Metastable Quasimolecules in Excited Gases

V. N. MALNEV, R. A. NARYSHKIN

Taras Shevchenko Kiev National University, Physics Department
(6 Glushkova Prosp., 03022 Kiev, Ukraine
E-mail: malnev@i.com.ua, naryshkin@univ.kiev.ua)

Quasimolecules, which consist of two differently excited atoms in a resonantly excited gas, are considered. The energy of dissociation and typical sizes of such molecules are calculated in the first order of quantum-mechanical perturbation theory with the help of the dipole-dipole interaction operator. It is shown that there exist metastable quasimolecules, whose dipole radiative transition to the ground state (two non-excited atoms) is forbidden. The lifetime of such molecules is estimated and it is shown that quasimolecules may considerably affect the transport processes in a resonantly excited gas.

1. Introduction

It is well known (see e.g. [1]) that the interaction energy between atoms which do not form stable molecules can be calculated by means of quantum-mechanical perturbation theory using a dipole-dipole interaction operator. Particularly, the interaction between atoms in the ground state is described with the help of the van-der-Waals potential

$$U_{VW}(R) = -\frac{\text{const}}{R^6}, \quad R \gg a,$$

where $R$ is a distance between the atoms, and $a$ is a typical size of an atom. The potential $U_{VW}(R)$ is obtained in the second order of perturbation theory and always corresponds to attraction. The above-mentioned forces are the so-called van-der-Waals forces, which form a relatively shallow potential well (approximately $10^{-3}$ eV for He$_2$ [2] and $2 \times 10^{-2}$ eV for Kr$_2$ [3] that corresponds to approximate temperatures 10 K and 200 K respectively), so that the formation of stable molecules in such gases at room temperature does not happen.

The situation changes cardinally if one of the atoms is in an excited state, from which the dipole transition to the ground state is possible. In this case, the dipole-dipole interaction operator gives a non-zero contribution even in the first order of perturbation theory due to the fact that non-perturbed wave functions must account for an exchange of excitations between the atoms. The transition of the excitation from one atom to the other in this case replaces the exchange interaction that leads to the chemical valence. Such an interaction between the atoms is conventionally called a resonance interaction. It is described with the help of the potential

$$U_R(R) = \pm \frac{\text{const}}{R^3},$$

and can have a character of not only attraction, but also repulsion.

The dissociation energies of bound states, which can be formed at the expense of the resonance dipole-dipole interaction, turn out to be of the order of 1 eV according to the below-presented estimations. This means that quasimolecules, which consist of atoms in the ground and an excited states, can be formed at room temperature. It should be emphasized that a relatively large energy of the resonance interaction is related, as mentioned above, to the exchange of excitations realized between identical atoms through the dipole-dipole interaction operator.

It is worth noting that in the case of differently excited identical atoms, when the dipole transitions from excited states to the ground state are forbidden, the formation of quasimolecules (so-called excimers) is also possible [4]. In contrast to resonantly excited quasimolecules, when the attractive part of the potential energy of the interaction as a function of $R$ can be calculated analytically, the potential energy curves of the molecular states of excimer molecules, as known, can be calculated only by numerical methods.

The presence of even relatively low concentrations of resonantly excited molecules may essentially affect the collective properties of excited gases and plasma. The thermodynamic functions of resonantly excited gases were first considered in [5]. Quasimolecules of two differently excited one-electron atoms in such gases were discussed in [6], and a role of quasimolecules in resonantly excited gases was considered in [7].

The purpose of the present paper is an analytical calculation of the long-range part of the potential energy curves of molecular states of the resonantly excited quasimolecules formed from identical atoms with the closed electron shells and atoms with one valent electron
that do not form stable molecules in the ground state at room temperature. We also show that a radiative transition of resonantly excited quasimolecules to the ground state (two non-excited atoms) is forbidden in the dipole approximation. Therefore, the considered quasimolecule is metastable and its lifetime appears to be of the order of $10^{-5}$ sec.

