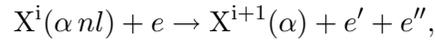


Chapter 3

Collision processes

3.1 Electron impact ionization

Collisions of atoms and ions with electrons, protons and other particles can also have effect upon the gas ionization degree in nebulae. The collisional ionization rate increases rapidly at higher values of gas temperature. In planetary nebulae the most effective are the electron impacts in which an essential fraction of kinetic energy will be wasted for the atom ionization:



where e and e' are the electron states before and after the ionizing collision with ions X^i . Here e'' is the removal electron, α is the quantum number set of the atomic remnant and nl is the same for removal electron. For nebulae the rate of collisional ionization in atom impacts with heavy particles is relatively small and can be neglected.

The number of collisional ionization acts resulting from the ion X^i impacts with electrons per unit volume and unit time is given by

$$\dot{N} = n(X^i) n_e q_{1c}(T_e),$$

where $q_{1c} = \langle v \sigma_{1c} \rangle$ is the collisional ionization rate. The ionization cross-section σ_{1c} and, consequently, the ionization rate for different atoms have been determined by numerous authors. Most often are used the approximation expressions for q_{1c} found by Lotz (1967, 1968) for atoms from H to Ca. Shull & Van Steenberg (1982) using the experimental and theoretical cross-sections of collisional ionization have found simple approximation formula for collisional ionization of all ionization stages of C, N, O, Ne, Mg, Si, Ar, Ca, Fe and Ni in the form

$$q_{1c}(T_e) = \frac{A_{1c} \sqrt{T_e} \beta \exp(-\beta)}{\alpha I} \text{ cm}^3/\text{s}, \quad (3.1)$$

where as in the previous chapter $\beta = I/kT_e = T_c/T_e$; $I = kT_c$ is the ionization energy from the ground state. For most cases $a \approx 0.1$. The last value holds always if $kT_e > 1$ eV. The values of A_{1c} and T_c are given in Table 5. The formula for the collisional ionization rates for atoms and ions of isoelectronic series from H to Ni have been generalized in the paper by Arnaud & Rothenflug (1985) and they gives the form

$$q_{1c}(T_e) = \frac{6.69 \cdot 10^{-7}}{(kT_e)^{3/2}} \sum_j F(\beta_j) \frac{\exp(-\beta_j)}{\beta_j} \text{cm}^3/\text{s}, \quad (3.2)$$

where $\beta_j = I_j/kT_e$ and I_j is the ionization energy from level j and

$$F(\beta_j) = A_j\{1 - \beta_j \cdot f_1(\beta_j)\} + B_j\{1 + \beta_j - \beta_j(2 + \beta_j) \cdot f_1(\beta_j)\} + C_j \cdot f_1(\beta_j) + D_j \cdot \beta_j \cdot f_2(\beta_j), \quad (3.3)$$

$$f_1(\beta) = e^\beta E_1(\beta), \quad f_2(\beta) = e^\beta \int_1^\infty \frac{e^{-t\beta}}{t} \ln t dt.$$

The numerical values of I_j , A_j , B_j , C_j and D_j are given in Table 10. Integral exponential function $E_1(\beta)$ can be calculated by the usual manner (see, for example, Abramowitz & Stegun (1964)). The function $f_2(\beta)$ can be expressed with error about 1% in the following form (Hummer (1983)):

$$f_2(\beta) = P(\beta)/(Q(\beta) \beta^2), \quad (3.4)$$

where

$$P(\beta) = \sum_{j=0}^{13} \beta^{-j} p_j, \quad Q(\beta) = \sum_{j=0}^{14} \beta^{-j} q_j$$

The values of parameters p_j and q_j in series expansion of $f_2(\beta)$ given in above cited paper.

