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IN THE PDX TOKAMAK

By

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ABSTRACT

Measurements of the H_α line shape and of the spatial distribution of the H_α emissivity in the PDX tokamak are interpreted in terms of molecular dissociation reactions at the plasma edge. The influx of molecules is shown to be roughly proportional to the edge emission intensity over a wide range of temperatures. The H_2 particle lifetime is estimated for various types of discharges in PDX.

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I. INTRODUCTION

The Doppler broadened Balmer alpha line from some plasmas can be resolved to reveal two groups of atoms with energies of roughly 0.3 and 3 eV which correspond to the "slow" and "fast" dissociation product atoms from H_2 .¹ Usually these plasmas have low densities. Examples include capillary spectrum lamps, ion sources, and the microwave-heated Elmo bumpy torus.² The width of the H_α line obtained in recycling studies on tokamaks³ is comparable to that for dissociative excitation of H_2 , but only in the TFR experiment⁴ was it pointed out that molecular dissociation might be responsible for at least part of the observed line shape. The spectral features discussed here may, of course, be combined with other Doppler broadened components associated with the temperatures of the vessel walls or plasma ions.

Here we examine the reactions of the H_2 molecule and its products H_2^+ and H at the edge of large tokamaks in order to estimate the number of H_α photons produced per entering molecule. Our observations of the D_α line shape from the PDX tokamak confirm the presence of atoms with the dissociation energies. Deconvolution of the H_α background signals from the 56 spatial channels of the television Thomson scattering system (TVTS) shows that the H_α emissivity is localized at the edge of the discharge in a region whose thickness is determined by the penetration depth of H_2 and its dissociation products. The data from PDX are interpreted in terms of dissociation processes to yield an estimate of the incident H_2 flux and of the gross particle confinement time.

II. H_α EMISSION PROCESSES

Almost sixty years ago Blackett and Franck⁵ reported suprathermal broadening of H_α produced by electron-impact dissociation of H_2 . By varying

the pressure in the target region and by coating the walls of the tube in order to suppress or enhance the recombination of atoms at the surface, they were able to vary the linewidth in accordance with the primary species (H or H_2) responsible for the emission. More recent work on dissociation of H_2 gas has shown that there are two groups of dissociation product atoms ($E \sim 0.3$ and 2-8 eV) detectable by time-of-flight^{1,6} and high resolution spectroscopic^{7,8} methods. Implicit in Blackett and Franck's work is the idea that the emission of H_α in a low-temperature hydrogen plasma should be a composite process involving electron reactions with the several kinds of heavy particles present in the discharge (see, for example, Ref. 9). In this section we consider the reactions responsible for H_α production in a tokamak edge plasma and estimate the number of photons per entering molecule for the combined reactions of electrons with H, H_2 , and H_2^+ under these conditions.

The edge of a large tokamak plasma is characterized by a low electron density ($n_e \sim 10^{13} \text{ cm}^{-3}$) and moderately hot electrons ($T_e \sim 100 \text{ eV}$). Because the plasma fully absorbs any entering molecules, the H_α emissivity in this region can be modelled by a one-dimensional local influx of H_2 supplied through inlet ports or desorbed from the walls. The H_2 is lost in three parallel electron-impact reactions (H^* denotes a product atom which may, or not, be excited):

and

H_α can be produced in reactions (1) and (2) or by electron impact on H atoms and on H_2^+ ions; i.e.,

or

Radiative recombination, dissociation of H_3^+ , and charge exchange are unimportant as sources of H^* because of the low density and small depth of the emitting region.

Atoms produced by electron bombardment of H_2 gas belong to one of two energy groups.^{1,6-8} When H_2 is excited to bound states ($1s\sigma_g$) ($n\ell\lambda$) lying above the dissociation energy, slow excited atoms with $E \sim 0.2-0.6$ eV are formed. Excitation into doubly-excited repulsive states ($2p\sigma_u$) ($n\ell\lambda$) yields product atoms in the fast group (2-8 eV). Excitation of H_2 to the lowest (repulsive) excited state ($b^3\Sigma_u^+$), either directly or by cascading, causes dissociation into two ground state atoms with a wide range of energies, typically in the fast group. The relative number of slow excited product atoms is greatest for $n=2$ and decreases as n becomes larger.⁷ The behavior of D_2 is similar to H_2 with small isotopic effects.⁸ Figure 1 shows the kinetic energy distributions of slow and fast $H(2s)$ atoms produced by dissociative excitation of H_2 .¹ Similar energy distributions are found for $n > 3$.^{7,8} Note that when the electron energy is increased from 40 to 80 eV, the energies of the fast $H(2s)$ atoms are shifted slightly upward. This causes variations with

T_e in the width of the flat-topped Doppler-broadened spectrum from fast dissociation products in plasmas. According to the energy level diagrams for H_2^+ , reactions (2), (5), and (6) yield dissociation products with similar energies. The proton energy distribution for fast electron impact on H_2 [reaction (2)]¹⁰ is also shown in Fig. 1 to illustrate the wide range of dissociating states of H_2 and H_2^+ , although the 10-12 eV tail of this distribution would form a tiny fraction of the atoms produced by molecular processes in any plasma region where molecules could exist. None of the kinetic energy distributions of Fig. 1 is Maxwellian. All cut off well below 15 eV, the lowest atom energy detectable in practice by charge exchange or secondary emission techniques.

