Quantum optics with novel coherent light sources

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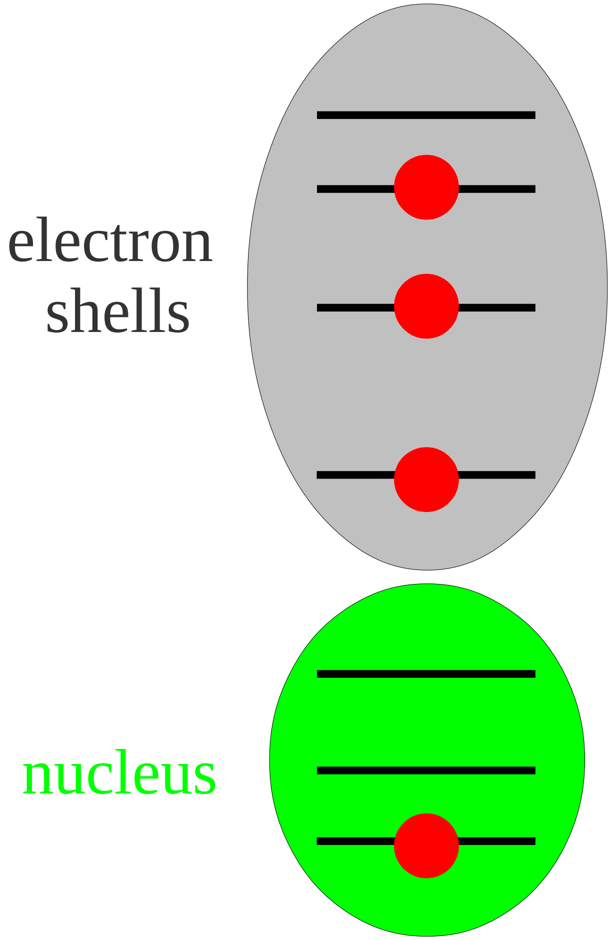
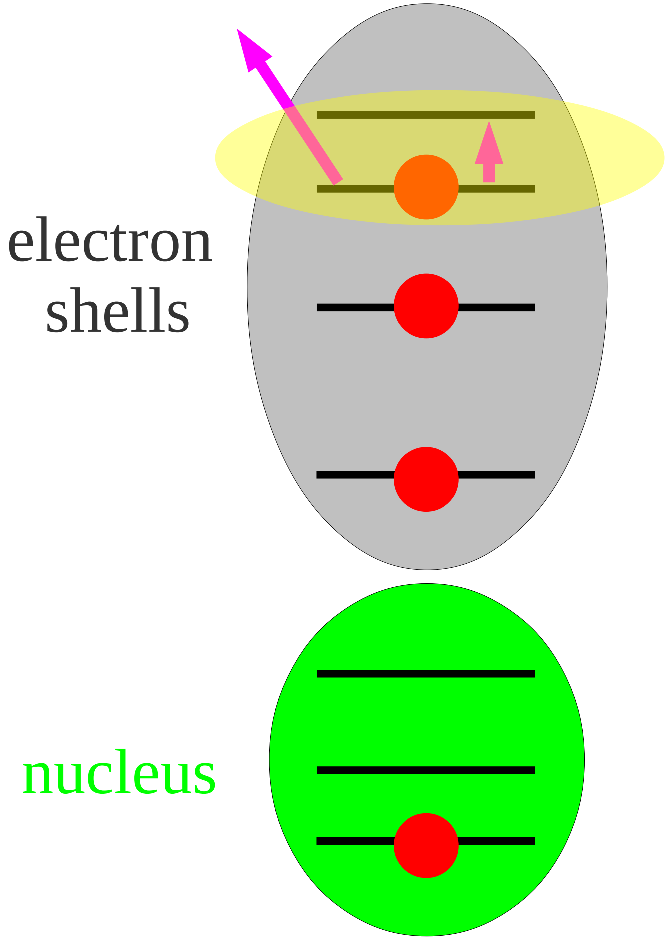
Institute of Theoretical Physics, CAS, Beijing, 04. April 2012

Introduction

Light-matter interactions



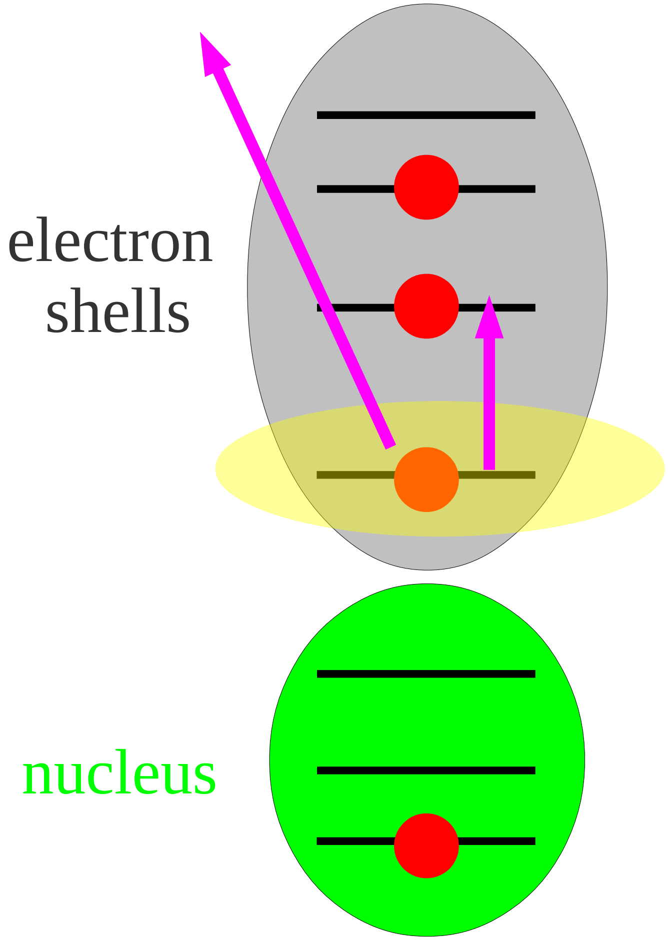
Introduction



Light-matter interactions

- IR/optical driving fields: excite/ionize outer electrons

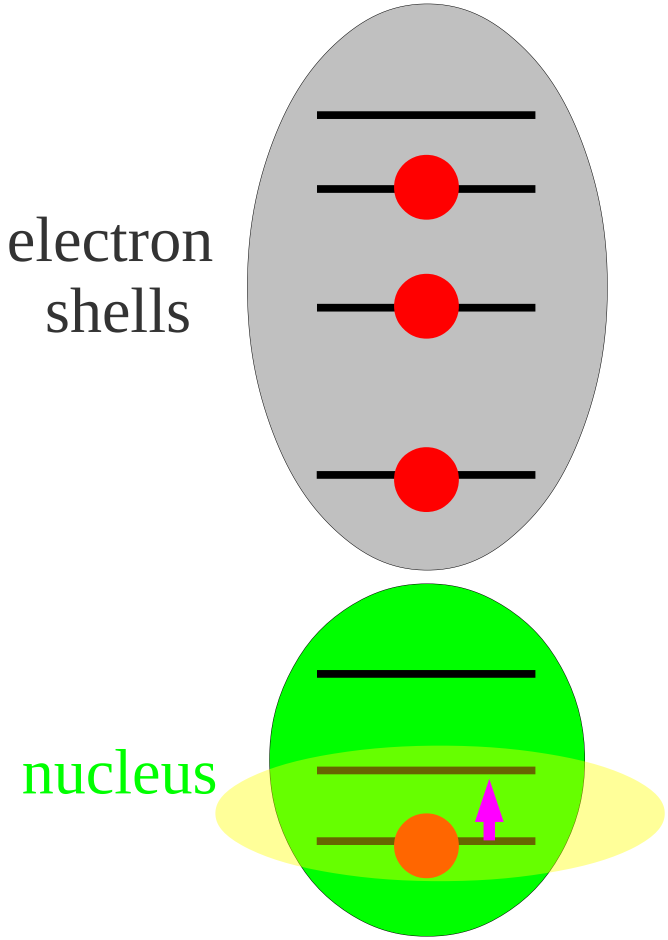
Introduction



Light-matter interactions

- IR/optical driving fields:
  excite/ionize outer electrons
- Higher frequencies/intensities:
  excite / ionize core electrons

Introduction



Light-matter interactions

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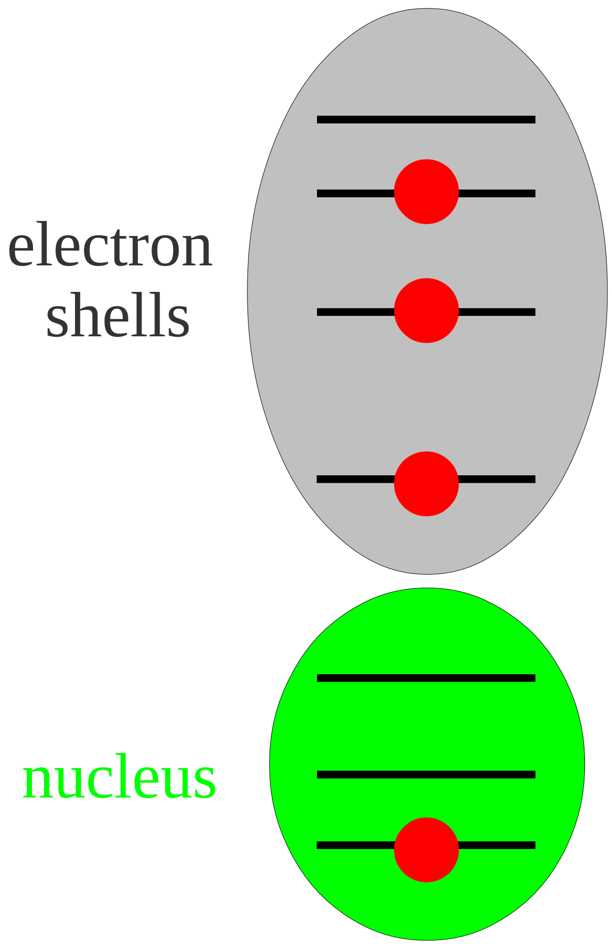
- Higher frequencies/intensities:
  excite / ionize core electrons
- Even higher frequencies/intensities:
  excite nucleus

Introduction



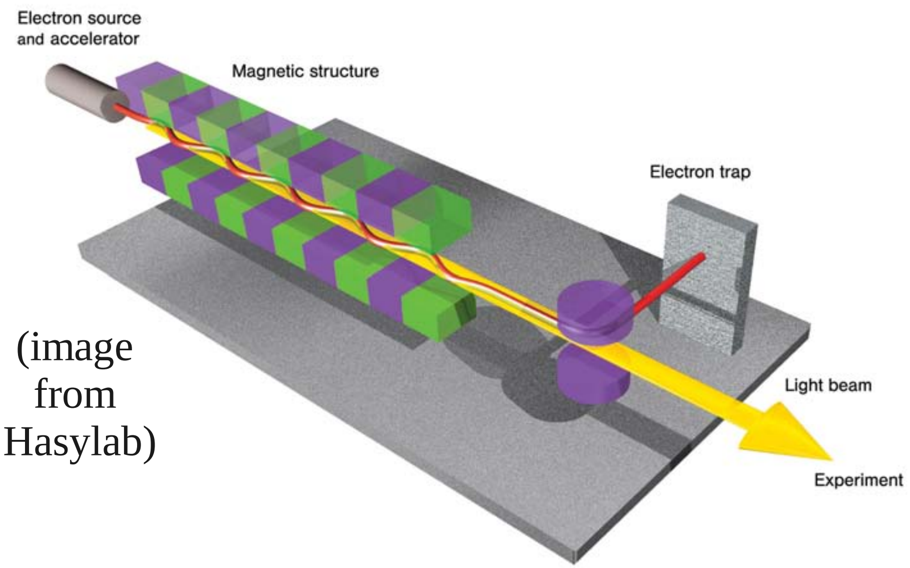
Light-matter interactions

- IR/optical driving fields:
  excite/ionize outer electrons
- Higher frequencies/intensities:
  excite / ionize core electrons
- Even higher frequencies/intensities:
  excite nucleus

What can be done is to a large degree determined by the availability of light sources

full quantum control ⟷ ? ⟷ uncontrolled pump + passive observation

Free electron laser



(image from Hasylab)

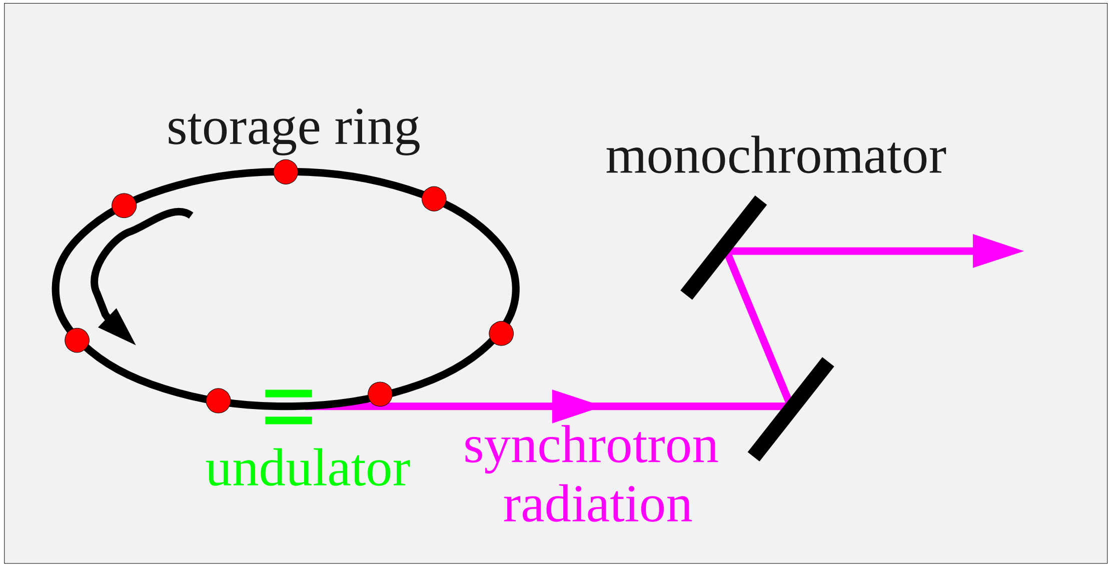
Working principle

- Photon energy up to few keV
- Full transverse coherence, upgrade to full longitudinal coherence possible
- High Brilliance
- Short pulses

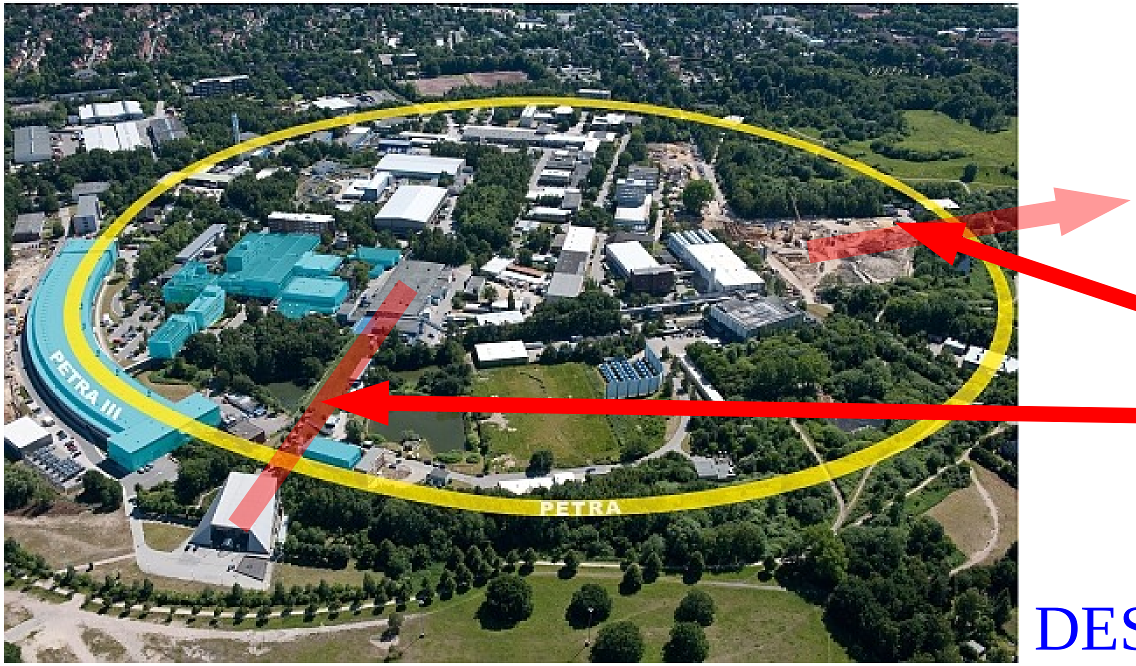
SLAC linear accelerator

(image from SLAC)

Synchrotron



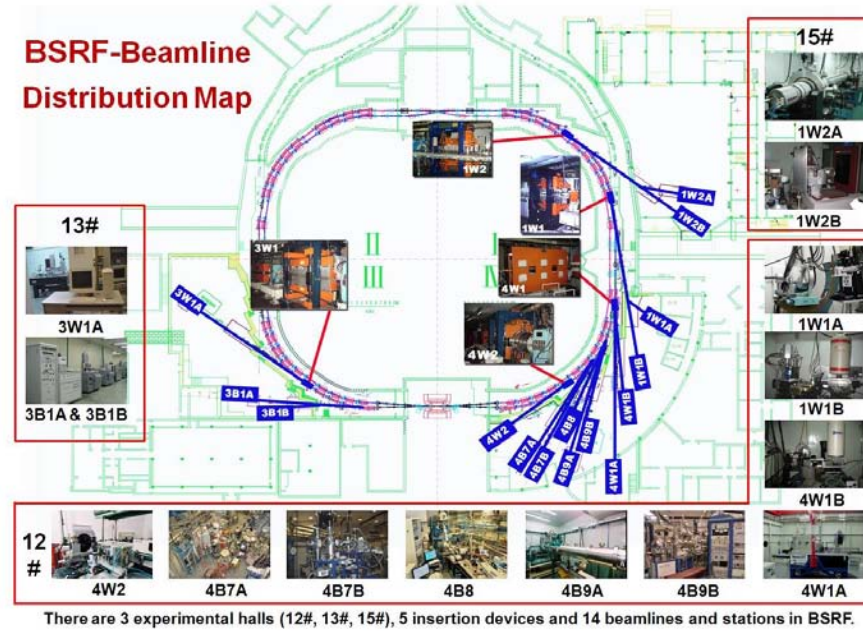
- Photon energy up to many MeV
- Some spatial coherence
- Little to no temporal coherence, but monochromator can be used
- High Brilliance
- Longer pulses



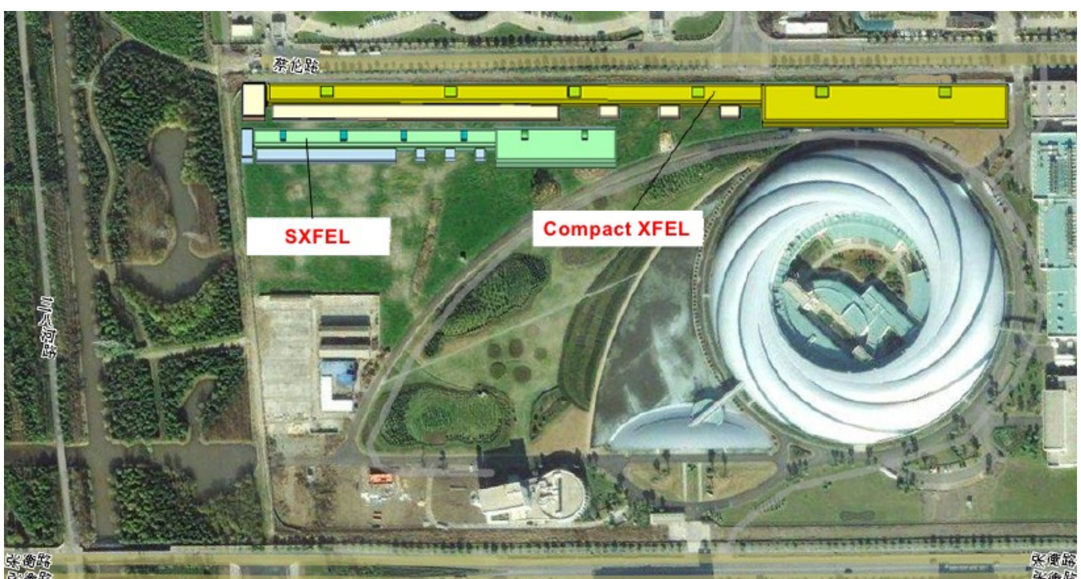
(image from DESY)

Novel light sources in China

National Synchrotron Radiation Laboratory (USTC, Hefei)



Beijing Synchrotron Radiation Facility (CAS)



Shanghai synchrotron facility
Free electron laser
(Shanghai, CAS)

New machines always bring new opportunities

Applications in the x-ray range

Quantum

- Quantum-enhanced measurements, e.g. sub-λ resolution, squeezing
- Foundations of quantum mechanics, e.g. entanglement of macroscopic objects

Nonlinear

- Enhanced spectroscopy and measurements
- Probe fragile targets
- Combine different frequencies, e.g. resonant photon + x-ray for high position resolution

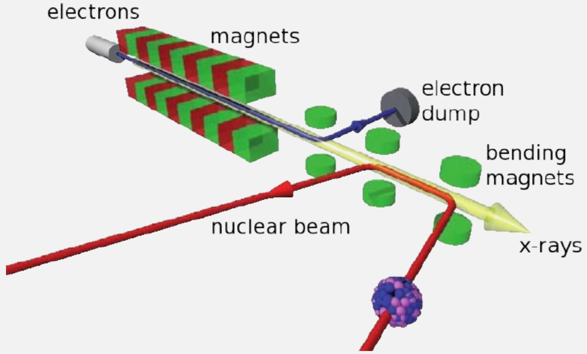
Control

- Enhanced sample preparation
- Design material properties
- Separate signal and background/noise

