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Modified Nuclear Lifetime in Plasmas

G. Gosselin*, V. Méot, P. Morel
Comissariat à l'Energie Atomique
Centre DAM/Ile-de-France, BP 12, 91680 Bruyères-le-Châtel, France
E-mail: gilbert.gosselin@cea.fr
E-mail: vincent.meot@cea.fr
E-mail: pascal.morel@cea.fr

In plasmas, the electronic environment in the immediate vicinity of the nucleus is modified, and thus, the plasma conditions influence key processes driving the lifetime of a nuclear level. A correct lifetime prediction requires every de-excitation process to be evaluated jointly with its corresponding excitation process.

For heavy nuclei, the nuclear lifetime of discrete levels is often strongly dependent on internal conversion which involves bound electrons. In plasma, many of these electrons are no longer in a bound state and the internal conversion rate can be significantly reduced. Its coupling with its inverse process, Nuclear Excitation by Electron Capture (NEEC), can lead to greatly increased nuclear lifetimes.

In some cases, an atomic transition can be coupled with a nuclear transition in a process called Nuclear Excitation by Electron Transition (NEET) if their energies are closely matched. This can accelerate the de-excitation of the excited nuclear level, and reduce its lifetime.

We developed a model able to deal with these processes in plasma under thermodynamic equilibrium. It evaluates internal conversion, NEEC and NEET rates in plasma. Depending on the particular situation, we use either an average atom description or a Multi Configuration Dirac Fock (MCDF) approach to describe the electronic environment of the atom. Large variations of several excited nuclear level lifetimes have been predicted.

A complete description of the nuclear lifetime must also include some other nuclear levels through which indirect nuclear excitation or de-excitation may occur. This particular situation may provide a fast method to populate or depopulate nuclear isomers.

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1. Introduction

In most astrophysical plasmas, it is usually a very good approximation to consider that the hypothesis of thermodynamic equilibrium is valid. It does mean that the ionic and electronic populations follow Maxwell-Boltzmann distributions. In the case of nuclear levels, the situation may be a little more complicated, especially when dealing with long-lived isomer levels. When a nuclear lifetime is long, the most efficient deexcitation processes usually involve coupling between the atom and the nucleus via the electromagnetic field. In a plasma, such as found in stars, the electronic environment of the nucleus is quite different from under laboratory conditions. The atom can be highly ionized, and the remaining bound electrons face a much less screened nucleus. This can severely affect processes such as internal conversion and result in strongly modified nuclear lifetimes of some levels.

In this presentation, three main classes of effects will be addressed : lifetime enhancement due to internal conversion inhibition when electrons are no longer bound, lifetime decrease due to the appearance in some specific thermodynamic conditions of Nuclear Excitation by Electron Transition (NEET) and lifetime decrease when the de-excitation of a nuclear level can occur through the intermediate excitation of an upper level.

2. Lifetime enhancement through internal conversion

One of the most common de-excitation process of a long-lived nuclear level is internal conversion : the energy of an excited nucleus is transmitted via a virtual photon to a bound electron which is ejected from the atom. It is usually characterized by the internal conversion coefficient :

$$\alpha = \frac{\lambda_{IC}}{\lambda_{\gamma}}$$

defined as the ratio between the internal conversion rate and the radiative deexcitation rate.

In plasma one must also take into account its reverse process, usually named Inverse Internal Conversion (IIC) or Nuclear Excitation by Electron Capture (NEEC) : a free electron from the continuum is captured onto an empty space in an atomic shell and its excess energy is ceded to the nucleus.

From the Fermi Golden Rule, one can express the microscopic internal conversion rate and the microscopic NEEC cross section [1]. Under the hypothesis of thermodynamic equilibrium, a relativistic average atom model gives the binding energy of each atomic shell involved in internal conversion. However, its variations as a function of temperature can lead to the total inhibition of internal conversion on some atomic levels, when their energies become larger than the transition nuclear energy.

However, the numerous electronic configurations of the atom do not have the exact same binding energy for a given shell, so a statistical energy distribution must be taken into account. Moreover, each individual configuration is broadened due to natural width, Stark effect, Doppler and collisions. Together these effects create a transition broadening which gets the

internal conversion variations smoothed over a range of temperature. The transition rates, which also include photon absorption and emission, for ^{193}Pt in plasma at 10^{-2} g/cm^3 density is shown Fig 1.

