International Journal of Engineering, Mathematical and Physical Sciences
ISSN: 2517-9934
Vol:4, No:1, 2010

Laser Excited Nuclear γ -Source of High Spectral Brightness

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***Abstract*—**This paper considers various channels of gamma-quantum generation via an ultra-short high-power laser pulse interaction with different targets.We analyse the possibilities to create a pulsed gamma-radiation source using laser triggering of some nuclear reactions and isomer targets. It is shown that sub-MeV monochromatic short pulse of gamma-radiation can be obtained with pulse energy of sub-mJ level from isomer target irradiated by intense laser pulse. For nuclear reaction channel in light- atom materials, it is shown that sub-PW laser pulse gives rise to formation about million gamma-photons of multi-MeV energy.

***Keywords*—**High power laser, short pulse, fast particles, isomer target.

I. INTRODUCTION

TO date, many physical problems call for using a source of γ-radiation and vast scope of these problems ranging from non destructive gamma flaw detection to medical examinations [1]. It should be noted that, presently, the intensity of ordinary radioactive sources cannot be higher than 10-100 GBk, whereas much higher intensity is necessary for many investigations.

Commonly, synchrotron radiation is used as a high-intensity γ -source, its activity being about PBk. However, significant success notwithstanding, the use of the synchrotron radiation as a γ -source features some essential drawbacks. First, it is impossible to obtain the high intensity γ -radiation in very narrow frequency range, because the synchrotron radiation spectrum is continuous. Hence narrow-frequency-band experiments with a high-power γ -source appear to be impossible, because the power of such a γ - radiation source drops as the frequency range narrows and difficult to cut a narrow MeV spectral range by any filters. Second reason is that synchrotron radiation source is an expensive for some applications.

In this paper, we consider two possibilities for laser exited monochromatic γ -source. First by using isomers targets as a high-intensity frequency-conversion γ -source. The nuclei are prepared in the isomeric state by high intensity laser or accelerator. Then the isomeric ground-state nuclei are pumped to an exited isomeric state, wherefrom an active γ -transition arises by the X -ray radiation from laser plasma produced by the action of high-intensity laser pulse on a solid-state target.

The second direction connected with laser acceleration of fast ions to generate nuclear reactions with high γ yield at an interaction of fast protons with different targets.

II. BASIC CONCEPT OF A LASER TRIGGERING MONOCHROMATIC NUCLEAR γ - SOURCE

To produce MeV range energy photon emission we should use nuclear excitation instead of atom one because even for high Z ions the energy of quanta estimated as RyZ^2 can not exceed 100 KeV.

As direct excitation of nuclear by laser field has very low efficiency we will consider some indirect processes when laser energy transforms into electron energy enough effectively at first and then through another channels to nuclear excitation.

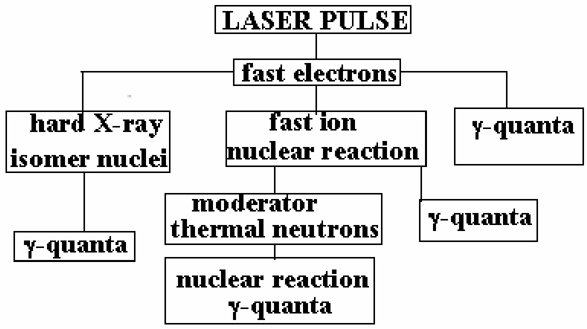

Fig. 1 Laser - γ-radiation conversion schema

On this Figure 1 we suggest for future analysis the different channels of γ – photon production with help of high power laser radiation. We will not consider the right hand side channel because it was already discussed in [18].

III. INDUCED γ - FLUORESCENCE OF ISOMERIC NUCLEI

Let's at first consider the main idea of a high-intensity γ - source using isomer nuclei (see Fig.2).

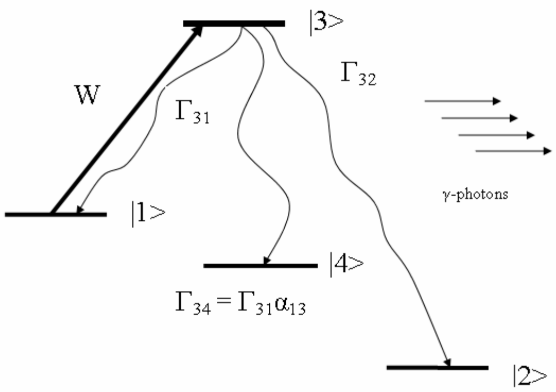

Fig. 2. Three level schema for isomer nuclear pumped by X-ray radiation

We assume that the |3>-|2> active γ -transition is pumped in two steps. First, atoms in the |1> nuclear isomeric state should be prepared, say, by interaction of a target with an intensive thermal neutron beam in accelerator or by laser accelerated ions. During the second step, an active γ - transition is pumped by the X-ray radiation from laser plasma, which is produced under the action of high intensity laser pulse on a solid-state target near the region where the isomeric target are trapped (see Fig.2 of [2]).

