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MOLECULAR BEAM SAMPLING OF METASTABLE ATOMS FROM A HOLLOW CATHODE ARC AS A PROBE FOR THE ELECTRON TEMPERATURE

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Introduction. In a hollow cathode arc (HCA) discharge in noble gases fast metastable atoms are produced by electron impact and heavy particle collisions. These metastables are sampled through an orifice in the end anode. In a time-of-flight machine we have measured the centre-line intensity and the velocity distribution of the beam of metastable atoms.

Molecular beam sampling of ground state atoms gives accurate information on the ion velocity distribution and qualitative information on the ion and neutral density. The fractional intensity of the metastables relative to the intensity of the ground state atoms gives information on the electron temperature.

Experimental set up. A detailed description of the apparatus is given elsewhere ¹⁾. Fig. 1 shows a schematic of the HCA. We have measured both with a long arc (arc length $L_o = 20$ cm) and a short arc ($L_o = 1$ cm). Typical electron densities are $n_e = 10^{19} - 10^{20} \text{ m}^{-3}$.

Theory. The general expression for the product of the centre-line intensity $I(o)$ ($\text{s}^{-1} \text{sterad}^{-1}$) and the normalized velocity distribution function $P(v)$ of the beam of metastables is given by

$$I(o) P(v) d^2\Omega dv = \left[\int_0^\infty n(z,v) T(z,v) A dz \right] \frac{d^2\Omega}{4\pi} dv \quad (1)$$

with A the area of the sampling orifice at $z=0$ and z the coordinate along the beam axis. The function $n(z,v)$ ($\text{m}^{-3} \text{s}^{-1} \text{m}^{-1}$) is the production of metastables per unit volume, per unit of time and per unit of velocity and $T(z,v)$ is the transmission probability of a metastable through the plasma slice between z and $z=0$.

Fast metastable atoms are produced by charge exchange and elastic collisions with ions. We consider two processes : firstly a collision of a ground state atom with an ion followed by successive excitation by a collision with an electron and secondly a collision of a metastable with an ion with charge and excitation transfer.

The first process can be related directly to our model calculations and experimental work on the sampling of ground state atoms. For fast ground state atoms the view depth λ_n into the plasma, i.e. the mean free path, is determined mainly by elastic collisions with ground state atoms and ions and in most cases ionisation can be neglected. For metastable atoms, however, the view depth $\lambda_m = v_m / (n_e \langle Qv \rangle_{e \text{ ion}, m})$ is fully determined by the deexcitation and ionisation by collisions with electrons and the relation $\lambda_m \ll \lambda_n$ holds. In this model the centre-line intensity $I(o)_m$ of metastable atoms is given by

$$I(o)_m d^2\Omega = I(o)_n P_{\text{exc}} (z \leq \lambda_m) d^2\Omega \quad (2)$$

with $I(o)_n$ the centre-line intensity of ground state atoms and $P_{\text{exc}} (z \leq \lambda_m)$ the probability that a ground state atom will be excited to a metastable state in the plasma slice with thickness λ_m in front of the end anode. We implicitly assume that $T(z,v)=1$ for $z \leq \lambda_m$ and zero elsewhere. The probability $P_{\text{exc}} (z \leq \lambda_m)$ is equal to the product of the excitation rate v_{exc} and the transit time $\tau = \lambda_m / v_n$ of the ground state atom in this plasma slice. With $v_{\text{exc}} = n_e \langle Qv \rangle_{e \text{ exc}}$ we write Eq. (2) as

$$I(o)_m d^2\Omega = I(o)_n \frac{\langle Qv \rangle_{e \text{ exc}}}{\langle Qv \rangle_{e \text{ ion}, m}} d^2\Omega \quad (3)$$

where we have used $v_m = v_n$, i.e. we neglect the momentum transfer of the electron. The ratio of the reaction constants for excitation and ionisation depends strongly on the electron temperature. For argon this ratio ²⁾ is given in fig. 2. For $\langle Qv \rangle_{e \text{ exc}}$ we only consider direct excitation to a metastable state. For $\langle Qv \rangle_{e \text{ ion}, m}$ we have included the 4s-4p excitation process because for electron temperatures $T_e \geq 2$ eV and electron densities $n_e \geq 10^{19} \text{ m}^{-3}$ the ionisation rate of the 4p levels is much larger than the rate of spontaneous radiative decay to the 4s levels.

