Nuclear isomers in intense electromagnetic fields

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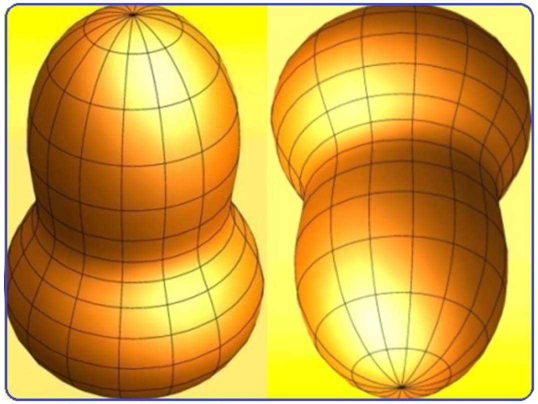

SDANCA-15

Sofia, October 8th, 2015

Max Planck Institute in Heidelberg

Light-nuclei interaction (Theory)

Wen-Te Liao
Jonas Gunst
Xiangjin Kong
Jörg Evers
Hans A. Weidenmüller
Christoph H. Keitel

Astroparticle physics

Quantum dynamics - interaction of laser light with matter

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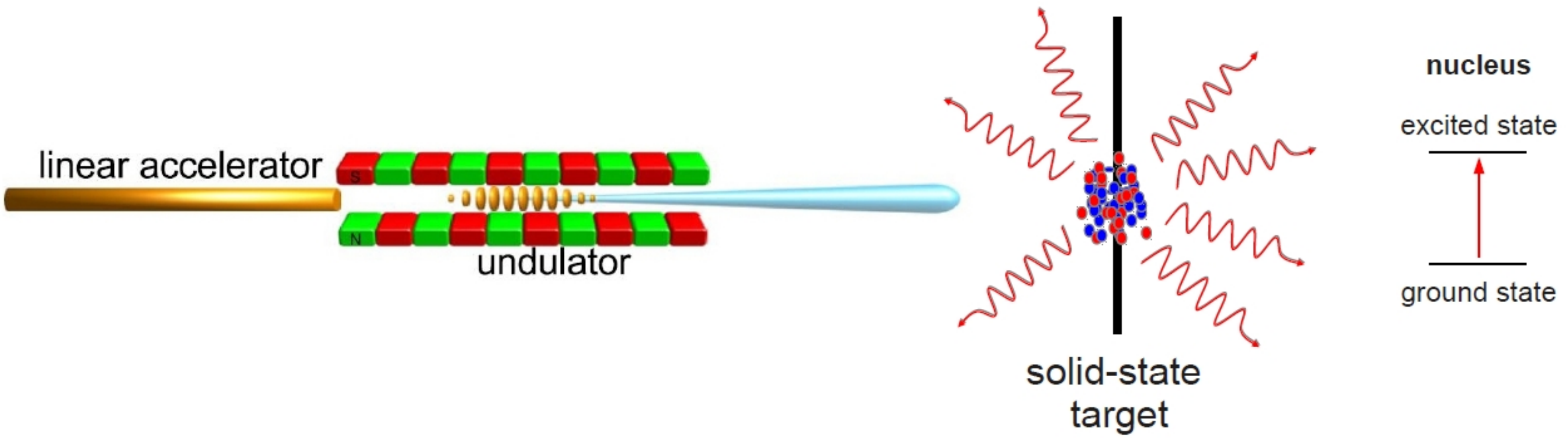
Outline – what could one attempt with light and isomers?

Part 1. Isomer triggering with the X-ray Free Electron Laser (XFEL)

Part 2. Nuclear quantum optics with ^{229}Th

Isomer triggering with the XFEL

Stronger XFEL excitation

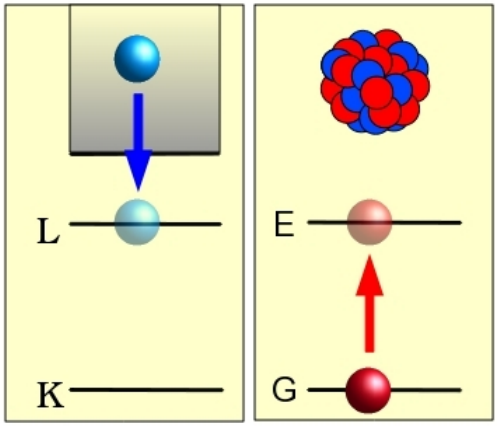


Secondary nuclear processes become possible in the plasma environment:

