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ELECTRON TEMPERATURE MEASUREMENTS IN LOW DENSITY PLASMAS BY HELIUM SPECTROSCOPY

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Abstract

The method using relative intensities of singlet and triplet lines of neutral helium to measure electron temperature in low-density plasmas is examined. Calculations from measured and theoretical data about transitions in neutral helium are carried out and compared with experimental results. It is found that relative intensities of singlet and triplet lines from neutral helium can be used for T_e determination only in low-density, short-duration plasmas. The most important limiting processes are excitation from the metastable 2^3S level and excitation transfer in collisions between electrons and excited helium atoms. An evaluation method is suggested, which minimizes the effect of these processes.

1. Introduction

Since it was first proposed by Cunningham 1954, a method to measure plasma electron temperature by the use of helium singlet-to-triplet line intensity ratios has been widely used. A development of the method has been presented by Eastlund et al. (1973). The basis for the method is that the dependence on electron energy of the cross sections for excitation by electron impact differs widely between singlet and triplet lines of neutral helium. The electron temperature is calculated from measured line intensities with the help of excitation cross sections, obtained in collision chamber experiments. However, many warnings have been given against the effect of processes in a plasma that could influence the helium line intensities and invalidate the method (Drawin, 1964, 1967; de Vries and Mewe,1965; Mewe,1967).

The present work is an examination of the processes that are important for the intensities of lines originating in the 4^1S, 5^1S, 4^1D, 5^1D, 4^3S, 5^3S, 4^3D and 5^3D levels at low electron densities (between 10^{14} and 10^{18} m^{-3}). (Line intensities are throughout this paper in photons$\cdot m^{-3} \cdot s^{-1}$). Calculations are done from measured and theoretical data about transitions in neutral helium. The result is that excitation from metastables and excitation transfer in collisions between excited atoms and electrons can influence some helium line intensities severely if the electron density is above 10^{16} m^{-3} and/or the time scale of the experiment is more than a few microseconds.

The excitation transfer process is shown to change the relative population of levels with the same main and spin quantum number, for instance 4^3S, 4^3P, 4^3D and 4^3F. With increasing electron density, this approaches what could be seen as a "local thermal equilibrium" within each such group of levels, where their relative population is determined by their statistical weight. However, since this redistribution only involves levels with the same main quantum number, it is still far from what is usually meant by local thermal equilibrium.

The two lines 4472 Å (4^3D-2^3P) and 4713 Å (4^3S-2^3P) offer a striking example of how the relative line intensities are influenced by the excitation transfer process. The two cross sections for excitation from the ground state have closely the same electron energy dependence. 4713 would therefore be around three times as strong as 4472, independent of electron temperature, if only excitation from the ground state were important. Measured relative line intensities differ with as much as a factor of eighteen from this. 4472 is found to be up to six times as strong as 4473 in a series of experiments where a plasma stream (density varied between $3 \cdot 10^{16}$ and $4 \cdot 10^{18}$ m^{-3}) collides with a stationary cloud of neutral helium (density varied between $5 \cdot 10^{18}$ and 10^{20} m^{-3}). This is explained by that the excitation transfer process favours the 4472 Å line, which has the greater statistical weight of the upper level. The experimental results show good agreement with the theoretical calculations.

Finally, a method to obtain T_e from measured line intensities in a way that minimizes the effect of disturbing processes is proposed, together with limits on its applicability.

2. Data used in calculations

For a description of the calculations, a list of cross sections used, transition probabilities etc. is useful:

I) For excitations from the ground state, the cross sections measured by St John et al (1964) are used together with the measurements close to threshold by Smit et al (1963). For levels, where the cross sections have not been measured, an extrapolation procedure was used: the cross sections for excitation from the ground state to higher lying levels were assumed to vary as n^{-3}, where n is the main quantum number. The energy dependence of high n excitation cross sections was taken to be the same as that of the low n cross sections having the same orbital quantum number.

II) Theoretical transition probabilities for $n \leq 8$ have been compiled by Gabriel and Heddle (1960) for the S, P, D and F levels. An extrapolation procedure was used to find values for higher n and levels with orbital quantum numbers greater than 3.

III) The natural lifetimes of many levels have been measured by Thompson and Fowler (1975). For the remaining levels they are either calculated from the transition probabilities given by Wiese et al (1966) or obtained by extrapolation from known lifetimes according to Bethe and Salpeter (1957): for a fixed orbital quantum number, the lifetimes are assumed to vary as n^3.

IV) Excitation to the metastable states 2^1S and 2^3S goes mainly by excitation from the ground state, either directly or by excitation to higher-lying states followed by radiative transfer (cascading) to the metastable states. Effective "total" cross sections for excitation to 2^1S and 2^3S have been calculated from the cross sections and transition probabilities in I and II above. Excitation transfers $He(2^3S) + e \rightarrow He(2^1S) + e$ also contribute to the $He(2^1S)$ population. The cross section for this process is taken from Drawin (1966).

V) De-excitation from the 2^3S level is dominated by ionizing collisions with electrons. The cross section for this process is taken from Drawin (1966). For 2^1S the dominating de-excitation process is $2^1S \rightarrow 2^1P$ excitation through collisions with electrons, followed by $2^1P \rightarrow 1^1S$ cascading. The $2^1S \rightarrow 2^1P$ excitation cross section has been calculated by Flannery et al (1964).

