Nuclear transitions for quantum control and metrology

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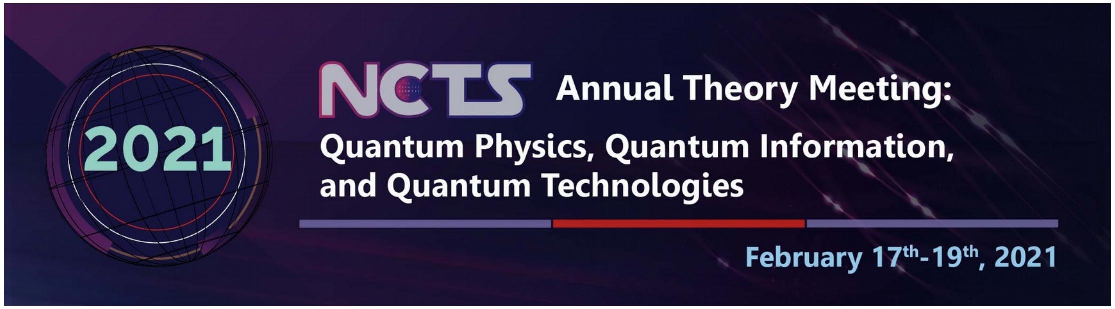
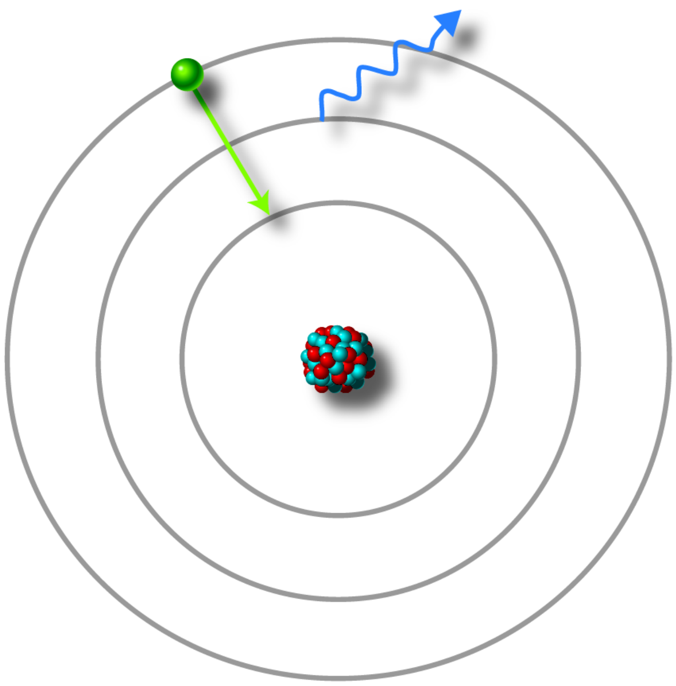
Max Planck Institute for Nuclear Physics, Heidelberg



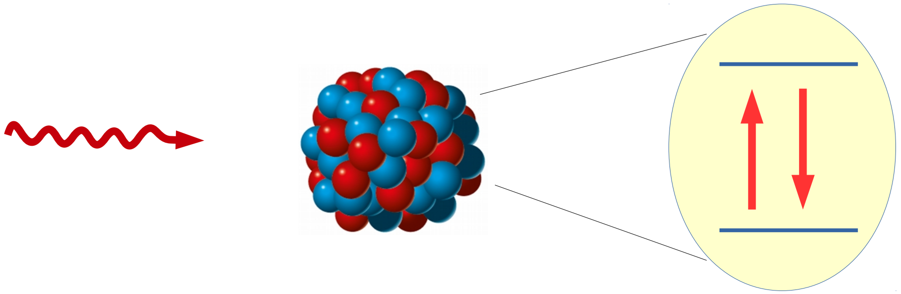
NCTS Annual Theory Meeting, 17 February 2021

Quantum dynamics with atoms and nuclei

Optical, IR



What about nuclear quantum dynamics?



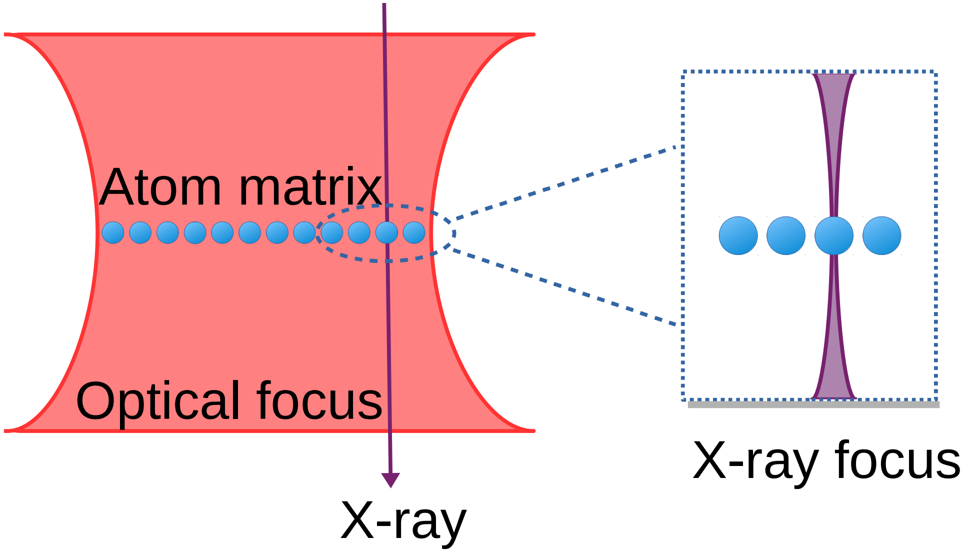
Higher frequencies:
X-ray, VUV

Mutual control of LASER LIGHT and ATOMS

Revolutionized atomic physics, technology and metrology!

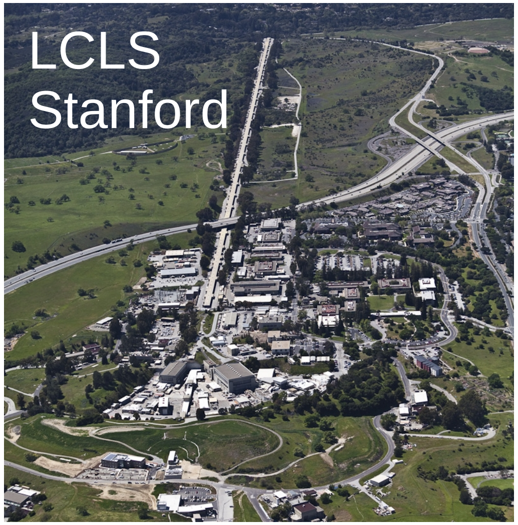
Incentives for x-ray quantum control

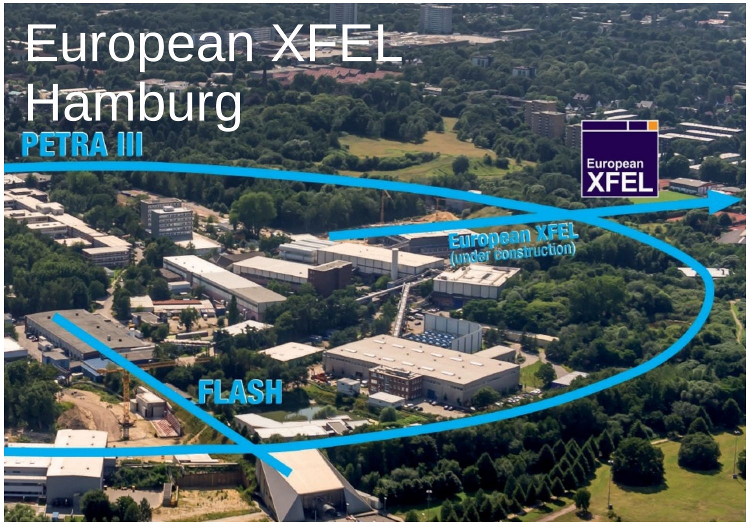
- Robustness, efficient detection
- Deeper penetration
- Focusing - diffraction limit



→ *Ultimate miniaturization of photonic circuits*

→ *Sensing with unprecedented spatial resolution*





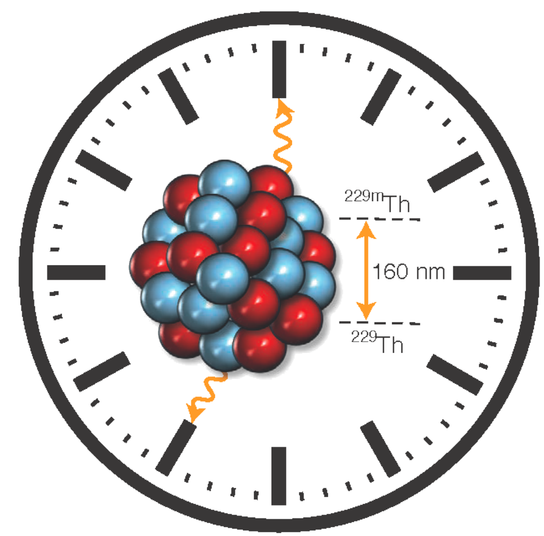
Special nuclear incentives

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

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

ISOLATION FROM ENVIRONMENT

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

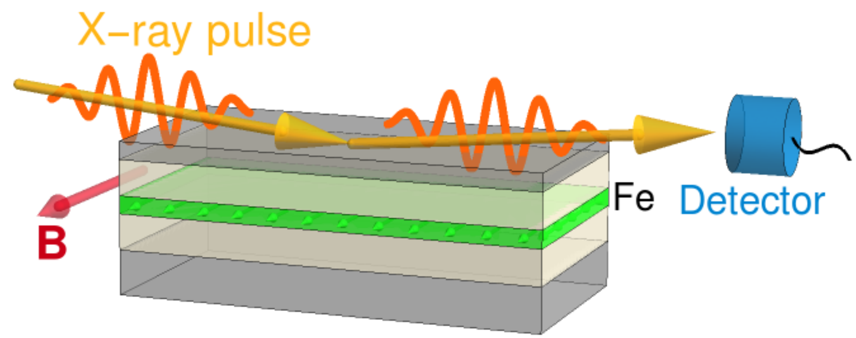
thorium nuclear clock

European Commission

Outline

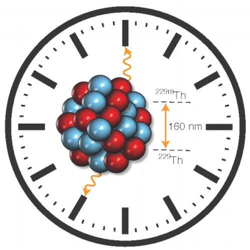
I. X-ray coherent control

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



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

Nuclear clock
Energy determination
Electronic bridge



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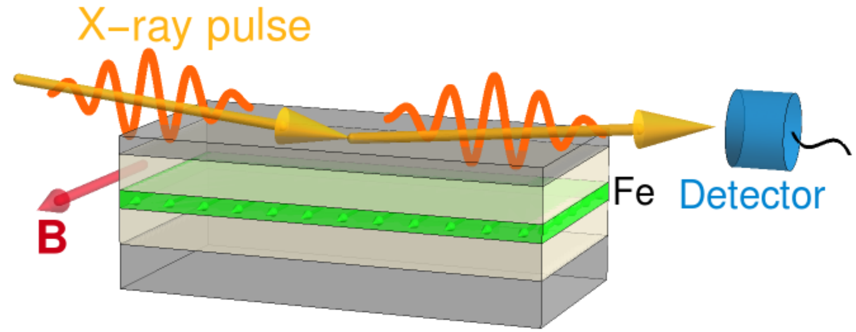

