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Relaxation times for establishing steady state populations in optically thin helium plasmas*

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Abstract. Population densitites of HeI and HeII excited states are calculated from a collisional radiative model for non-LTE optically thin helium plasmas. Effect of direct ionisation-excitation of HeI to HeII states on the population density of HeII states is shown. Relaxation times for HeI states calculated from the CR model is reported for T_e from 3 to 18 eV and n_e from 10^9 to 10^{16} cm^{-3}.

Keywords. Non-LTE plasmas; collisional radiative model; relaxation time.

1. Introduction

Relaxation times of the bound states play an important role in understanding the behaviour of transient non-local thermodynamic equilibrium (LTE) plasmas. In plasmas where both collisional as well as radiative processes are important, such relaxation times are determined in a complicated way by the relative cross-sections of various atomic processes. In those systems which are partially or completely optically thick to one or more line radiation originating inside the plasma, such considerations become further complicated due to excitations caused by such radiation. Relaxation times of hydrogen atoms and hydrogenic ions have been calculated by McWhirter and Hearn (1963) and Drawin (1970). McWhirter and Hearn's calculations involve optically thin plasmas, and the calculations of Drawin involve both optically thin and optically thick plasmas.

Cacciatore *et al* (1976) have solved time-dependent rate equations for hydrogenic plasma and they find that only in the near quasi-steady state condition McWhirter and Hearn's formulation of the relaxation time gives reasonable values. They show certain improvements in the values of relaxation time over those calculated by Drawin. However, in the case of helium plasma, the simple approximation as given by them (eq. 27 of Cacciatore *et al* 1976) cannot be used due to the presence of two metastable states above the ground state. Limbaugh and Mason (1971) have shown that helium plasma takes a long time $\sim 10^{-4}$ sec to attain quasi-steady state at low electron density (10^{12} cm^{-3}).

Calculations of dependable relaxation times in helium plasmas, in fact, are considerably difficult. First, numerous sub-levels in the singlet as well as in the triplet

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system exist which have widely different cross-sectional properties. Second, in the helium system two types of positive ions He^+ and He^{++} exist and a multitude of processes occur which connect the three heavy particles, He, He^+ and He^{++}, which need simultaneous treatment, especially at relatively high temperatures. Recently, in our laboratory, we have been involved in some experiments on helium plasmas (Ghosh and Hegde 1977) and in this connection developed a collisional-radiative model which we believe is a considerable improvement over the earlier helium models in so far as selection of neutral states and simultaneous treatment of the neutral and the ionic states. Earlier, Johnson (1967) used separated HeI sublevels, up to $n=5$ and an upper limit of levels as $n=25$. The calculations of Drawin *et al* (1973) used separated sub-levels up to $n=2$ and for $n > 2$ the singlet and triplet levels of a given principal quantum number were grouped separately. Park (1971) suggested a scheme in which singlet and triplet levels are grouped together. In none of these models, however, HeII levels are considered. Whereas this is quite reasonable at low electron temperatures, with increasing electron temperature the role played by the HeII states cannot be ignored. Mewe (1967) attempted to combine the HeI and HeII systems but the atomic processes of HeI and HeII were not simultaneously considered and some important processes like direct ionisation-excitation from HeI to HeII states were not included. In this paper we present the relaxation times of various HeI states calculated from an improved model for optically thin conditions.

2. Collisional-radiative model

The collisional-radiative model used in this work incorporates for HeI, completely separated sublevels up to $n=5$, and for the states $n=6$–12 all levels of the same