VI) Theoretical cross sections for the $2^3S \rightarrow 3^3S$, $2^3S \rightarrow 3^3D$, $2^1S \rightarrow 3^1S$ and $2^1S \rightarrow 3^1D$ excitations by electron impact have been calculated by Flannery et al (1964). They used both the Born and the VPS (Vainstein, Presnyakov and Sobelman) approximation, and state that the difference between them (typically a factor of 3) can be taken as a measure of the uncertainty. Since we need cross sections for excitation to higher lying levels than Flannery et al:s calculations cover, these have been extrapolated in the following way: the shape of the cross section (as a function of electron energy W_e) is assumed to be the same for all cross sections for excitation to levels with the same or-

bital quantum number. The relative magnitude is assumed to be 1,1/3 and 1/6 for excitations to the levels with main quantum number n = 3,4 and 5, respectively. These relative magnitudes are founded on the relative magnitudes of the $2^{1,3}S \rightarrow 3^{1,3}P$ and $2^{1,3} \rightarrow 4^{1,3}P$ cross sections calculated by Flannery et al and the $2^{1,3} \rightarrow 4^{1,3}P$ and $2^{1,3} \rightarrow 5^{1,3}P$ cross sections given by Drawin (1966). The error in this extrapolation procedure is estimated to be less than the difference between the Born and VPS approximations.

VII) For ionization by electron impact from highly excited states, the dominating process is not a one-step ionization but a multi-step process, each step giving a small change in main quantum number n. Saraph (1964) has given relevant cross sections, which have been used to estimate an "effective ionization cross section" as a function of the main quantum number of the excited state.

VIII) For optically allowed excitation transfers between excited states with the same main quantum number, the Born approximation (Drawin, 1966) for electron collisions has been used. For this, the dipole moments for these transitions in excited helium are needed. They are very close to the corresponding dipole moments for hydrogen, which are used instead. Values are given by Bethe and Salpeter (1957).

For all transitions listed above, the cross section curves have been closely approximated by analytical functions and integrated over Maxwellian electron distributions to give rate coefficients $\langle \sigma v_e \rangle$ for electron temperatures between 2 and 200 eV (1 eV = 7736.6 K).

3. Result of calculations

The processes considered here either populate or depopulate the upper line levels in other ways than in collision chamber experiments. With the electron density below 10^{18} m^{-3}, volume recombination is unimportant (de Vries and Mewe 1965). Furthermore, when the density of helium in the ground state is below 10^{20} m^{-3}, excitation transfers in He-He collisions can be neglected (Lin and StJohn, 1962; Kay and Hughes, 1967). This leaves three groups of processes that will be studied below:

a) The effect on the cascading to low-lying levels from collisions between electrons and helium atoms in the higher-

lying levels where the cascading originates.

b) Excitation transfer between excited states by electron impact.

c) Excitation by electron impact from the metastable 2^1S and 2^3S states.

What follows is mainly a description of the results. The details of the calculations will be published elsewhere.

Cascading

There are mainly two processes through which collisions between highly excited helium atoms and electrons influence the cascading: ionization and excitation transfer. The cross sections for both processes increase with increasing main quantum number as n^4, while the lifetimes for levels with the same azimuthal quantum number increase as n^3. The probability for some kind of collision with electrons during a natural lifetime of an excited state therefore increases very rapidly with n. When many such transitions occur during the natural lifetimes of the levels, the population distribution between levels with the same main quantum number tends towards that determined by the statistical weight of the levels. This includes a redistribution between the singlet and the triplet system for the following reason:

For F levels with $n \geq 5$, there is no clear distinction between the singlet and the triplet system, since the coupling between the spin vector and the orbital motion of the excited electron becomes greater than the spin-spin coupling between the electrons (Lin and Fowler, 1961). Kay and Hughes (1967) have shown experimentally that the cascading from these mixed levels is shared between the singlet and the triplet system as 1:3, as according to the statistical weight of the levels n^1F and n^3F. This redistribution of the highly excited levels gives a redistribution of the cascading from these levels to the lower-lying levels. Another process of importance is ionization by electron impact out of the highest-lying excited levels. The effect of excitation transfer and ionization on the cascading to the 4^1S, 5^1S, 4^1D, 5^1D, 4^3S, 5^3S, 4^3D and 5^3D levels are calculated for electron densities between 10^{14} and 10^{17} m^{-3}. (At lower electron densities than 10^{14} m^{-3}, the cas-

cading is independent of n_e, and at $n_e > 10^{17}$ m^{-3} other processes than cascading are dominating). The uncertainty in these calculations is estimated to be less than a factor 1.5. It comes mainly from the extrapolation procedures described in I and II above. The uncertainties in the ionization and excitation transfer cross sections (VII and VIII above) is less important for the final result.

The results of the calculations are given in table I in the form of values of the ratio R between the number of excitations through cascading and the number of excitations from the ground state. The values R(I) when a fraction I of the resonance radiation to n^1P levels with $n > 4$ is imprisoned, is:

$$R(I) = I \cdot R(100\%) + (1-I) \cdot R(0\%)$$

R(100%) and R(0%) are found in table I.
Degrees of imprisonment for various geometries have been calculated by Phelps (1958).

These calculations were done for an electron temperature of 10 eV. An estimate gives that the cascading contributions vary less than a factor of 2 from the values given in table I, when T_e varies between 5 and 100 eV. With increasing temperature, they increase for triplet levels and decrease for singlet levels. This variation is mainly a result of the difference in energy dependence between the excitation cross sections from the ground state to the singlet and triplet levels.

