Effect of laser radiation on nuclear decay processes

V. I. Gol'danskiĭ and V. S. Letokhov

Institute of Chemical Physics, USSR Academy of Sciences
Institute of Spectroscopy, USSR Academy of Sciences
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The possibility is discussed of observing the effect of ionization of radioactive atoms by laser radiation on the rate of internal conversion (for the case of Tc^{99m}) and *K* capture (for the case of Be^7).

An alluring goal–to influence nuclear decay and excitation processes directly by a strong light field–is unrealizable in practive because of the need of having inaccessibly high intensities of the light field. Therefore it is more realistic to attempt to affect nuclear processes which involve the electrons surrounding the nucleus, since the latter are to a high degree subject to the action of a strong light field. In this article we consider two possibilities of this type: control of nuclear internal conversion (with Tc^{99} as the example) and control of K capture (with Be^7 as the example).

1. EFFECT ON INTERNAL CONVERSION

The main process responsible for transitions of nuclei between levels with a small energy difference (tens of keV or less) is internal conversion. For energy differences which are very low on a nuclear scale (several keV or less) internal conversion can occur only in the outer electron shells. It is well known that, under the action of a high-power pulse of laser radiation, matter which is initially in a gaseous or condensed state will be transformed to a high-temperature plasma with a rather high degree of ionization.[1, 2] If the ionization removes the electrons in which internal conversion occurs, we can obtain a decrease in the rate of decay of a nucleus by internal conversion. However, observation of this effect of a decrease in the number of conversion electrons is difficult because of the presence of a large number of electrons in the plasma. At the same time the presence or absence of conversion has practically no effect on the rate of parallel nuclear decay channels, for example, decay by the parallel conversionless γ transition. However, the situation can be radically improved if we affect the conversion transition of the nucleus between close-lying excited levels (Fig. 1a). In this case the slowing down of the population of the lower level (1) of the first transition can be detected by the decrease in the number of γ rays emitted in the subsequent transition $1 \to 0$.

In order to suppress internal conversion in a transition with transition energy ΔE_{21}, it is necessary to ionize all electrons which contribute to the internal conversion process, i.e., electrons with ionization potential $E_i < \Delta E_{21}$. For this purpose the electron temperature of the laser plasma must satisfy the condition[3] $kT_e \gtrsim (1/5)\Delta E_{21}$.

The most suitable candidate for carrying out such an experiment is the nucleus Tc^{99}. A diagram[4, 5] of the lower levels and transitions of Tc^{99} is shown in Fig. 1b. The energy of the $2 \to 1$ transition for Tc^{99} is $\Delta E_{21} = 2$ keV. Therefore only electrons of the outer shells with an ionization potential less than 2 keV can take part in the conversion. To remove these electrons it is sufficient to produce a Tc^{99} plasma with an electron temperature $kT_e \gtrsim 400$ eV. As a result the population of the level with energy 140 keV in the internal conversion process will be cut off, which will give a sharp reduction, by a factor $\Gamma_{12}/\Gamma_2 \approx 70$ in the limit of complete ionization in the γ-ray intensity. If in a time Δt_i the η-th part of an aggregate containing N_0 Tc^{99m} atoms is transferred to a state with ionization of electrons having an ionization potential $E_i \leq 2$ keV, then the number of γ rays emitted during this time is reduced from $n_1^0 = N_0\Gamma_{12}\Delta t_i$ to $n_1 = (1-\eta)N_0\Gamma_{12}\Delta t_i + N_0\Gamma_2\Delta t_i$. For $(1-\eta)\Gamma_{12} \gg \Gamma_2$, which always occurs for incomplete ionization of all atoms of the aggregate, the γ rays with energy 142 keV corresponding to the channel $2 \to 0$ can be neglected. Then the criterion for observation of a decrease in γ activity in the background of the statistical fluctuations is the condition $(n_1^0 - n_1) \gg \sqrt{n_1^0}$, from which have the inequality

$$\eta(N_0\Gamma_{12}\Delta t_i)^{1/2} \gg 1. \quad (1)$$

In the general case condition (1) can be written in the form

$$6.1\eta(I[\text{Curies}]\Delta t_i[\text{nsec}])^{1/2} \gg 1. \quad (2)$$

For $\Delta t_i = 10$ nsec and $\eta \approx 1$ the activity of the Tc^{99} aggregate must amount to at least 0.1 Curie (the weight of the aggregate not less than 2×10^{-8} g). For $\eta \ll 1$ the required activity of the aggregate rises by η^{-2} times, so that for convincing demonstration of the effect it is important to ionize the main part of the aggregate.

2. EFFECT ON K CAPTURE

Another important nuclear decay process involving electrons is K capture of an electron by the nucleus. By ionizing all electrons of the atoms by the action of a laser pulse on the material, we can deprive the nucleus of the possibility of capturing an electron and thereby suppress the K-capture process. To observe this effect, the most suitable process is again K capture accompanied by excitation of a new nucleus and the subsequent emission of a γ ray (Fig. 2a). A decrease in the rate of

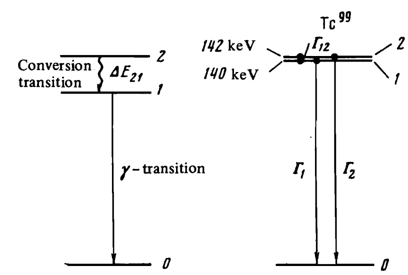

FIG. 1. Diagram of successive transitions with internal conversion and γ-ray emission: a) general scheme, b) the example of the technetium nucleus Tc^{99m}: $\Gamma_{12}^{-1} = 6.04$ hours, $\Gamma_2^{-1} = 430$ hours, $\Gamma_1^{-1} = 2 \times 10^{-10}$ hours.

