

Laser enhanced radioactive decay and selective transmutation of nuclei

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Abstract

We have investigated intense narrow-band electromagnetic radiation sources - ranging from visible to X- and to gamma-ray region - and their applications to direct interactions in photon-nucleus couplings and indirect photon-electron and electron-nucleus interactions. In particular, we discuss means of selective excitation of nuclear resonance states by narrow-band photons. During relaxation an excited mother nucleus may end into its isomeric or initial ground-state or decay via various channels into new daughter nuclei. In the latter case the mother nucleus is transmuted into a daughter which may have beneficial properties regarding for instance radioactivity. One potential application could be the destruction of long-lived nuclear waste isotopes into faster decaying ones. The essential presumption is that the excitation process is both selective and efficient enough as compared to parasitic background phenomena. The paper consists of 1) a brief discussion of generation of short wave length narrow-band light sources, 2) an exploration of exciting nuclear states by induced photon absorption and of their decay channels, and 3) an assessment of the feasibility of this method e.g. for nuclear waste transmutation or other applications. According to our findings, the method is promising for basic nuclear physics studies but still calls for proper laser sources and is not yet suitable for processing any larger amounts of nuclides.

Key words: laser induced radioactivity, graser, X-ray laser, transmutation, gamma transitions, beta decay

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1 Introduction

New, intense sources of short-wavelength radiation have been introduced in recent years. Coherent sources in the soft X-ray region have been amply demonstrated, however, genuine gamma lasers (grasers) are still to be seen. Most of the X-ray transitions are based on highly ionized atoms having clear analogous visible transitions like for example those of neon in an ordinary He-Ne laser. Free electron lasers (FEL) and high-energy electron accelerators equipped with an optical wiggler have demonstrated high-intensity strongly collimated X- and γ -ray beams. The intensities are of the same order as in modern synchrotrons and even exceeding them.

Ultraintense table-top lasers are a new source of intense, energetic radiation. Besides their extreme intensities up to 10^{20} W/cm², the laser pulses are extremely short, down to femtoseconds, which opens interesting new possibilities for studying transient phenomena. Table-top laser pulses can create energetic ions and electrons up to tens of MeVs from solid and gas targets. These can be converted to very energetic bremsstrahlung photons or may induce nuclear reactions producing neutrons. The radiation sources discussed generally have a peaked, rather broad spectrum and in some circumstances they are partly spatially collimated like gamma ray torches. In certain experiments in gas jets, one has been able to produce well-collimated electron bunches having a narrow energy spectrum.

In this paper we discuss the applications of intense short wavelength electromagnetic radiation for manipulating nuclei. Especially we are interested in using narrow-band EM radiation to excite nuclei to pre-defined energy levels. Such ideas have been discussed already in the mid 80'es in the context of enhancement of beta decay by rf-fields or intense visible lasers [1,2]. Also photon transitions involved in a few-level configurations were considered [3,4]. Here these ideas have been revisited because of the remarkable progress EM sources have recently taken place.

This paper is focused on stimulation of gamma radiation to influence nuclear reactions. As an example one could excite a long-lived nuclide from its ground state into a excited state which in contrast would have a fast decay channel outside the considered levels. The EM radiation would enhance the mother-daughter reaction rates. Here we are investigating simple single-photon transitions - not the multi-photon processes disputed earlier [1,2]. The decay channel could involve particle emission, e.g. (γ, n) , (γ, p) , (γ, α) reactions, beta-gamma decay or gamma-induced fission. Similar transmutation is well-known in utilizing particles, neutrons, protons, alphas, etc. There the source is usually a thermal or fast reactor or an accelerator driven system (ADS) instead of the photon beams considered here.

Selective processing by laser isotope separation LIS, is a well established method for both diagnostics applications and for processing of finite amounts of isotopes. In some cases nuclear tracers could be extracted by milking their precursor nuclei by EM excitation. Just for the basic scientific interest lasers could also couple the electron core to the nucleus and in this way the nuclear part would be manipulated e.g. in EC decay. These considerations are, however, beyond this paper.