Table 1. Energy levels of HeI used in the collisional-radiative model

Level No. (p)	State	Energy E_p (cm^{-1})	g_p	Level No. (p)	State	Energy E_p (cm^{-1})	g_p
1	1^1S	0	1	17	4^3F, 4^1F	191452	28
2	2^3S	159856	3	18	4^1p	191493	3
3	2^1S	166278	1	19	5^3S	193347	3
4	2^3P	169078	9	21	5^1S	193663	1
5	2^1P	171135	3	21	5^3p	193801	9
6	3^3S	183237	3	22	5^3D	193917	15
7	3^1S	184865	1	23	5^1D	193919	5
8	3^3p	185656	9	24	5^3F, 5^1F, 5^3G, 5^1G	193921	64
9	3^3D	186102	15	25	5^1p	193943	3
10	3^1D	186105	5	26	6(n)	195251	144
11	3^1p	186210	3	27	7	196070	392
12	4^3S	190298	3	28	8	196595	512
13	4^1S	190940	1	29	9	196954	648
14	4^3p	191217	9	30	10	197213	800
15	4^3D	191445	15	31	11	197398	968
16	4^1D	191447	5	32	12	197543	1152

Energy levels of HeII used in the model
$E_i=109677\times 4\,(1-1/i^2)+198331$ cm^{-1} and $g_i=2i^2$

principal quantum number are grouped together as shown in table 1. In addition to these HeI states, 13 states of HeII, i=1–13, are included in the model, thus making a total of 45 levels. The collisional and radiative processes included in the model are as follows:

(i) electron impact excitation-deexcitation processes between HeI states involving rate coefficients $K(p, q)$ and $K(q, p)$,
(ii) radiative transitions with $A(p, q), p > q$,
(iii) atom-atom collisions for excitation-deexcitation, ionisation, recombination, with rate coefficients $KN(p, q)$, $KN(q, p)$, $KN(p, i{=}1)$, $KN(i{=}1, p)$,
(iv) electron impact excitation-deexcitation, ionisation, recombination processes of HeII states with rate coefficients $K(i, j)$, $K(j, i)$, $K(i, c)$, $K(c, i)$,
(v) HeII spontaneous decay with $A(i, j)$, $i > j$, and
(vi) He^{++} radiative recombination with rate coefficient $\beta\,(i)$.

In addition, we include the following processes:

$$\mathrm{He}(p)+e \xrightarrow{K(p,\,i)} \mathrm{He}^{+}(i)+e+e$$

$$\mathrm{He}^{+}(1)+e+e \xrightarrow[i=1]{K(i,\,p)} \mathrm{He}(p)+e$$

$$\mathrm{He}^{+}(1)+e \xrightarrow[(p)]{\beta(p)} \mathrm{He}(p)+h\nu$$

which are direct ionisation-excitation, three-body and radiative recombinations from the HeII ground state, respectively. Putting $n_e/n^{+}(1)=X$ and $n_e/n^{++}=Y$, one obtains the following equilibrium relations:

$$K(p, q)\, n_E(p) = K(q, p)\, n_E(q)$$

$$(n_e/X)\, K(i{=}1, p) = K(p, i{=}1)\, n_E(p)$$

$$K(i, j)\, n_E^{+}(i) = K(j, i)\, n_E^{+}(j)$$

$$(n_e/Y)\, K(c, i) = K(i, c)\, n_E^{+}(i).$$

$n(p)$ and $n^{+}(i)$ denote number densities of HeI and HeII states and n_e, n^{++} denote number densities of electrons and doubly charged ions respectively; $n_E(p)$ and $n_E^{+}(i)$ represent Saha equilibrium population densities respectively of HeI and HeII states; c denotes the second continuum. For the above processes the time derivatives of excited state populations, after incorporating the equilibrium densities and considering only collisional-radiative processes, can be written as

$$\frac{\dot{n}(p)}{n_E(p)} = -\rho(p)\left[n_e \left\{\sum_{i=1}^{13} K(p, i) + \sum_{q\neq p}^{32} K(p, q)\right\} + n(1) \sum_{q\neq p}^{32} KN(p, q) + \sum_{p>q} A(p, q)\right]$$

$$+\sum_{p\neq q}^{32} \rho(q)\, KN(p,q)\, n(1)\, \frac{n_E(q)}{n_E(p)} + \sum_{p\neq q}^{32} \rho\,(q) K(p,q)\, n_e$$

