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PLASMA EFFECTS IN CESIUM CHARGE-EXCHANGE CELL FOR NEGATIVE ION PRODUCTION*

BY

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ABSTRACT

The generation of plasma in a cesium charge-exchange cell is analyzed and associated plasma effects discussed. For low beam current densities and $T_e \leq 0.5$ eV no problems should occur. For high beam current densities (>0.1 A/cm²), the process $D^- + Cs^+ \rightarrow D + Cs$ may become important. Methods for limiting the process are suggested.

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INTRODUCTION

One technique for producing negative ions (e.g. D^-) is to pass a low energy (0.5-5 keV) positive ion or atomic beam through a charge exchange cell of cesium or other low electron affinity vapors. In additions to the desired formation of negative ions, the beam will ionize some of the vapor producing a background plasma. The plasma can have a number of effects on the beam which we wish discuss. Among these are:

(a) Space charge neutralization and ambipolar potentials. The background plasma will adjust itself to neutralize the beam to the first approximation, thus cancelling the beam space charge. Ambipolar potentials will remain which will bend the beam trajectories, either focussing or defocussing the beam. Instabilities are possible, resulting in time dependent effects.

(b) Stripping

Collisions with the plasma particles will strip negative ions, reducing the negative beam fraction.

(c) Charge exchange

The process $D + Cs^+ \rightarrow D^0 + Cs^0$ has a large cross-section and will reduce the number of negative ions.

(d) Plasma effects on the charge-exchange medium.

The plasma production can reduce the vapor density, although probably not significantly unless electron temperatures become large enough to ionize. Excitation of the vapor by the plasma can change the electronic level for charge exchange, and thus the effective cross section.

The purpose of this note is to estimate the magnitude of these effects and to determine the conditions for them to become important. Our results will be specifically oriented towards a deuterium beam in a cesium cell.

THE PLASMA

Our system consists of a beam containing positive ions, neutrals, and negative ions, of a background of neutral and ionized cesium and deuterium, and of electrons. In the charge exchange cell cesium is much more plentiful and easier to ionize than deuterium gas which can thus be neglected. In addition, the charge exchange cross section for converting D^+ into D^0 is very large, ($\approx 9 \times 10^{-15} \text{ cm}^2$ at 1 keV), so the density D^+ in the beam is very low and can be neglected.

Even with the above approximations, there are a large number of possible collisional processes involving the beam (D^0 and D^-), cesium (Cs and Cs^+) and electrons; we neglect any Cs^- or multiply charged cesium. The processes which involve the transfer of a single charge are listed in Table 1; cross sections for multiple charge transfer are quite small.

Process (1) and (12) are the usual charge exchange processes which yield D^- beams; we take

$$J_{b-} = F J_{bo} \approx 0.32 J_{bo} \quad (1)$$

with

$$F = F_-^\infty / (1 - F_-^\infty).$$

The primary plasma loss mechanism is transport with loss rates which we can represent by n_+/τ_+ and n_e/τ_e . Because of their greater mobility electrons will be lost rapidly unless the ambipolar potential is positive. Consequently we have $n_e = n_0 \exp(\phi/T_e)$. The potential and associated electric field will adjust themselves so that $n_+ = n_e + n_{b-}$; the particle balance equations and this quasineutral condition will yield a relationship between τ_e and τ_+ .