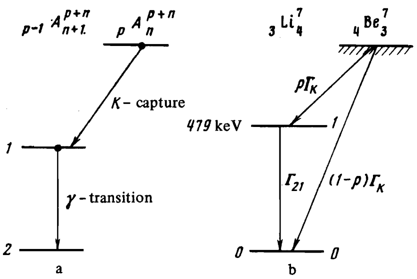

FIG. 2. Diagram of successive transitions with K capture and emission of a γ ray: a–general scheme, b–the example of the beryllium nucleus Be^7; Γ_K^{-1} = 53 days, $\Gamma_{21}^{-1} = 7.7 \times 10^{-14}$ sec, $\rho = 0.12$.

K capture by the nucleus ${}_pA_n^{p+n}$ should bring about a drop in intensity of radiation in the $1 \rightarrow 0$ transition of the nucleus ${}_{p-1}A_{n+1}^{p+n}$. In contrast to the case of the effect on internal conversion, for affecting K capture it is necessary to ionize all electrons around the nucleus. Since the multiplicity of ionization in typical experiments with a high-temperature laser plasma does not exceed $z \approx 10$–20, only light elements are suitable for such an experiment.

The most convenient candidate is the nucleus ${}_4Be_3^7$, which is converted by the electron K capture to the nucleus ${}_3Li_4^7$. A diagram of the levels and transitions for these nuclei[4, 5] is shown in Fig. 2b. We note that it has been proposed previously to use Be^7 atoms in a high-temperature plasma to suppress the K-capture process.[6] We suggest that this experiment is much easier to accomplish in a laser plasma.

The nucleus Be^7 has a half-life for 100% K capture $T_{1/2}$ = 53 days, 88% of the decays giving Li^7 in the ground state and 12% in an excited state with energy 480 keV. The ionization potential of the fourth electron of beryllium is E_i = 216 eV. For a plasma electron temperature $kT_e \gtrsim 40$ eV the overwhelming majority of Be^7 nuclei should be completely ionized. This will lead to a slowing down of the process $Be^7 \rightarrow Li^7$ and a decrease in the number of γ-ray counts with energy 480 keV. If the η-th part of an aggregate containing N_0 atoms of Be^7 is transferred in a time Δt_i to a state with electron temperature $kT_e \gtrsim 40$ eV, then the number of γ rays detected during the time will be reduced from a level $n_1^0 = N_0\Gamma_K\rho\Delta t_i$ to a level $n_1 = (1-\eta)N_0\Gamma_K\rho\Delta t_i$, where Γ_K is the K-capture rate and ρ is the fraction of decays accompanied by excitation of a new nucleus. For the Be^7 example discussed we have $\Gamma_K = T_{1/2}^{-1} = 2.2 \times 10^{-7}\ \text{sec}^{-1}$, $\rho = 0.12$. The condition for observation of the effect of a drop intensity of 480-keV γ rays can be written in a form similar to Eq. (2):

$$6.1\eta(\rho I[\text{Curies}]\Delta t_i[\text{nsec}])^{1/2} \gg 1; \qquad (3)$$

here $I = N_0\Gamma_K$ is the activity of the Be^7 aggregate, and Δt_i is the duration of the completely ionized state of the Be^7 atoms. If the entire aggregate ($\eta \approx 1$) is transferred to a completely ionized state in Δt_i = 10 nsec, then to observe the effect its activity must amount to about 1 Curie (the weight of a pure source of Be^7 with this activity is 2×10^{-8} g).

3. DISCUSSION

The experiments proposed in the present article can be accomplished by the known technology applicable for obtaining a high-temperature laser plasma. A fixed or moving aggregate containing a radioactive source is evaporated by a focused laser pulse. The power of the pulse is chosen from the condition of obtaining the necessary degree of ionization. The dispersing plasma contains mainly ions. The duration of existence of the ionized state Δt_i can be increased substantially by use of magnetic containment of the plasma. For $\Delta t_i \approx 1$ μsec the source activity necessary for detection of the effect can be reduced to a level of the order of 10^{-3} Curie.

Investigation of the kinetics of the pulsed reduction and recovery of the rate of internal conversion and K-capture processes in a dispersing laser plasma may provide further information on the electron-nuclear interaction, in particular regarding the contribution of conversion in the outer electron shells. It is also possible to obtain further information on the kinetics of ionization and recombination in a laser plasma. The latter possibility may be important for diagnostics of a high-temperature dense plasma, because of its transparency for γ rays. Naturally, for experiments with a hot plasma it is necessary to choose radioactive nuclei with a high nuclear-transition energy ΔE_{21} (in the case of internal conversion) and a high ionization potential for the last electron (in the case of K capture).

[1] N. G. Basov and O. N. Krokhin, Zh. Éksp. Teor. Fiz. **46**, 171 (1964) [Sov. Phys. JETP **19**, 123 (1964)].

[2] J. M. Dawson, Phys. of Fluids 7, 981 (1964).

[3] Ya. B. Zel'dovich and Yu. P. Raĭzer, Fizika udarnykh voln i vysokotemperaturnykh gidrodinamicheskikh yavlenniĭ (Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena), Nauka, 1966.

[4] B. S. Dzhelepov and L. K. Peker, Skhemy raspada radioaktivnykh yader (Decay Schemes of Radioactive Nuclei), AN SSSR, 1958.

[5] É. E. Berlovich, S. S. Vasilenko, and Yu. N. Novikov, Vremena zhizni vozbuzhdennykh sostoyaniĭ atomnykh yader (Lifetimes of Excited States of Nuclei), Nauka, 1972.

[6] C. A. Accardo, Phys. Rev. Lett. 1, 180 (1958).

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