CORRECTIONS TO CHARGE EXCHANGE SPECTROSCOPIC
MEASUREMENTS IN TFTR DUE TO ENERGY-DEPENDENT
EXCITATION RATES

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ABSTRACT

The use of charge exchange spectroscopy to determine plasma rotation speeds and ion temperature is complicated by the energy dependence of the excitation cross sections. The Doppler-broadened spectral line shape is distorted by the relative velocity between the neutral hydrogen atoms of the injected beam and impurity ions. The asymmetric nature of the energy dependence of this cross section causes a non-motional shift of the line center and a non-thermal change in the line width. These effects vary with the angles between the beam direction, rotation velocity direction, and direction of the viewing sightline. When viewing two neutral beams at different angles on TFTR, the two measurements of $v_\phi(r)$ show discrepancies of about 20 to 30% with each other. The calculation of the spectral intensity profiles, using the excitation rates available, overcorrects these discrepancies and indicates the need for better excitation coefficients.

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INTRODUCTION

The use of charge exchange recombination spectroscopy (CXRS) has recently provided radial profiles of both ion temperature and rotation speeds for TFTR.¹ Prior to this, CXRS measurements of $T_i(r)$ and $v_\phi(r)$ were obtained on other tokamaks such as DIII,^{2,3} PBX,⁴⁻⁶ PDX,⁷ and ISX-B.⁸ Given the widespread acceptance of the CXRS technique for $T_i(r)$ and $v_\phi(r)$ measurements in hot plasmas, the complex nature of this measurement continues to require much attention to the atomic physics issues of this process. The emphasis in the present study is on corrections that arise from the energy dependence of the charge exchange excitation cross sections in determining the plasma ion temperature and rotation speed. This issue gains added urgency in light of the very high temperatures and/or rotation speeds obtained in large machines such as TFTR, where the spread of ion thermal speeds is large enough that the charge exchange rate coefficients change appreciably across the speed distribution.

In the CXRS diagnostic method, the plasma is diagnosed internally by observing the emission from the charge exchange reaction between fast neutral atoms and plasma ions

The product ions are left in excited states and the emission from these states produces the observed photons. The Doppler broadening of the emitted light gives T_i , and the Doppler shift gives v_ϕ . The calculated spectral line intensity

at wavelength λ is expressed as

$$B^\lambda = \frac{1}{4\pi} \sum_k \sum_{J=1}^3 \langle \sigma(k)v \rangle_J^\lambda \int N_J(k) N_z dl, \quad (2)$$

where $\langle \sigma(k)v \rangle_J^\lambda$ is the effective rate coefficient for charge exchange with a neutral atom in the J^{th} beam component and the k^{th} quantum state to produce excitation of a transition at wavelength λ , N_z is the impurity species density, and $N_J(k)$ is the beam density of the J^{th} energy component in level k . The sums are over all possible quantum states of the beam atom and the energy components of the beam (i.e., $E_0, E_0/2, E_0/3$ for an H^0 beam). There is also an integration over the length of the emitting region along the optical line of sight. Since the lifetime of the excited state is short, the emission is usually well localized at the position of the beams. Ignoring any atomic fine structure effects and assuming a thermal velocity distribution, the spectral distribution of an emission line, given by integrating the rate coefficient along the direction perpendicular to the line of sight, is

$$\langle \sigma v \rangle_J^\lambda = A \int \int dv_y dv_z \sigma_{ex}(|\vec{v} - \vec{v}_B|) |\vec{v} - \vec{v}_B| e^{-|\vec{v} - \vec{v}_B|^2 / \sigma_{th}^2}, \quad (3)$$

where the sightline is assumed to be along the x-axis. The charge exchange excitation cross section σ_{ex} depends on the relative velocity between the viewed particle velocity, $\vec{v}$, and the beam velocity, $\vec{v}_B$. The particles have a Gaussian distribution whose maximum is shifted from zero by the rotation velocity $\vec{v}_\phi$. σ_{th}^2 is given by $2kT/M$, where T is the ion temperature, M is the ion mass, and A is a normalizing factor.

