Perspectives on XFELO driving atomic nuclei

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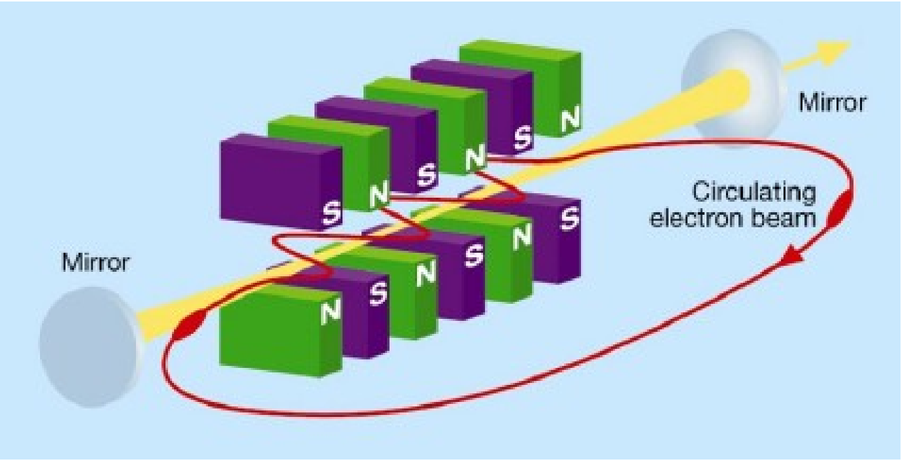
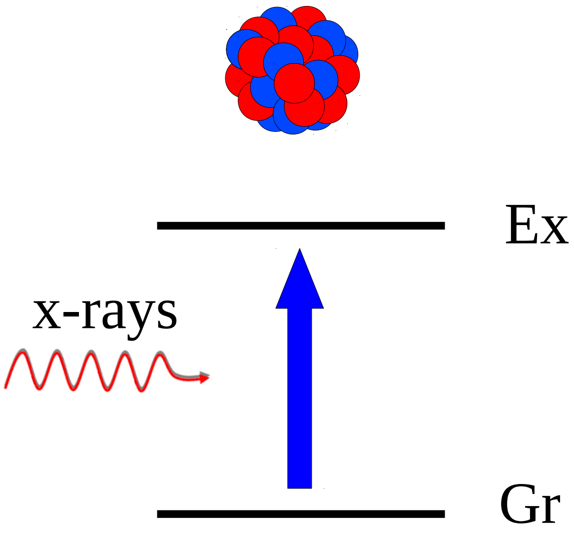
SLAC NATIONAL ACCELERATOR LABORATORY

XFELO Science Workshop, 29 June 2016

Few perspectives ...

… why atomic nuclei should meet the XFELO





• scaling in frequency from optical lasers + atoms

• scaling in brilliance from synchrotrons + nuclei

• special nuclear incentives

Previous experiences ...

- scaling in frequency from optical lasers + atoms

*coherent control**, *non-linear optics,*
dark states, slow light, entanglement,
electromagnetically induced transparency,
revolution in atomic physics, etc.

* relies on driving and control over most of the atomic state population!

CAN WE ACHIEVE SOMETHING SIMILAR WITH NUCLEI AND X-RAYS?

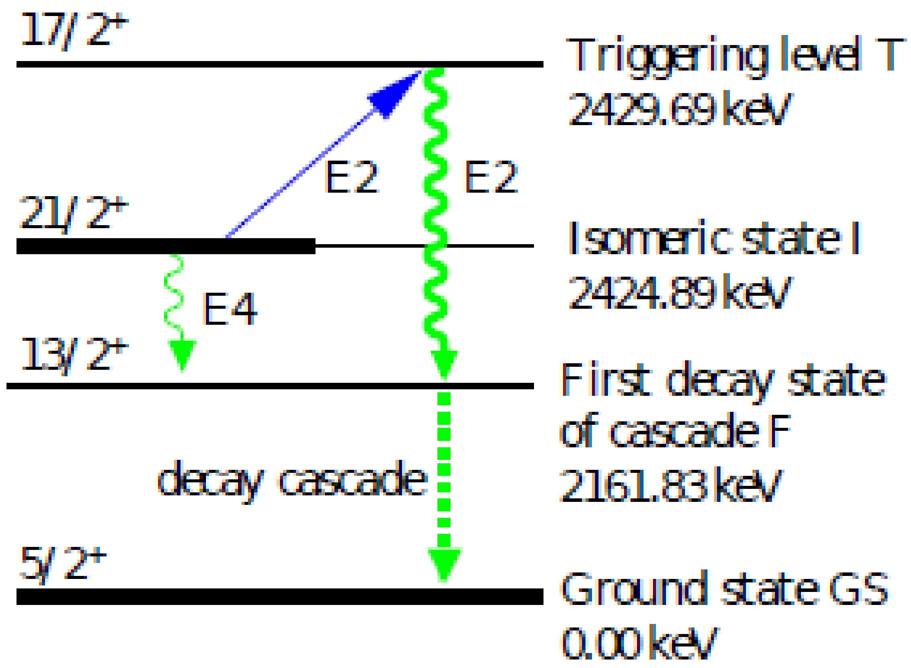
Special nuclear incentives ...

GAMMA-RAY LASERS

FREQUENCY STANDARDS

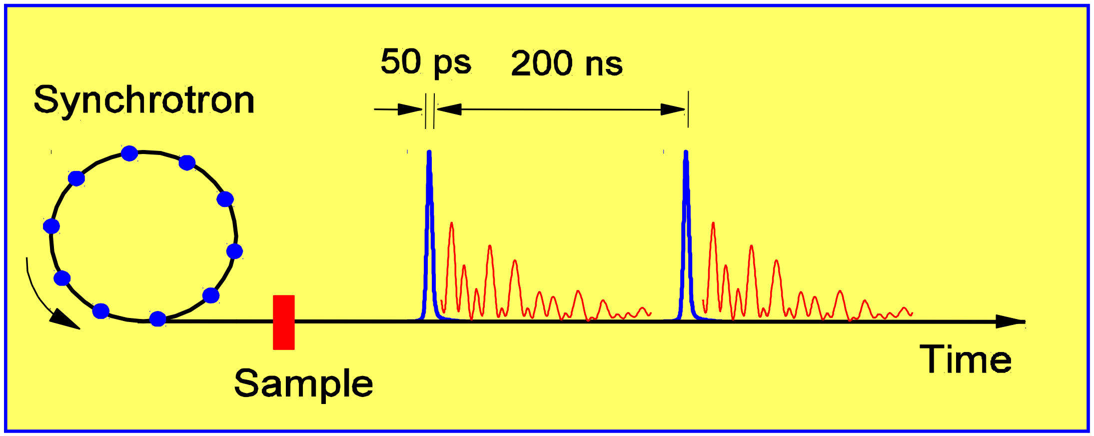
NUCLEAR ISOMERS

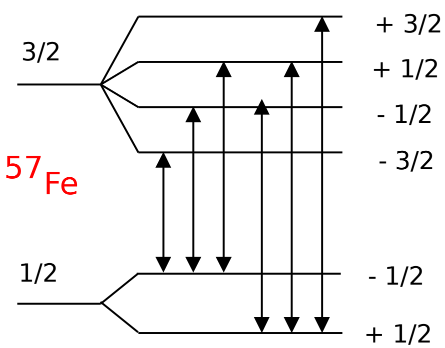
- long-lived nuclear states
- nuclear batteries
- astrophysical interest



Previous experiences ...

• scaling in brilliance from synchrotrons + nuclei





@ 14.413 keV

Nuclear Forward Scattering (NFS) of Synchrotron Radiation

nuclear condensed matter physics based on the Mössbauer effect,
*control of nuclear decay for ensembles of nuclei**, *storing single x-ray photons*

* relies on weak excitation, a single nucleus only!

WHAT HAPPENS WHEN THE XFELO COMES INTO PLAY?
…to be discussed more in the Mössbauer session.

Nuclei @ XFELO … Outline

- Stronger photoexcitation

  … due to improved temporal coherence

- Applications: nuclear STIRAP, nuclear pump-probe experiments

  … relying on coherence and efficient excitation

- Nuclear reactions starting from excited states

  … new for nuclear physics; possibly in plasmas

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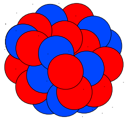
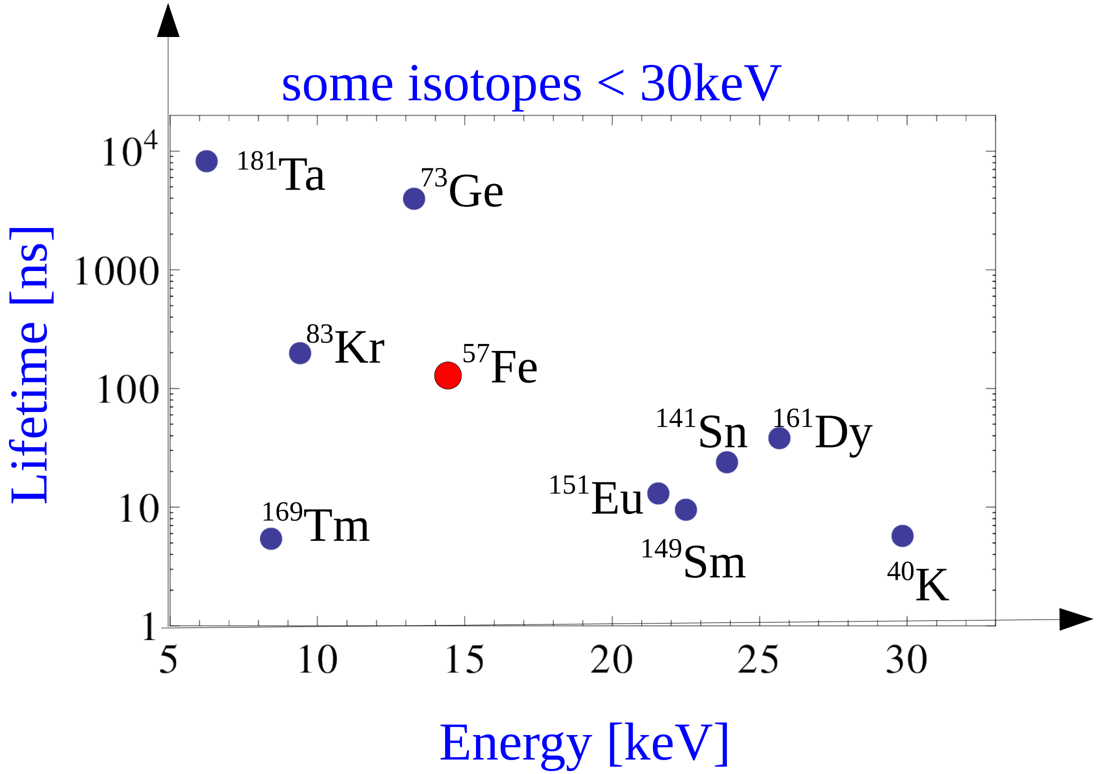
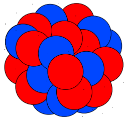
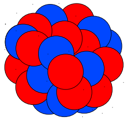
Nuclear transition energies