Let's estimate the number of excited nuclei at X-ray irradiation of isomer plasma with level schema shown in Fig.2. Plasma thermal radiation pumps low energy transition |1> – |3> of nuclear isomer. As the result, a part of isomer nuclei during plasma irradiation transits to the state |3> with following spontaneous decay in the low lying state |2>, what produce radiation of γ - quanta of energy corresponding of the transition |3> – |2>. Isomer nuclei can decay not only into the state |2> but also come back to the state |1> with irradiation of X-ray quantum of pump. Another process is an electron internal conversion when pumping quantum is absorbing by electron shell and after there is a non-emitting transition into the state denoted as |4> in the Fig.2. The probabilities of the corresponding transitions are proportional to the radiation widths of nuclear levels and electron conversion coefficients. In particularly for the isomer of Mo the coefficient of internal conversion is very small (0.0361) and it does the probability of the transitions |1> - |4> very low.

Now we describe in details the process of nuclear level excitation in our model. The probability of nuclear transition from isomer state |1> into excited state |3> during the time τ of X-ray pumping (about laser pulse duration) is determined by the perturbation theory [3] as

$$w_{13} = \tau \frac{2\pi}{\hbar} \left| < 3 \left| \hat{V} \right| 1 > \right|^2 \delta(\varepsilon_3 - \varepsilon_1 - \hbar\omega), \qquad (1)$$

where $\hat{V}$ - is operator of nuclear interaction with e.m. field. In the case of magneto-dipole transitions with multi-polarity M1 the operator of interaction $\hat{V}_{M1}$ with external field can be written as

$$\hat{V}_{M1} \sim \mu_p H \hat{s}, \qquad (2)$$

where $\mu_p = e\hbar / m_p \tilde{n}$ - is nuclear magnetic momentum, coexisting to the proton mass, $\hat{s}$ - is the spin operator, and for the transition of multi-polarity E2 the operator of interaction $\hat{V}_{E2}$ can be written as [3]

$$\hat{V}_{E2} \sim Q_{\alpha\beta} \partial E_\alpha / \partial r_\beta, \qquad (3)$$

where $Q_{\alpha\beta}$ - is the tensor of nuclear Quadra-pole momentum, which components are equal (by order of magnitude) er_n^2 ($r_n \sim A^{1/3} \cdot 10^{-13}$ cm is characteristic scale of nuclear of atomic weight A). Taking into account a finite width of upper excited level Γ_3, the δ - function in (1) is changing by its asymptotic

$$\delta(\varepsilon_3 - \varepsilon_1 - \hbar\omega) \approx \frac{\hbar\Gamma_3 / 2\pi}{(\varepsilon_3 - \varepsilon_1 - \hbar\omega)^2 + (\hbar\Gamma_3 / 2)^2} \qquad (4)$$

In the matrix element $|V_{13}|^2$ it is convenient to separate Pointing vector of a pumping wave $cH^2 / 4\pi$ ($cE^2 / 4\pi$) and the rest matrix element of magneto-dipole (quadruple) momentum to write the emission width of nuclear transition [3]:

$$\Gamma_{31}^{(M1)} = \frac{4\omega^3 |\mu s_{13}|^2}{3c^3\hbar}, \quad \Gamma_{31}^{(E2)} = \frac{\omega^5 |Q_{13}|^2}{15c^5\hbar} \qquad (5)$$

As the result the formula (1) for the probability E2 of the transition |1> – |3> of nuclear isomer can be written through cross-section σ_x of radiation absorption of pump quantum and flux (s^{-1}cm^{-2}) of pump quanta $I_x = cE^2 / 4\pi\hbar\omega$

$$w_{13} = \tau I_x \sigma_x, \qquad (6)$$

where the value $\tau I_x = \tau c E^2 / 4\pi\hbar\omega$ is the total number N_x of pump quanta, propagating through a unit area of isomer target and

$$\sigma_x = \frac{60\pi c^2}{\omega^2} \frac{\hbar^2 \Gamma_{13}^{(E2)} \Gamma_3}{(\varepsilon_3 - \varepsilon_1 - \hbar\omega)^2 + (\hbar\Gamma_3 / 2)^2} \qquad (7)$$

The flux (s^{-1}cm^{-2}) of pump quanta of thermal X-ray radiation is determined by Plank distribution $dI_x = \omega^2 d\omega / \pi^2 c^2 (\exp(\hbar\omega / T) - 1)$, instead of the formula $I_x = cE^2 / 4\pi\hbar\omega$, correct for monochromatic pump.