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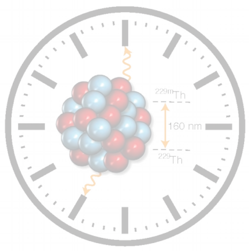
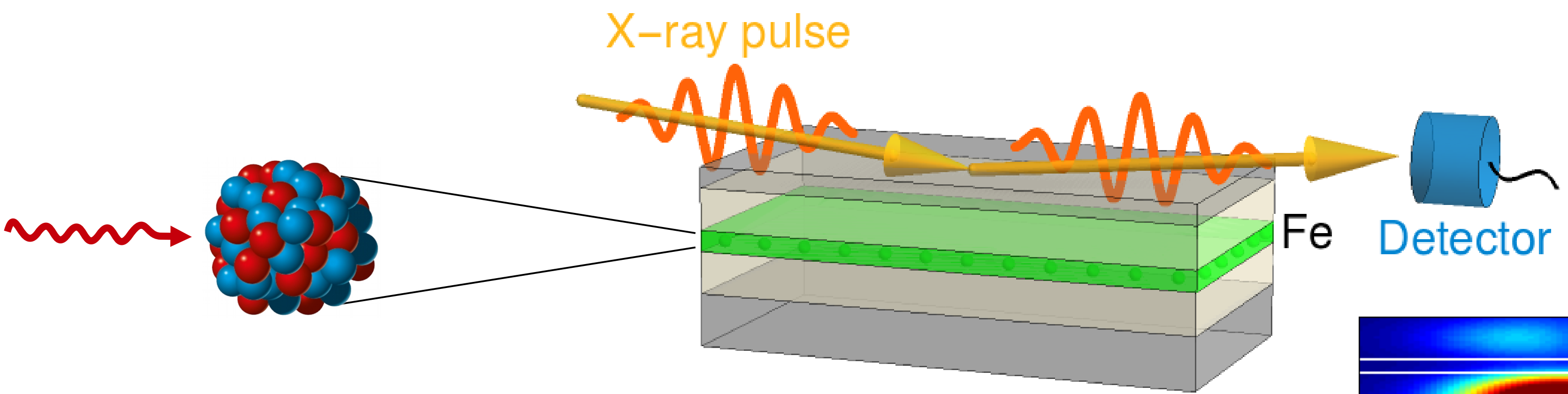
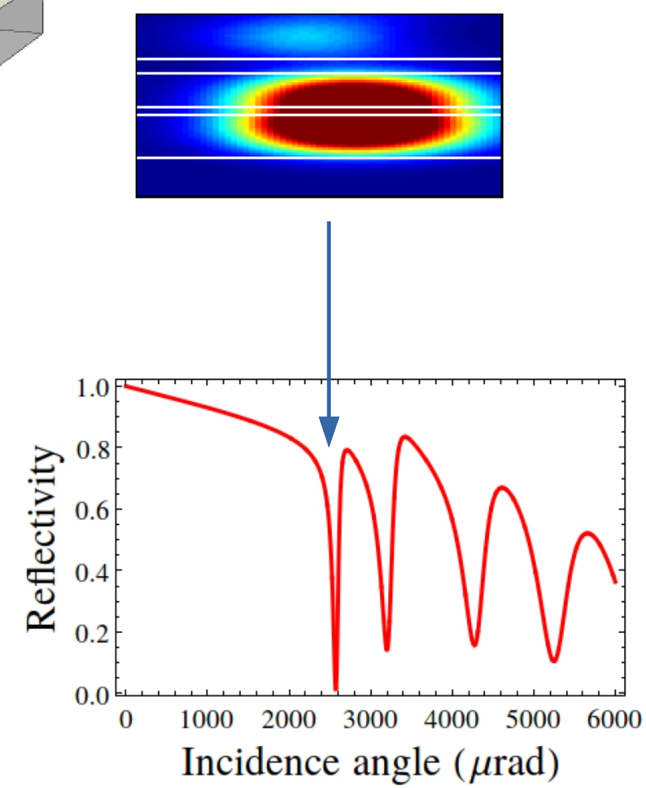


Thin-film x-ray cavities

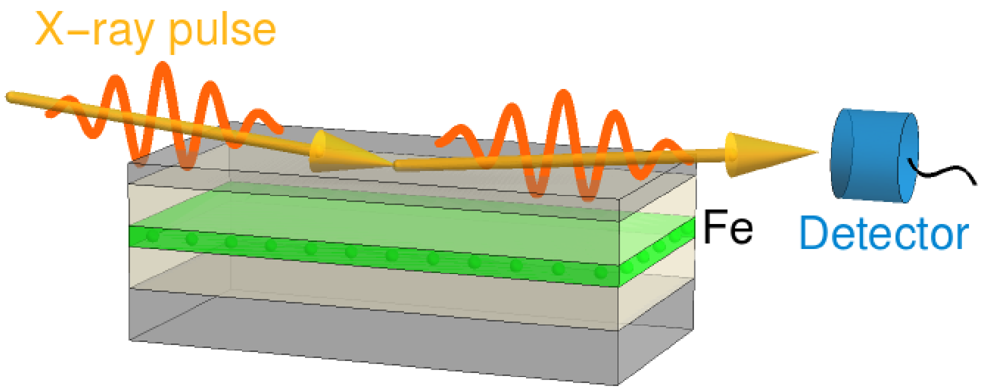


^{57}Fe, 14.4 keV Mössbauer transition



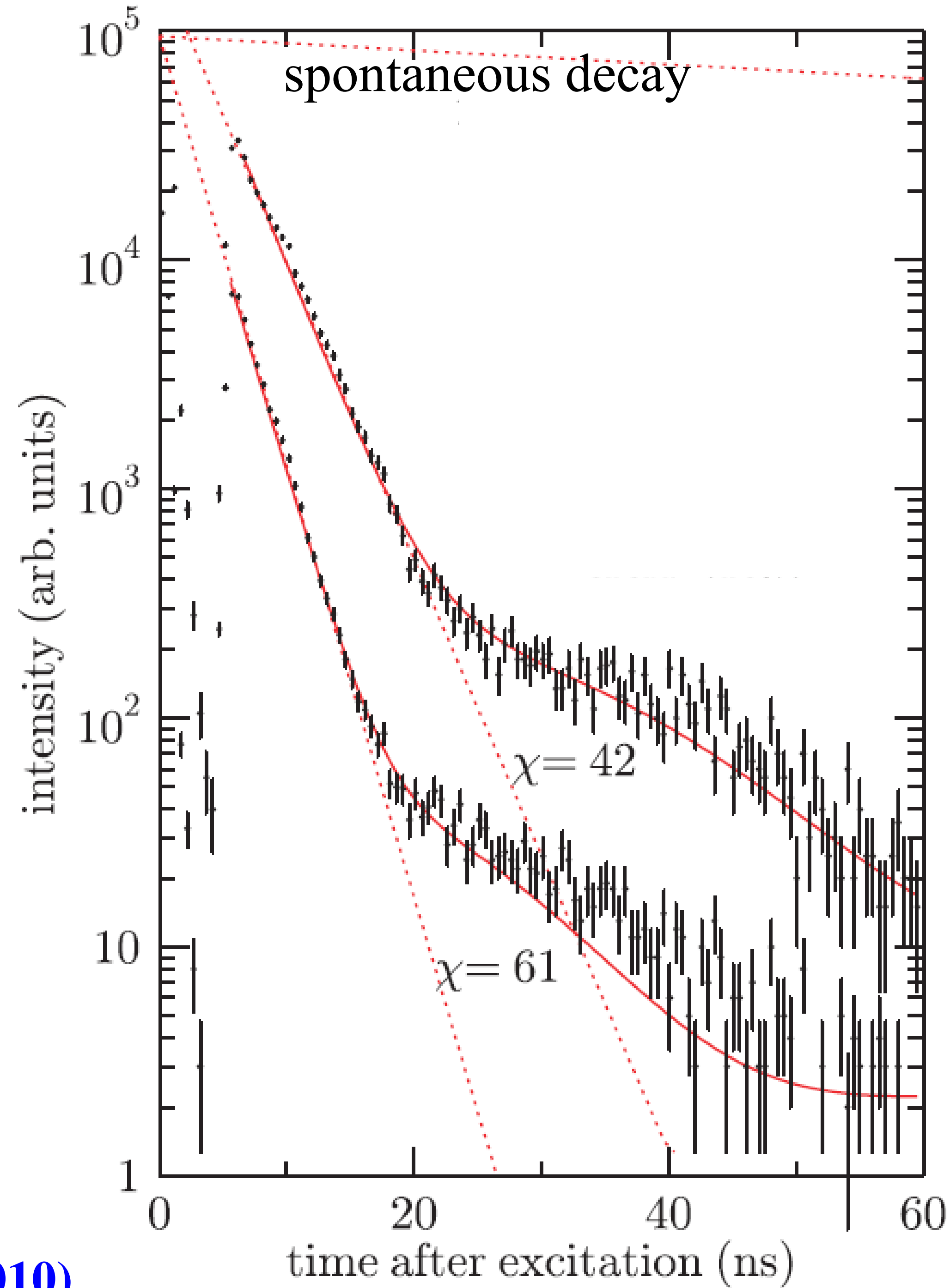
- Grazing incidence, detect reflectivity
- “resonant angle” from rocking curve
- Nuclear resonances interact with cavity field

Faster exponential decay



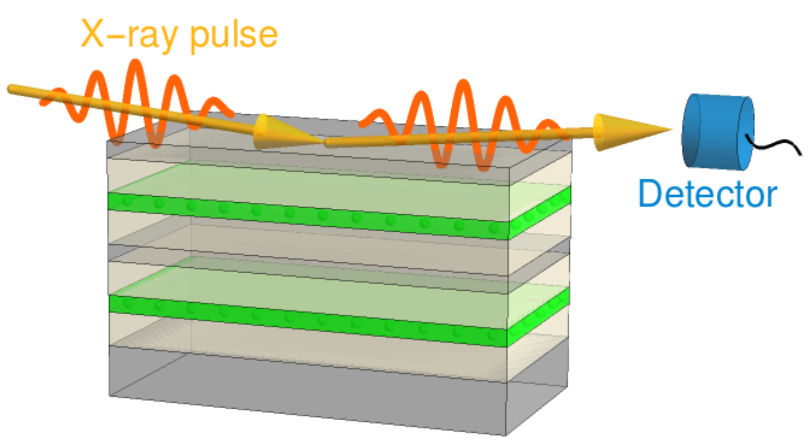
χ is the coherent decay enhancement factor

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

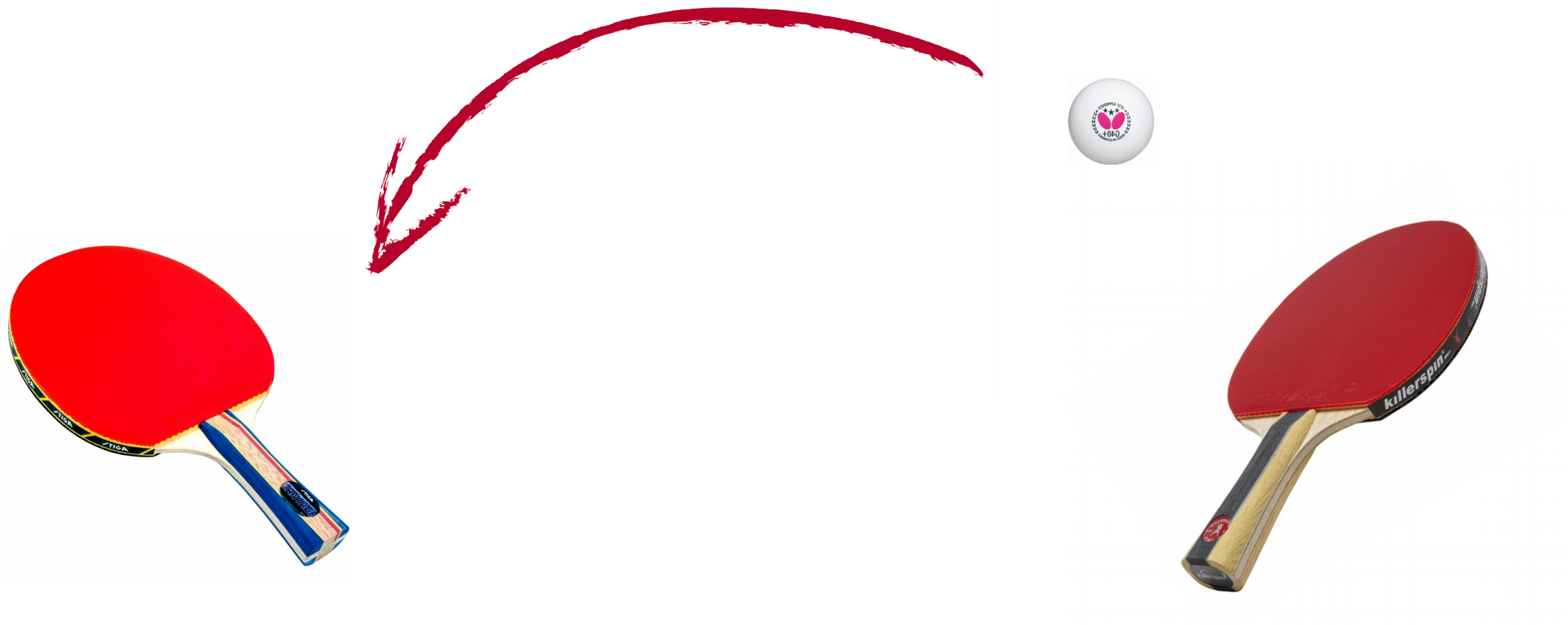


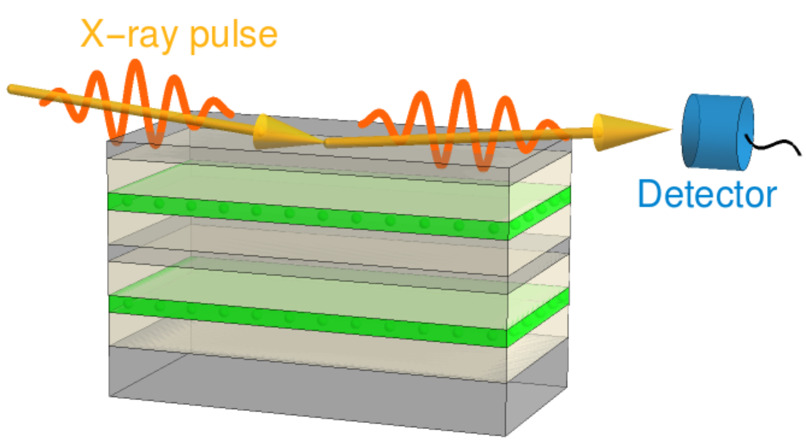
R. Röhlsberger *et al.*, Science 328, 1248 (2010)

