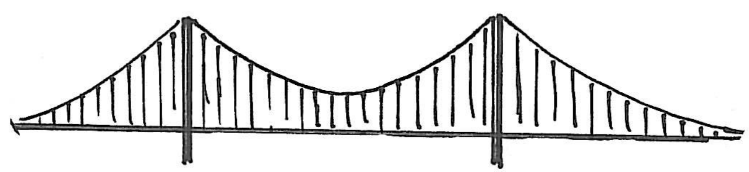
Nuclear excitation with zeptosecond multi-MeV laser pulses

Adriana Pálffy and Hans A. Weidenmüller

Max Planck Institute for Nuclear Physics, Heidelberg, Germany

Nuclear Fusion: From NIF to the Stars



San Francisco, August 11th, 2014

New experimental developments ...

Experimental promise of coherent MeV photons!

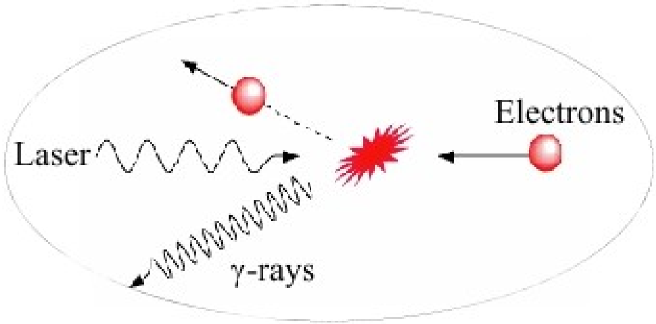
Challenge: the theory of laser-induced nuclear reactions

ELI beam
(intense & optical)

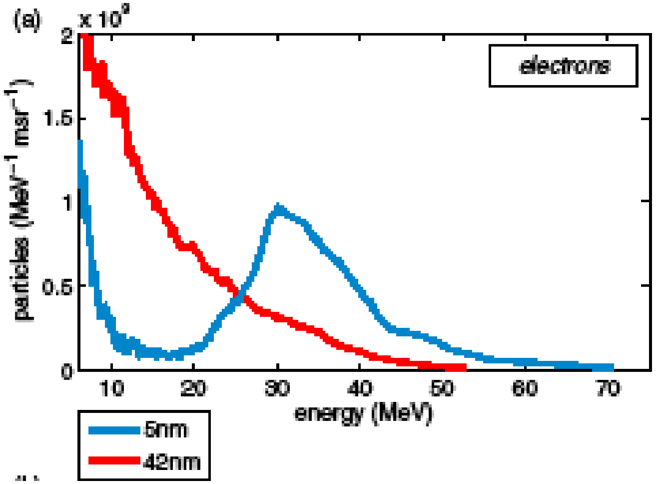
thin Carbon foil
electron sheet

Compton backscattering

of another laser

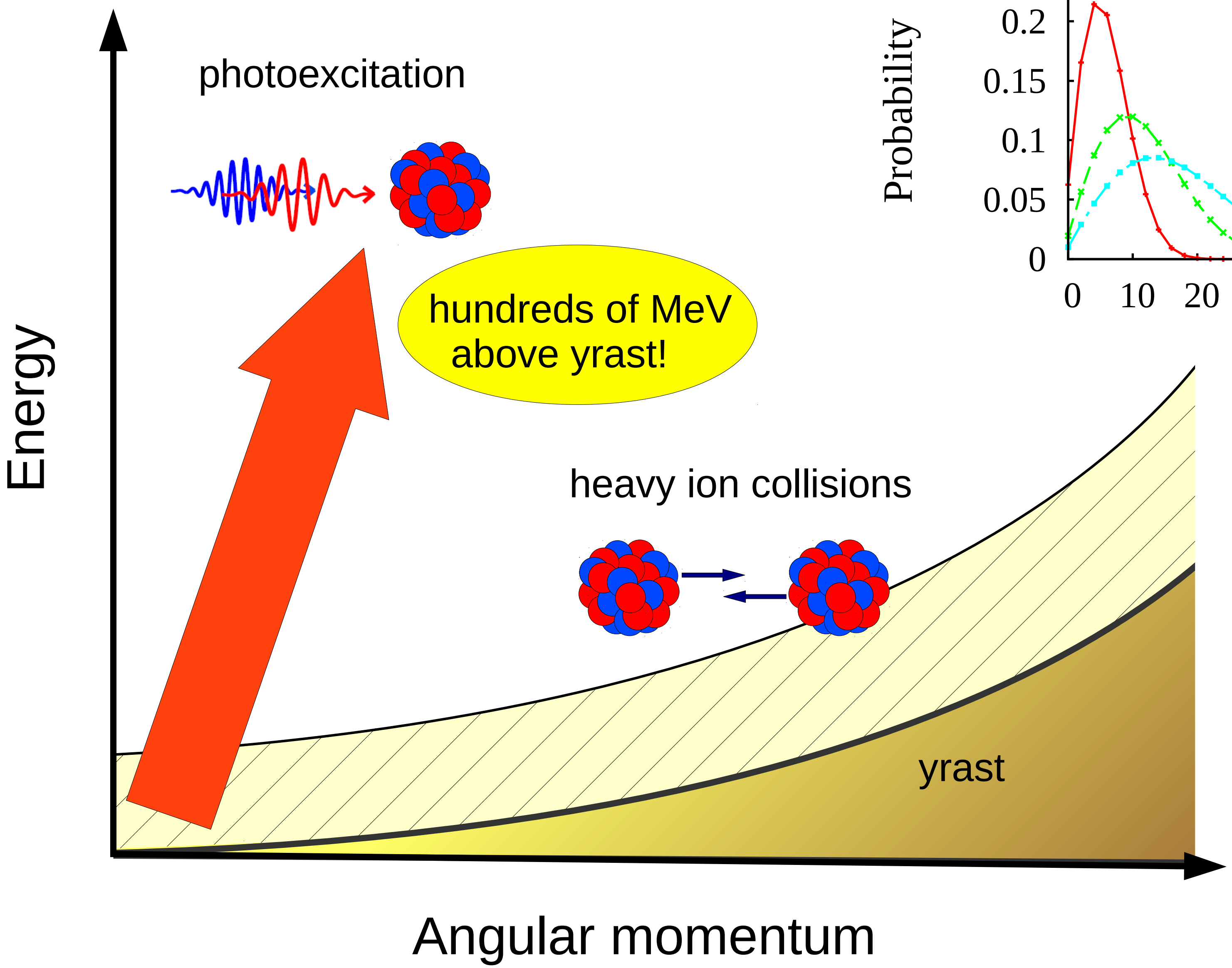


Mono-energetic & tunable γ-ray beam
(unlike bremsstrahlung)

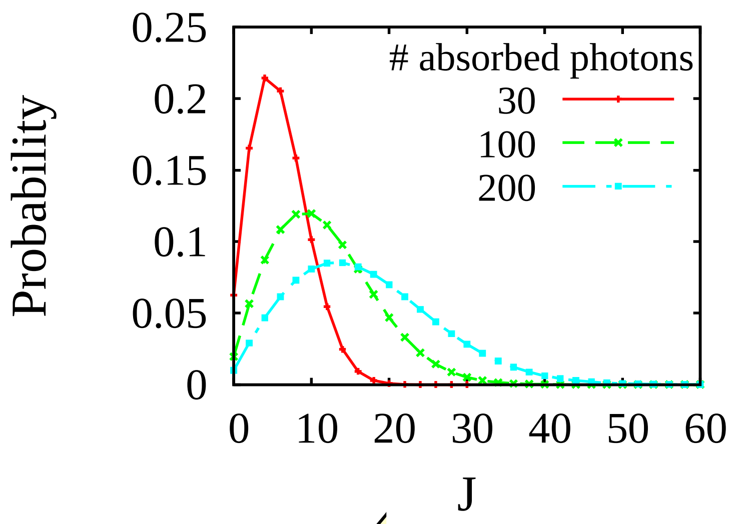


G. Mourou and T. Tajima, Science 331 (2011) 41

Far from yrast



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



Nuclear excitation mechanism

ELI photons

$N > 10^3$

$E \sim 10$ MeV

$T \sim 10^{-19}$ s

PERTURBATIVE

Giant Dipole Resonance once or twice

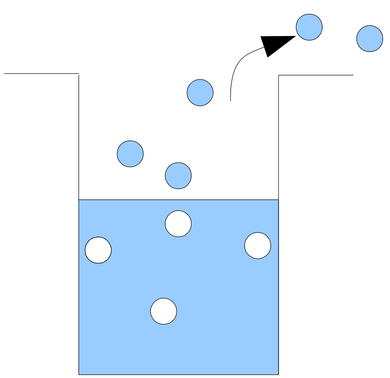
H. A. Weidenmüller, Phys. Rev. Lett. 106 (2011) 122502
B. Dietz and H. A. Weidenmüller, Phys. Lett. B 693 (2010) 316

