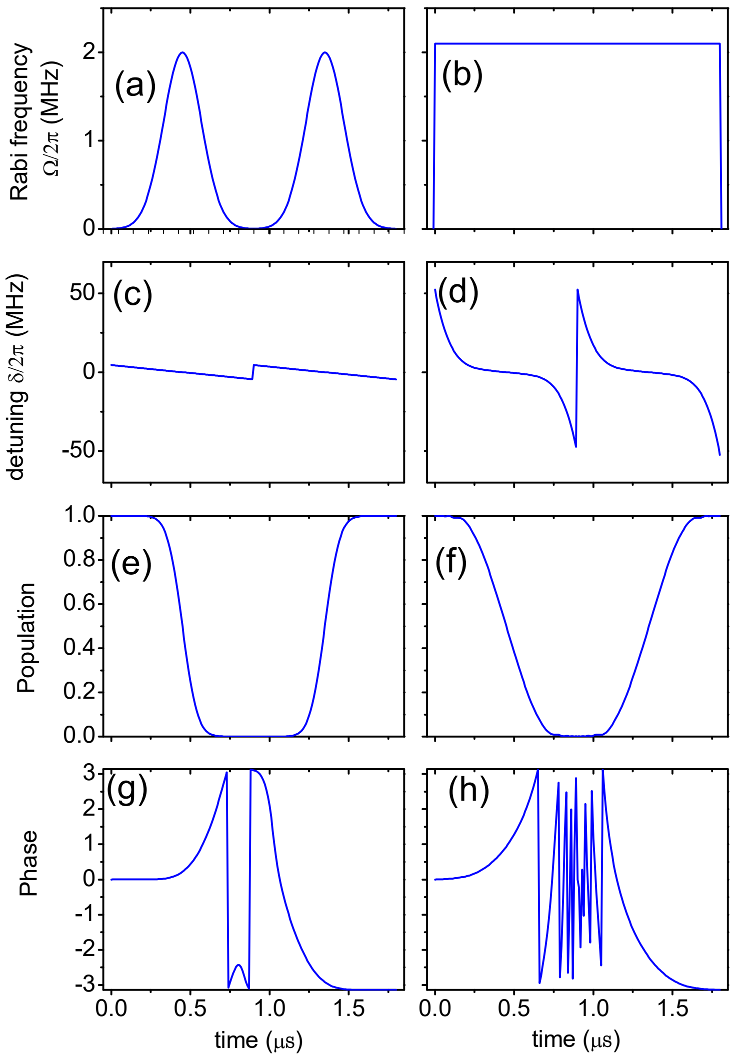
$$S = \frac{i}{2}\int_0^T \Omega_-(t)dt$$



Key point

How can we control the interaction strength?

Chirped excitation with nonlinear detuning



Hamiltonian:

$$\hat{\mathbf{H}}(t) = \frac{\hbar}{2}\begin{pmatrix} -\delta(t) & \Omega(t) \\ \Omega(t) & \delta(t) \end{pmatrix}$$

Gaussian pulses with linear detuning:

$$\Omega_j(t) = \Omega_0 \exp\left[-\left(t - t_j\right)^2 / 2w^2\right]$$

$$\delta_j(t) = s_1\left(t - t_j\right)$$

Constant energy and nonlinear detuning:

