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Estimation of the laser equilibrium spectrum induced plasma photons

S.f. Elarabiy, G.K.Rashed, E.Elessawi, A.M.EL Barouni
Sf_elarabi@yahoo.com
Department of Physics and Material Science, Tajoura Nuclear Research Centre, Libya
P .O .Box: 30878

Abstract

The Planck spectrum of the laser equilibrium induced plasma photons was estimated in this work for the isomeric nuclides $^{73}_{32}Ge$, $^{83}_{36}Kr$, $^{153}_{63}Eu$, $^{155}_{64}Gd$, $^{189}_{76}Os$ and $^{157}_{64}Gd$ in order to evaluate the first order efficiency for the laser induced plasma life time, and the first order effective cross-section of the nuclear photo-excitation. The obtained results are in the same order of magnitude of the published results.

1-Introduction

The laser-matter interactions at intensities up to $\approx 10^{16} - 10^{17} Wcm^{-2}$ produce sub - relativistic plasmas with much lower temperature of electrons, typically in the KeV energy range (with the hot electron temperature up to 50KeV). These electron energies are sufficient to excite, either directly or indirectly (via bremsstrahlung or characteristic X-ray line emission from the hot dense plasma), the low-lying nuclear levels [1, 2].

In particular, the possibility of exciting the nuclear states in longer-living isomers via the action of the laser-produced plasma is extremely attractive. The decay of these isomers through electromagnetic transitions is normally strongly inhibited; therefore, the interaction of their levels with externally introduced photon fluxes provides an important probe of nuclear structure. At the same time, certain isomers can store large amounts of energy for a relatively long time, thus their triggered depopulation (following the laser-induced excitation) can in principle stimulate powerful pulses of γ-rays [3].

The basic alternativemechanisms of excitation of low-lying nuclear levels:-

Direct photo excitation, inelastic electron scattering, inverse internal electron conversion (IIEC, sometimes called nuclear excitation by electron capture ,NEEC), nuclear excitation by electron transition (NEET), and inverse electronic bridge (IEB). The analysis of these processes indicates that in dense plasmas with temperature T close to the excitation energy E_N of low-lying nuclear levels, resonance mechanisms (direct photo absorption, IIEC, and IEB) are the most efficient [4,5], and should dominate the nuclear excitation. The hot dense plasmas resulted at the surface of sample by a high-intensity plus can serve as in nuclear-photonic and nuclear-electronic excitations [5].

1.1 Photo-excitation

The effective nuclear excitation occurs when the plasma temperature is $T \sim E_N$, where E_N is the energy of the nuclear transition between the levels with energies E_f and E_i .

Laser-produced plasma allows one to produce ions of a high charge and to ensure conditions for the excitation of low-lying nuclear levels.

Laser-produced plasma consisting of nuclei with low lying metastable level (isomeric nuclei) with lifetimes greater than $10^{-8} - 10^{-9}$s, then we can expect that, after rapid heating and cooling of such a plasma, isomeric nuclei will radiate a weak γ emission, specifically at frequencies of electron-nuclear transitions [6].

The aims of this work is the estimation of the Planck spectrum of plasma photons, evaluation of the efficiency for the plasma with a life time and evaluation of the

Where$N(E)$is the photon number density in the energy window between $E$and $E + dE$.

The photo-absorption rate per unit atom is then

$$R_\gamma = \int_0^\infty N(E)\sigma_\gamma(E)dE \quad (8)$$

$$\sim \frac{2}{e^{Em/(KT-1)}}\frac{\Gamma_\gamma}{h} \quad (9)$$

Where $\sigma_\gamma(E)$is the photo-absorption cross-section, and$\Gamma_\gamma$is the gamma decay width of the nuclear transition from the ground to low-lying isomer state.

$$\Gamma_\gamma = \left(\frac{\ln 2}{T_{\frac{1}{2}}}\right)(h) \quad (10)$$

$T_{\frac{1}{2}}$is the nuclear level half-life, where$T_{\frac{1}{2}} = \frac{\tau}{1.44}$,$\tau$is the mean life of a level having an energy width Γ, assuming also the equilibrium state of the plasma and the Planck energy distribution of photons given by expression of the Planck spectrum of photons represented as [3] :-

$$n_p(E) = \frac{1}{\pi^2}\frac{E^2}{exp(E/T)-1} \quad (11)$$

To evaluate the efficiency$\varepsilon$for the plasma life-timeτ, we must know the spectrum of the plasma photons. This spectrum depends on the experimental conditions.

