

<u>The resonant non-elastic processes in</u> <u>slow atom–Rydberg atom collisions in</u> <u>laboratory and astrophysical plasmas</u>

A.A. MIHAJLOV

Institute of Physics, P.O.Box 57, Pregrevica 118, Belgrade, Serbia mihajlov@ipb.ac.rs



- Dr. A. A. MIHAJLOV,
- Dr. V. A. SREĆKOVIĆ,
- Dr. Lj. M. IGNJATOVIĆ

Institute of Physics, P.O.Box 57, Pregrevica 118, Belgrade, Serbia

Collaboration

- Prof. M.S. DIMITRIJEVIĆ,

Astronomical Observatory, Volgina 7, 11060 Belgrade, Serbia

- Prof. A.N. KLYUCHAREV,

Department of Physics, Saint-Petersburg State University, Ulianovskaya 1, 198904 St. Petersburg, Petrodvorets, Russia

- Prof. Yu. N. GNEDIN

Central Astronomical Observatory, , Saint-Petersburg, Pulkovo "THE ATOMIC COLLISION PROCESSES IN STELLAR ATMOSPHERES", "ENERGY TRANSFER PROCESSES IN PHOTO- AND IONOSPHERE PLASMAS" and "ALKALI-METAL GEOCOSMICAL PLASMAS"





INTRODUCTION

- The aim of this presentation is to show and discuss the significant of some resonant non-elastic processes in atom–Rydberg atom collisions in laboratory and astrophysical plasmas.

- The processes of the (n - n')- mixing in the symmetric case and the chemiionization processes in both symmetric and non- symmetric cases are included in the considerations.

- In this context the important results in connection with the mentioned resonant non-elastic processes in stellar atmospheres are presented here. Also, the directions of further research of such processes are discussed.

THE (n – n')- MIXING PROCESSES IN THE COLLISIONS OF RYDBERG ATOMS WITH GROUND- STATE PARENT ATOMS

EXCITATION PROCESSES

$$A^{*}(n) + A = \begin{cases} A^{*}(n' = n + p) + A \\ A + A^{*}(n' = n + p) \end{cases}, \ n \gg 1, \ p \ge 1$$

DEEXCITATION PROCESSES

$$A^{*}(n) + A = \begin{cases} A^{*}(n' = n - p) + A \\ A + A^{*}(n' = n - p) \end{cases}, \ n - p \gg 1, \ p \ge 1 \end{cases}$$

THE CHEMI-IONIZATION PROCESSES IN SYMMETRIC AND NON-SYMMETRIC ATOM-RYDBERG ATOM COLLISIONS: associative (ai) and Penning (pi) ionization

Symmetric case

$$A^{*}(n, l) + A \to A_{2}^{+} + e;$$
(1) (ai)

$$A^{*}(n, l) + A \to A + A^{+} + e;$$
(2) (pi)

$$A^{*}(n, l) + A \to A + A^{+} + e;$$
(5)

Non-symmetric cases:

$$I_{B} < I_{A}$$

weakly non-symmetric case: $I_B \ll I_A$ Strongly non-symmetric case: $I_A - I_B \sim I_B$

$$A^*(n,l) + B \to AB^+ + e; \tag{3}$$
 (ai)

$$A^*(n,l) + B \to A + B^+ + e,$$
 (4) (pi)

$\alpha(u, v) \top D = \alpha \top D \top C,$

THE CHEMI-RECOMBINATION PROCESSES ARE DEFINED AS THE INVERSE PROCESSES IN RESPECT TO THE PROCESSES (1) - (4).

Schematic illustration of atom–Rydberg atom collisions and the resonant non-elastic processes on the base of the dipole resonant mechanism (DRM)



- $\boldsymbol{\epsilon}_n$ the energy of the Rydberg state with the given n
- $\boldsymbol{\epsilon}_k$ the energy of the free electron

 $U_1(R)$ and $U_2(R)\,$ - adiabatic energies of the ground and first excited electronic states of the molecular ion $(A_2^{\,+}\,{\rm or}\,AB^+)$

R – internuclear distance

Illustration of the differences between symmetric and non-symmetric cases



 R_{ni} – the upper border of the chemi-ionization zone for the given *n* in the symmetric case.

 I_n - the ionization potential of the Rydberg atom $A^*(n)$

Chemi-Ionization Processes in the Decay Approximation on the basis of DRM

The symmetric case, without (n-n')-mixing

The manner of application of the dipole resonant mechanism in the decay approximation according to [39] is characterized by several basic elements. As first it is assumed that the relative motion of the nuclei in or collisions is described by a classical trajectory characterized by the collision parameter p and the initial (collisional) energy E, under condition that

$$\rho \ll r_n \sim n^2$$

where is the mean radius of the atom, as it is illustrated by Fig. 1, and that the trajectories are considered which, for given and, pass through the chemi-ionization zone, that is, the region

 $R \leq R_{i;n}$,

where is the internuclear distance, and the boundary value is determined by the ionization energy of the atom and the corresponding parameters of the ion-atom subsystem (or).

Within this approximation the ion-atom subsystem is described by means of the electronic states of the corresponding molecular ions,

or , denoted here as and , supposing that , where and are the ionization potentials of the atoms and , and that

 $U_{12}(R) \equiv U_2(R) - U_1(R) > 0$

where and are the potential curves corresponding to the respective states and. Here is the ground electronic state of the molecular ion, or, in the general case, one from a group of states asymptotically correlated to the same state of the subsystem or at, to which the ground state is correlated.

Similarly to that, here is the first excited electronic state of the molecular ion, or, in the general case, one from a group of excited states asymptotically correlated to the same state of the subsystem or at , to which the first excited state is correlated.

In the decay approximation the chemi-ionization processes are treated as a result of the transition

 $|2, R > |n, l \rightarrow |1, R > |k, l' >$

of the complete system from an initial state to a final state, which is caused by DRM. This event can be treated as a simultaneous transitions of the outer electron and of the ion-atom subsystem, namely: and respectively, which is also illustrated in Fig.1.

It is assumed that transitions (16) predominantly take place within narrow neighborhoods of the resonant points which are the roots of the equation $\varepsilon_{nk} \equiv \varepsilon_k - \varepsilon_n = U_{12}(R)$,

where and are the energies of the outer electron in the initial (bound) and the final (free) state, and the splitting term is defined by (15). During the collision the chemi-ionization process is described by the ionization rate $W_{i;n}(R)$, which implies that, for a given the outer electron passes to the free state with energy. In accordance with [39] the quantity can be presented in the form

$$W_{i;n}(R) = \frac{4}{3\sqrt{3}n^5} \cdot D_{12}^2(R) \cdot G_{nk}, \quad D_{12} \ R = <2; R \mid D(R) \mid 1; R >,$$

where is the operator of the dipole momentum of the considered ion-atom subsystem, and is the corresponding (bound-free) Gaunt factor (see [40]).

