Nuclear Reactions Induced by a Zeptosecond Multi-MeV Laser Pulse: A Progress Report

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1. Motivation

New developments in laser instrumentation: Within a few years' time, expect to have coherent laser beams of several MeV mean energy per photon and 10^{-19} s length in time. Aim: Study laser-induced nuclear reactions.

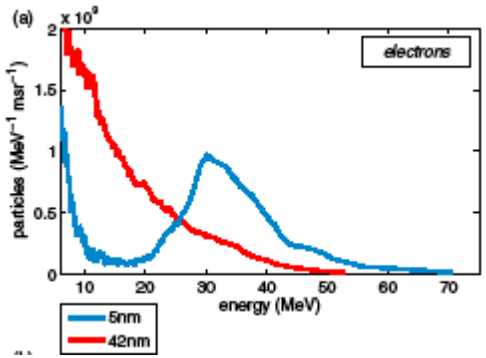
Three experimental steps toward that goal:

(i) European laser facility ELI ("Extreme Light Infrastructure") provides high-intensity laser beams. Here: "Nuclear Physics Pillar" under construction in Romania.

http://www.extreme-light-infrastructure.eu

(ii) Passage of that laser beam through extremely thin diamond-like Carbon foil (about 5 nm) ejects "sheet" of electrons of several 10 MeV energy.

(iii) Compton backscattering of another laser beam on that "sheet" (a mirror) produces coherent laser pulse with 10 or 20 MeV mean photon energy and 10^{-19} s length. (Relativistic contraction of backscattered pulse).



D. Kiefer at al., Eur. Phys. J. D 55 (2009) 42

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

Challenge: Theory of laser-induced nuclear reactions. Is there any difference to atom-laser interactions?

2. Reaction Mechanisms

Consider short strong laser pulse. Strong: $N = 10^2 - 10^4$ coherent photons per pulse, energy per photon E_L ¼ 5 – 10 MeV. Short: Energy spread of pulse σ ¼ 10 – 50 keV corresponds to length in time of 10^{-19} s or so.

Three possible scenarios for nuclear excitation:

(i) When single photon is absorbed, collective excitation (Giant Dipole Resonance, GDR) dominates. Two successive photons cause double GDR excitation (second harmonic) etc. (perturbative regime). Excitation to higher harmonics becomes increasingly unlikely.

(ii) Number N of photons in laser pulse is so high and/or mean photon energy is so large that perturbation expansion breaks down. The compound nucleus (CN) is excited and equilibrates while more photons are absorbed (quasi-adiabatic regime). Excitation energies of up to several 100 MeV possible. No analogue of CN regime in atom-laser interactions.

(iii) Individual nucleons absorb photons and are immediately ejected. The target nucleus evaporates by multiple nucleon emission (non-adiabatic regime).

Which parameter values separate these possibilities? Question of time scales.

Consider dipole absorption only (dominant process) on medium-weight or heavy nuclei.

Photon energy E_L ¼ several MeV. Pulse width σ ¼ 50 keV. N coherent photons per pulse.

For photon energy of about 5 MeV, dipole width Γ_{dip} ¼ few keV. Because of photon coherence consider $N\,\Gamma_{dip}$ ¼ 100 keV to 10 MeV. And ~ / ($N\,\Gamma_{dip}$) is typical time between successive photon absorption processes. Note $\sigma < N\,\Gamma_{dip}$.

Nuclear relaxation processes have "spreading width" Γ_{spread} ¼ 5 MeV and relaxation time ~ / Γ_{spread} .

Perturbative regime: $\Gamma_{spread} > N\,\Gamma_{dip}$ and, thus, N · 100 or so.

Quasi-adiabatic regime: Γ_{spread} ¼ $N\,\Gamma_{dip}$.

Non-adiabatic regime: $\Gamma_{spread} << N\,\Gamma_{dip}$.