Excitation transfer between states with n = 4 and n = 5

The cross sections for optically allowed excitation transfers between excited states with the same main quantum number is typically a factor of 10 greater than the cross sections for any other kind of collisions with electrons. The effect of such collisions is that excitation to levels with the same main and spin quantum number (for example 4^1S, 4^1P, 4^1D and 4^1F) are redistributed within this group before spontaneous (radiative) decay. With increasing electron density, this approaches what could be seen as a "local thermal equilibrium" between a limited number of levels, where their relative population is determined by their

statistical weight. However, since this redistribution only involves levels with the same main quantum number, it is still far from what is usually understood by local thermal equilibrium. The population of the levels are found by solving the coupled rate equations for all levels that are connected through excitation transfer. This has been done for imprisonments in the range 0 - 20 %. Cross sections, transition probabilities and natural lifetimes from sections I, II, III and VII above were used. The effect on the intensities of eight spectral lines is shown in fig. 1 for an electron temperature of 10 eV and zero imprisonment. For two of the lines, the result for 5, 10, 30 and 100 eV electron temperature is shown in fig. 2, still with zero imprisonment. It is seen that the excitation transfer process is little affected by variations in electron temperature. The results with non-zero imprisonment are not shown here, but used in the last section of this paper to give the influence of imprisonment on the proposed T_e determination method. These calculations were done disregarding excitation transfer involving changes in n. The curves are drawn solid, when this process influences line intensities less than a factor of 1.5. The effect of redistribution of cascading (table I) is also disregarded, but it influences the line intensities little compared to excitation transfer.

Excitation from the metastables 2^1S and 2^3S

Call the ratio (excitations from the metastable levels 2^1S or 2^3S)/(excitations from the ground state) $\Big| X_i$ for excitations to a level i. In a plasma where the metastables have equilibrium population this ratio is independent of both the electron and the neutral helium density. What is needed to calculate the values X_i is the total cross sections for excitation to and de-excitation from the metastable states (sections IV and V above), cross sections for excitation from the ground state to i (section I) and from the metastables to i (section VI). The weakest point in this collection of cross sections is that we have no reliable estimate of the cross section for $2^3S \rightarrow$ singlet levels excitations. These might be of importance compared to excitations from 2^1S, since the 2^3S level is much more densely populated than the 2^1S level. The next weakest point is the uncertainty in the remaining cross sections for excitations from the metastables to the levels

i. Here, the Born and VPS approximations from section VI are used as high and low estimates, respectively, giving a measure of how the uncertainty affects the final results.

The ratios X_i for an equilibrium metastable population for excitations $2^1S \rightarrow 4^1S$, 5^1S, 4^1D and 5^1D turn out to be almost independent of T_e in the range 5 to 200 eV. The values are given in table II. The X_i values for excitations $2^3S \rightarrow 4^3S$, 5^3S, 4^3D and 5^3D are found in table III. The time it takes to reach equilibrium is approximately given by the relaxation time τ_r for the build-up of metastable populations, table IV. The τ_r values for 2^1S are uncertain with a factor of 2. This depends on the uncertainty of the cross section for $2^1S \rightarrow 2^1P$ excitation, which is the dominating de-exciting process for 2^1S.

Table III shows that the contribution to triplet levels from 2^3S always is greater than the contribution from the ground state in a steady-state plasma, even if the lowest values are used. It should be noted in connection with table II that excitations $2^3S \rightarrow$ singlet levels probably are more important than excitations $2^1S \rightarrow$ singlet levels.

4. Experiments

In the experiments we used an electrodless conical thetapinch to accelerate a hydrogen plasma, which was guided a distance of two and a half meters by a slowly expanding longitudinal magnetic field to a region where it collided with a cloud of helium. The apparatus is described by Lindberg (1977). Light from the collision was analyzed in a 1.5 meter spectrograph, which permits simultaneous photoelectrical observation of up to 12 spectral lines with photomultipliers, individually calibrated against a tungsten filament lamp. Both relative and absolute measurements of line intensities are possible.

The thetapinch usually delivers a plasma with density around $4 \cdot 10^{18}$ m^{-3}, electron temperature of 5-10 eV, and 5-10 μs time duration to the collision region. In order to obtain lower plasma densities, the thetapinch parameters and the shape of the guiding magnetic field were varied, and copper grids

were inserted in the plasma stream. The electron density could by these means be varied between $3 \cdot 10^{16}$ m^{-3} and $4 \cdot 10^{18}$ m^{-3}. It was measured with biased floating double probes (Lindberg and Kristoferson, 1970). An advantage with this experiment is that the helium and the plasma densities can be varied independently of each other. A difficulty is that the electron temperature probably is affected by the copper grids and other means used to vary the plasma density.

The effect of excitation transfer can, however, be demonstrated in spite of this possible variation in T_e.

Experimental observations on the line intensities are then taken from the beginning of the collision between the plasma stream and the helium cloud, so that excitation from the metastable level 2^3S can be disregarded. This means that the relative intensities of the lines are determined by excitation from the ground state and excitation transfer, so that they can be found from the solutions of the coupled rate equations, as described in section 4 above.

In figure 3 are shown both calculated and experimentally obtained intensity ratios of the two lines 4472 Å ($4^3D - 2^3P$) and 4713Å ($4^3S - 2^3P$). It is noticed that the calculated values vary slowly with T_e, so that it is possible to compare them to measured values in spite of the uncertainty in electron temperature in the experiment. This is a result of two things: firstly, the cross sections for excitation from the ground state have closely the same energy dependence for the two lines. Secondly, the rate coefficients $\langle \sigma v_e \rangle$ for excitation transfer vary very slowly with T_e between 5 and 200 eV.

