Nuclear reactions in a laser-radiation field

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Induced nuclear reactions (inelastic scattering and compound nucleus formation) in the presence of a strong electromagnetic field are considered for s neutrons near p resonances of the compound nucleus. Expressions are obtained for the cross sections as functions of the resonance parameters and the laser-radiation power. The feasibility of observing induced nuclear reactions is discussed.

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INTRODUCTION

Induced transitions in collisions of ordinary[1] and exotic[2] atoms in the field of a strong electromagnetic wave have been discussed in the literature.[1,2] It has been shown that processes that are forbidden or occur with low probability in collisions of free atoms or ions may have large cross sections in the presence of sufficiently intense laser radiation. In collision theory, such processes have come to be called "radiation collisions."

The mechanism of nuclear reactions is of course different from that of atomic collisions. But in this case, too, we may ask whether a strong electromagnetic field might not affect the cross sections for collisions of nuclear particles, e.g., for neutron-nucleus collisions. The radiative capture of a neutron by a nucleus is a well investigated nuclear reaction.[3] As a rule, however, this reaction is accompanied by the spontaneous emission of hard photons with energies of the order of 1 MeV or higher. The probability for the spontaneous emission of optical quanta in the radiative capture of a neutron is low. Nevertheless, the induced capture of a neutron with transition of the neutron + nucleus system from the continuum to a weakly-bound compound-nucleus level (free-bound transitions) is possible in a sufficiently intense laser field.[4] Our earlier estimates[4] of the cross sections for induced capture of a neutron by a nucleus, however, showed that not every level of the compound nucleus can be excited in the presence of an external laser field of moderate intensity. If the neutron width of the level corresponds to optical-model estimates, the laser power necessary for observing induced capture should be so high as to be achievable only in very short ($\sim 10^{-9}$ sec) pulses.

Because of the Porter-Thomas fluctuations, the neutron widths of the compound-nucleus levels may actually differ substantially from the average values predicted by the optical model. The observed p levels of the compound nucleus in the region of neutron-resonance energies have anomalously large neutron widths. To clarify the actual possibility of observing induced excitation of p levels of the compound nucleus, therefore, it is necessary:

a) to generalize the theory to the case of an induced transition of the neutron + nucleus system from an s state of the continuum to a final p state of the compound nucleus that also lies in the continuum (free-free transitions); and

b) to estimate the intensity of the laser radiation necessary for observing the induced capture of a neutron by a nucleus for known p levels of the compound nucleus in the region of neutron-resonance energies (<1 keV).

Both these problems are solved in this paper.

1. INDUCED TRANSITIONS OF THE NEUTRON + NUCLEUS SYSTEM IN THE CONTINUUM

In an external electromagnetic field, the neutron + nucleus system may undergo a transition from a continuum s state to a p state with the emission (or absorption) of a field quantum. As a result, the energy of the system must change by an amount equal to the energy $\hbar\omega$ of a field quantum (~1 eV for the optical region), i.e., the neutron is scattered inelastically. If the energy of the final p state of the system is close enough to that of a compound-nucleus level whose neutron width is sufficiently large, then, other conditions being equal, the inelastic scattering cross section must increase. Let us examine this process in more detail.

The effective charge e_{eff} for electric dipole transitions of the neutron + nucleus system is[3]

$$e_{\text{eff}}=\frac{Z}{A+1}e, \tag{1}$$

where A is the mass number of the target nucleus and Ze is its charge. In the dipole approximation, the potential for the interaction of the neutron + nucleus system with the external electromagnetic field has the form

$$V=-e_{\text{eff}}\mathbf{r}_n\mathbf{E}(\mathbf{r}_n, t), \tag{2}$$

where $\mathbf{r}_n$ is the relative coordinate and $\mathbf{E}(\mathbf{r}_n, t)$ is the strength of the electric component of the electromagnetic field

