A new mechanism of atomic excitation is considered, a simultaneous collision with another atom and with a photon. The atomic excitation cross section is calculated. It is shown that for experimentally achievable electromagnetic field intensities and for other real parameter values the cross section is comparable to that of atomic excitation by electron impact.

§ 1. Introduction

The study of mechanisms of atomic excitation in an intense electromagnetic field acquired much interest in recent years. Most attention was paid to multiphoton atomic ionization and multiphoton light absorption in solids, as indicated by the large and still increasing number of publications on these problems [1]. "Mixed" mechanisms, where not only an electromagnetic field but also other agents participate in the atomic excitation process, were investigated very much less. In multiphoton absorption the energy of several photons is given to the atom simultaneously (their energies may not coincide), while the "simultaneous" process is also possible without intermediate levels. In the presence of such levels cascade atomic excitation is also possible, when the atom, absorbing one atom at a time, passes from the lowest to the highest level through the intermediate ones.

From the point of view of collision theory n-photon absorption is a collision of "n + 1" particles, the atom and "n" photons. The problem naturally arises of the possibility of atomic excitation by simultaneous collisions of other type particles with it, such as a photon and an electron or a photon and another atom (in the latter case the atom can be given the electronic excitation energy of the other atom, its kinetic energy, and all that simultaneously). As in two-photon absorption, no intermediate levels are required here. Although the possibility of such processes is, in principle, doubtless, it is important to clarify the conditions under which they play an important or even dominant role in atomic excitation. For atomic excitation by a simultaneous collision with an electron and a photon these conditions were discussed in [2]. In particular, it was shown there that an intermediate level not only causes cascade processes, but also increases considerably the atomic excitation probability by simultaneous collisions. The possibility of separating these two processes is also discussed in [2].

In the present paper we consider one of the mixing mechanisms of atomic excitation, by a simultaneous collision with another atom and with a photon.

We assume that as a result of collisions atom A passes from state "2" to state "1", and atom B from 1 to 2 (Fig. 1). Atom B is excited due to the electronic transition 2'-1' energy, the photon energy, and the kinetic energy change of the relative atomic motion. We turn to calculate the cross section of this process.

§ 2. System Hamiltonian

We first assume that A and B are hydrogenlike ions. The system Hamiltonian is of the form
$H = H_a(p_a, R_a) + H_b(p_b, R_b) + U(p_a, p_b, R_a, R_b) + F(p_a, p_b, R_a, R_b),$

\begin{equation}
F = \sum_{j=a, b} \frac{\varepsilon}{m_j \omega} E_0 \cos \omega t \cdot \nabla R_j - \sum_{j=a, b} \frac{\varepsilon}{m_j \omega} E_0 \cos \omega t \cdot \nabla r_j.
\end{equation}

Here $H_a$ and $H_b$ are the Hamiltonians of ions A and B, including nuclear motion, $U$ is the interaction energy of the ions, and the operator $F$ describes the interaction of ions with the electromagnetic field in the dipole approximation. In the Hamiltonian $H$ we omit a term, proportional to the square of the electromagnetic field intensity, as in what follows we will be interested in single-photon processes only. Notations: $E_0$ and $\omega$ are the electric vector amplitude and the electromagnetic field frequency, $m_j$ is the mass and $Z_j$ the charge of the nucleus, and $\mathbf{p}_j$ and $\mathbf{R}_j$ are the radius vectors of the electron and of the nucleus in the laboratory system.

The solution of the problem becomes easier if a convenient coordinate system is chosen. We transform first to center-of-mass coordinates of each ion $\mathbf{R}_c^j$, with electron coordinates $\mathbf{r}_j$ measured from the corresponding nucleus

\begin{equation}
\mathbf{r}_j = \mathbf{p}_j - \mathbf{R}_j, \quad \mathbf{R}_c^j = \mathbf{R}_j + \frac{m_j}{M_j} \mathbf{r}_j, \quad M_j = m_j + m, \quad j = a, b.
\end{equation}

We further introduce center-of-mass coordinates of the whole system $\mathbf{R}_c$ and coordinates of the radius-vector $\mathbf{R}$ joining the ion centers of mass

\begin{equation}
\mathbf{R}_c = \mathbf{R}_c^a - \frac{M_a}{M_c} \mathbf{R}, \quad \mathbf{R} = \mathbf{R}_c^a - \mathbf{R}_c^b, \quad M_c = M_a + M_b.
\end{equation}

In the new variables the system Hamiltonian looks as follows

\begin{equation}
U = \frac{Z_a Z_b \varepsilon^2}{|\mathbf{R} + \frac{m}{M_a} \mathbf{r}_a - \frac{m}{M_b} \mathbf{r}_b|}\left|\begin{array}{l}
\frac{Z_a \varepsilon^2}{M_a} - \frac{m}{M_a} \mathbf{r}_a - \frac{m}{M_b} \mathbf{r}_b - \frac{m}{M_b} \mathbf{r}_b \\
\frac{Z_b \varepsilon^2}{M_b} - \frac{m}{M_a} \mathbf{r}_a - \frac{m}{M_b} \mathbf{r}_b - \frac{m}{M_a} \mathbf{r}_a \\
\frac{Z_c \varepsilon^2}{M_c} - \frac{m}{M_a} \mathbf{r}_a - \frac{m}{M_b} \mathbf{r}_b - \frac{m}{M_a} \mathbf{r}_a
\end{array}\right| + \frac{\varepsilon^2}{|\mathbf{R} + \frac{m}{M_b} \mathbf{r}_b - \frac{m}{M_a} \mathbf{r}_a|}
\end{equation}

\begin{equation}
F = 2F(X) \cos \omega t = 2 \left[ a_x \mathbf{V} + a_y \mathbf{V}_y + a_z \mathbf{V}_z \right] \cos \omega t,
\end{equation}

\begin{equation}
a_x = - \frac{i e \hbar \mathbf{E}_0 (m_a + Z_a m_a)}{2 \omega \mathbf{p}_a M_a}, \quad a_y = - \frac{i e \hbar \mathbf{E}_0 (m_b + Z_b m_b)}{2 \omega \mathbf{p}_b M_b},
\end{equation}

\begin{equation}
M = \frac{M_a M_b}{M_a + M_b},
\end{equation}

\begin{equation}
a_c = i e \hbar \mathbf{E}_0 (-2 + Z_a + Z_b) / 2 \omega M_c, \quad x = i e \hbar \mathbf{E}_0 (Z_a - 1) M_a / 2 \omega M_c, \quad \mathbf{v}_j = \frac{m m_j}{M_j}, \quad j = a, b.
\end{equation}

Here $H_a(r_a)$ is the Hamiltonian describing electron motion relative to the ion A nucleus, $H_b(r_b)$ is the same Hamiltonian for ion B, and $X$ is the set of coordinates, $\mathbf{R}, \mathbf{R}_c, r_a, r_b$.

§ 3. Calculation of Ionic Excitation Cross Section

The triple collision of ions and a photon can be considered as light scattering by a "quasimolecule," consisting of ions A and B. Although no ion absorbs a photon $h\omega$, absorption is possible by a simultaneous change of states of two electrons (two-electron transitions in the quasimolecule). To first order in the interaction with the electromagnetic field the photon absorption cross section is expressed by the following equation