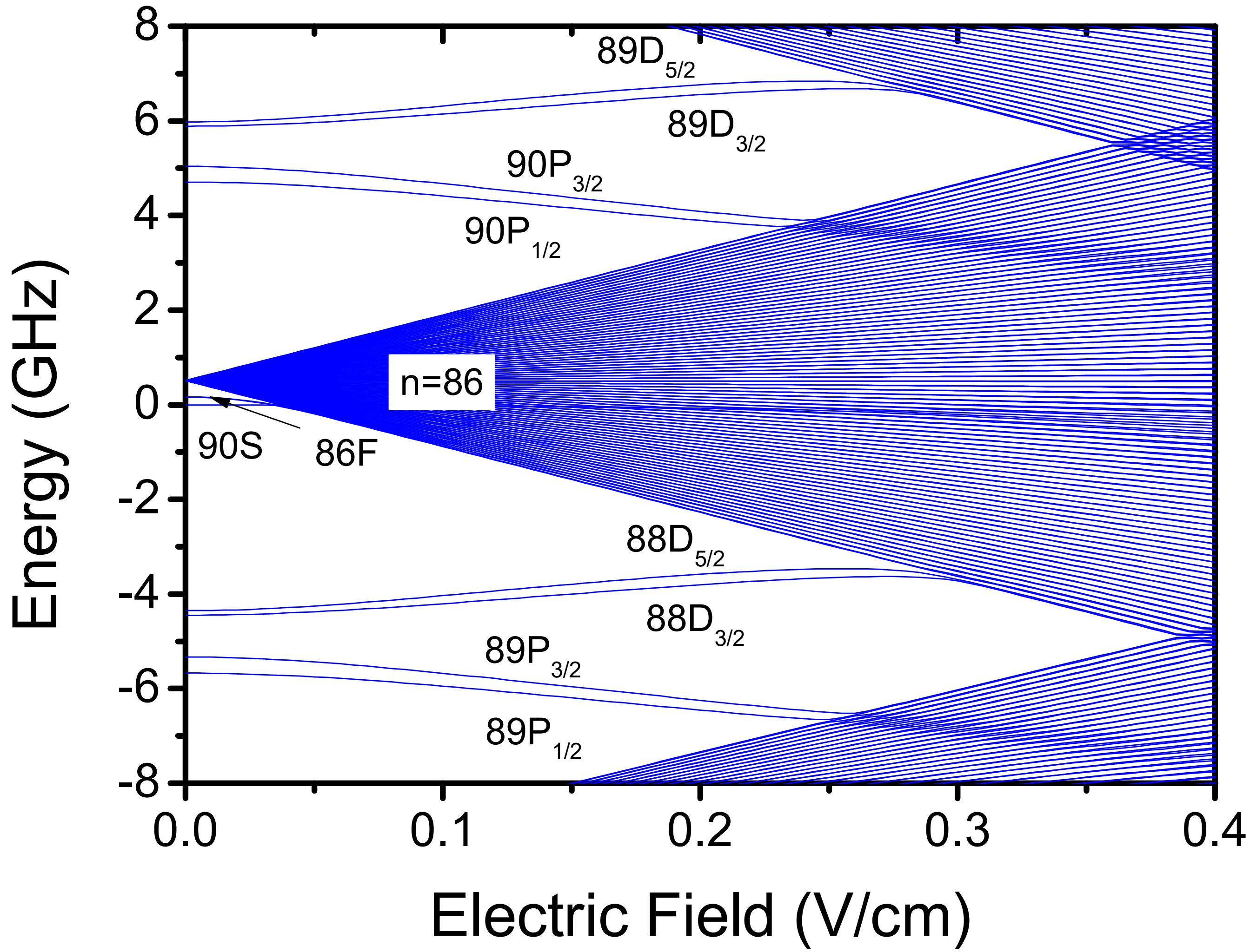
$$\Omega_j(t) = \Omega_0$$

$$\delta_j(t) = s_1\left(t - t_j\right) + s_2\left(t - t_j\right)^5$$

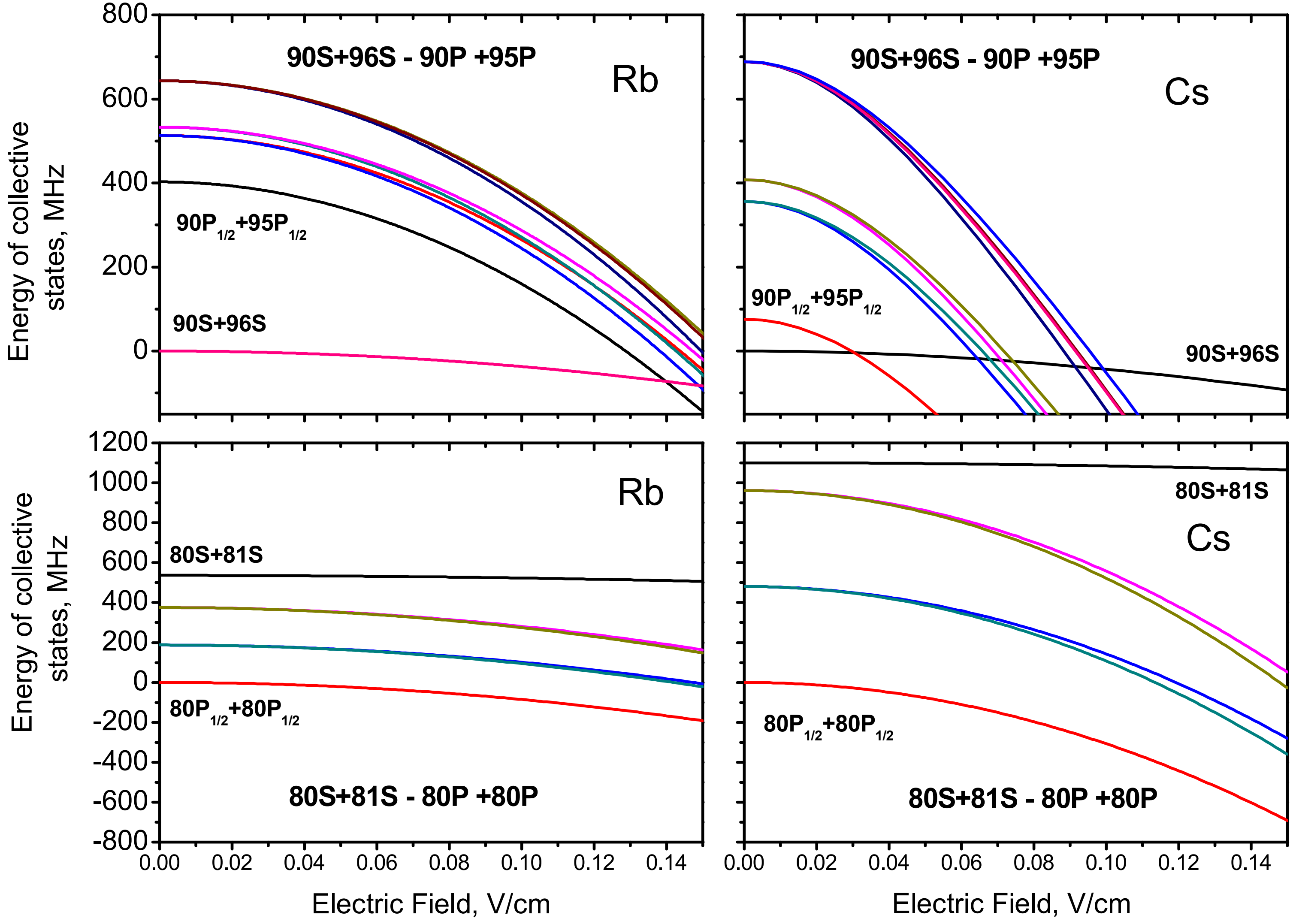
Key point

- We need an isolated Förster resonance

Stark map for Cs

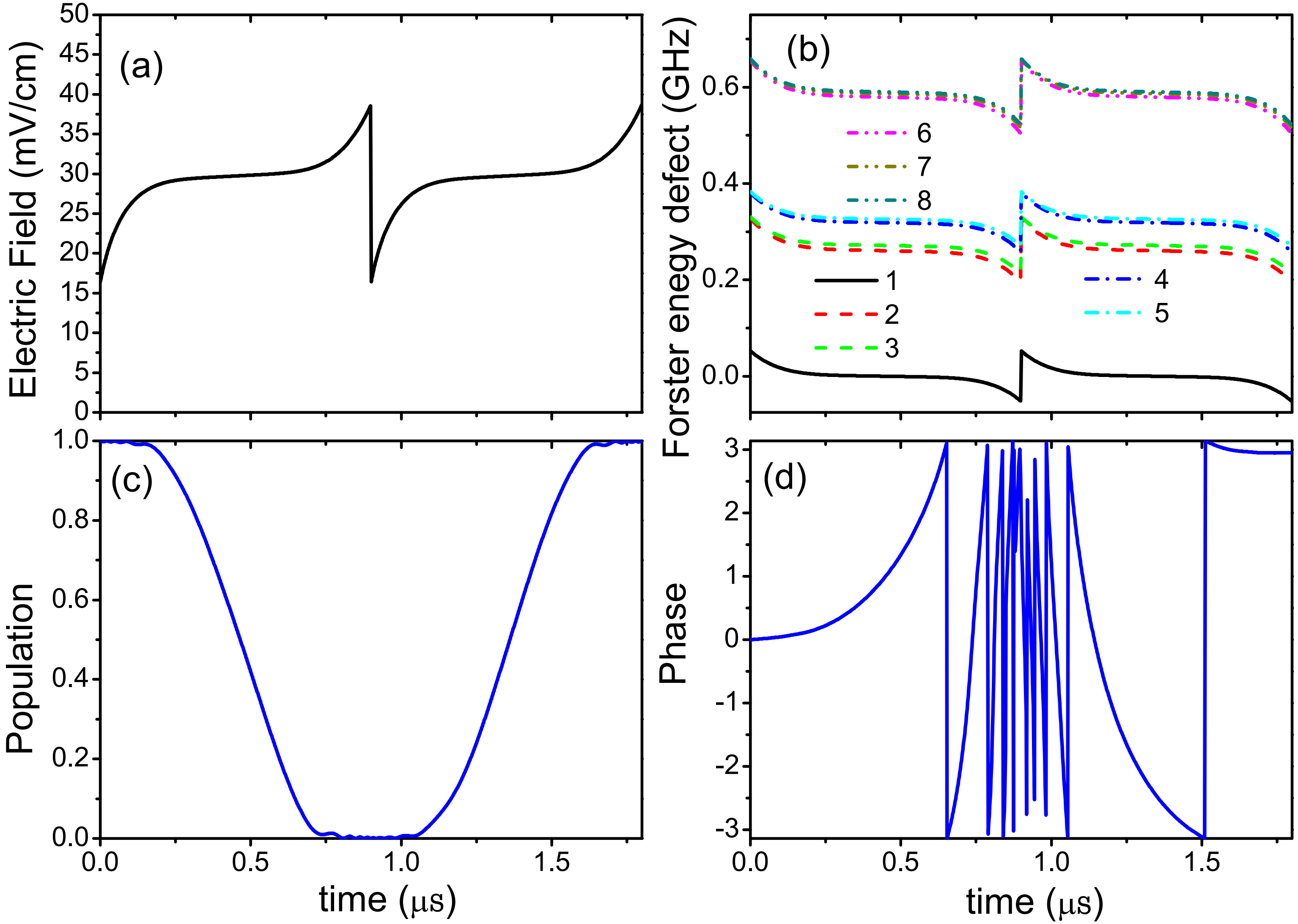


Förster resonances in electric field

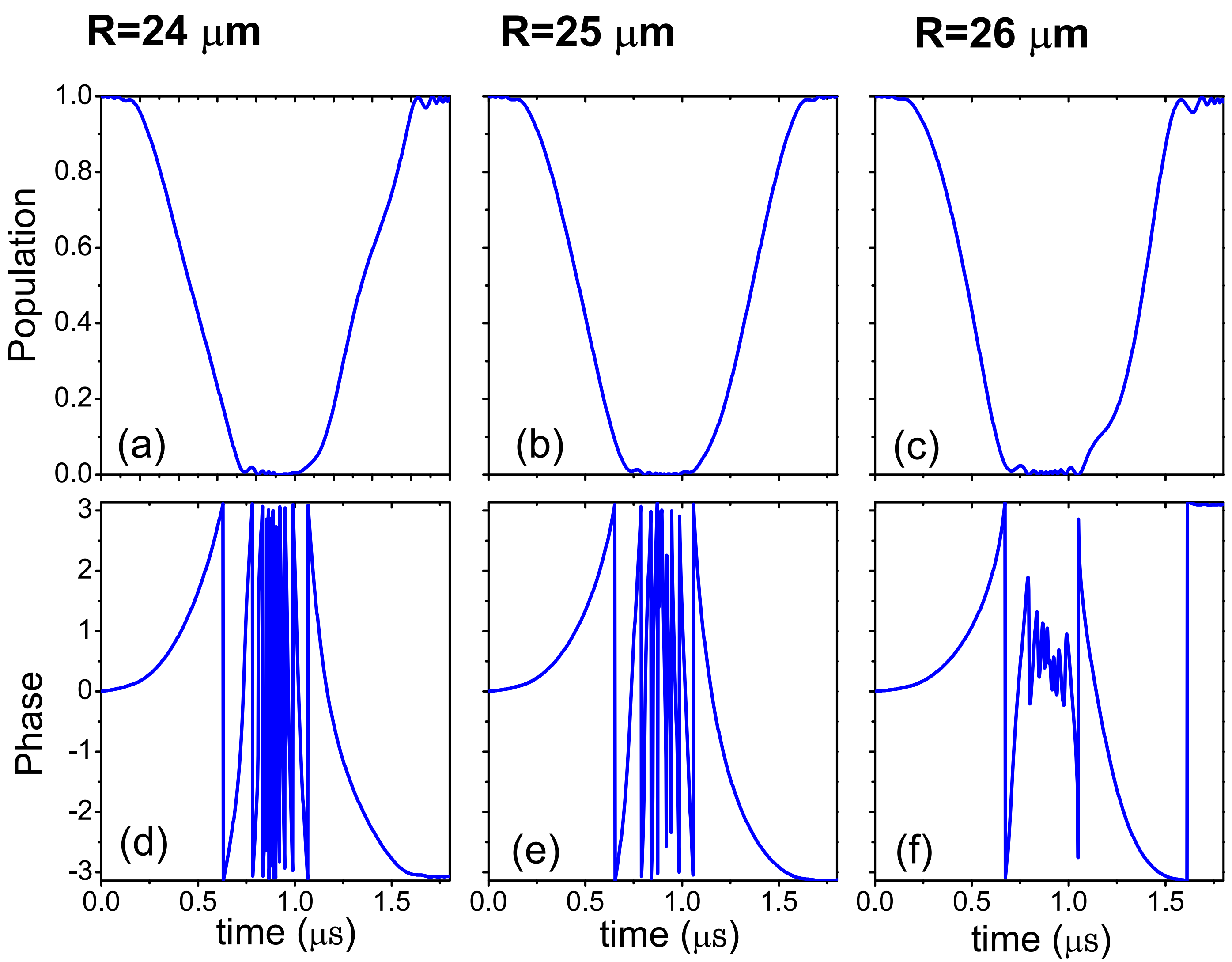


Adiabatic passage of Förster resonance

$$90S + 96S \rightarrow 90P + 95P$$

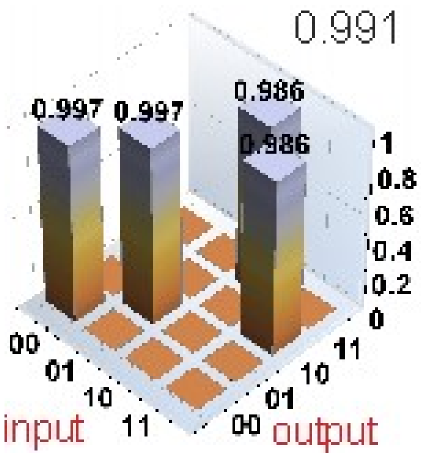


Adiabatic passage of Förster resonance

