TID-4500, UC-20
Controlled Thermo-
nuclear Processes

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UCRL-51247

CHARGE EXCHANGE PROCESSES IN 2XII

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MS. date: June 22, 1972

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CHARGE EXCHANGE PROCESSES IN 2XII

Abstract

The processes leading to charge exchange loss of the 2XII plasma are discussed, with the background gas presumed to be either deuterium or methane molecules. The mean free path for these molecules impinging on the plasma is found to be a small fraction of the plasma radius. The background gas density during plasma confinement, as determined by a fast atom detector in the median plane, is two to three orders of magnitude higher than the initial background gas density. Electric fields in the plasma

may sweep the molecular reaction products out of the median plane, causing the charge exchange losses from these products to go undetected. These additional losses outside the median plane are estimated to be two to five times larger than observed by the fast atom detector located in the median plane. When these additional losses are taken into account, the total charge-exchange loss rate from the plasma is still at least a factor of ten less than is required to explain the observed plasma decay.

Introduction

The observation of what are apparently stable density decays in the 2XII operation¹ has prompted an effort to interpret these decays as being limited by charge exchange. The diagnostic information available is of three kinds: an interferometry signal which measures $\int n_e dl$ as a function of time in the median plane, a fast atom detector (FAD) signal measuring the charge exchange flux emitted in the median plane from an area approximately 1 cm^2 in extent and within an angular range of a few milliradians, and a mass spectrometric analysis indicating a background gas prior to the injection pulse which consists of methane at a base pressure in the range 10^{-8} to 10^{-9} mm Hg.

Coengsen et al.¹ have compared the time-dependent decay of the interferom-

etry signal with the FAD signal and have concluded that the apparent loss rate of the plasma exceeds that which can be accounted for with charge exchange losses by a factor which is about 100 at early times and declines to about 40 late in the decay. Such a comparison of rates can be made without recourse to the details of the charge exchange process. Implicit in their analysis is the assumption that the small solid angle accepted by the FAD is a portion of the lowest mode loss cone angular distribution.

In this paper we examine the various sources and mechanisms for charge exchange, use the FAD signal to determine the background gas density, and infer a charge exchange loss rate outside the median plane. The background gas

density calculated in this way is orders of magnitude larger than the densities implied by the initial base pressure. The nature of the background gas during plasma confinement is therefore uncertain. There is the possibility of a large flux of cold D_2

gas accompanying the injected ions, which would result in a dilution of the initial CH_4 background. At present, both D_2 and CH_4 appear as strong candidates for the background gas, and we shall consider each of these cases separately.

The Charge Exchange Flux from the 2XII Plasma Immersed in a D_2 Gas

The D_2 gas impinging laterally upon the plasma is subject to ionization, dissociation, and charge exchange. The electron temperature for the stable 2XII decays (Case A of Ref. 1) is nominally taken to be 250 eV. At this electron temperature the principal processes leading to the destruction of the impinging D_2 gas are

the bar indicating a keV ion or atom. The ionization data for reaction (A) are summarized by Kieffer and Dunn²; for an electron temperature of 250 eV, $\overline{\sigma v}(A) \approx 5.4 \times 10^{-8} \text{ cm}^3 \text{ sec}^{-1}$. Reaction (B) proceeds via an electron exchange collision through the antibonding triplet Σ_u^3 state of the molecule; the reaction rate is large over a rather narrow energy interval. The σv values for D production based on the data of Corrigan³ are shown in Fig. 1. Integrating over a Maxwellian electron energy distribution with a temperature of 250 eV with Corrigan's data gives $\overline{\sigma v}(B) \approx 9 \times 10^{-10} \text{ cm}^3 \text{ sec}^{-1}$. At

this electron temperature only a few percent of the molecules undergo reaction

Fig. 1. The reaction rate coefficient, σv , for electron dissociation of deuterium molecules plotted as a function of the incident electron energy. (Based on data of Corrigan,³)

(B). The σv values for reaction (C) are shown in Fig. 2. Since the ion energy distribution in 2XII changes form during the course of the decay, the reaction rate (C) will also vary. The $\overline{\sigma v}(C)$ values, calculated for different times using the measured ion energy distribution, are summarized in Table 1.

If s is the distance measured normal to and inward from the edge of the plasma,

and v_0 the mean D_2 molecular velocity in this direction, the attenuation of the D_2 gas density toward the center of the plasma is given by

$$\frac{dn(D_2)}{ds} = -\frac{n(D_2) \ln e}{v_0} [\overline{\sigma v}(A) + \overline{\sigma v}(B) + \overline{\sigma v}(C)]$$

$$= -\frac{n(D_2)}{\lambda(D_2)} \quad (1)$$

Fig. 2. The reaction rate coefficient, σv , for charge exchange of energetic deuterium ions incident upon deuterium atoms or deuterium molecules, plotted as a function of the incident deuteron energy.

Table 1. Values of $\sigma v(C)$ at various times after the start of the plasma injection pulse.

