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"HORIZONTAL" THERMAL EQUILIBRIUM DUE TO EXCITATION TRANSFER BETWEEN EXCITED STATES OF NEUTRAL He IN TRANSIENT PLASMA

Nils Brenning

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Department of Plasma Physics
Royal Institute of Technology
100 44 Stockholm, Sweden

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Nils Brenning
Royal Institute of Technology, Department of Plasma Physics, S-100 44 Stockholm, Sweden

Abstract

The populations of the levels and the intensities of the spectral lines emitted by neutral helium in a plasma is influenced by excitation transfer between excited levels through collisions with electrons even at very low electron densities. These processes are studied theoretically and experimentally with the following conclusions:
(a) Excitation transfer is important for intensities of spectral lines emitted from plasma where the electron density exceeds a few times 10^{16} m^{-3}. (b) With increasing electron density, the relative populations of levels with the same main and spin quantum number approach that determined by their statistical weight. This could be regarded as a "horizontal" thermal equilibrium, developed when the helium levels are very far from thermal equilibrium in other respects.

"Horizontal" thermal equilibrium due to excitation transfer between excited states of neutral He in transient plasma

Intensity ratios between singlet and triplet lines of neutral He atoms have previously been used to determine electron temperature in low-density plasmas (Eastlund *et al* 1973, McWhirter 1965). The usefulness of the method is limited to low-density transient plasma by a number of processes that influence the line intensities.

One of these is excitation transfer, which seriously influences the method in a density range where it has previously been used. For levels with the same main and spin quantum number this process is rapid enough to cause substantial redistribution at very low plasma densities.

In the present letter it is shown that for plasma densities above a few times $10^{16}m^{-3}$, the line intensities differ markedly from the values they would have in the absence of excitation transfer and with increasing density approach values that correspond to thermal equilibrium between populations of the levels involved, even when the helium remains very far from thermal equilibrium in other respects.

In another paper (Brenning 1977) the plasma diagnostic consequences are considered and a modified method developed, which can be used in a considerably wider parameter range.

In Fig 1 arrows between the energy levels indicate optically allowed transitions between excited states with the same main quantum number. The Born-Bethe approximation gives remarkably large theoretical cross sections for such excitation transfers due to collisions between electrons and excited atoms. Maximum values of typically $10^{-16}m^2$ are found for transitions between levels with main quantum number 4 or 5. Furthermore, they are always a factor of ten greater than the cross sections for any other kind of collisions with electrons. For the population of excited levels of neutral helium in a plasma this has the following consequences:

Even at very low electron densities (a few times $10^{16}m^{-3}$) there is time for a few excitation transfers during the natural lifetimes of the levels. The effect of this is that excitations 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 "horizontal" thermal equilibrium between a limited number of levels, where their relative population is proportional to their statistical weight.

In that electron density region, where excitation transfer is important, but "horizontal" thermal equilibrium is not yet fully established, the relative intensities of the spectral lines are determined by a number of processes. The levels are populated by excitation from the ground state, excitation transfer from neighbouring levels, and through cascading from higher levels. They are depopulated through spontaneous (radiative) decay and excitation transfer to neighbouring levels.

The population of a level, as a function of these processes, is determined by the coupled rate equations for the whole group of levels with the same main and spin quantum number. For atomic data needed to solve these equations, experimental values have been used when available. For excitations from the ground state, the cross sections measured by St John <u>et al</u> (1964) are used together with the measurements close to threshold by Smit <u>et al</u> (1963). Natural lifetimes are taken from the recent measurements by Thompson and Fowler (1975) for most of the levels, and calculated from the transition probabilities given by Wiese <u>et al</u> (1966) for the rest. For the transitions indicated by arrows in Fig. 1, the Born-Bethe approximation is used, as given by Drawin (1966):

$$\sigma_{ij} = 4\pi \frac{E_1^H}{E_{ij}} |Z_{ij}|^2 \left(\frac{E_{ij}}{E_e}\right)^2 \left(\frac{E_e}{E_{ij}} - 1\right) \ln \left(1.5 \frac{E_e}{E_{ij}}\right)$$

E_1^H is 13.59 eV, E_e is the electron energy, E_{ij} the energy difference $|E_i - E_j|$ between the levels i and j, and Z_{ij} is the dipole length for the transition $i \rightarrow j$. The dipole lengths for these transitions in excited helium are very close to the corresponding dipole lengths for hydrogen, which are used instead. Values are given by Bethe and Salpeter (1957).