Pumping by thermal radiation

To calculate the probability of excitation in (6) one should integrate the distribution over all spectra of pump quanta:

$$w_{13} = \frac{\tau}{\pi^2 c^2} \int_0^\infty \frac{\omega^2}{\left(e^{\frac{\hbar\omega}{T}} - 1 \right)} \sigma_x(\omega) d\omega \qquad (8)$$

Because sharp dependence of cross-section (7) on energy of pump quanta the integral (8) is easy to calculate and as the result the number of excited (by resonant X-ray quanta) nuclei from isomer state |1> to the active state |3> can be written as $N_3 = w_{13} N_{10}$ [4]:

$$N_3 = 120 N_{10} \frac{2J_3 + 1}{2J_1 + 1} \frac{\Gamma_{31}}{\Gamma_3} \Gamma_3 \tau \left(\exp(\frac{\varepsilon_3 - \varepsilon_1}{T_e}) - 1 \right)^{-1}, \qquad (9)$$

where N_{10} - is the initial number of isomer nuclei in the state |1>, irradiated by pump quanta. This amount of isomer is located in the volume about laser spot area S_L multiplied on l_x - absorption length of pump quantum. The formula (9) describes the initial stage of excitation process when the number of active nuclei is proportional to the pump duration τ. The statistic weights of initial and final states are taken into account in (9) by introducing of the coexisting spin $J_{1,3}$.

Let's consider now the process of γ-quantum generation at the decay of the state |3>, which after excitation can decays into the state |1> or |2> and as well into the state |4> responsible for electron conversion of emitted quanta. The lifetime τ_3 excited state |3> can be estimated as

$$\tau_3^{-1} = \Gamma_{31}(1+\alpha_{31}) + \Gamma_{32}(1+\alpha_{32}), \quad (10)$$

where α_{31}, α_{32} are the coefficient of internal conversion for the transitions |3> – |1> and |3> – |2> and Γ_{ik} - are the radiation widths of the transitions. Therefore the probability is equal to the multiplication $\tau_3\Gamma_{32}$, that at the decay of the state |3> the generation of γ-quantum is occur (the probability of absorption of this quantum by electron shell is equal to $\tau_3\alpha_{32}\Gamma_{32}$).

The total number of γ - quanta obtained during laser plasma emission one can obtain by multiplication of number of excited nuclei (9) on probability of generation of γ - quantum [4]:

$$N_\gamma = N_3\Gamma_{32}\tau_3 \approx 10^2\, N_{10}\frac{2J_3+1}{2J_1+1}\Gamma_{31}\Gamma_{32} \bullet \tau\,\tau_3\left(\exp(\frac{\varepsilon_3-\varepsilon_1}{T_e})-1\right)^{-1} \quad (11)$$

Here the limit of pump duration is $\tau \sim \tau_3$. The formula (11) permits to estimate the possibility ($N_\gamma > 1$) of radiation de-excitation of isomer nuclear state, at known structure of nuclear and electron levels, by thermal X-ray radiation.

Pumping by K_α line radiation

A spectral brightness of thermal X-ray pump in nuclear transition is not so high. From this reason we analyse a possibility of plasma line X-ray emission at energy approximately equal to nuclear transition energy. For this case the best candidate is K_α - line because the energy of this X-ray quantum can be very high. Let's estimate an intensity of K_α - line emission from a flow of fast electrons interacted with over- dense plasma. The efficiency (ratio of line intensity to laser intensity) η_κ of laser radiation to K-α one for foil and non-relativistic laser intensity is determined by the following formula [5]

$$\eta_\kappa \approx 0.7*10^{-4}\eta(\frac{10^{-2}Z^2}{1+10^{-6}Z^4})\kappa^{1+\delta}\exp(-\kappa) [1-\exp(-\frac{50d_\mu}{Z^2})]\left(1+(\frac{l}{d})^\alpha R_b^{N_c}\right) \quad (12)$$

Here

$$\kappa = (\frac{Z}{13})^{1-\xi}\frac{0.97}{(\eta I_{16})^{2/3}},\ \xi = 0.25,\ \delta = 0.67,\ d_\mu = d/1\mu m,$$

$I_{16} = I/10^{16}Wcm^{-2}$, where d is foil thickness in μm, l is electron free path in the target, Z – target nuclear charge, I – laser intensity, η -absorption coefficient. Number of electron circulations in a foil is $N_c = [\frac{l}{d}]$ - where [..] is the whole number. Here also $R_b \sim 1$ is the reflection coefficient of fast electron from electrostatic barrier and $\alpha \le 1$ is the constant. The temperature of fast electron is estimated from $T_h \approx 3.2(\eta I/10^{15}Wcm^{-2})^{1/2}$ [keV] and its free path from the calculation by the code [6]. A non-relativistic laser intensity is optimal for KeV energy of K_α quanta generated from light $Z \le 30$ laser targets. To produce hard K_α - quanta better to use heavy target material and relativistic laser intensity.