So far rough ideas only – essentially unexplored field

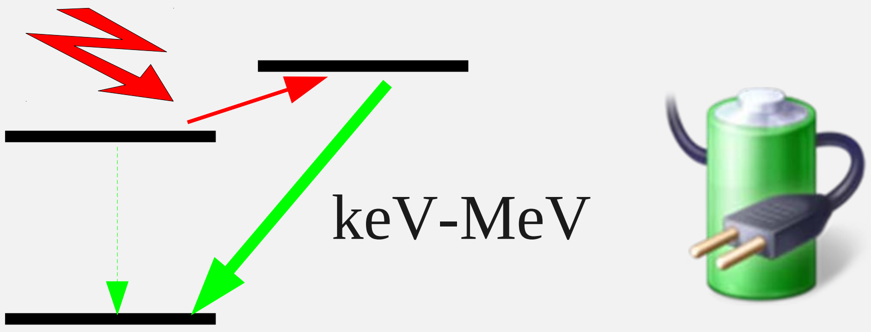
X-ray and γ-ray quantum optics @ MPIK

Direct laser driving of nuclei



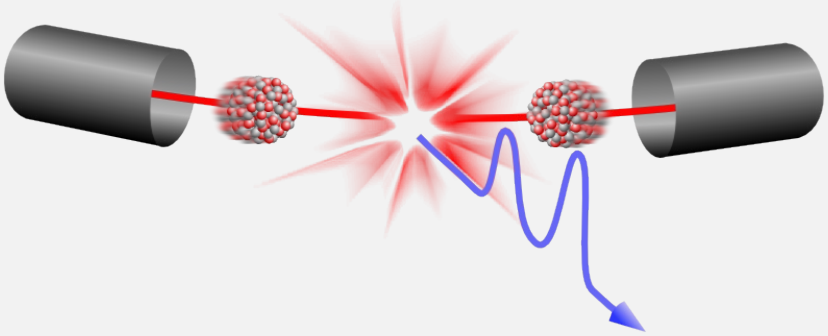
T. Bürvenich, J. Evers, C. H. Keitel,
PRL 96, 142501 (2006)

Isomer triggering



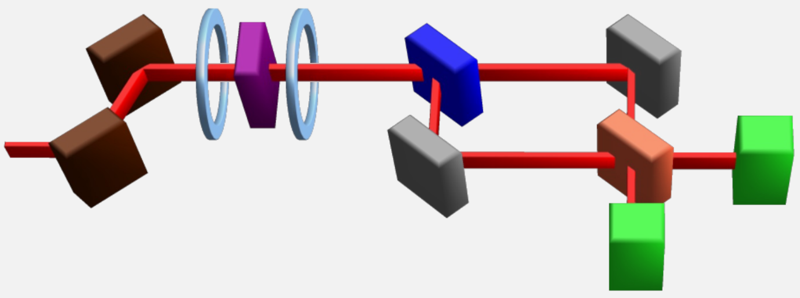
A. Pálffy, J. Evers, C. H. Keitel,
PRL 99, 172502 (2007)

Yoctosecond physics



A. Ipp, C. H. Keitel, J. Evers,
PRL 103, 152301 (2009)

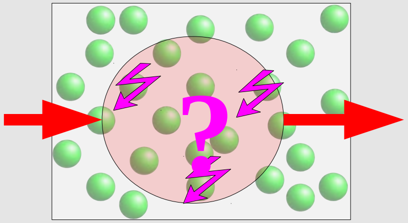
X-ray cooperative light scattering



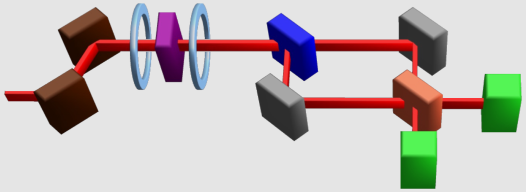
A. Pálffy, C. H. Keitel, J. Evers, PRL 103,
017401 (2009); PRB 83, 155103 (2011)

Outline

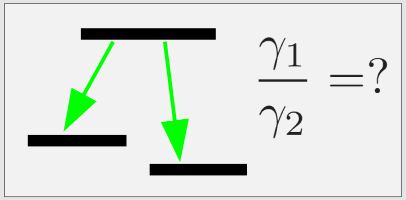
Introduction



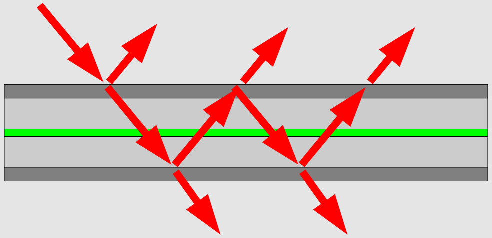
X-ray entanglement generation



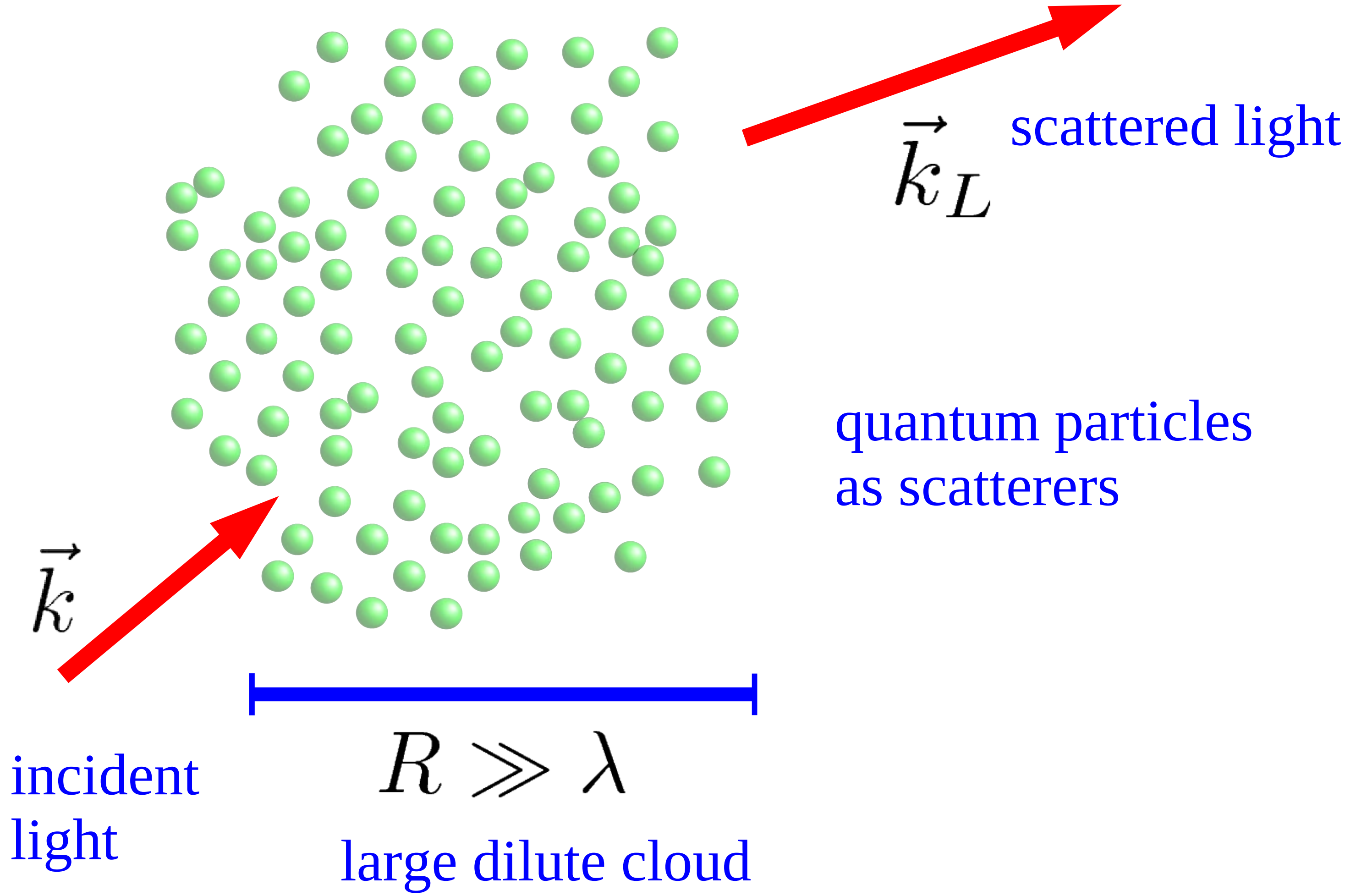
X-ray branching ratio control



Outlook: Engineering advanced level schemes

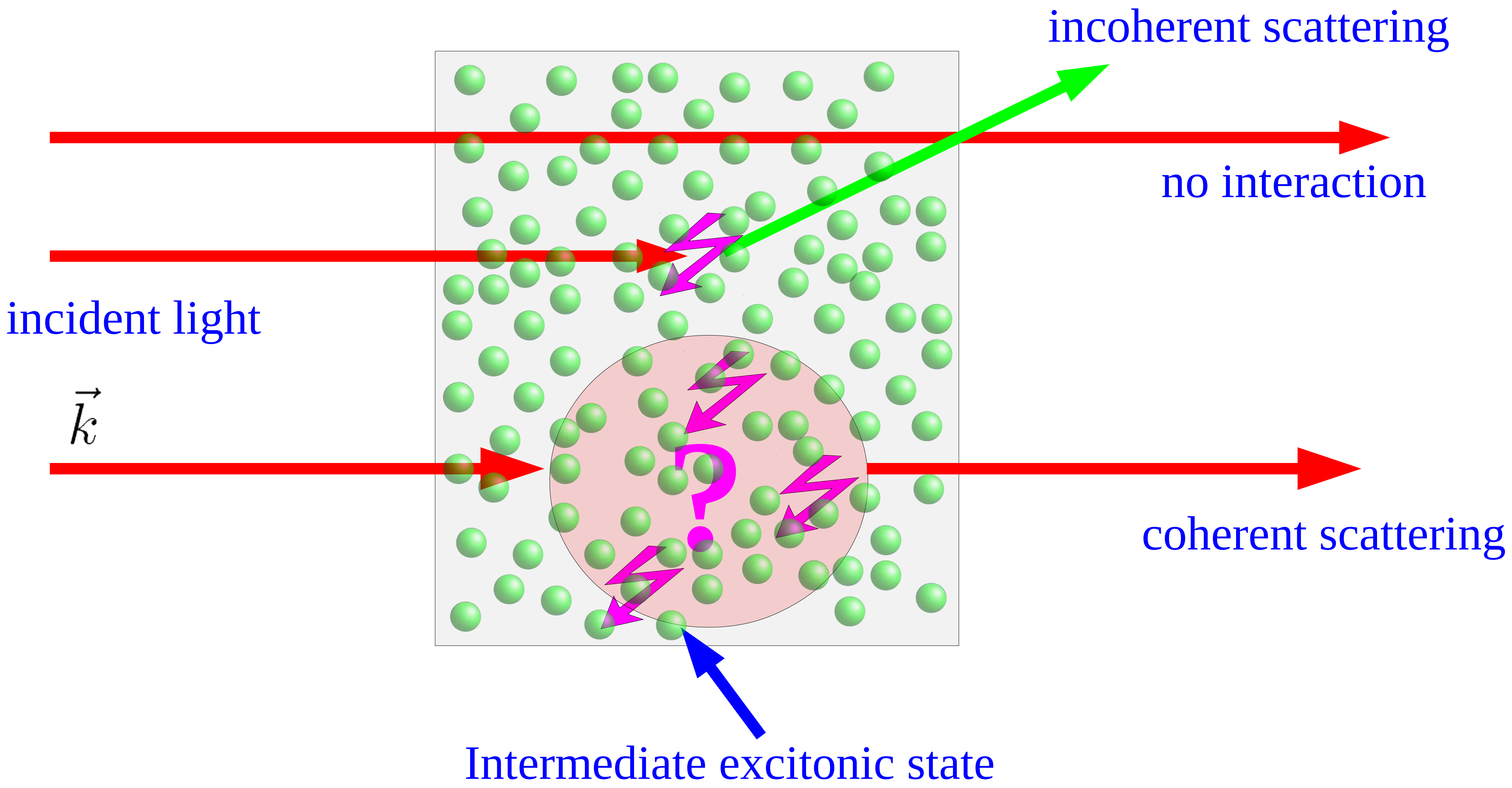


Cooperative light scattering



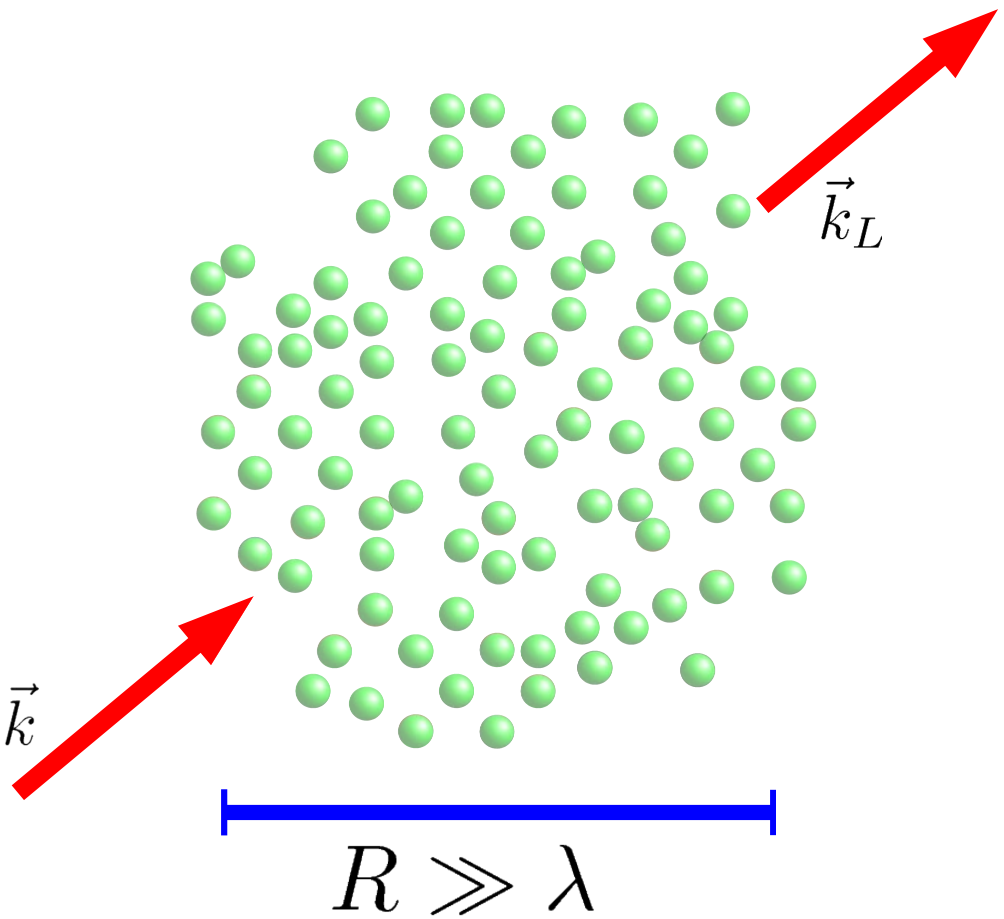
- no recoil
- stationary particles

Elementary processes



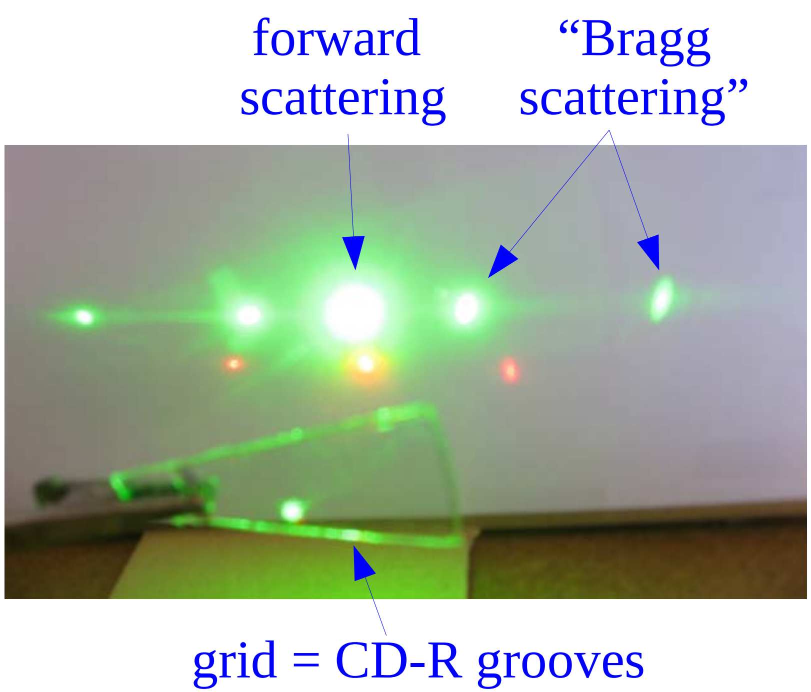
$$|\Psi\rangle = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} e^{i\vec{k}\vec{r}_i} |g_1, \ldots, g_{i-1}, e_i, g_{i+1}, \ldots, g_N\rangle$$

Coherent forward scattering

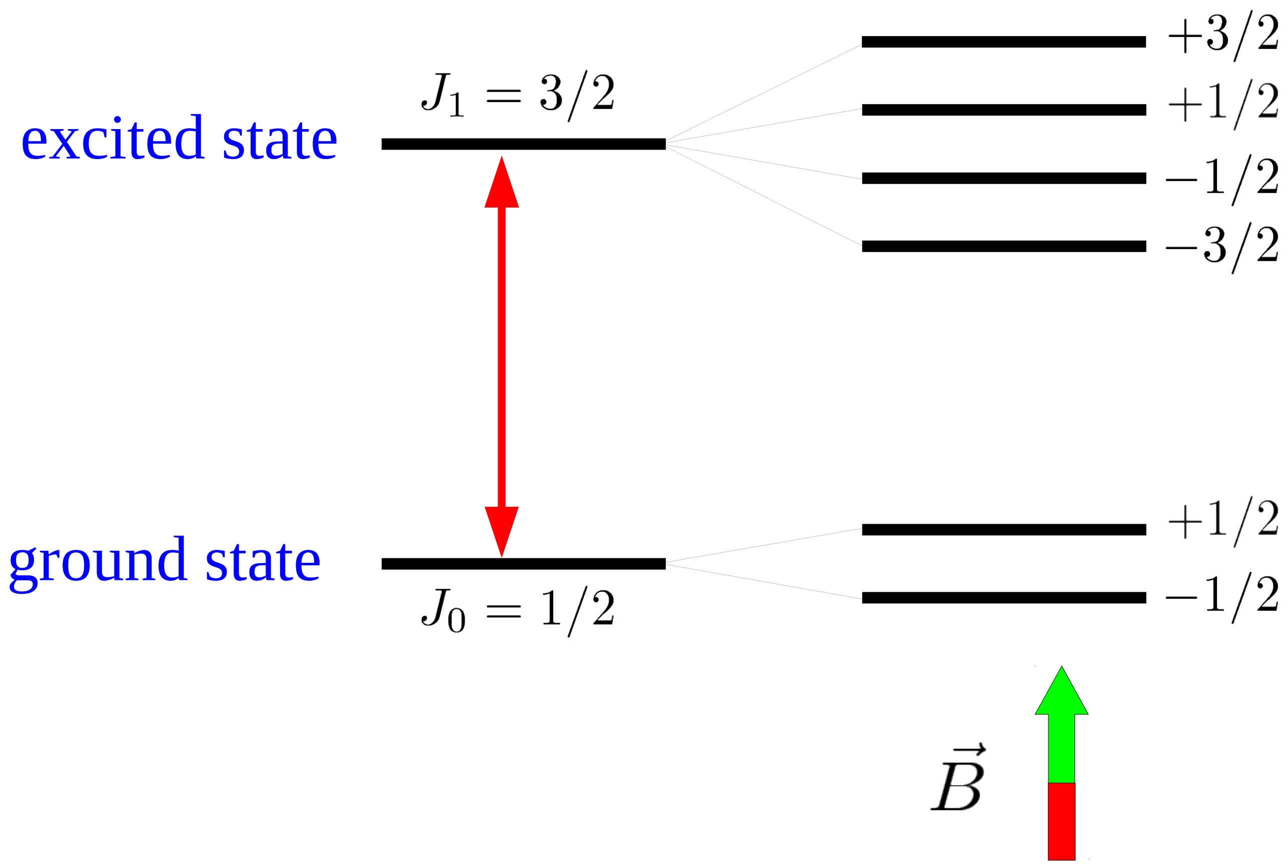


$$\lim_{N\to\infty} \sum_{i=1}^{N} e^{i(\vec{k}-\vec{k}_L)\vec{r}_i} \sim \delta(\vec{k}-\vec{k}_L)$$

- Coherent scattering occurs in forward direction
- Similarity to multi-slit / grid diffraction but constructive interference only in forward / Bragg direction



