Influence of inelastic Rydberg atom-atom collisional process on kinetic and optical properties of low-temperature laboratory and astrophysical plasmas

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Abstract. Elementary processes in plasma phenomena traditionally attract physicist’s attention. The channel of charged-particle formation in Rydberg atom-atom thermal and sub-thermal collisions (the low temperature plasmas conditions) leads to creation of the molecular ions – associative ionization (AI), atomic ions – Penning-like ionization (PI) and the pair of the negative and positive ions. In our universe the chemical composition of the primordial gas consists mainly of Hydrogen and Helium (H, H⁺, H₂, He, He⁺). Hydrogen-like alkali-metal Lithium (Li, Li⁺, Li⁻) and combinations (HeH⁺, LiH⁻, LiH⁺). There is a wide range of plasma parameters in which the Rydberg atoms of the elements mentioned above make the dominant contribution to ionization and that process may be regarded as a prototype of the elementary process of light excitation energy transformation into electric one. The latest stochastic version of chemi-ionisation (AI+PI) on Rydberg atom-atom collisions extends the treatment of the "dipole resonant" model by taking into account redistribution of population over a range of Rydberg states prior to ionization. This redistribution is modelled as diffusion within the frame of stochastic dynamic of the Rydberg electron in the Rydberg energy spectrum. This may lead to anomalies of Rydberg atom spectra. Another result obtained in recent time is understanding that experimental results on chemi-ionization relate to the group of mixed Rydberg atom closed to the primary selected one. The Rydberg atoms ionisation theory today makes a valuable contribution in the deterministic and stochastic approaches correlation in atomic physic.

1. Introduction
Elementary processes in low-temperature plasma have traditionally been of interest for the physics of atom-atom collisions. There is a wide range of plasma parameters at which atoms and molecules play an important, and sometimes even major, part in ionization and may be considered as a prototype of elementary processes of transformation of radiant energy into electrical one. The program of Russian science research for 2008-2012 in the area “Current problems in physics” includes “… low-temperature plasma physics and the essentials of its use in production processes”.

The advantages of such technologies include:
1. Relatively easy operation and control of plasma parameters.
2. Wide range of reagent energy in plasma.
3. Comprehensive processing of raw materials, environmental safety.
4. Control of the composition of the resulting product.
5. The possibility of processing substances of various chemical composition and phase state (gaseous, liquid, solid).

Some examples of plasma technologies:
- Plasma power engineering.
- MHD converters of thermal energy into electrical one, thermionic energy converters, gas lasers.
- Coal-based plasma power plants.
  - Over 50% of electrical and thermal energy in the world is produced based on coal (in Russia – 30%), while brown coal reserves are sufficient for 500-600 years.
- Producing nano-coatings, such as nitrides, carbonitrides, borides, etc., fullerenes, nanotubes.
- Producing superhard boron nitride, which is not found in nature.
- Comprehensive utilization of toxic wastes, including fluorine containing compounds, etc.

The low temperature plasma physics includes branches devoted to elementary processes and their applications in up-to-date science-driven technologies. The interest to the work in these areas, that first showed over 100 years ago, today not only has not decreased, but quite the opposite – it is growing. First of all, it is caused by the search for new renewable energy sources, issues of energy saving, development of plasma chemistry and nanotechnologies. Even in the seemingly non-related issues of hot plasma physics, the low-temperature plasma in near-wall areas of fusion devices is the source of objectionable admixtures of heavy particles in the reactor core. One should mention also the projects on recovering the heat, emitted in nuclear reactors based on the fission principle, using various versions of plasma devices up to creating plasma generators of laser emissions, and also plasma methods of utilizing waste products of human life.

In spite of a large number of published works, the interest to this field of research is not waning. In this connection one cannot but mention the series of monographs by B. M. Smirnov on the role of excited atoms in low temperature nonequilibrium plasma, published in the period from 1968 to 1982 and introducing a new scientific field – plasma chemistry, that arose at the interface between physics of atomic collisions and chemistry of gas reactions leading to a change in the type of colliding particles or, in other words, to chemical transformations involving ions and excited atoms and molecules. Studying the physics of ionization processes in heavy particles collisions, we, in turn, are dealing with fundamental assumptions of the physics of collisions involving excited atoms, the physics of low temperature plasma, thus obtaining the opportunity to discover new phenomena and relationships. One such result has been the observation of the phenomenon of low temperature nonequilibrium plasma formation when gaseous medium is exposed to light with wavelengths corresponding to resonant optical transitions in atoms (photoresonant plasma). Such plasma at the initial stage of its development cannot be described using a traditional scheme of gaseous discharge development, which made it possible to research nonideal nonequilibrium plasma in the absence of an external electric field.

