Laser-nucleus interaction with keV and MeV photons

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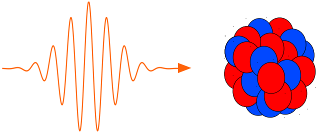
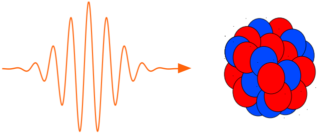
Laser-nucleus interaction



Goal:
explore nuclear
properties

Laser-nucleus interaction

Light source???
Frequency?



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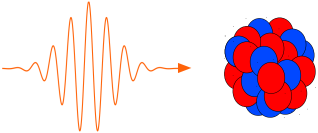


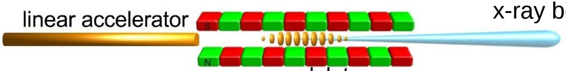
Goal:
explore nuclear properties

Part I

X-ray free-electron Laser (XFEL)

LCLS

European XFEL



XFEL photons

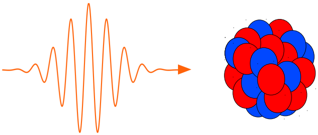
N ~ 10^{12}

E ~ 1-20 keV

T ~ 100 fs

Laser-nucleus interaction

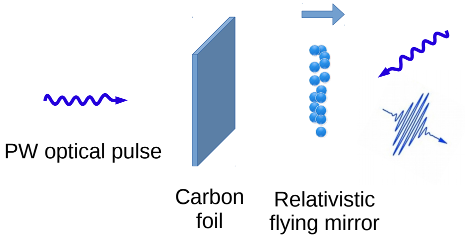
Light source???
Frequency?



Goal:
explore nuclear properties

Part II

Extreme Light Infrastructure – Nuclear Pillar



Compton backscattering of a second laser

ELI photons

N > 10^3

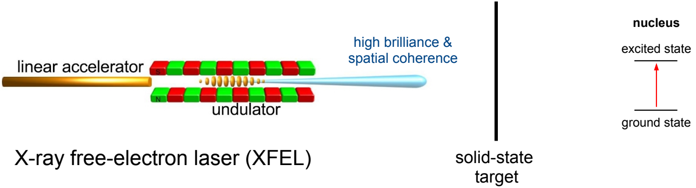
E ~ 10 MeV

T ~ 10^{-19} s

Part I:

keV photons

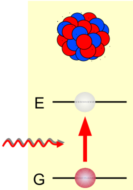
More about keV photons



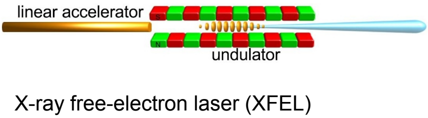
Direct laser–nucleus interaction:

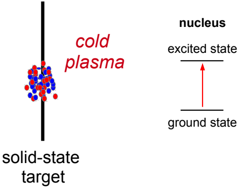
- resonant x-rays available by today's x-ray light sources
- small transition widths
- small size of nuclei
- screening from electrons

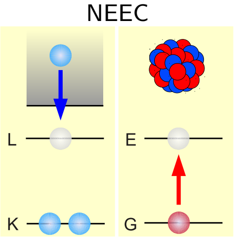
photoexcitation



Secondary nuclear excitation







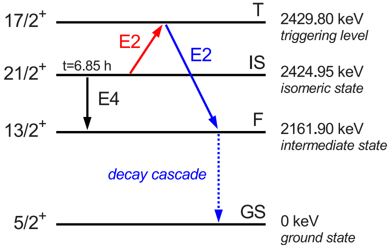
Secondary nuclear processes, like NEEC (**N**uclear **E**xcitation by **E**lectron **C**apture) become possible:

- time–reversed process of internal conversion (IC)
- resonant process

Test case: isomer triggering of ^{93m}Mo

Idea of isomer triggering

Depopulate long-lived isomeric state by excitation to a triggering level which is linked to freely radiating states.



