Nuclear Excitation by a Strong Zeptosecond Multi-MeV Laser Pulse

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Abstract

Within a few years' time, the "Nuclear Physics Pillar" of ELI (Extreme Light Infrastructure) is expected to produce coherent strong short laser pulses with several MeV energy per photon. We discuss theoretical expectations for the nuclear reactions induced by such pulses with medium-weight and heavy nuclei.

Keywords: *Statistical nuclear theory; compound-nucleus reactions; gamma-induced reactions*

1 Introduction

This work is motivated by recent developments in laser instrumentation. Within a few years' time, coherent laser beams with energies of several MeV per photon and 10^{-19} s length in time are expected to become available for the study of laser-induced nuclear reactions. Three steps are expected to lead towards that goal:

(i) The "Nuclear Physics Pillar" of ELI [1] (Extreme Light Infrastructure) presently under construction in Romania provides a very-high-intensity but otherwise conventional laser beam.

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

(iii) That sheet acts like a mirror for the photons of a second (conventional) laser beam. Compton backscattering of the photons produces a coherent laser pulse with several MeV energy per photon and $\approx 10^{-19}$ s length in time.

Recent experiments have shown that passage of a laser beam through a thin Carbon foil does indeed produce electrons with energies of several 10 MeV, see Fig. 1. The production of a very thin sheet of electrons and the coherent backscattering of another laser beam on that sheet are presently under intense investigation [3].

These developments pose a challenge to nuclear theory. What kind of processes do we expect at which rate when a laser beam with coherent photons of several MeV per photon and 10^{-19} s time duration hits a nucleus? What is the difference to the so far widely studied atom-laser interaction?

2 Reaction mechanisms

To answer these questions, we consider a short strong laser pulse with $N = 10^2 - 10^4$ coherent photons per pulse, with a mean photon energy E_L of 5–10 MeV, and with an energy spread σ of 10−50 keV corresponding to a length in time of about 10^{-19} s. Such a pulse seems extremely strong. But comparison with the atomic case shows that for nuclei it is still actually rather weak. In atoms, the electric field strength of a strong

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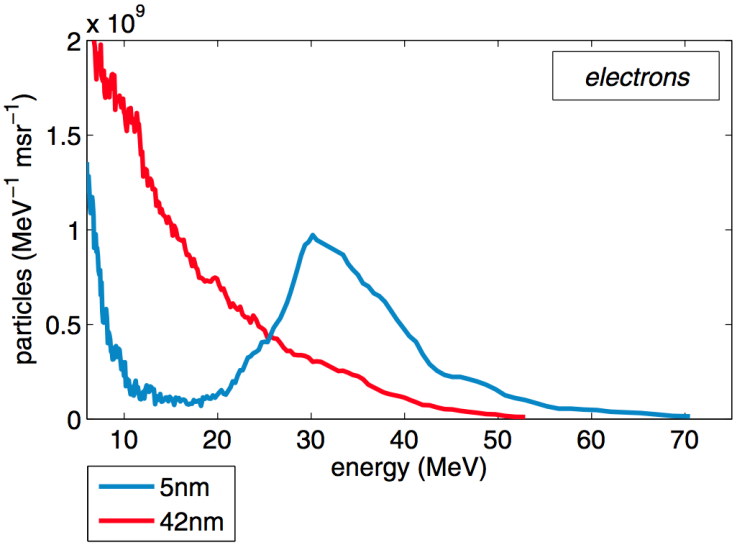

Figure 1: Energy distribution of electrons ejected from two Carbon foils of different thicknesses by a conventional laser beam. Taken from Ref. [2].

laser pulse distorts the nuclear Coulomb potential. Thus, the field strength is of order (eV/ Bohr radius) in magnitude. A corresponding field strength in nuclei would have to be of order (MeV/fm), i. e., about 10 orders of magnitude stronger. That is far more than what is achieved by a laser pulse with the above-mentioned specifications. Thus, even such a strong laser pulse provides only a fairly weak perturbation for nuclei. The difference is due to the fact that nuclei are governed by the strong interaction.