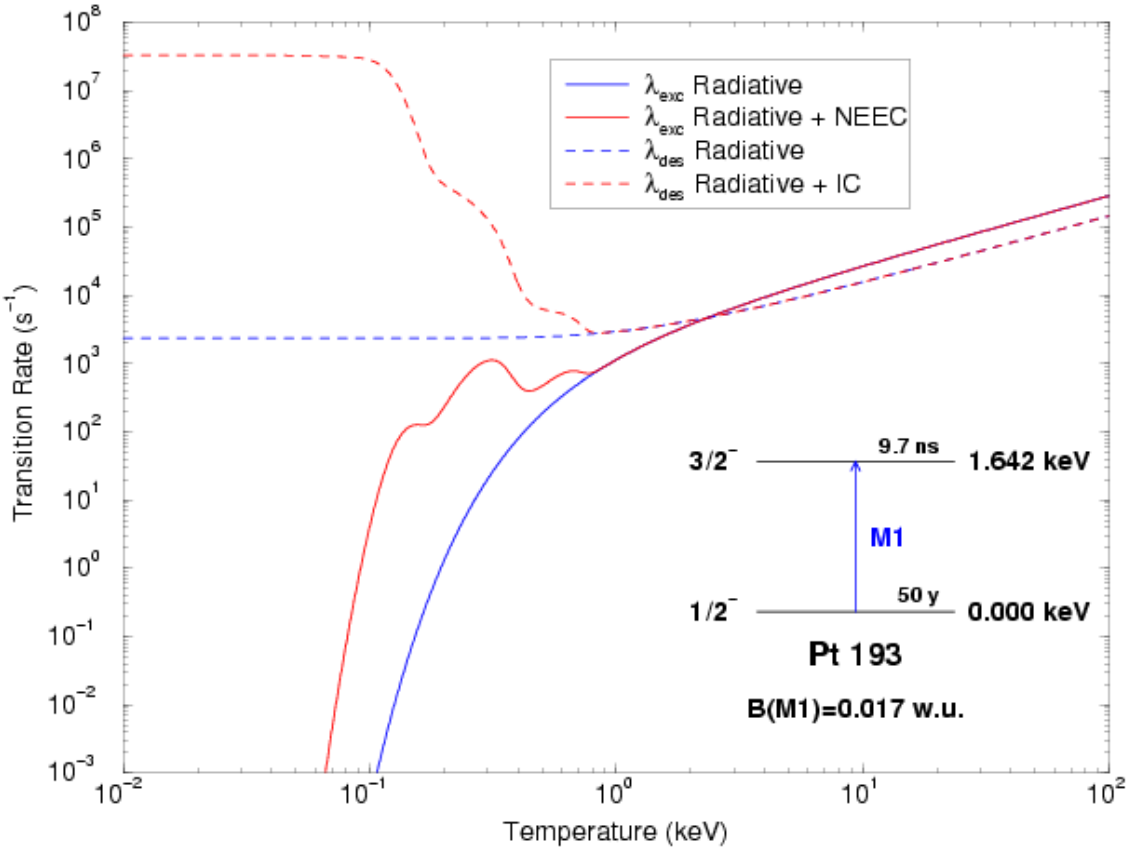

Fig 1 : Radiative, NEEC and IC transition rates

The lifetime of the excited level is then given by :

$$\tau = \frac{\ln 2}{\lambda_{exc} + \lambda_{des}}$$

In Fig 2, the global lifetime of ^{193}Pt is given as a function of temperature. It considers internal conversion and NEEC as well as photon absorption and emission (both spontaneous and stimulated).