- IS - T: theoretically predicted
- T - F: experimentally confirmed
- transition energy: 4.85(8) keV
- level width of T: $\sim 10^{-7}$ eV
- isomer production: $^{93}_{41}$Nb(p,n) $^{93m}_{42}$Mo reactions

Results - Direct photoexcitation

Parameter	LCLS	SACLA	European XFEL	XFELO
E_{max} (eV)	10300	19600	24800	25000
BW	2×10^{-3}	2.2×10^{-3}	8×10^{-4}	1.6×10^{-7}
T_{pulse} (fs)	100	100	100	1000
T_{coh} (fs)	2	10	0.2	1000
P_{peak} (W)	4×10^{10}	10^{10}	2×10^{10}	4.1×10^{9}
I_{peak} (W/cm^2)	3.9×10^{17}	9.8×10^{16}	2.0×10^{17}	4.0×10^{16}
I_{eff} (W/cm^2)	5.2×10^{9}	1.2×10^{9}	6.5×10^{9}	6.7×10^{12}
ρ_{trig}	1.9×10^{-20}	1.7×10^{-20}	2.4×10^{-21}	4.5×10^{-14}

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$$I_{eff} = \frac{\Gamma_d}{\Gamma_{laser}} I_{peak}$$

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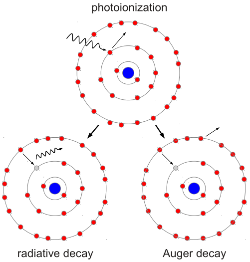
ρ_{trig} = "population of triggering level after a single pulse"

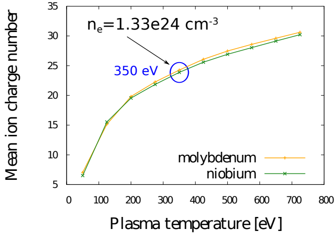
XFEL-induced plasma



Peculiarities:

- direct production of inner shell holes
- x–rays penetrate deep into material
- rapid heating (100 fs)

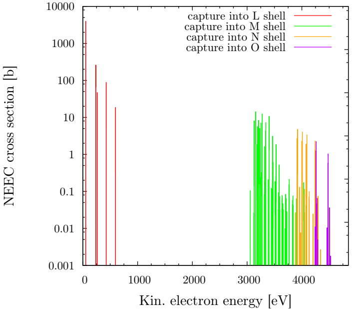
Our estimates:



- T_e estimate from deposited laser energy
- FLYCHK: calculation of charge state distribution and n_e (rate equation model)

FLYCHK - H. K. Chung *et al.*, High En. Density Phys. **1**, 3 (2005)

Results - NEEC in a stationary plasma



$$\lambda_{neec}^{q} = \sum_{\alpha_d} \int dE \, \sigma_{neec}^{i \to d}(E) \phi_e(E, T_e)$$

J. Gunst, Yu. A. Litvinov, C. H. Keitel, A. Pálffy, PRL 112, 082501 (2014)

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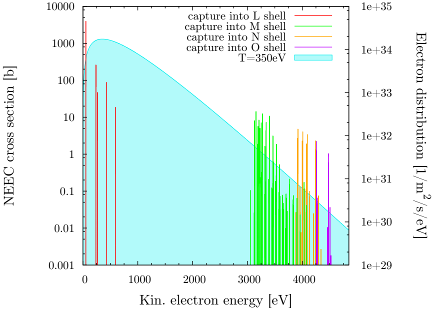

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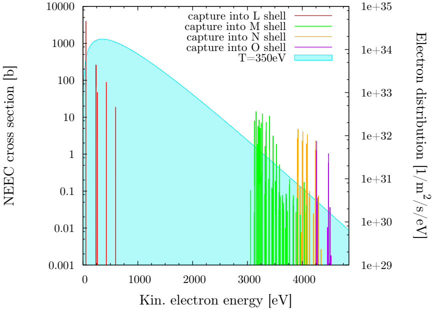

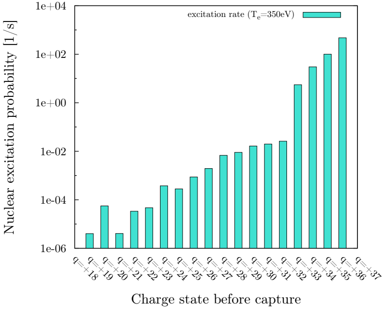

$$\lambda_{neec}^{q} = \sum_{\alpha_d} \int dE\, \sigma_{neec}^{i\to d}(E)\phi_e(E, T_e)$$

$$\lambda_{neec} = \sum_{q} P_q\, \lambda_{neec}^{q}$$

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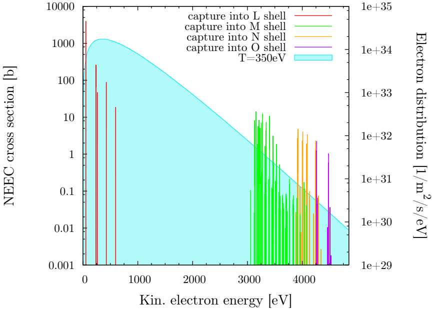