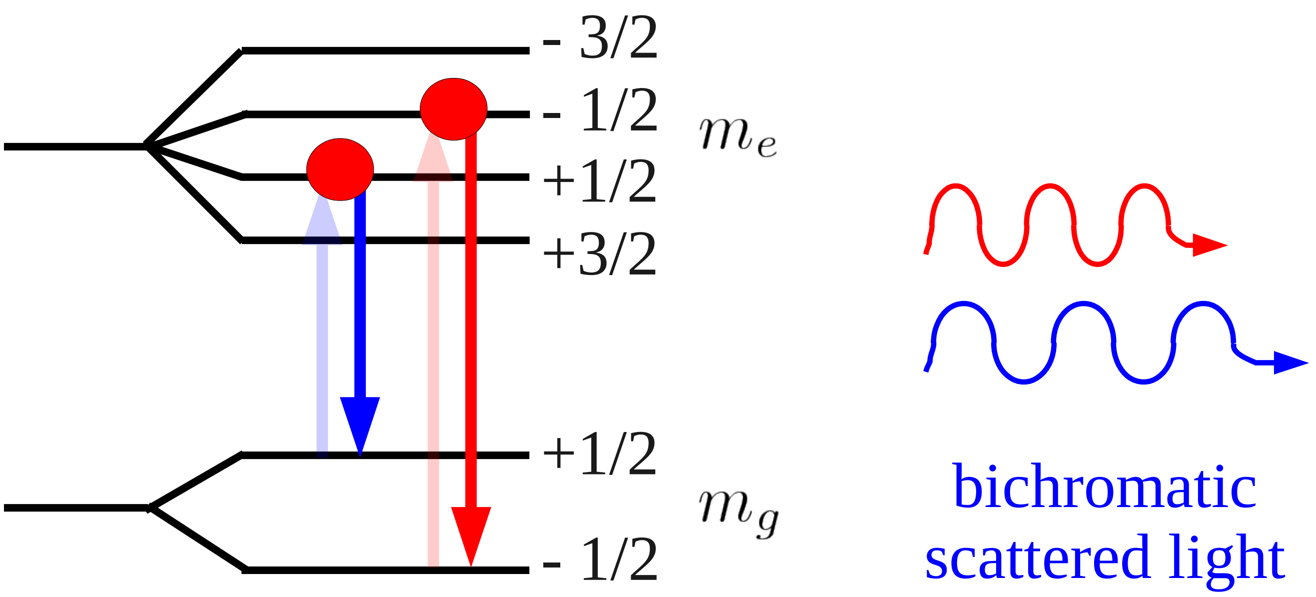
^{57}Fe iron Mößbauer transition



- magnetic dipole transition
- recoil suppressed due to Mößbauer effect

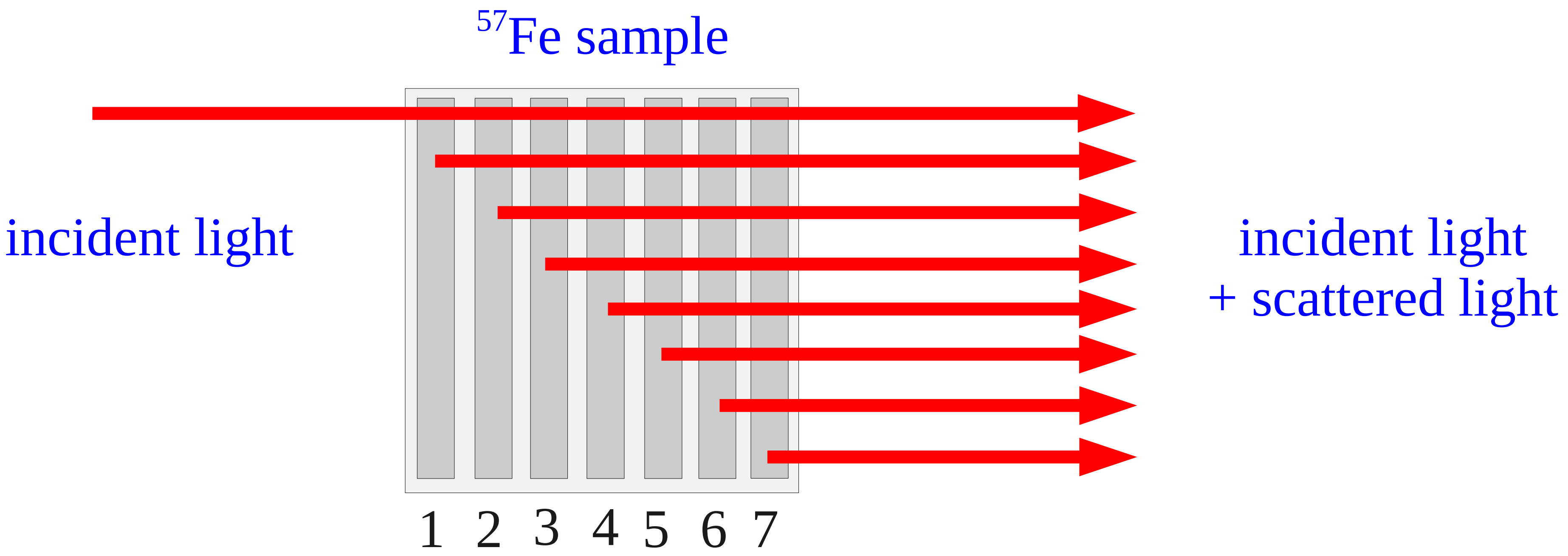
$$\lambda = 0.86 \text{ Å}$$
$$\hbar\omega_0 = 14.4 \text{ keV}$$
$$\hbar\Gamma = 4.7 \times 10^{-9} \text{ eV}$$
$$1/\Gamma = 141 \text{ ns}$$

Temporal beats



- Scattering on two transitions with same dipole moment, but different transition frequencies
- Expect beats in the time-dependent intensity

Multiple scattering



- As a model, separate sample into thin layers
- Due to forward scattering, first layer is driven only by incident field
- Layer n > 1 is in addition driven by “upstream” layers, causing phase shifts
- Initial phase synchronization due to incident pulse is dephased
- Alternative view: synchrotron excitation does not correspond to radiation eigenmode of the sample

J. P. Hannon and G. T. Trammell, Hyperf. Int. 123/124, 127 (1999)

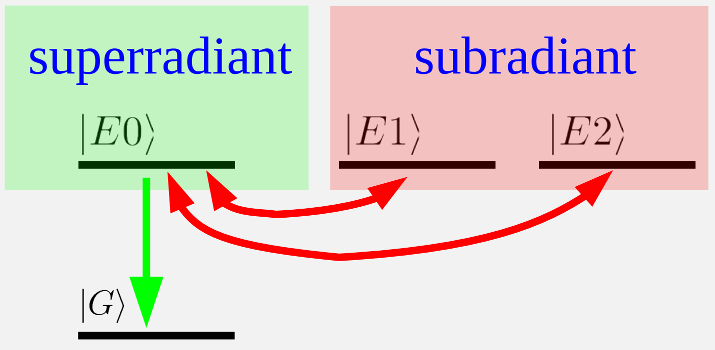
Superradiance

Dicke case (small dense sample)

$$|\Psi\rangle = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} |g_1, \ldots, g_{i-1}, e_i, g_{i+1}, \ldots, g_N\rangle$$

$$\langle G|\vec{d}|\Psi\rangle = \sqrt{N}\, \langle g_i|\vec{d}|e_i\rangle$$

$$\gamma \longrightarrow N\,\gamma$$



$$|G\rangle = |ggg\rangle$$

$$|E0\rangle = \frac{1}{\sqrt{3}}\left(|egg\rangle e^{i\vec{k}\vec{r}_1} + |geg\rangle e^{i\vec{k}\vec{r}_2} + |gge\rangle e^{i\vec{k}\vec{r}_3}\right)$$

$$|E1\rangle = \frac{1}{\sqrt{2}}\left(|egg\rangle e^{i\vec{k}\vec{r}_1} - |geg\rangle e^{i\vec{k}\vec{r}_2}\right)$$

$$|E2\rangle = \frac{1}{\sqrt{6}}\left(|egg\rangle e^{i\vec{k}\vec{r}_1} + |geg\rangle e^{i\vec{k}\vec{r}_2} - 2|gge\rangle e^{i\vec{k}\vec{r}_3}\right)$$

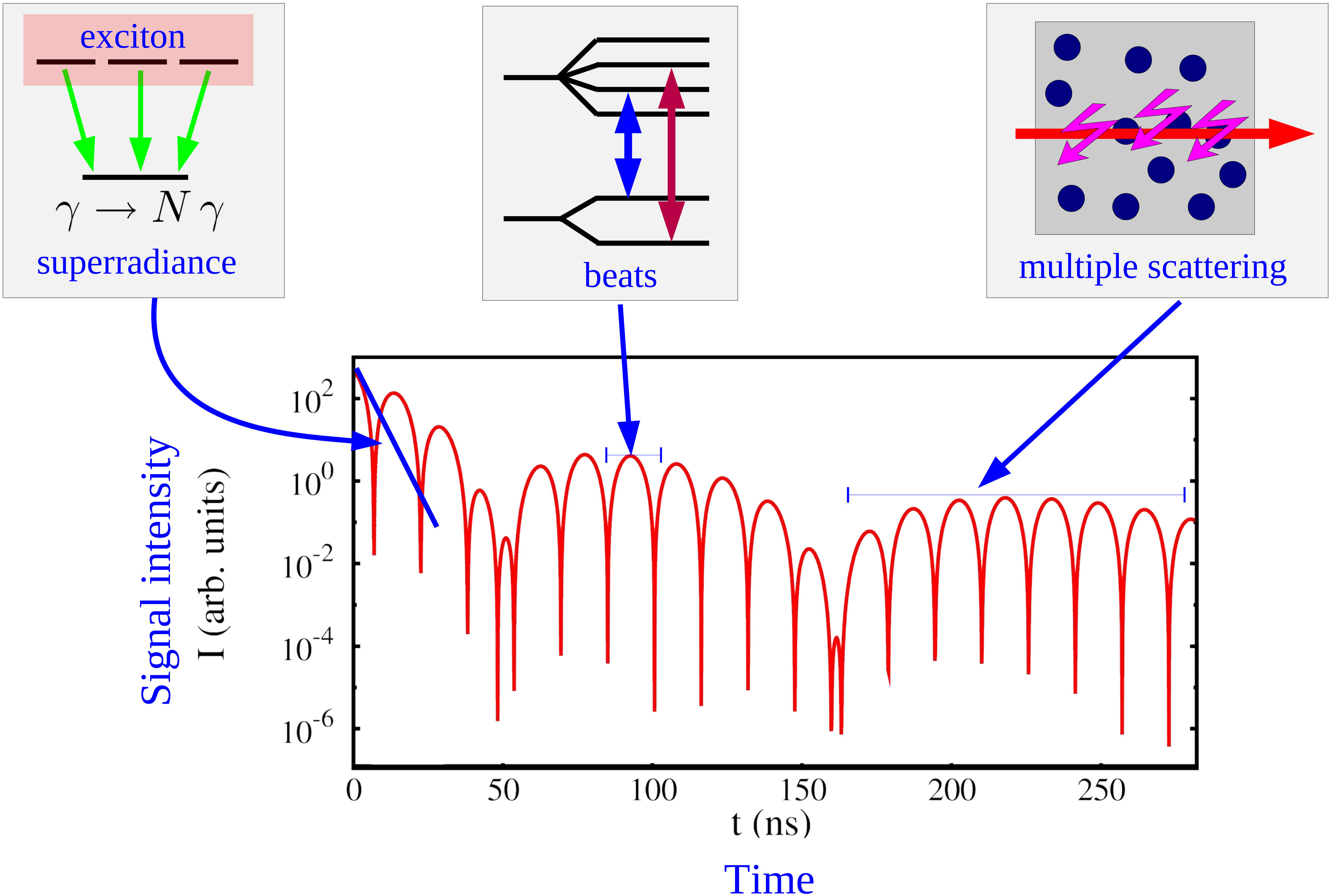
NFS case (large dilute sample)

$$|\Psi\rangle = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} e^{i\vec{k}\vec{r}_i} |g_1, \ldots, g_{i-1}, e_i, g_{i+1}, \ldots, g_N\rangle$$

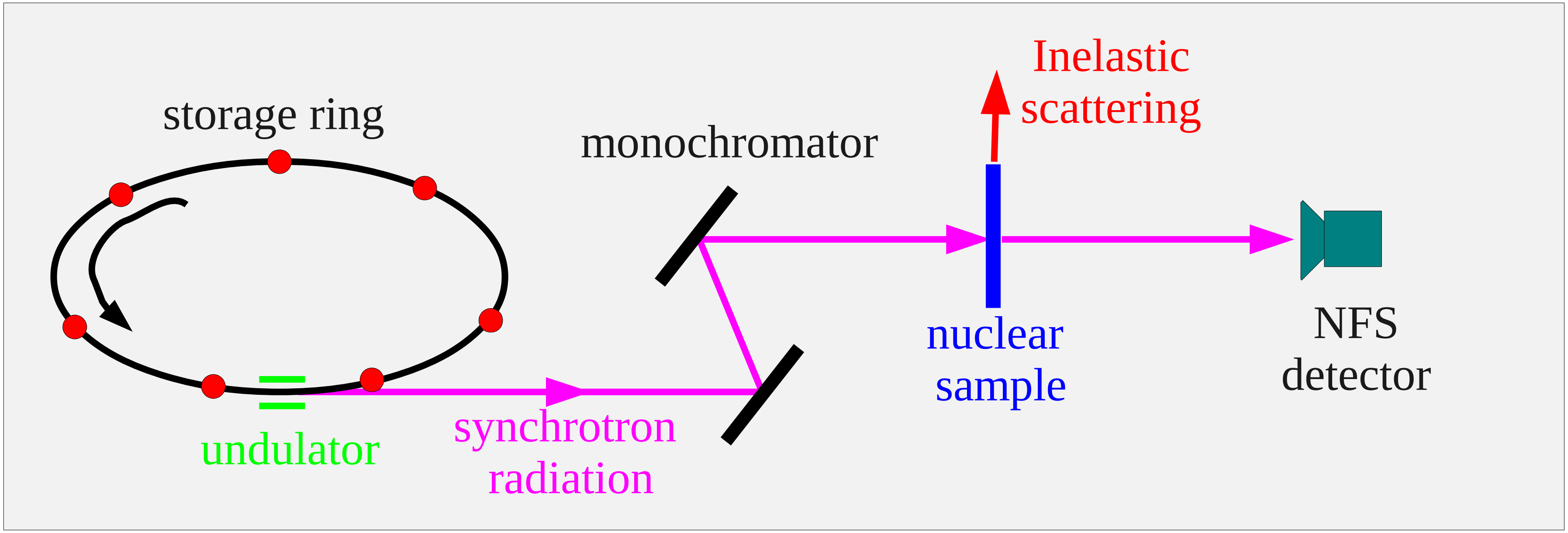
- Superradiant state dynamically coupled to subradiant states
- Imperfect preparation of superradiant state in thick samples → dephasing

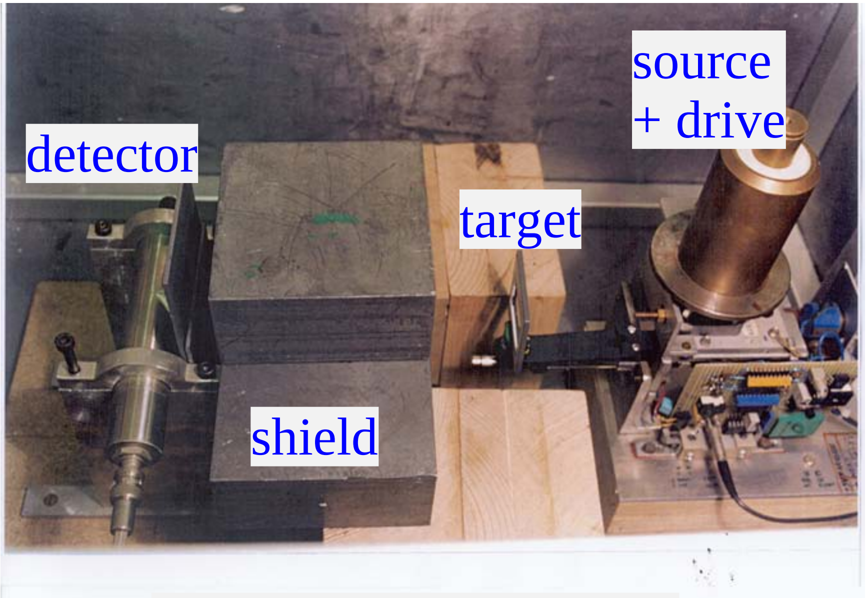
M. O. Scully et al., Phys. Rev. Lett. 96, 010501 (2006)

(Some) characteristic features in NFS spectra

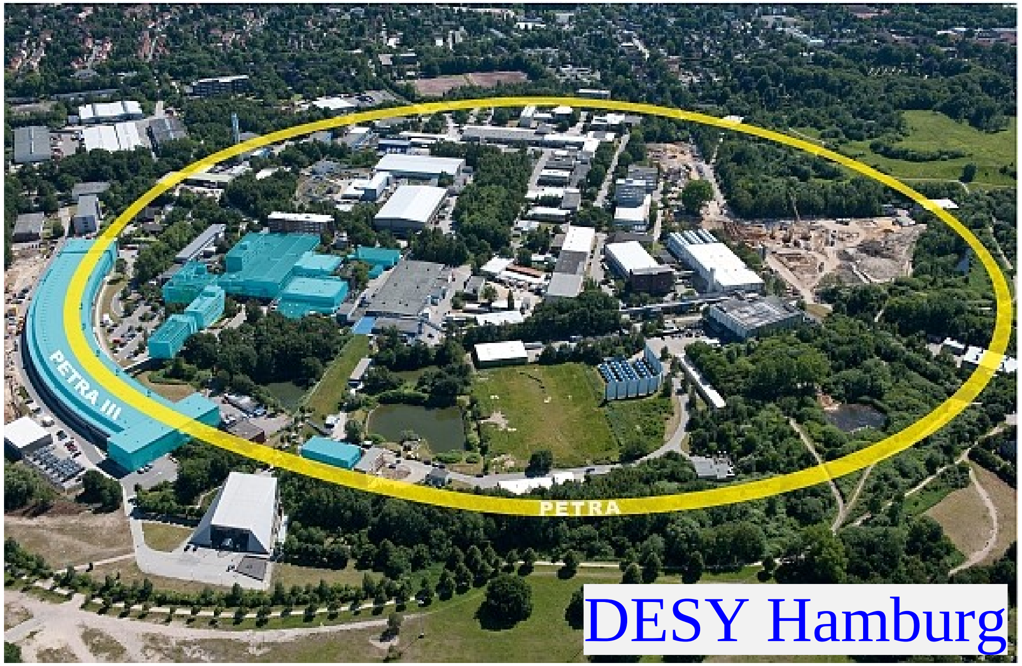


Experimental realization





Student lab Uni Mailand



DESY Hamburg

Example: Coherent control via magnetic switching

- The level structure depends on applied magnetic field: Zeeman splitting
- In certain crystals (e.g. $FeBO_3$), the magnetic crystal field is very strong ($\sim$ 30 T), and can be aligned using a weak external field (few Gauss)
- This allows to switch the direction of a very strong effective magnetic field in few ns in the lab

VOLUME 77, NUMBER 15 PHYSICAL REVIEW LETTERS 7 OCTOBER 1996

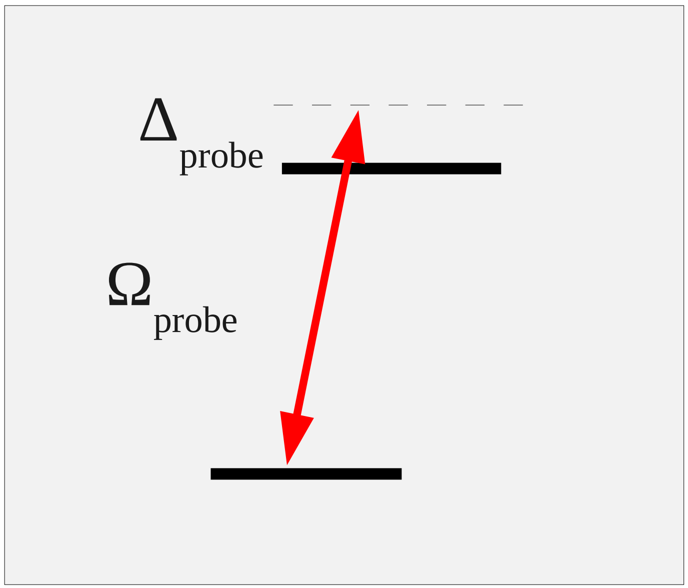
Storage of Nuclear Excitation Energy through Magnetic Switching

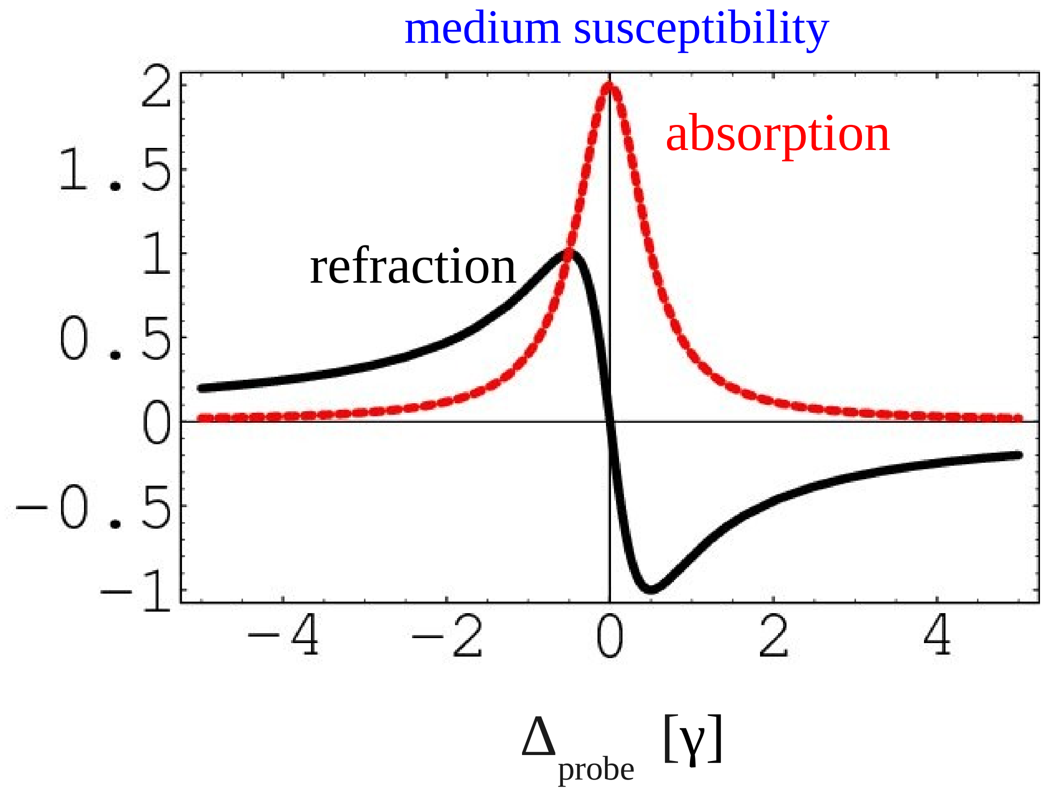
Yu. V. Shvyd'ko,[1] T. Hertrich,[2] U. van Bürck,[2] E. Gerdau,[1] O. Leupold,[1] J. Metge,[1] H. D. Rüter,[1] S. Schwendy,[1] G. V. Smirnov,[3] W. Potzel,[2] and P. Schindelmann[2]
[1]*II. Institut für Experimentalphysik, Universität Hamburg, D-22761 Hamburg, Germany*
[2]*Physik-Department E15, Technische Universität München, D-85748 Garching, Germany*
[3]*RRC, "Kurchatov Institute", SU-1123182 Moscow, Russia*
(Received 8 May 1996)

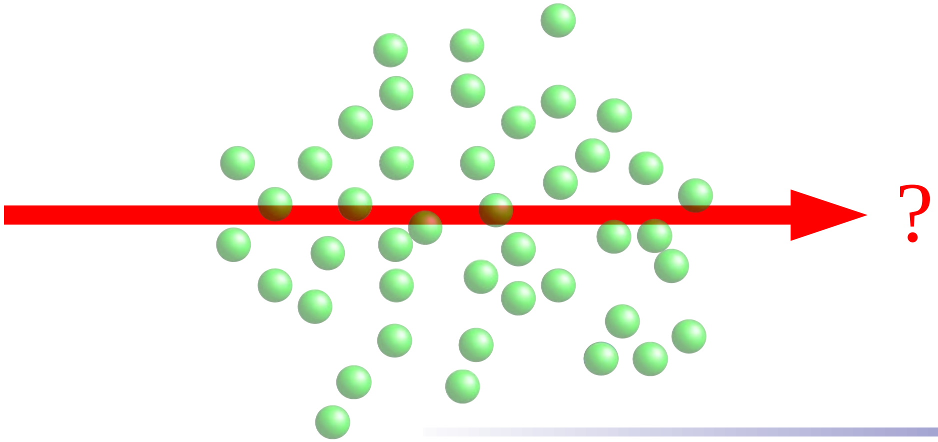
The decay rate of ^{57}Fe nuclei in an $^{57}FeBO_3$ crystal excited by 14.4 keV synchrotron radiation pulses was controlled by switching the direction of the crystal magnetization. Abrupt switching some nanoseconds after excitation suppresses the coherent nuclear decay. Switching back at later times restores it, starting with an intense radiation spike. The enhanced delayed reemission is due to the release of the energy stored during the period of suppression. Suppression and restoration originate from drastic changes of the nuclear states and of the interference within the nuclear transitions.