2. Quasimolecule of Helium He$^*_2$

Consider an interaction of two helium atoms, one of which is in the ground state, while the other is in the excited $P$-state. Let us denote the nuclei of these atoms as A and B and assume that the distance between them equals $R$. We will use two coordinate systems, which describe the electrons of the atoms, and match their origins with the corresponding nuclei (A and B). Next, we direct the $z$ axes of these coordinate systems along the line that connects these nuclei, and denote the electrons belonging to the first atom (nucleus A) by indices 1 and 2. The electrons belonging to the second atom (nucleus B) are denoted by indices 1' and 2'.

The electron wave function of atom A (in the ground state) calculated with the help of the variational method looks like [8]

$$
\psi(1, 2) = \frac{\alpha^3}{\pi a^3} e^{-\alpha r_1 + r_2} a, \quad \alpha = 27/16 \quad (1)
$$

and represents the product of two hydrogen-like wave function for each electron in the field of the nucleus with an effective charge $Z_{\text{eff}} = \alpha = 27/16$:

$$
\bar{\psi}_0(r) \equiv |0\rangle = \frac{\alpha^{3/2}}{\sqrt{\pi} a^{3/2}} e^{-a r}, \quad (2)
$$

Here and below, $a$ designates Bohr’s radius:

$$
a = \frac{\hbar^2}{m_e e^2} \approx 0.529\text{Å} \quad (3)
$$

We take the electron wave function of the excited $P$-state of a helium atom in the form of an antisymmetrized product of the hydrogen-like wave functions of an $S$-electron in the field of a nucleus with charge $Z = 2$ and a $P$-electron in the field of the atomic residue with charge $Z = 1$ [8]:

$$
\Psi(1', 2') = \frac{1}{\sqrt{2}} [\psi_0(1') \varphi_i(2') \pm \psi_0(2') \varphi_i(1')], \quad i = x, y, z, \quad (4)
$$

where

$$
\psi_0(r) \equiv |0\rangle = \frac{\beta^{3/2}}{\sqrt{\pi} a^{3/2}} e^{-\beta r}, \quad \beta = 2, \quad (5)
$$

and

$$
\begin{align*}
\varphi_x(r) &\equiv |x\rangle = R_{n1}(r) \sqrt{\frac{3}{4\pi}} \sin \theta \cos \varphi, \\
\varphi_y(r) &\equiv |y\rangle = R_{n1}(r) \sqrt{\frac{3}{4\pi}} \sin \theta \sin \varphi, \\
\varphi_z(r) &\equiv |z\rangle = R_{n1}(r) \sqrt{\frac{3}{4\pi}} \cos \theta.
\end{align*} \quad (6)
$$

The degenerated wave functions (6) are chosen such that they transform as vector components under rotations of the coordinate system.

Henceforth, we restrict ourselves by the description of the interaction of atoms in the dipole-dipole approximation. As is well known [5], the resonance interaction (between atoms in the ground and an excited states) is inversely proportional to $R^3$ and shown to be the most intensive for low-excited states. Therefore, we will consider the lowest excited $P$-state with the principal quantum number $n = 2$, for which

$$
R_{21}(r) = \frac{2}{\sqrt{3}} \frac{\gamma^5/2}{a^{3/2}} e^{-\gamma r}, \quad \gamma = \frac{1}{2}. \quad (7)
$$

The wave function in the zero-order approximation is a linear combination

$$
\Psi(1, 2, 1', 2') = \sum_{i=1}^{12} C_i \psi_i(121'2') \quad (8)
$$

of the following 12 wave functions:

$$
\begin{align*}
|000x\rangle, |00x0\rangle, |0x00\rangle, |x000\rangle, \\
|000y\rangle, |00y0\rangle, |0y00\rangle, |y000\rangle, \\
|000z\rangle, |00z0\rangle, |0z00\rangle, |z000\rangle.
\end{align*} \quad (9, 10, 11)
$$

Wave functions (9)–(11) are the products of the one-particle wave functions (2), (5), and (6) with the electron coordinates taken in the order $121'2'$, e.g. $\psi_q(121'2') = |00y0\rangle = \bar{\psi}_0(r_1) \bar{\psi}_0(r_2) \varphi_0(r_{1'}) \varphi_0(r_{2'})$.