$$\mathbf{E}=\mathbf{E}_0\cos(\omega t-\mathbf{k}\mathbf{r}_n). \tag{3}$$

We may use perturbation theory to find the cross section for inelastic scattering with transition of the neutron from an initial state of energy ε_p to a state of energy $\varepsilon_p \pm \hbar\omega$. Then the cross section for inelastic scattering of a neutron by a nucleus in the field of wave (3) can be written in the form

$$d\sigma_{np}=\frac{2\pi m}{\hbar^2 k_0}\sum_1 |V_{01}|^2\delta(\varepsilon_p\mp\hbar\omega-E_1), \tag{4}$$

where $k_0=(2m\varepsilon_p)^{1/2}/\hbar$ is the wave vector of the incident neutron, the sign $\sum_1$ indicates summation over the final states, and

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$$V_{01}={}^1/_2 e_{\rm eff}(\varphi_0^* \mathbf{E}_0 \mathbf{r} \varphi_1)$$

is the matrix element, φ_0 and φ_1 being the initial- and final-state wave functions.

In treating the scattering of slow neutrons by nuclei, we need consider only the s wave in the initial state. We shall assume that the target nucleus has zero spin; then the wave function for the initial state in the region $r_n > R$ (R is the nuclear radius) will have the form

$$\varphi_0=e^{i\delta_0}(j_0(\zeta_0)\cos\delta_0-\eta_0(\zeta_0)\sin\delta_0), \tag{5}$$

where δ_0 is the s-wave phase shift, $\zeta=k_0 r_n$, and j_0 and η_0 are the zeroth-order spherical Bessel and Neumann functions. The wave function for the scattered neutron, which is in a p state (for simplicity we treat the neutron as a spinless particle), is

$$\varphi_1=3ie^{i\delta_1}(j_1(\zeta_1)\cos\delta_1-\eta_1(\zeta_1)\sin\delta_1)P_1(\cos\theta), \quad r_n>R, \tag{6}$$

where $\zeta_1=k_1 r_n$, $P_1(\cos\theta)$ is the Legendre polynomial of first degree, δ_1 is the p-wave phase shift, θ is the angle between $\mathbf{k}_1$ and $\mathbf{r}_n$, and j_1 and η_1 are the first-order spherical Bessel and Neumann functions. The p-wave phase shift near the compound-nucleus level is given by[5]

$$\exp(2i\delta_1)=\exp(2i\delta_{\rm pot})\left(1-\frac{i\Gamma_n}{E_1-E_n+i\Gamma/2}\right), \tag{7}$$

where Γ_n, Γ, and E_n are the neutron elastic width, the total width, and the energy of the resonance, respectively, E_1 is the neutron energy, and $\delta_{\rm pot}$ is the p-wave potential-scattering phase shift. We use (2), (5), and (6) to calculate the matrix element

$$V_{10}=e_{\rm eff}(E_0/2)\int d\mathbf{r}_n\, \varphi_0^* r_n \cos\theta' \varphi_1, \tag{8}$$

where θ' is the angle between $\mathbf{r}_n$ and $\mathbf{E}_0$, which may be easily expressed in terms of the angle θ and the angle θ_0 between $\mathbf{k}_1$ and $\mathbf{E}_0$:

$$\cos\theta'=\cos\theta\cos\theta_0+\sin\theta\sin\theta_0\cos(\varphi-\varphi_0). \tag{9}$$

Employing a well-known theorem of quantum mechanics[5] $[(\ddot{r})_{01}=\omega^2(r)_{01}=(\partial U/\partial r)_{01}]$, we obtain

$$V_{01}=\frac{e_{\rm eff}E_0}{2\omega^2}\int d\mathbf{r}_n \ddot{r}_n \varphi_0^* \varphi_1 \cos\theta' = \frac{e_{\rm eff}E_0}{2m\omega^2}\int d\mathbf{r}_n \frac{\partial U}{\partial r_n}\cos\theta' \varphi_0^* \varphi_1, \tag{10}$$

in which $U(r_n)$ is the effective nuclear potential for the neutron. For estimates we shall represent this potential by a square well; then

$$\partial U/\partial r_n=-U_0\delta(r_n-R), \tag{11}$$

where U_0 is the depth of the well. After integrating and taking Eqs. (5), (6), (8), (9), and (11) into account, Eq. (10) takes the form

$$V_{01}=i2\pi e_{\rm eff}E_0 U_0 \varphi_0^*(k_0 R)\varphi_1(k_1 R)R^2/m\omega^2. \tag{12}$$