In Section 2 we give estimates to excitation rates. Section 3 is devoted to a survey of available EM sources and Section 4 provides some case nuclei and their transitions to amplify our considerations. Finally some concluding remarks are presented.

2 Selective excitation of nuclei

The basic process considered is shown in Figure 1. The mother nuclide X which is assumed to have a reasonably long half-life is excited from its ground state to a higher energy level 2. The states 1 and 2 can both decay into the daughter nuclide(s) Y (or Z) via different channels at different spontaneous rates. An immediate application would be for instance the transmutation of long-lived nuclear waste nuclide X into a more benign (less toxic or faster decaying) daughter nuclide Y. Such a process is well known in neutron capture which sometimes exhibits resonance levels although generally a continuum of excited states is involved. Here we focus on sharp EM resonances in analogy to laser induced selective excitation for isotope separation and to selective optical pumping. The energy level scheme usually involve gamma transitions of the mother nucleus and its decay via beta-gamma channel to a daughter.

To check the feasibility of inducing EM radiation for exciting nuclei we have identified several possible show-stoppers: what is the EM induced excitation rate, what is the possible selectivity, role of parasitic processes, are there some superior competing alternatives like neutrons, are there any specific advantages based on the sharp resonance structures, is the technology far too un-mature, etc. Rather than making a comprehensive analysis we try to provide some interesting case examples to better define the research issues.

2.1 Gamma reaction rates

We consider the level scheme of Fig. 1. We assume that the ground level 1 of the mother nuclide decays to a daughter nuclide at a rate A_{13} . The excited state 2 decays back to the state 1 at a spontaneous-emission rate A_{21} and to

the ground level of the daughter nuclide at a rate A_{23} . In the $X \rightarrow Y$ radioactive decay the beta–gamma channels from level 2 to the final reservoir state(s) 3 of Y are combined into a single effective decay channel. The induced electromagnetic transitions have the rates $B_{12}W$ (absorption) and $B_{21}W$ (emission) with the analogy to Einstein’s A and B coefficients. Here W is the radiation energy density of the external gamma beam. The stimulated EM couplings from 2 to 3 or from 1 to 3 are ignored.

The level populations are given by the simple rate equations

$$\frac{dN_1}{dt} = (A_{21} + B_{21}W) N_2 - (A_{13} + B_{12}W) N_1 \quad (1)$$

$$\frac{dN_2}{dt} = B_{12}W N_1 - (A_{21} + A_{23} + B_{21}W) N_2 \quad (2)$$

$$\frac{dN_3}{dt} = A_{13}N_1 + A_{23}N_2 \quad (3)$$

These equations are readily solved numerically and, furthermore, extended to more complicated level schemes.

Let us first consider excitation from level 1 to level 2 where the populations are assumed to change little in a single, short laser pulse and initially only the level 1 is occupied. The laser pulse has a top-hat profile, its length is denoted by τ and the repetition rate of the pulses by T . Usually one has $\tau \ll T$ implying that the levels 1 and 2 decay mainly in the absence of the EM field and, therefore, the relative decay rate η between the channels $1 \rightarrow 2 \rightarrow 3$ and $1 \rightarrow 3$ is

$$\eta = B_{12}W\tau \frac{1 - \exp(-A_{23}T)}{1 - \exp(-A_{13}T)} \quad (4)$$

For a long-lived ground state 1 the expression simplifies further to

$$\eta = \frac{B_{12}W\tau}{A_{13}T} [1 - \exp(-A_{23}T)] \quad (5)$$

At a rapid repetition rate, i.e. $A_{23}T \ll 1$ the duty cycle dependence disappears and then only the induced photon fluence from $1 \rightarrow 2$ multiplied by the branching ratio matters, i.e. $\eta \rightarrow B_{12}W\tau(A_{23}/A_{13})$.

