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Influence of Neutral Injection on the Velocity Distribution of Excited Atoms in a Plasma

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** See Appendix 1*

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INFLUENCE OF NEUTRAL INJECTION ON THE VELOCITY DISTRIBUTION OF EXCITED ATOMS IN A PLASMA

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ABSTRACT

The velocity distribution of excited atoms in a plasma is shown to be non-thermal. In the neutral beam/plasma interaction zone the distribution may be highly anisotropic in the local plasma rest frame. Outside this zone the distribution, under present-day Tokamak conditions, approximates the thermal distribution of the plasma ions and hence appears to be thermal. These considerations are fundamental to the interpretation of photon diagnostic data on plasma rotation and ion temperature.

INTRODUCTION

A knowledge of the velocity distribution of plasma ions, often summarised in the parameters of temperature and rotation velocity, is essential to an understanding of plasma behaviour during neutral injection [1,2,3]. One diagnostic technique which has received considerable attention as a means of profiling this distribution is Doppler spectroscopy of the line radiation emitted in the decay of excited atoms in the plasma [4]. The technique actually measures the statistical frequency of decays from the population of emitting atomic species, as a function of velocity along the detector line of sight. It is then, tacitly, assumed that this velocity distribution may be described by the same temperature and rotation velocity which characterise the plasma ions. One may note that there is no *a priori* justification for this assumption since excited atomic states generally decay in a time of the order of μs whilst the thermalisation time is typically $\sim$ ms. to be precise, the decay frequency is given by the formation rate for the excited state of interest, times the appropriate branching ratio for the observed transition.

During neutral injection, a significant population of "halo" atoms may build up outside the immediate neutral beam/plasma interaction zone. This occurs in a large tokamak (or dense plasma) by 'diffusion' of atoms via a series of charge-exchange events. An optical diagnostic viewing a region of the plasma core which does not include the neutral beam/plasma interaction zone, will therefore see line emission resulting from collisions between plasma ions and atoms having a near-thermal velocity distribution. Further, line radiation from the neutral beam/plasma interaction region (excluding radiation from the beam itself) will be dominated by charge-transfer from the beam neutrals to the plasma ions. We therefore focus our attention on the analysis of these formation rates.

Consider an ensemble of particles of type i with velocity distribution $f_i(\underline{v}')$. Let these particles interact with a second ensemble of particles of type j with velocity distribution $f_j(\underline{v}'')$, with an interaction cross section $\sigma(|\underline{v}'' - \underline{v}'|)$ for formation of daughter particles having the same velocity $\underline{v}'$ as their parent particle i. This picture is physically useful for describing interactions where the momentum transfer is very small, such as atomic excitation or electron transfer in fast collisions. The rate of formation of daughter particles as a function of their velocity projected along a particular direction $\underline{n}$ is then given by

$$g(v) = \int d^3\underline{v}' \int d^3\underline{v}''\ f_i(\underline{v}')f_j(\underline{v}'')\ \sigma(|\underline{v}' - \underline{v}''|)\,|\underline{v}' - \underline{v}''|\ \delta(v - \underline{n}\cdot\underline{v}') \quad (1)$$

Using Eq.(1) the above mentioned explicit effects which will appear during neutral injection will now be considered.

In the former case to be considered here, where the formation of excited states is due primarily to plasma ion-atom electron transfer and excitation collisions not in the immediate neutral beam interaction zone, the distribution functions of the particle species $f_i(\underline{v}')$, $f_j(\underline{v}'')$ are Maxwellian's with local plasma density and temperature. Further, provided that $\sigma(|\underline{v}' - \underline{v}''|)|\underline{v}' - \underline{v}''|$ is a reasonably slowly varying function of the interaction energy, the collision integral, Eq.(1) is simplified considerably and can be readily evaluated. When $\sigma(v) \propto v$, the distribution function of the secondary particles $g(v)$ is Maxwellian, with a distribution of velocities characterised by the local plasma temperature. More generally, when $\sigma(\underline{v}' - \underline{v}'') \propto |\underline{v}' - v''|^{-n}$, $g(v)$ is non-Maxwellian. However, for plasma temperatures below 10 keV the total cross section for excitation is dominated by electron impact [4]. In this case the impact velocity distribution is so broad that the formation rate for secondary particles has essentially the same velocity distribution as the slow primary particles. Consequently, $g(v)$ remains nearly Maxwellian and is characteristic of the local plasma ion temperature.

We now consider the latter case where the formation of excited states is due to electron capture from the neutral beam.

To evaluate the formation rate in this case, we take the velocity distribution for the neutral beam as

$$f_i(\underline{v}) = \delta(\underline{v} - \underline{v}_o) \;, \tag{2}$$

where $\underline{v}_o$ is the beam velocity.