The efficiency is calculated using an approximate formula [3]:-

$$\varepsilon = \int_0^\infty \sigma(E)\tau n(E)d\omega \quad (12)$$

From equation (11) expression (12) can be represented in a simple form suitable for numerical estimates:- effective cross-section of the nuclear photo excitation for the low-lying nuclear levels of the following isotopes$^{153}_{63}Eu$, $^{155}_{64}Gd$, $^{157}_{64}Gd$, $^{184}_{76}Os$, $^{73}_{32}Ge$ and $^{83}_{36}Kr$.

Theory:-

A photon of energyεhas an angular frequency ωgiven by [7] :-

$$\varepsilon = \hbar\omega = \hbar\,(2\pi f) \quad (1)$$

$\hbar = \frac{h}{2\pi}$where h is the Planck's constant.

The momentum of a photon with this energy has magnitude

$$P = \hbar\omega \,/\, c \quad (2)$$

Since photon have zero rest mass.

The number of photon states in which the photon has a frequency in the range$(\omega)$to $(\omega + d\omega)$ in the volume V[7] :-

$$f(\omega)d\omega = \frac{V\omega^2 d\omega}{\pi^2 c^3} \quad (3)$$

The number of photons in the frequency rangeω to $(\omega + d\omega)$

$$dN_\omega = \frac{V}{\pi^2 c^3}\frac{\omega^2 d\omega}{\exp(\beta\hbar\omega)-1} \quad (4)$$

Where$\beta = \frac{1}{KT}$

$K$is the Boltzmann’s constant,

$T$is the plasma temperature

The energy of the radiation in this frequency range [7] :-

$$dE_\omega = \hbar\omega dN_\omega = \frac{V\hbar}{\pi^2 C^3}\frac{\omega^3 d\omega}{\exp(\beta\hbar\omega)-1} \quad (5)$$

The energy density

$$u(\omega, T)d\omega = \frac{\hbar\omega^3 d\omega}{\pi^2 C^3\,[\exp(\beta\hbar\omega)-1]} \quad (6)$$

1.2-Photo absorption

At the thermal equilibrium of the plasma in the system of interest the photon flux is described by a Planck’s distribution [8] :-

$$d\left(\varphi_\gamma(E)\right) = \frac{c}{\pi^2(\hbar c)^3}\frac{E^2}{e^{E/(KT-1)}}\,dE$$

$$\approx N(E)\,dE$$

$$\varepsilon^{(1)} = \frac{\Gamma_N^r \tau}{exp(E_N/T)-1} \quad (13)$$

Where Γ_N^r is the radiation width of the nuclear transition, and E_N is the energy of the nuclear transition between the final and the initial levels with energies E_f and E_i respectively The effective cross-section of the nuclear photo excitation can be evaluated in terms of the nuclear transition wave length λ_N (where $\lambda_N = \frac{2\pi}{E_N}$) , the radiation width Γ_N^r of the nuclear level and the plasma temperature T.The effective cross-section of the nuclear photo excitation can be given from the following equation [3]:-

$$\sigma_{eff}^{(1)} \approx \lambda_N^2 \frac{\Gamma_N^r}{T} \quad (14)$$

Γ_N^r is the radiation width of the nuclear transition, for the electric nuclear transition, Γ_N^r can be obtained from the following formula [10]:-

$$\Gamma_N^r = 8\pi \frac{E_N^{2L+1}}{[(2L+1)!!]^2} \frac{L+1}{L} B(EL; J_i \longrightarrow J_f) \quad (15)$$

Where L is the multi polarity of the transition, E_N is the energy of the nuclear transition in (eV) and $B(EL, J_i \longrightarrow J_f)$, is the reduced probability of the electric nuclear transition.