The interaction operator in the dipole-dipole approximation has the form

$$
V = \frac{(\mathbf{d}_1 + \mathbf{d}_2)(\mathbf{d}_{1'} + \mathbf{d}_{2'}) - 3(\mathbf{d}_1 + \mathbf{d}_2, \mathbf{n})(\mathbf{d}_{1'} + \mathbf{d}_{2'}, \mathbf{n})}{R^3},
$$

where $\mathbf{n} = R / R$, and the dipole moments of electrons in their proper coordinate systems are equal to

$$
\mathbf{d}_{1,2} = -e r_{1,2}, \quad \mathbf{d}_{1',2'} = -e r_{1',2'}. \quad (13)
$$
In the first order of the stationary perturbation theory the secular equation
\[
\det[V_{ij} - \Delta E \delta_{ij}] = 0
\]
(determinant of the 12-th order) constructed of matrix elements of the interaction operator on functions \((9)-(11))\) brakes into 3 blocks for each of the set of functions \((9)-(11))\). Namely, for sets \((9)-(10))\) we have
\[
\begin{vmatrix}
-\Delta E & 0 & A & A \\
0 & -\Delta E & A & A \\
A & A & -\Delta E & 0 \\
A & A & 0 & -\Delta E
\end{vmatrix} = 0,
\]
and, for set \((11))\), we have a similar equation with value \(-2A\) in the place of \(A\).

Here, constant \(A\) corresponds to 24 non-zero matrix elements of the dipole-dipole interaction operator on wave functions \((9)-(11))\). This value can be calculated as
\[
A = \langle \bar{0}0 x 0 | V | x 0 \bar{0} \rangle = \frac{1}{R^3} \langle 0 | 0 \rangle^2 \langle x | d_x | 0 \rangle^2
= \frac{e^2}{R^3} \int dV \left( \frac{(\alpha \beta)^{3/2} e^{-(\alpha + \beta) \frac{r}{\pi}}}{\pi a^3} \right)^2
\times \left[ \int dV \frac{\alpha^{3/2} e^{-\alpha \frac{r}{\pi}}}{\sqrt{\pi a^{3/2}}} \varphi_x (r, \theta, \varphi) \cos \theta \cos \varphi \right]^2
= \frac{e^2 a^2}{R^3} \frac{2^{16} \alpha^6 \beta^5 \gamma^5}{(\alpha + \beta)^9 (\alpha + \gamma)^{10}}.
\]
The substitution of constants \(\alpha = 27/16\), \(\beta = 2\), and \(\gamma = 1/2\) gives
\[
A \approx 0.06 \frac{e^2 a^2}{R^3}.
\]

From the secular equation, which reduces to 3 equations of the 4-th order, namely to \(\Delta E^4 - 4A^2 \Delta E^2 = 0\) for \(x, y\)-functions \((9)-(10))\) and to \(\Delta E^4 - 16A^2 \Delta E^2 = 0\) for \(z\)-functions \((11))\), we obtain the energy of states, into which the 12-fold degenerated energy level of the system of two non-interactive atoms is split:
\[
\Delta E = \pm 2A, 0, 0
\]
for \(x, y\)-functions and
\[
\Delta E = \pm 4A, 0, 0
\]
for \(z\)-functions.