X-ray ping-pong

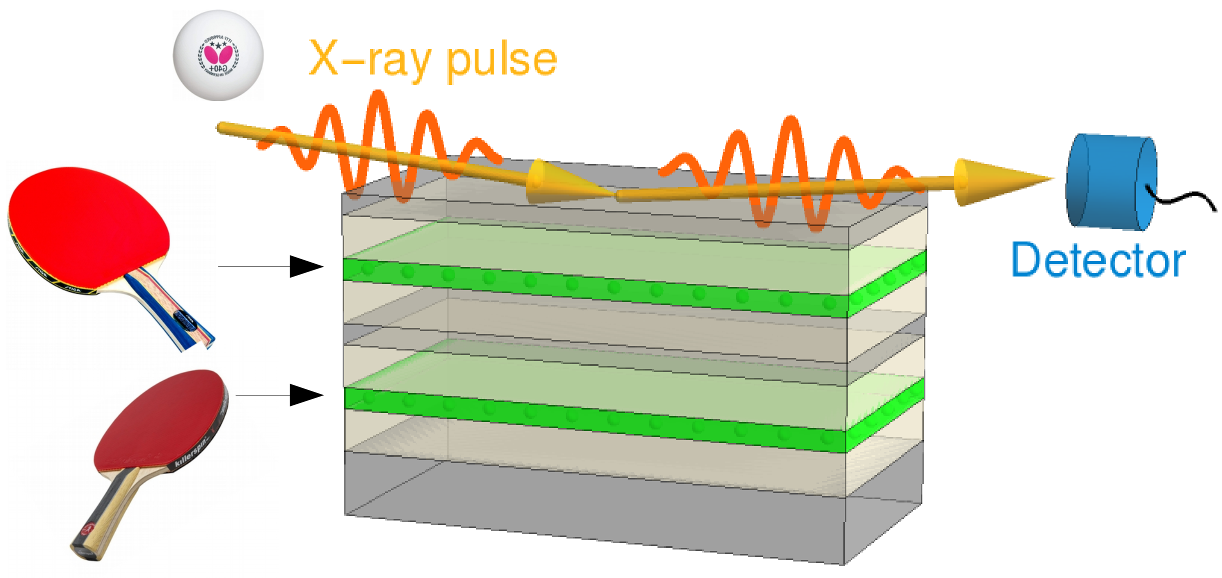


X-ray ping-pong





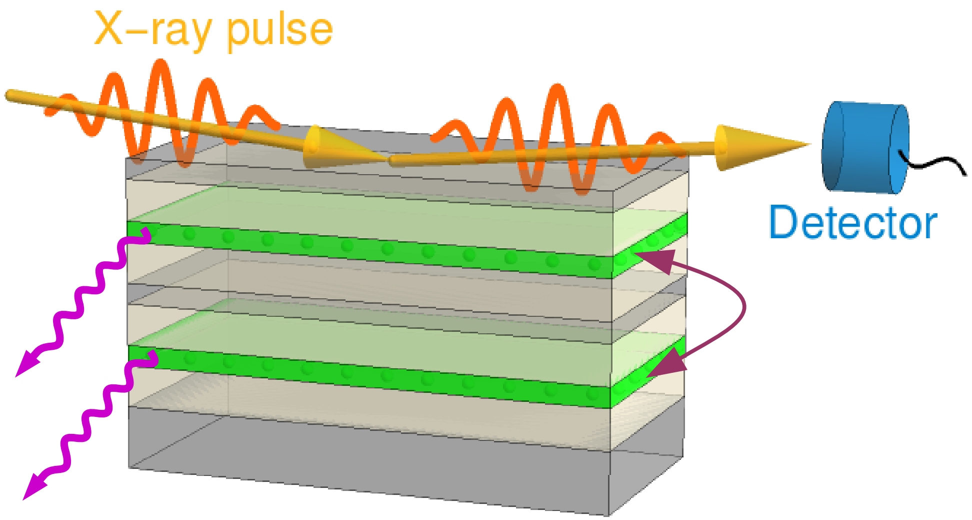
X-ray ping-pong

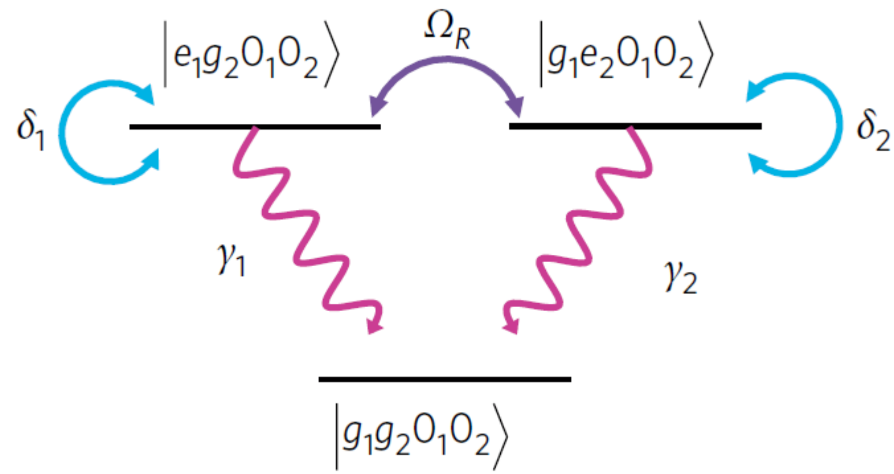


Strong coupling: the interaction between field and system is larger than the system decay rates.

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

Coupled cavities

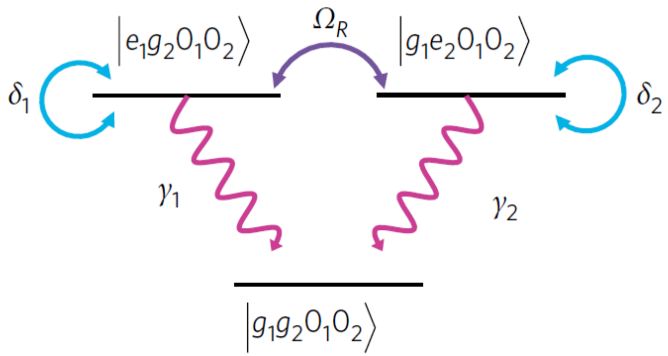




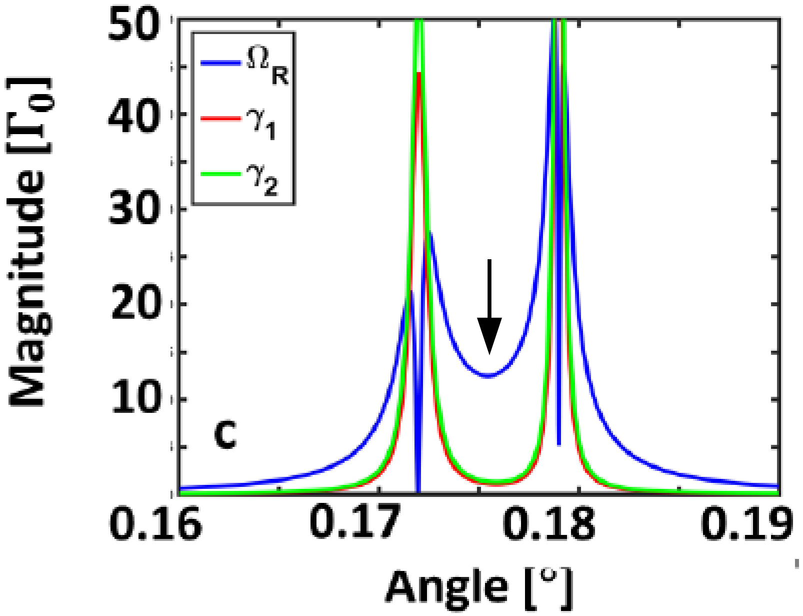
Rich 3-level system, where many processes can occur.

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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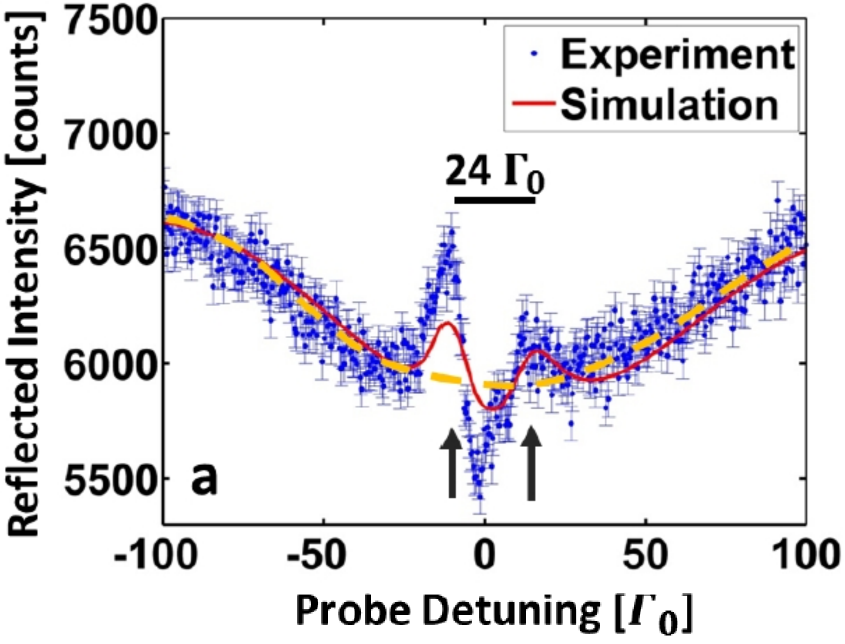
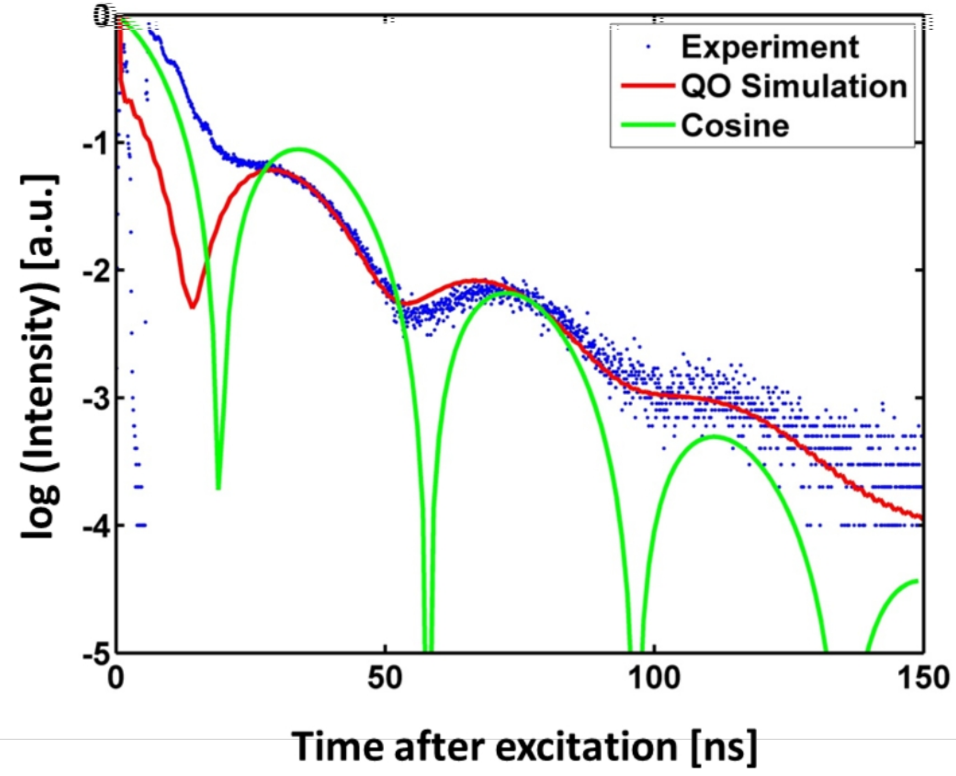
Experimental results

