Quantum optics and nuclear physics

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LEAPS meets Quantum Technology
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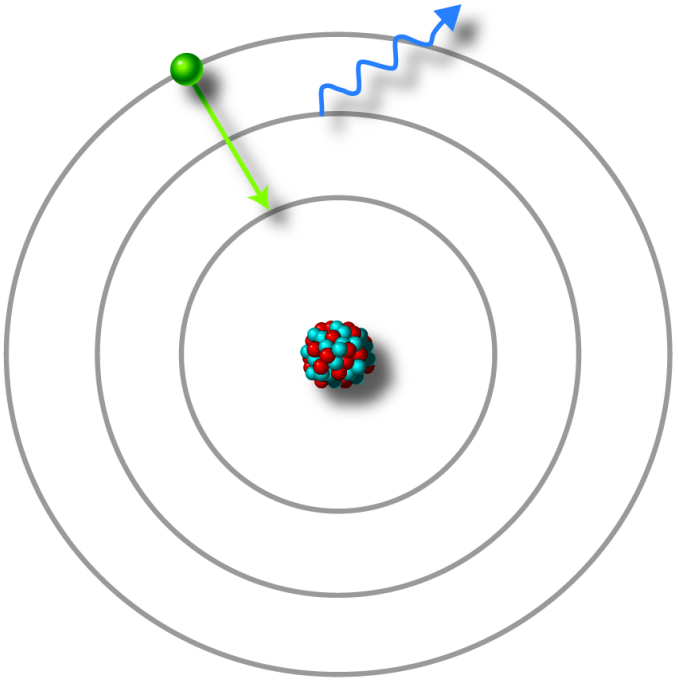
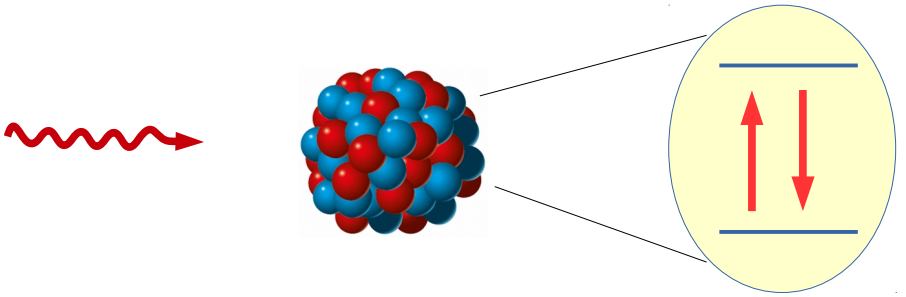
Julius-Maximilians-
UNIVERSITÄT
WÜRZBURG

Quantum dynamics with atoms and nuclei

Optical, IR



What about nuclear quantum dynamics?



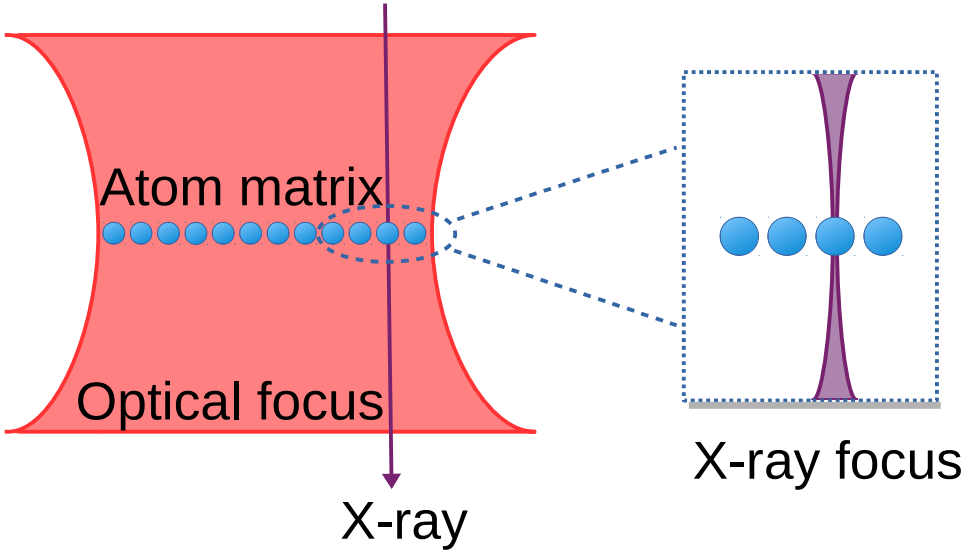
Higher frequencies:
X-ray, VUV

Mutual control of LASER LIGHT and ATOMS

Revolutionized atomic physics, technology and metrology!

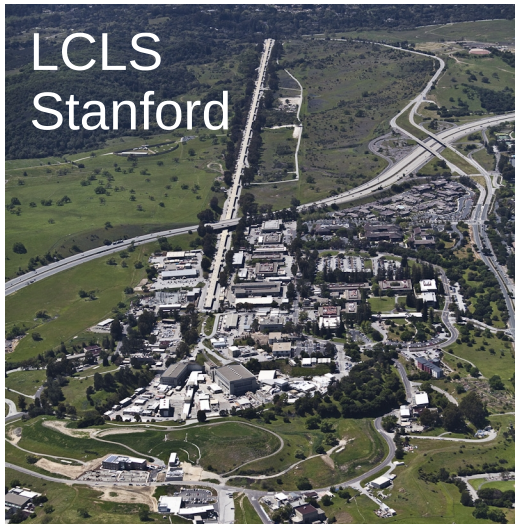
Incentives for x-ray quantum control

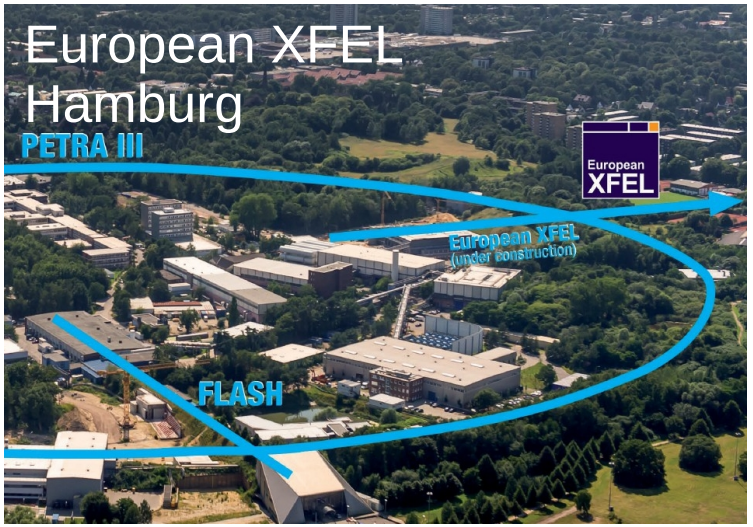
- Robustness, efficient detection
- Deeper penetration
- Focusing - diffraction limit



→ *Ultimate miniaturization of photonic circuits*

→ *Sensing with unprecedented spatial resolution*





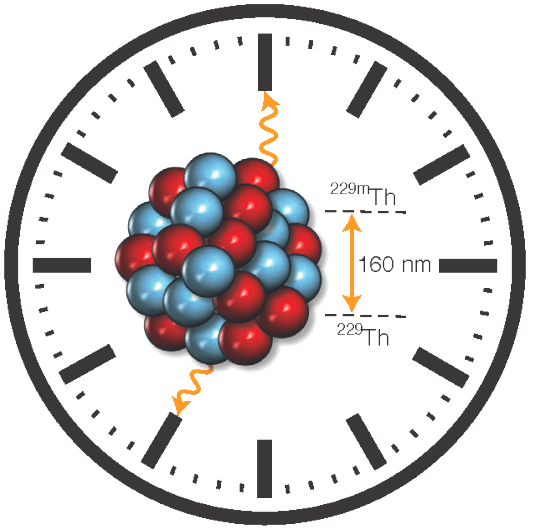
Special nuclear incentives

FREQUENCY STANDARDS

THE SECOND

1967, hyperfine transition of
6s electron in the ^{133}Cs atom. $\sim 10^{-16}$ frequency uncertainty

Use a nuclear transition instead? A “nuclear clock”?



NARROW TRANSITION WIDTHS

$$^{229}\mathrm{Th} \qquad \Delta E/E \simeq 10^{-20}$$

ISOLATION FROM ENVIRONMENT

- Better frequency standard
- Variation of fundamental constants
- Oscillator involving the strong force

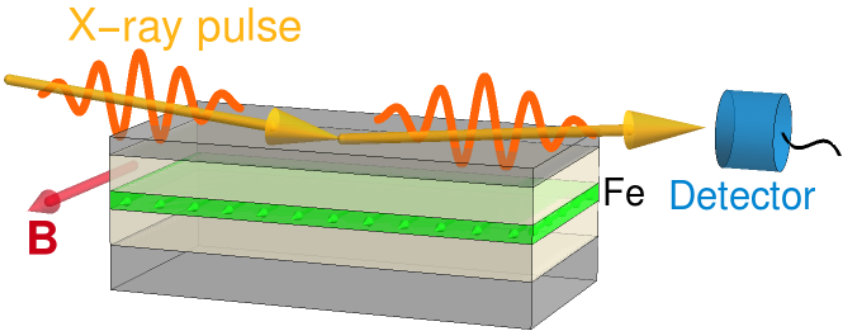
thorium nuclear clock

European Commission

Outline

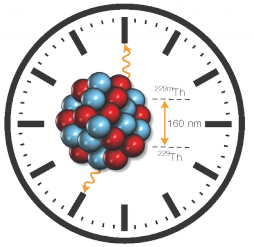
I. X-ray coherent control

Thin-film cavities
Superradiance
X-ray ping-pong



II. Towards a nuclear frequency standard with ^{229}Th

Nuclear clock
Energy determination
Electronic bridge



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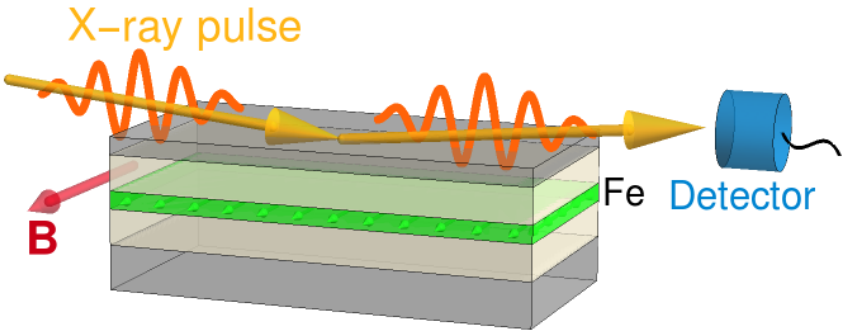

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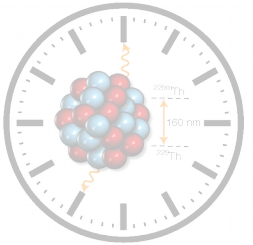
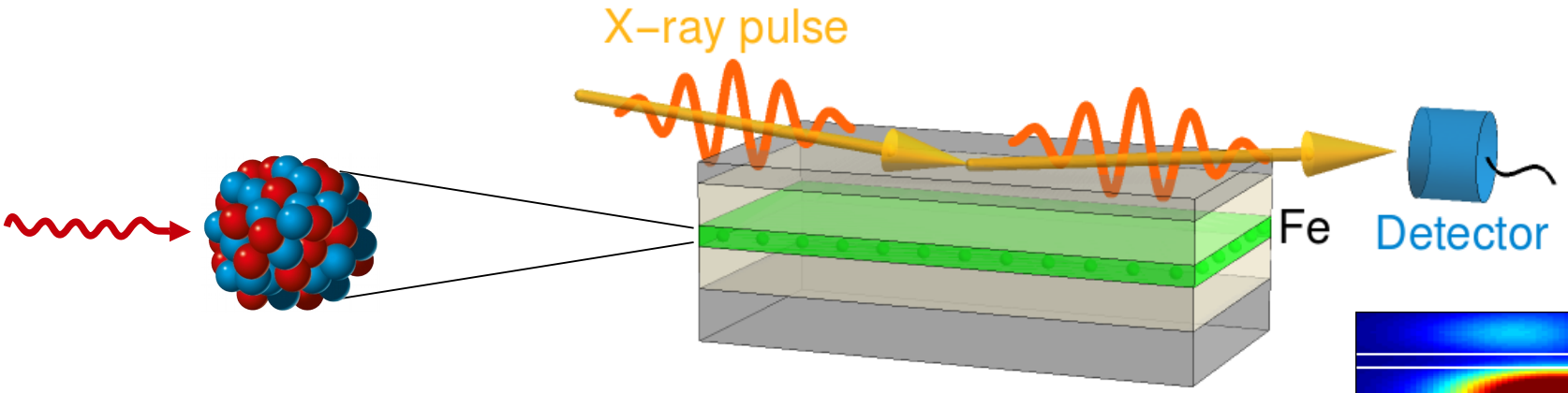
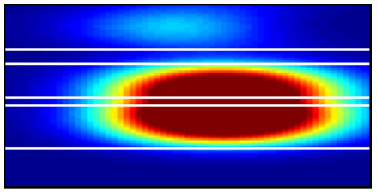
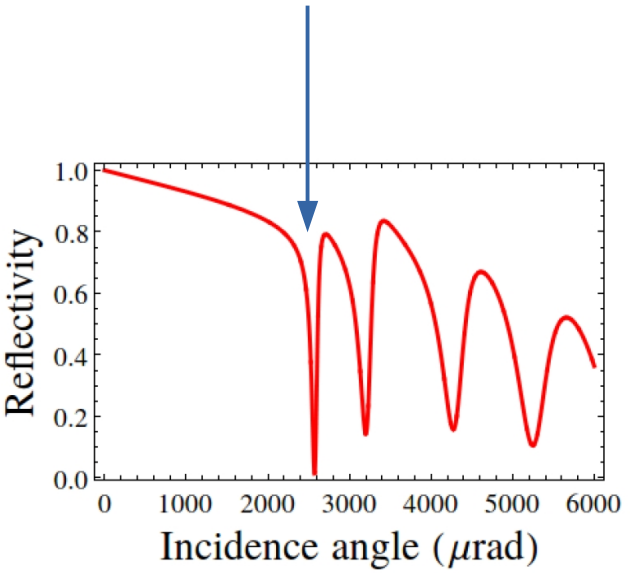