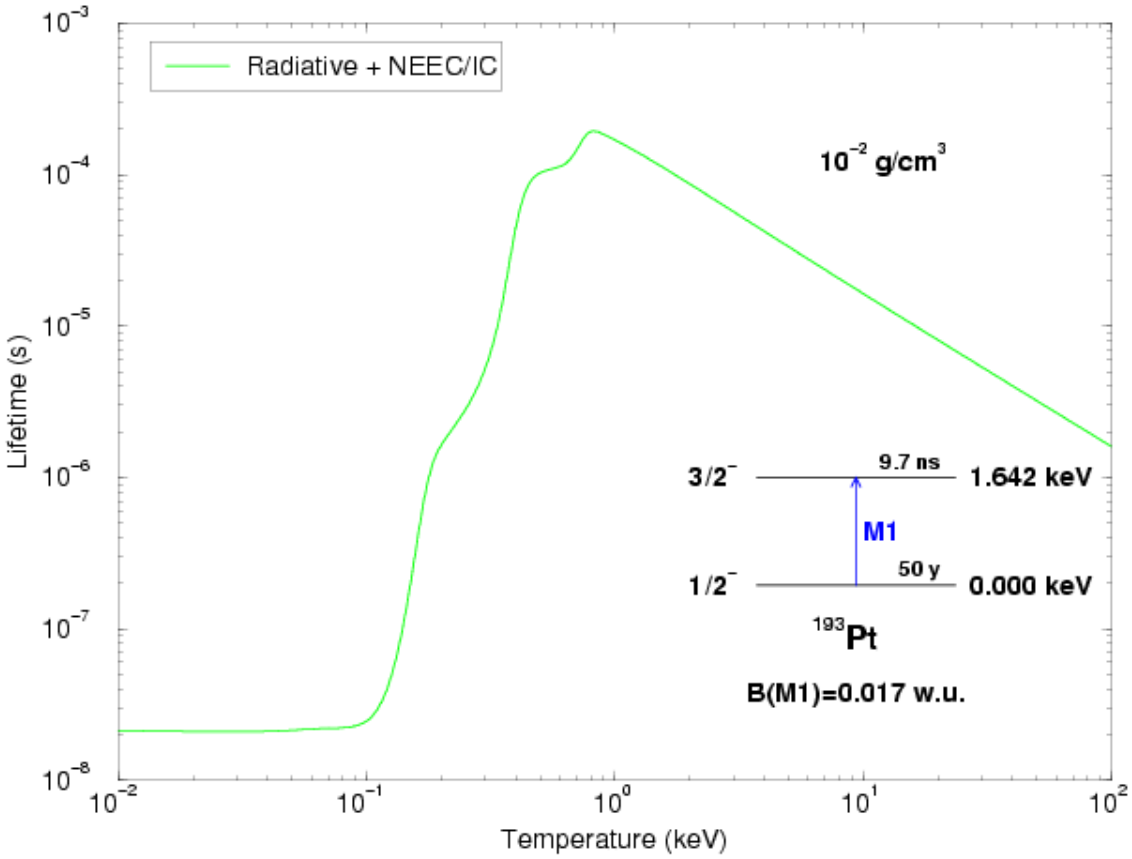

Fig 2 : Nuclear lifetime of ^{193}Pt taking into account radiative and NEEC/IC processes

The lifetime enhancement comes from the progressive disappearance of the electrons from the atomic shells involved in internal conversion. The small structures at 200 eV and 500 eV occur when the O and N shells are depopulated by the increasing temperature of the plasma. For higher temperature, above 1 keV, stimulated photon emission becomes the major deexcitation process and the lifetime begins to decrease.

3. NEET lifetime decrease

For low energy nuclear transitions, a new deexcitation process may be observed. In plasma, some electronic levels are only partially populated. When the energy of an electronic transition nearly matches a nuclear transition energy, a process known as Bound Internal Conversion (BIC) may occur. It is the reverse process of NEET.

The microscopic transition rate can be deduced from the time dependent quantum theory of perturbations. Interactions with the plasma are reduced to a width value for each of the initial and final states. These statistical widths are the same as in the IC model described above, except no Doppler is to be taken into account.

When the mismatch in energy is close to zero, one obtains a NEET probability, as shown in Fig 3, increasing rapidly, as t^3, until the characteristic time of the initial state has been reached [2]. Thereafter, the probability is an asymptotic value which is highest for the lowest densities. It is the value given by other simpler NEET model [3].