Eq.(1) then reduces to

$$g(v) = \int d^3\underline{v}' \; f_j(\underline{v}') \; \sigma(|\underline{v}' - \underline{v}_o|)\,|\underline{v}' - \underline{v}_o| \; \delta(v - \underline{n}\cdot\underline{v}') \tag{3}$$

For injection into Maxwellian plasmas, where the ion distribution function

$$f_j(v) = \frac{1}{\pi^{3/2} v_{th}^3} \exp\{-\,(v/v_{th})^2\},$$

where v_{th} is the ion thermal speed, and for an interaction cross-section of the form

$$\sigma(|\underline{v}_o - \underline{v}'|) = \sigma(v_o)\,|\underline{v}_o - \underline{v}'|^{-n},$$

Eq.(3) then becomes

$$g(v) = \frac{1}{\pi^{3/2} v_{th}^3}\,\sigma(v_o) \int_0^\infty v'^2 dv' \int_0^\pi \sin\theta' d\theta' \int_0^{2\pi} d\phi' \; \delta(v - v' \cos\theta')$$

$$\cdot\{v_o^2 + v'^2 - 2v_o v' \cos\gamma\}^{-\alpha} \exp\{-(v'/v_{th})^2\}, \tag{4}$$

where $\alpha = (n-1)/2$, $\cos\gamma = \cos\theta_o \cos\theta' + \sin\theta_o \sin\theta' \cos\phi'$, and the geometry of an interaction event viewed along the line of sight of a photon detector is illustrated in Fig.1.

Following integration of Eq.(4) over the variables θ', ϕ', we obtain for the particular case where $\theta_o \sim 0$, $v_o \gg v_{th}$ the shifted Maxwellian

$$g(v) = A(v_o,\theta_o) \; \exp\{-(v-\Delta v)^2/v_{th}^2\} ,$$

where the velocity shift is given by

$$\Delta v = \frac{v_{th}^2}{2v_o} (n - 1) \cos\theta_o ,$$

and the width of g(v) is the same as that of the plasma ion velocity distribution.

The shift Δv can be very large. Consider for example a Maxwellian H plasma with an ion temperature of 3 keV and neutral injection of 80 keV H. The plasma is assumed to have zero rotation velocity and the formation cross section for the excited state of interest is assumed to have the form v^{-6}. This cross section dependence is in accordance with both the total capture cross section in H gas and the H_α formation cross section in the case of capture from molecular H_2 [5]. In this particular case the mean projected velocity of the excited H neutrals formed by electron capture, Δv, is 4 x 10^7cm/sec, or about half the sound speed. Even viewing at 60° to the beam direction, Δv is still $\sim$ 2 x 10^7cm/sec. The velocity shift clearly becomes zero for observation orthogonal to the beam direction.

Depending on experimental geometry, neutral injection velocity, and plasma ion thermal velocity, significant corrections may be needed when estimating plasma rotation velocity from observations of Doppler shifts during neutral injection.

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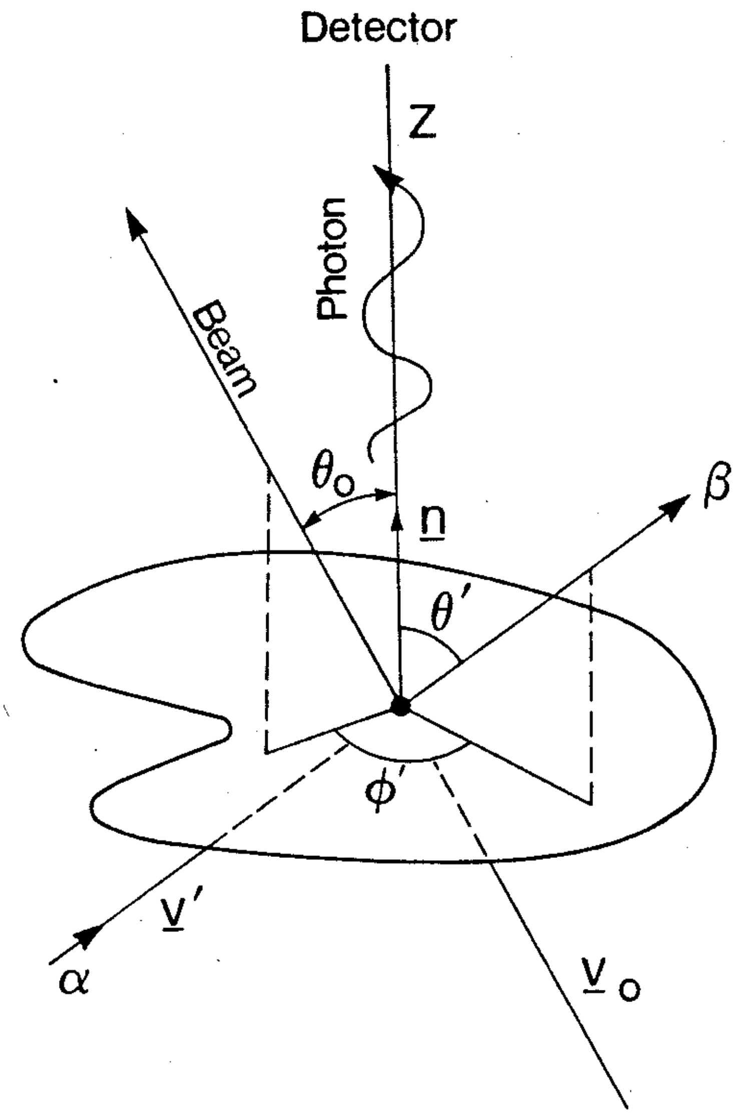
FIGURE CAPTION

Fig.1 Geometry of the change exchange event, with the axis of symmetry defined by the detector line of sight. Incoming beam particle with $\underline{v}_o$ interacts with plasma ion/neutral atom (α) moving with velocity $\underline{v}'$ giving excited neutral atom (β) formed through charge exchange excitation.



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