For a bulk target the number N_{ph} of X-ray quanta generated by laser pulse is

$$N_{ph} \approx N_{eh}n_a\sigma_z l_{ph} \approx \frac{\eta\varepsilon_L}{\varepsilon_{eh}}n_a\sigma_z l_{ph} \approx \frac{\eta\varepsilon_L}{\varepsilon_{eh}}n_a\sigma_z(\varepsilon_{eh})l_{ph}, \quad (13)$$

where $\varepsilon_{eh} = m_e c^2\left(\sqrt{1+0.7I_{18}}-1\right)$, $\eta \sim 0.4-0.5$, n_a~6 10^{22} cm^{-3} target atom density, K_α photon free path l_{ph} in the target is calculated by the code [7] and for Ag at $\varepsilon_{eh} > 1$ MeV $\sigma_z(\varepsilon_{eh}) \approx \sigma_0 \ln(\frac{\varepsilon_{eh}}{0.1MeV}),\ \sigma_0 = 5barn$. Anyway such target is non-optimal because fast electrons can penetrate in a target on the distance $> l_{ph}$ and K-α photons lose its energy. Thus an optimal target is a foil of thickness about absorption length of K-α кванта (for Ag about 30 μm), in which a circulation of electrons reflected from foil edges is possible. In this case electron energy is using more effectively because radiation from electron free path can leave a target. Such transition coexists to the changing of l_{ph} on effective length of electron interaction with a target l_{in}. Then conversion efficiency coefficient (in energy) can be written as

$$\eta_k = (N_{ph}\varepsilon_{ph}/E_L) \approx (N_{eh}n_a\sigma_z\varepsilon_{ph}l_{in}/E_L) \approx \approx \eta(\varepsilon_{ph}/\varepsilon_{eh})n_a\sigma_z l_{in}, \quad (14)$$

Where

$$l_{in} \approx l_{ph}[1-\exp(-d/l_{ph})] \bullet \bullet[1+(l_{eh}/d)^\alpha(1-R_b^{N_c})]\mu. \quad (15)$$

Here the coefficient $\mu = d/d+4r_{Dh}$ is the ratio of time, which electron spend in the target to the full time of electron movement during one cycle, $r_{Dh} = \sqrt{\varepsilon_{eh}/4\pi e^2 n_{eh}}$, $n_{eh} = N_{eh}/\pi r_L^2 c\tau_L$, r_L - laser beam radius and τ_L - laser pulse duration. It is known that the dependences of electron free path and absorption coefficient can be approximated by power lows:

$$l_{eh} = l_0(\varepsilon_{eh}/\varepsilon_0)^\delta,\ 0 \le \delta \le 2,$$
$$\eta = \eta_0(\varepsilon_{eh}/\varepsilon_0)^\varsigma,\quad 0 \le \varsigma \le 1, \quad (16)$$

Where the parameters: l_0, ε_0, η_0 are determined from the simulations at laser intensity 10^{19} W/cm^2. Taking into account (15,16) one can rewrite (14) as following

$$\eta_k \approx \eta(\varepsilon_{ph}/\varepsilon_{eh})\sigma_z d(l_{eh}/d)^{\alpha}\mu \approx$$
$$\approx \frac{\eta_0(\varepsilon_{ph}/\varepsilon_0)n_a\sigma_z d\, l_0(\varepsilon_{eh}/\varepsilon_0)^{\varsigma+\delta-1}}{d+4\sqrt{\varepsilon_{eh}/4\pi e^2 n_{eh}}}, \quad d << l_{ph}, \alpha \sim 1 \tag{17}$$

At the moment the maximal experimental conversion efficiency [8] is ~ 10^{-3} at laser intensity 10^{20} W/cm^2.