$$+\sum_{q>p} \rho(q)\; A(q,p)\; \frac{n_E(q)}{n_E(p)} + n_e\, K(p, i=1) + \frac{n_e^2}{X n_E(p)}\, \beta(p) \tag{1a}$$

and

$$\frac{\dot{n}^+(i)}{n_E^+(i)} = -\,\rho^+(i) \left\{ n_e \left[K(i,c) + \sum_{i\neq j}^{13} K(i,j) \right] + \sum_{i>j} A\,(i,j) \right\}$$

$$+\sum_{i\neq j}^{13} \rho^+(j)\, K(i,j)\cdot n_e + \sum_{j>i} \rho^+(j)\, \frac{n_E^+(j)}{n_E^+(i)}\, [A\,(j,i)]$$

$$+\sum_{p=1}^{32} \rho(p)\cdot n_e\, \frac{n_E(p)}{n_E^+(i)}\, K\,(p,i) + n_e\, K(i,c) + \frac{n_e^2\, \beta\,(i)}{Y n_E^+(i)} \tag{1b}$$

where $\rho\,(p) = n(p)/n_E(p)$, $\rho^+(i) = n^+(i)/n_E^+(i)$. The first four terms, in the square brackets in (1a) represent the processes which contribute to the so-called relaxation time, defined (at low pressure) as follows:

$$\tau\,(p) = \frac{1}{n_e[\sum_q K(p,q) + \sum_i K(p,i)] + \sum_{p>q} A(p,q)}. \tag{2}$$

Here, contribution from $KN\,(p,q)$ is neglected since it is small compared to other terms.

The $A(p,q)$ values for HeI are taken from the tables of Wiese *et al* (1966). For calculation of collisional ionisation rate coefficients $K(p, i=1)$, Gryzinski's (1965) formulation is used. For collisional excitation coefficients $K(p,q)$ several cases arise: (i) optically allowed transitions (2^1p—1^1S, 3^3p—2^3S, etc.), (ii) optically forbidden transitions without change in multiplicity ($1^1\,S$—2^1S, $1'S$—$3'D$, etc.), (iii) optically forbidden transitions with change in multiplicity (1^1S—2^3S, 1^1S—2^3P, etc.), and these can be of two types, those which involve the ground state and those which do not. Cross-sections for these processes are taken from Drawin (1967). Those cross-sections for the optically forbidden transitions not involving the ground state which are unavailable from Drawin (1967), are taken from the compilations of Moisewitsch and Smith (1968). Ionisation excitation coefficients for transitions HeI(p)–HeII(i) are calculated using the following expression for excitation cross-section

$$q_{pi}(x) = 2\pi\, a_0^2 \left[\frac{E_1^H}{E_{pi}} \right]^2 g\,(x), \tag{3}$$

where $g(x)=\frac{x-1}{x^2}\ln(1{\cdot}25x),\ x=E_e/E_{pi},$

E_e is the electron energy, E_1^H is the hydrogen atom ground state ionisation potential, and E_{pi} is the energy difference $E_{pi}=E_i-E_p$. It may be stated here that (3) has the same form as some of the electron impact excitation of HeI states. The formula is extended to HeI–HeII ionisation-excitation. Ionisation-excitation cross-section value $q_{pi}(x)$ calculated from the above equation matches closely the cross-section presented by Drawin (1967) for the case HeI $(1)+e\rightarrow He^+(4)+e+e$ from the experimental results of Hughes and Weaver (1963). It should be pointed out here that cross-sections for simultaneous ionisation-excitation to HeII states from the HeI ground state were studied by Dalgarno and McDowell (1965) and their cross-sections are more than one order of magnitude lower than those obtained from the above equation. All the cross-sections used in this work are integrated over Maxwellian energy distribution of electrons (for a particular electron temperature T_e) using the Gaussian quadrature method. The ionisation-excitation rate constants for two values of T_e are presented in table 2.