The 6-fold degenerated level with zero energy and the levels with positive energies \((+2A, +4A)\) are “dissociable” levels and they do not form any bound states. We are interested in the levels with negative energies: the doubly degenerated \((x, y)\) level with the energy \(-2A\) and the wave function \((a linear combination whose coefficients are eigenvectors of the correspondent secular equation)
\[
\Psi_{\pm 2A}^{(x)} = \frac{1}{2} \left( |\bar{0}0 x 0\rangle + |\bar{0}00 x\rangle - |\bar{0}x 00\rangle - |\bar{0}x00\rangle \right),
\]
and the non-degenerated level with the energy \(-4A\) and the wave function
\[
\Psi_{\pm 4A}^{(z)} = \frac{1}{2} \left( |\bar{0}0 z 0\rangle + |\bar{0}00 z\rangle + |\bar{0}z 00\rangle + |\bar{0}z00\rangle \right).
\]
The eigenvalues (energies) are written as indices in wave functions \((20)-(22))\).

According to the classification of electron levels of diatomic molecules (see e.g. \((1))\), the considered excited \(P\)-states of a quasimolecule with energies \(-2A\) and \(-4A\) belong to \(^1\Pi_u\) and \(^1\Sigma_g\) states, respectively.

Let us now consider determination of the equilibrium distance \(R\) between the nuclei. It is impossible to find it by accounting for only the long-range dipole-dipole attractive forces. Therefore, we have to consider repulsion forces that act at small distances between the atoms. We calculate the equilibrium distance using the following simple model: we assume that the electron shells of two atoms are not deformed by the interaction, and that the equilibrium distance is attained only when the maxima of their electronic probability densities are in contact with each other (notice that even this configuration corresponds to the essential overlapping of the wave functions).

The maximum of the electron probability density of a helium atom in the ground state can be found from the equation
\[
\frac{d}{dr} \left( \psi^2 \bar{\psi} \right) = \frac{d}{dr} \left( \frac{\alpha^3}{\pi a^3} r^2 e^{-2a r} \right) = 0,
\]
which gives
\[
r_{\text{max}} = a / \alpha = 16 / 27 a \approx 0.6 a.
\]
In a similar way, we find the maximum of the electron probability density of a helium atom in the excited \(P\)-state. In this case, the most probable value of \(r\) equals
\[
r^* = 4 a.
\]
but the wave function, in addition, depends on the angle coordinates \( \theta, \varphi \). Accounting for that, we find the maximum of the distribution of the the probability density of \( x, y \)-wave functions \( |\varphi_1|^2 = |\varphi_x|^2 + |\varphi_y|^2 \) to be at

\[
\begin{align*}
    r_{\text{max}} &= r^* \sin^2 \theta = 4 a \sin^2 \theta. \\
    \text{From contact condition of the surfaces} \quad &r_{0(x,y)} \simeq 1.203 a, \quad (\theta \simeq 28.4^\circ). \\
    \text{Similarly, for} \quad z\text{-functions we have:} \\
    r_{\text{max}} &= r^* \cos^2 \theta = 4 a \cos^2 \theta,
\end{align*}
\]

wherefrom we get

\[
    r_{0(z)} \simeq 4.6 a, \quad (\theta = 0^\circ). \tag{29}
\]

At last, knowing the equilibrium distances between the nuclei, we are able to calculate the corresponding binding energies (dissociation energies with the opposite sign):

\[
    \Delta E^{(x,y)} = -1.875 \text{ eV}, \tag{30}
\]

\[
    \Delta E^{(z)} = -0.067 \text{ eV}. \tag{31}
\]

We must emphasize that the total energy of a quasimolecule relative to the energy of non-interacting helium atoms in the ground state is larger than the calculated dissociation energy by the value (experimental data \[^{[9]}\]):

\[
    E(1s2p) - E(1s^2) \simeq -57.787 \text{ eV} + 79.005 \text{ eV} \simeq 21.22 \text{ eV}. \tag{32}
\]

This energy must be used in considerations of radiation energy of quasimolecules (see the next section).