The matching of K-α line with isomer transition demands a full database. Anyway some combinations are known, for example the element with Z_{nu}=16, A=32 (Sulphur - S) is acceptable for isomer nuclei of Rb^{86} with excitation energy 3.4 KeV. We can estimate an energy of the basic state for – hydrogen like spectrum $E_{K\alpha}$ = 3,482 KeV. It is closest to 3.4 кэВ. Besides the following statements are valid: the atom of sulphur in the target is partially ionized, therefore high atoms levels are free. At transition between these levels and ground state $E_{k_\alpha} = (3.482\text{kev})(1-1/n^2)$. By selecting the number n of high level it is possible to hit in a nuclear level. We can also remark, that Doppler width of X-ray pumping is about electron volt at $\omega_x < \omega_i$ and it can help us to be very close near nuclear level. The flux of K-α pump in the spectral interval $\Gamma_{K-\alpha}$ - width of the line from (6) is equal $dI_x = \eta_\kappa I d\omega / \Gamma_{K-\alpha}$. The width of pump line is wider compare to the width of isomer level $\Gamma_{K-\alpha} >> \Gamma_3 \sim \Gamma_{3D}$, therefore one should insert the pump flux into (6) and integrate on nuclear line width. As the result instead of (11) for thermal pump, for this case the number of nuclear γ - quanta is determined by the following formula

$$N_\gamma \approx \frac{4\cdot 10^2 \hbar^2 c^2}{E_{K_\alpha}{}^2}\eta_\kappa I\tau N_{10}\frac{2J_3+1}{2J_1+1}\frac{\Gamma_{31}}{\Gamma_{K-\alpha}}\Gamma_{32}\,\tau_3 \tag{18}$$

Let's consider now the non-stationer model of isomer nuclei excitation by laser plasma radiation for obtaining of γ-quanta of energy of transition |3>-|2>. The equations for the elements of density matrix of nuclear level system can be written as the equation of the populations N_{1-4} of coexisting states

$$\frac{d}{d\tau}N_1 = W(\tau)s + \gamma_{13}N_3, \quad \frac{d}{d\tau}N_2 = \gamma_{23}N_3,$$
$$\frac{d}{d\tau}N_3 = -W(\tau)s - 2N_3, \quad \frac{d}{d\tau}N_4 = \gamma_{43}N_3, \tag{19}$$

And the equation for non-diagonal matrix element S of the transition |1> -|3> is as following

$$\frac{d}{d\tau}s = -2W(\tau)(N_1 - N_3) - s. \tag{20}$$

In the equations (19), (20) the time is normalized on τ_3. The X-ray pump pulse has a Gauss temporal profile $W(\tau) = G\exp\left[-\left(\tau-\tau_0\right)/\tau_p\right)^2\right]$ of duration τ_p and time of switching is τ_0. The un-dimensional matrix element in (19) is as $G = <3|\hat{V}|1> \tau_3/\hbar$, and $\gamma_{13} = \Gamma_{31}\tau_3$, $\gamma_{23} = \Gamma_{32}\tau_3$, $\gamma_{43} = \Gamma_{31}\alpha_{13}\tau_3$. This matrix element is calculated from the formulas (2,3) where pump field (E or H) is determined from pump intensity. For thermal X-ray radiation one can get from the equation $cE^2/4\pi \sim \sigma T^4$ the fields as $E \approx H \approx (4\pi\sigma/c)^{1/2}T^2$. For K-α radiation pump one can get $E \approx H \approx (4\pi\eta_\kappa I/c)^{1/2}$.

The numerical solution of the system (19,20) is shown in the Fig.3.

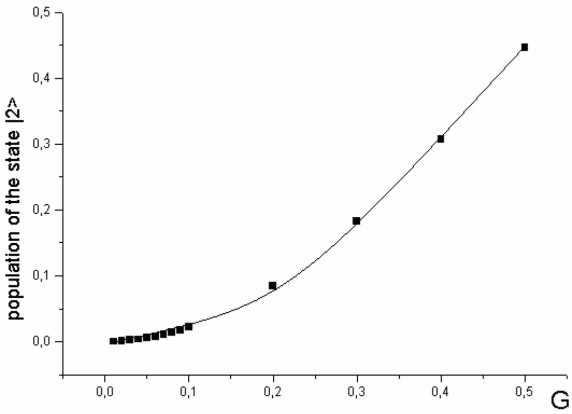

Fig. 3. The dependence of the population of the level |2> on normalized pump amplitude for $\gamma_{13} = 10^{-8}$, $\gamma_{23} \simeq 1$, $\gamma_{43} = 10^{-5}$, $\tau_p = 1$

It is demonstrates that the population of the level |2> is determined by G (relative pump intensity) and τ_p (relative pump duration in the units of τ_3). The population of the state |2> linearly grows on τ_p at $\tau_p < 1$ as was show above. Beside it is clear from Fig.4 that the population of the state |2> becomes significant if $G \geq 0.1$ ($<3|\hat{V}|1> \sim 0.1\hbar/\tau_3$), and $\tau_p \geq 0.1$. The temporal dynamics of nuclear level populations is shown in the Fig.4 for $\tau_p = 1$, $G = 0.5$ and $\tau_0/\tau_p = 6$.

