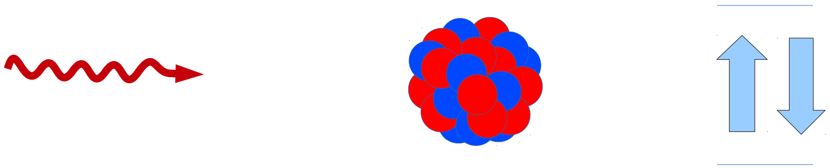
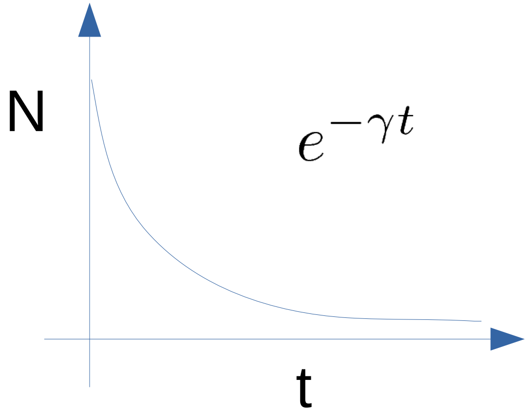
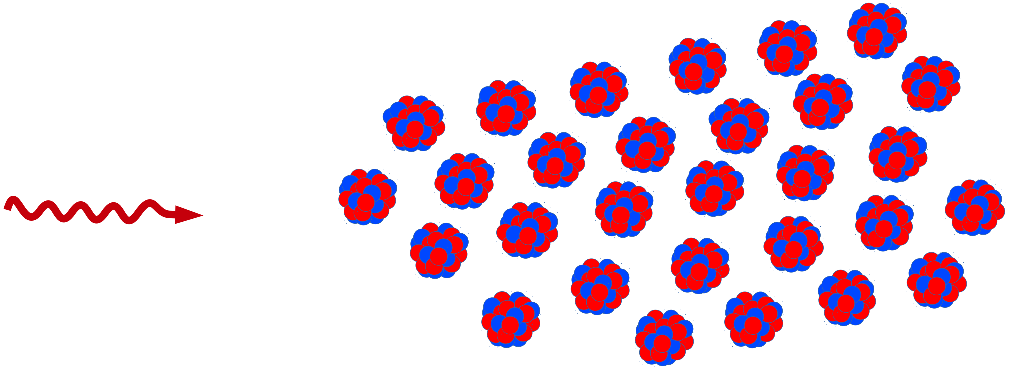
X-ray interaction with Mössbauer nuclei

One versus many

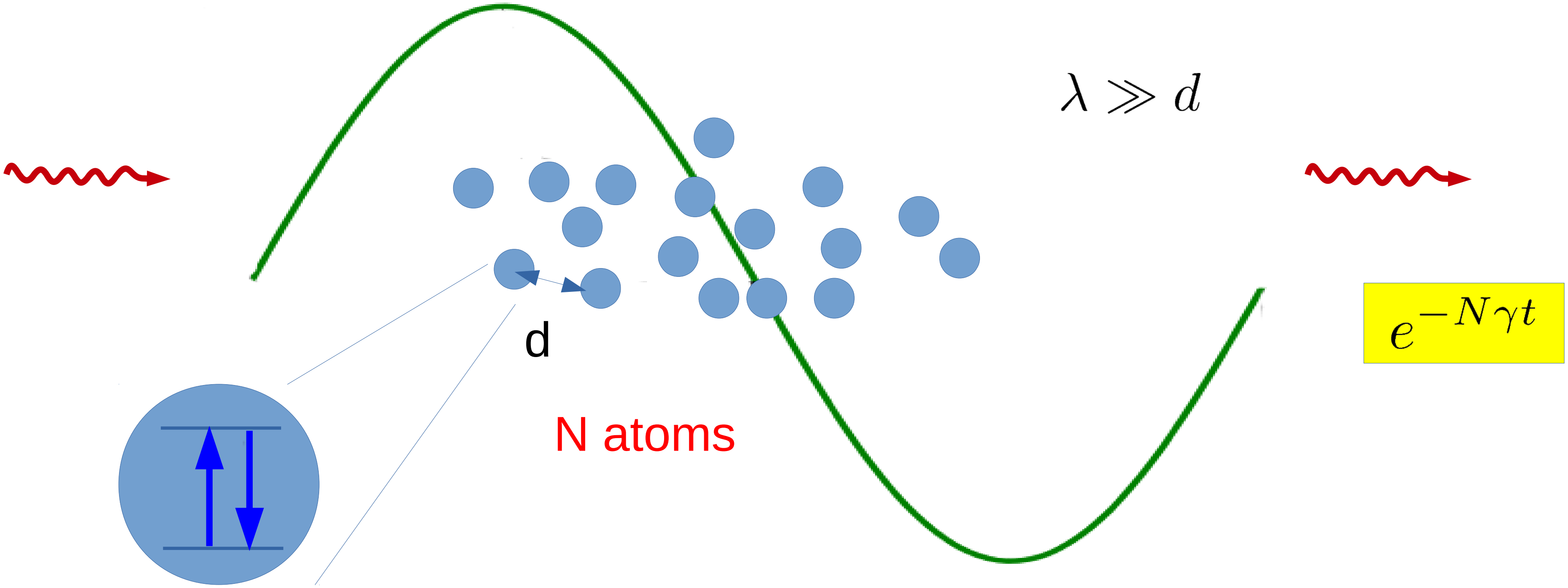






?

Superradiance in atoms



$\lambda \gg d$

d

N atoms

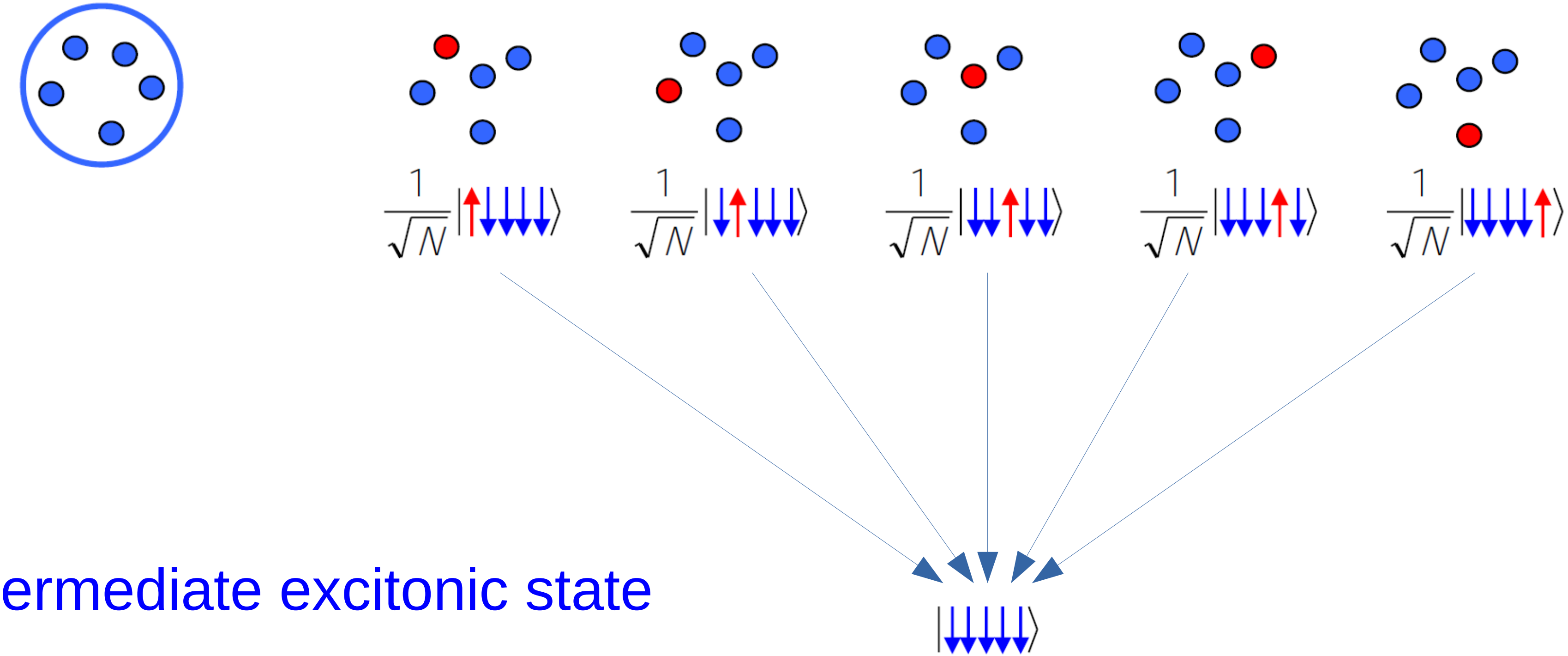
$e^{-N\gamma t}$

Many atoms are in the excited state, we don't know which one decays ...

Nuclei

→ Internuclear distance comparable to the wavelength $\lambda \simeq d$

→ Only one nucleus excited throughout the sample, but we do not know which one!