- typically very narrow widths
- not so many candidates

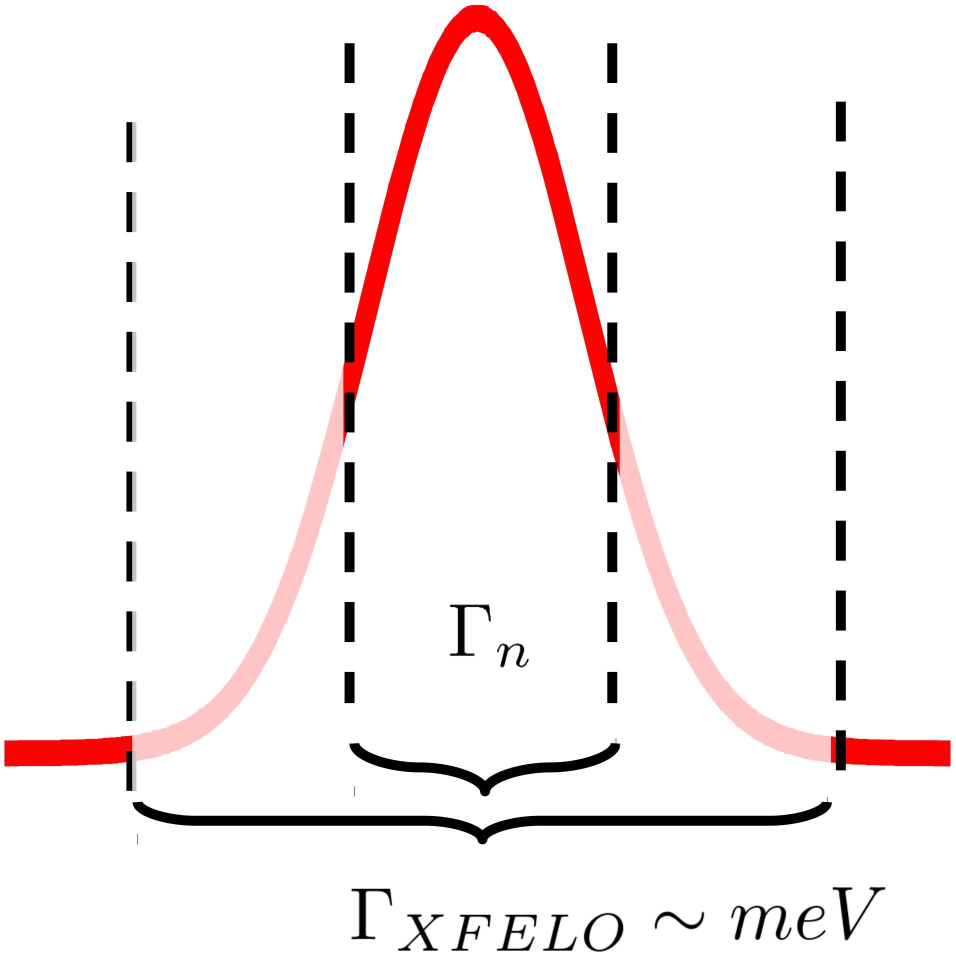


Nuclear transition widths

Nuclear widths are very narrow! $\Gamma_n \sim 10^{-8} - 10^{-5}\ eV$

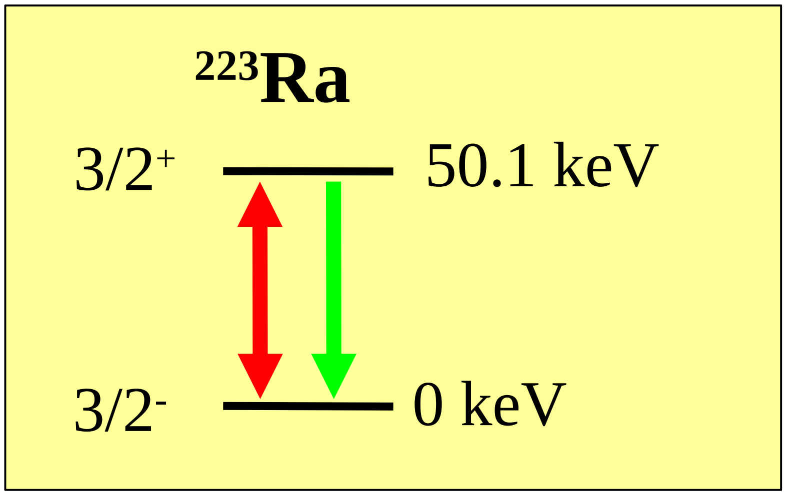
$$I_{eff} = I \frac{\Gamma_n}{\Gamma_{XFEL}}$$

effective intensity!



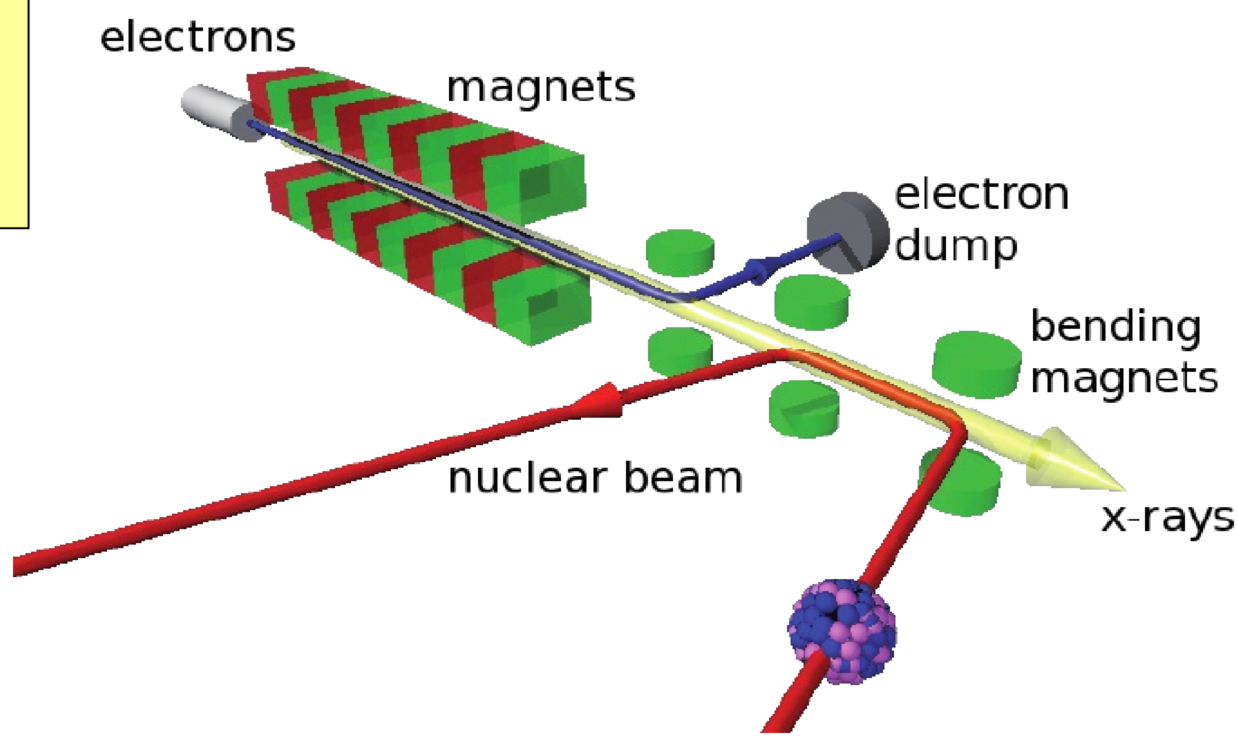
Accelerated nuclei as targets

bridge the gap between nuclear excitation and photon energies...