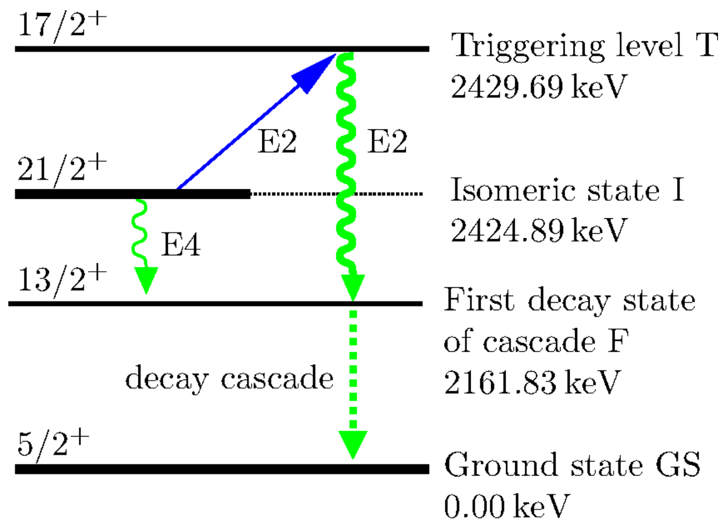
- Secondary photoexcitation

- Coupling to the atomic shell

Nuclear excitation by electron capture - NEEC



Isomer triggering



Partial level scheme of ${}^{93}_{42}\mathrm{Mo}$

Triggering mechanisms

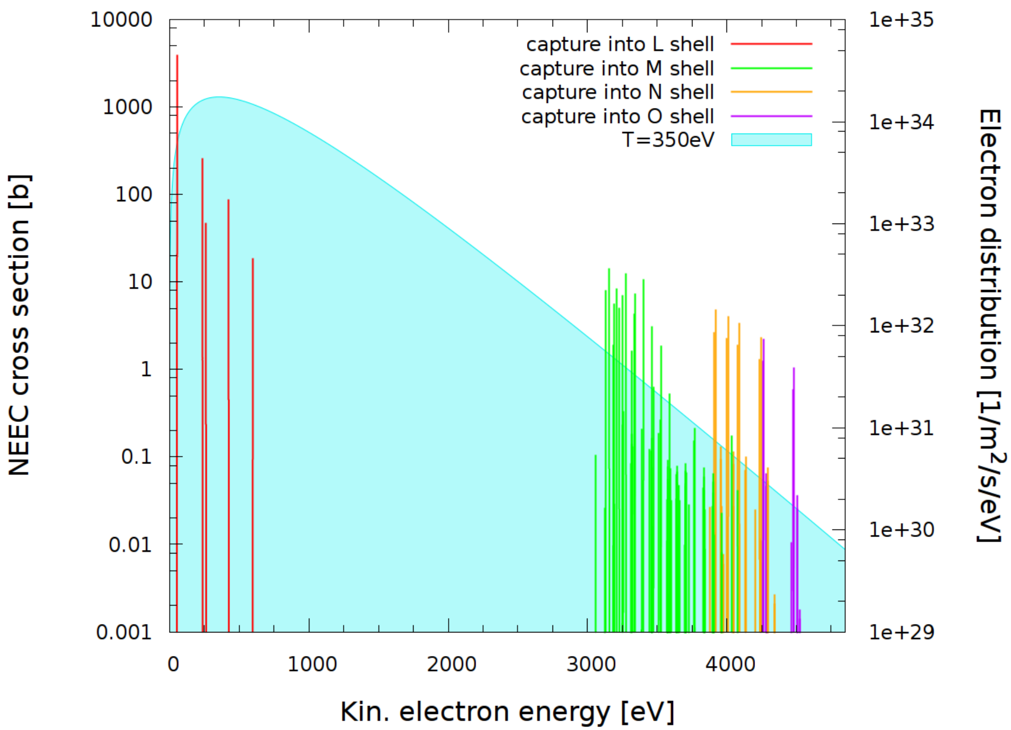
- Photoexcitation
- Coulomb excitation
- NEEC

Typically, $\sigma_{neec} \simeq 100 \times \sigma_{ph}$ for low-lying triggering levels