2. Ionization processes involving Rydberg atoms

In physics literature, Rydberg name began to be used for highly excited states of atoms and molecules after the publication of Rydberg’s pioneer work on atom spectroscopy in 1890.

Atoms in highly excited states exist in the interstellar medium exposed to ultraviolet and X-rays from space objects, and to high energy particles with shock waves resulting from supernova explosions and interstellar clouds collisions. Thus, astronomers observe infrared radiation caused by transitions between excited states of a hydrogen atom with the values of principal quantum number $n$ of the order of 10. Based on infrared radiation, one can judge on the population of Rydberg atom states in stellar atmospheres, atmospheres of cooling stars (dwarfs), planetary nebulas, and clouds of interstellar gas, as the lines of recombination spectrum of Rydberg states correspond to this range of wavelengths.

In the 1980s laser methods of investigating Rydberg atoms (RA) became widely accepted. This not only allowed increasing the effectiveness of classical single-photon light excitation, but made it
possible to use two-photon excitation “violating” the rule of non-conservation of orbital quantum number L in the optical transition, and the methods of intra-Doppler spectroscopy free from the necessity of accounting for Doppler broadening of spectrum lines, etc. New, unconventional for classical spectroscopy, research methods emerged, for example, the method of “photon echo”.

Interest to the processes of collisional ionization in highly excited atoms is caused by their fundamental significance for atomic physics and the wide possibilities of their practical use in laser atom cooling, Bose-Einstein condensation, controlling excitation processes of single atoms, creating quantum computer logical units, quantum teleportation, etc. It should be noted that the first results of quantitative research on ionization processes involving RA within the wide variation range of principal quantum number values were obtained in Refs. [1] (experiment) and [2,3] (theory). Contemporary systems of laser excitation allow obtaining RA in concentrations comparable to those of atoms in unexcited states. Even with the selective laser excitation of resonant (first excited) atomic levels, Rydberg states may be populated due to what is known as “energy pooling processes”.

Based on the state of colliding particles in the entrance and exit reaction channels, the whole aggregate of ionization processes in atomic and molecular collisions can be divided into processes of collisional ionization and those of chemi-ionization. This somewhat arbitrary differentiation is caused in the first place by the ratio of the potential energy (excitation energy) of colliding particles to their kinetic energy (relative motion energy).

The range of kinetic energies of atoms, being of interest for low temperature plasma physics, is $10^9$–$10^3$ K, which corresponds to conditions from Bose-Einstein condensate to the plasma of high-current arc. In experiments on laser atom cooling, the following division of collisions is accepted, based on the relative energy motion: thermal collisions (0.1-1 eV), subthermal collisions ($10^{-3}$ eV) and cold collisions (< $10^{-3}$ eV); each range of gaseous medium temperatures has its own corresponding set of primary processes leading to ionization.

Authors of Ref. [4] suggested a dipole resonant mechanism leading to quantum transitions of a highly excited (Rydberg) electron in inelastic collisions involving Rydberg atoms. In the course of such a collision it is possible to identify the charge transfer mechanism of the Rydberg atom’s positive

Figure 1 a) – the main part of the interaction is the interaction of the outer electron $e_R$ and the colliding atom B; b) – $e_R$ interacts with $A^+ – B$ subsystem.
nucleus on the unexcited colliding atom, at the distances lesser than the radius of the excited atom (see Figure 1). In this case the loosely bound outer electron there is in the field of a variable dipole moment depending on the internuclear distance. In the zone of thermal particle velocities such a field, induced by the charge transfer process, may be evident at significant distances. It should be noted that the principal contribution into the theoretical development of such processes was made by E. Fermi in 1934, who suggested treating a Rydberg atom as a system comprising an ion core and a quasi-free Rydberg electron (RE).