For photons of several MeV energy, the product of wave number and nuclear radius is small compared to unity, and it is justified to consider only dipole absorption, the dominant mode of gamma absorption in nuclei. The dipole width $\Gamma_{\rm dip}$ is strongly energy dependent but, for photon energies of several MeV, has a typical value of several keV. Because of the large number N of photons in the pulse (and since the number N_0 of photons absorbed from the pulse always obeys $N_0 \ll N$) we use the semiclassical approximation throughout the reaction. The characteristic parameter is then $N\Gamma_{\rm dip} \approx 10^2 - 10^4$ keV. The competition between the rate $N\Gamma_{\rm dip}/\hbar$ for dipole absorption and the nuclear relaxation rate $\Gamma_{\rm spr}/\hbar$ (where the spreading width $\Gamma_{\rm spr}$ has a typical value of 5 MeV) defines three regimes for laser-induced nuclear reactions:

(i) The perturbative regime $N\Gamma_{\rm dip} \ll \Gamma_{\rm spr}$. Here, one-step excitation of the Giant Dipole Resonance (GDR) dominates. Double or multiple excitation via absorption of several photons turns out to be unlikely.

(ii) The quasi-adiabatic regime $N\Gamma_{\rm dip} \approx \Gamma_{\rm spr}$. The rates for photon absorption and equilibration are about equal. The nucleus remains close to equilibrium during the entire process. Multiple photon absorption leads to excitation energies up to several 100 MeV. Equilibration is caused by the residual interaction in nuclei. The process seems to have no analogue in laser-atom interactions and constitutes a new regime for the interaction of laser light with matter [4].

(iii) The sudden regime $N\Gamma_{\rm dip} \gg \Gamma_{\rm spr}$. The residual interaction is irrelevant. Nucleons absorb photons individually until their energy exceeds the binding energy whereupon they are ejected. If the laser pulse lasts long enough, the nucleus completely evaporates.

In this paper we discuss processes (i) and (ii).

3 Perturbative regime: collective excitation

In the perturbative regime, excitation of the GDR is the dominant process. In Ref. [5] the GDR and its harmonics were modeled as doorway states coupled to a large number of background states. The latter were described in terms of a random-matrix model. The Brink–Axel hypothesis was used (every excited nuclear state possesses its own GDR). With these assumptions it was shown that in the perturbative regime, the GDR is only singly excited. Multiple photon absorption is an unlikely process.

For an even-even target nucleus the GDR is spread over a large number of states with spin/parity 1^-. In medium-weight and heavy nuclei these have typical spacings of 10 eV. A photon with an energy spread $\sigma \approx 50$ keV excites an entire band of 10^3-10^4 such states coherently. Such coherent excitation precludes the observation of individual excited states. The relevant observable is the decay in time of the compound nucleus. That decay provides information on amplitude correlations that are not available otherwise. For photon energies below (right above) neutron threshold, the decay process is exponential (non-exponential) in time. The non-exponential time dependence is a direct consequence of the Porter–Thomas distribution of neutron decay widths [6]. Examples are shown in Figures 2 and 3, both taken from Ref. [6].

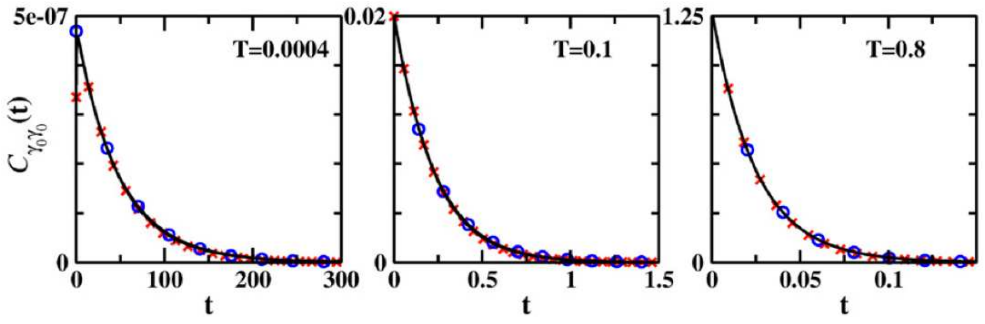

Figure 2: Decay in time of the compound nucleus excited by photon absorption to states below neutron threshold with average level spacing d. Time is in units of h/d. Decay is calculated for 50 gamma decay channels all with the same transmission coefficients T.