Competition in the nuclear excitation process between

resonant XFEL photons – direct photoexcitation
plasma electrons – NEEC

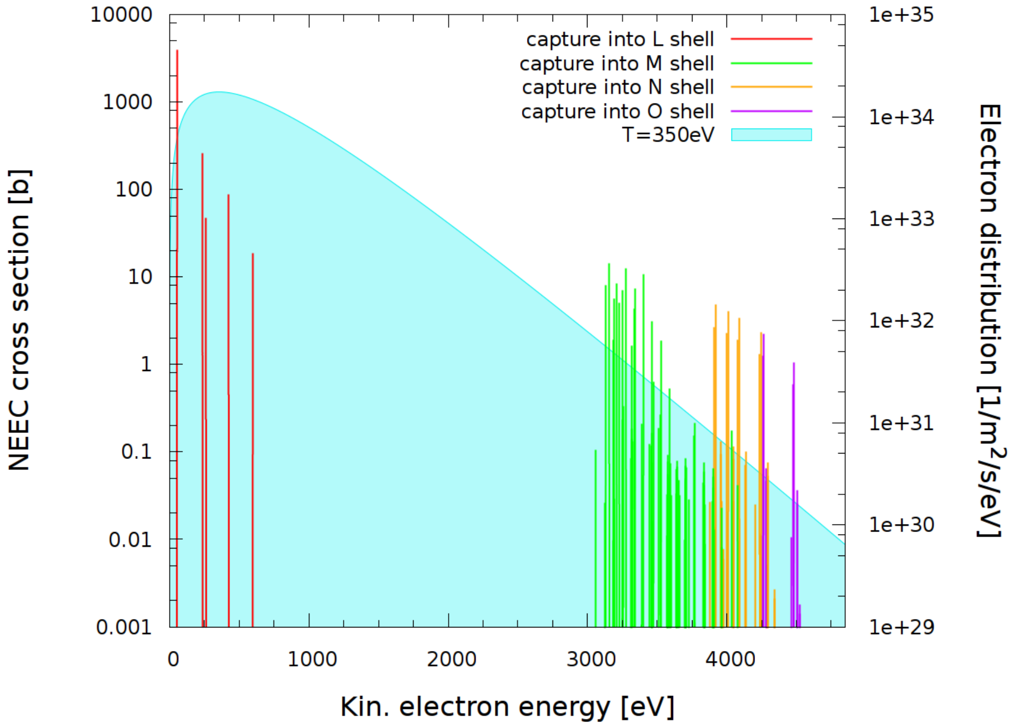
NEEC wins overhand as secondary process

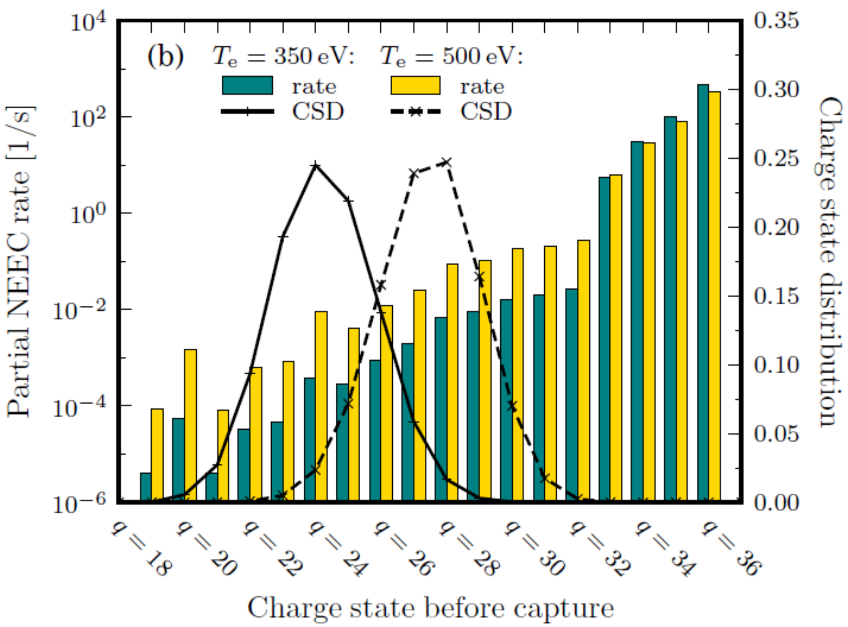


NEEC cross sections, available electron energies and charge states in the plasma

J. Gunst, Y. Litvinov, C. H. Keitel and AP, Phys. Rev. Lett. 112, 082501 (2014)

NEEC wins overhand as secondary process



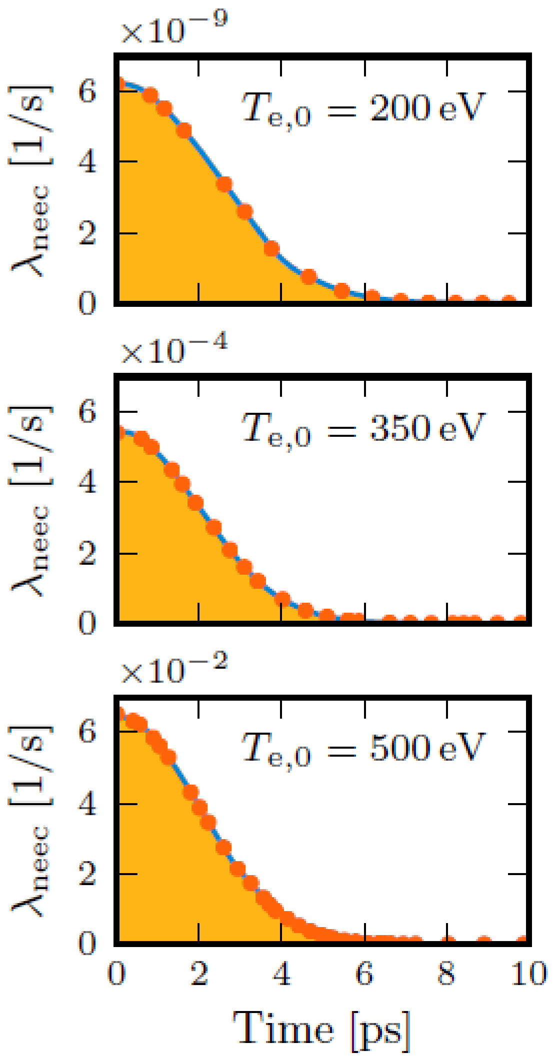


NEEC cross sections, available electron energies and charge states in the plasma

NEEC excitation 5 orders of magnitude larger than direct photoexcitation!!!

J. Gunst, Y. Litvinov, C. H. Keitel and AP, Phys. Rev. Lett. 112, 082501 (2014)

NEEC wins overhand as secondary process



- Plasma expansion after pulse - thermodynamical model
- Atomic processes included via FLYCHK code
- Time for NEEC much longer than XFEL pulse duration
- For Mo advantageous plasma parameters for NEEC
- Total rates still too small for experimental observation of isomer triggering in Mo

NEEC excitation 5 orders of magnitude larger than direct photoexcitation!!!