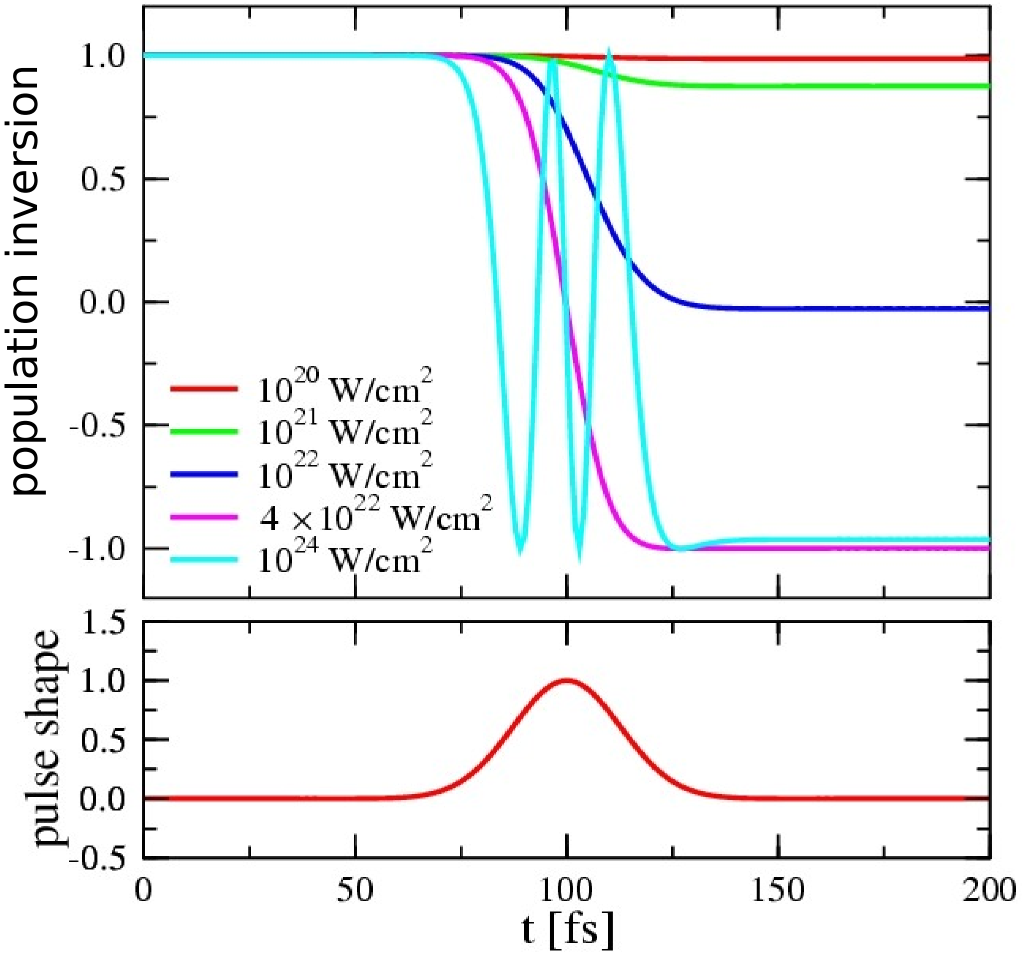
Doppler shift

$$E_n = (1+\beta)\gamma E_L$$



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

Nuclear Rabi flopping



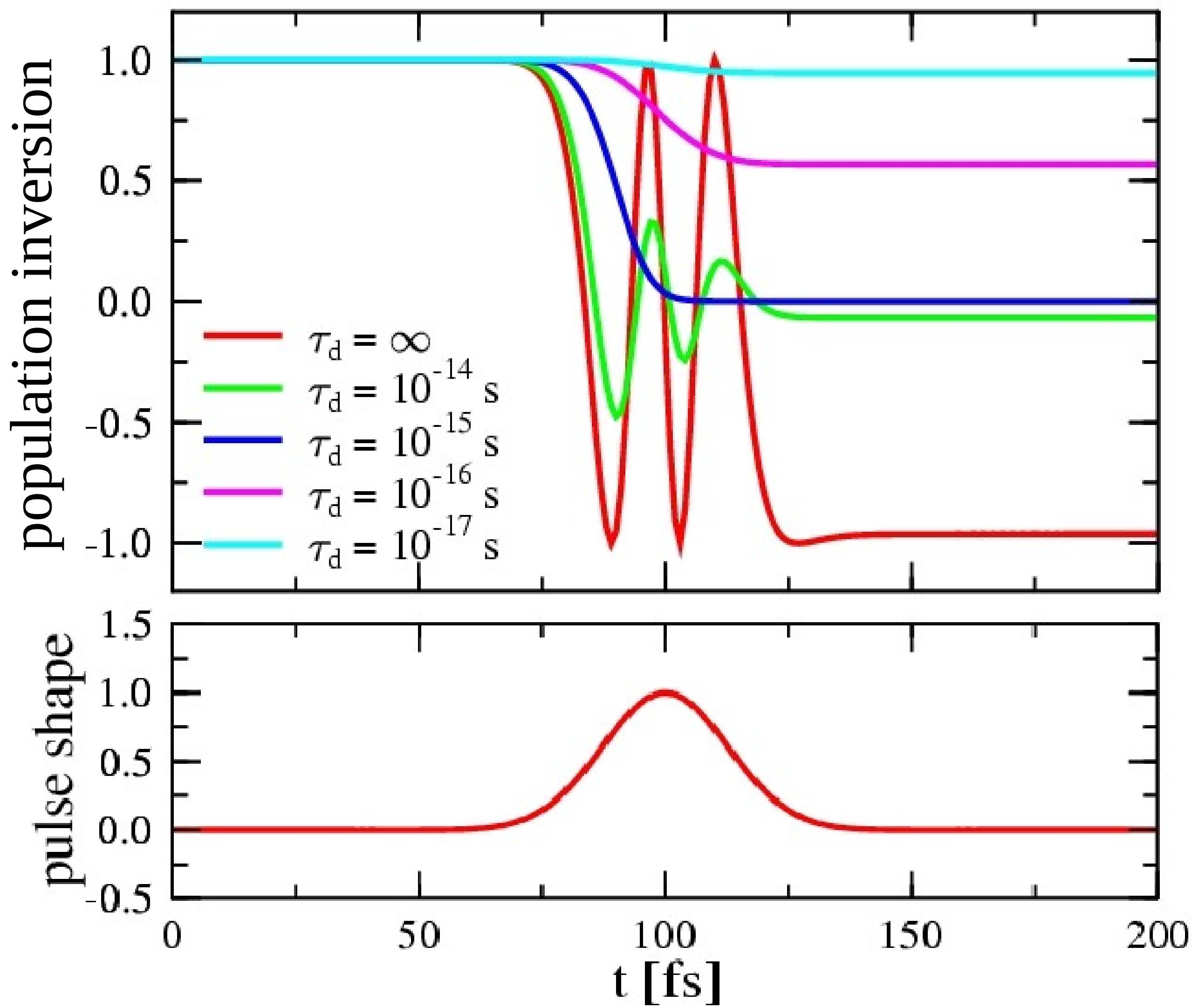
Population inversion in ^{223}Ra

- resonant laser-nucleus interaction allows to induce Rabi flopping of nuclear population
- potential application: model-free determination of nuclear parameters

T. Bürvenich, J. Evers and C. H. Keitel, Phys. Rev. Lett. 96, 142501 (2006)

Coherence in nuclear Rabi floping

coherence ⟷ intensity



strongly incoherent

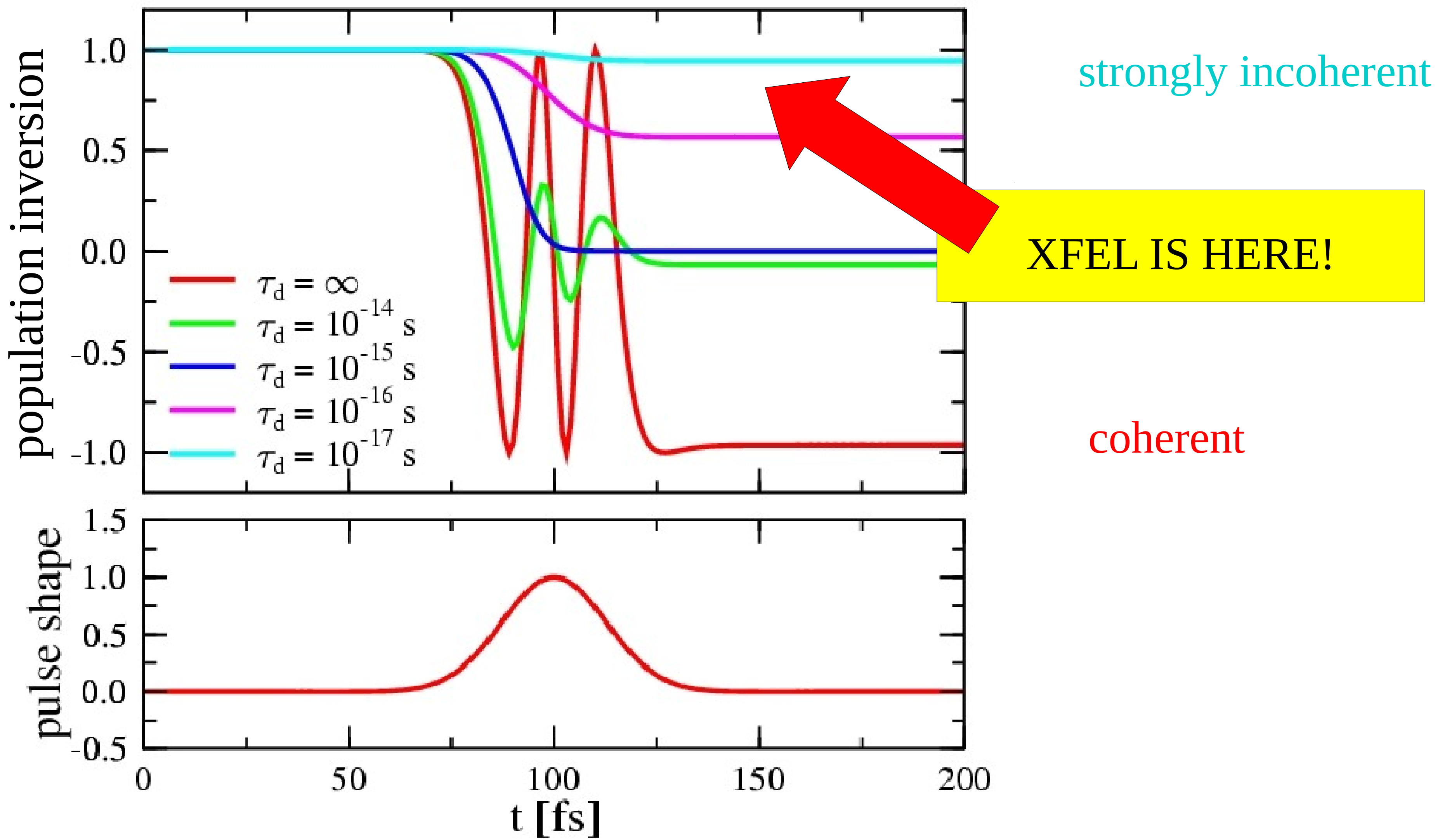
partially coherent

coherent

T. Bürvenich, J. Evers and C. H. Keitel, Phys. Rev. Lett. 96, 142501 (2006)

Coherence in nuclear Rabi floping

coherence ⟷ intensity



T. Bürvenich, J. Evers and C. H. Keitel, Phys. Rev. Lett. 96, 142501 (2006)

XFELO photoexcitation

Several orders of magnitude more efficient than LCLS for instance due to

- temporal coherence
- high repetition rate

See talk by Jörg Evers tomorrow
– predictions of strong excitation up to population inversion in thin-film cavities!

→ EXPLOIT THIS POSSIBILITY AND TRANSFER ATOMIC PHYSICS SCHEMES TO NUCLEAR SYSTEMS!

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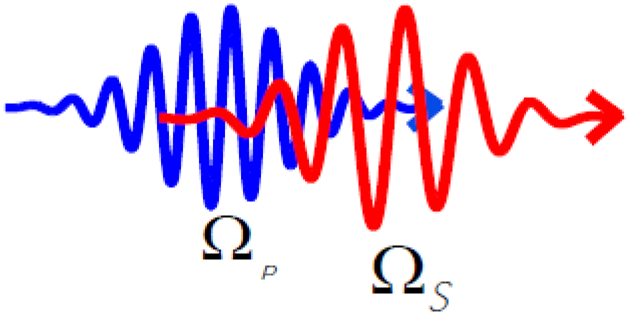
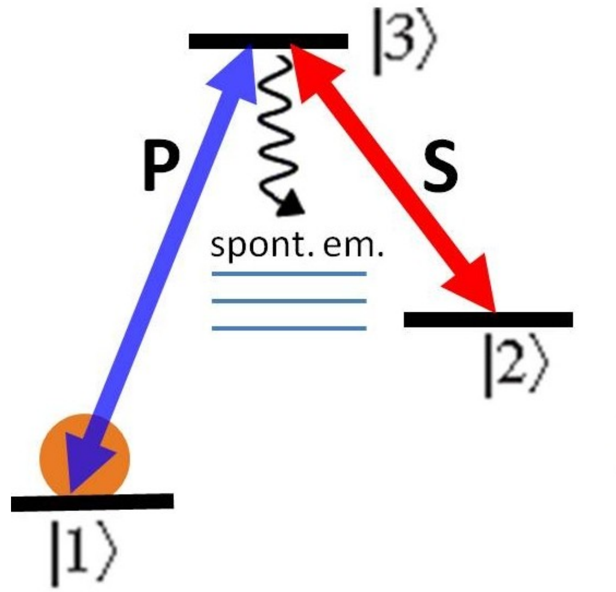
STIRAP