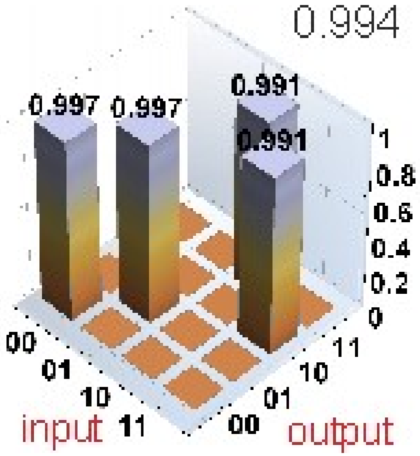


CNOT truth table

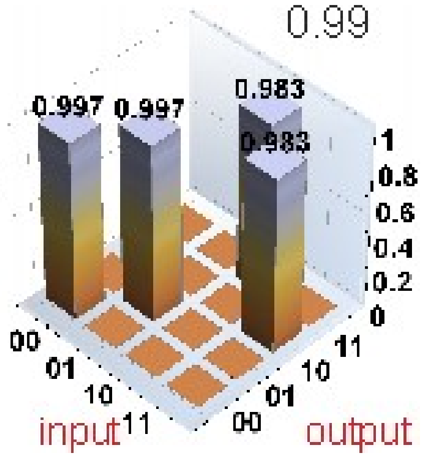
R=24 μm



R=25 μm



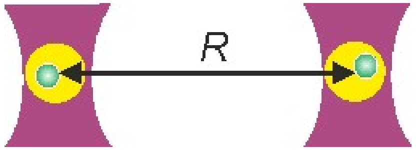
R=26 μm

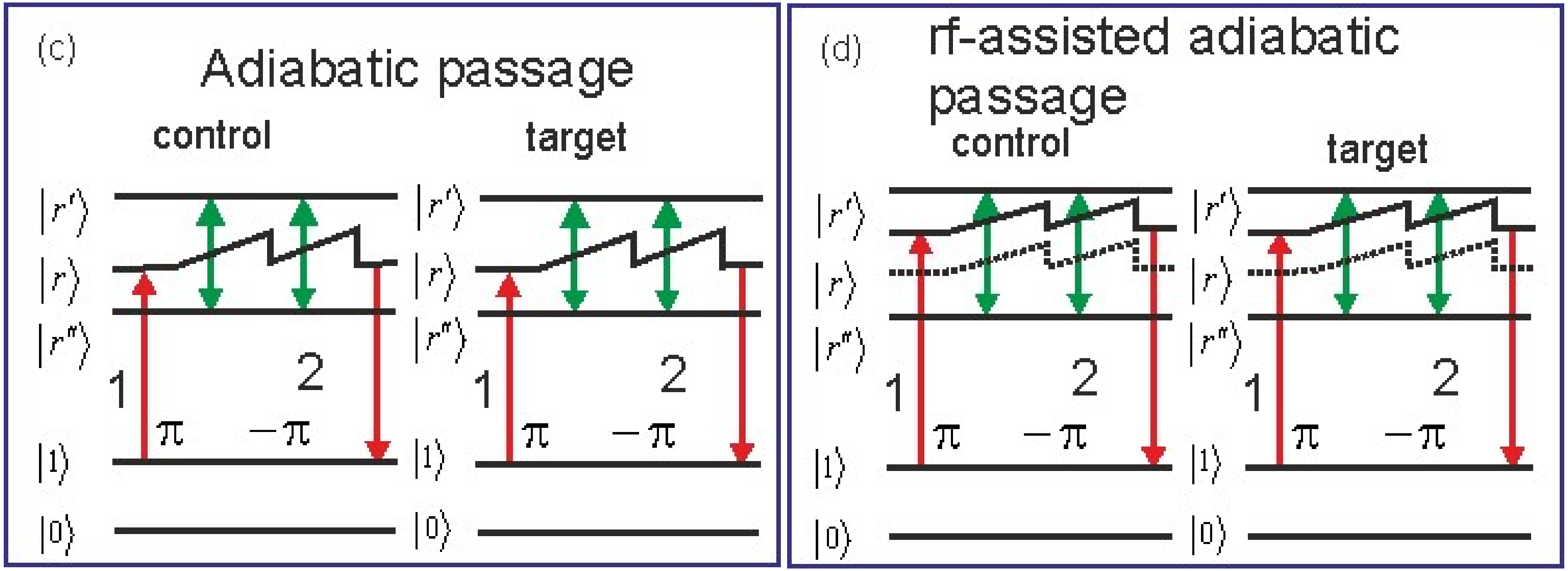


Key point

rf field provides access for more resonances…

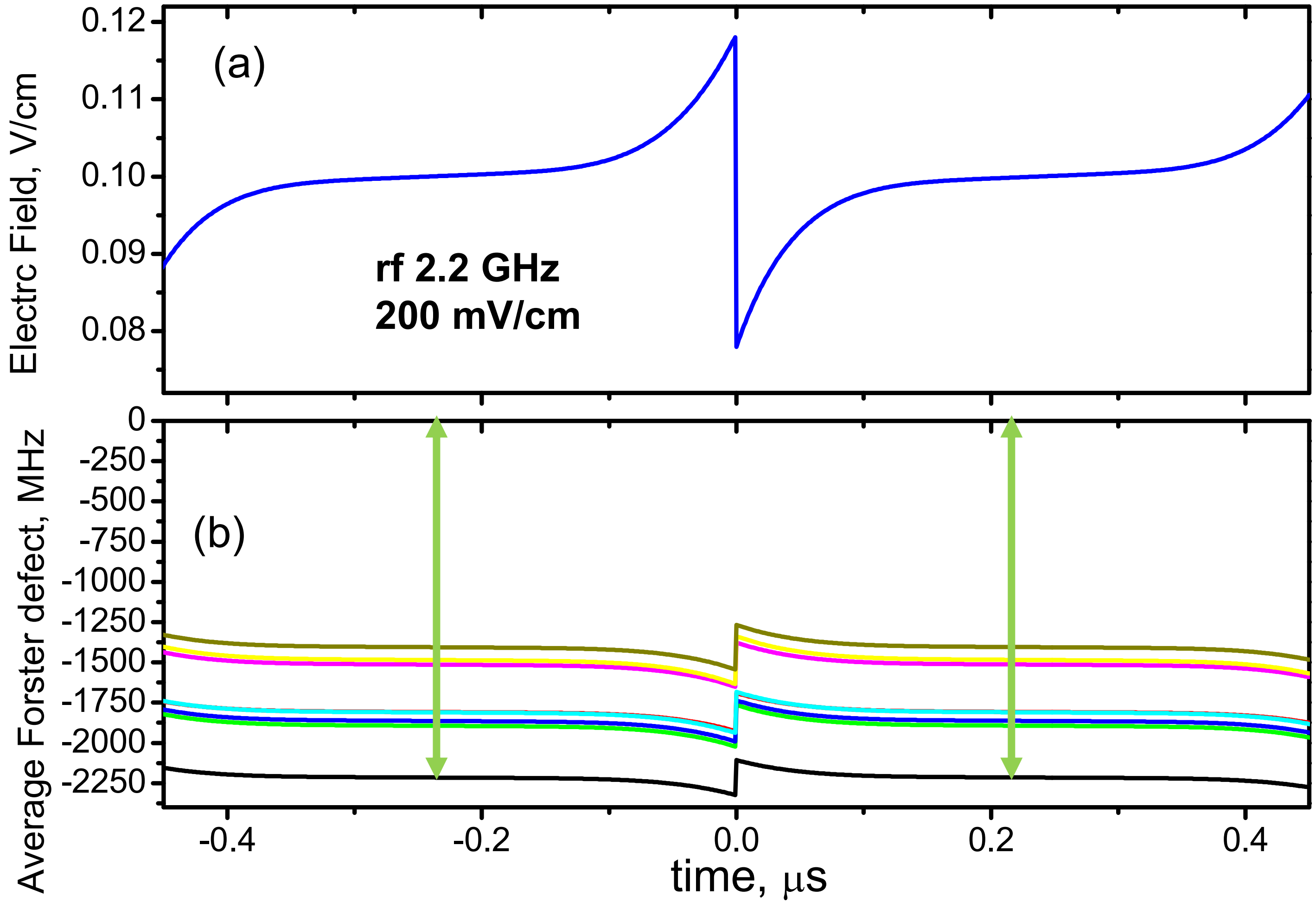
Scheme of CZ gate



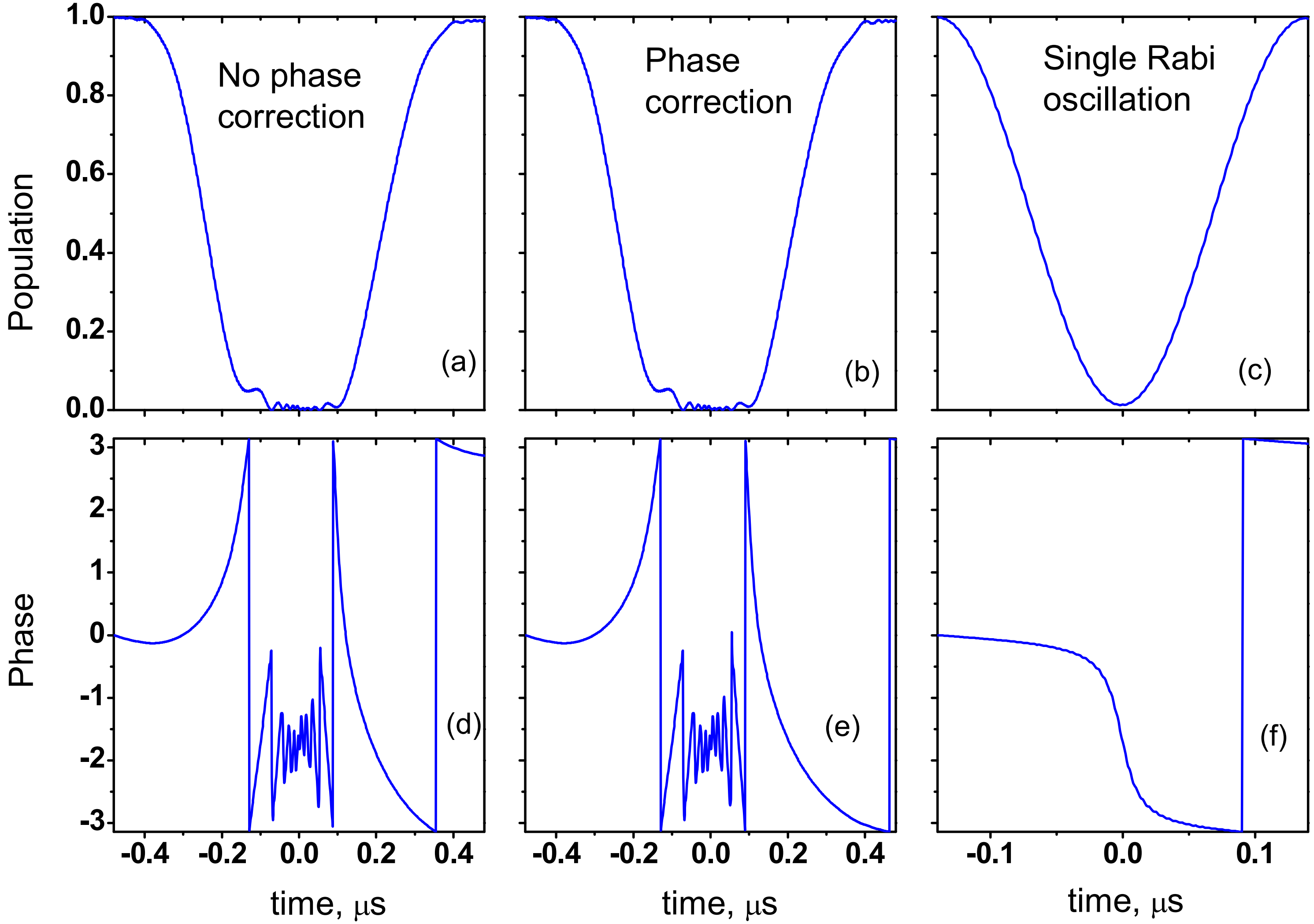


RF assisted Forster resonance in Cs

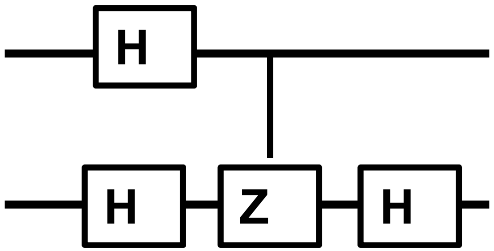
$$80S_{1/2} + 80S_{1/2} \rightarrow 80P_{1/2} + 79P_{1/2}$$