J. Gunst, Y. Wu, N. Kumar, C. H. Keitel and AP, arXiv: 1508.07264 (2015)

Nuclear quantum optics with ^{229}Th

A possible nuclear frequency standard

THE SECOND

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

nuClock ^{229m}Th, E=7.8 eV

NARROW TRANSITION WIDTHS

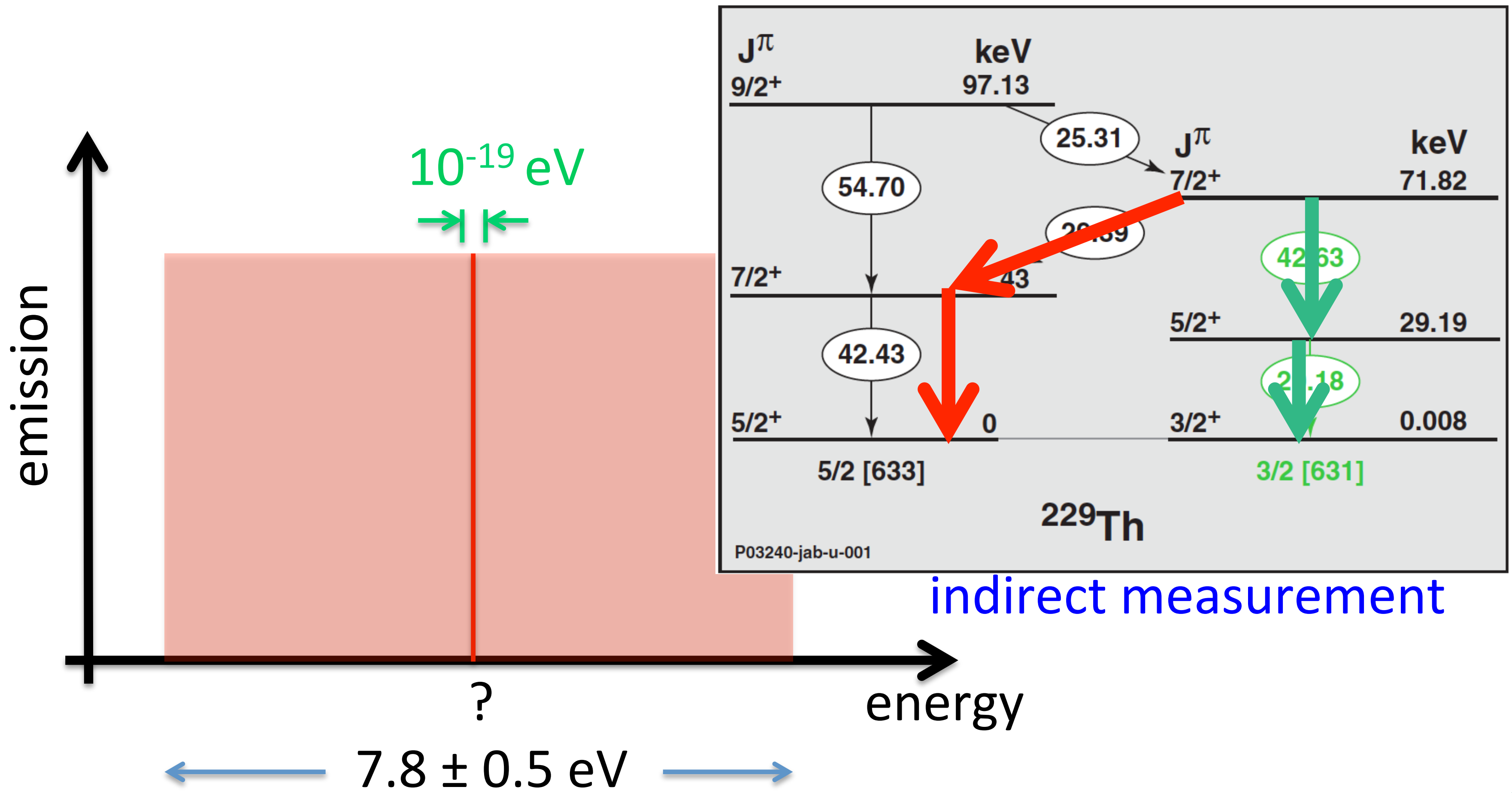
$$^{229}\mathrm{Th} \quad \Delta E/E \simeq 10^{-20}$$

ISOLATION FROM ENVIRONMENT

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

fine structure constant, strong interaction parameter

Critical Problems- 1 eV Uncertainty is Too Large



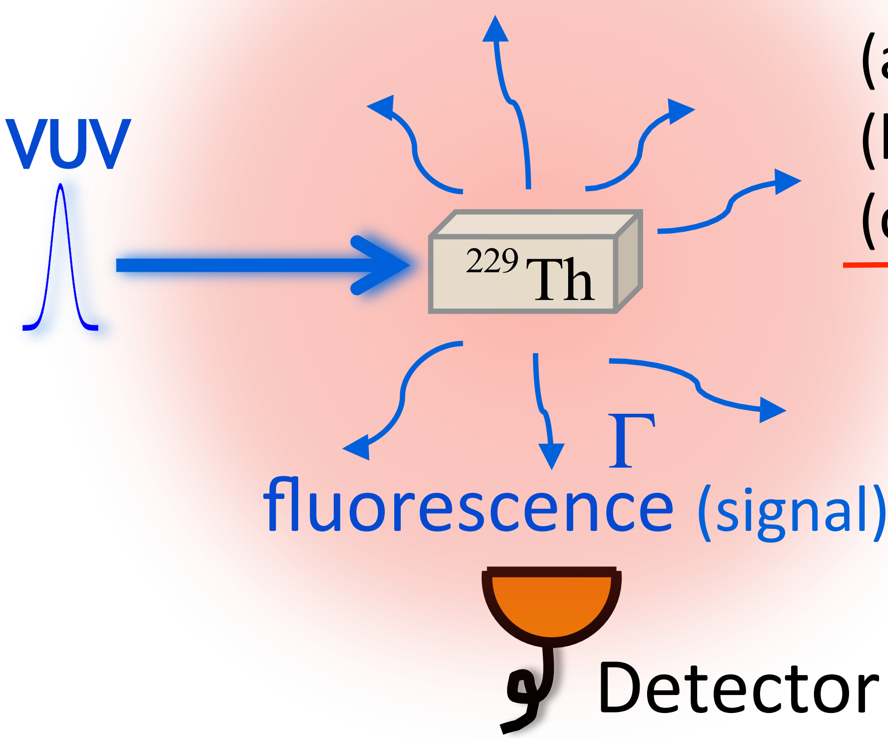
B. R. Beck, et. al, PRL. 98, 142501 (2007)