STImulated Raman Adiabatic Passage





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

K. Bergmann, H. Theuer, B.W. Shore, Rev. Mod. Phys. 70, 1003 (1998) 1003

STIRAP

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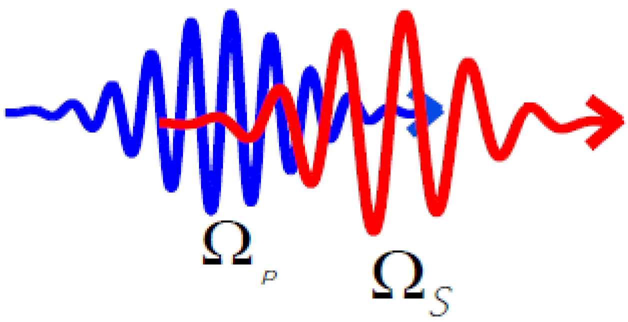
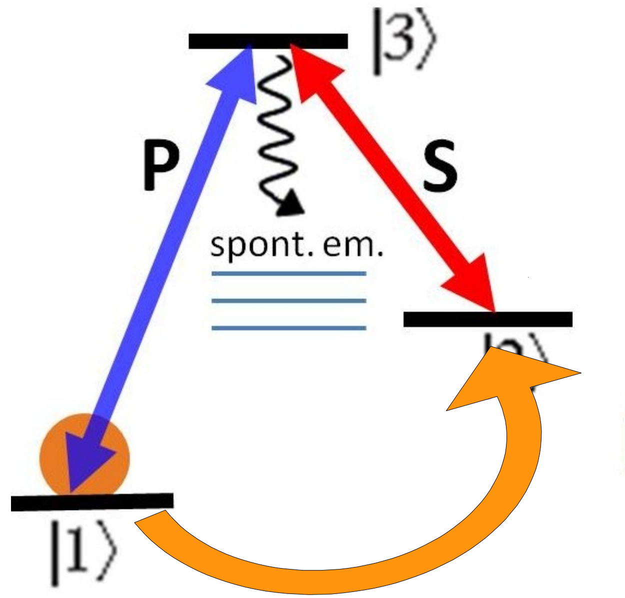
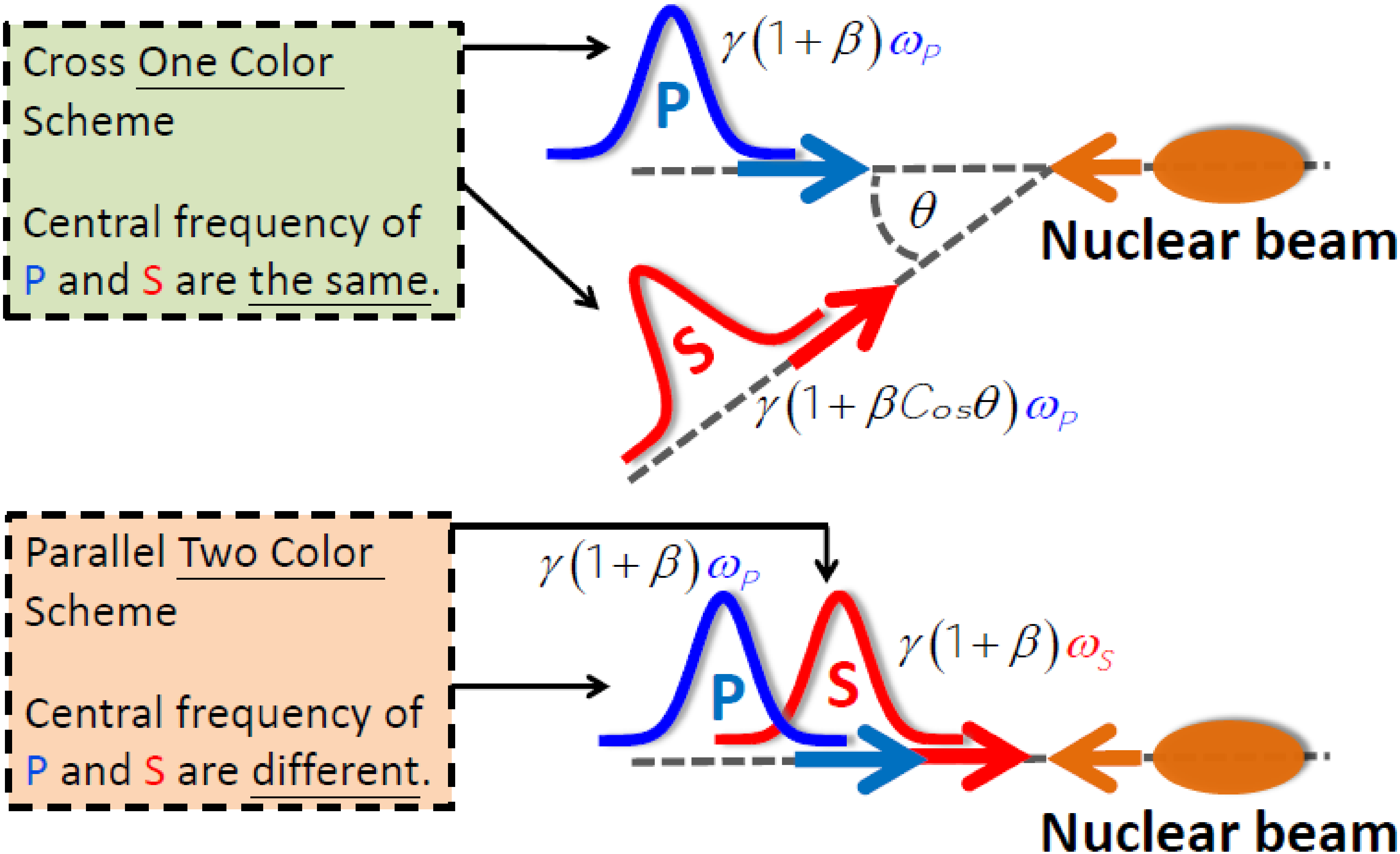




Robust coherent population transfer → **ISOMER TRIGGERING?**

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

STIRAP



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

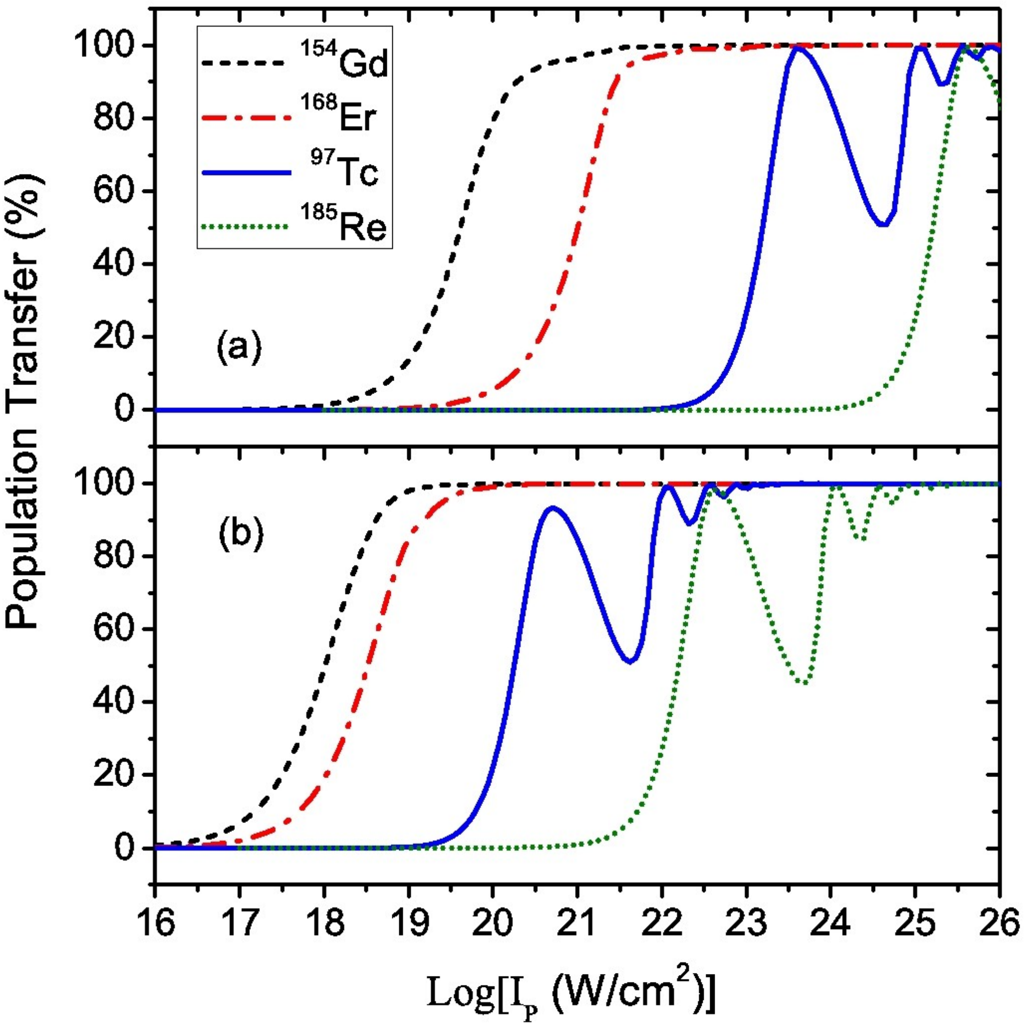
STIRAP

Seeded XFEL

TABLE I. The nuclear data.

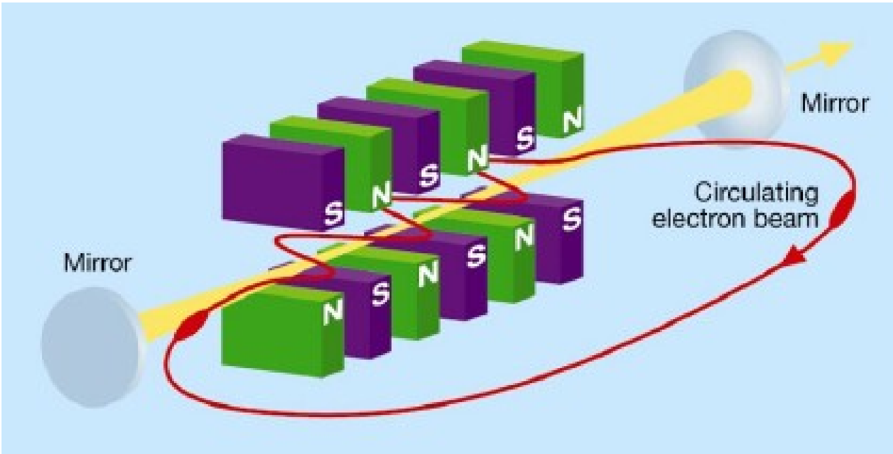
Element	Line width of |3> (meV)	E_3 (keV)	E_2 (keV)	E_1 (keV)
^{185}Re	0.04	284.200	125.359	0
^{97}Tc	0. 60	656.900	324.476	96.57
^{154}Gd	300.00	1241.291	123.071	0
^{168}Er	130.00	1786.123	79.804	0

XFELO

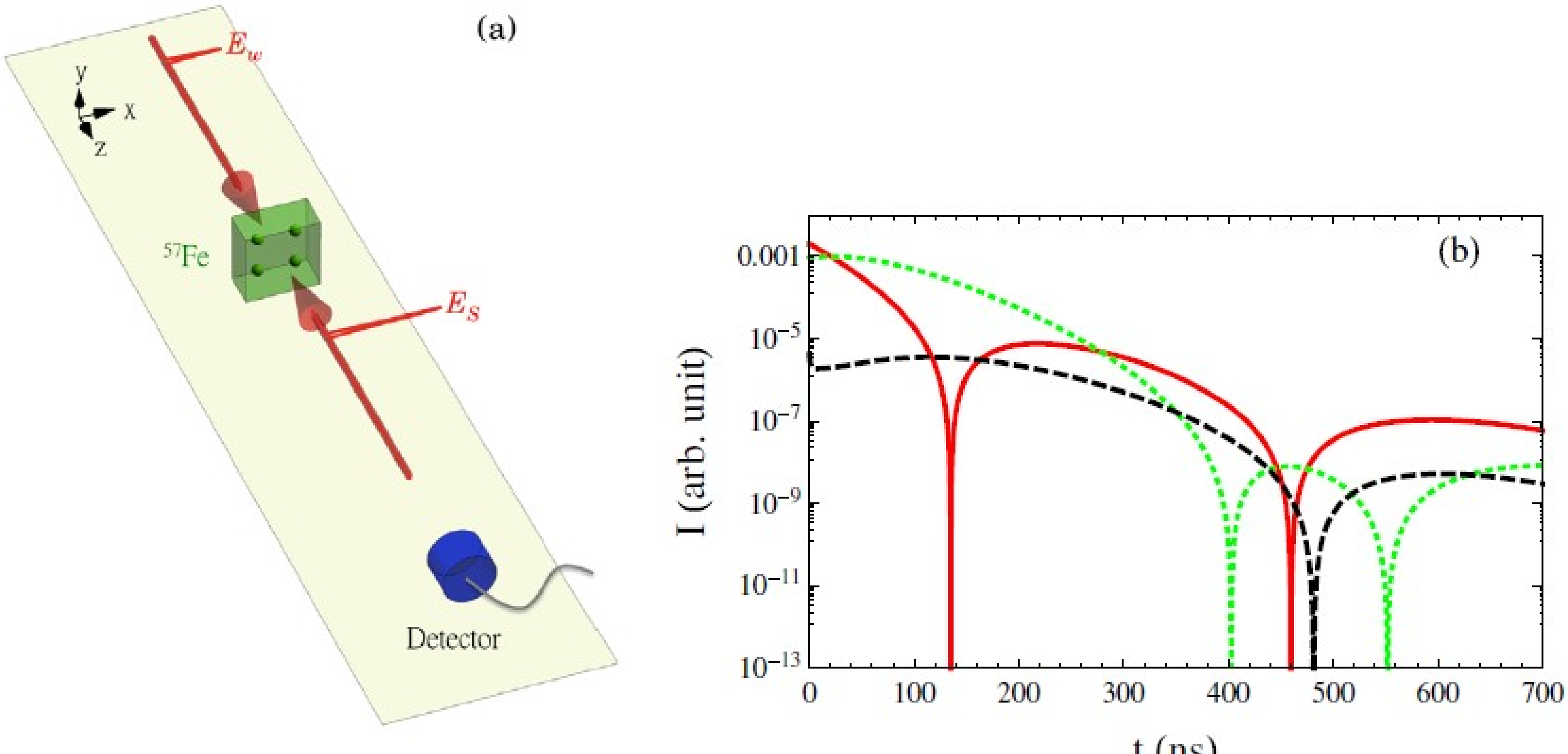


W.-T. Liao, AP and C. H. Keitel, Phys. Lett. B 705, 134 (2011)