Thin-film x-ray cavities



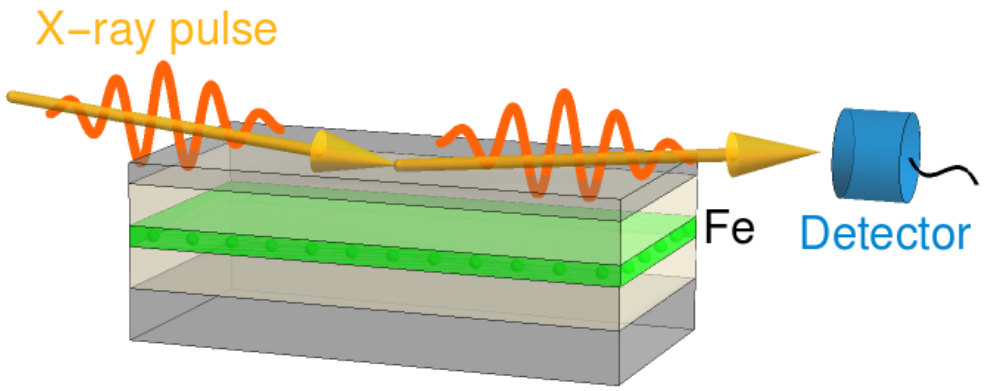
^{57}Fe, 14.4 keV Mössbauer transition





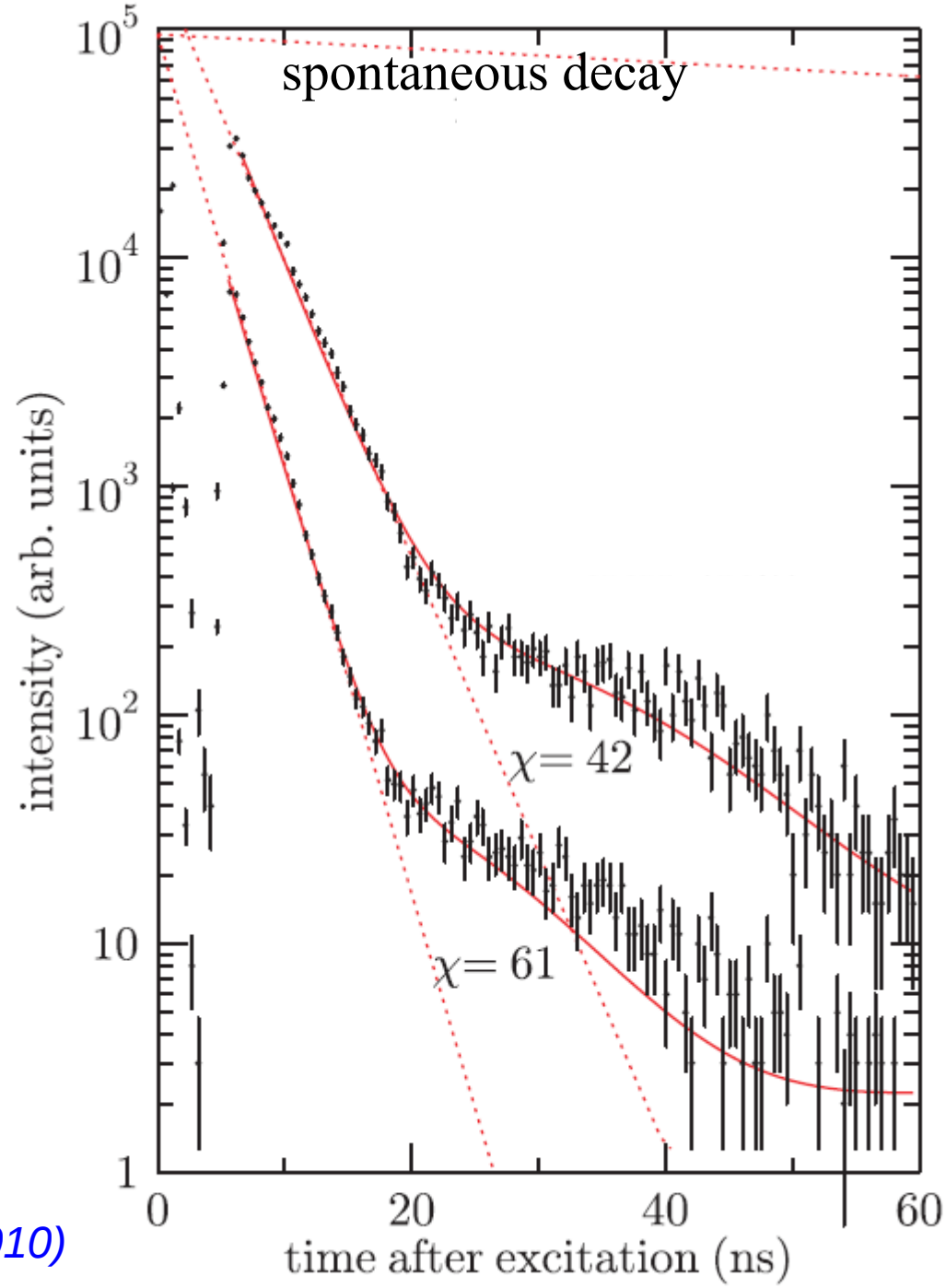
- Grazing incidence, detect reflectivity
- “resonant angle” from rocking curve
- Nuclear resonances interact with cavity field

Faster exponential decay



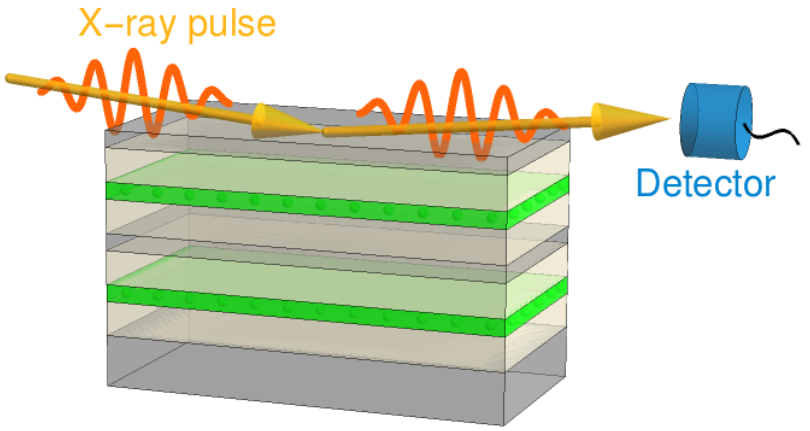
χ is the coherent decay enhancement factor

The collective effects are our "control knob" on the system!



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

X-ray ping-pong



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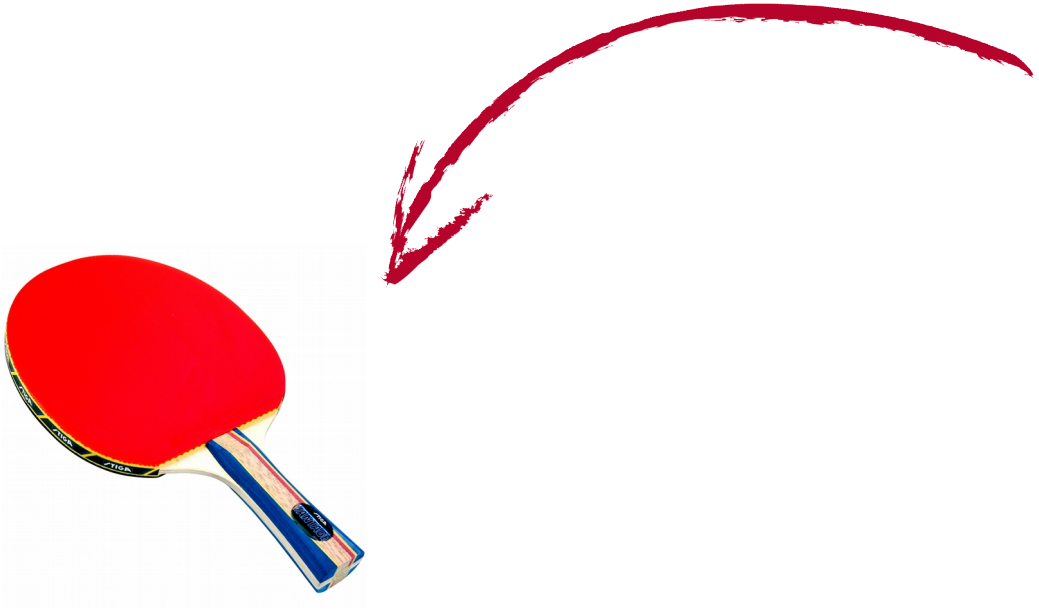

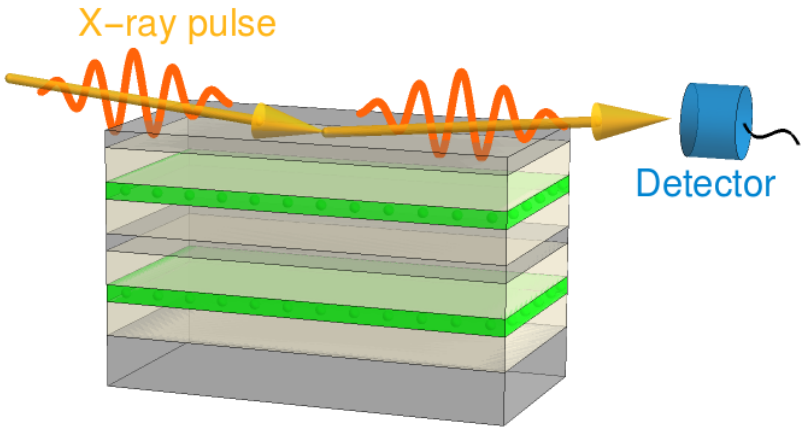

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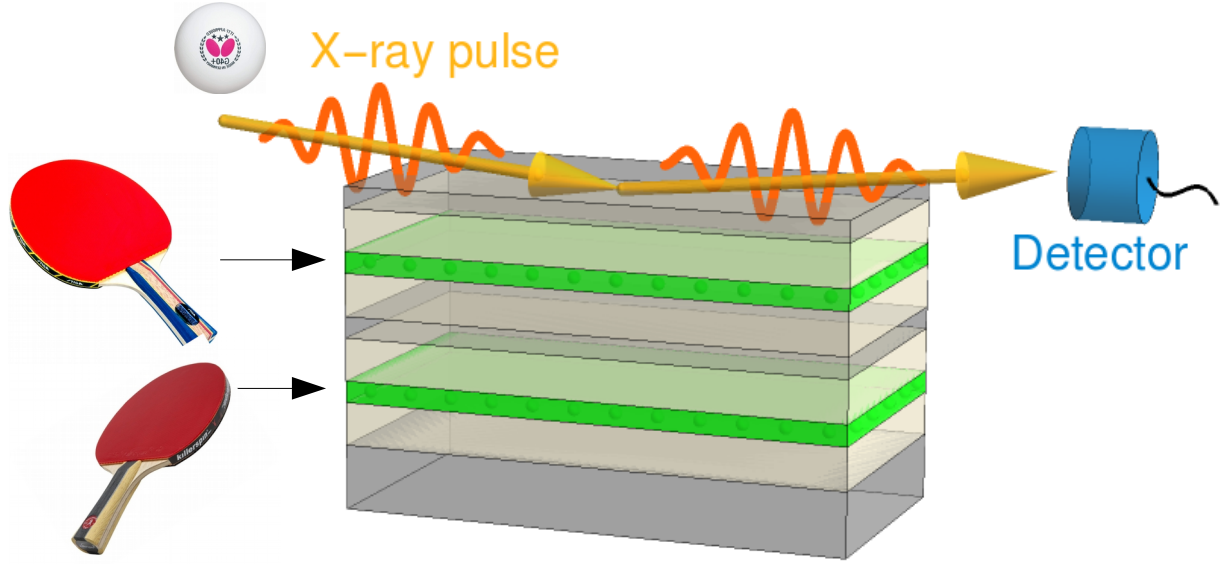
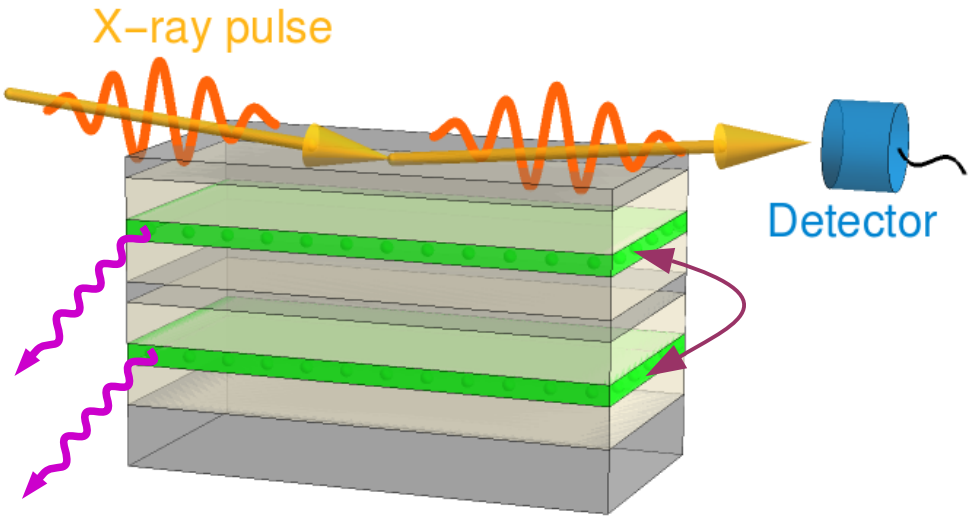