A detailed calculation of the number of H_α photons per incident molecule would require better information than is now available on many of the reactions involved. However, the yield per molecule can be estimated from experimental data on dissociative excitation of H_2 and excitation of H and from comparison with calculations of dissociative excitation and recombination of H_2^+ . This estimate is accurate enough to allow interpretation of the linewidth and spatial distribution of H_α in PDX and, thereby, to provide information on the plasma boundary conditions such as the rate of molecular influx and the energies of incident atoms.

Dissociative excitation (and dissociative ionization) of H_2 , the best known process, may yield H_α with a local probability of

$$P(H_2) = \frac{\text{rate of dissociative excitation of } H_2 \text{ to } H_\alpha}{\text{total loss rate for } H_2}.$$

For $T_e = 15-100$ eV, $P(H_2) = 0.007 \pm 0.002$, i.e., one H_2 molecule produces 0.007 H_α photons by dissociative excitation.^{11,12} For $T_e \sim 20$ eV, about 2/3

of all H_2 becomes H_2^+ which may be heated slightly (< 1 eV) by Coulomb collisions with plasma ions. Product atoms from electron-impact reactions of H_2^+ may be in the $n=3$ state, but no experimental data are available. A comparison with calculations of dissociative recombination of H_2^+ to $H(n=2 \text{ and } 3)$ ¹³ and of dissociative excitation to $H(n=2)$ ¹⁴ suggests that for $T_e = 10-100$ eV, $P(H_2^+) = 0.015 \pm 0.005$ in the sense of the ratio given above. Finally, for $T_e \sim 20$ eV roughly 2/3 of the ultimate products from H_2 are H atoms as opposed to protons. (At high temperatures the limit is 1/2.) In a one-dimensional model (surface width $\gg$ depth) half these atoms move toward the plasma interior and the rest move toward the wall, where they have a sticking (recombination) probability η . Those atoms which are immediately reflected will lose little kinetic energy and, owing to their higher velocity, can penetrate further into the plasma than the H_2 from which they originate. The probability of obtaining an H_α photon from an H atom for $T_e = 10-200$ eV is $P(H) = 0.03 \pm 0.01$.^{12,15} Here charge exchange is included with ionization as a loss process since the charge-exchanged atoms will have energies $E \sim T_i \gg E_{\text{dissoc}}$.

The composite H_α yield per molecule is, therefore,

$$f = P(H_2) + \frac{2}{3} P(H_2^+) + \frac{2}{3} \times 2 \times \frac{(2-\eta)}{2} \times P(H) = 0.055 - 0.019\eta.$$

The second term in the first equality includes the approximate fraction of H_2 that goes into H_2^+ , while the third term includes the fraction of H_2 going ultimately into atoms times the number of atoms per molecule times the fraction of these atoms that enter the plasma. Under the assumptions used

here the maximum error in the first term on the right is 0.010 and 0.007 in the second for $T_e = 10-100$ eV. Taking $n = 0.3$, we find $f \sim 0.05$ photons/molecule. The overall error in f is probably less than 30%. Roughly 1/3 of the H_α emission is produced by reactions involving molecules, while the remainder is produced by electron impact on atoms with energies close to the dissociation energies.

III. OBSERVATIONS ON PDX

The D_α line shape for diverted discharges confirms the presence in the PDX plasma of two groups of atoms with the dissociation energies. A Fabry-Perot interferometer (FPI) was set up to analyze the H_α and D_α light viewed by the TVTS system. The collecting optics are focussed on a 3-mm-diameter ruby laser beam propagating radially inward in the machine midplane and view the plasma simultaneously along a total of 56 chords across the minor cross section of the plasma column. A polarizer included in the collecting optics eliminates Zeeman splitting in the ~ 20 kG magnetic field and a viewing dump prevents reflections. The light guide relay optics in the focal plane of the collecting lens were modified so that any one of the 56 chords could be viewed by the FPI and a 100 Å wide interference filter.