Shevelko et al. (1983) using the cross sections of collisional ionization calculated in the Coulomb-Born approximation found more simple analytical expression for the collisional ionization rate $q_{1c}(T_e)$ for the outermost shell $(nl)^q$, namely

$$q_{1c}(T_e) = \frac{10^{-8} q \cdot [I_H/I]^{3/2} \exp(-\beta) \cdot \sqrt{\beta} A}{\beta + \chi}, \quad (3.5)$$

where as former, $\beta = I/kT_e$ and I is the ionization energy (from the ground level) and the quantities A and χ are the parameters, the values of which for some atomic shells are presented in Table 11. The error estimation of this approximation for collision ionization rate is about 6% for $0.1 < \beta < 10$. Eq.(3.5) is applicable for all elements, but at small values of Z the error increases.

The rate of collisional ionization (in units cm^3s^{-1}) for complex ions can also be calculated using the formula by Burgess & Chidichimo (1983)

$$q_{1c}(T_e) = 2.17 \cdot 10^{-8} \bar{C} \sum_j q_j (I_H/I_j)^{3/2} \cdot \beta_j^{1/2} E_1(\beta_j) \cdot \omega,$$

$$\omega = [\ln(I/I_j + \beta_j^{-1})]^{\tau/((I+kT_e)/I_j)}, \quad (3.6)$$

$$\tau = (1/4) \cdot \{[(100Z + 91)/(4Z + 3)]^{1/2} - 5\}. \quad (3.7)$$

In expression Eq.(3.6) q_j is the number of electrons in shell j and I_j is the corresponding ionization energy. Summation over all shells of the atomic configuration takes into account also the electron excitation from internal shells and the processes of autoionization. The values of parameters \bar{C} , I_j and q_j are given in Table 12. If the contribution of autoionization is negligible then the letter "a" has been added to the ion symbol and if it is essential then the letter "b". Symbol (*i*) added to q_j values denotes presence of strong resonances in ionization cross sections for corresponding shells, but symbol (*ii*) denotes presence of large number of weak resonances. For light ions with $2 \leq Z \leq 5$ we can take $\bar{C}=2.30$ ($\pm 19\%$). This value is well consistent with the value 2.2 found by Seaton (1964). If we incorporate approximately the contributions of autoionization then $\bar{C}=2.70$, which is close to the value 2.77 found by Lotz (1968). Comparison of the collision ionization rates given by Arnaud & Rothenflug (1985) with corresponding data by other authors showed that the discrepancy with the data by Summers (1974) and by Burgess

& Chidichimo can reach from 1.2 to 2 times, but the consistency with reformulated results by Lotz (1967, 1968) is good.

References to the many modern collision ionization data for astrophysically important ions are given by Butler (1993), see also Appendix A.

3.2 The electron impact excitation

Excitation of atoms by electron impacts is the main mechanism of the formation the spectral lines between low excited levels in the spectra of gaseous nebulae. The electron impact excitation rates usually are expressed via the effective collision strengths γ_{ij} :

$$q_{ij} = \frac{8.6287 \cdot 10^{-6}}{g_i T_e^{1/2}} \gamma_{ij} \exp(-\beta_{ij}). \quad (3.8)$$

Here g_i is the statistical weight of the lower state i . The coefficient of collisional deactivation can be written in the form

$$q_{ji} = \frac{8.6287 \cdot 10^{-6}}{g_i T_e^{1/2}} \gamma_{ij}, \quad (3.9)$$

and it is interrelated to the coefficient of collisional excitation by the relation

$$q_{ij} = \frac{g_j}{g_i} \exp(-\beta_{ij}), \quad (3.10)$$

The quantity γ_{ij} is determined by integrating the collision strength Ω_{ij} over the Maxwell electron velocity distribution :

$$\gamma_{ij} = \int_0^\infty \Omega_{ij} \exp(-\beta_{ij} u) d(\beta_{ij} u). \quad (3.11)$$

In the formulae (3.8 - 3.11) $\beta_{ij} = E_{ij}/kT_e$ and $u = E/E_{ij} - 1$ is the energy E of removed electron in the ionization threshold units.