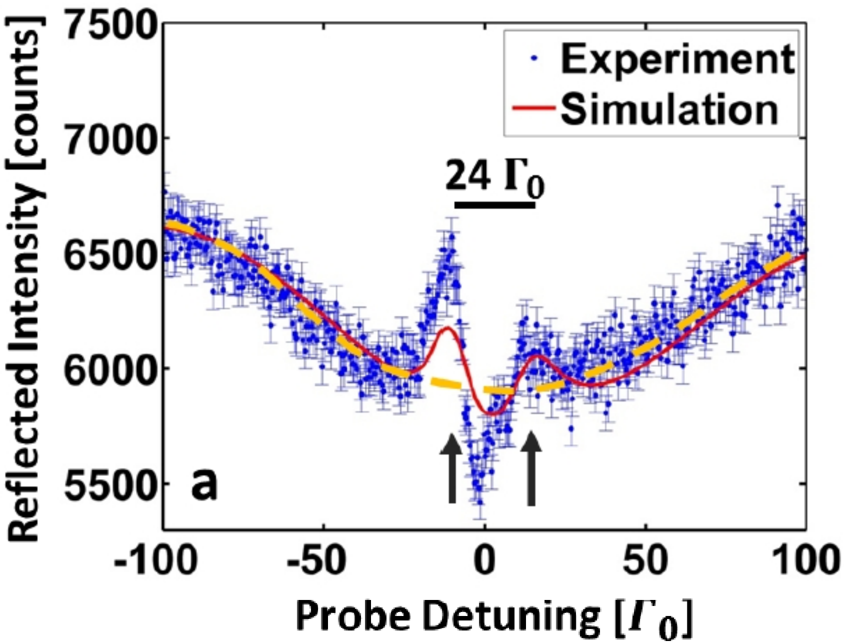


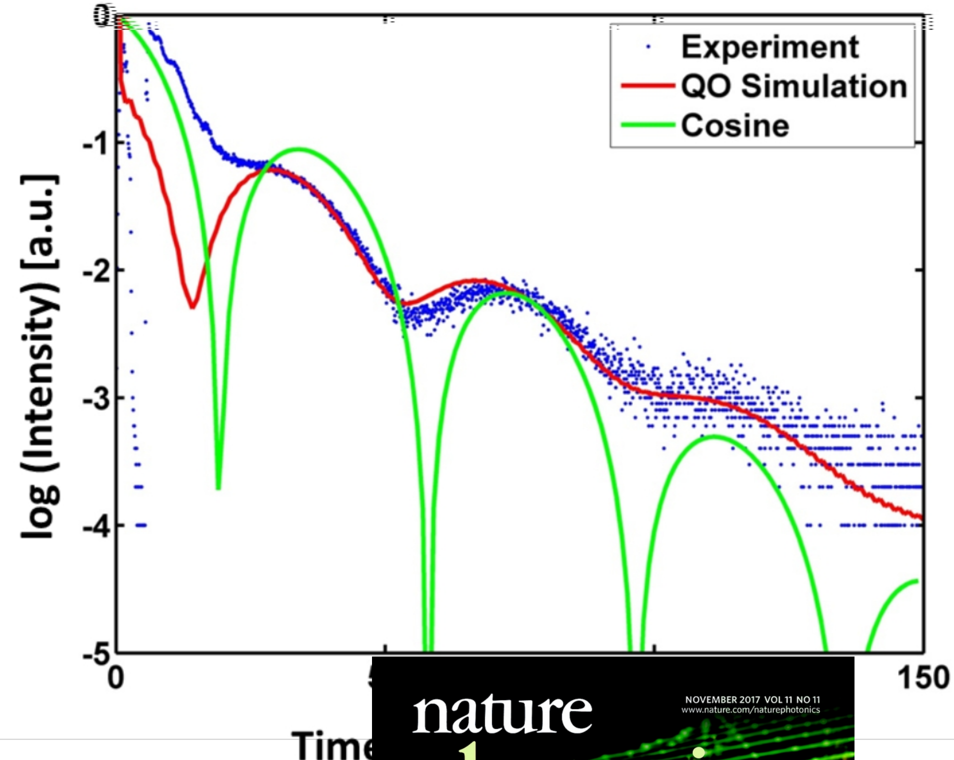


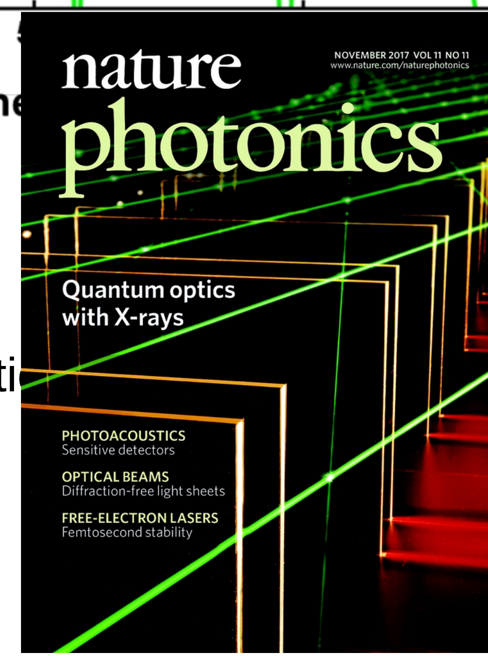
The resonance line is split and one can observe Rabi oscillations as known from the strong coupling regime!

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

Experimental results







The resonance line is split and one can observe Rabi oscillati
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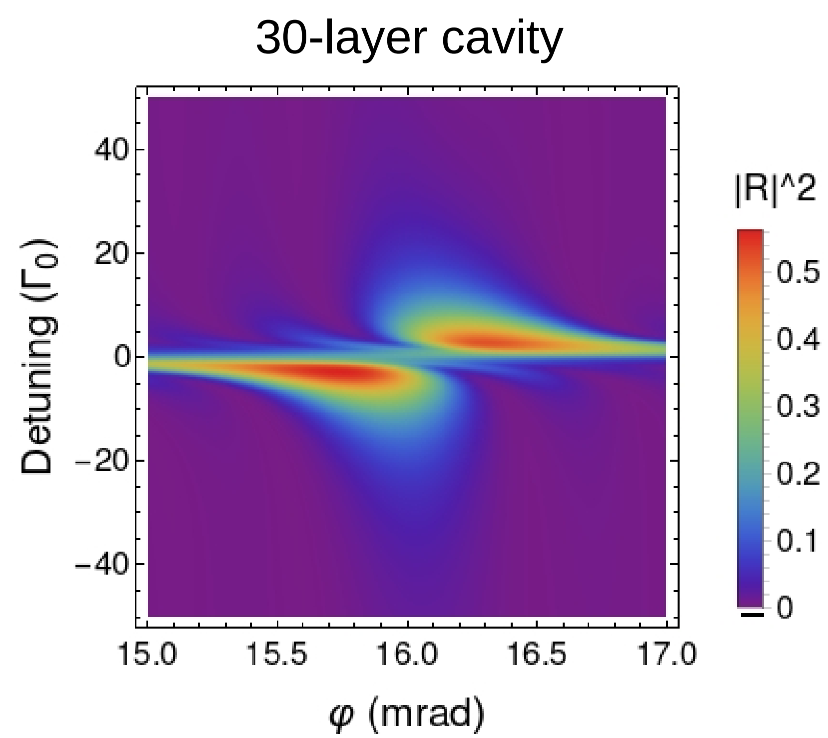
Haber, Kong, ... Palffy, Röhlsberger, Nature Photon. 11, 720 (2017)

Green function formalism

- based on Green function for layered system
- can be used for any multilayer structure
- fully quantum - quantized electromagnetic field
- Heisenberg equations for nuclear coherences
- input-output formalism to retrieve reflectivity



$$\left(\mu_0\omega_p^2/\hbar\right)\mathbf{d}_i^*\cdot\mathbf{G}_{1\mathrm{D}}\left(\mathrm{z}_i,\mathrm{z}_j,\omega_p\right)\cdot\mathbf{d}_j \approx \frac{1}{4\pi\epsilon_0}\frac{4\omega_0^3|\mathbf{d}|^2}{3\hbar c^3}i\frac{4\pi}{\varphi} \times \left[p\left(\mathrm{z}_i\right)q\left(\mathrm{z}_j\right)\Theta\left(\mathrm{z}_i-\mathrm{z}_j\right)+p\left(\mathrm{z}_j\right)q\left(\mathrm{z}_i\right)\Theta\left(\mathrm{z}_j-\mathrm{z}_i\right)\right]$$

$$J_{lm} = \sqrt{N_l N_m}\left(\mu_0\omega_p^2/\hbar\right)\mathbf{d}^*\cdot\mathrm{Re}\left[\mathbf{G}_{1\mathrm{D}}\left(z_l,z_m,\omega_p\right)\right]\cdot\mathbf{d}$$ Spin-exchange - H

$$\Gamma_{lm} = \sqrt{N_l N_m}\left(2\mu_0\omega_p^2/\hbar\right)\mathbf{d}^*\cdot\mathrm{Im}\left[\mathbf{G}_{1\mathrm{D}}\left(z_l,z_m,\omega_p\right)\right]\cdot\mathbf{d}$$ Decay rate - $\mathcal{L}$

X. Kong, D. Chang, AP, PRA 102, 033710 (2020)

Starting point for design of photonic devices!

Outline

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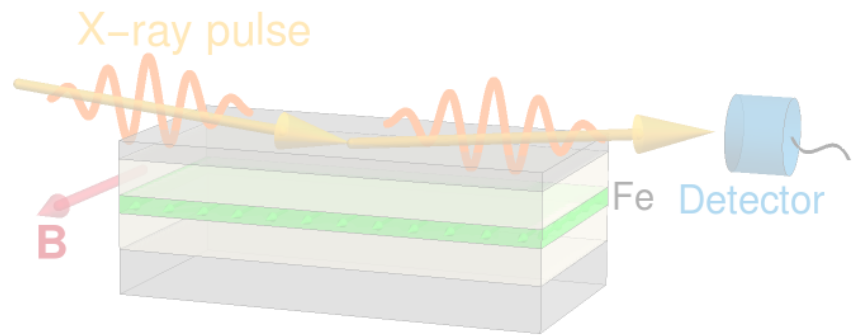

II. Towards a nuclear frequency standard with ^{229}Th

Nuclear clock
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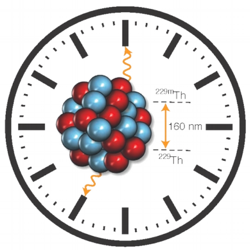
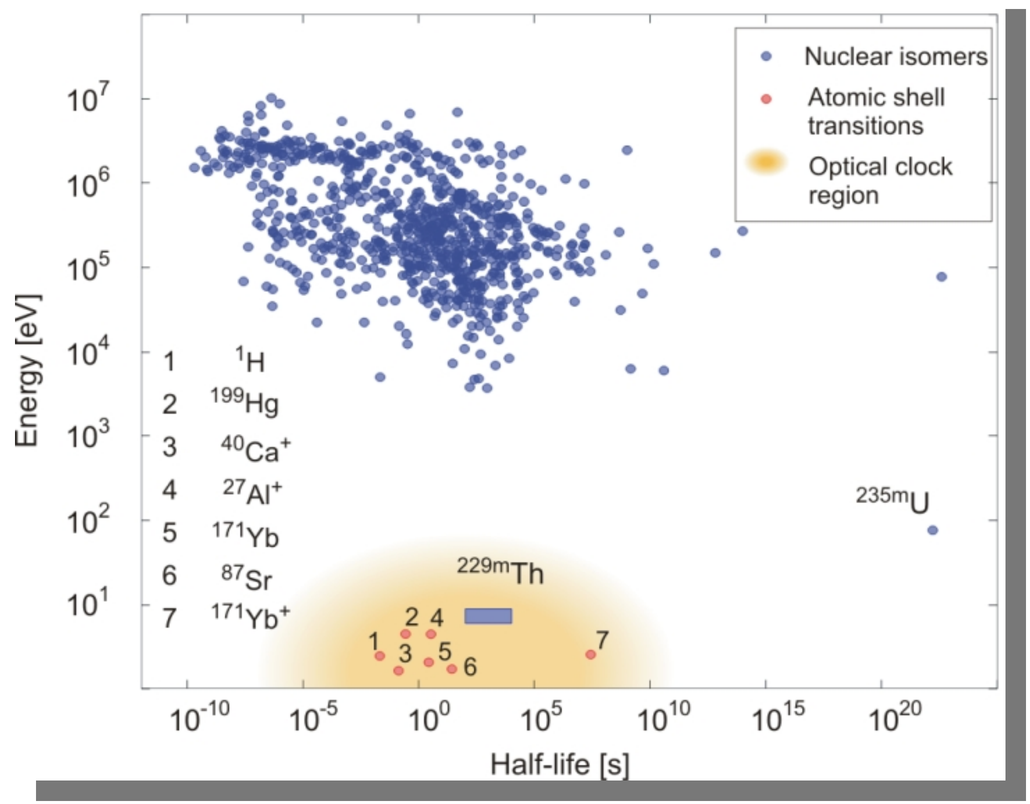
Electronic bridge



