A mechanism for creating an inversion of populations of energy levels

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ABSTRACT

The possibility of the Gadolinium nuclei energy levels population inversion under neutron bombardment is theoretically shown. In the process two isotopes of gadolinium take part. Light isotope Gd^{155} capturing neutron transforms to heavy isotope Gd^{156} at that heavy nucleus is in an excited metastable state. The population inversion is investigating during several tens of second when the neutron flux intensity is 10^{13} $cm^{-2} \cdot s^{-1}$.

Keywords: active medium, isotopes, nuclei, neutrons capture, exiting, inversion of population, pumping

INTRODUCTION

Active medium of the gamma-laser with neutron pumping is some matter in which the nucleus energy level population inversion is created due to radiation capture reaction and inelastic neutron scattering by nuclei.

Classical laser geometry assumes that the nucleus should pass from the lowest state with the energy E_0 into excited state with the energy E_2. The nucleus should remain in such condition for a relatively short period of time, as the transfer to the level E_1 ($E_1 < E_2$) on which the nucleus can remain longer must happen immediately. This is the so-called metastable level. The possibility of induced gamma quantum radiation appears when passing from the metastable level E_1 to the basic level E_0. As soon as the number of nuclei which are in the metastable condition increases the number of nuclei in the lowest state, the generation process begins.

The multilevel pumping scheme is possible. In this case there is an intermediate metastable level E_1 between the metastable E_2 and the lowest E_0 levels. Induced radiation occurs when the nuclei pass from the E_2 level to the E_1 level. In this particular case the inverse population condition is fulfilled, if the lifetime of the upper level (E_2) is several orders greater than the lifetime of the lowest level (E_1).

Attention of researchers has long been drawn to metastable nuclei of hafnium-178m2 (Hf-178m2), which form from hafnium-178 (Hf-178, a stable isotope with 27.28 % content in natural mixture). According to contemporary data the radiated gamma quantum energy equal to 2.446 MeV when passing to the basic level and the half-decay period of 31 year correspond to metastable nuclei of Hf-178m2. These parameters are 2.534 MeV and 68 μs for metastable nuclei of Hf-178m3 (higher energy level) and 1.147 MeV and 4 s for Hf-178m1, correspondingly. There was a reason to hope that a metastable hafnium isomer could be used for creating an active medium of compact gamma ray lasers.

It was supposed that transition of some Hf-178 nuclei into isomeric state Hf-178m2 made it possible to combine the energy source and the irradiator using hafnium oxide as a laser crystal component.

DARPA agency was concerned with the development of the so-called “hafnium bomb” on the basis of Hf-178m2 isomer from 1998 till 2004. However, even the use of high power X-ray radiation sources for pumping the active medium which contained Hf-178 nuclei did not allow discovering the induced decay effect. In 2005 it was shown [1] that it was impossible to release excess energy from Hf-178m2 nuclei using technologies existing at that time.

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When the active medium is pumped by neutrons, the combination of processes excited and occurring in the medium becomes complicated, opening up new possibilities.