It is understood that the chemi-ionization process takes place within the interval, where is the moment of the collision system's entrance into the reaction zone defined by the relation (14), where is a root of the equation, - the moment of leaving the zone, and is taken to be the moment when the collision system reaches the minimal internuclear distance. In accordance with [39] the probability of the chemi-ionization process in an or collision with given and is expressed by, where is the time, - the probability of the collision system's entering the reaction zone just in the initial state, i.e. in the symmetric in non-symmetric case, and - the probability of this state's decay, which must satisfy the equation

$$\frac{dp_{i;n}(t;\rho,E)}{dt} = \left[1 - p_{i;n}(t;\rho,E)\right] \cdot W_{i;n}(R(t)), \quad -t_0 \le t \le t_0,$$

with an initial condition

$$p_{i;n}(-t_0;\rho,E)=0$$

One can see that the solution of this equation can be presented in the form

$$p_{i;n}(t;\rho,E) = 1 - \exp(I_{i;n}(t;t_0)), \quad I_{i;n}(t;t_0) = \int W_{i;n}(R(t))dt.$$

From here it follows that the probability of chemi-ionization for given and , e.g. is defined by relations

$$P_{i;n}(\rho, E) = p_{in}[1 - \exp(2I_{i;n}(t_0))], \qquad I_{i;n}(t_0) = \int_{0}^{t_0} W_{i;n}(R(t)) dt.$$

Than, taking that, where is the internuclear radial velocity, we can presented in the form

$$P_{i;n}(\rho, E) = p_{in}[1 - \exp(2 \cdot \int_{R_{min}}^{R_{i,n}} \frac{W_{i;n}(R)dR}{v_{rad}(R;\rho, E)})], \quad v_{rad}(R;\rho, E) = \sqrt{\frac{2}{\mu}[E - U_2(R) - \frac{E\rho^2}{R^2}]}$$
(i1)

where is given by Eq. (18).

After that, the cross-section for the considered chemi-ionization process and the corresponding rate coefficient can be presented by means the usual expressions

$$\sigma_{ci;n}(E) = \int_{0}^{\rho_{\max}(E,n)} P_{i;n}(\rho,E) \cdot 2\pi\rho d\rho \qquad \qquad K_{ci;n}(T) = \int_{E_{\min}(n)}^{\infty} \sqrt{2E/\mu} \cdot \sigma_{ci;n}(E) \cdot f(E;T) dE \qquad (i2)$$

where is given by Eqs. (18) and (23), the parameters and are determined by the behavior of the potential curve and the splitting term, and is the corresponding distribution function over at a given temperature, which depends on the considered conditions (a single beam, crossed beams, a cell).

The non-symmetric case, without (n-n')-mixing

In Eqs. (i1) and (i2) the upper boundary distance $R_{i;n}$ is replaced by $R_{i;n}$, where the value of $\tilde{R}_{i;n}$ is determined by the behavior of the corresponding dipole matrix element D_{12} . This behavior is illustrated on the example of the ion HeNe⁺.



X. J. Liu et ai. Phys Rev A. (2010)

It is taken in to account the decay of the initial electronic state of the considered atom-Rydberg atom system in the region of the internuclear distances from $R_{i;n}$ to $\check{R}_{n;mix}$, where $\check{R}_{n;mix}$, is the upper boundary of the (n-n')-mixing region with n'=n+1

We introduce an initial Rydberg state of an outer electron $|n\rangle = |n, l, m\rangle$ and blocks of Rydberg states $|n'\rangle = |n', l', m'\rangle$ with fixed quantum numbers l' and m', satisfying:

$$n + p_1 \leq n' \leq n + p_2$$
, (13)

where in the general case we have

$$p_2 \ge p_1 \ge 1$$
. (14)

Every block containing $p_2 - p_1 + 1$ discrete states corresponds to a block of continuous states characterized by quantum numbers n^v , l^r and m^r , where n^v is continuously changed from $n + p'_1$ to $n + p'_2$, and energies ϵ_{a^v} , satisfying

$$\int_{\varepsilon_{mp_1}}^{\varepsilon_{mp_2}} \rho_{g,\pi^*}(l', m') d\varepsilon_{g''} = p_2 - p_1 + 1, \quad (15)$$

$$\int_{\epsilon_{mp'_{i}}}^{\epsilon_{mp'_{i}}} f_{e,\pi^{*}}(l,m;l',m') \rho_{e,\pi^{*}}(l',m') d\epsilon_{e'} - f(n,p_{1},p_{2};l',m'). \quad (16)$$

Here $\rho_{n;n'}(l',m')$ is the density of continuous states $|n'',l',m'\rangle_l f_{n;n''}(l,m;l',m')$ is the oscillator strength for $|n,l,m\rangle \rightarrow |n'',l',m'\rangle$ transitions and $f(n,p_1,p_2)$ is the total oscillator strength for the transition of the outer electron from the $|n,l,m\rangle$ state to a given block of Rydberg states. We will assume that $\epsilon_{n'} = -Ry/n'^2$ in order to have an appropriate distribution of continuous states, and

$$\rho_{n;e'}(l', m') = \frac{dn''}{dc_{e'}} = \frac{n'^3}{2Ry}.$$
 (17)

From equation (15) it follows that the parameters $p'_{1,2}$ must satisfy the expression

$$p'_2 - p'_1 = p_2 - p_1 + 1.$$
 (18)

While in [18] we had $p'_1 = p_1$ and $p'_2 = p_2 + 1$, here p'_1 and p'_2 are given as:

$$p'_1 = p_1 - \Delta p$$
, $p'_2 = p_2 + 1 - \Delta p$, $0 \le \Delta p < 1$, (19)

where it is assumed that $\Delta p = \Delta p(n, p_1, p_2)$.

Let $|2, R; n, l, m\rangle = |2, R\rangle |n, l, m\rangle$ be the initial state of the system $H^*(n) + H$ in the domain of internuclear distances satisfying (5). The described resonant mechanism generates transitions into the final states $|1, R; n', l', nn'\rangle = |1, R\rangle |n', l', m'\rangle$ in the vicinity of the point $R = R_{\pi,\pi'}$. Because these transitions are treated as results of continuous decay of the initial state, the total transition probability of the outer electron from the state $|n, l, m\rangle$ inche blocks of Rydberg states defined by equation (13) is identified with the total transition probability into blocks of continuous states. These are described in a quasi-static approximation, similarly to the chemi-ionization processes in [4], and are characterized by the decay rate

$$W_{a,l,m}^{a^{*}} = \frac{2\pi}{\hbar} \sum_{\vec{l},n^{*}} |\langle n, l, m; 2, R_{a,n^{*}}|V_{d}|1, R_{a,n^{*}}; n^{*}, l^{'}, m^{'}\rangle|^{2} \rho_{n,n^{*}}(l^{'}, m^{'}).$$
 (20)

Here $[1, R_{n;e'}; n'', t', m') = [1, R_{n;e'}]n'', t'm')$, dipole interaction operator V_d is given by equation (9), and $R_{e;n'}$ is the internuclear distance which satisfies:

$$U_2(R_{\pi;\pi^2}) - U_1(R_{\pi;\pi^2}) = \epsilon_{\pi;\pi^2},$$
 (21)

where

 $\epsilon_{n;n''} = \epsilon_{n'} - \epsilon_{n}. \qquad (22)$

States $|1, R; n'', l', m'\rangle$ will be treated through matrix elements in (20). Namely, we will assume that: the expression for element $\langle n, l, m; 2, R|V_l|1, R; n'', l', m'\rangle$ can be obtained from the expression for element $\langle n, l, m; 2, R|V_l|1, R; n', l', m'\rangle$ by substituting n' with n''; the squares of moduli of matrix elements $|\langle n, l, m; 2, R|V_l|1, R; n', l', m'\rangle|^2$ can be written [19] as

$$\begin{split} |\langle n, l, m; 2, R| V_d | 1, R; n', l', m' \rangle|^2 \\ &- \frac{m^2 \hbar^4}{c^2} (\epsilon_{n'} - \epsilon_n)^4 |\langle n, l, m| r_R | n', l', m' \rangle|^2 |\langle 1, R| d_R | 2, R \rangle|^2. \end{split}$$
(23)