The conditions $k_0 R \ll 1$ and $k_1 R \ll 1$ are always satisfied for slow neutrons, and we may also assume that $\delta_{0,1} \ll 1$; hence, by expanding (12) in the appropriate way and neglecting potential scattering, we obtain an expression for the cross section in the form

$$\frac{d\sigma_{np}}{d\Omega}=\frac{3}{4}k_0^2\frac{\Gamma_{np}\Gamma_n}{(\varepsilon_p\pm\hbar\omega-E_n)^2+\Gamma^2/4}\cos^2\theta_0, \tag{13}$$

where Γ_{np} is given by

$$\Gamma_{np}=\frac{1}{3}\frac{e_{\rm eff}E_0^2}{(\hbar\omega)^2}\left(\frac{U_0}{\hbar\omega}\right)^2\left(R-\frac{\delta_0}{k_0}\right)^2\Gamma_n(\varepsilon_p)^{1/2}; \tag{14}$$

TABLE I. Induced neutron capture cross sections.

Isotope	E_n, eV	ε_p, eV	R, Fm	a, Fm	Γ_n, eV	$\overline{\Gamma}_n$, eV	$\hbar\omega$, eV	Γ, eV	$\Gamma_{np}e^{-2}E_0^{-2}$, cm²/eV	$\sigma_c e^{-2}E_0^{-2}/\sigma^0_{max}$, cm²/eV²
Mo^{98}	12.1	12.1 ±1	5.6	7	$0.6\cdot10^{-4}$	0.69	1	0.125	$9.4\cdot10^{-12}$	$1.6\cdot10^{-7}$
Th^{232}	8.35	8.35±1	7.4	9.65	$2.3\cdot10^{-7}$	$3\cdot10^{-3}$	1	0.03	$8.0\cdot10^{-14}$	$3.5\cdot10^{-7}$
U^{238}	4.41	4.41±1	7.4	9.4	$1.11\cdot10^{-7}$	$3.5\cdot10^{-3}$	1	0.03	$5.4\cdot10^{-14}$	$4.8\cdot10^{-7}$
U^{238}	10.25	10.25±1	7.4	9.4	$1.6\cdot10^{-6}$	$1.4\cdot10^{-2}$	1	0.03	$3.5\cdot10^{-13}$	$2.2\cdot10^{-7}$
La^{139}	0.734	0.025	6.2	4.9	$7.3\cdot10^{-8}$	$6.3\cdot10^{-2}$	0.709	0.045	$1.4\cdot10^{-13}$	$2\cdot10^{-6}$
La^{139}	0.734	1.734	6.2	4.9	$7.3\cdot10^{-8}$	$6.3\cdot10^{-2}$	1	0.045	$3\cdot10^{-13}$	$4\cdot10^{-6}$

here ε_p is a dimensionless quantity ($\varepsilon_p \equiv \varepsilon_p/1$ eV), and Γ_n and $\overline{\Gamma}_n$ are the elastic and reduced neutron widths, respectively, of the p resonance of the compound nucleus. On integrating (13) over the angles we obtain the usual formula for resonant neutron scattering:

$$\sigma_{np}=\frac{\pi}{k_0^2}\frac{\Gamma_{np}\Gamma_n}{(\varepsilon_p\pm\hbar\omega-E_n)^2+\Gamma^2/4}. \tag{15}$$