Rf-assisted adiabatic passage in Cs



Bell states for Cs

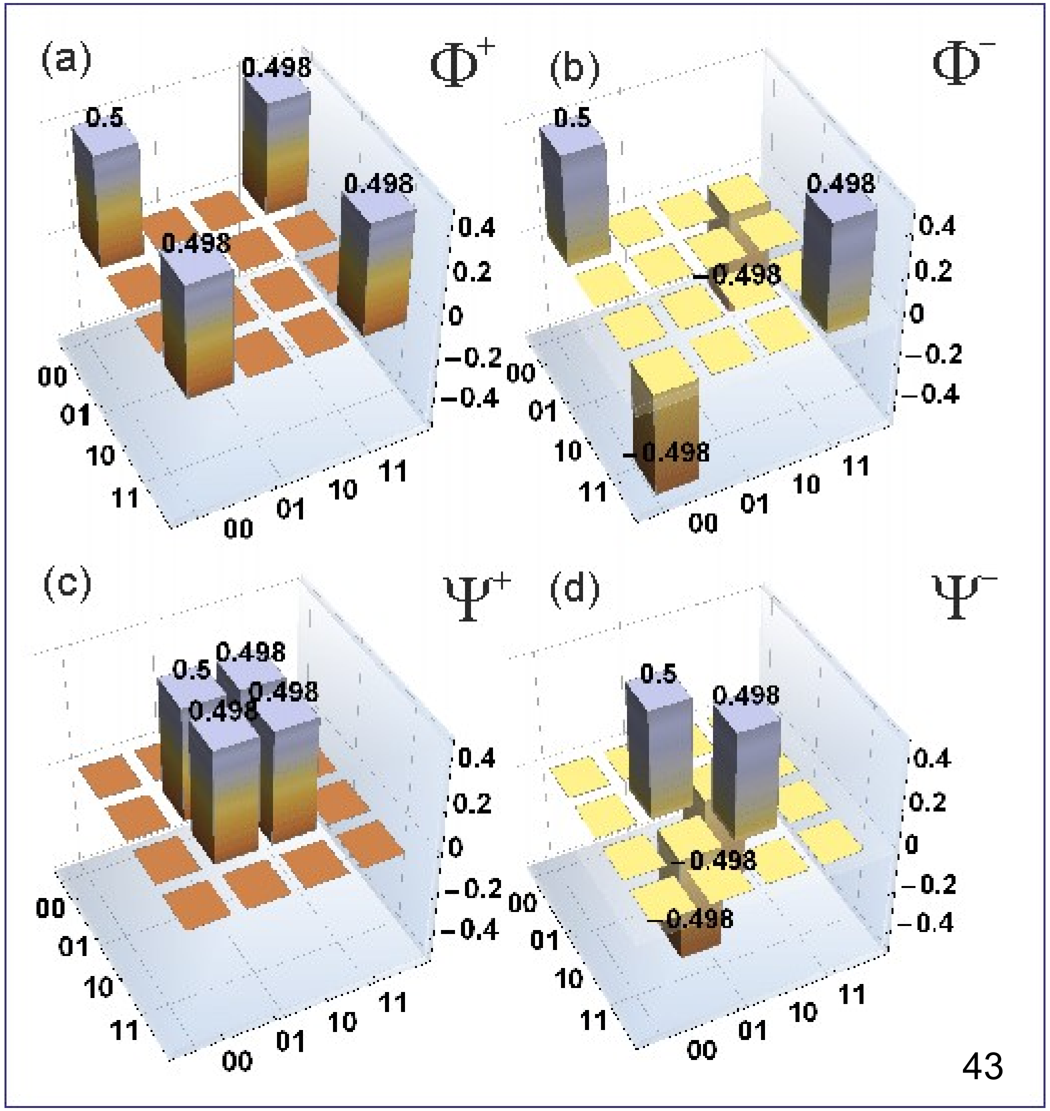


$$\Phi^+ = \frac{1}{\sqrt{2}}\left(|00\rangle + |11\rangle\right)$$

$$\Phi^- = \frac{1}{\sqrt{2}}\left(|00\rangle - |11\rangle\right)$$

$$\Psi^+ = \frac{1}{\sqrt{2}}\left(|01\rangle + |10\rangle\right)$$

$$\Psi^- = \frac{1}{\sqrt{2}}\left(|01\rangle - |10\rangle\right)$$



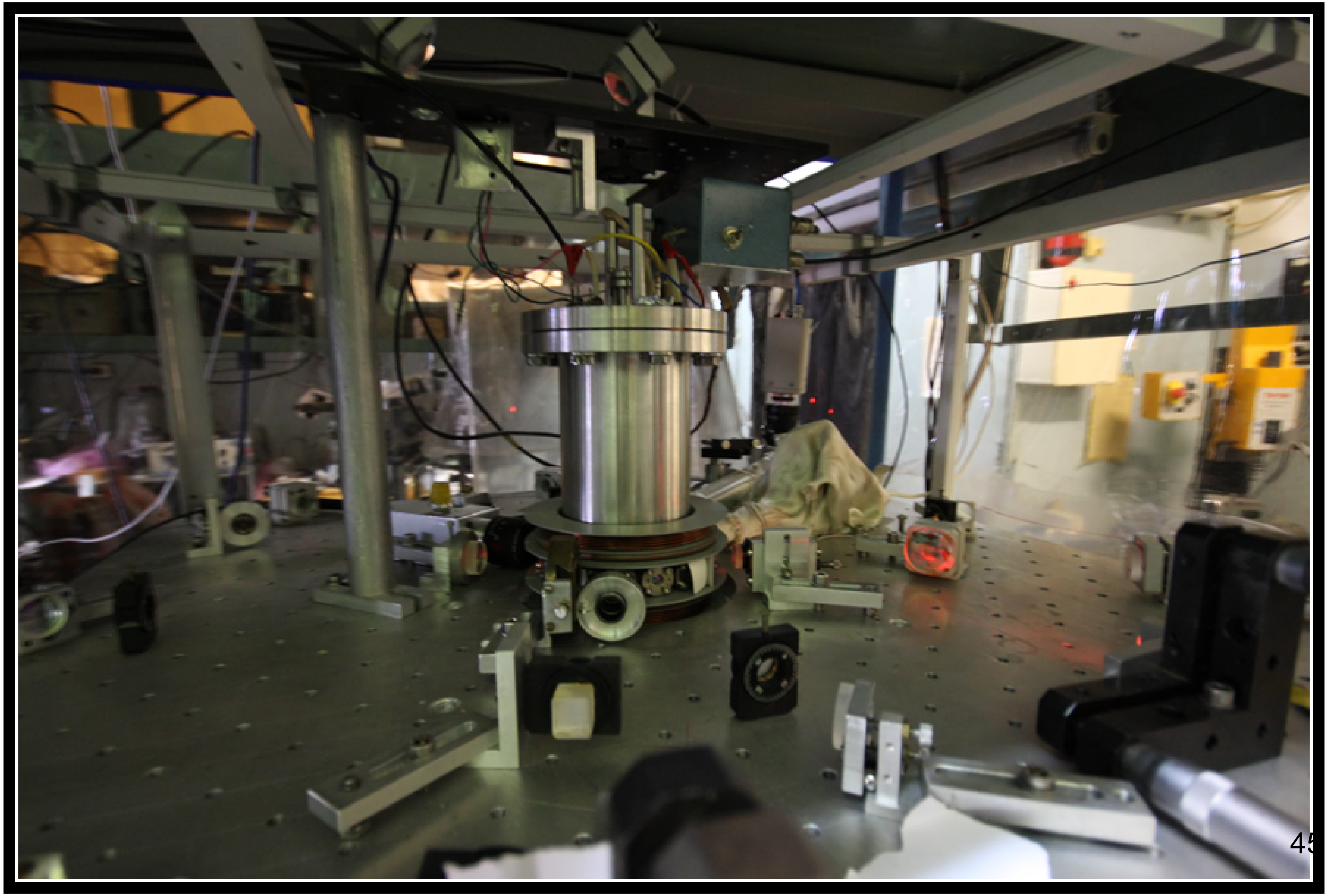
Outline

Quantum information with Rydberg atoms

CZ gate using adiabatic passage of Förster resonances

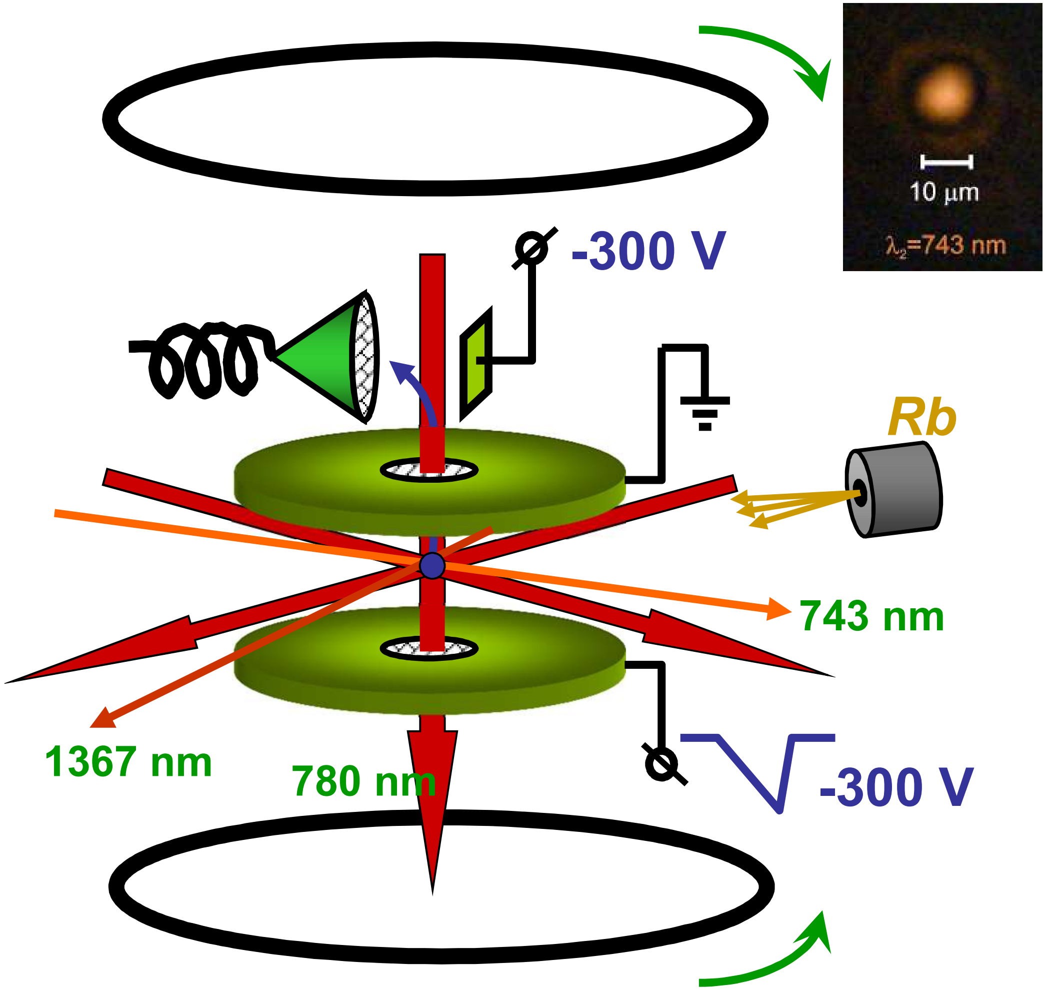
Rydberg experiment in Novosibirsk

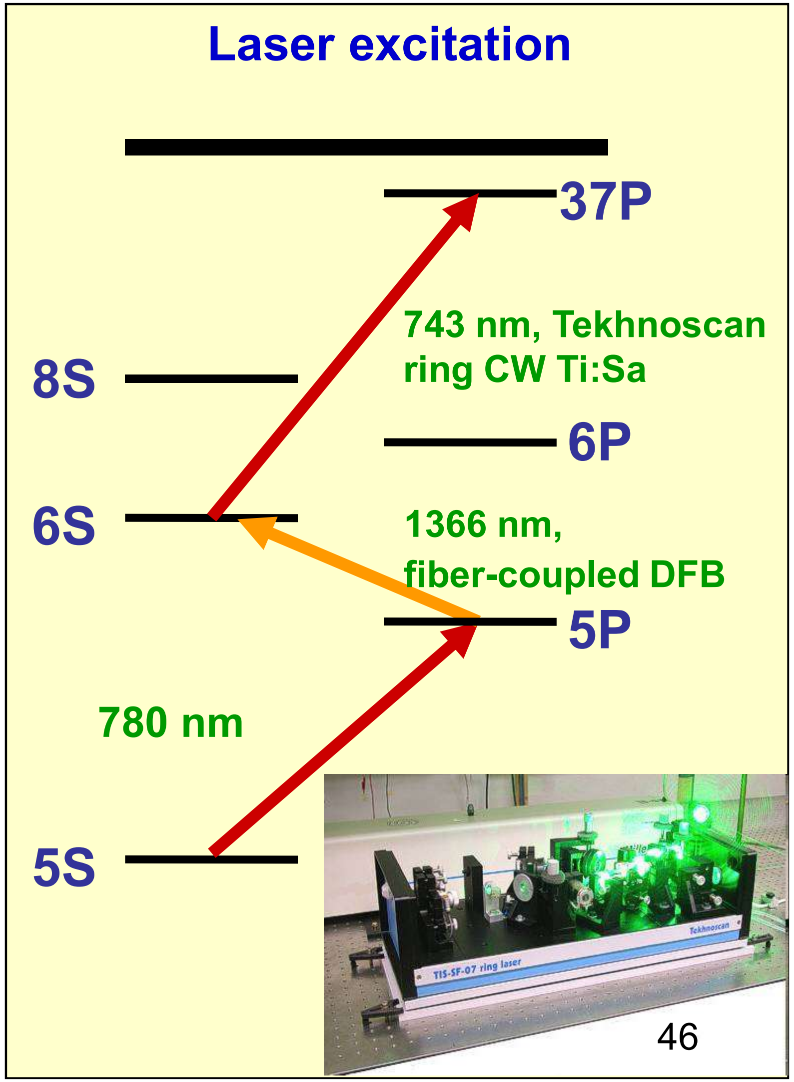
Experiments in Novosibirsk



Experimental setup

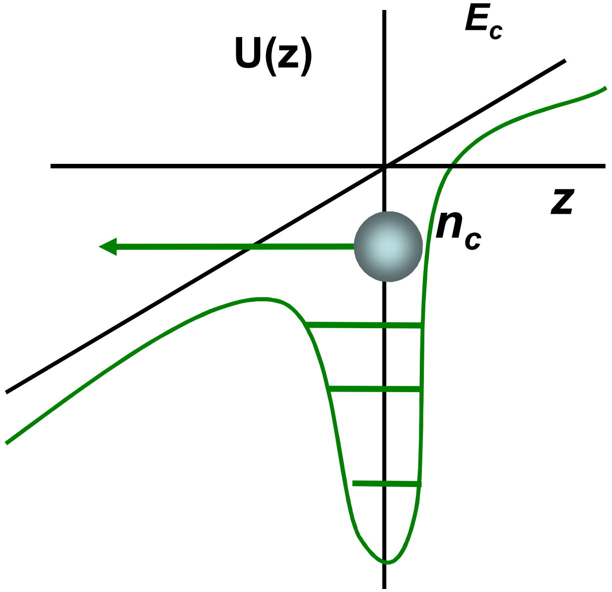
MOT with cold Rb Rydberg atoms

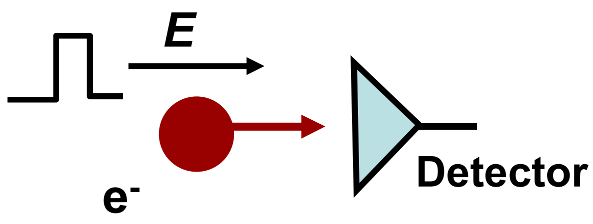




Detection of Rydberg atoms

Selective Field Ionization





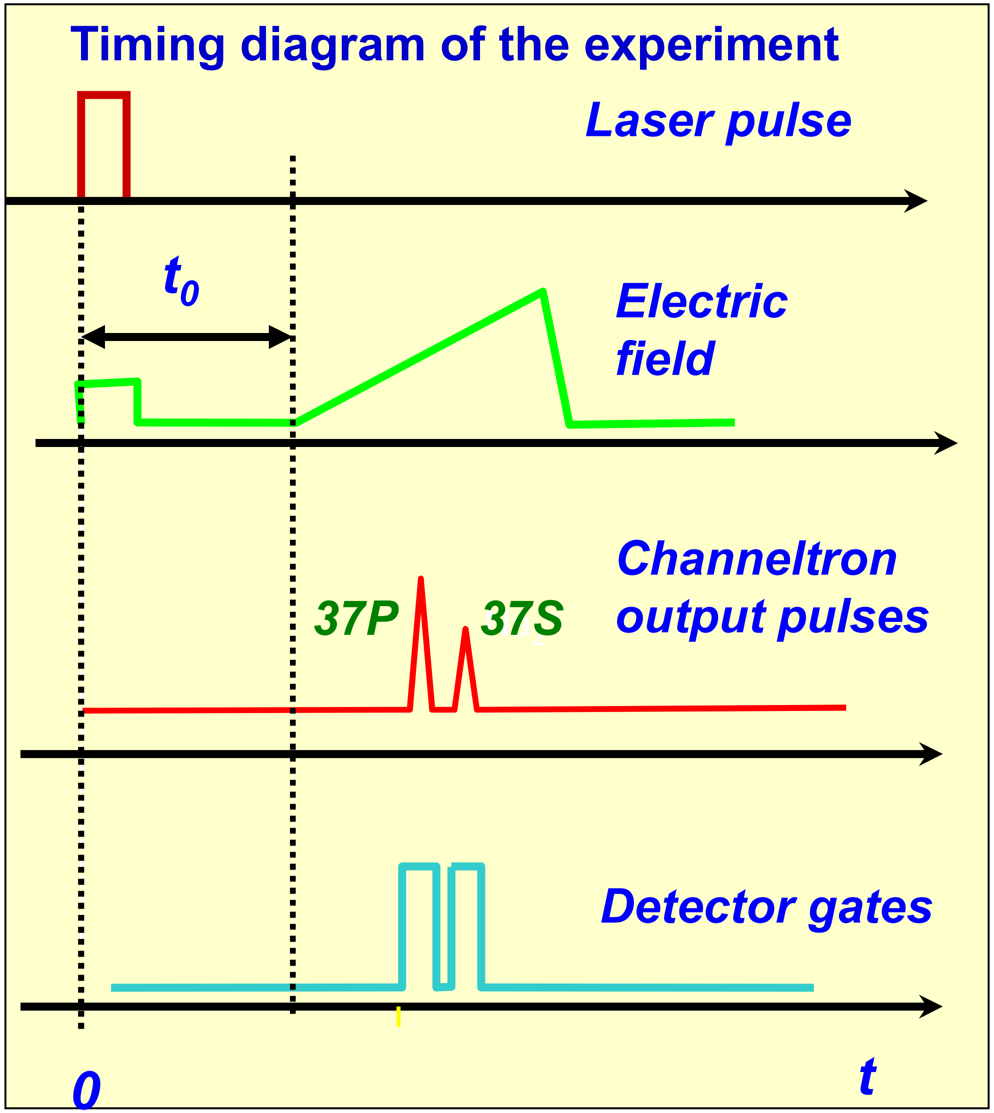
Rydberg atom in *nL* states ionizes in the critical field E_c

$$E_c \approx 3.2 \cdot 10^8 n_c^{-4} \quad (V/cm)$$

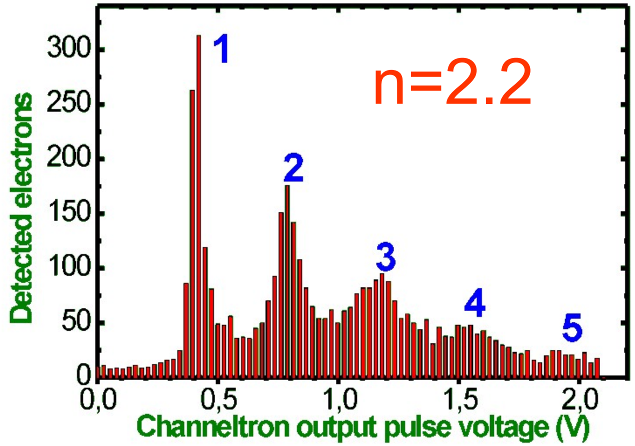
Key point

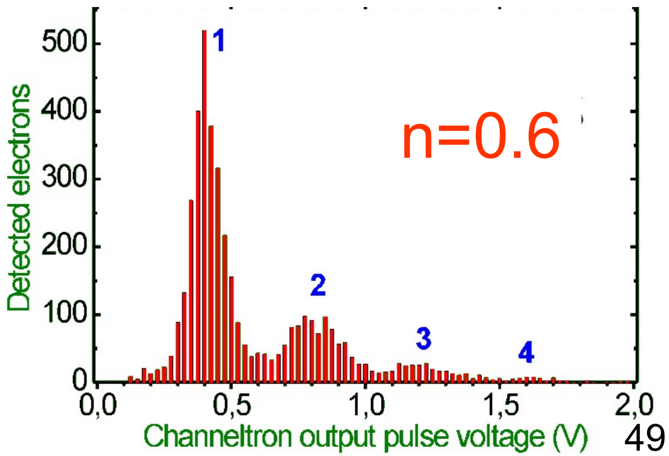
Our approach is based on counting of the number of atoms in each state after each laser pulse…

Timing diagram of the experiment

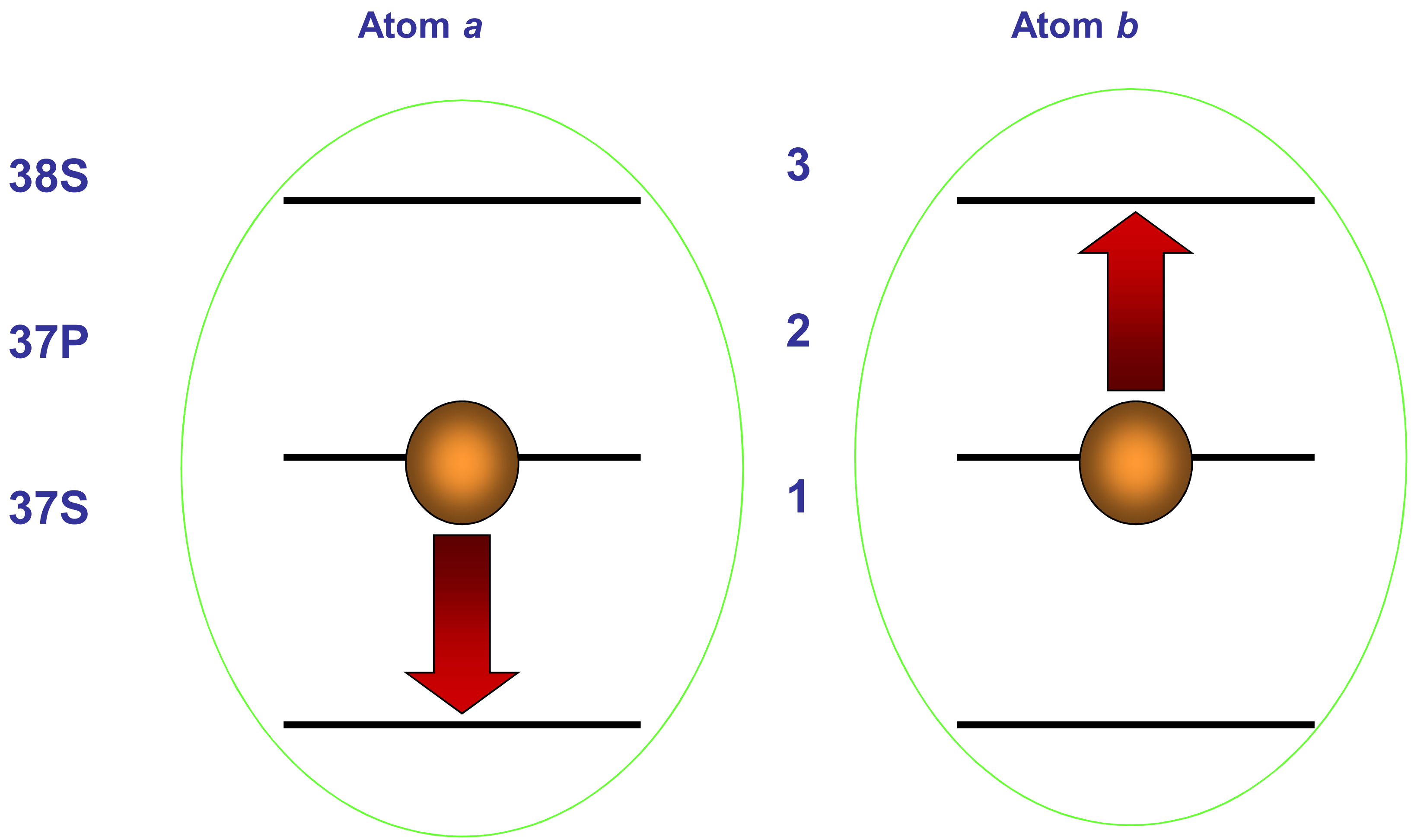


Histograms of the channeltron output for different average numbers of detected atoms per pulse