For sufficiently high ion temperatures and rotation speeds, the energy dependence of the cross section will affect the excitation rate and thus the emis-

sion spectral shape. As an indication of the magnitude of the effects of this line profile distortion, for typical conditions in high temperature TFTR plasmas, we estimate that the central v_ϕ derived from direct line measurements could differ from the actual values by up to 20-30%, and the T_i by about 10%, if the fully mixed excitation rates from Ref. 7 are accurate. Of course, this is just the effect we hope to take advantage of in efforts to measure the high energy alpha particles produced in an ignited plasma, but it must be made as small as possible for the determination of the bulk ion temperature and rotation speeds. In principle, judicious choices of viewing geometry, beam injection angle, and beam species can be made to minimize these distortions of the spectral line shape (e.g., mutually perpendicular beam injection, rotation velocity, and viewing sightline for best temperature measurements). However, such flexibility is usually not available in the experimental conditions, and thus a well-known and characterized effective charge exchange rate coefficient is necessary to determine accurately both the ion temperature and the rotation speed in given experimental conditions.

The knowledge of the effective cross section for a given impurity ion and a specified transition is, at present, based on a patchwork approach of combining theoretical calculations for a few energies with the effects of mixing energy levels due to ion-ion collisions and the motional Stark effects.⁷ Even assuming high quality cross sections were available for the charge transfer for all of the relevant excited states, plasma environmental effects such as level-mixing due to ion-ion collisions, motional and Zeeman mixing, fine structure broadening, and the population of excited states in the neutral atoms, all

conspire to reduce the level of confidence in purely theoretical corrections to the measured line widths and shifts. Experimentally, however, the validity of the available rate coefficients can be tested by comparing line shapes and shifts obtained from different viewing directions and different beam species mixes under the same plasma conditions. We report here the preliminary results of such an effort on the TFTR tokamak, where the $n=8-7$ transition of C^{+5} ($\lambda = 529.2nm$) was studied for T_i and v_ϕ measurements.

A. EXPERIMENTAL OBSERVATIONS

Observations of $T_i(r, t)$ and $v_\phi(r, t)$ using CXRS are made on the TFTR tokamak with the CHERS multispatial and multispectral imaging spectrometer system. A schematic of the available viewing sightlines is shown in Fig. 1. Charge exchange excited transitions can be observed from the intersection of the sightlines and the high power heating beam (55 keV/amu D^0 , 5-6 MW) or the low power diagnostic beam (60 keV/amu H^0 , ≈ 0.5 MW). The view of the spectrometer sightline in the plasma center is roughly colinear with the heating beam ($\approx 34^\circ$ angular separation) and the toroidal rotation velocity (-1.2°). The diagnostic beam is viewed from the counter-linear direction with an angle of $\approx 20^\circ$ from the perpendicular and roughly colinear ($\approx 20^\circ$) with the rotation velocity direction at the point of beam-sightline intersection. On a given plasma shot, twelve views, or radial positions, along one of the two beams are used for measurement. Comparison of the uncorrected ion temperature and rotation speed (from the raw data line-width and shift) from two beam sources is then made for identical discharges.

The need for a better quantitative understanding of the line excitation processes is evident from the comparison of v_ϕ obtained with these two different beam and viewing geometries. Figure 2 shows such a comparison of the uncorrected values of $v_\phi(r)$ for a strongly rotating plasma in TFTR. The v_ϕ deduced from the view of the DNB was on average higher than the v_ϕ deduced from the heating beam view, when the speed exceeded about 2.0×10^5 m/sec. As will be discussed below, this difference is in the direction expected when the estimated rate coefficients, viewing geometries, and beam species are considered. But even with correction for the energy dependence of the excitation rate, a disagreement remains between the v_ϕ measurements.