Intermediate excitonic state

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

- No recoil
- No spin flip
- No internal conversion

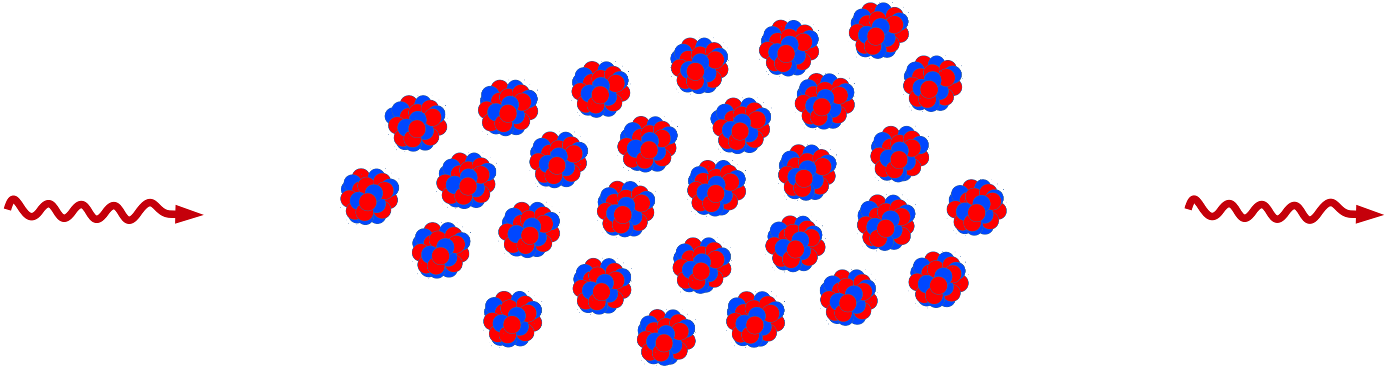
Privileged directions

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

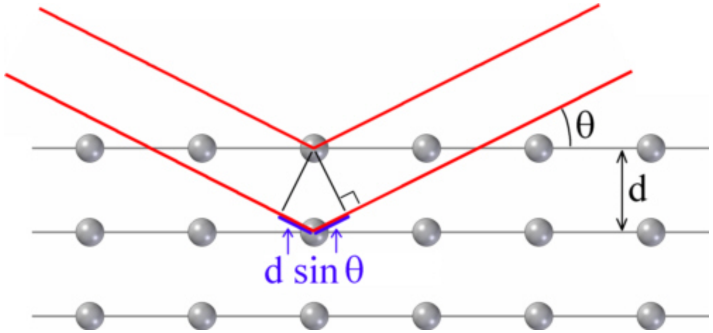
$$\boxed{e^{-N\gamma t}}$$

The phases add up constructively for

- the forward direction

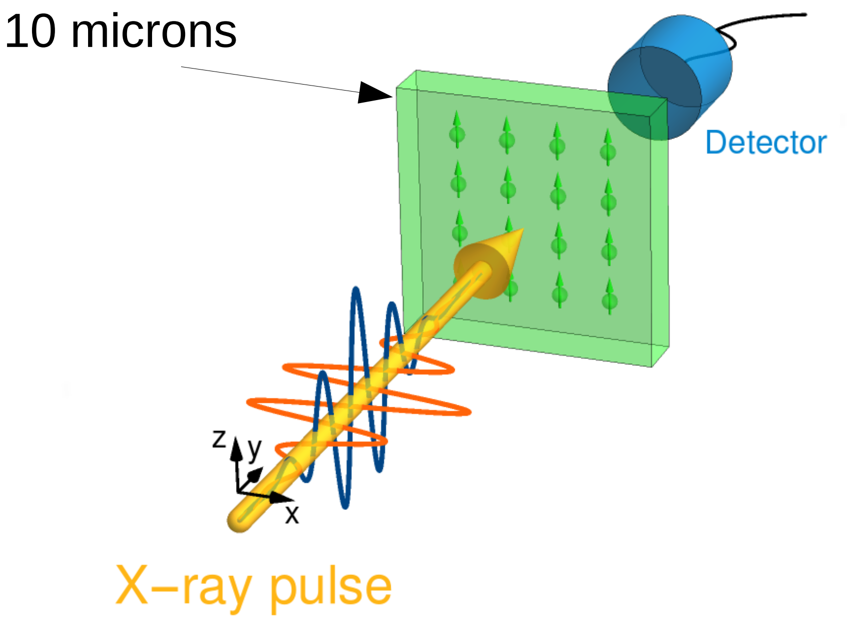


- the Bragg direction in single crystals



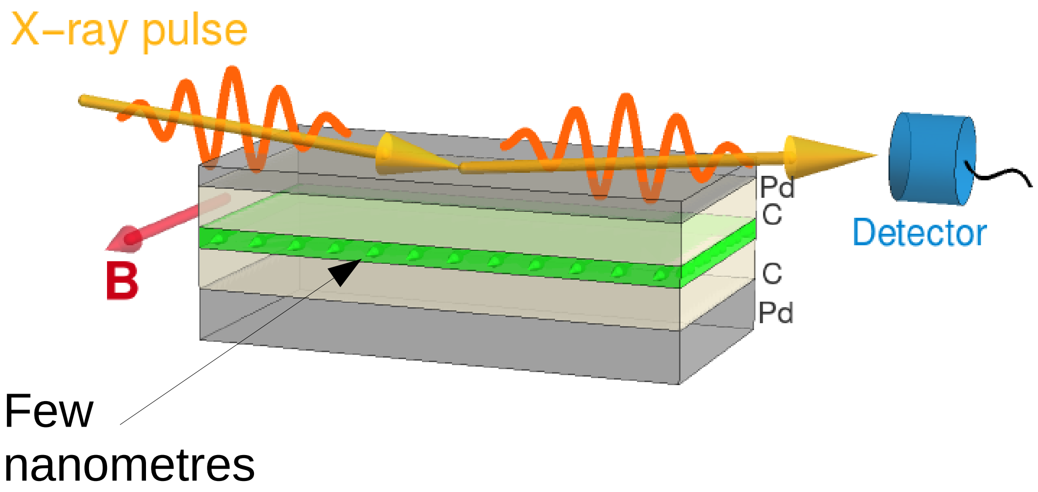
$$\lambda = 2d \sin\theta$$

Thin vs. thick



Forward scattering on thick target

- Many eigenmodes are excited
- Complicated time spectra

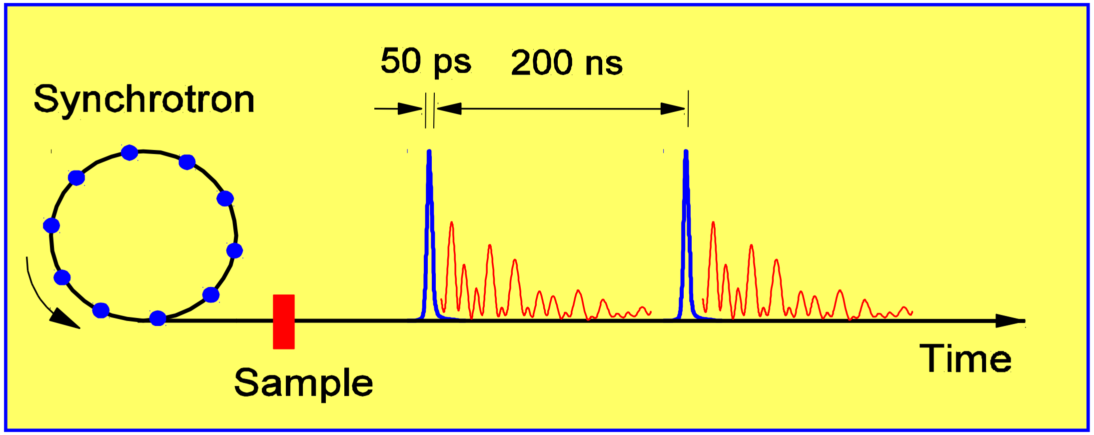


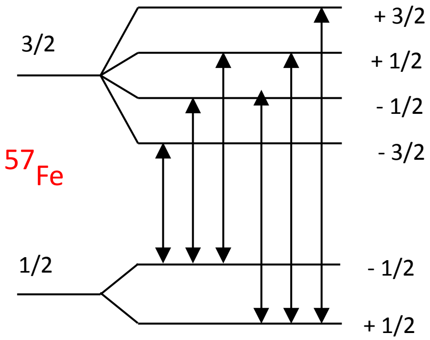
Grazing incidence on thin target

- Structured target – effective Bragg case
- Selective excitation of a single eigenmode
- Purely exponential decay

Nuclear forward scattering - thick samples

Synchrotron radiation





@ 14.413 keV

Nuclear Forward Scattering (NFS) of Synchrotron Radiation

nuclear condensed matter physics based on the Mössbauer effect

MHz repetition rate
10^9 photons/s after monochromator
meV pulse width
nuclear width approx. 5 neV

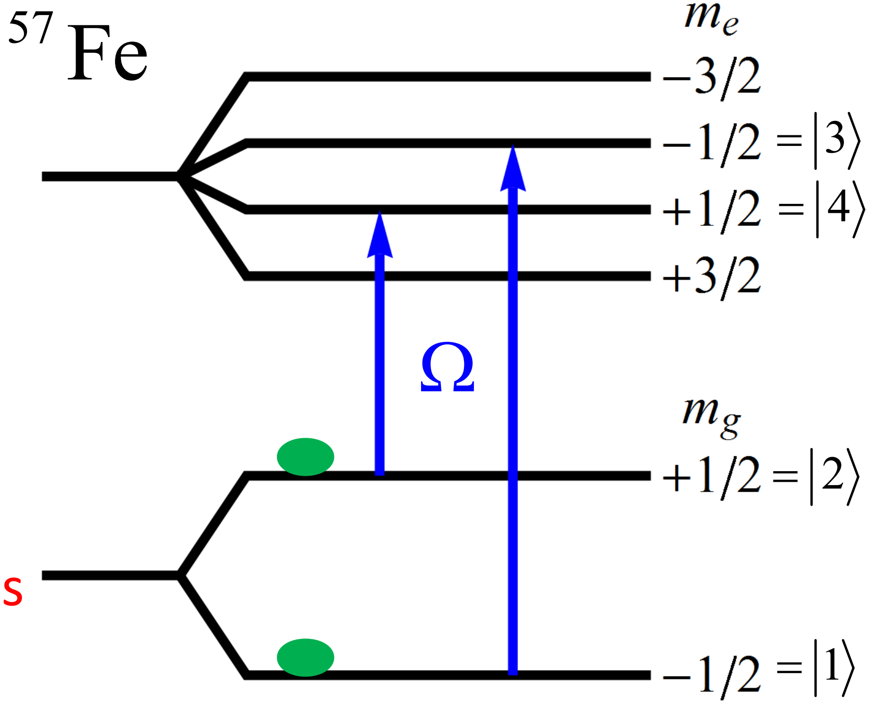
WEAK EXCITATION – A SINGLE RESONANT PHOTON PER PULSE AT MOST!

Maxwell-Bloch equations

$$\partial_t \widehat{\rho} = \frac{1}{i\hbar}\left[\widehat{H}, \widehat{\rho}\right] + \widehat{\rho}_s \, ,$$

$$\frac{1}{c}\partial_t \Omega + \partial_y \Omega = i\eta\left(\rho_{31} + \rho_{42}\right)$$

Transition Currents



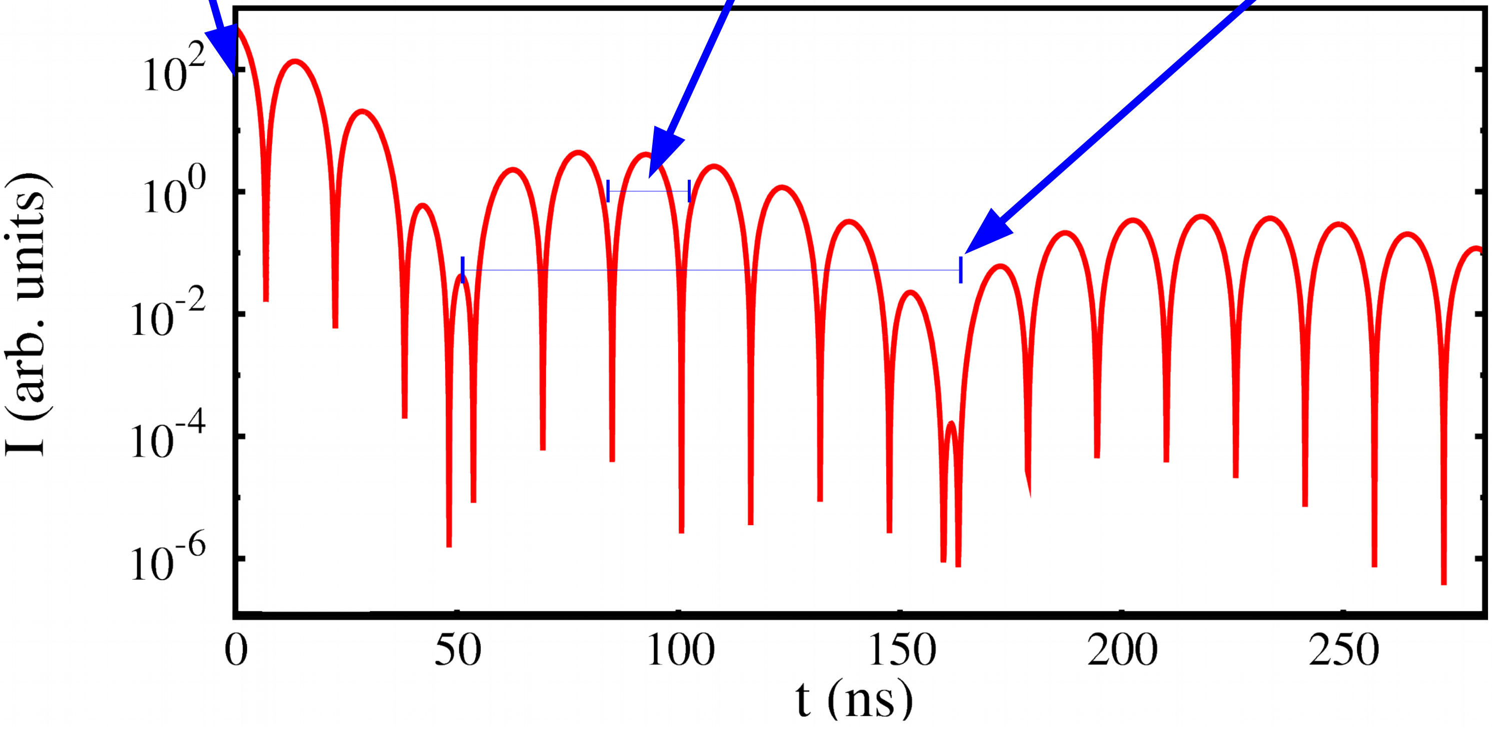
In both cases, classical fields although single photons!
Theory describes surprisingly well the experiments!

W.-T. Liao, AP and C. H. Keitel, Phys. Rev. Lett. 109, 197403 (2012)
X. Kong, W.-T. Liao and AP, New J. Phys. 16, 013049 (2014)

t=0: almost instantaneous excitation, prompt (electronic) scattering → background

quantum beats due to different transition frequencies in single or different nuclei