Here m is the mass of electrons, and rg and dg denote the projections of the outer electron radius \vec{r} and dipole momentum operator \vec{d} of the subsystem H⁺ + H onto the internuclear axis, respectively. Using equation (20) we then have

$$W_{g,l,m}^{a^{\prime\prime}} = \frac{2\pi m^2}{\hbar^2 \epsilon^2} \epsilon_{g,a^{\prime\prime}}^4 \sum_{\vec{P},n^{\prime\prime}} |\langle n, l, m | r_{\vec{R}} | n^{\prime\prime}(R), l^{\prime}, m^{\prime} \rangle|^2 |\langle 1, R | d_{\vec{R}} | 2, R \rangle|^2 \rho_{h,a^{\prime\prime}}(l^{\prime}, m^{\prime}).$$
(24)

The next step in our model is to introduce the average decay rate $W_{n;e^i}$ of the initial collisional system $H^{i}(n) + H$, defined as:

$$W_{x;x'} = \frac{1}{n^2} \sum_{l,n} W_{x;l,n}^{x'}$$
 (25)

In the quasi-static approximation we have

$$\sum_{l,m} \sum_{l',m'} |\langle n, l, m| r_{\mathbb{Z}} | n'', l', m' \rangle|^2 = \frac{1}{3} \sum_{l,m'} \sum_{l',m'} |\langle n, l, m| \bar{r} | n'', l', m' \rangle|^2.$$
(26)

Assuming that R in the domain relevant for the process is several times larger than the atomic unit length, we have [4, 12]

$$(1, R|d_R|2, R)|^2 = \frac{e^2R^2}{4}$$
. (27)

From equations (17), (24), (26) and (27), the average decay rate W_{s,t^c} is:

$$W_{e;e^i} = \frac{\pi m}{4\hbar^3} \epsilon^3_{\pi;e^i} \frac{n'^3}{2R_y} f_{e;e^i} R^2_{\pi;\pi^i},$$
 (28)

where $f_{n,n'}$ is the average oscillator strength for the $n \rightarrow n''$ transition, given by

$$\hat{h}_{n,n'} = \frac{1}{n^2} \sum_{l,n'} \sum_{l',n'} f_{n',n'}^{n',l',n'},$$
 (29)

$$f_{s;l,n}^{e^{s};l',n'} = \frac{2m}{2\hbar^{2}} (\epsilon_{s^{s}} - \epsilon_{s}) |\langle n, l, m| r_{R} | n''(R), l', m' \rangle|^{2}.$$
 (30)

The expression for $f_{\pi;\pi'}$ is obtained by substituting n' with n'' in the expression for $f_{\pi;\pi'}$ from [19]:

$$f_{n;\sigma^{*}} = \frac{2^{5}}{3\sqrt{3\pi}}n \left(\frac{n^{\prime\prime}}{n^{\prime/2} - n^{2}}\right)^{3} g_{\sigma;n^{*}},$$
 (31)



where $g_{n;n^*}$ is the Gaunt factor. After substituting ϵ_{n^*} and ϵ_n into equation (28) with their expressions, we have finally

$$W_{e;e'} = \frac{R_{a;e'}^2}{3\sqrt{3n^2}}g_{a;a'}$$
. (32)

This expression is the same as the decay rate of the initial state of the system $H^{*}(n) + H$, in the case of chemi-ionization processes [4]. In domain $n \gg 1$ a function $g_{n,n^{*}}$ is slowly changing for different n^{N} , and we can assume:

$$g_{e,n'} = g_{e,n'=n+p}$$
, (33)

for $n' - \Delta p \leq n'' < n' + 1 - \Delta p$. Note that the expression (32) was considered in [20] for processes (1) for n' > n, which are similar to chemi-ionization processes. However, the expression here is based on equation (31) applied for $f_{ne''}$.

Further procedures for rate coefficients for processes (1) are the same as for chemiionization processes (3), described in detail in [5]. Because of this, only the main steps will be presented here. For transitions $n \rightarrow (n^o, n^o + dn^o)$, illustrated in figure 3, the differential probability, differential cross-section and differential rate coefficient are given by:

$$dP_{n;e^{i}} = \frac{1}{2}(2W_{n;e^{i}}dt) = W_{n;n^{i}}\frac{dR}{v_{rad}(b, E, R_{n;e^{i}})},$$
 (34)

$$d\sigma_{\pi;\pi^*}(E) = 2\pi \int_0^{b_{max}(E,R_{spin})} dP_{\pi;\pi^*}b^2 db,$$
 (35)

$$dK_{\kappa;\pi^*}(T_n) = \int_{\ell_{\kappa,\mu^*}}^{\infty} f_{\tau_n}(E)v(E) d\sigma_{\pi;\pi^*}\sqrt{E} dE$$
, (36)

where b and E are the impact parameter and collisional energy, $R_{s;s^*}$ is defined by equation (21), and $v(E) = (2E/\mu)^{1/2}$ is the radial velocity:

$$v_{rad}(b, E, R_{s;x^*}) = \left\{ \frac{2E}{\mu} \left[E - U_2 \left(R_{s;x^*} - \frac{Eb^2}{R_{s;s^*}^2} \right) \right] \right\}^{1/2}$$
. (37)

 μ is the reduced mass of collisional particles, $f_{T_{a}}(E)$ is the Maxwell distribution function for atomic temperature T_{a} , normalized by the condition

$$\int_{-\infty}^{\infty} f_{T_{*}}(E) \sqrt{E} dE = 1.$$
 (38)

A parameter $b_{max}(E, R_{n;x^*})$ is calculated from the equation:

$$v_{nd}(b_{nxx}, E, R_{s,x'}) = 0,$$
 (39)

and $E_{\min}(n; n') = U_2(R_{n;e'})$. From equations (22) and (34)–(39) the differential rate coefficient $dK_{n;n'}$ is written as:

$$dK_{g,\pi^{+}}(T_{n}) = \frac{2\pi}{3\sqrt{3}} \frac{e^{2}}{\hbar a_{0}^{3}} n^{-5}g_{g,\pi^{+}}X(R_{g,\pi^{+}}) \left\{ R^{4} \exp\left[-\frac{U_{2}(R)}{kT_{n}}\right] \right\}_{R=R_{n}r^{+}} dR, \quad (40)$$

where a_0 is the atomic unit length, and $X(R_{g;g'})$ is:

$$X(R_{n;s^{s}}) = \frac{\Gamma(\frac{3}{2}, \frac{-U_{1}(R_{n;s^{s}})}{kT_{s}})}{\Gamma(\frac{3}{2})},$$
 (41)

 $\Gamma(3/2, x)$ i $\Gamma(x)$ being incomplete and complete gamma functions.

 $K_{n;n+p_1,n+p_2}(T_n)$ denotes the total rate coefficient of processes (1) for the transitions of an outer electron of the system $H^*(n) + H$ into all states with the principal quantum number n' from domain (13). This is calculated using

$$K_{n;n+p_1,n+p_2}(T_n) = \int_{n+p_1-\Delta p}^{n+p_2+1-\Delta p} dK_{n;n^*}(T_n). \tag{42}$$

A similar method to this for calculating $K_{x;x+p_1,x+p_2}(T_u)$ was applied in calculating the coefficient of continuous absorption from a block of Rydberg states, the rate coefficient for electron-ion photo-recombination with free electron transition in a given block of Rydberg states (see [21, 22]), and for electron-ion-atom recombination [1]. The oscillator strength was assumed to be a continuous function of the principal quantum number.

