Nuclear quantum optics with seeded FEL beams

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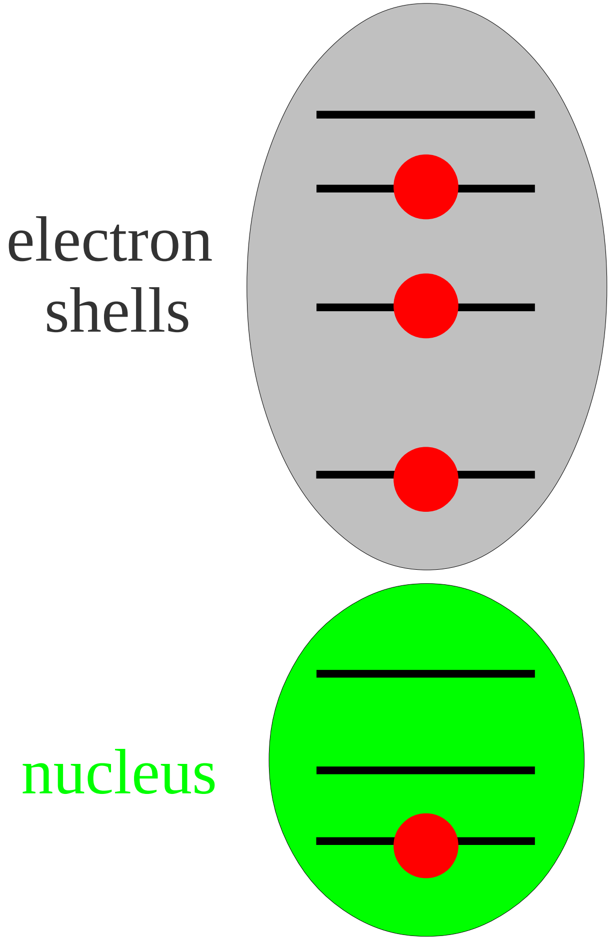
Science with seeded FEL beams, DESY, 20.07.2012

Motivation

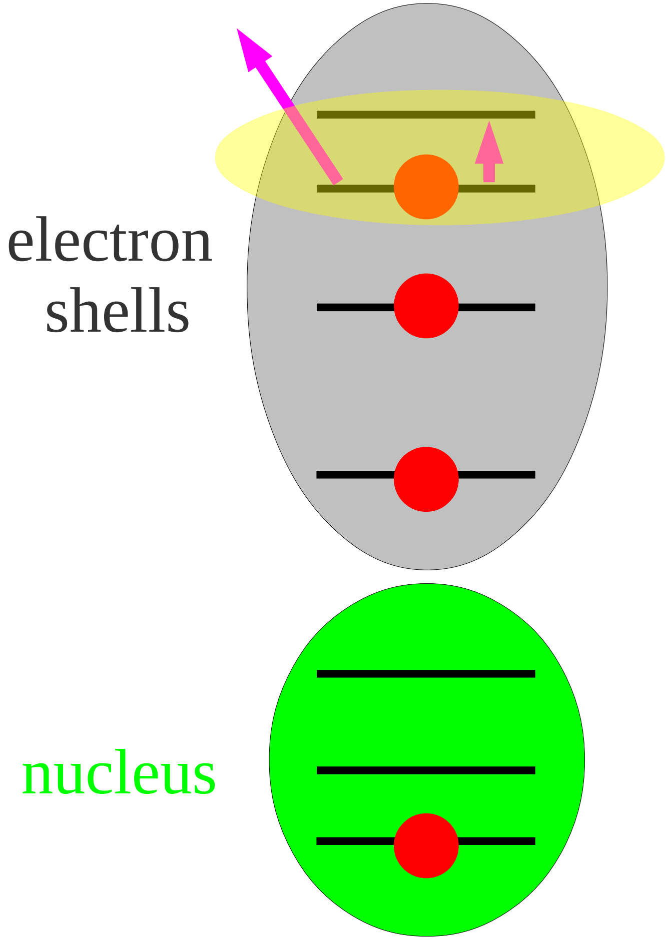
Light-matter interactions



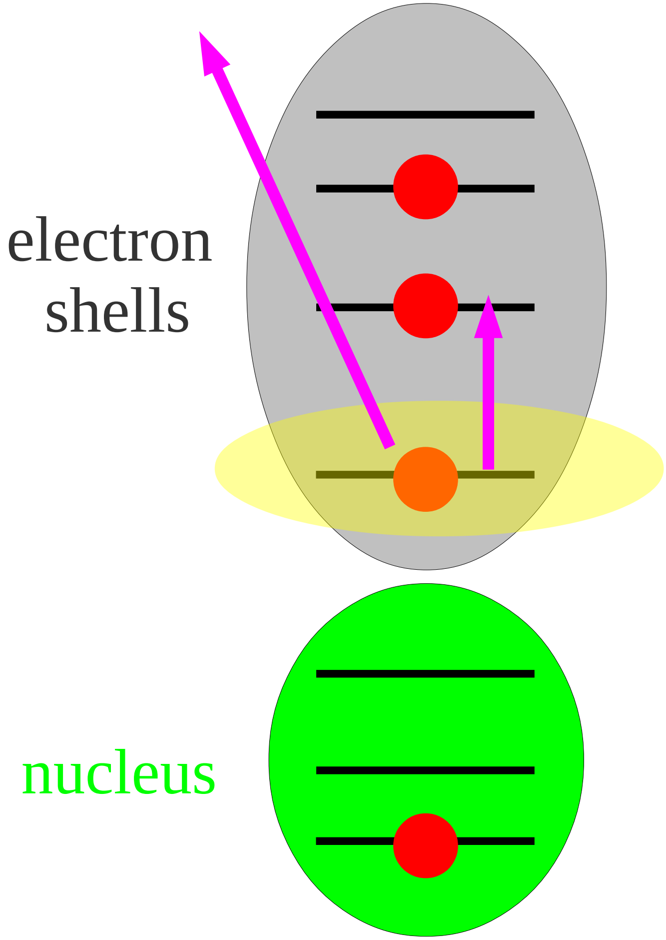
Motivation

Light-matter interactions

- Optical laser fields
  control dynamics of outer electrons



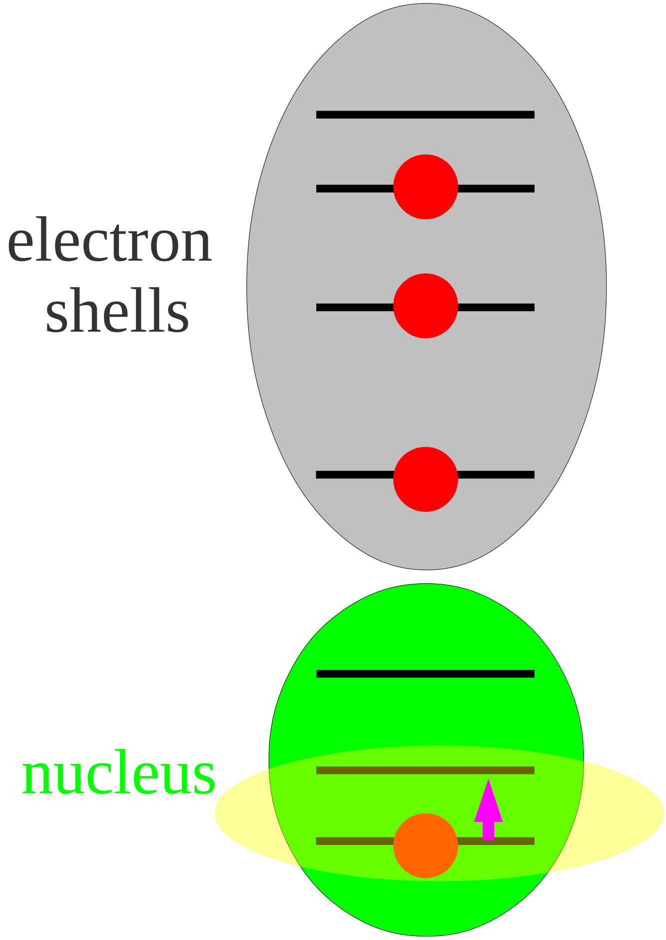
Motivation



Light-matter interactions

- Optical laser fields
  control dynamics of outer electrons
- Higher frequencies/intensities:
  excite / ionize core electrons

Motivation

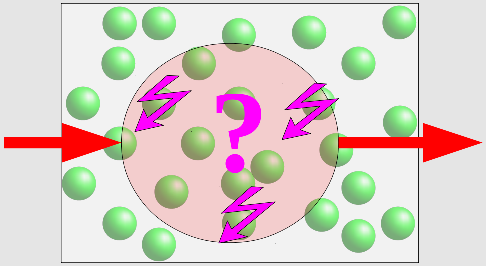


Light-matter interactions

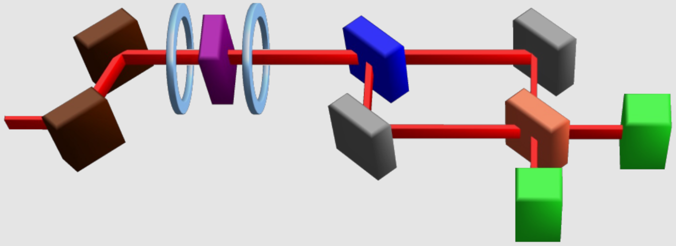
- Optical laser fields
  control dynamics of outer electrons
- Higher frequencies/intensities:
  excite / ionize core electrons
- Even higher frequencies/intensities:
  excite nucleus

Outline

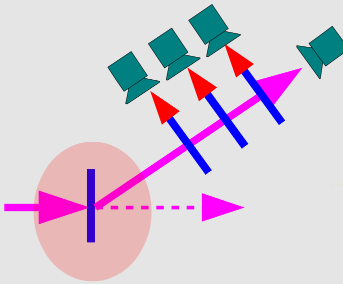
Introduction

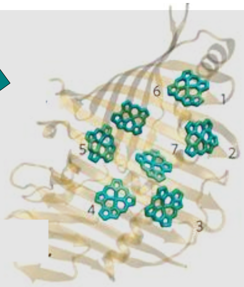


Nuclear quantum optics

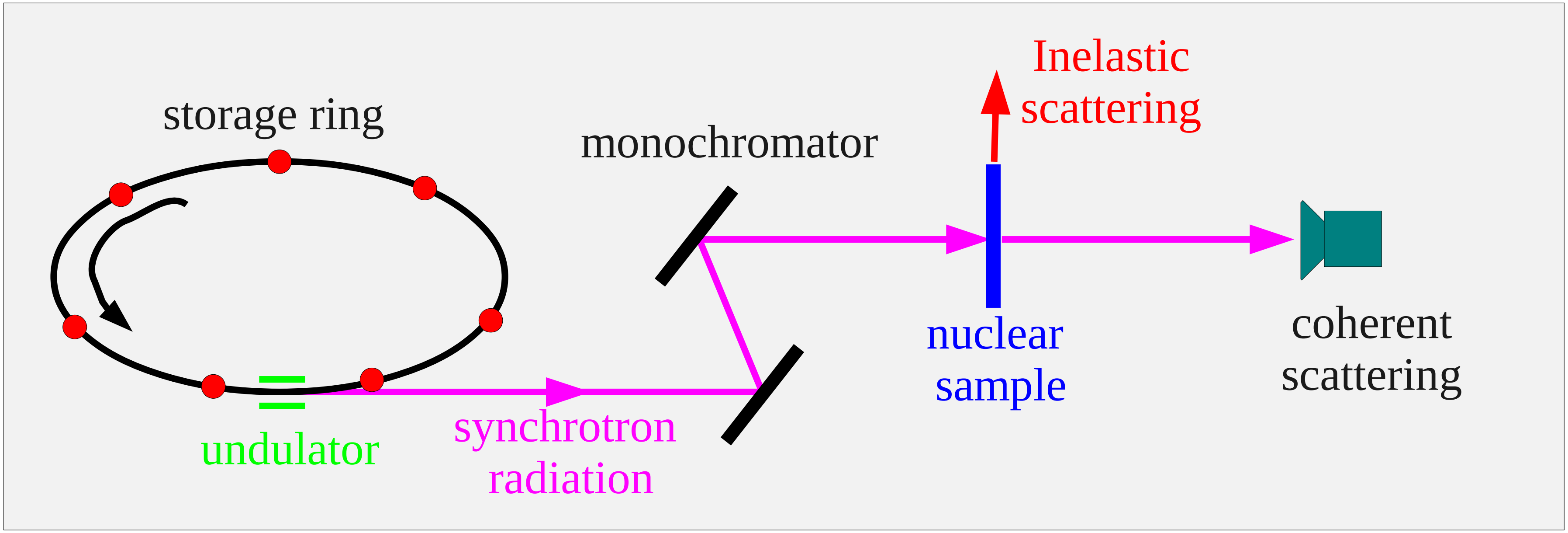


Future perspectives
with seeded FELs





Nuclear resonance scattering



storage ring

monochromator

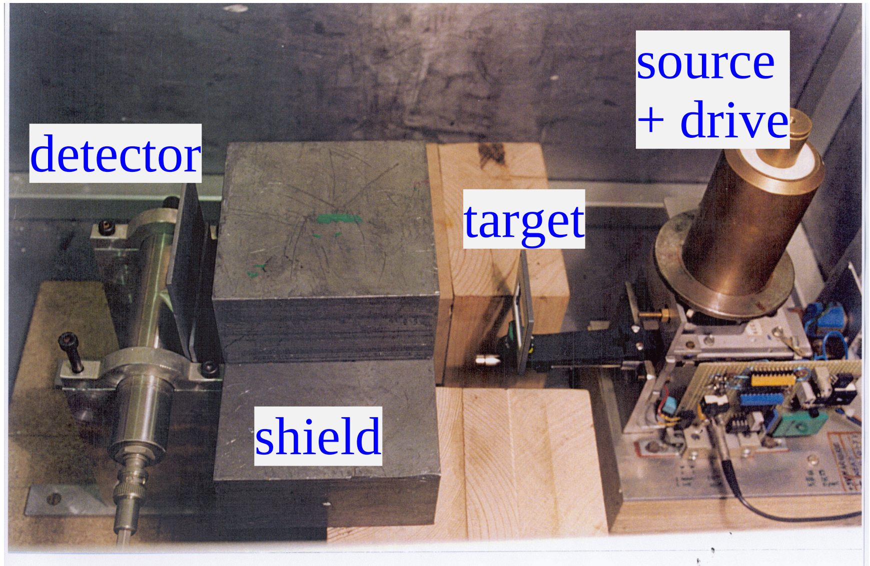
Inelastic scattering

undulator

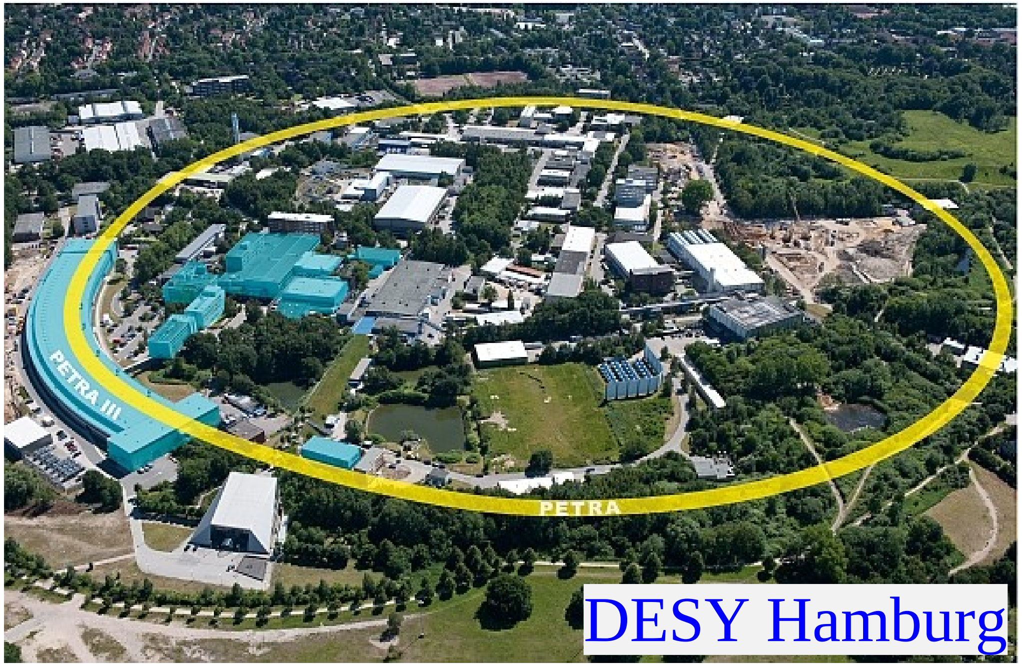
synchrotron radiation

nuclear sample

coherent scattering



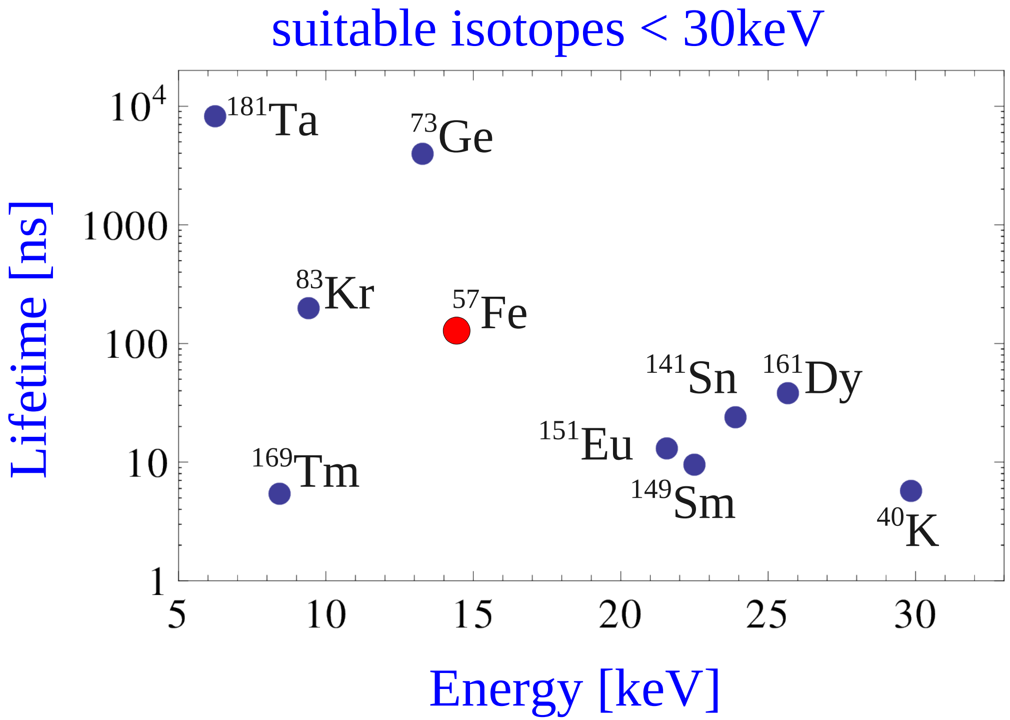
Student lab Uni Mailand



DESY Hamburg

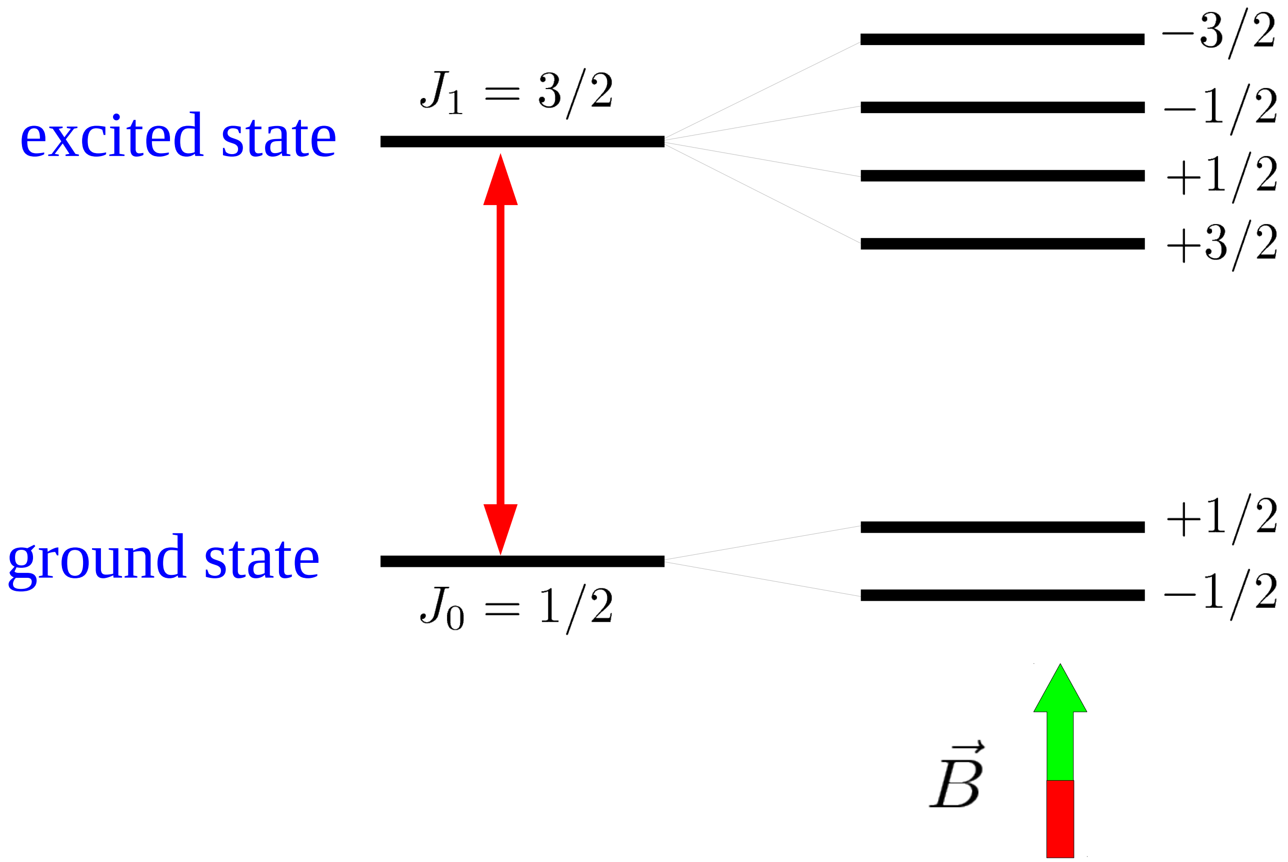
Nuclear resonance scattering

- Tool to investigate magnetic, structural and dynamic properties of matter
- Small linewidth of nuclear resonances (µeV-peV) is both essential feature and technical challenge
- Mößbauer effect leads to recoilless absorption and emission



W. Sturhahn, J. Phys.: Condens. Matter 16, S497 (2004)

^{57}Fe iron Mößbauer transition



- Iron is of significance in biology, earth science, ...
- "Working horse" of nuclear resonance scattering
- Q ~ $\omega_0 / \Gamma \sim 10^{12}$

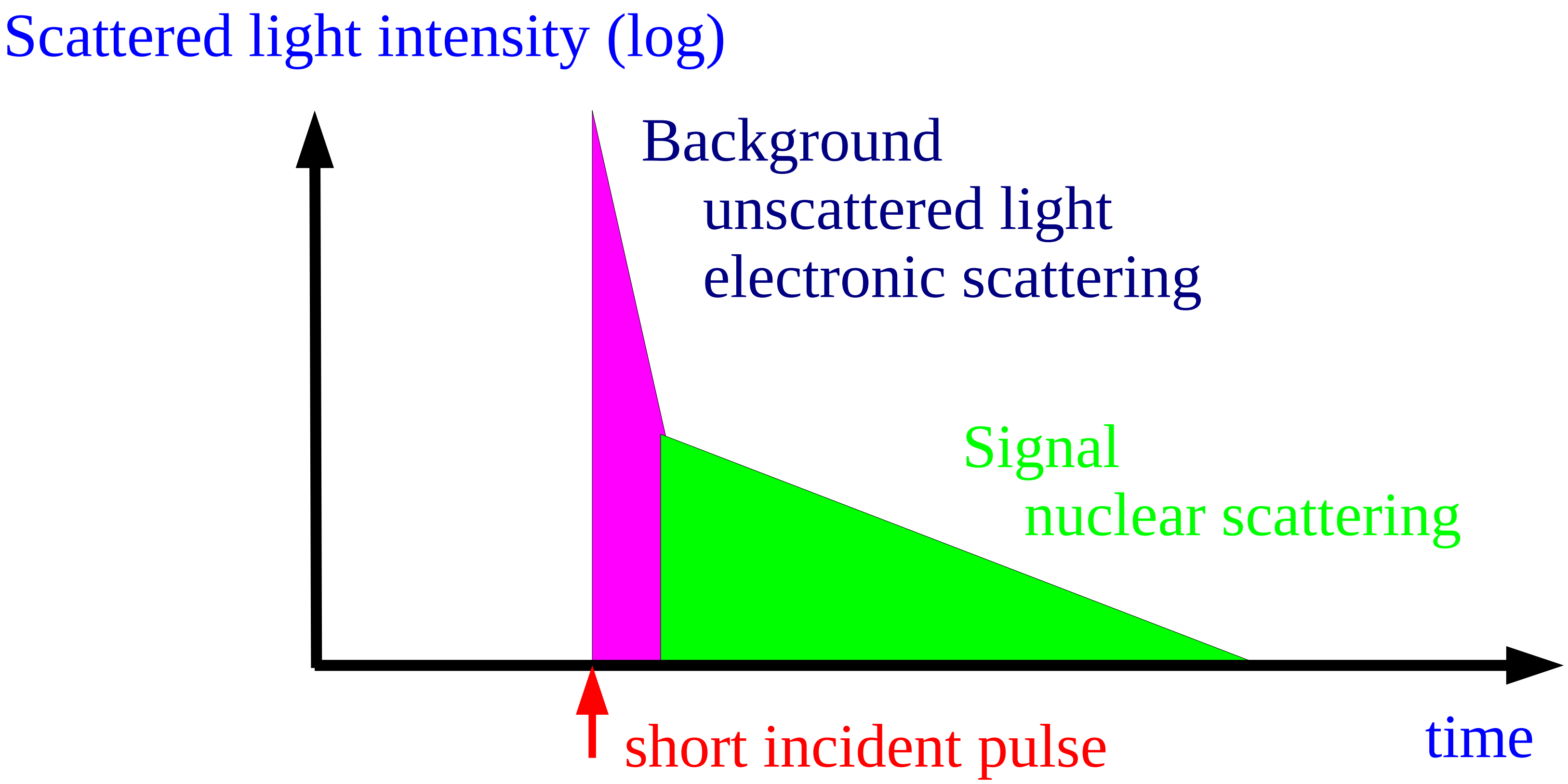
$$\lambda = 0.86\ \text{Å}$$

$$\hbar\omega_0 = 14.4\ \text{keV}$$

$$\hbar\Gamma = 4.7 \times 10^{-9}\ \text{eV}$$

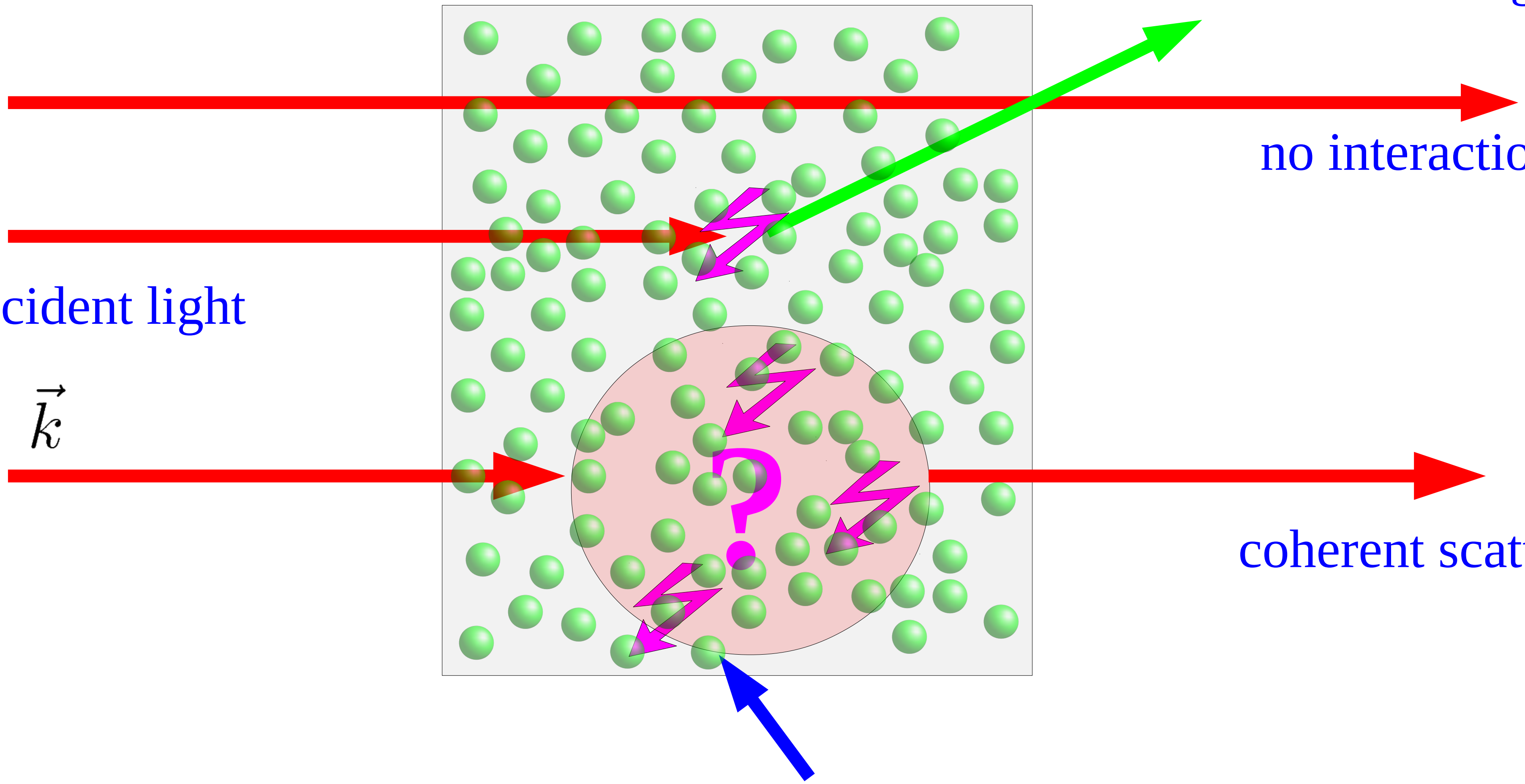
$$1/\Gamma = 141\ \text{ns}$$

Separating signal and background



- Nuclear resonances very narrow (µeV-peV)
- Nuclear scattering has delayed tail on time scale 1/Γ
  Example (^{57}Fe): 141 ns
- This allows to measure almost background-free using time gating