Time (μsec)	$\sigma v(C)$ ($10^{-8} \text{ cm}^3 \text{ sec}^{-1}$)
300	1.1
600	2.2
1000	2.3
1200	2.1

The mean directed velocity, v_0 , is calculated from

$$v_0 = \int v(\cos \theta) e^{-\beta^2 v^2} v^2 dv d(\cos \theta) d\phi,$$

$$\beta^2 = \frac{m}{3kT}.$$

$$v_0 = \frac{1}{2\sqrt{\pi}} \left(\frac{3kT}{m} \right)^{1/2}.$$

$$v_0 = 3.8 \times 10^4 \text{ cm sec}^{-1} \text{ at } T = 300^\circ\text{K}. \quad (2)$$

From Eq. (1), the mean free path is

$$\lambda(D_2) = \frac{v_0}{n_e [\bar{\sigma v}(A) + \bar{\sigma v}(B) + \bar{\sigma v}(C)]^{-1}}. \quad (3)$$

Values of λ are listed in Table 2, where we have assumed the electron temperature is 250 eV throughout the decay.

The deuterium atom fragments from reaction (B), which are Frank-Condon neutrals (FCNs), will penetrate further than the D_2 molecules; the atoms are emitted with a mean energy of approximately 2.5 eV. The principal destruction processes of the atoms are

At an electron temperature of 250 eV, $\bar{\sigma v}(D) = 3.5 \times 10^{-8} \text{ cm}^3 \text{ sec}^{-1}$. The σv values for reaction (E) are shown in Fig. 2; averaging these values over the measured ion energy distributions gives for the mean free paths

$$\lambda(D) = \frac{v_0}{n_e [\bar{\sigma v}(D) + \bar{\sigma v}(E)]^{-1}}, \quad (4)$$

using $v_0 \approx 1.6 \times 10^6 \text{ cm sec}^{-1}$. The values are listed in Table 2.

At a density of $10^{13} \text{ ions cm}^{-3}$ the FCNs form a layer about 1 cm deep and are about 30 times more penetrating than the D_2 gas. The molecular ion products of reactions (A) and (C), representing a fraction

$$\frac{\bar{\sigma v}(A) + \bar{\sigma v}(C)}{\bar{\sigma v}(A) + \bar{\sigma v}(B) + \bar{\sigma v}(C)} = 0.98$$

of the original molecules, will dissociate to provide an additional source of atoms by means of the reactions

Table 2. Values of $\lambda(D_2)$ and $\lambda(D)$ at various times after the start of the plasma injection pulse, assuming an electron temperature of 250 eV.

Time (μsec)	Mean free path, λ ($\frac{10^{13}}{n_e} \text{ cm}$) ^a	
	$\lambda(D_2)$	$\lambda(D)$
300	0.058	1.6
600	0.049	1.4
1000	0.049	1.3
1200	0.050	1.1

^aWhere n_e is the electron density (electrons cm^{-3}).

The experimental data of Dunn et al.⁴ and of Dance et al.⁵ yield $\overline{\sigma v}(F) \approx 12 \times 10^{-8} \text{ cm}^3 \text{ sec}^{-1}$. Reaction (G) has been measured in a crossed beam experiment by Vogler and Dunn⁶ using electron energies ranging from 1.5 to 7.5 eV. Combining these data with the Monte Carlo calculations of Wilkins⁷ at 0.026, 0.10, and 1.16 eV, one can fit the cross section to $\sigma = 5.2 \times 10^{-17} E^{-1} \text{ cm}^2$, where E is the incident electron energy in eV. Averaging over a Maxwellian, one obtains

$$\overline{\sigma v} = 8 \times 10^{-15} / \sqrt{\pi kT} \text{ cm}^3 \text{ sec}^{-1}. \quad (5)$$

For an electron temperature of 250 eV, $\overline{\sigma v} = 2.3 \times 10^{-10} \text{ cm}^3 \text{ sec}^{-1}$, and the reaction rate (G) can be ignored in comparison with (F).

The dissociative recombination reaction (G) and the cross section value used here require some further comment. The reaction rate of Eq. (5) based on Vogler and Dunn's crossed beam experiment yields a value of $2 \times 10^{-8} \text{ cm}^3 \text{ sec}^{-1}$ for $T = 300^\circ\text{K}$, which is consistent with Persson and Brown's statement⁸ that the rate in hydrogen discharge afterglow is less than $3 \times 10^{-8} \text{ cm}^3 \text{ sec}^{-1}$. Persson and Brown's value, however, is based upon a highly refined afterglow experiment employing very pure hydrogen. Earlier experiments in hydrogen⁹⁻¹¹ had yielded afterglow recombination rates in the range 0.4-to- $6.2 \times 10^{-6} \text{ cm}^3 \text{ sec}^{-1}$ at 300°K. While these afterglow experiments were conducted at much higher gas pressures than occur in the 2XII experi-

ment, which might allow for secondary ion molecule reactions to be important, the possibility does exist that the catalytic processes which caused the recombination rates to be so large in these early experiments may also be present under 2XII conditions. In this case reaction rate (G) could become comparable to rate (F).

The mean time for dissociation of the molecular ions, $(n\overline{\sigma v})^{-1}$, ranges from about 10^{-6} to 10^{-5} sec as the density falls from 10^{13} to $10^{12} \text{ ions cm}^{-3}$. If electric fields in the plasma are sufficiently large the molecular ions will be swept out of the region of the median plane before dissociation can occur; in this case there would be no appreciable atomic layer near the median plane, and the FAD signal would be due to charge exchange in the molecular layer only. The formation of the atomic layer only outside the median plane would imply that the combined charge exchange losses of both the molecular and the atomic layer averaged over the plasma volume would be larger than indicated by the present FAD signal.

Electric fields are generated in the plasma due to spatial variations of the *ambipolar potential and because of the microscopic granular nature of the plasma resulting from the distribution of ions and electrons (Holtmark fields)*. Fluctuations of the electron density will cause the Holtmark fields to appear as a random time sequence of very short electric pulses. The existence of these fields will cause the molecular ions to migrate toward the mirror region.