Using the experimental and theoretical excitation cross sections for transitions between hydrogen states Giovanardi et al. (1987) have determined the effective collision strengths $\gamma_{ij}(T_e)$

for 15 lower states. For 4 lowest levels the transitions between sublevels with different orbital quantum numbers have been considered. The effective collision strengths were approximated by expression

$$\gamma_{ij} = a + bT_e + cT_e^2 + dT_e^3, \quad (3.12)$$

The values of polynomial fit parameters a , b , c and d are given in Table 13. The effective collision strengths for HeII have been found by Hummer and Storey (1987). These can be well presented by the same polynomial fit for temperatures up to 10^5 K. The values of corresponding coefficients are also given in Table 13.

The values of q_{ij} computed for HI by using the expressions (3.8) and (3.10) and data of Table 13 at different values of T_e are given in Table 14, where are also given the total coefficients of electron impact excitation summed over all levels $j \leq 15$. This quantity is useful for calculating the ionization state of HI atoms in the nebulae.

The coefficients of collisional excitation of complex ions have been given by Clark et al. (1982). The collisional strengths for different atoms and ions of isoelectronic sequences of H, He, Li, Be, B, Na, Mg have been presented by expression

$$\Omega(Z, X) = [Z + b_1 + d_1/Z]^{-2} [c_0 + c_1/X + c_2/X^2] + [Z + b_2 + d_2/Z]^{-2} (c_3 \ln(X) + c_4), \quad (3.13)$$

where $X = E/E_{ij} = u + 1$, Z is the nuclear charge number and the values of parameters b_1 , b_2 , c_0 , c_1 , c_2 , c_3 , d_1 and d_2 are given in Table 15. Integrating over the Maxwellian velocity distribution of electrons the corresponding coefficient of collisional excitation can be written in the form

$$q_{ij}(T_e) = F_1(Z)C_E \left[\frac{c_0 \exp(-\beta)}{\beta} + c_1 E_1(\beta) + c_2 E_2(\beta) \right] + F_2(Z)C_E \left[\frac{c_3 E_1(\beta)}{\beta} + \frac{c_4 \exp(-\beta)}{\beta} \right] \text{ cm}^3/\text{s}, \quad (3.14)$$

where $\beta = E_t/kT_e$, $C_E = 8.010 \cdot 10^{-8} \beta / [(2L + 1)(2S + 1)T_e^{1/2}]$, $F_1(Z) = [Z + b_1 + d_1/Z]^{-2}$, $F_2(Z) = [Z + b_2 + d_2/Z]^{-2}$ and $E_n(\beta)$ is the integro-exponential function of n th order:

$$E_n(\beta) = \int_1^\infty \frac{e^{-\beta t}}{t^n} dt.$$

For different atoms and ions of the above mentioned sequences the energy E_{ij} has been expressed in the form

$$E_{ij} = a_0 + a_1 Z + a_2 Z^2 + a_3 Z^3 + a_4 Z^4, \quad (3.15)$$

Values of the parameters a_0 , a_1 , a_2 , a_3 and a_4 are also given in Table 15.

The values of the transition probabilities and γ_{ij} for the large number of forbidden and intercombination lines which are observed in the spectra of planetary nebula are given in Table 17. An explication of used designations for the levels and their energies is given in Table 16. Due to limited space of the catalogue we present data only for ions of Be, B, O and Mg sequence which are taken from Mendoza (1983). The modern data can be found in the original papers cited in Appendix A.

Process of the atom and ion excitation by heavy particle collisions differs essentially from that by electron impacts. Large mass particles move much slower than electrons and pass nearby the excited atom during a long time interval. If the energy of the transition ΔE in the target atom or ion is comparable with the kinetical energy E of the colliding particle then the excitation cross sections are very small due to the fast oscillation of the target wave function with the phase $\Delta E t/h$. On the contrary, in the case if $\Delta E \ll E$ this phase is small and the total excitation cross section by a heavy particle is not small and can exceed the appropriate cross section for excitation by electron impacts. This means that the heavy particle collisions are the effective ones for the excitation of the fine structure transitions or for the orbital moment redistribution due to transitions between the high-excited Rydberg states.