With this atomic data, the coupled rate equations have been solved for a number of levels in neutral helium, and for electron temperatures between 5 and 100 eV.

For comparison with experiments, we have chosen the relative intensities of lines with upper levels in the same horizontal group. Theoretically expected line intensities have been calculated taking into account the relative populations of the upper levels, as well as the transition probabilities. In Fig.2 calculated relative line intensities for two pairs of lines are shown as functions of electron density. Experimental values, marked by error rectangles in the same figure, were obtained using a transient pulse of hydrogen plasma streaming through a thin ($10^{20}m^{-3}$) cloud of helium (Fig.3).

The agreement between theoretical and experimental results in Fig.2 is better for the line pair 4472 Å/ 4713Å than for 4922Å/ /5048Å. However, some discrepancy between the theoretical and the experimental results is expected for the following reasons.

Our means of varying the electron density probably also changes the electron temperature of the plasma, which is 5-10 eV for the highest densities. The temperature for plasma densities below $10^{18}m^{-3}$ is therefore unknown. However, the line intensity ratios chosen here are rather insensitive to variations in T_e, as shown by the theoretical curves in Fig. 2. Furthermore, the theoretical results are influenced by uncertainties in the experimentally and theoretically obtained cross sections, transition probabilities and lifetimes that are used in the calculations. Finally, other processes than excitation transfer can influence the line intensities, among them excitation from the metastable 2^1S and 2^3S levels, imprisonment of resonance radiation, and redistribution of the cascading due to the presence of the plasma. These processes are discussed in more detail elsewhere (Brenning 1977).

In order to minimize the effect of excitation from the metastable levels, we have taken experimental data from the first microsecond of the collision between plasma and helium cloud, when the built--up population of metastables is still small. The varying steepness of the signals in this time interval is the reason for the large and varying error margins for the experimental values in Fig.2. However, the agreement between experimental and theoretical results clearly demonstrates that excitation transfer, which has previously been disregarded in diagnostic applications, is important for line intensities when the electron density exceeds a few times $10^{16}m^{-3}$, and indicates that the levels involved approach "horizontal" thermal equilibrium with increasing electron density.

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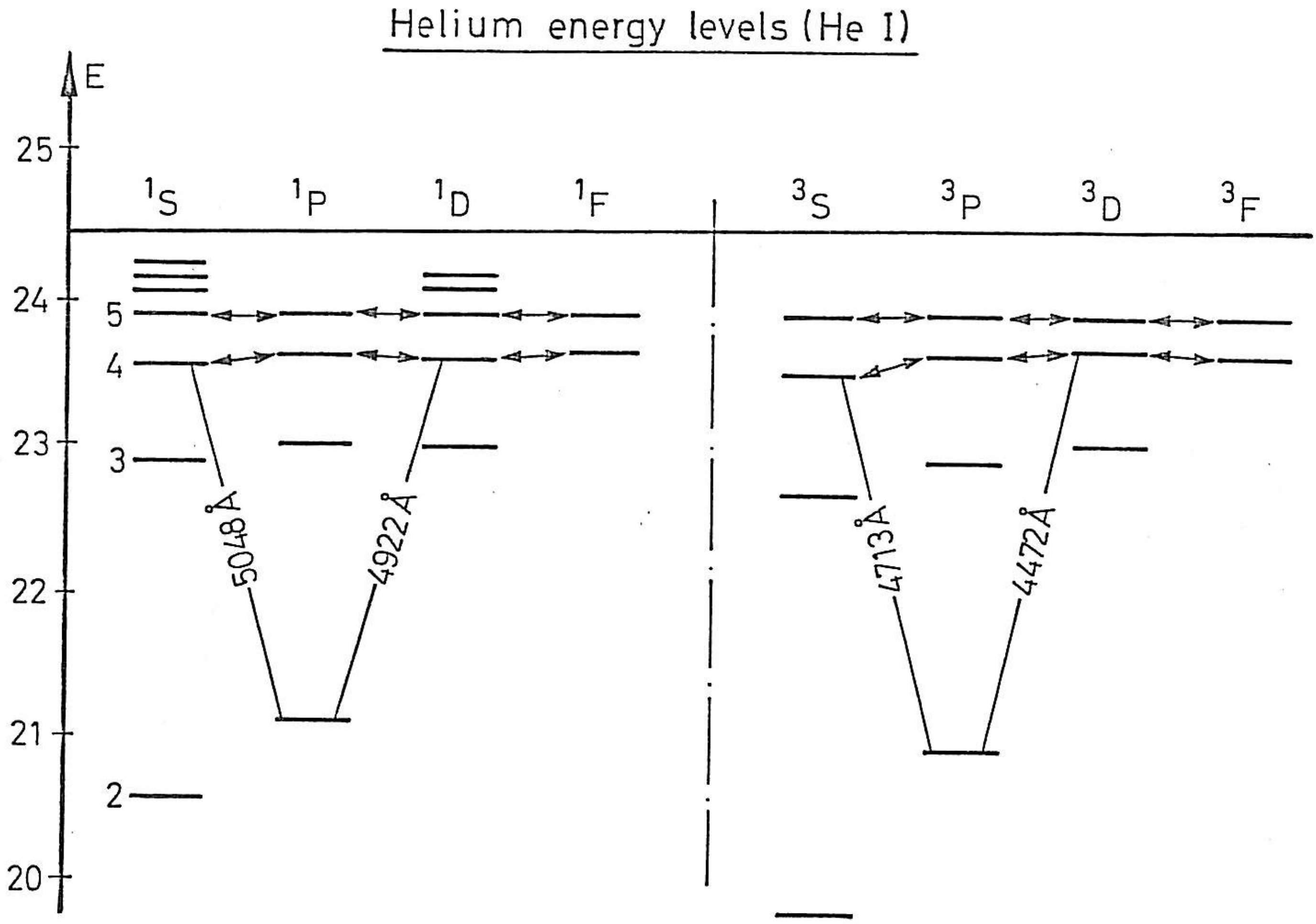