Collisions involving excited atoms and resulting in ionization are accompanied by interactions between the initial discrete state and not only ionization continuum, but also the Coulomb condensation of Rydberg atom energy terms. Thus, transitions in which upper highly excited states become populated are possible in addition to ionization. They, in turn, participate in the processes of associative and direct Penning ionization.

\[
\begin{align*}
X^{**} + X &\rightarrow X^+_e + e \quad \text{(AI)} \\
X^{**} + X &\rightarrow X + X^+ + e \quad \text{(PI)}
\end{align*}
\]

and also in the production of a pair of a positive and negative ions

\[
X^{**} + X \rightarrow X^+ + X^-.
\]

2.1. Chemi-ionization in RA-A collision

Due to unfailing interest in AI and PI processes involving RA, several methods of calculating respective reaction constants have been developed in comparatively short period of time.

In Duman and Shmatov’s [2] theory, quantum mechanical approach was used accounting for the character of nucleus-nucleus interaction in the course of collision. Calculation methods suggested by Mihajlov and Janev (1980) are based on quasi-classical process description. Both these theories can be applied to the range of internuclear distances of a collisional process \( R << r_n \), where \( r_n \sim n^2 \) is the mean value of the RA effective radius.

In this case inelastic ionization processes can be treated as the result of the interaction between the valence electron \( H \) and the dipole moment of the subsystem \( \Lambda^+ + A \), which may be interpreted as the mechanism of resonant charge transfer of the RA ion core on the colliding particle. It is possible to apply adiabatic approximation and the classical trajectory concept in these cases, provided the ratio of de Broglie wavelength \( \lambda \) of A atom to the characteristic dimension of RA is \( \lambda/2 \cdot r_n << 1 \). Besides, to differentiate between the degree of freedom of the atom and that of the electron within the scope of Born-Oppenheimer approximation, it is necessary for the velocity value of the relative motion of atoms \( v_r \sim E^{1/2} \) to be much smaller than the motion velocity on the orbit of the Rydberg electron. Here the atomic system of units is used (a.u.). The electron states in \( \Lambda^+ + A \) subsystem may be treated as the electron states of molecular ion \( \Lambda_2^+ \), correlating adiabatically with the electron states of the given subsystem with \( R \rightarrow \infty \), where \( R \) is the internuclear distance.

Let us assume that for internuclear distances \( R \) at which inelastic AI and PI processes occur, the valence electron of A atom may be considered as simultaneously belonging to \( \Lambda^+ + A \) subsystem. Then the main contribution to the inelastic process under consideration is made by the interaction within the range of \( R \) values, where the energy exchange between the RE and the electron component of \( \Lambda^+ + A \) subsystem is of almost resonant character.

Later on, Mihajlov and coauthors [5] extended the theory of such processes, that had originally been developed for hydrogen-like alkali atoms, to hydrogen and helium atoms with regard to astrophysical tasks. At the same time, the interest has not waned in AI and PI processes involving alkali atoms. See [6,7].
Figure 2 The total rate coefficients for chemi-ionization [19] in Li*(n)+Na collisions in the case of crossed beam.

Figure 3 Summarizing picture of the hemi-ionization constants in RA-A collisions as a function of the effective quantum number of excited states [8].

It should be noted that theoretical works appearing immediately after the publication of the first experimental data to a large extent encouraged further experimental studies in this field using the opportunities provided by contemporary laser technologies. Figure 2 shows the relationship K(n) of chemi-ionization rate constants for Rydberg states of lithium atoms (Li** + Na – asymmetrical case),
calculated under the dipole resonant model. The Figure 3 shows relationships $K(n)$ obtained in experiments of various kinds before 1990 by Klyucharev (1993).

2.2. *Ionization in binary collisions of Rydberg atoms.*
Ionization in collisions of two RAs remains a relatively little studied field of the physics of atom-atom collisions. In this case the total energy of atoms exceeds the A atom ionization potential. As a result, atomic RA-states, that are stable with respect to ionization, are converted into quasi-molecules, that can later be autoionized forming $A^+ - A^-$ states, whose excitation energy is less than the energy of $(RA)_2$ quasi-molecule with $R \rightarrow \infty$ (See Figure 4).