Critical Problems- Low Signal to Background Ratio

α induced spurious fluorescence (background)

(a) 0.3 photon/α decay
(b) ^{229g}Th lifetime 7880 yr
(c) 10^{18} ^{229}Th/cm^3

0.75 MHz in 4π



W. G. Rellergert, et. al, IOP Conf. Ser.: Mater. Sci. and Eng. 15, 012005 (2010)

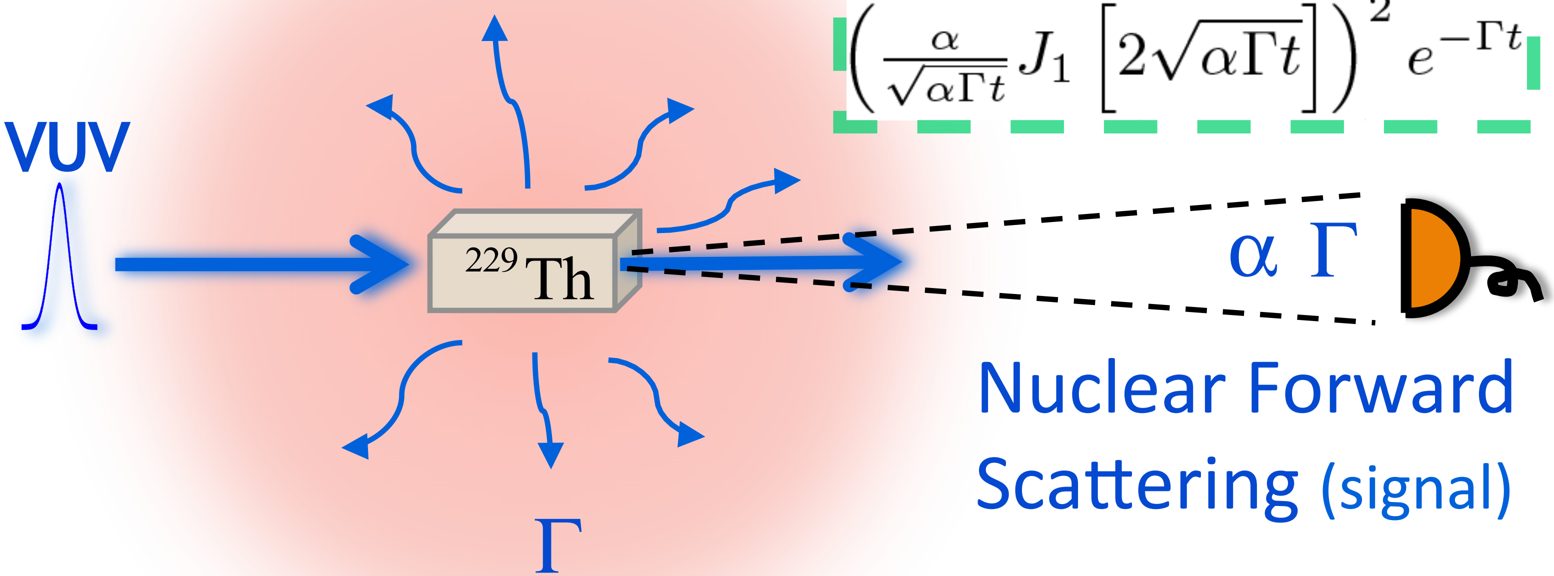
Forward Detection solves Critical Problems

α induced spurious fluorescence (background)

1.8 Hz in 1° × 1°

nuclear signature

$$\left(\frac{\alpha}{\sqrt{\alpha\Gamma t}} J_1\left[2\sqrt{\alpha\Gamma t}\right]\right)^2 e^{-\Gamma t}$$



fluorescence

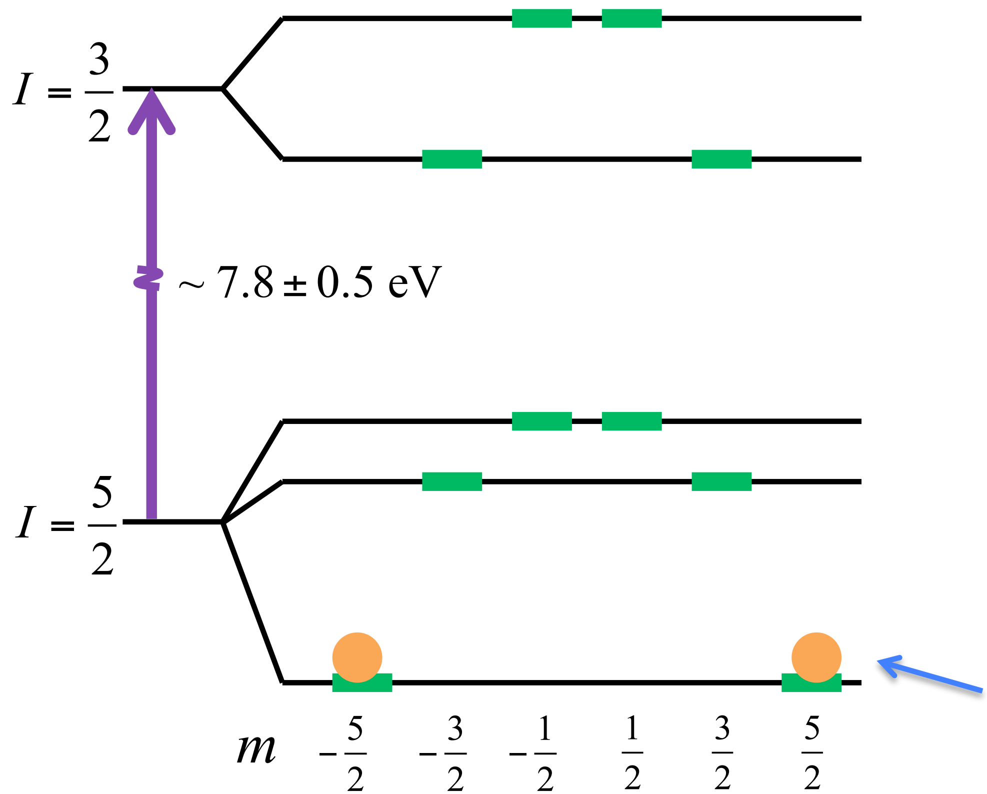
Nuclear Forward Scattering (signal)