The spatial variations of the ambipolar potential will be determined by the spatial variations of the magnetic field.¹² In 2XII

the mirror point is 64 cm from the median plane; for a distance out to 50 cm from the median plane the magnetic field can be fitted to two parabolic functions. Using the variable z to measure the distance along a field line from the median plane toward the mirror, the ambipolar potential is taken to be

$$\Phi(z) = \Phi_0 \left(1 - \frac{z^2}{a^2} \right), \quad (6)$$

where

$$\begin{aligned} a &= 70 \text{ cm for } 0 \leq z \leq 30 \text{ cm,} \\ a &= 60 \text{ cm for } 30 \leq z \leq 50 \text{ cm.} \end{aligned}$$

Between 50 cm and the mirror the electric field is assumed to be constant and equal to the value at 50 cm. The plasma potential, Φ_0 , is chosen to be 500 V, the value for the low energy cutoff in the ion distribution.¹ Integrating the equation of motion for an ion moving in this potential, $\ddot{z} = -\frac{e}{m} \frac{\partial \Phi}{\partial z}$, we obtain the following implicit equation relating z and t :

$$\begin{aligned} &\left(z^2 - z_0^2 + \dot{z}_0^2 / \alpha^2 \right)^{1/2} + z \\ &= (\dot{z}_0 / \alpha + z_0) e^{\alpha t}, \end{aligned} \quad (7)$$

where z_0 and $\dot{z}_0$ are the initial position and velocity, respectively, and $\alpha^2 = 2 \frac{e}{m} \left(\Phi_0 / a^2 \right)$. For a molecular ion originating 1 cm from the median plane, the time required to be swept into the mirror region is approximately 10 μsec .

Next, we compare the time required for a molecular ion to be swept a distance $\lambda(D)$ with the mean time for molecular dissociation. At a density of 10^{13} ions cm^{-3} Table 2 indicates $\lambda(D) \approx 1$ cm. Equation (7) above shows that an ion orig-

inating 1 cm from the median plane will move an additional 1 cm toward the mirror after 4 μsec ; but the mean dissociation time at this density is 1 μsec . In this case the atomic FCN layer will be generated rapidly compared to the molecular ion sweep time, and the atomic layer will develop in the median plane. On the other hand, if the density were 10^{12} ions cm^{-3} then $\lambda(D) \approx 10$ cm; the time for a molecular ion to move 10 cm is about 10 μsec , equal to the mean molecular ion dissociation time. It follows then that for densities below about 10^{12} ions cm^{-3} the atomic layer will not form in the median plane and the FAD signal will record only charge exchange in the molecular layer.

Fluctuating electric fields in the plasma will cause a diffusion of the molecular ions toward the mirrors. For a proper account of this process we must apply the complete Fokker-Planck equation, but we can estimate the diffusion in a simple way by integrating the equation of motion for an ion subject to a sequence of random electric pulses. These random pulses will affect both the radial and axial motions. A lower limit on the diffusion time is obtained if we consider the axial impulses only. We shall assume the random electric pulses can be represented by

$$\begin{aligned} \mathcal{E} &= \sum_{i=1}^N \mathcal{E}_0 \exp[-w^2(t - t_i)^2] \\ &\quad \times \sin(\beta t_i + \phi_i). \end{aligned} \quad (8)$$

In Appendix A it is shown that these random pulses acting on the z -motion of the

ions will generate a root-mean-square displacement equal to

$$\bar{z} = \sqrt{\langle z^2 \rangle} = \frac{e}{m} \epsilon_0 \frac{\sqrt{\pi}}{2\omega} \sqrt{\frac{N}{24}} T, \quad (9)$$

where T is the accumulated time measured from the first impulse. The mean value of the Holtsmark field is approximately¹³

$$\epsilon_H \approx 1.6e \left(\frac{4\pi n}{3} \right)^{2/3} \text{ esu cm}^{-1}, \quad (10)$$

which, for a density of 10^{13} ions cm^{-3} , amounts to 260 V cm^{-1} . The average value of the Holtsmark field in the z -direction is $\epsilon_0 = \frac{1}{4} \epsilon_H$. The mean times for the pulse width, ω^{-1} , range from the electron transit time between ions up to the time for an electron to move across a Debye sphere. Inspecting Eq. (10), and noting that for the fluctuations to be generated as rapidly as possible we must have $N = \omega T$, we see that the mean displacement varies as $\omega^{-1/2}$. The maximum displacement is obtained if we take for ω^{-1} the Debye transit time, i.e., the reciprocal of the electron plasma frequency, ω_{pe}^{-1} . At a plasma density of 10^{13} ions cm^{-3} ($\omega_{pe} \approx 1.7 \times 10^{11} \text{ sec}^{-1}$), the migration time for a molecular ion to move from the median plane to the mirrors is a few hundred microseconds. Thus the dc fields generated by the ambipolar potential appear to be more effective in sweeping out the cold ions than do the fluctuating fields.