Estimate for perturbative regime holds only if mean photon energy E_L equals dipole resonance energy E_{dip}. When $E_L = E_{dip}/2$, for instance, dipole width is reduced by factor 8 and Lorentzian form of GDR gives another reduction factor 10 or so. That suggests that nuclei may collectively be excited even by laser pulses with 10^4 photons per pulse!

Check these assertions. Work out experimental signal for collective excitation. Study what happens beyond critical values of N and E_L .

3. Collective Excitation

(perturbative regime)

H. A. Weidenmüller, Phys. Rev. Lett. 106 (2011) 122502

(i) Single photon absorption:

Write time-dependent Hamiltonian as

$\hat{H}(t) = H_{nuc} + H_{int}(t)$ with laser interaction modeled as

$H_{int}(t) = N^{1/2} f(t) H_{dip}$ and $f(t) = \exp [- \sigma^2 t^2/(2\sim^2) - i E_L t/\sim]$ where

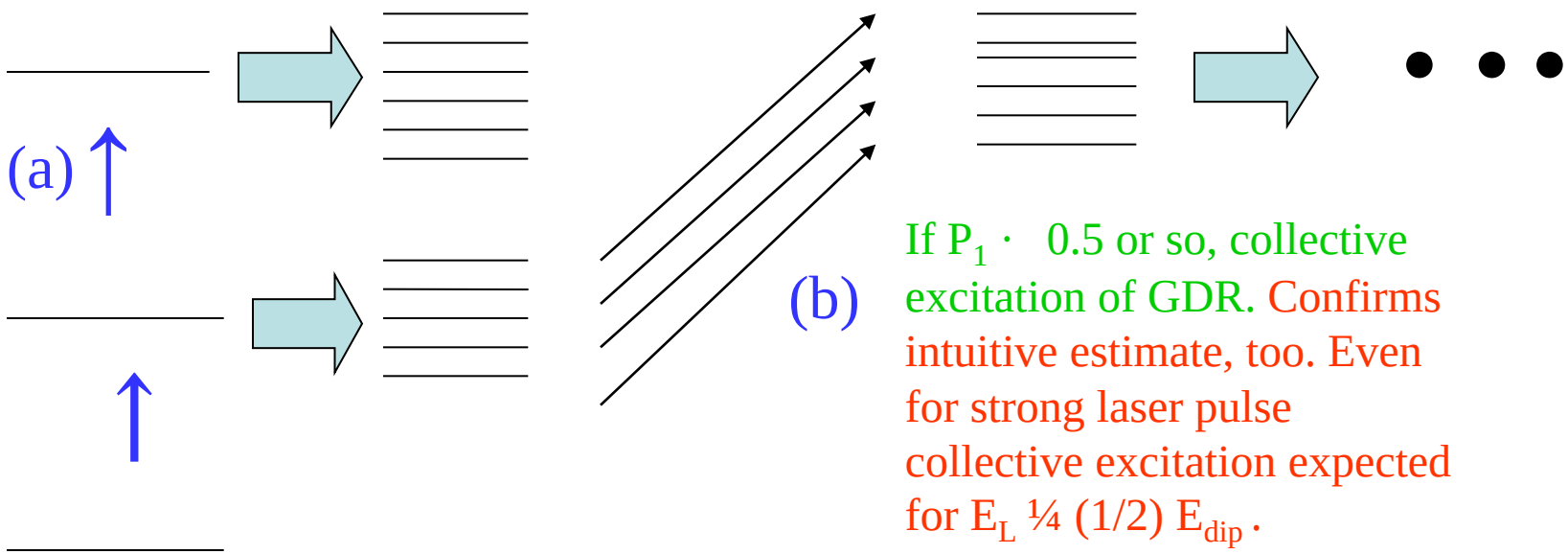
σ¼ 50 keV and E_L = several MeV. For H_{nuc} use doorway state model plus random-matrix model: Single absorption of photon populates Giant Dipole Mode. That mode coupled to large number of complex states. Use time-dependent perturbation theory to 1st order.