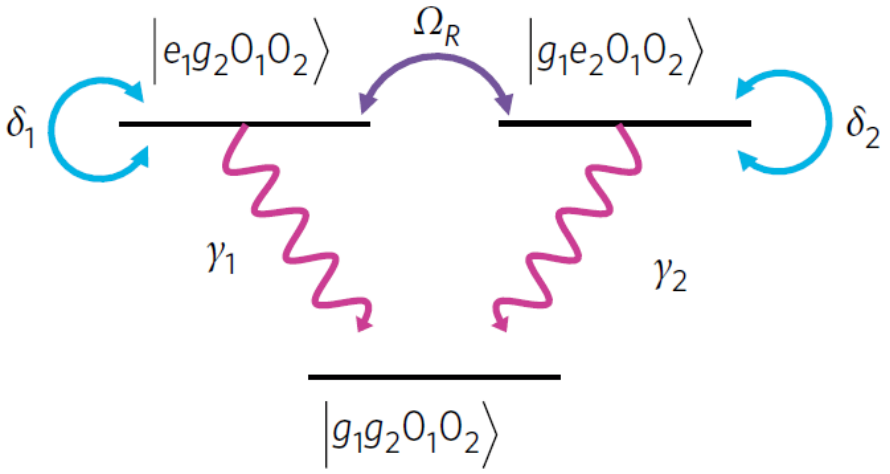
Detect oscillation

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.

Coupled cavities

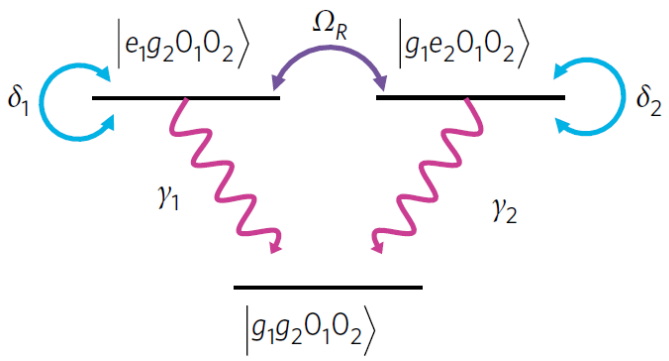




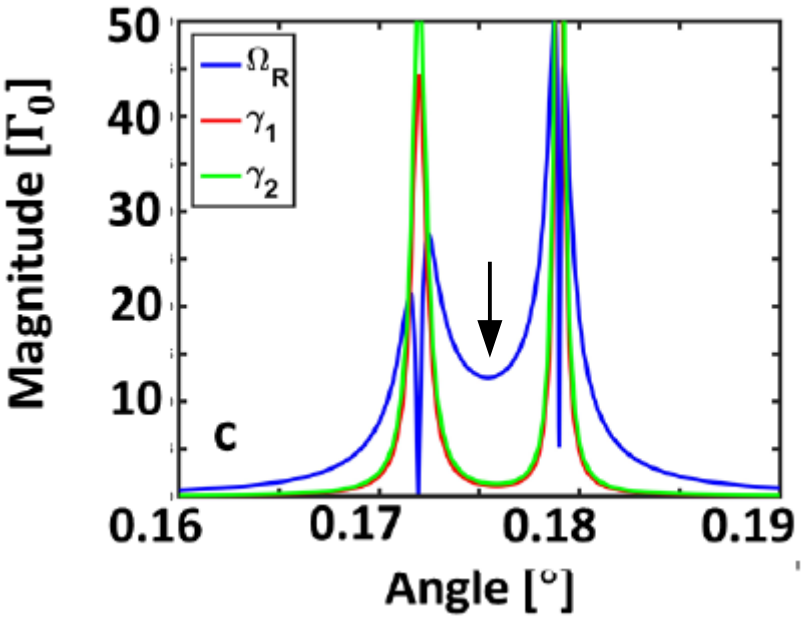
Rich 3-level system, where many processes can occur.

All parameters change with the x-ray incidence angle!

Mimicking the strong coupling regime



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



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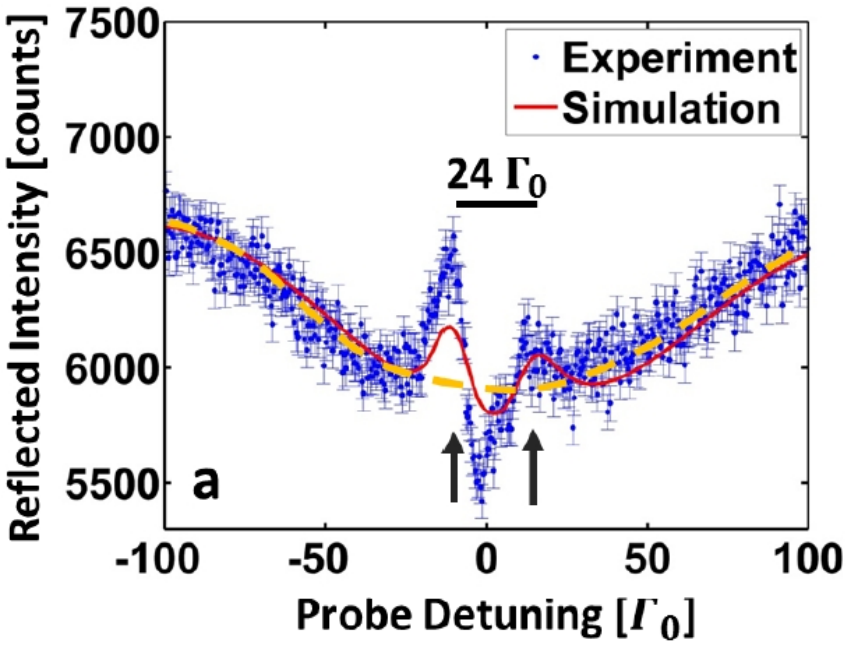
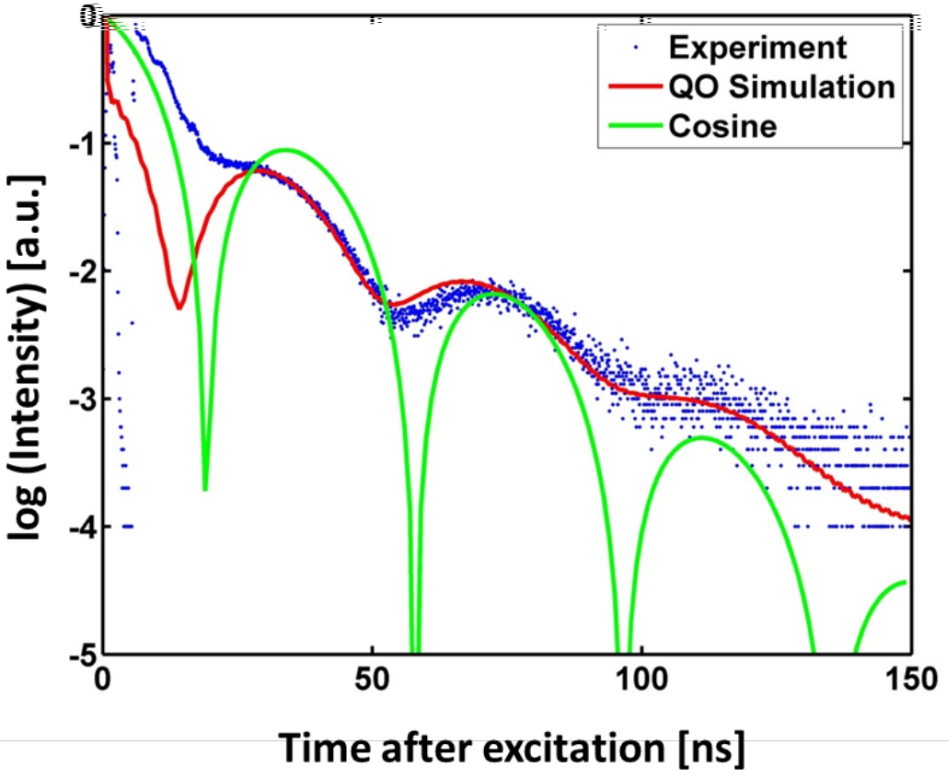
Experimental results





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

Haber, ... Pálffy, Röhlsberger*,*
Nature Photon. 11, 720 (2017)

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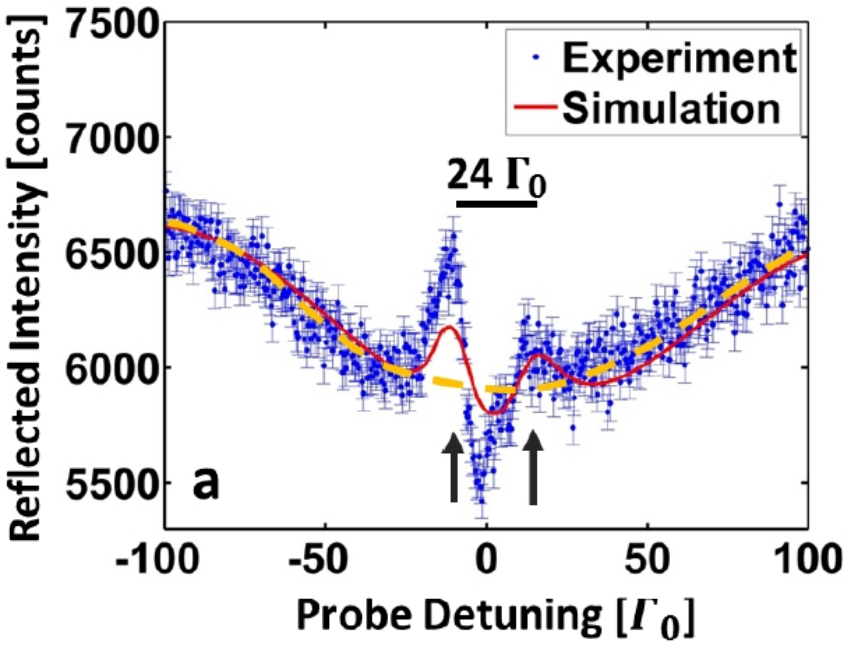

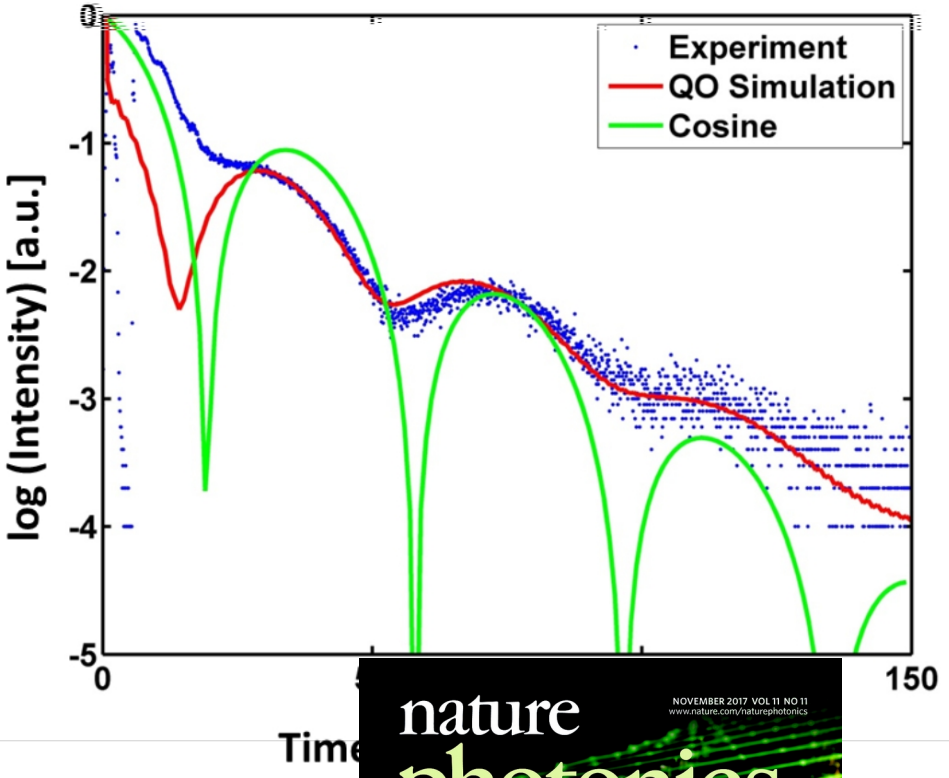

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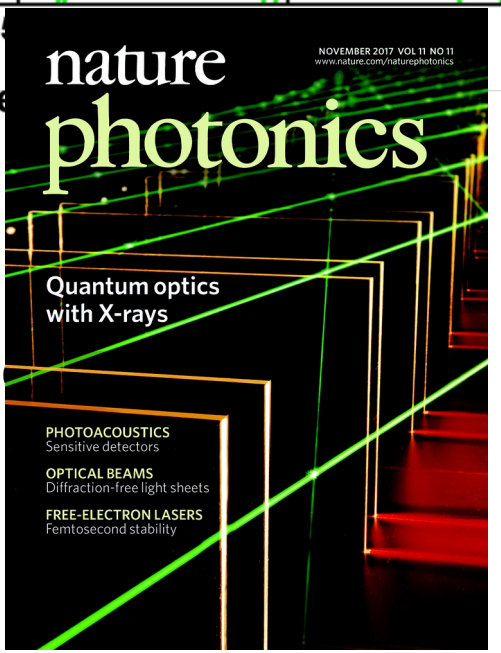