HASYLAB F4 beam line Phys. Rev. Lett. 77, 3232 (1996)

Optical response of a single resonance

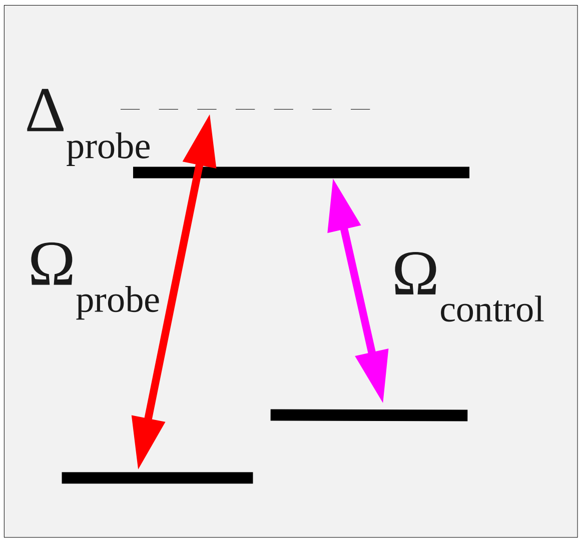


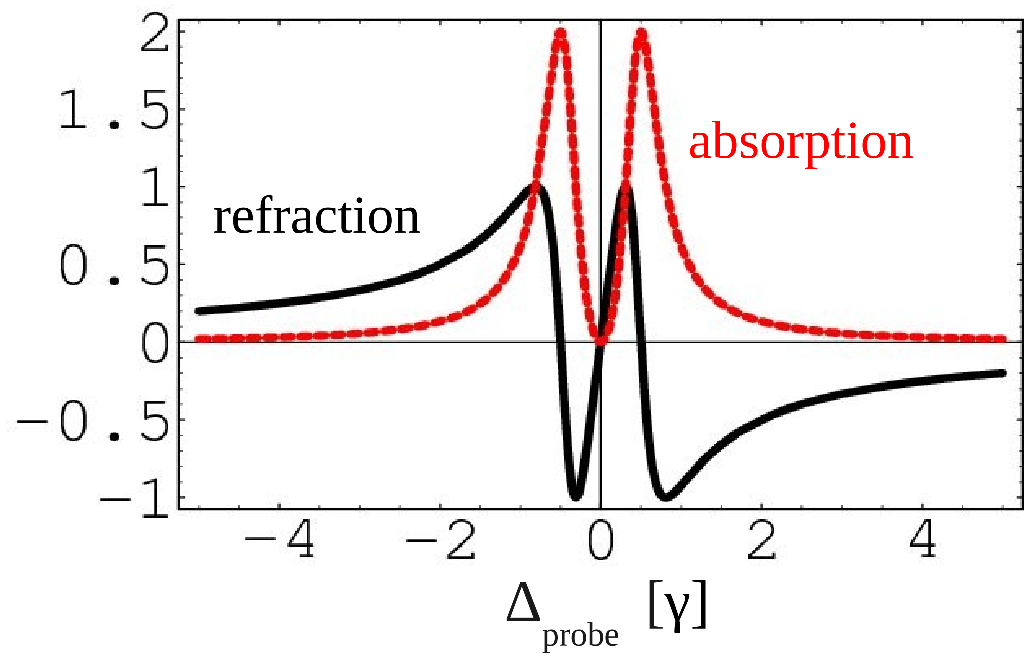




Electromagnetically induced transparency

Three-level Λ system





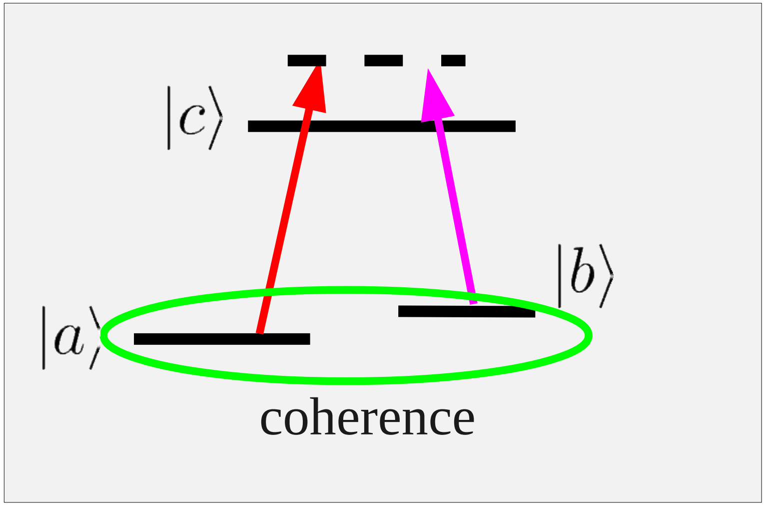
Medium is rendered transparent by shining light on it!

EIT is an archetype quantum optical effect with a multitude of applications

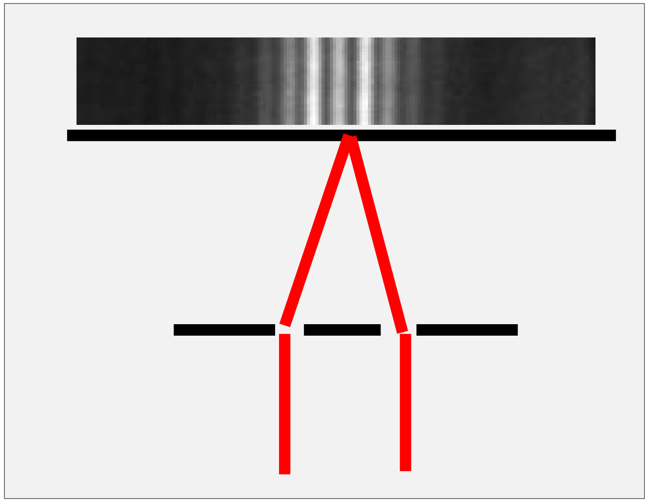
S. Harris, Physics Today 50, 36 (1997); M. Fleischhauer et al., Rev. Mod. Phys. 77, 633 (2005)

Electromagnetically induced transparency

Interpretation as coherence/interference effect:



EIT



double slit

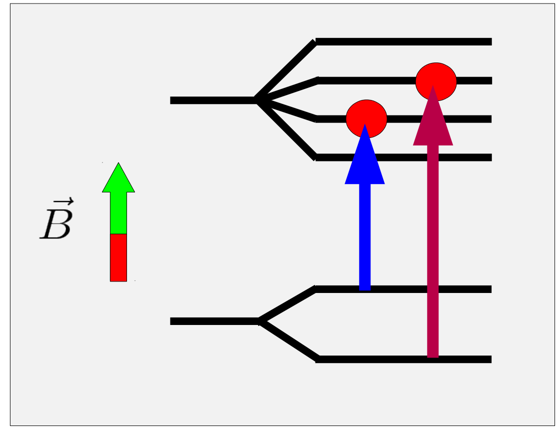
If EIT conditions are satisfied:

- laser fields drive atom to coherent superposition of $|a\rangle$ and $|b\rangle$
- interference: amplitudes for $|a\rangle \rightarrow |c\rangle$ and $|b\rangle \rightarrow |c\rangle$ cancel

no excitation of
the atom due to
destructive interference

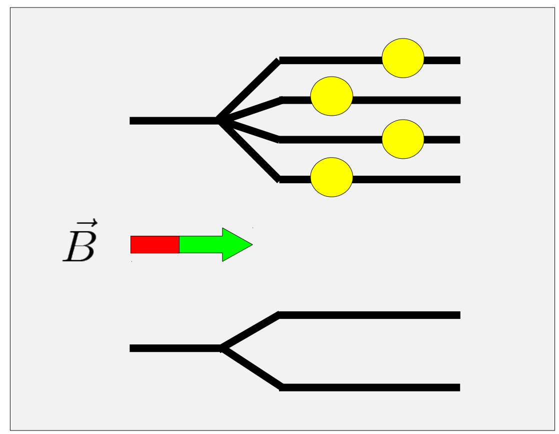
Coherent control of the exciton

Excite the sample



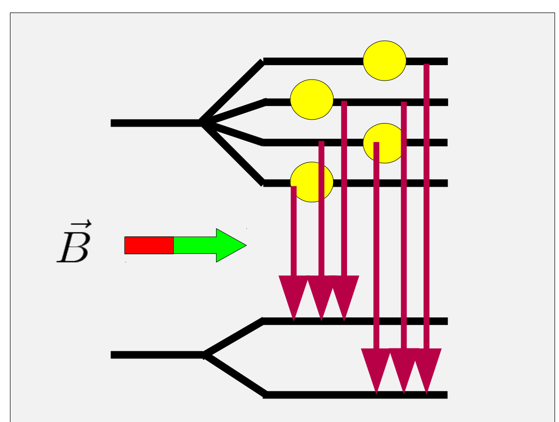
Rotate quantization axis

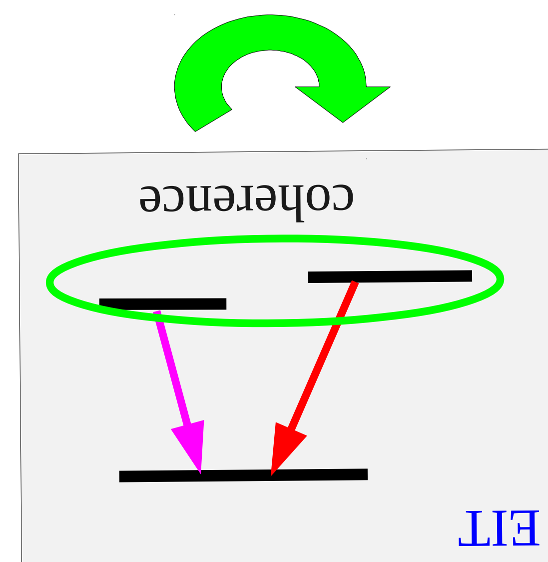
- Rotate applied magnetic field
- Experiment: 30T in 5ns possible in certain crystals



Deexcitation

- Destructive interference of all pathways possible
- Analogy to electromagnetically induced transparency

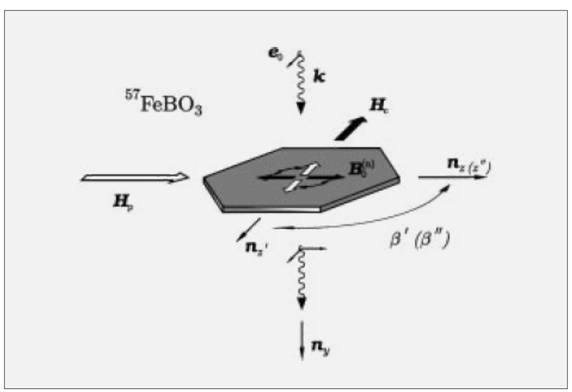




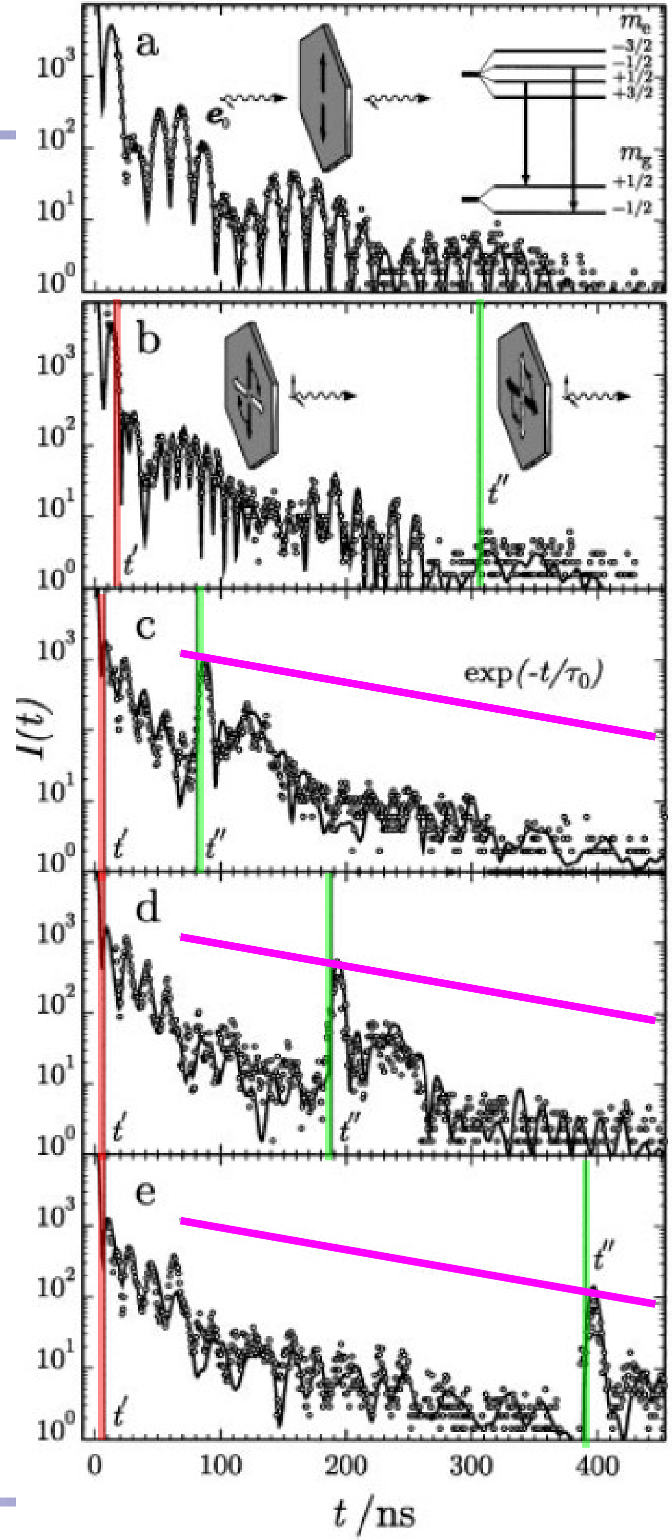
Control of coherent NFS

Experimental verification:

- Control of coherent NFS possible
- The coherent decay is (almost) fully suppressed after switching
- Revival of coherent decay after switching back
- Primary limitation: incoherent decay with natural lifetime



Yu. V. Shvyd'ko et al.,
Phys. Rev. Lett. 77, 3232 (1996)



No switching

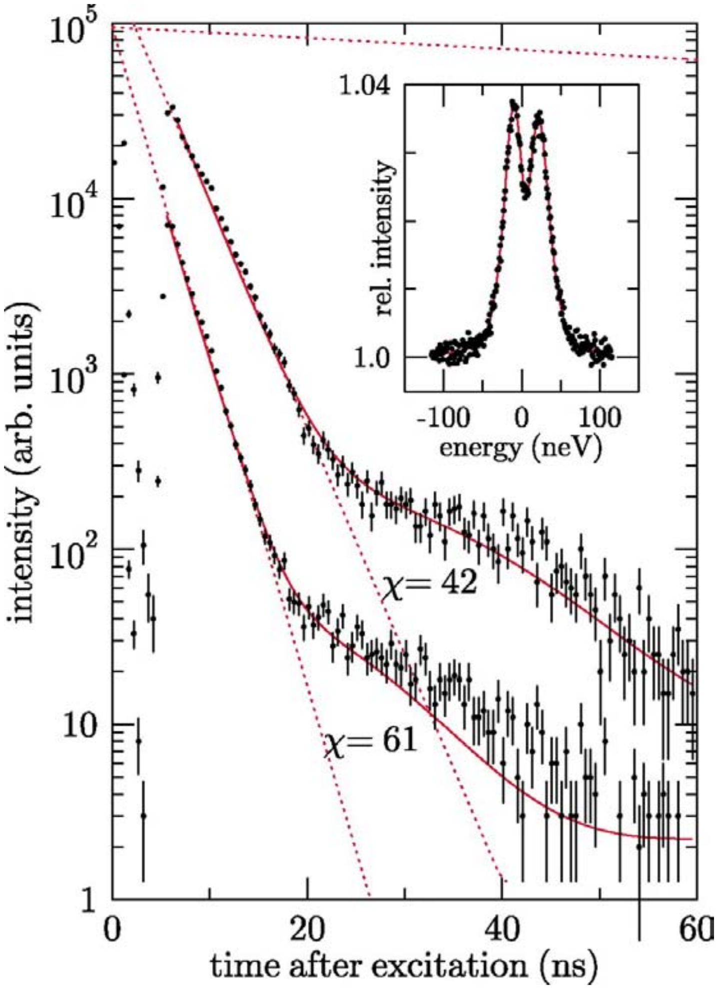
Apply switching

Switch back

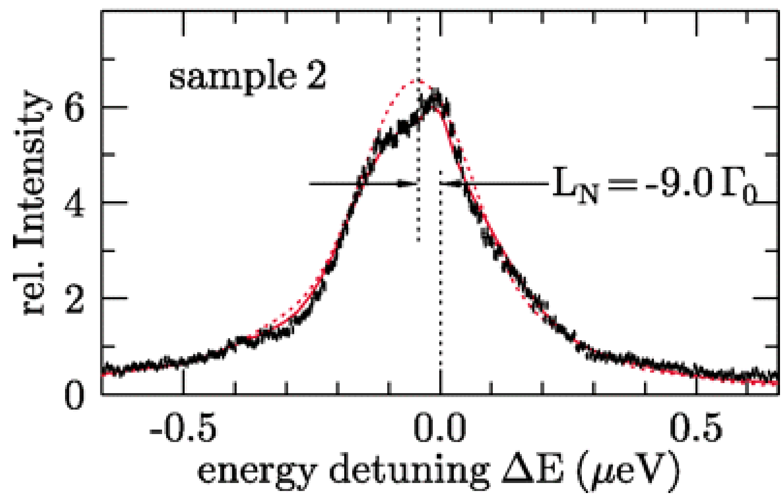
Decay with natural life time

Recent experiment: Collective Lamb Shift

- Lamb shift due to virtual photon exchange in ensembles of atoms
- Experimentally observed with nuclei using forward scattering
- Experimental challenge: Prepare purely superradiant state in thick sample; solution: embed nuclei in low-q cavity



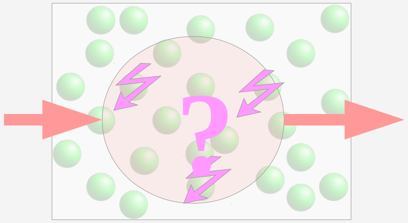
Lamb shift



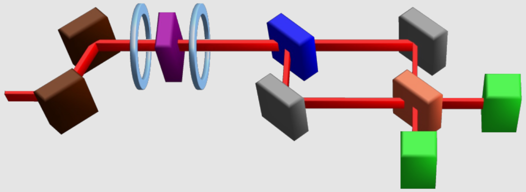
Röhlsberger et al, Science 328, 1248 (2010)

Outline

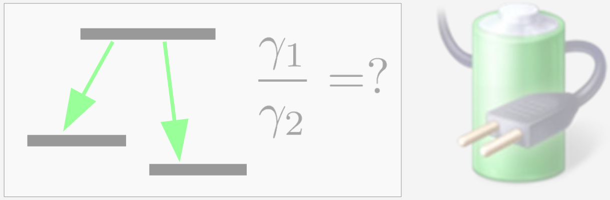
Introduction



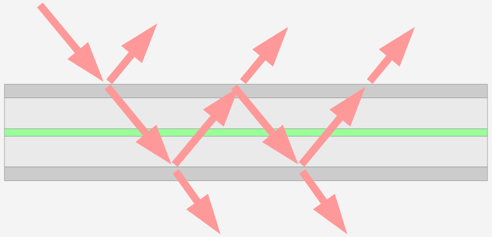
X-ray entanglement generation



X-ray branching ratio control



Outlook: Engineering advanced level schemes



keV single photon entanglement

Motivation

- Build up on experimentally demonstrated technique of nuclear switching
- Establish coherent control of x-rays on the single photon level
- First step towards nonlinear and quantum x-ray science
- High photon momentum: x-ray optomechanics, entanglement with more macroscopic objects
- More general: New parameter ranges, more complex quantum systems, more robust photons, less thermal background noise

Single photon entanglement

- Single photon impinging on 50/50 beam splitter gives output

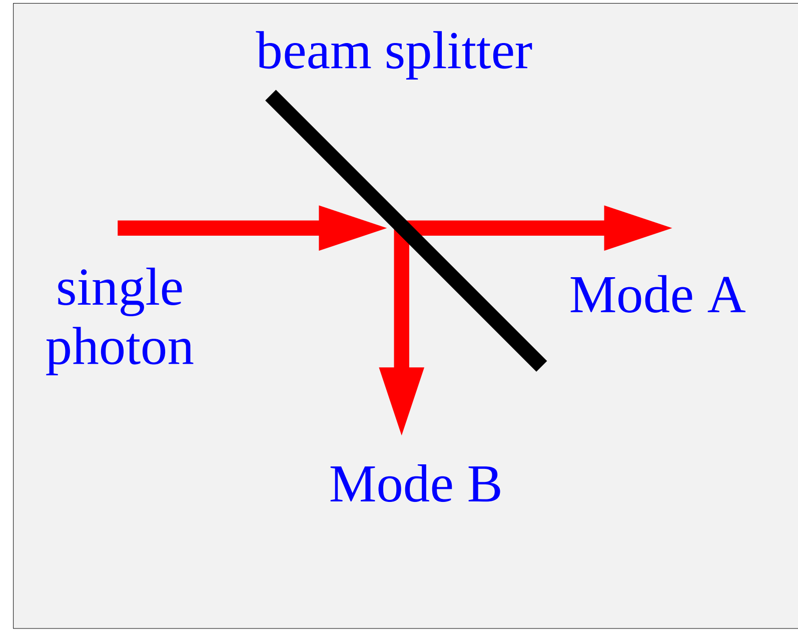
$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle_A|1\rangle_B + |1\rangle_A|0\rangle_B\right)$$