Elementary processes



inelastic scattering

no interaction

incident light

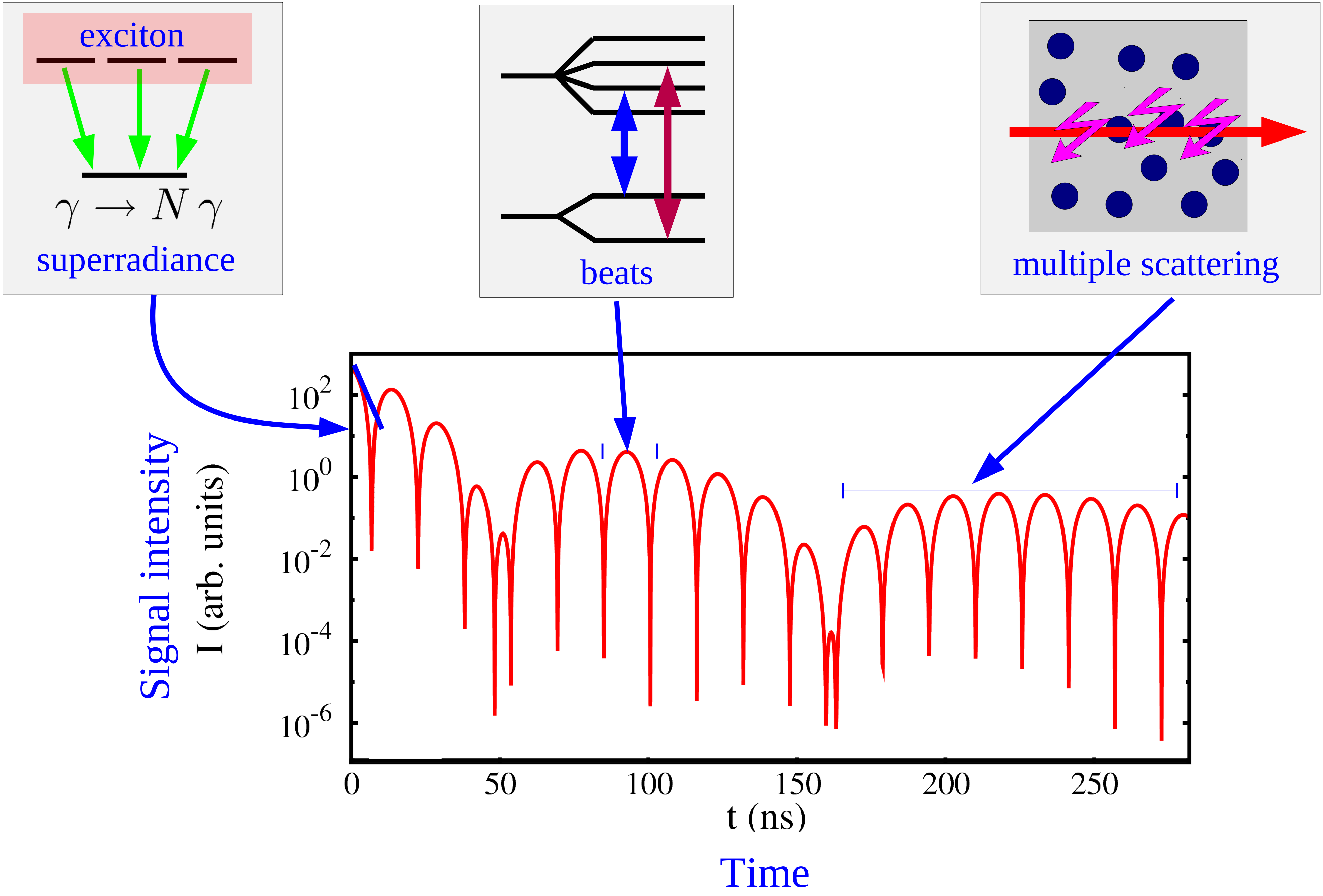
$\vec{k}$

coherent scattering

Intermediate excitonic state

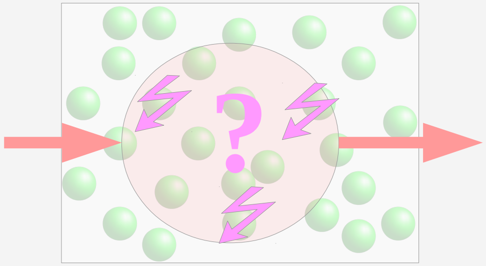
$$|\Psi\rangle = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} e^{i\vec{k}\vec{r}_i} |g_1, \ldots, g_{i-1}, e_i, g_{i+1}, \ldots, g_N\rangle$$

Characteristic features in forward scattering

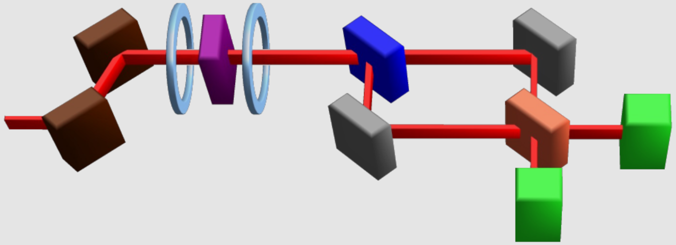


Outline

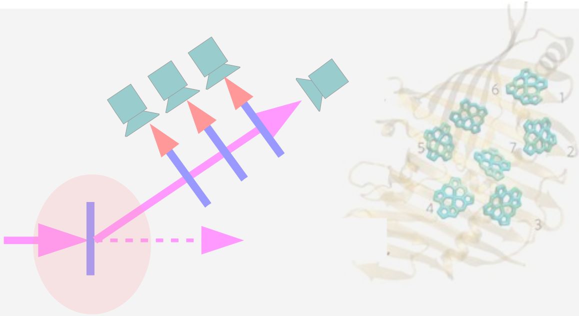
Introduction



Nuclear quantum optics



Future perspectives with seeded FELs

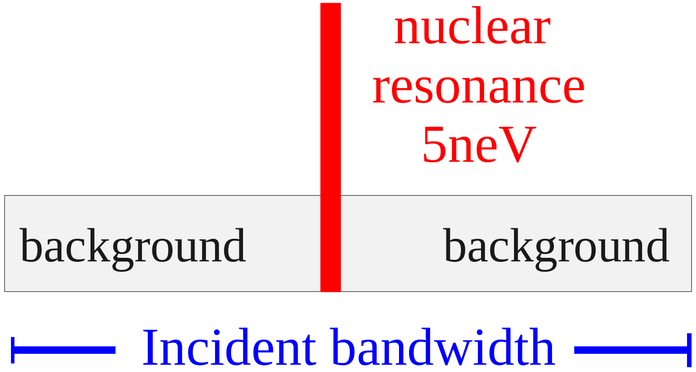


Synchrotron radiation vs. seeded FEL beams

	Synchrotron	Seeded XFEL
Bunch separation (ns)	200ns	200ns (microbunch)
Avg Flux (ph/s/Γ)	5×10^{4}	2×10^{8}
Fluence (ph/bunch/Γ)	10^{-2}	6×10^{3}

nuclear parameters
(for ^{57}Fe)
energy 14.4 keV
linewidth 5 neV

XFEL parameters
10^{12} photons/pulse
rel. BW 6×10^{-5}
rep. rate 30kHz


nuclear
resonance
5neV

background

background

Incident bandwidth

Geloni et al, arXiv:1111.5766

Synchrotron radiation vs. seeded FEL beams

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Two directions

photon hungry
(“proven concepts
with higher
count rate”)

Short, nonlinear,
coherent
(“new ideas”)

nuclear parameters
(for ^{57}Fe)
energy 14.4 keV
linewidth 5 neV

XFEL parameters
10^{12} photons/pulse
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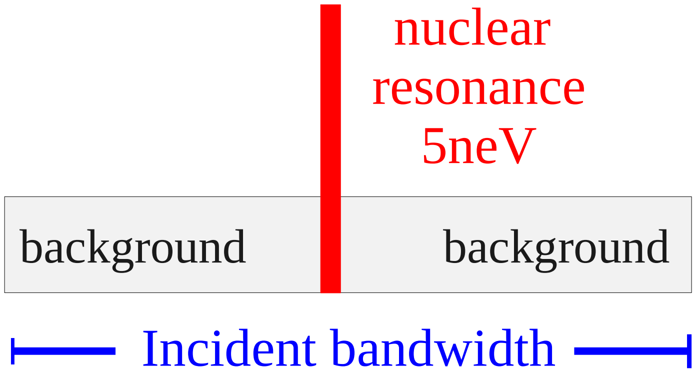

nuclear
resonance
5neV

background

background

Incident bandwidth

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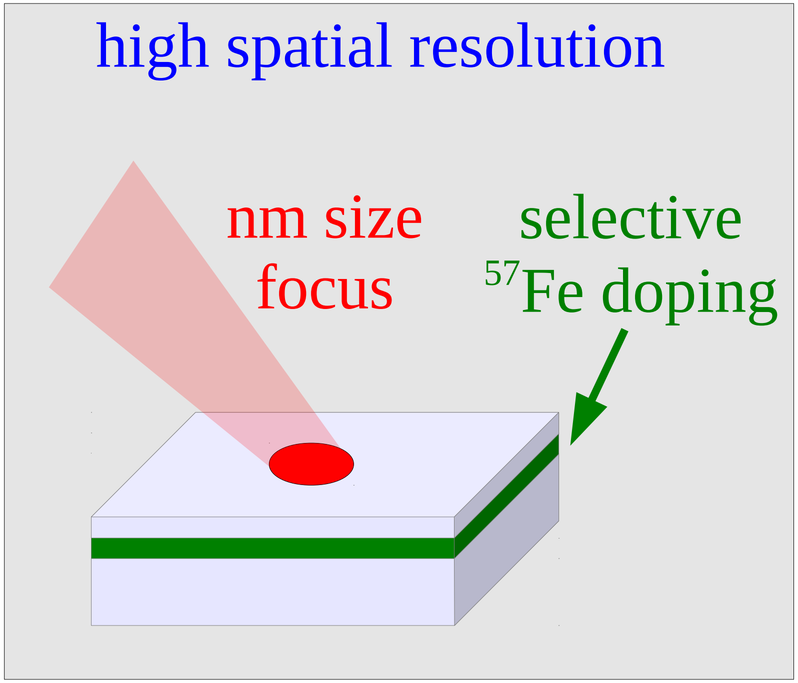
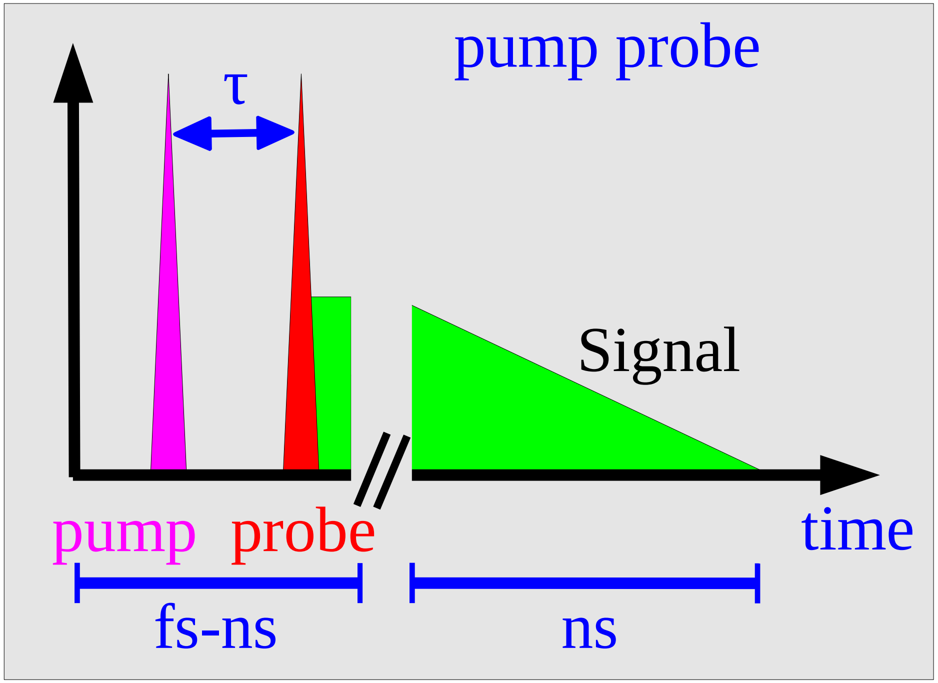
Nonequilibrium lattice dynamics

unique
XFEL/NRS
features

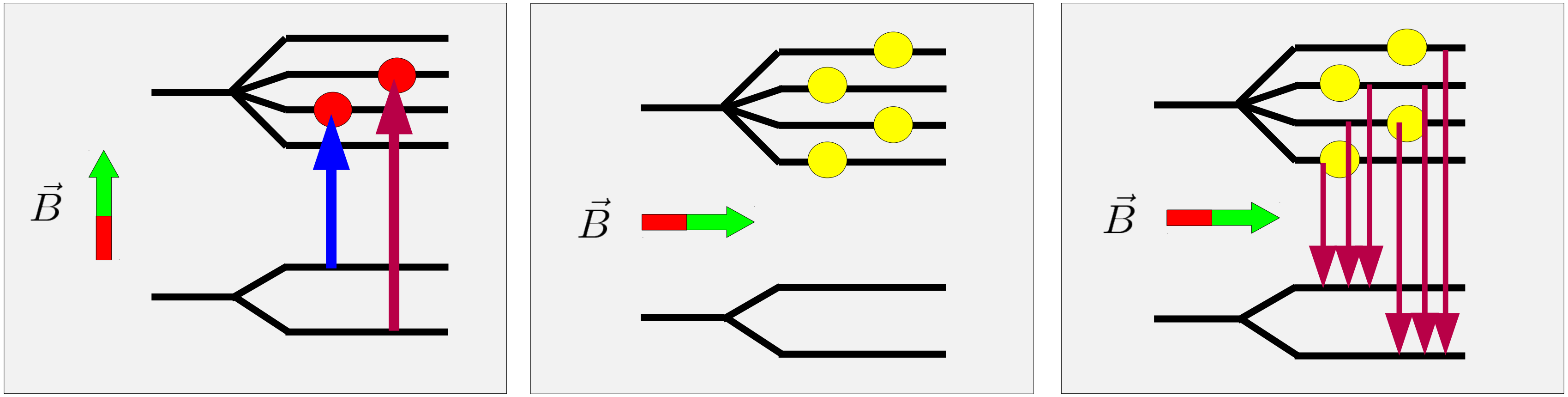
- Nuclei can not only monochromatize to sub-meV
- fs pulses capture snapshots of fast dynamics
- XFEL can produce double pulses with low jitter (< 5 fs)
- Small focus/isotope selective absorption provide high spatial resolution
- Long signal tail alleviates background / detection problems
- Example application: Heat transfer on nano scale



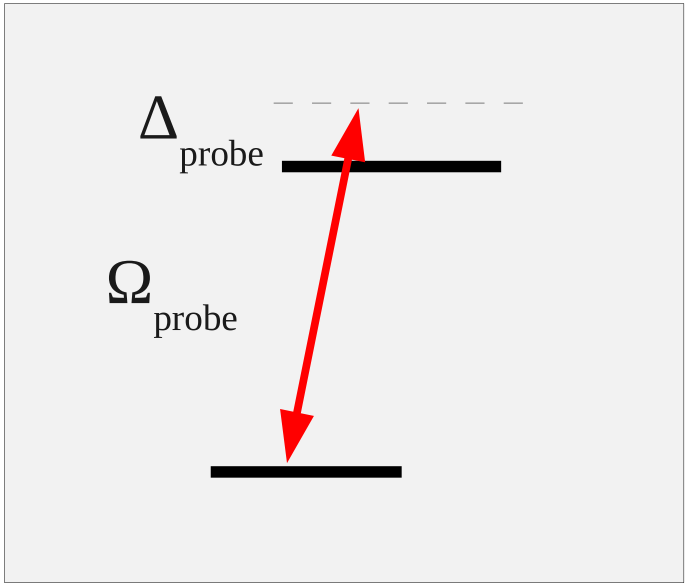


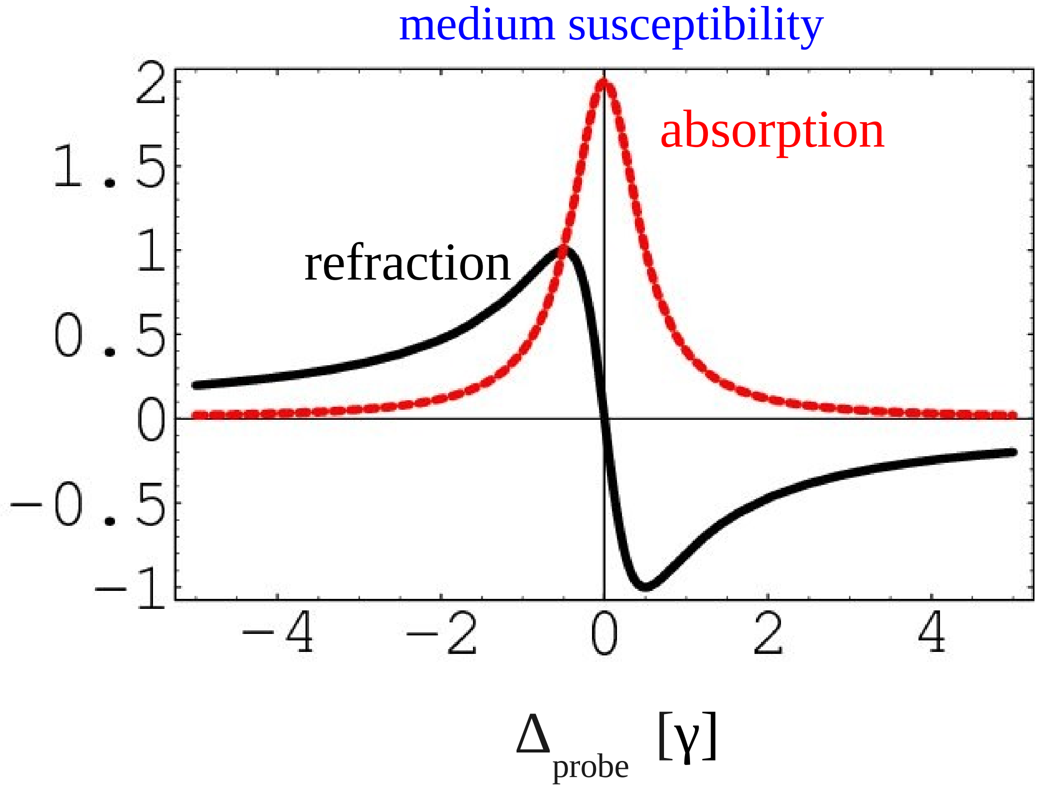
Geloni et al, arXiv:1011.3910 and HXRSS sumup; Shenoy and Röhlsberger, Hyperf. Int. 182, 157 (2008)

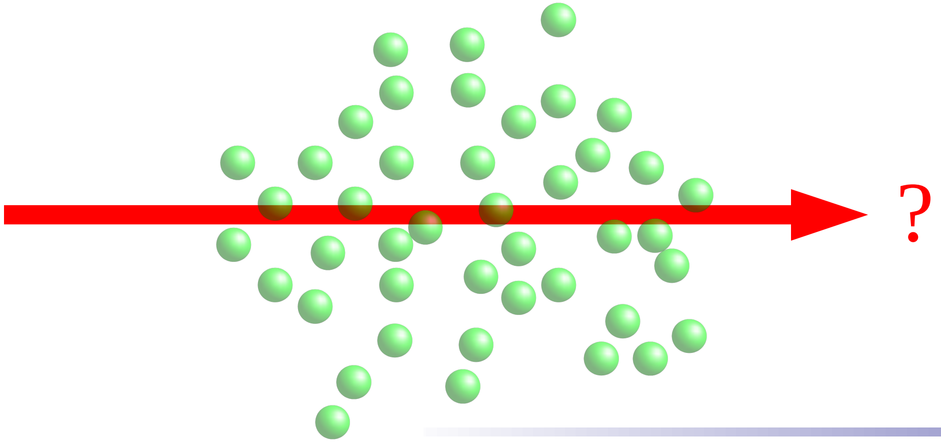
Nuclear quantum optics



Optical response of a single resonance

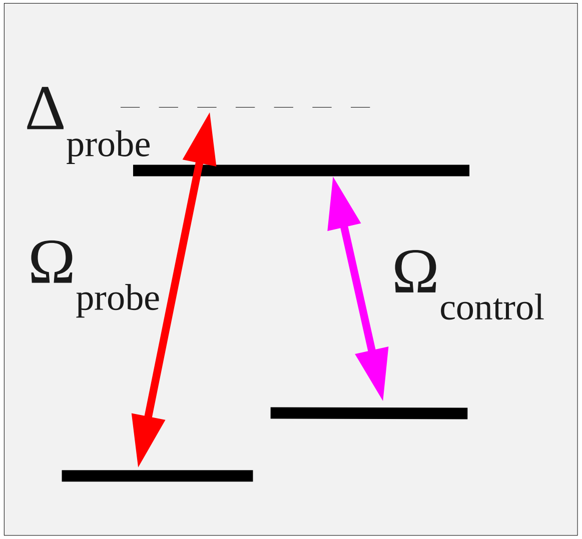


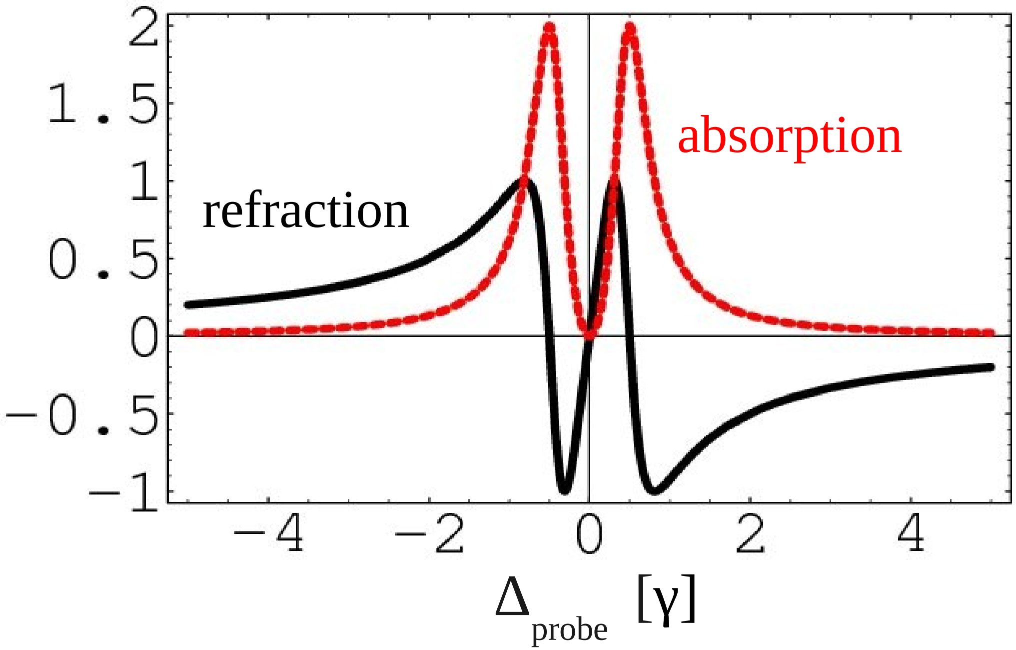




Electromagnetically induced transparency

Three-level Λ system





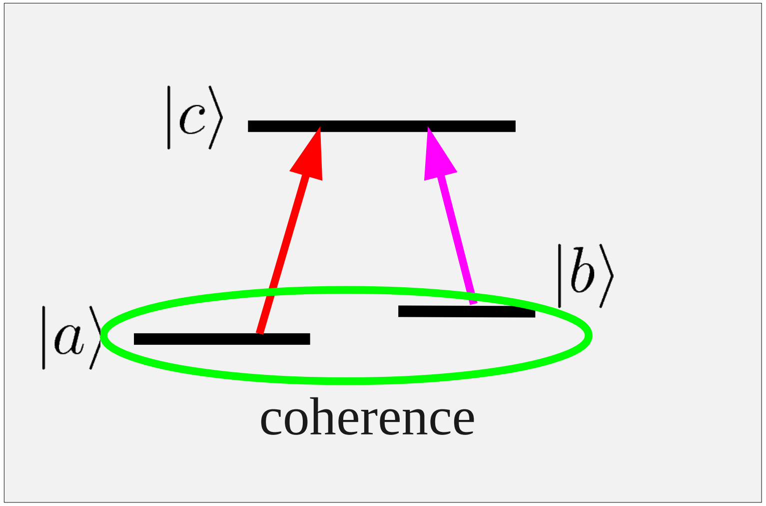
Medium is rendered transparent by shining light on it!

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

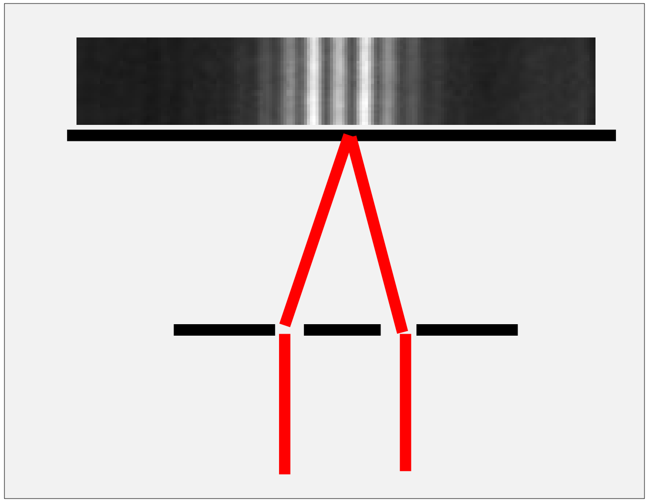
S. Harris, Physics Today 50, 36 (1997); M. Fleischhauer et al., Rev. Mod. Phys. 77, 633 (2005)

Electromagnetically induced transparency

Interpretation as coherence/interference effect:



EIT



double slit

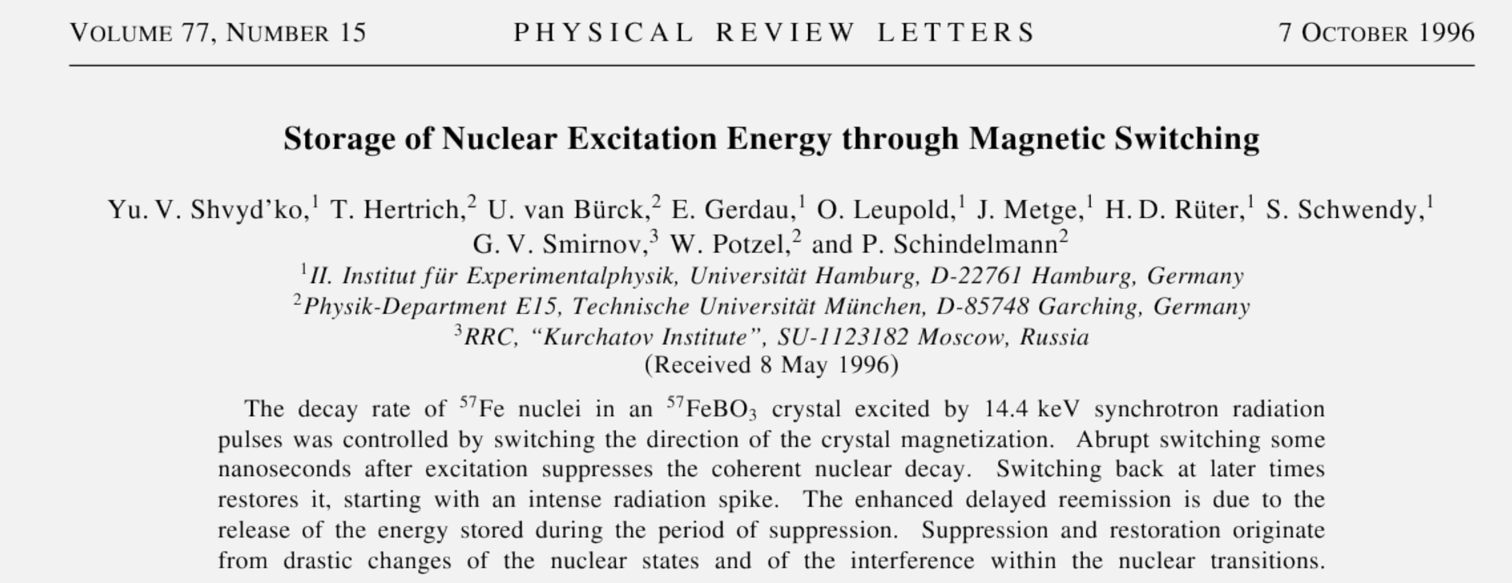
If EIT conditions are satisfied:

- 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

Magnetic switching

- The level structure depends on applied magnetic field: Zeeman splitting
- In certain crystals (e.g. $FeBO_3$), the hyperfine field is very strong ($\sim$ 30 T), and can be aligned via weak external fields (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

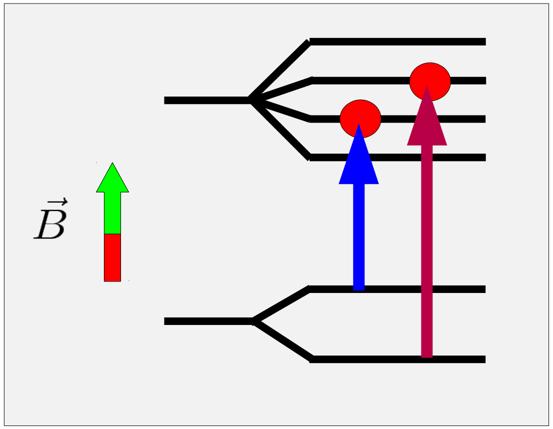
Yu. V. Shvyd'ko,[1] T. Hertrich,[2] U. van Bürck,[2] E. Gerdau,[1] O. Leupold,[1] J. Metge,[1] H. D. Rüter,[1] S. Schwendy,[1]
G. V. Smirnov,[3] W. Potzel,[2] and P. Schindelmann[2]
[1]*II. Institut für Experimentalphysik, Universität Hamburg, D-22761 Hamburg, Germany*
[2]*Physik-Department E15, Technische 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)

