Resonant electronic-bridge process of the isomeric transition of ^{235m}U induced by intense laser fields

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The effect of intense laser fields on the resonant electronic-bridge process involving the isomeric $E3$ transition of ^{235m}U, which has a photon energy of 73.5 eV, and an intermediate excitation of an electron from the $P1(6s_{1/2})$ electronic shell of binding energy 71 eV is investigated for lasers of photon energies 1.16 and 2.32 eV within the intensity range 10^{10}–10^{13} W/cm^2. It is found that in spite of the hindering effect of power broadening, the ratio η of the transition probability per unit time in the laser-assisted process to that of the laser-free γ decay can be enhanced by the intense laser field if the resonance condition is met.

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In a recent article [1] it was theoretically shown that the electronic-bridge process observed in 1985 [2] can be influenced by intense laser field. In this paper a special case of the resonant laser-assisted electronic-bridge process will be discussed. It can take place if an electron of an atom that contains an isomeric nucleus, after absorbing the γ photon released from the nucleus, emits a number of laser photons, reaches resonantly the energy of an intermediate electronic state, and finally decays by x-ray emission. A schematic diagram of the mechanism is given in Fig. 1.

The process to be discussed here consists of the isomeric $E3$ transition of a ^{355m}U, which has a photon energy 73.5 eV, an ensuing excitation of an electron of the $P1(6s_{1/2})$ electronic shell of binding energy 71 eV, and an emission of an x-ray photon the energy of which differs from that of the γ photon by an integer multiple of the laser photon energies [3]. Considering that the complex electronic structure of the U atom is described in such a one-electron approximation that neglects the splitting of shells of definite principal quantum number, it can also be supposed that there exists an intermediate state of U of binding energy 2.14 eV which is resonant to the emission of four laser photons of energy 1.16 eV or to the emission of two laser photons of energy 2.32 eV. The assumed magnitude of energy of the intermediate state is not too crucial since the phenomenon is much less sensitive to a small change in the laser photon energy than to a change of the order of resonance (the number of laser photons necessary to the resonance).

The ratio $\eta = W_{fi}^{\text{las}}/W_{fi}^{\text{spont}}$ of the yield W_{fi}^{las} of the laser-assisted, resonant electronic-bridge mechanism to the yield W_{fi}^{spont} of the spontaneous γ decay [4] as it was introduced in Ref. [1] can be given in the following form:

$$\eta = \frac{2[(2L-1)!!]^2 e^2}{9(L+1)(2L+1)} \frac{|J_{nk}|^2 |I_{L,nk}|^2}{\Delta^2 + (\hbar\gamma_n/2)^2} \left[\frac{c}{\omega_{ab}} \right]^{2L-2} F \ . \quad (1)$$

In the denominator $\Delta = \hbar(\omega_{ab} - N\omega - \omega_{n0})$ is the detuning, $\hbar\gamma_n = \hbar\gamma_{n0} + \hbar\gamma_{nf}$, $\hbar\gamma_{n0}$ is the natural linewidth of the state of principal quantum number n in the laser-field-free case and $\hbar\gamma_{nf}$ is the laser field contribution to the power broadened linewidth, $\omega_{ab} = \varepsilon_a - \varepsilon_b$, $\omega_{n0} = \varepsilon_n - \varepsilon_0$ where $E_a = \hbar\varepsilon_a$, $E_b = \hbar\varepsilon_b$ are the energies of the initial and final nuclear states, $E_n = \hbar\varepsilon_n$, $E_0 = \hbar\varepsilon_0$ are the energies of the intermediate and initial electronic states, respectively, and N is the number of emitted laser photons, necessary to fulfill the resonance condition. L is the multipolarity of the γ transition. Quantities J_{nk} and $I_{L,nk}$ depend on the electronic states concerned:

$$J_{nk} = \int R_{k0}(Z_{\text{eff}}(k), r) R_{n1}(Z_{\text{eff}}(n), r) r^3 dr \ , \quad (2)$$

$$I_{L,nk} = \int R_{k0}(Z_{\text{eff}}(k), r) R_{nL}(Z_{\text{eff}}(n), r) r^{1-L} dr \ , \quad (3)$$

with $R_{k0}(r)$, $R_{n1}(r)$, and $R_{nL}(r)$ as the radial parts of hydrogen-type solutions of principal quantum numbers k,n and orbital angular momentum quantum numbers $l=0$, $l=1$, and $l=L=3$, respectively. The different effective nuclear charges $Z_{\text{eff}}(k)$, $Z_{\text{eff}}(n)$ of states of different principal quantum numbers are to account for the shielding effect of other electrons of the atom in the