From lowest order in the EM field intensity W , we obtain

$$\eta = \frac{B_{12}W}{A_{13}} \frac{A_{23}}{A_{21} + A_{23} - A_{13}} [1 - \exp(-(A_{21} + A_{23} - A_{13})t)] \quad (6)$$

assuming that initially only the level 1 is populated.

In a quasi steady-state situation, i.e., when $A_{21} \gg B_{21}W$, the excited level

population ratio is about

$$N_2/N_1 \approx \frac{B_{12}W}{A_{21} + A_{23}}, \quad (7)$$

and, therefore, the effective decay rate (transmutation rate) to the final state is

$$A_{23}N_2 = \frac{A_{23}}{A_{21} + A_{23}} B_{12}W N_1. \quad (8)$$

The reduction of the population N_1 has to be multiplied by the total number of irradiated pulses to get an estimate of the amount of destructed mother nuclei.

The spontaneous decay rate A_{21} for the gamma transition $2 \rightarrow 1$ can be obtained from [5,6]

$$A_{21} = \frac{2(\Lambda + 1)}{\epsilon_0 \hbar \Lambda [(2\Lambda + 1)!!]^2} \left(\frac{\omega}{c}\right)^{2\Lambda+1} |M_{21}|^2, \quad (9)$$

where Λ is the multipolarity of the electromagnetic field, ϵ_0 is the vacuum permittivity, \hbar is the reduced Planck constant, ω is the frequency of the transition ($\omega = (E_2 - E_1)/\hbar$), c is the speed of light, and $|M_{21}|$ is the matrix element of the transition.

Similarly the absorption rate $B_{12}W$ is given by [5]:

$$B_{12}W = S(\omega) \frac{2\pi^2(\Lambda + 1)(2\Lambda + 1)}{\epsilon_0 \hbar \Lambda [(2\Lambda + 1)!!]^2} \left(\frac{\omega}{c}\right)^{2\Lambda-1} |M_{12}|^2, \quad (10)$$

where $S(\omega)$ is the photon fluence (cm^{-2}). We have assumed linearly polarised light to make the analysis simpler.

Both Eqs. (9) and (10) involve the same transition matrix element (since $|M_{21}| = |M_{12}|$ and they are related through [5,7])

$$A_{21} = \frac{\omega^2}{c^2 S(\omega) \pi^2 (2\Lambda + 1)} \times B_{12}W \quad \text{and} \quad B_{21} = B_{12}, \quad (11)$$

These are the familiar relations between Einstein's A and B coefficients. If the (partial) half life of the transition $2 \rightarrow 1$ is known, we obtain directly also the induced rates BW .

The energy density W and the fluence $S(\omega)$ are related to the peak laser intensity I , photon energy $\hbar\omega$, and pulse length τ by $W = I/c$. The average intensity is given by the duty cycle $I_{\text{ave}} = (\tau/T)I$. The quantity $S(\omega) = I/(\hbar\omega\Delta\omega)$ includes the effective line width $\Delta\omega$ defined by the convolution

$$\frac{1}{\Delta\omega} = \int_{-\infty}^{\infty} d\nu f(\nu)g(\omega - \nu) \quad (12)$$

The laser field has a spectral shape $f(\nu)$ and the nuclear transition the shape $g(\nu)$ and both are normalized such that their integral over ν equals unity. We assume that the nuclear transition has a Lorentzian shape $G(\nu) = (1/\pi\gamma)[1 + (\nu/\gamma)^2]^{-2}$ where γ is the respective line shape. Also for a short pulse laser one can approximately use a Lorentzian shape $f(\nu)$ with an effective line width of about $\Gamma \geq \tau^{-1}$. For a very monochromatic laser the effective line width $\Delta\omega$ is γ ; in the opposite case of a very sharp nuclear transition we obtain $\Delta\omega = \tau^{-1}$ implying that then S is just the total photon fluence divided by a factor π .