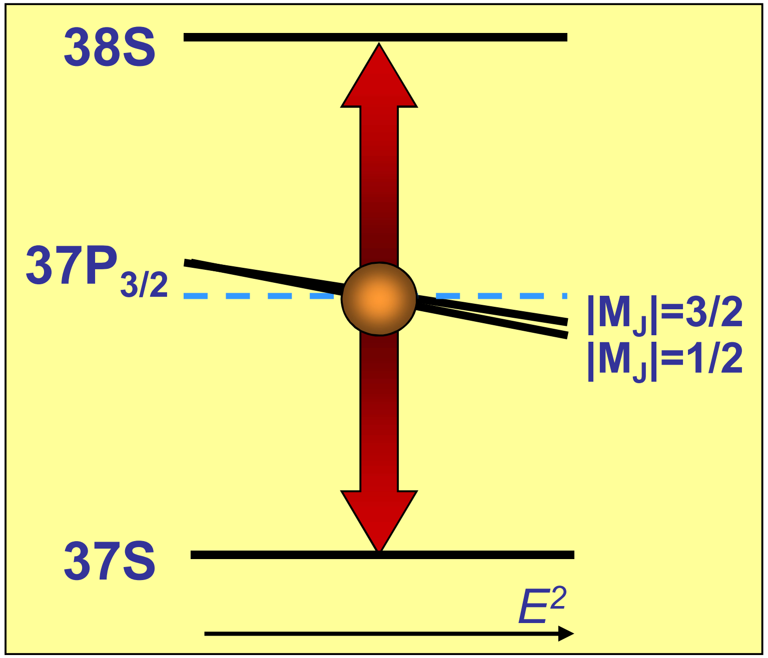


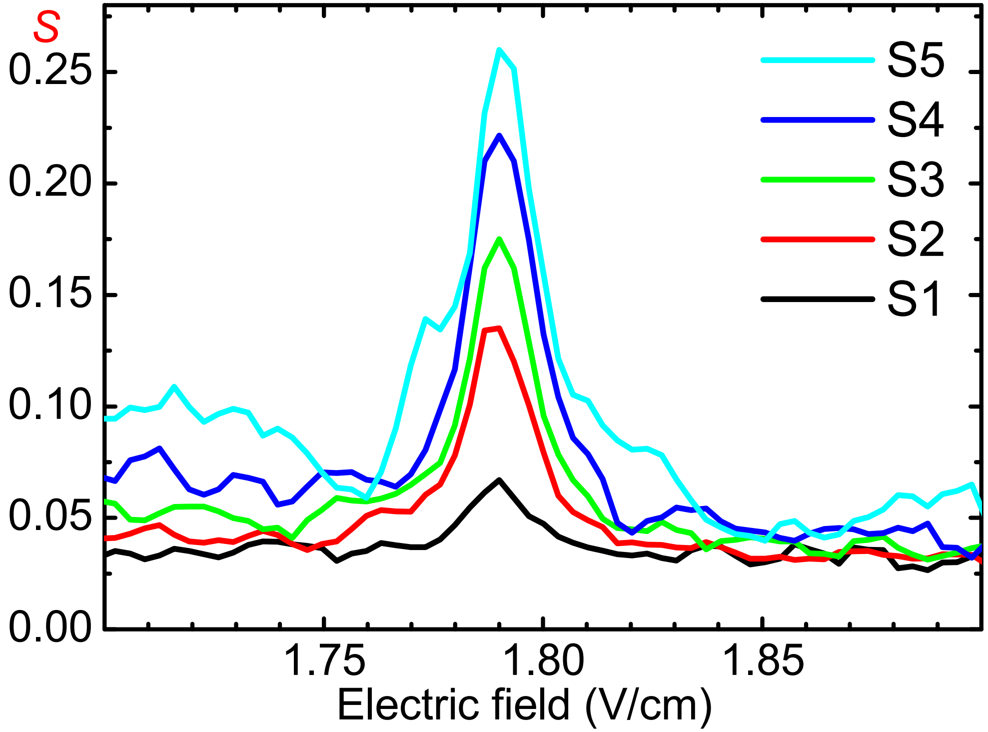


Förster resonance in Rb Rydberg atoms



Stark-tuned Förster resonances





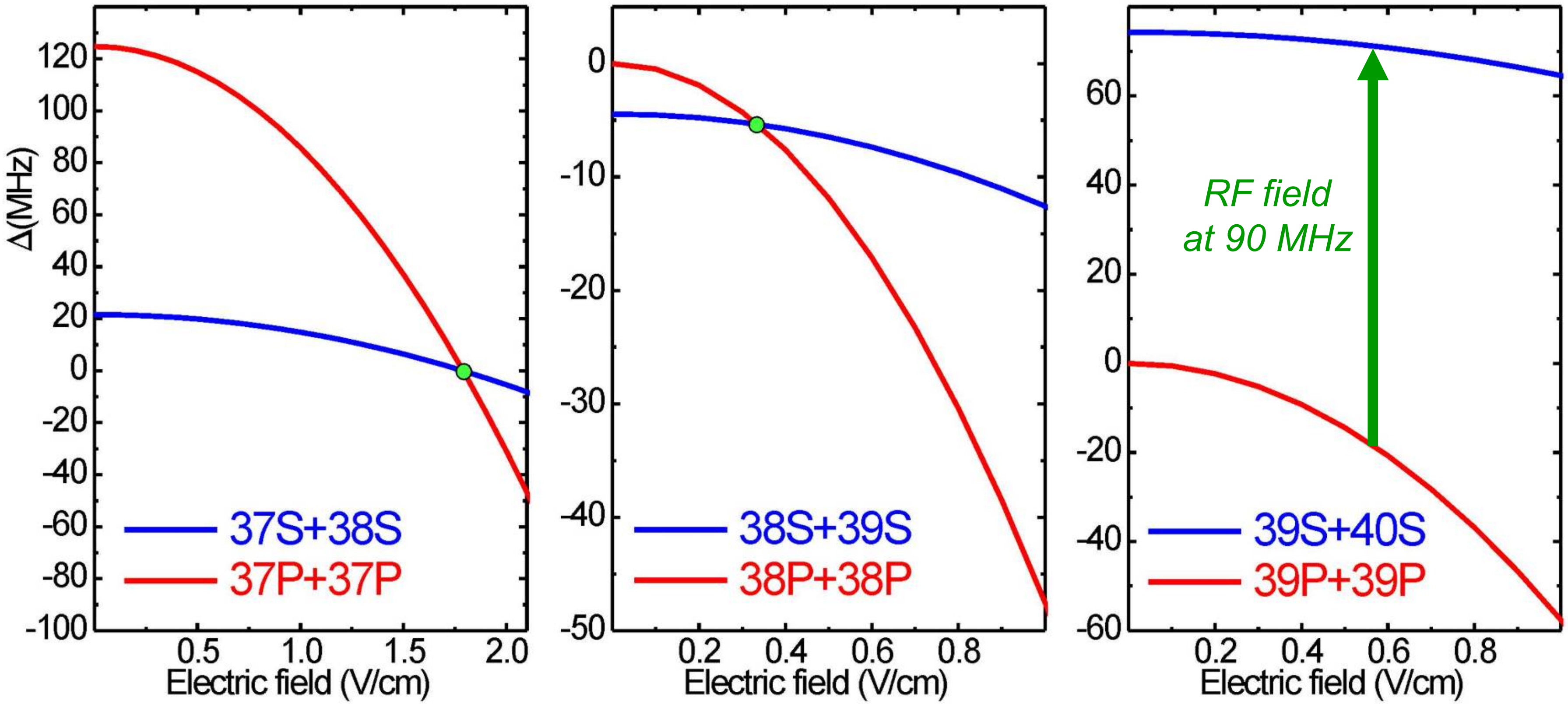
Fraction of atoms in 37S state for *N* detected atoms in all channels

$$S_N = \frac{n_N(37S)}{n_N(37P) + n_N(37S) + n_N(38S)}$$

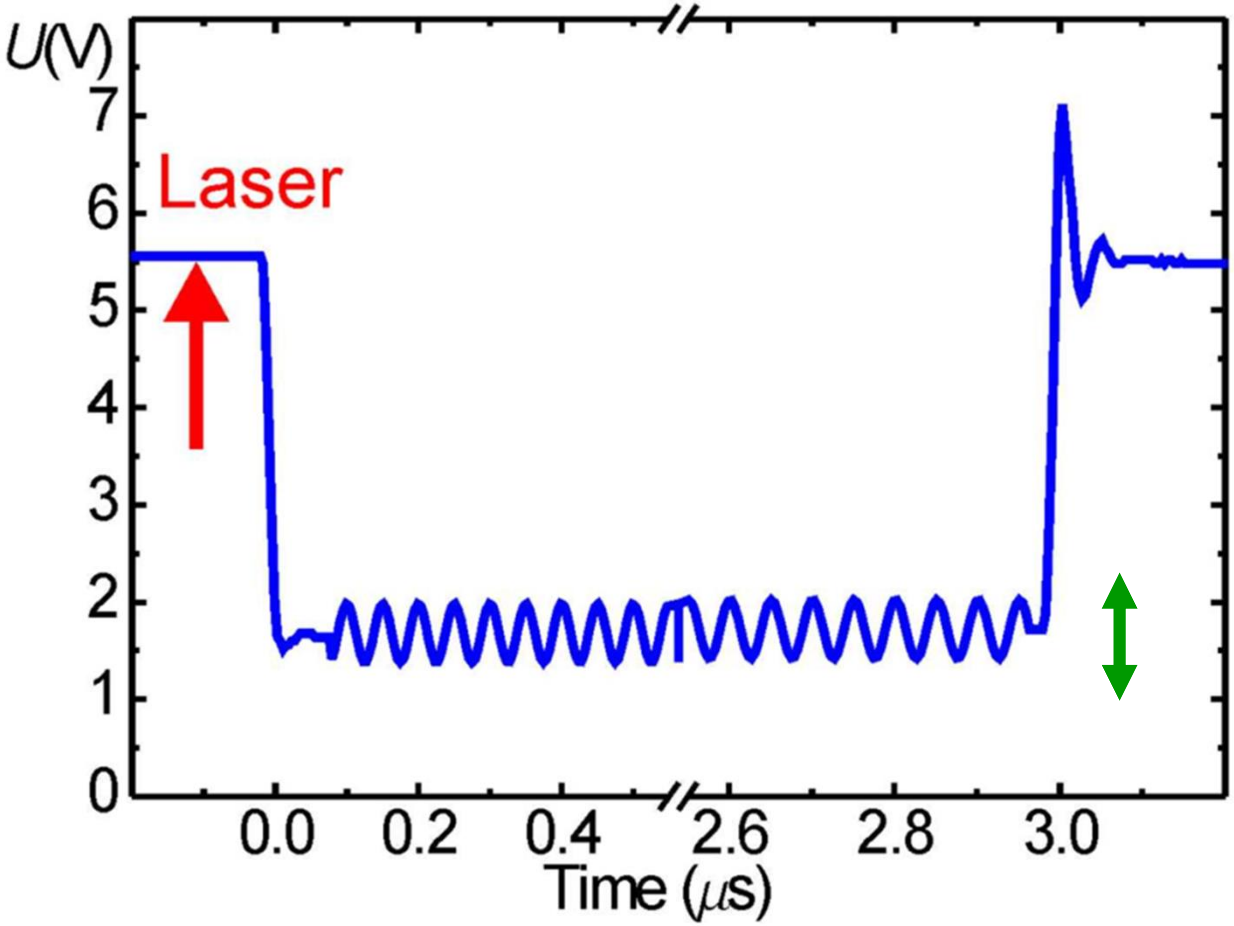
Key point

Non-accessible Förster resonances can be demonstrated using radiofrequency electric field …

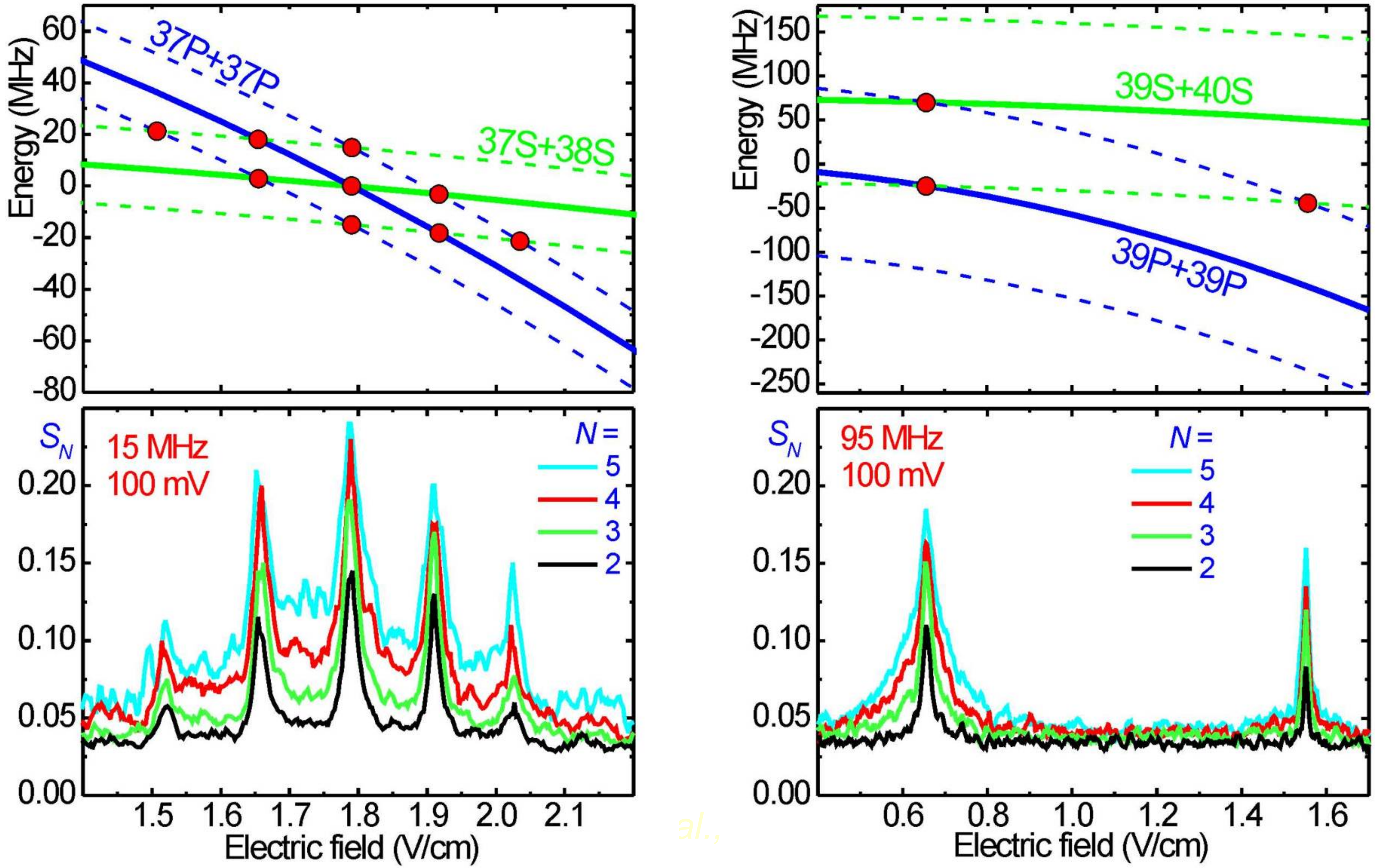
Förster resonances for Rb($nP_{3/2}$)