The spread of the experimental results in fig 3 can be attributed mainly to an unknown spread in electron temperature. However, the effect of excitation transfer is clearly seen. If excitation transfer could be neglected, the intensity ratio would be independent of electron density.

5. Summary and conclusions regarding T_e determination

The processes examined here put some limits to when the "ordinary" singlet-to-triplet line intensity ratio temperature determination is valid. The influences on line intensities calculated here must be compared with the T_e dependence of singlet-to-triplet line intensity ratios used in these determinations: typically these ratios vary by a factor 5-10, when T_e varies between 5 and 100 eV, with a change in the ratio of a factor 1.2 corresponding to a change of a factor 1.5 in electron temperature. This is now compared to the influence on line intensities from the processes above.

Excitation from the metastables in equilibrium population will give a dominating contribution to all triplet levels, and maybe also to the singlet levels. Since the involved cross sections are not well known enough, it is impossible to make corrections for this excitation process, and temperature determination becomes impossible in all steady-state plasmas. However, in a situation where the plasma density abruptly changes from zero to n_e at the time $t = 0$, the part of the excitations that come from the metastables is zero to begin with, building up in time towards the values in table II and III. If we require less than 20% of the excitations to the triplet levels to come from 2^3S, we get the following restrictions in the product $n_e t$: 4^3S: $n_e t < 5 \cdot 10^{11}$ $m^{-3}S$; 5^3S: $n_e t < 3 \cdot 10^{11}$ $m^{-3}S$; 4^3D and 5^3D: $n_e t < 10^{11}$ $m^{-3}S$.

These values of $n_e t$ are constant within a factor of 1.3 when T_e varies between 5 and 200 eV. They correspond to the Born approximation X_i values in table III, that give the higher estimate of the excitation from the metastables. Since excitation from metastables is less important to singlet levels than to triplet levels, the values above can serve as an estimate of when excitation from the metastables give an uncertainty less than a factor of 1.2 in singlet-to-triplet line intensity, roughly corresponding to an uncertainty of less than a factor of 1.5 in temperature determination.

Redistribution of the cascading from high-lying levels

will give an influence on the line intensities that is dependent of the degree of imprisonment of resonance radiation and the electron density (table I). If measured line strengths are used to give electron temperature with redistribution of cascading neglected, it gives an error in temperature that depends on which lines are used. With zero imprisonment and $n_e < 10^{16}$ m^{-3}, the possible error is around a factor 1.1-1.2 if lines from 4^1S, 5^1S, 4^1D, 5^1D, 4^3S or 5^3S are used, a factor of 1.2-1.4 for lines from 4^3D, and a factor 1.4-1.8 for lines with 5^3D for upper level.

Excitation transfer in atom-electron collisions.

The influence of this process is negligible at n_e 10^{16} m^{-3}. for the population of 4^1S, 4^1D, 5^1D, 4^3S, 5^3S and 4^3D, and at $n_e < 2 \cdot 10^{15}$ m^{-3} for 5^3D and 5^1S (figures 1 and 2). The possible error in T_e determination with an unfortunate choice of spectral lines can be illustrated by the following example: we have a T_e = 10 eV, $n_e = 10^{17}$ m^{-3} plasma of such short time duration that excitation via the metastables can be neglected. If excitation transfer is disregarded in the evaluation, the temperature we obtain from the intensity ratio of the lines 4922 Å (4^1D-2^1P) and 4713 Å (4^3S-2^3P) is $T_e \approx 20$ eV, while the lines 4472 Å (4^3D-2^3P) and 5048 Å (4^1S-2^1P) give $T_e \approx 1$ eV. If the degree of imprisonment is not zero, the effect of excitation transfer is increased.

6. Proposal of a measuring method

A method to side-step many of the difficulties above, and still use the singlet-to-triplet line intensity radio for T_e determination is the following:
The intensities N_λ of 5048 Å (4^1S-2^1P), 4922 Å (4^1D-2^1P) and 4713 Å (4^3S-2^3P) are measured. Then the quantity:

$$\varkappa = \frac{\sqrt{N_{5048} \cdot N_{4922}}}{K \cdot N_{4713}}$$

is calculated.

N_λ is measured in photons $m^{-3}s^{-1}$, and K is a correction factor for imprisonment of resonance radiation, which can be found in fig 4. Fig. 5 then gives the relation between $\varkappa$ and T_e. Excitation

transfer and excitation from 2^3S still give rather severe restrictions on experimental time and electron density. These are given in fig. 6.

The advantages with this method are:

1) It uses lines that are little influenced by redistribution of cascading (Table I).
2) The triplet line used (4713 Å) is the one least affected by excitation from 2^3S (Table III).
3) No lines from levels with main quantum number n = 5 are used. Those lines are both weaker and more sensitive to excitation transfer than the lines from n = 4 levels.
4) Even at electron densities when excitation transfer is very important for line intensities, the quantity $\varkappa$ is little affected.

7. Summary

It is found that relative intensities of singlet and triplet lines in neutral helium can be used for temperature determination only in low-density, short-duration plasmas. The most important limiting processes are excitation from the metastable 2^3S level and excitation transfer in collisions between electrons and excited helium atoms. An evaluation method is suggested, which minimizes the effect of these processes. Even then, the restrictions on electron density and experimental time are considerable.

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Table I: Values of the ratio R = (number of excitations through cascading from higher levels) / (number of excitations from ground state) at electron densities between 10^{14} and 10^{17} m^{-3}, and an electron temperature of 10 eV. The uncertaimty is estimated to be a factor 1.5.