The second process, i.e. charge and excitation

transfer of a metastable with an ion, has a very large cross-section Q_{exch} . No quantitative data are available, however, and we use an estimate $Q_{\text{exch}} = 500 \text{ \AA}^2$ in analogy to the charge transfer cross-section for Cs^+ on Cs ³⁾. We assume a homogeneous plasma with $T(z, v) = 1$ for $z \leq \lambda_m$ and zero elsewhere. Equation (1) is then written as

$$I(o)_m d^2\Omega = n_m n_i g Q_{\text{exch}} \frac{A\lambda_m}{4\pi} d^2\Omega \quad (4)$$

with n_m and n_i the number density of the metastables and the ions, respectively. Substitution of the expression for λ_m results in

$$I(o)_m d^2\Omega = \frac{n_m v_m A}{4\pi} \left[\frac{Q_{\text{exch}} g}{\langle Qv \rangle_{e^+ \text{ion}, m}} \right] d^2\Omega \quad (5)$$

which is the centre-line intensity of an effusive source of fast metastables multiplied by the extra factor in square brackets. The density n_m in table I has been calculated with a collisional radiative model ⁴⁾ for the plasma conditions in the upper part of table I.

In table I numerical values of the centre-line intensity $I(o)_m$ are given for the two models discussed, showing that excitation of fast ground state atoms is the dominant process of beam formation. Of course, the models used are simplified to a large extent. With the small value of $\lambda_m = 2 \cdot 10^{-4} \text{ m}$ as compared to the diameter $(4/\pi) \text{ \AA}^2 = 5 \cdot 10^{-4} \text{ m}$ of the sampling orifice, the assumption of a homogeneous plasma is not very realistic. To explain our experimental results we also have to assume a fairly high electron temperature at this very close distance to the end anode. However, the models used do give a qualitative picture of the production and destruction processes involved.

Experimental results. Measurements have been performed for Ar and Kr for both arc configurations. In this section we will only discuss the results for Ar in the long arc configuration. In fig. 3 the measured intensities and temperatures are given for Ar in the long arc configuration as a function of the density in the source chamber n_n . The measured temperatures for the metastables are a factor 3 higher than the temperature of the fast ground state atoms ¹⁾. Our models do not explain this difference. The highest intensities are measured in case of low density, high arc current and high magnetic field. For fast ground state atoms the intensity is proportional to n_n . In fig. 4 we

give the intensity of metastables relative to the intensity of the ground state atoms as a function of n_n . Comparing this with fig. 2 results in electron temperatures varying from 2-5 eV.

For the short arc configuration we find electron temperatures varying from 3 (high density) to 7 eV (low density). Within the assumptions of our very simple model we have developed a sensitive probe for the electron temperature in front of the end anode. For further insight in the production, a better description of the plasma near the end anode is necessary.

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Fig. 1 Schematic of the HCA

Fig. 2 The ratio of the excitation and deexcitation rates as a function of T_e .

Fig. 3 Experimental results for Ar ($L_0 = 20 \text{ cm}$).

Fig. 4 The ratio of the measured intensities for metastable and ground state atoms (Ar, $L_0 = 20 \text{ cm}$).

Table 1 Plasma parameters			
n_e	$2 \cdot 10^{19} \text{ m}^{-3}$	$\langle Qv \rangle_{e^+ \text{exc}}$	$1,7 \cdot 10^{-16} \text{ m}^3 \text{ s}^{-1}$ a)
n_n	$2 \cdot 10^{19} \text{ m}^{-3}$	$\langle Qv \rangle_{e^+ \text{ion}, m}$	$5 \cdot 10^{-13} \text{ m}^3 \text{ s}^{-1}$ a)
T_e	3.5 eV	λ_m	$2 \cdot 10^{-4} \text{ m}$
model 1		model 2	
$I(o)_n$	$1.3 \cdot 10^{15}$ b)	n_m	$2 \cdot 10^{16} \text{ m}^{-3}$ c)
$I(o)_m$	$2.1 \cdot 10^{12}$	$I(o)_m$	$6 \cdot 10^{19}$

a) Ref. 2. b) Ref. 1. c) Ref. 4.