The lower trace of Fig. 2 shows the D_α line shape during the early ohmic heating phase of a diverted discharge ($\bar{n}_e \sim 3 \times 10^{13} \text{ cm}^{-3}$, $B \sim 20$ kG) before the neutral beam gas supply is turned on (solid curve). The error bars represent the spread in values from several FPI traces during a single shot. Here the free spectral range of the FPI was 7.5 Å and its finesse was 40, for a resolution of 0.19 Å. The points are calculated for a distribution of Doppler-broadened fast and slow components with full-width-half-maxima (FWHM) of 0.9 and 0.28 Å, including fine structure, and an intensity ratio of 1.6.

The ideal spectrum is convoluted with an Airy instrument function having the above parameters. The FWHM of the observed D_α profiles before the neutral beam gas supply was turned on was $0.50 \pm 0.05 \text{ \AA}$. The upper trace of Fig. 2 shows the spectral intensity of D_α later in the discharge during the neutral beam pulse. The error bars on this curve represent the range of values observed from different viewing chords. Both the intensity and width of the D_α line increase gradually during the first 200 msec of the 300-msec-long neutral beam pulse. The same profile (within the measurement error) was observed when the neutral beam accelerator failed to turn on, so the increased width seems to be a result of the enhanced gas feed rate. The peak intensity is up to an order of magnitude greater than during the ohmically heated phase. The FWHM of the line is $0.70 \pm 0.05 \text{ \AA}$ at its widest. The calculated points on the upper curve correspond to a fast component width of $1.1 \text{ \AA}$ (before convolution) and a fast-to-slow intensity ratio of 4.3. The D_α line shapes were found to be the same in both ohmically heated and neutral beam heated plasmas whether the FPI viewed the inner or outer edges or the center of the discharge.

By deconvolving the H_α signal in the 56 spatial channels of the TVTS system, we were able to determine approximately the distribution of H_α emissivity in the discharge minor cross section. In circular, non-diverted discharges the highest emissivity occurs at the outer edges of the plasma. Low emissivities are found at the center (detector bandwidth $100 \text{ \AA}$). Figure 3 shows a typical emissivity contour diagram for one such discharge with a low density ($\bar{n}_e \sim 1 \times 10^{13} \text{ cm}^{-3}$), a low toroidal field (9 kG), a major radius of 143 cm, and a minor radius of 43 cm determined by a top rail limiter. Some of the apparent periodic structure in the contours at the center of the plasma is a result of the deconvolution procedure. Emissivity contour diagrams obtained

for diverted discharges under conditions similar to those for Fig. 2 also have an annular emission pattern with low central luminosity, but include a very intense luminous region, usually in the shape of two "tongues" (in the plane of the figure) which extend a short distance into the main plasma near the divertor throats. (The divertor throats are located at major radii of roughly 90 and 110 cm at the top and bottom of Fig. 3 and provide the path through which gas is fed to the plasma.) During very intense gas feed or "blow through" regimes¹⁶ the two tongues tend to merge into one. Then the emissivity within the tongues is up to 40 times that at the plasma center.

IV. DISCUSSION

The good agreement between the calculated points and the observed line shapes in Fig. 2 confirms the molecular origin of the D_α light (in the sense that "reexcitation" of dissociation product atoms is included). Thus, atoms with energies of roughly 0.3 and 2-6 eV that originate from molecules enter the plasma from its edge. Dissociative excitation D_α spectra have also been observed on the TFR tokamak⁴ at higher resolution (0.1 Å) than we have used. There the flat-topped fast dissociation product spectrum shows up clearly, along with a narrower peak corresponding to the slow dissociation products. The TFR data also included a broad component with an apparent FWHM of over 2 Å. This broad component can be attributed to circularly polarized Zeeman shifted light ($B = 40$ kG) from regions toroidally up- and downstream of the observation point, which is reflected into the observation port.² This explanation for the broad component is confirmed by the absence of such a "broad" component in the Lyman alpha¹⁷ profiles from the same device.

The data of Fig. 2 do not exclude the presence of Doppler-broadened light from the much hotter atoms in the plasma core, but a different

instrument is needed to detect them. A diverted-discharge plasma core with $\bar{n}_e = 3 \times 10^{13} \text{ cm}^{-3}$, $\bar{n}_H = 10^7 \text{ cm}^{-3}$ (estimated), $\bar{T}_e = \bar{T}_1 = 650 \text{ eV}$, and a diameter of 80 cm gives a Doppler broadened D_α profile of FWHM 9 Å with a maximum intensity 0.008 times that of the edge emission (FWHM 0.7 Å) at its peak. (The calculated brightness of the core D_α light is about 2×10^4 photons/cm²/sec at the surface, or less than a tenth of the observed brightness of the edge emission.) This intensity is lower than the apparent signal level of 1-2% in the traces of Fig. 2 at $\Delta\lambda = 1.5 \text{ Å}$ which can be attributed entirely to the broad wings of the Airy instrument function of the FPI and lies in the noise level of the experiment.