	Zero imprisonment				Complete imprisonment			
Electron density (m^{-3}) / Level	10^{14}	10^{15}	10^{16}	10^{17}	10^{14}	10^{15}	10^{16}	10^{17}
4^1S	5	5	4	3	55	50	38	10
5^1S	5	5	4	3	45	33	16	5
4^1D	4	4	4	4	42	42	42	42
5^1D	3	3	3	3	30	27	25	20
4^3S	11	8	4	3	11	8	4	3
5^3S	11	8	4	3	11	8	4	3
4^3D	26	35	47	70	33	50	70	130
5^3D	24	30	36	36	28	40	60	70

Table II: Values of the ratio X_i = (number of excitations from 2^1S)/(number of excitations from the ground state) for some singlet levels i and degrees I of imprisonment. 2^1S is in equilibrium population, and T_e is in the range 5 to 200 eV.

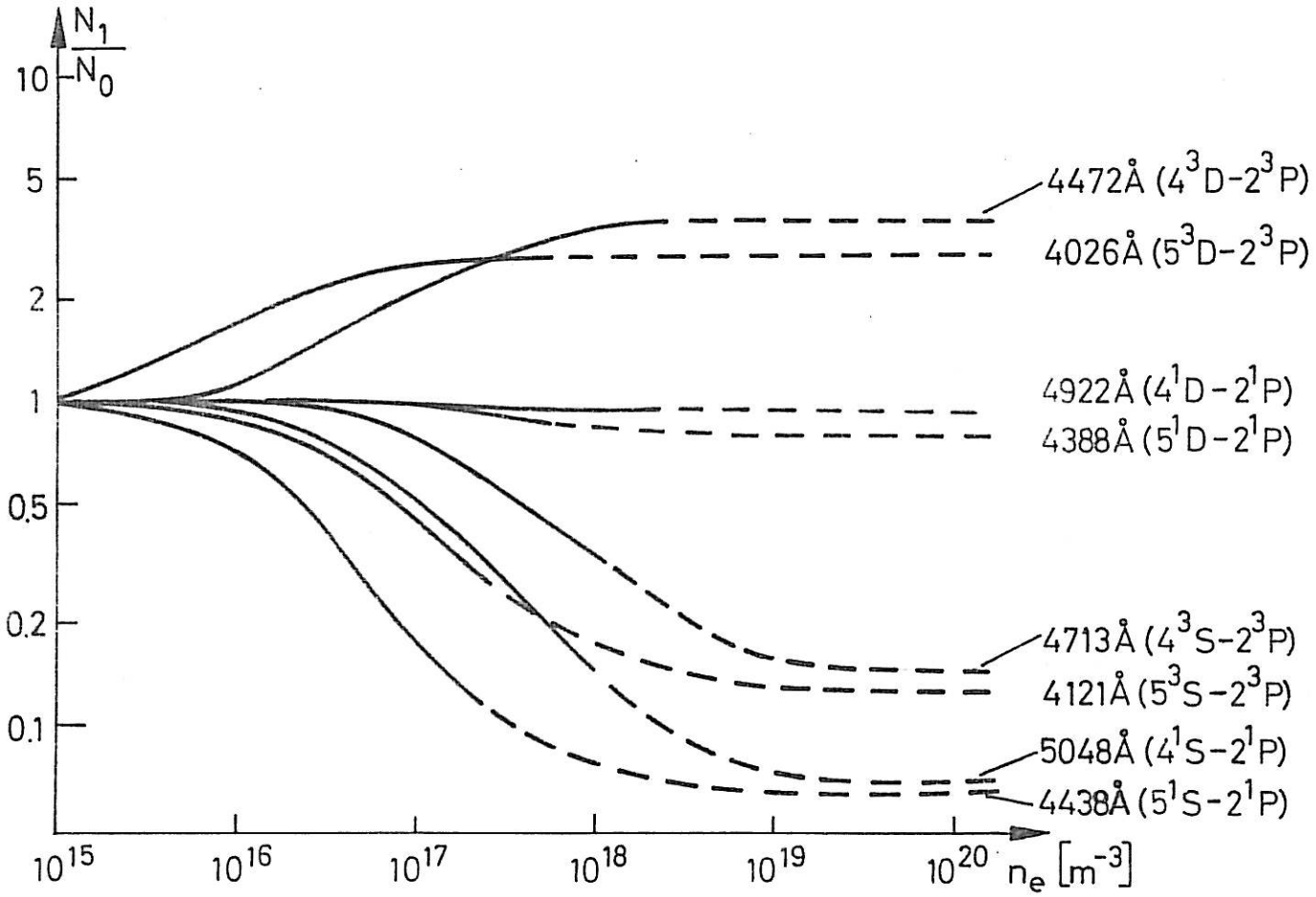
I / Level i	0%	10%	30%	50%
4^1S	0.02	0.05	0.10	0.14
5^1S	0.03	0.07	0.13	0.20
4^1D	0.09	0.18	0.35	0.53
5^1D	0.09	0.18	0.35	0.52

Table III: Values of the ratio X_i = (number of excitations from 2^3S)/(number of excitations from ground state) for some triplet levels i, when 2^3S is in equilibrium population. The high values correspond to the Born approximation and the low values to the VPS approximation. Independent of the degree of imprisonment.