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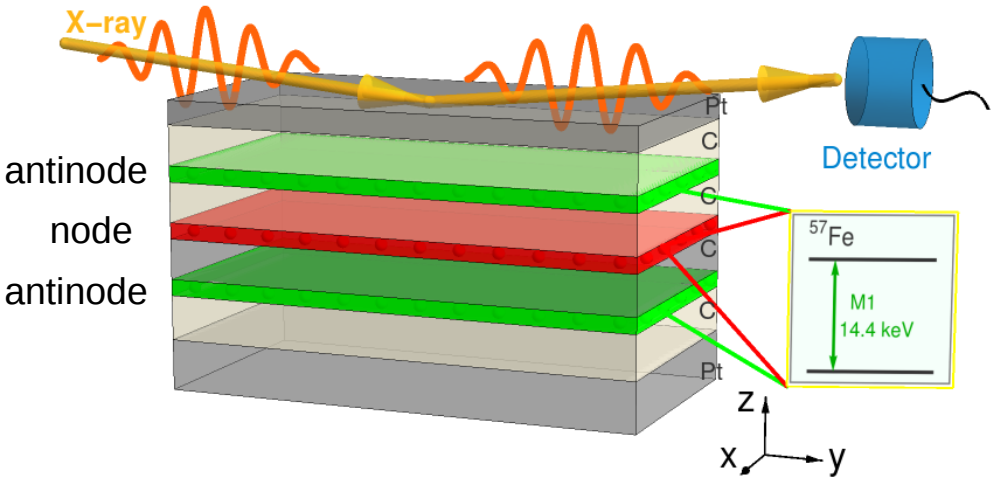
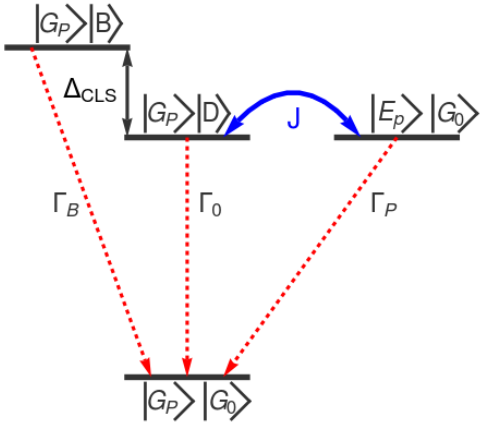
Dark states in many-layer structures

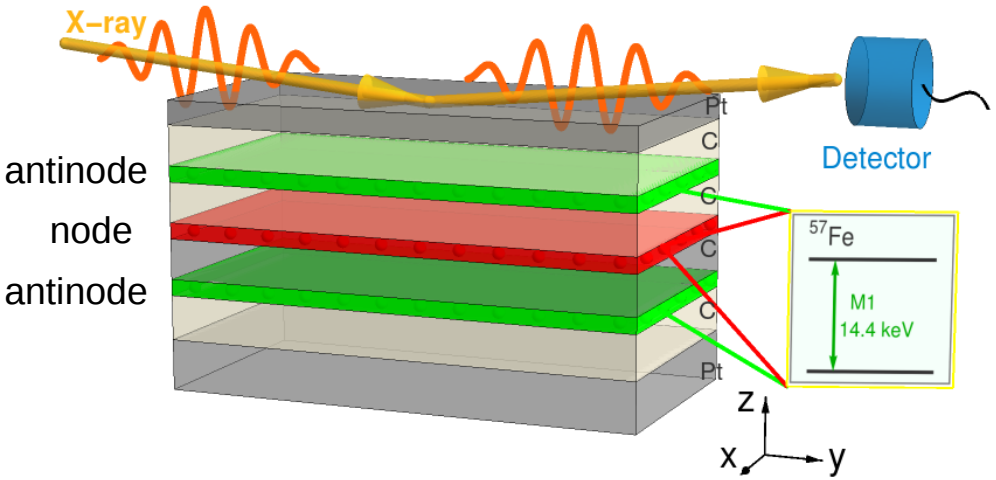




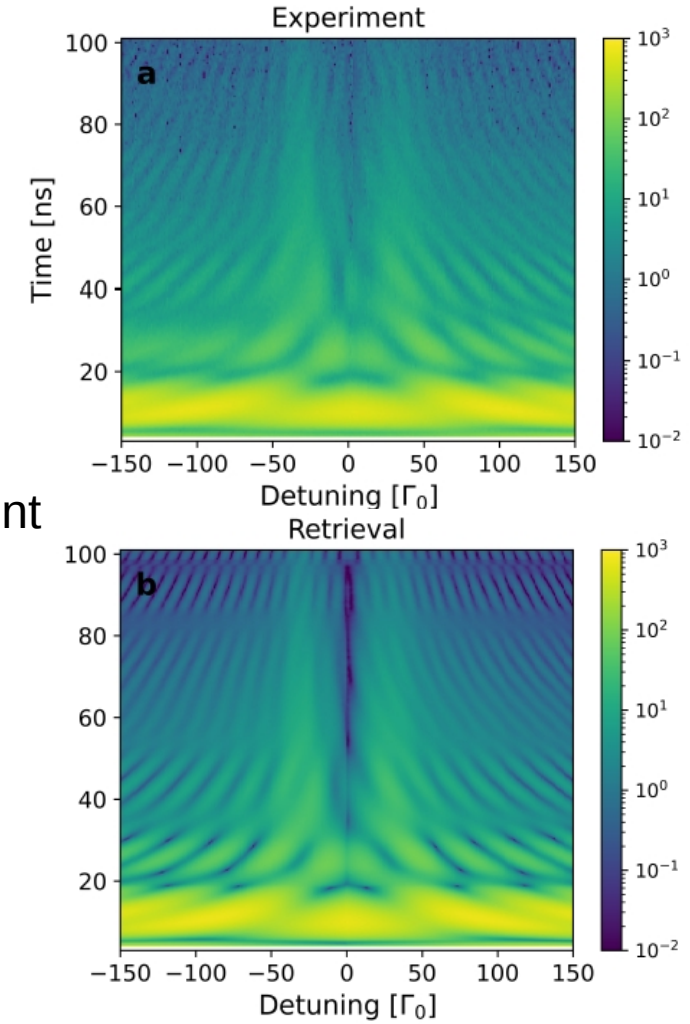
- Effective Jaynes-Cummings cavity QED Hamiltonian
- Strong-coupling regime via the dark-state field
- Effective photon-photon interaction, generation of non-classical states of light

"Atom-like mirrors", Mirhosseini, …, Chang, Painter, Nature 569, 692 (2019)

Dark states in many-layer structures



Spring-8
Experiment



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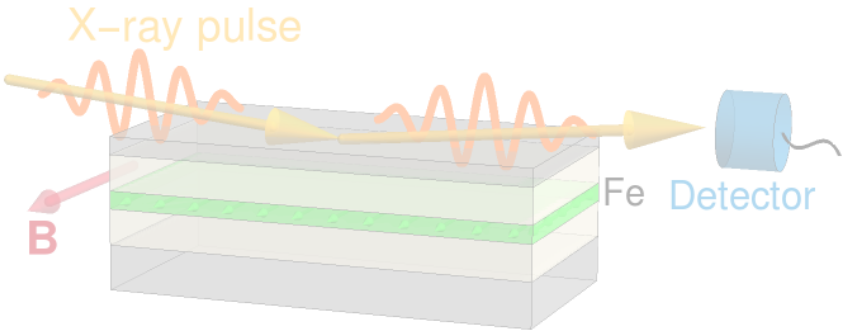
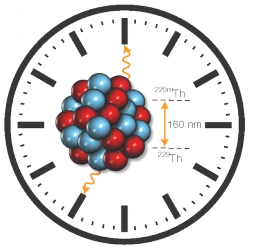
- Thin-film cavities
- X-ray ping-pong
- Versatile model



II. Towards a nuclear frequency standard with ^{229}Th

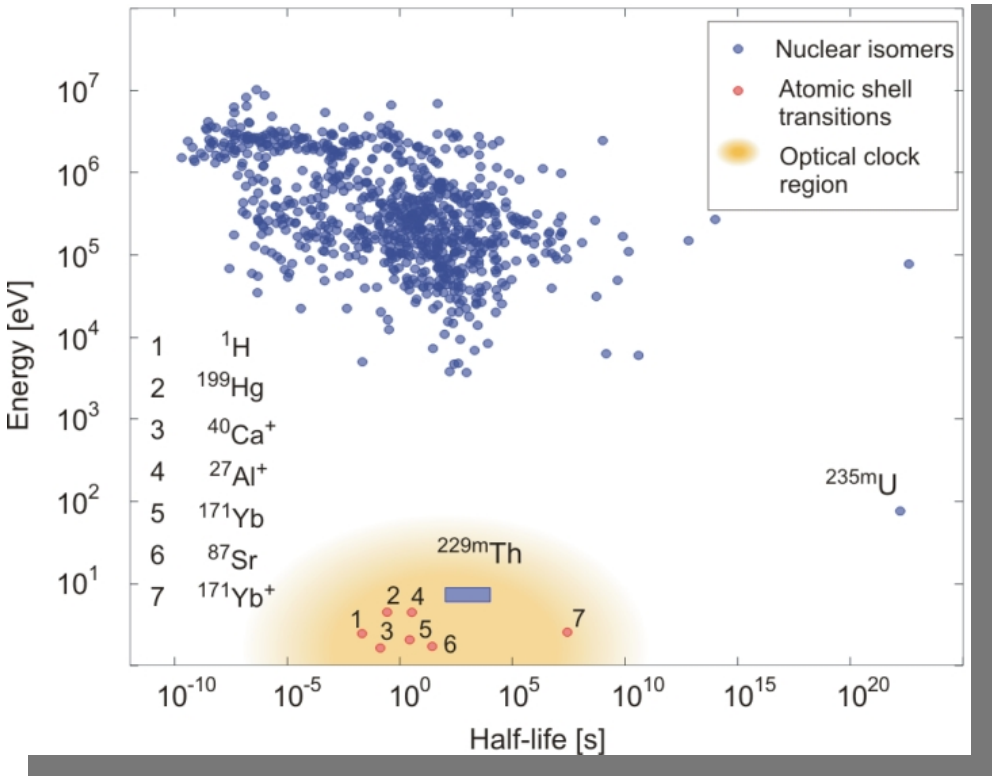
- Nuclear clock
- Energy determination
- Electronic bridge



^{229}Th 8 eV isomer

lowest excitation energy of all ca. 176,000 presently known excited nuclear states

E ~ 8.2 eV, λ ~ 150 nm, M1 (+E2) transition



- Promises a more precise clock
- Useful for independent secondary standard
- Search for dark matter
- Are fundamental constants constant in time?

To do:

Precise energy of nuclear transition

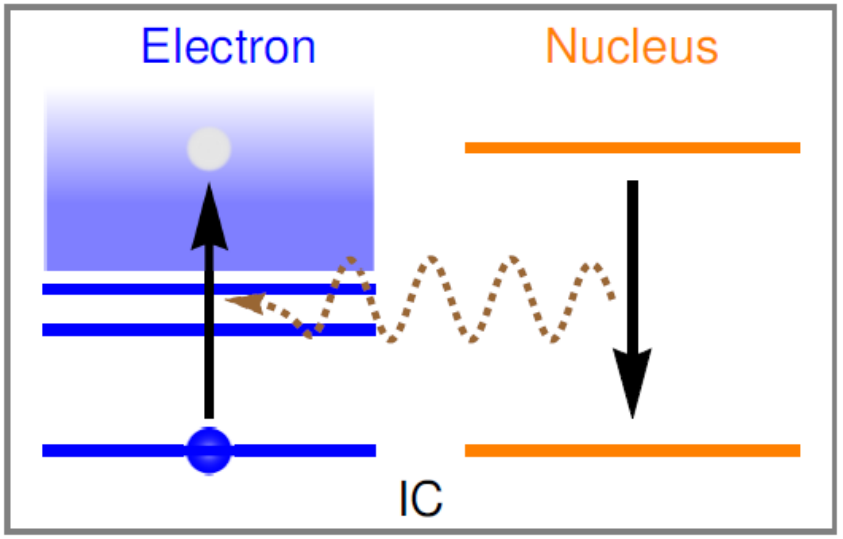
VUV narrow-band laser

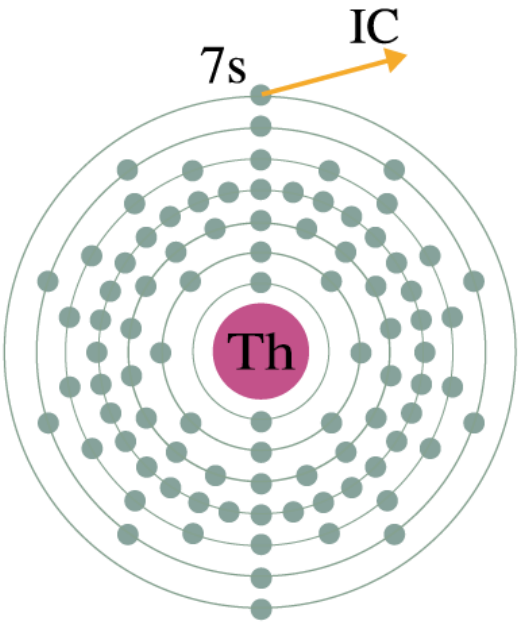
L. v .d. Wense et al., Nature 533, 47-53 (2016)

E. Peik et al., Quantum Sci. Technol. 6, 034002 (2021)

Coupling to atomic shells

For low-energy transition, **internal conversion** is the preferred decay channel!