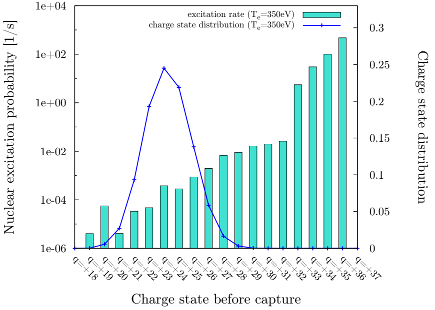

$$\lambda^q_{neec} = \sum_{\alpha_d} \int dE\, \sigma^{i\to d}_{neec}(E)\phi_e(E, T_e)$$

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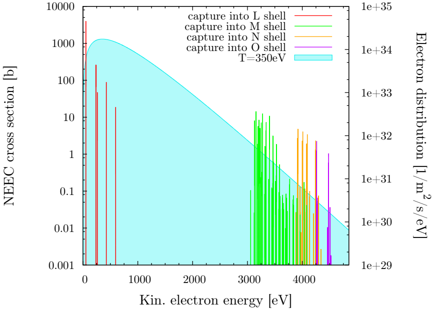

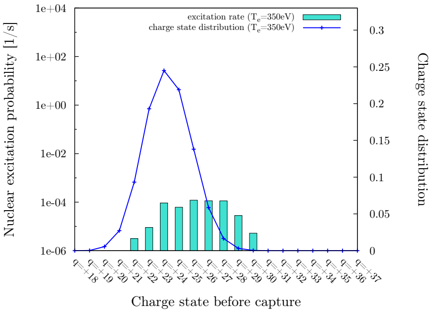

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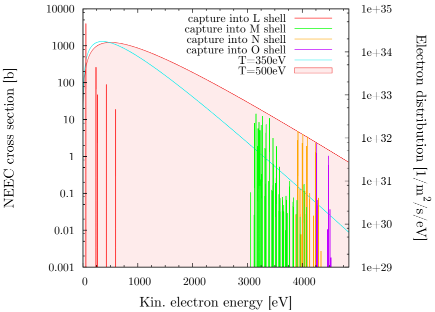

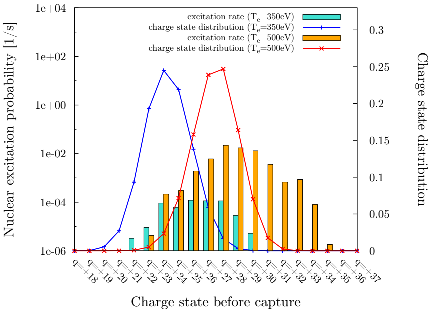

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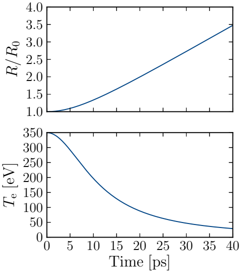
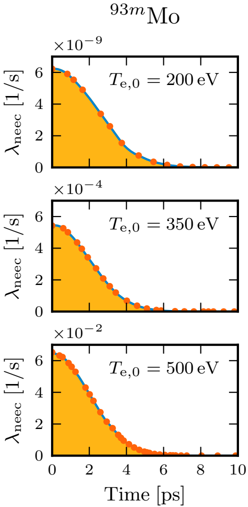
J. Gunst, Yu. A. Litvinov, C. H. Keitel, A. Pálffy, PRL 112, 082501 (2014)

Results - NEEC in an expanding plasma

Hydrodynamic model:

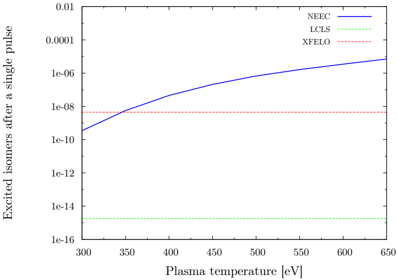
- quasi-neutral expansion
- uniform (but decreasing) electron and ion density
- atomic processes included





J. Gunst, Y. Wu, N. Kumar C. H. Keitel, A. Pálffy, Physics of Plasmas 22, 112706 (2015)

Comparison: photoexcitation - NEEC



^{93m}Mo triggering: 4.85 keV

NEEC $\gg$ photoexcitation

^{57}Fe nucleus: 14.4 keV

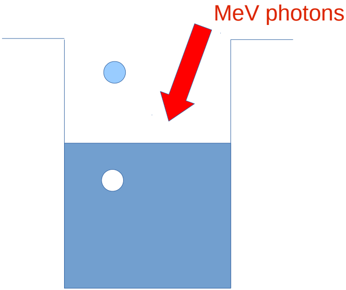
photoexcitation $\gg$ NEEC

Why?