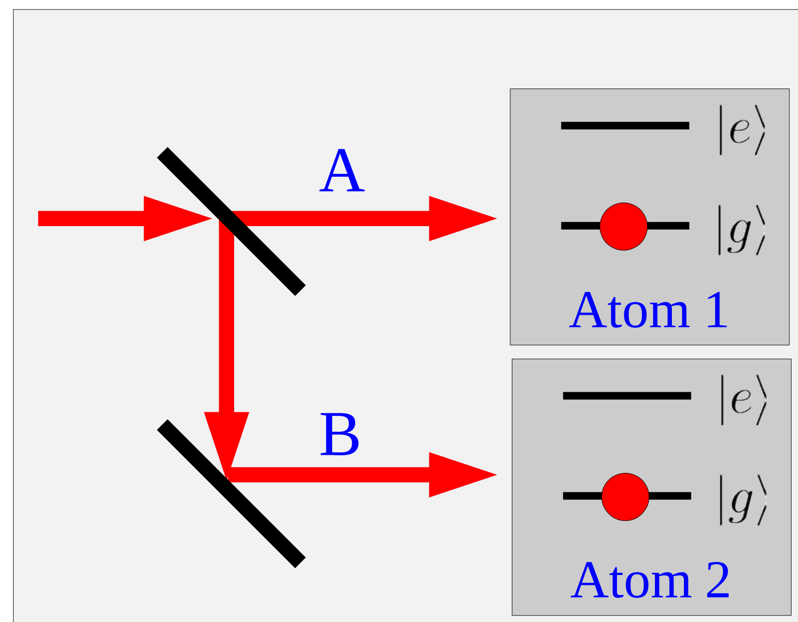
- The single photon entangles the two field modes A and B - the photon itself is not entangled

- Applications like Bell violation, teleportation etc. have been proposed

- Can be converted to other forms, e.g. "regular" entanglement between atoms

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|g_1 e_2\rangle + |e_1 g_2\rangle\right)$$





S. J. van Enk, Phys. Rev. A 67, 022303 (2003)

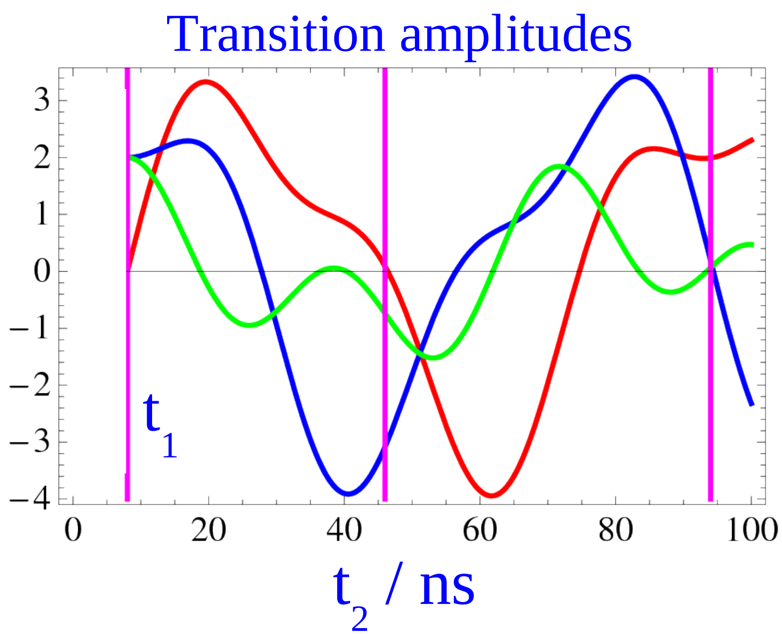
Advanced magnetic switching schemes

Rotation angle

- Determines new quantization axis and superposition states

Timing

- Important due to different transition energies
- Determine whether constructive/destructive interference occurs
- Example: Suppression at t_1 , how does t_2 affect further evolution?



$$\left\{\frac{1}{2} \to \frac{1}{2}, -\frac{1}{2} \to -\frac{1}{2}\right\}$$ linear

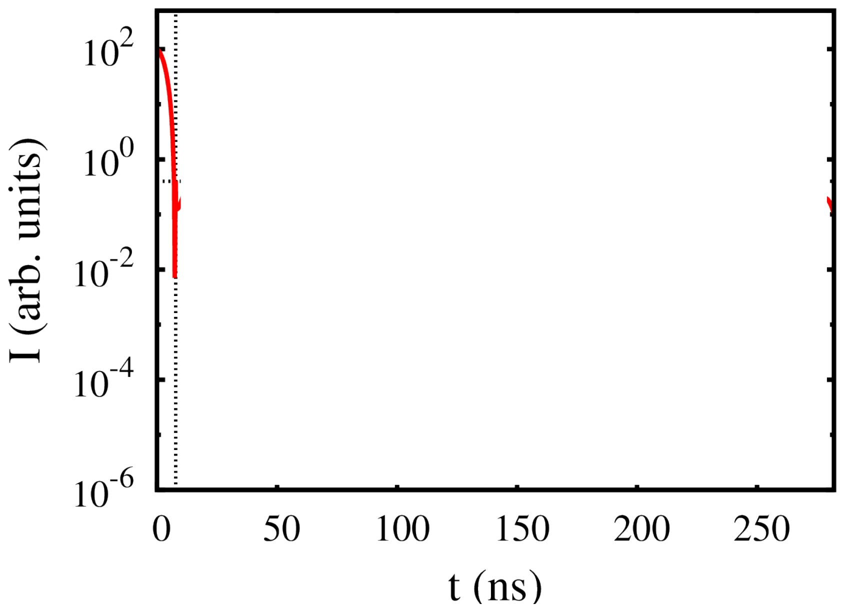
$$\left\{-\frac{1}{2} \to \frac{1}{2}, \frac{1}{2} \to -\frac{1}{2}\right\}$$ circular

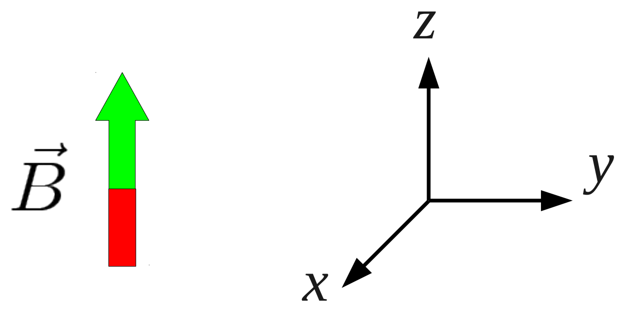
$$\left\{\frac{3}{2} \to \frac{1}{2}, -\frac{3}{2} \to -\frac{1}{2}\right\}$$ circular

A. Palffy and J. Evers, J. Mod. Opt. 57, 1993 (2010)

Step 1: Synchrotron excitation

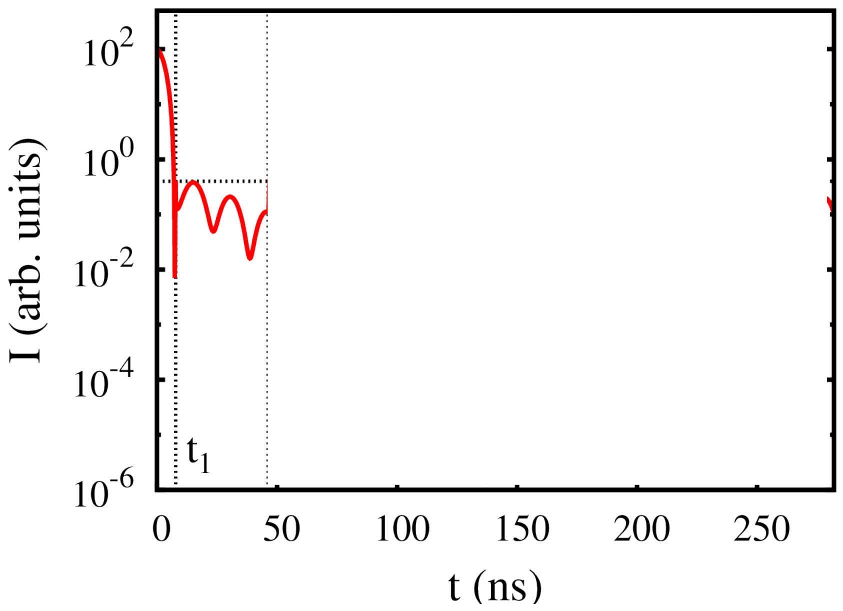
- Initially, magnetic field is in z direction



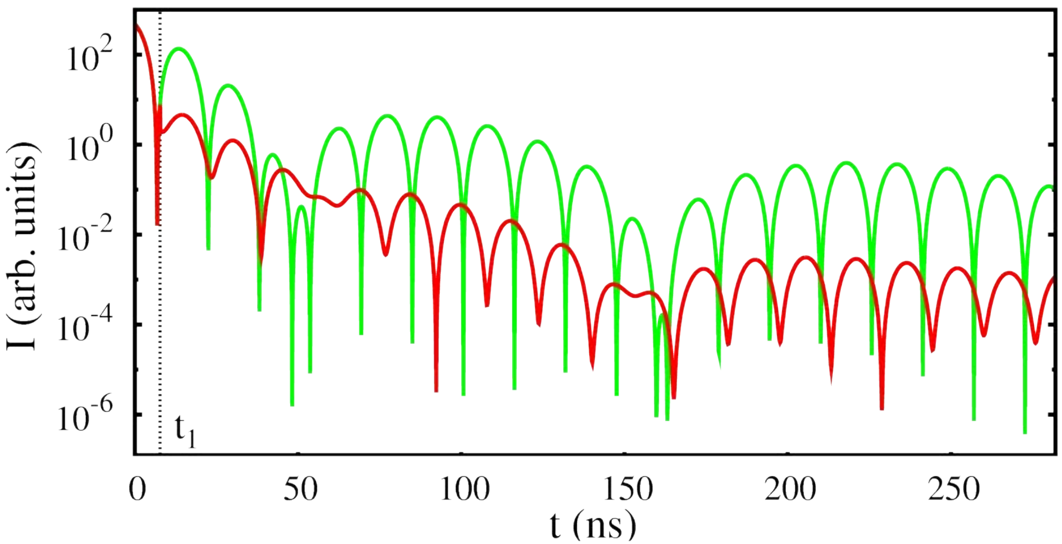


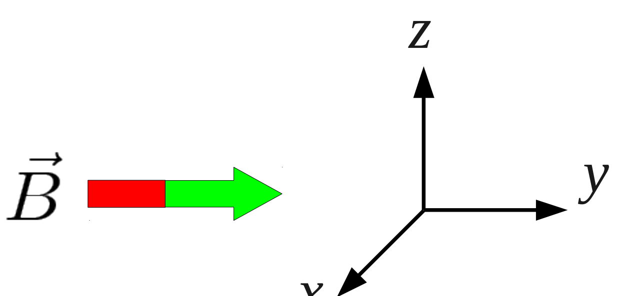
Step 2: Canceling coherent decay

- Initially, magnetic field is in z direction
- At time t_1, cancel decay by rotating into y direction



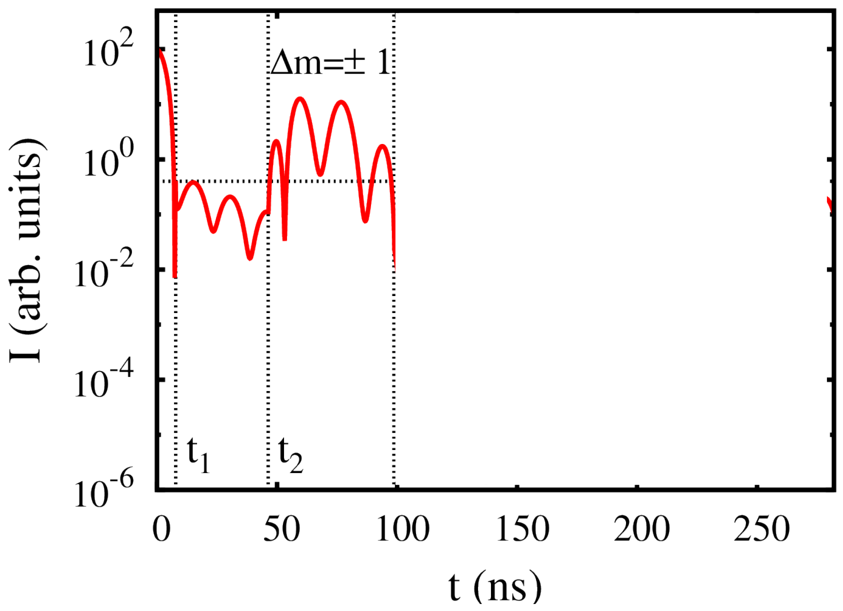
no switching - switching

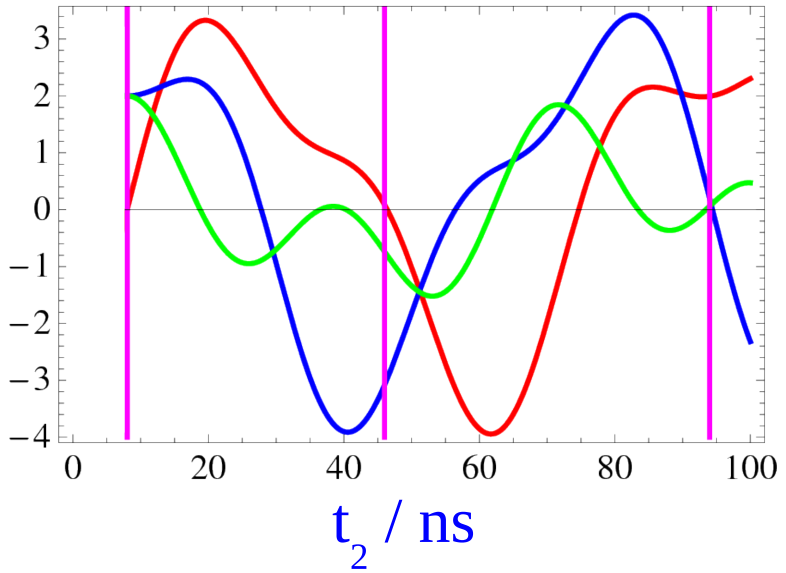




Step 3: Releasing circular polarization

- Initially, magnetic field is in z direction
- At time t_1, cancel decay by rotating into y direction
- At time t_2, enable decay on
  $$\Delta m = \pm 1$$
  but continue to suppress
  $$\Delta m = 0$$

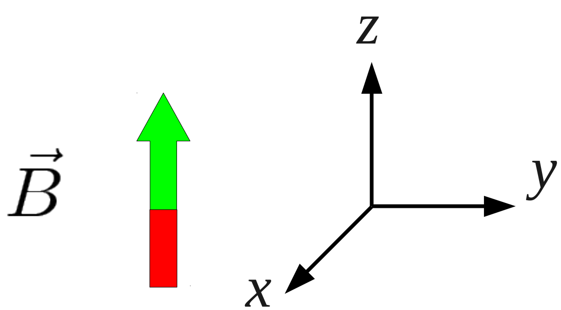




$$\left\{\frac{1}{2} \to \frac{1}{2}, -\frac{1}{2} \to -\frac{1}{2}\right\}$$

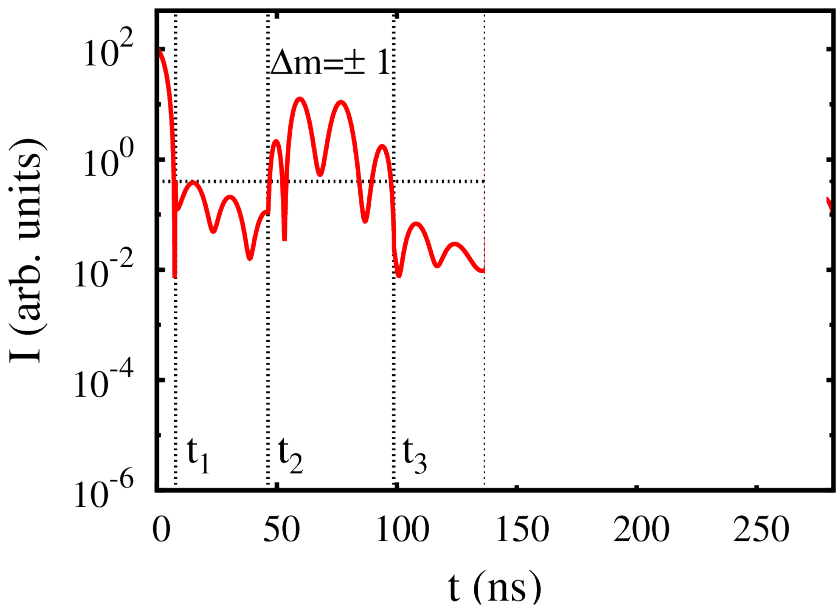
$$\left\{-\frac{1}{2} \to \frac{1}{2}, \frac{1}{2} \to -\frac{1}{2}\right\}$$

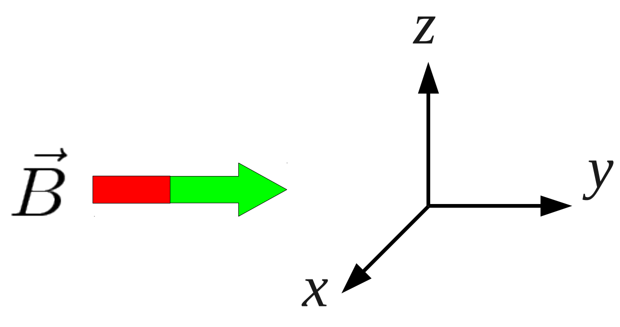
$$\left\{\frac{3}{2} \to \frac{1}{2}, -\frac{3}{2} \to -\frac{1}{2}\right\}$$



Step 4: Canceling coherent decay

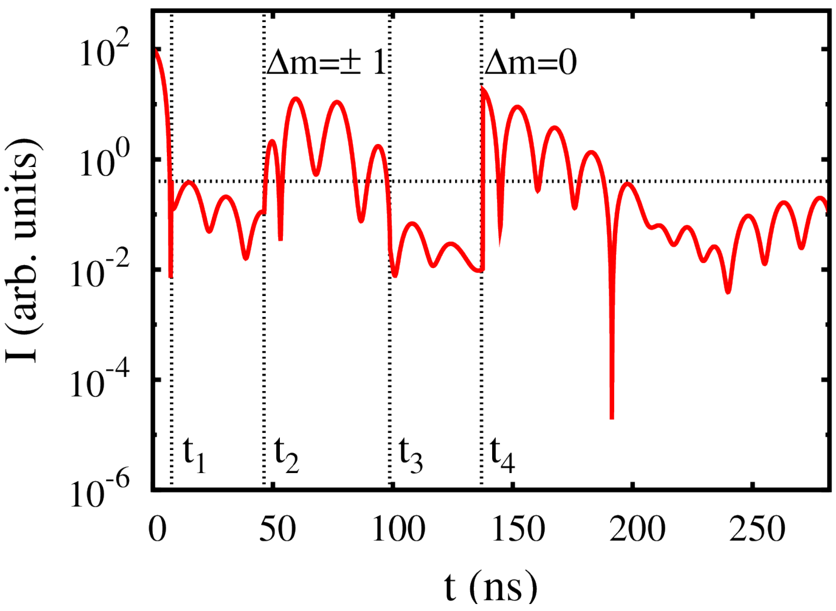
- Initially, magnetic field is in z direction
- At time t_1, cancel decay by rotating into y direction
- At time t_2, enable decay on
  $$\Delta m = \pm 1$$
  but continue to suppress
  $$\Delta m = 0$$
- At time t_3, cancel decay by rotating into y direction

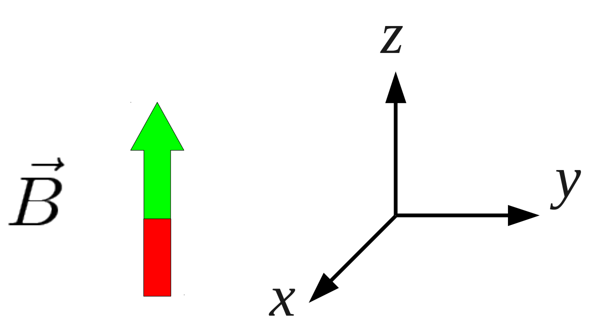




Step 5: Releasing linear polarization

- Initially, magnetic field is in z direction
- At time t_1, cancel decay by rotating into y direction
- At time t_2, enable decay on
  $$\Delta m = \pm 1$$
  but continue to suppress
  $$\Delta m = 0$$
- At time t_3, cancel decay by rotating into y direction
- At time t_4, enable decay on
  $$\Delta m = 0$$

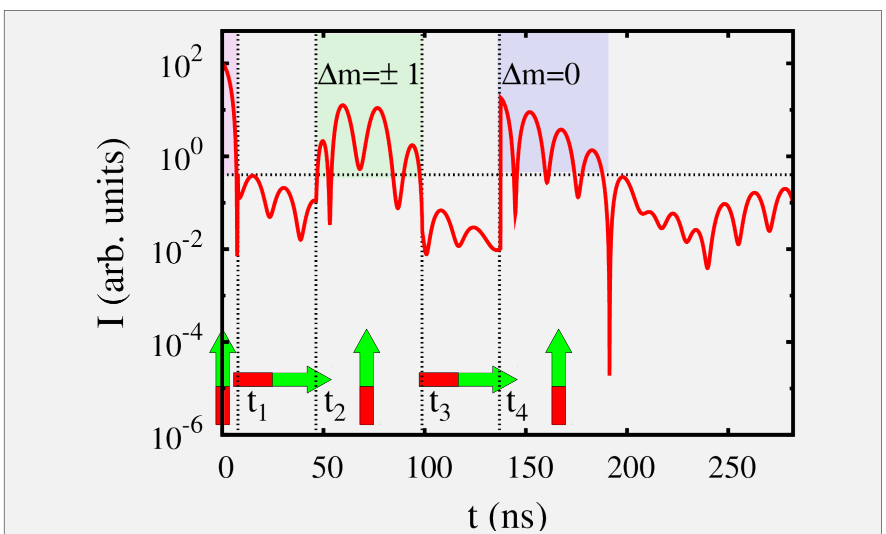


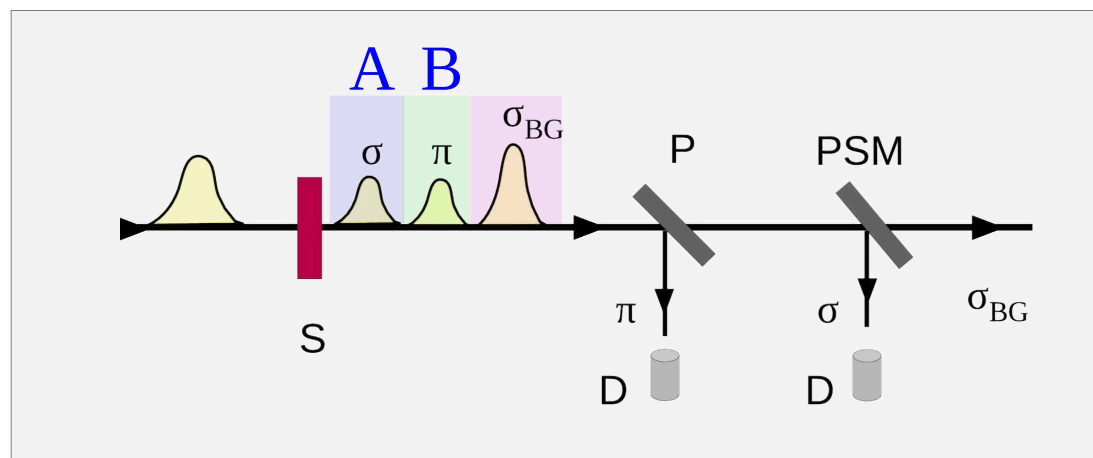


Temporal mode entanglement

Design advanced coherent control scheme:

- Coherently control exciton decay such that single excitation is distributed into three pulses
- Neglecting the background, the two signal pulses are time bin entangled
- Can extract signal from background and convert it to spatial mode entanglement using x-ray optics





$$|\Psi\rangle = \alpha|0\rangle_A|1\rangle_B + \beta|1\rangle_A|0\rangle_B$$

A. Palffy, C. H. Keitel, J. Evers, Phys. Rev. Lett. 103, 017401 (2009)

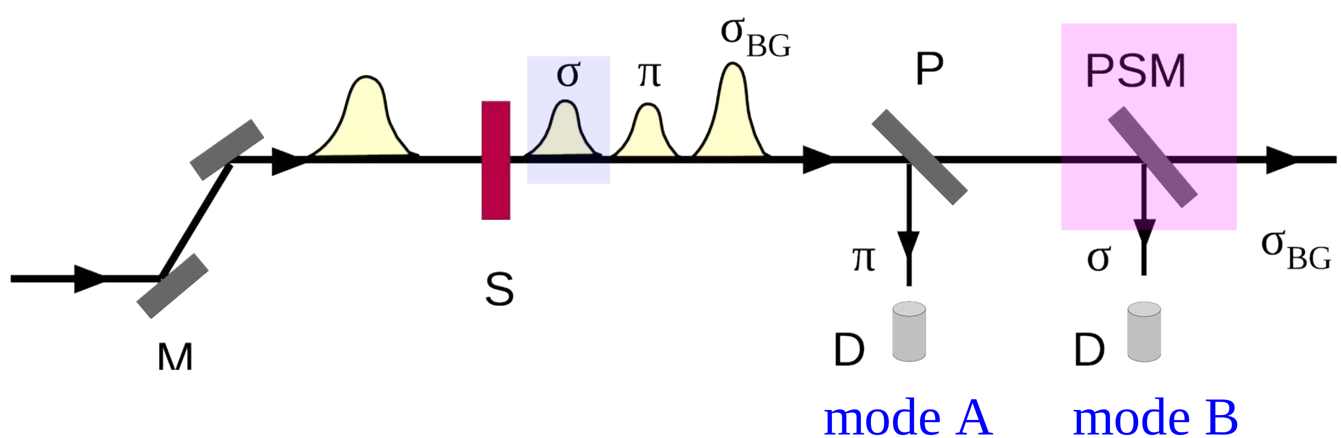
How to extract signal pulse ?