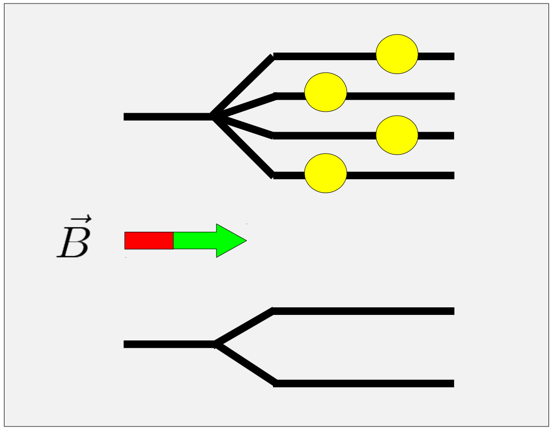
Coherent control of the exciton

Excite the sample



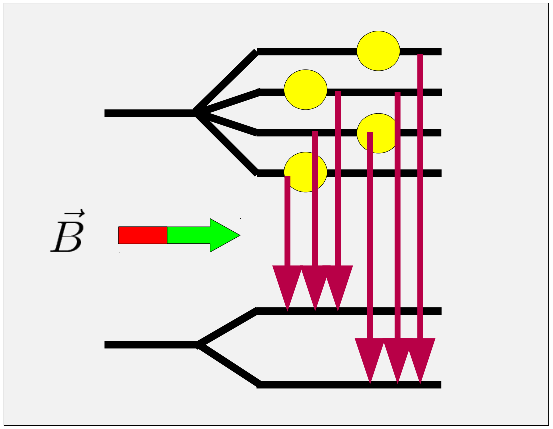
Rotate quantization axis

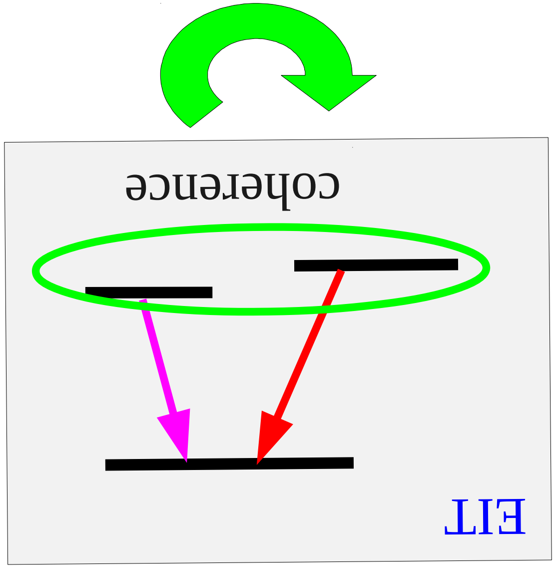
- Rotate applied magnetic field
- Experiment: 30T in 5ns possible in certain crystals



Deexcitation

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

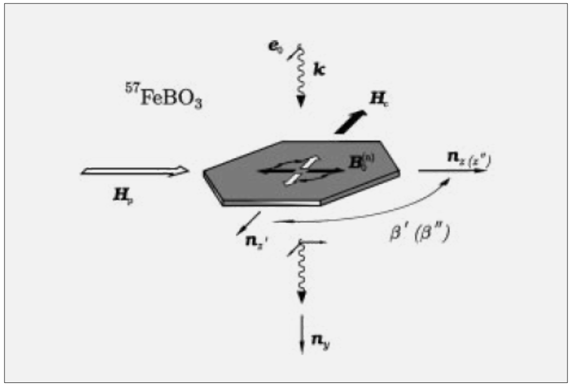




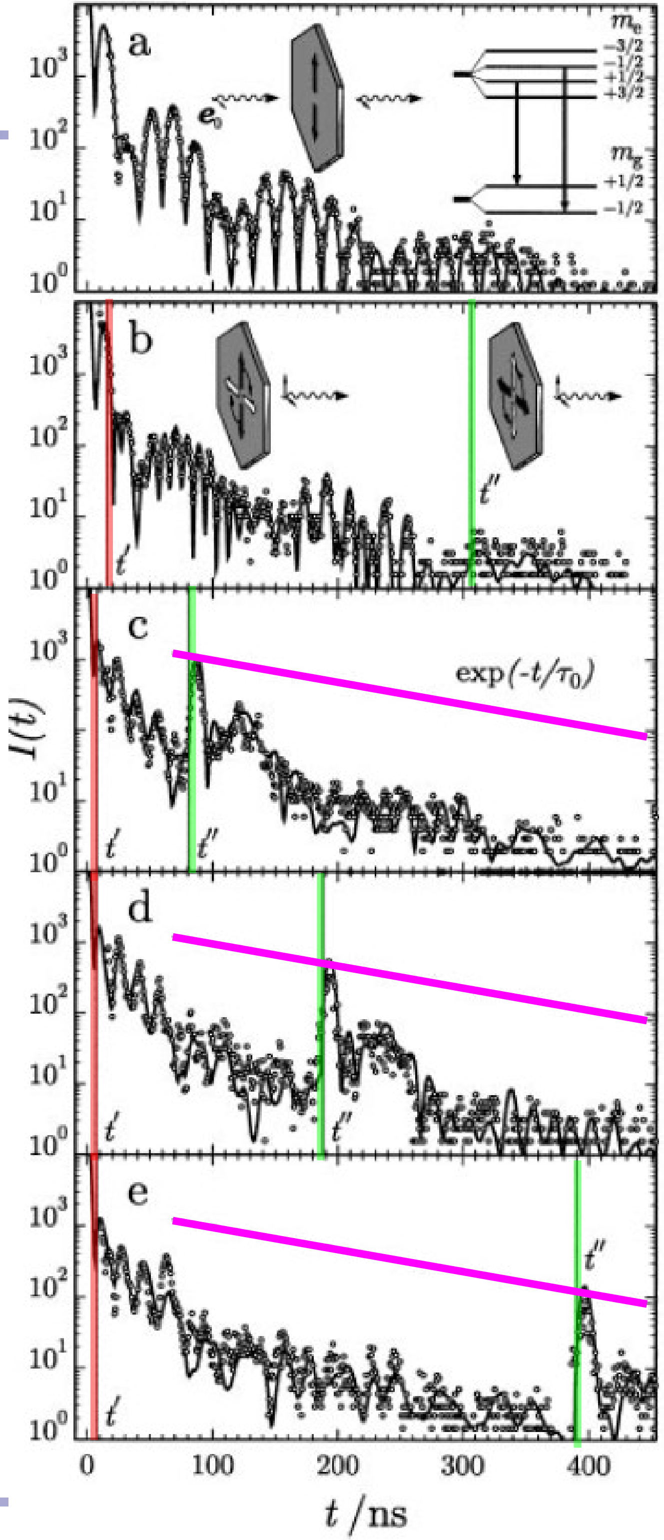
Exciton storage

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)



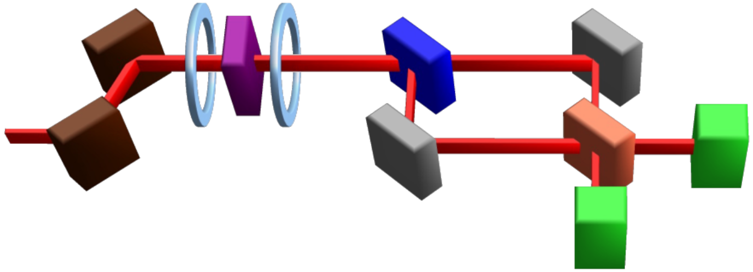
No switching

Apply switching

Switch back

Decay with natural life time

X-ray entanglement generation



Single photon entanglement

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

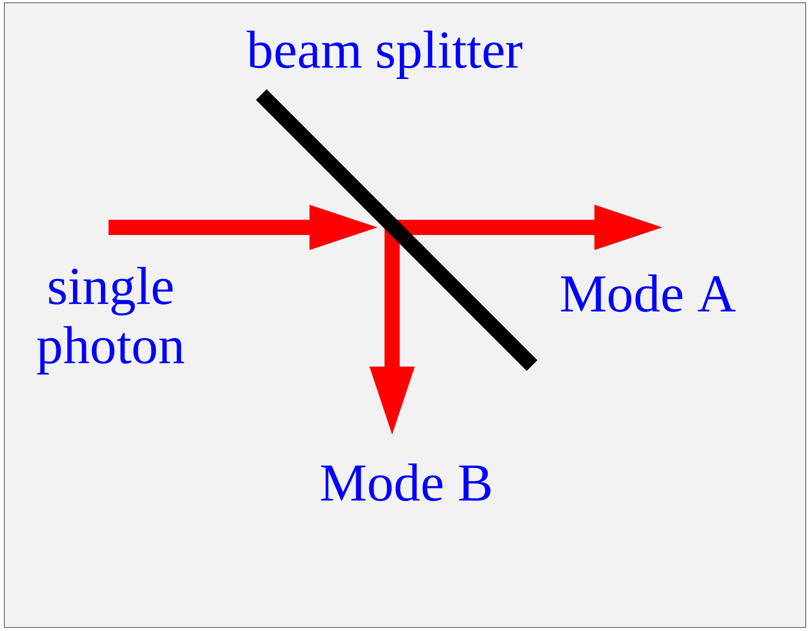
$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle_A|1\rangle_B + |1\rangle_A|0\rangle_B\right)$$

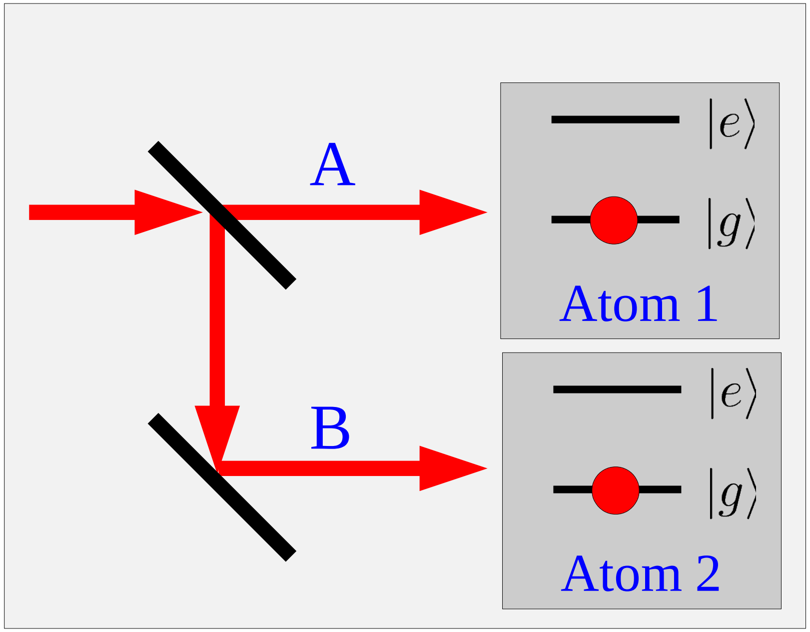
- The single photon entangles the two field modes A and B - the photon itself is not entangled

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

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

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



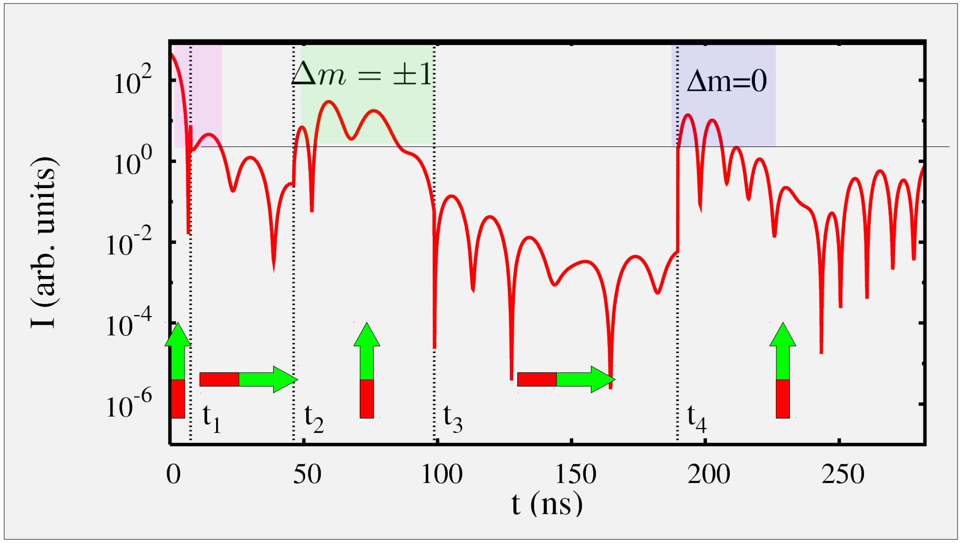


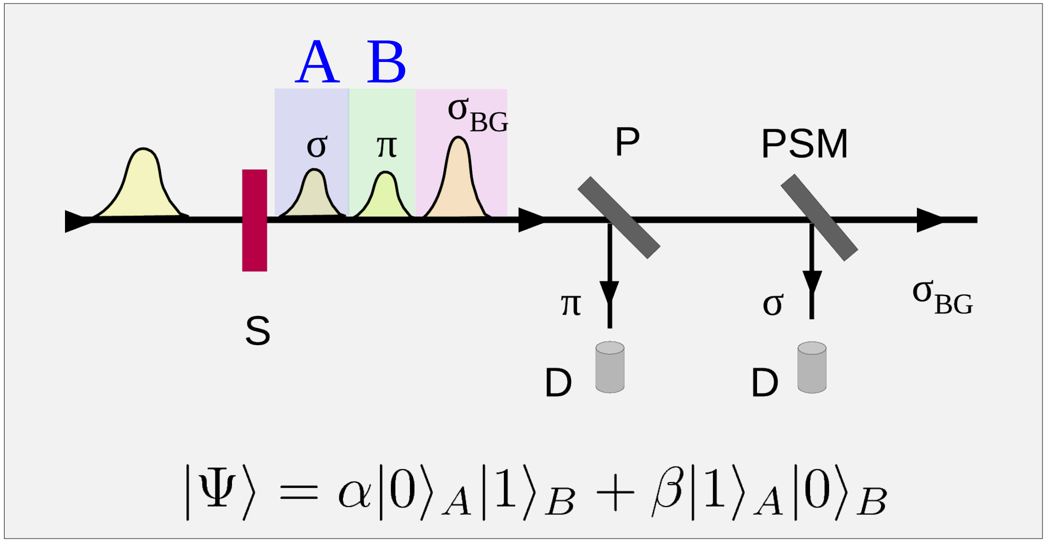
S. J. van Enk, Phys. Rev. A 67, 022303 (2003)

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



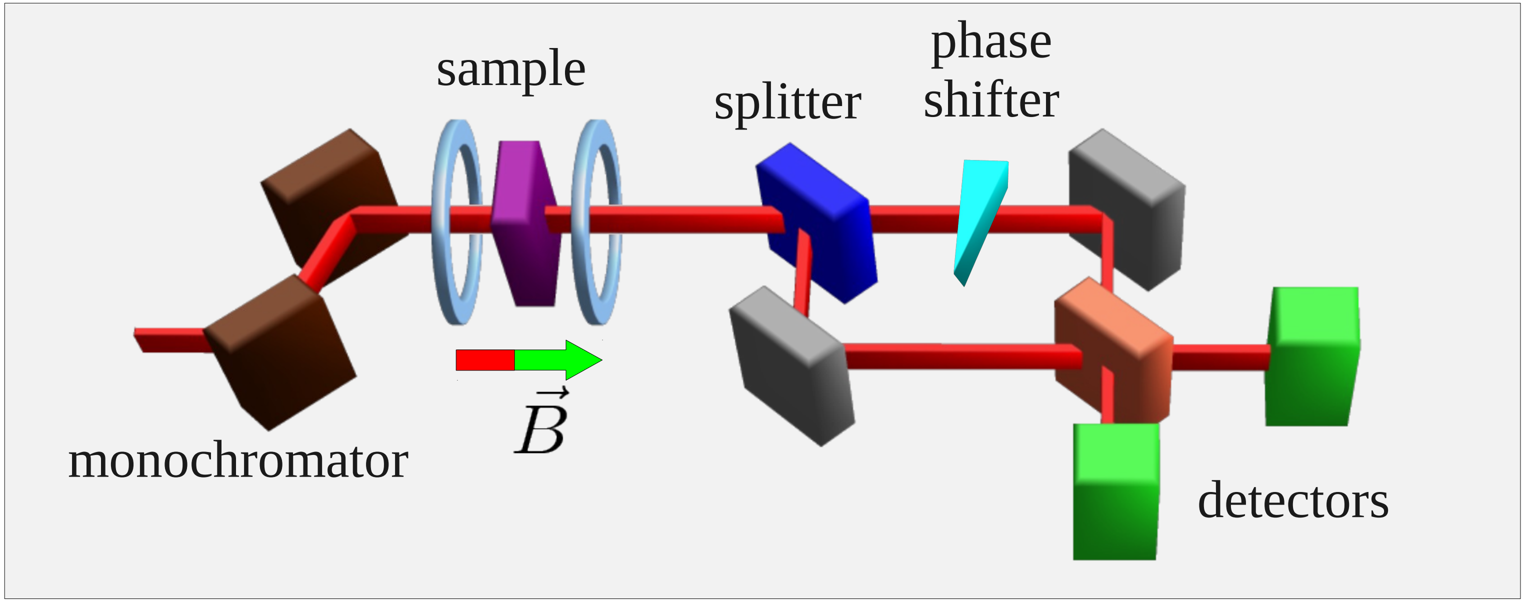


$$|\Psi\rangle = \alpha|0\rangle_A|1\rangle_B + \beta|1\rangle_A|0\rangle_B$$

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

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



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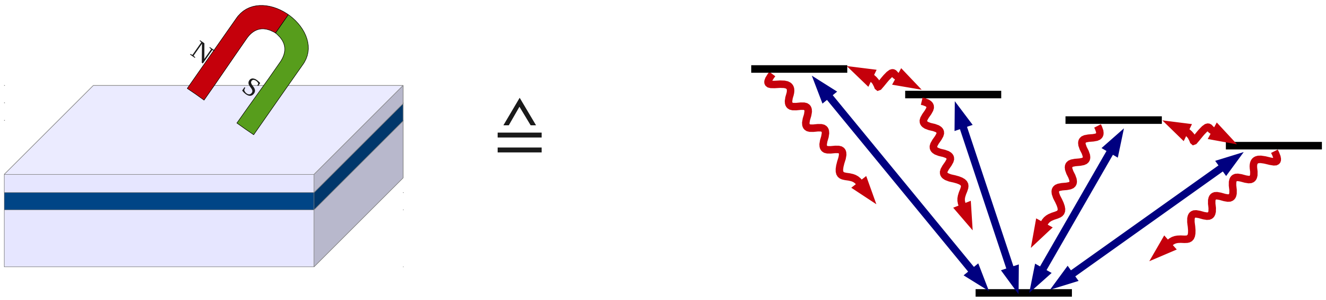
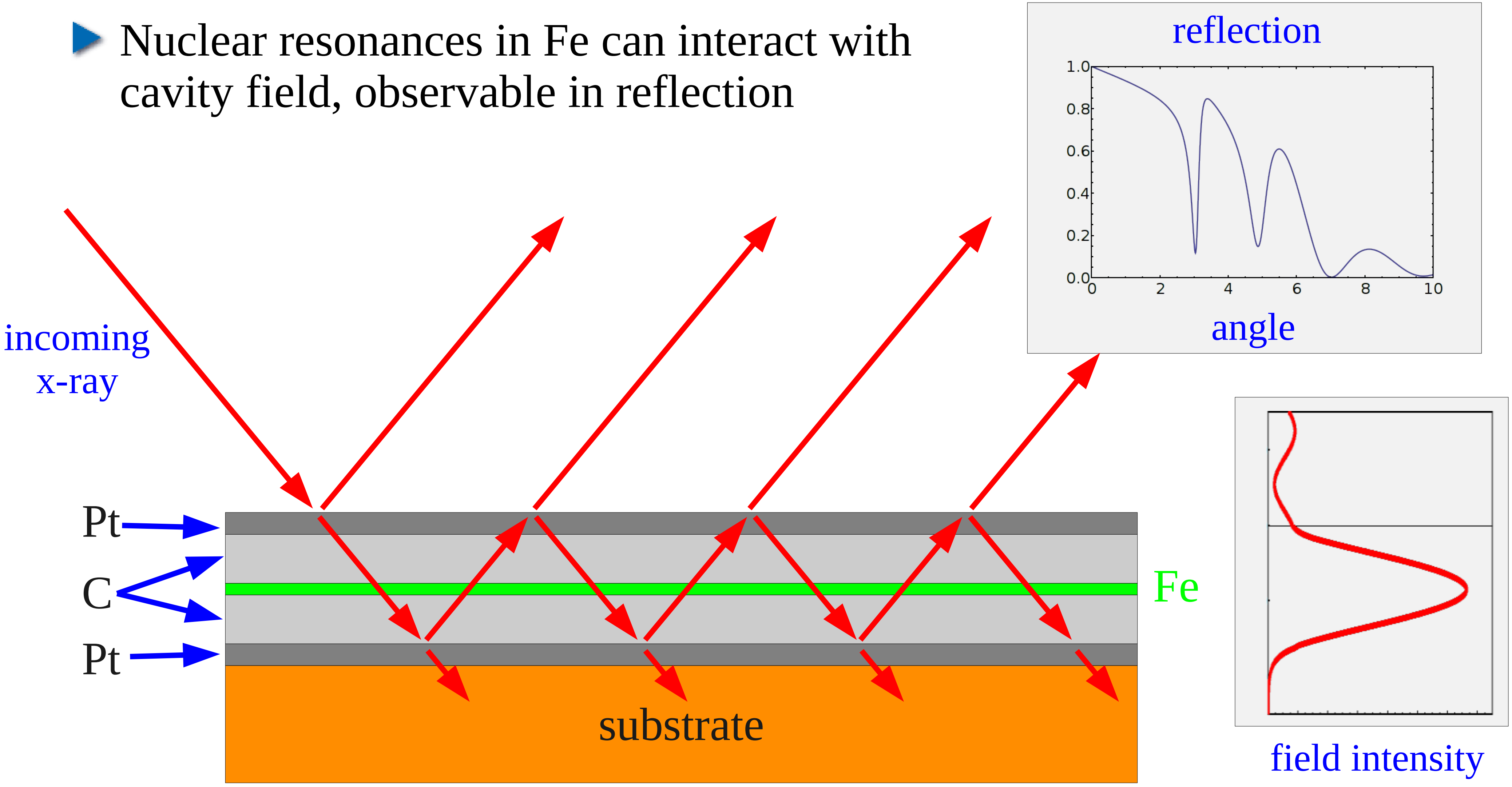
*) H.-W. Lee and Kim, Phys. Rev. A 63, 012305 (2000)

Engineering advanced quantum optical level schemes in nuclei

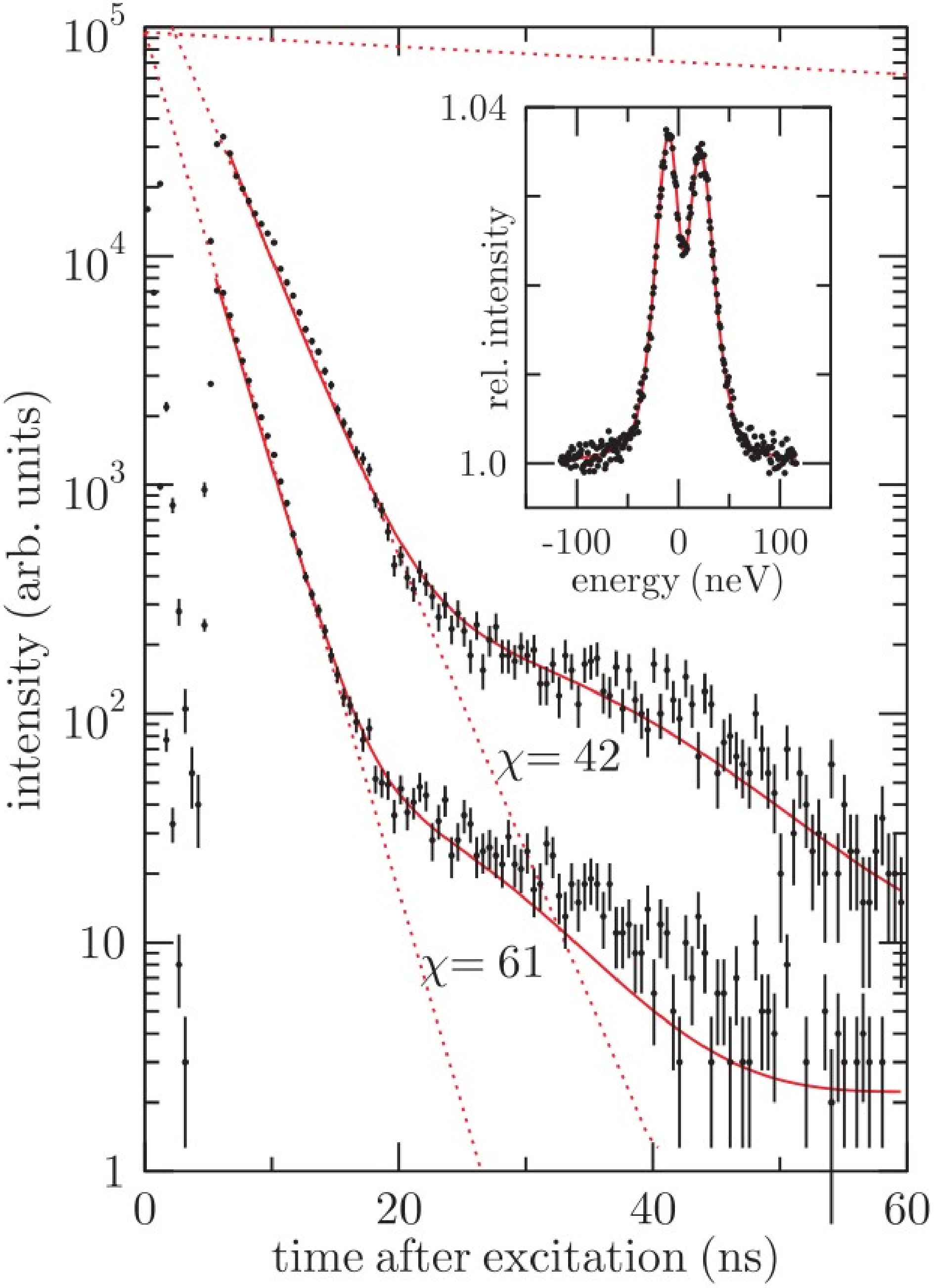


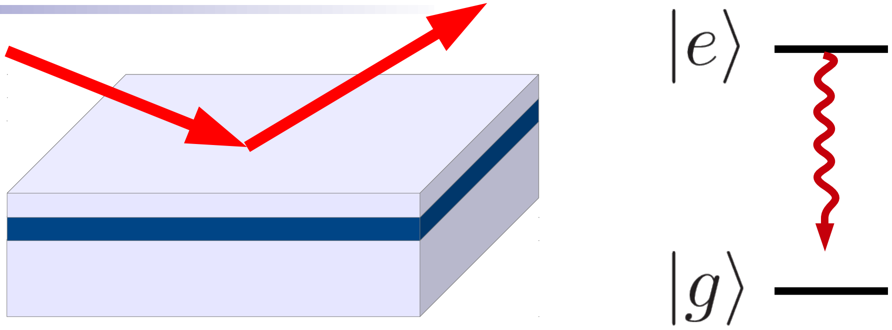
Thin film x-ray cavities

- nm-sized thin film cavity
- Cavity resonances give field enhancement
- Nuclear resonances in Fe can interact with cavity field, observable in reflection

