Atomic Processes

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Radiative and collisional processes in a plasma

Photoabsorption–photoemission

$$X_i^{+n} + h\nu_{ij} \rightleftharpoons X_j^{+n}$$

Photoionization–radiative recombination

$$X^{+n} + h\nu \rightleftharpoons X^{+(n)+1} + \mathrm{e}^-$$

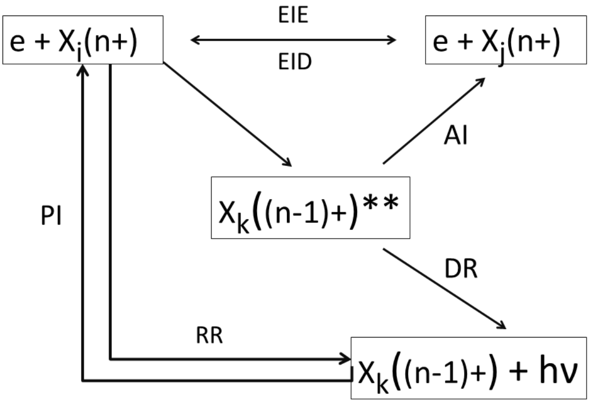
Electron impact excitation–electron impact de-excitation

$$\mathrm{e}^-(\epsilon) + X_i^{+n} \rightleftharpoons \mathrm{e}^-(\epsilon') + X_j^{+n}$$

Autoionization–dielectronic recombination

$$\mathrm{e}^- + X^{+n} \leftrightarrow (X^{+n-1})^{**} \leftrightarrow X^{+n} + \mathrm{e}^-$$
$$\leftrightarrow X^{+n-1} + h\nu$$

Radiative and collisional processes in a plasma



For collisional processes in a Maxwellian plasma,

$$g_i \sigma_{\mathrm{D}} p_i^2 = g_j \sigma_{\mathrm{R}} p_j^2$$

known as the *principle of detailed balance*.

Radiative transitions
He-like systems (Figure from Porquet & Dubau 2000)

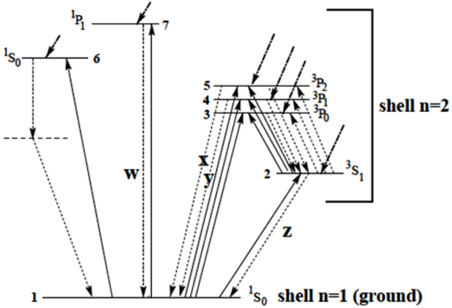


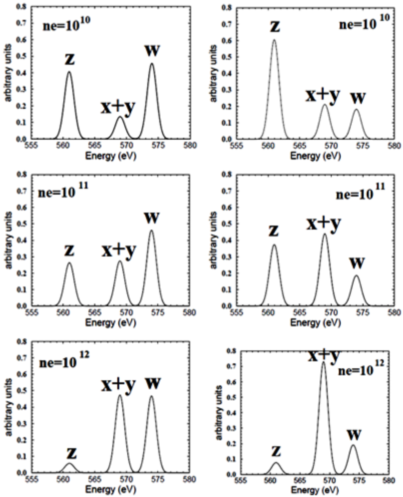
Fig. 1. Simplified Gotrian diagram for He-like ions. w, x, y and z correspond respectively to the resonance, intercombination and forbidden lines. *Full curves*: collisional excitation transitions, *broken curves*: radiative transitions and *thick dot-dashed curves*: recombination (radiative and dielectronic). *Note*: the broken arrow ($^1S_0$ to the ground level) correspond to the 2-photon continuum

$$R(N_e) = z/(x+y) = F/I$$

$$G(T_e) = (z+x+y)/w = (F+I)/R$$

Radiative transitions
Lines from the O VII can be used to characterize the plasma

Collisionally dominated plasmas



Plasmas dominated by recombinations

Figure from Porquet & Dubau (2000)