![Figure 4](image)

**Figure 4** Schematic illustration of potential curves quasicrossing for the collisions of two highly excited alkali-metal atoms.

\[
RA + RA \rightarrow A^+ + A^+ + e \quad (4)
\]

\[
RA + RA \rightarrow (A_2^+) + e \quad (5)
\]

\[
RA + RA \rightarrow A^+ + (A^-)^+ \quad (6)
\]

In [6] the data are given on Penning ionization constants in collisions of alkali Rydberg atoms. Autoionization widths of intermediate quasi-molecular states were expressed through cross-sections of photo-ionization from Rydberg atom levels and the strengths of transition lines between them. Cross-sections and line strengths were calculated in quasi-classical approximation, taking into account the quantum character of RE motion and approximation of a straight-line trajectory of particle motion. The dipole-dipole approximation of atom-atom interaction works better for subthermal collisions, as in this case the time of interaction increases at large R.

2.3. *Ionization-recombination processes involving RA in astrophysical objects.*
In plasma conditions with the temperature of plasma electrons $T_e$, highly excited atomic states may be produced due to recombination processes of various kinds. One can give the example of photo-recombination corresponding to the case of low electron concentrations.

\[
A^+ + e \rightarrow RA(n, L) + h\nu \quad (7)
\]

Processes of ion-electron recombination in low-temperature weakly ionized plasma are the effective channel of atom formation in highly excited states. This can be well illustrated by ionization
reactions involving RA in the helium enriched atmospheres of white dwarfs and in the solar photosphere, see e.g. [7]. In these conditions chemi-ionization proves to be an open, reverse to recombination, channel [9]:

\[ \text{He}^+(n) + \text{He} \leftrightarrow \text{He}^+_2 + e \]  
\[ \text{He}^+(n) + \text{He} \leftrightarrow \text{He}^+ + \text{He} + e \]  

The same statement is valid for the hydrogen of the solar atmosphere. As the temperature of particles increases, the role of these processes decreases. Thus, in white dwarf atmospheres, their contribution into ionization decreases relatively from 100 at \( T = 12000 \) K and 10 at \( T = 16000 \) K to 0.1 at \( T = 20000 \) K and 0.01 at \( T = 24000 \) K, when electron-atom collision processes come to the foreground.

\[ \text{He}^+(n) + e \rightarrow \text{He}^+ + e \]

In theory, according to [10], parameters of reactions (8, 9) dominate in the balance of recombination and ionization processes at temperatures within the range of \( 12000 \leq T \leq 30000 \) K. In the course of photorecombination leading to mutual neutralization of charged particles of hydrogen plasma, about 100\% of the total photorecombination flux results in the population of lower excited states of the hydrogen atom: \( 1 \leq n \leq 7 \) at \( T_e \geq 3500 \) K, 80\% at \( T_e \approx 1150 \) K and 70\% at \( T_e \approx 350 \) K. At \( T_e > 24000 \) K, excitation and ionization by electron impact, as well as three-body recombination, are dominating in the balance of Rydberg atom population.

**Figure 5** The chemi-ionization rate constants in hydrogen.

The role of processes (8, 9) in the RA population in the helium-enriched atmosphere of white dwarfs is noticeably bigger than it is in the hydrogen case of the solar photosphere, as helium ionization potential noticeably exceeds the same potential for the hydrogen atom. Therefore, at comparable values of pressure and temperature, the degree of helium atmosphere ionization is considerably less than in the hydrogen situation. In the solar photosphere, near its temperature minimum \( T \approx 4000 \) K, chemi-ionization–recombination balance plays an important role in the wide range of temperatures. In the helium-enriched atmosphere, the ratio of ionization fluxes to a
dissociative recombination channel in the RA population balance decreases from 0.6 (7000 K) to 0.16 (30000 K) for \( n = 3 \) and from 0.12 (7000 K) to 0.03 (30000 K) for \( n = 10 \). Figure 5 shows results from [5] of the aggregate chemi-ionization constant calculation for hydrogen for the ranges: \( n = 4 \div 25 \) and \( 10^3 \leq T \leq 6 \cdot 10^3 \) K, while analogous results for helium \( n = 3 \div 10 \) and \( 4 \cdot 10^3 \leq T \leq 3 \cdot 10^4 \) K can be found in [10].

In the space plasma with low density of charged particles in the balance of recombination population of Rydberg atoms, the processes of collisions with atoms and molecules of interstellar medium can be neglected compared to the emission to lower levels. Besides, the distribution of highly excited atoms over \( n \) in space plasma is affected by the relict radiation with temperature 2.8 K. In these conditions, the profile of RA spectrum lines is controlled by Doppler effect and processes of Stark broadening in electric fields, as well as by collisions with protons and electrons resulting in Lorenz type of profile. In its turn, Zeeman effect leading to level splitting and polarization of RA radiation makes it possible to receive a large body of data on magnetic properties of space objects. It should be also noted that astrophysicists have at their disposal the possibility of investigating the spectrum of radio emission from other galaxies, based on the effect of RA induced emission when such lines are absorbed.