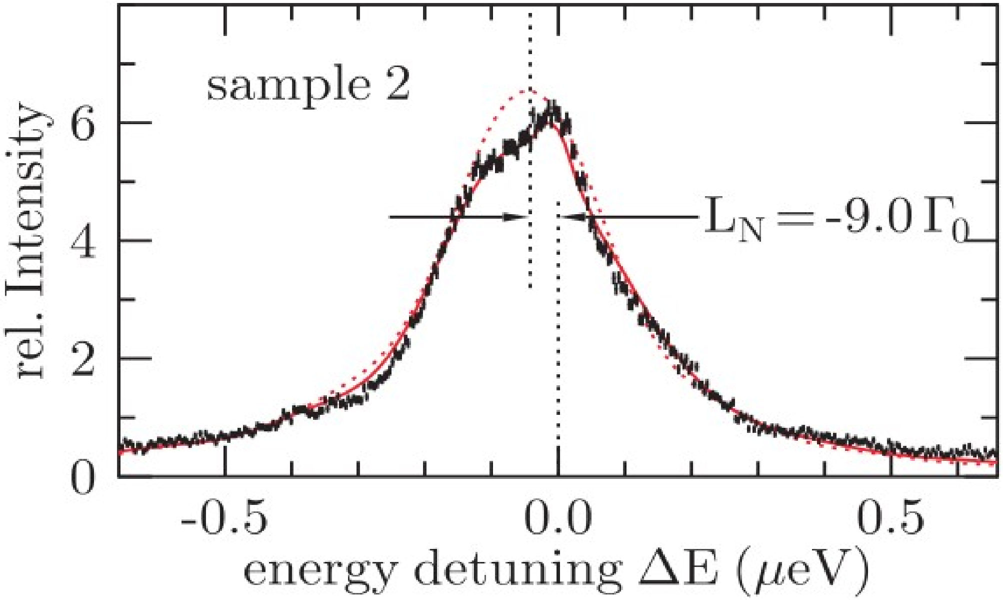


A single iron layer



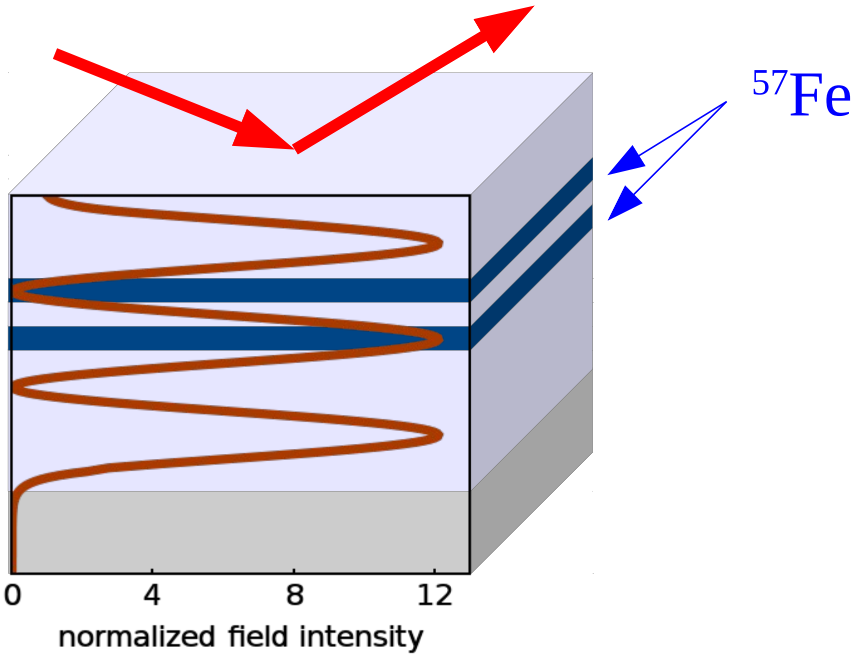


Superradiance +
cooperative Lamb shift

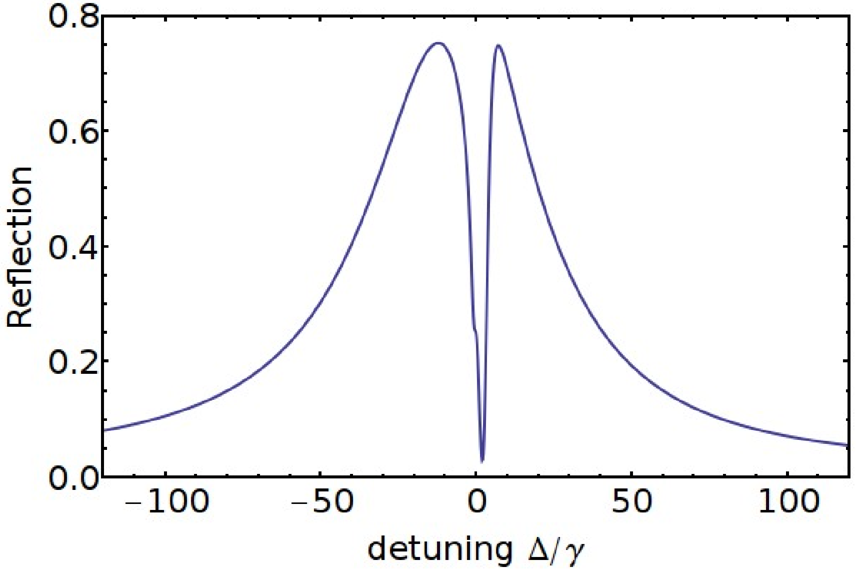


Röhlsberger et al, Science 328, 1248 (2010)

Two iron layers



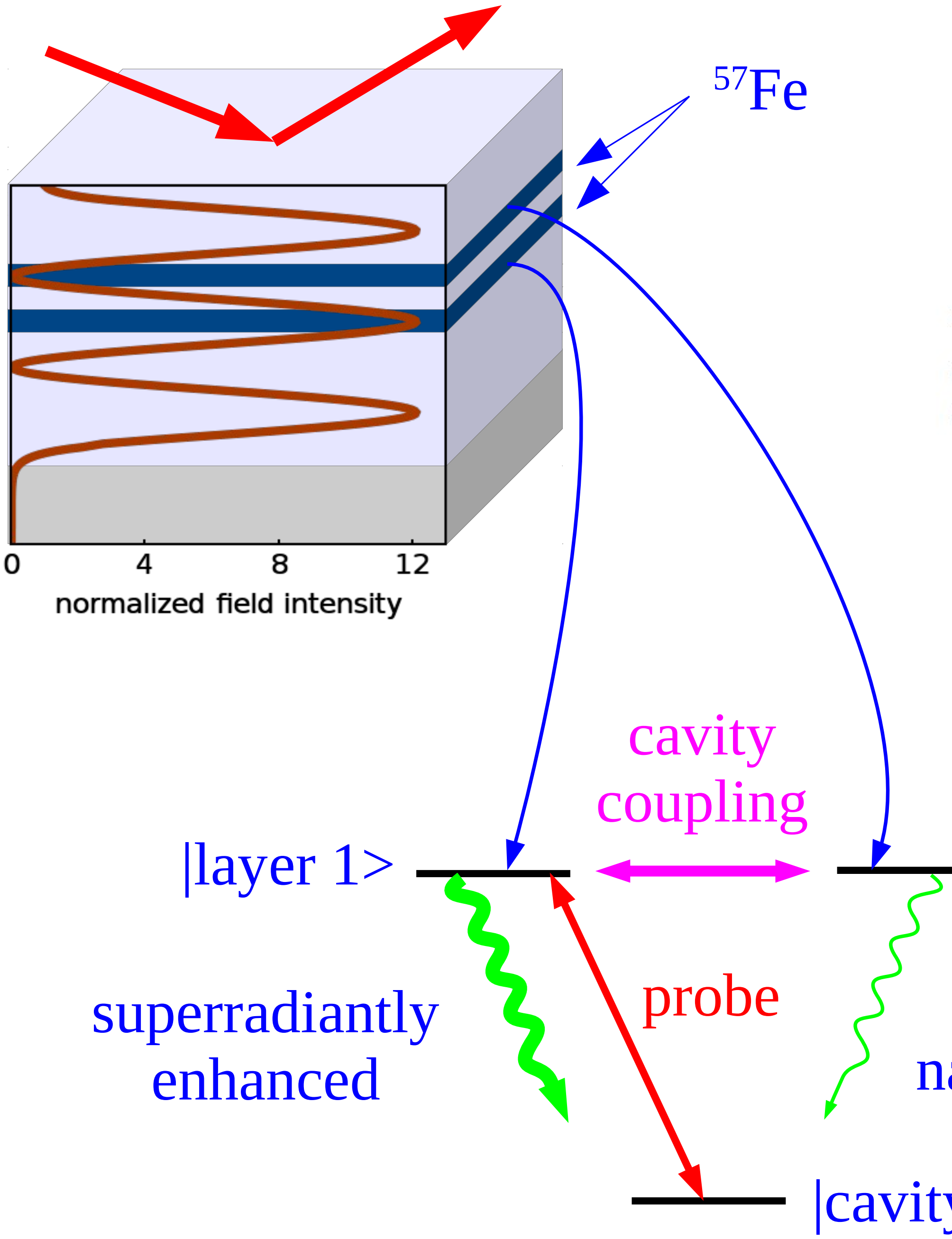
Reflection spectrum



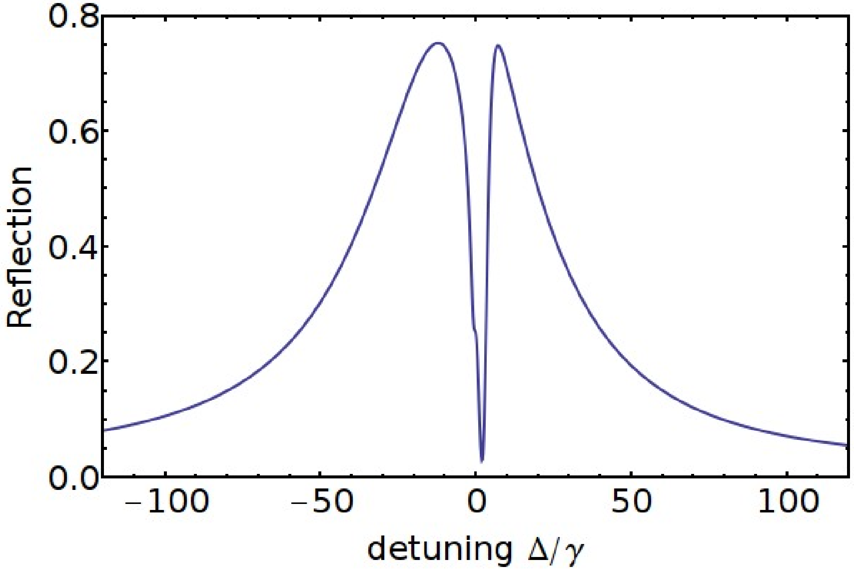
Looks like EIT!

Röhlsberger et al, Nature 482, 199 (2012)

Two iron layers



Reflection spectrum

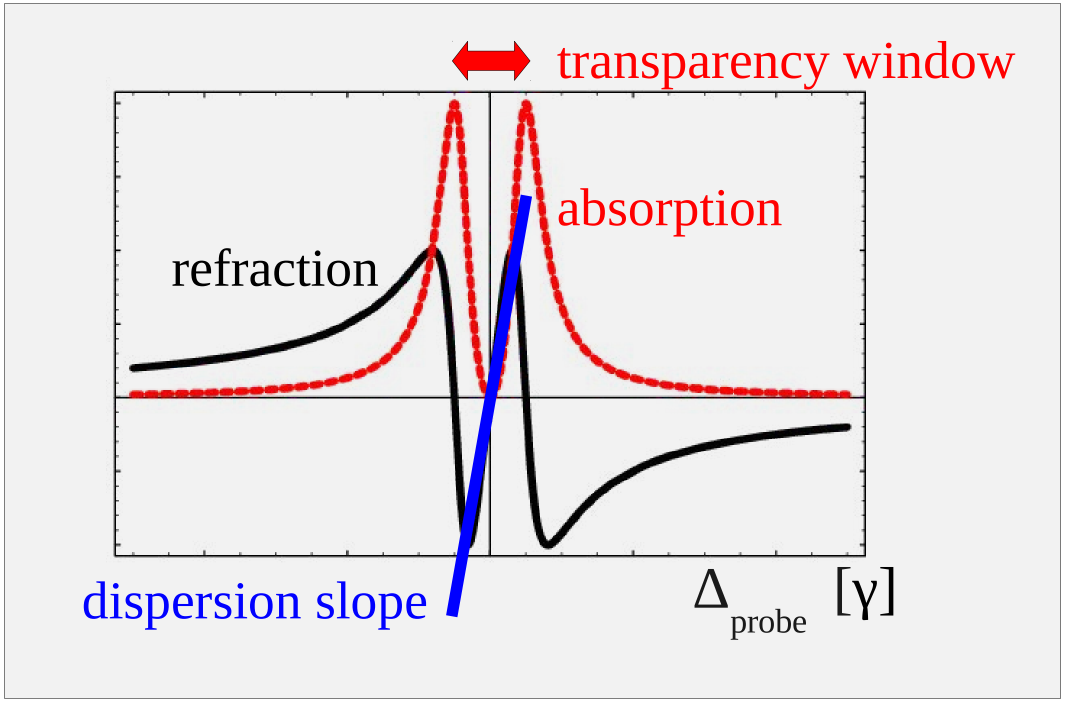


It is EIT!

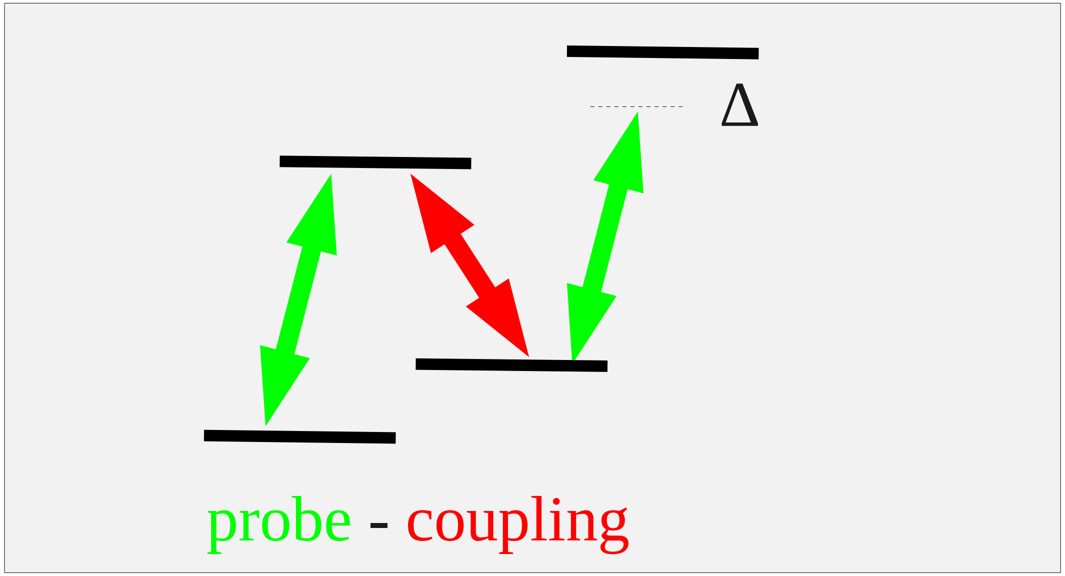
same nuclei acquire different properties

Röhlsberger et al, Nature 482, 199 (2012)

What would be desirable?



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

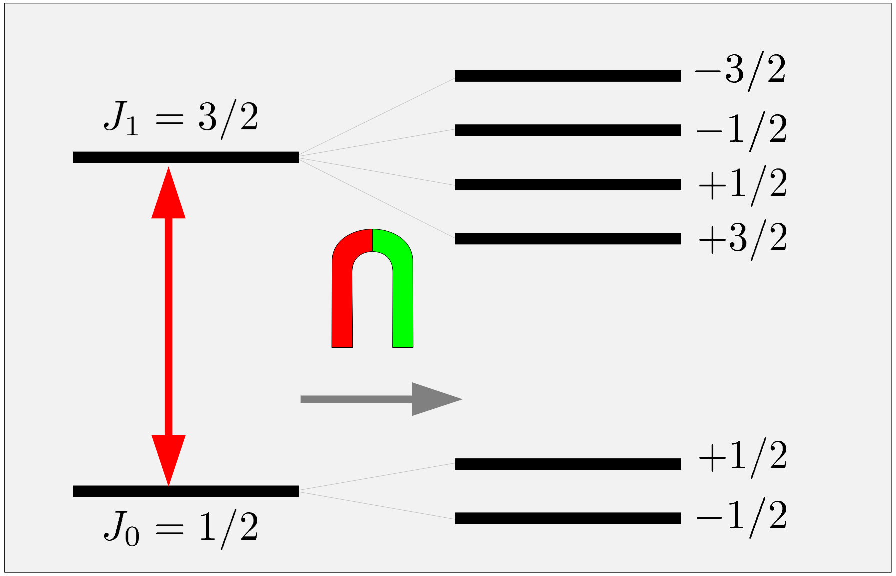


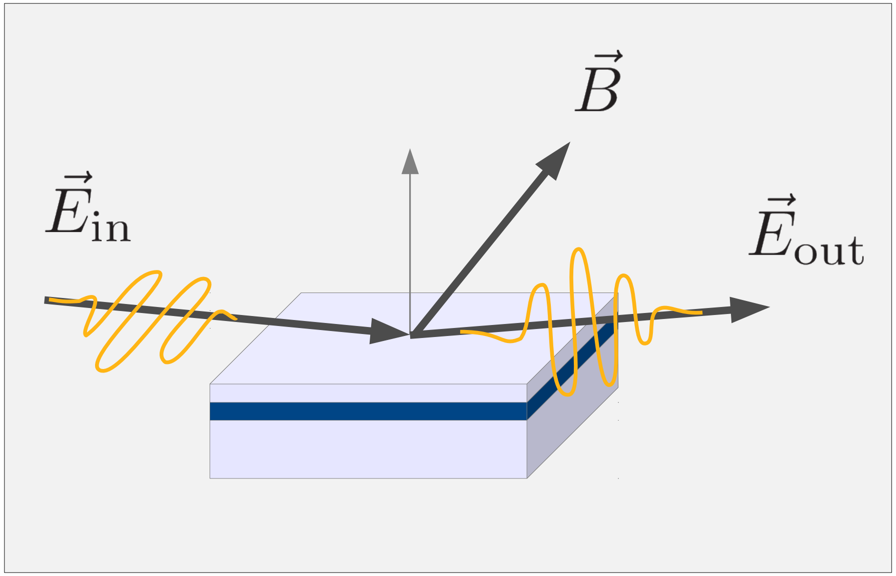
- More general level schemes offer wide range of applications
- Example: Strongly enhanced non-linear response

J. Evers, work in progress

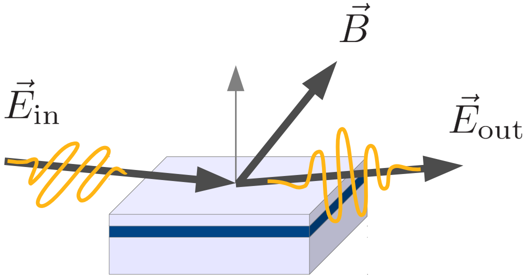
Exploit the hyperfine structure

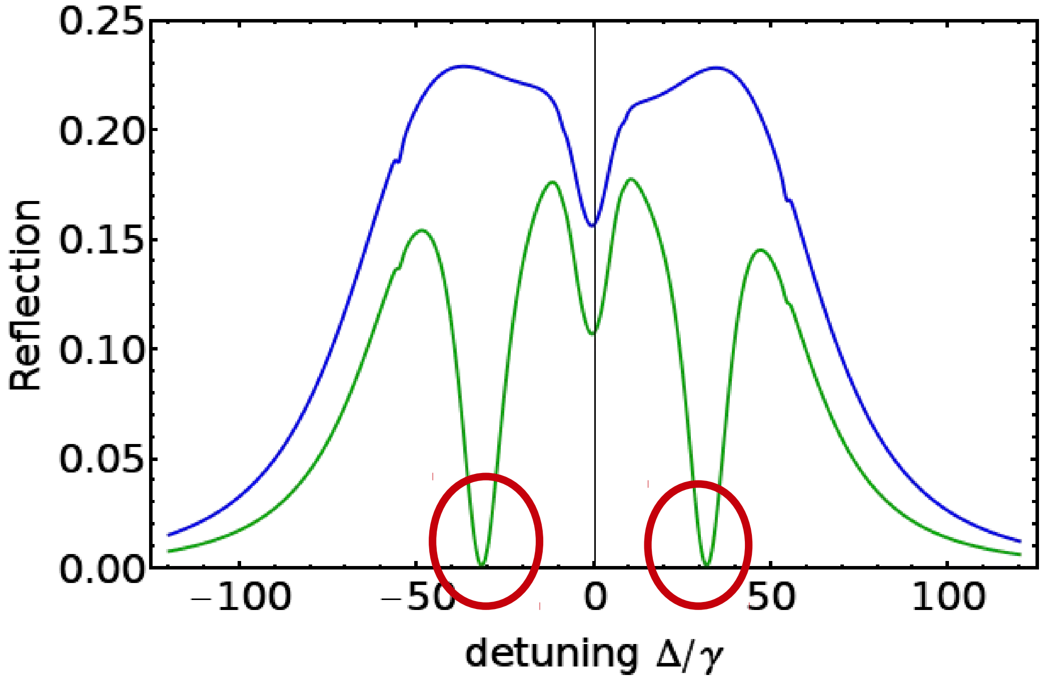
- So far, operated nuclei as 2-level systems
- Next, apply magnetic field to exploit magnetic hyperfine structure
- Many degrees of freedom: polarization, magnetization





Unexpected spectral signatures





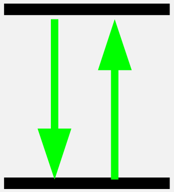
$$\vec{B} \parallel \hat{k}$$

$$\vec{B} \parallel \hat{k} + \hat{E}_{\text{in}}$$

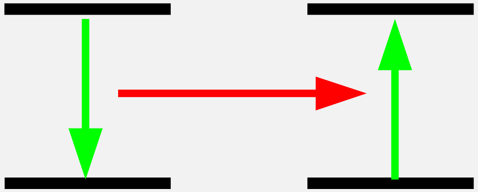
What's this? Only interference can create
zeros in overlapping resonances.
But can't be EIT – only one layer!

K. P. Heeg, R. Röhlsberger, J. Evers, in preparation

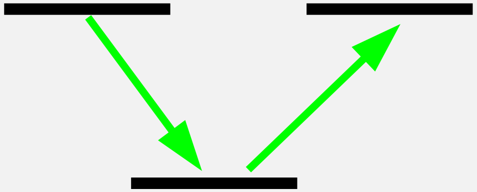
Fundamental light-matter interactions



decay, Lamb shift
(same atom, same transition)



dipole-dipole interaction
(other atom)

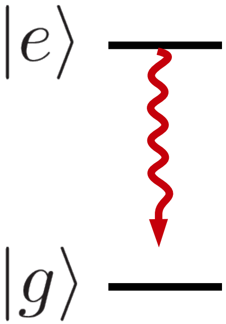


spontaneous coherences
(same atom, different transition)

- Spontaneously generated coherences can be generated by virtual photon exchange involving different states in the same atom
- Desirable consequences, but usually forbidden e.g. by selection rules
- Literally hundreds of theory papers on this topic
- So far only few indirect experimental observations
- Our calculations show that the “zeros” in spectrum are due to SGC
  ⟶ first direct experimental evidence

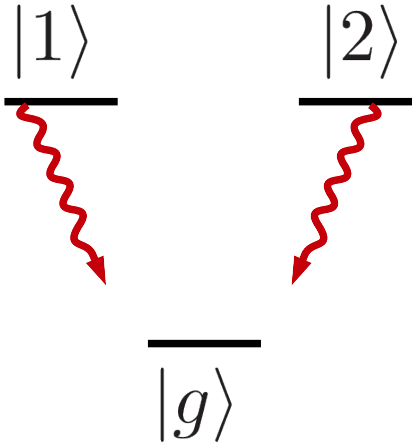
Quantum optical model

Two-level system



$$\frac{\partial}{\partial t}\rho = -\frac{\gamma}{2}\left(|e\rangle\langle e|\rho + \rho|e\rangle\langle e| - 2|g\rangle\langle e|\rho|e\rangle\langle g|\right)$$

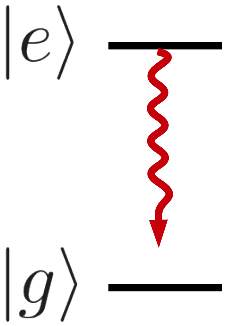
Three-level system



$$\begin{aligned}\frac{\partial}{\partial t}\rho = & -\frac{\gamma}{2}\left(|1\rangle\langle 1|\rho + \rho|1\rangle\langle 1| - 2|g\rangle\langle 1|\rho|1\rangle\langle g|\right)\\ & -\frac{\gamma}{2}\left(|2\rangle\langle 2|\rho + \rho|2\rangle\langle 2| - 2|g\rangle\langle 2|\rho|2\rangle\langle g|\right)\end{aligned}$$

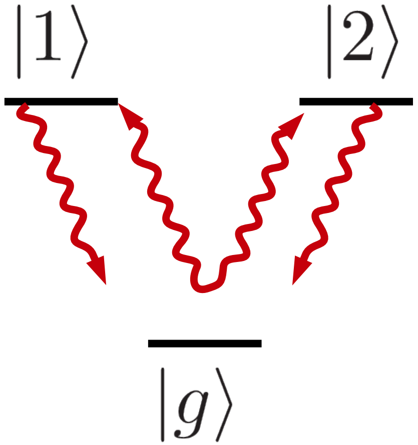
Quantum optical model

Two-level system



$$\frac{\partial}{\partial t}\rho = -\frac{\gamma}{2}\left(|e\rangle\langle e|\rho + \rho|e\rangle\langle e| - 2|g\rangle\langle e|\rho|e\rangle\langle g|\right)$$

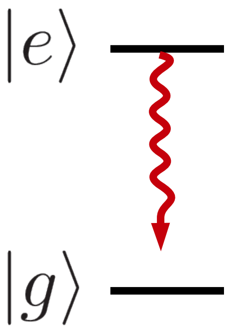
Three-level system with SGC



$$\begin{aligned}\frac{\partial}{\partial t}\rho = & -\frac{\gamma}{2}\left(|1\rangle\langle 1|\rho + \rho|1\rangle\langle 1| - 2|g\rangle\langle 1|\rho|1\rangle\langle g|\right)\\ & -\frac{\gamma}{2}\left(|2\rangle\langle 2|\rho + \rho|2\rangle\langle 2| - 2|g\rangle\langle 2|\rho|2\rangle\langle g|\right)\\ & -\frac{\gamma_C}{2}\left(|1\rangle\langle 2|\rho + \rho|1\rangle\langle 2| - 2|g\rangle\langle 2|\rho|1\rangle\langle g|\right)\\ & -\frac{\gamma_C}{2}\left(|2\rangle\langle 1|\rho + \rho|2\rangle\langle 1| - 2|g\rangle\langle 1|\rho|2\rangle\langle g|\right)\end{aligned}$$

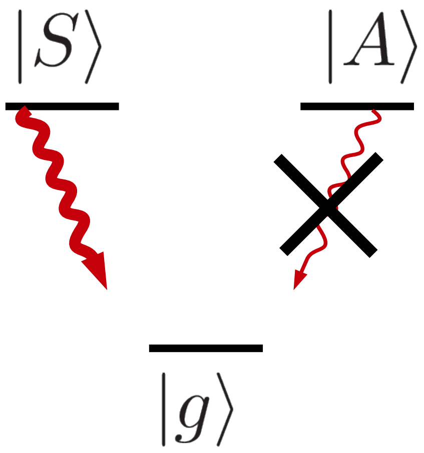
Quantum optical model

Two-level system



$$\frac{\partial}{\partial t}\rho = -\frac{\gamma}{2}\left(|e\rangle\langle e|\rho + \rho|e\rangle\langle e| - 2|g\rangle\langle e|\rho|e\rangle\langle g|\right)$$

Three-level system with SGC, diagonalized



$$\begin{aligned}\frac{\partial}{\partial t}\rho = &-\frac{\gamma+\gamma_C}{2}\left(|S\rangle\langle S|\rho + \rho|S\rangle\langle S| - 2|g\rangle\langle S|\rho|S\rangle\langle g|\right)\\ &-\frac{\gamma-\gamma_C}{2}\left(|A\rangle\langle A|\rho + \rho|A\rangle\langle A| - 2|g\rangle\langle A|\rho|A\rangle\langle g|\right)\end{aligned}$$

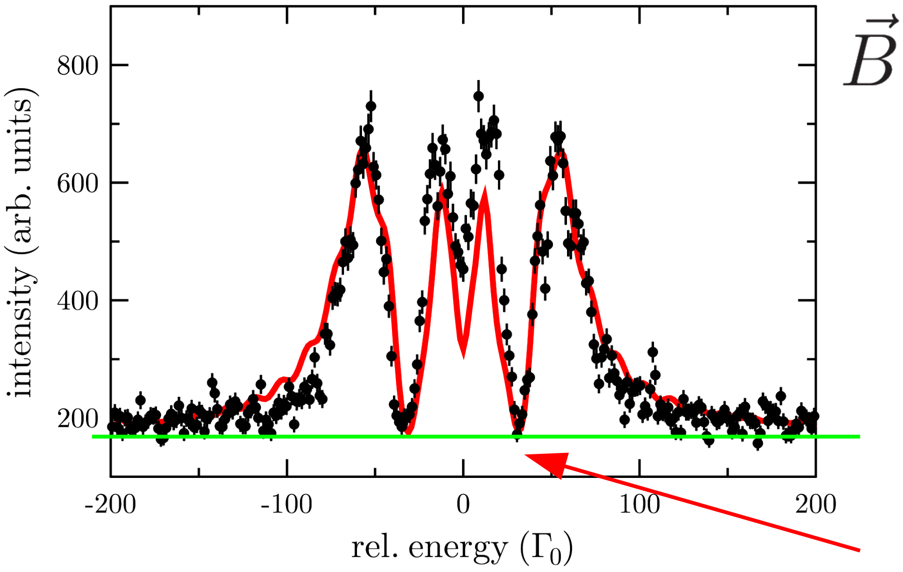
$$|S\rangle = \frac{1}{\sqrt{2}}\left(|1\rangle + |2\rangle\right)$$

constructive interference

$$|A\rangle = \frac{1}{\sqrt{2}}\left(|1\rangle - |2\rangle\right)$$

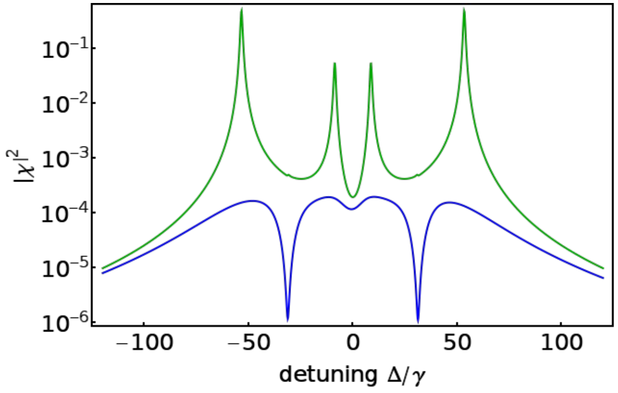
destructive interference
dark line in spectrum

Preliminary results (PETRA III, June 2012)

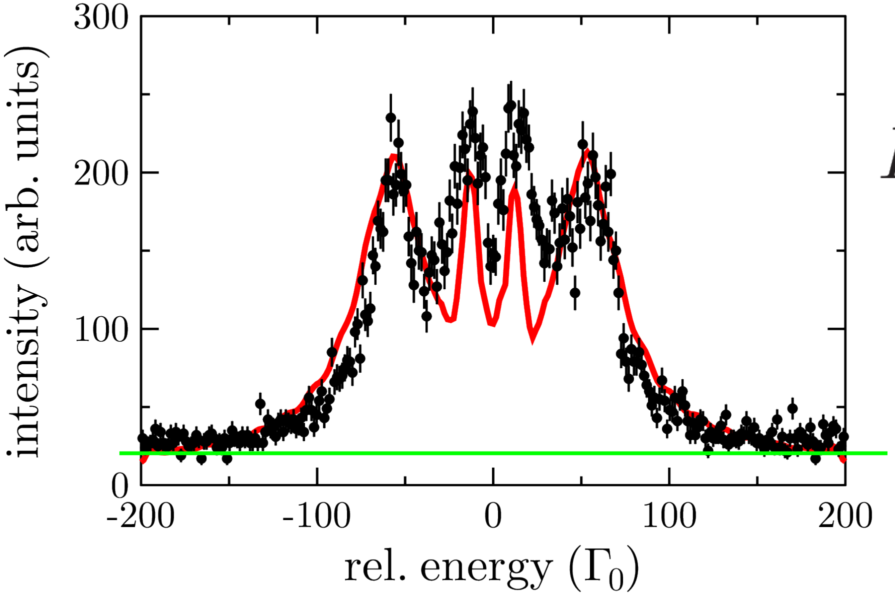


$$\vec{B} \parallel \hat{k} + \hat{E}_{\text{in}}$$

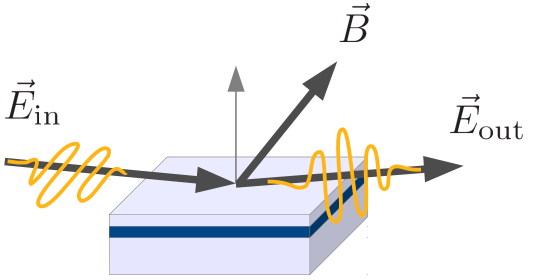
with/without SGC



really zero -
clean system,
no decoherence!



$$\vec{B} \parallel \hat{k}$$

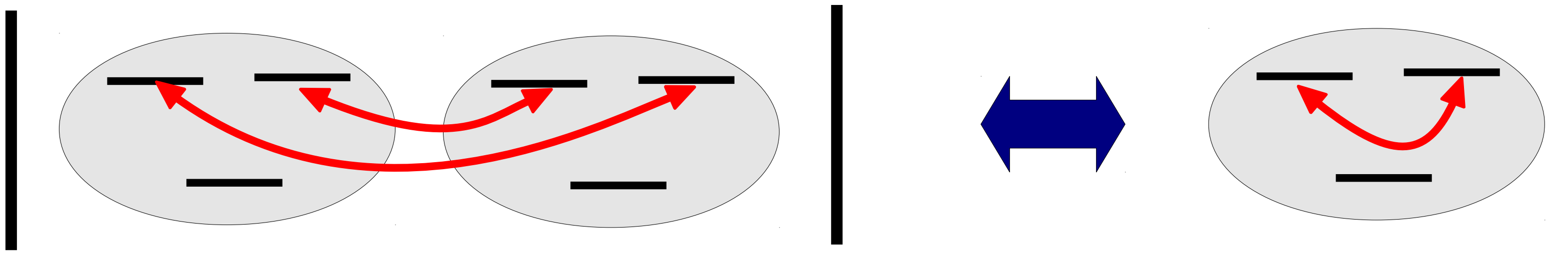


Measurement without time gating using polarizer/ analyzer setup

K. P. Heeg, R. Röhlsberger, J. Evers, in preparation

Why can SGC be observed in nuclei?