According to Eq. (11) the induced gamma transition cross-section, $\sigma = (2\Lambda + 1)(A_{21}/\Delta\omega)(\lambda/\pi)^2$ where λ is the wave length of the transition, is simply proportional to the wave length squared and multiplied by the spectral overlap efficiency $A_{21}/\Delta\omega$.

If the excited state half-life is not known we can use the Weisskopf approximations:

$$A_{21}^E \approx \frac{8\pi(\Lambda + 1)}{\Lambda [(2\Lambda + 1)!!!]^2} \frac{e^2}{4\pi\epsilon_0\hbar c} \left(\frac{\omega}{c}\right)^{2\Lambda+1} \left(\frac{3}{\Lambda + 3}\right)^2 c(R_0 A^{1/3})^{2\Lambda}, \quad (13)$$

$$A_{21}^M \approx \frac{8\pi(\Lambda + 1)}{\Lambda [(2\Lambda + 1)!!!]^2} \left[\mu_p - \frac{1}{\Lambda + 1}\right]^2 \left(\frac{\hbar}{m_p c}\right)^2 \frac{e^2}{4\pi\epsilon_0\hbar c} \left(\frac{\omega}{c}\right)^{2\Lambda+1} \left(\frac{3}{\Lambda + 2}\right)^2 c(R_0 A^{1/3})^{2\Lambda-2} \quad (14)$$

for the electric (E) and magnetic (M) transition, respectively. Here, e is the electron charge, $R_0 \approx 1.2$ fm, A is the mass number, μ_p is the magnetic dipole moment of the proton, and m_p is the proton mass.

2.2 Beta-gamma decay of excited states

The half-life of the ground level, i.e. the decay rate A_{13} , is usually known, but the rate coefficient A_{23} involves beta decay of an excited level 2 into intermediate excited levels of the daughter nucleus and a subsequent cascade of gamma-transitions to the end level 3. The calculation of A_{23} is much more complicated than that of A_{21} . Usually the gamma transition is much faster than the beta decay and therefore half-lives of beta transitions are given only for ground and some isomeric states, say Nb-94m and Tc-94m. From the 453 isomeric states of the NuDat data base [8] where the beta branching ratio was given we selected 184 tentative candidates for further study.

To find an allowed transition $2 \rightarrow 3$ one has as a first step to estimate the beta decay rates of excited levels. These are often given in terms of ft -values which are just the product of the Fermi integrals and the half-lives [6]. For superallowed and allowed decay rates we have $\lg(ft)=2.9-3.7$ or $4.4-6.0$, respectively. The Fermi integral depends on the end-point energy E - roughly as

E^4 - and on the charge number Z . Typically the half lives (energy range from 0.1 to 1 Mev) of allowed transitions range from 100 to 10^5 seconds and the superallowed half lives are about a factor about 100 faster. As on the other hand the gamma transitions are rather in the region $\mu\text{s} \dots \text{ns}$ or even faster, it is clear that the beta channel is hard to enter. In isomeric states (level 2) an appreciable fraction of branching between $2 \rightarrow 3$ and $2 \rightarrow 1$ takes place in several nuclides.

In many cases the isomeric EM transitions can be very slow. Instead of pumping directly from the highly forbidden transition $1 \rightarrow 2$, it may be more efficient to use the lambda-type transition $1 \rightarrow 4 \rightarrow 2$ of Figure 1. If the pulse length equals τ and the repetition rate is $1/T$ The effective transition rate, $\alpha_{\text{eff}} = N_3(T)/N_1(0)T$, is given by

$$\alpha_{\text{eff}} = \frac{A_{42}}{A_{41} + A_{42}} \frac{\tau}{T} B_{14} \tilde{W} [1 - \exp(-(A_{41} + A_{42})T)]. \quad (15)$$