To calculate the rate coefficient of processes (1) for fixed n and n' = n + p, denoted by $K_{n;n+p}(T_n)$, we will use that:

$$K_{n;n+p}(T_n) = K_{n;n+p_1,n+p_2}(T_n),$$
 (43)

for $p_1 = p_2 = p$, and

$$\zeta_{x;s+p_1,x+p_2}(T_u) = \sum_{p=p_1}^{p_2} K_{x;s+p}(T_u),$$
 (44)

for $1 \leq p_1 < p_2$. From (33), (40), (42) and (43) it follows that $K_{n;n+p}(T_n)$ can be written as:

$$K_{n;s+p}(T_{u}) = \frac{2\pi}{3\sqrt{3}} \frac{(ea_{0})^{2}}{\hbar} n^{-5} g_{n;s+p} \int_{\mathcal{B}_{uu}(n,s+p)}^{\mathcal{B}_{uu}(n,s+p)} X(R) \exp\left[-\frac{U_{2}(R)}{kT_{u}}\right] \frac{R^{4} dR}{a_{0}^{5}}, \quad (45)$$

where $R_{\min}(n, n + p)$ and $R_{\max}(n, n + p)$ are calculated from equations

$$\epsilon(R = R_{\min}) = \epsilon_{s+p+1-\Delta p} - \epsilon_s, \qquad \epsilon(R = R_{\max}) = \epsilon_{s+p-\Delta p} - \epsilon_s,$$
 (46)

$$U_{1}(R) = U_{2}(R) - U_{1}(R).$$
 (47)

$$\int_{n+1-\Delta p}^{n+2-\Delta p} \frac{2^5}{3\sqrt{3\pi}} n \left(\frac{n^0}{n^{\prime/2}-n^2}\right)^3 dn^{\prime\prime} - \frac{2^5}{3\sqrt{3\pi}} n \left[\frac{n+1}{(n+1)^2-n^2}\right]^3. \quad (48)$$

Within the domain $4 \le n \le 10$, the parameter Δp is practically constant, and we will assume its value $\Delta p = 0.380$, this corresponding to n = 5.

$$K_{n;n-p}(T_n) = K_{n-p;n}(T_n) \frac{(n-p)^2}{n^2} \exp\left(\frac{\epsilon_{n-p;n}}{kT_n}\right),$$
 (51)

$$W_{n;n"} = \frac{R_{n;n"}^2}{3\sqrt{3}n^5} g_{n;n"}$$

The (n-n') mixing rate coefficients: the case A=H(1s)

		Tabi	le 2. Excitat	ion rate coe	fficients K_{e_i}	$_{a+g}(T_{a})$ (10	-9 cm ³ s ⁻¹)).		
					T ₁	(10 ³ K)				
л	Р	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
	1	4,4232	5.0133	5.4997	5.9047	6.2456	6.5355	6.7845	7.0003	7.1887
	2	0.7228	0.8997	1.0576	1.1973	1.3205	1.4293	1.5256	1.6112	1.6876
4	3	0.2401	0.3155	0.3860	0.4506	0.5092	0.5621	0.6098	0.6528	0.6917
	4	0.1091	0.1483	0.1861	0.2216	0.2544	0.2844	0.3118	0.3367	0.3595
	5	0.0592	0.0824	0.1053	0.1270	0.1474	0.1662	0.1835	0.1994	0.2140
	1	3.3708	3.5901	3.7604	3.8960	4.0061	4.0972	4.1736	4.2385	4.2943
	2	0.7642	0.8574	0.9332	0.9956	1.0476	1.0916	1.1291	1.1614	1.1895
5	3	0.3020	0.3502	0.3906	0.4246	0.4534	0.4781	0.4995	0.5180	0.5343
	4	0.1524	0.1308	0.2050	0.2257	0.2435	0.2589	0.2723	0.2840	0.2944
	5	0.0887	0.1069	0.1227	0.1364	0.1482	0.1585	0.1676	0.1755	0.1825
	1	2.2484	2.3282	2.3886	2.4356	2.4731	2.5038	2.5292	2.5507	2.5690
	2	0.6072	0.6488	0.6812	0.7069	0.7278	0.7451	0.7596	0.7719	0.7825
6	3	0.2658	0.2902	0.3096	0.3252	0.3380	0.3487	0.3577	0.3654	0.3721
	4	0.1435	0.1591	0.1716	0.1818	0.1903	0.1974	0.2035	0.2087	0.2132
	5	0.0875	0.0982	0.1068	0.1139	0.1198	0.1248	0.1291	0.1328	0.1360
	1	1.4721	1.5029	1.5258	1.5434	1.5574	1.5687	1.5780	1.5859	1.5925
	2	0.4415	0.4599	0.4739	0.4848	0.4935	0.5006	0.5065	0.5116	0.5158
7	3	0.2065	0.2182	0.2272	0.2344	0.2401	0.2449	0.2488	0.2522	0.2550
	4	0.1166	0.1246	0.1308	0.1357	0.1397	0.1430	0.1458	0.1482	0.1502
	5	0.0735	0.0792	0.0837	0.0873	0.0902	0.0926	0.0946	0.0964	0.0978
	1	0.9787	0.9913	1.0007	1.0078	1.0134	1.0180	1.0217	1.0248	1.0275
	2	0.3144	0.3228	0.3291	0.3339	0.3378	0.3409	0.3435	0.3457	0.3475
8	3	0.1538	0.1595	0.1638	0.1672	0.1699	0.1721	0.1739	0.1755	0.1768
	4	0.0897	0.0938	0.0969	0.0993	0.1013	0.1029	0.1042	0.1053	0.1063
	5	0.0530	0.0610	0.0633	0.0651	0.0666	0.0678	0.0688	0.0697	0.0704
	1	0.6669	0.6724	0.6764	0.6795	0.6819	0.6839	0.6855	0.6868	0.6879
	2	0.2248	0.2288	0.2318	0.2340	0.2358	0.2373	0.2385	0.2395	0.2404
9	3	0.1136	0.1165	0.1186	0.1203	0.1216	0.1227	0.1236	0.1243	0.1249
	4	0.0679	0.0700	0.0716	0.0729	0.0738	0.0747	0.0753	0.0759	0.0764
	5	0.0447	0.0463	0.0476	0.0485	0.0493	0.0499	0.0504	0.0508	0.0512
	1	0.4663	0.4688	0.4707	0.4721	0.4732	0.4740	0.4748	0.4754	0.4759
	2	0.1629	0.1649	0.1663	0.1675	0.1684	0.1691	0.1697	0.1701	0.1706
10	3	0.0843	0.0859	0.0870	0.0878	0.0885	0.0890	0.0895	0.0899	0.0902
	4	0.0514	0.0525	0.0534	0.0540	0.0545	0.0550	0.0553	0.0556	0.0559
	5	0.0343	0.0352	0.0359	0.0364	0.0368	0.0372	0.0374	0.0377	0.0379