Proton collisions are most effective for generating transitions if $\Delta E \ll E$. For such transitions the excitation rates of neutral targets by proton impacts are $(M_p/m_e)^{1/2}$ times larger than those by electron impacts (Seaton (1955); see, also, Dalgarno (1984)). The proton collisions are effective for the fine structure levels excitation and for excitation of the transitions between sublevels nl :



Cross sections for this process have been calculated by Pengelly and Seaton (1964) in the framework of the semiclassical perturbation theory. At large values of n the proton collisions lead to the statistical equilibrium distribution of atoms on nl sublevels.

For large values of n and n' the proton impact excitations



are also effective (Burgess & Summer (1976)).

In excitation of the positive ions by proton impacts the Coulomb interaction must be taken into account. This interaction diminishes the proton-impact excitation rates and in turn increases the excitation rates by electron impacts. The role of this effect is negligible if $n \gg 1$ at typical in astrophysical objects values $T_e \approx 10^4 K$.

Proton collisions are very effective for excitation of the fine structure levels of CI, OI, OII and of many other ions. Numerous references in the field are presented in Appendix A. At low temperatures ($T \leq 10^3 K$) the excitation by proton collisions can more than ten times exceed the excitation by electron impacts (Rouef and Le Bourlot (1990), see Table 18 and also Fig. 3.1).

Excitation by collision with HI are effective for the fine structure levels. Collisions with **more heavy particles** are less effective than neutral hydrogen excitation due to their less abundances. The references in the field can be found in Appendix A.

3.4 Autoionization

The autoionization process comprises of collisional excitation of an atom or ion to autoionization states followed by autoionization decay. Similarly to the photoionization processes, autoionization by electron impacts generates the resonances in the cross sections. Autoionization is usually essential at $T_e \geq 10^5\text{K}$ for atoms and ions having more than two electrons. The number of autoionization acts per unit volume and unit time is

$$\dot{N}_\alpha = n(X^i) n_e \cdot q_\alpha(T_e), \quad (3.16)$$

where $q_\alpha(T_e)$ is the autoionization rate.

The most complete compilation of analytical expressions and corresponding data for determination of q_α is given in paper by Arnaud & Rothenflug (1985) the results of which we reproduce here.

1. The formula for lithium isoelectronic series is

$$q_\alpha(T_e) = 1.92 \cdot 10^{-7} \frac{b \exp(-\beta) G(\beta)}{Z_{\text{ef}}^2 (kT_e)^{1/2}} \text{ cm}^3/\text{s}, \quad (3.17)$$

where $\beta = I_\alpha/kT_e$,

$$G(\beta) = 2.22 f_1(\beta) + 0.67[1 - \beta f_1(\beta)] + 0.49\beta f_1(\beta) + 1.2\beta[1 - \beta f_1(\beta)] ,$$

$$b = [1 + 2 \cdot 10^{-4} Z^3]^{-1}, \quad Z_{\text{ef}} = (Z - 0.43) ,$$

$$I_\alpha = 13.6\{(Z - 0.835)^2 - 0.25(Z - 1.62)^2\} \text{ eV} , \text{ and function } f_i(\beta) \text{ is given by Eq.(3.3).}$$

Formula (3.17) corresponds to the $1s - 2p$ transition corrected for the contribution of other transitions by multiplying with coefficient 1.2. Comparison of the q_α values, given by Eq.(3.17) with existing measurements showed that the results can differ from them not more than about two times.