QUASIADIABATIC

Compound nucleus equilibrates about as fast as it is excited

STRONGLY NON-ADIABATIC

Nucleus evaporates by multiple nucleon emission



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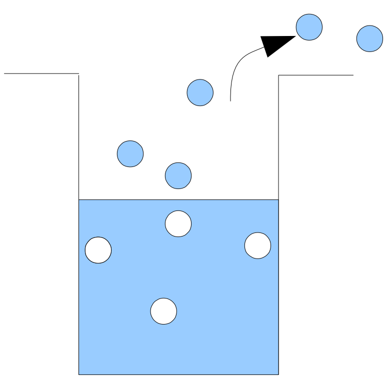
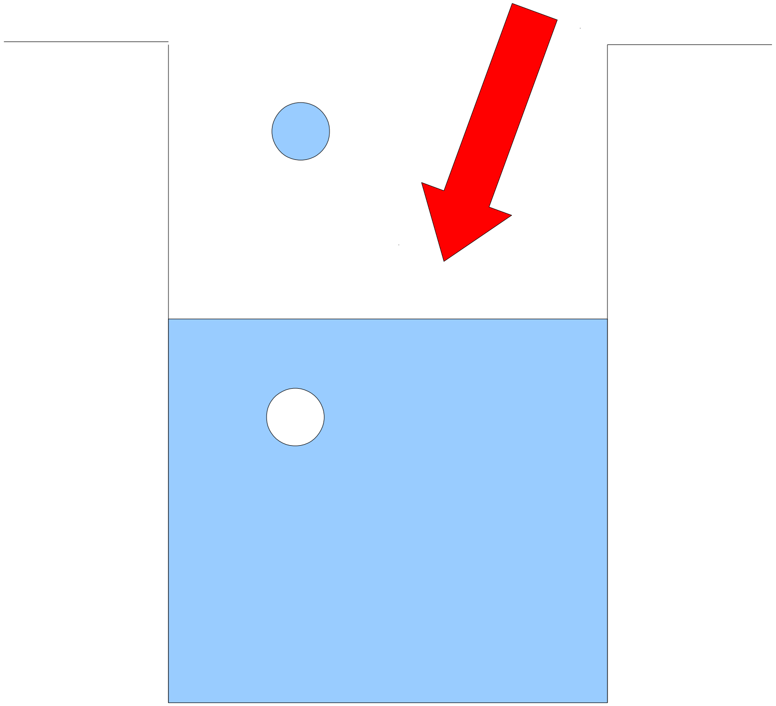
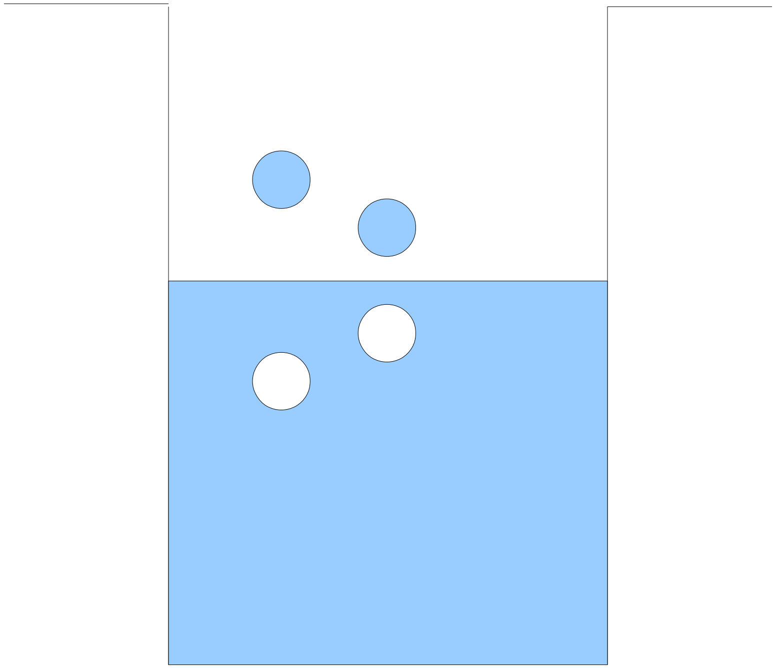


Competing channels





PHOTOEXCITATION

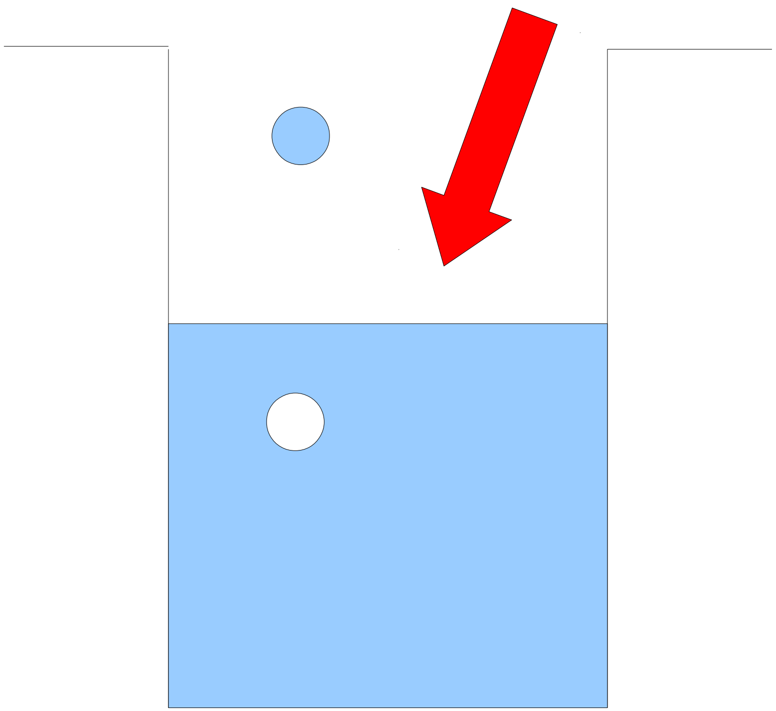
creates particle-hole pairs

RESIDUAL INTERACTION

nucleon-nucleon interaction
redistributes energy

Competing channels

Quasiadiabatic regime –
after each absorption, nucleus equilibrates!!!



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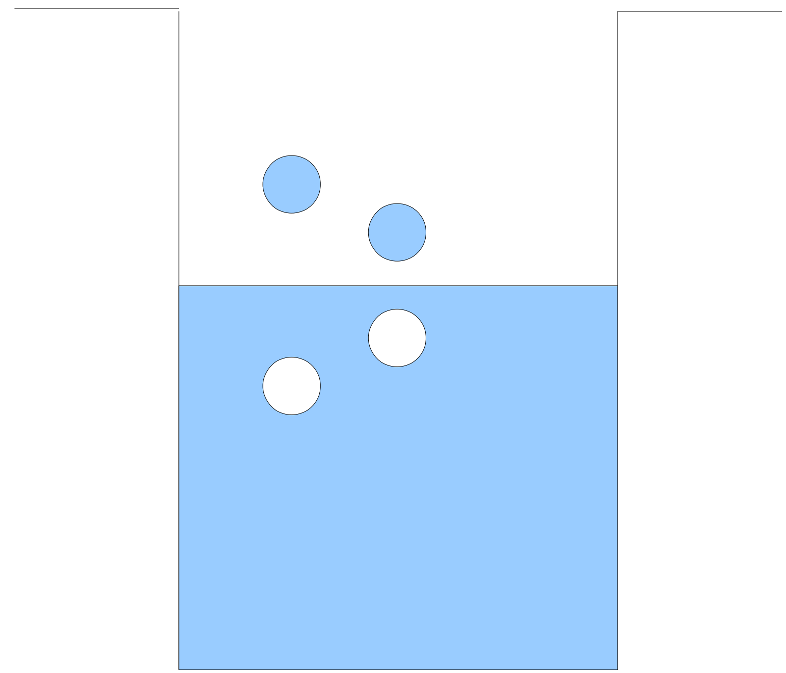