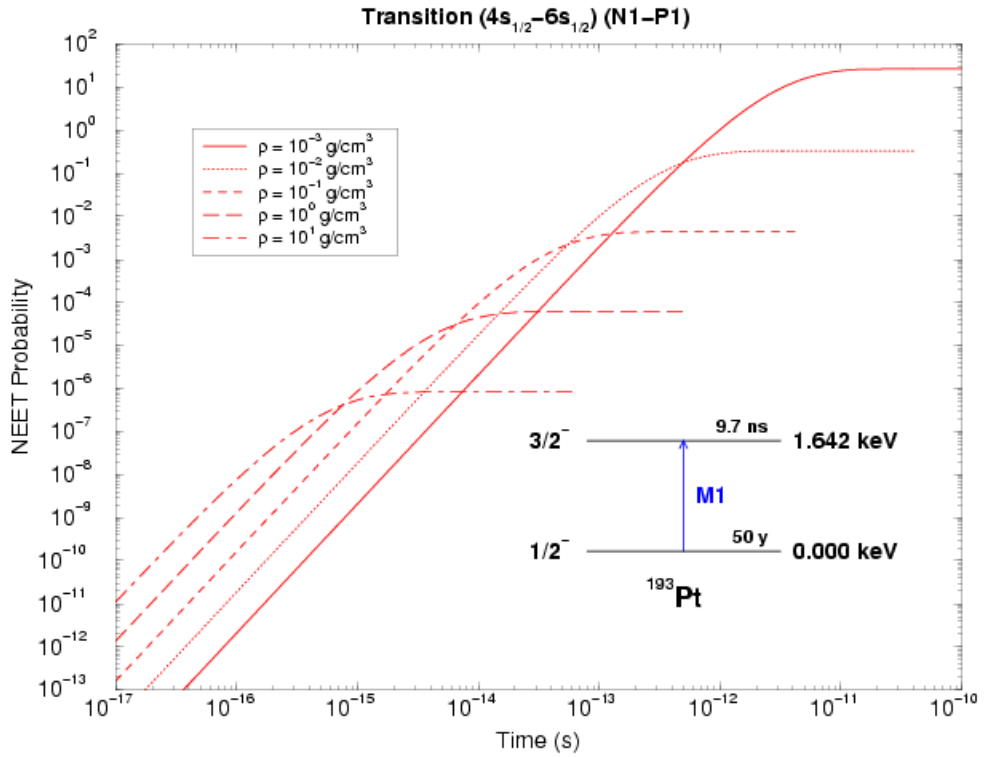

Fig 3 : NEET probability as a function of time under stationary conditions

The coupling matrix element is nearly the same as for IC with only a mismatch term added to the nuclear transition energy.

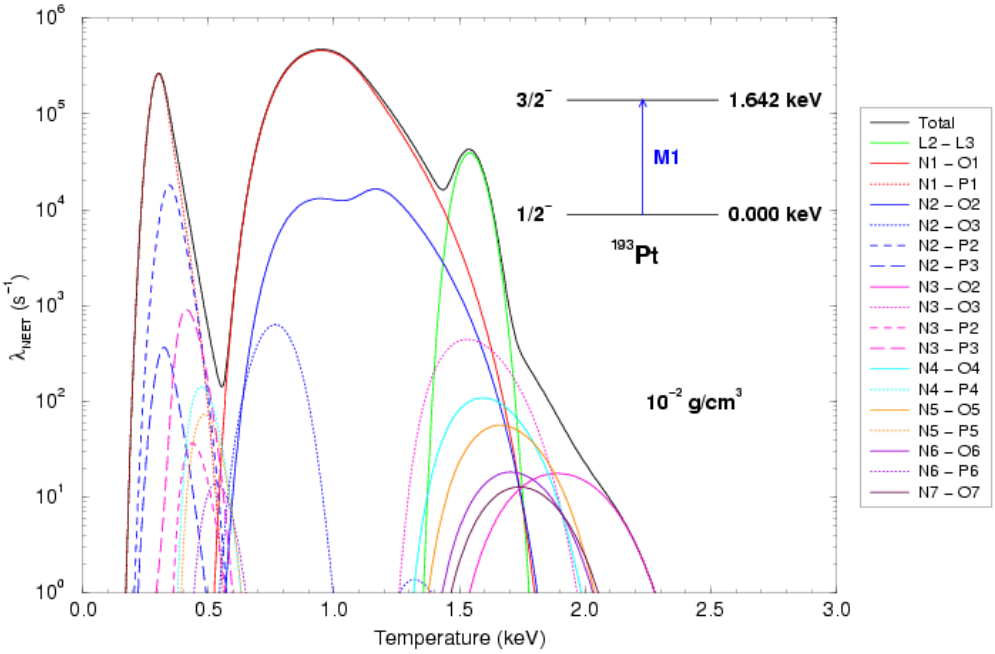

Fig 4 : NEET transition rates for various atomic transitions

The NEET and BIC rates are then obtained through a summation over all electronic configurations which allow a NEET transition. When the individual widths of each electronic configuration overlap with each other, the summation can be approximated by the gaussian envelop of the transitions, allowing computations within a reasonable time.