3. Results and discussion

By applying the quasi-steady state condition, $\dot{n}(p)=0$ for $p>1$ and $\dot{n}^+(i)=0$ for $p>1$ and $i>1$, the solutions of equations (1a) and (1b) can be written as follows:

$$\rho(p) = r_0(p)+r_1(p)\,\rho\,(1), \tag{4}$$

and

$$\rho^+(i) = r_0^+(i)+r_1^+(i)\,\rho(1)+r_2^+(i)\rho^+(1). \tag{5}$$

Table 2. Values of ionization-excitation coefficients $K(p, i)$ cm³ sec⁻¹ for HeI(p) → HeII(i) at T_e=11·2 eV and 5·9 eV

(p, i)	11·2 eV	5·9 eV
1^1S-1	$7{\cdot}73^{-10}$	$7{\cdot}20^{-11}$
1^1S-2	$2{\cdot}56^{-12}$	$8{\cdot}10^{-15}$
1^1S-3	$1{\cdot}03^{-12}$	$1{\cdot}77^{-15}$
1^1S-12	$5{\cdot}30^{-13}$	$5{\cdot}74^{-16}$
2^3S-1	$1{\cdot}00^{-7}$	$5{\cdot}67^{-8}$
2^3S-2	$3{\cdot}26^{-11}$	$5{\cdot}18^{-13}$
2^3S-3	$1{\cdot}20^{-11}$	$1{\cdot}02^{-13}$
2^3S-12	$5{\cdot}80^{-12}$	$3{\cdot}14^{-13}$
2^1S-1	$1{\cdot}47^{-7}$	$9{\cdot}07^{-8}$
2^1S-2	$3{\cdot}63^{-11}$	$6{\cdot}16^{-13}$
2^1S-3	$1{\cdot}33^{-11}$	$1{\cdot}21^{-13}$
2^1S-12	$6{\cdot}41^{-12}$	$3{\cdot}70^{-14}$
$n=10-1$	$2{\cdot}54^{-5}$	$2{\cdot}94^{-5}$
$n=10-2$	$6{\cdot}19^{-11}$	$1{\cdot}44^{-12}$
$n=10-3$	$2{\cdot}20^{-11}$	$2{\cdot}75^{-15}$
$n=10-12$	$1{\cdot}05^{-11}$	$8{\cdot}24^{-14}$

In equation (4), $r_0(p)$ gives the contribution towards $\rho(p)$ from the first continuum and $r_1(p)$. $\rho(1)$ is the contribution from the ground state of HeI. Similarly, r_0^+ (i) in (5) gives the contribution to $\rho^+(i)$ from the second continuum, $r_1^+(i)\ \rho$ (1) is the contribution from the ground state of HeI and r_2^+ (i) ρ^+ (1) is the contribution from the ground state of HeII. The solution for ρ (p) and ρ^+ (i) can be obtained in terms of $r_0(p)$, $r_1(p)$ and $r_0^+(i)$, r_1^+ (i) and r_2^+ (i) respectively. These coefficients are functions of n_e, T_e and T_g. Population densities $n(p)$ and $n^+(i)$ are obtained for given values of $n(1)$ and $n^+(1)$. Typical values of $r_0(p)$ and $r_1(p)$ and the contributions to $n(p)$ from the continuum and the ground state are given in table 3. It can be seen from the table that in the range of plasma parameters chosen, the major contribution to $n(p)$ comes from the ground state of HeI and only at high electron density, contribution from the continuum is comparable with that from the ground state. The calculations were repeated by including levels only upto $n=10$ and we find that variation in the r_0 and r_1 values is negligibly small (less than 1%). This means that $n=12$ taken here is sufficient to give fairly accurate non-LTE $n(p)$ values of the excited state of HeI. It may be mentioned here that the high lying levels ($n>10$) are energetically very close to the continuum and departure of n (p) from n_E (p) is small.