- Priblem: One part of signal has same polarization as background pulse

- Time gating not useful if following setup should be protected from high-intensity background; lighthouse effect difficult because of prcise timing of nuclear switching

- PSM: Piezo electric steering mirror or sub-ns control device based on crystal lattice deformation [1)]

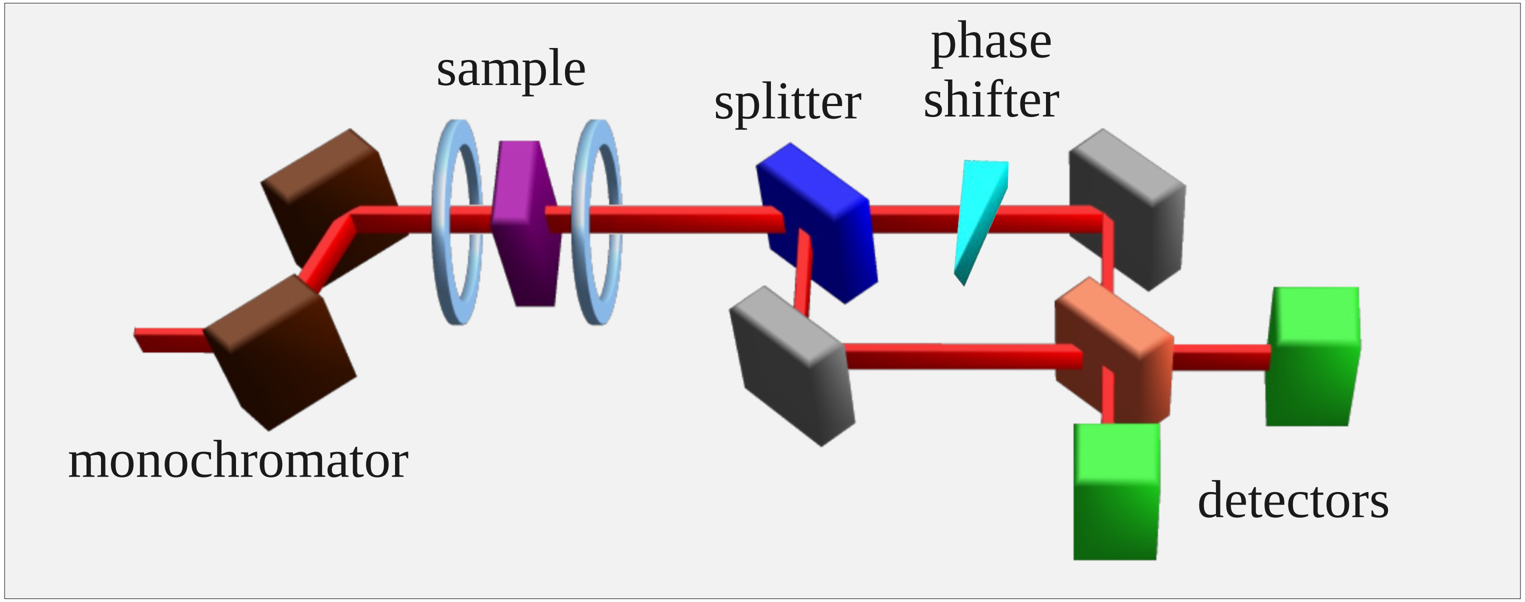
- Have about 180 ns “steering time” because of magnetic switching



1) A. Grigoriev et al., Appl. Phys. Lett. 89, 021109 (2006)

Proof-of-principle experiment

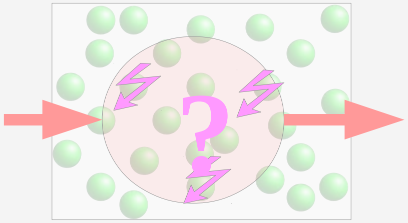
- Do not extract signal, use time gating to remove background
- Switching → two entangled overlapping pulses with opposite polarization
- Correlation measurement with interferometer, violate Bell-like inequality*)
- Need to eliminate "which-way"-information hidden in polarization
- "loophole": explanation of results also possible by non-local classical theory



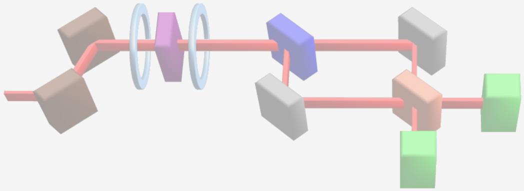
*) H.-W. Lee and Kim, Phys. Rev. A 63, 012305 (2000)

Outline

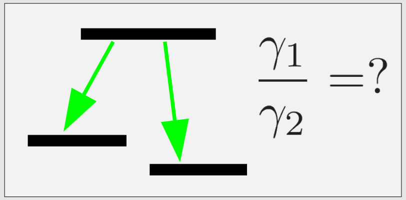
Introduction



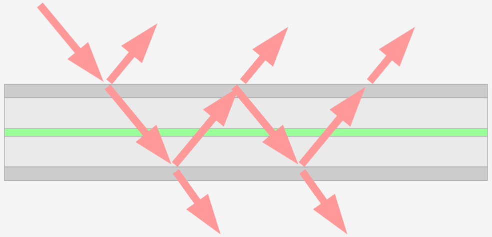
X-ray entanglement generation



X-ray branching ratio control



Outlook: Engineering advanced level schemes



Application: Isomer triggering

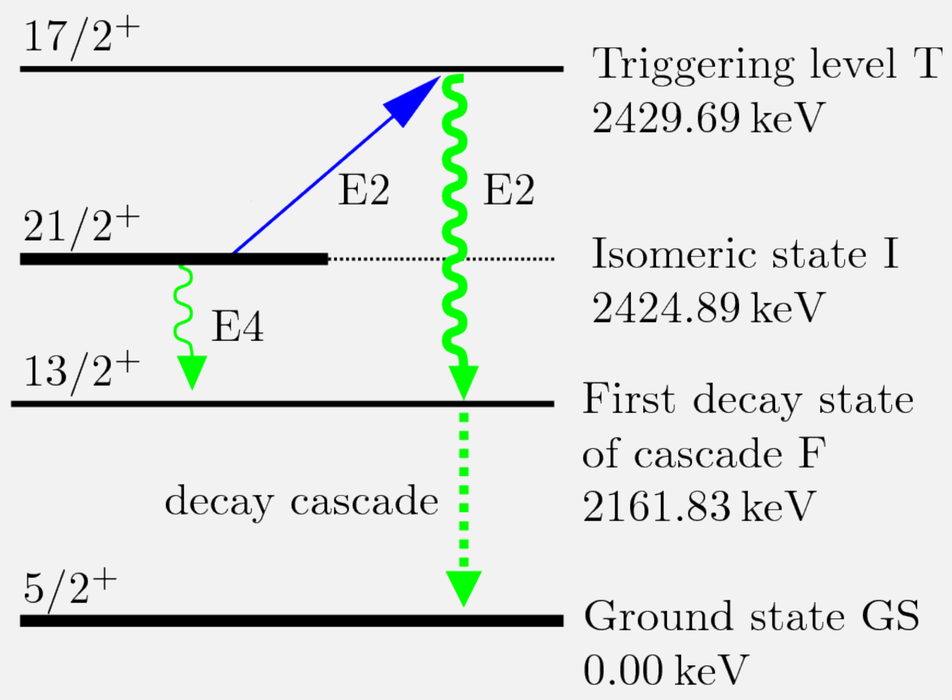
Nuclear isomers:

- long-lived nuclear states
- may “store” much energy

Motivation:

- “nuclear batteries”

- gamma-ray laser
- fundamental questions in astro- and nuclear physics



partial level scheme of $^{93}_{42}Mo$
($t_{1/2}$ = 6.85 h)

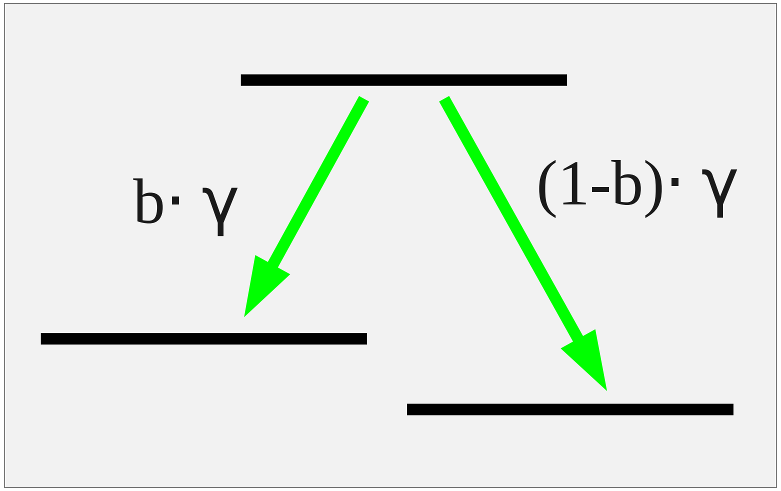
How to efficiently populate and trigger isomers?

See, e.g., P. M. Walker and J. J. Carroll, Nuclear Physics News 17, 11 (2007)

Branching ratio

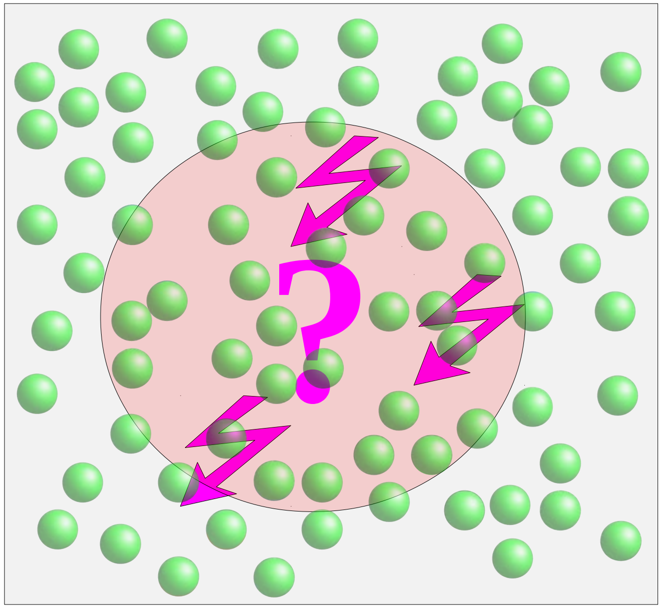
Single particle branching ratio:

- Determines ratio of spontaneous emission channels
- Property of the particle only



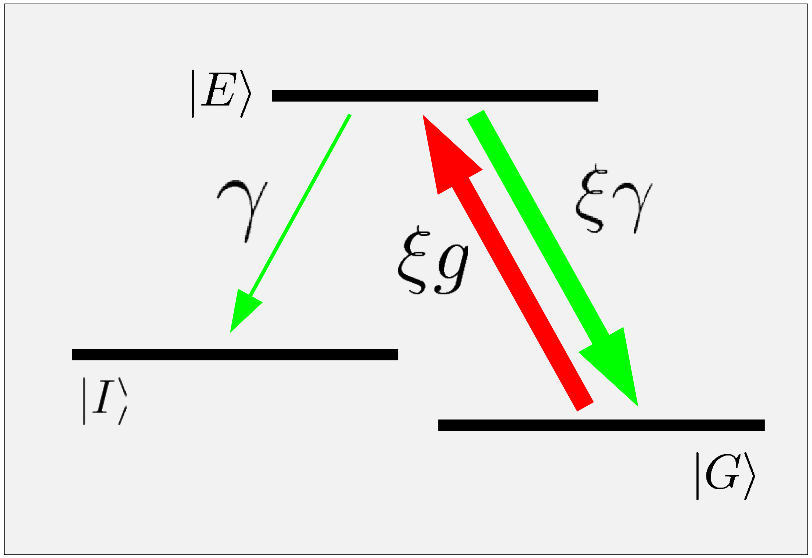
Branching ratio in ensembles

- Have cooperative modification of excitation and decay
- Determined by particle, ensemble and excitation properties, varies with time
- Need to define cooperative branching ratio



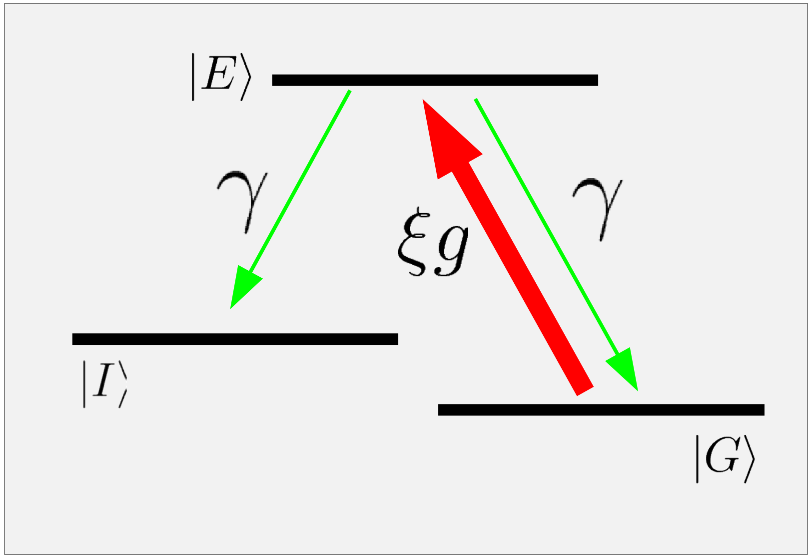
Motivation

- Aim: Efficiently pump from ground state $|G\rangle$ to isomeric state $|I\rangle$
- Cooperativity leads to enhanced excitation to $|E\rangle$, but also to fast decay
- In effect, little transfer to $|I\rangle$



Idea:

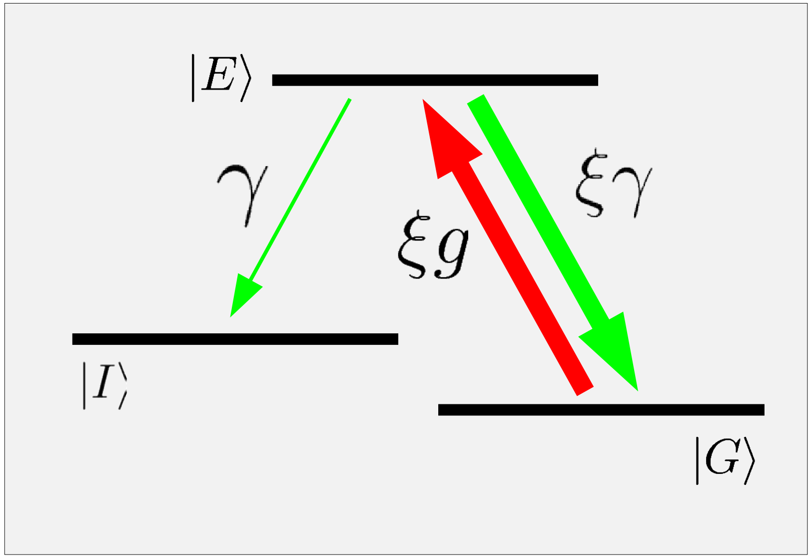
- Suppress cooperative emission
- Then cooperativity leads to enhanced excitation, but decay proceeds with single particle branching ratio
- In effect, enhanced pumping to $|I\rangle$



A. Palffy, C. H. Keitel, and J. Evers, Phys. Rev. B 83, 155103 (2011)

The ideal case

- Assume purely superradiant decay with rate ξ· γ
- Assume perfect coherent control of cooperative decay



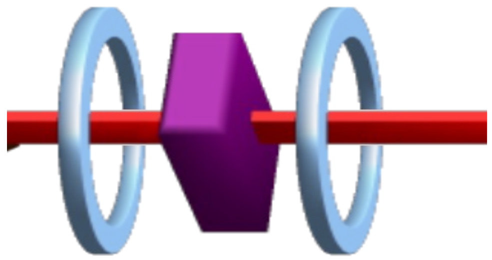
Result:

$$b_c^C / b_c^{NC} = \xi + 1$$

- Cooperative branching ratio is larger by factor ξ+1
- In addition, cooperative enhancement of excitation

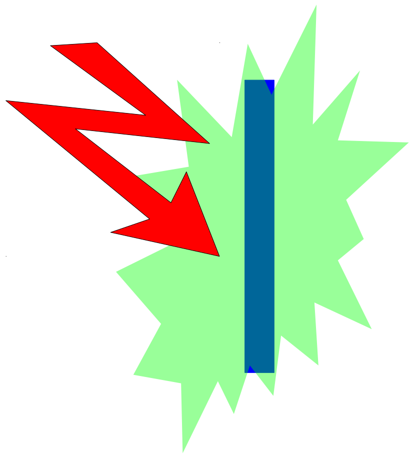
How to control?