This expression includes the lowest order contribution to the induced rate $1 \rightarrow 4$ included in the quantity \tilde{W} . This process is analogous to optical pumping by lasers in forbidden visible transitions. In fact, the rate α_{eff} may exceed that of the isomeric transition by many orders of magnitude. For instance, Y-85 (nucleus that we encountered just accidentally) has a ground state $(1/2)^-$ and a isomeric state $(9/2)^+$ of about 20 keV higher. The soft IT transition would be M4 and has a fully negligible rate at $1.7 \times 10^{-17} \text{ s}^{-1}$. If we couple these two states to a common $(5/2)^+$ state at 436 keV above the ground level, the spontaneous M2 transition $4 \rightarrow 1$ to the ground state takes place according to the Weisskopf approximation at a rate $A_{41} = 1.1 \times 10^7 \text{ s}^{-1}$ and the E2 transition, $4 \rightarrow 2$ to the isomeric state at a rate $A_{42} = 3.4 \times 10^8 \text{ s}^{-1}$.

3 EM sources

3.1 Intensity

Intense electromagnetic radiation with a short wavelength can be obtained by several means:

- intense X-ray and isotope sources,
- synchrotron sources,
- ultraintense pulsed lasers and table-top terawatt lasers,
- free electron lasers (FEL), and
- VUV and X-ray laser and in the future true gammalasers.

The best free-electron lasers available today are able to produce 25-fs pulses with a peak power at the GW level at wavelengths down to 32 nm [9]. In addition, the beam can be considered approximately diffraction-limited having the radius of $w_0 \approx 250 \mu\text{m}$. Stanford Linear Accelerator Center has an ongoing project, the aim of which is to downscale the FEL wavelength to 0.15 nm, increase the peak power of the 230-fs pulses to 10 GW, and obtain full transverse coherence. At DESY, Germany, one aims to reach 0.1 nm wave length (12 keV), and Stanford plans to reach 100 keV level with future devices. The FELs are capable of producing narrow-band radiation (0.1 % FWHM), however, they do suffer from low energy efficiency (in the ball park of 0.01% from electron beam to photons).

Synchrotrons are more efficient X-ray sources than FEL's, however, their emission is also more broadband. Bremsstrahlung can be very efficient at MeV energies, however, the radiation has very broad spectrum. Hence, it is difficult to achieve high spectral brightness necessary to excite narrow nuclear transitions.

An interesting concept is the so-called High Intensity Gamma-ray Source (HI γ S), where intra-cavity backscattering of the FEL photons from the injected electron beam produces γ -radiation [10]. At present, the gamma energies range from 2 – 50 MeV and the gamma flux is 10^8 s^{-1} corresponding to milliwatt powers.

Radiation sources driven by multi-terawatt lasers have the benefit of relative compactness for the energies achievable, however, they generally suffer from poor wall-plug efficiency combined with poorly collimated emission of energetic radiations having broad energy spectrum. They are an interesting tool as diagnostic of fast phenomena and they may even be used to produce small radioactive sources, however, they are totally unsuitable as radiation source for transmuting bulk quantities.

3.2 *Selectivity*

Efficient excitation of the nuclear transitions sets stringent demands on the radiation source. The spectral overlap between the EM source and the nuclear resonance line is accounted for Eq. (12). The same expression is applicable also if the effect of competing transitions coexisted and one were interested in selection of just the main resonance (cf. laser isotope separation with visible lasers). On one hand, to maximize the probability of the alternative decay through beta decay, one would like to drive long-lived levels. However, a long lifetime implies a narrow natural line width (1 ns lifetime corresponds to 4 μeV line width, ie. relative width of 10^{-10} for a 40 keV level). Hence, the benefit from the increased probability of the beta decay channel is partly lost in

the inefficiency of the excitation as all potential radiation sources have much broader emission spectrum.

