Induced neutron capture by nuclei in a laser radiation field

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An expression is obtained for the intensity of the high-frequency electric field which appears in the nucleus as a result of the resonant excitation of the electron cloud of an atom by a laser field. The induced capture cross section of a neutron by the nucleus in this field is calculated at a weakly bound level of a compound nucleus. It is pointed out that the induced neutron capture effect makes spectroscopic studies of these levels possible.

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In heavy nuclei the density of levels of a compound nucleus near the neutron binding is quite high ($\sim 10^6$ MeV). Therefore the value of the interaction cross section of thermal neutrons with heavy nuclei is determined in many cases by the S-level,

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which lies below the neutron binding energy ("negative level"). Almost nothing at all is known about the properties of the negative p-levels, which lie near the neutron binding energy.

A method is proposed in this paper for studying the negative p-levels of a compound nucleus, lying within an energy interval of the order of a few eV from the neutron binding energy.

Let us consider a medium, the atoms of which are excited by an external laser field. If the frequency ω of the field is near the frequency $\mathring{\omega}$ of the atomic transition, then in the saturated state the wave function of the atoms can be written in the form[1] $(\hbar = c = 1)$

$$\psi(\vec{\rho}, t) = e^{i\epsilon t/2}\phi_0(\vec{\rho})\left(\cos\Omega t - i\frac{\epsilon}{2\Omega}\sin\Omega t\right) - i\frac{V_{10}}{\Omega}e^{-i\epsilon t/2}\sin\Omega t\,\phi_1(\rho)$$
$$\times e^{-i\mathring{\omega}t}, \quad \Omega = (\epsilon^2/4 + |V_{10}|^2)^{1/2}, \tag{1}$$

where $\phi_0(\vec{\rho})$ and $\phi_1(\vec{\rho})$ are the stationary wave functions of the ground and excited states of the atom, $\omega = \mathring{\omega} + \epsilon$, $V_{10} = \mathbf{d}_{10}\mathbf{E}_0$, $\mathbf{E}_0$, is the amplitude of the electric field intensity of the laser, $\mathbf{d}_{10}$ is a matrix element of the dipole transition between stationary states.

Using (1), we obtain an expression for the charge density $n(\vec{\rho},t)$ and the current $\mathbf{j}(\vec{\rho},t)$ of the transition in the atom, arising as a result of the action of the external electromagnetic field.[2] The density and current, excited by the external electromagnetic field, create a varying electromagnetic field inside the atom. Ignoring delay, we obtain an expression for the intensity of the high-frequency electric field at the nucleus $(\omega \gg \Omega,\ \epsilon = 0)$

$$E(\mathbf{r}, t) = E_0(\mathbf{r}, t)f(t) = \frac{V_{10}}{\Omega}\int d\vec{\rho}\,\frac{\vec{\rho}}{|\vec{\rho}|}\,\phi_1^*\phi_0\sin 2\Omega t\sin\omega t\,. \tag{2}$$

Let us consider the capture, induced by the high-frequency intra-atomic field (2), of thermal neutrons in a negative level of p-parity, the binding energy of which lies in the optical band. In the center of inertia system the Hamiltonian of the interaction of the neutron with the laser-induced high-frequency field (2) can be represented in the form

$$\hat{V} = e_{\text{eff}}\ \mathbf{r}_n\mathbf{E}(\mathbf{r}_n, t), \tag{3}$$

where $e_{\text{eff}} = eZ/A + 1$ is the effective neutron charge in the center of nucleus + neutron system; $\mathbf{r}_n$ is the relative coordinate of the neutron; $\mathbf{E}(\mathbf{r}_n, t)$ is the intensity of the induced electric field (3) at the site of the neutron.

We will use the Heitler method[3] to calculate the cross section of nuclear reactions caused by the induced capture of a neutron in a negative level of a compound nucleus.