2. For ions of sodium isoelectronic series

$$q_\alpha(T_e) = 6.69 \cdot 10^{-7} \frac{\alpha \cdot I_\alpha}{(kT_e)^{1/2}} \exp(-\beta) \{1 + \Phi(\beta)\} \text{ cm}^3/\text{s}. \quad (3.18)$$

If $12 \leq Z \leq 16$ then $\Phi(\beta) = -\beta f_1(\beta)$, $I_\alpha = 26(Z - 10) \text{ eV}$ and

$$\alpha = 2.28 \cdot 10^{-17} (Z - 11)^{-0.7} \text{ cm}^2$$

If $18 \leq Z \leq 28$ then

$$\Phi(\beta) = -0.5[\beta - \beta^2 + \beta^3 f_1(\beta)], \quad (3.19)$$

and $I_\alpha = 11(Z - 10)^{3/2} \text{ eV}$, $\alpha = 1.3 \cdot 10^{-14} (Z - 10)^{-3.73} \text{ cm}^2$.

3. For the ions of isoelectronic series set from the magnesium series to the sulphur series ($Z < 16$) the expression for $\Phi(\beta)$ is given by Eq.(3.19) where

$$\alpha = 4.0 \cdot 10^{-13} Z^{-2} \text{ cm}^2 \text{ and}$$

$$I_\alpha = 10.3 (Z - 10)^{-1.52} \text{ eV} \quad \text{for the Mg isoelectronic sequence,}$$

$$I_\alpha = 18.0 (Z - 11)^{-1.33} \text{ eV} \quad \text{for the Al isoelectronic sequence,}$$

$$I_\alpha = 18.4 (Z - 12)^{-1.36} \text{ eV} \quad \text{for the Si isoelectronic sequence,}$$

$$I_\alpha = 23.7 (Z - 13)^{-1.29} \text{ eV} \quad \text{for the P isoelectronic sequence,}$$

$$I_\alpha = 40.1 (Z - 14)^{-1.10} \text{ eV} \quad \text{for the S isoelectronic sequence.}$$

For ions of other series the contribution of autoionization to the total collision excitation rate can be ignored.

3.5 Dielectronic recombination

The process of dielectronic recombination, described by scheme (2.7), proceeds in two stages. At the first stage the electron is captured in an autoionization state γ belonging to ion X^{i+1} . At the second stage there proceeds the radiative decay of the state γ with generation of a bound state of ion X^i .

At high temperatures $T_e \geq 10^5 - 10^6$ K the main contribution into the dielectronic recombination rate is given by the recombination processes to the autoionization states with large principal quantum numbers n . These states decay easily in electron collisions and due to external radiation field. Thus, the dielectronic recombination rate depends heavily on the physical conditions in plasma. At high electron densities $n_e > 10^{13} - 10^{15}$ cm³ both the collisional ionization from autoionization states and collisional population of them are essential.

The photons irradiated in the processes of dielectronic recombination due to transitions between autoionization states are named as the dielectronic satellites.

The number of dielectronic recombination acts for ion X^{i+1} per unit volume and unit time is

$$\dot{N}^{\text{di}} = n(X^{i+1}) n_e \alpha^{\text{di}}(X^{i+1}), \quad \text{cm}^3/\text{s}, \quad (3.20)$$

where $\alpha^{\text{di}}(T_e)$ is the dielectronic recombination rate.

The semiempirical formulae for dielectronic recombination rates have been given by Burgess (1965), Landini & Monsignori (1971), Jain & Narain (1976). The revised expression for $\alpha^{\text{di}}(T_e)$ with the modified values of excitation cross-sections of ions X^{i+1} due to electron collisions has been given by Alam & Ansari (1985). The differences of $\alpha^{\text{di}}(T_e)$ values found by various authors for many ion species reaches *1dec*. This is caused by the difficulties in computing the reliable values of excitation cross-sections, the main factor among these being the necessity to take into account transitions from all autoionization states and cascade transitions from these states.