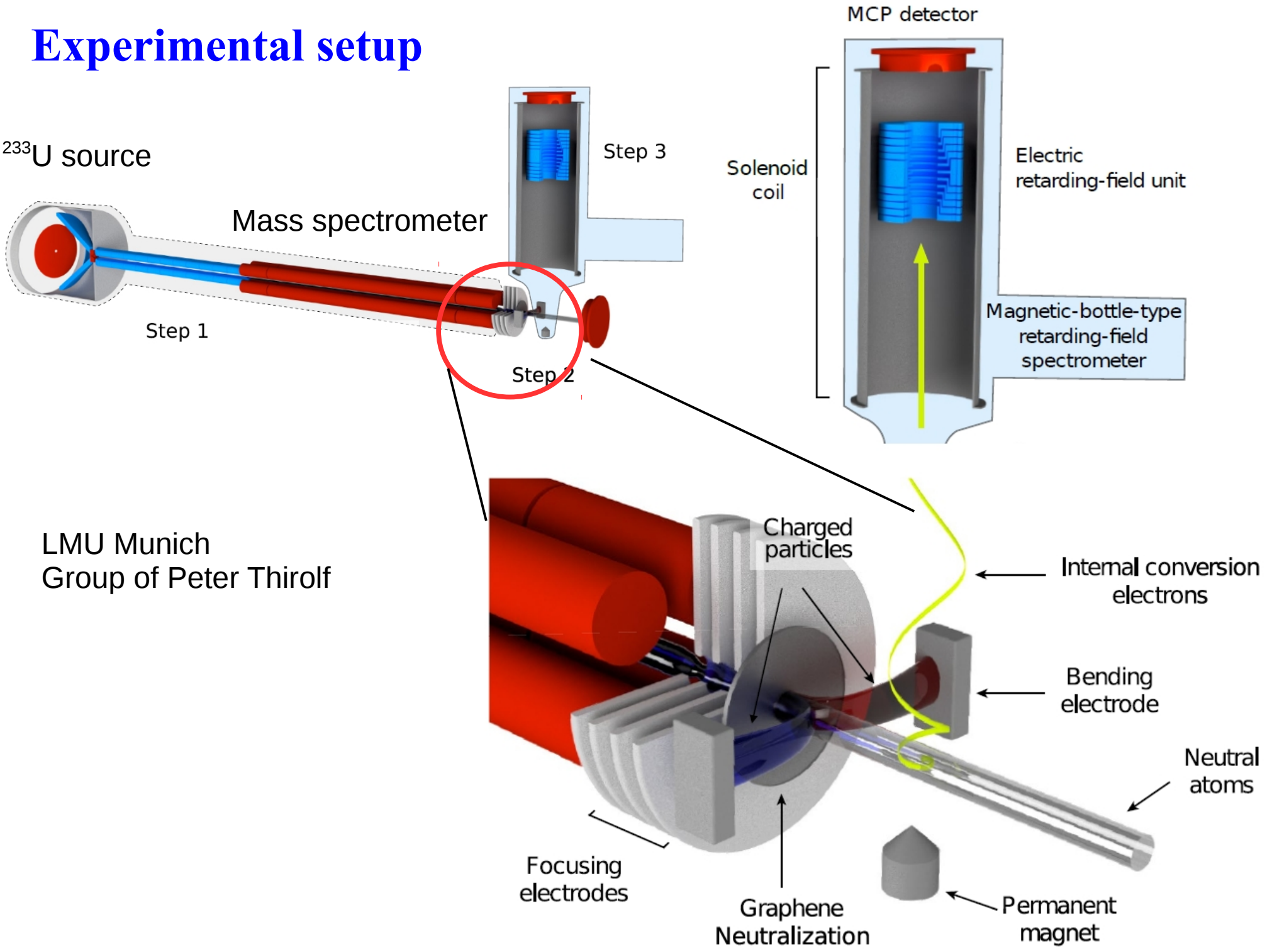




Radiative decay was never observed, but IC was – first direct evidence of isomer in 2016

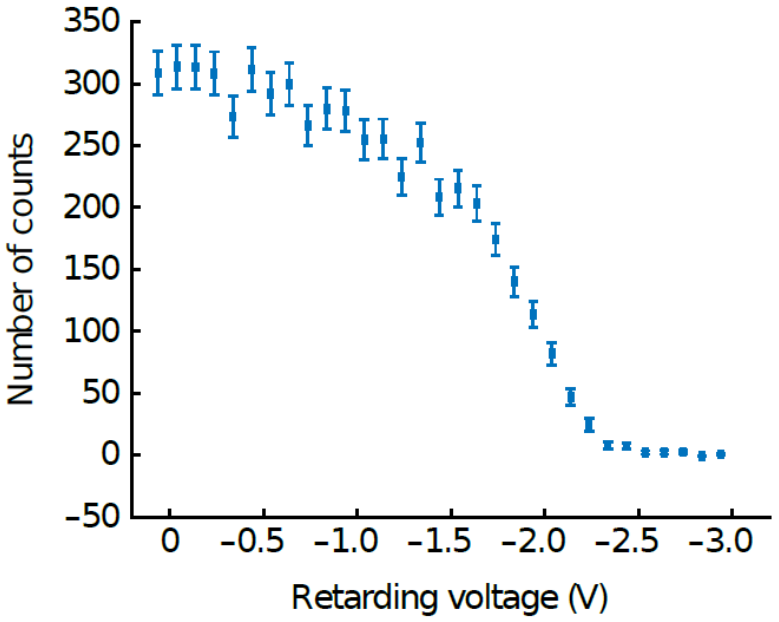
L. v .d. Wense et al., Nature 533, 47-53 (2016)

Experimental setup



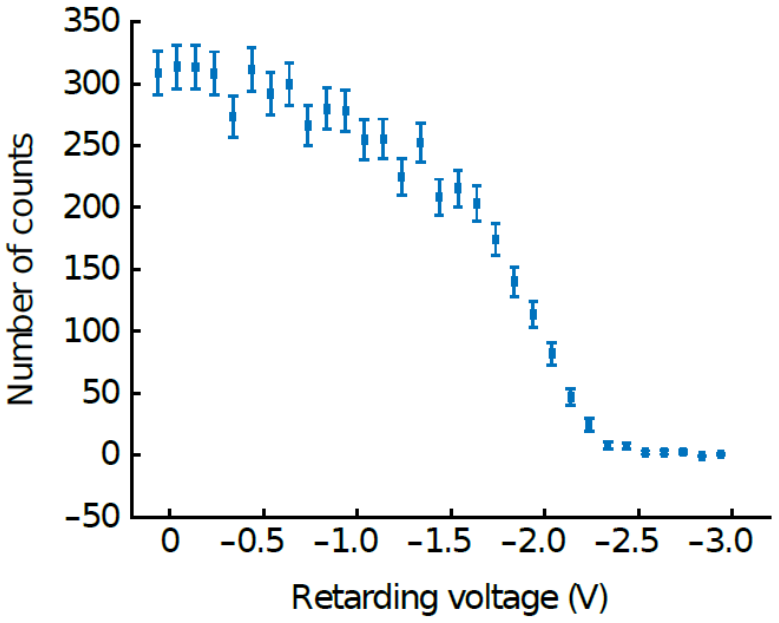
LMU Munich
Group of Peter Thirolf

Spectrum


350
300
250
200
150
100
50
0
−50
Number of counts
0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
Retarding voltage (V)

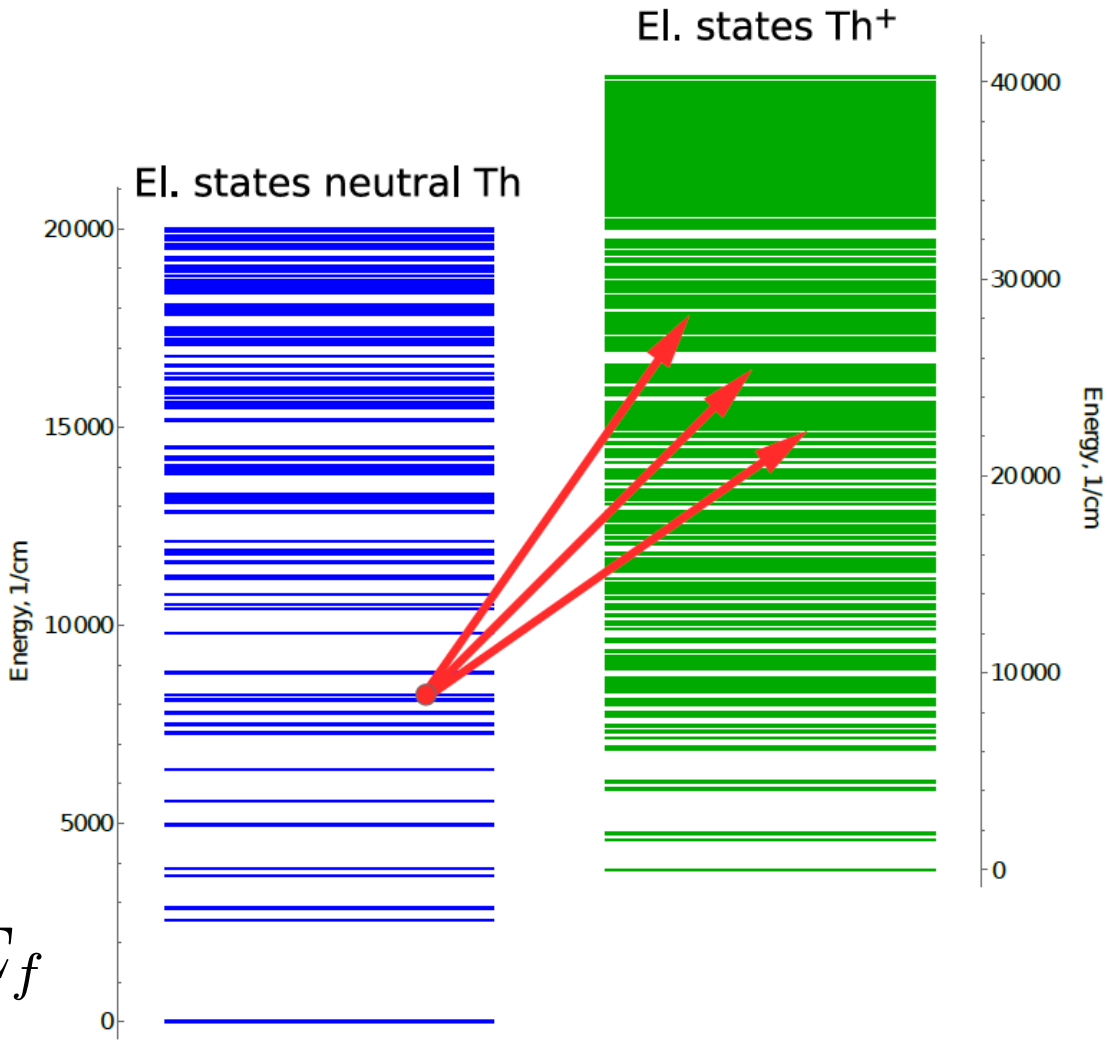
$E_m - ?$

Spectrum

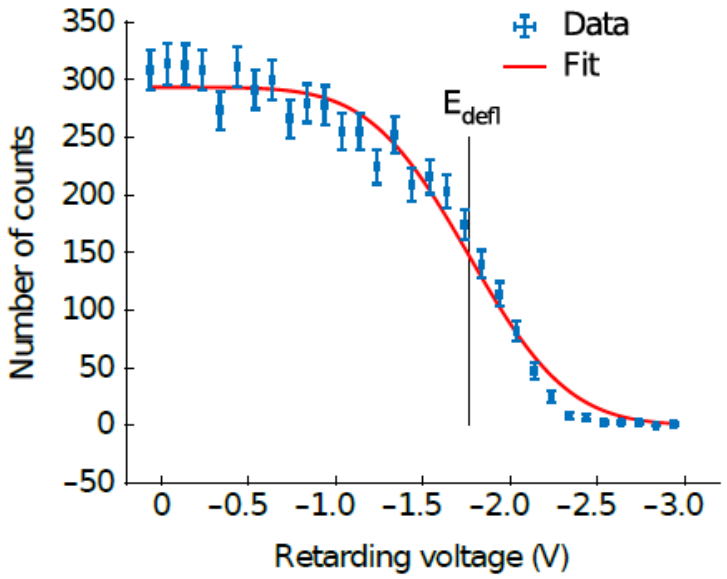


$E_m - ?$

$$E_{el} = E_m - IP + E_i - E_f$$



The isomer energy



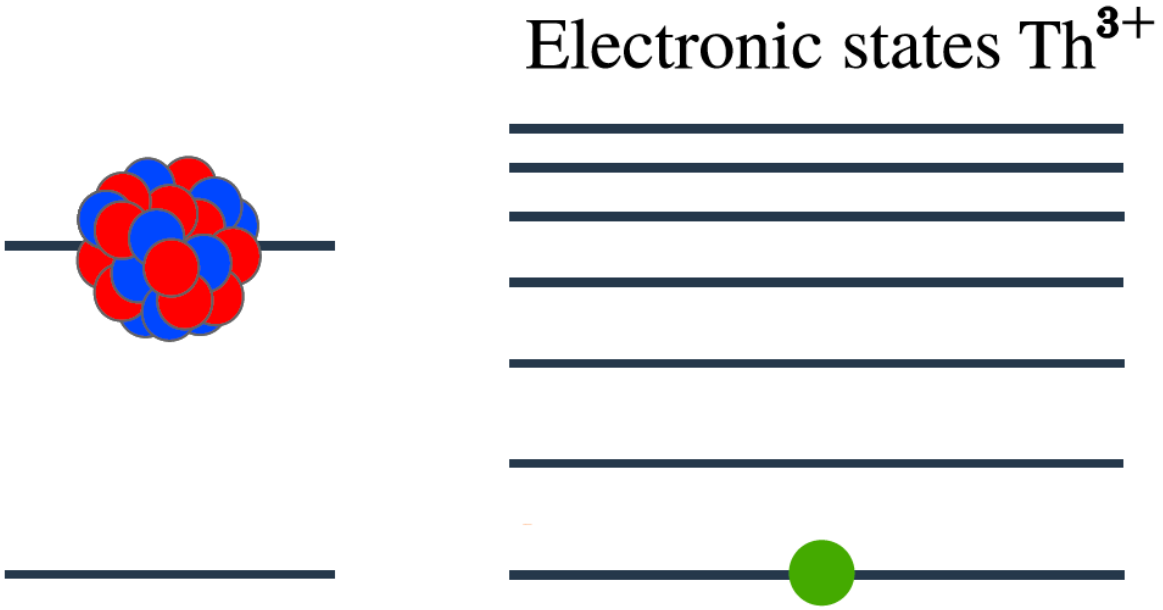
IC calculations to extract the energy value from the measured spectrum

$$E_m = 8.28 \pm 0.17\,\mathrm{eV}$$

B. Seiferle et al., Nature 573, 243 (2019)

Electronic bridge (EB)

Nuclear decay via IC not possible, energy is not sufficient to ionize a bound electron!