- intrinsic cross sections: $\sigma_{\rm photo}$ vs. $\sigma_{\rm neec}$
- initial plasma conditions
- match between electron distribution and NEEC resonance condition
- interaction times: $T_{\rm pulse}$ vs. $T_{\rm neec}$

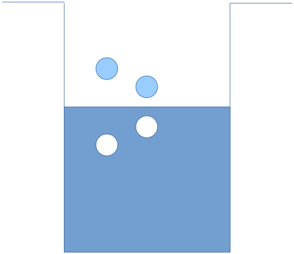
Part II:
MeV photons

Now: MeV photons



PHOTOEXCITATION

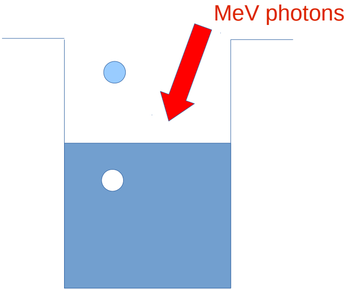
creates particle-hole pairs



RESIDUAL INTERACTION

redistributes energy over more particle-hole pairs

Now: MeV photons



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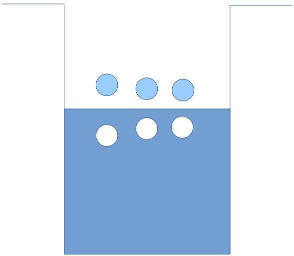

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Now: MeV photons

QUASIADIABATIC REGIME

PHOTOEXCITATION $\simeq$ RESIDUAL INTERACTION

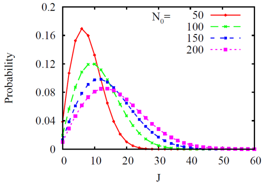
creates particle-hole pairs

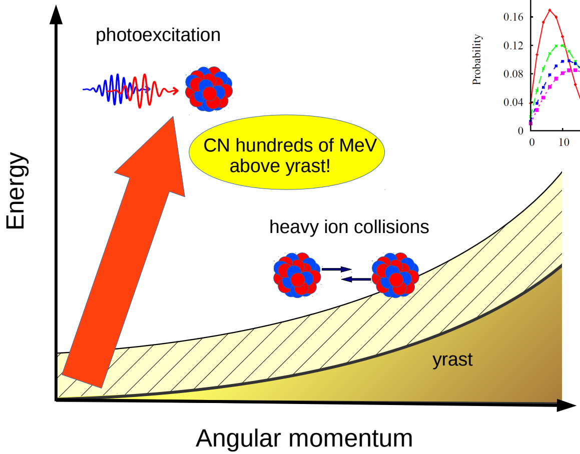
redistributes energy over more particle-hole pairs

after each photon absorption, the nucleus has time to equilibrate

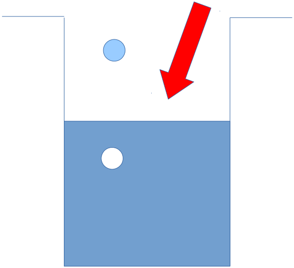
Excitation far from yrast

Dipole absorption $J \sim \sqrt{N}$





Competing channels



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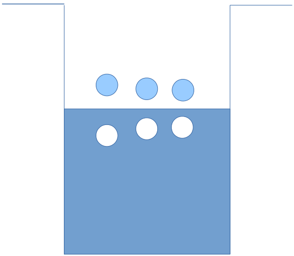

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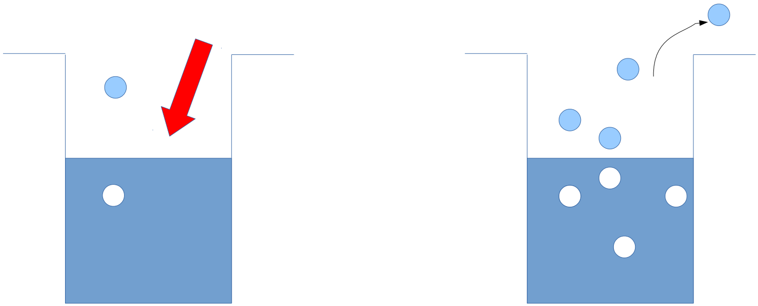