Usually the dielectronic recombination rate is computed in the Burgess (1965) approximation. This approximation holds for most ions at high electron temperatures $T_e > 10^5$ K. A simple approximation formula for $\alpha^{\text{di}}(T_e)$ has been given in papers by Aldrovandi & Pequignot (1973, 1976) who modified the Burgess approximation to the form

$$\alpha_{\text{H}}^{\text{di}} = A_{\text{di}} T_e^{-3/2} \exp(-T_0/T_e) [1 + B_{\text{di}} \exp(-T_1/T_e)]. \quad (3.21)$$

Here the index H marks the Burgess (**H**igh temperature) approximation. The same expression has been proposed also by Shull & Van Steenberg (1982), who also used the semiempirical formula by Burgess (1965) and improved the numerical values of approximation parameters A_{di} , B_{di} , T_0 and T_1 for all ions of chemical elements from C to Ni which are given in Table 5. The same expression holds also for He^+ .

Arnaud & Rothenflug (1985) started from the expression of $\alpha_{\text{H}}^{\text{di}}$ given in the paper by Aldrovandi & Pequignot (1973) and corrected by a factor proposed by Burgess & Tworkowski

(1976). For Li - like ions they obtained the following formula:

$$\alpha_{\text{H}}^{\text{di}} = 7.6 \cdot 10^{-11} A(z) \exp[-D(z)\beta] \beta^{3/2}, \quad \text{cm}^3/\text{s}, \quad (3.22)$$

where

$$\beta = I_0/kT_e, \quad z = Z - 2.$$

$$A(z) = (z + 1)^3 / z^2 (z^2 + 13.4)^{1/2} [1 + 0.16(z + 1) + 0.017(z + 1)^2],$$

$$D(z) = 3.0 \frac{(z + 1)^2}{z^2} / [1 + 0.015z^3 / (z + 1)^2].$$

In these formulae I_0 is the ionization potential for the ion studied and Z is its nuclear charge. The values of coefficients $\alpha^{\text{di}}(T_e)$ computed using Eq.(3.22) are smaller than the corresponding values found by Shull & Van Steenberg (1982), being multiplied by coefficients 0.19, 0.44, 0.36 and 0.41 for ions of O, Mg, Ca and Fe, respectively. For high-charge ions we can use the $\alpha^{\text{di}}(T_e)$ values from paper by Shull & Van Steenberg (1982), multiplying the values by 0.30 for ions of Ne and by 0.40 for ions of Si, S and Ar. The values of $\alpha^{\text{di}}(T_e)$ also based on the Burgess approximation for all ions of C – Ni and for some other isoelectronic sequences have been given in papers by Jacobs et al. (1977a, 1977b, 1980), where the autoionization processes have also been incorporated. The results of the last papers have been improved by Woods et al. (1981), Shull & Van Steenberg (1982).

A simple approximation formula for the total dielectronic recombination rate has been given by Romanik (1988) for ions of He, Li, Be and Ne sequences:

$$\alpha_{\text{H}}^{\text{di}} = T_e^{-3/2} \sum_i a_i \exp(-T_i/T_e) \quad \text{cm}^3/\text{s}. \quad (3.23)$$

In this expression all important radiative and autoionization processes have been taken into account. The numerical values of parameters T_i and a_i are given in Table 19.

At large electron temperature the high excited levels are populated predominantly by the dielectronic recombination which proceeds via electron capture into these states. For most elements at 10^5 – 10^6 K the dielectronic recombination dominates over the radiative recombination. At temperatures $T_e \approx 10^4$ K the efficiency of captures into high excited states is low. For ions of C, N, O, Ne, Al and Si the dielectronic recombination can proceed via captures into lower autoionization states. Due to presence of such states the process of dielectronic recombination is essential also at low temperatures $T_e = 5\,000 - 20\,000$ K which are dominant in nebulae. The capture processes to lower autoionization states determine the rate of low-temperature dielectronic recombination. Some of the ions of the above-mentioned elements have low metastable states. The number of autoionization captures and thus the dielectronic recombination rate in these cases depend on the population of corresponding metastable states and, consequently, on the electron concentration and temperature of nebula. The dielectronic recombination at low temperatures acts on the intensities of some emission lines observed in the spectra of nebulae.