W.-T. Liao, S. Das, C. H. Keitel and A. Pálffy, PRL 109, 262502 (2012)

Level Scheme of ^{229}Th inside Crystals

$$\langle Im|\hat{H}_{E2}|Im'\rangle = \delta_{mm'}\frac{Q\phi_{zz}}{4I(2I-1)}\left[3m^2 - I(I+1)\right]$$

^{229}Th:CaF$_2$

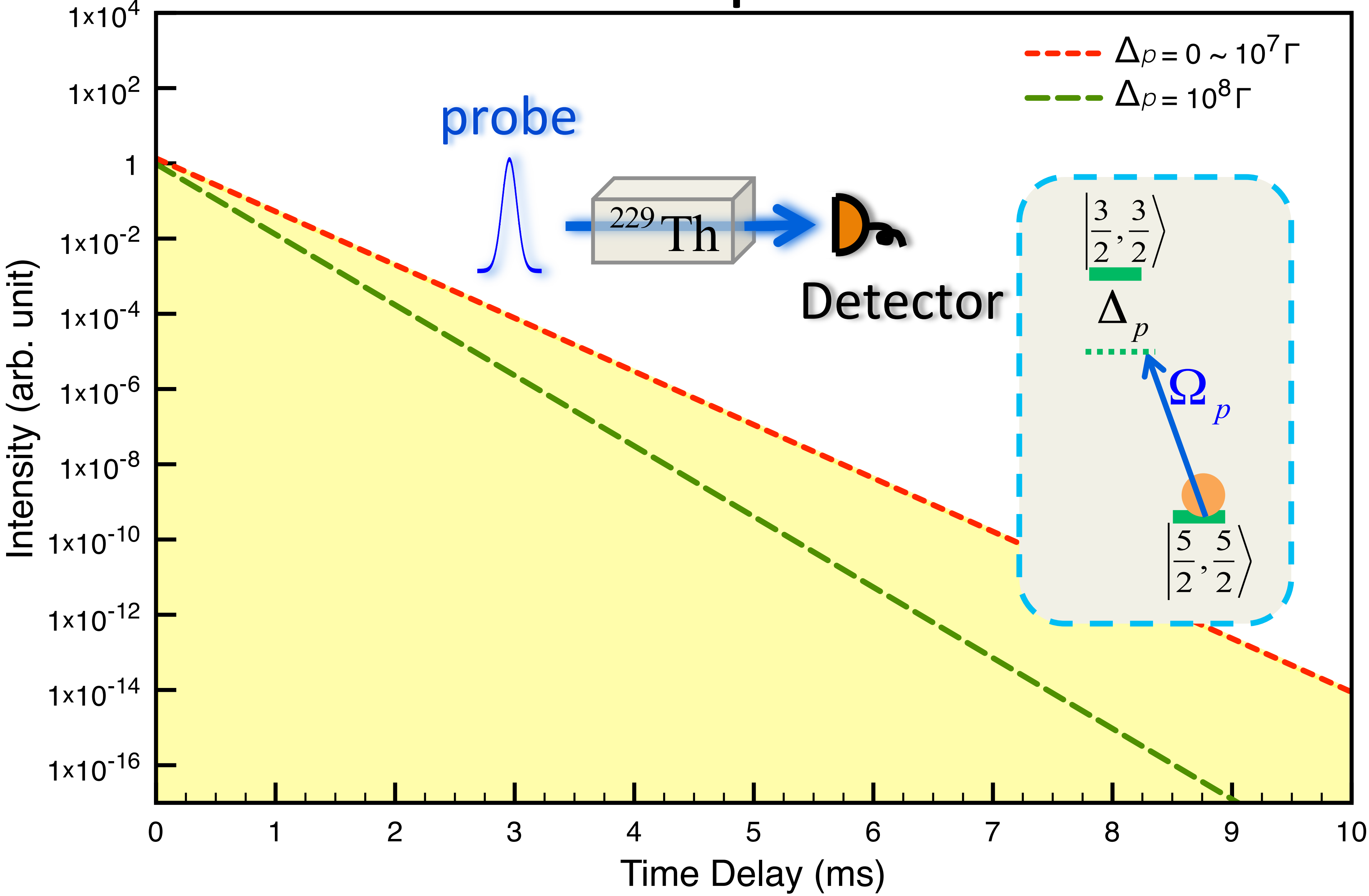


ϕ_{zz} = -5.1 × 10^{18} V/m^2
$Q_{5/2}$ = 3.149 eb
$Q_{3/2}$ = 1.8 eb
(eb = e × 10^{-24} cm^2)
quadruple splitting 10^{-7} eV