$P_1 = [2\pi N\Gamma_{dip} \Gamma_{spread}] / [(E_L - E_{dip})^2 + (1/4) (\Gamma_{spread})^2]$.

Valid if $P_1 << 1$. Confirms intuitive argument.

(ii) Double photon absorption:

Two possibilities: (a) Double excitation of Giant Dipole Mode (2nd harmonic); (b) Excitation of Giant Dipole Mode followed by decay into complex states followed by Giant Dipole excitation of each of the complex states (Brink-Axel mechanism). Model both possibilities with random matrices. Possibility (b) dominates and yields P_2 ¼ (1/2) $(P_1)^2$. Strongly suggests that higher-order terms are negligible.



If P_1 · 0.5 or so, collective excitation of GDR. Confirms intuitive estimate, too. Even for strong laser pulse collective excitation expected for E_L ¼ (1/2) E_{dip} .

How to verify collective excitation experimentally:

B. Dietz and H. A. Weidenmüller, Phys. Lett. B 693 (2010) 316.

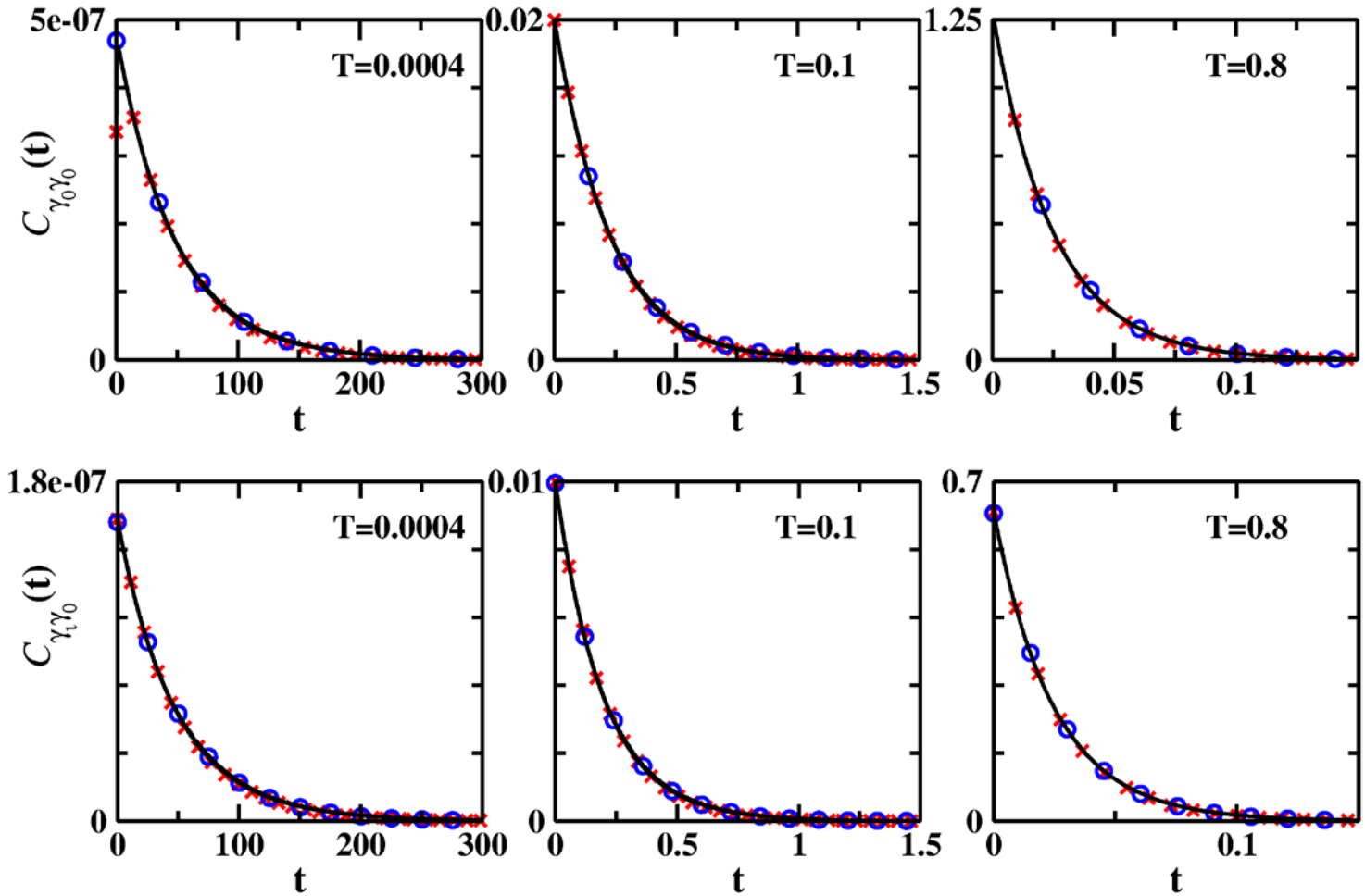
Photon of 5 to 8 MeV energy impinging on spin zero medium-weight or heavy target nucleus excites states with spin/parity 1^-. Average spacing of these states is about 10 eV << σ ¼ 50 keV. Therefore entire band of about 10^3 to 10^4 such states is excited coherently. Such coherent excitation precludes observation of individual states. Instead, measure decay in time of coherently excited band of states. That provides information not otherwise accessible.