The extent to which the absolute densities $n(p)$ predicted from the model agree with experimental measurements on helium plasmas is shown in table 4 by applying

Table 3. Values of $r_0(p)$, $r_1(p)$ coefficients and contributions from $r_0(p)$ and $r_1(p)$ to population densities of some HeI excited states

n_e cm^{-3}	p	$r_0(p)$	$r_1(p)$	$r_0(p)n_E(p)$ A	$\frac{r_1(p)\cdot n_E(p)\cdot n(1)}{n_E(1)}$ B	$n(p)=A+B$ (cm^{-3})
		$T_e=11{\cdot}2$ eV, $n(1)=2{\cdot}0^{14}$ cm^{-3}, $n^+\sim n_e$				
10^{10}	6 (3^3S)	5·5	$2{\cdot}34^{-8}$	$3{\cdot}6^{-3}$	$1{\cdot}82^{6}$	$1{\cdot}82^{6}$
	9 (3^3D)	3·2	$1{\cdot}80^{-9}$	$5{\cdot}6^{-2}$	$6{\cdot}79^{5}$	$6{\cdot}79^{5}$
	11 (3^1P)	3·3	$2{\cdot}10^{-8}$	$1{\cdot}1^{-2}$	$1{\cdot}58^{6}$	$1{\cdot}58^{6}$
	15 (4^3D)	3·8	$1{\cdot}04^{-9}$	$6{\cdot}3^{-2}$	$3{\cdot}70^{5}$	$3{\cdot}70^{5}$
	22 (5^3D)	2·3	$9{\cdot}89^{-10}$	$2{\cdot}2^{-2}$	$3{\cdot}40^{5}$	$3{\cdot}40^{5}$
10^{14}	6	1·7	$1{\cdot}78^{-5}$	$6{\cdot}18^{5}$	$1{\cdot}38^{9}$	$1{\cdot}38^{9}$
	9	1·1	$2{\cdot}34^{-6}$	$1{\cdot}93^{6}$	$8{\cdot}82^{8}$	$8{\cdot}83^{8}$
	11	1·7	$2{\cdot}28^{-5}$	$5{\cdot}98^{5}$	$1{\cdot}72^{9}$	$1{\cdot}72^{9}$
	15	0·97	$6{\cdot}38^{-7}$	$1{\cdot}6^{6}$	$2{\cdot}27^{8}$	$2{\cdot}28^{8}$
	22	0·98	$1{\cdot}40^{-7}$	$1{\cdot}57^{6}$	$4{\cdot}83^{7}$	$4{\cdot}98^{7}$
		$T_e=5{\cdot}9$ eV, $n(1)=2^{14}$ cm^{-3}				
10^{10}	6	0·36	$3{\cdot}29^{-8}$	$3{\cdot}99^{-3}$	$4{\cdot}12^{5}$	$4{\cdot}12^{5}$
	9	2·00	$2{\cdot}78^{-9}$	$1{\cdot}04^{-1}$	$1{\cdot}63^{5}$	$1{\cdot}63^{5}$
	11	0·14	$2{\cdot}48^{-8}$	$1{\cdot}42^{-3}$	$2{\cdot}91^{5}$	$2{\cdot}91^{5}$
	15	1·24	$1{\cdot}63^{-9}$	$5{\cdot}70^{-2}$	$8{\cdot}56^{4}$	$8{\cdot}56^{4}$
	22	1·47	$1{\cdot}52^{-9}$	$6{\cdot}48^{-2}$	$7{\cdot}57^{4}$	$7{\cdot}57^{4}$
10^{14}	6	1·85	$2{\cdot}42^{-5}$	$2{\cdot}03^{6}$	$3{\cdot}00^{8}$	$3{\cdot}02^{8}$
	9	1·14	$3{\cdot}89^{-6}$	$5{\cdot}93^{6}$	$2{\cdot}29^{8}$	$2{\cdot}34^{8}$
	11	1·88	$2{\cdot}25^{-5}$	$1{\cdot}95^{6}$	$2{\cdot}64^{8}$	$2{\cdot}65^{8}$
	15	1·00	$8{\cdot}91^{-6}$	$4{\cdot}65^{6}$	$4{\cdot}68^{7}$	$5{\cdot}13^{7}$
	22	0·99	$1{\cdot}78^{-7}$	$4{\cdot}34^{6}$	$8{\cdot}86^{6}$	$1{\cdot}30^{7}$