### 3. Lifetime of \( \text{He}_2^+ \) quasimolecules

Let us now discuss the lifetime of quasimolecules. For such a study, we have to use the radiation theory of molecular systems. The total probability of radiation is written in the form of a perturbation theory series, each member of which represents a multipole radiation of a certain type (electric or magnetic) and order (dipole, quadrupole etc). Moreover, it is well known that the increase of the order of multipolarity by 1 decreases the radiation probability by \( \sim (k a_0)^2 \) times, where \( a_0 \) is a characteristic size of the radiative system and \( k = 2\pi/\lambda = \omega/c \) is a wave number of the radiated light \[^{[10]}\].

In our case of a quasimolecule in the state \(^1\Pi_u\), the value of \( k a_0 \) is of the order of \( 10^{-2} \) (\( \hbar \omega \sim 20 \text{ eV}, \quad a_0 \sim 1\text{A} \)), which gives the decrease of the radiation probability in \( 10^4 \) times when we proceed to the radiation with multipolarity by 1 order higher. For example, a characteristic time of the dipole radiation of an excited atom is of the order of \( 10^{-9} \text{ sec} \), and in the case where a dipole transition is forbidden, the lifetime increases by 4 orders, i.e. up to \( 10^{-5} \text{ sec} \). Let us show that such a situation indeed takes place for helium quasimolecules \( \text{He}_2^+ \) in the state \(^1\Pi_u\).

A dipole matrix element for the transition of a quasimolecule to the ground state (two free atoms) is

\[
    \mathbf{d}_i \equiv \langle \Psi^{(x,y,z)} | \mathbf{d}_1 + \mathbf{d}_2 + \mathbf{d}_1' + \mathbf{d}_2' \mid \tilde{\psi}_0(1)\tilde{\psi}_0(2)\tilde{\psi}_0(1')\tilde{\psi}_0(2') \rangle, \tag{33}
\]

where \( \Psi^{(x,y,z)} \) are the correct wave functions of the zero-order approximation \[^{[20]}\]–\[^{[22]}\].

It is easy to see that after the interchange of electron pairs 1,2 and 1',2' which describe physically identical states, wave functions \[^{[20]}\] and \[^{[21]}\] change their signs as well as the integral \[^{[33]}\]. As a consequence, we get that this integral is equal to zero

\[
    \langle \Psi^{(x,y)} | \mathbf{d}_1 + \mathbf{d}_2 + \mathbf{d}_1' + \mathbf{d}_2' \mid \tilde{\psi}_0(1)\tilde{\psi}_0(2)\tilde{\psi}_0(1')\tilde{\psi}_0(2') \rangle = 0, \tag{34}
\]

and, therefore, the dipole transition from the state \(^1\Pi_u\) to the ground state is forbidden.

However, for the \(^1\Sigma_g\) state \( z\)-functions \[^{[22]}\), the symmetry does not forbid the dipole transition. In this case, only the matrix element of the \( z\)-component of the dipole moment is non-zero and turns out to be

\[
    \langle \Psi^{(z)} | (d_1 + d_2 + d_1' + d_2') \cdot \tilde{\psi}_0(1)\tilde{\psi}_0(2)\tilde{\psi}_0(1')\tilde{\psi}_0(2') \rangle = -\left( \frac{2\pi}{\hbar c} \right)^3 \frac{\beta^3}{\gamma^5} e a \simeq -0.49 ea. \tag{35}
\]

The probability of a dipole radiation of the excited system per unit time equals \[^{[10]}\]

\[
    w = \frac{4\omega^3}{3\hbar c^3} |\mathbf{d}_i|^2, \tag{36}
\]

wherefrom one can estimate the lifetime of the \(^1\Sigma_g\) state:

\[
    \tau = \frac{1}{w} \simeq \frac{3\hbar c^3}{4(h\omega)^3 (0.49 ea)^2} \simeq 0.18 \text{ ns}. \tag{37}
\]
We see that the $^1\Sigma_g$ state is short-lived and cannot be a metastable one in contrast to the $^1\Pi_u$, whose dipole radiation is forbidden and therefore a quasimolecule in this state is metastable and lives at least $10^{-5}$ sec, that is essentially greater than characteristic times of the dipole radiation $10^{-8} \pm 10^{-9}$ sec.