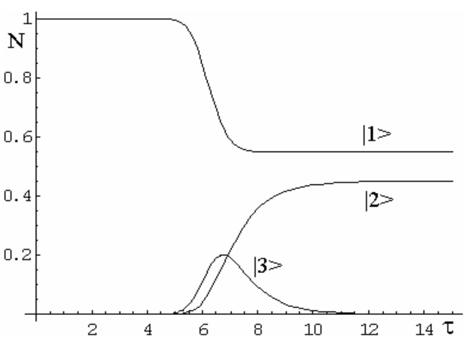

Fig. 4 The temporal dynamics of the populations of nuclear levels |1>, |2> and |3>. The time is normalized on τ_3, here $\tau_p = 1$, $G = 0.5$, $\tau_0/\tau_p = 6$

From this figure it is clear that at the initial time interval $\tau \in [6; 6.5]$ the population of all levels is changing linearly on time in accordance with the formula (9). At later time $7 \geq \tau \geq 6.5$ the normalized population of the upper level |3> saturates on the level of ~ 0.2, but the populations of the levels |1> and |2> continue to grow linearly on time. At time instant $\tau \geq 7$ the pump (of duration $\tau_p = 1$) is finished and the population of upper level |3> begins to fall down, but the populations of the levels |1> and |2> are saturated at the same time. Here the process of isomer state excitation (the changing of the population of level |1>) is finishing before that the process of emission of excited state (the changing of the population of level |3>). About ~ 40% of total amount of pump irradiated isomer nuclei decay at the chosen intensity and duration of the pump. As example of gamma quanta yield, we consider de-excitation of isomer ^{93}Mo. In this case it is enough thermal radiation obtained from interaction of laser pulse of energy 1 kJ and duration 300 ps at spot size 20 μm with Ag target. The number of emitted at such de excitation quanta of energy 268 KeV is about 100 during 4 ns and it is enough for experimental detection. Despite of a small number the spectral intensity of such radiation (power per frequency unit) is one order of magnitude higher compare to a conventional synchrotron radiation.

IV. Laser Triggering Nuclear Reaction Γ – Source

Following to Fig.1 we consider now hot electrons generation by laser pulse, acceleration of ions and then nuclear reactions for γ - photon production with help of these ions.

Production of fast electrons by a high-power laser pulse

First, we estimate the number of high-speed electrons produced by a laser pulse. Numerical simulations show that, in the relativistic intensity range, the absorption coefficient becomes independent from the angle of incidence, and the absorption is about 10 % without pre-pulse. Laser pre-pulse increases a scale of plasma inhomogenity L and absorption coefficient η. It was shown [10] that in the range 10^{18}-10^{20} W/cm^2 there is: $\eta \approx 0.1 + (0.1 + 0.06L)\mathrm{I}_{18} / (15 + \mathrm{I}_{18})^{0.8}$, where I_{18} - radiation intensity in units 10^{18} W/cm^2, L = ωL/c, $L \approx c_s t_{pl}$. Here c_s - ion sound velocity and t_{pl}.- pre-pulse duration. At pre-pulse intensity 10^{12} W/cm^2 we have L=10 at t_{pl}=10 ps and we will use L = 0, 10 in our numerical simulations.

The physical mechanism of formation of fast electrons is due to the light pressure, whereby an electron oscillating in an electric field is driven into plasma by the ponderomotive pressure force. Let suppose that $N_{ef}=K_e(I)\varepsilon_L/\varepsilon_e$ electrons will be accelerated during the laser pulse where ε_L is the laser pulse energy, $K_e(I)$ is the transformation coefficient of laser energy into fast electron energy, and ε_e is the energy of an electron. It was shown [9] that at laser intensity more then 10^{20} W/cm^2 $K_e(I) \approx \eta$. This means that all the absorbed energy being assumed to be transferred to the motion of high-speed electrons. The energy of an individual electron is usually specified by laser wave field strength inside the skin-layer [10] $\varepsilon_{eh} \approx mc^2[(1+(2-\eta)I_{18})]^{1/2}$. Now we can numerically estimate N_{ef} for the following plasma and laser pulse parameters: I=10^2, λ=10^{-4} cm, τ_i = 100 fs, n_{cr} = 10^{21} cm^{-3} (for materials with Z ~ 10, Z/A ~ 0.5, which holds true for most of light-atom elements, A- atomic number, Z-nuclear charge), and S = 10^{-6}cm^2. For the chosen parameters N_{ef} = 1.3 10^{10} electrons.