We shall now calculate the molecular background gas densities implied by the FAD signal. In the density range 10^{12} to 10^{13} ions cm^{-3} , the molecular mean free paths indicated in Table 2 are only a small fraction of the plasma radius. It

follows that the flux of charge exchange neutrals emitted by the plasma must be proportional to the flux of molecules impinging on the plasma. The fraction of molecular dissociation and ionization events leading to charge exchange is

$$f(\text{CXM}) = \frac{\overline{\sigma v}(\text{C})}{\overline{\sigma v}(\text{A}) + \overline{\sigma v}(\text{C})}. \quad (11)$$

Writing FADS for the FAD signal flux in units of the number of fast atoms $\text{cm}^{-2} \text{ sec}^{-1}$, we can determine the molecular gas density, n , assuming the charge exchange signal originates in the molecular layer only, by the relation

$$\text{FADS} = f(\text{CXM})nv_0. \quad (12)$$

The densities n as a function of time for case (A), from the data of Coensgen et al.,¹ are listed in the second column of Table 3. If the atomic layer is formed in the median plane the FAD signal is due to charge exchange events in both the molecular and atomic layers. The principal processes leading to ionization of the atomic layer are

The fraction of charge exchange events per atom ionized in the layer is

$$f(\text{CXA}) = \frac{\overline{\sigma v}(\text{H})}{\overline{\sigma v}(\text{H}) + \overline{\sigma v}(\text{I})}; \quad (13)$$

values range from 0.66 to 0.71 during the decay. The molecular gas density, n , is now determined by

$$\text{FADS} = f(\text{CXM})nv_0 + f(\text{CXA})nv_0; \quad (14)$$

Table 3. Background gas densities calculated from the free atom detector signal at various times after the start of the plasma injection pulse.

Time (μsec)	Density (10^{10} mol cm^{-3}) assuming:	
	Molecular layer	Molecular + atomic layers
300	20	7
600	3	1
1000	1	0.5
1200	0.8	0.4
2000	0.4	0.2

it is listed in the third column of Table 3.

Let us estimate the increase in the charge exchange losses over and above those implied by the FAD signal in the event that the atomic layer is not formed in the median plane but does exist in the region between the median plane and the mirrors. The factor increase in charge exchange flux outside the median plane would be

Molecular layer plus atomic layer signals
Molecular layer signal

$$\frac{f(\text{CXM}) + f(\text{CXA})}{f(\text{CXM})}; \quad (15)$$

this ratio is about 3 at 300 μsec , and a little more than 2 at later times. In the limiting case where the dissociative recombination reaction rate (G) exceeds the reaction rate (F), the additional atomic contribution would cause the ratio to range from 5 at 300 μsec to about 3 late in the decay.

In conclusion, should the principal component of the background gas be D_2 , there is the possibility of a larger FAD signal outside the median plane. The additional plasma loss resulting would be a factor of 2 to 5 times larger than is observed in the median plane. This additional loss is not sufficient, however, to meet the requirement of a factor of 40 to 100 which would be necessary to interpret the decay as due principally to charge exchange. The observed plasma decay rate remains at least an order of magnitude larger than can be explained by charge exchange processes on a D_2 background.

The Charge Exchange Flux from the 2XII Plasma Immersed in a CH_4 Gas

The problem of a methane gas background is more complex than that of a D_2 background because of the greater number of dissociation and ionization modes for methane, the large variety of molecular ion products, and the presence of both H and H_2 FCN products. For our purposes we need information on the partial cross sections leading to dissociation and ionization of CH_4 , and the number of H or H_2 products together with their

respective energy spectra. Although a great body of knowledge dealing with the dissociation of methane has been accumulated, information on the number of hydrogen products and their energy spectra to be expected under typical collision conditions is not readily available. We begin by discussing the pertinent reactions, then follow with an analysis of the literature for each of these reactions.

The principal dissociation modes of the molecule which result from electron or ion impact are

Ionization products occur in a number of ways; the principal modes are

Other ionizing reactions can be written down and may occur, but their frequency of occurrence is so small that they can be neglected. Also, collisions leading to double ionization have been observed but these represent at most about 1% of the ionization events.¹⁴

The charge exchange of plasma deuterium ions with methane leads to the following reactions:

In Appendix B we review the available literature for each of these reactions. It is concluded that reactions (a), (d), (e), and (g) are the principal sources of FCNs. The respective partial cross sections, the kinetic energy range, and the mean ki-

netic energy of the hydrogen fragments resulting from collisions with electrons in the energy range from 100 eV to 1 keV and D^+ collisions in the few-keV range are summarized as follows:

$$\sigma(\text{a}) \approx \sigma(\text{total CH}_4 \text{ electron ionization}),$$

$$2.4 \leq \text{KE}(\text{H}_2) \leq 5.0 \text{ eV},$$

$$\overline{\text{KE}}(\text{H}_2) \approx 3 \text{ eV}. \quad (\text{a})$$

$$\sigma(\text{d}) \approx 0.4\sigma(\text{total CH}_4 \text{ electron ionization}),$$

$$0 \leq \text{KE}(\text{H}) \leq 7 \text{ eV}, \quad \overline{\text{KE}}(\text{H}) \approx 1 \text{ eV}. \quad (\text{d})$$

$$\sigma(\text{e}) \approx 0.08\sigma(\text{total CH}_4 \text{ electron ionization}),$$

$$0 \leq \text{KE}(\text{H}_2) \leq 6 \text{ eV}, \quad \overline{\text{KE}}(\text{H}_2) \approx 3 \text{ eV}. \quad (\text{e})$$

$$\sigma(\text{g}) \approx 0.34\sigma(\text{total charge exchange}),$$

$$0 \leq \text{KE}(\text{H}) \leq 7 \text{ eV}, \quad \overline{\text{KE}}(\text{H}) \approx 1 \text{ eV}. \quad (\text{g})$$