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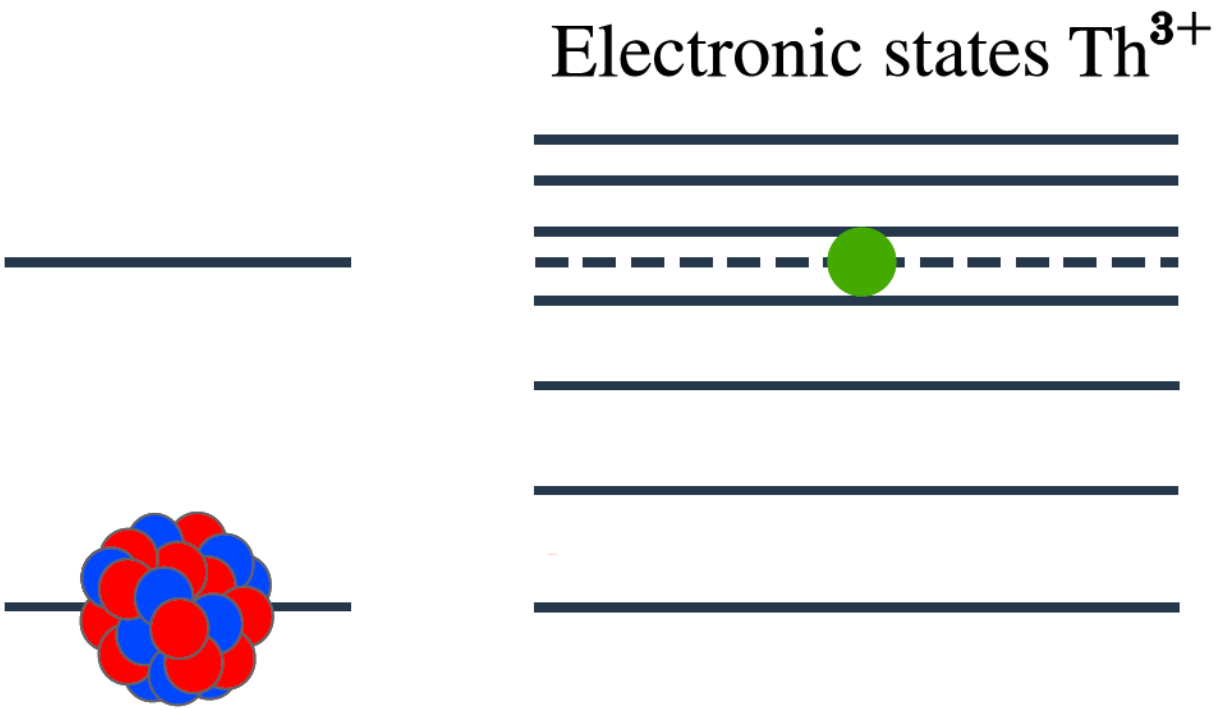
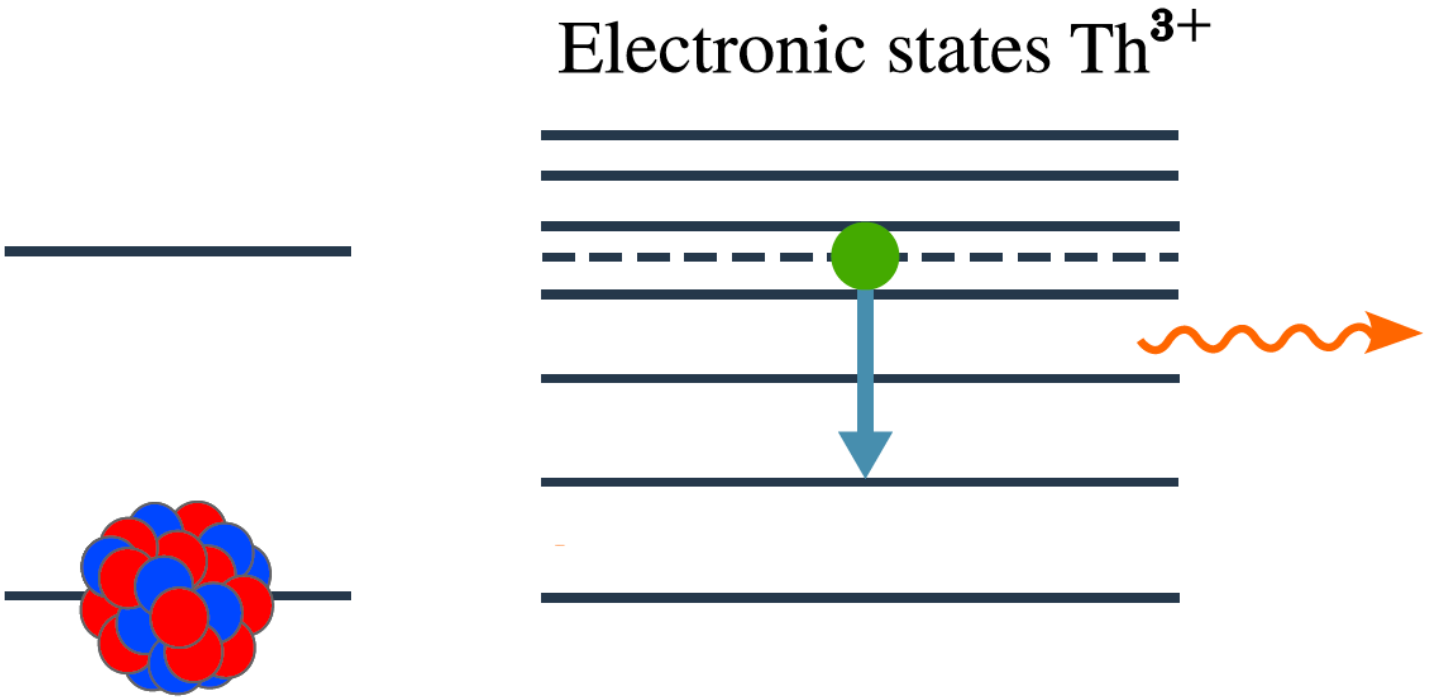


There is no electronic state at the right energy! Virtual state!

Electronic bridge (EB)

Nuclear decay via IC not possible, energy is not sufficient to ionize a bound electron!

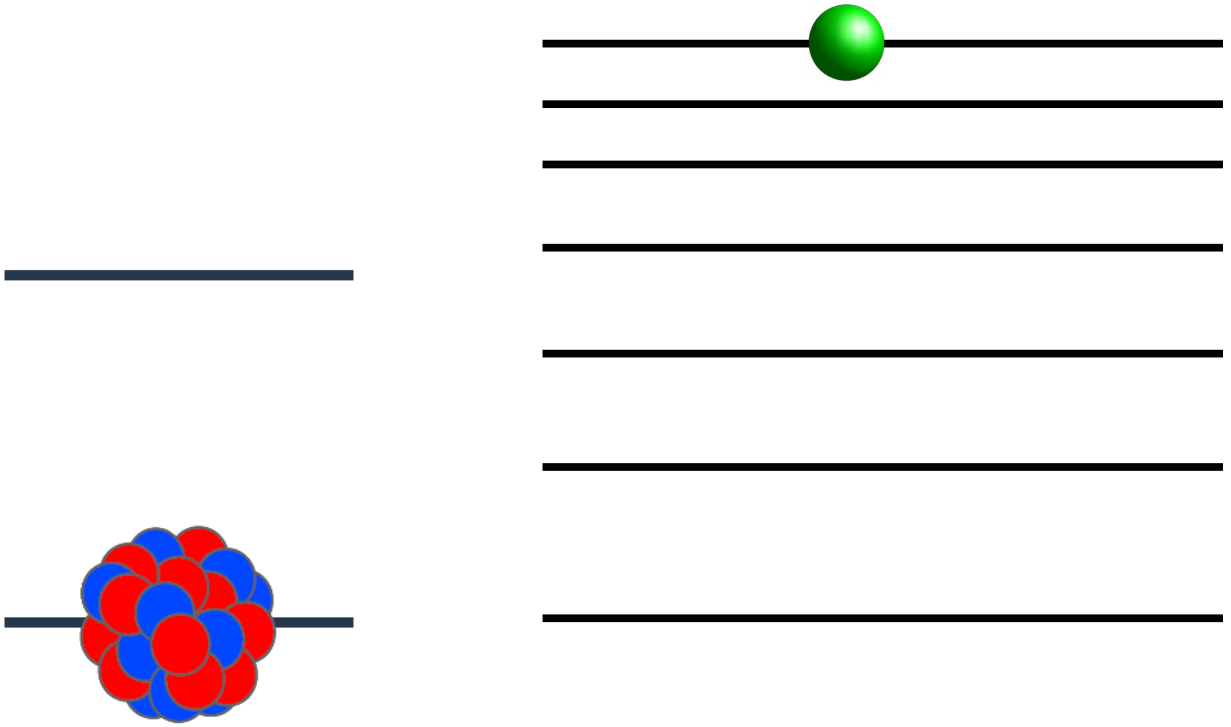


There is no electronic state at the right energy! Virtual state! Decays by emitting a photon!

S. G. Porsev et al, PRL 105, 182501 (2010)

Imagine EB with nuclear excitation

Excitation energy from the electronic shell does not match nuclear transition energy



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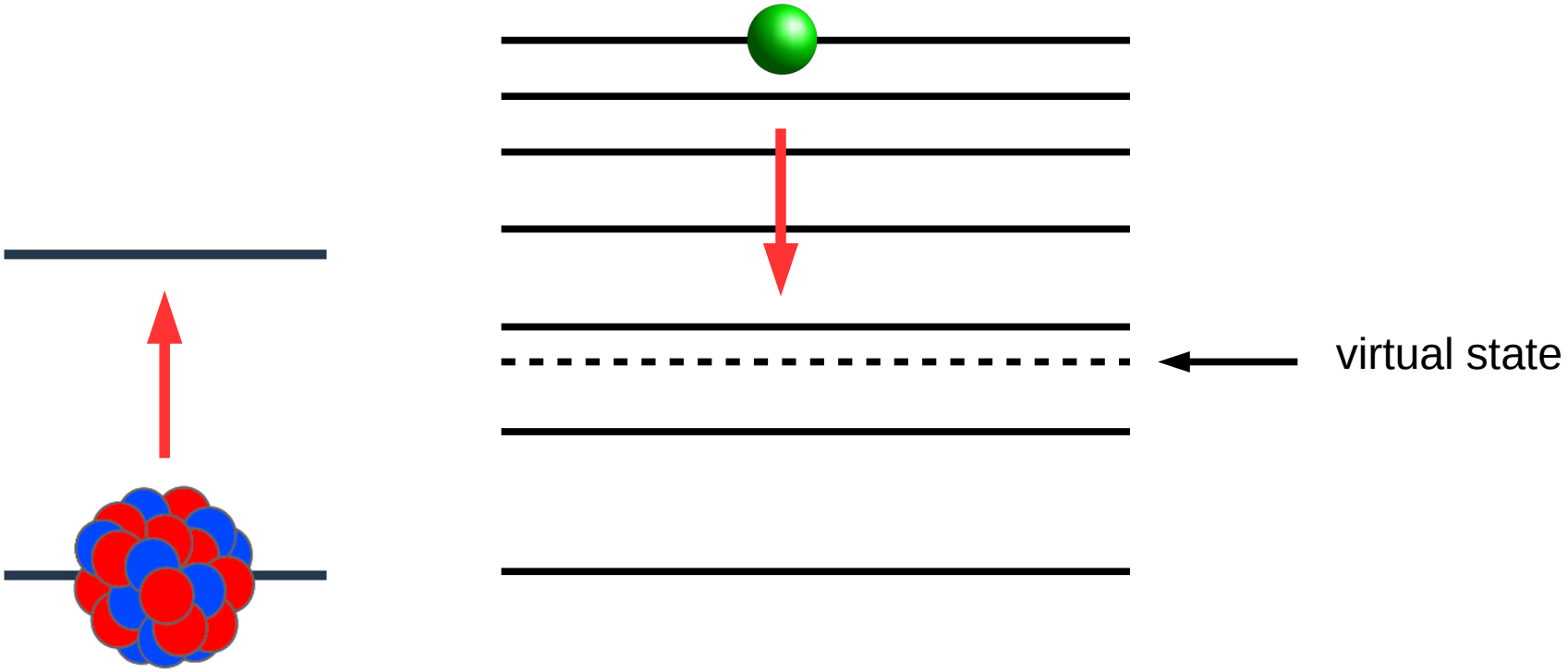