For studies of diverted discharges in PDX the Thomson scattering system was modified to include a sensitive, narrow-band polychromator for use at the outer edge of the plasma. The electron temperature and density profiles obtained with the regular and edge measurements make it possible to compute the spatial variation of the H_α emissivity at the outer edge of the plasma ($r \sim 175 \text{ cm}$) assuming an edge source of room temperature H_2 molecules. The calculated H_α emissivity peak [as a composite of reactions (1) and (4)] at the outer edge moves outward by about 3 cm when the neutral beam injectors are turned on, while the observed shift is about 4 cm. Because of the higher velocity of the fast dissociation product atoms, the luminous region extends 5 cm or more inside the separatrix (located at $r \sim 180 \text{ cm}$), although the emissivity from dissociative excitation of H_2 alone would not extend (and molecules could not exist) more than 1-2 cm inside the separatrix. Considering emission solely from electron impact on H_2 , the calculations show that during neutral beam injection the ratio of fast-to-slow component H_α increases by about 40% above the ratio for the ohmically heated plasma configuration. This is consistent with the widening of the D_α line in Fig. 2

after the neutral beams are turned on. While the mean-free paths for loss of D_2 and dissociation product atoms are weakly dependent on the edge temperature distribution, the ratio of fast to slow $D(n=3)$ produced by dissociative excitation of D_2 in a plasma is quite sensitive to T_e . Thus, for $T_e < 5$ eV, this ratio is close to zero, while for T_e between 10 and 100 eV, it is roughly equal to $(0.55 \ln T_e - 1.05)$ and above 200 eV it approaches 1.6.⁸

The H_α emissivity contour diagram of Fig. 3 for a non-diverted ohmically heated plasma can be used to estimate the effective particle lifetime or recycling time for H_2 in the discharge. The total number of H_α photons emitted from the plasma (assuming toroidal symmetry) is roughly $2\pi R \int \epsilon(r,z) dr dz$, where $\epsilon(r,z)$ is the local emissivity and R is the plasma major radius. The integral is taken over the part of the discharge cross section in which H_2 and its dissociation products can yield the H_α emission. From the H_α photon yield per molecule ($f \sim 0.05$), the discharge minor radius a , and the average electron density $\bar{n}_e$, we obtain $\tau_p = \pi a^2 \bar{n}_e / (40 \int \epsilon(r,z) dr dz)$ assuming that each molecule is the source of two electrons. The data of Fig. 3 give $\tau_p \sim 40$ msec. The H_2 influx at the outer edge ($z=0$, $r \sim 190$ cm) is roughly 3×10^{15} molecules/cm²/sec. In fact, the H_α luminosity is higher at the limiter,¹⁸ and recycling occurs more rapidly there, so that this estimate of the particle lifetime is somewhat high. In the case of limiterless diverted discharges, the H_α brightness is more toroidally uniform and the particle lifetime can be evaluated more reliably from the H_α brightness at the Thomson scattering location. Diverted ohmically heated and neutral beam heated plasmas similar to those of Fig. 2 were found to have particle lifetimes of ~ 40 msec. In stable high-confinement-mode diverted discharges τ_p can exceed 60 msec, while in the strong gas puffing (blowthrough) regime it is below 30 msec.

V. CONCLUSION

Observations and model calculations of the spectral and spatial intensity distributions of the narrow bandwidth (within 1.5 Å of the line center) Balmer alpha emission from the PDX tokamak show that the emitting atoms originate as molecules at the edge. The boundary conditions on the discharge must include these molecules and their products. H₂ particle recycling times of 25-65 msec have been observed in various types of discharge on this machine.

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FIGURE CAPTION

FIG. 1 The kinetic energy distributions of (1) slow H(2s) dissociation product atoms,¹ of fast H(2s) atoms produced by (2) 40 eV and (3) 80 eV electron impact on H₂,¹ and of (4) protons produced by 300 electrons acting on H₂.¹⁰

FIG. 2 D_α spectra from diverted ohmic (lower curve) and neutral beam heated (upper curve) plasmas in PDX. The points are model calculations.

FIG. 3 H_α emissivity contours in a circular, non-diverted ohmically heated discharge in PDX. The contour lines correspond to emissivities of roughly equal steps from 1×10^{12} to 10×10^{12} photons/sec/cm³, with the peak at r=128, z=45 cm. The long rectangular structures shown in the figure represent the limiters.

Fig. 1

Fig. 3

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