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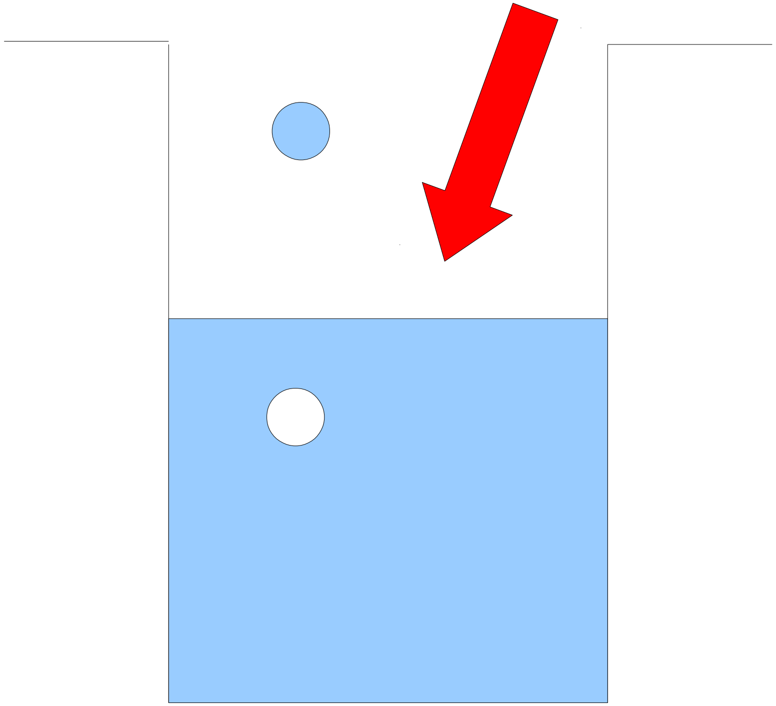

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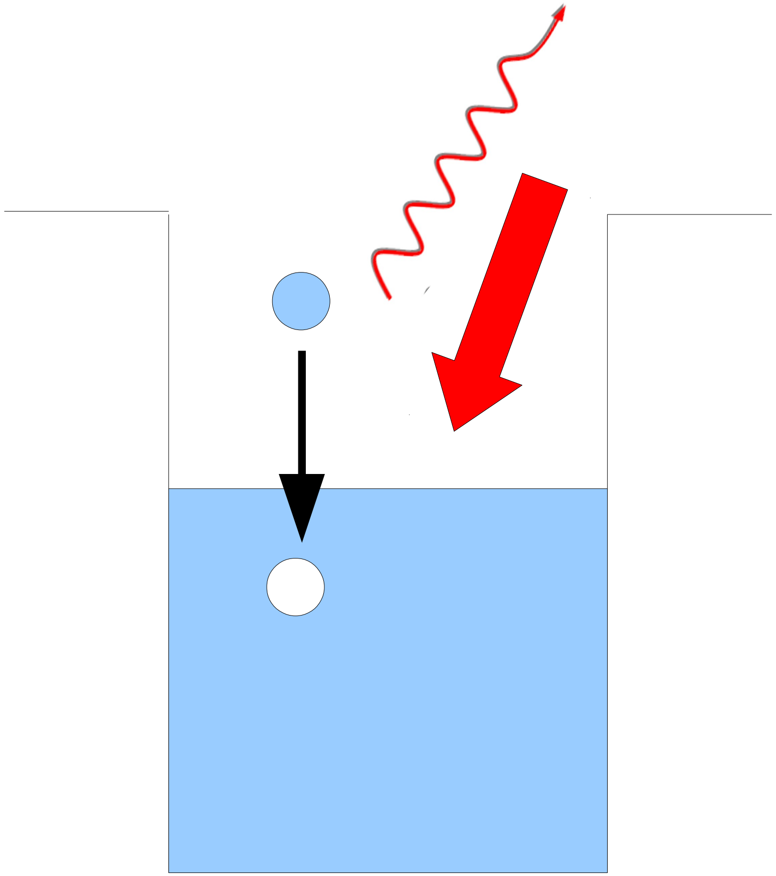
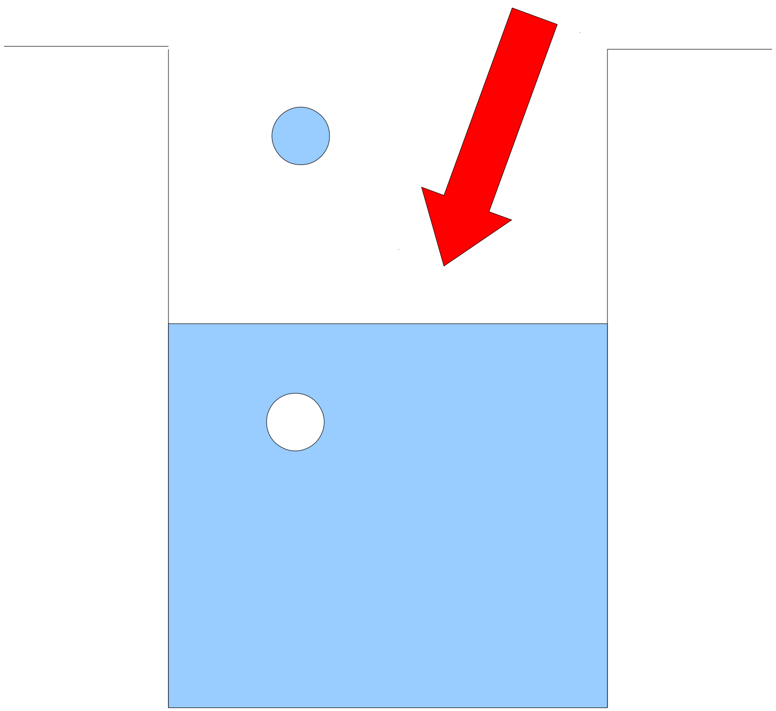
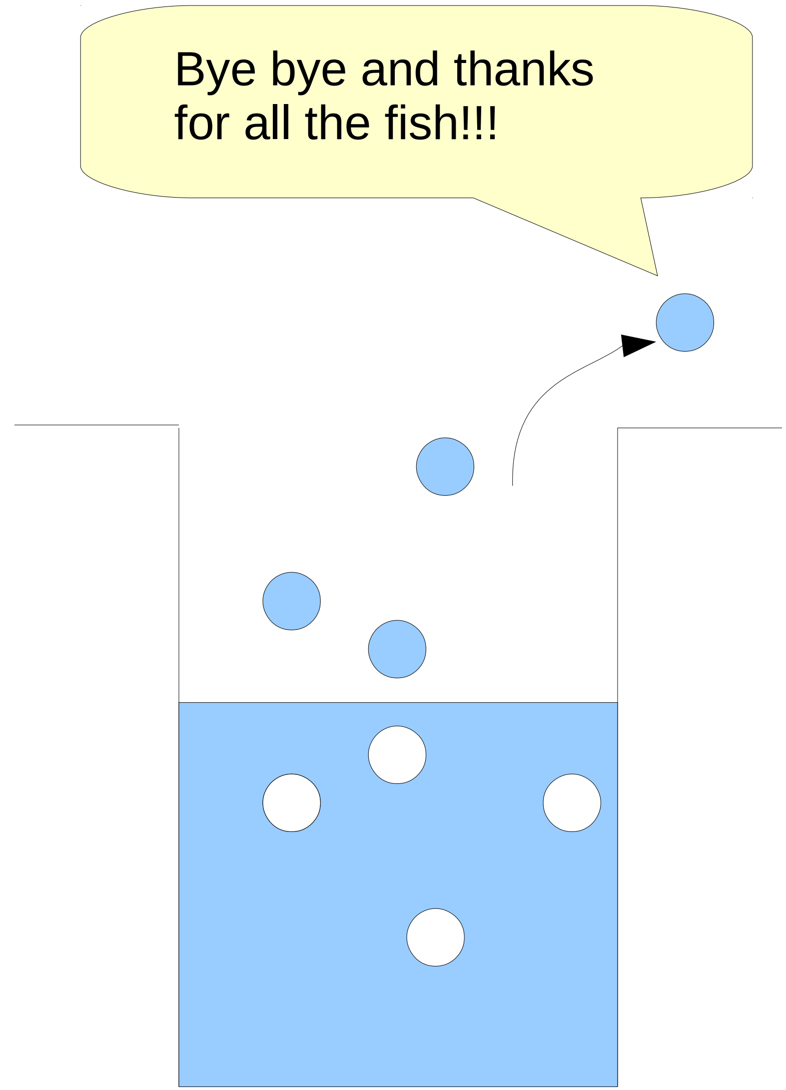


