Electron initiation of γ-ray transitions in a plasma

R. V. Arutyunyan, L. A. Bol'shov, and E. V. Tkalya

(Submitted 7 August 1987)
Pis'ma Zh. Eksp.Teor. Fiz. **46**, No. 9, 354–355 (10 November 1987)

The de-excitation of isomeric nuclei with closely spaced levels in the plasma is considered. An alternative method of pumping the Mössbauer transitions is proposed. It is shown that a de-excitation wave can in principle exist in a system of isomeric nuclei.

1. Nuclei which are excited to long-lived isomeric levels with energies of 10–100 keV can be de-excited as a result of spontaneous γ-ray emission, electron conversion, or prolonged $\alpha(\beta)$ decay (ranging from several seconds to hundreds of years). Random coincidence ($\Delta E \lesssim 0.5$ keV) of the nuclear levels can be used to sharply increase the de-excitation rate through transfer of the nuclei from the isomeric level to the short-lived adjacent level as a result of electron collision. More than a score of nuclei, such as ^{73}Se, ^{183}W, ^{242}Am, and ^{171}Lu, which have the indicated level structure, have been reported in the literature.

Let us assume that as a result of initiation of the plasma by one of the known methods (laser heating, z pitch, plasma focus, liner methods in which the plasma is compressed by the fields or by high-speed strikers, "explosive wires," etc.) the plasma becomes heated to a temperature $T \sim \Delta E$, i.e., 10^2–10^3 eV. Because of excitation of short-lived nuclear level during the anticonversion and because of resonant transfer of electron excitation or inelastic electron scattering,[1–3] the plasma emission spectrum reveals the presence of lines corresponding to γ rays with energies which are approximately equal to the energy of the isomeric state. The fraction of isomer nuclei that jump to the nearby level as a result of inelastic electron scattering during the typical time τ that the plasma exists can be estimated from the expression

$$\alpha \approx n_e (T_0) \tau \exp(-\Delta E/T_0) \sigma_{ee'} \sqrt{\Delta E/m}, \tag{1}$$

where $n_e(T)$ is the concentration of free electrons in the plasma of temperature T_0, m is the electron mass, and $\sigma_{ee'}$ is the characteristic cross section for the electron excitation of the nuclear transition with an energy ΔE.

For electrons with an energy of 10^3 eV the inelastic scattering cross section is $\sigma_{ee'} \sim 10^{-25}$ cm^2 if the electronic dipole transition between the isomeric level and the nearby level is unhindered. The value of α will therefore be equal to unity for a plasma with $n_e \tau = 10^{16}$–10^{18} cm$^{-3}\cdot$s and temperature $T_e \lesssim 10^3$ eV.

The isomeric nuclei implanted in the target in the experiments involving the production of hot plasma (LTF, explosive liners, etc.) can be used for plasma diagnostics in the range of parameters which are difficult to study experimentally; specifically, the density at the solid-state level and the temperature at the level of hundreds of electron-volts. Such a plasma can be diagnosed by recording the delayed conversion electrons or γ rays with energies of 10^4–10^5 eV, which are emitted by nuclei that have

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jumped to the short-lived level as a result of inelastic scattering of electrons during the time the plasma exists. From the viewpoint of plasma diagnostics, of considerable interest are the nuclei with anomalously low-lying isomeric levels, such as ^{235}U (73 eV), ^{229}Th ($\leqslant$100 eV), ^{110}Ag (1.1 keV), and other nuclei.

2. A plasma which contains isomeric nuclei with a short-lived nearby level may be an effective source of Mössbauer inverted nuclei. It is evident from (1) that from the standpoint of obtaining enough nuclei to achieve lasing under various conditions discussed in Ref. 4–6, the process by which these nuclei jump to the short-lived level can occur in the case of electric dipole transitions from the isomeric level to the short-lived level.

A direct pumping of nuclei by thermal neutrons to the short-lived level cannot realistically be achieved today through lasing, while pumping to the isomeric level with a lifetime of ~1–100 s is possible, since it requires a flux density 5–8 orders of magnitude lower, and since it can be realized by using the presently available reactor thermal-neutron sources.

A jump to the short-lived level due to the resonant photon absorption[7] imposes rigorous requirements on the spectral luminosity of the source. A more efficient use of the source power may involve the spectral transfer of energy to the reasonance-absorption line due to scattering.

3. If the rate at which the energy is released during the transition of long-lived isomer to the ground state through the short-lived nearby level is large enough to cancel the plasma loss due to radiation and thermal conductivity, a self-sustaining de-excitation of the isomers similar to chemical combustion can occur.

Let us determine the length scale of the region a, whose initial heating to $T \sim \Delta E$ will ignite the de-excitation wave in a medium containing the isomeric nuclei with a density n. The value of $a_{\min}$ can be estimated under the condition that the loss due to the radiant thermal conductivity is equal to the energy release due to the de-excitation of the isomeric nuclei in accordance with the mechanism discussed above:

$$\sigma_{ee'} \sqrt{\Delta E/m}\, \frac{nE}{C(T)}\, \frac{a^2_{min}}{\chi} \approx 1, \qquad (2)$$

where $\chi \approx (l_R c/3)[U'(T)/C(T)]$, l_R is the Russelandov range of the γ rays, c is the speed of light, $C(T)$ is the plasma specific heat, and $U(T)$ is the thermal radiation energy density.

In Eq. (2) the plasma decompression is ignored. This omission is valid if the leading edge of the radiant thermal conductivity is moving along with the shock wave.

For a system of isomeric nuclei with a density $n = 10^{22}$ cm^{-3}, $\Delta E = 10^2$ eV, and $E = 10^5$ eV the value of $a_{\min}$ is on the order of a centimeter for an unhindered electric dipole transition between the adjacent levels. The condition for the combined motion of the leading edge of the thermal conductivity and the shock wave is also satisfied in this case. The range of the parameters indicated above can be extended by compressing the target containing the isomeric nuclei. This can be assomplished by using various liners, high-speed strikers, lasers, and other methods.

The use of electrons to stimulate transitions in isomeric nuclei in a solid plasma may also be a useful independent method of measuring nuclear physical constants.

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Translated by S. J. Amoretty