Let us note, that the given estimation [57] of the quasimolecule lifetime agrees (by the order) with the experimental data for short-lived excited states of helium [11].

4. Quasimolecules of Atoms with One Valent Electron

Let us consider a system, which consists of two identical atoms, and where each atom has only one outer electron while all the other electrons form entirely occupied electronic shell (chemical elements of the first group). We assume that one of the atoms is in the ground S-state (i.e. the valent electron has ns$^1$-configuration), but the other one is in the excited P-state (np$^1$-configuration). The total electron wave function of each atom can be represented in the form of the product of the electron wave function $\Psi(r_1,\ldots,r_N)$ of entirely occupied electronic shell and the wave function $\psi_{s,p}(r)$ of the outer electron:

$$\Psi = \Psi(r_1,\ldots,r_N)\psi_{s,p}(r),$$

where $N = 2,8,10,18,\ldots$ is the number of electrons in the entirely occupied electronic shells.

The entirely occupied electronic shells have zero total spin and zero total angular momentum. Therefore, they do not take part in the chemical combinations and the chemical valence is conditioned only by the outer electrons [1]. Hence, the wave function $\Psi(r_1,\ldots,r_N)$ appears invariantly in all the equations where chemical combinations are considered and practically drops out from calculations. Taking this fact into account, we will further use only the wave function of the valent electron $\psi_{s,p}(r)$, but will keep in mind that the entirely occupied electronic shells must be considered for obtaining equilibrium distances between the nuclei of the atoms.

Thus, the problem reduces to the interaction of two hydrogen-like atoms, where one electron moves in the field of an atomic residue with effective charge $Z(r)$, which can be calculated if the wave function $\Psi(r_1,\ldots,r_N)$ is known. But such a procedure can be done only by numerical methods.

The angular part of the wave function of the outer electron is the spherical function $Y_{lm}(\theta,\varphi)$, but the radial one $R_{nl}(r)$ is considered unknown. Wave functions of the zero-order approximation of two non-interactive atoms with account for the excitation exchange are constructed similarly to what was done in Section 2. Namely, they are

$$|0x\rangle, \ |x0\rangle, \ |0y\rangle, \ |y0\rangle, \ |0z\rangle, \ |z0\rangle,$$

where

$$\psi_s(r) \equiv |0\rangle = R_{n0}(r) \frac{1}{\sqrt{4\pi}}.$$

We emphasize that we neglect the exchange interaction of the outer electron with the inner ones.

The dipole-dipole interaction operator is written in the form

$$V = \frac{(d_1d_{1'}) - 3(d_1n)(d_{1'}n)}{R^3},$$

where indices 1,1' correspond to electrons that belong to the different atoms with the distance between them being equal to $R$.

After solving the secular equation constructed with the help of interaction operator [42] and the set of degenerate wave functions [39], we get

$$\Delta E^{(x,y)} = \pm A, \ \ \ \Delta E^{(z)} = \pm 2A,$$

where $A$ is

$$A = \frac{e^2}{3R^3} \left( \int_0^\infty r^3 R_{n0}(r)R_{n'1}(r) \, dr \right)^2.$$

In the case of a hydrogen atom, the radial functions $R_{nl}(r)$ are known. Particularly, for $n = 1$ and $n' = 2$, we have

$$A \approx 0.555 \frac{e^2a^2}{R^3}.$$

With the help of the method described in Section 2, we estimate the equilibrium distance between the nuclei

$$R^{(x,y)} \approx 1.76 \ a \ (\theta \approx 32.8^\circ), \ \ \ \ R^{(z)} = 5 \ a \ (\theta = 0^\circ),$$

and get the following binding energies of quasimolecules

$$E^{(x,y)} \approx -2.77 \ eV, \ \ \ E^{(z)} \approx -0.24 \ eV.$$
in the states $^1\Pi_u$ and $^1\Sigma_g$, respectively.