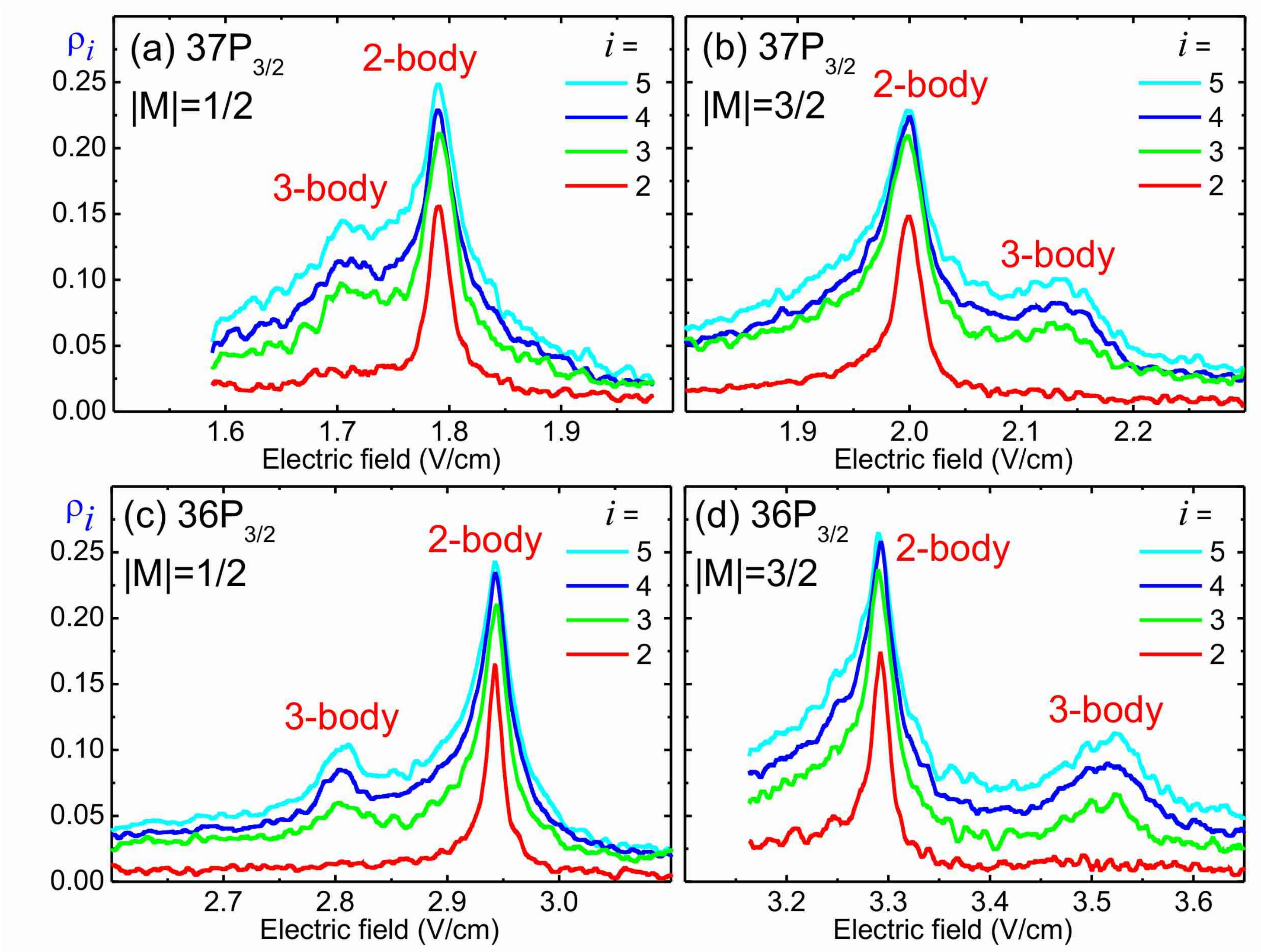
Electric Field



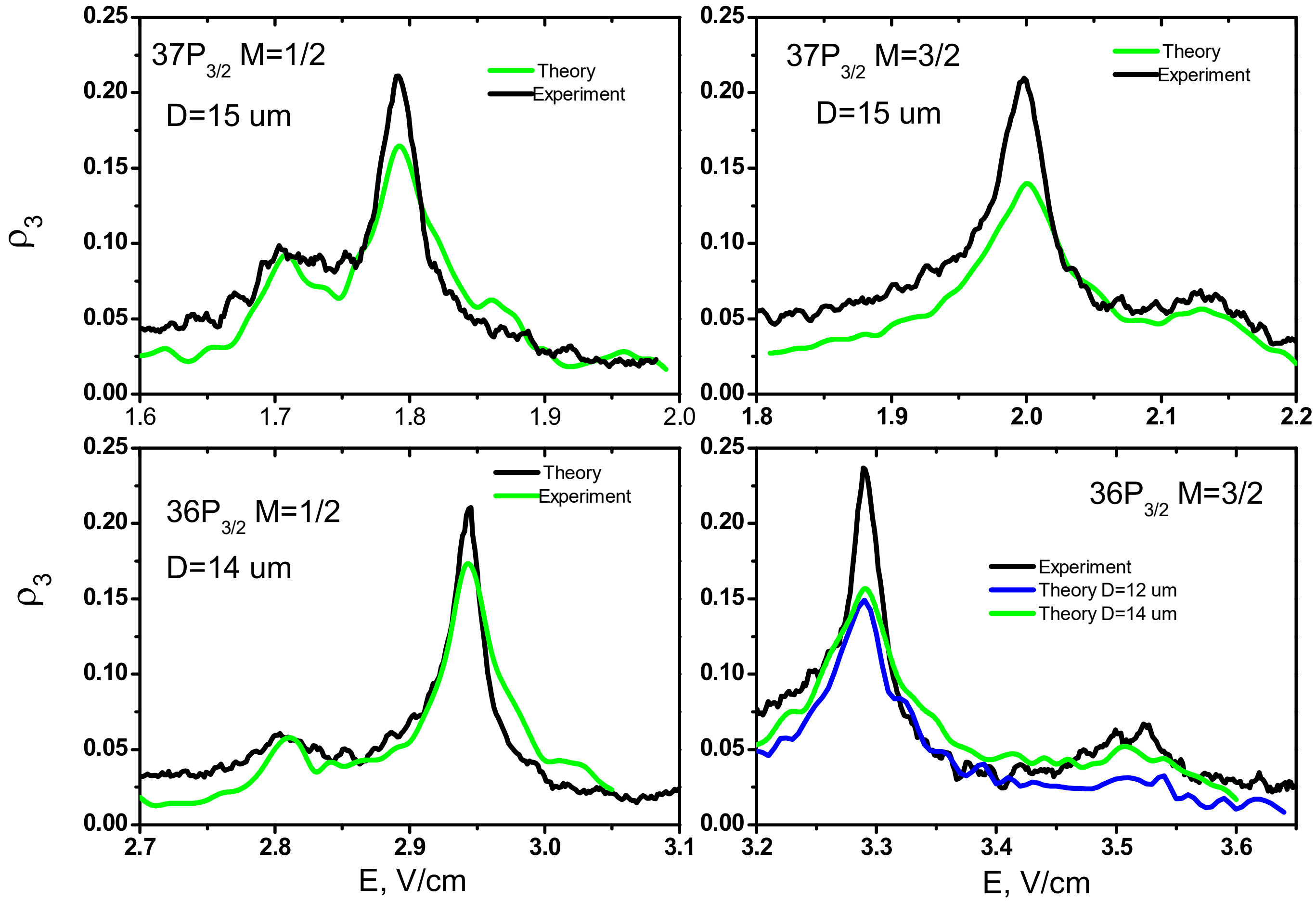
RF-assisted Förster resonances



Three-body Forster resonances



Three-body Forster resonances



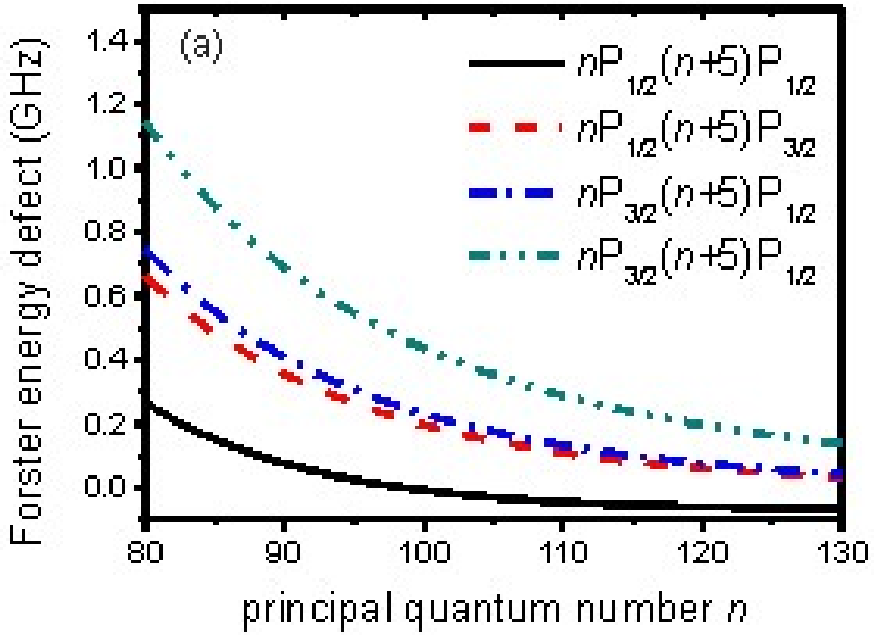
Conclusion

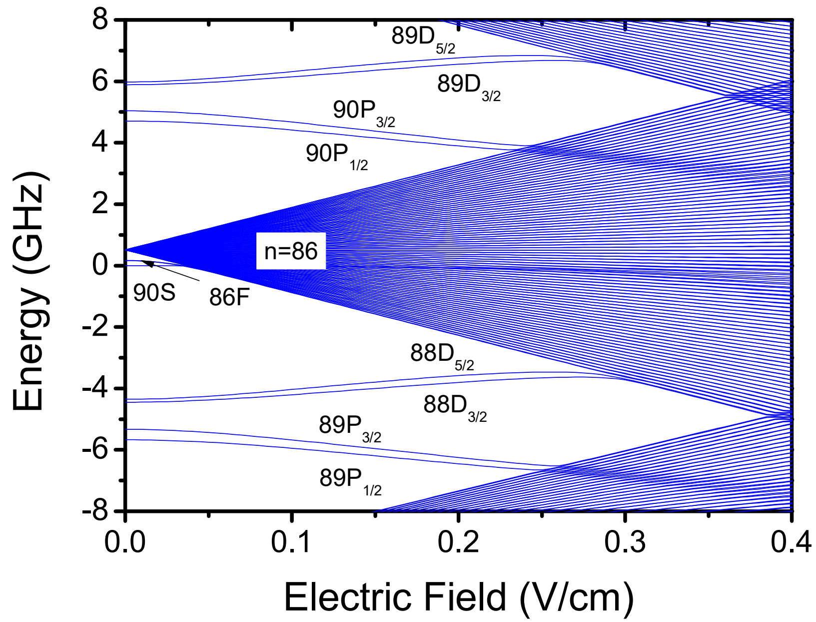
1. We have developed schemes of two-qubit gates using adiabatic passage of Stark-tuned Förster resonances for Rydberg atoms
2. We have studied experimentally Stark-tuned Förster resonances for ultracold Rb Rydberg atoms

1. I.I.Beterov, M.Saffman, E.A.Yakshina, D.B.Tretyakov, V.M.Entin, S.Bergamini, E.A.Kuznetsova, and I.I.Ryabtsev, "Two-qubit gates using adiabatic passage of the Stark-tuned Förster resonances in Rydberg atoms", Phys. Rev. A, 2016 v.94, p.062307;
2. 5. Ryabtsev, I.I., Beterov, I.I., Tretyakov, D.B., Entin, V.M., Yakshina, E.A., "Spectroscopy of cold rubidium Rydberg atoms for applications in quantum information", Physics-Uspekhi, 2016, v.59, p.196.;
3. E.A.Yakshina, D.B.Tretyakov, I.I.Beterov, V.M.Entin, C.Andreeva, A.Cinins, A.Markovski, Z.Iftikhar, A.Ekers, I.I.Ryabtsev, "Line shapes and time dynamics of the Förster resonances between two Rydberg atoms in a time-varying electric field", Phys. Rev. A, 2016, v.94, p.043417.

Adiabatic passage of Förster resonance

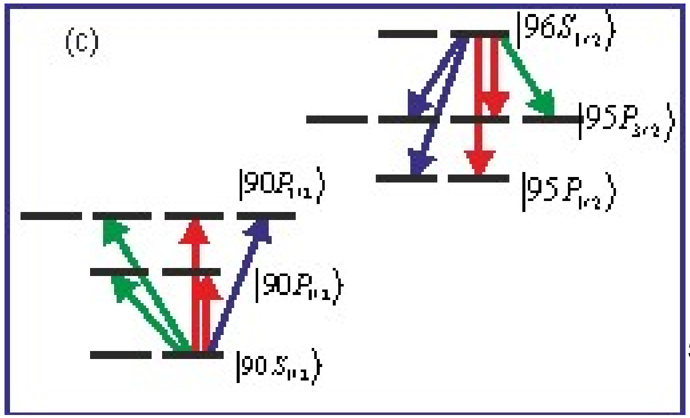
Cs 90S+96S - 90P+95P





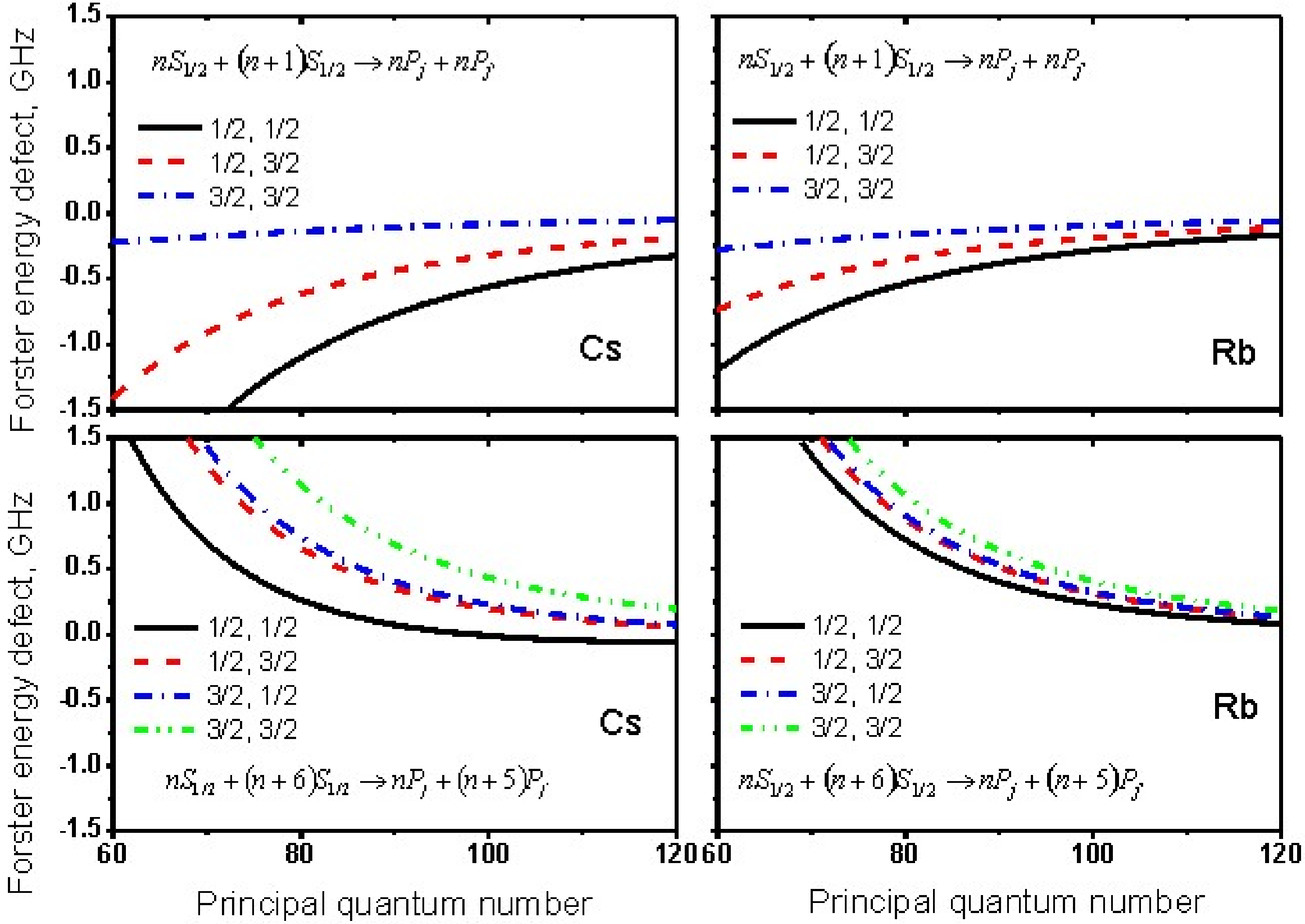
Problem: phase errors due to off-resonant interaction channels