To improve the spectral overlap of the EM spectrum and that of the level scheme it is beneficial to use a lambda-type excitation scheme where the transition $4 \rightarrow 1$ would be a very fast one. This would ensure that the level 4 is broad enough for excitation, but the selectivity would be still be adequate if the branching to the level 2 would dominate, i.e. $A_{41} \ll A_{42}$. Such a situation is easily found - the question is whether enough pumping $1 \rightarrow 4$ is obtained.

The giant resonance excitation requires quite high photon energy in the range of 10 MeV, however, the resonance itself is several MeV broad and typically has peak cross section of about 100 mb for medium-heavy nuclei. Such photons could be produced with high efficiency by driving a radiation converter by an electron linac. Furthermore, the high-energy photons are attenuated slowly in bulk so one could achieve transmutation probability in the ballpark of 1 % per photon. On the other hand, by investing the same energy in a particle beam one could generate copious amounts of neutrons, which could have nearly 100 % transmutation efficiency.

As the gamma resonance lines are typically very sharp the photon recoil is an issue. The center of absorption (emission) is at

$$\hbar\omega_{\text{abs,em}} = 2\Delta E[1 + (1 \mp (2\Delta E/Mc^2)^{1/2})^{-1}] \approx \Delta E(1 \pm \frac{\Delta E}{2Mc^2}) \quad (16)$$

where ΔE is the difference between the energy levels and M is the nuclear mass. Upper signs are for absorption and the lower ones for emission. Usually the frequency shift is large compared to the natural line width and, therefore emitted photons are not reabsorbed. An exception is of course the Mössbauer effect where the whole crystal takes the photon momentum. We also want to recall that photon recoil effects are applied in laser cooling of atoms and could be exploited in nuclear transitions, too.

For gaseous targets the transition frequencies experience Doppler effect which broadens the resonance lines. The Doppler width is measured by ku where k is the wave number of the transition and u the thermal velocity of the nucleus. The recoil effect still dominates: a simple calculation shows that $(\omega_{\text{abs}} - \omega_{\text{em}})/ku = (\Delta E/(Mc^2 E_{\text{th}})^{1/2})$ is still much above unity for a thermal energy of about 25 meV and in the 100 keV range of ΔE .

3.3 Efficiency

A significant complication to nuclear transmutation via photon excitation comes from their strong interactions with atomic electrons. For narrow line-

width photons, needed for selective excitation, both the absorption and scattering processes are equally detrimental in removing photons off the resonance.

In the relevant energy range from 10 keV to few MeV total attenuation cross section of photons varies from 1 Mb to 10 b for heavy elements and 100 kb to 1 b for light elements, respectively. Photon transmutation cross sections of the isomer nuclides presented in Tab. 1 vary from some 100 pb to 10 ab. Thus our efficiency for direct excitation to isomer levels remains extremely low. However, indirect excitation via properly selected higher lying excitation states can provide significant improvement to transmutation cross section. This is exemplified in the case of Y-85 discussed above where we found an enhancement of 15 orders of magnitude.

Transmutation efficiency via $(\gamma,2n)$ and (γ,n) reactions of the GDR is not very much affected by scattering reactions due to the large width, of the order of 10 MeV, of the resonance. However, at their energy range of tens of MeV pair production, which also fully destroys the photons, is the dominant competing process. GDR reactions, on the other hand have much larger cross sections being only a factor of 10 ... 100 below the pair production.

4 Potential candidate nuclides

One possible application of the method considered is transmutation of long-lived nuclear waste from present light water reactors. The relevant nuclides from fission products include Se-79, Sr-90, Zr-93, Tc-99, Pd-107, Sn-126, I-129, Cs-135, Cs-137 and Sm-151. Activation products comprise of Cl-36, Ni-59, Ni-63, Zr-93, Nb-94 and C-14 which is also produced among the fission products. The third important group arises from the actinides: Ra, Th, Pa, U, Np, Pu, Am, and Cm. A typical activity inventory in Finnish NPP spent fuel types at an average discharge burnup of 40 and 50 MWd/kgU is presented for instance in Ref. [11].