A possible nuclear clock

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



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

^{229}Th
E ~ 8.28 eV, λ ~ 150 nm
M1 (+E2) transition

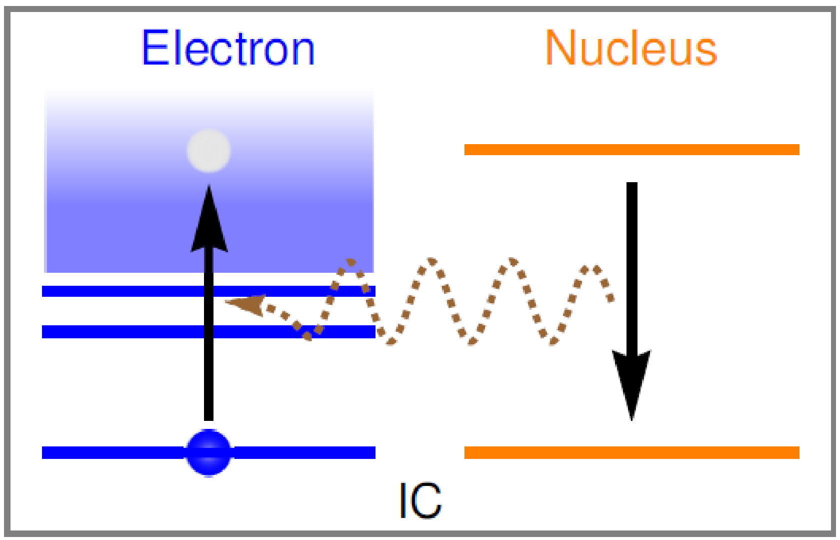
Insensitivity of ^{229m}Th nuclear transition frequency to external perturbations

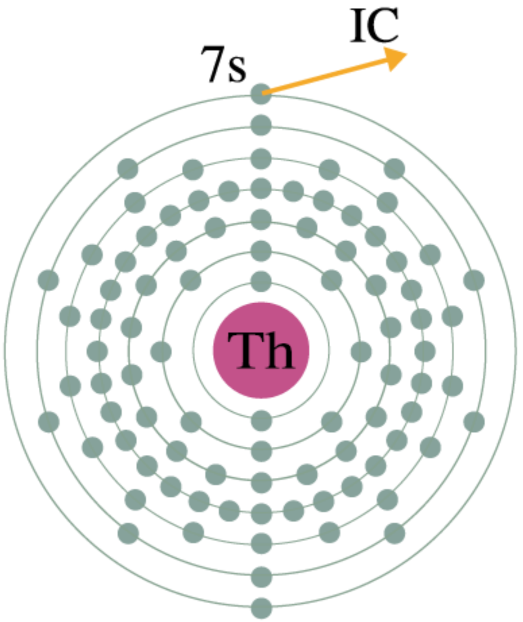
small nuclear moments
largely immune to systematic frequency shifts:

ultra-precise nuclear frequency standard ?
Tests for variation of fundamental constants?

Coupling to atomic shells

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

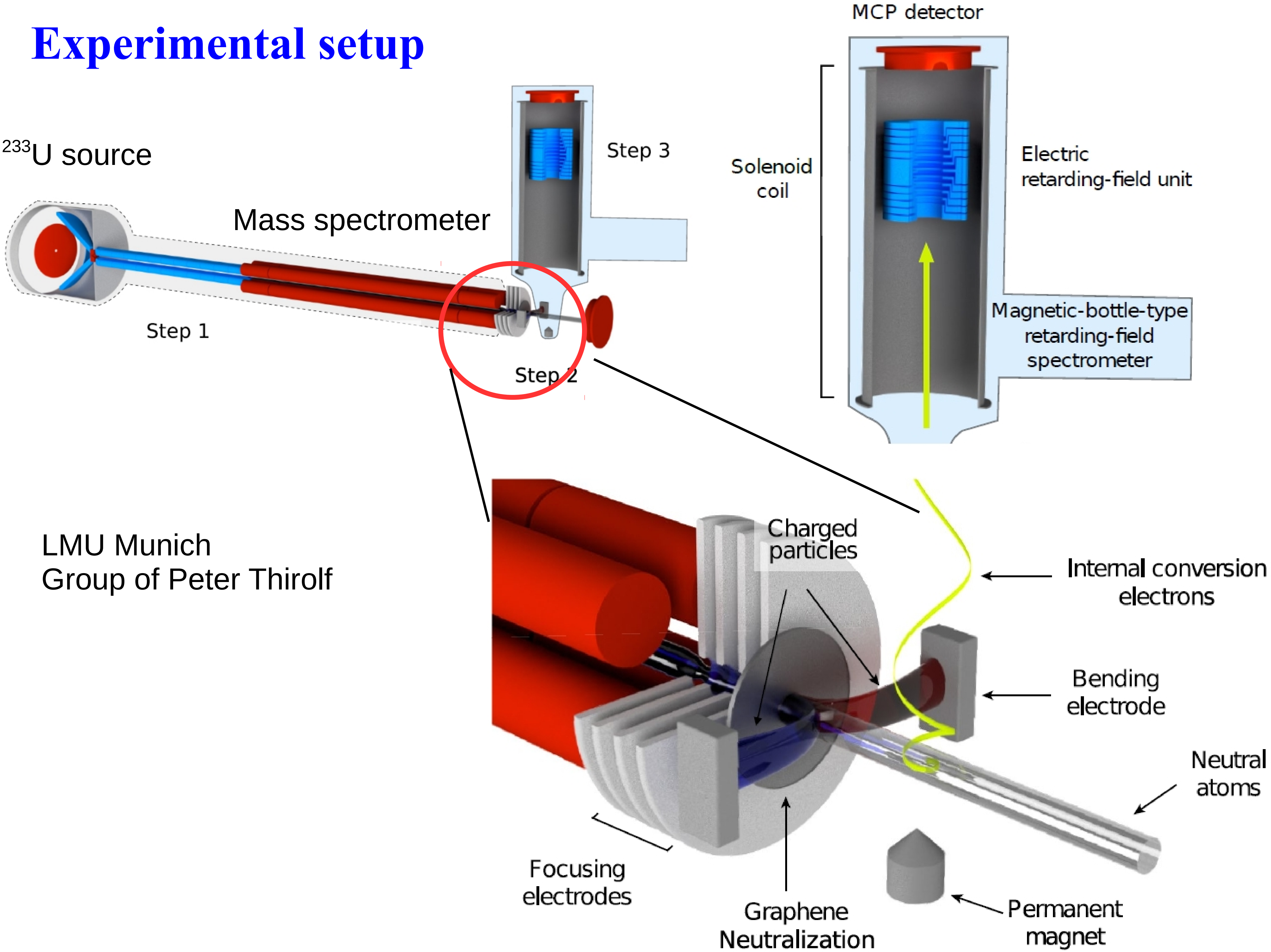




Radiative decay was never observed, but IC was – first direct evidence of isomer in 2016

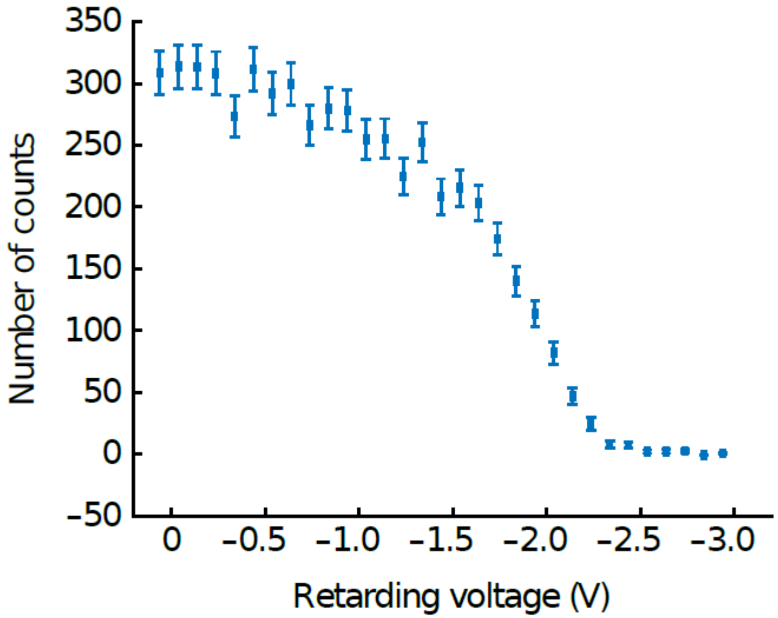
L. v.d. Wense, et al., Nature 533, 47-53 (2016)