The other cross sections large enough to be important in estimating the mean free path of the methane molecule are

$$\sigma(\text{c}) = 0.5\sigma(\text{total CH}_4 \text{ electron ionization}), \quad (\text{c})$$

$$\sigma(\text{f}) = 0.64\sigma(\text{total charge exchange}). \quad (\text{f})$$

The total electron ionization cross section is available from Kieffer and Dunn,² and the total charge exchange cross section from Berkner, Pyle, and Stearns.¹⁵

The rate of attenuation of the CH_4 molecules incident upon the plasma is

$$\begin{aligned} \frac{dn(\text{CH}_4)}{ds} = & -\frac{n(\text{CH}_4)n_e}{v_0} [\overline{\sigma v}(\text{a}) + \overline{\sigma v}(\text{c}) \\ & + \overline{\sigma v}(\text{d}) + \overline{\sigma v}(\text{e}) + \overline{\sigma v}(\text{f}) + \overline{\sigma v}(\text{g})], \end{aligned} \quad (15)$$

With $v_0 = 1.8 \times 10^4$ cm sec⁻¹, and with the respective $\overline{\sigma v}$ values inserted, the rate equation becomes

$$\frac{dn(\text{CH}_4)}{ds} = -3.3 \times 10^{11} n(\text{CH}_4) n_e \times [0.42 + 0.2 + 0.17 + 0.03 + 0.11 + 0.06], \quad (17)$$

where each entry in the brackets gives the fractional contribution of one of the respective rates shown in Eq. (16). Approximately 23% of the reactions produce H atoms with mean energies near 1 eV, 45% produce H₂ molecules with mean energies of about 3 eV, and 32% yield only ion fragments. The mean free paths for the methane molecule and the H₂ and H FCNs are, respectively,

$$\lambda(\text{CH}_4) = 3 \times \frac{10^{10}}{n_e} \text{ cm}, \quad (18)$$

$$\lambda(\text{H}_2) = 2 \times \frac{10^{13}}{n_e} \text{ cm}, \quad (19)$$

$$\lambda(\text{H}) = 1 \times \frac{10^{13}}{n_e} \text{ cm}. \quad (20)$$

The H₂ and H layers are distinguishable to some extent.

With the methane background gas, charge exchange from both the methane molecule and the neutral dissociation products will contribute to the FAD signal in the median plane. The neutral products CH₂, H₂, and H occur in reactions (a), (d), (e), and (g). Charge exchange and ionization data for CH₂ are not available. The ionization potential for CH₂ is 13.4 eV; hence, the absolute value of the energy defect for deuterium charge ex-

change on CH₂ is close to the value for deuterium charge exchange on D₂ (or H₂); the maxima of the two cross sections would be expected to occur at the same energy.¹⁶ As a result of the lower ionization potential of CH₂, both the ionization cross section and the charge exchange cross section will be larger than for D₂. For lack of any further data we shall make the plausible assumption that the ratio of charge exchange to ionization for CH₂ is the same as for D₂ (or H₂). The neutral reaction products will be emitted isotropically in the CH₄ layer, and only half will penetrate inward to contribute to the FAD signal. Adding up the contributions to the charge exchange signal from the methane layer and the neutral reaction product layers, we determine the methane gas density, n , from

$$\begin{aligned} \text{FADS} = & \left\{ f(\text{CH}_4) + \frac{1}{2} [0.42 \times 2.0f(\text{CXM}) \right. \\ & + 0.17f(\text{CXA}) + 0.03f(\text{CXM}) \\ & \left. + 0.06f(\text{CXM})] \right\} n v_0, \quad (21) \end{aligned}$$

where use is made of the ratios given by Eqs. (11) and (13). The contribution from the methane layer,

$$\begin{aligned} f(\text{CH}_4) = & [\overline{\sigma v}(f) + \overline{\sigma v}(g)] [\overline{\sigma v}(a) + \overline{\sigma v}(c) \\ & + \overline{\sigma v}(d) + \overline{\sigma v}(e) + \overline{\sigma v}(f) + \overline{\sigma v}(g)]^{-1}, \quad (22) \end{aligned}$$

is insensitive to ion energy and has the value 0.17. The methane densities as a function of time are listed in the second column of Table 4. These molecular densities are not too different from those listed in the second column of Table 3.

Table 4. Densities for CH₄ background gas calculated from the free atom detector signal at various times after the start of the plasma injection pulse.

Time (μsec)	Density (10 ¹⁰ mol cm ⁻³) assuming:	
	CH ₄ + neutral products	CH ₄ + all reaction products
300	20	5
600	5	1
1000	2	0.4
1200	1	0.3
2000	0.7	0.1

For reasons similar to those discussed in the previous section, the subsequent fragmentation of the ion products of the initial reactions may or may not lead to additional charge exchange events in the median plane, depending on the effectiveness of the plasma electric fields in sweeping out the ion products before dissociation of the fragments can occur. Relatively little data exists for the fragment dissociation reactions, but for the maximum charge exchange signal we shall assume the following sequences occur starting from some initial CH_x⁺ ion:

In effect, each CH₄⁺ ion is assumed to be a source of four H atoms, each CH₃⁺ ion a source of three H atoms, etc. If reactions (j) through (m) and the fragmenta-

tion of H₂ FCNs occur close to the median plane, the neutral methane density is derived from

$$\begin{aligned} \text{FADS} = & \left(f(\text{CH}_4) + \frac{1}{2} \{ 0.42[2f(\text{CXM}) \right. \\ & + 3f(\text{CXA})] + 0.84f(\text{CXA}) \\ & + 0.72f(\text{CXA}) + 0.03[f(\text{CXM}) \\ & + 3f(\text{CXA})] + 0.44f(\text{CXA}) \\ & \left. + 0.24f(\text{CXA}) \} \right) n_{\text{v}_0}. \quad (23) \end{aligned}$$

The terms within the braces {} refer to contributions from reactions (a), (c), (d), (e), (f), and (g), respectively. The densities are listed in the third column of Table 4.