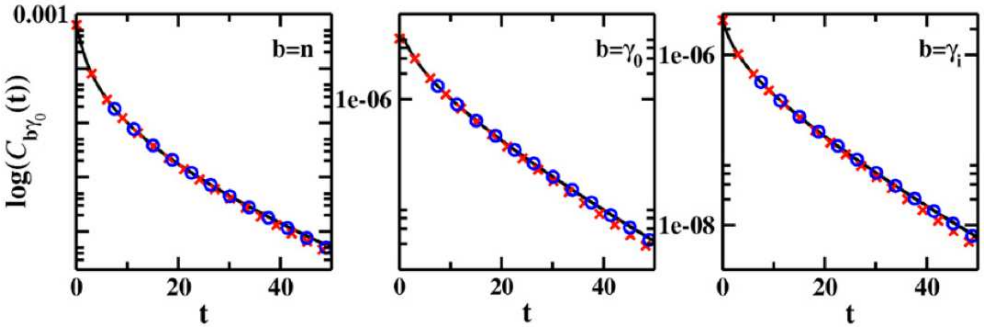

Figure 3: Decay in time of the compound nucleus excited by photon absorption to states right above neutron threshold with average level spacing d. Time is in units of h/d. Decay is calculated for 50 gamma decay channels all with the same transmission coefficients $T_\gamma = 0.0016$ and a single open neutron channel with transmission coefficient $T_\mathrm{n} = 0.4$. The index b denotes the exit channel, the index zero denotes the ground state.

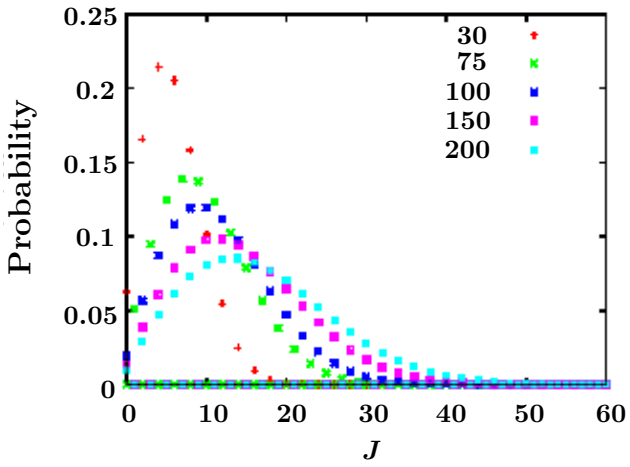

Figure 4: Distribution of spin values in the compound nucleus after absorption of N_0 photons (values in the legend above) versus spin.

4 Quasi-adiabatic regime

The absorption of N_0 dipole photons leads to a slow growth $\propto \sqrt{N_0}$ of the total spin of the compound nucleus, see Fig. 4. Even the absorption of 100 photons of 5 MeV each, producing states 500 MeV above the ground state, on average only leads to spin values around 10. Thus, multiple photon absorption excites states far above the yrast line, a domain of excitation energies hardly explored so far. In view of these small spin values we totally neglect spin in what follows. As is usual for compound-nucleus processes, the reaction is described in terms of rate equations. In addition to the rates $\Gamma_{\rm dip}/\hbar$ for dipole absorption and $\Gamma_{\rm spr}/\hbar$ for internal equilibration, we need the rates for induced gamma emission, for neutron evaporation, and for gamma-induced emission of neutrons and protons. These rates typically depend on nuclear level densities (total density, density of particle-hole states, density of accessible states, etc.). At excitation energies of several 100 MeV above yrast and for medium-weight and heavy nuclei, such level densities are huge (values like 10^{30} or 10^{40} times the mean single-particle level density are easily attained), and the reliable and quick calculation of such densities poses a challenge.

4.1 Level density

In Refs. [7, 8] we have developed a new approach that is specifically tailored to the problem. In short, the total level density is obtained by distributing A non-interacting fermions over a finite number of bound single-particle states defined in terms of a mean-field or a shell-model potential. Here A is the nuclear mass number. For an arbitrary set of single-particle energies, we derive exact analytical expressions for the low moments and low cumulants of the total level density. These are used to determine approximate expressions for the total level density and for particle-hole densities. The Fermi-gas model is used to calculate the density of accessible states.

The resulting total level density (in units of the inverse single-particle level spacing) for p particles distributed over $b = 51$ equally spaced single-particle states is shown in Fig. 5, taken from Ref. [7]. The performance of the approximation used in our approach is shown for several values of p in Fig. 6 (taken from Ref. [7]) by comparison with exact numerical calculations. The agreement is good in the center of the spectrum. Significant differences arise only in the tails. That pattern prevails for all our calculations.