INDUCED PHOTOEMISSION

particle-hole recombination and
photon emission

Competing channels





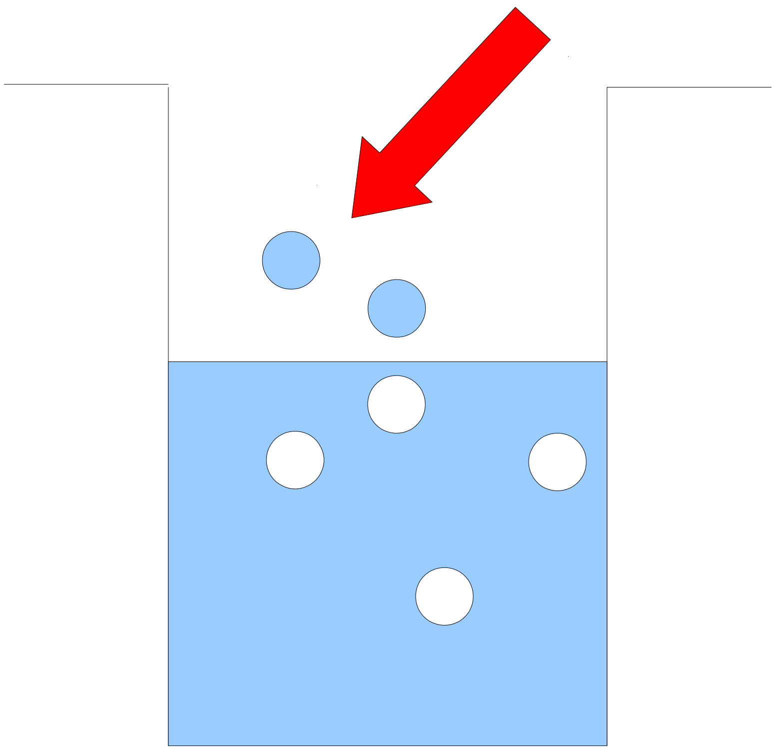
PHOTOEXCITATION

creates particle-hole pairs

NEUTRON EVAPORATION

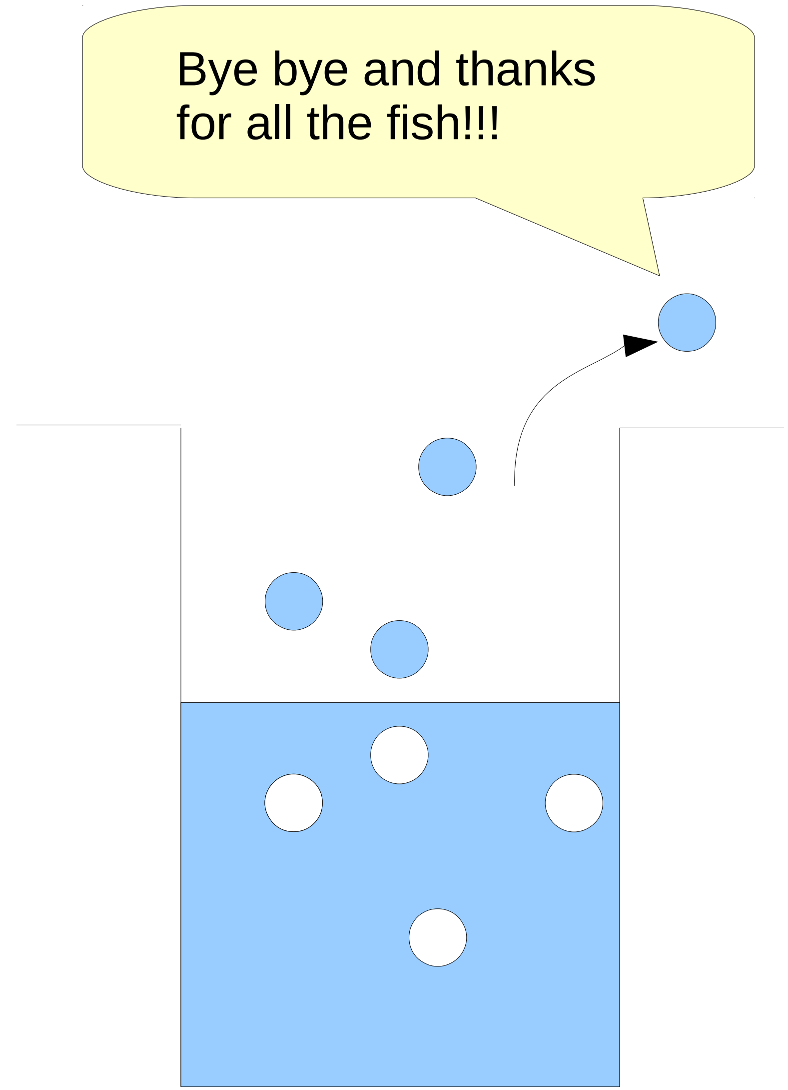
after several absorbed photons

Competing channels



PARTICLE EMISSION

single nucleons reach the continuum



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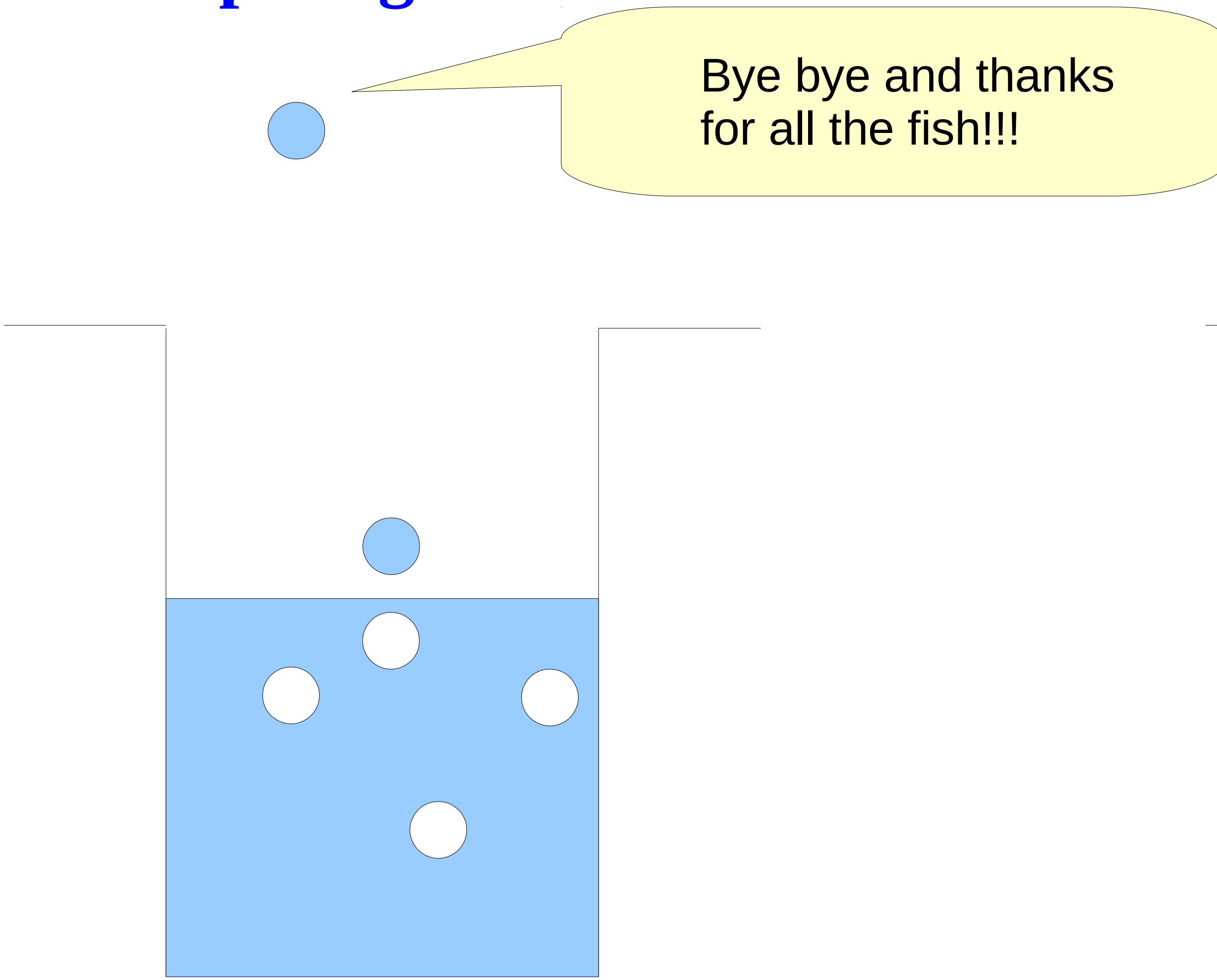