sub-Kelvin cooling via
spin-spin relaxation → kHz

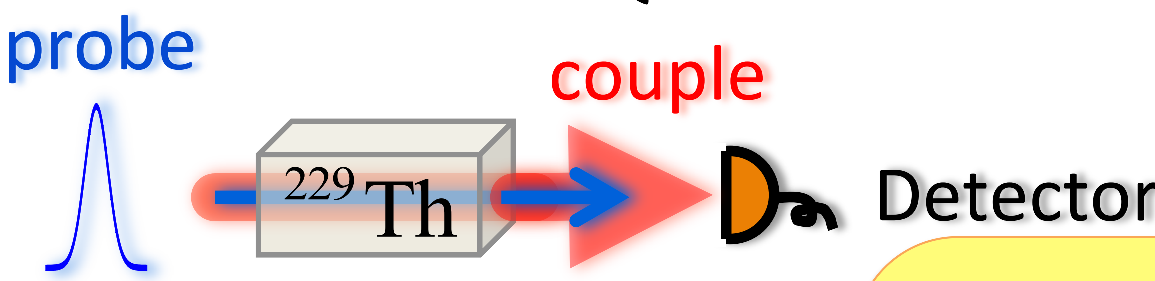
G. A. Kazakov, et. al., New J. Phys. 14 083019 (2012)
E. V. Tkalya, PRL 106, 162501 (2011)

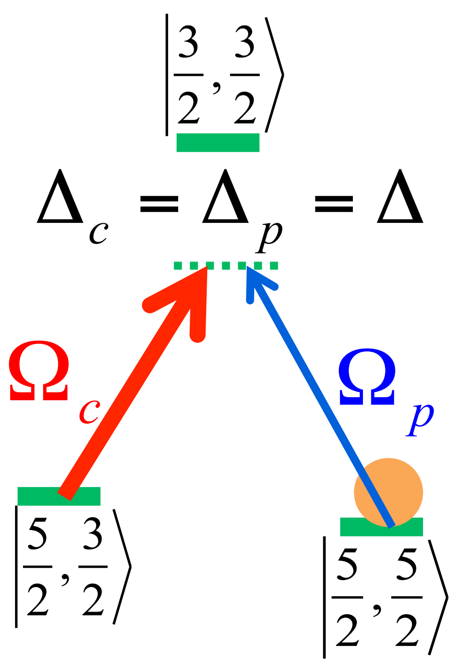
NFS Time Spectrum

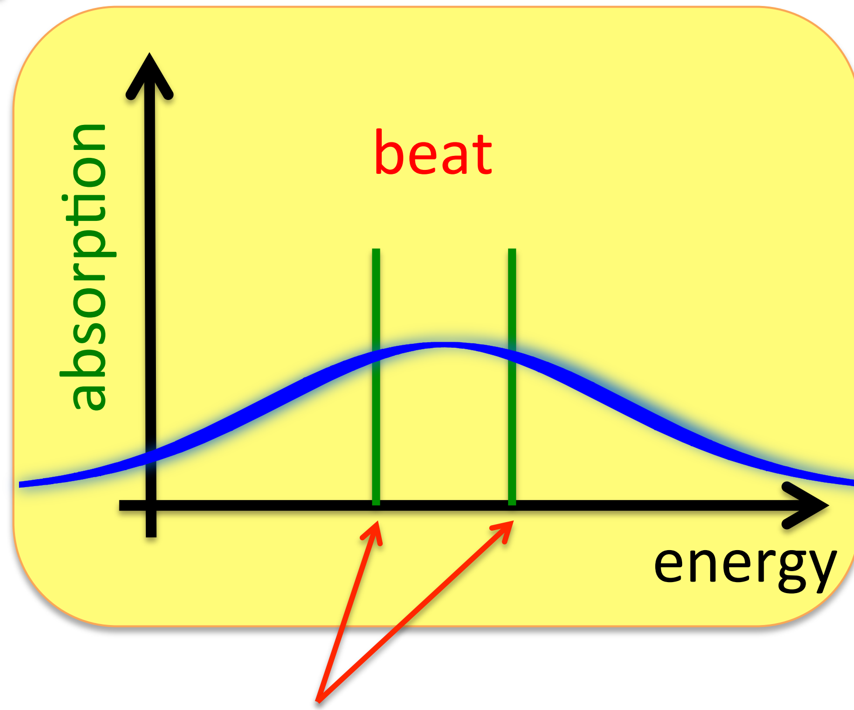


W.-T. Liao, S. Das, C. H. Keitel and A. Pálffy, PRL 109, 262502 (2012)