Pump probe experiments



use XFELO photoexcitation as pump
“strong pulse”



no S

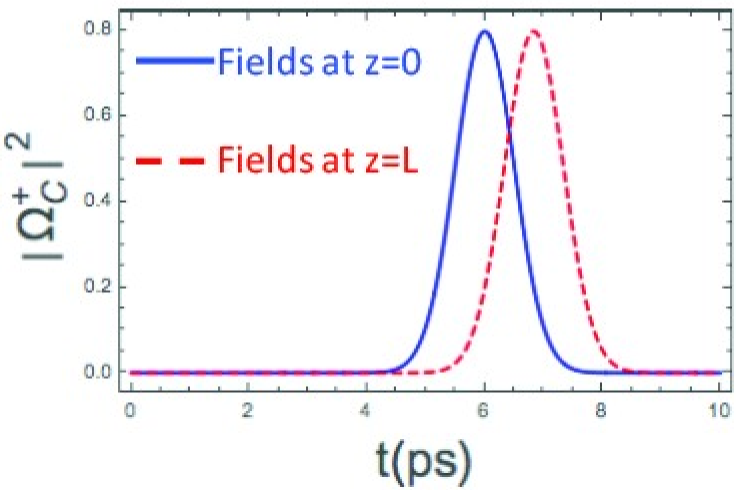
S 10 ns

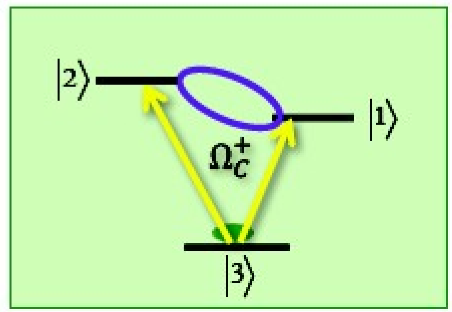
S 50 ns

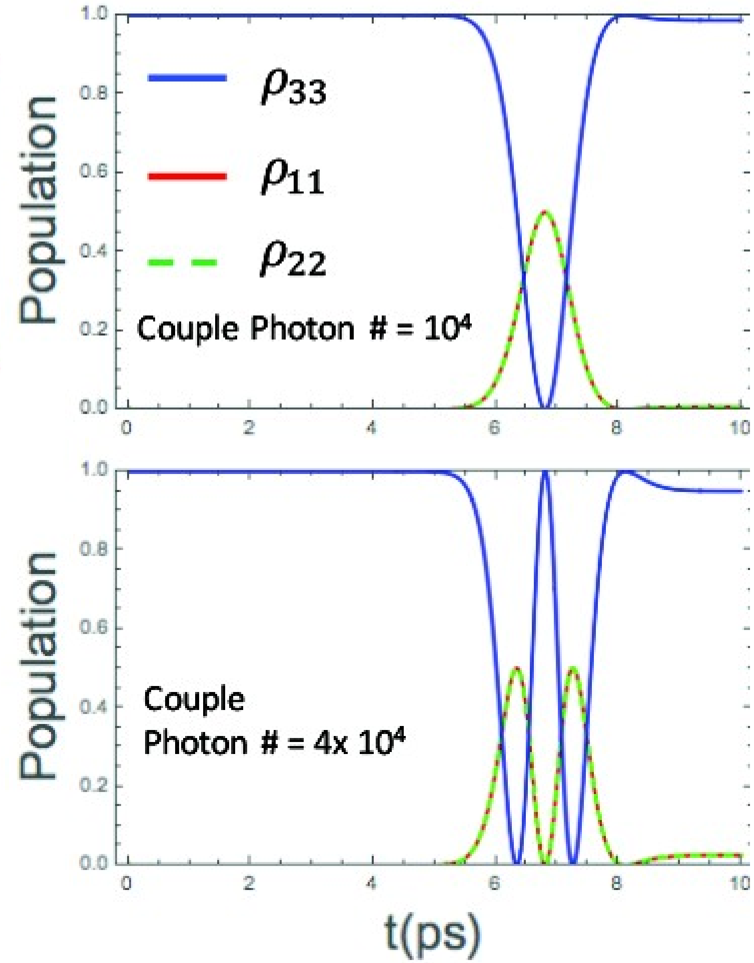
X. Kong, W.-T. Liao and AP, New J. Phys. 16, 013049 (2014)