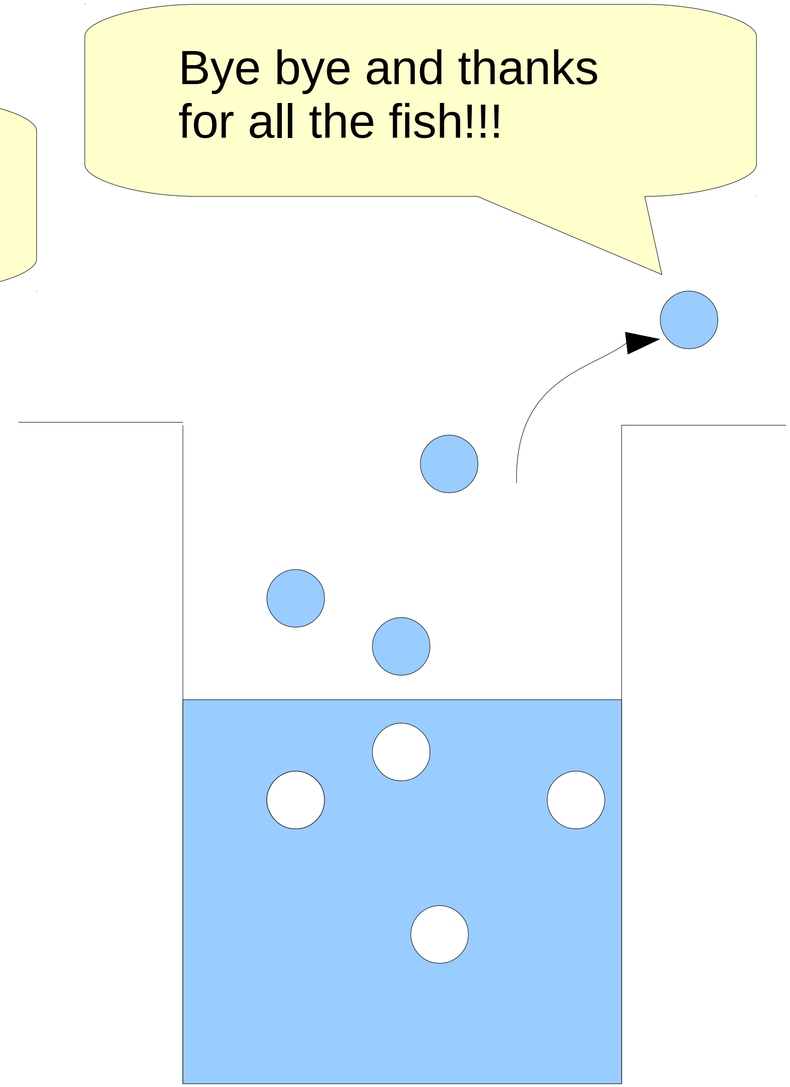

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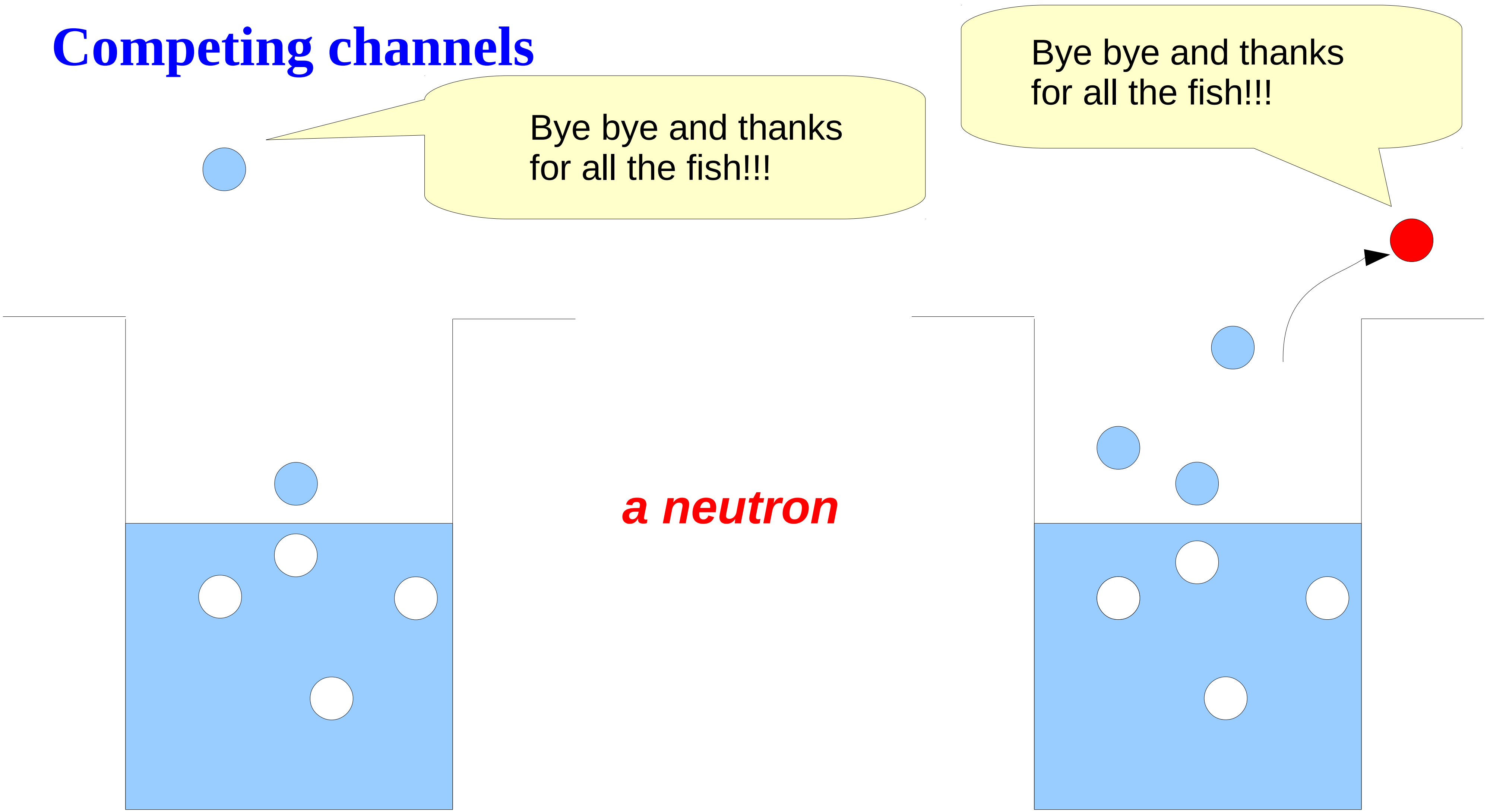