For the Fourier transform of the amplitude of the nuclear reaction, proceeding from a given negative level, we obtain the following expression

$$U_\nu(E) = \frac{V_{n\mathrm{p}} H_{n\nu}}{E - E_n - \omega + i\Gamma_{n\mathrm{p}}/2 + \gamma/2},$$

$$\gamma = 2\pi \sum_\nu |H_{n\nu}|^2 \delta(\epsilon_\mathrm{p} - E_\nu), \tag{4}$$

where $H_{n\nu}$ is the matrix element of the spontaneous decay of the negative level along any channel, for example, the emission of a γ quantum, fission, etc., γ is the total spontaneous width of the negative level, determining the splitting rate of this state into a continuous spectrum due to the action of the external electromagnetic field, $\Gamma_{n\mathrm{p}}$ is defined by the expression

$$\Gamma_{n\mathrm{p}} = 2\pi \sum_{\mathrm{p}'} |V_{n\mathrm{p}'}|^2 \delta(E_n - \epsilon_{\mathrm{p}'}). \tag{5}$$

Here $V_{n\mathrm{p}}$ is the matrix element of the Hamiltonian of the interaction of the neutron with the laser-induced high-frequency field

$$V_{n\mathrm{p}'} = e_{\mathrm{eff}} \int \Phi_n^* \mathbf{r}_n \mathbf{E}_o(\mathbf{r}_n) \phi_{p'} d\mathbf{r}_n . \tag{6}$$

Then, following the usual method, we write the expression for the cross section in the ν channel:

$$\sigma(\epsilon_\mathrm{p}) = \frac{2\pi}{\hbar} \sqrt{\frac{m}{2\epsilon_\mathrm{p}}} \sum_\nu |U_\nu(\epsilon_\mathrm{p})|^2 \delta(E_\nu - \epsilon_\mathrm{p})$$

$$= g\pi\lambda\!\!\!^{-2} \frac{\Gamma_{n\mathrm{p}}\gamma}{(\epsilon_\mathrm{p} - \hbar\omega + |E_n|)^2 + (\Gamma_{n\mathrm{p}} + \gamma)^2/4}, \tag{7}$$

where $\lambda\!\!\!^- = \hbar/\sqrt{2\pi\epsilon_\mathrm{p}}$ is the wavelength of the neutron. In order to calculate the width $\Gamma_{n\mathrm{p}'}$, which arises in the induced electromagnetic field, we write the matrix element $V_{n\mathrm{p}}$, in the form

$$V_{n\mathrm{p}} = e_{\mathrm{eff}} E_o(0) < \Phi_n^* | Z_n | \phi_\mathrm{p} > = \frac{e_{\mathrm{eff}} E_o(0)}{\sqrt{3}\omega^2} < \Phi_n^* | \ddot{r}_n | \phi_\mathrm{p} >$$

$$= - \frac{e_{\mathrm{eff}} E_o(0)}{\sqrt{3}\omega^2 M} < \Phi_n^* | \frac{\partial U}{\partial r} | \phi_\mathrm{p} >, \tag{8}$$

where $\Phi_n^*(\mathbf{r}_n)$ is the wave function of the bound state of the compound nucleus, $\phi_\mathrm{p}(\mathbf{r}_n) = \sin(kr + \delta_0)/kr$, s is a wave in the continuous neutron spectrum, $U(r)$ is the potential for a nucleon in the nucleus. To evaluate (8) let us make use of the rectangular well model. In this model we have

$$\frac{\partial U}{\partial r} = - U_o \delta(r - R), \tag{9}$$

Here U_0 is the effective depth of the well, R is the radius of the nucleus.