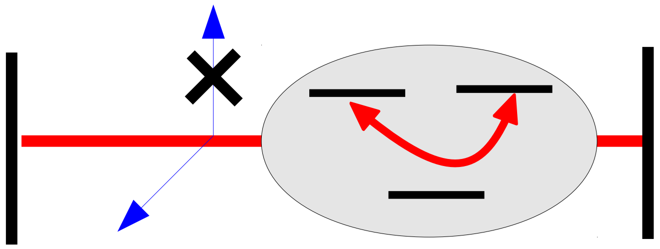
Option 1: “Quantum simulator”



In cavity: many-body system which
“microscopically” shows no SGC

probed from outside
appears as single system
with SGC

Option 2: “Anisotropic vacuum”



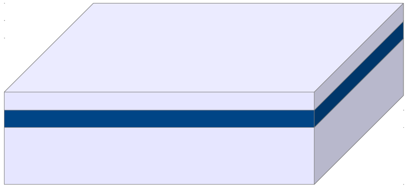
With nuclei, *superradiance* could favor
one polarization mode to
effectively induce an anisotropy

SGC can appear in atoms
in anisotropic environments
(proposal by G. S. Agarwal)

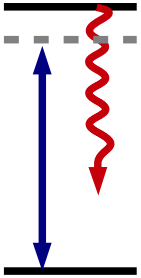
**No decision yet, but
both options promision!**

K. P. Heeg, R. Röhlsberger, J. Evers, in preparation

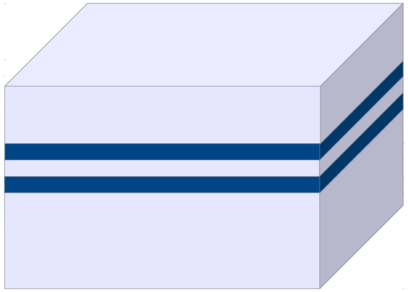
X-ray waveguides: Present status



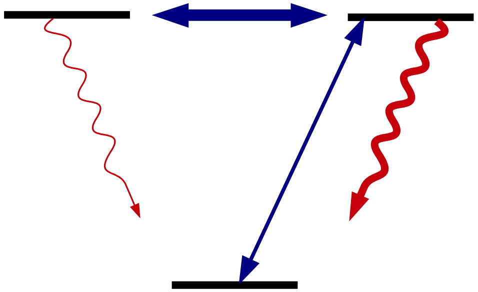
$\triangleq$



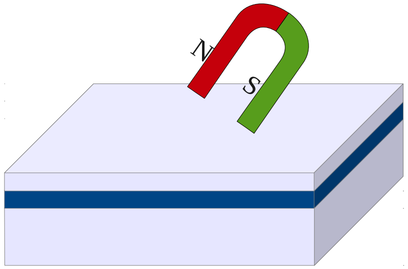
- Superrradiance
- Cooperative
  Lamb shift
  (first observation)



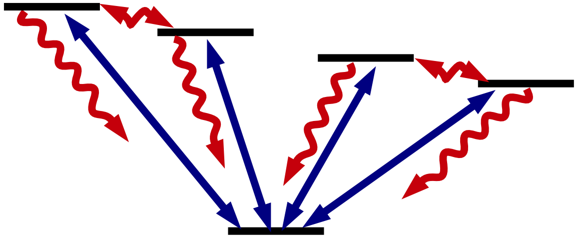
$\triangleq$



- EIT
- Novel mechanism to
  taylor level schemes



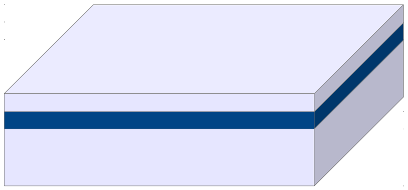
$\triangleq$



- Externally tunable
  level schemes
- Implementation and
  first direct observation
  of SGC

K. P. Heeg, R. Röhlsberger, J. Evers, in preparation

X-ray waveguides: Present status



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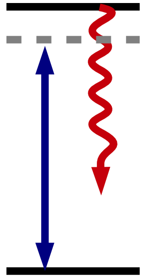

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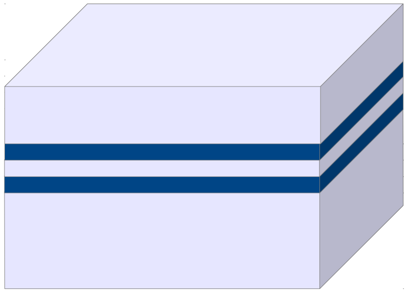

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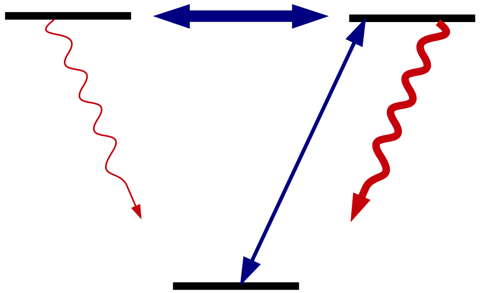
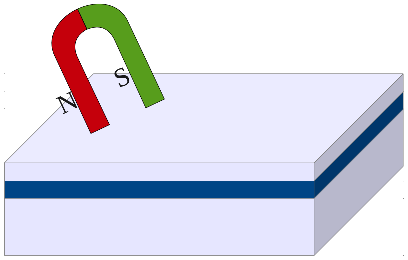


- EIT
- Novel mechanism to
  taylor level schemes



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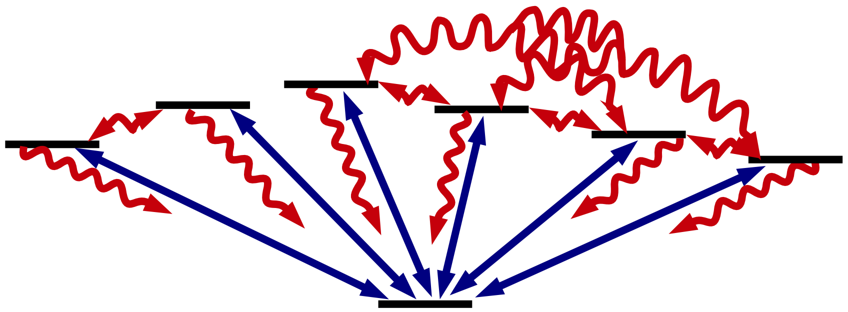

- Externally tunable
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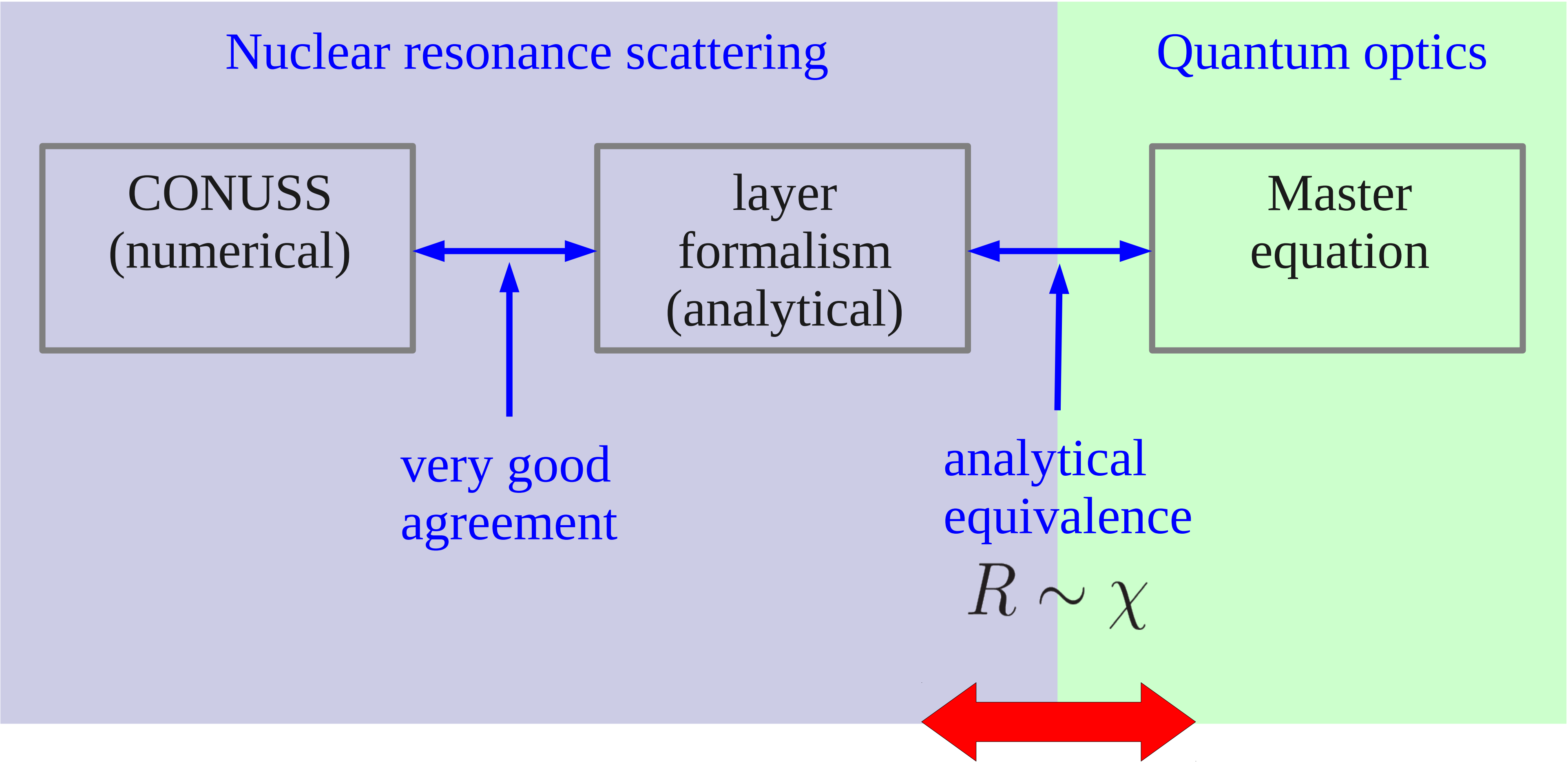
K. P. Heeg, R. Röhlsberger, J. Evers, in preparation

X-ray waveguides: Present status



Nuclear resonance scattering

Quantum optics

CONUSS (numerical)

layer formalism (analytical)

Master equation

very good agreement

analytical equivalence

$R \sim \chi$

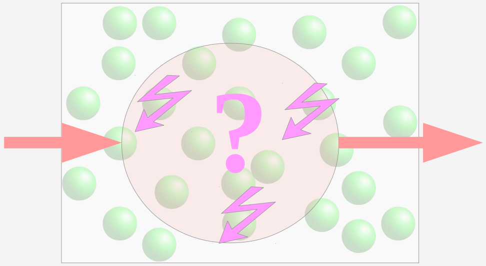
new input to both fields

promising basis for implementation of advanced quantum optical techniques in hard x-ray range

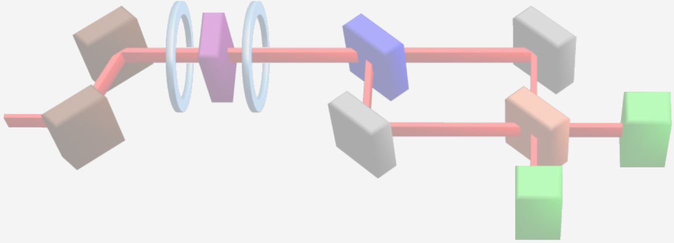
K. P. Heeg, R. Röhlsberger, J. Evers, in preparation

Outline

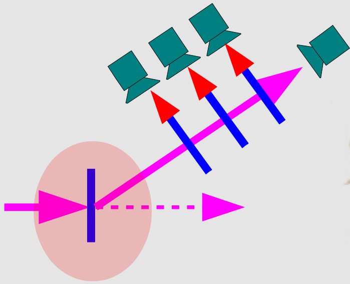
Introduction

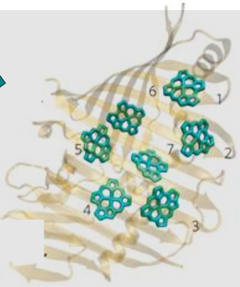


Nuclear quantum optics



Future perspectives
with seeded FELs





Synchrotron radiation vs. seeded FEL beams

	Synchrotron	Seeded XFEL
Bunch separation (ns)	200ns	200ns (microbunch)
Avg Flux (ph/s/Γ)	5×10^{4}	2×10^{8}
Fluence (ph/bunch/Γ)	10^{-2}	6×10^{3}

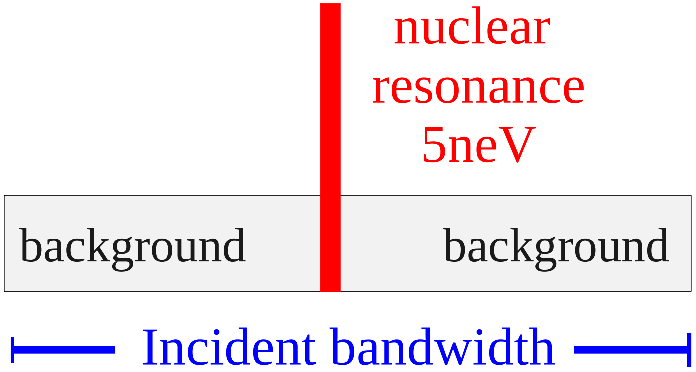
nuclear parameters
(for ^{57}Fe)
energy 14.4 keV
linewidth 5 neV

XFEL parameters
10^{12} photons/pulse
rel. BW 6×10^{-5}
rep. rate 30kHz

Two directions

photon hungry
("proven concepts
with higher
count rate")

Short, nonlinear,
coherent
("new ideas")



nuclear
resonance
5neV

background

background

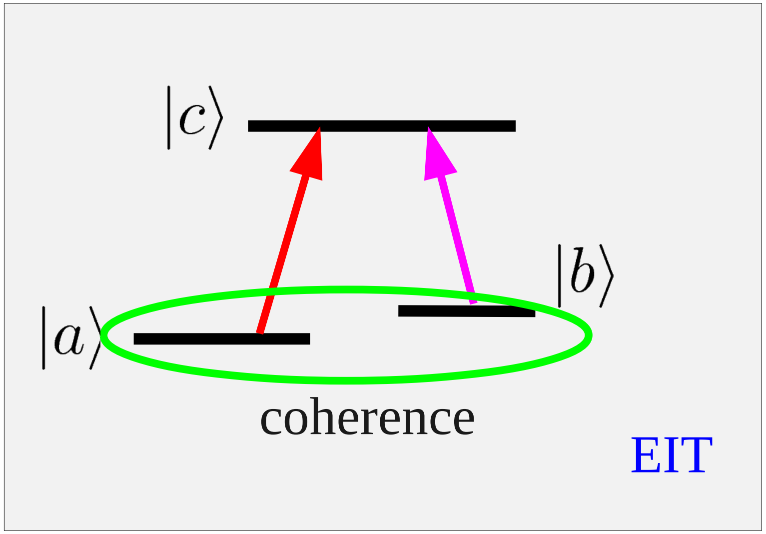
Incident bandwidth

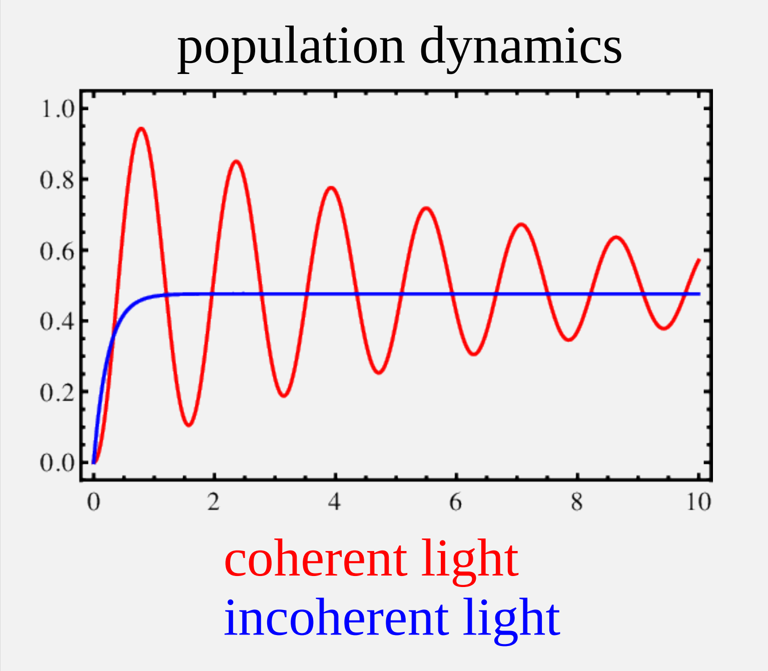
So far,
everything
with single photons!

Geloni et al, arXiv:1111.5766

Temporal coherence

- All quantum optical effects rely on coherence and interference
- Synchrotron experiments operates at the single photon level, and single photons interfere with themselves
- But: strong and coherent driving is key to most quantum optical effects
- Availability of temporally coherent pulse with many resonant photons within nuclear linewidth would enable entirely new possibilities





Can we enter the non-linear regime?

Synchrotron: $\dfrac{0.01 \text{ Photons @ } 14.4\text{keV}}{100\text{ps bunch} \times (\mu\text{m})^2 \times \Gamma} \Rightarrow I \sim 10^2 \dfrac{\text{W}}{\text{cm}^2}$

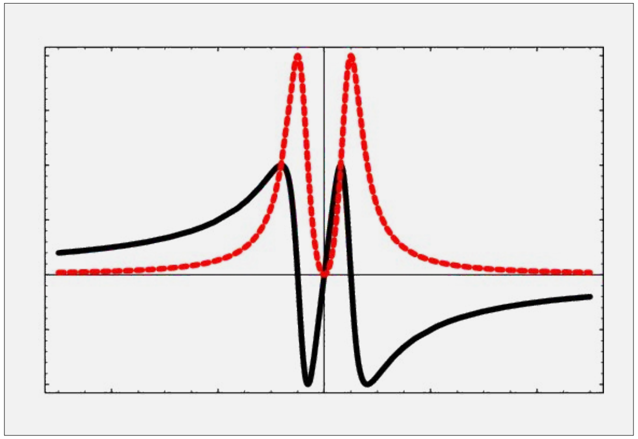
Seeded XFEL: $\dfrac{10^3 \text{ Photons @ } 14.4\text{keV}}{10\text{fs bunch} \times (\mu\text{m})^2 \times \Gamma} \Rightarrow I \sim 10^{10} \dfrac{\text{W}}{\text{cm}^2}$

EIT case: Kerr effect

$$n = n_0 + I_P n_2 \qquad \chi = \chi^{(1)} + 3I_P\chi^{(3)}$$

$$\chi^{(3)} = 4.3 \times 10^{-22} m^2/V^2$$

$$\Rightarrow n_2 I_P \approx 10^{-7} \text{ for } \quad 10^8 W/cm^2$$

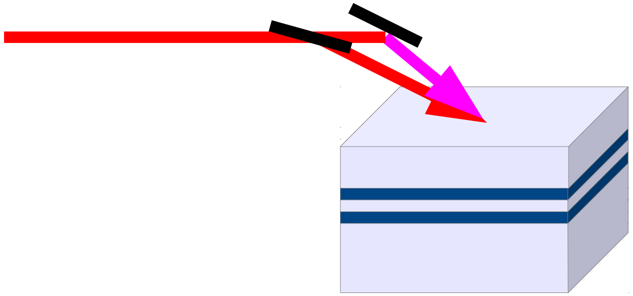


nonlinear phase shift ~ linear index achievable with seeded FEL
EIT: no linear absorption, strong enhancement via advanced schemes possible

Röhlsberger et al, Nature 482, 199 (2012)

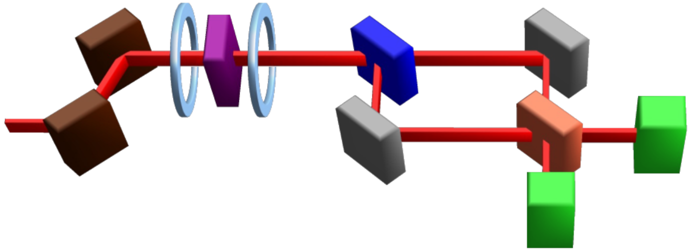
Immediate applications of multiple photons

Separate coupling and probe



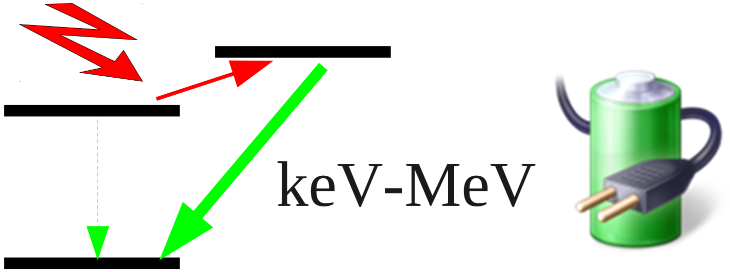
- Drive multiple modes simultaneously
- Beams could be individually and mutually temporally coherent

Quantum information and fundamental tests



- QIP protocol with qubit photons and quantum channel photons
- Entangled pairs of photons (downconversion or scheme by Rempe)

State preparation and pumping



- Isomer triggering
- X-ray induced emission with nuclei

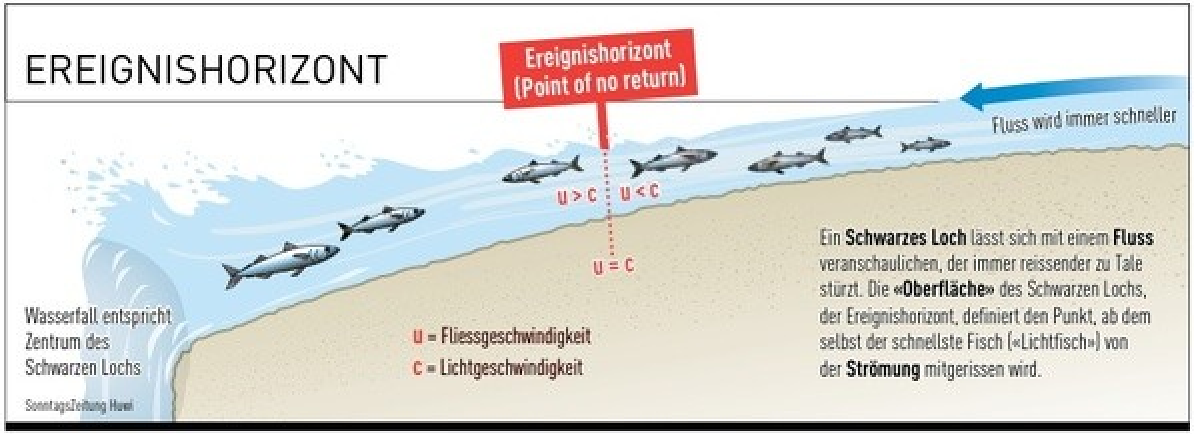
A. Pálffy, J. Evers, C. H. Keitel, Phys. Rev. Lett. 99, 172502 (2007)

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

Where could this lead?

Optical analogues of general relativity

- Interesting effects arise if medium moves faster than speed of light in the medium
- Difficult to move macroscopic objects at speed of light – thus make light slow
- Can create optical analogues of event horizons, black holes, Hawking radiation, ...
- Solid state nuclear systems are good candidates:
  - background free measurements
  - fast rotation and motion of nuclear media has already been exploited
  - slow light is likely to occur in existing systems, but not yet verified



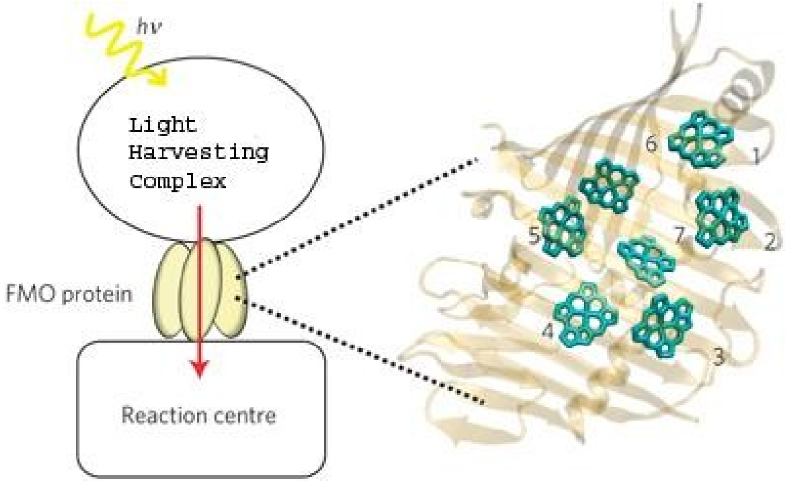
Ein **Schwarzes Loch** lässt sich mit einem **Fluss** veranschaulichen, der immer reissender zu Tale stürzt. Die «**Oberfläche**» des Schwarzen Lochs, der Ereignishorizont, definiert den Punkt, ab dem selbst der schnellste Fisch («Lichtfisch») von der **Strömung** mitgerissen wird.

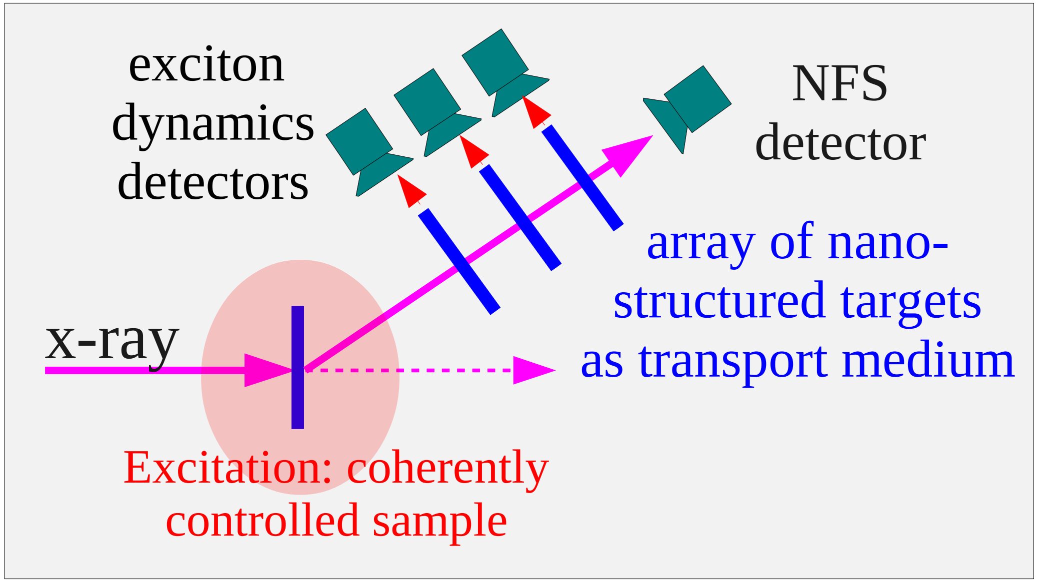
U. Leonhardt and T. G. Philbin, Prog. Opt. 53, 69-152 (2009)
G. Shenoy and R. Röhlsberger, Hyperf. Int. 182, 157 (2008)

Where could this lead?