Radiative transitions

$R(N_e)$ and $G(T_e)$ in different He-like ions

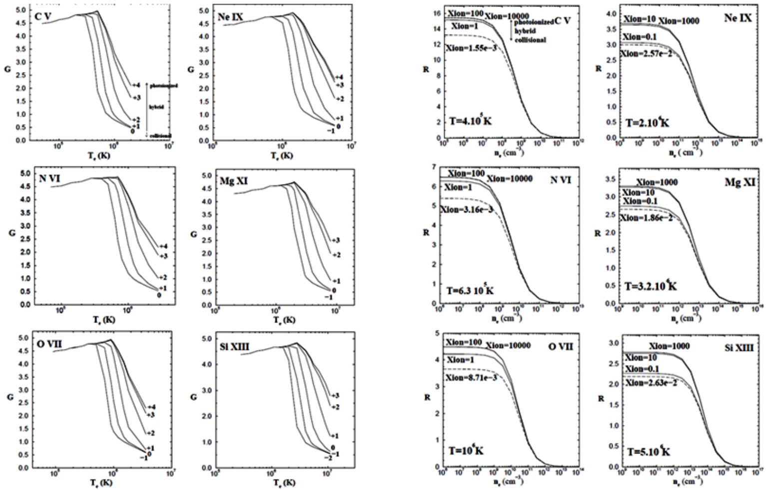
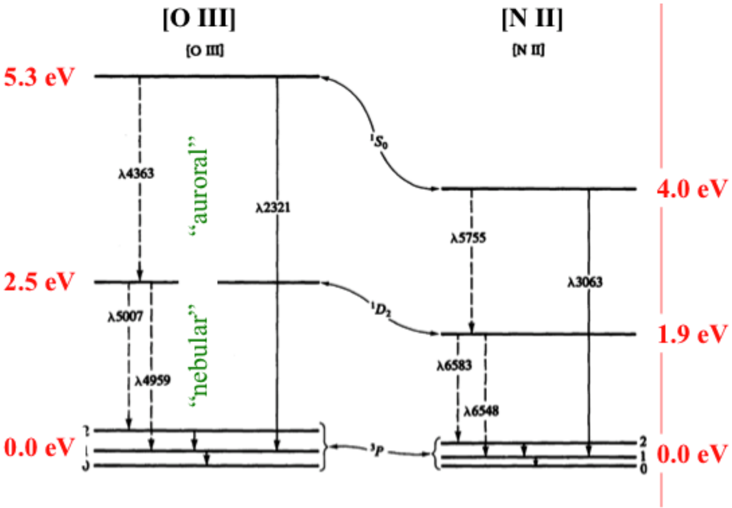


Figure from Porquet & Dubau (2000)

$np^{2,4}$ configurations (Fig. from Osterbrock & Ferland 2005)



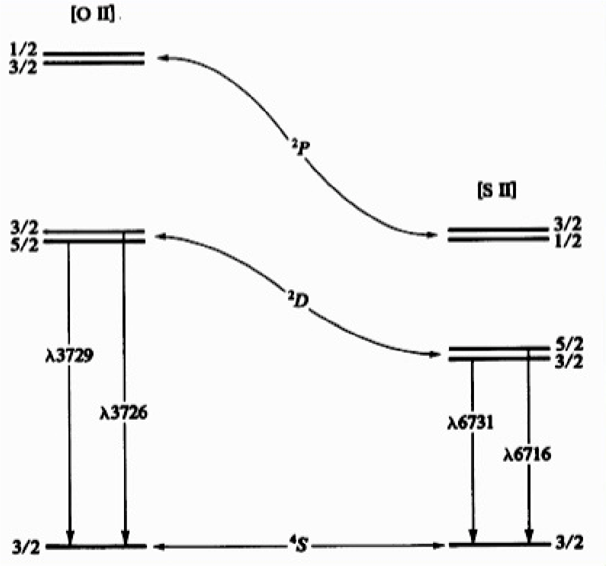
Radiative transitions

$$g_j A_{ji}^{\mathrm{E1}} = 2.6774 \times 10^9 (E_j - E_i)^3 S_{ij}^{\mathrm{E1}} \quad \mathrm{s}^{-1}$$
$$g_j A_{ji}^{\mathrm{E2}} = 2.6733 \times 10^3 (E_j - E_i)^5 S_{ij}^{\mathrm{E2}} \quad \mathrm{s}^{-1}$$
$$g_j A_{ji}^{\mathrm{M1}} = 3.5644 \times 10^4 (E_j - E_i)^3 S_{ij}^{\mathrm{M1}} \quad \mathrm{s}^{-1}$$
$$g_j A_{ji}^{\mathrm{E3}} = 1.2050 \times 10^{-3} (E_j - E_i)^7 S_{ij}^{\mathrm{E3}} \quad \mathrm{s}^{-1}$$
$$g_j A_{ji}^{\mathrm{M2}} = 2.3727 \times 10^{-2} (E_j - E_i)^5 S_{ij}^{\mathrm{M2}} \quad \mathrm{s}^{-1}$$
$$g_j A_{ji} = -g_i A_{ij} \qquad \text{(detailed balance)}$$