dynamical beat (Bessel function) in thicker samples due to multiple scattering



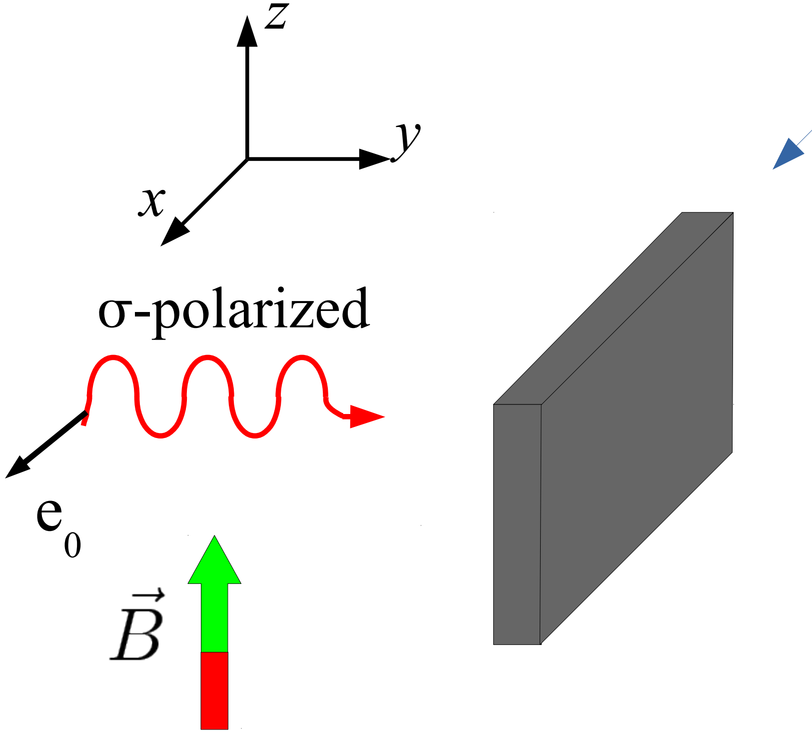
Signal intensity

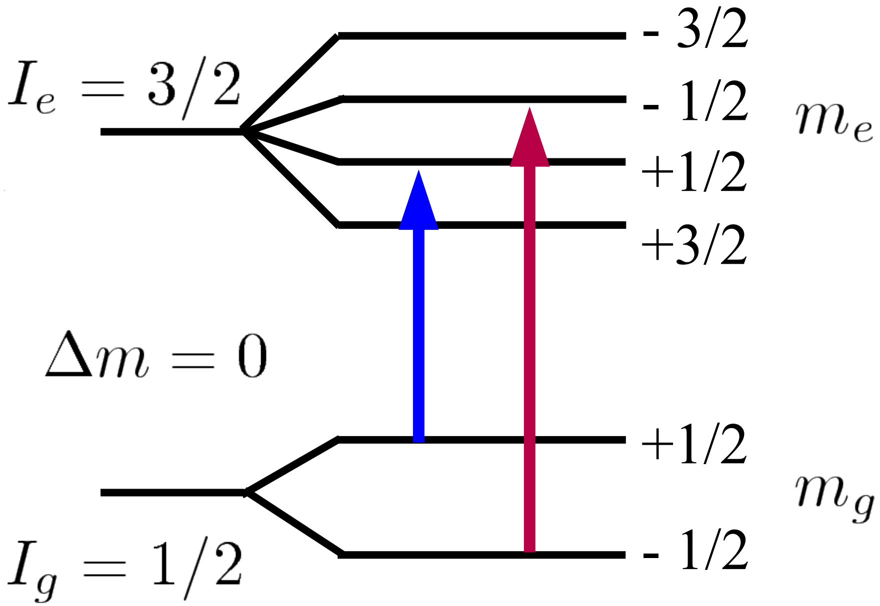
Time

Natural lifetime $t_0 = 141$ ns

How to control the decay

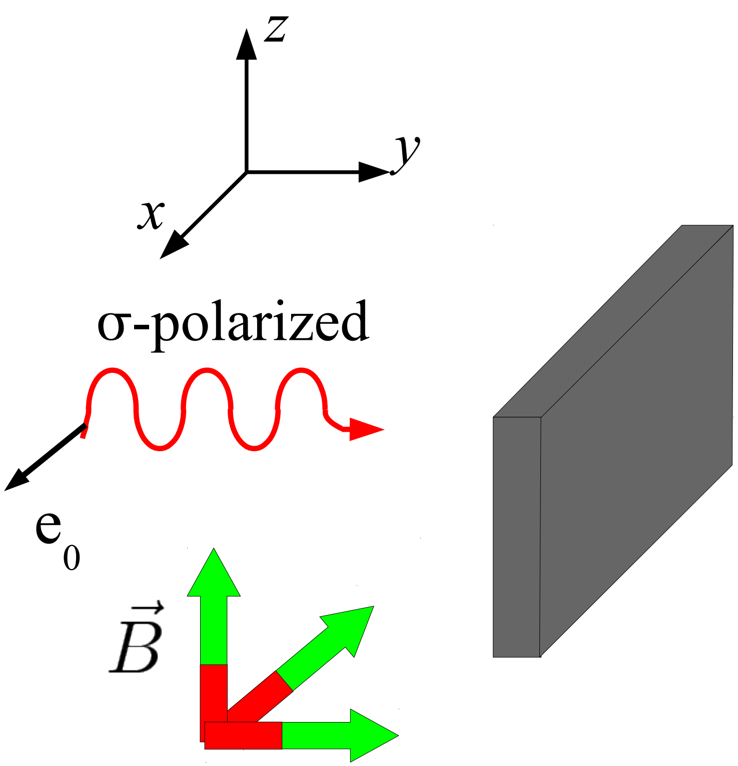
typically 10-micron-thick!

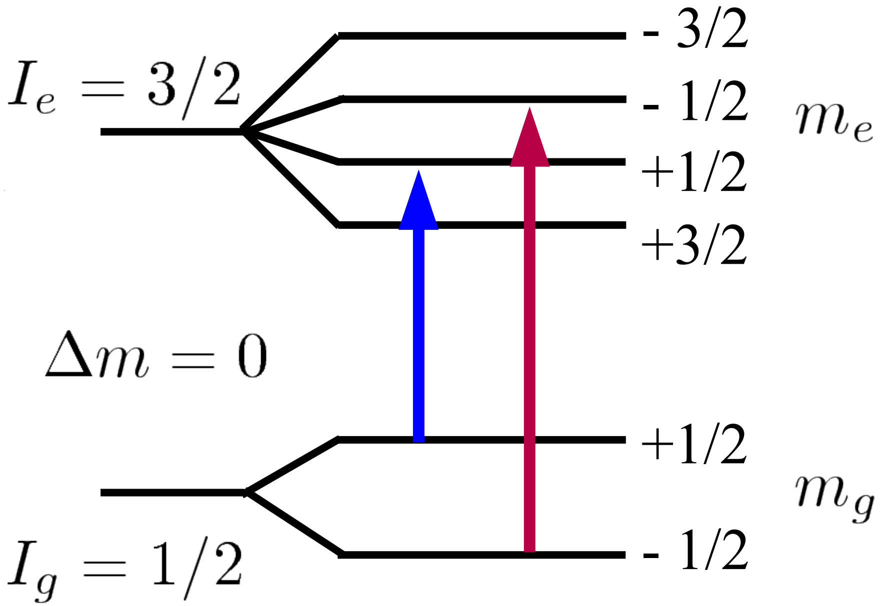




rotation of the nuclear hyperfine magnetic field

Magnetic switching

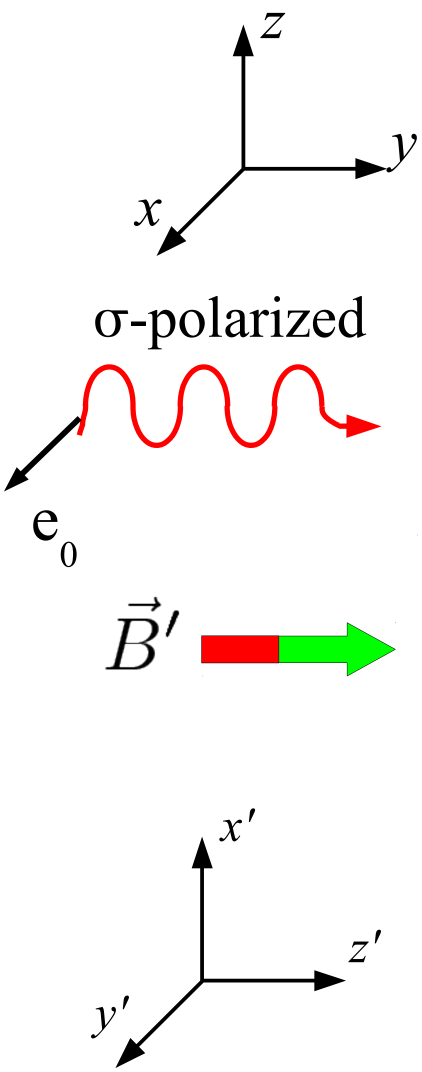


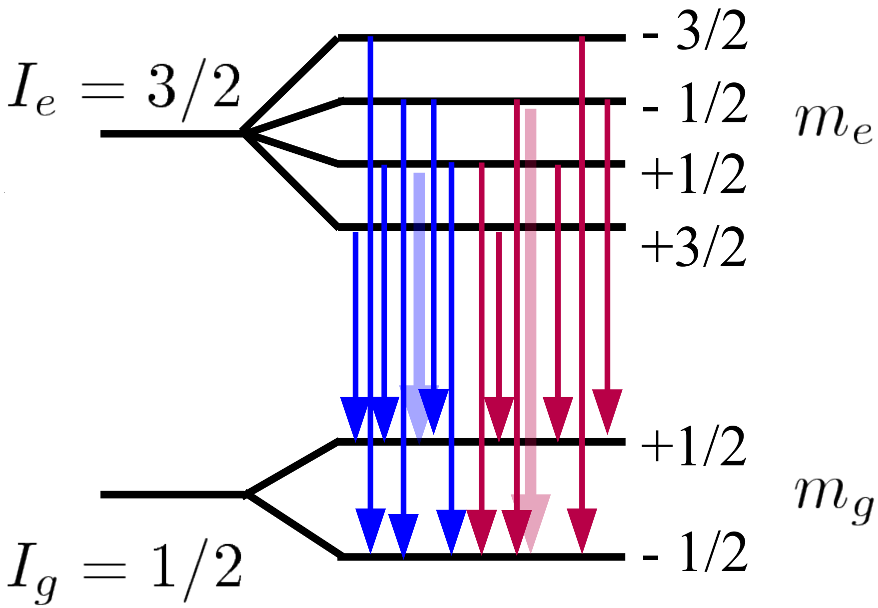


rotation of the nuclear hyperfine magnetic field

Magnetic switching

each monochromatic transition is transformed into a sextet!

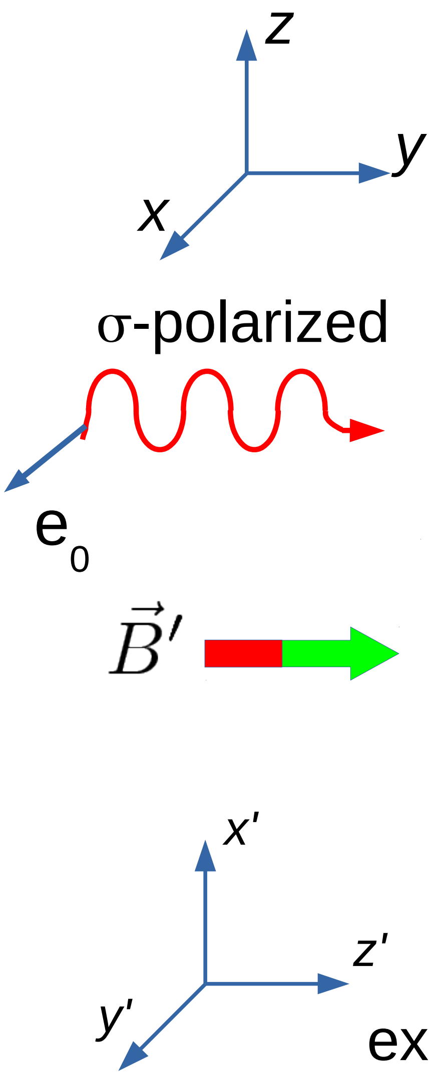


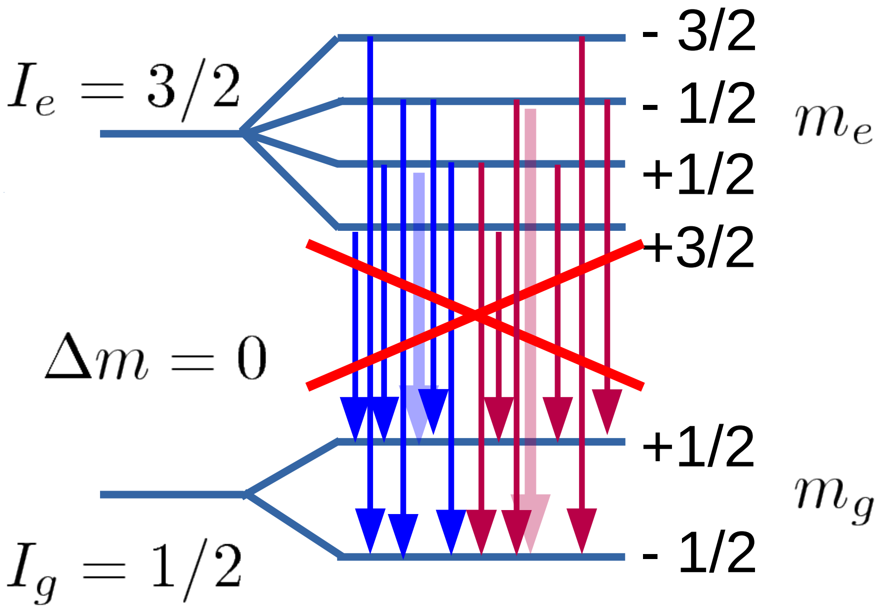


- redistribution of nuclear state population
- the new transition currents interfere

Magnetic switching

for certain switching TIME and ANGLE, the currents interfere destructively!

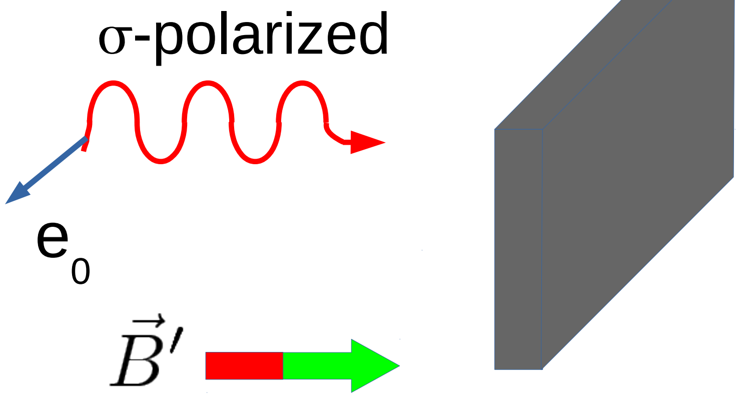


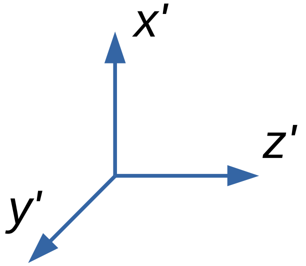


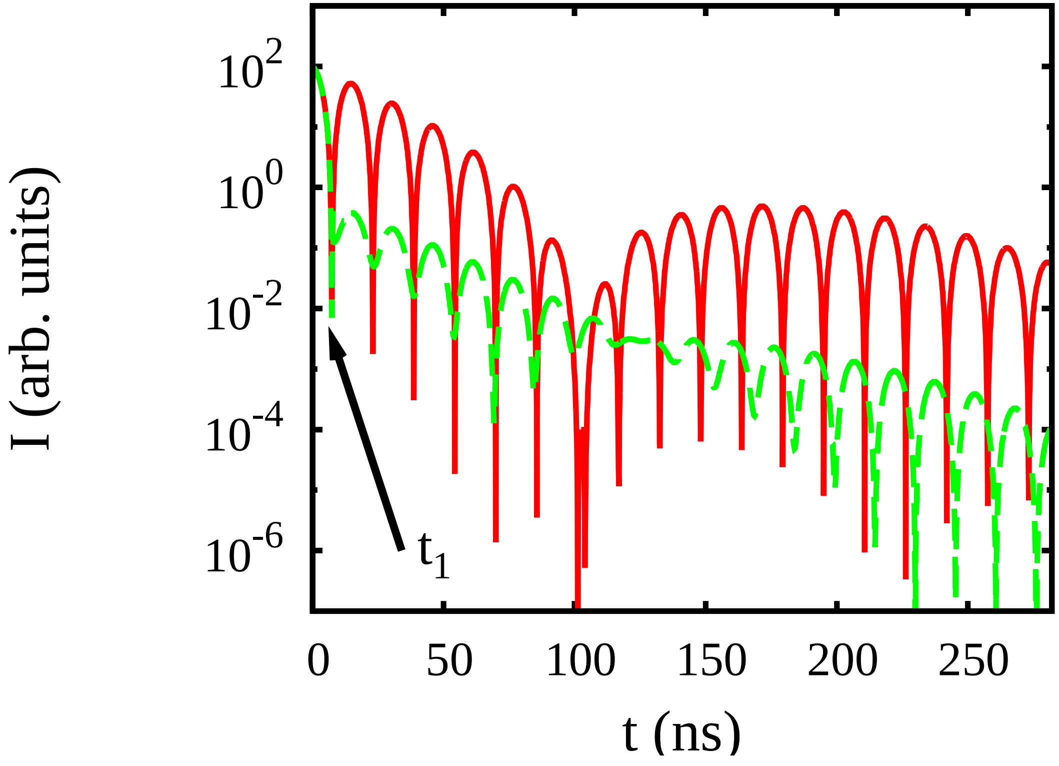
THE COHERENT DECAY IS SUPPRESSED!