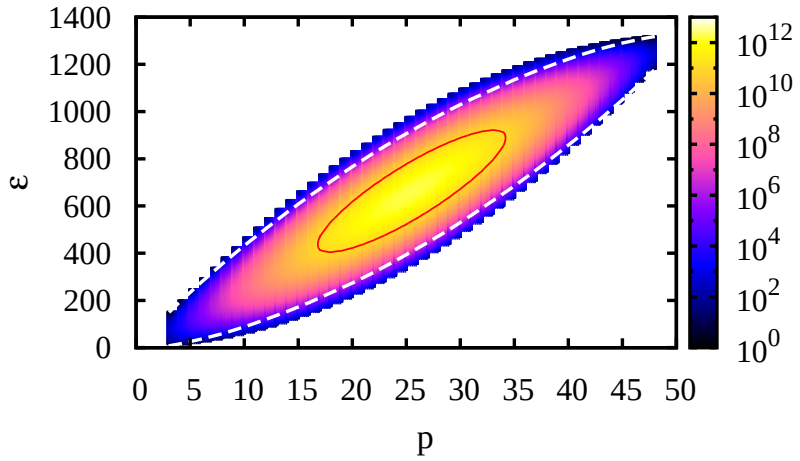

Figure 5: Contour plot of the level density for p particles in $b = 51$ equally spaced single-particle states as a function of energy ε (in units of the single-particle level spacing). Because of the exclusion principle, only states within the colored domain are accessible. The full line depicts the constant level density contour at 10^{11}.

For medium-weight and heavy nuclei, the constant-spacing model is unrealistic. In the calculations reported in Ref. [8] we have, therefore, used smooth single-particle level densities that increase linearly or quadratically with energy. Typical results for the level density for two choices of the single-particle density are shown in Fig. 7, taken from Ref. [8].

In summary, we have developed an analytic, fast-to-implement approach to the calculation of the total level density, and to particle-hole densities. The approach works well for high excitation energies and large particle numbers. It seems desirable, of course, to develop an approximation that is uniformly good in all parts of the spectrum. The huge numbers attained by the nuclear level density (measured in units of the mean single-particle density) preclude such a possibility: for the constant-spacing

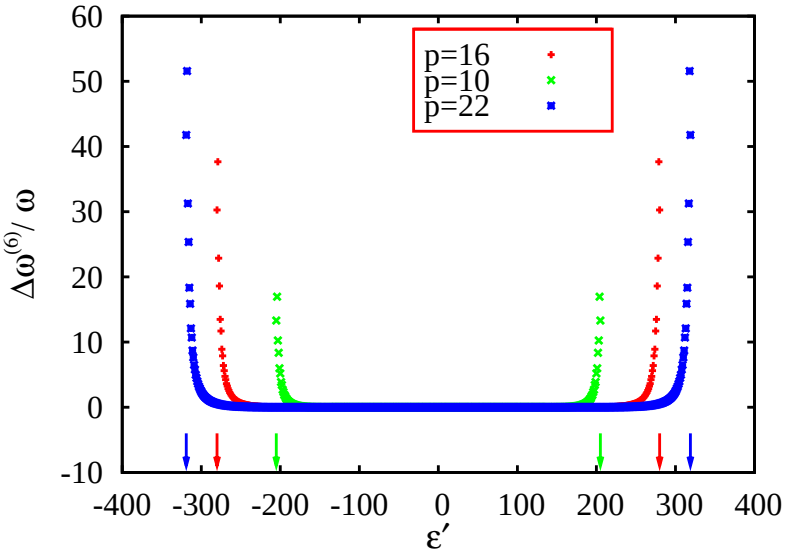

Figure 6: Relative difference between approximate and exact values of the level density for a constant-spacing model with $b = 51$ single-particle states and p fermions.