Table 4. Comparison of experimentally observed values of HeI population densities (Johnson 1967) with present calculations using optically thin condition

States	Expt.	Present calc.	Expt.	Present calc.
T_e eV	10·8		8·5	
n_e	$4{\cdot}2^{12}$		$1{\cdot}9^{13}$	
$n(1)$	$8{\cdot}8^{11}$		$6{\cdot}3^{12}$	
4^1S	$6{\cdot}6^{5}$	$4{\cdot}79^{5}$	$2{\cdot}2^{6}$	$2{\cdot}60^{6}$
5^1S	$2{\cdot}4^{5}$	$1{\cdot}24^{5}$	$6{\cdot}4^{5}$	$6{\cdot}06^{5}$
3^1P	$6{\cdot}9^{5}$	$3{\cdot}00^{5}$	$7{\cdot}4^{6}$	$4{\cdot}50^{6}$
4^1P	$3{\cdot}3^{5}$	$2{\cdot}02^{5}$	$2{\cdot}0^{6}$	$2{\cdot}40^{6}$
5^1P	$1{\cdot}2^{5}$	$1{\cdot}06^{5}$	$5{\cdot}0^{5}$	$7{\cdot}65^{5}$
3^1D	$5{\cdot}1^{5}$	$3{\cdot}28^{5}$	$4{\cdot}0^{6}$	$3{\cdot}57^{6}$
4^1D	$3{\cdot}0^{5}$	$1{\cdot}64^{5}$	$1{\cdot}5^{6}$	$1{\cdot}23^{6}$
5^1D	$9{\cdot}5^{4}$	$6{\cdot}00^{4}$	$4{\cdot}3^{5}$	$2{\cdot}78^{5}$
3^3S	$2{\cdot}7^{6}$	$1{\cdot}85^{6}$	$1{\cdot}2^{7}$	$1{\cdot}60^{7}$
4^3S	$7{\cdot}4^{5}$	$5{\cdot}60^{5}$	$2{\cdot}6^{6}$	$4{\cdot}00^{6}$
5^3S	$1{\cdot}9^{5}$	$9{\cdot}55^{4}$	$5{\cdot}8^{5}$	$6{\cdot}00^{5}$
3^3P	$2{\cdot}1^{6}$	$2{\cdot}42^{6}$	$9{\cdot}7^{6}$	$2{\cdot}00^{7}$
4^3P	$4{\cdot}9^{5}$	$4{\cdot}99^{5}$	$1{\cdot}8^{6}$	$2{\cdot}60^{6}$
5^3P	$1{\cdot}5^{5}$	$9{\cdot}00^{4}$	$4{\cdot}7^{5}$	$4{\cdot}40^{5}$
3^3D	$1{\cdot}3^{6}$	$7{\cdot}70^{5}$	$7{\cdot}8^{6}$	$9{\cdot}40^{6}$
4^3D	$3{\cdot}3^{5}$	$3{\cdot}11^{5}$	$1{\cdot}5^{6}$	2.40^{6}
5^3D	$1{\cdot}0^{5}$	$1{\cdot}30^{5}$	$4{\cdot}0^{5}$	$6{\cdot}90^{5}$

