# Theoretical interpretation of experimental results on excitation of the isomer $^{235m}$U (76.8 eV) in a plasma

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The formation of a low-lying (76.8 eV) isomer of $^{235}$U which has been observed experimentally {R. V. Arutyunyan *et al.*, Yad. Fiz. **53**, 36 (1991) [Sov. J. Nucl. Phys. **53**, 23 (1991)]; Preprint IAÉ-5087/6, I. V. Kurchatov Institute of Atomic Energy, Moscow, 1990} in a plasma produced by an electron beam could occur through the excitation of higher-lying states as the result of an inelastic scattering of beam electrons by uranium nuclei.

A series of successful experiments[1,2] on the excitation of the low-lying isomer state $1/2^+$ (76.8 eV) $^{235m}$U was carried out at the Triton installation at the Kurchatov Institute of Atomic Energy in 1989. The experiments were carried out in a plasma produced by an electron beam at the surface of highly enriched (to 99.99%) metallic uranium. The measured excitation efficiency $\zeta$, which is defined as the ratio of the number of isomers formed, $N^*$, to the total number of $^{235}$U nuclei in the plasma, $N$, was about $10^{-12}$.

For the particular plasma in the experiments of Refs. 1 and 2 [which had a lifetime $\tau = 30$ ns, a product $n_e\tau = 10^{12}$–$10^{13}$ cm$^{-3}$·s ($n_e$ is the electron density), a temperature $T = 20$ eV, and a volume $V = 10^{-4}$–$10^{-5}$ cm$^3$], the value found for $\zeta$ was very large. The yield of isomer nuclei observed in Refs. 1 and 2 cannot be explained by any of the existing mechanisms for excitation of nuclei by photons or plasma electrons, e.g., inverse internal conversion,[3] inelastic scattering of electrons by nuclei,[4] direct photoabsorption of equilibrium thermal emission from the plasma,[5] the inverse electron bridge,[6] and the excitation of nuclei in atomic transitions (see the analysis of Ref. 7). Of these mechanisms, inverse internal conversion leads to the highest efficiency. The value of this efficiency, found from the expression $\zeta_{\rm IIC} \simeq n_e \tau \sigma v_e$ ($\sigma$ is the cross section for the excitation of the 76.8-eV state in the course of inverse internal conversion) for the plasma parameter values listed above, is $10^{-14}$–$10^{-15}$, well below the efficiency observed in Refs. 1 and 2.

Another factor which suggests the need for caution here is an unsuccessful attempt[8] to observe excitation of $^{235}$U in a plasma produced by the beam from a $CO_2$ laser at the surface of a ceramic uranium dioxide sample with a 6% concentration of the isotope $^{235m}$U.

We will accordingly take a look at a mechanism for the formation of isomers in the experiments of Refs. 1 and 2 which is, in a sense, an alternative to processes in which a plasma plays a key role. The electrons of the beam in Refs. 1 and 2 had an energy of 500 keV. Among the $^{235}$U levels with energies $< 500$ keV there are three states (see Fig. 1, which was constructed from the data of Ref. 9) of the $K\,[Nn_z\Lambda]$

  

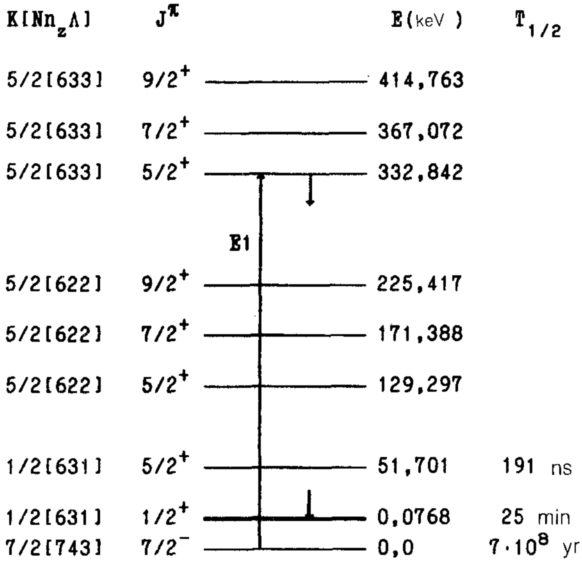


FIG. 1. Fragment of the energy-level diagram of the nucleus $^{235}$U, with one possible transition.