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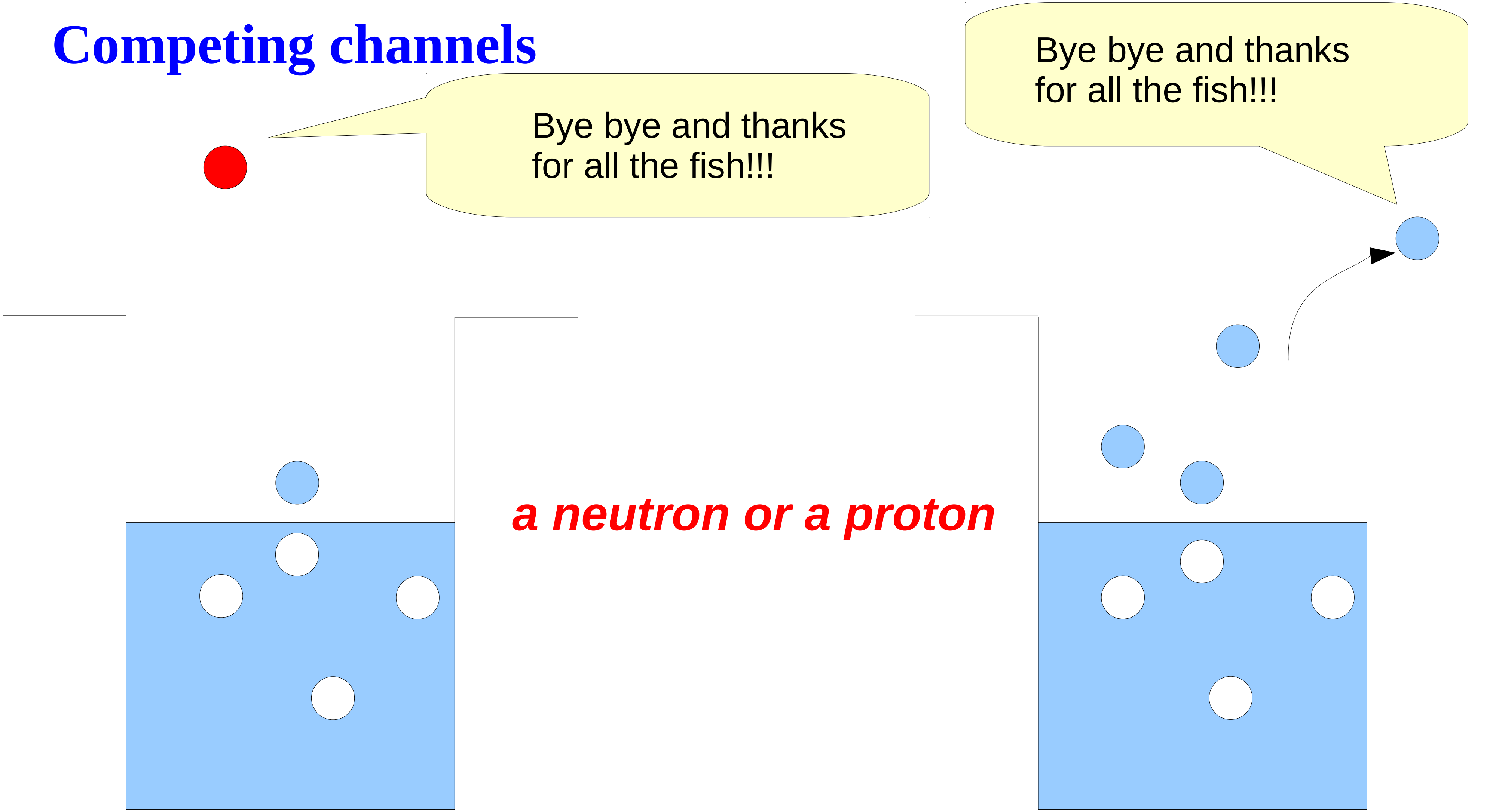

PARTICLE EMISSION

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NEUTRON EVAPORATION

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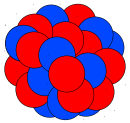
Quasiadiabatic regime



Assume complete nuclear equilibration between two photon absorptions

→ Effective absorption rate of an equilibrated compound nucleus

$$(N\Gamma)_{\mathrm{eff}}(E) = N\Gamma_{\mathrm{dip}}\ \rho_{\mathrm{acc}}(E)/\rho_{\mathrm{acc}}(E_g)$$

COMPETING WITH

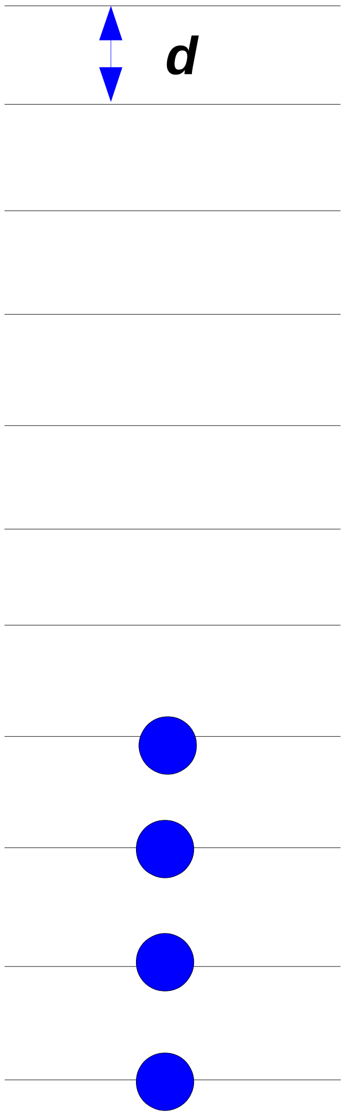
- Induced dipole emission $$(N\Gamma)_{\mathrm{ind}}(E) = (N\Gamma)_{\mathrm{eff}}(E)\ \rho_A(E-E_L)/\rho_A(E)$$
- Induced nucleon emission $$(N\Gamma)_{\mathrm{cnt}}(E) = N\Gamma_{\mathrm{dip}}\ \rho_{\mathrm{cnt}}(E)/\rho_{\mathrm{acc}}(E_g)$$
- Neutron evaporation $$\Gamma_n(E) = (2\pi)^{-1}\int_{E_g(A-1)}^{E-E_n} \mathrm{d}E' \rho_{A-1}(E')/\rho_A(E)$$
- Fission $$\Gamma_f(E) = (\hbar\omega_1/(2\pi))\exp\{-E_f \mathrm{d}\ln\rho_A(E)/\mathrm{d}E\}$$

Level densities needed!

New theoretical formalism for high energies and high particle-hole numbers!

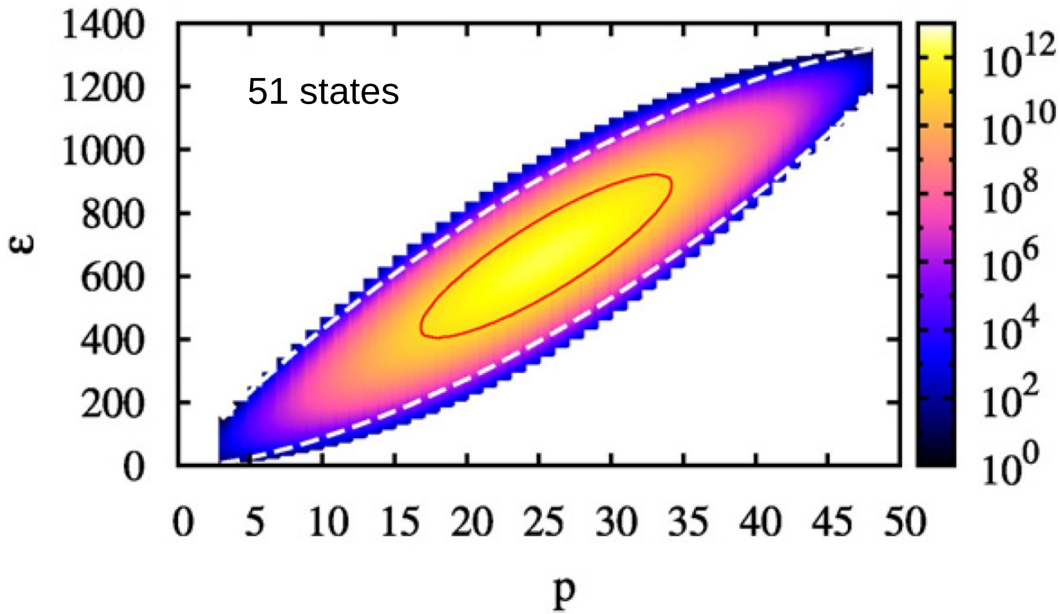
Shell model with finite number of bound states
A spinless non-interacting fermions distributed

$$\rho_p(E,J,\pi) = \frac{1}{2}\rho_p(E)\,\frac{2J+1}{2\sqrt{2\pi}\;\sigma_{2p}^3}\exp\left\{-\frac{[J+(1/2)]^2}{2\sigma_{2p}^2}\right\}$$