$B(EL\uparrow)$ can be obtained from the level decay rate (r) where

$\Gamma_\gamma = rh$,from which

$$r = \frac{\Gamma_\gamma}{h}, \quad (16)$$

where Γ_γ is the gamma decay width

$$r = 5.49 \times 10^{22} \frac{(L+1)}{L[(2L+1)!!]^2} \left[\frac{E_\gamma}{197}\right]^{2L+1} B(EL\downarrow) \quad (17)$$

Then

$$B(EL\downarrow) = \frac{r}{5.49\times10^{22} \frac{(L+1)}{L[(2L+1)!!]^2} \left[\frac{E_\gamma}{197}\right]^{2L+1}} \quad (18)$$

E_γ the energy of the nuclear transition in MeV.

Where $B(EL\downarrow)$ is the reduced probability of electric nuclear transition from the higher level to the lower level, from which $B(EL\uparrow) = GB(EL\downarrow)$, G is a statistical spin-factor, where $G = \frac{(2J^*+1)}{(2J+1)}$

Where J and J^* are the nuclear spin of the ground and excited levels respectively.

2-Results and Discussion

1. Table (1), gives the level decay rates (r) for different isomeric nuclides, different electric multi-polarities (EL) and different nuclear transitions.The nuclides under study are ${}^{73}_{32}Ge$, ${}^{83}_{36}Kr$, ${}^{153}_{63}Eu$, ${}^{155}_{64}Gd$, ${}^{157}_{64}Gd$, ${}^{189}_{76}Os$. The gamma decay width (Γ_γ) was obtained from equation (10), and depend on (h) and proportional inversely with the nuclear level half-life, which is calculated from the mean life of a level having an energy width.

The obtained values of Γ_γ varies between the minimum value of $9.0\ E-22\ KeV$ for ${}^{83}_{36}Kr$ with an electric multi-polarity $(E3)$ and a transition energy of $32.15\ KeV$ to the maximum value of $3.0E-08\ KeV$ for ${}^{153}_{63}Eu$ with an electric multi-polarity $(E1)$ and a transition energy of $14.06\ KeV$.

The level decay rate (r) is given by equation (16), from which it depends directly on the gamma decay width.

From table (1), it's clear that the minimum value of (r) is 2×10^4 for ${}^{83}_{36}Kr$ with an electric multi-polarity $(E3)$ and a transition energy of 13.28keV,and the maximum value of (r) is 9×10^8 for ${}^{189}_{76}Os$ with an electric multi-polarity $(E2)$ and a transition energy of $33.335\ KeV$.

Table(1):The level decay rates for different isomeric nuclides, different multi-polarities and different transition energies.

Isomeric nuclide [11]	Electric multi-polarity(EL) [11]	Transition energy (keV) [11]	$\Gamma_\gamma(keV)$	Level decay rate (s^{-1})
$^{73}_{32}Ge$	E2	13.28	2×10^{-12}	5×10^{5}
$^{83}_{36}Kr$	E3	32.15	9×10^{-22}	2×10^{4}
$^{153}_{63}Eu$	E1	14.06	3×10^{-8}	7×10^{9}
	E1	97.43	3×10^{-11}	73×10^{6}
	E2	19.81	1×10^{-9}	4×10^{8}
$^{155}_{64}Gd$	E1	26.53	9×10^{-10}	2×10^{8}
	E1	86.55	9×10^{-10}	2×10^{8}
	E1	45.3	5×10^{-09}	1×10^{9}
	E1	105.3	5×10^{-09}	1×10^{9}
$^{157}_{64}Gd$	E1	9.365	1×10^{-11}	3×10^{6}
	E1	63.93	1×10^{-11}	3×10^{6}
$^{189}_{76}Os$	E2	33.34	4×10^{-09}	9×10^{8}

2. Table (2), gives the obtained results of the reduced transition probabilities of (B) for different electric multi-polarities (EL) and different nuclear transitions.

The obtained values of the reduced transition probabilities varies between the minimum value of $1\times10^{-5}e^2fm^6$ for $^{83}_{36}Kr$with an electric multi-polarity $(E3)$ and a transition energy of $32.15\ KeV$, and also with the same value for $^{153}_{63}Eu$ with an electric multi-polarity $(E2)$ and a transition energy of $19.81\ KeV$, to the maximum value of 2×10^{-2} for $^{189}_{76}Os$ with an electric multi-polarity $(E2)$, and a transition energy of $33.34\ KeV$.