Substituting (9) into (8), we obtain

$$V_{np} \approx -e_{\text{eff}}\ E_0(0)\frac{U_0}{\sqrt{3}\,M\omega^2}\ C_n^*\phi_n^*(R)\sin(kR+\delta_0)\ R/k, \tag{10}$$

where C_n is the amplitude of the one-particle component in the wave function of the compound nucleus; $\phi_n(R)$ is the one-particle wave function. The value of $C_n^*\phi_n(R)$ at the surface of the nucleus can be estimated from the expression for the average neutron width

$$\bar{\Gamma}_n \approx p_n(E_n)\hbar v_F R^2|C_n|^2|\phi_n(R)|^2, \tag{11}$$

where v_F is the velocity of the particles on the Fermi surface, $p(E_n)\cong 4(|E_n|/U_0)^{1/2}$ is the dielectric constant for a neutron with energy $|E_n|$ in a potential well of depth U_0. Using (10), we obtain $(U_0-\epsilon_F \ll U_0)$

$$\Gamma_{np} \approx \frac{e^2_{\text{eff}}\ E_0^2(0)U_0^2}{12(\hbar\omega)^4}\ \bar{\Gamma}_n(R+\delta)^2\sqrt{\frac{|E_n|}{1\,\text{eV}}} \tag{12}$$

for $\epsilon_p \sim 0.025$ eV, $|E_n|\sim 1$ eV, $\bar{\Gamma}_n \sim 10^{-4}$ eV and $(R+\delta)^2 \sim (0.3R)^2$ the numerical estimate of the width is $\Gamma_{np}\sim e^2E_0^2(0)\times 10^{-17}$ eV. We estimate the intensity value of the induced electric field at the nucleus from the formula (3). For atoms with $Z\sim 100$ and an ionization potential $I_0 \sim 5$ eV $E_0(0) \lesssim 10^8$ V/cm. Therefore we obtain a value of the order of ~ 0.1 eV for the field width. The expression (7) for the cross section must be averaged over the initial neutron energy distribution

$$\bar{\sigma} = \frac{2}{\sqrt{\pi (kT)^3}}\int_\infty^0 d\epsilon\sqrt{\epsilon}\,\sigma(\epsilon)\ e^{-\epsilon/kT}. \tag{13}$$

The integral in (13) is simplified in the following limiting cases:

1) resonance is not achieved $(|E_n|-\omega)/kT \gg 1$, then

$$\bar{\sigma} \approx g\sqrt{2\pi}\,\lambda_T^2\frac{\gamma\Gamma_{np}}{(|E_n|-\omega)^2+(\Gamma_{np}+\gamma)^2/4} \tag{14}$$

2) resonance is achieved $(|E_n|-\omega)/kT\sim 0$, $(\Gamma_{np}+\gamma)/kT \ll 1$ and

$$\bar{\sigma} \approx g(2\pi)^{3/2}\,\lambda_T^2\, e^{-\frac{||E_n|-\omega|}{kT}}\ \frac{\gamma\Gamma_{np}}{kT(\Gamma_{np}+\gamma)} \tag{15}$$

and if $\Gamma_{np}+\gamma \gg kT$

$$\bar{\sigma} \approx g\sqrt{2\pi}\,\lambda_T^2\frac{\gamma\Gamma_{np}}{(\Gamma_{np}+\gamma)^2} \tag{16}$$

here $\lambda\!\!\!^{-}_T = \hbar\sqrt{2mkT}$. If the electron transition frequency corresponds to the resonance case and the level width of the compound nucleus ($\sim$0.1 eV)$\gamma \gg kT$, then the average cross section is described by (16). Then, in accordance with (12), the average cross section value can turn out to be close to $\lambda\!\!\!^{-}{}^2_T$.

The weakly bound S-levels of a compound nucleus (with a binding energy of $\sim$1 eV) appear in the interaction cross section of thermal neutrons with nuclei in the vicinity of the rare earths and actinides (for example, in U^{235}). The density of the p-levels of a compound nucleus is three times greater than for the S-levels. Therefore the existence of the weakly bound p-levels of a compound nucleus, which can be excited by means of the process considered above, is extremely probable for the lanthanides and actinides.

Thus, spectroscopy of the negative levels of a compound nucleus is possible in the case of resonance excitation of the electron cloud of appropriate atoms. Neutron capture in the negative levels should be accompanied by a considerable increase in the cross section values of elastic and inelastic interactions of thermal neutrons with the nuclei of the atoms.

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