Electron temperature (eV) / Level i	5	10	20	50	100	200
4^3S	2.4-11	1.6-5.1	1.3-3.6	1.0-3.2	1.0-2.4	0.8-1.5
5^3S	3.3-17	2.2-7.1	1.8-5.1	1.5-4.5	1.4-3.3	1.0-2.1
4^3D	12-51	8.5-24	7.8-20	6.4-16	5.1-13	4.2-10
5^3D	12-50	8.2-24	7.6-19	6.2-16	4.9-12	4.2-10

Table IV: Reduced relaxation time $n_e t_r$ m^{-3}·s for build-up of equilibrium population of metastables. The values for 2^1S are uncertain with a factor of 2.

Level \ Te (eV)	5	10	20	50	100	200
2^3S	$2.9 \cdot 10^{13}$	$1.15 \cdot 10^{13}$	$9.1 \cdot 10^{12}$	$7.1 \cdot 10^{12}$	$7.1 \cdot 10^{12}$	$7.7 \cdot 10^{12}$
2^1S	$3 \cdot 10^{11}$	$1.8 \cdot 10^{11}$	$1.7 \cdot 10^{11}$	$1.9 \cdot 10^{11}$	$2.2 \cdot 10^{11}$	$3.1 \cdot 10^{11}$



ıre 1 The effect on the intensities of eight spectral lines from excitation transfer at T_e = 10 eV and zero imprisonment. N_o would be the intensity if only excitation from the ground state were important. N_1 is the calculated intensity with excitation transfer considered. The results are uncertain where the curves are dotted.

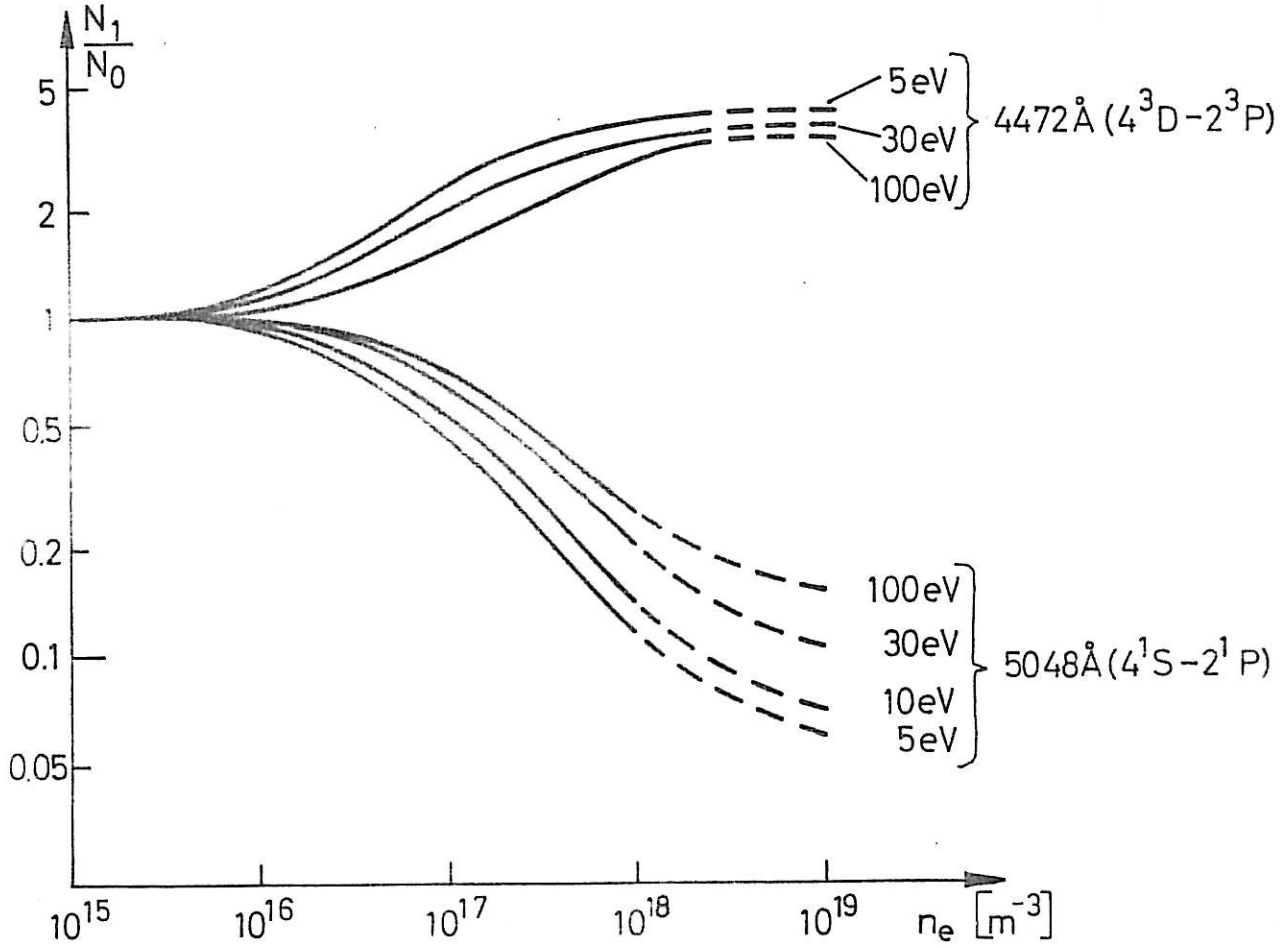


Figure 2 The effect on the intensities of two spectral lines of excitation transfer with zero imprisonment and T_e between 5 and 100 eV. The results are uncertain, where the curves are dotted.