experimentally observed: Yu. V. Shvyd'ko *et al.*, PRL 77 (1996) 32

Magnetic switching



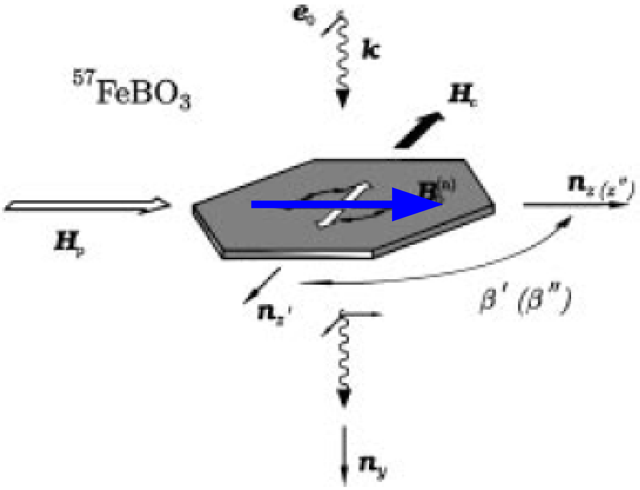




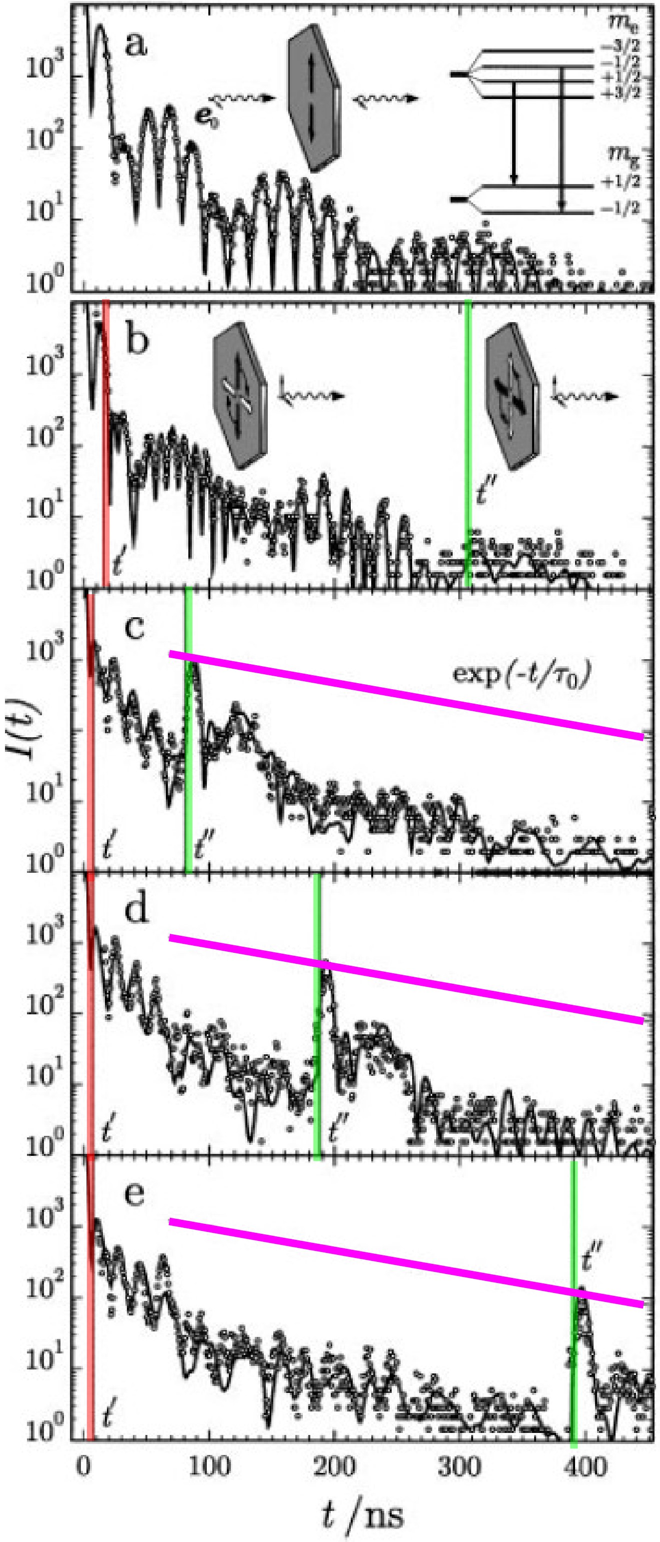
switching at the minima, complete suppression of dominant first order scattering is achieved

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

Unary logical operations

Logical Identity

in	out
π	π
σ	σ

Logical False

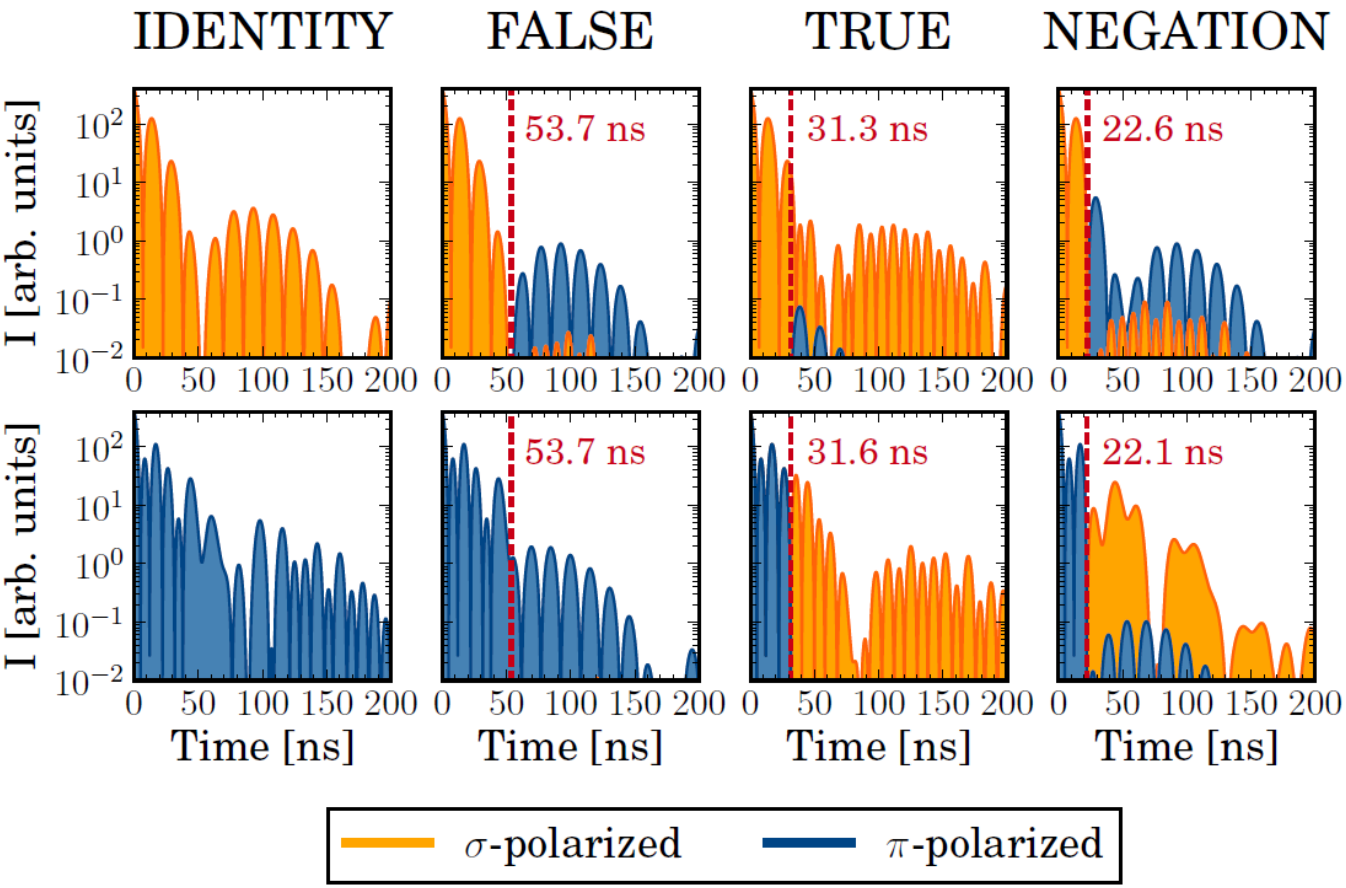
in	out
π	π
σ	π

Logical True

in	out
π	σ
σ	σ

Logical Negation

in	out
π	σ
σ	π



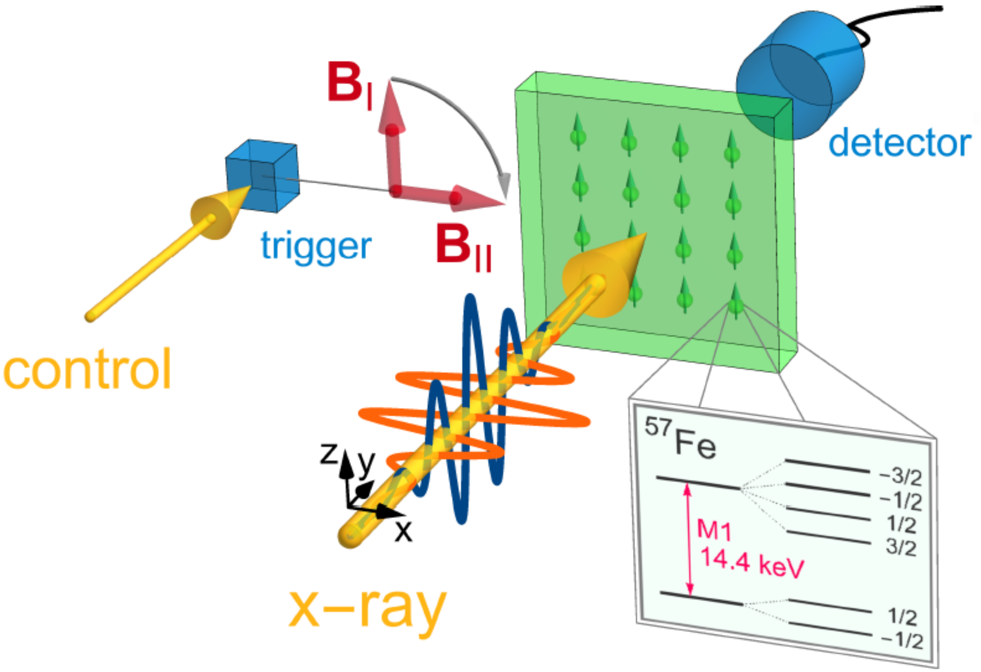
Destructive C-NOT

in		out
C	T	T
0	0	0
0	1	1
1	0	1
1	1	0

in		out
C	T	T
π	π	π
π	σ	σ
σ	π	σ
σ	σ	π

if $C = \pi$: apply IDENTITY

if $C = \sigma$: apply NEGATION



- all unary gates can be operated within a single setup
- switching time determines the nature of the gate
- detection of temporally synchronized control photon can be used as triggering signal
- arrival time needs to become polarization-dependent