The case A=He(1s²)

n	P	$T_{\rm a} \ (10^3 {\rm K}$	6)							
		4.0	4.5	5.0	6.0	8.0	10.0	12.0	16.0	20.0
4	1	1.005	1.080	1.143	1.243	1.378	1.462	1.520	1.594	1.638
	2	0.195	0.221	0.244	0.283	0.338	0.374	0.400	0.434	0.455
	3	0.072	0.084	0.095	0.114	0.142	0.161	0.175	0.194	0.206
	4	0.035	0.041	0.048	0.058	0.075	0.087	0.095	0.107	0.114
	5	0.020	0.024	0.028	0.035	0.045	0.053	0.058	0.066	0.071
5	1	0.682	0.707	0.728	0.760	0.800	0.824	0.841	0.861	0.873
	2	0.170	0.182	0.191	0.207	0.227	0.239	0.248	0.258	0.265
	3	0.072	0.078	0.083	0.092	0.103	0.111	0.116	0.122	0.126
	4	0.038	0.042	0.045	0.050	0.058	0.062	0.066	0.070	0.072
	5	0.023	0.025	0.027	0.031	0.036	0.039	0.041	0.044	0.046
6	1	0.432	0.441	0.448	0.459	0.473	0.481	0.486	0.493	0.497
	2	0.124	0.128	0.132	0.138	0.146	0.151	0.154	0.157	0.160
	3	0.056	0.059	0.062	0.065	0.070	0.073	0.075	0.077	0.079
	4	0.031	0.033	0.035	0.037	0.040	0.042	0.044	0.045	0.046
	5	0.019	0.021	0.022	0.024	0.026	0.027	0.028	0.029	0.030
7	1	0.276	0.279	0.282	0.286	0.292	0.295	0.297	0.299	0.301
	2	0.086	0.088	0.089	0.092	0.095	0.097	0.098	0.100	0.101
	3	0.041	0.042	0.044	0.045	0.047	0.049	0.049	0.050	0.051
	4	0.024	0.025	0.025	0.027	0.028	0.029	0.029	0.030	0.031
	5	0.015	0.016	0.016	0.017	0.018	0.019	0.019	0.020	0.020
8	1	0.181	0.183	0.184	0.186	0.188	0.189	0.190	0.191	0.192
	2	0.059	0.060	0.061	0.062	0.064	0.065	0.065	0.066	0.066
	3	0.030	0.030	0.031	0.032	0.033	0.033	0.034	0.034	0.034
	4	0.018	0.018	0.018	0.019	0.020	0.020	0.020	0.021	0.021
	5	0.011	0.012	0.012	0.013	0.013	0.013	0.014	0.014	0.014
9	1	0.122	0.123	0.124	0.125	0.126	0.126	0.127	0.127	0.128
	2	0.042	0.042	0.043	0.043	0.044	0.044	0.045	0.045	0.045
	3	0.021	0.022	0.022	0.022	0.023	0.023	0.023	0.024	0.024
	4	0.013	0.013	0.013	0.014	0.014	0.014	0.014	0.015	0.015
	5	0.009	0.009	0.009	0.009	0.009	0.010	0.010	0.010	0.010
10	1	0.085	0.086	0.086	0.086	0.087	0.087	0.087	0.088	0.088
	2	0.030	0.030	0.031	0.031	0.031	0.031	0.032	0.032	0.032
	3	0.016	0.016	0.016	0.016	0.017	0.017	0.017	0.017	0.017
	4	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.011	0.011
	5	0.006	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007

The (n-n')-mixing processes in the solar photosphere (A=H)





Fig. 3. The behavior of N_e and N(1) in $[cm^{-3}]$ as functions of height h within the considered part of the Solar atmosphere from model C of Vernazza et al. (1981)



Fig.4. The behavior of the temperature T and the parameter $\eta = N(1)/N_e$ as functions of height h within the considered part of the Solar atmosphere from model C of Vernazza et al. (1981)

Fig. 5. The behavior of the parameter $F_{n,n+p} = (K_{n,n+p} \cdot \eta)/\alpha_{n,n+p}$, characterizing the relative efficiency of atom-atom and electron-atom (n - n')- mixing processes, as a function of height h for n = 4 and p = 1-5. The atom-atom rate coefficient $K_{n,n+p}$ is given by Eqs. (10)– (12) and the parameter η - by Eq. (14). The electron-atom rate coefficient $\alpha_{n,n+p}$ is taken from Vriens & Smeets (1980).

we compare the studied collision processes only with other relevant collision processes, omitting the radiative decay of hydrogen Rydberg states. The radiative decay, which causes the deviation from LTE in the considered part of the Solar atmosphere, is already included in Vernazza's model, so that the "optical part" of this model does not need to undergo any changes. We show that the "collision part" of Vernazza's model has to be changed by adding atomic collision processes (1)–(8).

The relative efficiency of processes (7) and (8) in comparison to process (6) is characterized by the parameter $F_{n;nep}(T)$

$$F_{n;n\pm p}(T) = \frac{K_{n;n\pm p}(T)N(n)N(1)}{\alpha_{n;n\pm p}(T)N(n)N_e} = \frac{K_{n;n\pm p}(T)\eta_{en}}{\alpha_{n;n\pm p}(T)},$$
(15)

where N(n) is the excited atom states population for given n, the parameter η_{ea} is defined by Eq. (14), and $\alpha_{e,n\pm p}(T_e)$ is the rate coefficient for the electron-atom process (6) taken from Vriens & Smeets (1980).

The (n-n')-mixing processes in the DB White dwarfs atmospheres (A=He)



Chemi-ionization

		Calculated Value	les of Coefficient	$K_{\rm ci}$ (cm ³ s ⁻¹) as a	a Function of <i>n</i> an	d <i>T</i>	
T (K)				n			
	2	3	4	5	6	7	8
4000	0.150E-11	0.619E-09	0.126E-08	0.576E-09	0.554E-09	0.463E-09	0.366E-09
4250	0.202E-11	0.549E-09	0.106E - 08	0.617E-09	0.583E-09	0.482E-09	0.378E-09
4500	0.260E - 11	0.501E-09	0.900E-09	0.656E-09	0.611E - 09	0.500E-09	0.389E-09
4750	0.324E-11	0.488E-09	0.833E-09	0.694E-09	0.637E - 09	0.517E-09	0.400E-09
5000	0.403E-11	0.495E-09	0.815E-09	0.730E-09	0.662E - 09	0.533E-09	0.410E-09
5250	0.504E-11	0.501E-09	0.800E-09	0.765E-09	0.686E - 09	0.548E-09	0.420E-09
5500	0.623E-11	0.500E-09	0.782E-09	0.799E-09	0.709E-09	0.563E-09	0.428E-09
5750	0.756E-11	0.493E-09	0.764E-09	0.832E-09	0.731E-09	0.576E-09	0.437E-09
6000	0.909E-11	0.490E-09	0.757E-09	0.864E-09	0.752E-09	0.589E-09	0.445E-09
6250	0.108E - 10	0.502E-09	0.766E-09	0.895E-09	0.772E-09	0.602E-09	0.453E-09
6500	0.128E - 10	0.519E-09	0.783E-09	0.924E-09	0.791E-09	0.613E-09	0.460E-09
7000	0.175E-10	0.540E-09	0.808E-09	0.981E-09	0.827E-09	0.635E-09	0.473E-09
7500	0.232E-10	0.574E-09	0.848E-09	0.103E-08	0.860E - 09	0.655E-09	0.485E-09
8000	0.300E - 10	0.609E-09	0.891E-09	0.108E - 08	0.892E - 09	0.674E-09	0.497E-09
8500	0.380E-10	0.650E-09	0.939E-09	0.113E-08	0.920E-09	0.691E-09	0.507E-09
9000	0.470E - 10	0.688E-09	0.986E-09	0.118E - 08	0.948E-09	0.707E-09	0.516E-09
9500	0.574E-10	0.733E-09	0.104E - 08	0.122E - 08	0.973E-09	0.722E-09	0.525E-09
10000	0.689E - 10	0.787E-09	0.109E-08	0.126E-08	0.997E-09	0.736E-09	0.533E-09