Table 5a. r_0^+ (4), r_1^+ (4) and r_2^+ (40 of HeII (i=4) at 11·2 eV and 5·9 eV

n_e	$r_0^+(4)$		r_1^+ (4)		$r_2^+(4)$	
	11·2 eV	5·9 eV	11·2 eV	5·9 eV	11·2 eV	5·9 eV
10^{10}	0·34	0·20	$2{\cdot}94^{-8}$	$2{\cdot}06^{-10}$	$5{\cdot}70^{-10}$	$6{\cdot}5^{-10}$
10^{12}	0·36	0·23	$2{\cdot}92^{-6}$	$2{\cdot}05^{-8}$	$2{\cdot}05^{-8}$	$6{\cdot}2^{-8}$
10^{14}	0·60	0·40	$2{\cdot}00^{-4}$	$1{\cdot}80^{-6}$	$4{\cdot}00^{-6}$	$4{\cdot}8^{-6}$

it to the Stellarator *C* work (Johnson 1967). The present model has also been applied to the helium population densities in Nagoya TPD plasma machine (Hegde and Ghosh 1977) and to line emission enhancement of helium plasmas in magnetic field (Hegde and Ghosh 1979). In tables 5a and 5b $r_0^+(i)$, $r_1^+(i)$ and $r_2^+(i)$ for HeII i=4 level is given and also, the n^+ (4) calculated using (5) are also given at two different temperatures. It can be seen from the tables that at higher temperature, $n^+(4)$ is mainly from the ground state of HeI. At sufficiently high electron density, HeII excited states get populated from the ground state of HeII and the second continuum. The $r_0^+(i)$ and other coefficients do not change more than 1% if the total number of levels increased is upto i=15. Thus, simultaneous ionisation-excitation is important in certain range of plasma parameters. On the basis of line intensity ratios of

Table 5b. Contribution to the population density of HeII (4) from continuum and HeI, HeII ground states

$n(1)=2^{14}$ cm^{-3} and $n^+(1)\approx n_e$

T_e	n_e cm^{-3}	$r_0^+(4)\cdot n_E^+(4)$ cm^{-3} (A)	$r_1^+(4)\cdot n_E^+(4)\cdot\rho(1)$ cm^{-3} (B)	$r_2^+(4)\cdot n_E^+(4)\rho^+(1)$ cm^{-3} (C)	$n^+(4)$ cm^{-3} ($A+B+C$)
11·2 eV	10^{10}	$6{\cdot}52^{-6}$	$1{\cdot}41^{4}$	$9{\cdot}43^{-1}$	$1{\cdot}41^{4}$
	10^{12}	$6{\cdot}90^{-2}$	1.40^{6}	$1{\cdot}02^{4}$	$1{\cdot}41^{6}$
	10^{14}	$1{\cdot}53^{3}$	$9{\cdot}60^{7}$	$7{\cdot}90^{7}$	$1{\cdot}75^{8}$
5·9 eV	10^{10}	$1{\cdot}35^{-5}$	$2{\cdot}81^{2}$	$1{\cdot}77^{-2}$	$2{\cdot}81^{2}$
	10^{12}	$1{\cdot}51^{-1}$	$2{\cdot}80^{4}$	$1{\cdot}88^{3}$	$2{\cdot}82^{4}$
	10^{14}	$3{\cdot}95^{2}$	$2{\cdot}45^{6}$	$1{\cdot}36^{6}$	$3{\cdot}81^{6}$

Table 6. Relaxation times of optically thin helium plasmas at T_e=3, 5, 10 and 18 eV.