Experimental setup



LMU Munich
Group of Peter Thirolf

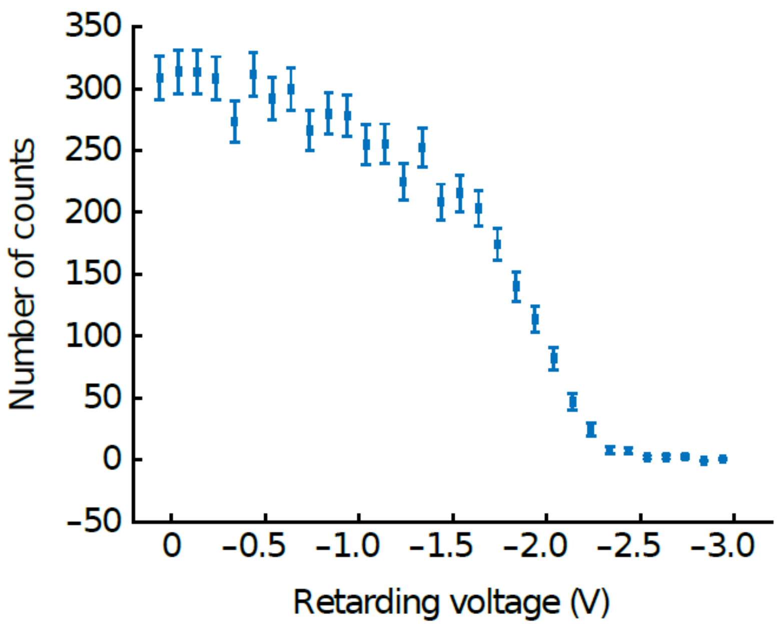
Spectrum



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

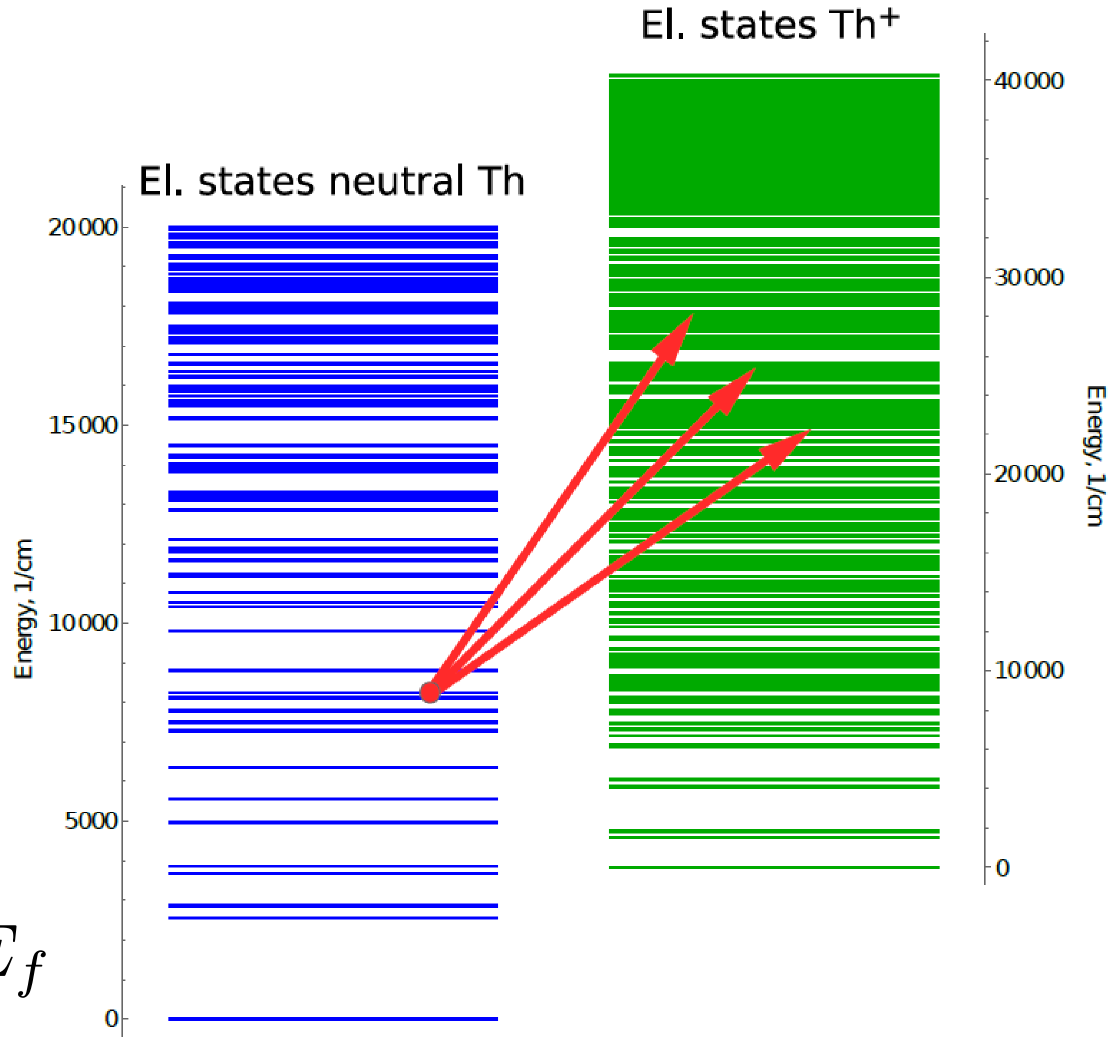
$E_m - ?$

Spectrum

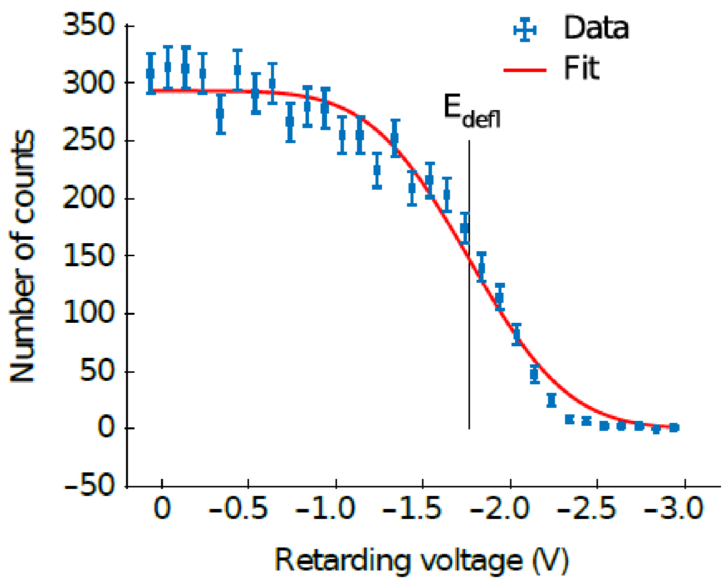


E_m – ?

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



The isomer energy



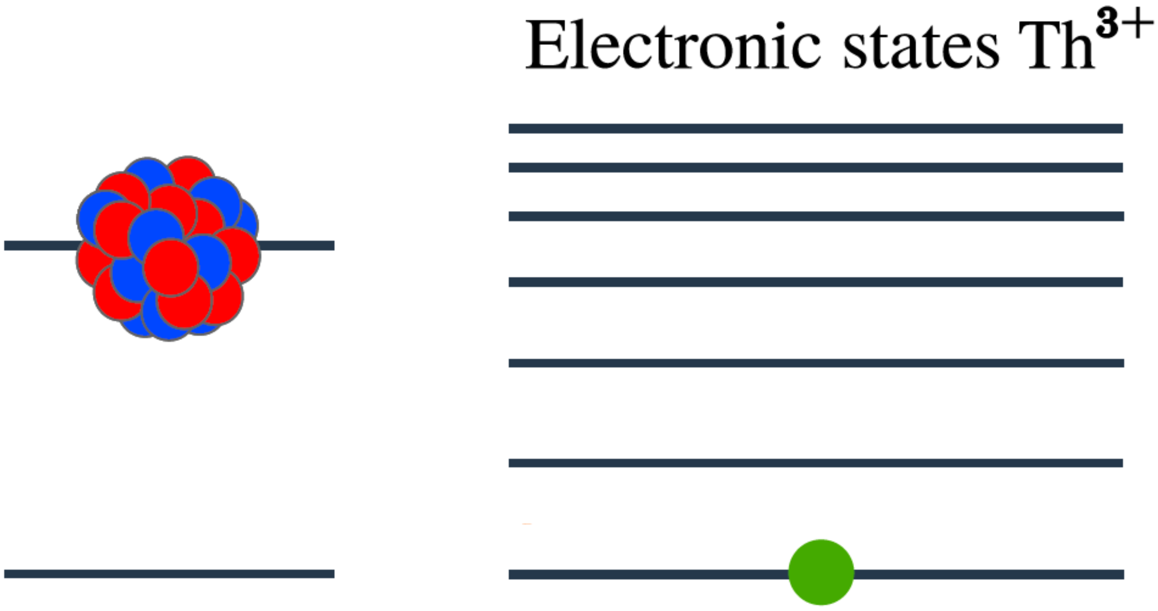
IC calculations to extract the energy value from the measured spectrum

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

B. Seiferle *et al.*, Nature **573**, 243246 (2019)

Electronic bridge

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



Electronic bridge (EB)

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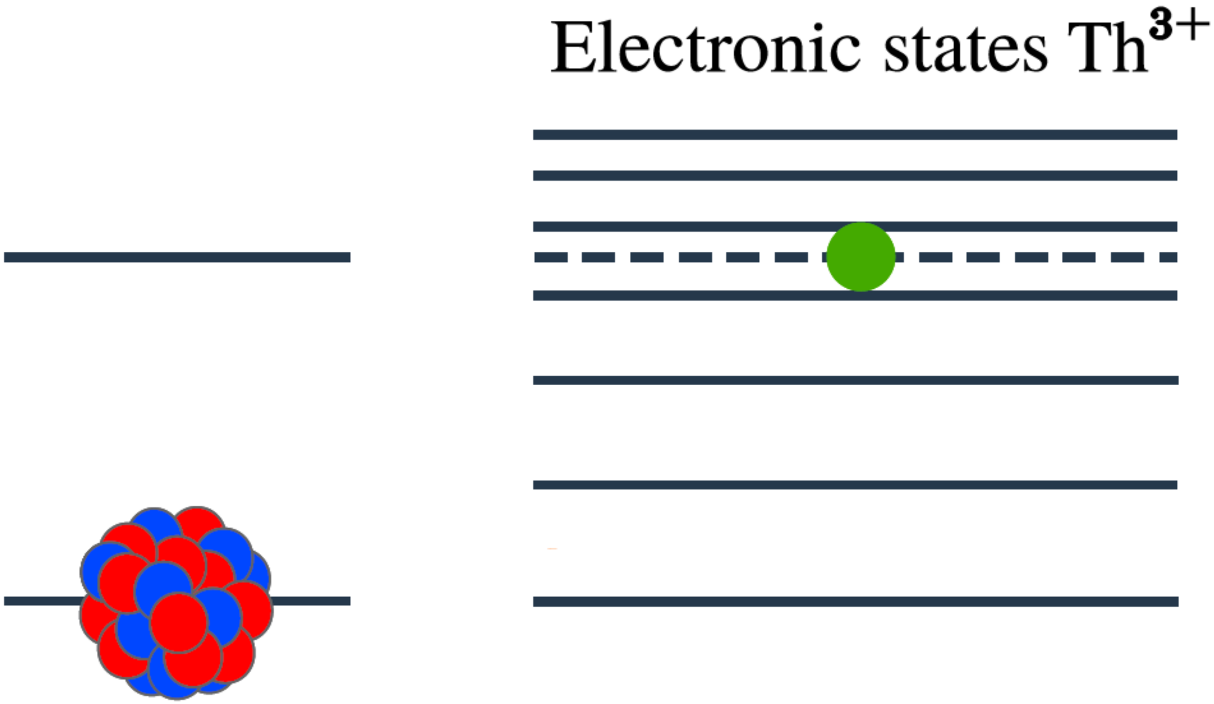
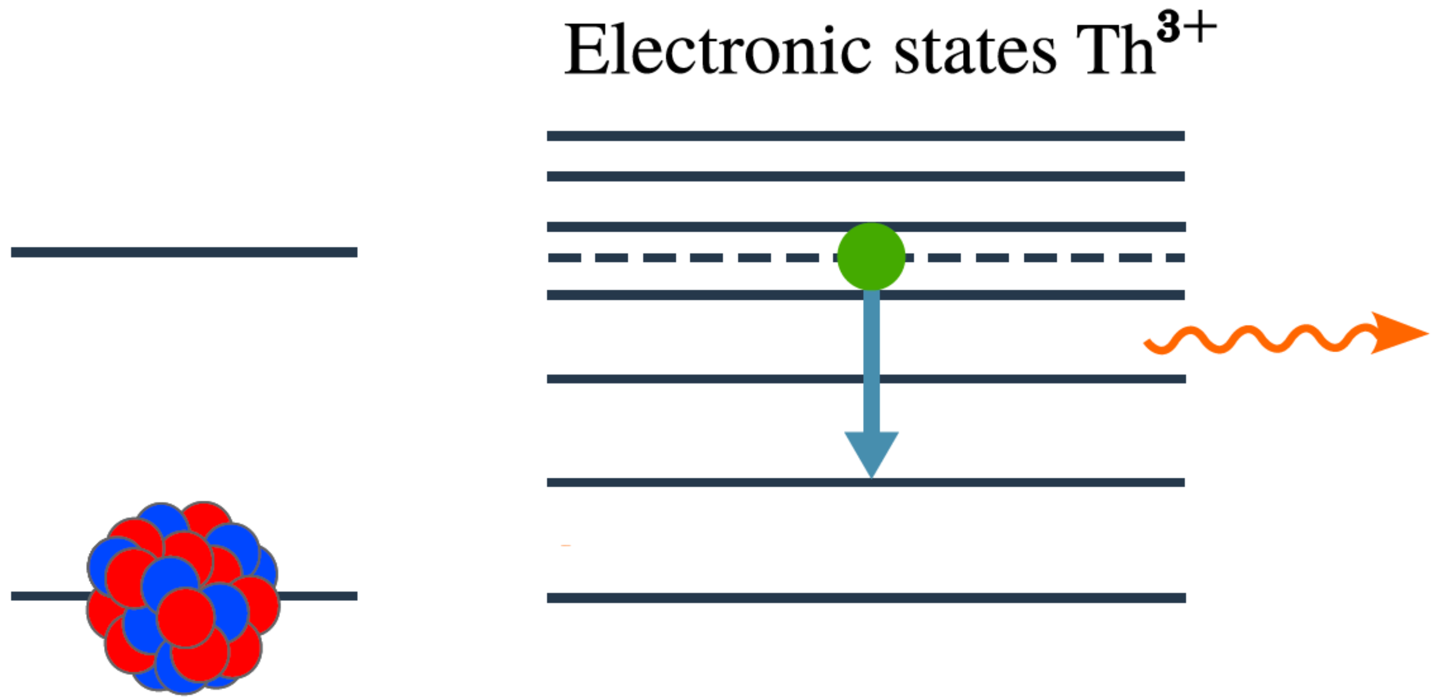


There is no electronic state at the right energy! Virtual state!