Quantum transport

- Designer quantum channels
- Start from a clean system, then add decoherence / dephasing at will
- Model complex bath by perturbing the transport sites independently using laser, E/B field, vibrations, ...
- Does optimal transport require coherence/ decoherence/ entanglement/...?
- What are experimental signatures applicable to complex transport systems?
- How can we control quantum mechanical energy transport to exploit it for applications?
- Need many photons to monitor transport “online”




exciton dynamics detectors

NFS detector

array of nano-structured targets as transport medium

x-ray

Excitation: coherently controlled sample

J. Evers, work in progress

Other perspectives

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
- Combine different frequencies, e.g. resonant photon + x-ray for high position resolution
- Optomechanics

Control

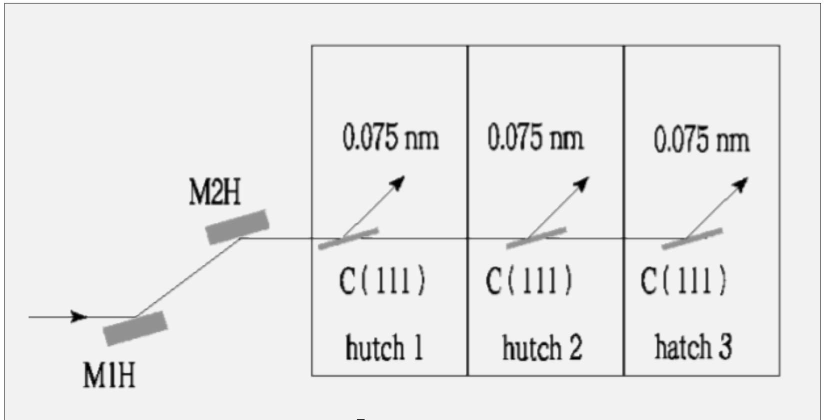
- Nuclear Rabi flopping
- Enhanced sample preparation, material properties
- Separate signal and background/noise

So far rough ideas only – largely unexplored field

“Wish list”

Exciting possibilities, but

- Resonant driving of Mößbauer nuclei mandatory, ^{57}Fe requires 14.4 keV
- X-ray distribution system should be compatible with nuclear resonances
- Many photons per nuclear linewidth to achieve qualitative difference to synchrotrons
- Long pulses / low initial bandwidth favorable for “non-ultrafast” applications (more photons in resonance)
- Temporally coherent single or mutually coherent double pulses desirable for advanced quantum optical schemes



Geloni, arXiv:1111.5766

The team

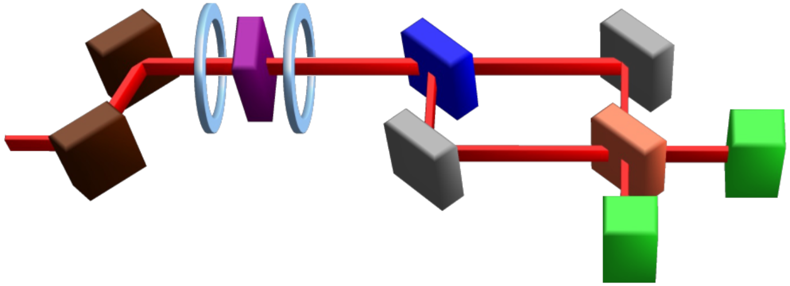
Martin Gärttner	PhD student
Qurrat-ul-Ain Gulfam	PhD student
Kilian Heeg	PhD student
Mihai Macovei	PostDoc
Adriana Pálffy	former PostDoc, now group leader
Andreas Reichegger	Master student
Lida Zhang	PhD student

working on x-ray quantum optics

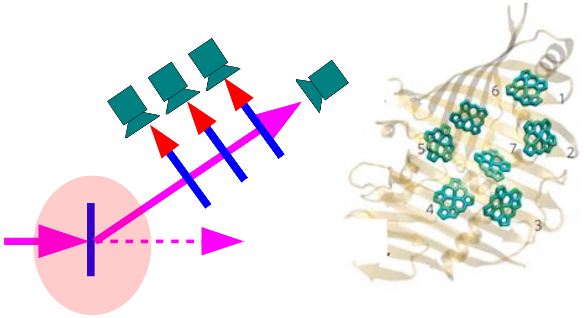
Collaboration (DESY)
Ralf Röhlsberger
Hans Christian Wille
Kai Schlage

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

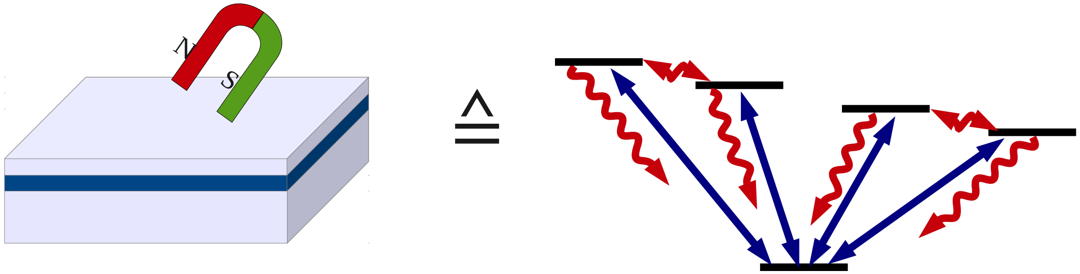
Summary



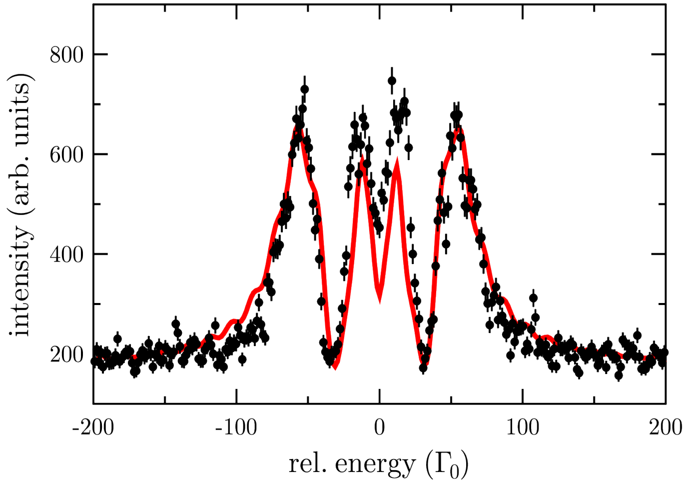
X-ray entanglement



Quantum transport



Tunable nuclear level schemes

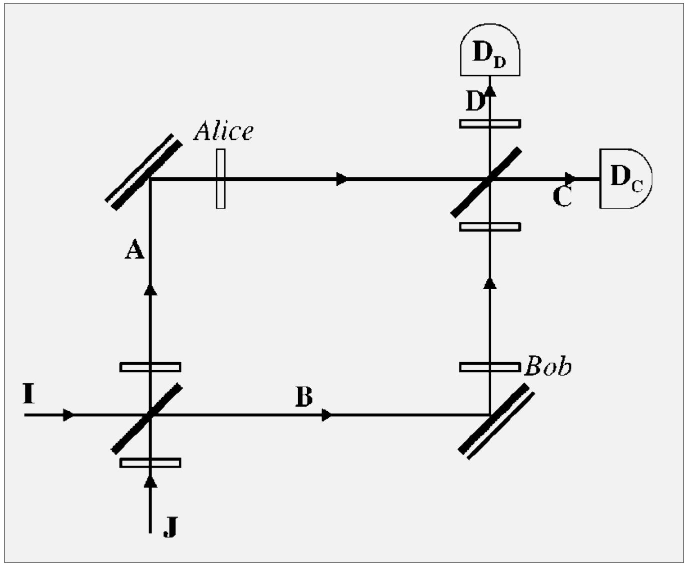


spontaneously generated coherences

Thank you!

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)

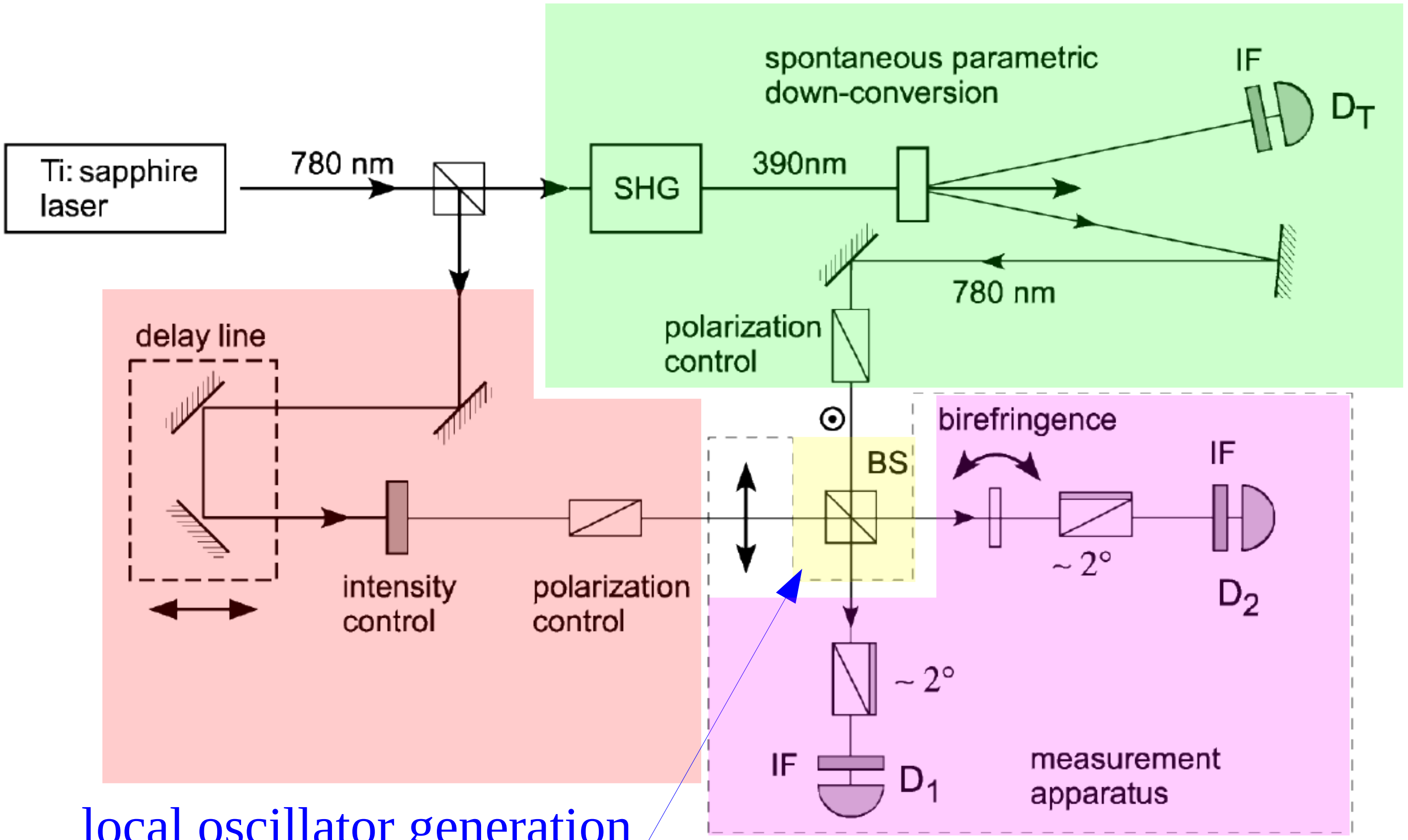
$$(G_N - G_A) \cap (G_N - G_B) \subseteq (G_N - G_{AB})$$

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

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

Experimental evidence with local oscillator

single photon generation



local oscillator generation

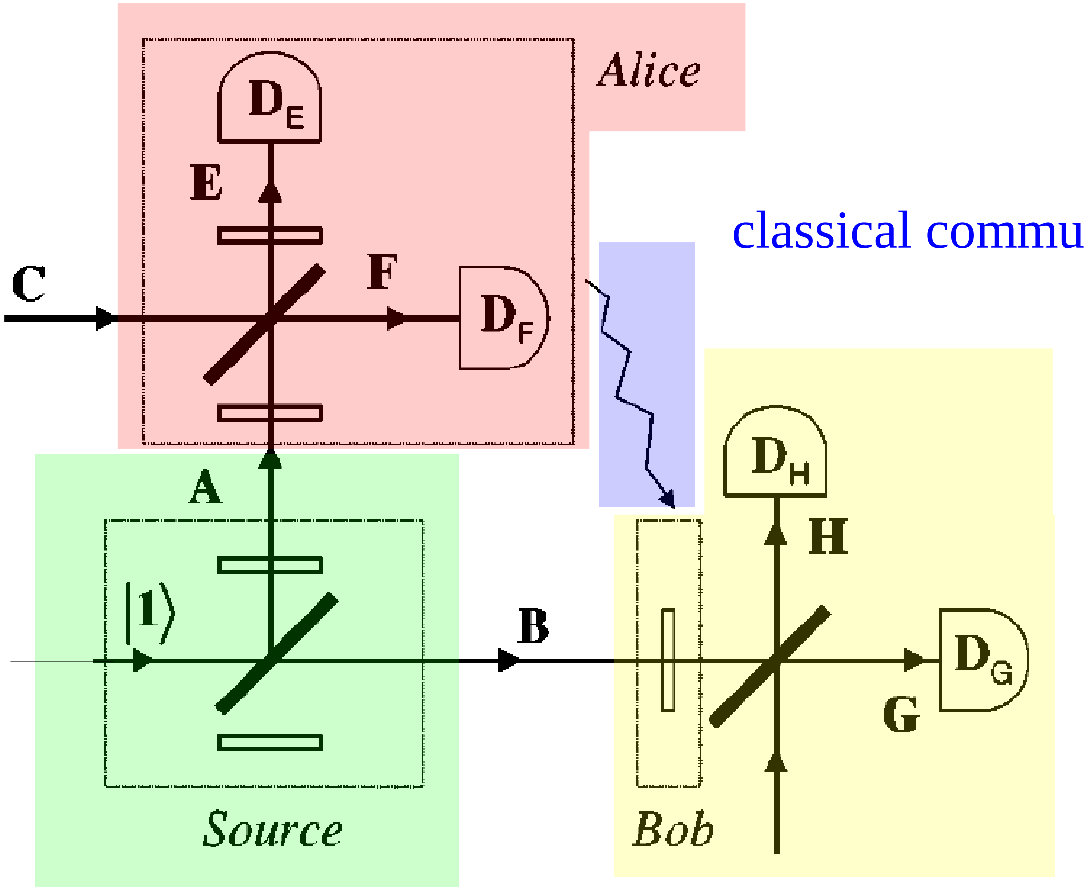
coincidence detection

entanglement generation,
mixing with LO

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



Sender

input
state

classical communication

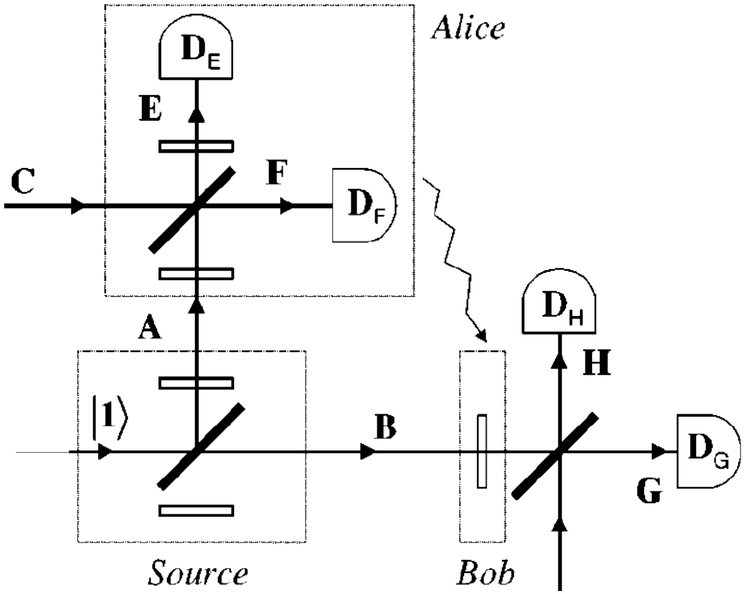
single
photon

entanglement
generation

Possible verification
at receiver side

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

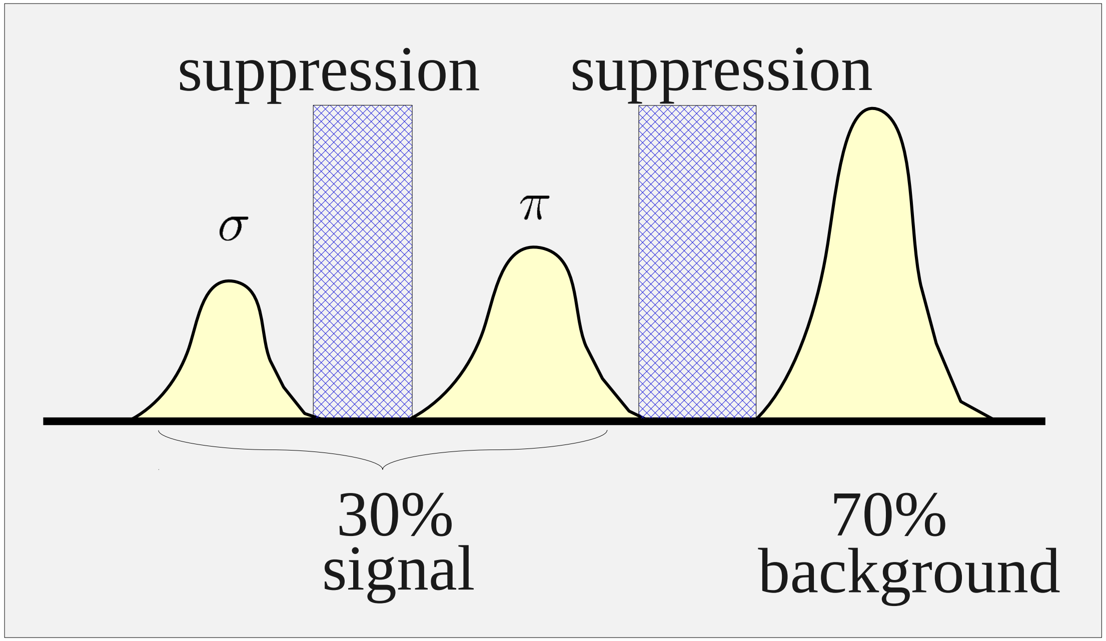
H.-W. Lee and Kim, Phys. Rev. A 63, 012305 (2000)

Efficiency estimate

- Assumed rate of excited nuclei: ~ 10^6 / s
- Of stored excitation, 70% background, 30% signal
- Loss at polarizer: Only about 10% of photons are kept
- Single photon entanglement rate: ~ 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)

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)

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

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

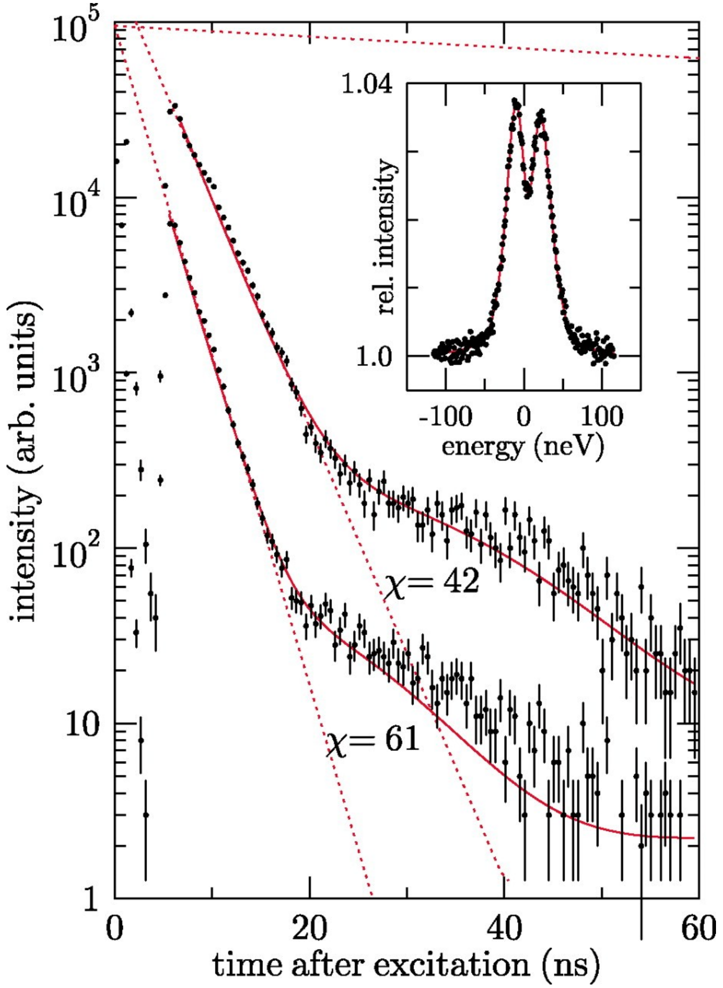
Iterative solution,
incident pulse

$$\mathcal{E}^{(0)} \sim \delta(t)$$

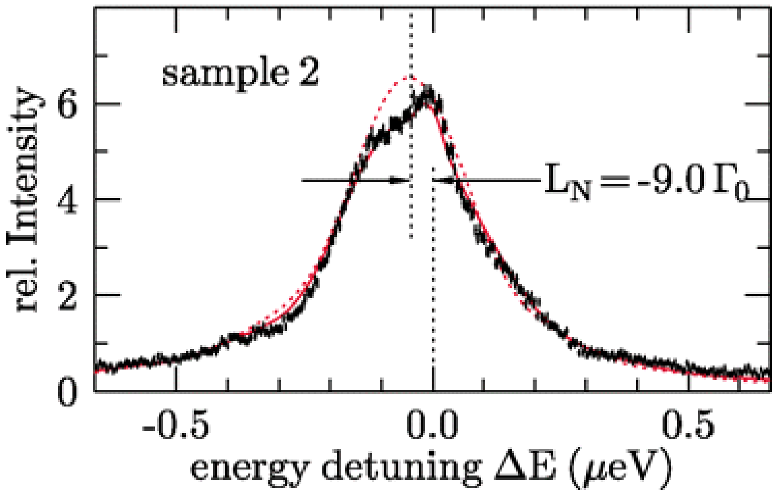
Y. V. Shvydko, Hyperf. Int. 123/124, 275 (1999)

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

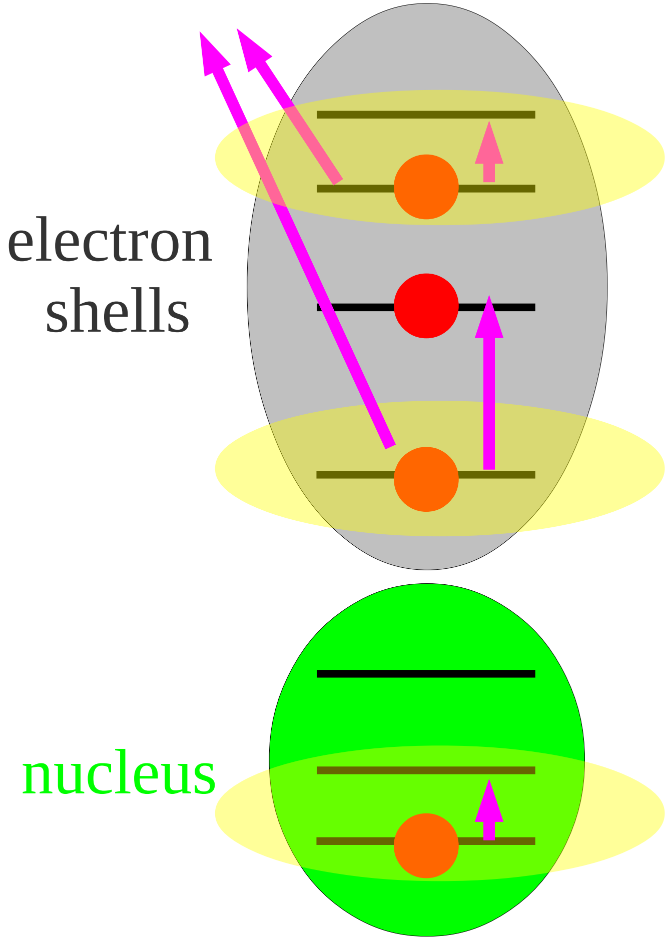


Lamb shift



Röhlsberger et al, Science 328, 1248 (2010)

Motivation



Light-matter interactions

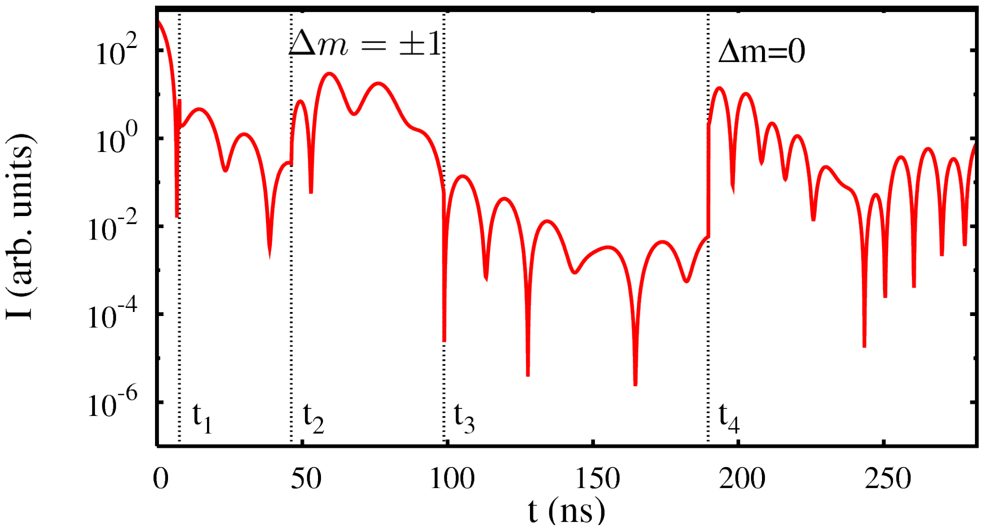
- optical driving fields:
  excite/ionize outer electrons
- Higher frequencies/intensities:
  excite / ionize core electrons
- Even higher frequencies/intensities:
  excite nucleus

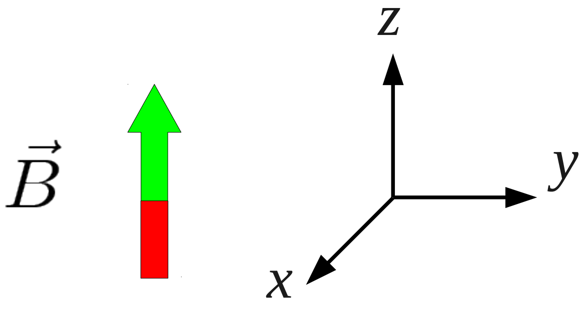
These scenarios appear similar

But the methods and applications
are quite different

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
$$\Delta m = 0$$





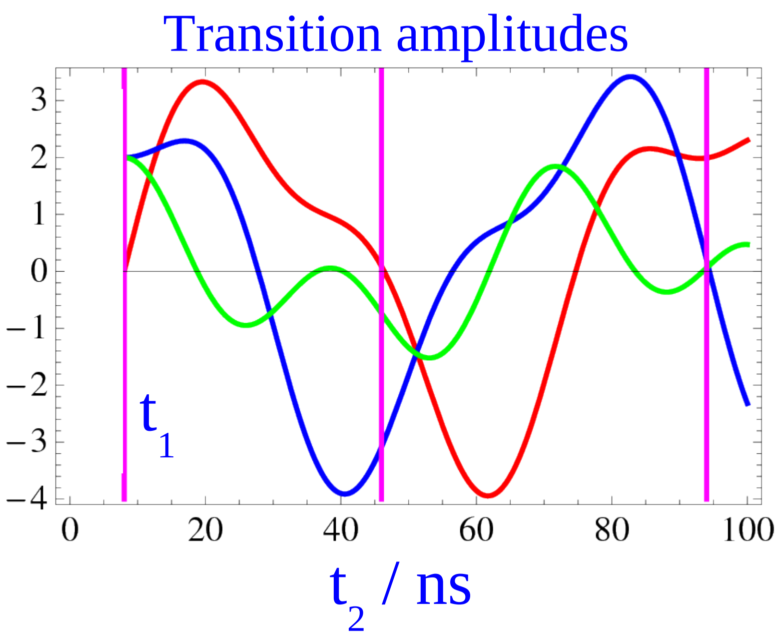
Advanced magnetic switching schemes

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?