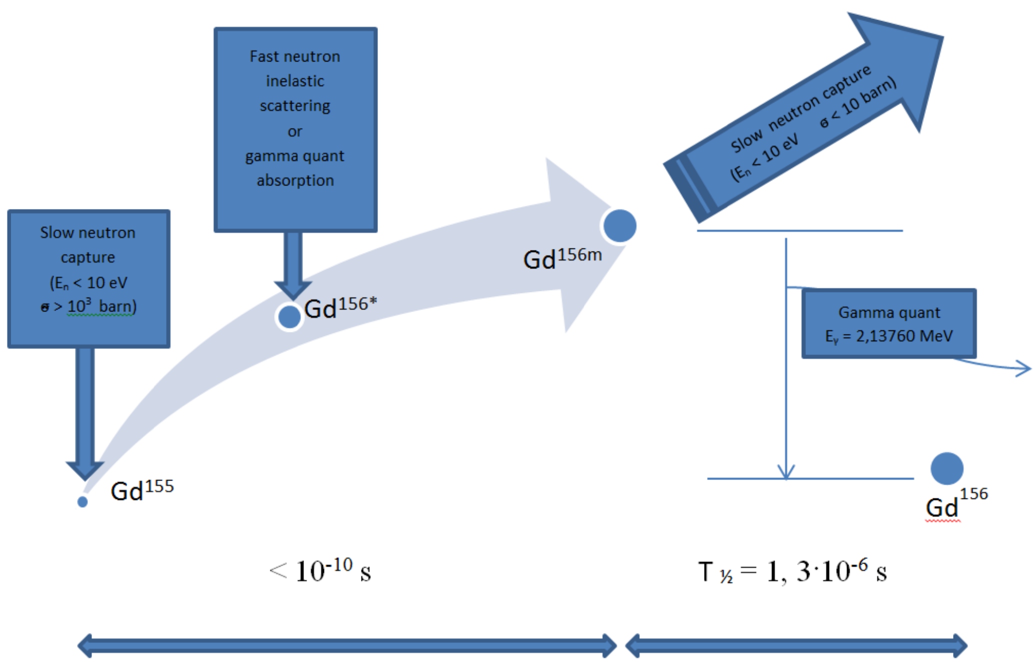
THE POSSIBILITY OF METASTABLE NUCLEI PUMPING BY NEUTRON BOMBARDMENT

The metastable Hf-178m2 nuclei are formed not only at inelastic scattering of fast neutrons on Hf-178m2 nuclei, but also at neutron capture by the nuclei of hafnium 177 (Hf-177, a stable isotope with 18.6 % content in natural mixture). As a result of neutron capture the compound nucleus of Hf-178* in a very excited state is formed. The excitation energy is equal to the sum of neutron-binding energy and neutron kinetic energy. The lifetime of the compound nucleus in the excited state is not more than 10^{-13} s, and the excitation is removed by releasing high-energy gamma-quantum. The nucleus passes either to the basic state or to one of metastable states.

Neutron inelastic scattering cross-section on Hf-178 nuclei does not exceed 2.5 barns in a wide neutron energy range. It leads to the impossibility of pumping only by means of inelastic scattering, even if the neutron flux density is $\sim 10^{14}$ $sm^{-2} \cdot sec^{-1}$. The inverse population condition at pumping only due to inelastic scattering will be achieved in a huge period of time.

The balance of Hf-178 nuclei which are in an isomeric state m2 becomes better, if it is taken into account that they are formed due to neutron capture by Hf-177 nuclei. The cross-section of this process is hundreds of barns for thermal neutrons and is more than 1 barn for neutrons with the energy to 100eV. The inverse population condition will be achieved in a considerably shorter period of time, if the neutron capture is considered. Taking into account the neutron capture by Hf-178 nuclei and nuclei of its isomers (the process cross-section is about tens of barns) in the result of which these nuclei disappear, the inverse population condition can be basically not achieved.

Let us consider an active medium in which the following processes occur under the neutrons influence: the nucleus **X** + a neutron → the nucleus **Y** in an excited state → the nucleus **Y** in an isomeric (metastable) state → the nucleus **Z** in the basic state. For example, $Gd^{155}+n \rightarrow Gd^{156*} \rightarrow Gd^{156m} \rightarrow Gd^{156}$ [2]. The nuclei Y and Z undergo the radiation neutron capture, that is they are "bombarded". The isomer Gd^{156m} has the half-decay period of 1.3 µs and decays releasing gamma quantum with the energy of 2.1376 MeV. The scheme of this process is shown on Fig.1.



$Gd^{155}+n \rightarrow Gd^{156*} \rightarrow Gd^{156*} + \Delta E \rightarrow Gd^{156m} \rightarrow Gd^{156}$

Fig. 1 Gadolinium nuclei pumping by neutrons bombardment scheme

For evaluating the possibility of active medium neutron pumping by means of radiation neutron capture it is necessary to solve the differential equation system:

$$\begin{cases} \dfrac{dx}{dt} = -\sigma_1 x\Phi \\ \dfrac{dy}{dt} = \sigma_1 x\Phi - \sigma_2 x\Phi - \lambda y \\ \dfrac{dz}{dt} = -\sigma_3 z\Phi + \lambda y \end{cases} ,$$

where **X**, **Y**, **Z** are nuclei concentration, **Φ** is the neutron flux density, **σ** is the microscopic cross section of neutron capture, **λ** is the decay constant of isomers nuclei.

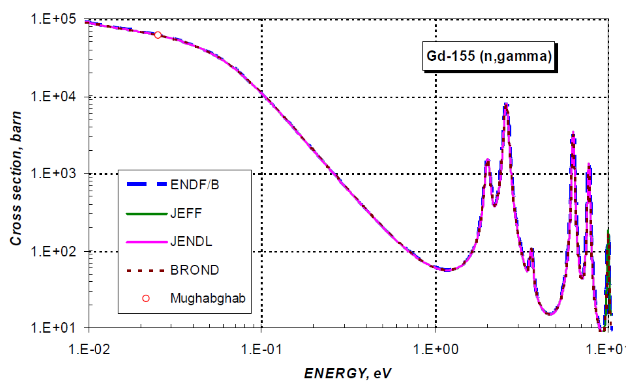
To determine the possibility to achieve the inverse population condition when pumping the active medium created by Gd nuclei and the neutrons with the flux density **Φ** up to
10^{16} sm^{-2}·sec, the following formulae can be used:

$$\frac{y(t)}{z(t)} \approx \frac{\lambda t - (\sigma_1 - \sigma_2)\Phi t}{S\lambda},$$

where

$$S = \frac{1-(\lambda + 2\sigma_3\Phi)t}{\lambda + \sigma_3\Phi} - \frac{1-(\sigma_1 - \sigma_2 + 2\sigma_3)\Phi t}{(\sigma_1 - \sigma_2 + \sigma_3)\Phi} + \frac{(\lambda - (\sigma_1 - \sigma_2)\Phi)(1-\sigma_3\Phi t)}{(\sigma_1 - \sigma_2 + \sigma_3)\Phi(\lambda + \sigma_3\Phi)}.$$

Values of cross sections for neutrons capture by gadolinium nuclei [3] are presented on Fig. 2.