Chemi-recombination

$T(\mathbf{K})$											
	2	3	4	5	6	7	8				
4000	0.190E - 27	0.732E-27	0.390E-27	0.114E - 27	0.977E-28	0.831E-28	0.709E-28				
4250	0.130E-27	0.458E - 27	0.257E-27	0.102E-27	0.880E - 28	0.753E-28	0.645E-28				
4500	0.918E-28	0.305E - 27	0.177E-27	0.914E - 28	0.799E-28	0.688E - 28	0.591E-28				
4750	0.666E-28	0.223E-27	0.135E-27	0.828E-28	0.730E-28	0.631E-28	0.544E-28				
5000	0.506E-28	0.174E - 27	0.110E-27	0.755E-28	0.671E-28	0.582E-28	0.503E-28				
5250	0.403E-28	0.138E-27	0.912E-28	0.693E-28	0.619E-28	0.540E-28	0.467E - 28				
5500	0.331E-28	0.111E-27	0.763E-28	0.639E-28	0.575E-28	0.502E-28	0.436E-28				
5750	0.275E-28	0.889E-28	0.645E - 28	0.592E-28	0.535E-28	0.469E-28	0.407E-28				
6000	0.233E-28	0.731E-28	0.558E-28	0.551E-28	0.500E-28	0.440E-28	0.382E-28				
6250	0.201E-28	0.627E - 28	0.498E-28	0.514E-28	0.469E-28	0.413E-28	0.360E-28				
6500	0.176E-28	0.548E-28	0.451E-28	0.482E-28	0.441E-28	0.389E-28	0.339E-28				
7000	0.139E-28	0.421E - 28	0.374E-28	0.427E-28	0.393E-28	0.348E-28	0.304E-28				
7500	0.114E-28	0.341E-28	0.322E-28	0.382E-28	0.354E-28	0.314E-28	0.275E-28				
8000	0.964E-29	0.284E - 28	0.283E-28	0.345E-28	0.321E-28	0.286E - 28	0.250E-28				
8500	0.834E-29	0.243E-28	0.253E-28	0.314E - 28	0.293E-28	0.261E-28	0.229E-28				
9000	0.731E-29	0.211E-28	0.229E - 28	0.287E - 28	0.269E - 28	0.240E - 28	0.211E - 28				
9500	0.654E-29	0.187E-28	0.209E-28	0.264E - 28	0.248E - 28	0.222E - 28	0.195E-28				
10000	0.590E-29	0.169E-28	0.194E-28	0.245E-28	0.230E-28	0.206E-28	0.181E - 28				

 1_{2} 4.522 **C** 105 11.2 82

The chemi-ionization/recombination in the solar photosphere (A=H)

Chemi-ionization

Figure 3. Behavior of the quantity $F_{i;ea}^{(ab)}(n)$ given by Equation (5), as a function of height h.

$$F_{i}(n,T) = \frac{I_{ci}(n,T)}{I_{i;ea}(n,T)} = \frac{K_{ci}(n,T)}{K_{ea}(n,T)} \cdot N_{1}N_{e},$$
 (28)

which characterize the relative efficiency of partial chemiionization processes (1, 2) together and the impact electron-atom ionization (5) in the considered plasma. The total chemi-ionization and recombination rate coefficients $K_{ci}(n, T)$ are determined here by the method described in the previous section, and impact ionization rate coefficients $K_{ea}(n, T)$ are taken from Vriens & Smeets (1980). In Figure 3, the behavior of the quantities $F_{i,ea}(n, T)$ for $2 \le n \le 8$ as functions of height *h* is shown, according to the data $(N_1, N_e, \text{ and } T)$ from Vernazza et al. (1981) for solar photosphere. One can see that the efficiency of the considered chemi-ionization processes in comparison with the electron-atom impact ionization is dominant for $2 \le n \le 6$ and becomes comparable for n = 7 and 8.

However, in order to compare the relative influence of the chemi-ionization processes (1) and (2) together to that of the

Figure 4. Behavior of the quantity $F_{i;es}(2; 8)$ given by Equation (29), as a function of height h.

impact electron-atom ionization process (5) on the whole block of the excited hydrogen atom states with $2 \le n \le 8$, we will calculate quantity $F_{i,ea;2-8}(T)$, given by

$$F_{i,ea;2-8}(T) = \frac{\sum_{n=2}^{8} I_{ci}(n, T)}{\sum_{n=2}^{8} I_{i;ea}(n, T)} \\ = \frac{\sum_{n=2}^{8} K_{ci}(n, T) \cdot N_n}{\sum_{n=2}^{8} K_{ea}(n, T) \cdot N_n} \cdot N_1 N_e, \quad (29)$$

which can reflect the influence of the existing populations of excited hydrogen atom states within a non-LTE model of the solar atmosphere. In Figure 4, the behavior of the quantity $F_{i,ea;2-8}(T)$ as functions of height *h* is shown according to the same data from Vernazza et al. (1981). As one can see, the real influence of the chemi-ionization processes on the total populations of states with $2 \le n \le 8$ remains dominant with respect to the concurrent electron-atom impact ionization processes almost in the whole photosphere (50 km $\lesssim h \lesssim 750$

Chemi-recombination

Then, in order to compare the relative influence of chemi-recombination processes (3) and (4) together and electron-electron- H^+ ion recombination process (6) on the same block of excited hydrogen atom states with $2 \le n \le 8$, we calculated quantity $F_{r,\text{eei; }2-8}(T)$, given by

$$F_{r,\text{eei};2-8}(T) = \frac{\sum_{n=2}^{8} I_{\text{cr}}(n, T)}{\sum_{n=2}^{8} I_{r;\text{eei}}(n, T)} = \frac{\sum_{n=2}^{8} K_{\text{cr}}(n, T)}{\sum_{n=2}^{8} K_{\text{eei}}(n, T)} \cdot \frac{N_{1}}{N_{e}},$$
(30)

taking rate coefficients $K_{\text{eei}}(n, T)$ also from Vriens & Smeets (1980). In Figure 5, the behavior of this quantity as a function of height *h* is shown. One can see that the considered chemi-recombination processes dominate with respect to the concurrent electron–electron–ion recombination processes within the region 100 km $\leq h \leq 650$ km. Consequently, the considered chemi-recombination processes are also very significant for the optical properties of the solar photosphere.

Figure 6. Behavior of the quantity $F_{r;ph}(2; 8)$ given by Equation (31), as a function of height h.

Finally, we compared the relative influence of chemirecombination processes (3) and (4) together and photorecombination electron- H^+ ion process (7), also within the block of the excited hydrogen atom states with $2 \leq n \leq 8$. For that sake we calculated quantity $F_{r,ph;2-8}(T)$, given by

$$F_{r,\text{ph};2-8}(T) = \frac{\sum_{n=2}^{8} I_{\text{cr}}(n,T)}{\sum_{n=2}^{8} I_{r;\text{ph}}(n,T)} = \frac{\sum_{n=2}^{8} K_{\text{cr}}(n,T)}{\sum_{n=2}^{8} K_{\text{ph}}(n,T)} \cdot N_{1},$$
(31)

taking rate coefficients $K_{\rm ph}(n, T)$ from Sobel'man (1979). This is necessary since in Mihajlov et al. (1997) only the states $4 \leq n \leq 8$ were considered. Still, it was a natural expectation that the inclusion of states with n = 2 and 3 will increase the influence of photo-recombination electron-ion processes. The behavior of quantity $F_{r,{\rm ph};2-8}(T)$ as a function of h is shown in Figure 6. One can see that here a domination of the chemirecombination processes with $2 \leq n \leq 8$ over the electron-ion photo-recombination processes is confirmed (although to a slightly lesser extent) in a significant part of the photosphere (-50 km $\leq h \leq 600$ km).