Electronic bridge (EB)

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

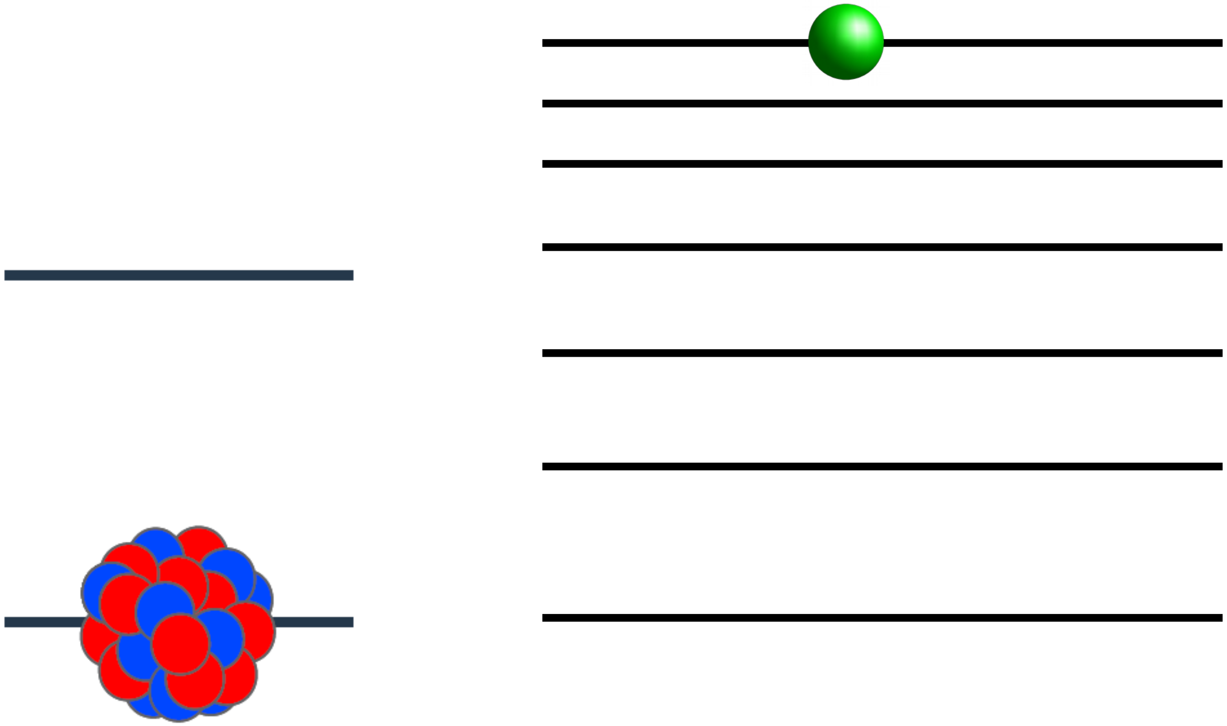


There is no electronic state at the right energy! Virtual state! Decays by emitting a photon!

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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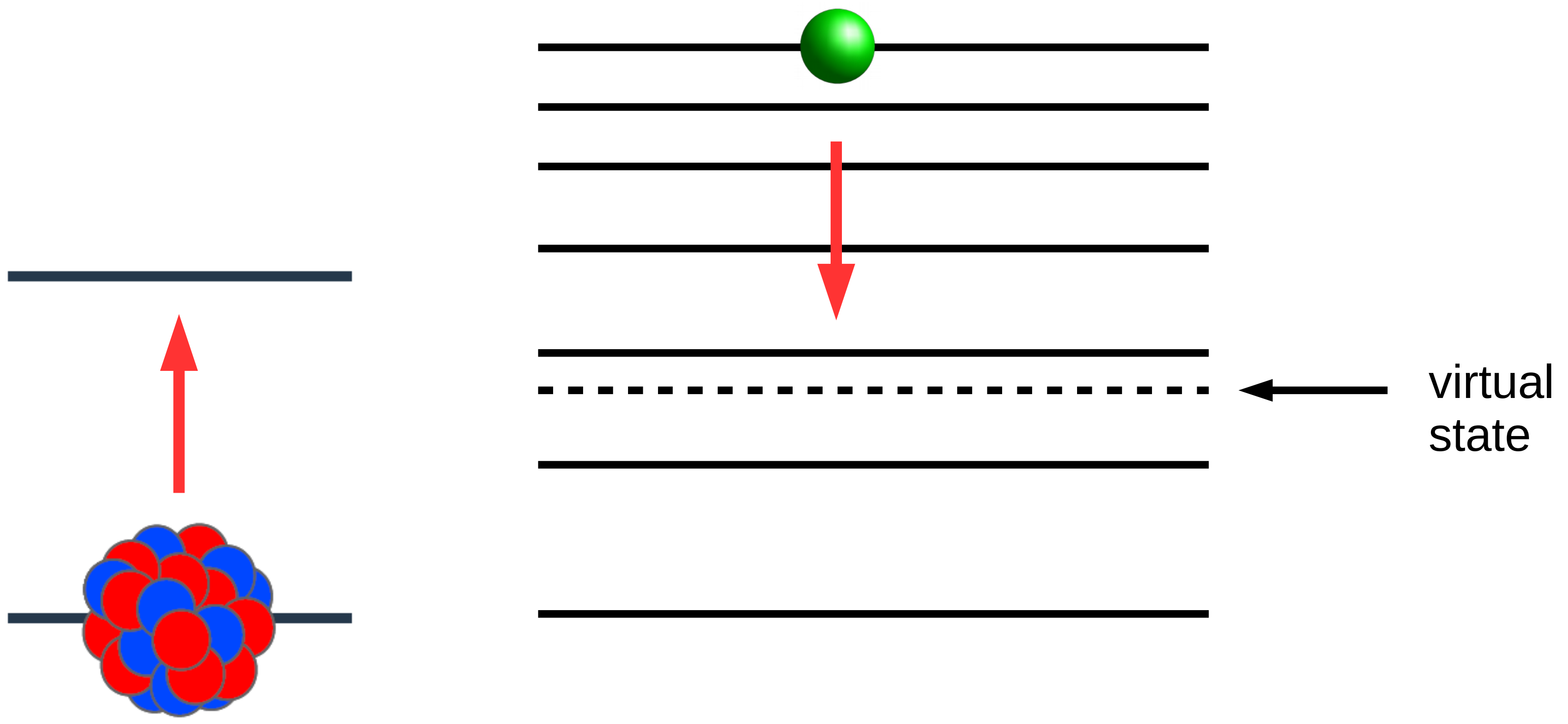

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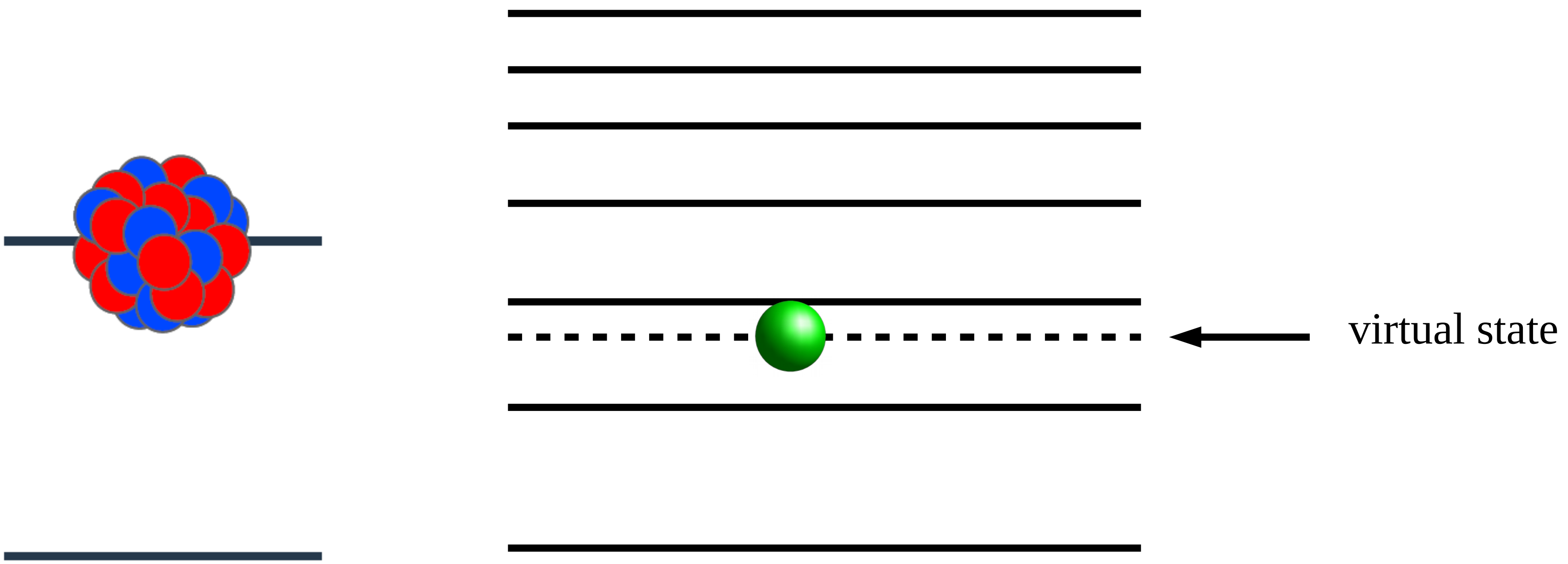
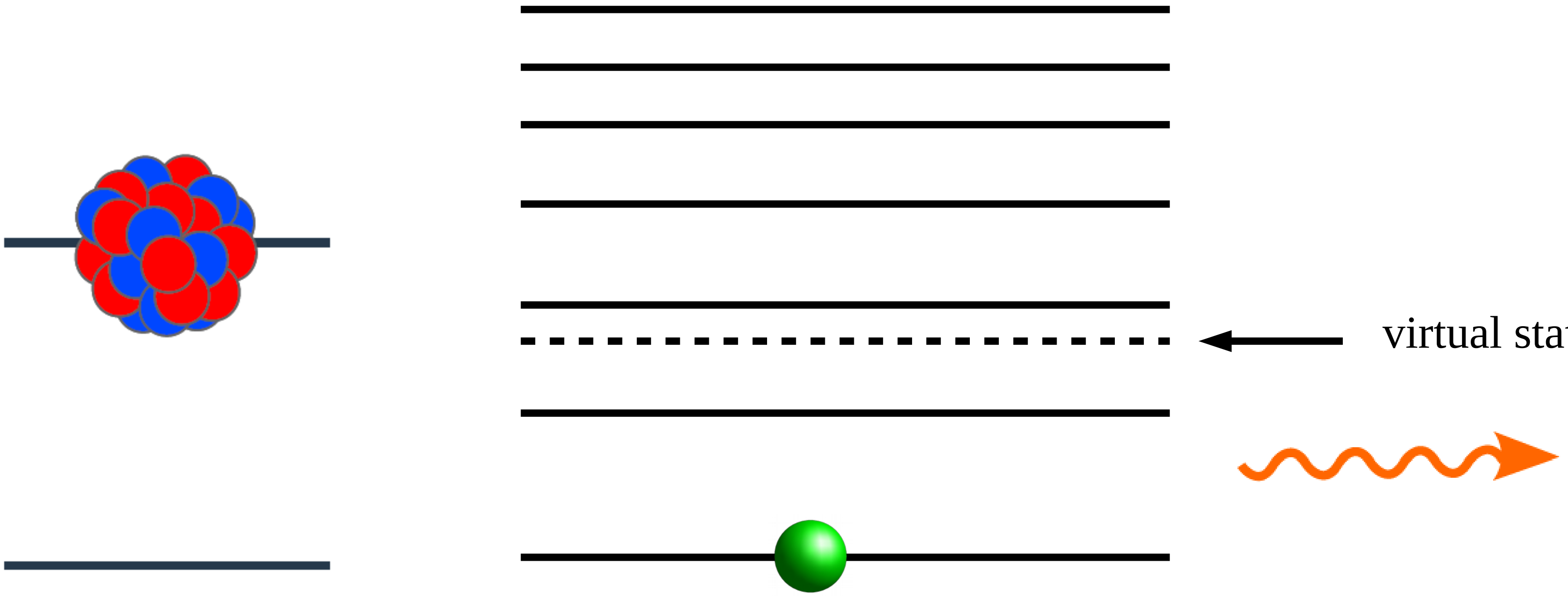