In the time range of 100 years or more the radiotoxicity of spent nuclear fuel in a once-through cycle plutonium and Am-241 are the largest contributors; Cs-137 and Sr-90 with their half-lives of about 30 years are responsible of about 10% of the radiotoxicity at this time. For 10 000 years plutonium is the dominant source of radiation. It is evident that transmutation must be accompanied by chemical partitioning of U and Pu and the minor actinides, i.e. full P&T has to be employed.

In the OECD/NEA Study [12], see also [13] transmutation of Tc-99, Pd-107, I-129 and Sm-151 yield reasonable transmutation half-lives $T_{\text{trm}} = \ln 2/\sigma\Phi$ of the order of 50 a or less in a thermal or fast neutron spectrum. Radiotoxicity

arguments suggest that only Tc-99 or I-129 are feasible for destruction by neutrons.

Based on the above considerations it is of interest to make a preliminary study whether the cumbersome nuclei are curable by photon induced reactions. As a case the transmutation of I-129 via giant resonances of (γ, n) reactions have been experimentally demonstrated [14,15]. With visible and UV lasers very hard gamma rays in the range of tens of MeVs are obtained by irradiating high-Z targets with an ultraintense laser pulse. FEL excitation has been reported in [16].

As the nuclide I-129 is often selected as a reference test case we also have considered its transmutation, but with application of sharp gamma transitions. Iodine-129 decays to Xe-129 with an extremely long half-life 1.6×10^7 a. The daughter Xe-129 has the following energy level structure $(1/2)^+$ (ground level), $(3/2)^+$ (40 keV), $(11/2)^-$ (236 keV), $(3/2)^+$ (318keV), $(5/2)^+$ (322 keV), $(1/2)^-$ (411 keV), etc. The lowest I-129 levels are $(7/2)^+$ (192 keV above the ground state of Xe-129), $(5/2)^+$ (220 keV, half-life 16.8 ns), $(3/2)^+$ (470 keV, 0.1 ns). The beta channel from I-129 is from $(7/2)^+$ to Xe-129 at $(3/2)^+$ which relaxes to the ground state via the M1 transition at about 1 ns half-life. Unfortunately we do not know the beta-decay rate from the $(5/2)^+$ state to the two available Xe-129 states $(3/2)^+$ and $(1/2)^+$. If this were much faster than the ground state decay rate enhancement could be obtained by pumping directly the I-129 level to the $(5/2)^+$ state or by a lambda cascade through the $(3/2)^+$ level. In the lambda configuration the E2 and M1 transitions at 278 keV and 250 keV have a rather favorable branching ratio 59%:41%. Under these assumptions I-129 could be transmuted, but the efficiency would be extremely low and of no practical use. Even the demonstration of the effect could be challenging because of the long life times and the soft gammas involved.

In conclusion I-129 has to be transmuted by other ways. Carbon-14 has its lowest excited state above 6 MeV and such narrow band lasers do not exist. Technetium-99 and Nb-94 have both rather promising level structures and could serve for demonstration purposes. So is also the case Y-85 which we analyzed to some extent above. In a systematic data base study like in Table 1 one can find numerous other cases for further studies.

5 Discussion

In our preliminary survey we found no immediate obvious application to transmute nuclei by the proposed sharp gamma excitation cascades. Even if we had the X- or gamma ray lasers, basic difficulties arise from the fact that most of the gammas are lost in the parasitic absorption by electrons and furthermore

the nuclear resonances are too narrow to properly match with the sources.

From basic physics the process is of course of great interest. Excitation of gamma-active nuclear transitions are clearly demonstrated in the Mössbauer effect. Such applications thus remain for the emergence of narrow-band X- or gamma lasers. Table-top lasers and FELs are still too broad.