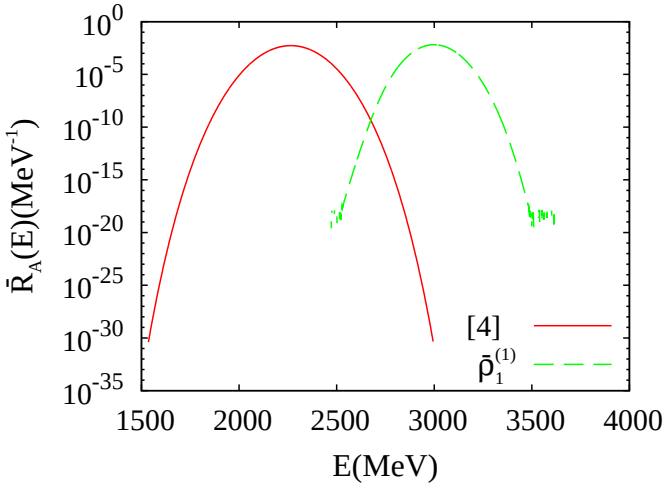

Figure 7: Plot of the normalized level density $R_A(E)$ versus energy E (in MeV) for $A = 100$ particles in $B = 148$ states for the constant-spacing model (full line) and for a smooth single-particle level density that rises linearly with energy (dashed line).

model with 100 particles in 200 single-particle states, the level density ranges over 60 orders of magnitude. That is the accuracy with which exact analytical expressions (if available) would have to be evaluated. This shows that different approximations are needed in different parts of the spectrum.

4.2 Implications for photon-induced reactions

We consider absorption of photons with energy $E_L = 5$ MeV. For clarity we first neglect both neutron evaporation and stimulated nucleon emission. The rate for induced photon emission increases with increasing excitation energy. At the maximum E_0 of the total level density, that rate becomes equal to the rate for photon absorption: excitation beyond E_0 is not possible. The occupation probability of excited nuclear states is nearly stationary and hovers around E_0 while the laser pulse lasts. With E_0 amounting typically to several 100 MeV, excitation of the compound nucleus to energies several 100 MeV above yrast is a novel feature of laser-induced photon absorption.

The picture changes when neutron evaporation is taken into account. The use of the Weisskopf formula and of our results for the total level density shows that the neutron emission becomes competitive with photon absorption only at high excitation energies (several 10 MeV below E_0). The emitted neutrons have predominantly small energies around 10 or 20 MeV and populate highly excited states several 10 MeV below E_0 in the daughter nucleus. These in turn undergo photon absorption and neutron emission, leading to highly excited states in the nucleus having two neutrons less than the target nucleus. In this way, the reaction traverses a chain of nuclei with equal proton numbers and ever decreasing neutron numbers. The reaction terminates after emission of n_0 neutrons where n_0 is determined by the duration in time of the laser pulse. This shows that, depending on the length in time of the laser pulse, laser-induced reactions offer the possibility to generate and study nuclei far off the valley of stability, differing by n_0 neutrons from the target nucleus.

The picture changes once again when emission of nucleons directly induced by photon absorption is taken into account. The emission produces neutrons and protons with nearly equal probabilities. That spreads the distribution of final nuclei, filling the gap between the valley of stability and a nucleus differing by n_0 neutrons from the target nucleus.

5 Conclusions

Coherent laser beams with photon energies around 5 to 10 MeV and pulse lengths of 10^{-19} s are expected to be available within a few years' time. The nuclear reactions induced by such short and intense laser pulses differ from laser-atom reactions in two essential aspects: (i) The nucleus is a strongly interacting system, the laser-nuclear interaction is, therefore, comparatively weak, and (ii) the nucleus may equilibrate, and the excitation of a long-lived compound nucleus at excitation energies several 100 MeV above yrast is possible. That defines a new regime of laser-matter interactions and opens the possibility to study nuclear level densities at such energies.

The competition between the absorption rate for photons and the nuclear equilibration rate defines three regimes. In the perturbative regime, even a strong short laser pulse only leads to single excitation of the GDR. Multiple photon absorption is unlikely. Coherent excitation of a broad band of excited states is observable via the time-decay function. For photon energies larger than neutron threshold, the decay in time is non-exponential. In the quasi-adiabatic regime, about one photon is absorbed per nuclear relaxation time. Up to 100 or more photons may be absorbed, with little angular momentum transfer to the compound nucleus, leading to the large excitation energies above yrast mentioned above. The decay by neutrons and induced emission of neutrons and protons produces a distribution of final nuclei that extends from the valley of stability to a nucleus that differs from the target nucleus by minus n_0 neutrons. Here n_0 is determined by the duration time of the laser pulse. This offers the possibility to study proton-rich nuclei far from the valley of stability.

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