Imagine EB with nuclear excitation

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

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

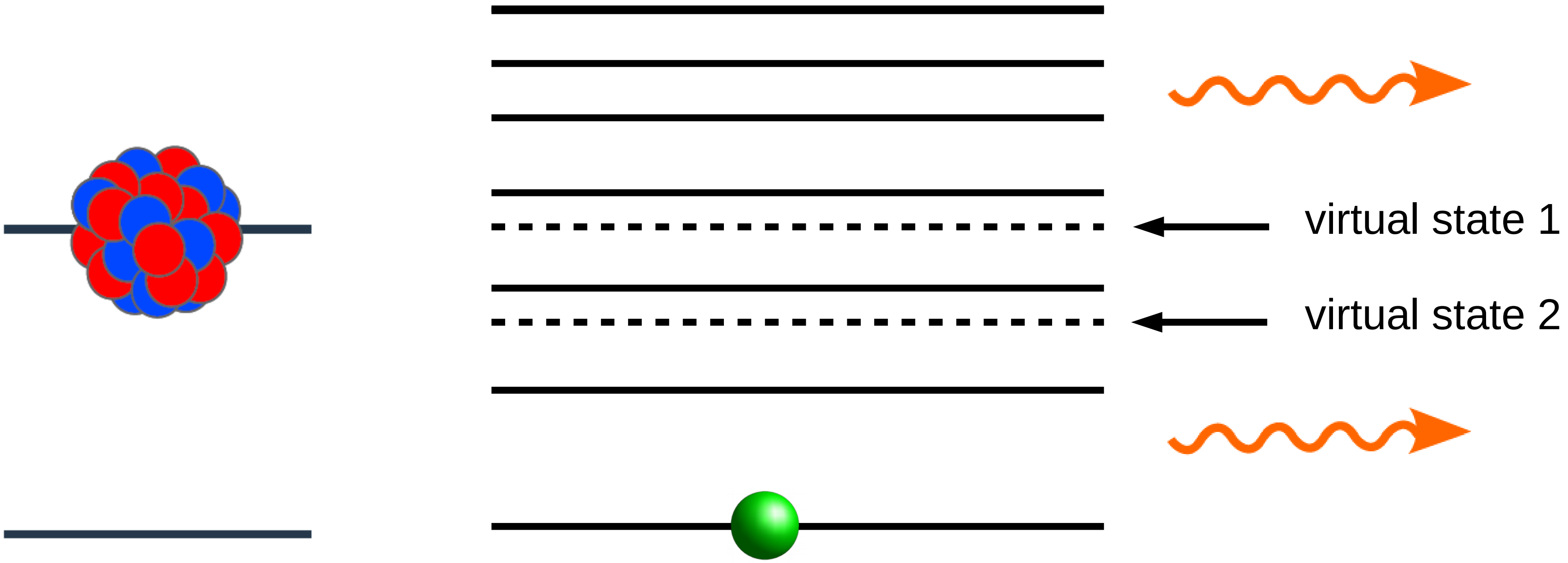


Imagine EB with nuclear excitation

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

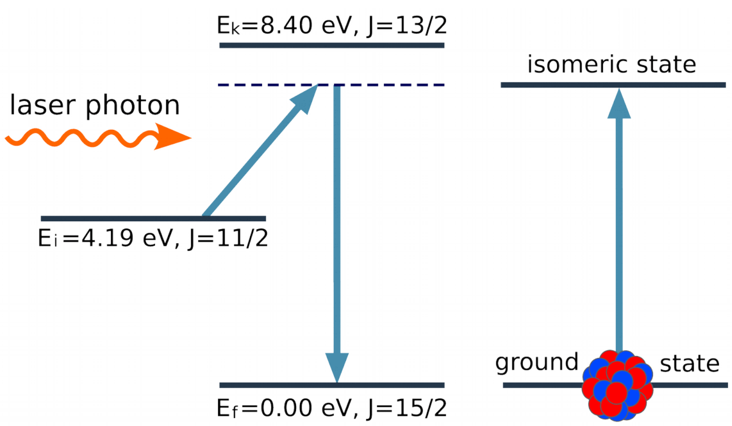
$$E_{el} = E_{nucl} + \hbar\omega$$

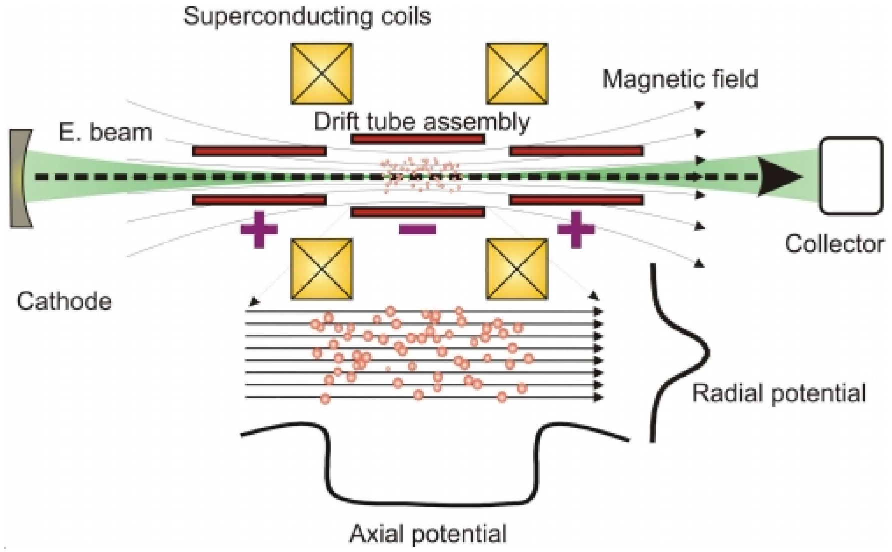
via VS1: photon + nuclear excitation
via VS2: nuclear excitation + photon



… in highly charged ions

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



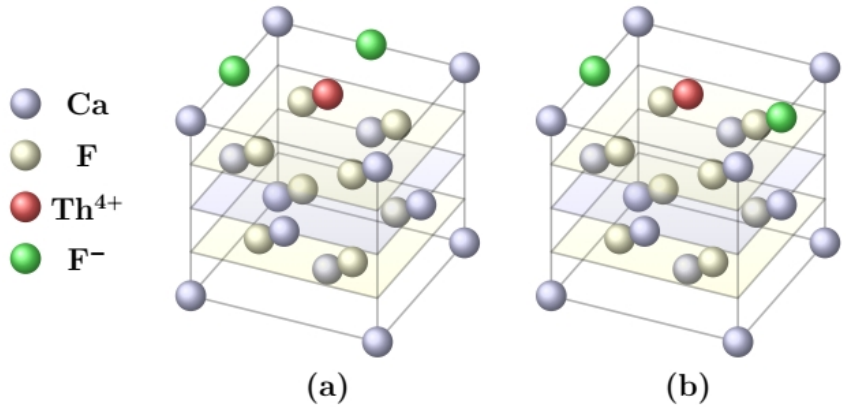


- Open 4f shell, many electronic M1 transitions allowed
- Initial state populated (17% in steady state) by collisions in EBIT
- EB nuclear excitation scheme, allows sub-meV determination of isomer energy
- 1 day scanning campaign

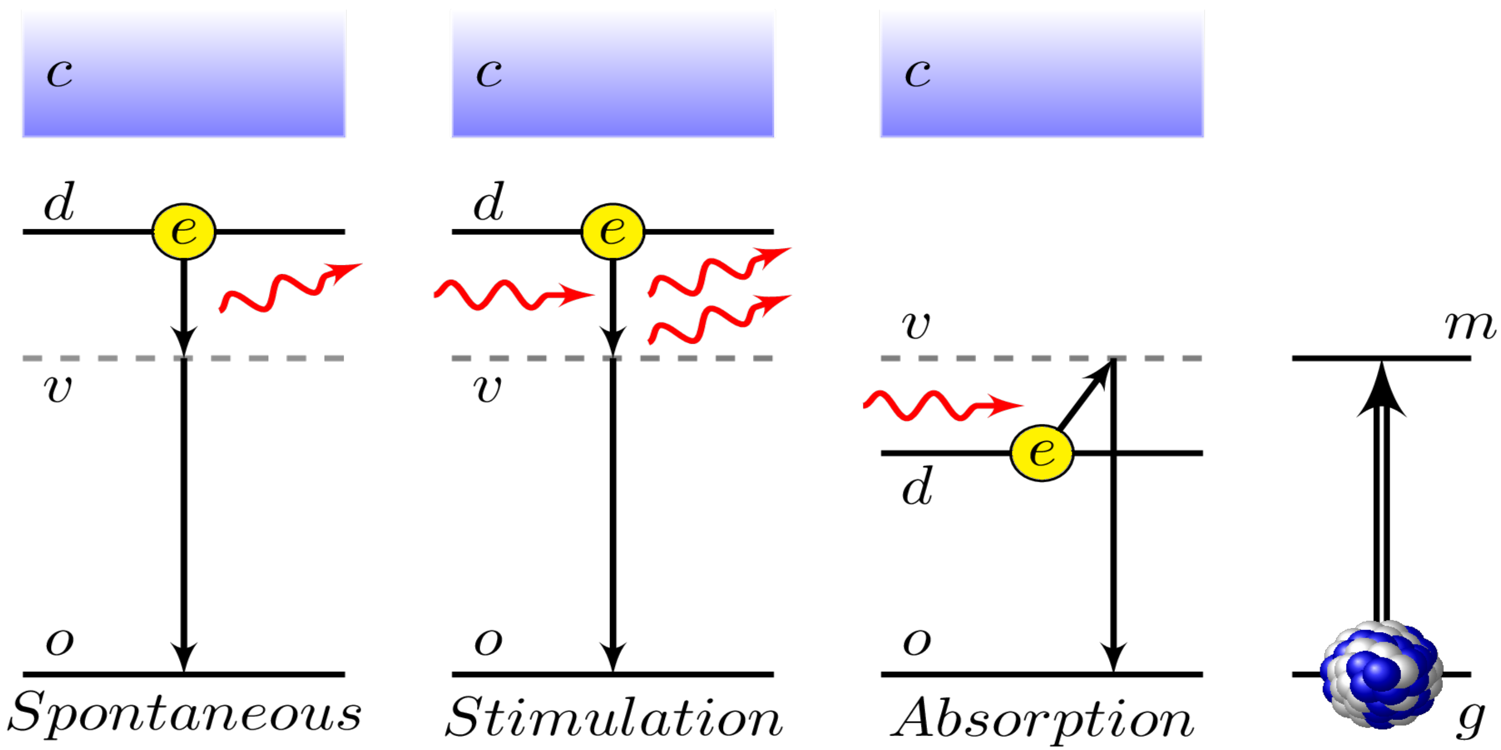
P. V. Bilous, H. Bekker, … , AP, PRL 124, 192502 (2020)

in VUV-transparent crystals

CaF_2

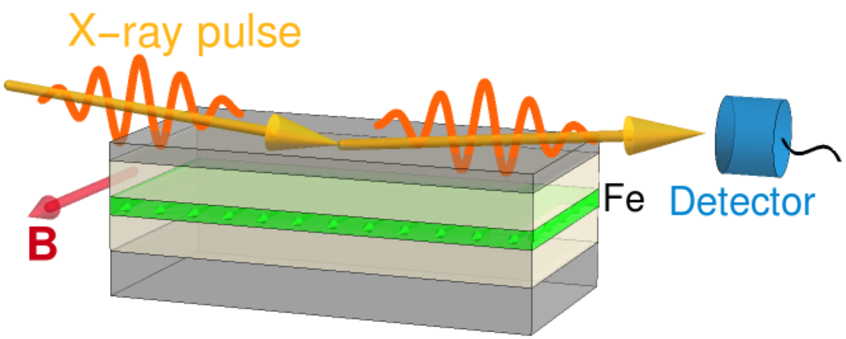


- Doping of [229]Th introduces defect states
- 2p interstitial F electron moves to 5f dopant Th
- EB scheme allows 2 orders of magnitude faster excitation/quenching.



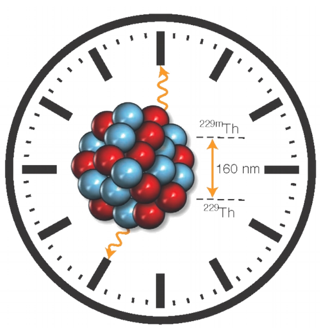
B. S. Nickerson, M. Pimon, … , AP, PRL 125, 032501 (2020)

Conclusions



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

Exploit this for quantum applications/imaging?



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
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Sergei Kobzak

Theory Division:
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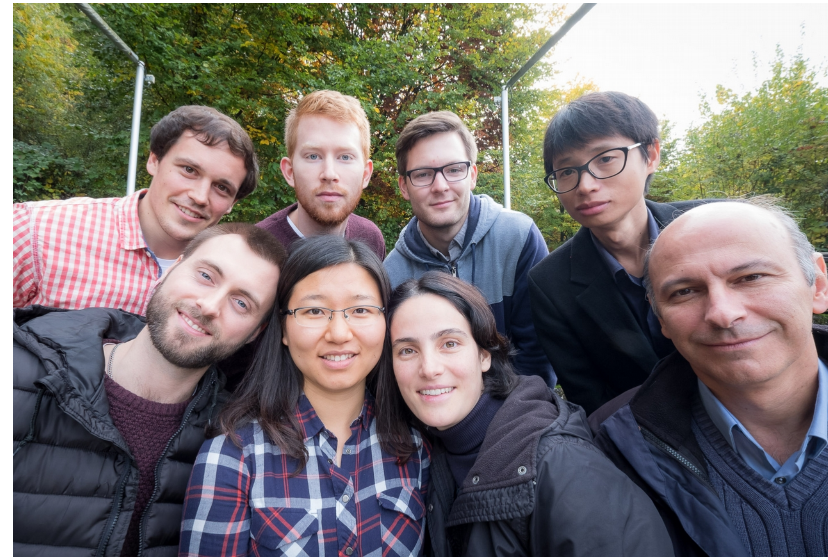
Jörg Evers



TRR 306
QuCoLiMa
Quantum Cooperativity of Light and Matter

DESY.

Ralf Röhlsberger
Lars Bocklage

European Commission

DFG

LMU
LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

Peter Thirolf
Benedict Seiferle
Lars von der Wense

thorium nuclear clock

Heisenberg-Programm
DFG Deutsche Forschungsgemeinschaft

isoQuant SFB1225

nuClock

THANK YOU FOR YOUR ATTENTION!