Magnetic switching:



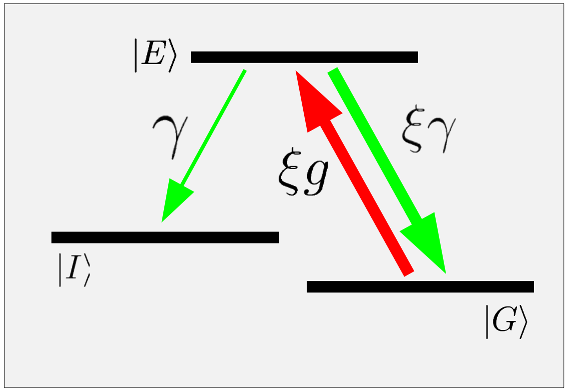
- Turn off cooperative decay by interference
- The incoherent decay with single-particle branching ratio remains

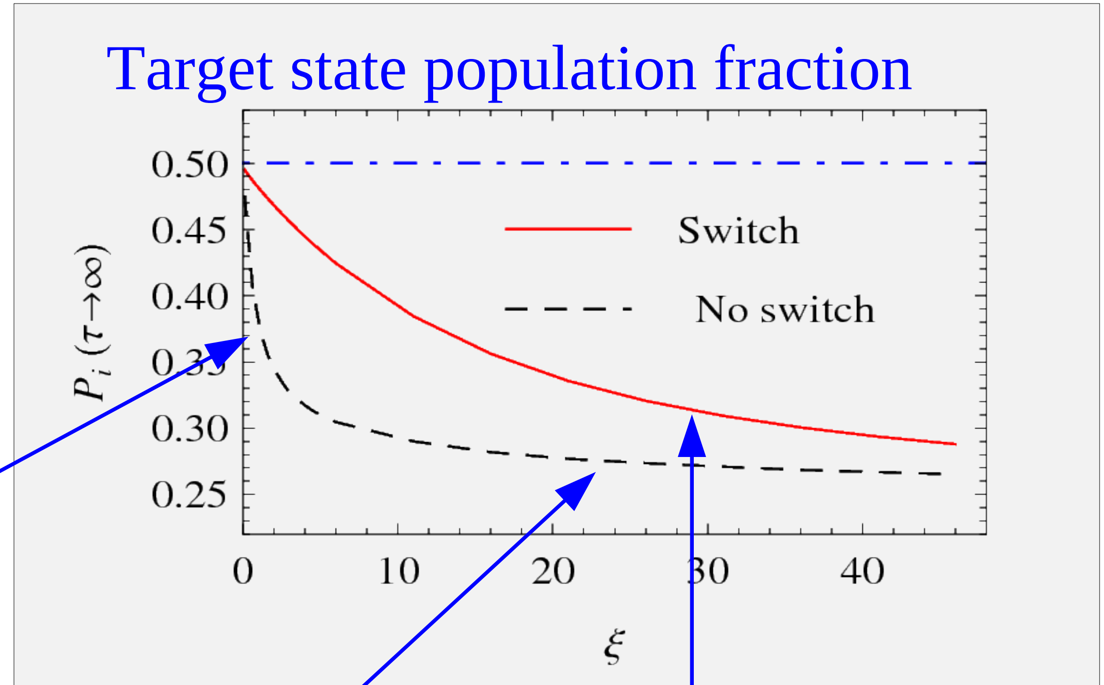
Destroy phase coherence:



- Use short pulse of incoherent light, spatially inhomogeneous magnetic field, or similar to destroy spatial coherence
- Without the coherence, uncorrelated decay without cooperative enhancement
- Can be done immediately after excitation, does not require sophisticated pulse control

The magnetic switching case





superradiant decay to initial state

population of sub-radiant states levels off decay to initial state

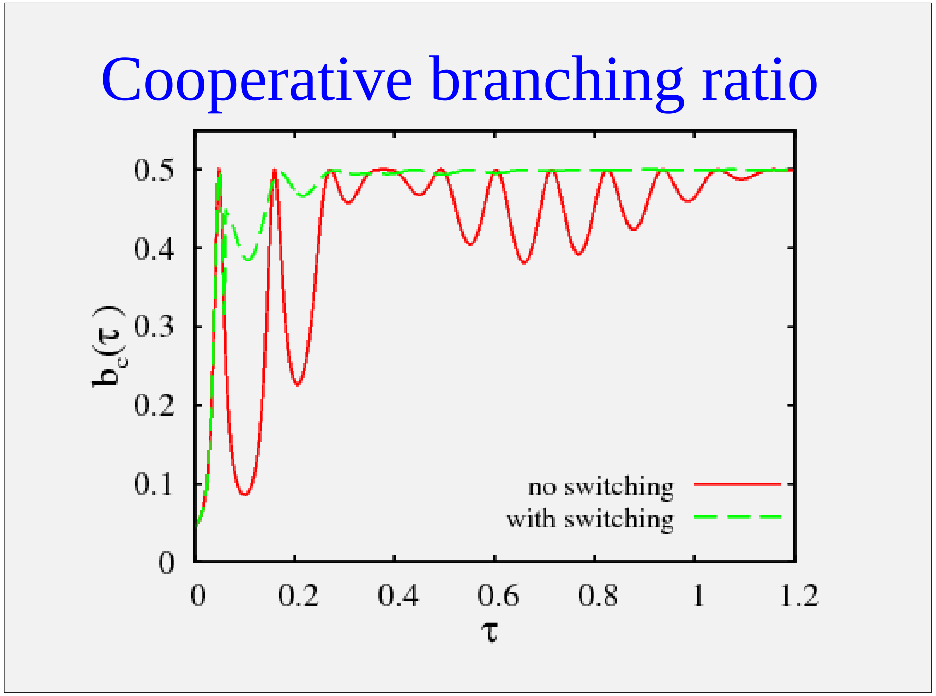
→ limit to enhancement

Switching improves result, but significant decay before trapping can be achieved

→ better results with phase destruction

A. Palffy, C. H. Keitel, and J. Evers, Phys. Rev. B 83, 155103 (2011)

The magnetic switching case

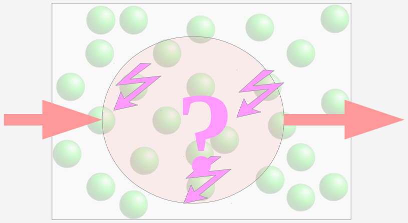


- Branching ratio time dependent as expected
- Cooperative branching ratio smaller than single-particle ratio due to superradiance
- After switching, single-particle branching ratio is achieved
- With destruction of phase coherence, single-particle ratio can immediately be achieved

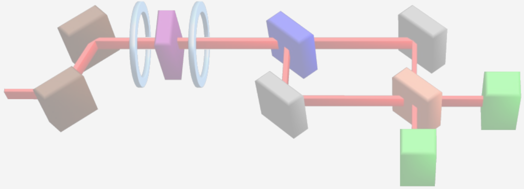
A. Palffy, C. H. Keitel, and J. Evers, Phys. Rev. B 83, 155103 (2011)

Outline

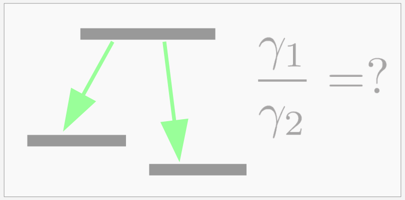
Introduction



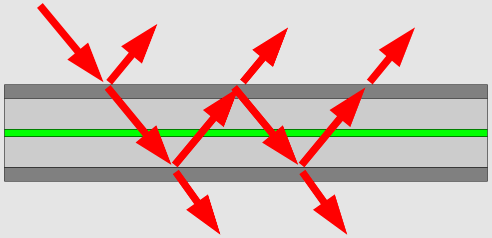
X-ray entanglement generation



X-ray branching ratio control

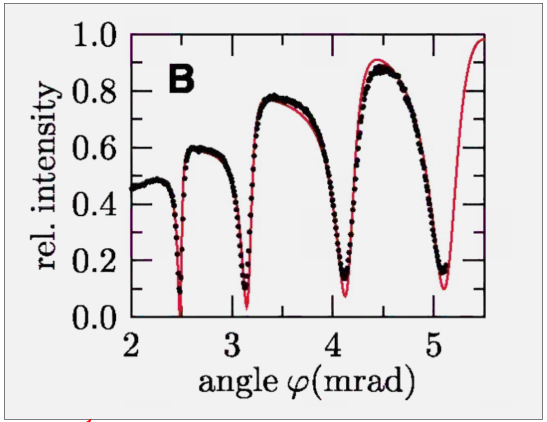


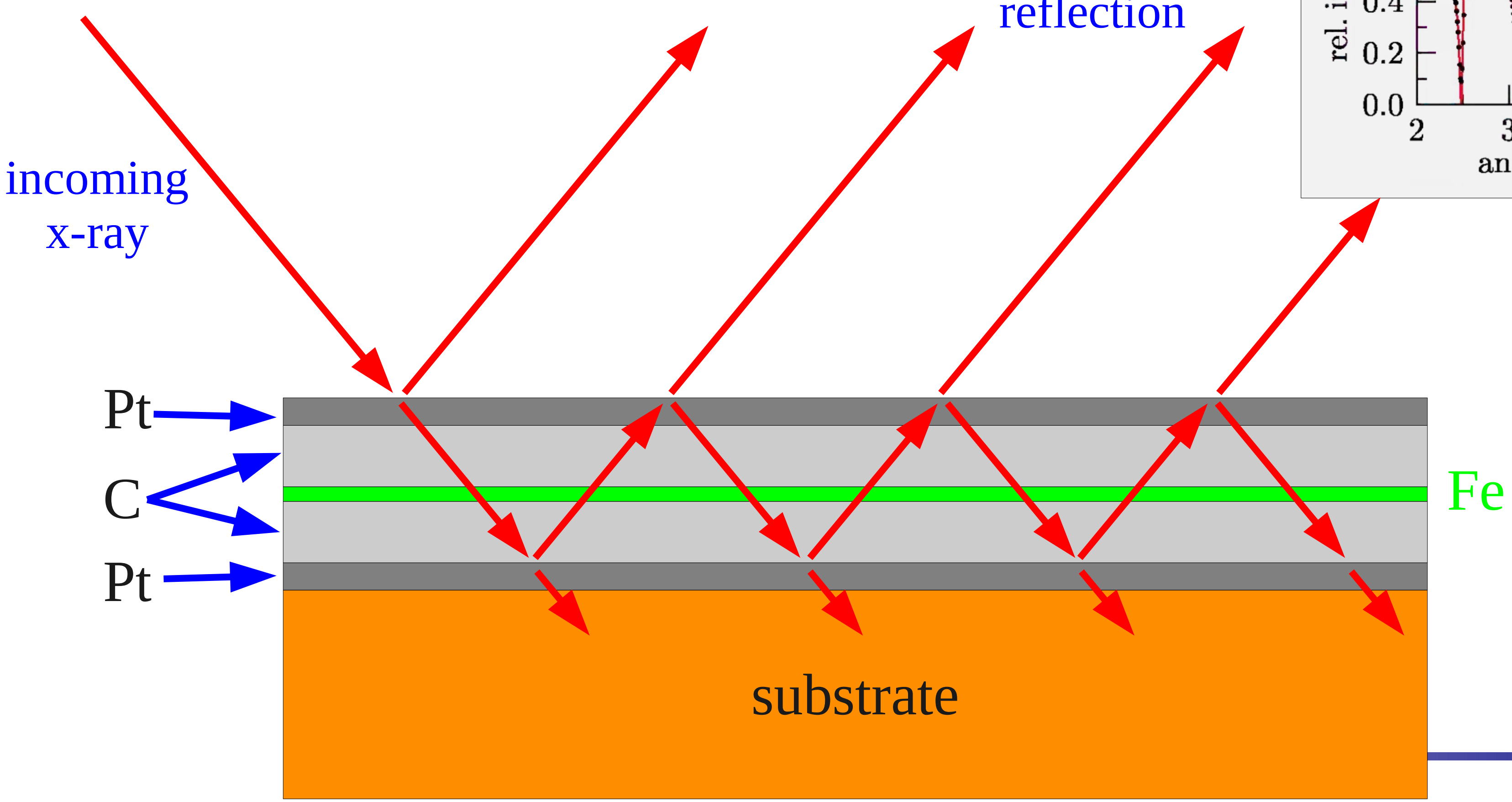
Outlook: Engineering advanced level schemes

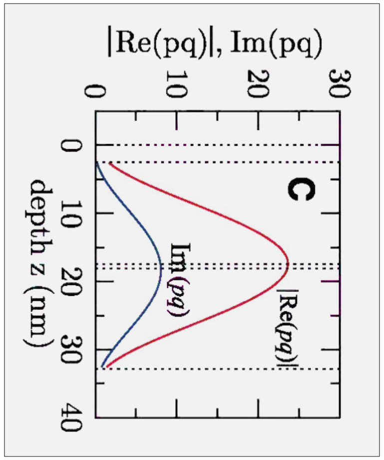


X-ray cavities

- nm-sized thin film cavity: Pt (electron rich) as mirror, C (little electrons) as spacer
- Cavity is probed in grazing incidence, because of low index of refraction change
- Cavity resonances give field enhancement,
  can be observed in reflection
- Nuclear resonances in Fe can interact with cavity field







Purcell effect and cooperativity

- Look at cavity with 2 active layers
  - (A) in cavity field maximum
  - (B) in cavity field minimum
- (A) couples strongly to the cavity, rapidly emits excitation into cavity field (Purcell effect + cooperative light emission)
- (b) has suppressed coupling to cavity because of intensity minimum

Lifetime of nuclear excitation in (B) much longer than that of one in (A)

Material is the same!

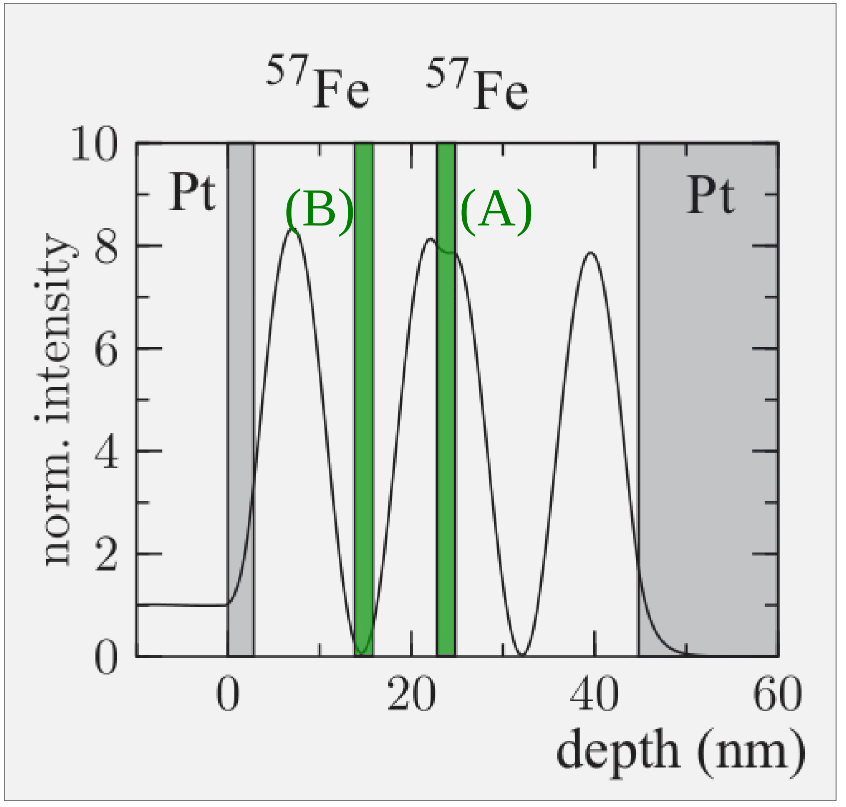
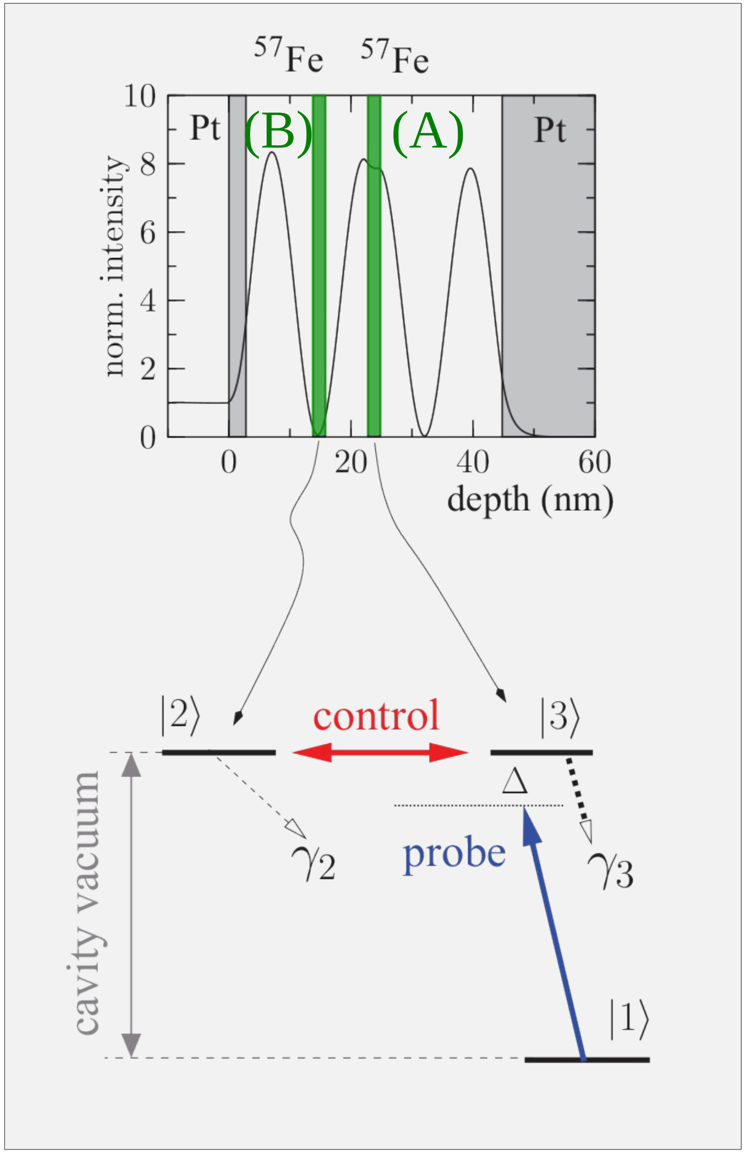


Image: Röhlsberger et al, Nature 482, 199 (2012)

Engineering a 3-level Λ level scheme

The level scheme

- State |1> : no excitations in (A), (B) but photon in cavity
- State |3>: excitation in (A), no photon in cavity
- State |2>: excitation in (B), no photon in cavity

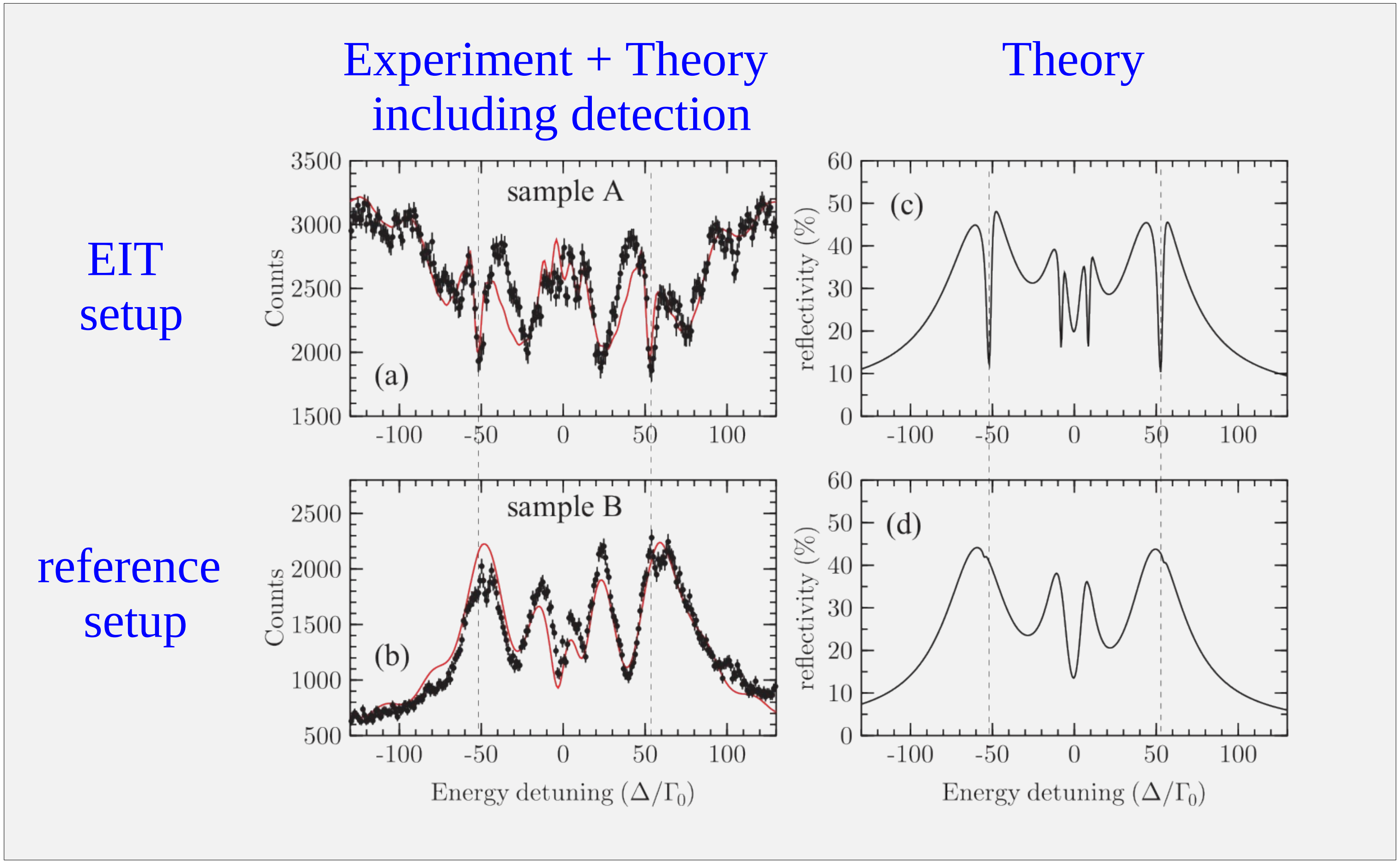


Why is this a Λ level scheme?