The chemi-ionization/recombination rate coefficients: the case A=He(1s²)

Chemi-ionization

				Kci[*10 ¹⁰ cm ³ /s]				
T(K)	n=3	n=4	n=5	n=6	n=7	n=8	n=9	n=10
7000	3.59	3.82	2.91	2.03	1.40	0.99	0.70	0.52
8000	4.57	4.43	3.19	2.20	1.49	1.05	0.75	0.54
9000	5.63	4.90	3.45	2.36	1.60	1.09	0.78	0.55
10000	6.48	5.36	3.70	2.46	1.63	1.13	0.80	0.58
11000	7.38	5.81	3.89	2.56	1.70	1.15	0.82	0.59
12000	8.24	6.17	4.09	2.66	1.77	1.18	0.83	0.60
13000	8.93	6.61	4.26	2.77	1.79	1.21	0.85	0.61
14000	9.66	6.95	4.43	2.86	1.86	1.25	0.87	0.62
15000	10.37	7.23	4.57	2.91	1.88	1.26	0.88	0.63
16000	11.12	7.53	4.71	3.00	1.93	1.28	0.89	0.64
17000	11.80	7.84	4.85	3.00	1.95	1.30	0.90	0.64
18000	12.41	7.99	4.95	3.06	1.97	1.32	0.90	0.64
19000	12.92	8.24	5.05	3.09	1.99	1.32	0.91	0.66
20000	13.58	8.40	5.15	3.12	2.01	1.35	0.92	0.66
21000	14.13	8.75	5.20	3.16	2.05	1.36	0.93	0.66
22000	14.57	8.93	5.31	3.22	2.05	1.36	0.94	0.67
23000	15.15	9.11	5.36	3.32	2.07	1.38	0.94	0.66
24000	15.47	9.29	5.46	3.35	2.09	1.38	0.95	0.68
25000	15.93	9.57	5.46	3.35	2.12	1.38	0.96	0.68
26000	16.25	9.87	5.52	3.38	2.14	1.39	0.96	0.68
27000	16.92	9.87	5.58	3.42	2.14	1.40	0.97	0.68
28000	17.08	9.96	5.63	3.45	2.16	1.42	0.97	0.68
29000	17.61	10.06	5.75	3.49	2.16	1.42	0.98	0.69
30000	17.79	10.06	5.75	3.52	2.18	1.43	1.00	0.70

Chemi-recombination

			Kr[10 ³⁰ cm ³ /s]					
	n=3	n=4	n=5	n=6	n=7	n=8	n=9	n=10
7000	28.51	17.74	12.69	9.80	7.81	6.43	5.47	4.60
8000	22.24	14.13	10.22	7.89	6.50	5.30	4.50	3.87
9000	16.98	11.52	8.51	6.64	5.41	4.50	3.75	3.26
10000	13.84	9.69	7.40	5.71	4.60	3.83	3.23	2.80
11000	11.52	8.24	6.36	4.96	4.00	3.37	2.86	2.46
12000	9.91	7.17	5.53	4.41	3.55	2.99	2.49	2.14
13000	8.70	6.36	4.91	3.87	3.15	2.60	2.21	1.94
14000	7.64	5.71	4.36	3.48	2.86	2.36	1.98	1.74
15000	6.86	5.07	3.96	3.12	2.60	2.14	1.80	1.58
16000	6.16	4.65	3.59	2.86	2.38	1.94	1.65	1.42
17000	5.59	4.22	3.30	2.66	2.16	1.78	1.53	1.30
18000	5.07	3.83	3.06	2.41	2.00	1.65	1.42	1.22
19000	4.65	3.55	2.77	2.21	1.84	1.55	1.30	1.12
20000	4.32	3.30	2.60	2.07	1.70	1.42	1.21	1.04
21000	4.00	3.06	2.41	1.94	1.58	1.33	1.13	0.96
22000	3.71	2.83	2.28	1.80	1.50	1.25	1.06	0.90
23000	3.40	2.68	2.14	1.69	1.41	1.17	0.98	0.85
24000	3.19	2.52	2.00	1.58	1.32	1.11	0.93	0.81
25000	3.06	2.36	1.86	1.48	1.23	1.03	0.87	0.76
26000	2.83	2.23	1.74	1.41	1.17	0.97	0.83	0.70
27000	2.71	2.12	1.65	1.34	1.10	0.92	0.78	0.67
28000	2.57	2.00	1.58	1.26	1.05	0.88	0.74	0.64
29000	2.41	1.92	1.50	1.22	1.00	0.84	0.71	0.60
30000	2.28	1.82	1.44	1.14	0.97	0.80	0.68	0.57

The chemi-ionization/recombination in the DB white dwarfs atmospheres (A=He)

The comparing with the e-He*(n) ionization and e-e-He+ (1s) recombination processes

Fig. 4.—Parameter $F_{ip}^{(ab)}(n, T)$ as a function of the logarithm of Rosseland optical depth log τ , for principal quantum numbers n = 3-10, with $T_{eff} = 12,000$ K and log g = 8.

The relative importance of chemi-ionization (eqs. [1a]–[1b]) and chemi-recombination (eqs. [2a]–[2b]) processes in comparison with electron-excited atom impact ionization (eq. [3]), electron-electron-ion recombination (eq. [4]) and electron-ion photorecombination (eq. [5]) processes is characterized by parameters $F_{\dot{p}}^{(ab)}(n,T)$ and $F_{\rm phr}^{(ab)}(n,T)$, defined as ratios of the corresponding fluxes:

$$F_{ir}^{(ab)}(n,T) = \frac{I_i^{(ab)}(n,T)}{I_i^{(ea)}(n,T)} = \frac{I_r^{(ab)}(n,T)}{I_r^{(eei)}(n,T)} ,$$

From equations (11)-(12) and (20)-(23), it follows that these parameters can be shown in the form

$$F_{ir}^{(ab)}(n,T) = \frac{K_i^{(ab)}(n,T)}{\alpha_i^{(ea)}(n,T)} \cdot \eta_e^a = \frac{K_r^{(ab)}(n,T)}{\alpha_r^{(eel)}(n,T)} \cdot \eta_e^a , \qquad (24)$$

$$F_{\rm phr}^{(ab,ei)}(n,T) = \frac{K_r^{(ab)}(n,T) \cdot N({\rm He})}{\alpha_{\rm phr}^{(ei)}(n,T)} , \qquad (25)$$

where η_e^a denotes He atom and free electron densities ratio

$$\eta_e^a = \frac{N(\text{He})}{N(e)}. \quad (26)$$

The comparing with the e-He+ (1s) photo-recombination processes

T_{eff}=12 000K

T_{eff} =14 000K

$$F_{\rm phr}^{(ab,ei)}(n,T) = \frac{I_r^{(ab)}(n,T)}{I_{\rm phr}^{(ei)}(n,T)} .$$
(23)

The investigation of the chemi-ionization/recombination processes for the case A=H(1s) in M red dwarf atmosphere with T_{eff} =3800K (modeling by means PHOENIX code)

The influence on the hydrogen spectral line shapes:

The investigation of the chemi-ionization processes in the laboratory conditions: Ne*+Ne, He*+He, He*+Ne

The state dependence of associative ionization of the *ns* and *nd* Rydberg series of Ne atoms with 5 < n < 18 at thermal collision energies is investigated experimentally using a combination of synchrotron radiation and mass spectrometry in a single-beam experiment. The *n* dependence of the collisional and associative ionization of the Ne Rydberg atoms have been calculated using the **dipole resonant mechanism**, in particular the associative ionization rates for $5 < n_{eff} < 20$ have been calculated for cell, single beam, and crossed beam conditions. Refinements of the **theory** implemented previously have been necessary in order to apply the theory to the collisions of rare gas atoms. The new **experimental** results described here were obtained at the branch line of the gas phase photoemission beam line at the Italian synchrotron light source, **Elettra**.