The obtained values of the reduced probabilities obtained in this work varies directly with level decay rate (r) and inversely with E_γ to the power $(2L+1)$ where $(L)$is the multi-polarity of the transition.

Table(2):The reduced transition probabilities.

Isomeric nuclide [11]	Electric multi-polarity(EL) [11]	Transition energy (keV) [11]	$B(EL)e^2fm^{2L}$
$^{73}_{32}Ge$	E2	13.28	9×10^{-3}
$^{83}_{36}Kr$	E3	32.15	1×10^{-5}
$^{153}_{63}Eu$	E1	14.06	2×10^{-3}
	E1	97.43	5×10^{-4}
	E2	19.81	1×10^{-5}
$^{155}_{64}Gd$	E1	26.53	7×10^{-4}
	E1	86.55	2×10^{-5}
	E1	45.3	8×10^{-3}
	E1	105.3	6×10^{-3}
$^{157}_{64}Gd$	E1	9.365	2×10^{-3}
	E1	63.93	7×10^{-4}
$^{189}_{76}Os$	E2	33.34	2×10^{-2}

3. Planck energy distribution of photons laser induced plasma photons. The Planck spectrum of photons as a function of transition energy and plasma temperature (T) at equilibrium $(T{\sim}E)$ given by equation (11), where$E$ is expressed in (eV).

From table (3) which gives the Planck's spectrum of photons $n(p)$ for the given isomeric nuclides, for different electric multi-polarities and different transition energies.

The Planck's spectrum of photons $n(p)$ varies between the minimum value of 3.26×10^{6} photon for $^{157}_{64}Gd$ with an electric multi-polarity of $(E1)$ and a transition energy of $9.365\ KeV$, to the maximum value of 3.40×10^{8} photon for $^{153}_{63}Eu$ with an electric multi-polarity of $(E1)$ and a transition energy of $97.43\ KeV$.

Table(3):The Planck's spectrum of photons n(p).

Isomeric nuclide [11]	Electric multi-polarity(EL) [11]	Transition energy (keV) [11]	$n(p)(photons)$
$^{73}_{32}Ge$	E2	13.28	4.63×10^{6}
$^{83}_{36}Kr$	E3	32.15	1.12×10^{7}
$^{153}_{63}Eu$	E1	14.06	4.90×10^{6}
	E1	97.43	3.40×10^{8}
	E2	19.81	6.91×10^{6}
$^{155}_{64}Gd$	E1	26.53	9.25×10^{6}
	E1	86.55	3.02×10^{7}
	E1	45.3	1.58×10^{7}
	E1	105.3	3.67×10^{7}
$^{157}_{64}Gd$	E1	9.365	3.26×10^{6}
	E1	63.93	2.23×10^{7}
$^{189}_{76}Os$	E2	33.34	1.16×10^{7}

4-The first order efficiency$\varepsilon^{(1)}$

The first order efficiency $\varepsilon^{(1)}$ for the plasma life-time (τ) depends on the Planck energy distribution of photons and it depends directly on the radiation width of the nuclear transition, and inversely on the value of $[\exp(E_N/T)-1]$ where E_N is the energy of the nuclear transition between the final and the initial levels with energies E_f and E_i.

The first order efficiency $\varepsilon^{(1)}$is expressed from equation (13), andΓ_N^r is expressed from equation (15).

The obtained results ofΓ_N^r varies between the minimum value of $1\times10^{-9}KeV$ for $^{83}_{36}Kr$ with an electric multi-polarity of $E3$ and a transition energy of $32.15\ KeV$, to the maximum value of $4.7\times10^{-1}KeV$ for $^{189}_{76}Os$ with an electric multi-polarity of $E2$ and a transition energy of $33.34\ KeV$.