- |3> decays fast due to Purcell + cooperativity
- Compared to that, |2> and |1> metastable
- Control is generated by scattering between the layers
- Probe field by absorption of cavity photon by nucleus in (A)

Image: Röhlsberger et al, Nature 482, 199 (2012)

Experiment: Nuclear EIT

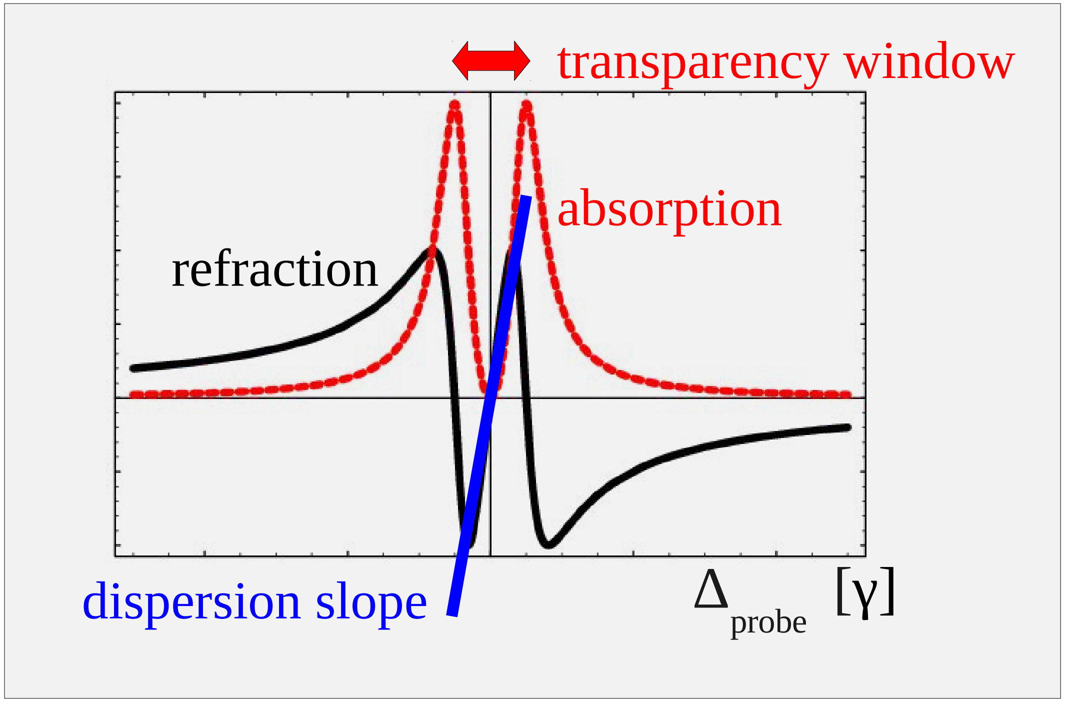


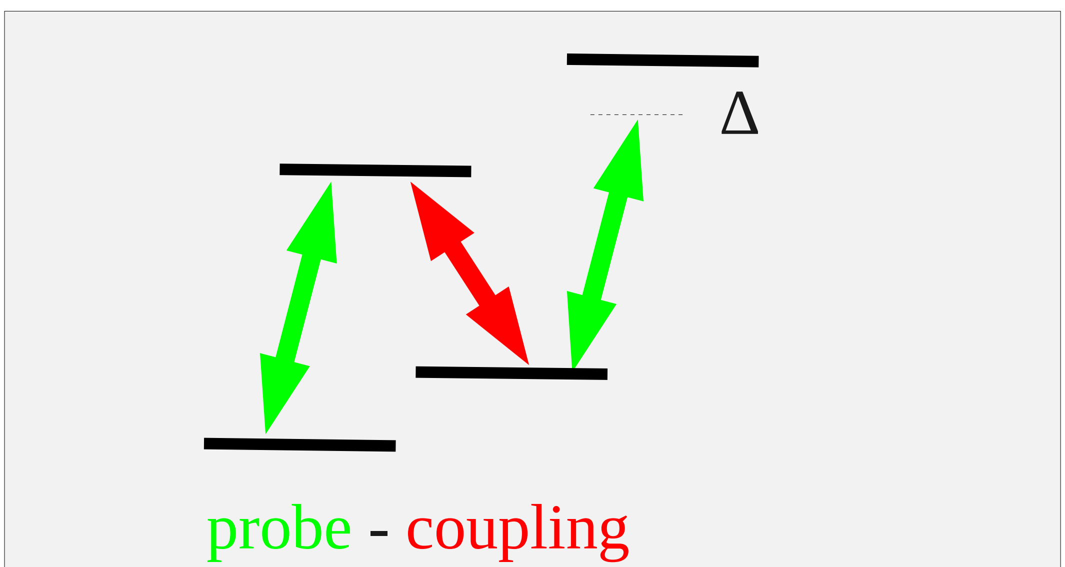
EIT as an archetype quantum optical coherence effect observed with x-rays interacting with nuclei

EIT with a single light field due to clever cavity engineering

Image: Röhlsberger et al, Nature 482, 199 (2012)

Our current work: engineer advanced schemes





- Broad transparency window to propagate of broadband input pulses
- Steep dispersion slope for strong effect on propagated pulse (e.g. delay)
- (time delay)·(transparency bandwidth) is constant → need to tune for best trade-off

- More general level schemes offer wide range of applications
- Example: Strongly enhanced non-linear response

K. P. Heeg, R. Röhlsberger, J. Evers, work in progress

The team

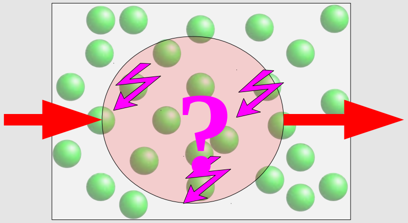
Martin Gärttner	PhD student
Qurrat-ul-Ain Gulfam	PhD student
Kilian Heeg	PhD student
Mihai Macovei	PostDoc
Andreas Reichegger	Master student
Sandra Schmid	PostDoc
Lida Zhang	PhD student

Acknowledgements: Ralf Röhlsberger (DESY Hamburg)
Adriana Palffy (former group member @ MPIK)

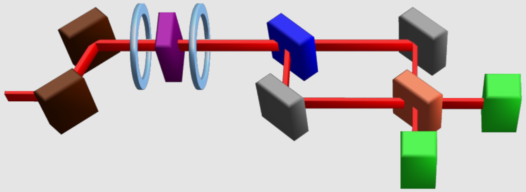
Funding: MPG, DFG, DAAD,
IMPRS-QD, CQD

Summary

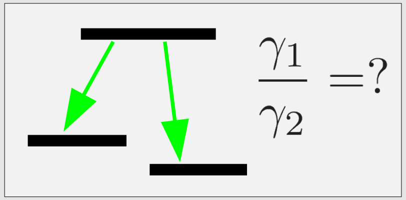
Introduction



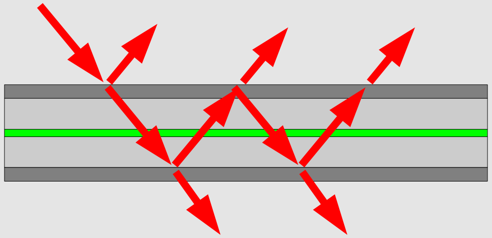
X-ray entanglement generation



X-ray branching ratio control



Outlook: Engineering advanced level schemes



Thank you!

PhD / PostDoc applications welcome in Heidelberg!

NFS

Theoretical description

Wave equation

$$\left(\Delta - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\vec{E} = \frac{4\pi}{c}\frac{\partial}{\partial t}\vec{I}$$

Slowly varying envelope approximation

$$\frac{\partial}{\partial z}\vec{\mathcal{E}} = -\frac{2\pi}{c}\vec{\mathcal{I}}$$

Nuclei as source term (2nd order)

$$\vec{I} = \mathrm{Tr}\left(\vec{j}\rho_{\mathrm{nuclei}}\right)$$

Iterative solution,
incident pulse

Final wave equation

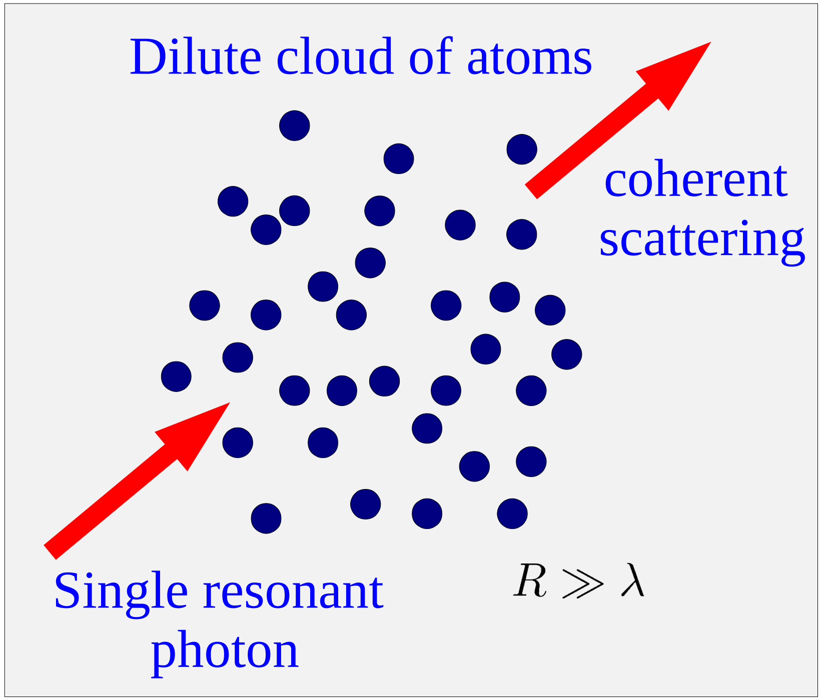
$$\frac{\partial\vec{\mathcal{E}}(z,t)}{\partial z} = -\sum_{\ell} K_{\ell}\vec{J}_{\ell}(t)\int_{-\infty}^{t} d\tau\,\vec{J}_{\ell}^{\dagger}(\tau)\cdot\vec{\mathcal{E}}(z,\tau)$$

sum over transitions — de-excitation — excitation

Y. V. Shvydko, Hyperf. Int. 123/124, 275 (1999)

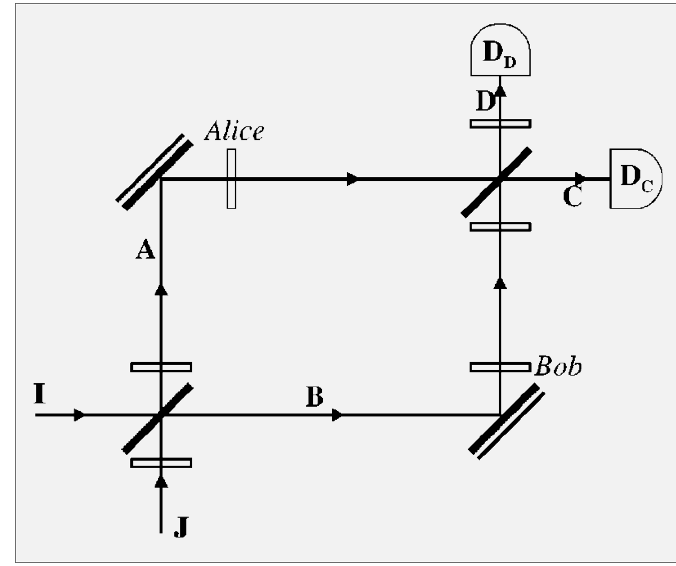
A few numbers - classification of the system

- Incident light bandwidth ∼meV, Fe transition width ∼neV
  → on average typically less than 1 excited nucleus per shot, “single photon”
- Solid state densities ($n \sim 10^{23}$ / cm^3) but short wavelength ($\lambda \sim 10^{-10}$ m)
  → $n\lambda^3 \sim 0.1$ → “dilute” medium
- High resonant scattering amplitude, Mößbauer effect
  → large optical depth, multiple scattering
- Sample of macroscopic size compared to wave length ($R / \lambda \gg 1$)
- Focus on coherent forward scattering
  → Treatment of cooperative effects much simplified (e.g., no radiation trapping)



Possible proof-of-principle experiment

- Without phase shifts: All N photons go to C (G_N)
- With phase shift by Alice:
  $N_A = \sin^2(\phi_A/2)\,N$ photons go to D (G_A)
- With phase shift by Bob:
  $N_B = \sin^2(\phi_B/2)\,N$ photons go to D (G_B)
- With both phase shifts:
  $N_{AB} = \sin^2[(\phi_A - \phi_B)/2]\,N$ go to D (G_{AB})

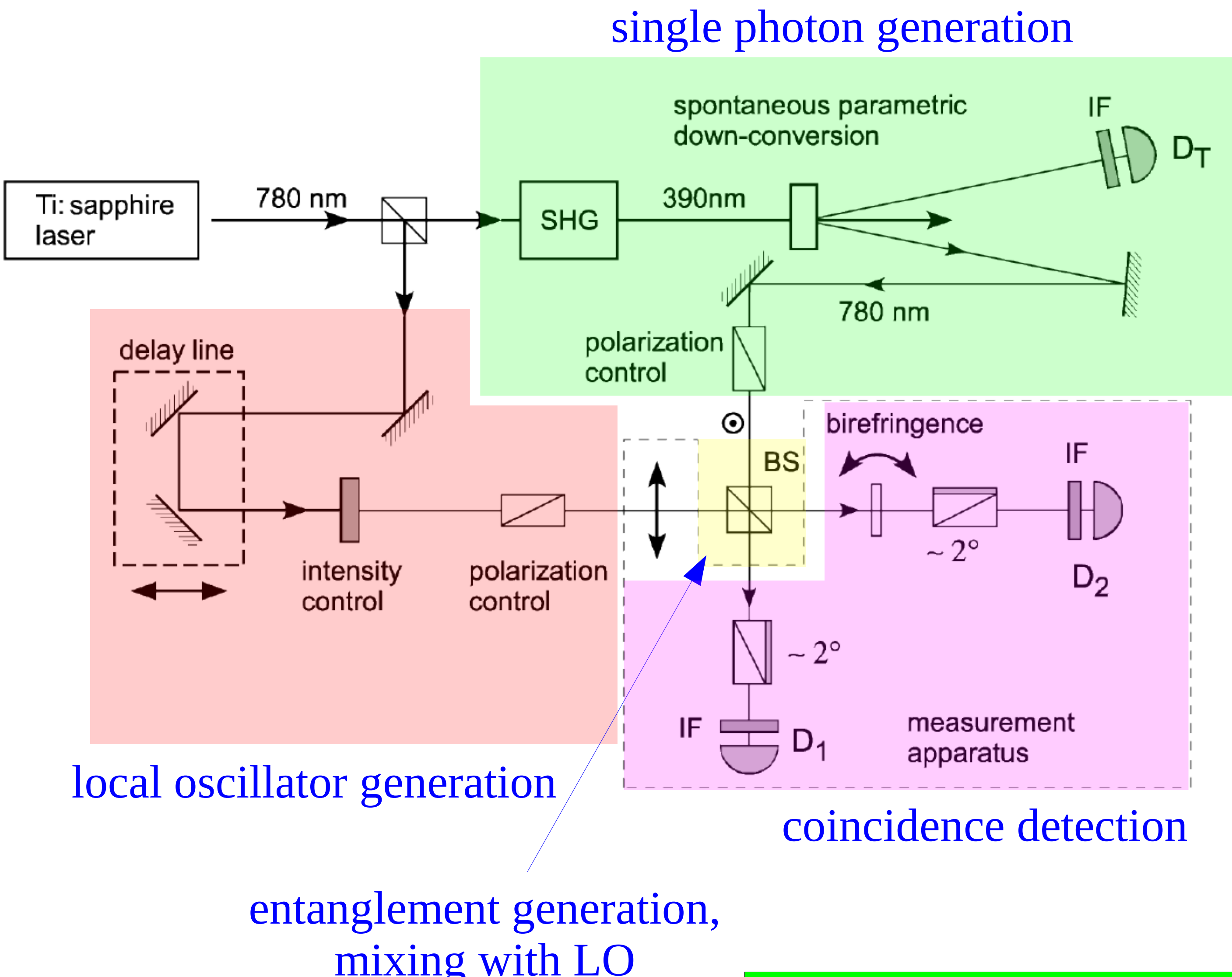


- Locality assumption: photons which arrive at C both
  if (Alice shifts but not Bob) and if (Bob shifts but not Alice)
  will still arrive at C if
  (Alice and Bob shift)

$$(G_N - G_A) \cap (G_N - G_B) \subseteq (G_N - G_{AB})$$

$N_{AB} \leq N_A + N_B$ violated for some phase shifts

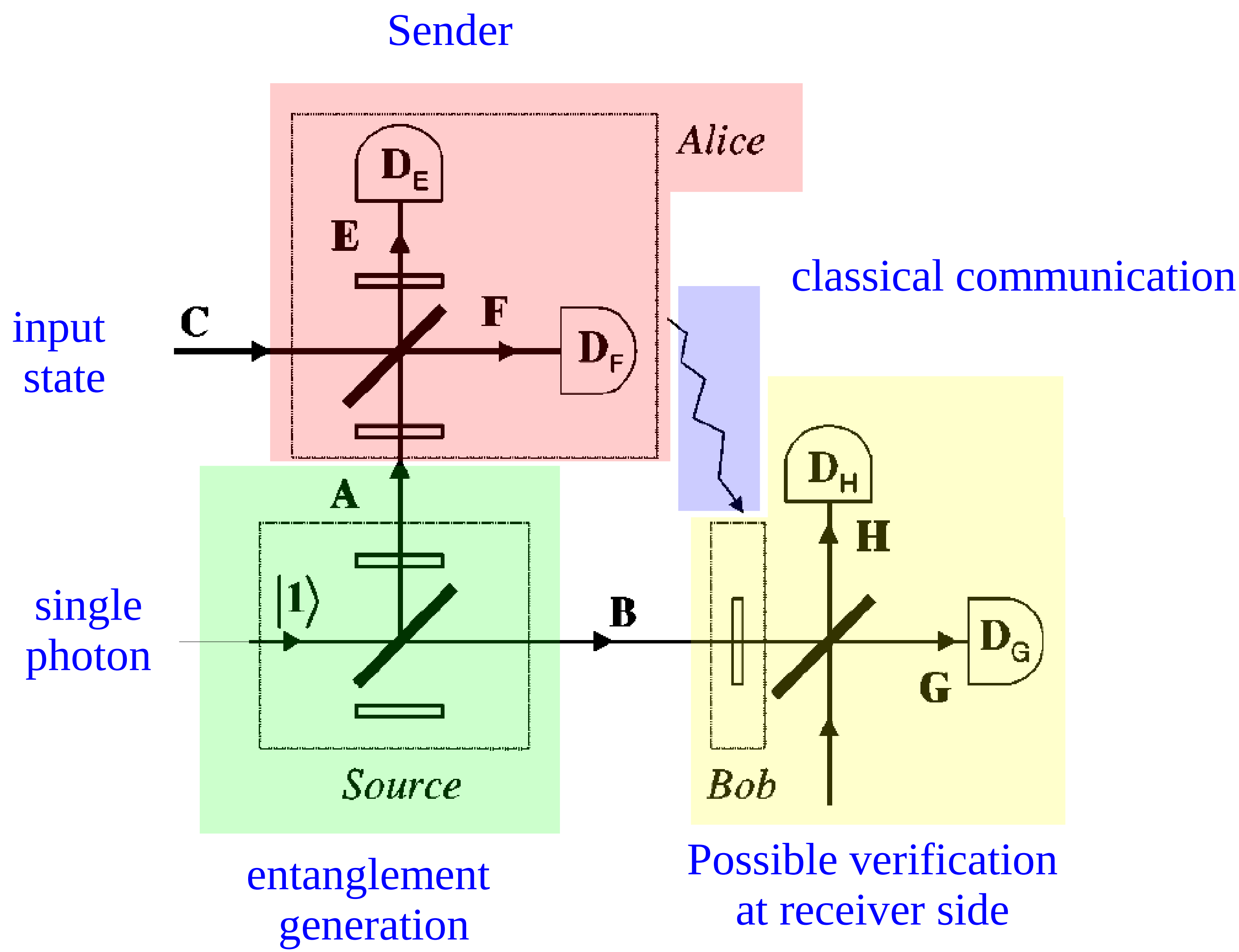
Experimental evidence with local oscillator



Visibility (91± 3)% with background correction
Visibility (66± 2)% without background correction
71% limit for violation of Bell inequality

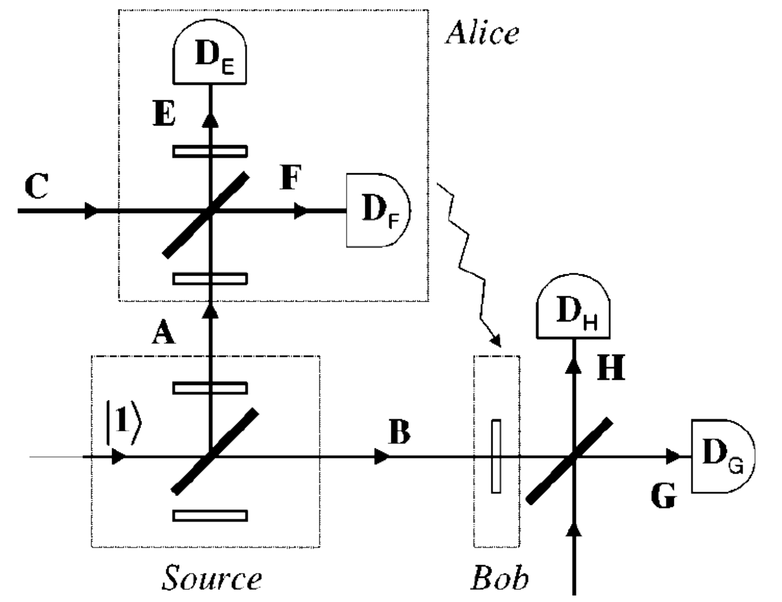
B. Hessmo et al, Phys. Rev. Lett. 92, 180401 (2004)

Single photon entanglement teleportation scheme



H.-W. Lee and Kim, Phys. Rev. A 63, 012305 (2000)

Teleportation algebra



entanglement input

$$
\begin{aligned}
|\Psi\rangle &= \frac{1}{\sqrt{2}}\left(|1\rangle_A|0\rangle_B + |0\rangle_A|1\rangle_B\right)\left(a|1\rangle_C + b|0\rangle_C\right) \\
&= \frac{1}{2}|0\rangle_E|1\rangle_F\left(a|1\rangle_B + b|0\rangle_B\right) \\
&+ \frac{1}{2}|1\rangle_E|0\rangle_F\left(a|1\rangle_B - b|0\rangle_B\right) \\
&+ \frac{1}{2}\left(\frac{1}{2}|0\rangle_E|2\rangle_F - \frac{1}{2}|2\rangle_E|0\rangle_F + \frac{1}{\sqrt{2}}|0\rangle_E|0\rangle_F\right)\left(a|0\rangle_B + b|1\rangle_B\right) \\
&+ \frac{1}{2}\left(\frac{1}{2}|0\rangle_E|2\rangle_F - \frac{1}{2}|2\rangle_E|0\rangle_F - \frac{1}{\sqrt{2}}|0\rangle_E|0\rangle_F\right)\left(a|0\rangle_B - b|1\rangle_B\right)
\end{aligned}
$$

teleported state

measurement Alice

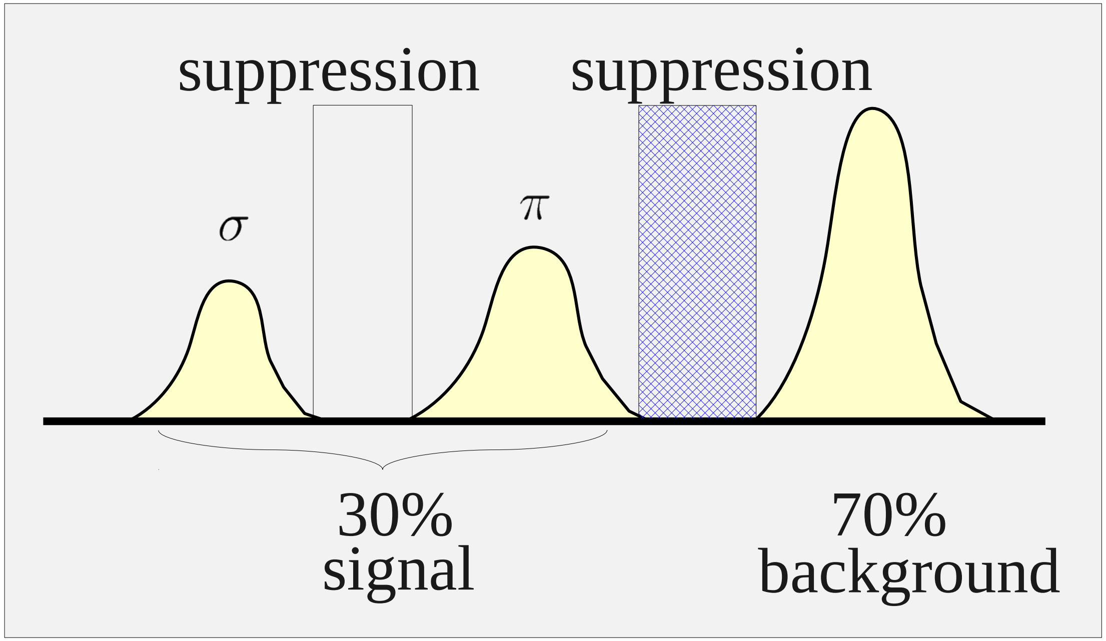
H.-W. Lee and Kim, Phys. Rev. A 63, 012305 (2000)

Efficiency estimate

- Assumed incoming flux after monochromator: 10^9 photons / s
- Assumed rate of excited nuclei: 5×10^5 / s
- Of stored excitation, 70% background, 30% signal
- Loss at polarizer: Only about 10% of photons are kept
- Single photon entanglement rate: 15×10^3 / s

Signal and background separated!

Incident photon flux can be increased until multiple excitations occur



A. Palffy, C. H. Keitel, J. Evers, Phys. Rev. Lett. 103, 017401 (2009)