It is well known [11] that the electron kinetic energy within the first part of a laser pulse at the vicinity of its maximum can be as high as $\varepsilon_{eh}/mc^2 = (v_E/c)^2/2$ (here v_E is electron oscillation velocity) but the second part of this pulse will brake electron because it can not obtain any energy in vacuum from plane wave if it was at rest initially. Anyway this electron can get the energy from electromagnetic wave if it inertially penetrates into a target and laser pulse reflects from this target. Pre-plasma with the length approximately equal laser pulse length can significantly increase electron energy. If we have initial electron momentum in pre-plasma P_{e0} one can easily estimate that its maximum energy $\varepsilon_{eh}/mc^2 \approx (P_{e0}/mc)(v_E/c)^2 \approx (P_{e0}/mc)I_{18}$

From this formula we see that electron energy can be tens MeV level for relativistic electron generated in pre-plasma by Brunel effect for example.

Fast ion generation

In the case of a target with the small Z, ions are vigorously accelerated under the action of the ponderomotive pressure force. Moreover, at the given energy the nuclear reaction cross section drops as Z increases; therefore, this channel works for light-atom elements.

The maximum energy that can be gained by the accelerated ions based on the simple self-similar, isothermal, fluid model (for example, equation (10) of [12]) is given by

$$\varepsilon_{im} \approx 2Z_i\varepsilon_{eh}\left[\ln(\tau_{ip} + \sqrt{\tau_{ip}^2 + 1})\right]^2, \quad (21)$$

where $\tau_{ip} = \omega_{pi}t_{acc} / \sqrt{2e}$ is the normalized acceleration time ($t_{acc} \approx 1.3t_L$ [13]), ion charge Z_i, mass m_i (for protons Z_i = 1, $m_i = m_p$) and ion plasma frequency $\omega_{pi} = [Z_i^2e^2 n_{eh}/m_i]^{1/2}$.

When laser intensity I_{18} = 10^3, the ion energy amounts to 500A KeV. If A > 10, such energy is sufficient for some nuclear reactions to be proceed via ion-ion collisions.

Let's go now to the analysis of physical mechanism of particles fly out from target to vacuum and inside dense plasma. Most part of fast electrons accelerates by pondermotive force inside plasma but the electrons in under dense plasma (transparent for laser radiation) fly out from plasma at specular direction by reflected part of laser pulse action. The shape of pondermotive potential and laser pulse spatial profile influence to the angle of fast electron movement into vacuum θ_e are considered in [14].

During laser pulse duration the relativistic electrons (at laser intensity $I \approx 10^{19}$W/cm^2) fly out from a target on the distance more then laser spot size on a target. As result a boundary area of target obtains positive charge and ions accelerate into target and vacuum directions by ambipolar electric field.

We analyse this process by simulations with help of kinetic relativistic code [14]. To check the simulation results for ion acceleration into target we calculated also the parameters for ions flying out into vacuum and compared these results with experimental results because in our experiments only this part of ions have been recorded [15]. In the simulations as in experiment fast ions fly out at normal direction to the target surface at the angle diagram ~15°. The difference between theoretical and experimental results connected with collision-less simulation model. This ion beam can be used for farther generation of nuclear reactions considered in [16].

To increase this energy much more we can use foil target with inhomogeneous plasma density. In this case shock wave which has been born in front side by laser pulse will accelerate ions according to (8) in main part of foil but when it propagates through decreasing plasma density profile on back side it accelerates ions much more [17] at least ten times in energy compare to homogeneous plasma slab.

Production of γ - photons via ion-ion collisions

As the result of laser ion acceleration there is some ion distribution about energy which depends from laser time and space profile. A nuclear reaction cross-sections have complicated behavior and depend from particle energetic distribution parameters. We model these cases by the next formula for the number of nuclear reactions:

$$N_{nur} = n_a \int_0^\infty d\varepsilon \frac{dN_i}{d\varepsilon} \int_0^\varepsilon d\varepsilon \sigma(\varepsilon) \left| \frac{d\varepsilon}{dx} \right|^{-1} \quad (22)$$

here from Bete formula[19]:

$$\frac{d\varepsilon}{dx} = -\frac{m_a m_i}{m_a + m_i} \frac{2\pi e^4 Z_i^2 Z_a}{m\varepsilon} n_a \ln(4m\varepsilon \frac{m_a + m_i}{I_Z\, m_a m_i}),$$

where n_a ,m_a , Z_a – concentration, mass and charge of target atoms, I_Z – their ionisation potential.