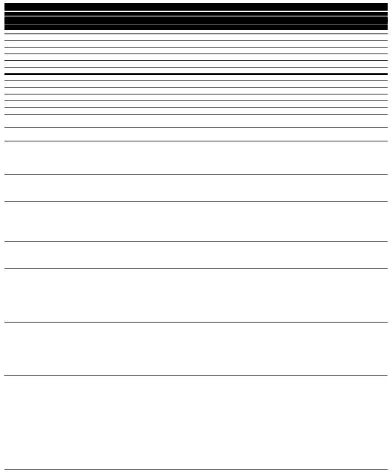
STEP I: CONSTANT SPACING MODEL

“Corrected” Gaussian, 2nd, 4th, and 6th moments



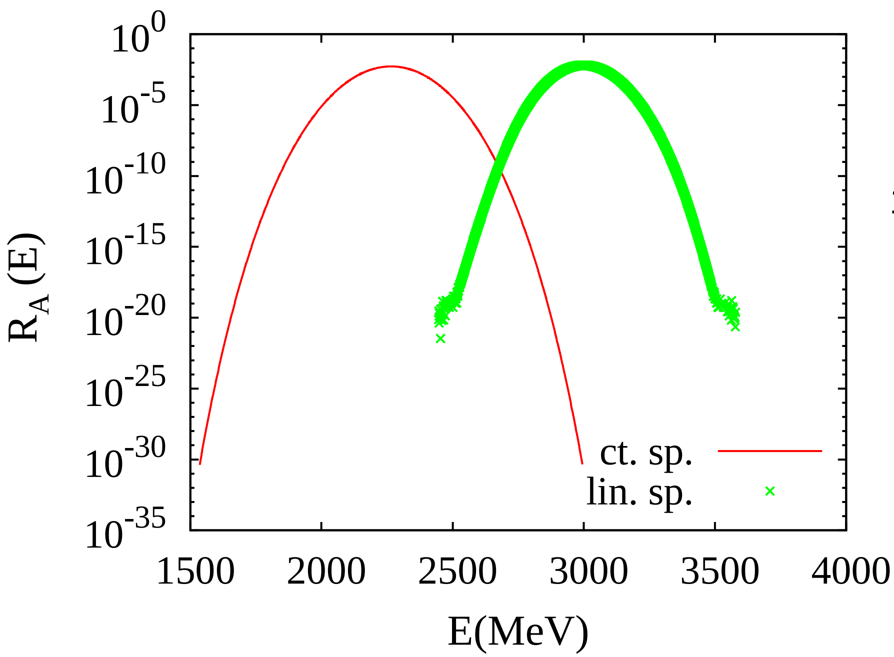
AP and H. A. Weidenmüller, Phys. Lett. B 718, 1105 (2013)

Level densities



STEP II: REALISTIC SPACING

More realistic case, level spacing linear or quadratic in energy



148 states
A=100

$$\rho_1^{(1)}(\varepsilon) = \frac{2A}{F^2}\varepsilon \qquad \rho_1^{(2)}(\varepsilon) = \frac{3A}{F^3}\varepsilon^2$$

Shift in energy
Slight asymmetry
Narrower width

AP and H. A. Weidenmüller
Nucl. Phys. A 917, 15 (2013)

Density of accessible states - Fermi gas model

Comparison

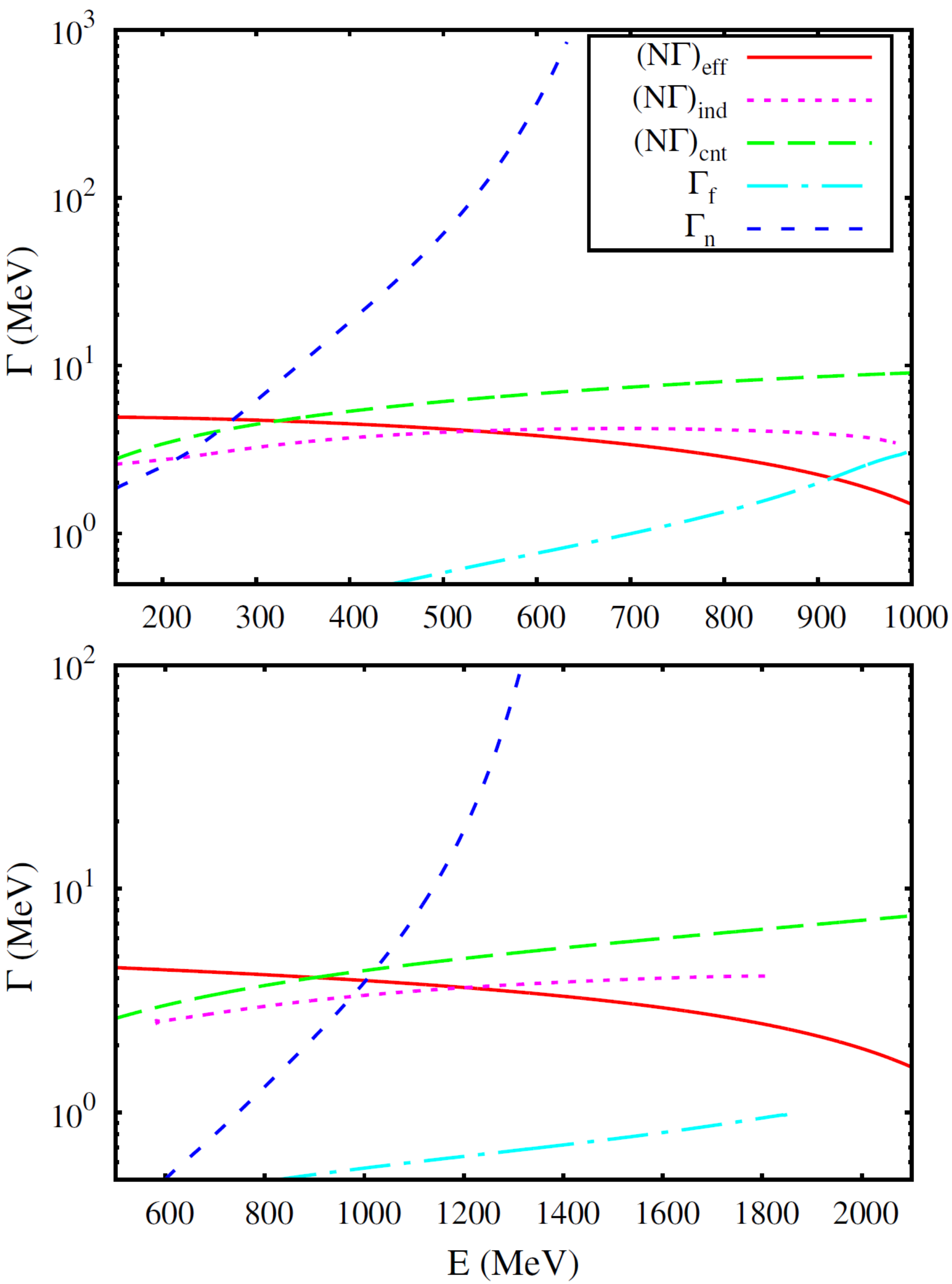
$$\rho_1^{(1)}(\varepsilon) = \frac{2A}{F^2}\varepsilon$$

$$A = 100$$

$$N\Gamma_{\rm dip} = 5\ {\rm MeV}$$

$$\rho_1^{(2)}(\varepsilon) = \frac{3A}{F^3}\varepsilon^2$$

$$A = 200$$



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

!!! At maximum of level density, photon absorption and emission are equally probable!!!