In the case of ^{193}Pt, many couples of atomic transitions contribute to a NEET rate higher than 10^5 s^{-1} as Fig 4 illustrates. The two main contributions are $4s_{1/2}$-$6s_{1/2}$ around a temperature of 300 eV and $4s_{1/2}$-$5s_{1/2}$ around 1 keV. Fig 5 shows the modified lifetime of the nuclear level, when also taking into account NEET and BIC processes.

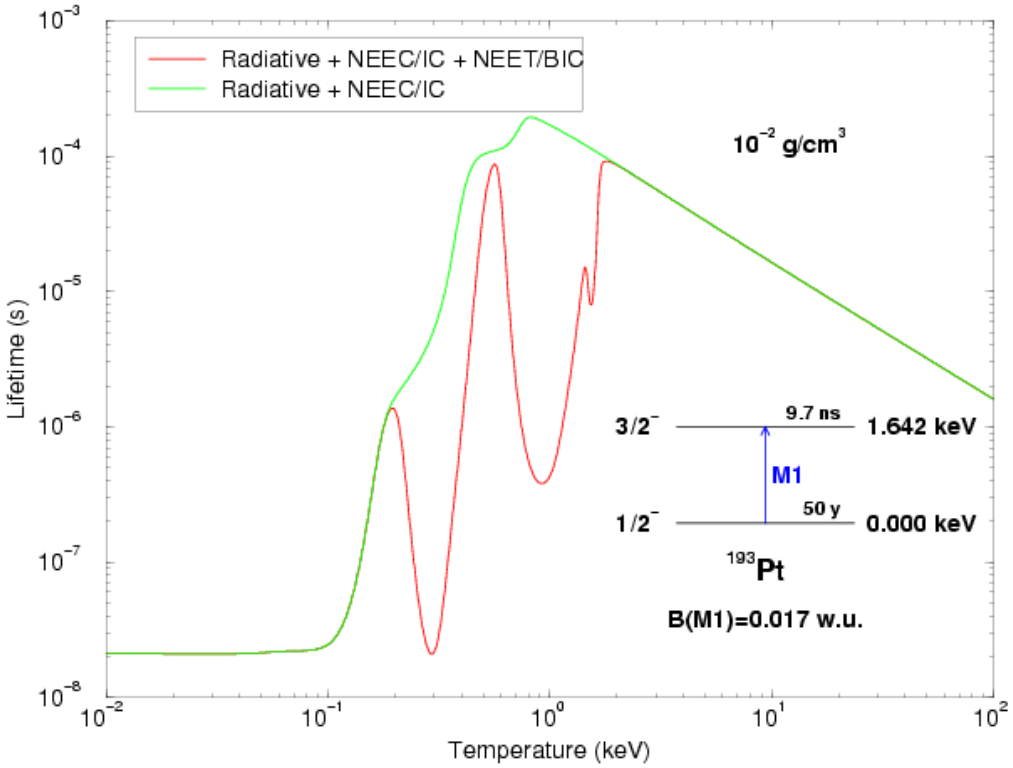

Fig 5 : Nuclear lifetime of ^{193}Pt taking into account all processes

These processes open a new channel of deexcitation of the isomer state of ^{193}Pt which decreases its lifetime by two of three orders of magnitude around the resonance temperatures.

4. Indirect nuclear deexcitation

In plasma, another channel to deexcite an isomer state can be to first excite an upper level which itself decays down to lower levels. The different excitation and deexcitation processes exposed above are available to induce the excitation to the upper level and its deexcitation.

In the case of ^{93}Mo, the lifetime of the 2424.89 keV level can be reduced from around 7 hours to less than 1 second, as shown in Fig 6.