Finally, we calculate the factor increase in the charge exchange flux outside the median plane should the plasma electric fields effectively sweep the reaction ion products out of the central region. In analogy with Eq. (17), we calculate the ratio of CH₄ layer + neutral products layer + ion fragment layer signals to CH₄ layer + neutral products layer signals,

$$\frac{\text{CH}_4 + \text{neutrals} + \text{ion fragments}}{\text{CH}_4 + \text{neutrals}}. \quad (24)$$

This ratio is 4.5 at 300 μsec and declines monotonically to a value of 4.0 at later times. Should this larger charge exchange flux occur outside the median plane it would not constitute a sufficient loss of plasma to explain the observed decay; so again in the case of CH₄ background gas, as with D₂, the observed decay rate is an order of magnitude or more larger than can be explained by the FAD signal.

Conclusions

The processes leading to charge exchange loss of the 2XII plasma have been discussed, assuming the background gas to be either deuterium or methane molecules. The mean free path for these gas molecules impinging on the plasma is found to be a small fraction of the plasma radius. The fast atom detector signal indicates a background gas density during plasma confinement which is two to three orders of magnitude higher than the initial background gas density. The charge exchange flux observed by the fast atom detector, which is located in the median plane, may be a factor of 2 to 5 lower than the flux outside the median plane for

the following reason: Electric fields present in a stable plasma will sweep the ionized molecular fragments into the mirror region in a time of about $10 \mu\text{sec}$, and these fragments have a mean dissociation time which ranges from 1 to $100 \mu\text{sec}$ as the density ranges from 10^{13} to 10^{11} ions cm^{-3} . An accurate measure of the charge exchange losses will require making neutral atom flux measurements outside the median plane. But even when the observed charge exchange losses are increased by the factor of 2 to 5 suggested above, they are still at least an order of magnitude too small to account for the observed plasma loss.

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Appendix A

Ion Motion Under the Influence of Random Short Electric Pulses

In this appendix we consider the motion of an ion acting under the influence of a random series of short electric pulses. The random fields are assumed to have the form

$$\mathcal{E} = \sum_{i=1}^N \mathcal{E}_0 \exp \left[-\omega^2 (t - t_i)^2 \right] \sin (\beta t + \phi_i), \quad t_N < t. \quad (\text{A1})$$

If we set

$$\exp \left[-\omega^2 (t - t_i)^2 \right] = \frac{\sqrt{\pi}}{2\omega} \delta(t - t_i), \quad (\text{A2})$$

the acceleration of an ion becomes

$$\ddot{z} = \frac{e}{m} \mathcal{E}_0 \frac{\sqrt{\pi}}{2\omega} \sum_{i=1}^N \delta(t - t_i) \sin (\beta t + \phi_i). \quad (\text{A3})$$

Our objective is to calculate the root-mean-square displacement in z as a function of time. The first integral of Eq. (A3) gives

$$\dot{z} = \frac{e}{m} \mathcal{E}_0 \frac{\sqrt{\pi}}{2\omega} \sum_{i=1}^N \sin (\beta t_i + \phi_i), \quad t_N < t. \quad (\text{A4})$$

Let

$$\Delta \dot{z}_i = \frac{e}{m} \mathcal{E}_0 \frac{\sqrt{\pi}}{2\omega} \sin (\beta t_i + \phi_i), \quad (\text{A5})$$

and, integrating with respect to time, we obtain

$$z = \sum_{i=1}^N \Delta \dot{z}_i (t - t_i) \theta(t - t_i), \quad t_N < t. \quad (\text{A6})$$

Here $\theta(t - t_i) = 0$ for $t < t_i$, $\theta(t - t_i) = 1$ for $t > t_i$. Then

$$\langle z^2 \rangle = \frac{1}{T} \int_0^T z^2 dt = \frac{1}{T} \left[\sum_{i=1}^N \Delta \dot{z}_i (t - t_i) \theta(t - t_i) \right]^2 dt. \quad (A7)$$

$$\begin{aligned} \langle z^2 \rangle = \frac{1}{T} \int_0^T \left\{ \sum_{i=1}^N [\Delta \dot{z}_i (t - t_i) \theta(t - t_i)]^2 \right. \\ \left. + 2 \sum_{i < j} \Delta \dot{z}_i \Delta \dot{z}_j (t - t_i)(t - t_j) \theta(t - t_i) \theta(t - t_j) \right\} dt. \end{aligned} \quad (A8)$$

The second term in this integrand will be small compared to the first because of the random phases for the z_j . Then

$$\langle z^2 \rangle = \frac{1}{T} \left(\frac{e}{m} \right)^2 \mathcal{E}_0^2 \frac{\pi}{4\omega^2} \int_0^T \sum_{i=1}^N (t^2 - 2tt_i + t_i^2) \theta(t - t_i) \sin^2(\beta t_i + \phi_i) dt. \quad (A9)$$