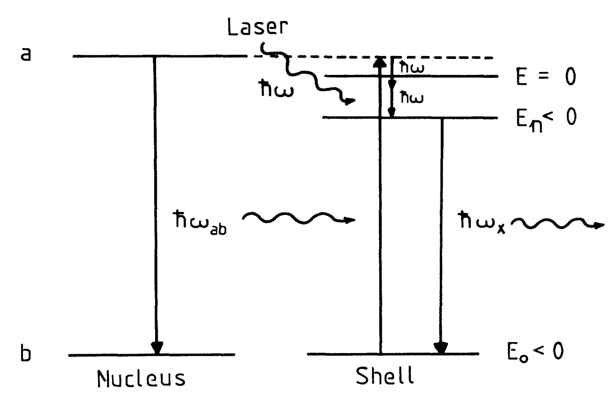

FIG. 1. Schematic diagram of the resonant laser-assisted electronic-bridge process. $\hbar\omega_{ab}$, $\hbar\omega_x$, and $\hbar\omega$ are the energies of the γ transition, the emitted x-ray photon, and the laser photon, respectively.

one-electron approximation.

The last factor F in Eq. (1) resolves in a sum that lends it a channel-like structure:

$$F=\sum_K f_K \tag{4}$$

and

$$f_K=\left[\frac{\omega_{xK}}{\omega_{ab}}\right]^3 F_K \tag{5}$$

with $\hbar\omega_{xK}=\hbar(\omega_{ab}-N\omega+K\omega)$ standing for the energy of the outcoming x-ray photon, K the channel number, and

$$F_K=\sum_m \left[\sum_{\mu_1,\mu_2} \langle 1m|\mu_1\mu_2\rangle\langle Lm|\mu_1\mu_2\rangle \times J_K(\lambda_{n_1n_2})J_N(\lambda_{n_1n_2})\right]^2 . \tag{6}$$

In F_K $\langle 1m|\mu_1\mu_2\rangle$ and $\langle LM|\mu_1\mu_2\rangle$ represent Clebsch-Gordan coefficients $\langle 1m|[(n-1)/2]\mu_1[(n-1)/2]\mu_2\rangle$ and $\langle Lm|[(n-1)/2]\mu_1[(n-1)/2]\mu_2\rangle$ with $\mu_1=(m+n_1-n_2)/2$ and $\mu_2=(m-n_1+n_2)/2$ [5]. L is determined by the nuclear transition to be equal to $(L=)3$ in our case. The argument λ of the Bessel functions of the first kind, J_N and J_K is

$$\lambda_{n_1n_2}=\frac{\frac{3}{2}n(n_1-n_2)E_0ea_B}{Z_{\text{eff}}\hbar\omega} . \tag{7}$$