Decay time of these states large compared to other time scales: Below neutron threshold that time governed by gamma decay, above neutron threshold by neutron decay. Decay effectively happens after laser pulse has passed target nucleus.

Within random-matrix approach to mixing of GDR with non-collective states, time scales and decay laws for both gamma decay and neutron decay can be worked out theoretically. Parameters are mean spacing of states, number of gamma decay channels, And "transmission coefficients" (average strength of coupling of band of states to each channel).

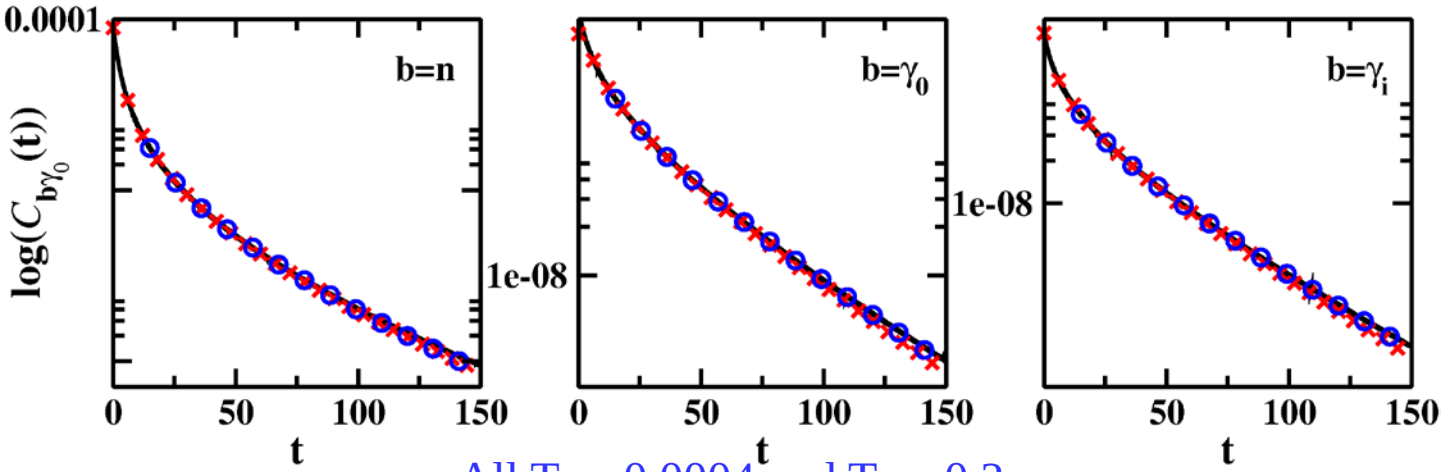
Non-exponential decay for single open neutron channel as experimental signal.