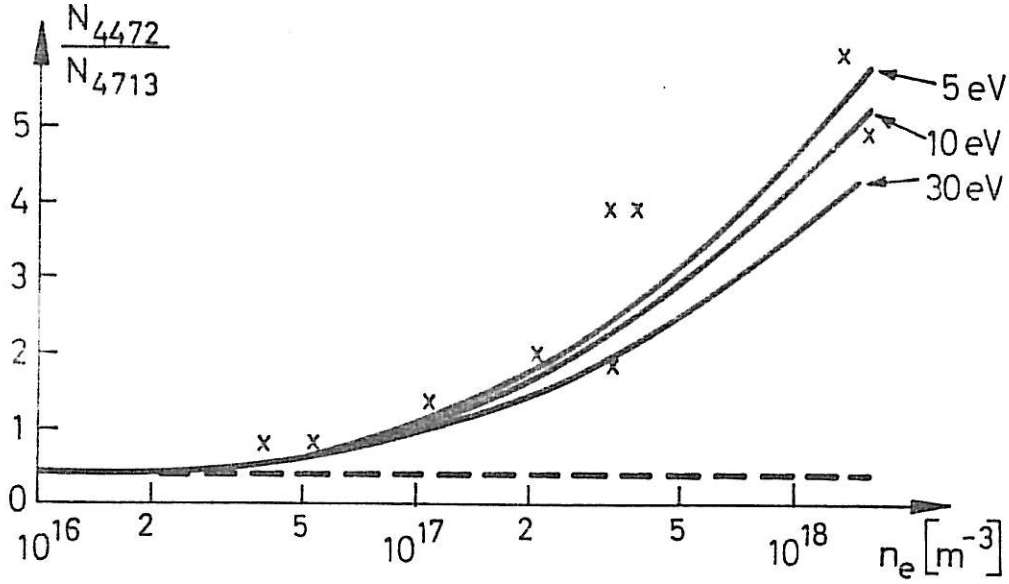


Figure 3 Intensity ratio for the two lines 4472 Å (4^3D-2^3P) and 4713 Å (4^3S-2^3P) as measured (crosses) and calculated from excitation transfer rate equations of 5, 10 and 30 eV (solid lines). Excitation from the ground state alone would give the same value (dotted line) for all electron temperatures and densities.

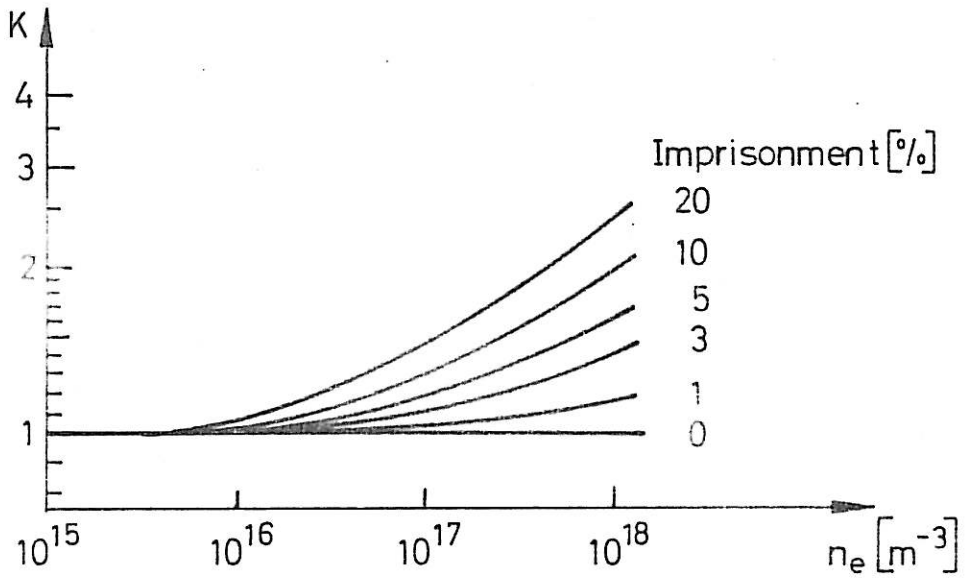


Figure 4 Factor K to be used in connection with fig. 4, as a function of electron density and degree of imprisonment I.