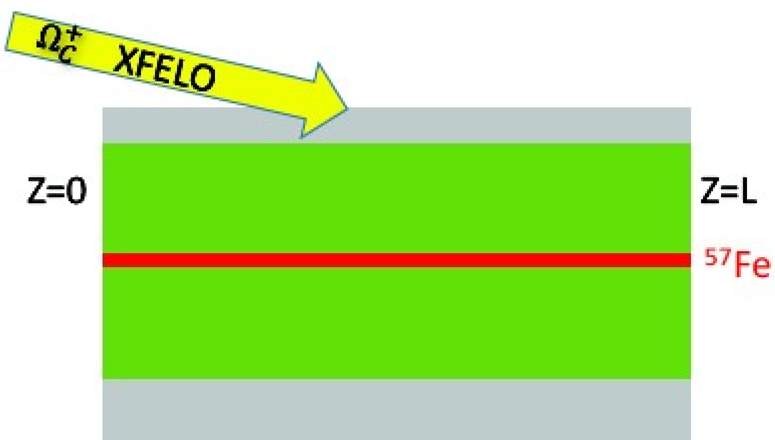
More elaborated thoughts of Wen-Te Liao

Nuclear Rabi Oscillation









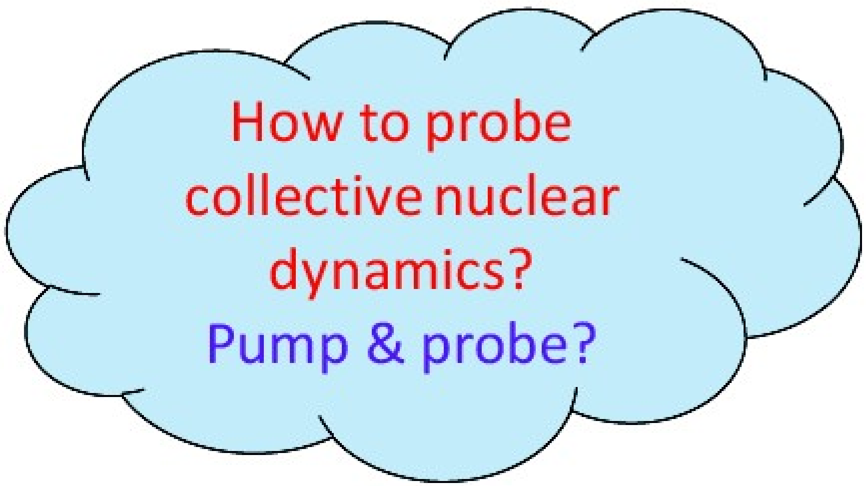
$g\sqrt{N} = \sqrt{6.3\times10^6}$

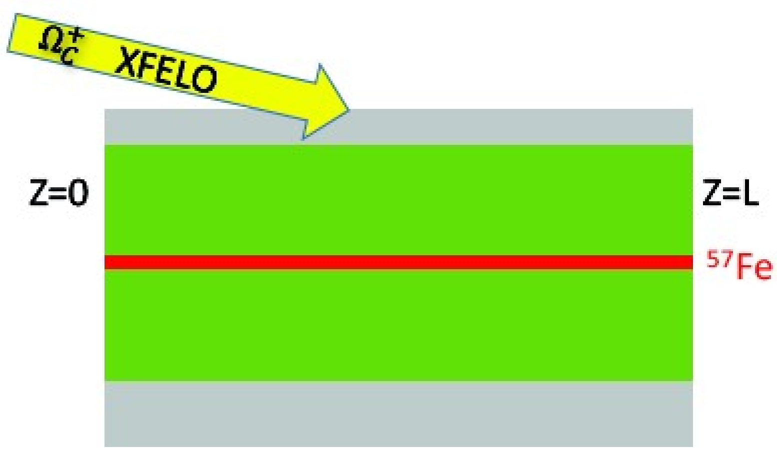
$\gamma' = 19.4\,\gamma$

$\gamma = 7.1\ MHz$

More elaborated thoughts of Wen-Te Liao

Nuclear Rabi Oscillation





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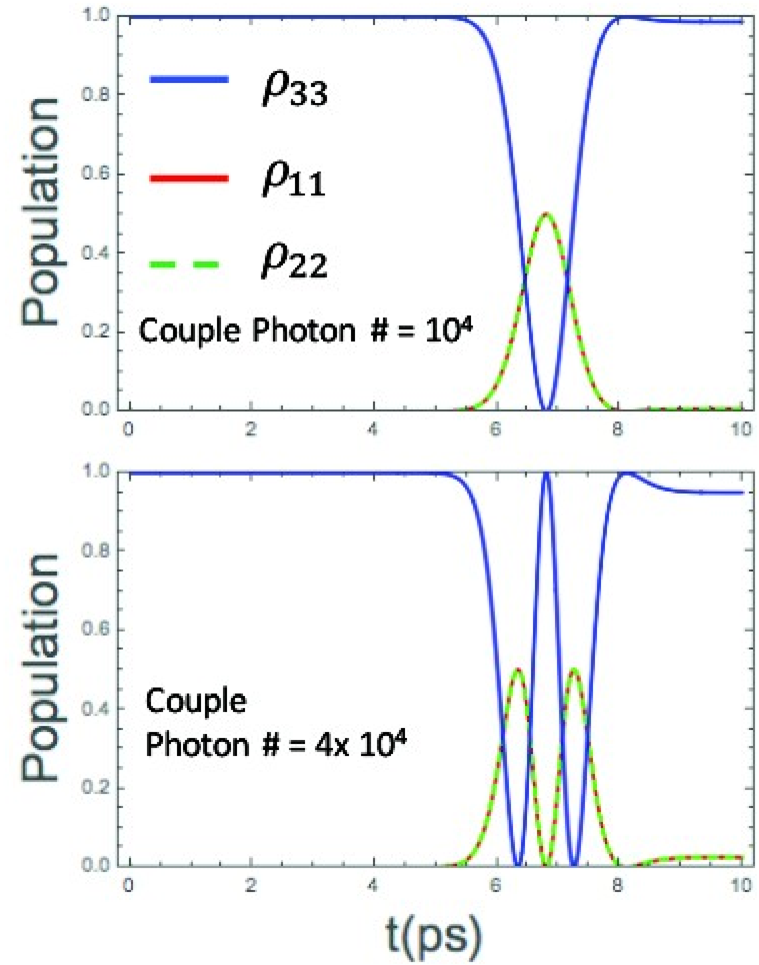
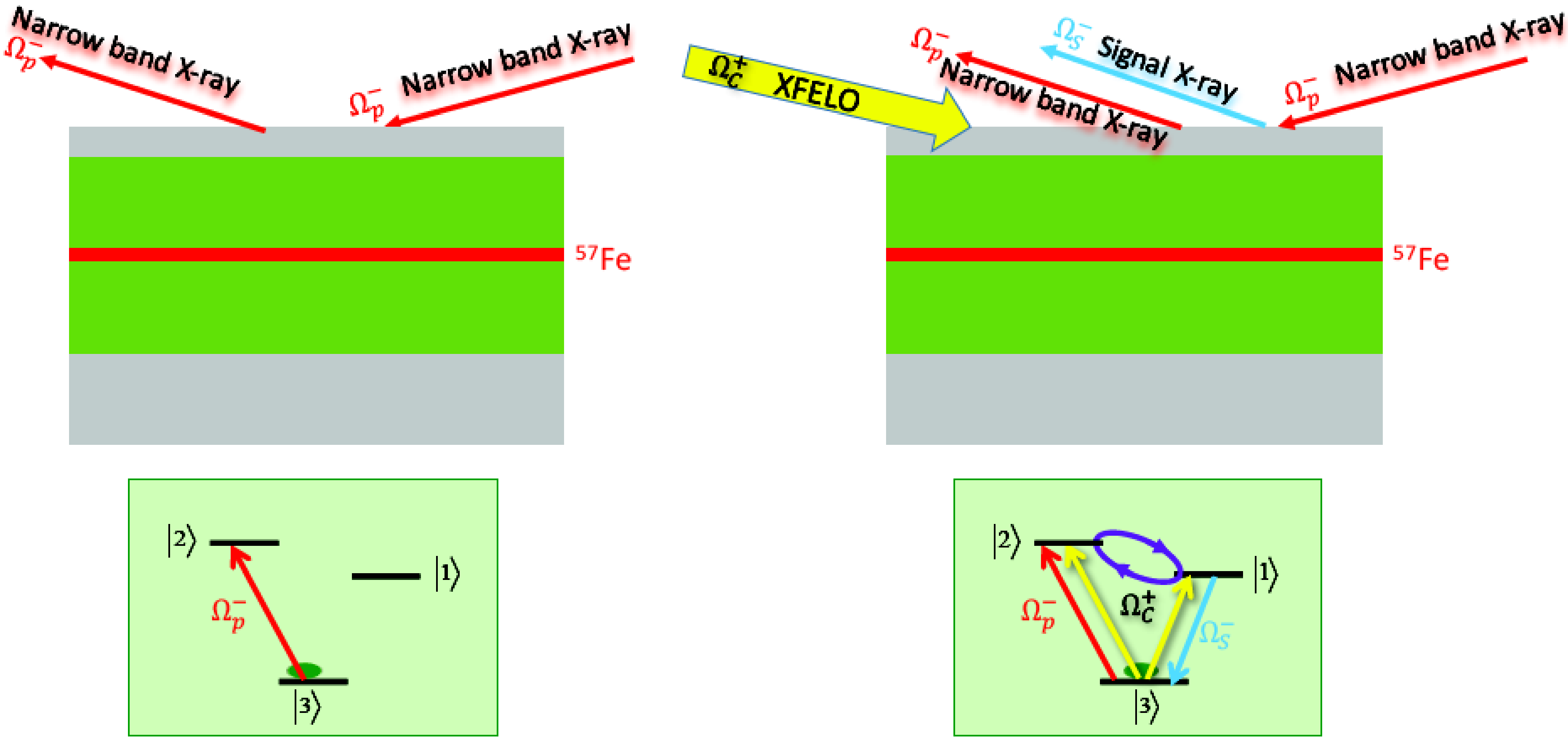