Transition amplitudes

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

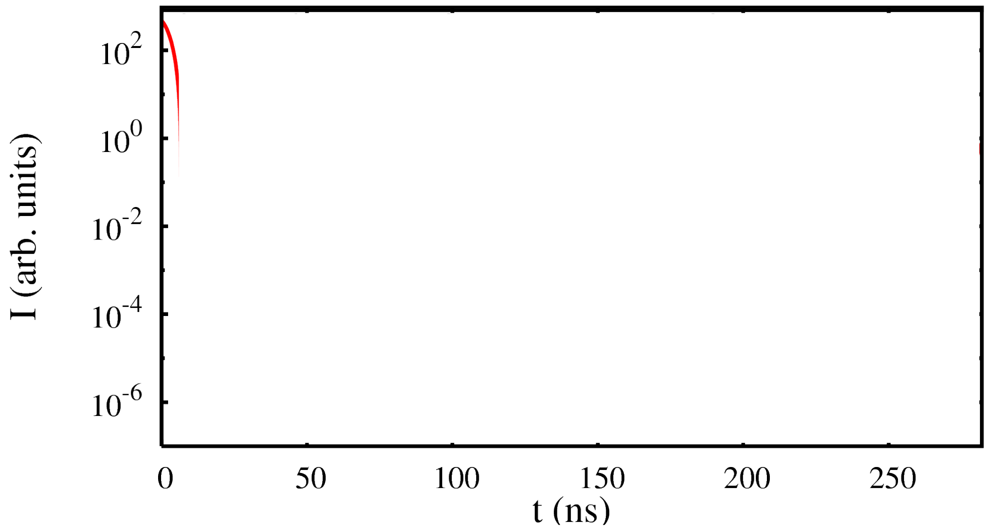
$\left\{-\frac{1}{2} \to \frac{1}{2}, \frac{1}{2} \to -\frac{1}{2}\right\}$ circular

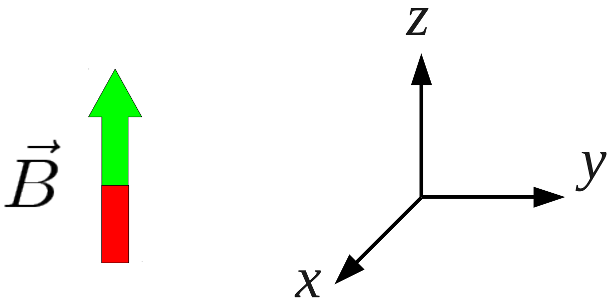
$\left\{\frac{3}{2} \to \frac{1}{2}, -\frac{3}{2} \to -\frac{1}{2}\right\}$ circular

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

Step 1: Synchrotron excitation

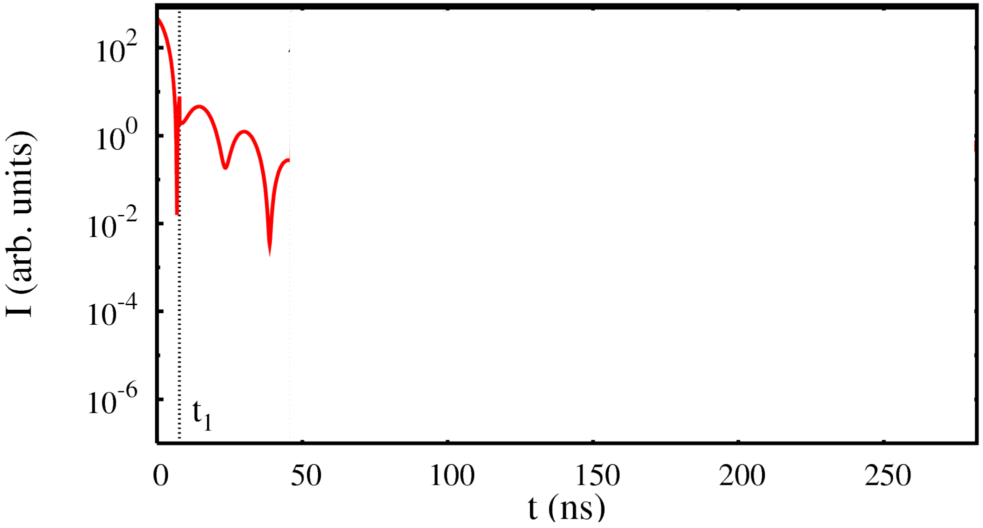
- Initially, magnetic field is in z direction

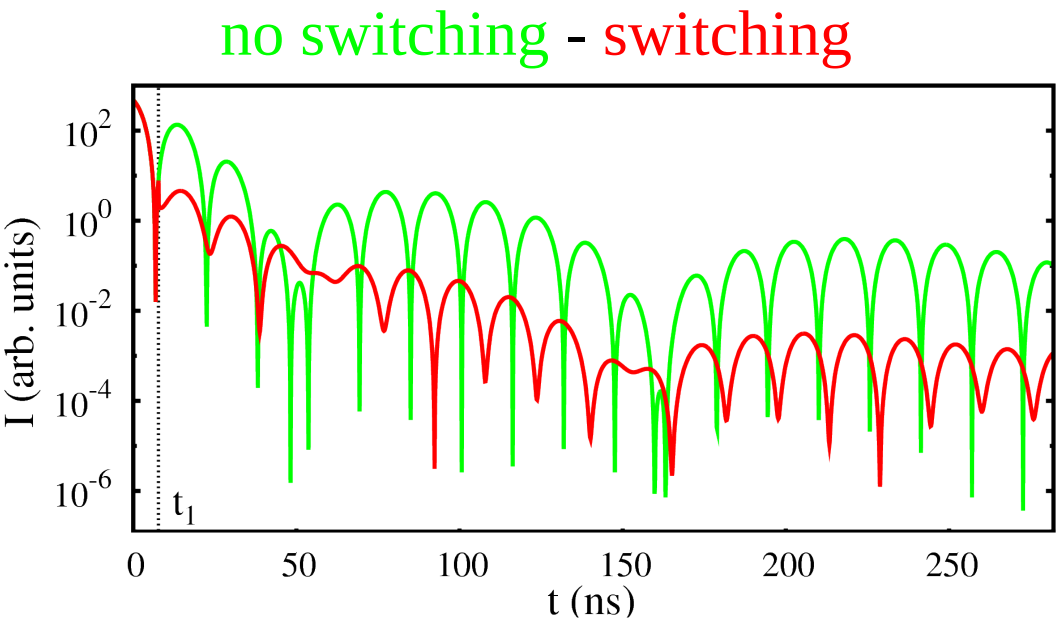


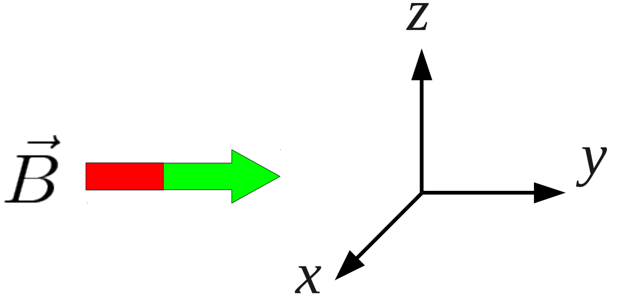


Step 2: Canceling coherent decay

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







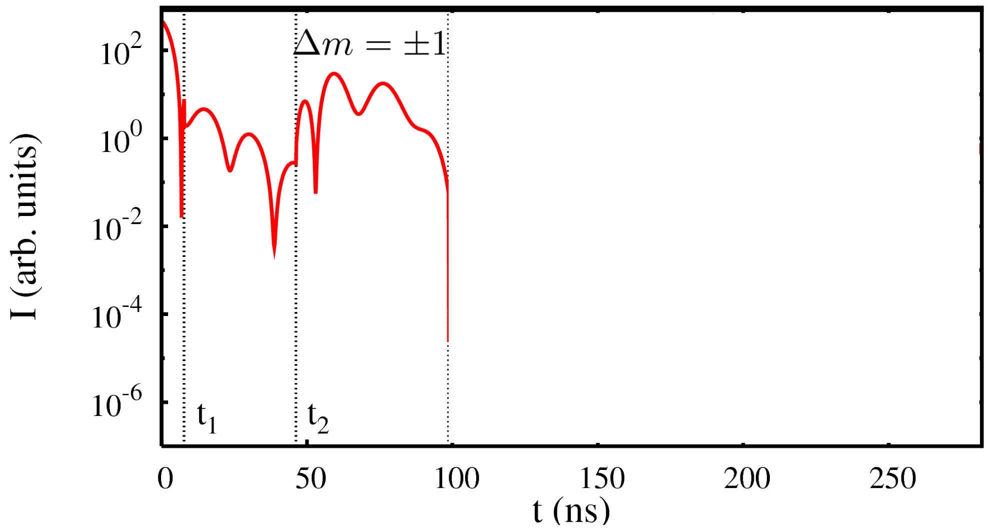
Step 3: Releasing circular polarization

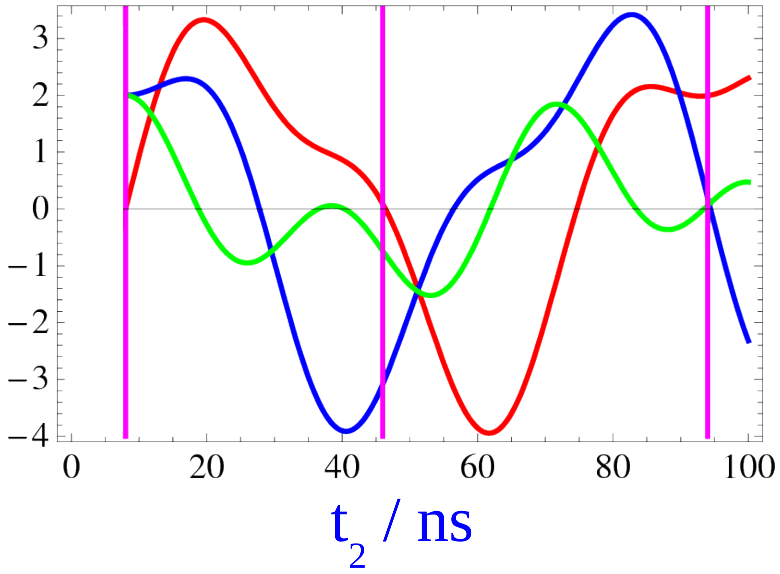
- Initially, magnetic field is in z direction
- At time t_1, cancel decay by rotating into y direction
- At time t_2, enable decay on

$$\Delta m = \pm 1$$

but continue to suppress

$$\Delta m = 0$$

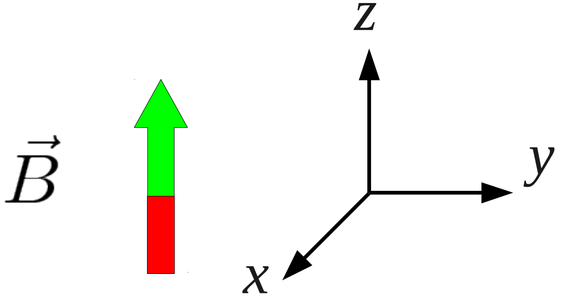




$$\left\{\frac{1}{2}\rightarrow\frac{1}{2}, -\frac{1}{2}\rightarrow-\frac{1}{2}\right\}$$

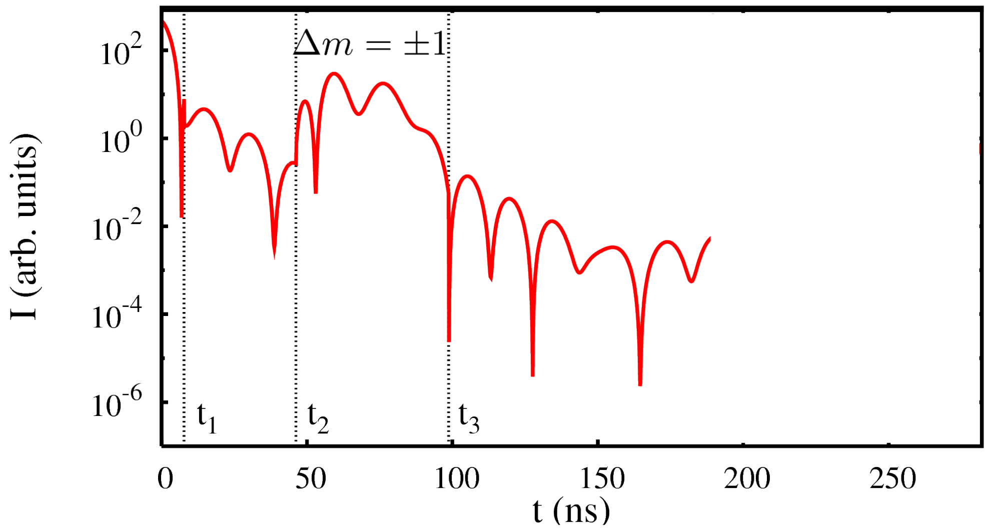
$$\left\{-\frac{1}{2}\rightarrow\frac{1}{2}, \frac{1}{2}\rightarrow-\frac{1}{2}\right\}$$

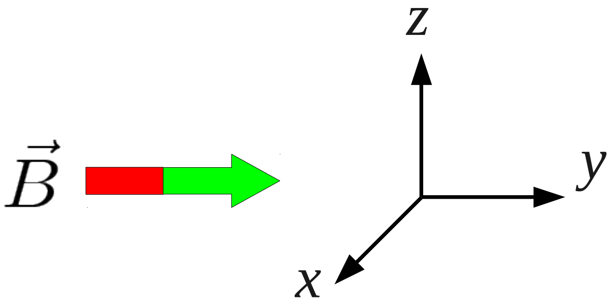
$$\left\{\frac{3}{2}\rightarrow\frac{1}{2}, -\frac{3}{2}\rightarrow-\frac{1}{2}\right\}$$



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





Engineering multi-level schemes

How to implement EIT in x-ray cavity?

➡ Next talk

How can one

- Control and systematically study EIT without building many cavities?
- Engineer more complex level schemes?

➡ Poster by Kilian Heeg

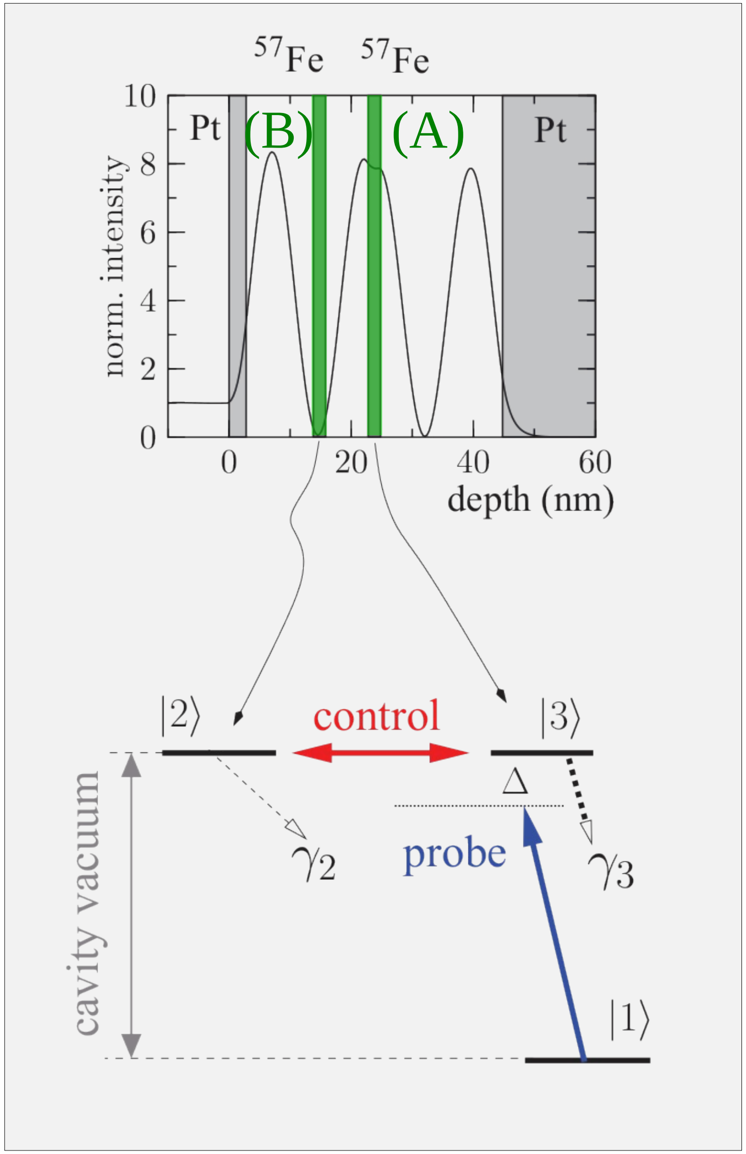
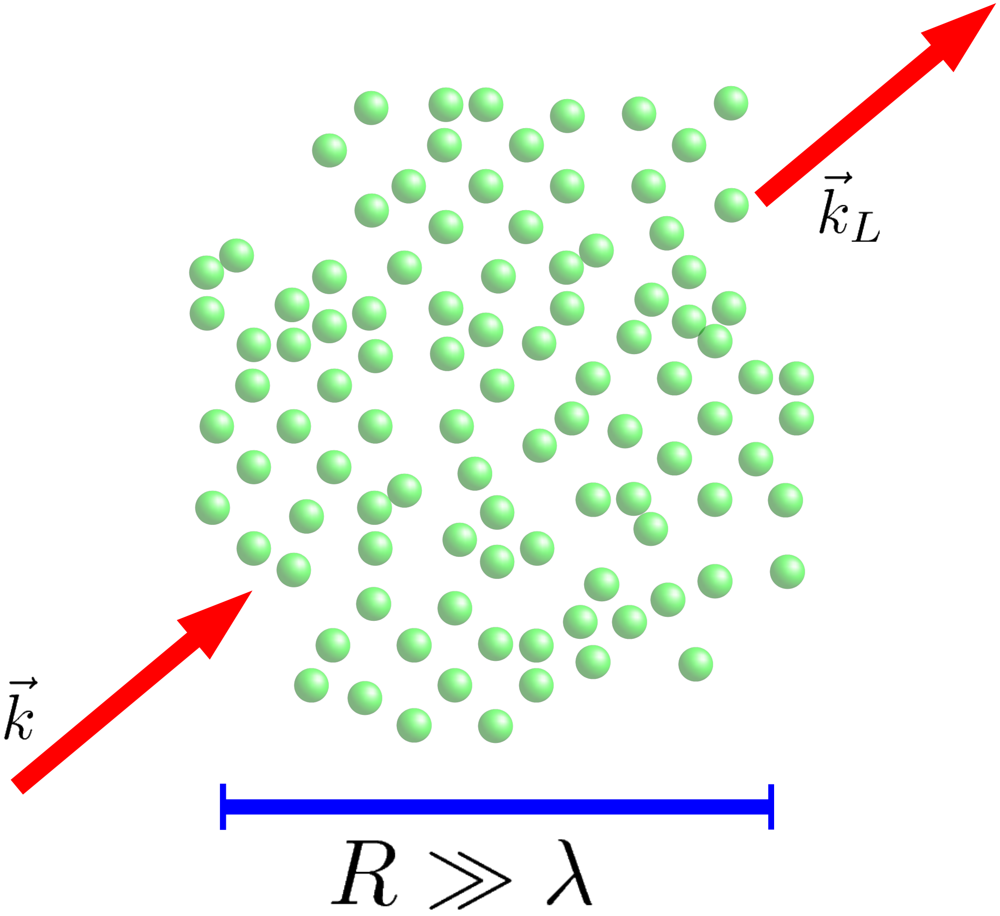


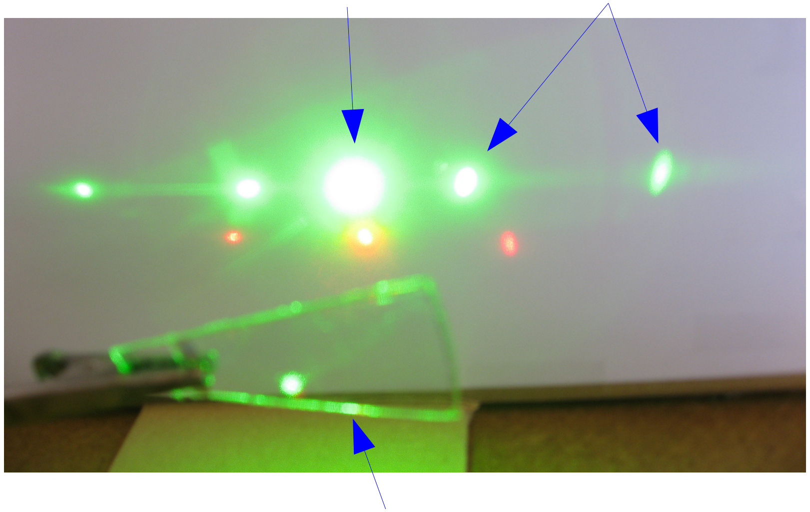
Image and setup: Röhlsberger et al, Nature (2012)

Coherent forward scattering

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



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

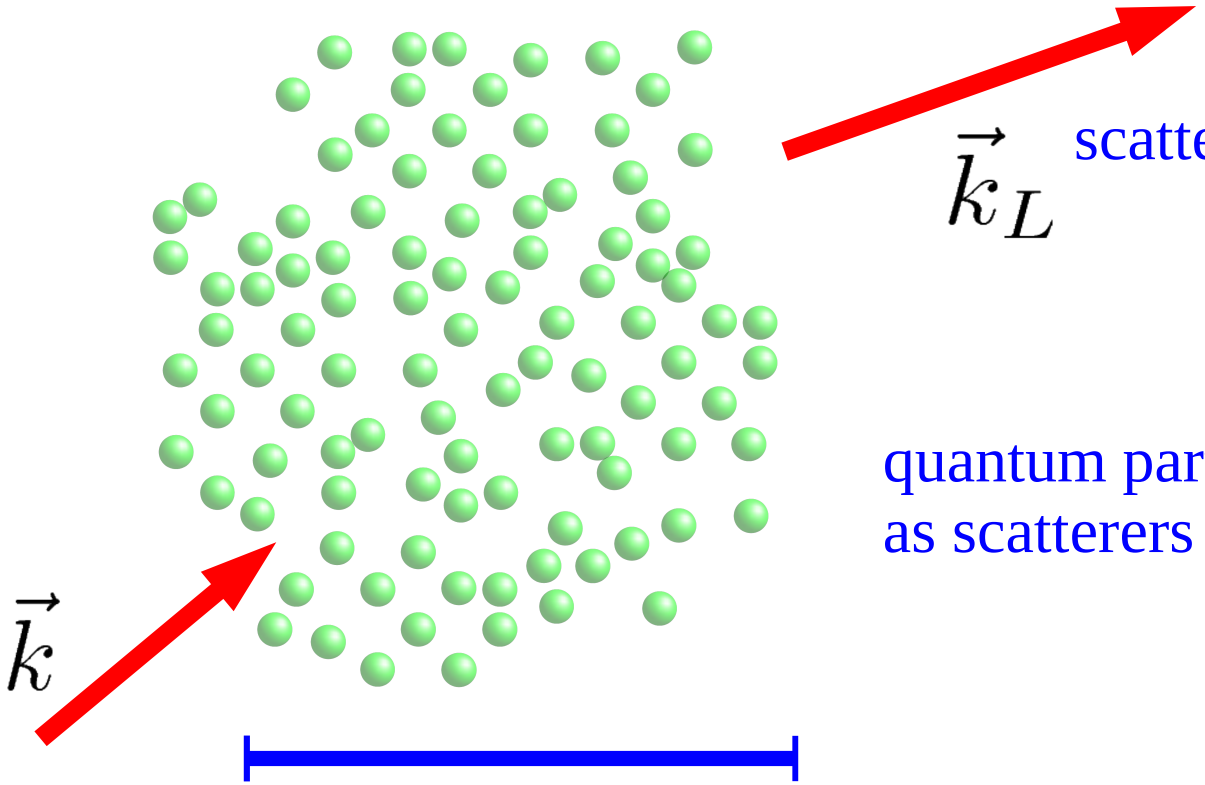


forward scattering

“Bragg scattering”

grid = CD-R grooves

Cooperative light scattering



$\vec{k}_L$ scattered light

quantum particles
as scatterers

$\vec{k}$

incident
light

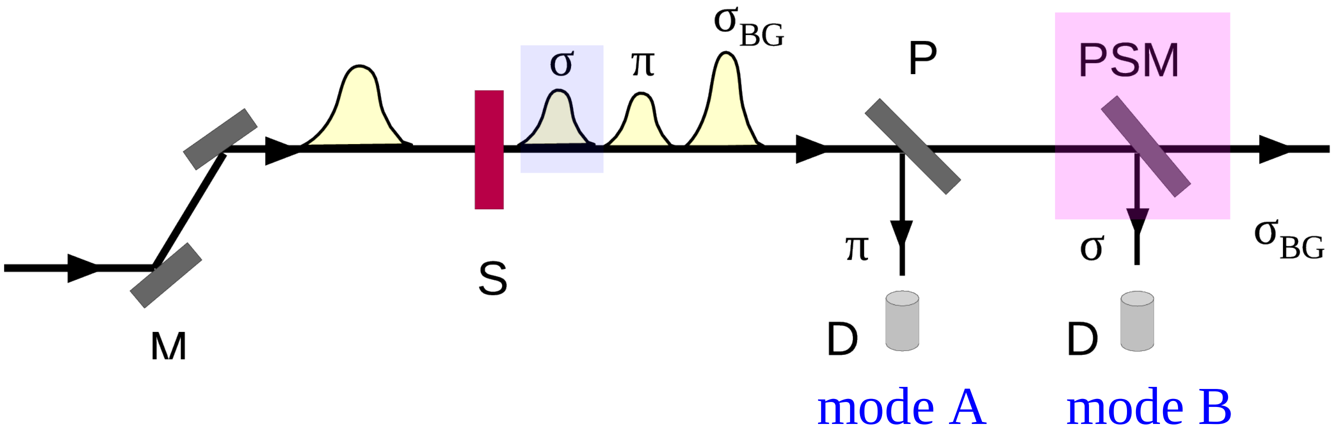
$R \gg \lambda$

large dilute cloud

- no recoil
- stationary particles

How to extract signal pulse ?

- Problem: 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 precise 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



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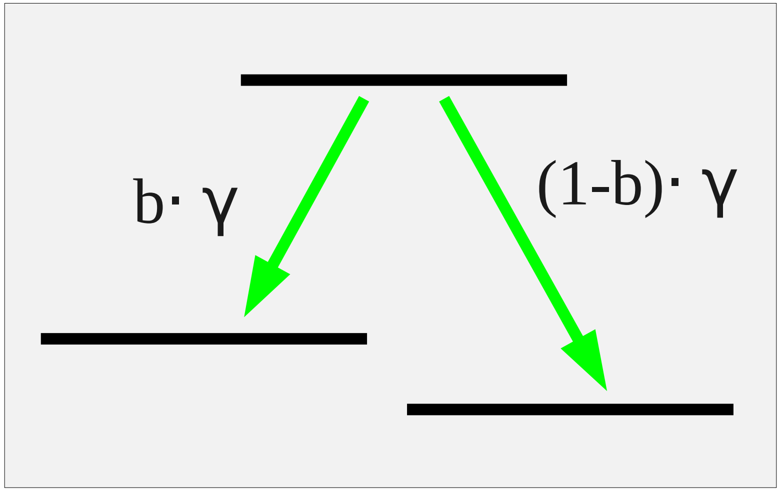
1) A. Grigoriev et al., Appl. Phys. Lett. 89, 021109 (2006)

Branching ratio

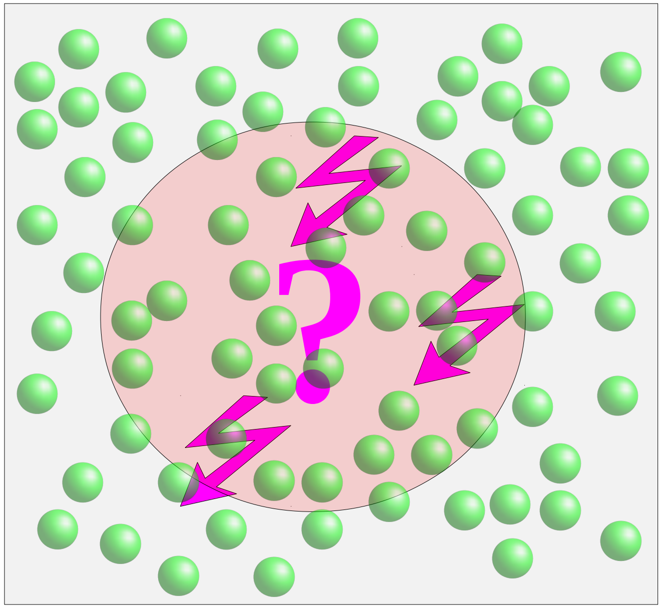
Single particle branching ratio:

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

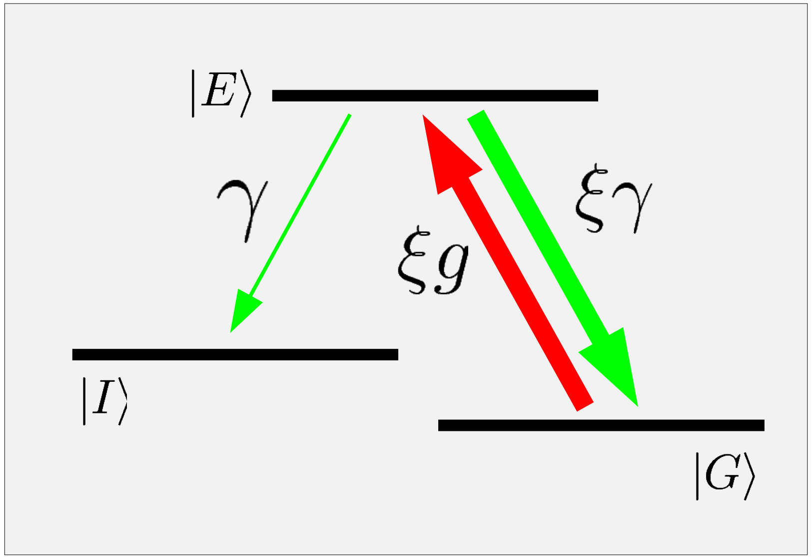


Branching ratio in ensembles

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

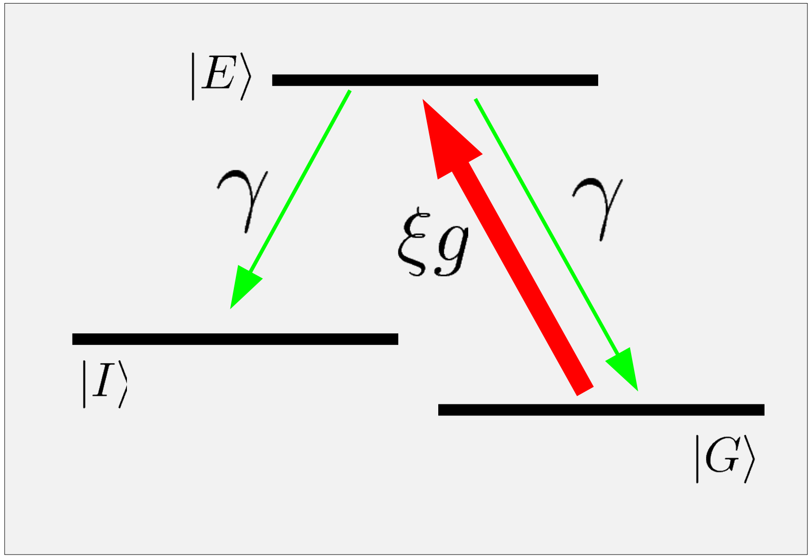


Motivation



- 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:

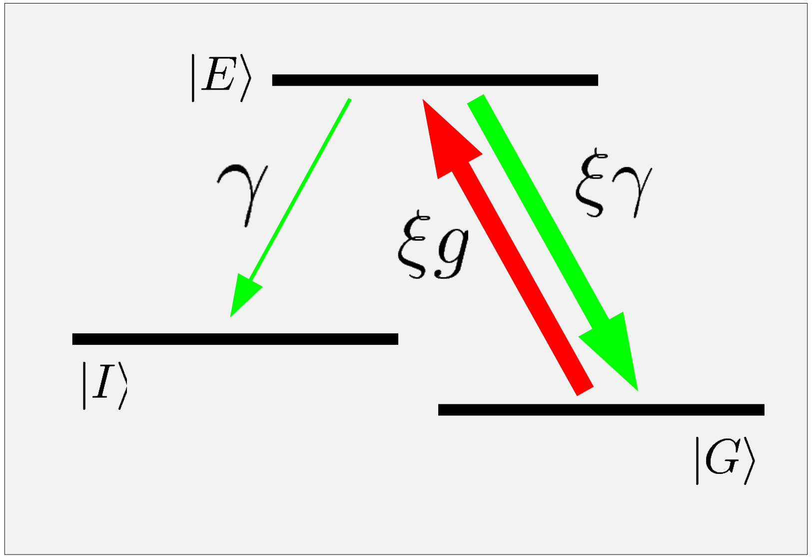


- Suppress cooperative emission
- Then cooperativity leads to enhanced excitation, but decay proceeds with single particle branching ratio
- In effect, enhanced pumping to $|I\rangle$

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

The ideal case

- Assume purely superradiant decay with rate $\xi \cdot \gamma$
- Assume perfect coherent control of cooperative decay



Result:

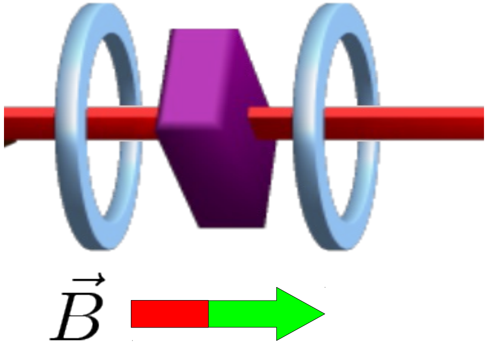
$$b_c^C / b_c^{NC} = \xi + 1$$

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

How to control?