FIG. 7. (Color online) (a) Experimental data (symbols) for the relative associative ionization rates of the *ns* and *nd* Rydberg series of Ne under single-beam (sb) conditions together with the calculated values (lines) for both the single-beam and cell conditions and (b) experimental data (symbols) for the absolute associative ionization cross sections of the *ns* and *nd* Rydberg series of Ne under crossed beam (cb) conditions taken from Ref. [10] together with the calculated values (lines) for crossed beam conditions.

He*(n)+He

Rate coefficients: 300K

300 K	
-	
<u> </u>	к пепе [сшэ/s]
3	8.08E-24
4	1.14E-19
5	5.00E-14
6	5.76E-13
7	1.99E-12
8	3.84E-12
9	5.43E-12
10	6.41E-12
11	6.80E-12
12	6.74E-12
13	6.38E-12
14	5.89E-12
15	5.33E-12
16	4.78E-12
17	4.25E-12
18	3.76E-12
19	3.32E-12
20	2.93E-12

The e-He^{*}(n) ionization and e-e-He⁺ recombination rate coefficients

		Kea[Te] [cm ³ /s]						Krec[Te] [cm ⁶ /s]		
n	300K	10000K	15000K	20000K	25000K	300K	10000K	15000K	20000K	25000K
3	5.14E-33	1.18E-07	2.32E-07	3.26E-07	4.00E-07	1.84E-25	5.09E-27	3.03E-27	2.07E-27	1.52E-27
4	2.27E-21	6.80E-07	9.98E-07	1.20E-06	1.34E-06	1.12E-24	2.42E-26	1.39E-26	9.25E-27	6.67E-27
5	8.01E-16	2.01E-06	2.54E-06	2.83E-06	2.99E-06	4.44E-24	7.83E-26	4.37E-26	2.85E-26	2.02E-26
6	1.05E-12	4.31E-06	5.00E-06	5.30E-06	5.42E-06	1.35E-23	2.00E-25	1.09E-25	6.96E-26	4.87E-26
7	9.45E-11	7.72E-06	8.43E-06	8.64E-06	8.64E-06	3.41E-23	4.33E-25	2.31E-25	1.46E-25	1.01E-25
8	1.99E-09	1.23E-05	1.29E-05	1.29E-05	1.27E-05	7.56E-23	8.36E-25	4.39E-25	2.73E-25	1.88E-25
9	1.77E-08	1.81E-05	1.84E-05	1.80E-05	1.75E-05	1.51E-22	1.48E-24	7.64E-25	4.71E-25	3.21E-25
10	9.09E-08	2.52E-05	2.49E-05	2.40E-05	2.31E-05	2.80E-22	2.45E-24	1.25E-24	7.62E-25	5.16E-25

The chemi-ionization rate coefficients: He*(n)+Ne and He *(n)+ He

	K _{He Ne}	K _{He He}		K _{He Ne}	K _{He He}	
	[CIII%]5]	[CIII9/S]		[CIII9/S]	[CIII%5]	
n	300 K	300 K		600 K	600 K	
3	3.85E-10	8.08E-24		4.14E-10	4.01E-12	
4	1.26E-10	1.14E-19		1.36E-10	4.88E-12	
5	4.44E-11	5.00E-14		4.83E-11	5.25E-12	
6	1.82E-11	5.76E-13		1.99E-11	2.71E-12	
7	8.51E-12	1.99E-12		9.27E-12	4.93E-12	
8	4.38E-12	3.84E-12		4.77E-12	6.53E-12	
9	2.43E-12	5.43E-12		2.65E-12	7.28E-12	
10	1.44E-12	6.41E-12		1.57E-12	7.36E-12	

The chemi-ionization cross sections: He*(n)+Ne

Temperature dependence of the ionization cross section. Our results together with other authors

The comparing of the chemi-ionization rate coefficients: Ne *(n)+ Ne, He *(n)+ He and He*(n)+Ne

300K

n

Conclusions

- It is needed to continue with the experimental investigations of the chemi-ionization processes in symmetric and non-symmetric atom-Rydberg atom collisions in order to obtain new and more precision data. Further improvement of the corresponding theoretical methods.

- Further investigation of the chemi-ionization/recombination processes in the plasmas of the stellar atmospheres by means the relevant modeling code (PHOENIX) in order to study their influence on the inner plasma kinetic.

References

The (n-n')-mixing:

- A. A. Mihajlov 1982 Proc. Int. Conf. Plasma Phys. (Goeteborg, Sweden) pp 11P–II–23
- A.A. Mihajlov, Lj. M. Ignjatović, Z. Djurić and N. N. Ljepojević, J. Phys. B. 37, 4493–4506, (2004).
- A.A. Mihajlov, Lj.M. Ignjatović and M.S. Dimitrijević, A&A, 437, p. 1023-1027, (2005).
- A. A. Mihajlov, Lj. M. Ignjatović, V.A. Srećković and Z. Djurić, JQSRT, 109, 853-862, (2008)
- V. A Srećković, A. A Mihajlov, Lj. M Ignjatović, M. S.Dimitrijević, A&A, Vol552, id.A33, 3 pp. (2013)

The chemi-ionization/recombination:

- Lj.M. Ignjatović and A.A. Mihajlov, "Rate coefficient for the chemi-ionization in slow Li*(n)+Li and Na*(n)+Na collisions", Phys. Rev. A, 437, 022715, (2005).
- Lj. M. Ignjatović, A. A. Mihajlov and A. N. Klyucharev, "The rate coefficients of the chemi-ionization processes in slow Li*(n)+Na collisions", J. Phys. B: At. Mol. Opt. Phys., 41, 025203 (7pp), (2008).

- A. Mihajlov, Lj. M. Ignjatović, M. S. Dimitrijević and Z. Djurić, "Symmetrical chemi-ionization and chemi-recombination processes in low temperature layers of helium-rich DB white dwarf atmospheres", The Astrophysical Journal Supplement Series, 147, 369–377, (2003).
- A.A. Mihajlov, D. Jevremović, P. Hauschildt, M.S. Dimitrijević, Lj.M. Ignjatović and F. Alard, "Influence of chemi-ionization and chemi-recombination processes on the population of hydrogen Rydberg states in atmospheres of late type dwarfs", Astronomy and Astrophysics, 403, p.787-791, (2003).
- A. A. Mihajlov, D. Jevremović, P. Hauschildt, M. S. Dimitrijević, Lj. M. Ignjatović and F. Alard, "Influence of chemi-ionization and chemi-recombination processes on hydrogen line shapes in M dwarfs", Astronomy and Astrophysics, 471, p. 671-673, (2007)
- A. A. Klyucharev, N. N. Bezuglov, A. A. Metveev, A. A. Mihajlov, Lj. M. Ignjatović and M. S. Dimitrijević, "Rate coefficients for the chemi-ionization processes in sodium- and other alkalimetal geocosmical plasmas", New Astronomy Reviews, 51/7, pp. 547-562, (2007),
- Gnedin, Yu. N.; Mihajlov, A. A.; Ignjatović, Lj. M.; Sakan, N. M.; Srećković, V. A.; Zakharov, M. Yu.; Bezuglov, N. N.; Klycharev, A. N "Rydberg atoms in astrophysics"New Astronomy Reviews, Volume 53, Issue 7-10, p. 259-265.(2009)
- Mihajlov, A. A., Ignjatović, Lj, M.; Srećković, V. A.; Dimitrijević, M. S. The Astrophysical Journal Supplement, Volume 193, Issue 1, article id. 2, 7 pp. (2011)
- Mihajlov, A. A.; Sreckovic, V. A.; Ignjatovic, Lj. M.; Klyucharev, A. N. "The Chemi-Ionization Processes in Slow Collisions of Rydberg Atoms with Ground State Atoms: Mechanism and Applications"Journal of Cluster Science 23:47-75 (2012)

Thank you for your attention