More elaborated thoughts of Wen-Te Liao

Nuclear Four-Wave Mixing using XFELO

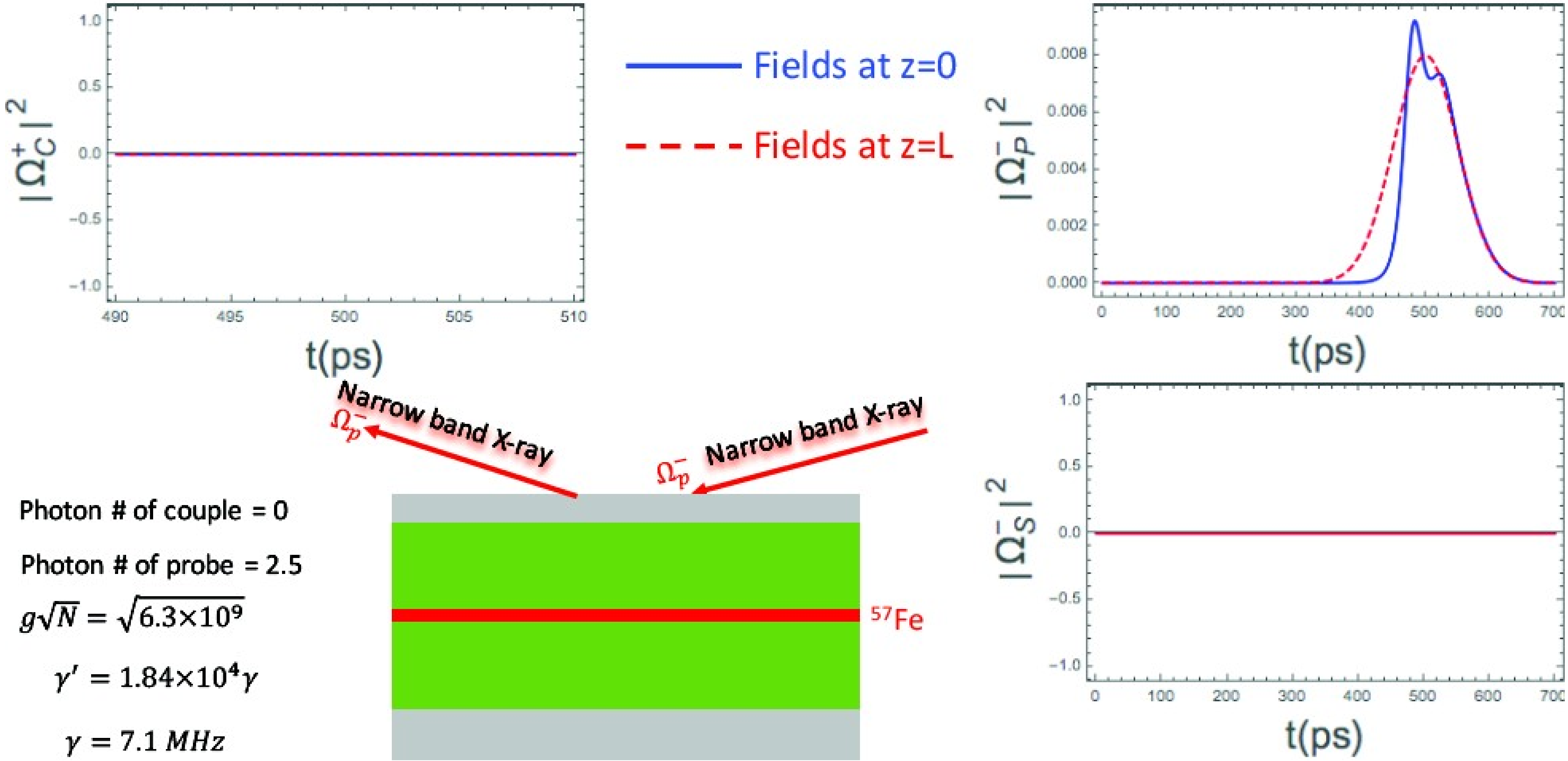


Case 1 without XFELO

Case 2 with counter-propagating XFELO

More elaborated thoughts of Wen-Te Liao

Nuclear Four-Wave Mixing using XFELO



Photon # of couple = 0

Photon # of probe = 2.5

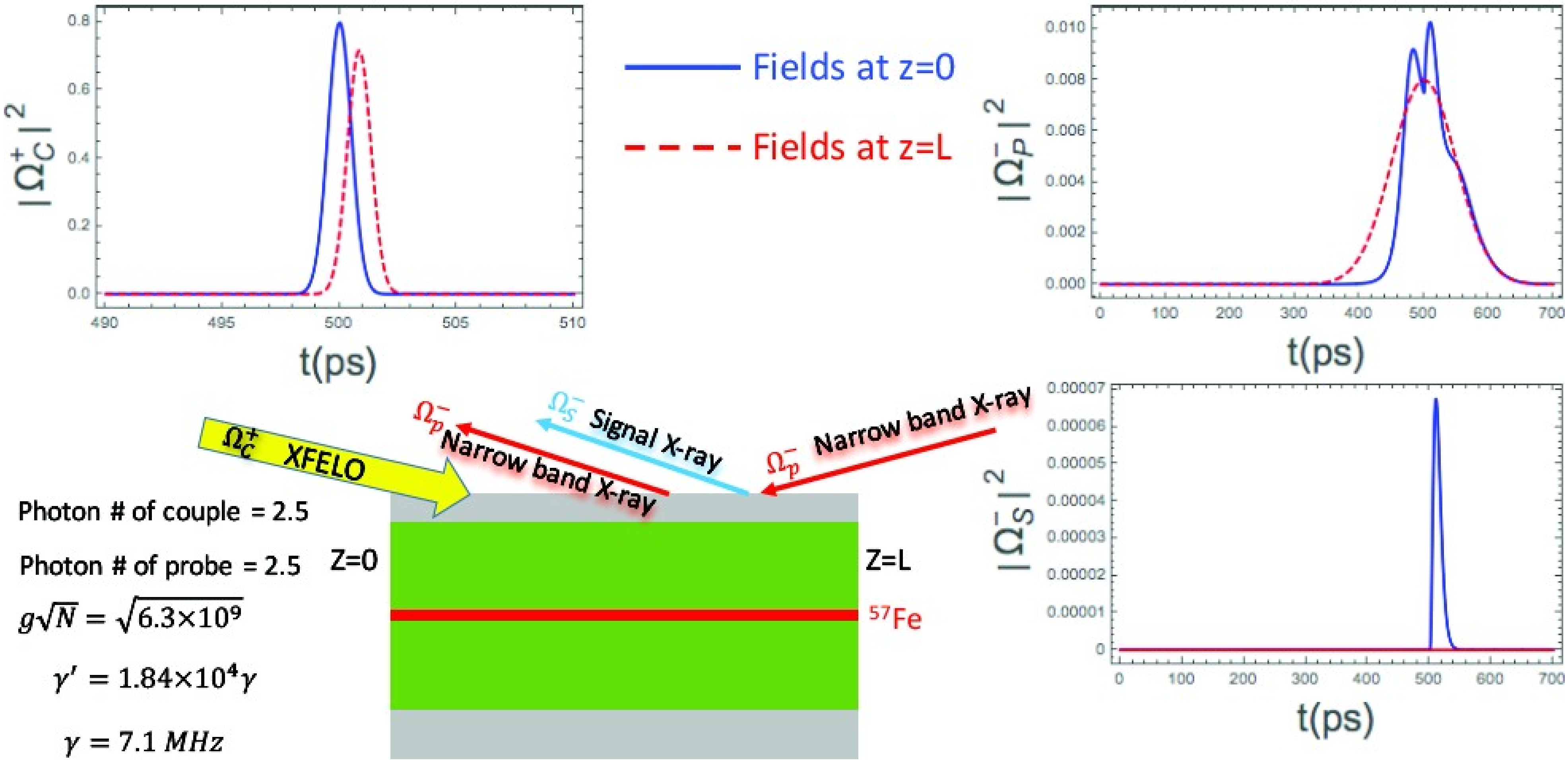
$g\sqrt{N} = \sqrt{6.3\times10^9}$

$\gamma' = 1.84\times10^4\gamma$

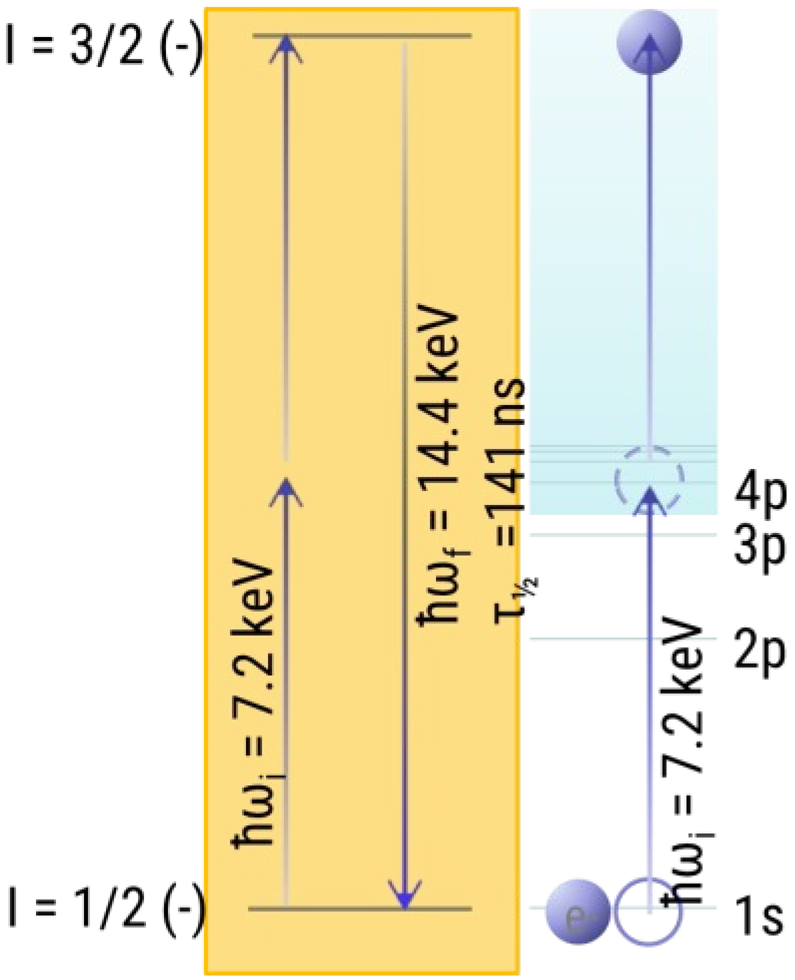
$\gamma = 7.1\ MHz$

More elaborated thoughts of Wen-Te Liao

Nuclear Four-Wave Mixing using XFELO



Two-photon excitation of Fe (see slides by A. Kaldun)



famous 14.4 Mössbauer transition
can be excited by two 7.2 keV photons
and perhaps assisted by an electron bridge!

Nuclei @ XFELO … Outline

- Stronger photoexcitation

  … due to improved temporal coherence

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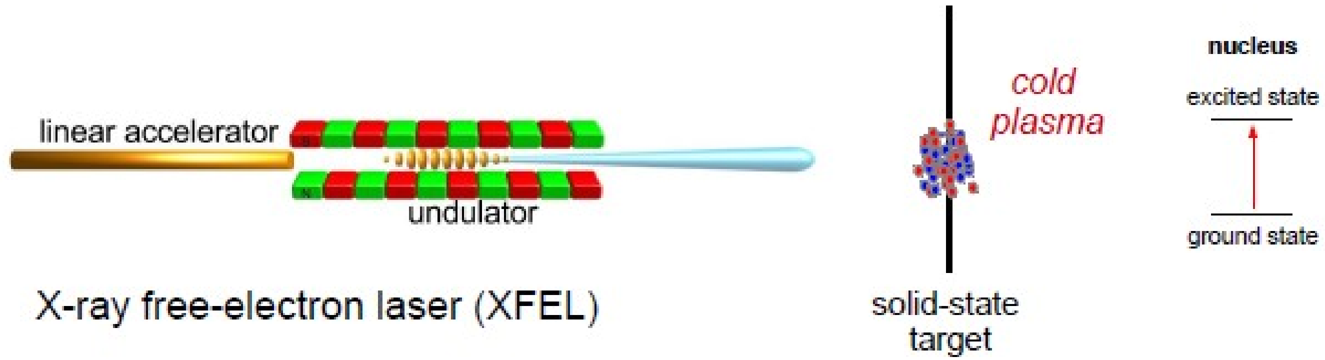
  … relying on coherence and efficient excitation

- Nuclear reactions starting from excited states

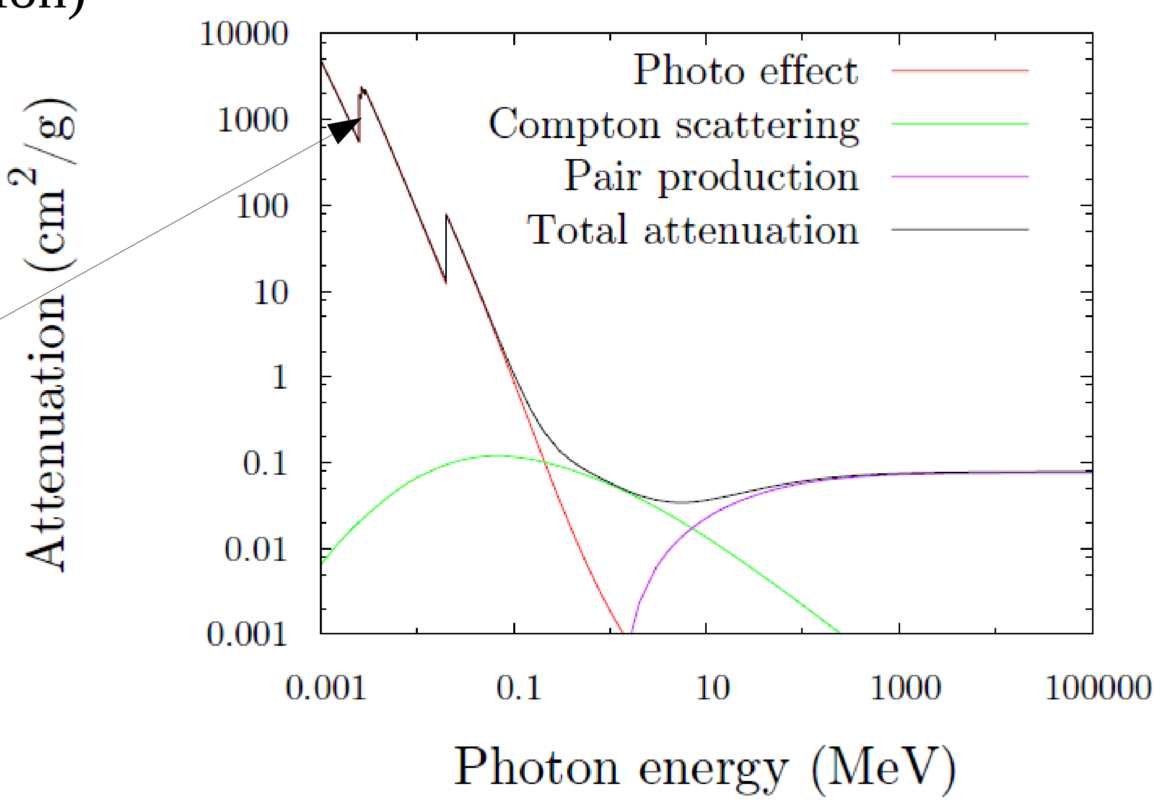
  … new for nuclear physics; possibly in plasmas

XFELO vs. XFEL concerning plasma



after thermalization plasmas may have similar parameters
(depending on total energy deposition)

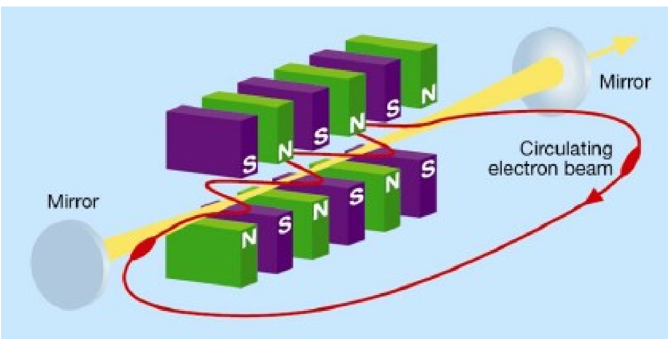
interesting transient effects may occur if XFELO is tuned at a sharp shell edge

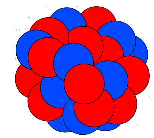


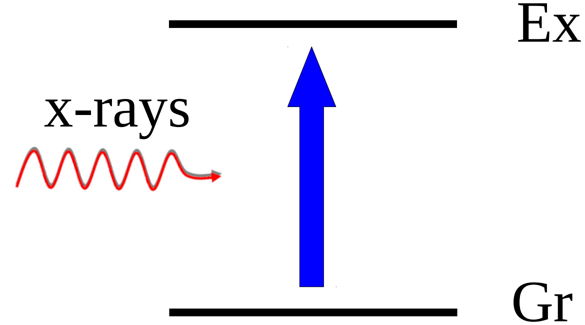
XFELO and nuclear reactions

We can use the efficient XFELO photoexcitation to probe for the first time nuclear reactions from excited nuclear states!

Scenario I







\+ nuclear reaction (collision) with alpha, n, p, other nuclei

→ why plasma? Because due to reduced electron screening the reaction may be more efficient

→ all these reactions would require additional beams – protons, neutrons, etc.

We will need table-top laser-driven sources for such experiments!