Parameters are transmission coefficients T_c in open channels and mean level spacing d.
Choose 50 open gamma channels with equal $T_\gamma = T$.
(i) Neutron channel is closed.

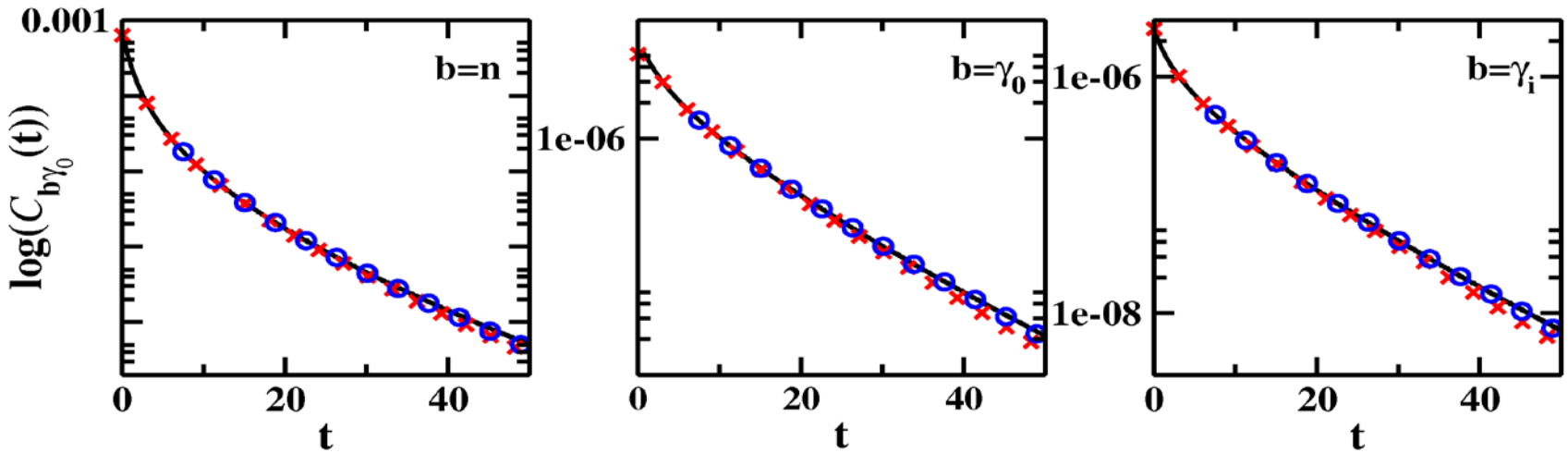


Time is in units of h / d. Decay is always purely exponential (blue circles). Exponent given by total gamma decay width.

(ii) Single neutron channel is open. (Plus 50 gamma channels as before).



All $T_\gamma = 0.0004$ and $T_n = 0.2$.



All $T_\gamma = 0.0016$ and $T_n = 0.4$.

Non-exponential decay. Fits (blue circles) with $t^a \exp[-bt]$ give $b \approx 50\, T_\gamma$ and $a \approx 3/2$ for neutron channel and $a \approx 1/2$ for gamma channel as expected.

4. Quasi-Adiabatic Regime

A. Pálffy and H. A. Weidenmüller, arXiv1206.1542

Perturbation theory fails if N or E_L are too large. But for N Γ_{dip} ¼ Γ_{spread} dipole absorption is quasi-adiabatic: About 1 photon absorbed per relaxation time ~ ~ / Γ_{spread}.