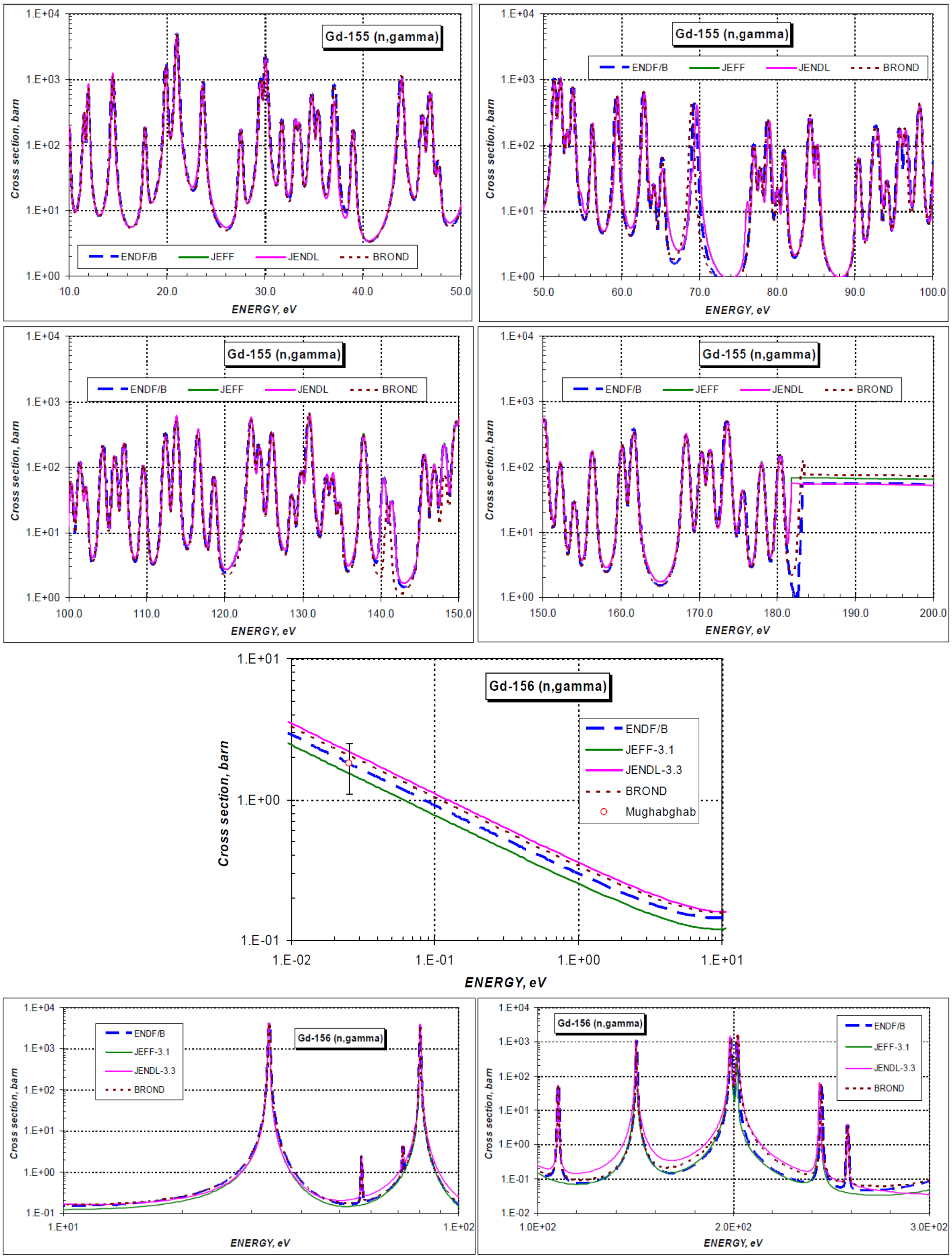


Fig. 2 Gadolinium nuclei cross sections data [3]

Evaluation for nuclei Gd^{155} and Gd^{156} shows that the condition $\frac{y(t)}{z(t)} \approx 1$ is achieved within several tens if seconds when the flux density **Φ** equal to 10^{13} $sm^{-2} \cdot sec^{-1}$.

CONCLUSION

Pumping the active medium created by Gd^{155} and Gd^{156} nuclei by the neutrons with the flux density **Φ** equal to 10^{13} $sm^{-2} \cdot sec^{-1}$ is principally possible, the condition of the population inversion is achieved within several tens if seconds. The wavelength of the radiation generated by the medium is 0.0006 nm.

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