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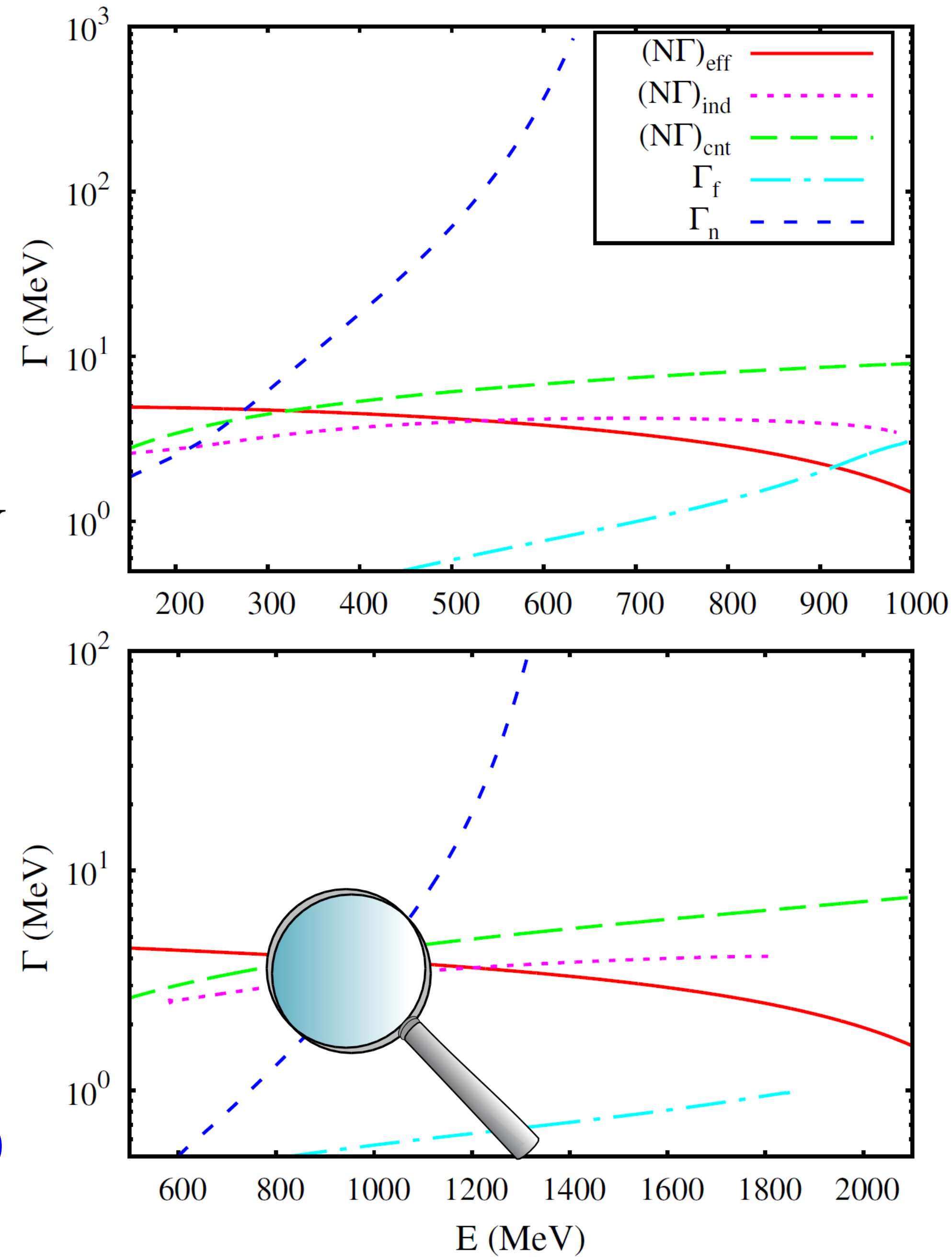

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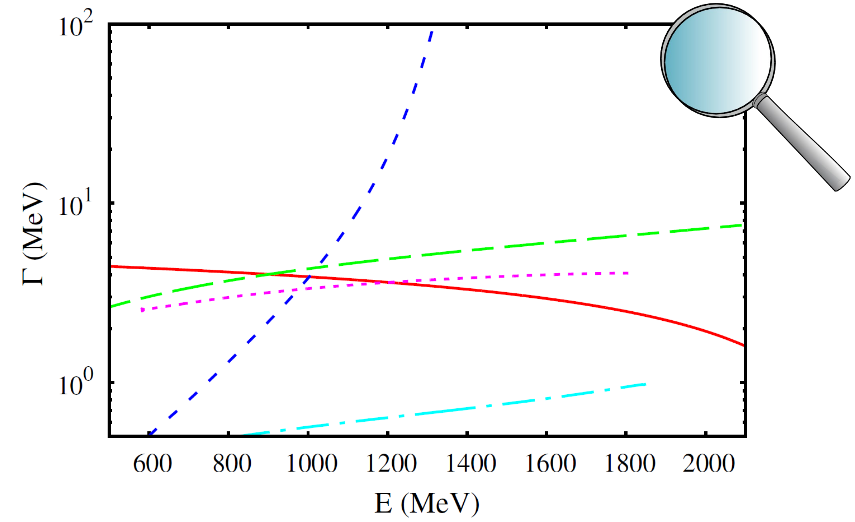
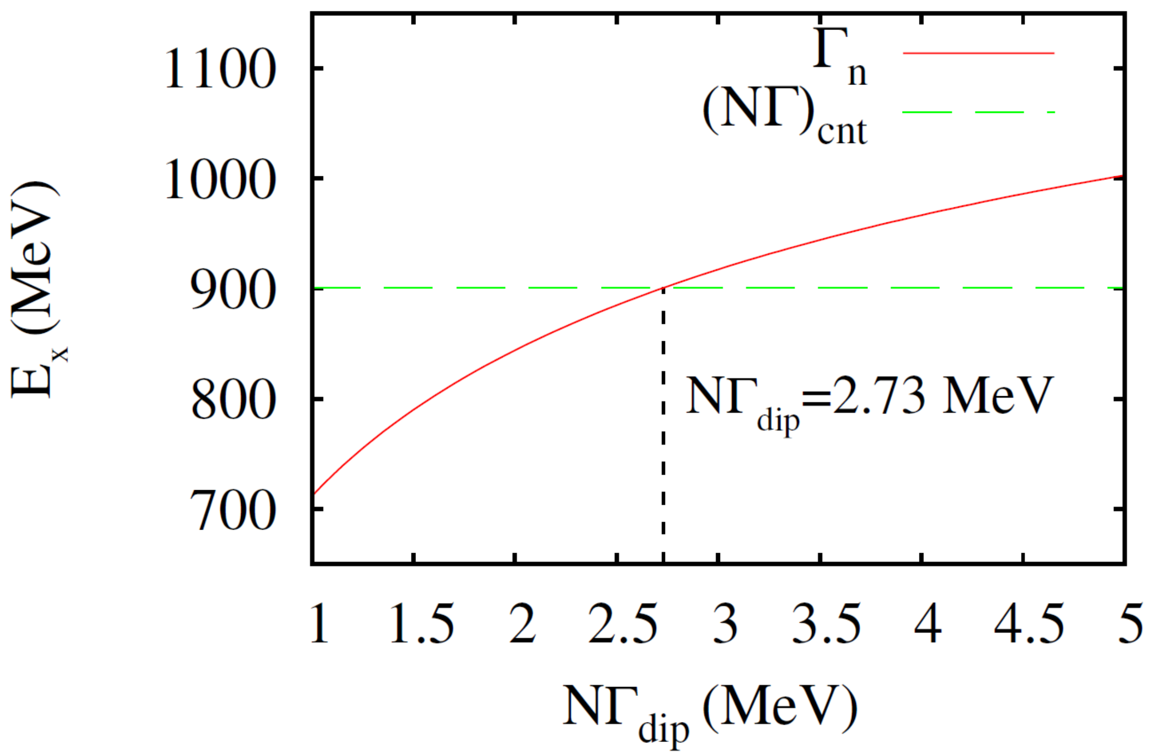


Emission of slow neutrons feeds states of similar energy in the daughter nuclei



Nucleon emission – p or n - details depend on exact binding energies and absorption rates

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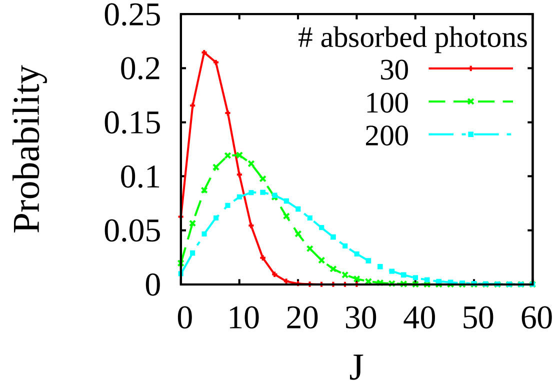
Phys. Rev. Lett. 112, 192502 (2014)

For a 50 zs pulse, proton-rich reaction products – FAR FROM STABILITY

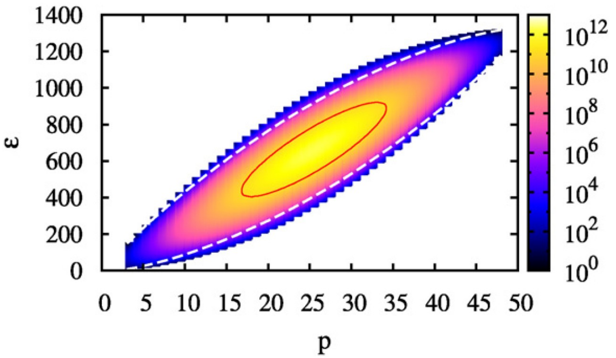
Conclusions



→ nuclear excitation with a multi-MeV zs coherent laser pulse

Quasi-adiabatic regime 1 photon absorbed / nuclear relaxation time

leads far from yrast and far from stability!!!



→ nuclear reaction theory + newly developed method for nuclear level densities

AP and H. A. Weidenmüller
Phys. Lett. B 718, 1105 (2013)
Nucl. Phys. A 917, 15 (2013)

→ End of reaction chain determined by duration of laser pulse – 50 zs

proton-rich nuclei due to strong neutron evaporation

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Phys. Rev. Lett. 112, 192502 (2014)