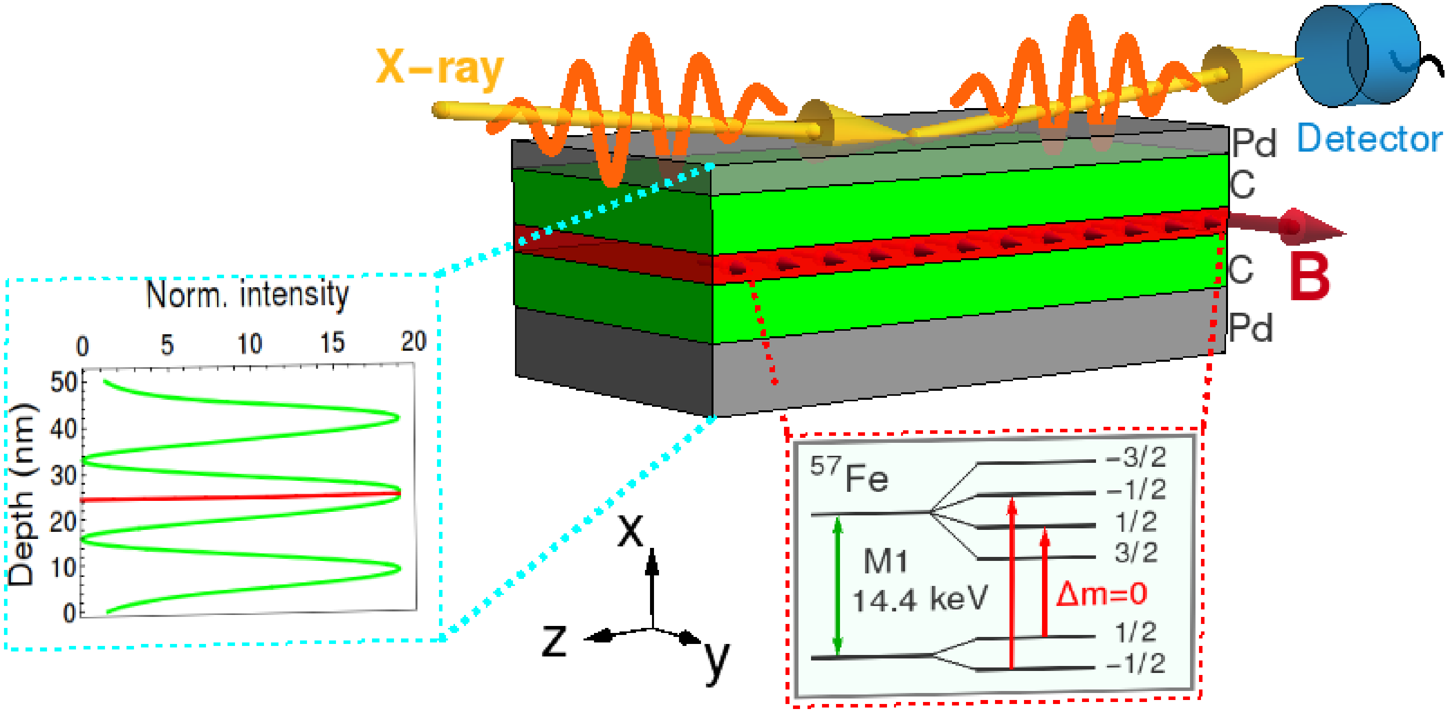
Destructive C-NOT

switching at $t_0 = 22.3$ ns
but only *if* $C = \sigma$

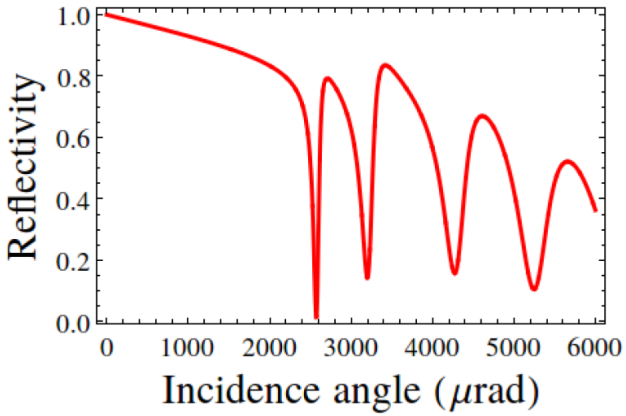
Gunst, Keitel, Palffy, Sci. Rep. 6, 25136 (2016)

Grazing incidence off thin-film nanocavities

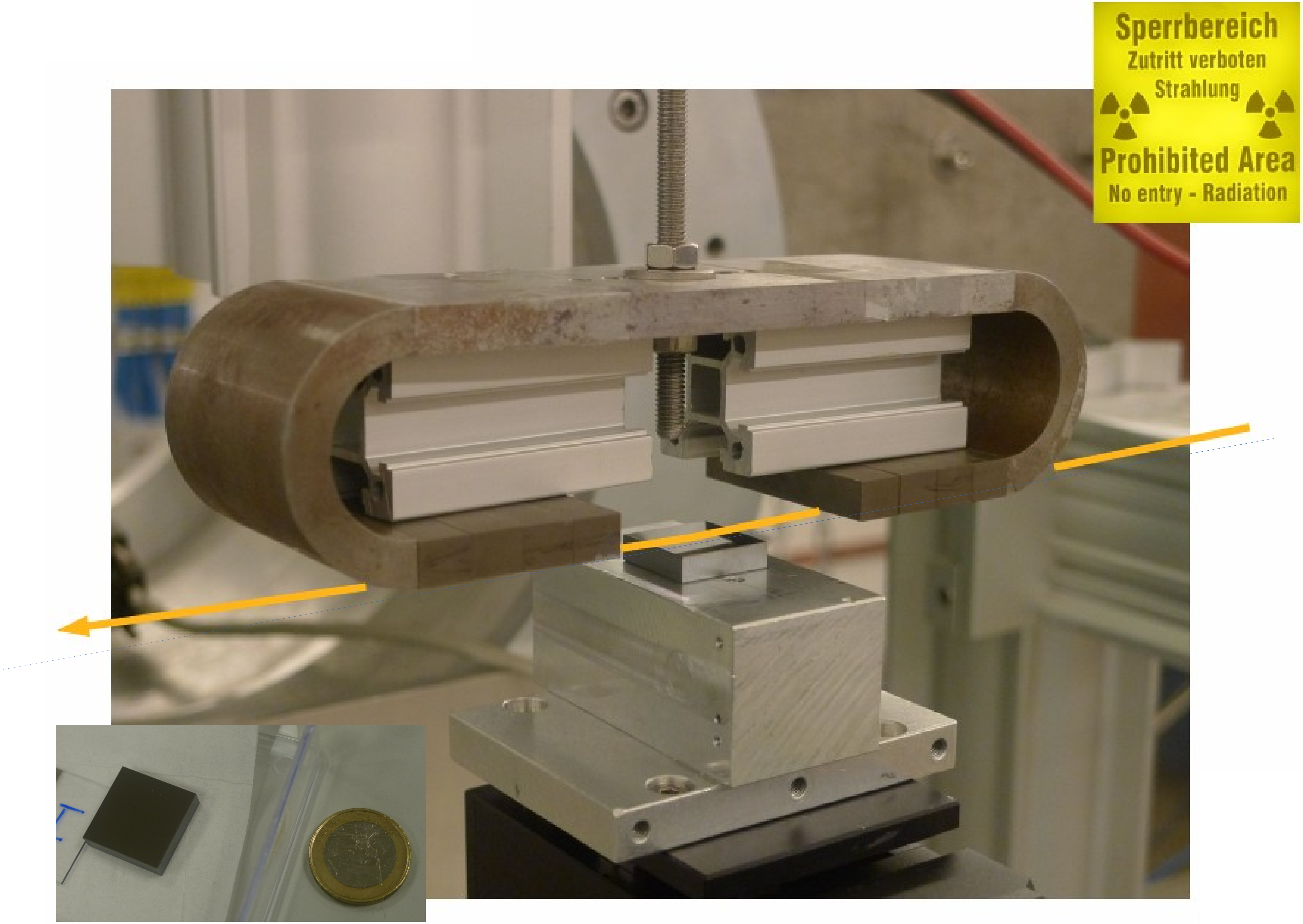
Thin-film x-ray cavities



- Grazing incidence, detect reflectivity
- “resonant angle” from rocking curve
- Nuclear resonances interact with cavity field

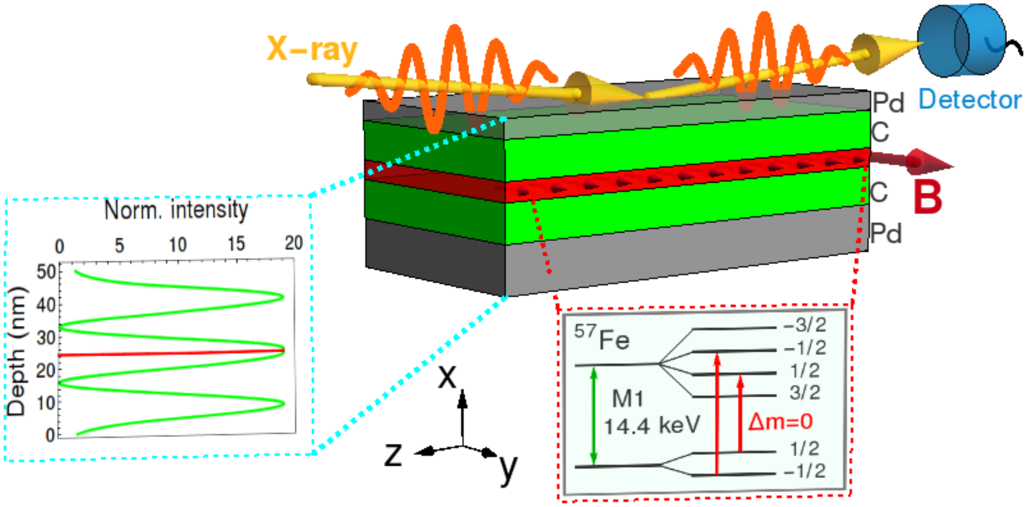


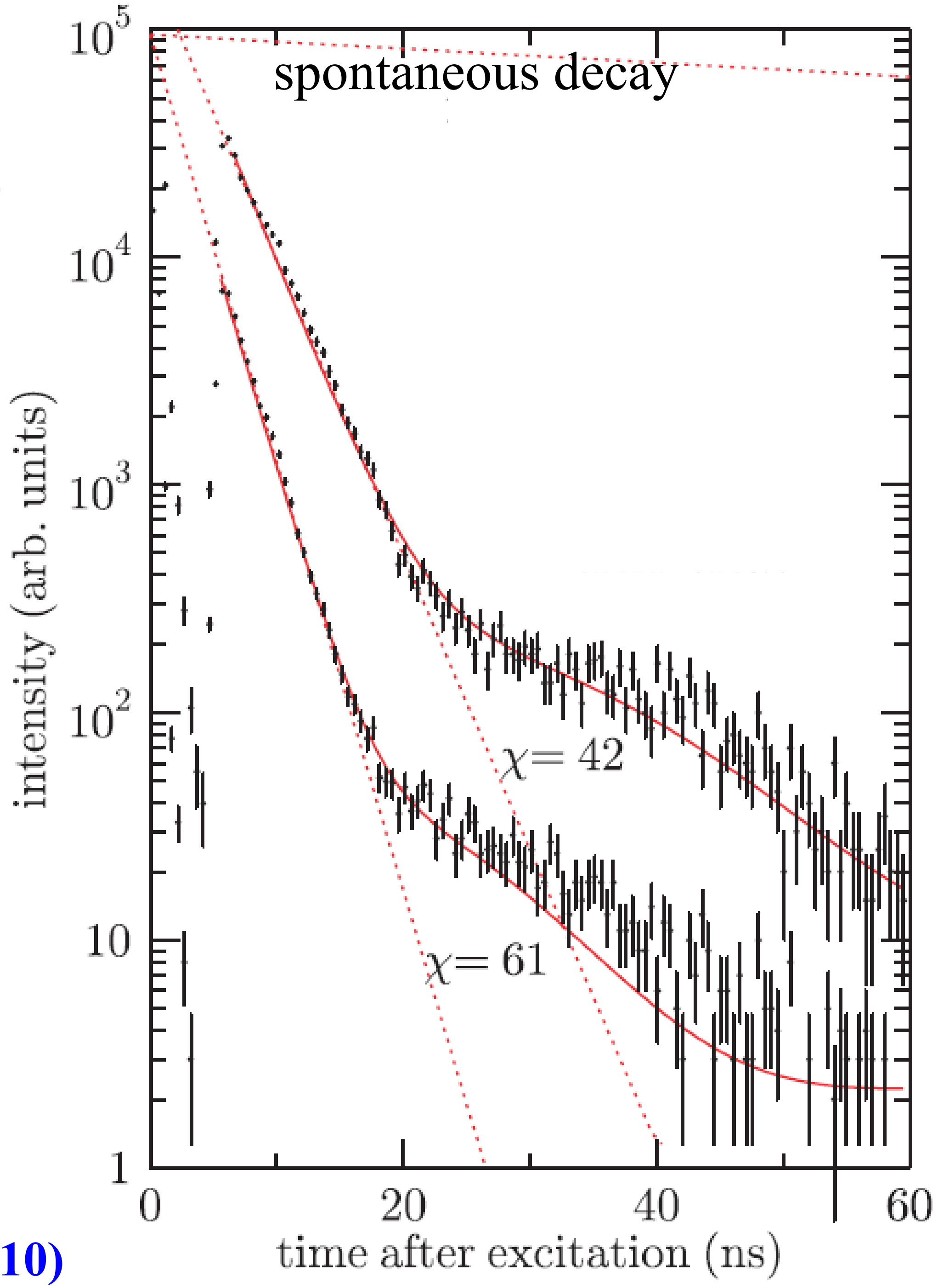
Experiments at Petra III or ESRF



courtesy Jörg Evers

Faster exponential decay



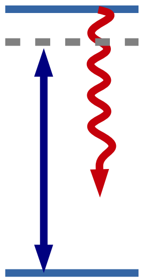


χ is the coherent decay enhancement factor

… even here not forever, but long enough!