Solution: modification of the electric pulse shape

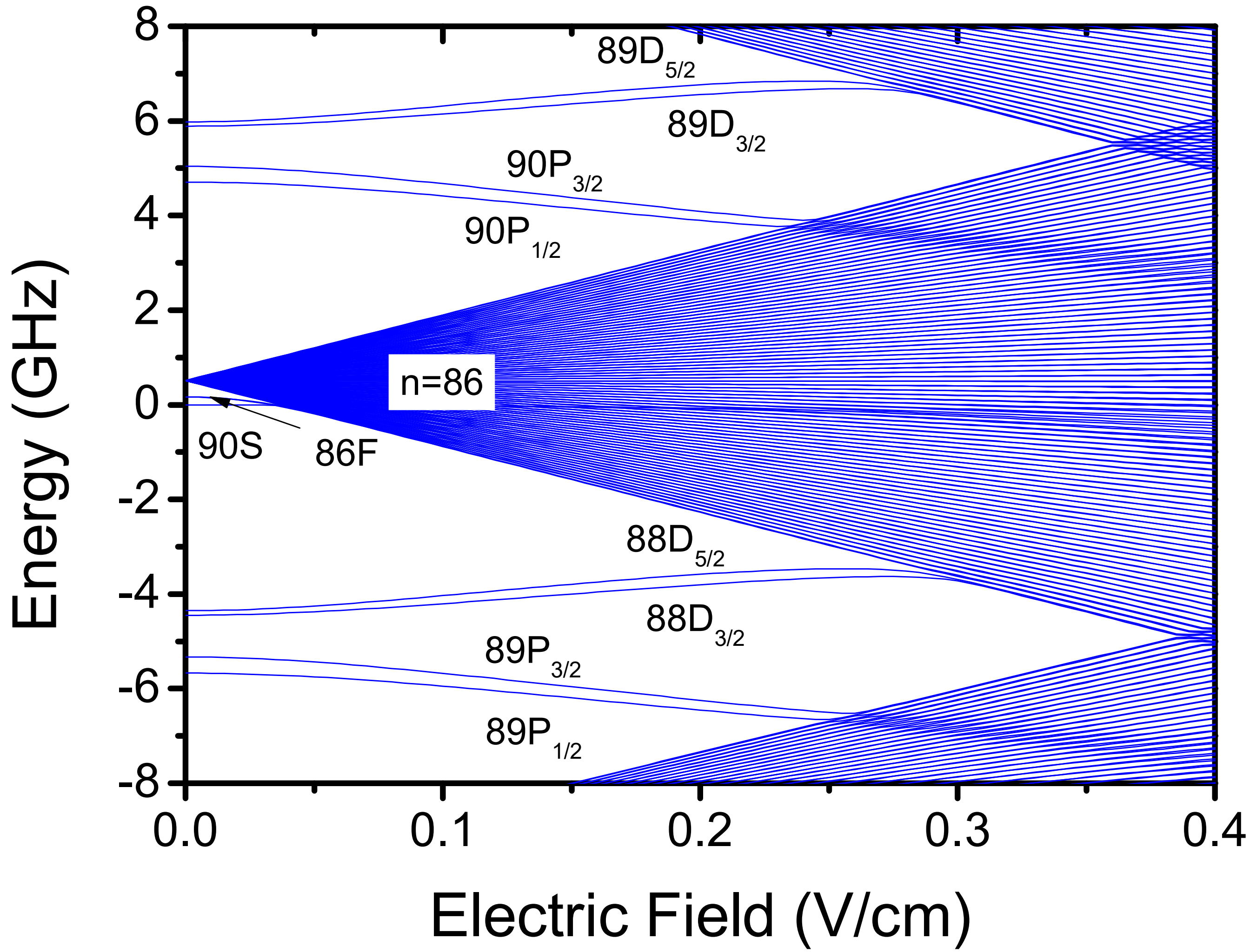


Förster energy defect

$$\delta_0 = U_{nP} + U_{n'P} - U_{nS} - U_{(n'+1)S}$$



Stark map for Cs



RF-assisted adiabatic passage

Hamiltonian:

$$\hat{\mathbf{H}}(t) = \frac{\hbar}{2}\begin{pmatrix} -\delta(t) & \Omega(t) \\ \Omega(t) & \delta(t) \end{pmatrix}$$

Rf-assisted adiabatic passage:

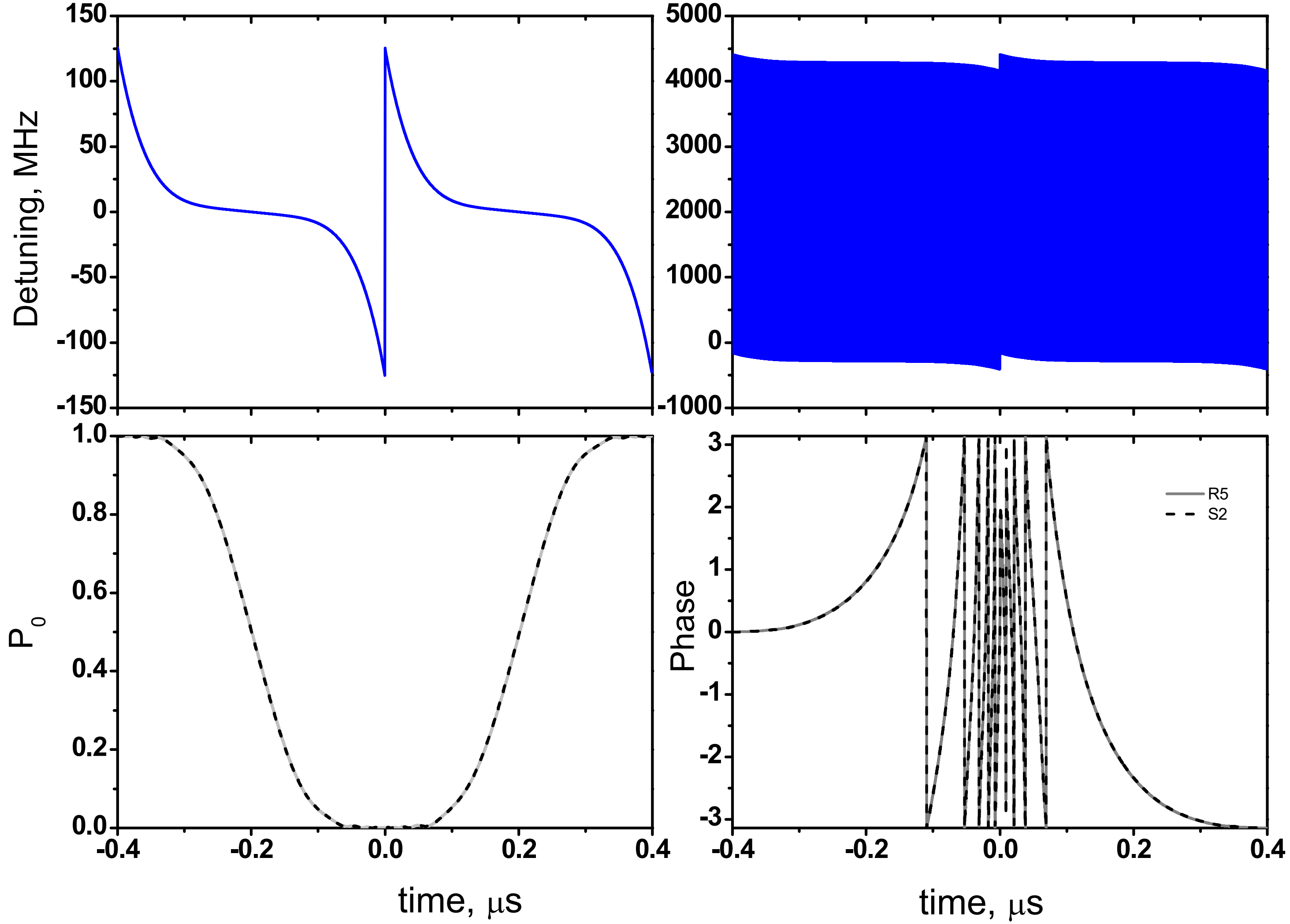
$$\delta(t) \rightarrow \delta'(t) + \delta_0 + A\sin\left(\omega_{rf} t\right)$$

Using expansion for frequency modulation with $\delta_0 = \omega_{rf}$

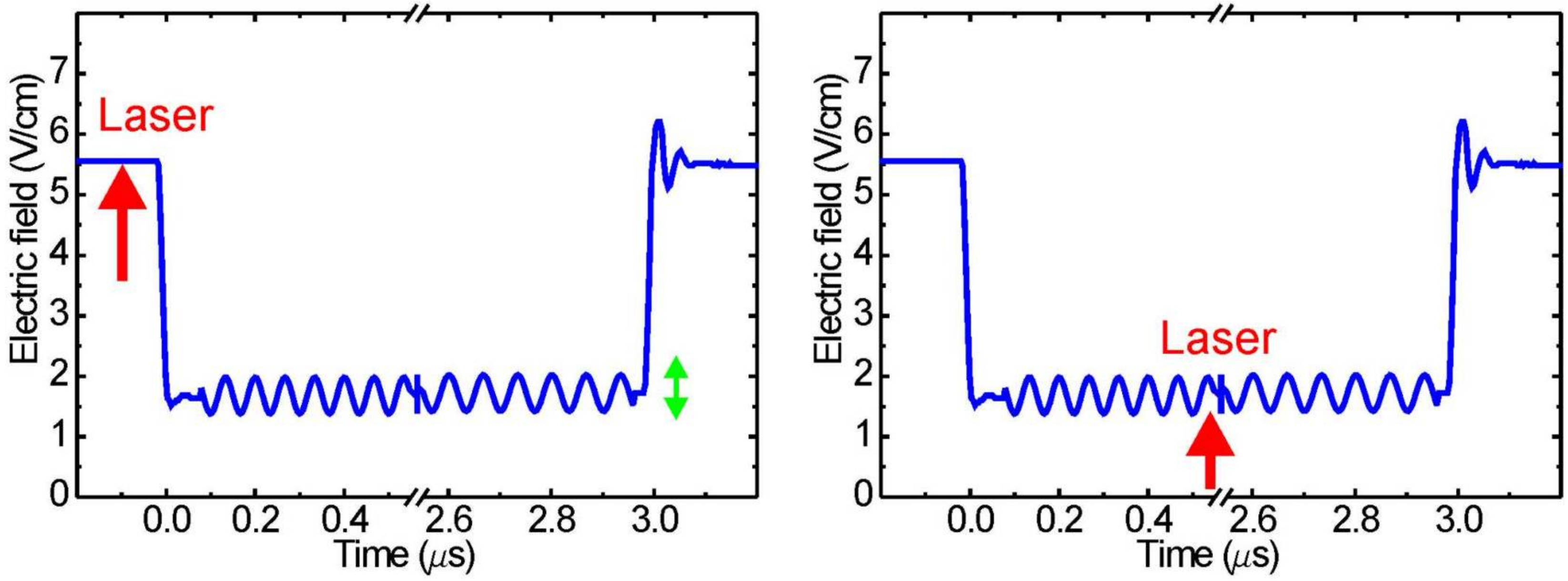
$$\hat{\mathbf{H}}(t) = \frac{\hbar}{2}\begin{pmatrix} -\delta'(t) & \Omega(t) J_1\left(A/\omega_{RF}\right) \\ \Omega(t) J_1\left(A/\omega_{RF}\right) & \delta'(t) \end{pmatrix}$$