For other atoms, the radial functions are unknown, and we use the experimental atomic radii $r_{\text{at}}$ [12] for estimations of the dissociation energies of quasimolecules and assume that $A = \frac{4}{2\pi^2}$. The results of calculations (by the method of Section 2) for $n = n'$ are listed in the Table:

| Atom | $r_{\text{at}}, \text{Å}$ | $R^{(x,y)}$, Å | $E^{(x,y)}$, eV | $R^{(z)}$, Å | $E^{(z)}$, eV |
|------|-----------------|---------------|---------------|---------------|---------------|
| Li   | 2               | 1.920         | 3.70          | -0.34         | 5.95          | -0.29         |
| Na   | 3               | 1.858         | 4.53          | -0.29         | 7.02          | -0.16         |
| K    | 4               | 2.272         | 5.54          | -0.16         | 8.50          | -0.09         |
| Rb   | 5               | 2.475         | 6.03          | -0.12         | 9.36          | -0.07         |
| Cs   | 6               | 2.655         | 6.47          | -0.10         | 10.04         | -0.05         |

The typical sizes of quasimolecules can be roughly estimated by the formula $R_M = 2R(z)$. Hence, the typical sizes of quasimolecules from Li to Cs lie in the interval from 6 to 10 Å. This means that the corresponding effective scattering cross-sections are approximately in one order of magnitude larger than the gas-kinetic ones.

As well as for helium quasimolecules, the dipole transition appears to be forbidden in the case of the atoms with one valent electron due to the fact that the symmetry of the wave function remains unchanged with respect to the exchange of the nuclei. Thus, the quasimolecules are metastable only in the $x,y$–states.

5. Conclusions

The analytic calculations of the molecular states of diatomic quasimolecules, which are formed of the atoms in the ground and an excited states, are carried out. The calculations are performed in the first order of perturbation theory with the use of the dipole-dipole interaction operator for atoms with entirely occupied electronic shells and atoms with one valent electron. The results describe molecular states at the distances $R$ greater than the typical size of atoms. At distances $R^{(x,y,z)}$ (phenomenological parameters of the theory) of the order of atom sizes, where the repulsion of atoms predominates, the potential energy is modelled by a solid wall. The dissociation energy of such molecules, according to our estimation, appears to be of the order of 1 eV. In contrast to excimer molecules, whose typical lifetime varies from 0.1 to 10 ns [4], quasimolecules are metastable. The estimation shows that their radiation decay is forbidden for dipole transitions and is of the order of $10^{-5}$ sec.

The above-described quasimolecules exist in active media that are used for the generation of laser radiation [4], [9], [11]. It is worth noting that, even for the simplest excimer molecule $\text{He}_2^*$ there exist over 60 molecular potential curves [4]. This fact essentially complicates theoretical analysis of systems containing a noticeable quantity of excited atoms from the point of view of identification of certain spectral levels.

The presence of excimers and quasimolecules essentially affects collective properties of the excited gases. For example, one can affect the diffusion and the thermal conductivity coefficients in excited gases with regard for the fact that quasimolecules have much bigger effective cross sections than the gas-kinetic ones. In particular, the presence of quasimolecules leads to a deceleration of the processes of diffusion and thermal conductivity.

The presence of diatomic quasimolecules may also assist a more active process of formation of clusters which consist of many atoms [13]. The formation of quasimolecules with a finite lifetime $\tau$ and their decay (dissociation) can be considered as a photo-stimulated chemical reaction. As known [14], the anomalous sound absorption may be observed in this case at the expense of the mechanism of the second viscosity at frequencies $\omega \tau \sim 1$. Furthermore, a theory of non-equilibrium phase transitions in many-particle systems with finite lifetime is being intensively developed [15]. The most essential conclusion of such a theory is that there exist additional restrictions on the decay of systems into two coexistent phases (in our case — phases with different concentrations of excited atoms), which requires additional improvements [16].

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