B. CALCULATION OF V_ϕ , T_i CORRECTIONS

An illustration of the effect of the energy dependence of the effective rate coefficient is given in Fig.3a, which shows the evaluation of the line profile via Eqs. (2) and (3) for parameters typical of TFTR plasmas. The values of $\sigma(E)v$ are taken from the unified distorted wave approximation (UDWA) values plotted in Ref.7 under the assumption of full l-mixing in the $n=8$ state of C^{+5} . This $\sigma(E)v$ curve is shown in Fig.4. The calculated profiles in Fig.3a represent the extreme case where the viewing sightline, beam velocity, and plasma rotation velocity are all all colinear. For comparison, the other extreme is shown in Fig.3b where the beam direction is at right angles to the sightline, and there is very little shift between the centers of the beam components. The beam density fractions were taken to be 0.47:0.29:0.24 for the $E_0, E_0/2, E_0/3$ components, respectively. These values are indicative of

the species mix expected near the center of the plasma column.

In making these intensity profile calculations, only the ground state of the beam atom was used. The recent work by Isler and Olsen¹⁰ indicates the charge exchange rate of C^{+6} by $n=2$ hydrogen atoms at 20 keV can be as much as two orders of magnitude larger than the excitation rate of C^{+6} by $n=1$ hydrogen atoms at 40 keV. Thus, even with excited state populations of the beam atoms on the order of 1% of the ground state populations, there can be a contribution from them to the C^{+6} excited state populations in the energy range of ≤ 20 keV.

The calculations of the corrections to T_i and v_ϕ used the excitation rate shown in Fig.4 from Fonck's earlier work.⁷ A standard beam attenuation code⁹ (with no multistep processes included) is used to estimate the beam species mix as a function of radius in the plasma. Using these beam density fractions, and beam energies, the methodology consists of calculating "measured" v_ϕ and T_i resulting from "real" v_ϕ and T_i values, and observation angles for the two beams. These corrected values are plotted in Fig.5 for the data in Fig.2. If the effective rate coefficient had the correct energy dependence, the corrected values from the two views should coincide. However, the unmodified UDWA rates appear to overcorrect the HB data when the v_ϕ exceeds about 4.0×10^5 m/sec. The corrected HB and DNB values could show better agreement if we assumed that the actual rate coefficients at low energies (i.e., $E \leq 40$ keV/amu) were larger than those shown in Fig.4. This assumption is reasonable given the unreliability of the UDWA cross sections at low energy and our neglect of excited neutrals in the beam. At present,

it suffices to say that the remaining discrepancy between the corrected $v_\phi(r)$ values for the two beams indicates the energy dependence of the excitation rate curve is not adequately well known.

Given the importance of these observations in increasing confidence in the line profile measurements via CXRS, further systematic studies with different neutral atomic species, impurity ion species, and atomic transitions, along with more detailed theoretical estimates, are planned to provide reasonably accurate and reliable corrections to measured T_i and v_ϕ values over a wide range of plasma parameters.

C. CONCLUSIONS

The measurements of T_i and v_ϕ from two different viewing positions on TFTR provide a means of assessing the influence of the charge exchange excitation rate and its energy dependence. A calculation is made of the corrections due to this energy dependence for a typical radial profile of toroidal rotation and ion temperature. The present form of the excitation rate over-corrects the rotation velocities as measured from the two different views. This study focuses on the $n=8$ to $n=7$ transition of hydrogenic carbon. Further experiments and more complete theoretical modelling are planned to explore the physics of the excitation cross section and its energy dependence.

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FIGURE CAPTIONS

Fig.1 The geometry of the neutral beamlines and the CHERS viewing sightlines on TFTR for the DNB and the heating beam(NB3).

Fig.2 A toroidal rotation speed profile $v_\phi(r)$ as measured from two viewing locations. Circles represent the DNB data. Crosses represent the heating beam data. $R_{plasma}=273$.

Fig.3a The spectral line components for the three neutral beam populations, with the sightline parallel to the beam direction and the direction of rotation. The resulting composite profile is shown (solid line). Also shown is the assumed Gaussian distribution for comparison (dotted line).

Fig.3b Same as 3a but with beam direction perpendicular to sightline and rotation.

Fig.4 Charge exchange excitation coefficient for the C^{+5} ($n=8 \rightarrow 7$) transition as a function of relative energy. Obtained from UDWA theory with full l-mixing imposed.

Fig.5 The $v_\phi(r)$ profiles from the DNB and the heating beam as corrected for the energy-dependent excitation rate coefficients.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

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