Nuclear excitation with zeptosecond multi-MeV laser pulses

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Nuclear Fusion: From NIF to the Stars

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New experimental developments ...

Experimental promise of coherent MeV photons!

Challenge: the theory of laser-induced nuclear reactions

ELI beam (intense & optical) \(\rightarrow\) thin Carbon foil \(\rightarrow\) electron sheet

Compton backscattering of another laser

Mono-energetic & tunable $\gamma$-ray beam (unlike bremsstrahlung)

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

Angular momentum

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

Energy

Photoexcitation

Hundreds of MeV above yrast!

Heavy ion collisions

# absorbed photons

Angular momentum
Nuclear excitation mechanism

**ELI photons**
- $N > 10^3$
- $E \sim 10\text{ MeV}$
- $T \sim 10^{-19}\text{ s}$

**PERTURBATIVE**
Giant Dipole Resonance once or twice


**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!!!

PHOTOEXCITATION
creates particle-hole pairs

RESIDUAL INTERACTION
nucleon-nucleon interaction redistributes energy
Competing channels

PHOTOEXCITATION creates particle-hole pairs

INDUCED PHOTOEMISSION
particle-hole recombination and photon emission
Competing channels

PHOTOEXCITATION creates particle-hole pairs

NEUTRON EVAPORATION after several absorbed photons

Bye bye and thanks for all the fish!!!
Competing channels

PARTICLE EMISSION
single nucleons reach the continuum

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Quasiadiabatic regime

Assume complete nuclear equilibration between two photon absorptions

Effective absorption rate of an equilibrated compound nucleus

\[(N\Gamma)_{\text{eff}}(E) = N\Gamma_{\text{dip}} \rho_{\text{acc}}(E) / \rho_{\text{acc}}(E_g)\]

COMPETING WITH

- Induced dipole emission
  \[(N\Gamma)_{\text{ind}}(E) = (N\Gamma)_{\text{eff}}(E) \rho_A(E - E_L) / \rho_A(E)\]

- Induced nucleon emission
  \[(N\Gamma)_{\text{cnt}}(E) = N\Gamma_{\text{dip}} \rho_{\text{cnt}}(E) / \rho_{\text{acc}}(E_g)\]

- Neutron evaporation
  \[
  \Gamma_n(E) = (2\pi)^{-1} \int_{E_g(A-1)}^{E-E_n} \text{d}E' \rho_{A-1}(E') / \rho_A(E)
  \]

- Fission
  \[
  \Gamma_f(E) = (\hbar\omega_1 / (2\pi)) \exp\left\{-E_f \text{d} \ln \rho_A(E) / \text{d}E\right\}
  \]
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, 2\textsuperscript{nd}, 4\textsuperscript{th}, and 6\textsuperscript{th} moments

Level densities

More realistic case, level spacing linear or quadratic in energy

![Graph showing level densities](image)

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

Shift in energy
Slight asymmetry
Narrower width

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Density of accessible states - Fermi gas model
Comparison

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

\[ A = 100 \]

\[ N\Gamma_{\text{dip}} = 5 \text{ MeV} \]

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

\[ A = 200 \]

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!!! At maximum of level density, photon absorption and emission are equally probable!!!
$\rho_1^{(1)}(\varepsilon) = \frac{2A}{F^2 \varepsilon}$

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Comparison

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.

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

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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!!!
- End of reaction chain determined by duration of laser pulse – 50 zs
- proton-rich nuclei due to strong neutron evaporation

nuclear reaction theory + newly developed method for nuclear level densities

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