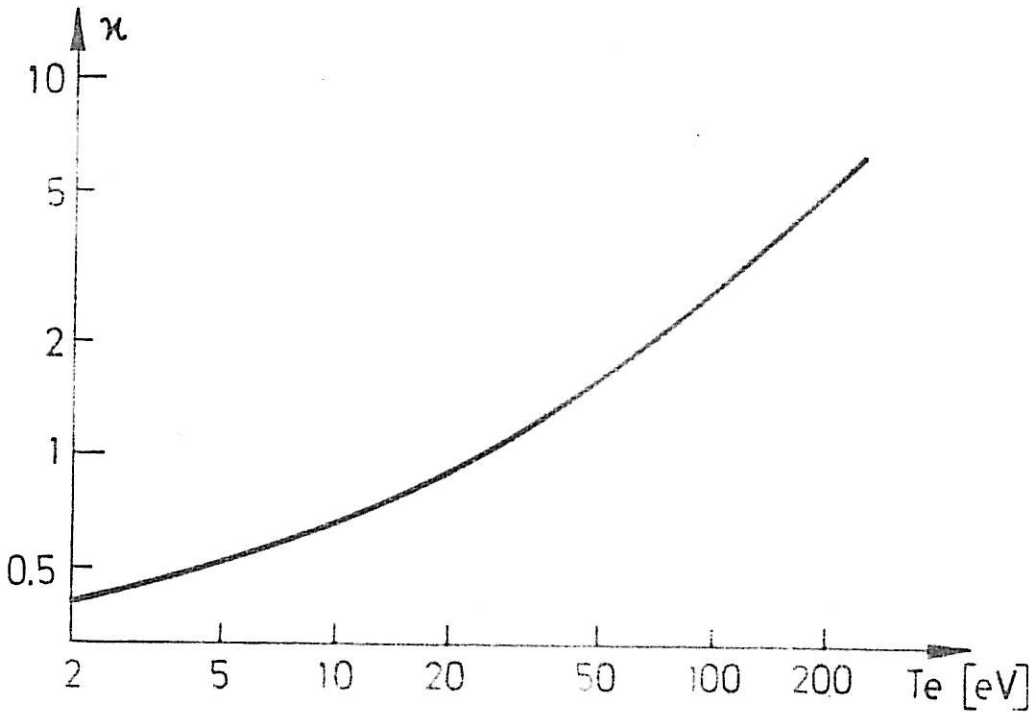


Figure 5 The relation between the quantity $\varkappa = \sqrt{N_{5048} \cdot N_{4922}} / K \cdot N_{4713}$ and the electron temperature. K is found in fig, 3 as a function of the degree I of imprisonment. $\varkappa$ is uncertain with a factor Δ, that can be found in fig. 5 as a function of electron density and experimental time.

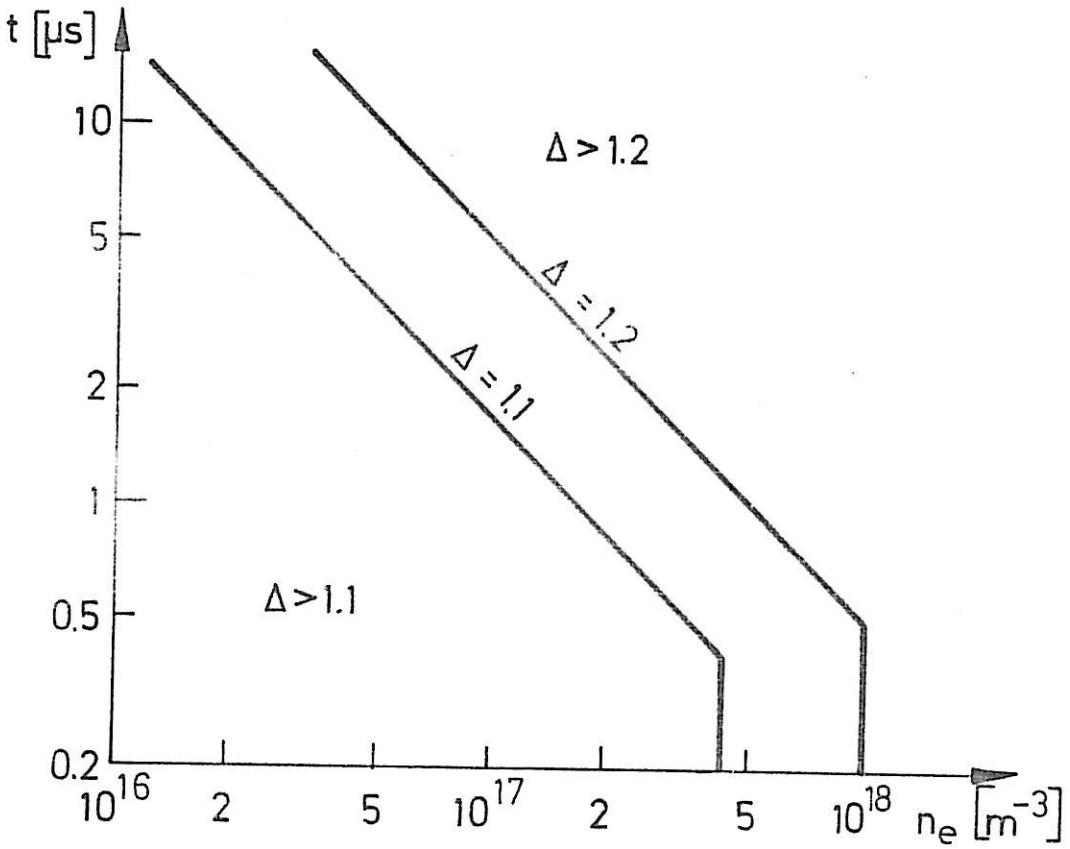


Figure 6 Uncertainty factor Δ in the quantity $\varkappa$ in fig. 5 as a function of electron density n_e and experimental time in an idealized experiment, where the density is zero for $t < 0$ and ne for $t \geqslant 0$.

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ELECTRON TEMPERATURE MEASUREMENTS IN LOW DENSITY PLASMAS BY HELIUM SPECTROSCOPY

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The method to use relative intensities of singlet and triplet lines of neutral helium to measure electron temperature in low-density plasmas is examined. Calculations from measured and theoretical data about transitions in neutral helium are carried out and compared to experimental results. It is found that relative intensities of singlet and triplet lines from neutral helium only can be used for T_e determination in low-density, short-duration plasmas. The most important limiting processes are excitation from the metastable 2^3S level and excitation transfer in collisions between electrons and excited helium atoms. An evaluation method is suggested, which minimizes the effect of these processes.

Key words: Helium spectroscopy, Plasma diagnostics, Plasma spectroscopy