2.4. **Cold and ultracold collisions.**

Cold and ultracold collisions hold a special place in current research on atomic and molecular physics, and processes in condensed matter. Deep understanding of the physics of such processes encourages the development of new methods of controlling elementary processes, precise measuring of their parameters, and processes of weak interactions between particles. This was the beginning of new trends in atomic physics research: Bose-Einstein version of matter condensation at low gas pressures, atomic interferometry, optic lattices for atomic motion control, etc. Today all these are included under new optical physics, where cold atomic collisions play the central part. If the values of de Broglie wavelength are of the order of \( 10^{-3} \) nm, the processes of particle collisions are traditionally classified as classical physical interactions (low temperature plasma, molecular beams). While the temperature interval \( 1 \mu K \div 1 mK \) of atomic collisions can be realized by the methods of intra-Doppler spectroscopy, the temperatures \( 1 \mu K \div 1 mK \) obtained in magneto-optical traps have made it possible to realize the idea of Bose-Einstein condensate (BEC) in the physics of optical phenomena. Even in case of “intra-Doppler” cooling, the scale of interatomic interactions becomes comparable with the de Broglie wavelength of particles, which leads to the observation of new wave interferential interactions. At below \( 1 \mu K \), when critical concentration of condensed phase is reached, the effects of quantum degeneracy begin to show in the ensemble of particles. Besides, the kinetic energy imparted to the particle in the atomic collision becomes lower than the energy imparted to it by a scattered photon. This type of collisions is known as ultracold ones. The first publication on quantum effects in cold and subcold collisions is Ref. [11].

It is clear that in the conditions when the collisions involving excited (non-metastable) particles may be considered as cold (or ultracold), emission time becomes much less than colliding particles interaction time, which prohibits the processes of atomic collisions. For cold and ultracold atoms in the light field, the scales of time length and spectrum line widths are different from their classical analogs. Thus, nonhomogeneous Doppler broadening of the spectrum line may become less than its natural width, interaction time – several times longer than the time of particle spontaneous emission, de Broglie wavelength – several orders greater than atomic dimensions. Compared to thermal range, only small number of partial scattered waves will contribute into the wave function of Schrodinger equation. Extremely small values of Doppler broadening in these cases allow to obtain ultrahigh resolution in the methods of molecular spectroscopy. In case of cold atoms, multiple interaction between pseudo-bound particles and photons is possible, allowing investigation of the fine effects of the emission intensity and polarization on the interaction mechanisms in collisional processes.

Physics terminology in the field of cold and ultracold collisions, distinguishes two ionization types: photoassociative photoionization (PAPI)
Blangé an coauthors in [12] demonstrated that in the thermal range of collision energy ($T \approx 10^2$ K), AI process involving two resonant excited $3^2R$ sodium atoms results in the population of the same lower vibrational excited states of Na$_2^+$ ion, as PAAI reaction (13) does at $T = 10^2$ K. This appears to confirm that in both cases the pattern of molecular terms involved in reaction is the same.

3. Characteristic properties of stochastic ionization of Rydberg collision complex

Theoretical papers cited above did not take into account the possibility of multiple crossings of the initial energy-term of the excited quasi-molecule A$_2^*$ of the ion molecular attraction term A$_2^+$, although, in [4] dipole resonant mechanism was initially suggested as a mechanism of transitions between the levels of a highly excited atom in collisions with the ground-state atoms of the same type.

$$Na(3^2S) + Na(3^2S) + h\nu \rightarrow Na_2^*,$$  
$$Na_2^* + h\nu \rightarrow Na_2^+ + e,$$  
(11)  
(12)

and photoassociative autoionization (PAAI)

$$Na(3^2S) + Na(3^2S) + h\nu \rightarrow Na_2^*$$  
$$Na_2^* + h\nu \rightarrow Na_2^{**}$$  
$$Na_2^{**} \rightarrow Na_2^+ + e$$  
(13)  
(14)  
(15)

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**Figure 6** Qualitative illustration of the quasicrossing of covalent and ionic potential curves in "diffusion" model

