Accelerated decay of nuclear isomers during atomic-shell ionization

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The resonant decay of low-lying isomer levels through an atomic shell is discussed for several nuclei. The acceleration of the decay (by a factor of about 50 in the case of ^{197}Au) is discussed. The role played by a dynamic nuclear-exchange effect is examined. © *1994 American Institute of Physics.*

Internal electron conversion of γ rays is the dominant mechanism for the decay of most low-lying nuclear isomer levels. The probability for the process here depends directly on the presence of electrons in the corresponding atomic shells. Ionization of one of these shells leads directly to an increase in the lifetime of the nuclear state.

In this letter we consider the case in which the ionization of one of these atomic shells is accompanied not by a decrease but by a sharp increase in the total probability for the nuclear transition and, correspondingly, by a significant decrease in the lifetime of an isomer level. The reason for the acceleration is that a new decay mechanism, often more effective than internal conversion, comes into play. Specifically, we are talking about the process which is the inverse of nuclear excitation by electron transition (NEET), i.e., the resonant excitation of a nucleus upon the transition of an electron between atomic shells when the energies and multiplicities of the nuclear and atomic transitions are the same. This possibility was first pointed out in the case of muonic atoms in Ref. 1. It was later discussed in detail for ordinary atoms.[2] The widely used label NEET was proposed in Ref. 2.

There are at least three reasons why the process which is the inverse of NEET warrants interest. First, this process has a probability higher than conversion for certain nuclei, as was mentioned above. Second, here one should observe a dynamic nuclear-volume effect (so-called anomalies analogous to those in the internal-conversion coefficients). Third, a study of the inverse process may constitute an important step toward an understanding of NEET itself, which, being a constituent part of the processes by which a nucleus interacts with an atomic shell in higher-order perturbation theories, has yet to be reliably confirmed experimentally.

Let us take a more detailed look at the resonant decay of a nucleus through an atomic shell. This process is described by the same second-order Feynman diagram which describes internal conversion of γ rays. The only difference from conversion is that now it is the initial electron state, not the final one, that is bound. If the process is to go, there must be a vacancy in one of the upper atomic shells, to which an electron undergoes a transition from a lower shell as the result of a nonradiative transfer of excitation energy from the nucleus to the atom. The overall mechanism is illustrated in

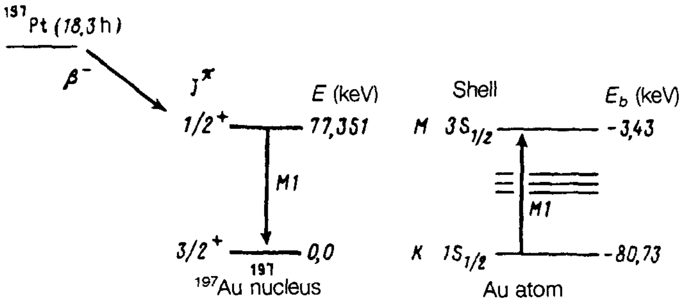

FIG. 1.

Fig. 1. A sample containing $^{197\text{m}}$Au isomers is subjected to x rays with energies sufficient to ionize the M_{I} shell of the gold atoms. The ionization opens up a new mechanism for the decay of the isomer $^{197\text{m}}$Au: one involving the process which is the inverse of NEET ("new" here means in addition to γ-ray emission and internal conversion). As the nucleus decays (with the result that the electron goes from the K shell to the M_{I} shell), a vacancy forms in the K shell. This vacancy decays, in a process involving the emission of characteristic x rays. The x rays can be detected experimentally. Let us calculate the probability for this mechanism.

A theory for NEET is set forth in detail in Refs. 3 and 4; a theory incorporating the dynamic effect of the final size of the nucleus is set forth in Refs. 5 and 6. Since the probabilities for the direct and inverse processes are related, we can immediately write the following expression for the probability W for the process of interest here, i.e., the inverse of NEET, where we are drawing on results from Refs. 3–6:

$$W=\Gamma_{M_I}\left\{\left(1+\frac{\Gamma_K}{\Gamma_{M_{\text{I}}}}\right)\frac{E^2_{\text{int}}(M1;\ e^-_K\to e^-_{M_I};\ N_{\text{is}}\to N_{\text{gr}}}{(\omega_N-\omega_A)^2+(\Gamma_M+\Gamma_K)^2/4}\right\}. \tag{1}$$