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Table 1

A selection of isomer states leading to greatest decay enhancements in our test case.

Nuclide	IT level [MeV]	Half life [s]	IT branch [%]	IT trans.	Decay mode	Half life [s] 2	Speed up factor
YB-176	1.05E+00	1.14E+01	9.00E+01	M8	2B-	5.05E+24	1.40E+17
IN-115	3.36E-01	1.62E+04	9.50E+01	M4	B-	1.39E+22	2.32E+12
NB-94	4.10E-02	3.76E+02	9.95E+01	M3	B-	6.41E+11	2.06E+05
HF-182	1.17E+00	3.69E+03	4.20E+01	M8	B-	2.84E+14	4.73E+04
SE-79	9.58E-02	2.35E+02	9.99E+01	E3	B-	9.31E+12	4.53E+04
SB-124	1.09E-02	9.30E+01	7.50E+01	M2	B-	5.20E+06	9.71E+03
SB-126	1.77E-02	1.15E+03	1.40E+01	E3	B-	1.07E+06	3.48E+01
CO-60	5.86E-02	6.28E+02	9.98E+01	M3	B-	1.66E+08	6.29E+00
PB-202	2.17E+00	1.27E+04	9.05E+01	E9	ECA	1.66E+12	6.00E+00
AG-105	2.55E-02	4.34E+02	9.97E+01	E3	EC	3.57E+06	3.82E+00
SN-113	7.74E-02	1.28E+03	9.11E+01	M3	EC	9.94E+06	3.27E+00
AG-113	4.35E-02	6.87E+01	6.40E+01	E3	B-	1.93E+04	2.32E+00
AG-102	9.30E-03	4.62E+02	4.90E+01	M3	EC	7.74E+02	1.87E+00
AG-111	5.98E-02	6.48E+01	9.93E+01	E3	B-	6.44E+05	1.54E+00
BR-76	1.03E-01	1.31E+00	9.94E+01	E3	EC	5.83E+04	1.40E+00
TB-151	9.95E-02	2.50E+01	9.38E+01	E5	ECA	6.34E+04	1.39E+00
I -130	4.00E-02	5.30E+02	8.40E+01	M3	B-	4.45E+04	1.29E+00
KR-85	3.05E-01	1.61E+04	2.14E+01	M4	B-	3.40E+08	1.26E+00
AG-115	4.12E-02	1.80E+01	2.10E+01	E3	B-	1.20E+03	1.26E+00
SE-73	2.57E-02	2.39E+03	7.26E+01	E3	EC	2.57E+04	1.21E+00
BR-82	4.59E-02	3.68E+02	9.76E+01	M3	B-	1.27E+05	1.14E+00
IR-192	5.67E-02	8.70E+01	1.00E+02	E3	ECB-	6.38E+06	1.13E+00
TC-96	3.40E-02	3.09E+03	9.80E+01	M3	EC	3.70E+05	1.10E+00
GA-74	6.00E-02	9.50E+00	7.50E+01	E3	B-	4.87E+02	1.07E+00

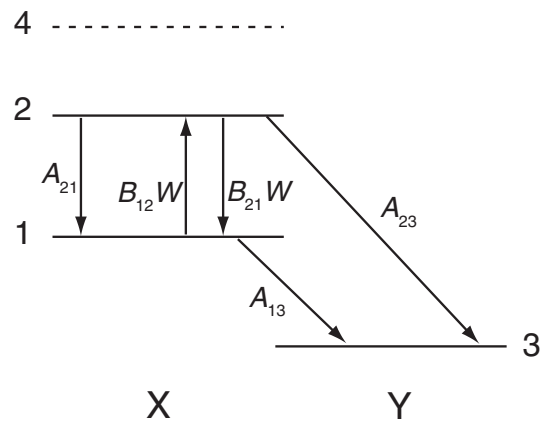


Fig. 1. Energy-level scheme of the radioactive decay process $X \rightarrow Y$.