Now

$$\begin{aligned} \int_0^T \sum_{i=1}^N t^2 \theta(t - t_i) dt &= \sum_{i=1}^N \int_{t_i}^T t^2 dt = \frac{1}{3} NT^3 - \frac{1}{3} \sum_{i=1}^N t_i^3, \\ -2 \int_0^T \sum_{i=1}^N tt_i \theta(t - t_i) dt &= -2 \sum_{i=1}^N t_i \int_{t_i}^T t dt = -T^2 \sum_{i=1}^N t_i + \sum_{i=1}^N t_i^3, \\ \int_0^T \sum_{i=1}^N t_i^2 \theta(t - t_i) dt &= \sum_{i=1}^N t_i^2 \int_{t_i}^T dt = T \sum_{i=1}^N t_i^2 - \sum_{i=1}^N t_i^3. \end{aligned} \quad (A10)$$

Using

$$\begin{aligned} \sum_{i=1}^N t_i &= \frac{1}{2} NT, \\ \sum_{i=1}^N t_i^2 &= \frac{1}{3} NT^2, \end{aligned}$$

$$\sum_{i=1}^N t_i^3 = \frac{1}{4} NT^3, \quad (\text{A11})$$

one obtains

$$\int_0^T \sum_{i=1}^N \left(t^2 - 2tt_i + t_i^2 \right) \theta(t - t_i) dt = \frac{1}{12} NT^3. \quad (\text{A12})$$

Equation (A8) becomes

$$\langle z^2 \rangle = \frac{1}{T} \left(\frac{e}{m} \right)^2 \epsilon_0^2 \frac{\pi}{4\omega^2} \sum_{i=1}^N \left[\frac{1}{2} - \frac{1}{2} \cos 2(\beta t_i + \phi_i) \right] \left[\frac{1}{12} NT^3 \right]. \quad (\text{A13})$$

Since the phases $\beta t_i + \phi_i$ are random, the cosine term will average to zero. The mean square displacement in z becomes

$$\langle z^2 \rangle = \frac{1}{96} \left(\frac{e}{m} \right)^2 \epsilon_0^2 \frac{\pi}{\omega^2} NT^2. \quad (\text{A14})$$

Appendix B

Dissociation and Ionization Reactions for Methane

Here we list the most important dissociation and ionization reactions for methane, followed by a discussion of the literature relevant to these reactions. Our purpose is to elucidate the partial cross sections for these processes, and to determine the number and kinetic energies of the reaction products which might be present in the 2XII experiment.^{1*}

The principal dissociation modes of the molecule which result from electron or ion impact are

Ionization products occur in a number of ways; the principal modes are

Other ionizing reactions can be written down and may occur, but their frequency of occurrence is so small that they can be ignored. Also, collisions leading to double ionization have been observed, but these represent at most about 1% of the ionization events.²

The charge exchange of plasma deuterium ions with methane leads to the following reactions:

*References cited in this appendix are listed at the end of the appendix.

For 2X analysis the partial cross section and the kinetic energy of the reaction products for each of these reactions is required. To this end we review the available data for each of these reactions.

The dissociation process (a) is the principal part of the photoabsorption cross section below the ionization limit,³ and it is discussed in detail by Lindholm.⁴ At the onset of dissociation the molecule is electronically excited into an unstable configuration, causing it to dissociate into an excited CH_2 singlet state, which is about 0.72 eV above the ground state,⁵ and a normal H_2 molecule. Lindholm estimates the dissociation energy of CH_4 into $\text{CH}_2 + \text{H}_2$ (ground states) to be 4.8 eV. Since the onset of the dissociation occurs at an excitation energy of 8.31 eV, the kinetic energy of the dissociation products is at least $8.31 - (4.8 + 0.72) \approx 2.8$ eV. Excitations of this mode continue up to about 9.2 eV before another electronic state is excited, and thus the kinetic energies must be in the range 2.8 to 3.7 eV.

Excitations from 9.2 to 11.7 eV yield a CH_2 fragment in a single state about 1.64 eV above the CH_2 ground state⁵; the energy range of this fragment is $(9.2 \text{ to } 11.7) - (4.8 + 1.64) = 2.8 \text{ to } 5.2$ eV.

Excitations from 11.7 to about 14 eV yield a CH_2 fragment in a still more highly excited electronic state, 3.4 eV above the ground state, to give a fragment energy range of $(11.7 \text{ to } 14.0) - (4.8 + 3.4) = 3.5 \text{ to } 5.8$ eV.

From the stepwise appearance of the photoabsorption cross section, the matrix elements leading to these three final states are comparable. Also, the total photoexcitation cross section is comparable to the total photoionization cross section.³ Since the cross section for high energy ($>> 10$ eV) electron collisions is proportional to the same matrix element as photoabsorption, we can conclude that the collision cross section leading to reaction (a) is comparable to the total ionization cross section, and the fragment kinetic energies will be principally in the range 2.8 to about 5.8 eV. From momentum conservation, the H_2 fragment energy will range from 2.4 to 5.0 eV.