The dielectronic recombination rate at low temperatures (applied to the conditions of gaseous nebulae) has been calculated by Storey (1981), Nussbaumer & Storey (1983, 1984, 1986, 1987). Corresponding coefficient $\alpha_L^{\text{di}}(T_e)$ has been expressed by the following approximation

$$\alpha_L^{\text{di}}(T_e) = \left(\frac{a}{t} + b + ct + dt^2\right) t^{-3/2} \exp(-f/t) 10^{-12} \text{ cm}^3/\text{s}. \quad (3.24)$$

This expression describes the dielectronic recombination on the ground or the metastable state.

In Table 20 are presented the values of parameters a, b, c, d and f and values t_l and Y for ions of C, N, O, Ne, Mg, Al and Si taken from the papers by Nussbaumer & Storey (1984, 1986, 1987). In the table the quantity E is the calculated excitation energy of the term, the value of t_l has been chosen such that the maximum error in the fit formula Eq.(3.24) were less than 20 % . The value Y is the rate α^{di} at $T_e = 10^4$ K in units of $10^{-12} [\text{cm}^3\text{s}^{-1}]$. For ions of Mg, Al, Si and Ne also the values of total dielectronic recombination rates $\alpha^{\text{di}}(\text{total}) = \sum \alpha_{\text{ef}}^{\text{di}}(LS)$ have been given in Table 20. In this formula the summation is carried out over both ground and metastable states.

More exact calculations of the dielectronic recombination rates for ions CII, NIII and OIV have been carried out in the paper by Badnell (1988). These quantities do not differ from the results by Nussbaumer & Storey (1984, 1986, 1987) more than 10–20%. Necessity to take into account the forbidden autoionization transitions in the calculation of dielectronic recombination rate has been demonstrated by Beigman & Chichkov (1980).

The total recombination rate can be written in the form

$$\alpha = \alpha^{\text{rad}}(T_e) + \alpha_{\text{H}}^{\text{di}}(T_e) + \alpha_L^{\text{di}}(T_e). \quad (3.25)$$

If $T_e \leq 10^3$ K then this rate is dominantly the radiative recombination $\alpha^{\text{rad}}(T_e)$ and at $T_e > 10^5$ K dominates the dielectronic recombination via the captures to high excited autoionization states $\alpha_{\text{H}}^{\text{di}}(T_e)$, see Eq.(3.21). For intermediary temperatures $T_e = 10^3 - 10^4$ K for many ion species the dominating process is the dielectronic recombination via low excited autoionization states ($\alpha_L^{\text{di}}(T_e)$). The contribution of individual recombination transitions to the total recombination rate is visualized in Fig.10 of the monograph by Nikitin et al. (1988).

3.6 The charge transfer reactions

In charge transfer reactions an electron (usually the outermost one) is transported from atom or ion X to ion X^+ :



The electron transition is realized via quasimolecular state X^+Y or XY^+ . The energy defect ΔE equals to the difference of binding energies of atomic systems X^+Y and XY^+ .

In the case of direct reaction an electron of atom Y is transferred to ion X^+ . Such charge transfer is ionization of Y and recombination to X^+ . The opposite charge transfer is called the inverse charge transfer. The rates of direct and inverse reactions are not equal and the ratio depends on the gas temperature.

For energies of colliding particles $\Delta E \leq 100$ eV the most important process is the electron capture by the outermost shell. At large energies of colliding particles more effective are the processes of electron capture by internal shells. For atoms of alkali metals the electron capture by internal shells is essential already at $E > 20$ eV.

The reactions of type



are named the reactions of resonance charge transfer, the role of such processes is minor for gaseous nebulae.