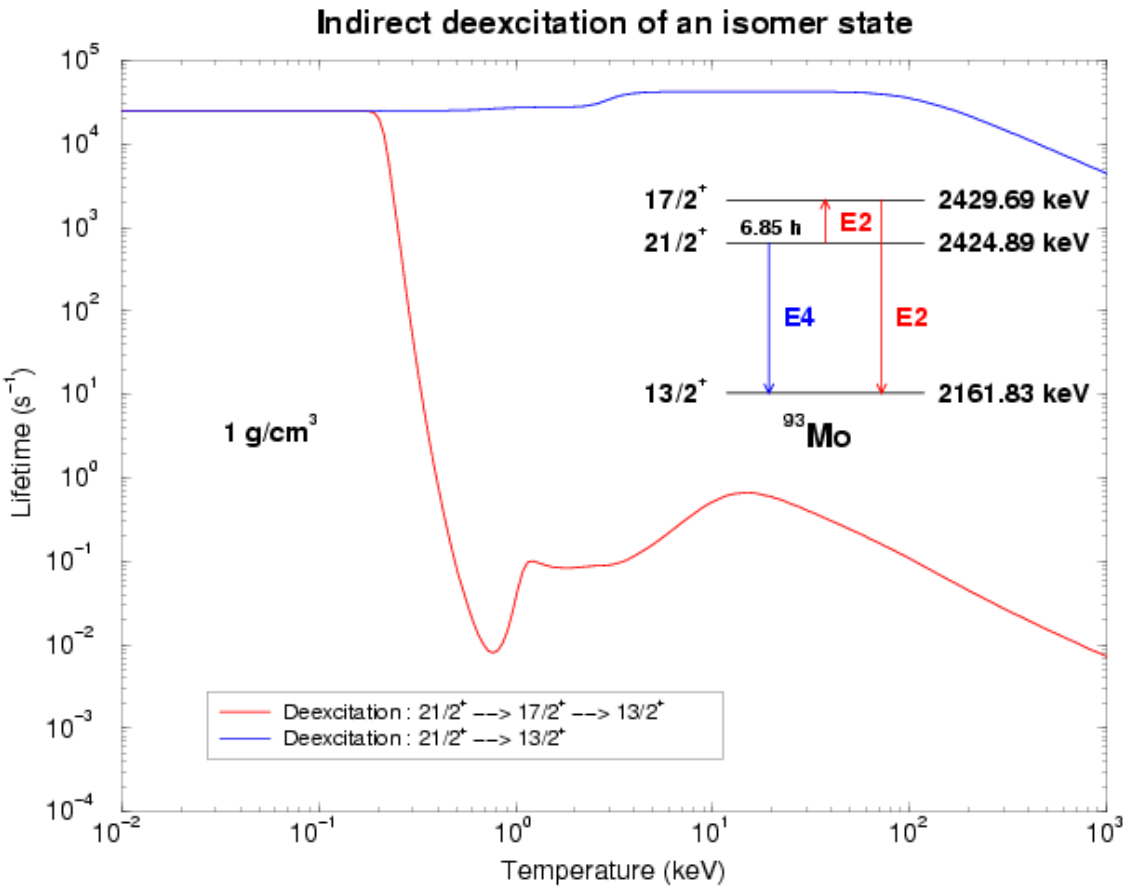

Fig 6 : Indirect deexcitation of ^{93}Mo isomer level

Calculations led on a dozen different isomers showed that the indirect deexcitation process becomes more efficient as soon as the temperature is around 1/20 of the transition energy to get from the isomer to the upper level.

5. Conclusion

In plasma, the lifetime of an excited nuclear level can be greatly modified by interactions of the nucleus with the plasma components, mainly electrons and photons. The laboratory deexcitation processes, photon emission and internal conversion, are modified by the appearance of stimulated photon emission and by internal conversion inhibition due to the atom ionization. New deexcitation processes also appear, such as bound internal conversion when an electronic transition matches in energy the nuclear transition, or by indirect deexcitation when an isomer state decays by first exciting an upper level.

All these different processes can contribute to modify nuclear level lifetimes by several orders of magnitude. In higher temperature plasmas, inelastic electron scattering will become significant. One will then be able to have a complete overview of electromagnetic phenomena influencing nuclear lifetimes.

[1] G. Gosselin, P. Morel, *Enhanced nuclear level decay in hot dense plasmas, Phys. Rev.* **C70** (2004), 064603

[2] P. Morel, V. Méot, G. Gosselin, D. Gogny, W. Younes, *Evaluation of nuclear excitation by electronic transition in 235U plasma at local thermodynamic equilibrium*, *Phys. Rev.* **A60** (2004) 063414

[3] M. Harston, J. F. Chemin, *Mechanisms of nuclear excitation in plasmas, Phys. Rev.* **C59** (1999) 2462