Here $\Gamma_{K,M_{\text{I}}}$ are the widths of the vacancies in the atomic levels in the initial state of the electron (in the K shell) and in the final state (in the M_{I} shell), ω_N and ω_A are the energies of the nuclear and $M1$ atomic transitions, respectively, the subscript "is" means the isomer state of the nucleus, and "gr" means the ground state of the nucleus. The quantity E^2_{int} in (1) is the square modulus of

$$H_{\text{int}}=\int d^3Rd^3rj^{\mu}_{K\to M_{\text{I}}}(\mathbf{r})D_{\mu\nu}(\omega_N;\ \mathbf{r}-\mathbf{R})J^{\nu}_{\text{is}\to\text{gr}}(\mathbf{R}),$$

the energy of the interaction of the electron current $j^{\mu}_{K\to M_{\text{I}}}(\mathbf{r})$ and the nuclear current $J^{\nu}_{\text{is}\to\text{gr}}(\mathbf{R})$ in second-order perturbation theory $[D_{\mu\nu}(\omega_N;\mathbf{r}-\mathbf{R})$ is the photon propagator], averaged over the initial states and summed over the final ones.[3] The integration in the expression for H_{int} is carried out over the regions $R<r$ and $R>r$. The region $R>r$ can contribute substantially to the interaction energy (this is the dynamic nuclear-volume effect) for l -forbidden nuclear $M1$ transitions and for $E1$ transitions which are forbidden in terms of asymptotic quantum numbers.

The expression in braces (curly brackets) in (1) is the relative probability for excitation of the atom in a nuclear transition, per vacancy in the M_{I} shell. We denote this probability by P. Using the relative probability for NEET (P_{NEET}) from Refs. 3–6, we can write the following obvious expression for this probability:

$$P=(\Gamma_K/\Gamma_{M_{\mathrm{I}}})[(2J_{\mathrm{gr}}+1)/(2J_{\mathrm{is}}+1)][(2j_{M_{\mathrm{I}}}+1)/(2j_K+1)]P_{\mathrm{NEET}}.$$

Here J and j are the total angular momenta of the nuclear and electronic states, respectively.

Using the widths of vacancies in atomic shells from Ref. 7, along with the relative probabilities P_{NEET} from Ref. 6, we find some values for W. For ^{197}Au we find $W=1.4\times10^{-5}$ eV (here we are using a system of units with $\hbar=c=1$), if there is no anomaly in the l -forbidden nuclear $M1$ transition shown in Fig. 1; $W=1.3\times10^{-5}$ eV if there is an anomaly and if we use the penetration parameter $\lambda^{(0)}=1.8$ from the experiments of Ref. 8 (this value of W corresponds to a new lifetime for the isomer level, $T_{1/2}=3.28\times10^{-11}$ s); and $W=1.2\times10^{-5}$ eV ($T_{1/2}=3.83\times10^{-11}$ s) with $\lambda^{(0)}=3.4$ from the experiments of Ref. 9. For ^{193}Ir we find $W=6.7\times10^{-7}$ eV ($T_{1/2}=6.86\times10^{-10}$ s) in the absence of an anomaly and $W=4.9\times10^{-7}$ eV ($T_{1/2}=9.34\times10^{-10}$ s) for a penetration parameter $\lambda^{(0)}=9.7$, as predicted theoretically in Ref. 10 (there are no corresponding experimental data).

Under ordinary conditions, the lifetime of the isomer state in ^{197}Au indicated in Fig. 1 is[11] 1.91×10^{-9} s. When there is a vacancy in the M_{I} shell, the probability for the decay of the $1/2^+$ (77.351 keV) isomer level in ^{197}Au increases by a factor of more than 50. Furthermore, it depends on the magnitude of the anomaly, on which there are conflicting experimental data.[8,9]

The same comments apply to the nucleus ^{193}Ir. A calculation for the mechanism which is the inverse for NEET reduces the lifetime of the $1/2^{\,+}$ (73.041 keV) state by a factor of several units. Under ordinary conditions, this lifetime is 6.09×10^{-9} s.

Finally, a vacancy in an M_{I} shell tends to decay by its own ordinary mechanisms, such as x-ray emission and the Auger process. The relative probability P for excitation of the atom in a nuclear transition, accompanied by the formation of a hole in the M_{I} shell, is therefore small. Nevertheless, the value $P\approx0.6\times10^{-6}$ for gold-197 appears to be measurable.

An experimental test of NEET has, as we know, proved to be an extremely involved matter.[3,12] It might be more fruitful to study the inverse process in synchrotron-radiation experiments of the type described in Ref. 13 or in plasma experiments of the type described in Ref. 14 (with the distinction, of course, that now it is the "upper" atomic shell that must be ionized).

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