Dominating in the conditions of gaseous nebulae are the reactions of charge transfer in collision with neutral hydrogen and helium:



and



However, in some cases also other reactions of type (3.26) for element different from H and He can be important. The number of direct (or recombination) charge transfer acts (Eq.(3.28) and Eq.(3.29)) in the unit volume per unit time is

$$\vec{N}_{ch} = n(X^{i+1}) n(Y^0) \vec{k}(X^i, Y^0) \quad (3.30)$$

and the same number for inverse (or ionization) charge transfer (see also Eqs.(3.28-3.29)) is

$$\overleftarrow{N}_{ch} = n(X^i) n(Y^+) \overleftarrow{k}(X^i, Y^+), \quad (3.31)$$

where Y^0 corresponds to H^0 or He^0 and Y^+ to H^+ or He^+ . The quantities \vec{k} and \overleftarrow{k} are the corresponding charge transfer rates (cm^3/s).

The values \vec{k} and \overleftarrow{k} for different ions, the lines of which are observed in the nebulae, are summarized by Table 21. Before the charge transfer reaction the ion X^{i+1} is predominantly in the ground state, but in the result of the charge transfer reaction the excited states of ion X^i can be populated.

The quantities \vec{k} and \overleftarrow{k} are interrelated by the following formula of statistical thermodynamics:

$$\vec{k} = \overleftarrow{k} \cdot \exp(-\Delta E/kT_e). \quad (3.32)$$

The main direct and inverse charge transfer reactions of the types Eq.(3.28) and Eq.(3.29) are essential in the low-density astrophysical plasma conditions have been considered by Arnaud & Rothenflug (1985). They found the following approximation formula for computation of the charge transfer rates:

$$\vec{k} = A \cdot (T_e/10^4)^B \cdot \left\{ 1 + C \exp [D(T_e/10^4)] \right\} \quad cm^3/s. \quad (3.33)$$

In this expression the dependence of corresponding coefficients on T_e has been described analytically. The values of parameters A , B , C and D are given in Table 22, where in the column 2 the range of T_e values has been given for which approximation formula (3.33) holds.

Some valuable data about charge transfer reactions are given by Suchkov & Shchekinov (1983). They used for reactions with H^0 and He^0 the approximation $C=0$, i.e. in their formulation

$$\vec{k} = k_0 T_e^\alpha$$

The values of coefficients k_0 and α are compiled in Table 23. The data for charge transfer rates in impacts between atoms and ions of heavy elements are given by Pequignot & Aldrovandi (1986). The values of \vec{k} for each pair of ions (upper value) and the values of ΔE (lower value) are given in Table 24. The charge transfer reaction between the heavy elements can be essential in the interstellar medium, in HI regions of nebulae and in the atmospheres of cool stars.

In the conditions of low-density astrophysical plasma, especially in gaseous nebulae, the charge transfer reactions (e.g., $O^+ + H^0 \leftrightarrow O^0 + H^+$) often determine the atom ionization state. This fact was first demonstrated by Chamberlain (1956), who found that $O^+ / O^0 \simeq H^+ / H^0$ in the most of the gaseous nebulae. This relation holds due to high rates of the corresponding charge transfer reaction. The rates of this reaction have been computed by Field & Steigman (1971). Steigman et al. (1971) have given the rates of reaction $N^+ + H^0 \leftrightarrow N^0 + H^+$. More exact values of charge transfer rates have been found by Fehsenfeld & Ferguson (1972) for reaction $O^+ + H^0 \leftrightarrow O^0 + H^+ + 0.22$ eV, and by Butler & Dalgarno (1979) for reaction $N^+ + H^0 \leftrightarrow N^0 + H^+ + 0.95$ eV (see Table 21).

Tarter et al. (1979) studied the effect of double charge transfer on the ionization state of gas medium:



finding these to be negligible.

Unfortunately, the exactness of numerical values of charge transfer rates k for many reactions is low and the results by different authors can differ to *dex* due to low quality of methods of computation of charge transfer rates. Unknown are the reaction rate dependence on T_e for many reactions and the values of k for multiply ionized atoms. Probably the low precision of charge transfer rates is one of factors for giving inexact results for calculated ionization degree of elements in the gaseous nebulae.