Fig. 1. Energy level diagram for neutral helium. The arrows indicate excitation transfer with large electron impact cross sections.

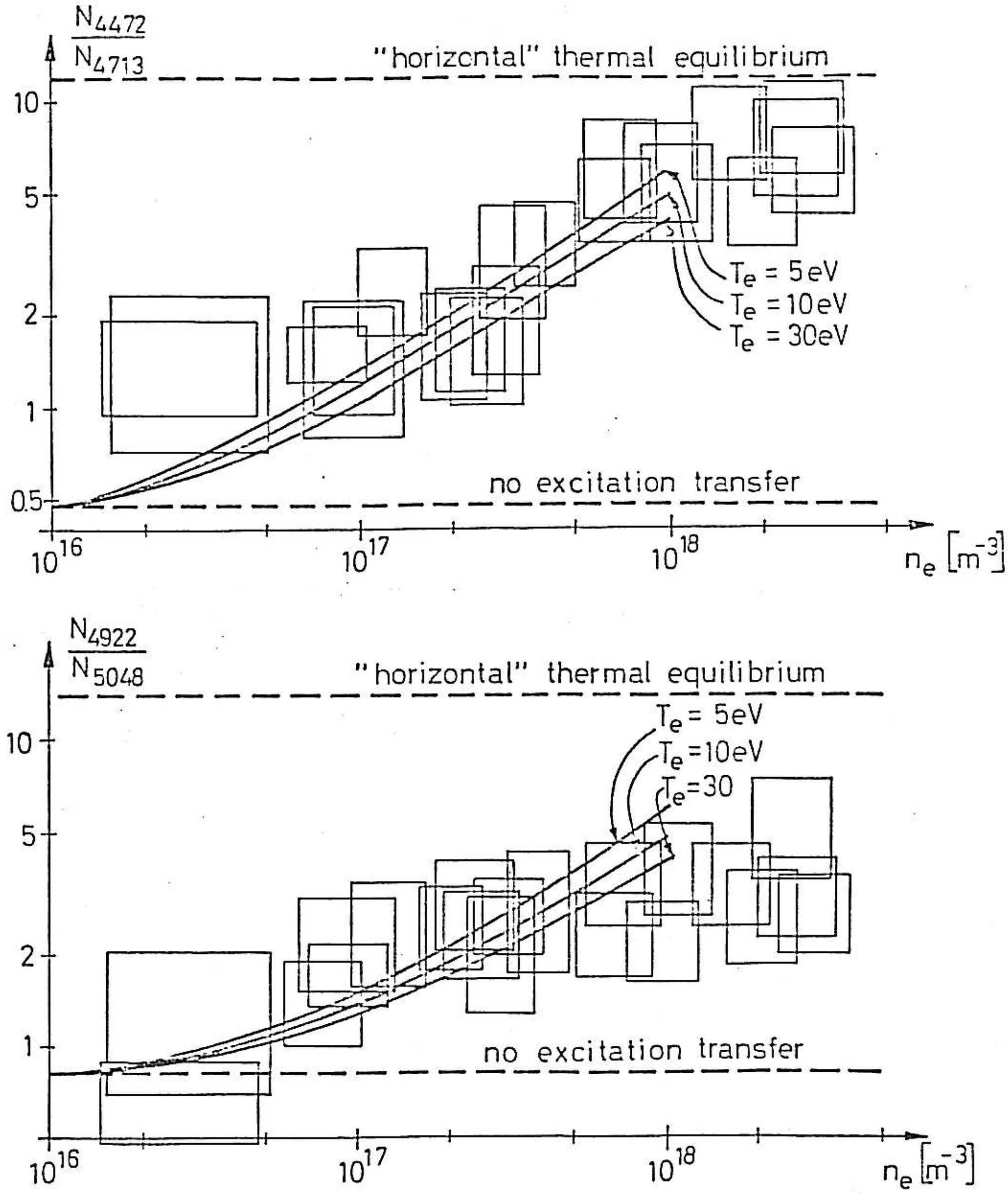

Fig. 2. Calculated and measured ratios between line intensities (photons $\cdot$ m^{-3} $\cdot$ s^{-1}) for two pairs of neutral helium lines, 4472 Å (4^3D - 2^3P)/4713 Å (4^3S - 2^3P) and 4922 Å (4^1D - 2^1P)/5048 Å (4^1S - 2^1P). The solid lines represent the theoretically expected line intensity ratios from the solution of the coupled rate equations. These are extended to the density $n_e=10^{18}$ m^{-} which is the upper limit of applicability of the theory. Results are shown for three different temperatures of the plasma electrons that bring about the equilibrium. The dashed lines represent the same ratios in the high- and low-density limits. The high-density limit corresponds to perfect "horizontal" thermal equilibrium, and the low-density limit to the cause of no excitation transfer between the levels - which is the situation previously assumed in diagnostic applications.