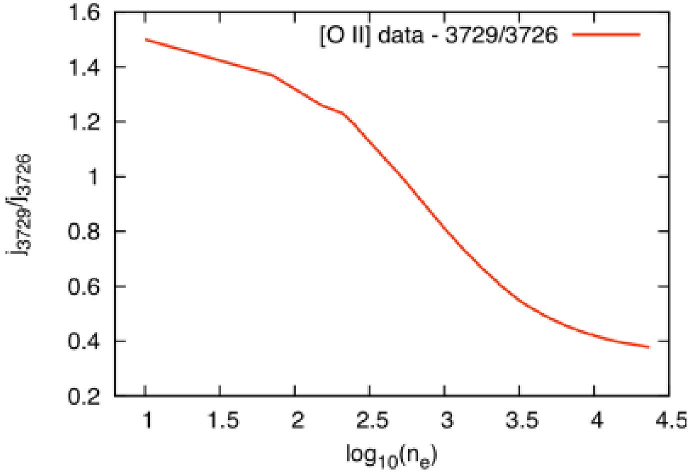
Table : Selection rules for radiative transitions

Type	$\Delta\pi$	$\Delta\ell$	ΔS	ΔL	ΔJ
Allowed (E1)	Yes	±1	0	$0, \pm1$	$0, \pm1$
Intercombination (E1)	Yes	±1	1	$0, \pm1$	$0, \pm1$
Forbidden (E2)	No	$0, \pm2$	0	$0, \pm2$	$0, \pm2$
Forbidden (M1)	No	0	0	0	$0, \pm1$

Radiative transition
np^3 configuration (Fig. from Osterbrock & Ferland 2005)



Radiative transition
Density sensitive $\lambda 3729/\lambda 3726$ ratio in O II



Radiative transitions
Density sensitive $\lambda 3729/\lambda 3726$ ratio in O II

Consider the density sensitive line ratio

$$R(N_e) = \frac{I(^2D^{\rm o}_{5/2} - \ ^4S^{\rm o}_{3/2})}{I(^2D^{\rm o}_{3/2} - \ ^4S^{\rm o}_{3/2})}$$

For $N_e \to \infty$,

$$R(\infty) = \frac{3}{2}\frac{A(^2D^{\rm o}_{5/2} - \ ^4S^{\rm o}_{3/2})}{A(^2D^{\rm o}_{3/2} - \ ^4S^{\rm o}_{3/2})}$$

Table : Observed and computed values for $R(\infty)$

Ion	Observed	MZ	G
N I	≤ 0.51	0.54	0.65
O II	0.35	0.35	0.42
S II	0.45	0.44	0.39

MZ: Zeippen (1982); Mendoza & Zeippen (1982).
G: Garstang (1968).

Electron impact excitation and de-excitation

The collisional rate for transitions with $E_j > E_i$ is given by $C_{ij} = n_e q_{ij}$, the *rate coefficient* being in units of $\mathrm{cm}^3\,\mathrm{s}^{-1}$

$$q_{ij} = \frac{8.631 \times 10^{-6}}{\omega_i T^{1/2}} \exp\left(-\frac{\Delta E_{ij}}{k_B T}\right) \Upsilon_{ij}$$

$$q_{ji} = \frac{8.631 \times 10^{-6}}{\omega_j T^{1/2}} \Upsilon_{ji} \ ,$$

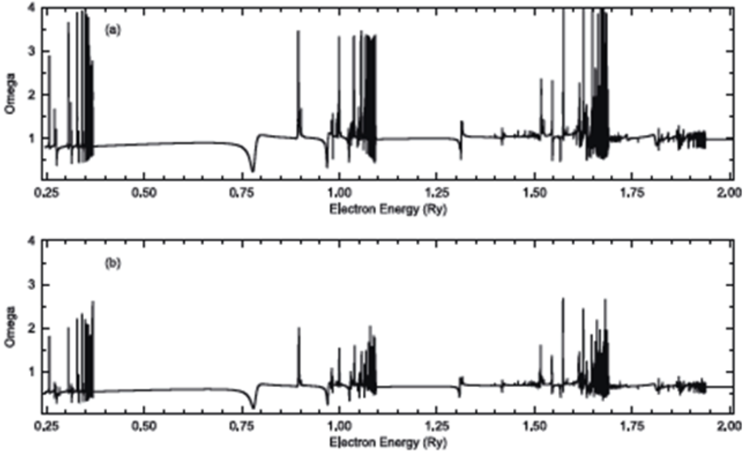
where the *effective collision strength* Υ_{ji} implies a Maxwellian average over the collision strength (cross section) for the transition

$$\Upsilon_{ji}(T_e) = \int_0^\infty \Omega_{ij}(\epsilon_j) \exp\left(-\frac{\epsilon_j}{k_B T_e}\right) \mathrm{d}\left(\frac{\epsilon_j}{k_B T_e}\right) \ .$$