$= 5/2[633]$ band ($K$ is the rotation number, and $[Nn_z\Lambda]$ are the quantum numbers in the Nilsson model) which are excited fairly efficiently in the course of inelastic scattering electrons from the ground state. No experimental data are available on the matrix elements for $E1$ transitions from the ground state to the states of this band. However, an interpolation of the results calculated in Ref. 10 for transitions between the 7/2[743] and 5/2[633] bands into the deformation region characteristic of $^{235}$U yields a value for the reduced branching ratio for these nuclear transitions: $B(E1;\, 7/2[743]\rightarrow 5/2[633])\approx 2\times 10^{-6}\,\text{fm}^2$. As a result, we find the value $\sigma_{ee'}\approx 3\times 10^{-33}$ cm$^2$ for the cross section for excitation of the level with an energy of 332.842 keV. We can estimate the branching ratio of the isomer nuclei from the formula

$$N^* = n_U h \sigma_{ee'} Q \beta, \tag{1}$$

where $n_U$ and $h$ are respectively the density and thickness of the layer of uranium atoms deposited on the substrate, $Q$ is the total charge passed (the beam current was 150 kA), and $\beta$ is the population of the 76.8-eV state during decay of the level excited in the $(e,e')$ process. Analysis of the data in Ref. 9 yields the value $\beta\approx 0.28$ for the decay of the 332.842-keV level. From (1) we find $N^* = 10^3$–$10^4$. Since we are describing a fairly crude experiment, we can ignore the differences between the excitation cross sections for the levels with $J^\pi = 5/2^+$, $7/2^+$, and $9/2^+$ of the 5/2[633] band (these differences are insignificant in this case). We can also ignore the insignificant differences in the populations of the isomer during their decays. When all three states are taken into account, we find that the value above is multiplied by a factor of about 3.

We now consider the 5/2[622] band. In the $E1$ transition from the ground state to the levels with 129, 171, and 225 keV, the selection rules in terms of the asymptotic quantum numbers are violated to the greatest extent. From Ref. 10 we have $B(E1;$ $7/2[743] \rightarrow 5/2[622]) \approx 2\times10^{-7}$ fm$^2$. However, noting that $\beta$ for the states of the 5/2[622] band is slightly higher than that for the levels of the 5/2[633] band, the resultant branching ratio for the isomer during excitation of the three states of the 5/2[622] band shown in th is figure in the course of inelastic electron scattering is also $10^3$–$10^4$ nuclei.

The estimate $N^* \approx 10^4$ thus agrees well with the measurements of Refs. 1 and 2. It might seem at first glance that an experiment in which the beam electrons have an energy just below 129 keV would be a suitable test here. However, it is quite likely that a beam with an electron energy less than 51 keV would have to be used, in order to draw a conclusion about the mechanism for the formation of the isomers. If the doubly $K$-forbidden transitions to the states of the 1/2[631] band are suppressed by a factor no greater than $10^4$ (this assumption is consistent with the phenomenological values which have been adopted), the measured number of isomers could also form in a transition through, for example, the $5/2^+$ state (51.701 keV).

Finally, it was assumed in the analysis of the experimental results in Refs. 1 and 2 that the plasma expansion time is longer than the pulse from the accelerator. We have adopted the same assumption here. Estimates show that this assumption does indeed hold and that the dumping time is on the order of $10^{-6}$ s. In principle, this point is also important for the model proposed here, since the lateral expansion of the plasma on each side could have a negative influence on the effect (in the experimental geometry of Refs. 1 and 2, there was essentially no expansion off to the side). As for the temperature, we note that in experimental layouts like that in Refs. 1 and 2 the temperature should have been high enough for an expansion of the plasma along the beam axis after the end of the accelerator pulse. In other words, the isomers which were formed would not reach the detection system.

We wish to stress that the high-current accelerators used to produce hot, dense plasmas could, in view of the mechanism discussed above, serve as tools for studying low-lying isomer states of nuclei as in Refs. 1 and 2. As an example one might suggest the stable nucleus $^{201}$Hg, for which we do not yet know the lifetime of the first excited state, at 1.561 keV.

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