If fast ions leave skin depth area before laser pulse finished we have stationary ion distribution in energy. In this case from ion kinetic equation we obtain next equation for fast ion number:

$$F \frac{\partial N_i}{\partial \varepsilon} = \frac{\partial N_i}{\partial x} \approx n_{i0} S,$$

where

$$F \approx -Zmc^2 \frac{\partial}{\partial x} \sqrt{1 + I_{18}} \approx \frac{1}{2l_s} \frac{\varepsilon(\varepsilon + 2Zmc^2)}{\varepsilon + Zmc^2}$$

- force acting to ions.

From these equations we obtain the next ion distribution:

$$\frac{\partial N_i}{\partial \varepsilon} \approx n_{i0} S l_s \frac{(\varepsilon + Zmc^2)}{\varepsilon(\varepsilon + 2Zmc^2)} \theta(\varepsilon - \varepsilon_m) \quad (23)$$

Here $\theta(\varepsilon - \varepsilon_m)$ – step function and ε_m – maximum of ion energy from (21).

By way of example, we consider reaction p + t = γ + ^{4}He, whose maximum cross-section is ∝ 2 mbarn for a 8-MeV energy of a proton and the energy of photon is near 5 MeV. Such a reaction can proceed in a tritium target on a substrate. The number of photons produced in proton tritium nuclear collisions can be estimated from the equation (22):

$$N_\gamma^{(t+p)} = N_p \sigma^{(t+p)} n_{nu}^{(t)} l_{ef}^{(i)}$$

where N_p is the total number of high-speed protons with energy ε and l^i_{eff} is their free path length

$$l_{ef}^{(i)} = \varepsilon^2 / 2\pi Z_t n_{nu}^{(t)} \varepsilon^4 \ln(4\varepsilon / I_Z)$$

For numerical estimates, we can use the following parameters: n_{nu} = 6 10^{22} cm^{-3}, ionization potential I_Z = 10 eV. The thickness of the T- ice target is near 1 mm then l^i_{ef} = 1 mm and does not depend from energy. The number of fast protons $N_p \approx N_{he}$ - number of fast electrons from quasi-neutrality. The dependencies of photon number $N\gamma^{(t+p)}$ from laser intensity I are shown on Fig.7 for L=10.

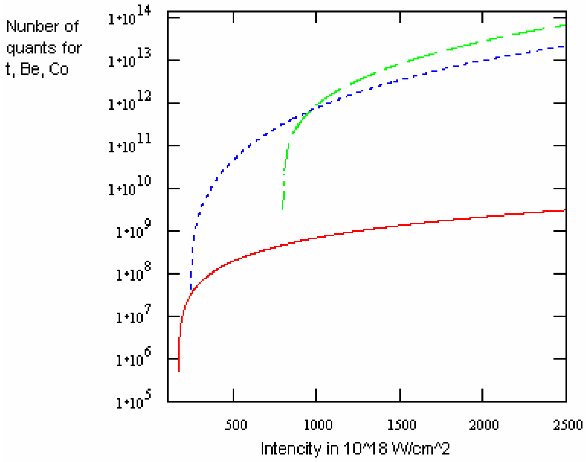

Fig. 7 γ-quanta yield from laser intensity, here $N\gamma^{(t+p)}$ at L=10 - red line, $N\gamma^{(Be+p)}$ - blue line, $N\gamma^{(Co+p)}$ - green line

On Fig.7 there are the number of γ-quanta for Be^{10} (E_γ = 0.2 MeV) and Co^{60} (E_γ = 2 MeV) targets with thickness more then l_{ef} in next nuclear reactions: p+Be^{10}→B^{11}+γ; p+Co^{60}→Ni^{59}+γ+2n. In these targets the γ-quanta yield more compare to T-ice target more from reaction cross-section and more thickness but the yield increasing is at more laser intensities because the high Z nuclei have higher Qoulomb barrier.

V. Conclusion

1. It has been shown the feasibility of a pulsed monochromatic high-activity γ-source with X-ray pumping of active γ - transition of isomeric nuclei confined in foil target.
2. The laser intensity being ~10^{19} W/cm^2, nuclear reactions proceed in a target, resulting in the γ-line radiation production. In light-atom materials irradiated by a laser beam with 10^{20} W/cm^2 intensity the γ-photon yield reaches 10^{-4} of the number of high-speed ions due to proton-triton collisions.
3. It is shown, that the extension of fast ions has a preferred direction lengthways of target normal. The fraction of laser energy, converted in energy of fast ions makes 1-3 %. So high conversion coefficient confirms the perspective to use laser for ion acceleration and nuclear reaction generation.
4. The received acceleration rate (number of fast particle per time unit) exceeds another methods of acceleration.

Thus, a high-power laser pulse can be used as a γ photon-emitting source for diagnostics in physics of solids, biology, and also for stimulating nuclear reactions.

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