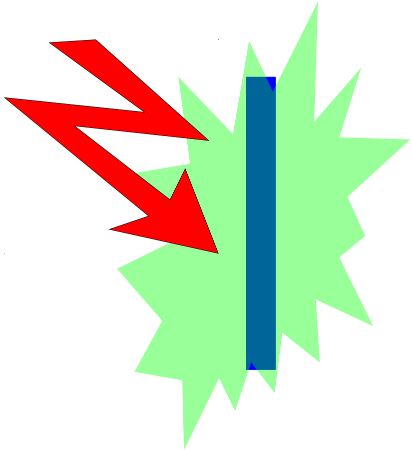
Magnetic switching:

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

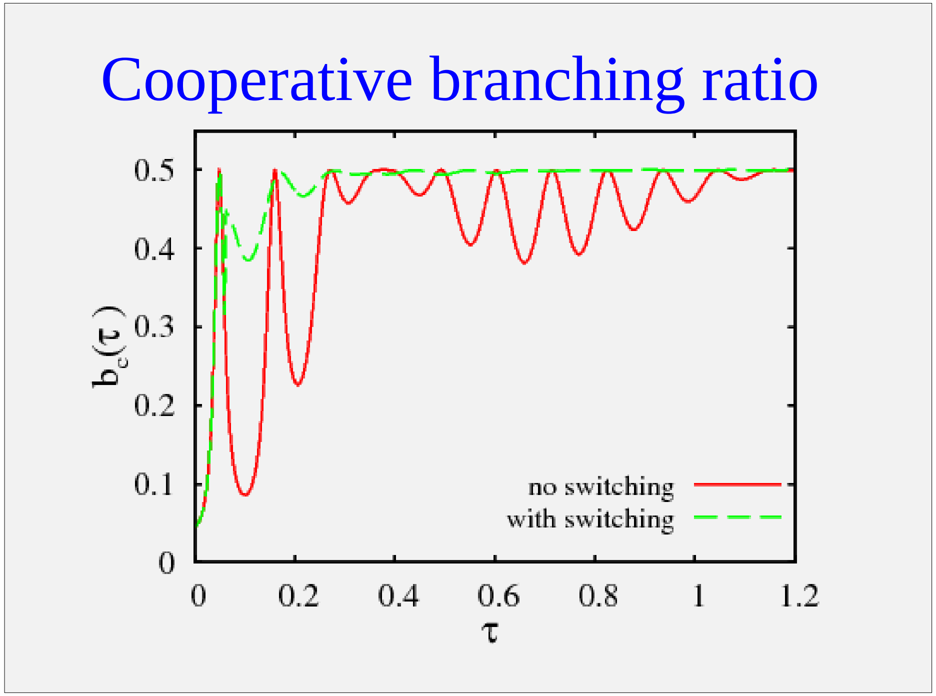


Destroy phase coherence:

- 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

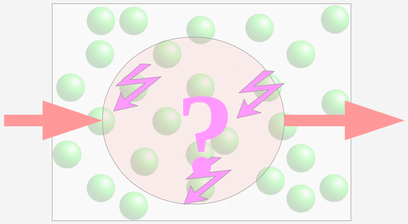


- Branching ratio time dependent as expected
- Cooperative branching ratio smaller than single-particle ratio due to superradiance
- After switching, single-particle branching ratio is achieved
- With destruction of phase coherence, single-particle ratio can immediately be achieved

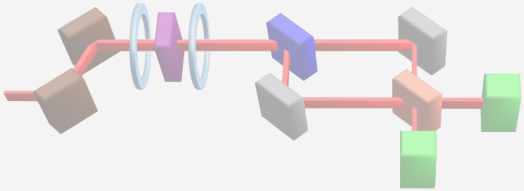
A. Palffy, C. H. Keitel, and J. Evers, Phys. Rev. B 83, 155103 (2011)

Outline

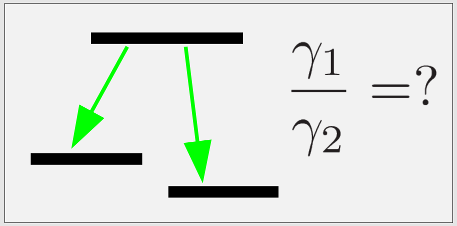
Introduction



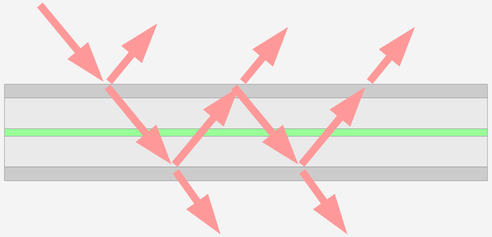
X-ray entanglement generation



X-ray branching ratio control

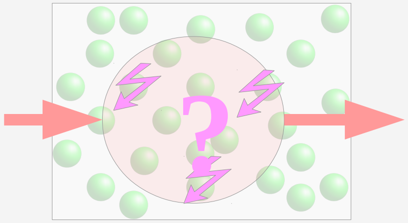


Outlook: Engineering advanced level schemes

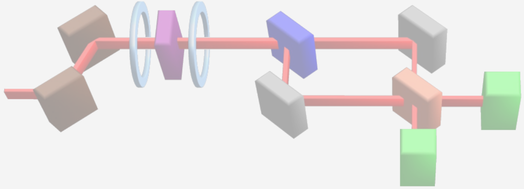


Outline

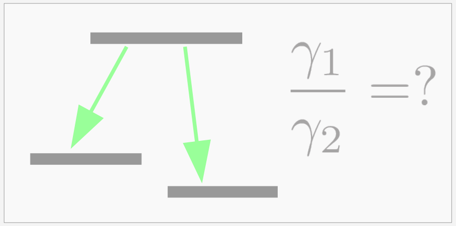
Introduction



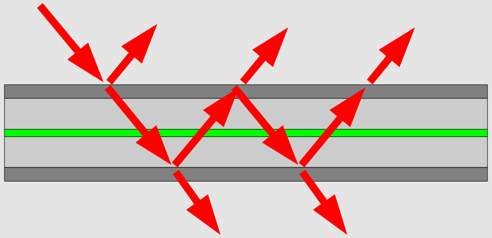
X-ray entanglement generation



X-ray branching ratio control

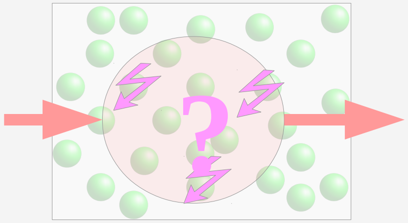


Outlook: Engineering advanced level schemes

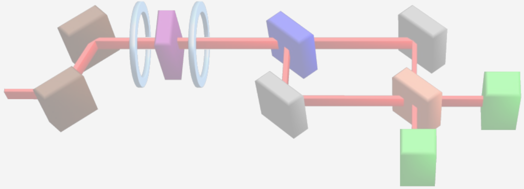


Outline

Introduction



X-ray entanglement generation



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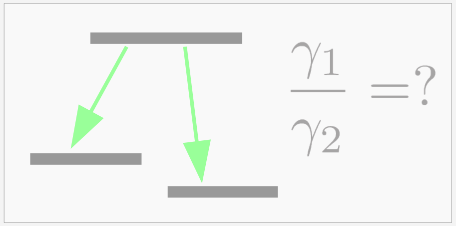
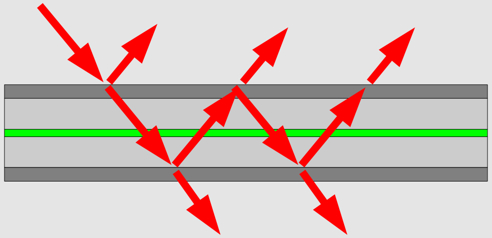
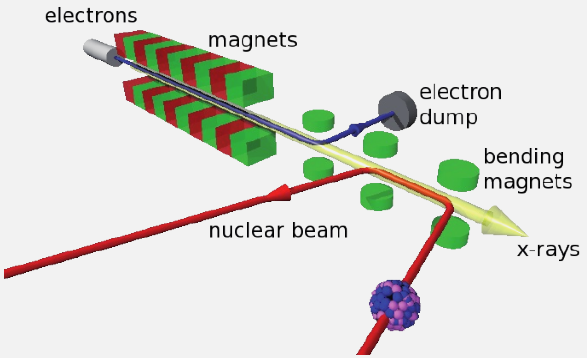


Outlook: Engineering advanced level schemes



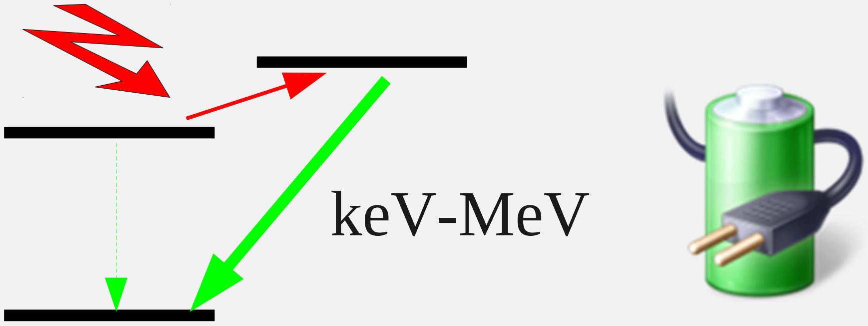
X-ray and γ-ray quantum optics @ MPIK

Direct laser driving of nuclei



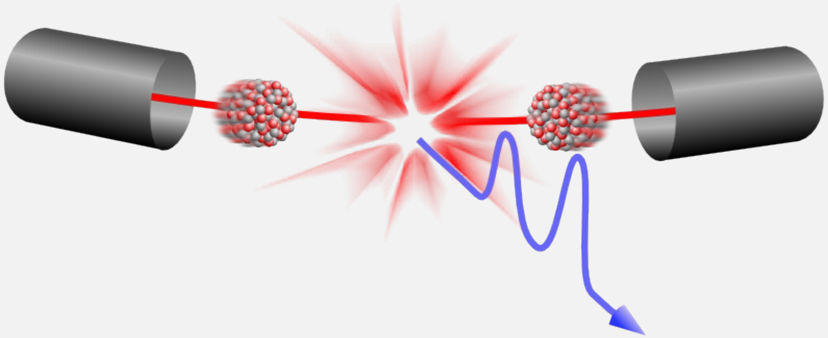
T. Bürvenich, J. Evers, C. H. Keitel,
PRL 96, 142501 (2006)

Isomer triggering



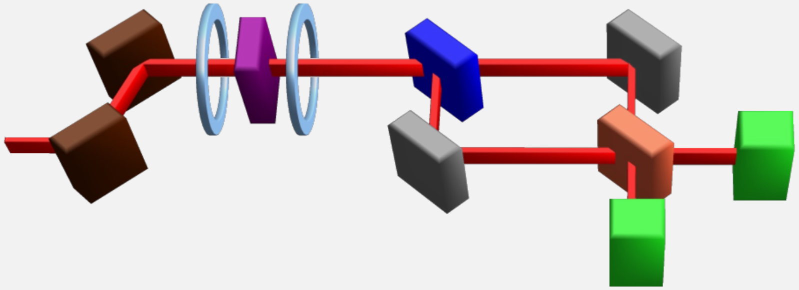
A. Pálffy, J. Evers, C. H. Keitel,
PRL 99, 172502 (2007)

Yoctosecond physics



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

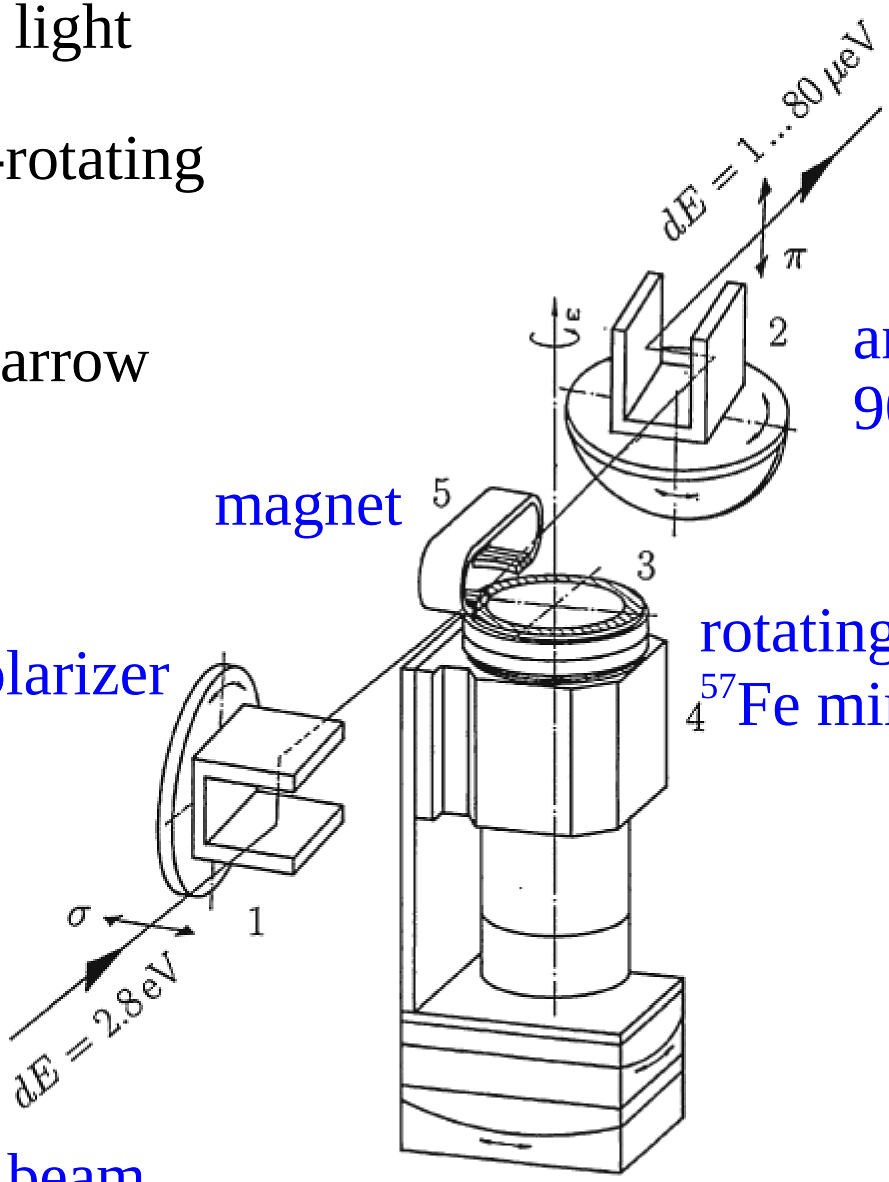
X-ray cooperative light scattering



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

Low-energy condensed matter excitations

- Polarizer/Analyzer blocks all light
- Only exception: polarization-rotating scattering via iron nuclei
- This process is restricted to narrow linewidth of iron (few neV)
- Tunable via Doppler shift due to mirror rotation
- Method was shown to work, but not enough signal from synchrotron sources for inelastic scattering



signal beam

analyzer
90° rotated

magnet

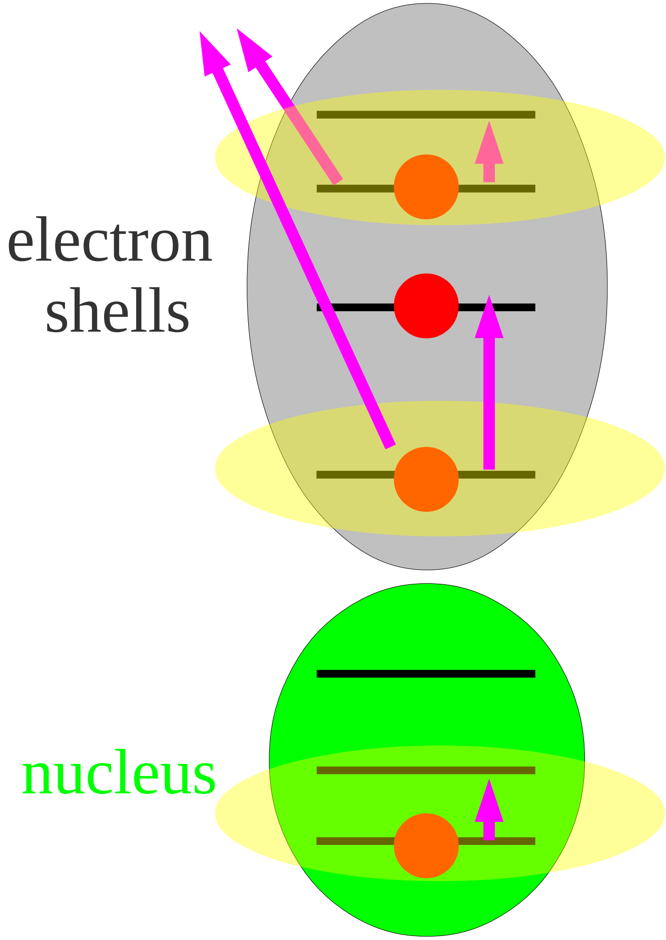
rotating
^{57}Fe mirror

polarizer

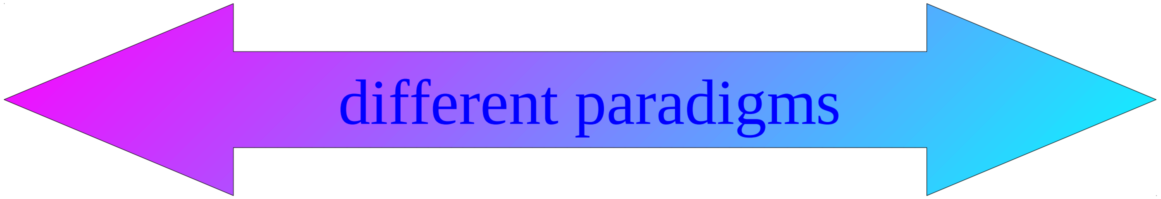
incident beam

Röhlsberger et al, Nucl. Instrum. Methods A 394, 251 (1997)

Motivation



Light-matter interactions



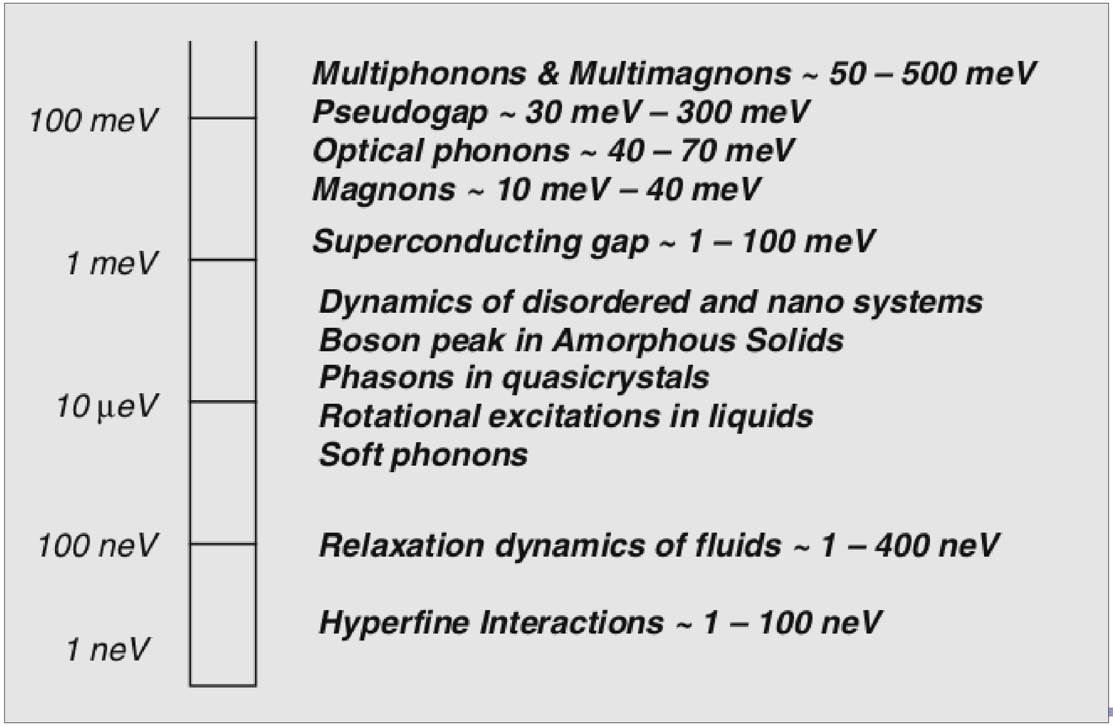
uncontrolled pump
+ passive observation

full quantum
control

- X-ray physics could greatly benefit from moving more towards quantum control
- What can be done is to large degree determined by availability of light sources
- New possibilities with seeded FEL?

Low-energy condensed matter excitations

- Spectroscopy with μeV bandwidth tunable over ~meV scale
- Advantage of x-rays:
  - very high energy and angular resolution
  - reach more parts of phase space due to high brilliance
  - smaller samples accessible
- XFEL could make this feasible for inelastic scattering

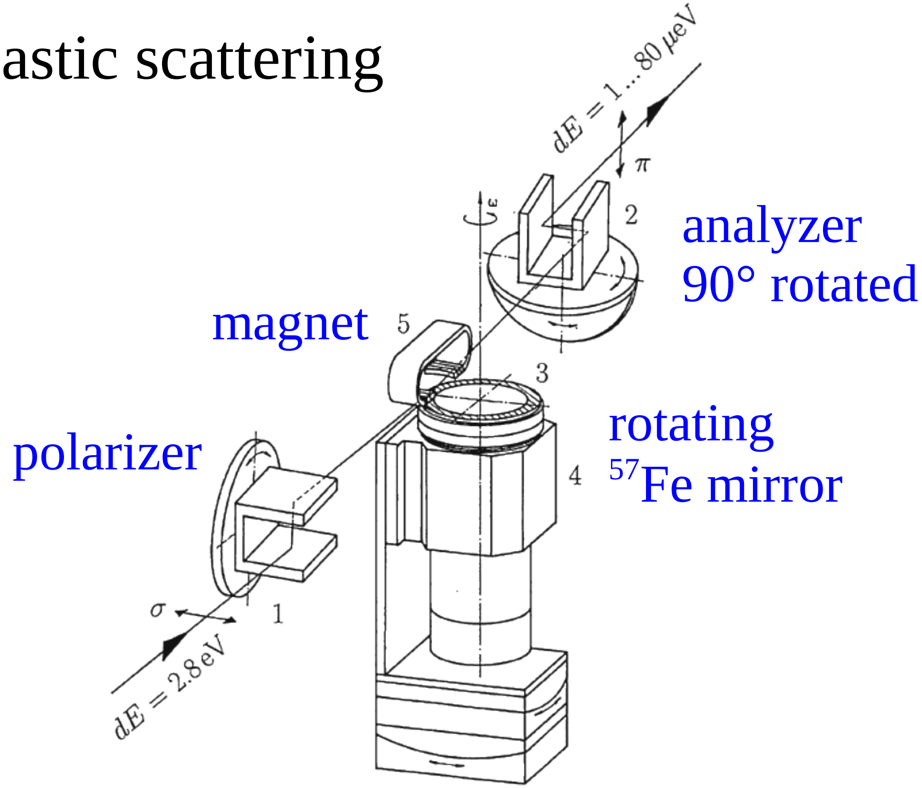


Multiphonons & Multimagnons ~ 50 – 500 meV
Pseudogap ~ 30 meV – 300 meV
Optical phonons ~ 40 – 70 meV
Magnons ~ 10 meV – 40 meV
Superconducting gap ~ 1 – 100 meV

Dynamics of disordered and nano systems
Boson peak in Amorphous Solids
Phasons in quasicrystals
Rotational excitations in liquids
Soft phonons

Relaxation dynamics of fluids ~ 1 – 400 neV

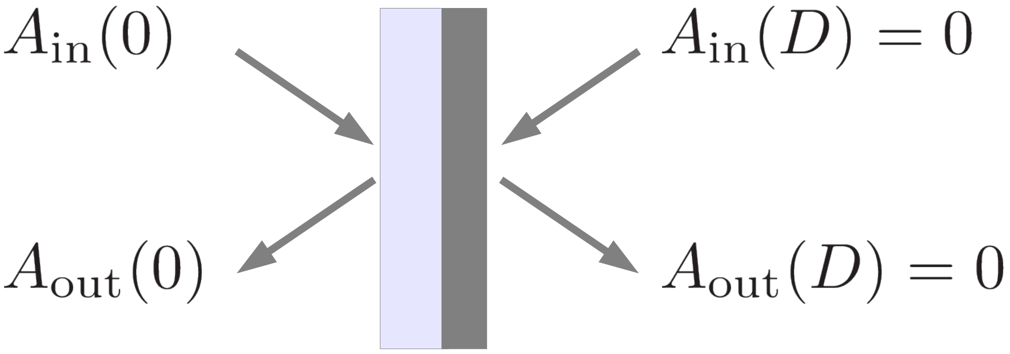
Hyperfine Interactions ~ 1 – 100 neV



Röhlsberger et al, Nucl. Instrum. Methods A 394, 251 (1997)

Layer formalism

- How to calculate R?



field amplitude:

$$\boldsymbol{A}(z) = \begin{pmatrix} A_{\text{in}}(z) \\ A_{\text{out}}(z) \end{pmatrix}$$

propagation equation:

$$\frac{d}{dz}\boldsymbol{A} = i\boldsymbol{F}\boldsymbol{A}$$

scattering amplitudes

$$f_N \sim \frac{1}{\hbar\omega - E + i\gamma/2}$$

reflectivity: $R = \frac{A_{\text{out}}(0)}{A_{\text{in}}(0)}$

Probing fast dynamics at the nanoscale

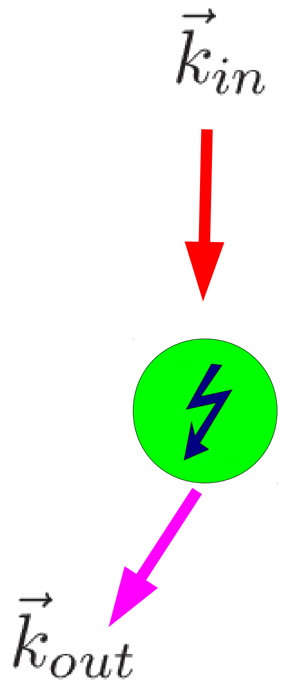
- Scattering is characterized by the scattering function S

transition rate $R \sim \left| S(\vec{Q}, \omega) \right|^2$

- Measurements in energy domain not favorable if
  - scattering medium changes with time (diffusion, molecular motion, short-lived quasiparticles, ...)
  - strong interaction leads to broadening of resonances

Then it is favorable to measure in time domain:

$$S(\vec{Q}, t) = \int S(\vec{Q}, \omega)\, e^{i\omega t}\, d\omega$$



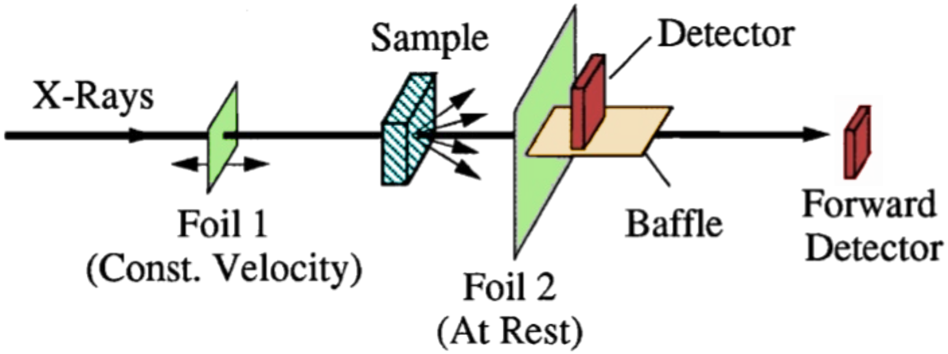
$$\vec{Q} = \vec{k}_{out} - \vec{k}_{in}$$
$$\omega = \omega_{out} - \omega_{in}$$

- Need high Q and t range, large signal/noise ratio
- Example application: correlated electron materials

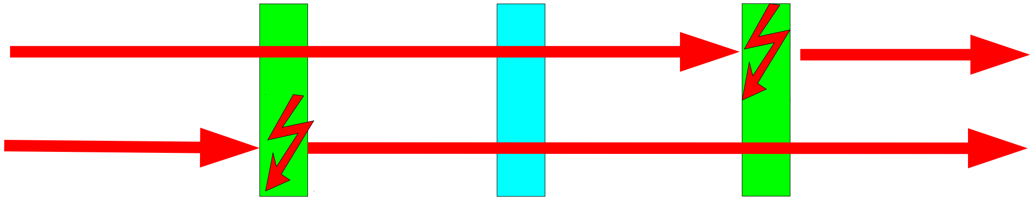
A. Q. R. Baron et al, Phys. Rev. Lett. 79, 2823 (1997); SwissFEL Science Case

Scattering function in the time domain

Setup with NRS in two ^{57}Fe foils



Two interfering scattering pathways



$$\begin{aligned} E_m(\mathbf{q},t) \propto\ & G_1(t)\, e^{-i(\omega_0+\Omega)t} \int \rho_m(\mathbf{r},t)\, e^{i\mathbf{q}\cdot\mathbf{r}}\, d\mathbf{r} \\ +\ & G_2(t)\, e^{-i\omega_0 t} \int \rho_m(\mathbf{r},t=0)\, e^{i\mathbf{q}\cdot\mathbf{r}}\, d\mathbf{r} \end{aligned}$$

beat pattern
(foil velocity)

electron density in sample

Spatial coherence and
large resonant flux
could enable position
and time resolved study
of scattering function
over large parameter space

A. Q. R. Baron et al, Phys. Rev. Lett. 79, 2823 (1997)