From detailed balance,

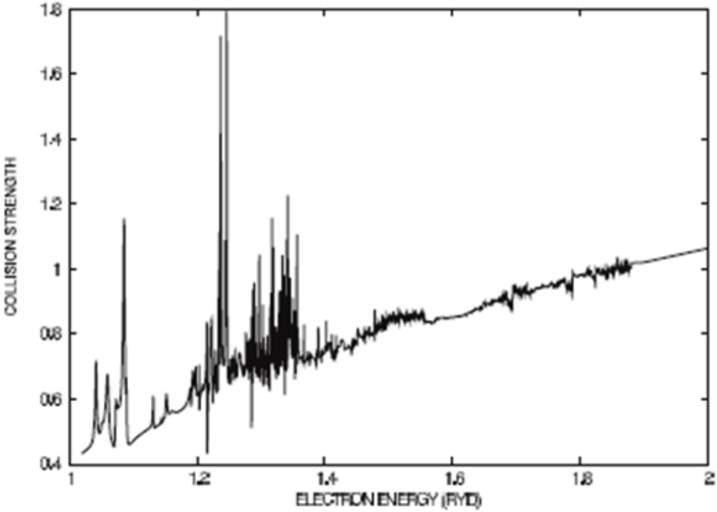
$$\Upsilon_{ij} = \Upsilon_{ji} \ .$$

Electron impact excitation and de-excitation



Collision strengths for the forbidden transitions of O II by Kiselius et al (2009): (a) $^4S^o_{3/2} - \ ^2D^o_{5/2}$. (b) $^4S^o_{3/2} - \ ^2D^o_{3/2}$.

Electron impact excitation and de-excitation



Collision strengths for the allowed transition of N II $2s^2 2p^2\ {}^3P_1 -\ 2s2p^3\ {}^3P^o_1$ by Tayal (2011) showing the typical logarithmic increase with energy.

Photoionization and radiative recombination

The photoionization cross section is given by

$$\sigma_{\rm pi} = \frac{4\pi^2 \alpha \omega_{ij}}{3} S_{ij} \ ,$$

and by the principle of detailed balance (Milne relation), the electron–ion recombination cross section can be written

$$\sigma_{\rm rc} = \sigma_{\rm pi} \frac{g_j}{g_s} \frac{(I+\epsilon)^2}{2mc^2\epsilon} \ .$$

The recombination rate coefficient in units of $\mathrm{cm^3\,s^{-1}}$ is

$$\alpha_r(T) = 1.8526 \times 10^4 \ \frac{g_j}{g_s} \frac{1}{T^{3/2}} \int_0^\infty (\epsilon + I)^2 \exp\left(-\epsilon/kT\right) \sigma_{\rm pi} \mathrm{d}\epsilon \ .$$

Photoionization and radiative recombination

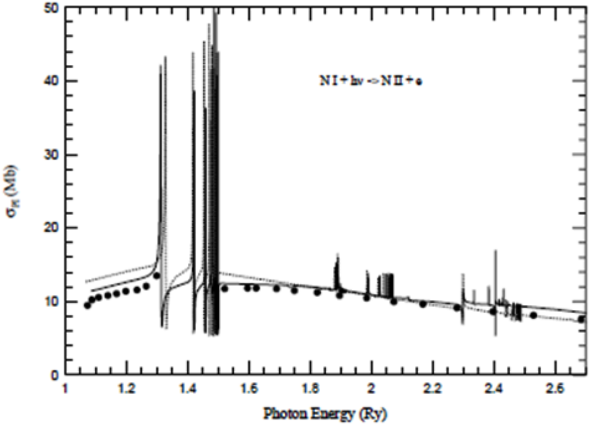
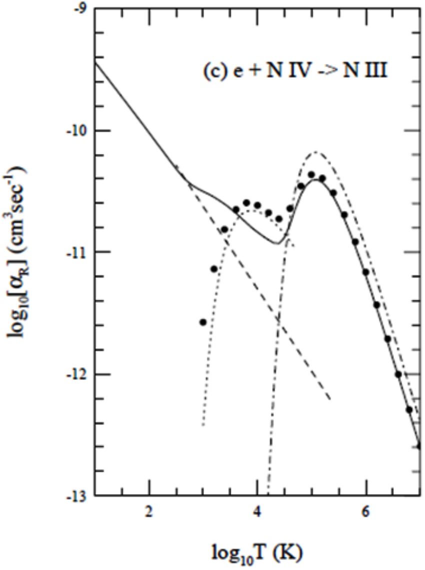


FIG. 3.—Comparison of the present *total* photoionization cross sections (*solid line*) for the ground state of N I, $^4S^o$, with the OP cross sections (*dotted line*) and the experimental values of Samson & Angel (1990; *filled circles*).

Figure from Nahar & Pradhan (1997)

Photoionization and radiative recombination



Total recombination rate coefficient for N III. Solid and dashed curves by Nahar & Pradhan (1997), filled circles from Badnell (1987, 1988). Figure from Nahar & Pradhan (1997).