XFELO and nuclear reactions

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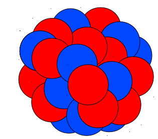
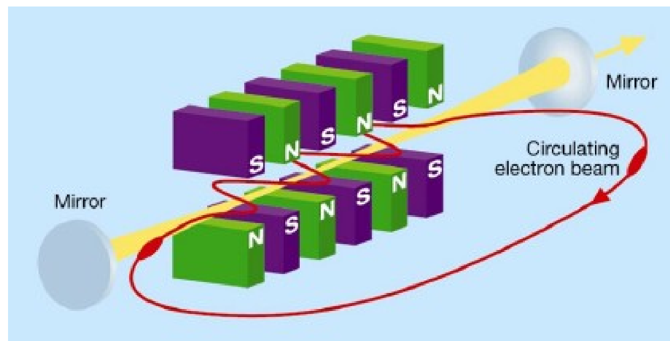
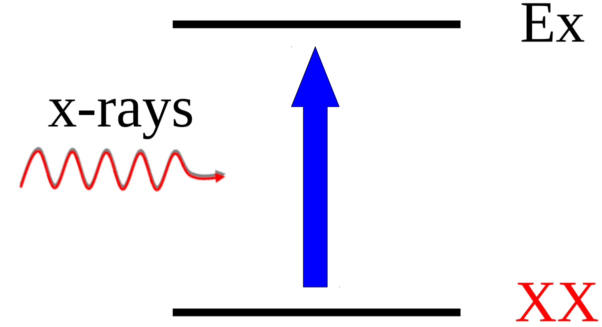
Scenario II



nuclear reaction (collision) with alpha, n, p, other nuclei

+





→ XX state can be a nuclear isomer or a compound nucleus state – for instance isomer triggering possible.

XFELO and nuclear reactions

Scenario II

nuclear reaction
(collision) with
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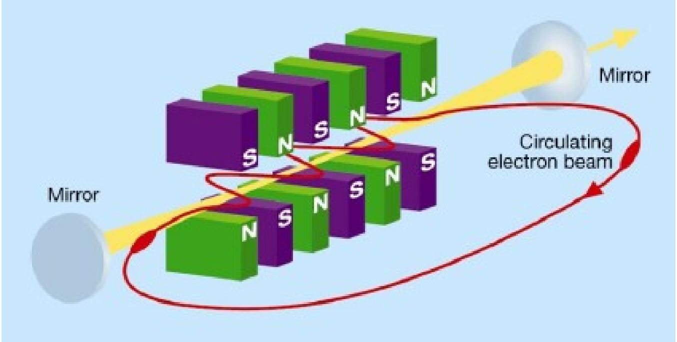
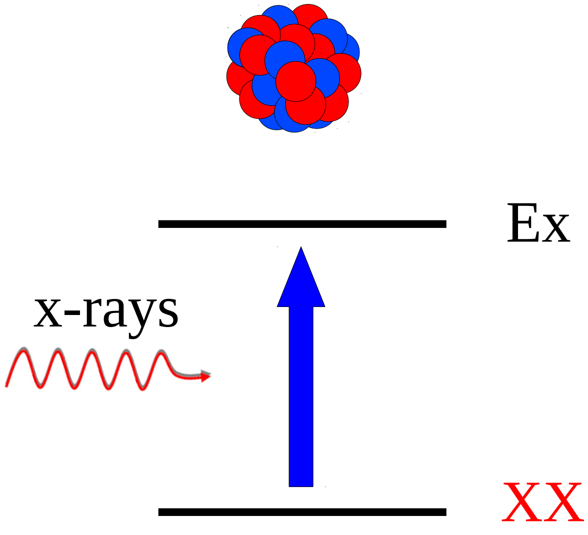
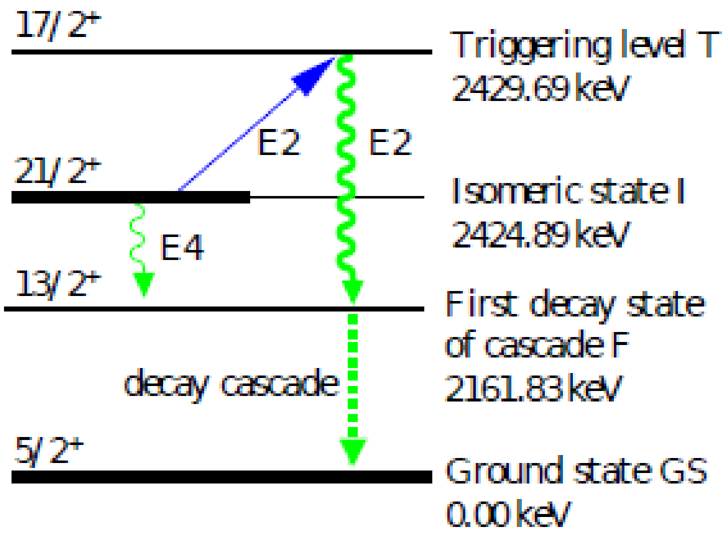
+

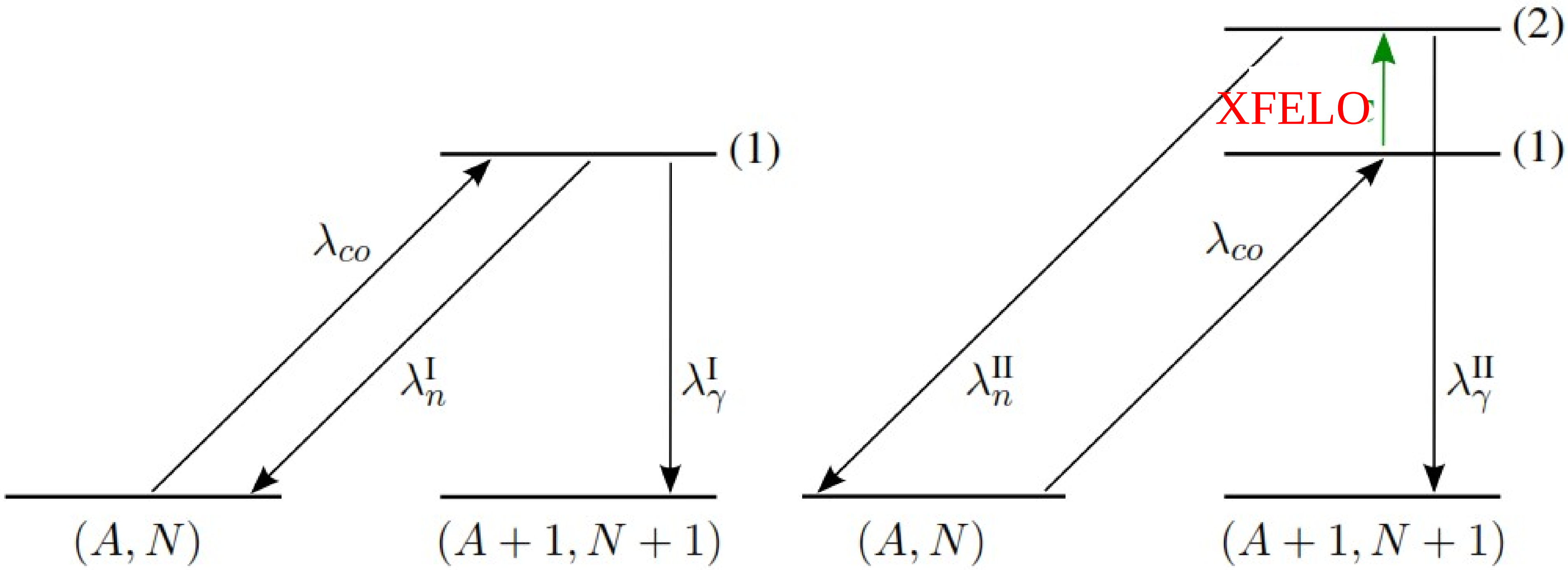






$^{93}_{41}\mathrm{Nb(p,n)}\ ^{93m}_{42}\mathrm{Mo}$ reactions

Excitation step after neutron capture



branching ratios can be very different!

$$\left(\frac{\lambda_n}{\lambda_\gamma}\right)_I \neq \left(\frac{\lambda_n}{\lambda_\gamma}\right)_{II}$$

- photoexcitation, relevant for r-process – Lee A. Bernstein @ UCB, LLNL

Summary & Requirements

Driving nuclear transitions...

can be done much more efficiently with XFELO

Possible applications borrowed from atomic systems...

nuclear coherent population transfer, pump-probe experiments, 4-wave mixing

Closer to nuclear physics...

exploit efficiency of XFELO to probe for the first time nuclear reactions starting from excited nuclear states

Needed:
most importantly, tunability for addressing nuclear resonances!
Intensity, repetition rate, BW depending on the envisaged application
Average vs. peak brilliance an issue depending on whether excitation after one pulse or excitation after 1 s is of interest.

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Thank you for your attention!

(Rough) plasma estimates

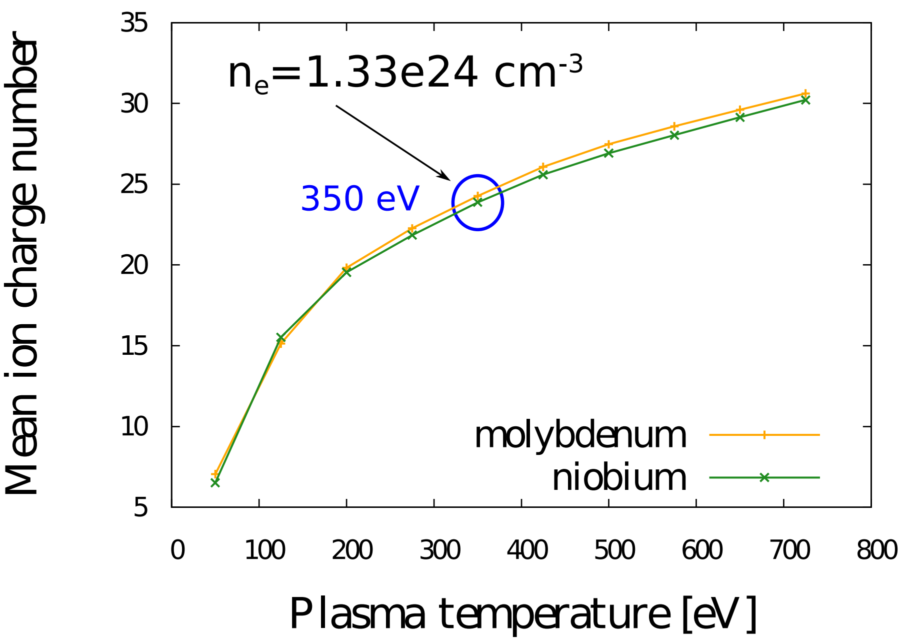
XFEL-induced plasma:
inner-shell holes, uniform radiation,
rapid heating, cold ions

LETTER

doi:10.1038/nature10746

Creation and diagnosis of a solid-density plasma with an X-ray free-electron laser

S. M. Vinko[1], O. Ciricosta[1], B. I. Cho[2], K. Engelhorn[2], H.-K. Chung[3], C. R. D. Brown[4], T. Burian[5], J. Chalupský[5], R. W. Falcone[2,6], C. Graves[7], V. Hájková[5], A. Higginbotham[1], L. Juha[5], J. Krzywinski[7], H. J. Lee[7], M. Messerschmidt[7], C. D. Murphy[1], Y. Ping[8], A. Scherz[7], W. Schlotter[7], S. Toleikis[9], J. J. Turner[7], L. Vysin[5], T. Wang[7], B. Wu[7], U. Zastrau[10], D. Zhu[7], R. W. Lee[7], P. A. Heimann[2], B. Nagler[7] & J. S. Wark[1]



- electrons equilibrate quickly
- uniform electron temp. T_e and density n_e
- T_e estimate from deposited laser energy
- FLYCHK: calculation of charge state distribution and n_e (rate equation model)
- ions stay at room temperature and solid–state density
- hydrodynamic expansion is neglected
- plasma lifetime $\sim$ 100 ps

FLYCHK
H. K. Chung et al. HEDP 1, 3 (2005)