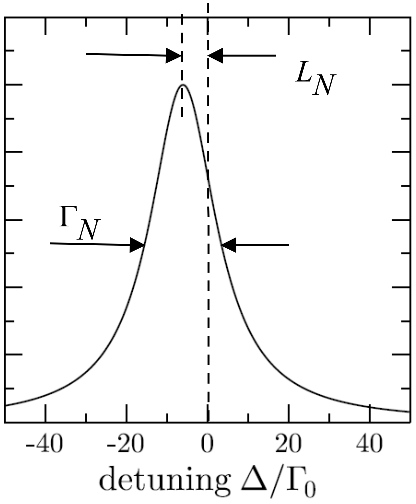
R. Röhlsberger *et al.*, Science 328, 1248 (2010)

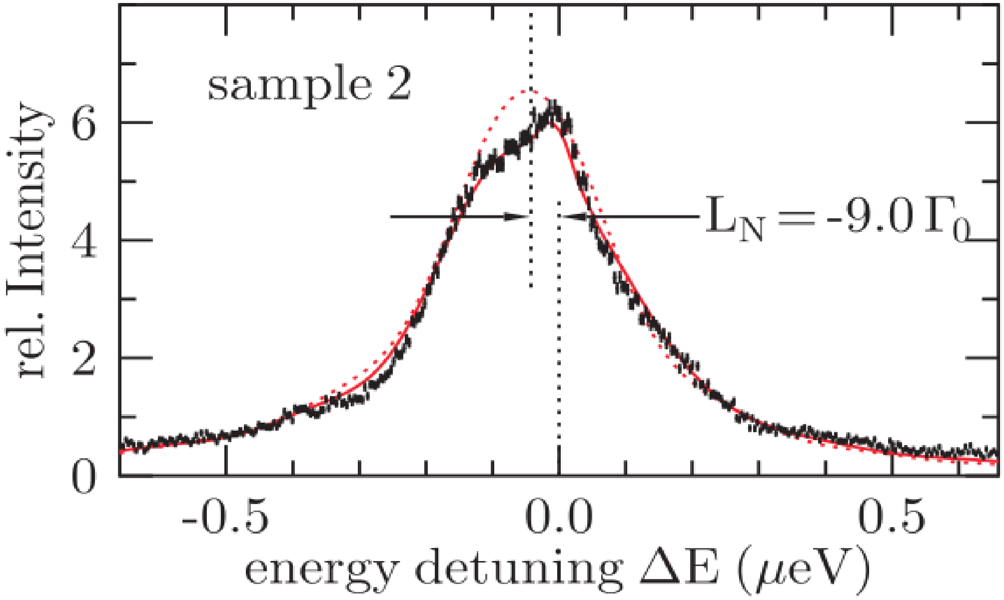
Collective Lamb shift



Lamb shift – interaction with virtual photons

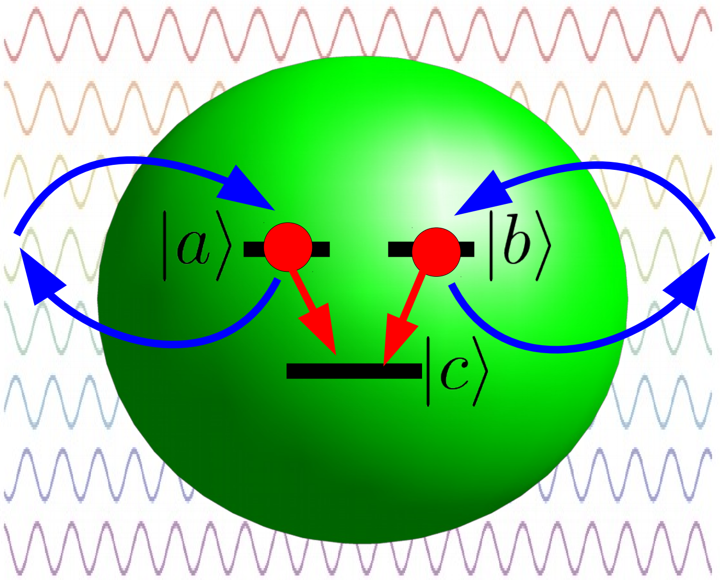
Collective Lamb shift – interaction with virtual photons between identical nuclei





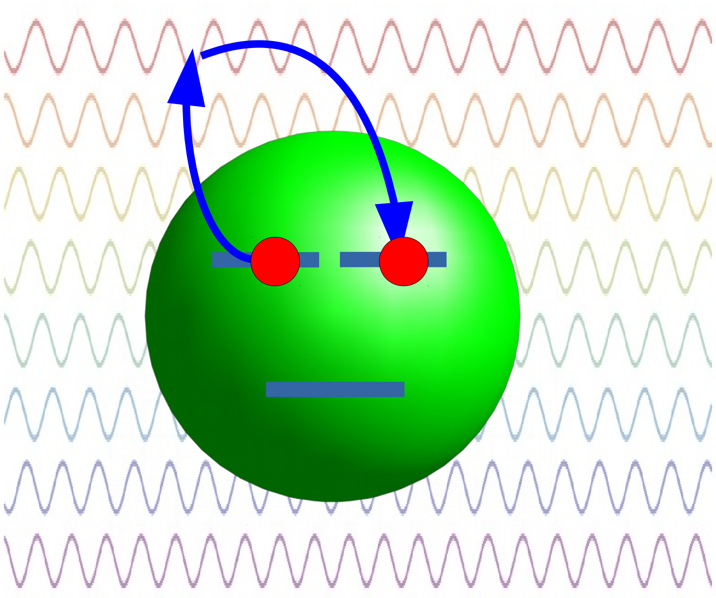
R. Röhlsberger *et al.*, Science 328, 1248 (2010)

Spontaneously generated coherence



interaction with vacuum modes
creates decoherece – spontaneous decay

Spontaneously generated coherence



in very special cases,
interaction with vacuum
can bring coherence!

$\vec{d}_1 \cdot \vec{d}_2 \neq 0$

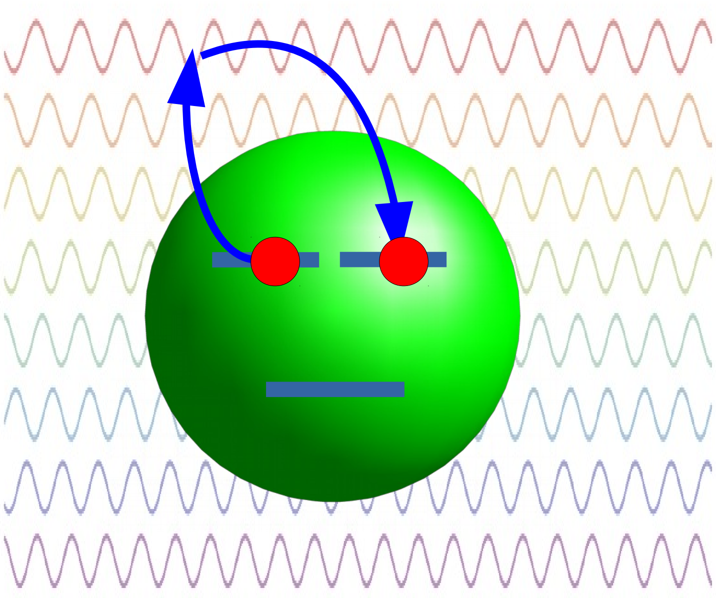
non-orthogonal
dipole moments

$E_1 \approx E_2$

approx. same
transition energy

K. P. Heeg *et al.*,
Phys. Rev. Lett. 111, 073601 (2013)

Spontaneously generated coherence



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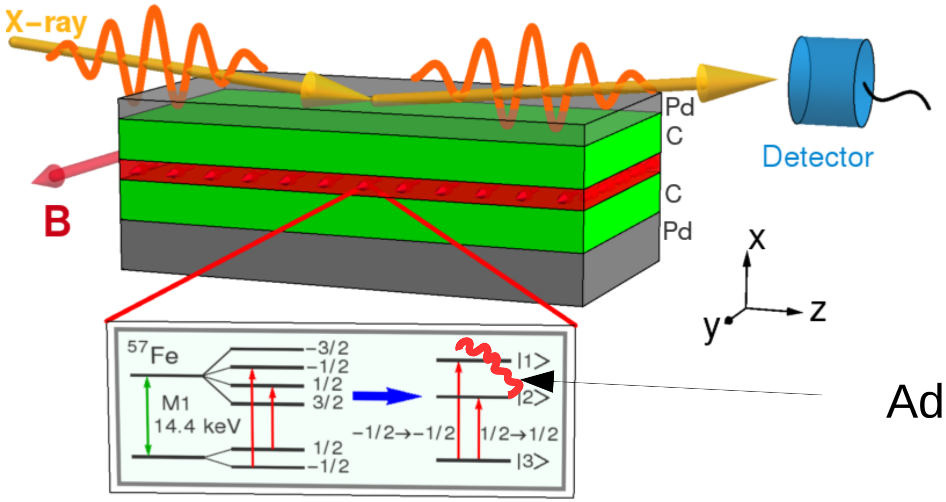
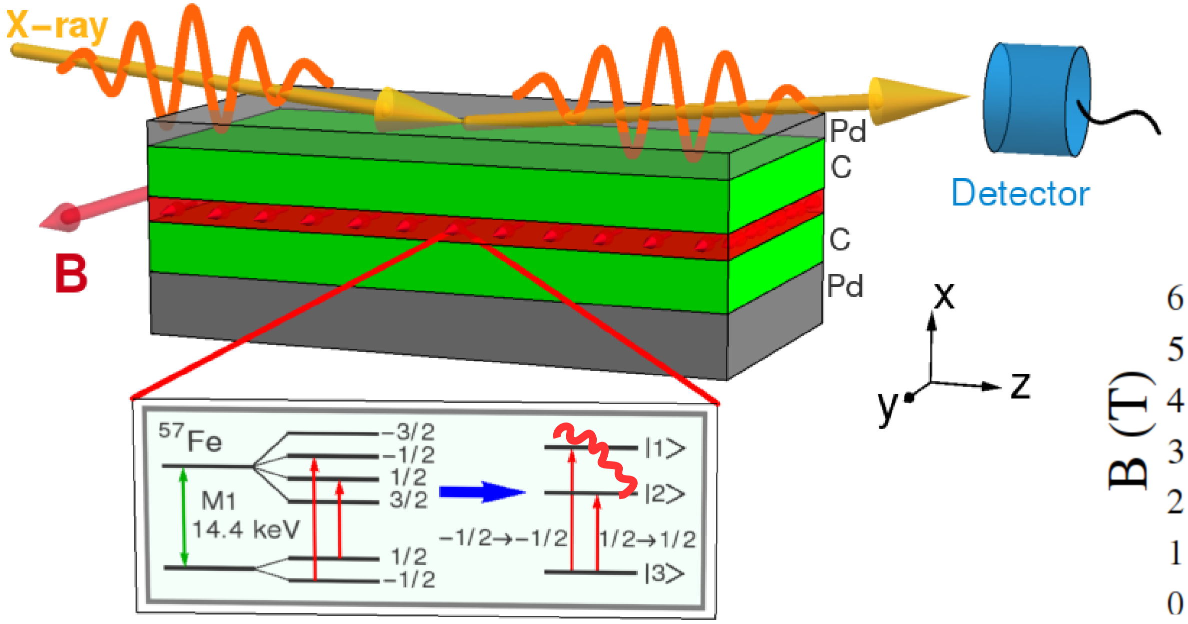
K. P. Heeg *et al.*,
Phys. Rev. Lett. 111, 073601 (2013)