It follows from Eq. (14) that Γ_{np}, and therefore also the cross section, is proportional to the power of the laser radiation. It should be emphasized that perturbation theory was used in deriving Eq. (15) and that Γ_{np} cannot be arbitrary ($\Gamma_{np} < \Gamma$). If all the parameters (Γ_n, Γ, E_n, and δ_1) of the p level of the compound nucleus are known, Γ_{np} can be estimated without difficulty. The total width Γ of the compound-nucleus level is determined, as a rule, by neutron elastic-scattering and radiative-capture processes. For the heaviest nuclei, we must add fission to these processes, i.e., $\Gamma=\Gamma_n+\Gamma_\gamma+\Gamma_f\equiv\Gamma_n+\gamma$, where γ is the width of the compound-nucleus level for decay via the radiative and fission channels. Taking these remarks into account, we see that the cross section σ_c for induced nuclear reactions (fission and radiative capture) must have the form

$$\sigma_c=\frac{\pi}{k_0^2}\frac{\Gamma_{np}\gamma}{(\varepsilon_p\pm\hbar\omega-E_n)^2+\Gamma^2/4}. \tag{16}$$

By estimating Γ_{np} and knowing the width γ of the given p level of the compound nucleus, we can evaluate σ_c. The results of estimates for a number of compound-nucleus p levels are presented in Table I. In all cases the depth of the potential-energy well was taken as 50×10^6 eV, and the nuclear radius, as $R=1.2A^{1/3}$ Fm. The corresponding experimental values were taken for the quantities $a_0=\delta_0/k_0$, Γ_n, and Γ. The last column of Table I gives the ratio of the cross section σ_c for induced neutron capture to the cross section $\sigma^0_{\rm max}$ for neutron capture at the peak of the corresponding p resonance in the absence of an external field. The case in which the scattering amplitude in the initial s state has a resonance associated with a level of the compound nucleus and there is also a corresponding level in the final p state is of interest. The compound nucleus U^{239} has two such levels at 6.67 and 4.41 eV, respectively.[6] The energy separation $\hbar\omega=2.26$ eV between these levels falls within the energy range of optical quanta. Table II shows the results of a calculation of the cross section for induced capture of a neutron at the 6.67 and 4.41 eV resonances of U^{238}, with the 6.67→ 4.41 eV transition.

It is evident from the calculations that the cross-sec-

TABLE II.

$\hbar\omega$, eV	$\Gamma_n(6.67)$, eV	$\lvert a\rvert^2$, cm²	$\Gamma_{np}e^{-2}E_0^{-2}$, cm²/eV	$\sigma_{np}e^{-2}E_0^{-2}/\sigma_{max}$ (6.67) cm²/eV²
2.26	$1.5\cdot10^{-3}$	$0.3\cdot10^{-21}$	$0.3\cdot10^{-11}$	$2\cdot10^{-10}$

tion ratio may turn out to be of the order of unity when the intensity of the electric component of the electromagnetic field reaches the quite moderate value $E_0 \sim 3 \times 10^3$ V/cm.

CONCLUSION

The estimates presented above show that it is quite feasible to observe induced nuclear reactions. For this purpose one will need a laser that provides a radiation flux of at least 10^4 W/cm^2. A pulsed laser of that power should be pulsed in synchronism with a pulsed neutron source. When the laser is off the cross section for the nuclear reaction (radiative capture or fission) will be small. When a laser of the indicated power is on, and if the condition $\varepsilon_p \pm \hbar\omega \approx E_n$ is satisfied, the nuclear reaction cross section should be appreciably larger and should increase linearly with increasing laser power. The target must contain enough atoms of the investigated isotope and must be transparent to the laser radiation. The necessary intensity of the laser radiation is far below the threshold for breakdown.

It should be emphasized that the laser power may not be increased *ad libitum* since perturbation theory breaks down when $\Gamma_{np} \sim \Gamma$, and then a more accurate theory must be used.

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