n_e	1^1S	2^3S	2^1S	2^3P	2^1P	3^3D	3^1D	3^1P	$n=6$
10^9	6·34+1*	2·38−3	1·50−3	9·78−8	5·55−10	1·42−8	1·57−8	1·73−9	1·04−8
	1·44+2	1·54−3	1·18−3	9·78−8	5·55−10	1·42−8	1·57−8	1·73−9	1·04−8
	1·76+2	1·48−3	1·14−3	9·78−8	5·55−10	1·42−8	1·57−8	1·73−9	1·04−8
	2·32+2	1·46−3	1·12−3	9·78−8	5·55−10	1·42−8	1·57−8	1·73−9	1·04−8
10^{11}	5·50−1	2·38−5	1·50−5	9·76−8	5·55−10	1·41−8	1·56−8	1·72−9	9·98−9
	1·40+0	1·54−5	1·18−5	9·73−8	5·55−10	1·41−8	1·56−8	1·72−9	1·03−8
	1·73+0	1·48−5	1·14−5	9·73−8	5·55−10	1·41−8	1·56−8	1·72−9	1·01−8
	2·32+0	1·45−5	1·12−5	9·72−8	5·55−10	1·42−8	1·56−8	1·72−9	1·01−8
10^{13}	4·92−3	2·38−7	1·50−7	7·80−8	5·54−10	1·08−8	1·13−8	1·50−9	2·12−9
	2·00−2	1·54−7	1·18−7	6·33−8	5·53−10	9·93−9	1·03−8	1·55−9	2·38−9
	2·65−2	1·48−7	1·14−7	6·09−8	5·53−10	9·89−9	1·03−8	1·56−9	2·50−9
	3·75−2	1·45−7	1·12−7	5·89−8	5·52−10	9·92−9	1·04−8	1·57−9	2·70−9
10^{15}	9·10−5	2·38−9	1·50−9	3·70−9	4·40−10	4·40−10	3·92−10	1·08−10	2·66−11
	3·69−4	1·54−9	1·18−9	1·76−9	3·90−10	3·25−10	2·98−10	1·37−10	3·09−11
	4·97−4	1·48−9	1·14−9	1·59−9	3·81−10	3·20−10	2·95−10	1·46−10	3·29−11
	7·26−4	1·45−9	1·12−9	1·46−9	3·74−10	3·24−10	2·99−10	1·62−10	3·64−11
10^{16}	9·24−6	2·38−10	1·50−10	3·83−10	1·53−10	4·53−11	4·01−11	1·14−11	2·67−12
	3·73−5	1·54−10	1·18−10	1·79−10	1·06−10	3·31−11	3·03−11	1·47−11	3·09−12
	5·03−5	1·48−10	1·14−10	1·61−10	9·98−11	3·27−11	2·99−11	1·58−11	3·30−12
	7·37−5	1·45−10	1·12−10	1·47−10	9·51−11	3·31−11	3·04−11	1·77−11	3·65−12

*Read 6·34+1 as $6{\cdot}34\times10^1$ sec. The four numbers in each group correspond to the relaxation times at 3, 5, 10 and 18 eV respectively.

HeI and HeII lines, the population density $n^+(4)$ obtained is compared with the calculated value using this model and the values do compare closely (Hegde and Ghosh 1979).

For computation of the relaxation time, $K(p, q)$ and $K(p, i)$'s are first calculated for a wide range of electron temperature T_e. The relaxation times for all the levels considered are then calculated by using (2) for an extended range of n_e. Numerical values of the relaxation times for a few levels of the helium system are given in table 6.

From table 6, the levels can be classified into three categories: (a) the ground state, (b) the metastable 2^1S and 2^3S, and (c) all other excited states. It can be seen from the table that all the excited states other than the metastables have very low relaxation times even at low electron density and temperature. This is because they mainly relax via optical radiation to the lower states. The optical transition probabilities are of the order of 10^7–10^8 sec^{-1}, and the relaxation times are about 10^{-7}–10^{-8} sec. Only at higher electron densities, 10^{14}–10^{16} cm^{-3}, collision effects dominate and relaxation times reduce further and eventually they all reach relaxation times of the order of 10^{-10} sec where one can assume the levels to be near LTE. The metastable states have rather high relaxation times at low electron densities, but as the electron density increases the relaxation time decreases and, at 10^{13}–10^{15} cm^{-3}, have the same order as the other excited states. The ground state has very high relaxation time, and even at very high electron density, steady state approximation is difficult to apply.

These relaxation times indicate that the problem of calculation of helium population densities would perhaps be better handled if the solution is carried out in steps. That would be to solve first for $n(p)$ for $p>3$ in terms of $n(1^1S)$, $n(2^3S)$ and $n(2^1S)$, and then solve for $n(p)$ for all $p>1$ by putting $\dot{n}(2^3S)=0$ and $\dot{n}(2^1S)=0$ for, the latter states have relaxation times several orders of magnitude lower than the ground state but much higher than the other excited states.

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