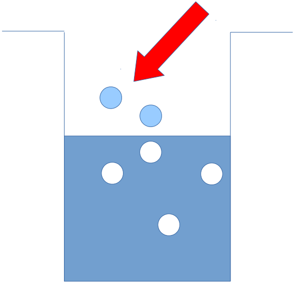
PHOTOEXCITATION

creates particle-hole pairs

NEUTRON EVAPORATION

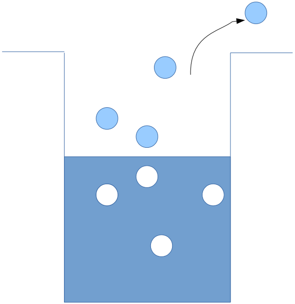
after several absorbed photons

Competing channels



PARTICLE EMISSION

single nucleons reach the continuum



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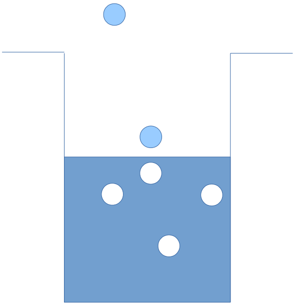

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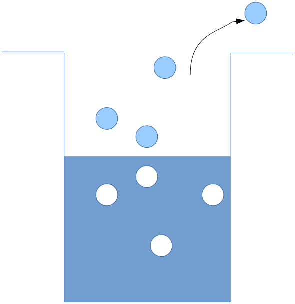

NEUTRON EVAPORATION

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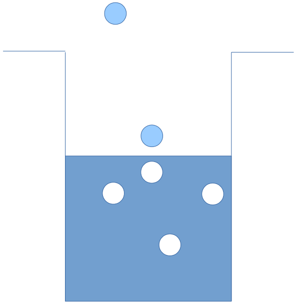
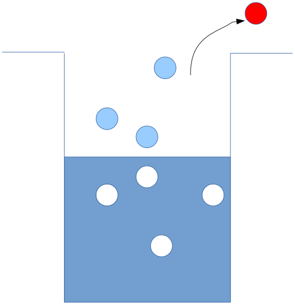


a neutron



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single nucleons reach the continuum

NEUTRON EVAPORATION

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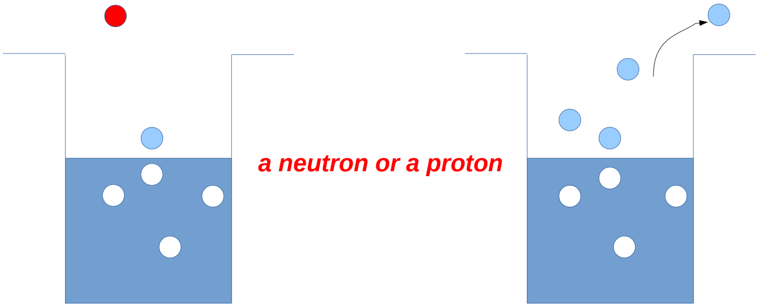
Competing channels



PARTICLE EMISSION

single nucleons reach the continuum

NEUTRON EVAPORATION

after several absorbed photons

Results - Quasiadiabatic regime

Examples of rates – based on newly developed nuclear level densities calculation method

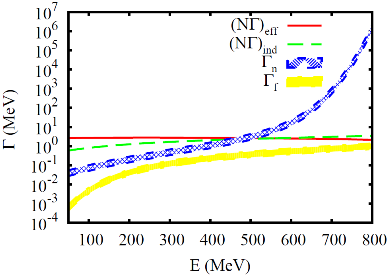
$(N\Gamma)_{\text{eff}}(E)$ - Effective absorption of an compound nucleus