Qualitative Expectations:

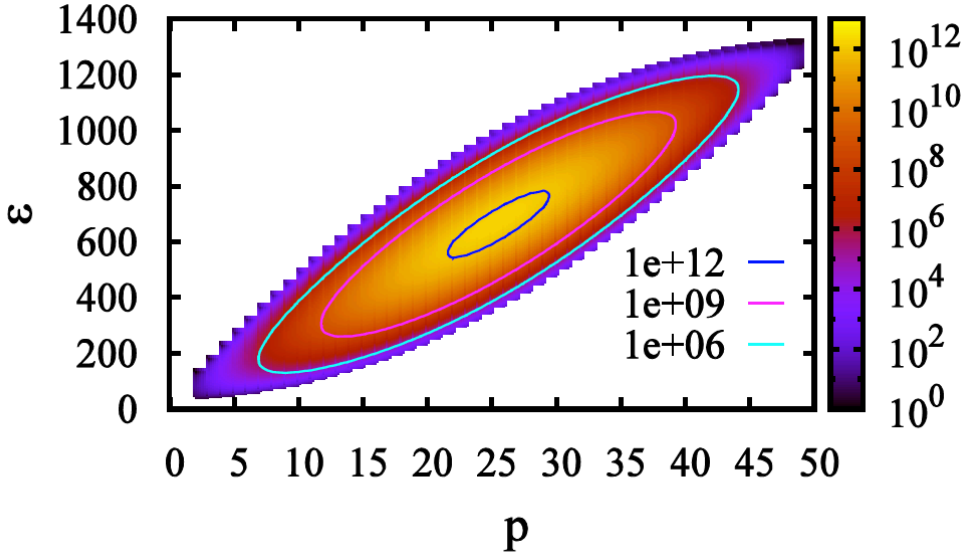
Many photons successively absorbed. Compound nucleus (CN) excited up to several 100 MeV. Each photon carries one unit of angular momentum. Spin distribution in CN has maximum at J_{max} ¼ $n^{1/2}$, grows very slowly with number n of absorbed photons. Neglect spin and focus on competition of nuclear relaxation, multiple dipole excitation, induced dipole emission, fission, neutron emission. Same processes in daughter nuclei.

Intended theoretical description:

Chain of linked master equations that involve densities of particle-hole states at high excitation energies and/or large particle-hole number.

Conceptually standard but a new regime: (i) CN spectrum not known at such excitation energies, (ii) production of daughter nuclei far off valley of stability is possible.

To set up master equation(s) need level densities of particle-hole states at high excitation energy and/or large particle-hole number. These not available so far. A challenging theoretical problem in its own right. Given the finite potential of the shell model, distribute A nucleons over the finite number of bound single-particle states, determine resulting level density. In simplest form: Distribute p spinless non-interacting Fermions over b equally spaced single-particle levels with spacing d, determine the resulting level density of many-body states for b >> 1. Cannot be done numerically. Analytical solution: For fixed p and b >> 1 level density versus energy ε is asymptotically Gaussian. (All energies and inverse level densities in units of d.)



Contour plot of the dimensionless level density for p particles in b = 51 equally spaced single-particle states. The exclusion principle admits only states with energies within the coloured domain. The full lines are lines of constant density.

A. Palffy and H. A. Weidenmüller, arXiv1206.1542

From here, calculate level densities also for more realistic cases.

That is as far as we have come.

5. Conclusions

Laser beams with average photon energies around 5 - 10 MeV, with pulse lengths of 10^{-19} s or so expected within a few years' time.

Energy or time scales determine three regimes.

In the adiabatic regime, even an intense short laser pulse may excite nuclei collectively. Observable is time-decay function. For a single open neutron channel, time decay is non-exponential.

In the quasi-adiabatic regime about one photon is absorbed per nuclear relaxation time. Excitation energies up to several 100 MeV are likely, with small angular momentum transfer. In contrast to laser-atom interactions, relaxation plays important role. Attractive residual interaction keeps nucleus together. Decay by neutron emission may lead to nuclei far off stability. Intended theoretical tool: Set of master equations. Level densities are needed, have been calculated.

In the non-adiabatic regime, nuclei evaporate. Perhaps not very interesting?

A novel regime of laser-matter interactions.