The attempt to account for this possibility by traditional means of the physics of atom-atom collisions could not yield any observable result due to a large number of energy-terms crossing points. A change in RE energy at each of the multiple crossings of energy-terms $\delta E \leq 1/n^2$, so that $\delta E/E_n \sim 1/n$, where $E_n = 1/n^2$ is the valence electron binding energy. This circumstance led the authors of [13] to the idea of "diffusion" approach to the problem of RA-A collisions (see Figure 6). They meant the diffusion in energy states of an excited quasi-molecule in the course of one collision. Besides, authors of [14] had successfully applied RE diffusion in discrete RA spectrum to explain the abnormally high value of photoionization cross-section in the experiments on laser irradiation of a gas target. It was logical to suppose that quasi-monochromatic electric dipole field produced in the course
of the resonant charge transfer, which is built into the model of a dipole resonant mechanism, may lead to the RE diffusion in discrete energy spectrum in the case of RA chemi-ionization as well. Thus, the dipole resonant model of chemi-ionization processes could be further developed, taking into account redistribution of initial excitation over the grid of energy terms of a Rydberg quasi-molecule. This redistribution was modeled as RE diffusion in the Rydberg energy spectrum of excited states, using diffusion equation of Fokker-Planck-Kolmogorov type. Results subsequently obtained in this field allowed making a conclusion on the resonant character of RE diffusion and it being influenced by the internal nonlinear dynamic resonances arising when overtones of RE motion frequency coincide with the electron transition frequency. As a result, RE motion in the energy spectrum turns into a random wandering over a grid of crossing quasi-molecule potential energy terms. This results in the time evolution of distribution $f(n, t)$ for RE.

The results of research in the field of non-linear mechanics indicate that what is known as dynamic chaos conditions should be treated as typical rather than exceptional situation for the time dynamics of Hamiltonian systems with a small number of degrees of freedom. In the physics of atom collisions, the chaos conditions may arise as a consequence of local instability of valence electron trajectory orbits relative to indefinitely small perturbations. In general, there are always regions of the phase space and parameters of interacting particles, for which the dynamics of Hamiltonian system is stochastic (see[15,16]).

An example of an important physical system with the properties of significant trajectory instability is a quasi-classical model of an alkali atom Rydberg electron (RE) in the quasi-monochromatic electric microwave field of a dipole resonant mechanism suggested by [4]. In [17] gives the results of numerical simulation of RA diffusion ionization for alkali atoms induced by RE trajectory chaotization on a Keplerian orbit, induced by the electric microwave field generated in the quasi-molecule system in a single atom-atom collision.

Let us briefly discuss the parameters of stochastic diffusion model (the region where dynamic chaos conditions exist).

1. For stochastic instability to develop, the intensity of the internal electromagnetic field should exceed the critical value that can be estimated using what is known as resonance overlapping criterion, while the range of values $n_{\text{eff}}$, in which stochastic diffusion of RE is possible, is determined by Chirikov’s criterion [18].

2. At the lower limit of $n$ stochasticity region $n_{\text{eff}} \geq n_{\text{min}}(R)$, the diffusion is limited due to an increasing energy gap between neighboring energy-terms of excited atomic states.

3. The corresponding upper limit $N_{\text{max}}(R) \geq n_{\text{eff}}$ is related to the emergence of the effective ionization channel for Rydberg quasi-molecule at large values of $n$.

4. Effective diffusion time $T_{\text{diff}}$ has to be less than the time of collision $\tau$ itself.

Thus, RE stochastic diffusion during the time of one collision has first of all to become evident in the range of subthermal and cold collisions.

4. Conclusion
Dipole resonant mechanism of RA deexcitation, suggested by Smirnov and Mihajlov (1971) and later extended by Mihajlov and Janev [3] to chemi-ionization processes, implies the generation of a microwave electric field in a single RA+A collision, which leads to the instability of RE motion in Keplerian orbit and eventually to the stochastic diffusion of RE over excited states and consideration of a larger number of initial quasi-molecular energy-terms than it follows from the “classical” consideration taking into account orbital moments of colliding particles. For RA with an alkali atom structure at certain conditions in a weak electric field it is possible that particular transitions become forbidden, leading to the closure of some “stochastic” ionization channels, which in principle may lead to the disappearance of infrared lines in the spectra of astrophysical objects.
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