The experimental values are marked by error rectangles

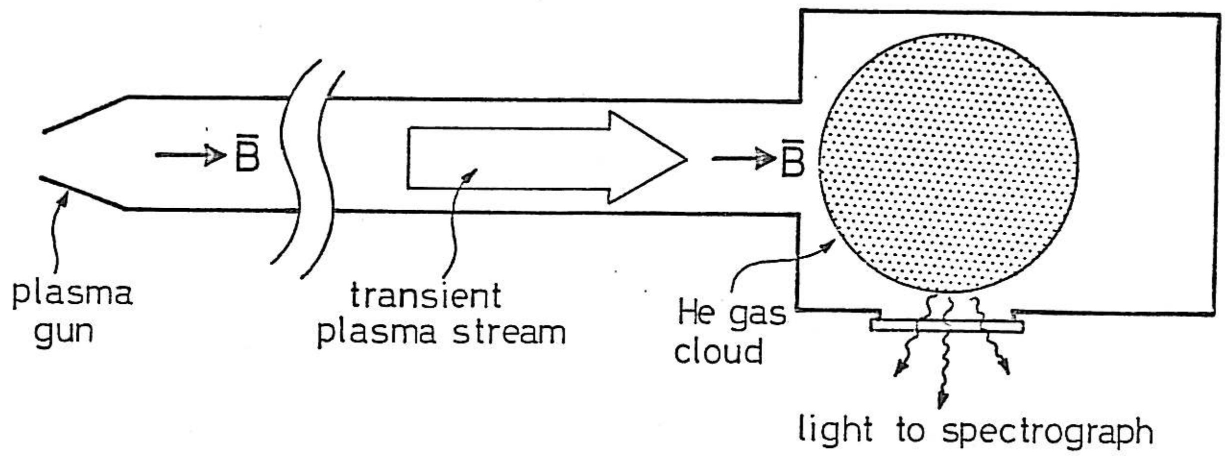

Fig. 3. The plasma was generated and accelerated by an electrodeless conical thetapinch[4] and guided a distance of 2.5 m by an expanding magnetic field to the helium cloud. The electron density was measured with biased floating double probes[5] and the light from the collision was analyzed in a 1.5 m spectrograph, which permits simultaneous photoelectrical observation of up to 12 spectral lines with photomultipliers, individually calibrated against a tungsten filament lamp. The electron density in the experiment was varied by th insertion of various grids in the plasma stream, and by varying the shape of the guiding magnetic field.

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Key words: Helium spectroscopy, Plasma diagnostics, Plasma spectroscopy, Thermal equilibrium.