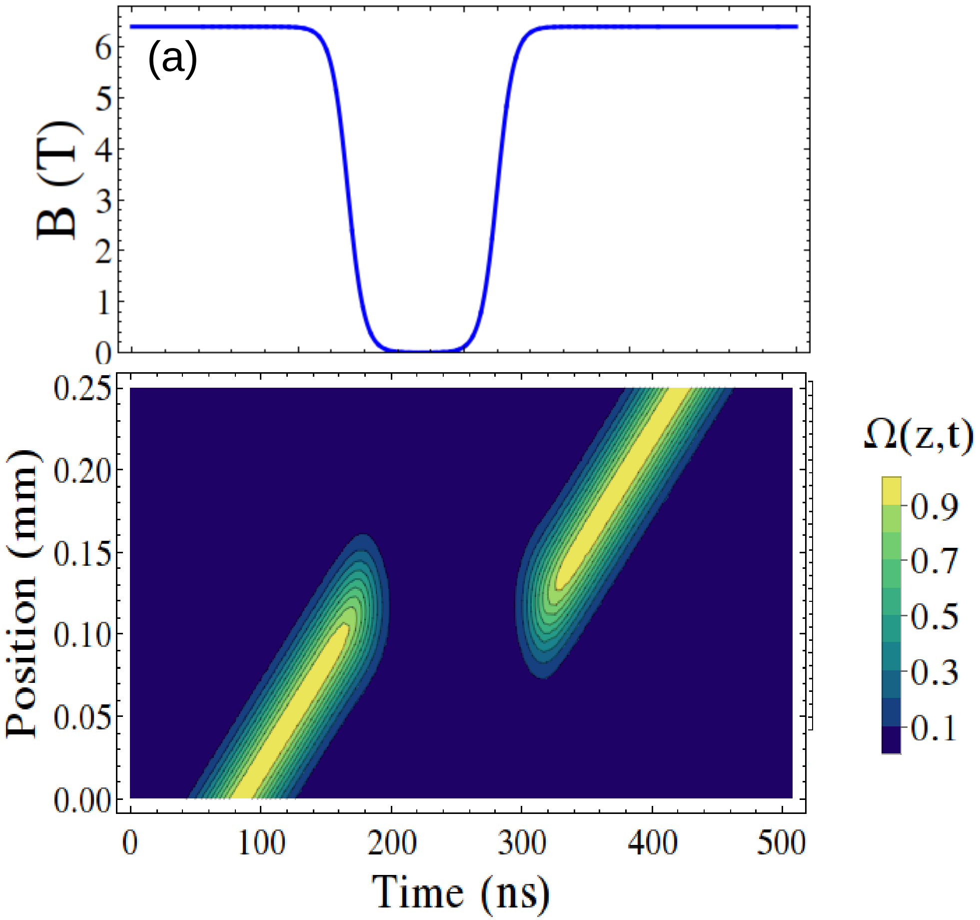


Additional coupling between upper levels

Coherent storage of single x-ray photons



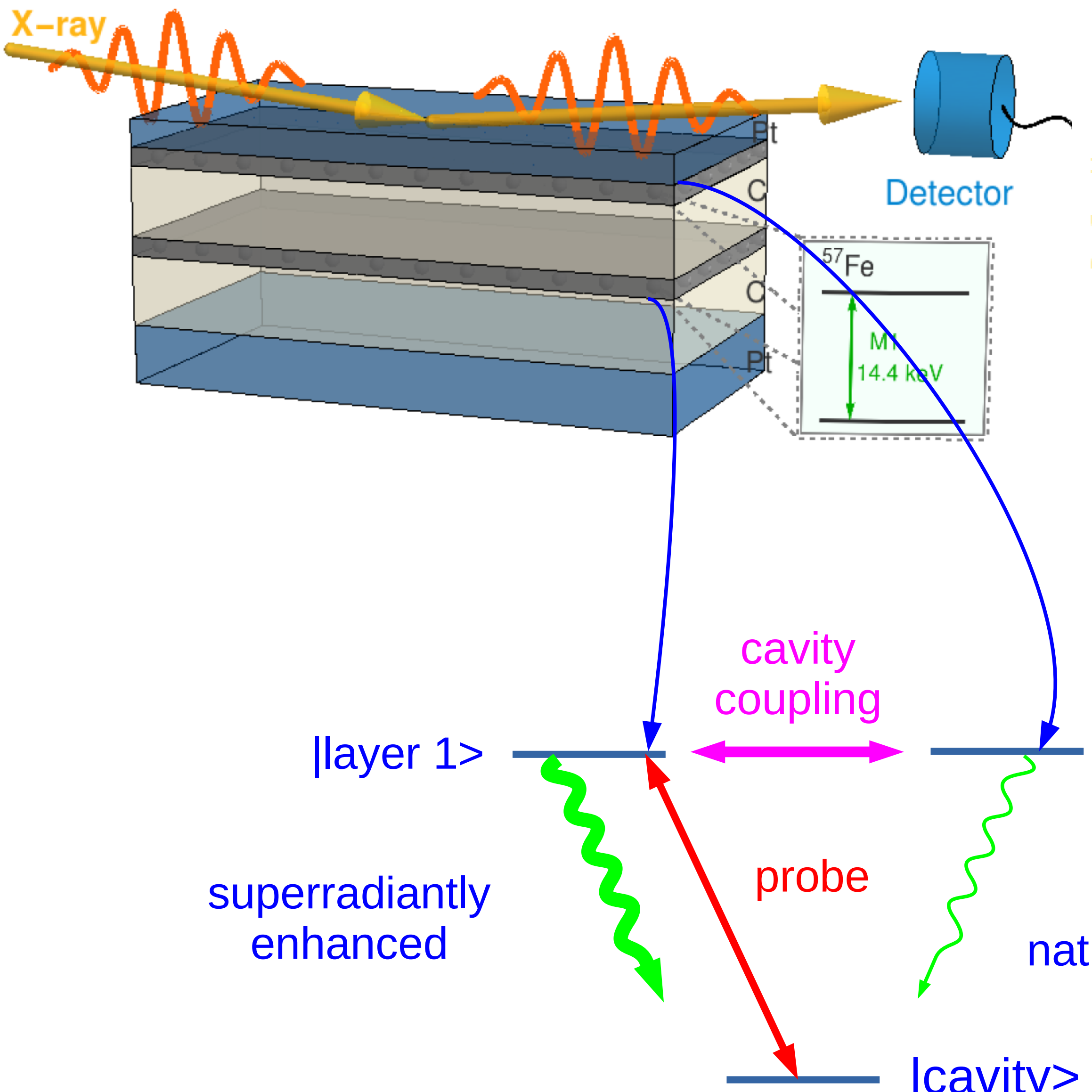
Kong and Palffy,
Phys. Rev. Lett. 116, 197402 (2016)



Similar to stopping light via EIT*,
by switching off the magnetic field,
x-rays are transferred to nuclear coherences

* electromagnetically induced transparency (EIT)

Two iron layers



cavity coupling

|layer 1>

|layer 2>

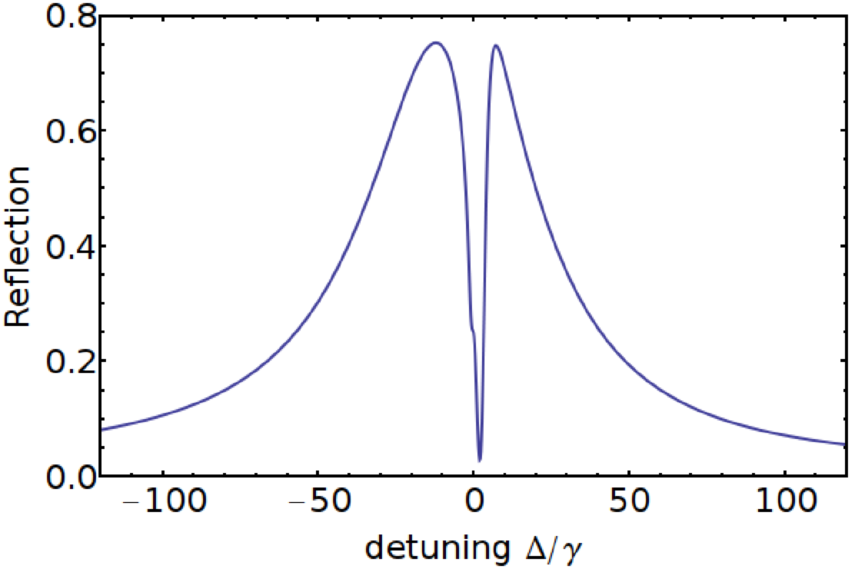
superradiantly enhanced

probe

natural decay

|cavity>

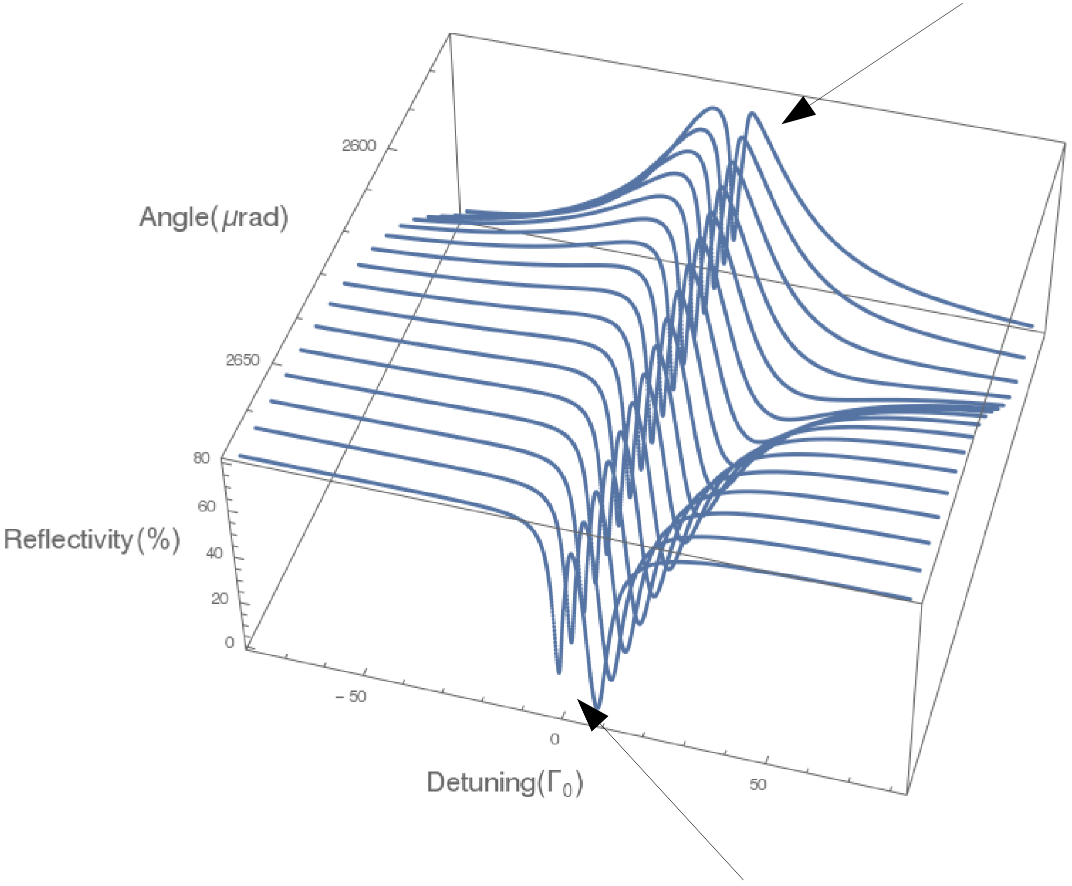
Reflection spectrum



Looks like EIT!