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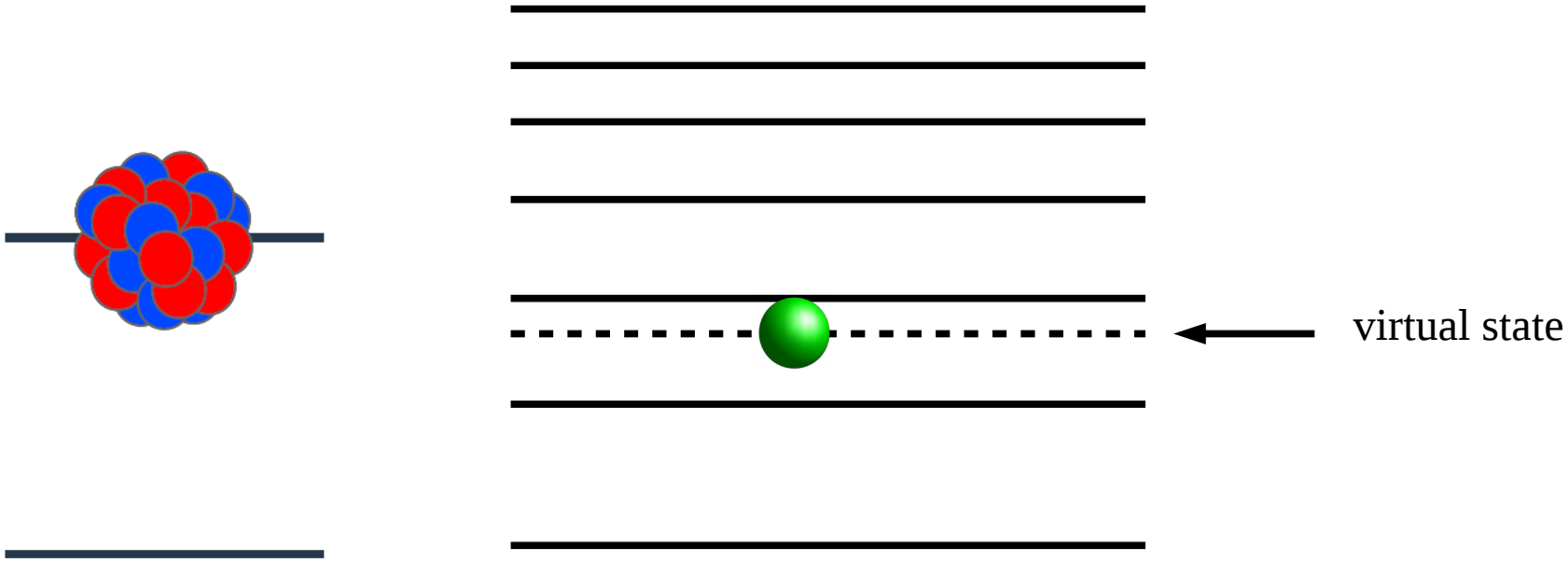
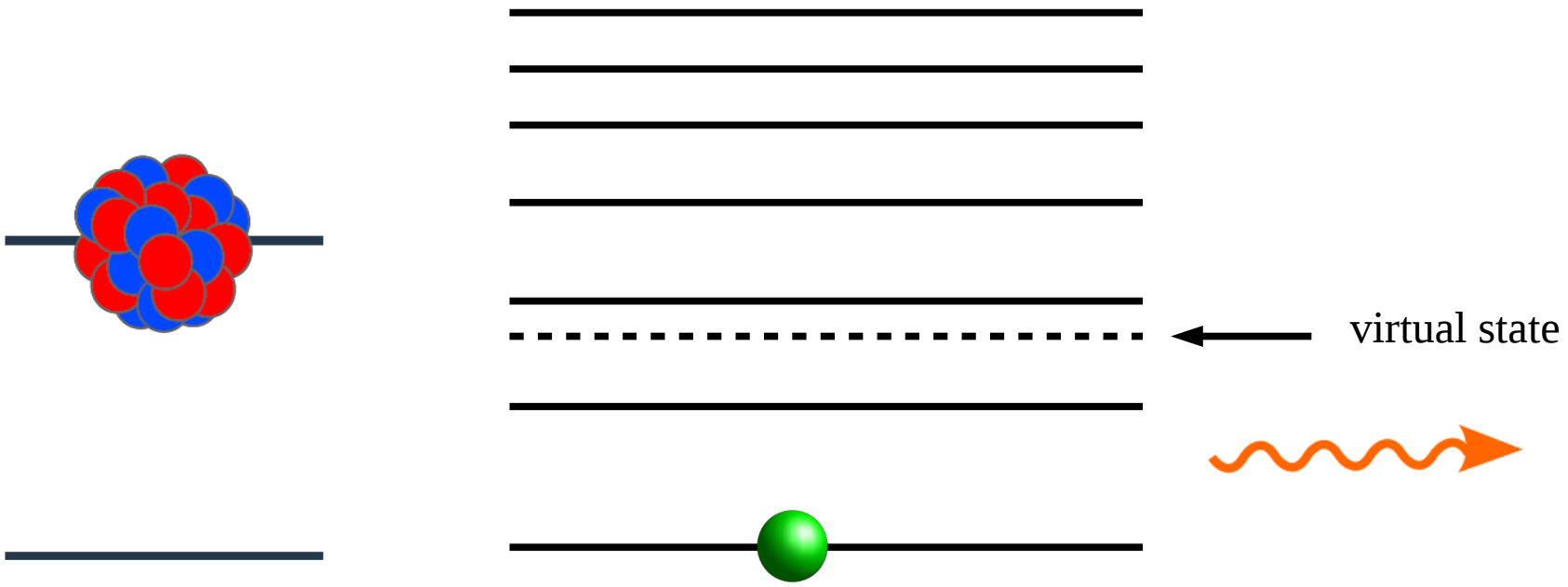


Imagine EB with nuclear excitation

Excitation energy from the electronic shell does not match nuclear transition energy

$$E_{el} = E_{nucl} + \hbar\omega$$

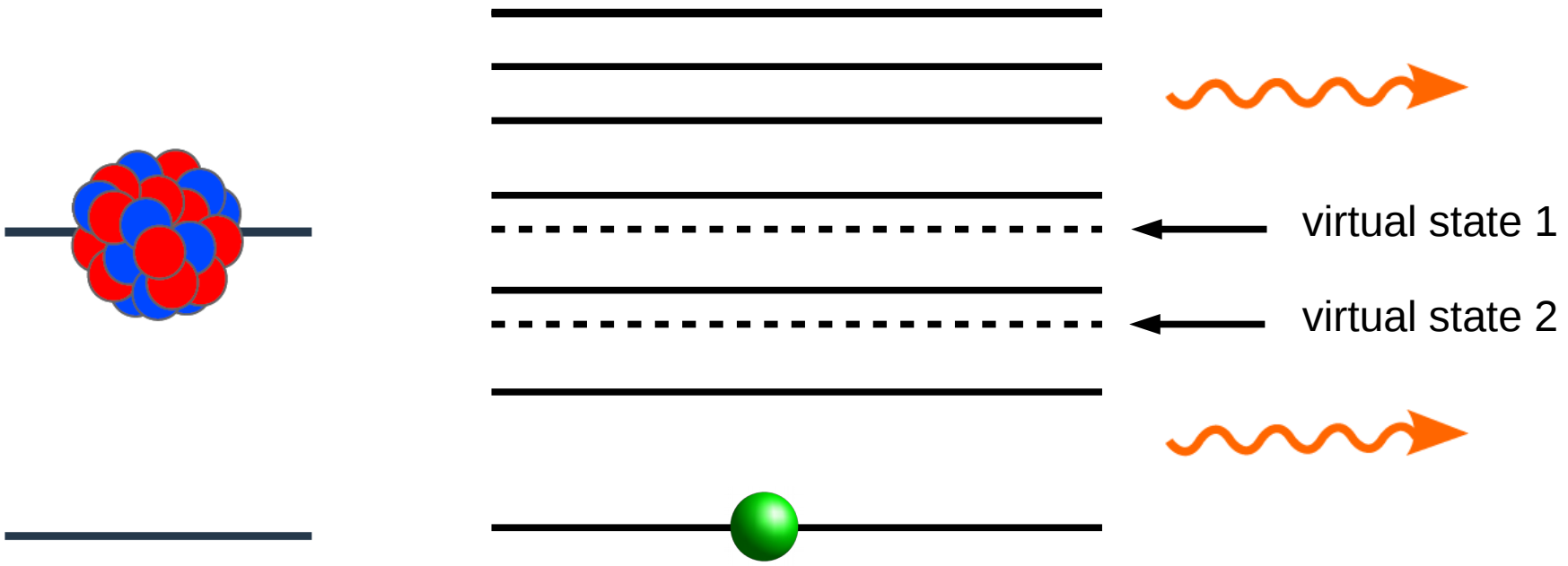


Imagine EB with nuclear excitation

Excitation energy from the electronic shell does not match nuclear transition energy

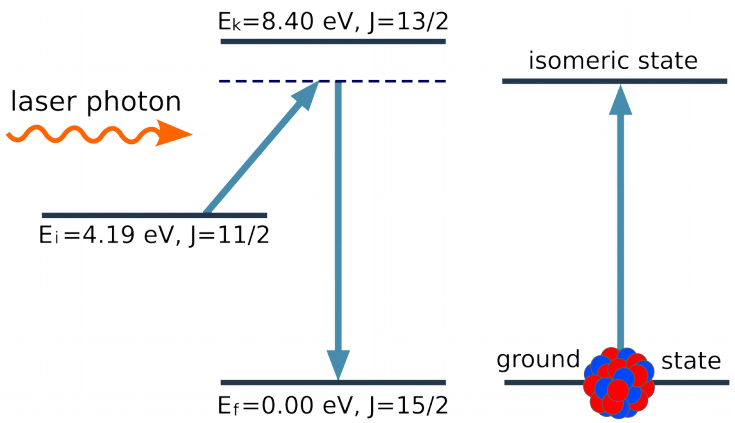
$$E_{el} = E_{nucl} + \hbar\omega$$

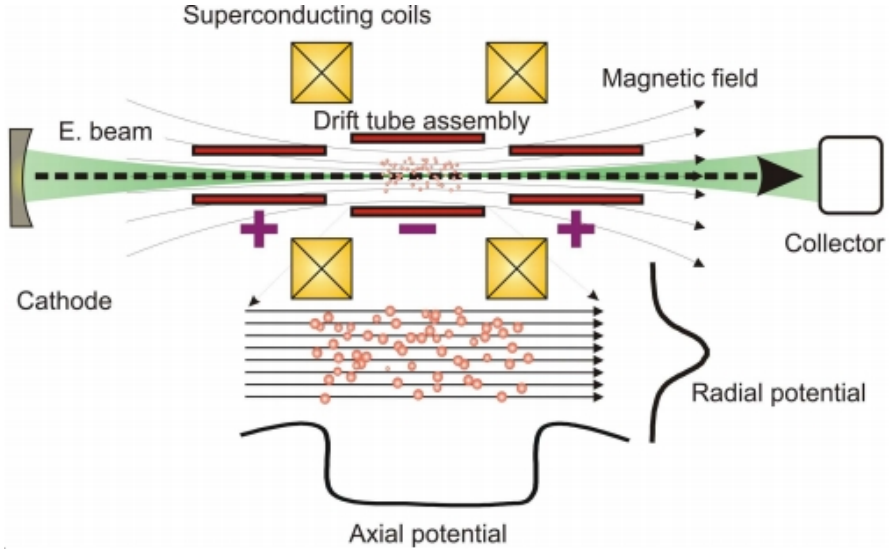
via VS1: photon + nuclear excitation
via VS2: nuclear excitation + photon



… in highly charged ions

Th^{35+} in an Electron Beam Ion Trap





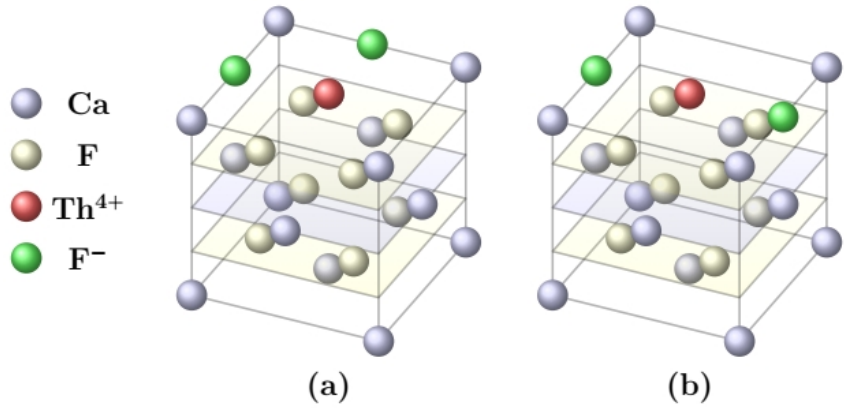
- Open 4f shell, many electronic M1 transitions allowed
- Initial state populated (17% in steady state) by collisions in EBIT
- EB nuclear excitation scheme, allows sub-meV determination of isomer energy
- 1 day scanning campaign