Electromagnetically induced Quantum Beat







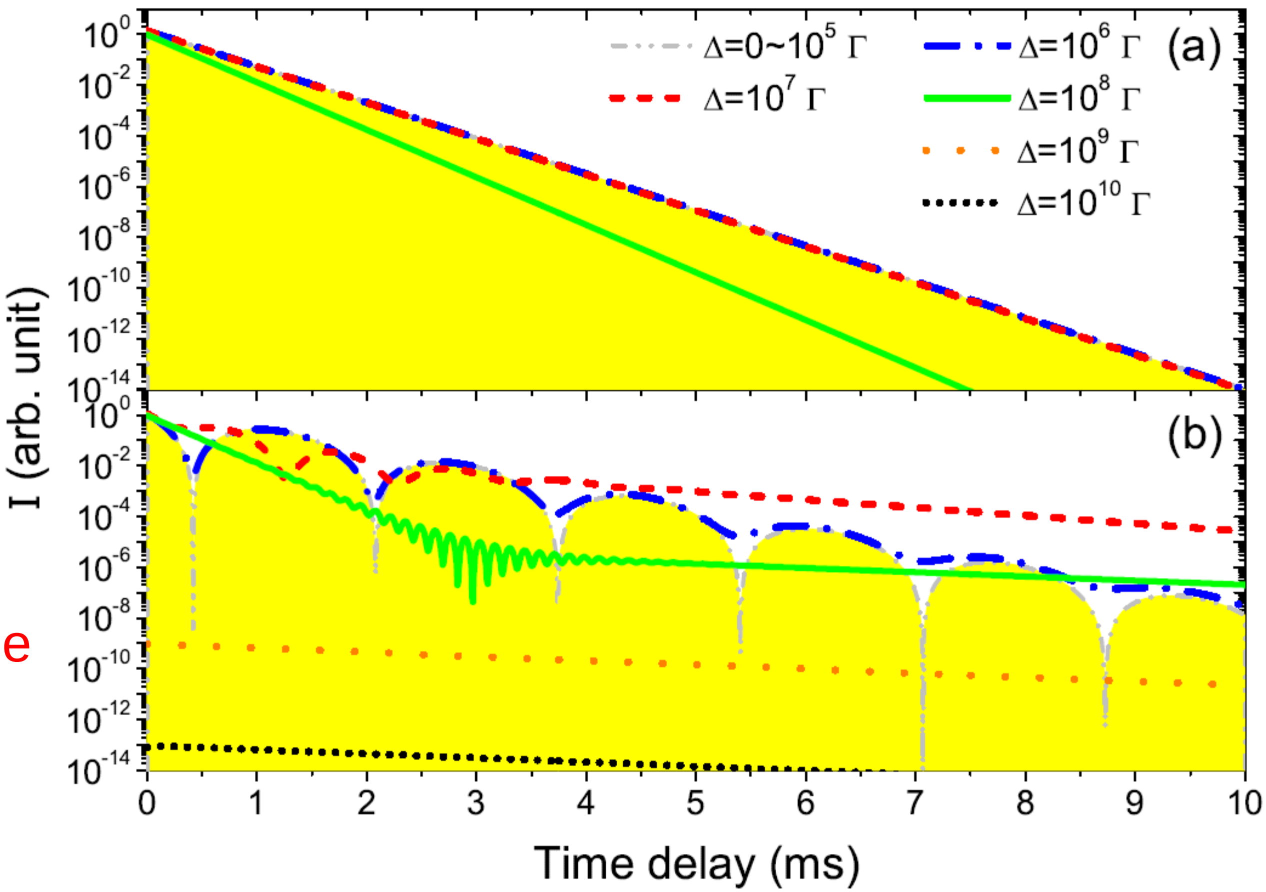
Autler-Townes splitting by Ωc ~ kHz
with coupling laser intensity 2 kW/cm^2

S. H. Autler and C. H. Townes, Phys. Rev. 100, 703 (1955)

Coherence enhanced optical determination

→ traditional fluorescence with one field

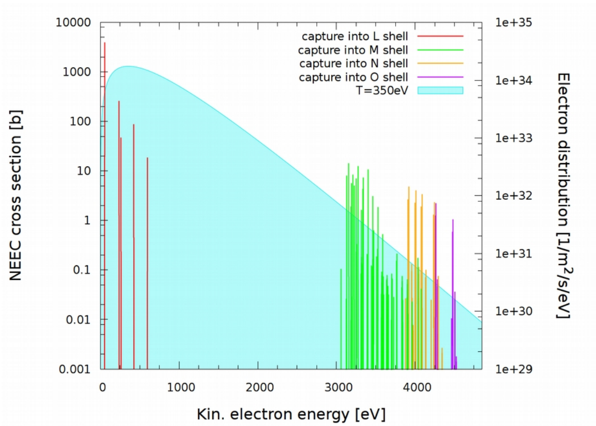
→ two-field Lambda scheme



W.-T. Liao, S. Das, C. H. Keitel and AP, Phys. Rev. Lett. 109, 262502 (2012)

Summary

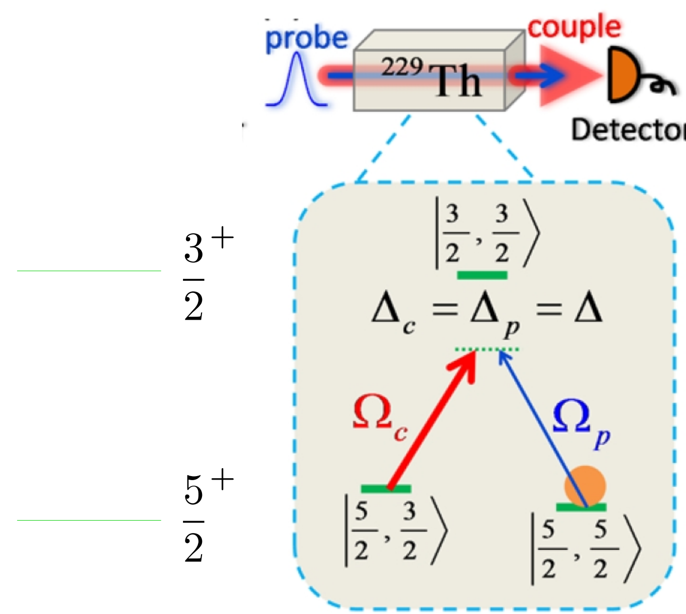
Part 1. Isomer triggering with the XFEL



NEEC exotic nuclear excitation mechanism predominates in dense plasmas for small E

Part 2. Nuclear quantum optics with ^{229}Th

coherence effects in ^{229}Th useful to determine the nuclear transition frequency



European Commission

joint efforts with PTB, TU Vienna, TU München, Jyväskylä, MPQ, U Heidelberg