R. Röhlsberger *et al.*, Nature 482, 199 (2012)

Changing the incidence angle



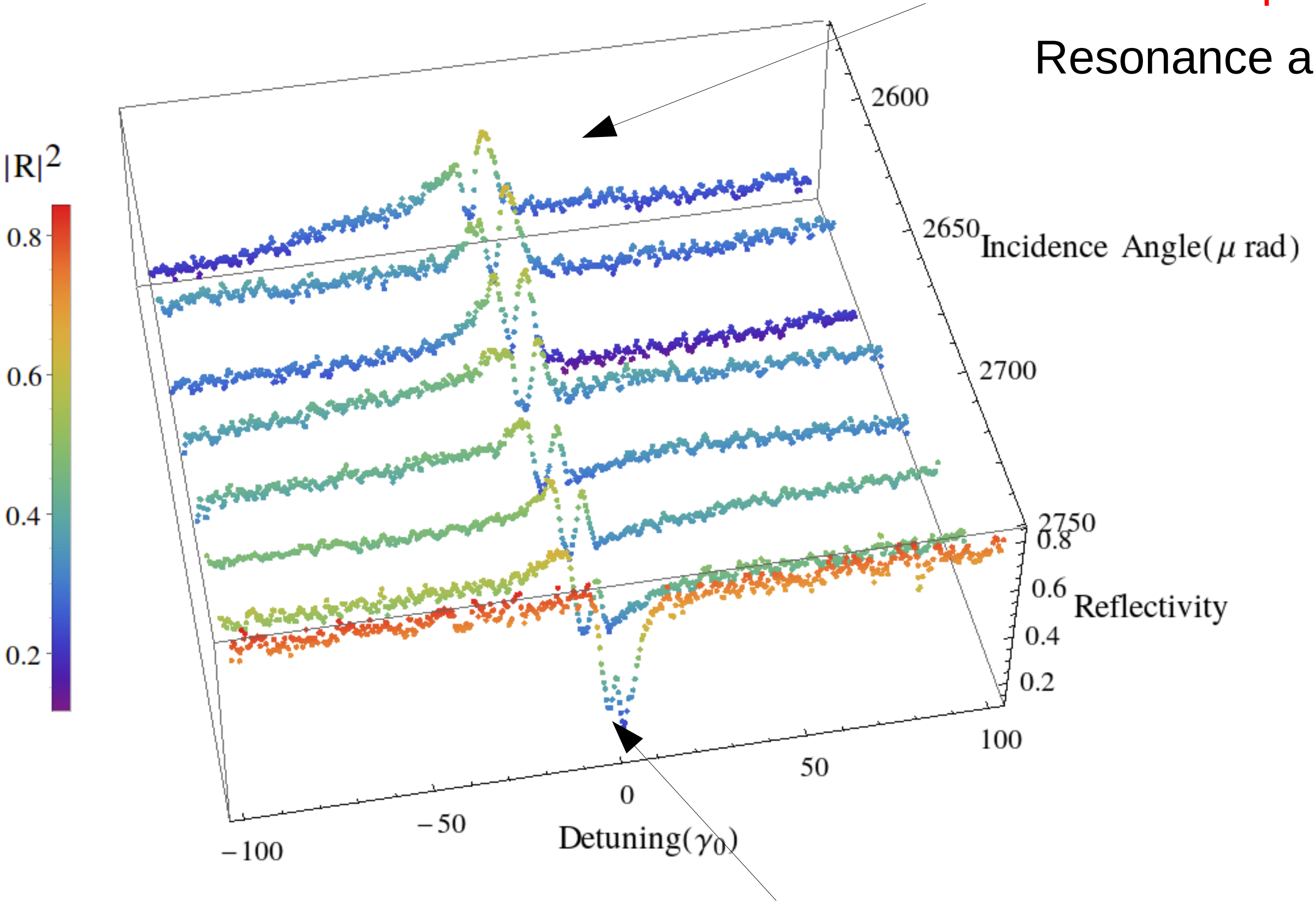
weaker coupling, EIT

Resonance angle

stronger coupling,
Autler-Townes splitting

Off-resonance angle

Changing the incidence angle



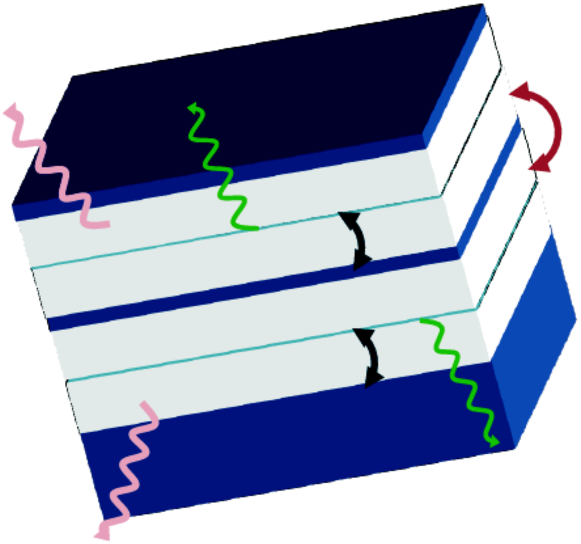
weaker coupling, EIT

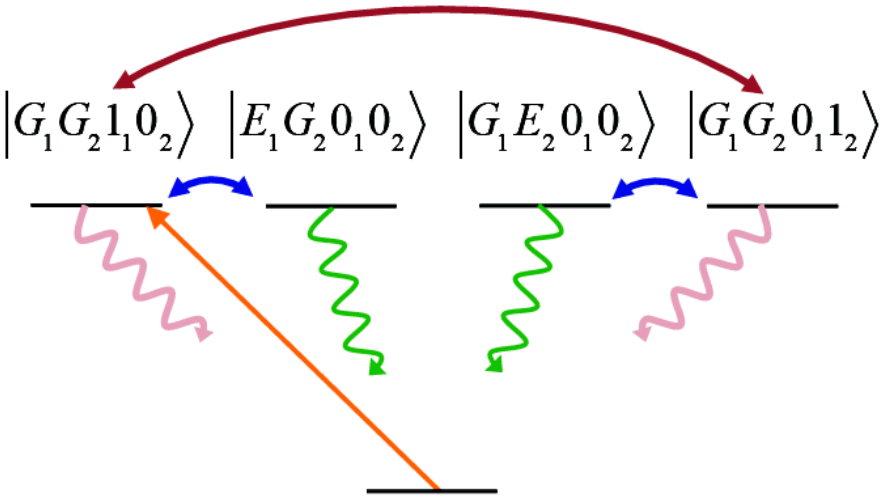
Resonance angle

stronger coupling,
Autler-Townes splitting

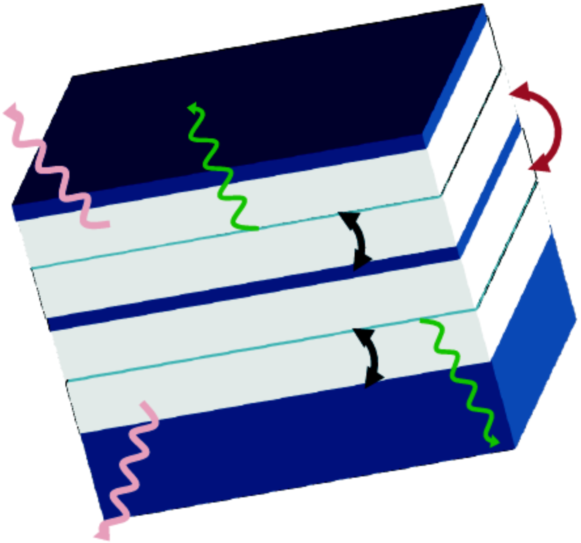
Off-resonance angle

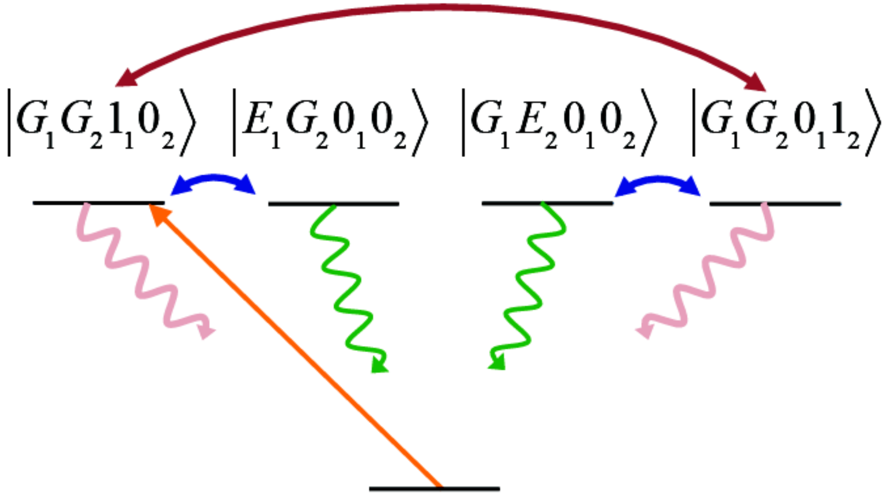
Mimicking the strong coupling regime



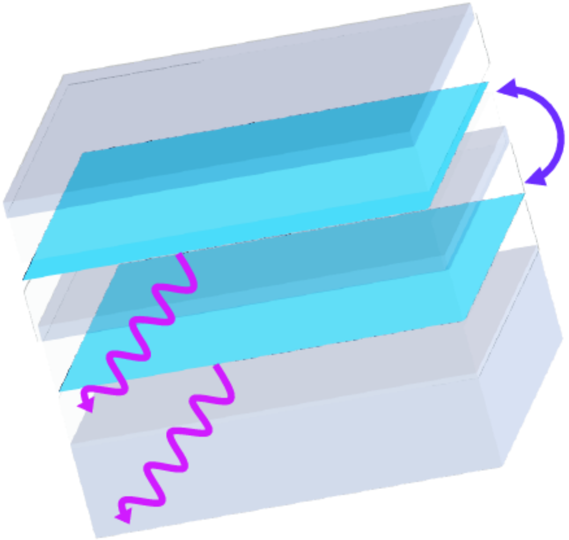


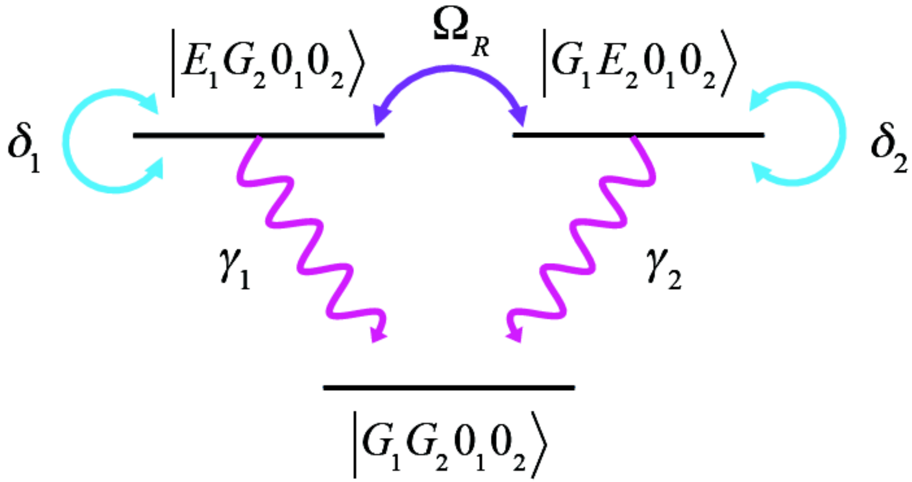
Mimicking the strong coupling regime





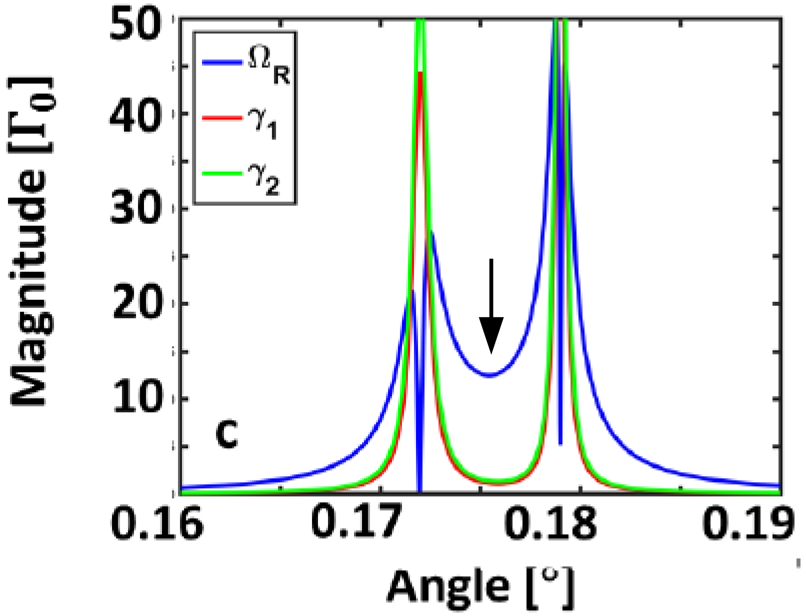
Adiabatical elimination of the cavity modes





Mimicking the strong coupling regime

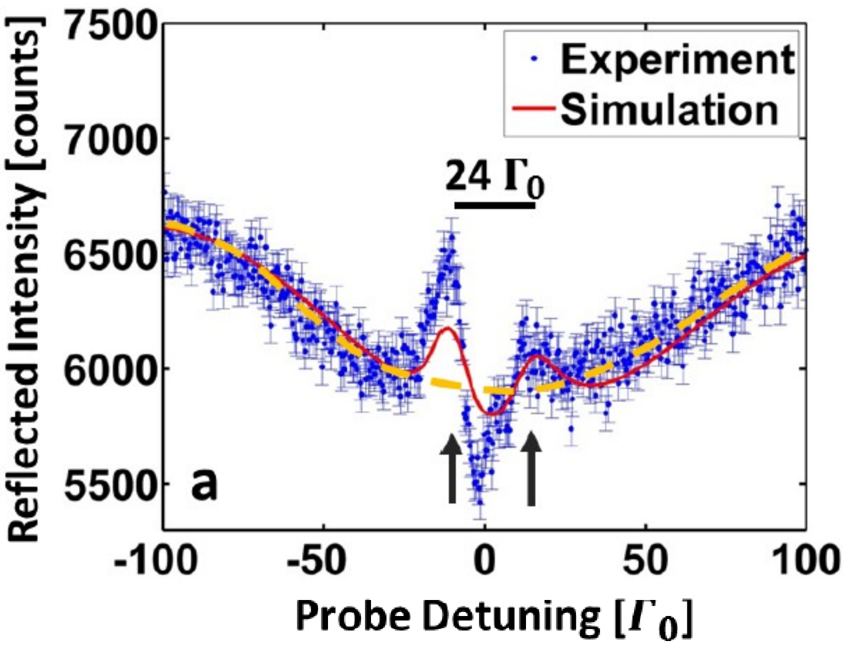
Coupling between the two layers
is stronger than decay rates at
a particular angle!

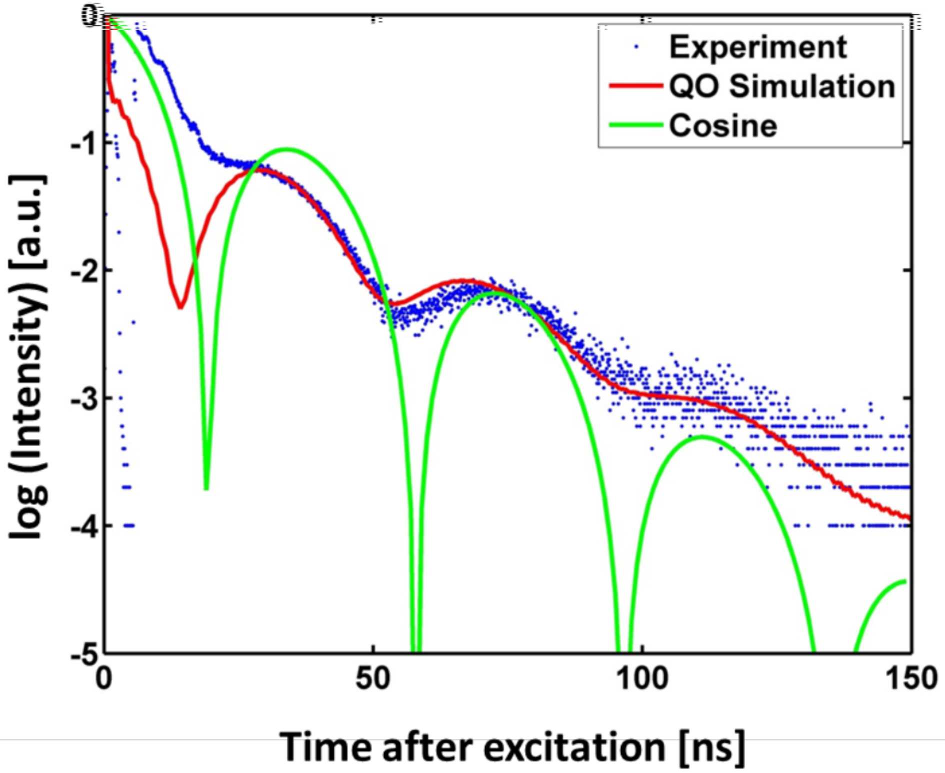


Strong coupling: the interaction between field and system is larger than the system decay rates.

→ Rabi oscillations of the system, photon is absorbed and re-emitted several times.

Experimental results



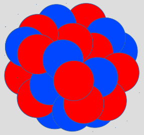


The resonance line is split and one can observe Rabi oscillations as known from the strong coupling regime!

Haber, Kong, ... Palffy, Röhlsberger, Nature Photon. 11, 720 (2017)

Summary

very successful quantum optics at a single-photon level

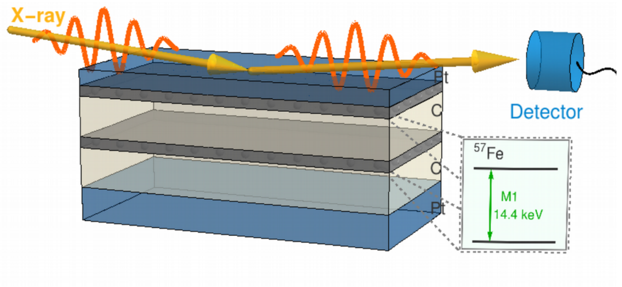


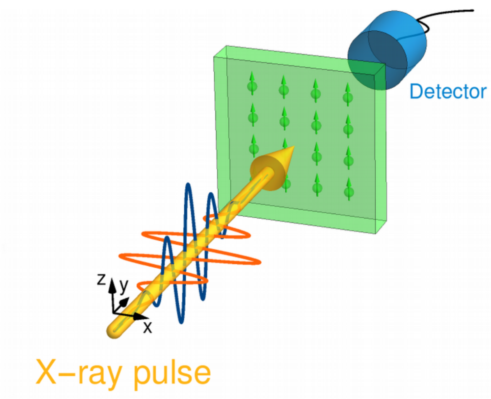
“clean” systems

unperturbed by environment

Q factor – ratio transition energy/width

- Pioneers of x-ray quantum optics
- Successful control at single-photon level
- Goal: design and establish new x-ray devices
  for quantum technologies, also beyond
  single x-ray photon regime
- Goal: develop such devices for sensing potentially
  for biological or medical samples





Quantum dynamics with x-rays

MONDAY

- Introduction
- X-ray sources
- The XFEL
- Diffraction, form factors

WEDNESDAY

- X-ray quiz
- 2-level system in semiclassical approximation
- Density matrix formalism
- X-ray atomic laser

FRIDAY

- Quantized field
- Wigner-Weisskopf theory of spontaneous emission
- Maxwell-Bloch equations
- Examples in nuclear forward scattering

TUESDAY

- Index of refraction
- Nonlinear Compton scattering
- Introduction to quantum optics

THURSDAY

- Reload 2-level system
- Coherence and interference effects
- EIT, STIRAP
- Nuclear quantum optics examples

THANK YOU FOR YOUR ATTENTION!