Table(4):The first order effiency as a function of the radiation width for the electric nuclear transition

Isomeric nuclide [11]	Electric multi-polarity(EL) [11]	Transition energy (keV) [11]	$\Gamma_N^r(eV)$	$\varepsilon^{(1)}$
$^{73}_{32}Ge$	E2	13.28	6×10^{-5}	4×10^{-14}
$^{83}_{36}Kr$	E3	32.15	1×10^{-9}	6×10^{-19}
$^{153}_{63}Eu$	E1	14.06	2×10^{-5}	1×10^{-14}
	E1	97.43	2×10^{-8}	1×10^{-17}
	E2	19.81	4×10^{-8}	2×10^{-12}
$^{155}_{64}Gd$	E1	26.53	7×10^{-7}	4×10^{-16}
	E1	86.55	7×10^{-7}	4×10^{-6}
	E1	45.3	4×10^{-6}	2×10^{-15}
	E1	105.3	4×10^{-6}	2×10^{-15}
$^{157}_{64}Gd$	E1	9.365	1×10^{-8}	6×10^{-18}
	E1	63.93	1×10^{-8}	6×10^{-18}
$^{189}_{76}Os$	E2	33.34	4.7×10^{-1}	3×10^{-10}

5-The effective cross-section of the nuclear photo-excitationσ_{eff}.

The first order effective cross-section can be evaluated in terms of the nuclear transition wave lengthλ_N, the radiation width Γ_N^r of the nuclear level and the plasma temperature T, can be evaluated using equation (14).

The obtained results given in table (5), shows that $\sigma_{eff}^{(1)}$ for the given isomeric nuclides varies between the minimum value of $1\times10^{-12}cm^2$ for $^{83}_{36}Kr$ with an electric multi-polarity of E3 and a transition energy $32.15\ KeV$ to the maximum value of $5\times10^{-4}cm^2$ for $^{189}_{76}Os$ with an electric multi-polarity of E2 and a transition energy of $33.34\ KeV$.

Table(5):The nuclear transition wave length(λ) and the effective cross-section of the nuclear photo-excition σ_{eff}

Isomeric nuclide [11]	Electric multi-polarity (EL) [11]	Transition energy (KeV)[11]	$\lambda(cm)$	$\sigma_{eff}(cm^2)$
${}^{73}_{32}Ge$	E2	13.28	4.7×10^{-4}	1×10^{-6}
${}^{83}_{36}Kr$	E3	32.15	2.0×10^{-4}	1×10^{-12}
${}^{153}_{63}Eu$	E1	14.06	4.5×10^{-4}	3×10^{-7}
	E1	97.43	0.6×10^{-4}	1×10^{-12}
	E2	19.81	3.2×10^{-4}	2×10^{-5}
${}^{155}_{64}Gd$	E1	26.53	2.4×10^{-4}	2×10^{-9}
	E1	86.55	0.7×10^{-4}	5×10^{-11}
	E1	45.3	1.4×10^{-4}	2×10^{-9}
	E1	105.3	0.6×10^{-4}	1×10^{-10}
${}^{157}_{64}Gd$	E1	9.365	6.7×10^{-4}	5×10^{-10}
	E1	63.93	1×10^{-4}	2×10^{-12}
${}^{189}_{76}Os$	E2	33.34	1.9×10^{-4}	5×10^{-4}

3. CONCLUSIONS

Direct photo-excitation is the only process leading to nuclear excitation in the first order of perturbation theory with respect to the electro-magnetic interaction constant e

The obtained values of the reduced probability of electric nuclear transition B$(EL\uparrow)$ varies directly with the level decay rate (r) , which in turn depends on the gamma decay width (Γ_γ) .

The radiation width (Γ_N^r) of the nuclear transition proportional directly with the nuclear transition energy between the initial and final levels and also proportional directly with the reduced probability of electric nuclear transition and also depends inversely with $[(2L+1)!!]^2$, where L is the multi-polarity of the transition.

The first order efficiency $\varepsilon^{(1)}$ for the plasma with life time τ, depends on the Planck spectrum of photons, which depends on turn on the transition energy and the plasma temperature, and it also depends directly on the radiation width of the nuclear transition, and inversely on the value of $[exp(E_N/T)-1]$, where E_N is the energy of the nuclear transition, and T is the plasma temperature.

The first order effective cross-section proportional directly with the nuclear transition wave length λ_N, and the radiation width Γ_γ^r of the nuclear level and inversely with the plasma temperature.

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