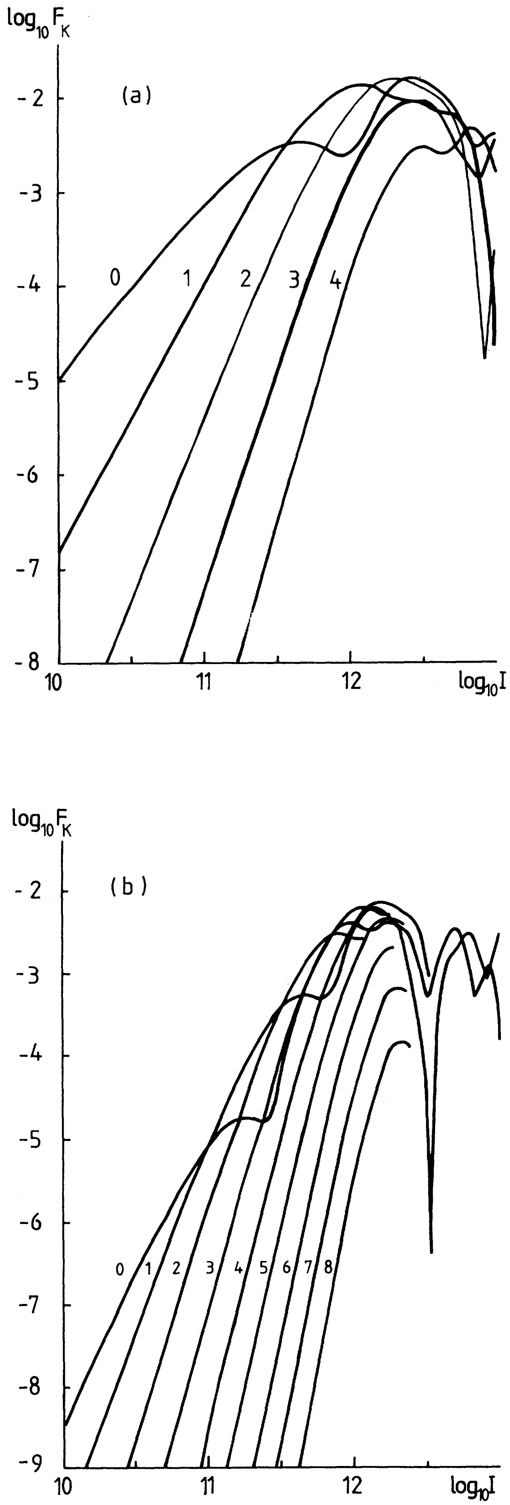

FIG. 2. $\log_{10} F_K$ vs $\log_{10} I$ ($\log_{10}$ is the logarithm to the base 10) from Eq. (6) with laser intensity I measured in W/cm^2. (a) Two photonic case ($\hbar$=2.32 eV), (b) Four photonic case ($\hbar\omega$=1.16 eV). Curves in both figures are numbered according to K. Curves of $K>1$ in (b) turned out to have very complex tails at higher intensities that defy illustration. Since they do not carry much information they are omitted.

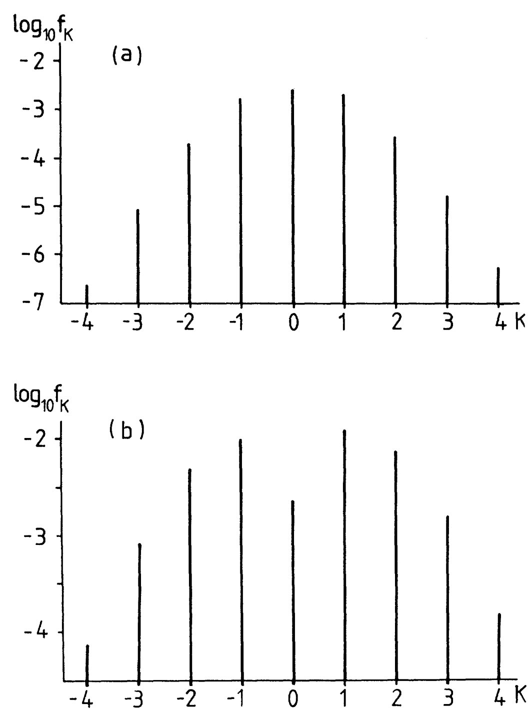

FIG. 3. $\log_{10} f_K$ vs K from Eq. (5). (a) and (b) are indicative of the different channel structure of f_K at laser intensities $I=10^{11.5}$ and 10^2 W/cm^2.