Reaction (b) does not appear to be of great importance. According to Lindholm, excitation to that electronic state which would result in dissociation into CH_3 and H in their respective ground states occurs to a bound portion of a stable electronic curve; any such excitations would relax back to CH_4 ground state by radiative emission in about 10^{-8} sec. Excitations leading to excited CH_3 can occur. Herzberg⁶ has identified an excited level at 5.8 eV; combining this with the 4.4-eV dissociation energy of CH_3 and H, an onset potential lying above 10.2 eV is indicated. Mahan and Mandal⁷ see no evidence of reaction (b) for photon energies up to 10 eV, confirming the above conclusion. But the possibility of this process forming part of the photoabsorption in Ditchburn's photolysis curve above 10.2 eV cannot be excluded. Since the structure in Ditchburn's curve is accounted for by the known excited CH_2 levels, it is unlikely that CH_3 formation could comprise a large part of the photoabsorption above 10.2 eV. Those (b) processes which nevertheless may be occurring would give fragment energies equal to the difference of the upper energy limit for photodissociation, about 14 eV and 10.2 eV; the H fragment kinetic energies would range up to 3.5 eV.

The partial cross sections for the ionization processes (c), (d), and (e) can be deduced from the differential ionization data of McCulloh et al.,² and the total ionization data of Rapp and Englander-Golden.⁸ In the former experiment and for the case of 1-keV electrons incident upon methane, the ionization fractions for several ionization modes are distinguished. Since the ratios for the different underlying electronic excitations are relatively insensitive to electron energy for electron energies well above the excitation threshold, we shall adopt these values for all incident electron energies above about 100 eV. Processes (c), (d), and (e) represent 50, 40, and 8%, respectively, of the total ionization.

Processes (d) and (e) give rise to energetic neutrals. Lindholm's analysis of (d) indicates an excitation to a shallow but stable electronic state of CH_4 ; those excitations which occur to the repulsive part of the bonding potential lying above the dissociation limit result in dissociation into a CH_3^+ ion and H atom in their respective ground states. The final excited electronic level of CH_3^+ is about 7 eV above the dissociation limit. The experimental charge exchange analysis of Von Koch⁹ shows that excitations leading to process (d) could give rise to H atoms with kinetic energies ranging from zero up to 7 eV. Some clue to the distribution of energies of emitted H atoms is given by the variation of the charge exchange cross section as a function of energy absorbed. This dependence indicates that the great majority of H atoms would be emitted with less than 2 eV, and with a mean of about 1 eV. Finally, Vroom and de Heer¹⁰ report Lyman and Balmer radiation from excited hydrogen atoms resulting from electron-methane collisions. Some portion of these may arise from process (d), but their data indicate less than 5% of the total ionization will result in excited atoms.

The process (e) proceeds through either of two modes, depending upon the excitation energy of the intermediate CH_4^+ ion.⁴ In the first mode dissociation into a weakly excited CH_2^+ ion and H_2 molecule occurs for excitations from 15.2 eV, the dissociation limit for the state, up to excitations of about 21 eV⁹; the H_2 energy ranges from zero up to 5 eV. The form of the partial charge exchange cross section leading to this mode indicates most H_2 is ejected with kinetic energies up to 1 eV, but with a long tail extending out to 5 eV. In the second mode the CH_2^+ is formed in a more highly excited state, with the onset occurring at 21 eV excitation, and the dissociation limit at 18.2 eV; consequently, at the onset of this mode, H_2 molecules are formed with kinetic energies of 2.4 eV. From Von Koch's data it is apparent that the probability of excitation is increasing for several volts beyond the onset. For a high energy electron collision this second mode would appear to contribute more H_2 fragments than the lower mode, and with H_2 energies extending from 2.4 to at least 6 eV.

The partial charge exchange cross sections leading to processes (f), (g), (h), and (i) are available for deuterium ion energies up to 1.8 keV,⁹ and total charge exchange cross sections are available from a few hundred eV up to a few hundred keV.¹¹ At 1.8 eV the partial cross sections are 64, 34, 0.8, and 0.2%, respectively. With increasing D^+ energy, the partial cross section is falling for process (f), rising for processes (g) and (i), and constant for (h).

Process (g) is the principal source of Frank-Condon neutrals in the charge exchange reactions. The excitation leading to this dissociation mode is similar to that for process (d), and we shall take 1 eV as the mean energy of the H atom fragment.

To summarize, processes (a), (d), (e), and (g) are the principal sources of Frank-Condon neutrals. The effective partial cross sections, the kinetic energy range, and the mean kinetic energy of the hydrogen fragments resulting from electron collisions in the range from 100 eV to 1 keV and D^+ collisions in the few-keV range are summarized as follows:

$$\sigma(a) \approx \sigma(\text{total } CH_4 \text{ electron collisional ionization}),$$

$$KE(H_2): 2.4 \rightarrow 5.0 \text{ eV},$$

$$\overline{KE}(H_2) \approx 3 \text{ eV}.$$

$$\sigma(d) = 0.4\sigma(\text{total } CH_4 \text{ electron collisional ionization}),$$

$$KE(H): 0 \rightarrow 7 \text{ eV},$$

$$\overline{KE}(H) \approx 1 \text{ eV}.$$

$$\sigma(e) = 0.08\sigma(\text{total } CH_4 \text{ electron collisional ionization}),$$

$$KE(H_2): 0 \rightarrow 6 \text{ eV},$$

$$\overline{KE}(H_2) \approx 3 \text{ eV}.$$

$$\sigma(g) = 0.34\sigma(\text{total charge exchange}),$$

$$KE(H): 0 \rightarrow 7 \text{ eV},$$

$$\overline{KE}(H) \approx 1 \text{ eV}.$$

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Printed in USA. Available from the National Technical
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