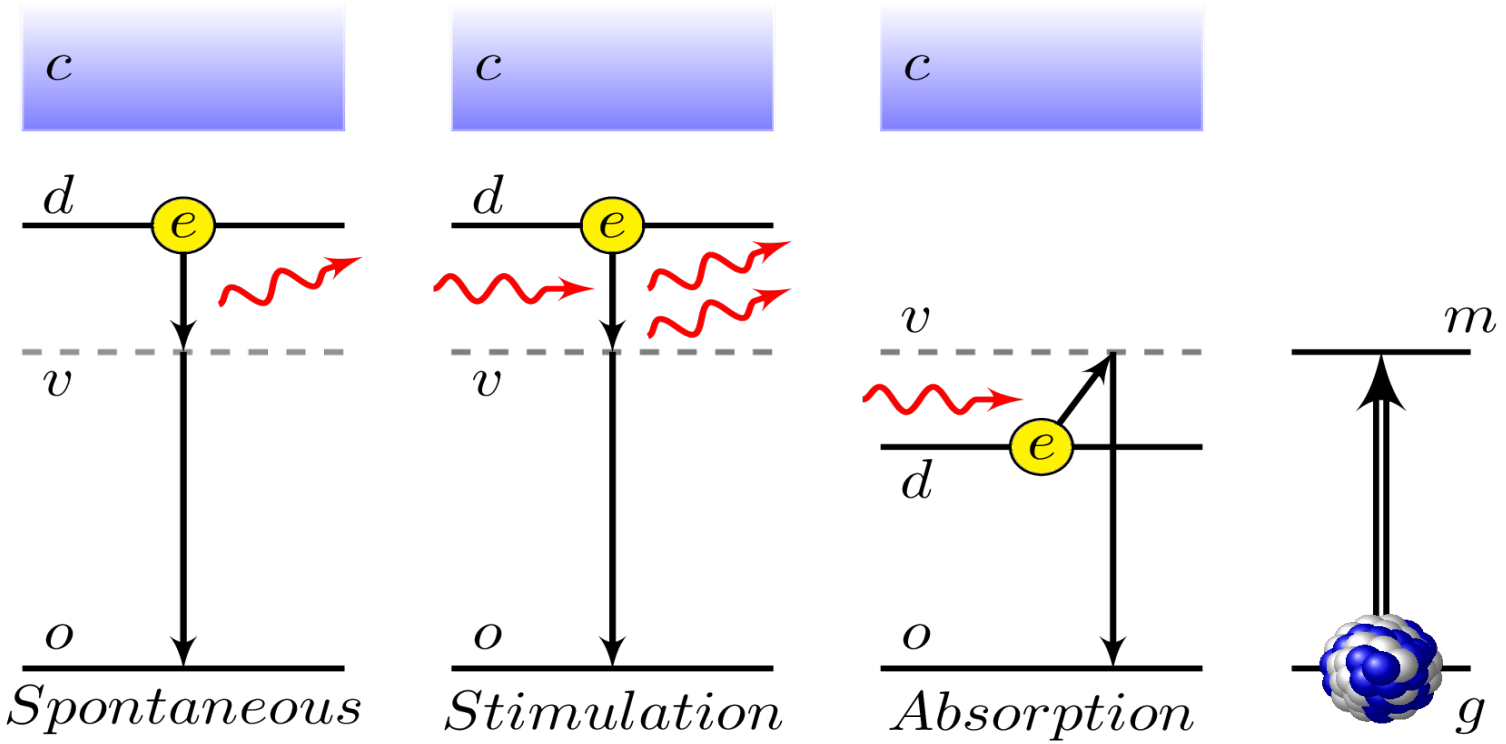
P. V. Bilous, H. Bekker, … , AP, PRL 124, 192502 (2020)

in VUV-transparent crystals

CaF_2

- Doping of ^{229}Th introduces defect states
- 2p interstitial F electron moves to 5f dopant Th
- EB scheme allows 2 orders of magnitude faster excitation/quenching.

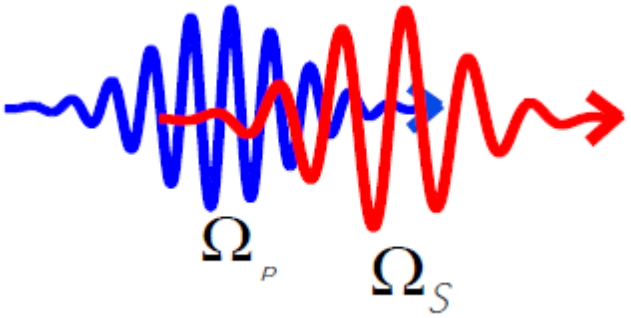


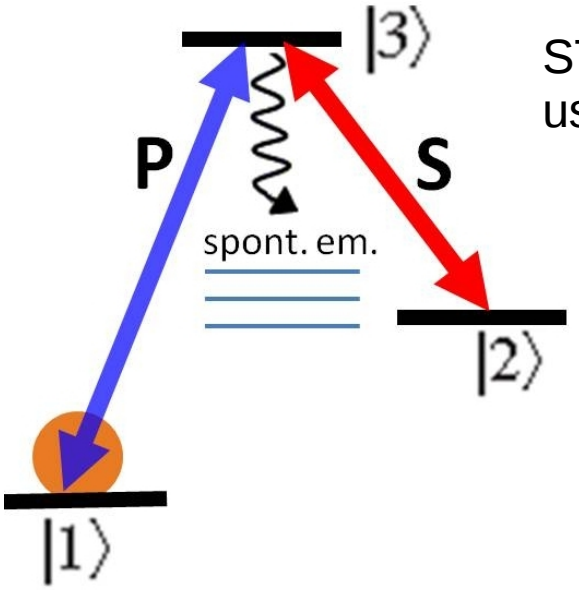


B. S. Nickerson, M. Pimon, … , AP, PRL 125, 032501 (2020)

Nuclear coherent population transfer

STImulated Raman Adiabatic Passage





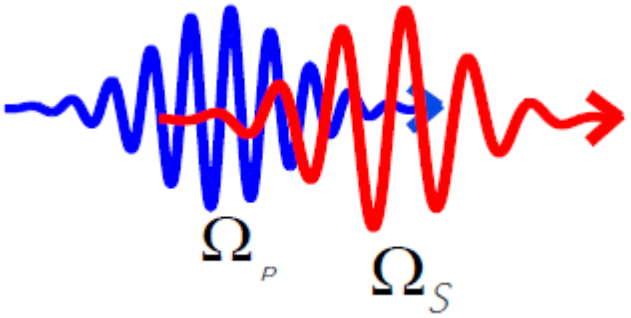
STIRAP for nuclear states using XFEL pulses

$$|D\rangle = \frac{\Omega_s}{\sqrt{\Omega_p^2 + \Omega_s^2}}|1\rangle - \frac{\Omega_p}{\sqrt{\Omega_p^2 + \Omega_s^2}}|2\rangle$$

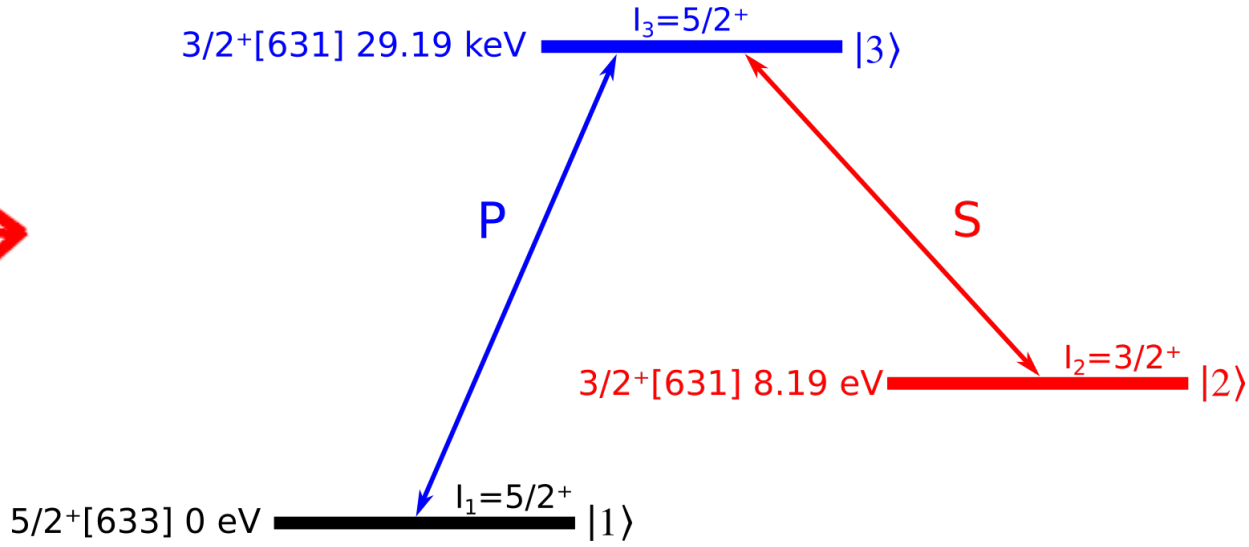
W.-T. Liao, AP and C. H. Keitel, Phys. Lett. B 705, 134 (2011)

Nuclear coherent population transfer

STImulated Raman Adiabatic Passage



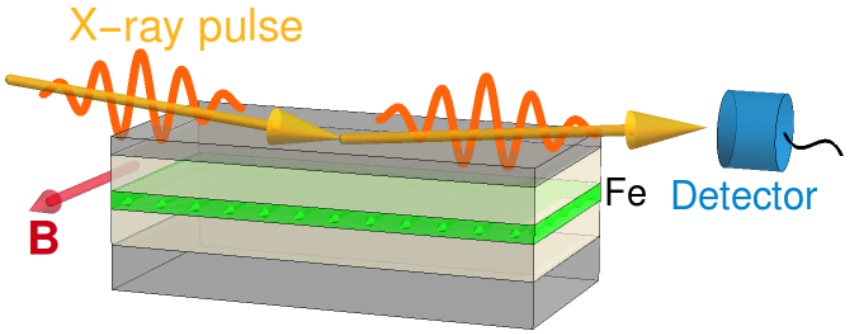
229-Th isomer pumping scheme



$$|D\rangle = \frac{\Omega_s}{\sqrt{\Omega_p^2+\Omega_s^2}}|1\rangle - \frac{\Omega_p}{\sqrt{\Omega_p^2+\Omega_s^2}}|2\rangle$$

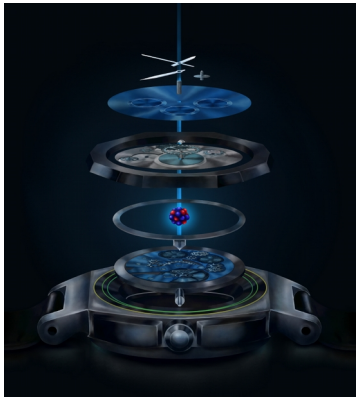
Kirschbaum, Minkov, AP, Phys. Rev. C in press (2022), arXiv:2203.15639

Conclusions



Successful quantum optics at single-photon level in thin-film cavitites – control of x-ray photons

Exploit this for quantum applications/imaging?



Art: Daria Bilous

Exciting prospectives of a nuclear clock at the borderline between nuclear and atomic physics and quantum optics.

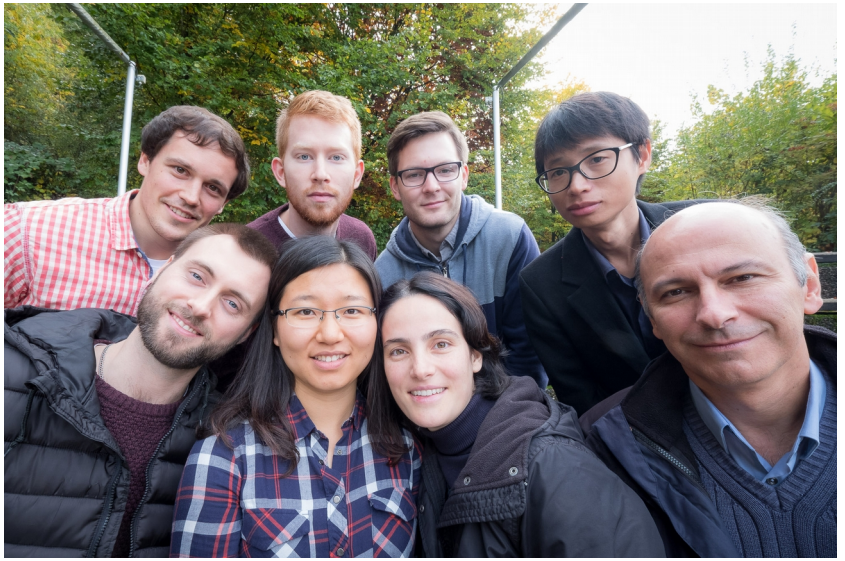
Start building the VUV laser for the 8.3 eV region!

Thanks

Atomic and nuclear quantum dynamics

Petar Andrejic
Xiangjin Kong
Brenden Nickerson
Pavlo Bilous
Nikolay Minkov
Sergei Kobzak

Christoph H. Keitel
Jörg Evers
Hans A. Weidenmüller



TRR 306
QuCoLiMa
Quantum Cooperativity of Light and Matter

Ralf Röhlsberger
Lars Bocklage

Peter Thirolf
Benedict Seiferle
Lars von der Wense

THANK YOU FOR YOUR ATTENTION!