RF-assisted adiabatic passage

$$\delta_0 = \omega_{rf} = 2000$$

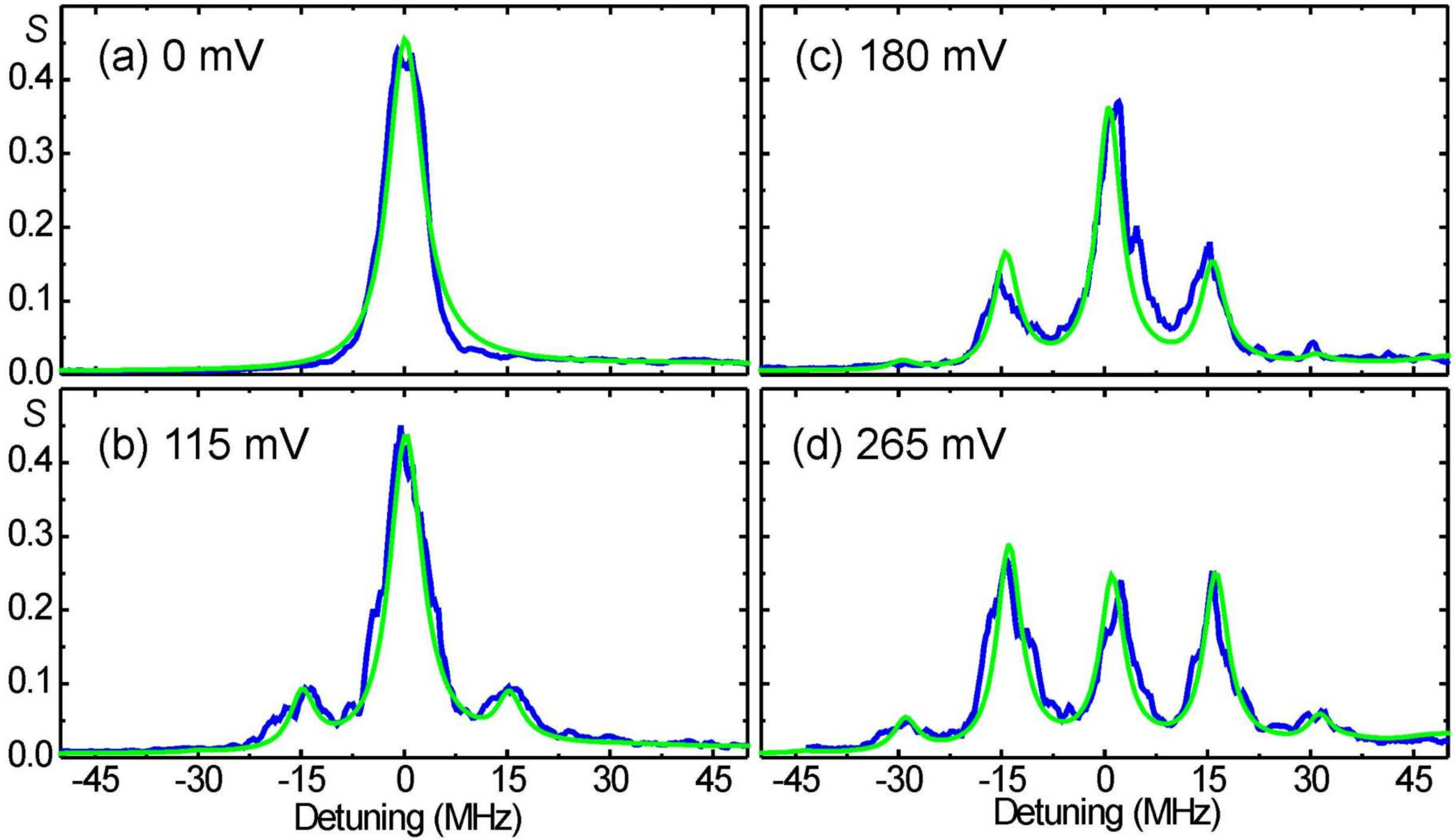


Observation of Floquet states



D.B.Tretyakov et al., arXiv:1404.0438

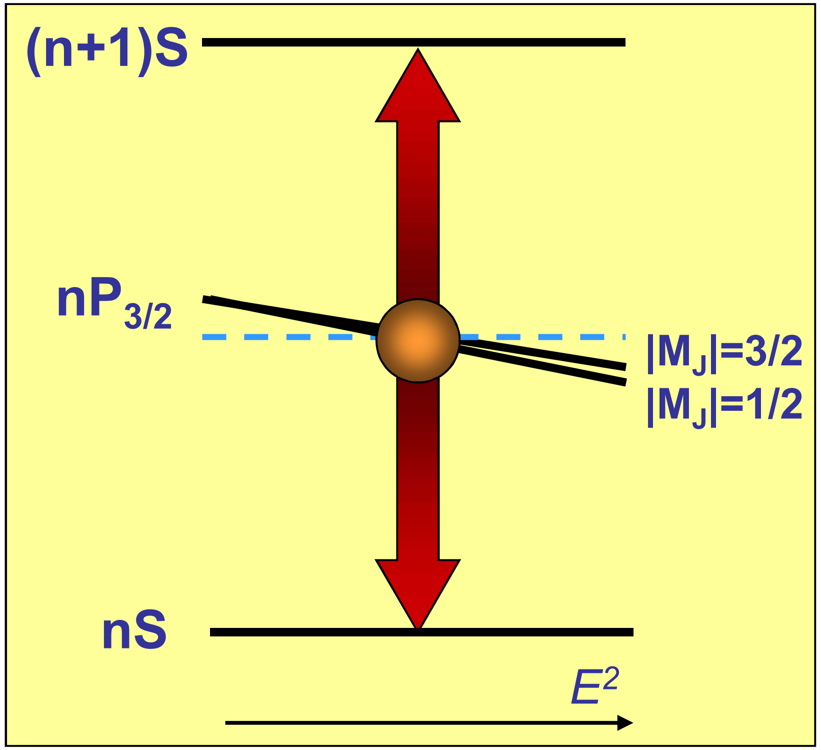
Observation of Floquet states



Laser spectroscopy of 37*P*, Rf modulation at 15 MHz

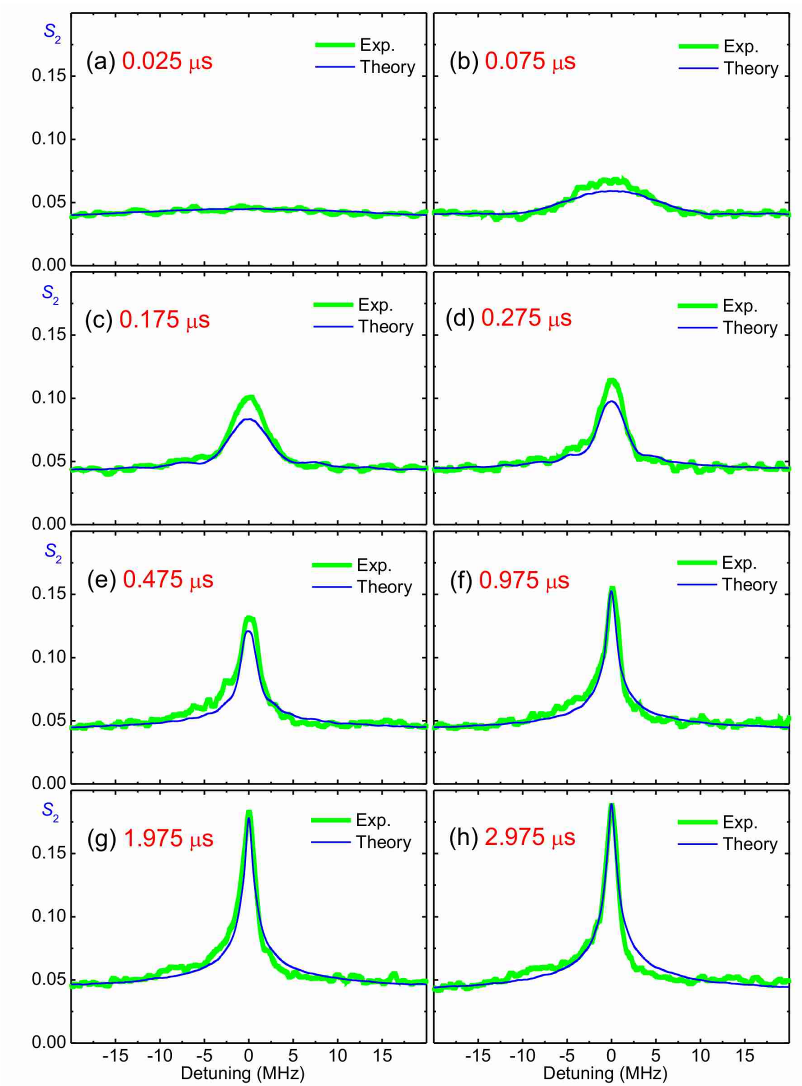
Förster resonances for Rb($nP_{3/2}$)

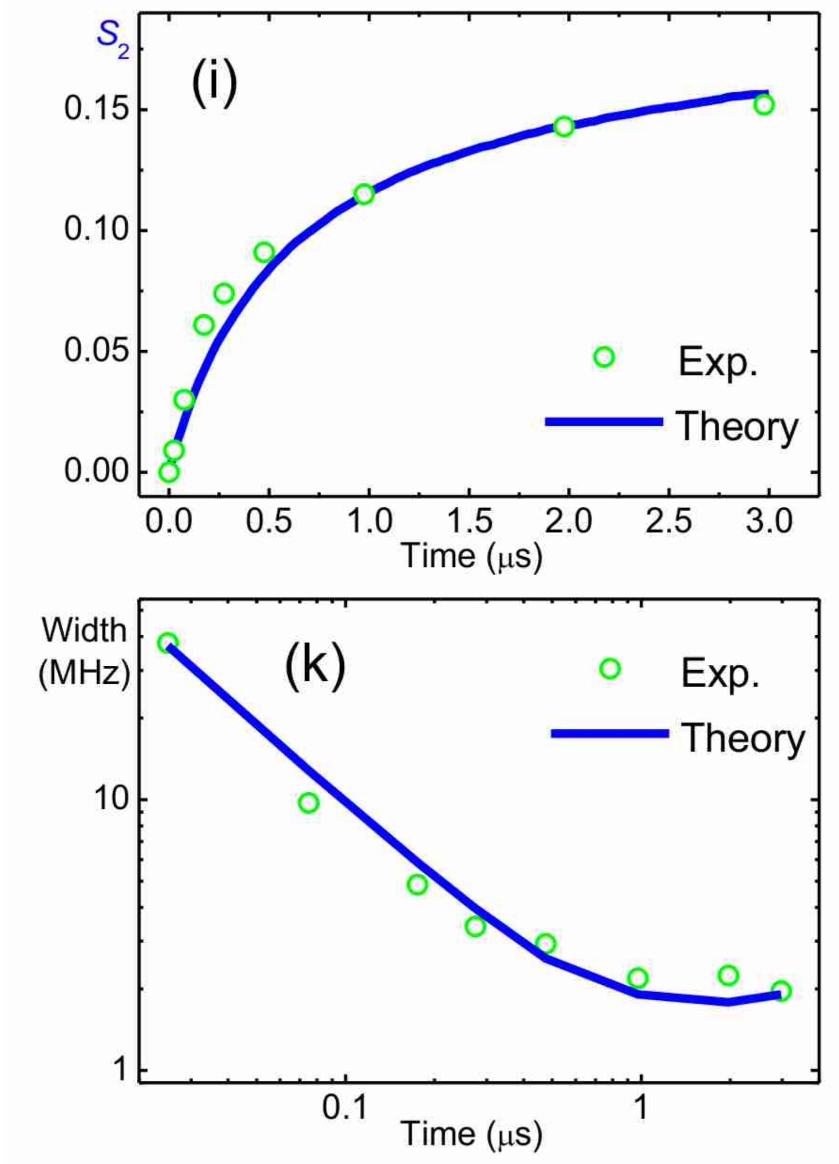
$$Rb(nP_{3/2}) + Rb(nP_{3/2}) \leftrightarrow Rb(nS_{1/2}) + Rb([n+1]S_{1/2})$$



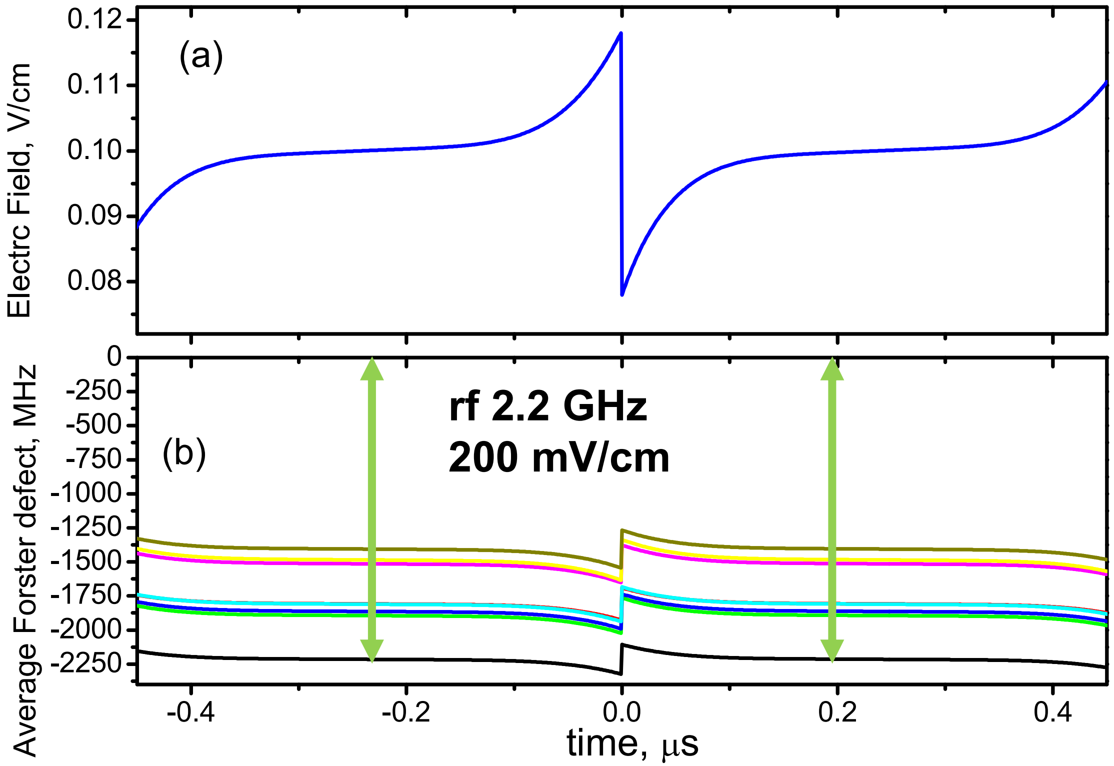
n	Δ_0 (MHz)	E_{cr} (V/cm)
35	382	4.5
36	228	3.1
37	105	1.9
38	5.6	0.4
39	-73	
40	-136	

Förster resonance at different interaction times





Förster defect in Cs



Förster resonance:

$$80S_{1/2} + 80S_{1/2} \to 80P_{1/2} + 79P_{1/2}$$

Forster energy defect:

$$\delta_0 = U_{80P} + U_{79P} - U_{80S} - U_{80S}$$

Differential polarizability:

$$\alpha_0 = \alpha_{80P} + \alpha_{79P} - \alpha_{80S} - \alpha_{80S}$$

Electric field:

$$E(t) = E_{dc}(t) + E_V \cos(\omega_{rf} t)$$

Förster energy defect in the electric field:

$$\delta(t) = \delta_0 - \frac{\alpha}{2} E(t)^2$$

Average Förster energy defect:

$$\langle \delta(t) \rangle = \delta_0 - \frac{\alpha_0}{2} E_{dc}(t)^2 - \frac{\alpha_0}{4} E_V^2$$