$(N\Gamma)_{\text{ind}}(E)$ - Induced dipole emission

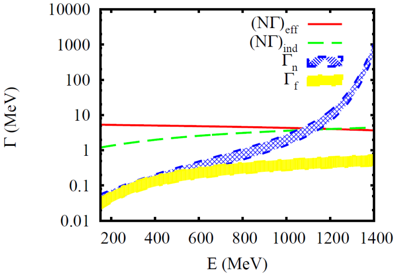
$\Gamma_n(E)$ - Neutron evaporation

$\Gamma_f(E)$ - Fission

Medium-weight, A=100



Heavy, A=200

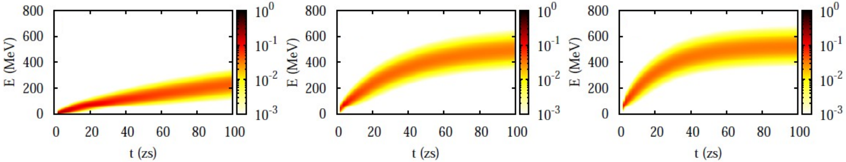


A. Pálffy and H. A. Weidenmüller, Phys. Rev. Lett. 112, 192502 (2014)

Time-dependent approach

Occupation probability for only dipole absorption and induced dipole emission

A=100, photon energy 5 MeV



Effective dipole widths (# of coherent photons in pulse)

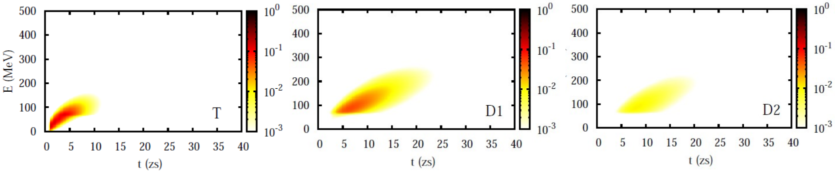
$N\Gamma_{\mathrm{dip}}$ = 1 MeV $N\Gamma_{\mathrm{dip}}$ = 5 MeV $N\Gamma_{\mathrm{dip}}$ = 8 MeV

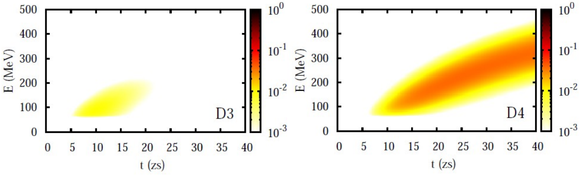
A. Pálffy, O. Buss, A. Hoefer, H. A. Weidenmüller, PRC 92, 044619 (2015)

Time-dependent approach

Dipole absorption and induced dipole emission + neutron evaporation (T + first 3 daughters)

A=100, photon energy 5 MeV, $N\Gamma_{\mathrm{dip}}$ = 5 MeV





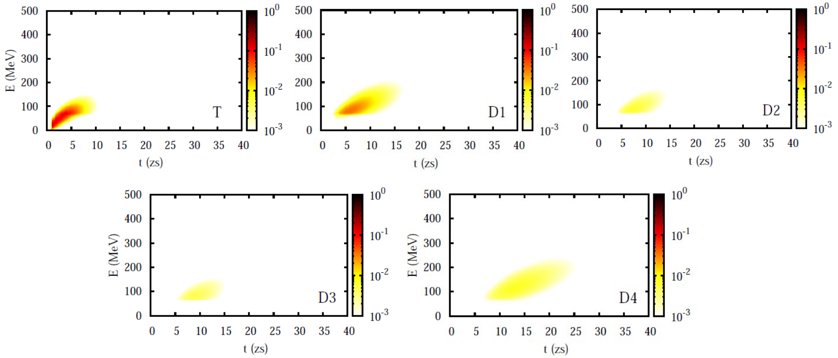
no neutron decay
“dump”

A. Pálffy, O. Buss, A. Hoefer, H. A. Weidenmüller, PRC 92, 044619 (2015)

Time-dependent approach

Dipole absorption and induced dipole emission + neutron evaporation (T + first 3 daughters)
+ fission

A=100, photon energy 5 MeV, $N\Gamma_{\mathrm{dip}}$ = 5 MeV



A. Pálffy, O. Buss, A. Hoefer, H. A. Weidenmüller, PRC 92, 044619 (2015)

Conclusions

keV photons

- resonant nuclear photoexcitation with an XFEL
- high intensity leads to plasma formation and secondary excitation channels
- secondary processes can dominate direct laser-nucleus interaction (^{93m}Mo triggering)

– Phys. Rev. Lett. **112**, 082501 (2014) –
– Physics of Plasmas **22**, 112706 (2015) –

MeV photons

- nuclear excitation with a multi-MeV zs coherent laser pulse
- far from yrast and far from stability
- proton-rich nuclei due to strong neutron evaporation

– Phys. Rev. Lett. **112**, 192502 (2014) –
– Phys. Rev. C **92**, 044619 (2015) –

Thank you for your attention!