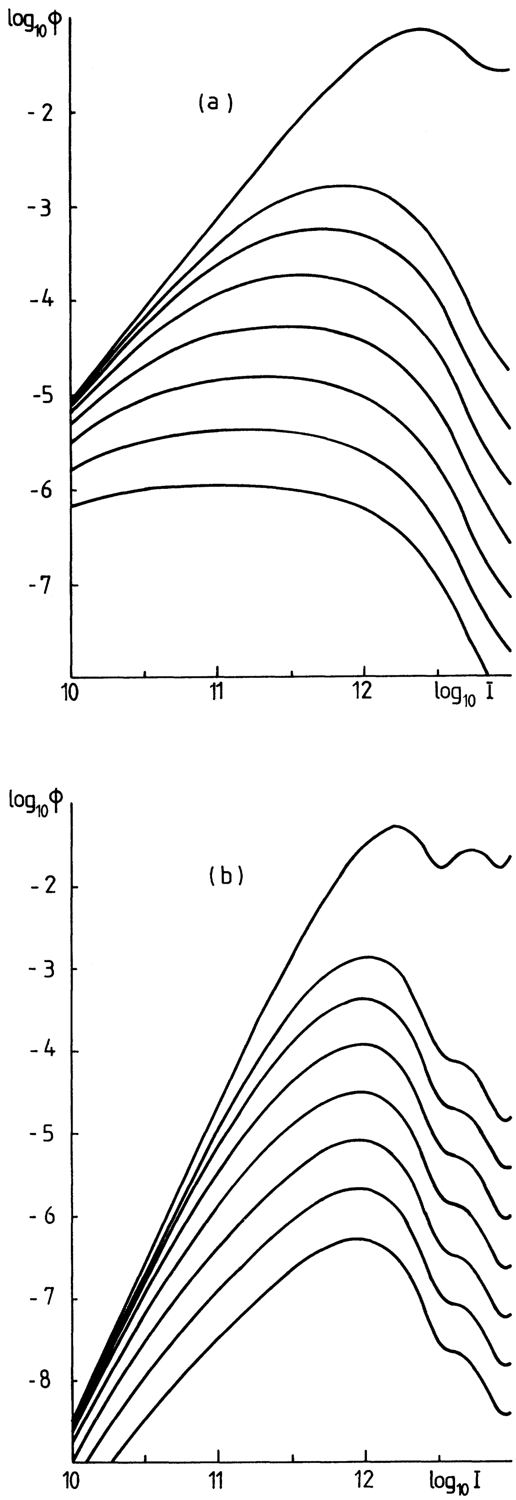

FIG. 4. $\log_{10}\Phi$ vs $\log_{10}I$ from Eq. (10) with laser intensity I measured in W/cm^2. (a) Two photonic case ($\hbar\omega=2.32$ eV). (b) Four photonic case ($\hbar\omega=1.16$ eV). The curves running from top to bottom correspond to the following values of α_n. $\alpha_n=0$; 0.031 25; 0.0625; 0.125; 0.25; 0.5; 1; and 2. (α_n is measured in 10^{-24} cm^3 units.) Accordingly, the uppermost curve gives F of Eq. (4). Since η is a multiple of Φ these curves also represent η.

Again n is the principal quantum number of the subshell, $n=n_1+n_2+|m|+1$, m is the magnetic quantum number, and n_1 and n_2 are the parabolic quantum numbers. E_0 is the amplitude of the laser field strength and a_B is the Bohr radius.

We are interested in the resonance case, i.e., $\Delta=0$, where the role of the power broadening may be important [6]. To illustrate this in a more explicit way Eq. (1) can be rewritten as

$$\eta=\eta_0\Phi(I)\ , \tag{8}$$

where

$$\eta_0=\frac{2[(2L-1)!!]^2e^2}{9(L+1)(2L+1)}\frac{|J_{nk}|^2|I_{L,nk}|^2}{\Delta^2+(\hbar\gamma_{n0}/2)^2}\left[\frac{c}{\omega_{ab}}\right]^{2L-2} \tag{9}$$

and

$$\Phi(I)=\{1+[\hbar\gamma_{nf}(I)/\hbar\gamma_{n0}]^2\}^{-1}F\ . \tag{10}$$

From Ref. [7] the laser-intensity-dependent part of the broadened linewidth can be given in the form

$$\hbar\gamma_{nf}(I)=1.31\times10^{-15}\alpha_n I \tag{11}$$

where I is the intensity of the laser in W/cm^2 and

$$\alpha_n=\frac{2\omega}{\hbar}\sum_j\frac{|\langle\varphi_n|-e\mathbf{r}\cdot\mathbf{e}_0|\varphi_j\rangle|^2}{\omega_{nj}^2-\omega^2} \tag{12}$$

is measured, similarly to the atomic polarizability, in 10^{-24} cm^3 units.

The numerical results for ^{235m}U based on the above formulas are presented in Figs. 2–4. The laser photon energies were 1.16 and 2.32 eV and the intensities ranged from 10^{10} to 10^{13} W/cm^2. The yield of the outcoming x-ray photons in the Kth channel is proportional to f_K. Since f_K is expressed with F_K, which is invariant to the change of sign of K, it is the functions $\log_{10}F_K$ versus $\log_{10}I$ which are plotted for the two and four photonic cases in Figs. 2(a) and 2(b). Figures 3(a) and 3(b) give $\log_{10}f_K$ versus K at two laser intensities for the case of two photonic resonance and are illustrative of the relative yields of the channels. In order to bring out the role of power broadening in the resonant, laser-assisted electronic-bridge mechanism it is instructive to plot the behavior of Φ for a range of α_n [Figs. 4(a) and 4(b)] [8] where the uppermost curve corresponds to $\alpha_n=0$, i.e., $\Phi=F$. As η and Φ differ by the constant factor η_0 the curves in Figs. 4(a) and 4(b) represent η too.

In order to be able to obtain numerical values for η the quantity η_0 given by Eq. (9) was also determined. From the binding energies of the electronic shells $Z_{\text{eff}}(6)=13.71$ and $Z_{\text{eff}}(8)=3.173$ for the initial ($k=6$) and intermediate ($n=8$) states, respectively. With these values $I_{3,86}=4.4\times10^{-5}a_B^{-4}$ and $J_{86}=-0.51a_B$; furthermore, $\hbar\gamma_n/2=5.3\times10^{-6}$ eV, which is estimated from the width of a $2p$-$1s$ transition of the same energy [9]. Thus $\eta_0=1.6\times10^9$.

It is known about multiphoton processes that the laser intensity dependence of their yield shows a power-law behavior at lower intensities whereas at higher intensities it saturates. Accordingly, these properties appear prominently in Figs. 2(a) and 2(b) and in the top curves of Figs. 4(a) and 4(b). Also, similarly to the observations obtained for above-threshold phenomena in multiphoton ionization [10], the yield of channel $K=0$ is relatively depressed by higher channels when the intensity grows (see Fig. 3).

Although Fig. 4 indicates that power broadening has a strong hindering effect, η_0 being a large number the ratio η can still remain significant for reasonably conceivable values of α_n. As calculations were made with realistic laser parameters that are available today it can be expected that the effect is accessible to experimental survey.

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