Table 1. Change Changing Processes for D^+ and D^- beams

Process	Rate	Cross Section*	Effect on**			Comments	References
			electrons	Cs ⁺ Ions	Cesium D ⁻ Beam		
1. $D^+ + Cs \rightarrow D^- + Cs^+$	$J_{0,n_{Cs}^{(1)}}_{0,0}$	$4.0 \times 10^{-16} \text{ cm}^2$	0	+	+	Generates the D^- beam	1,2,3,4
2. $D^+ + Cs \rightarrow D^+ + Cs^+ + e$	$J_{0,n_{Cs}^{(2)}}_{0,0}$	(10^{-15} cm^2)	+	+	0	Assumed same order of magnitude as process (11)	6,7
3. $D^+ + Cs \rightarrow D^+ + Cs + e$	$J_{0,n_{Cs}^{(3)}}_{0,0}$	(10^{-17} cm^2)	+	0	0	Estimated from $D^+ + D_2$ cross section.	
4. $D^+ + Cs \rightarrow D^+ + Cs$	$J_{0,n_{Cs}^{(4)}}_{0,0}$	very small	0	0	0	Neglect	
5. $D^+ + Cs^+ \rightarrow D^- + Cs^{++}$	$J_{0,n_{Cs}^{(1)}}_{0,+}$	very small	0	-	+	Neglect	
6. $D^+ + Cs^+ \rightarrow D^+ + Cs^{++} + e$	$J_{0,n_{Cs}^{(2)}}_{0,+}$	very small	+	-	0	Neglect	
7. $D^+ + Cs^+ \rightarrow D^+ + Cs$	$J_{0,n_{Cs}^{(3)}}_{0,+}$	(10^{-15} cm^2)	0	-	0	The reverse process is very rapid and cancels this	
8. $D^+ + Cs^+ \rightarrow D^+ + Cs^+ + e$	$J_{0,n_{Cs}^{(4)}}_{0,+}$	(10^{-17} cm^2)	+	0	0	Cross section quite uncertain	4
9. $D^+ + e \rightarrow D^+ + 2e$	$J_{0,n_{e}^{(1)}}_{0,0}$	small	-	0	0	1 keV Beam and $T_e = 0.5 \text{ eV}$ are inadequate to ionize D^+ .	
10. $D^+ + e \rightarrow D^-$	$J_{0,n_{e}^{(2)}}_{0,0}$	extremely small	-	0	+	Requires photon emission or third body.	
11. $D^- + Cs \rightarrow D^- + Cs^+ + e$	$J_{-n_{Cs}^{(1)}}_{-,0}$	$1.8 \times 10^{-15} \text{ cm}^2$	+	+	0		
12. $D^- + Cs \rightarrow D^- + Cs + e$	$J_{-n_{Cs}^{(2)}}_{-,0}$	$7.5 \times 10^{-16} \text{ cm}^2$	+	0	-	$\sigma_{-0}^{(2)} = \sigma_{00}^{(1)} [(1-F_-^\infty)/F_-^\infty]$	
13. $D^- + Cs \rightarrow D^- + Cs^-$	$J_{-n_{Cs}^{(3)}}_{-,0}$	very small	0	0	-	Neglect	
14. $D^- + Cs^+ \rightarrow D^- + Cs^{++} + e$	$J_{-,n_{Cs}^{(1)}}_{-,+}$	very small	+	0	0	Neglect	4
15. $D^- + Cs^+ \rightarrow D^- + Cs$	$J_{-,n_{Cs}^{(2)}}_{-,+}$	$1.5 \times 10^{-14} \text{ cm}^2$	0	-	-	Limits $n(D^-)$ for large plasma densities	
16. $D^- + Cs^+ \rightarrow D^- + Cs^+ + e$	$J_{-,n_{Cs}^{(3)}}_{-,+}$	$(2 \times 10^{-15} \text{ cm}^2)$	+	0	-	Estimated from process (11)	
17. $D^- + e \rightarrow D^- + 2e$	$J_{-,n_{e}^{(1)}}_{-,0}$	$< 10^{-15} \text{ cm}^2$	+	0	-	Can be important at high beam energies or $T_e \geq 10 \text{ eV}$.	
18. $D^- + e \rightarrow D^{--}$	$J_{-,n_{e}^{(2)}}_{-,0}$	extremely small	-	0	-	D^{--} unstable	
19. $Cs + e \rightarrow Cs^+ + 2e$	$n_{Cs} n_{e} \langle \sigma v \rangle_e$	$\langle \sigma v \rangle_e = 2.3 \times 10^{-11} \text{ cm}^3/\text{sec}$	+	+	0	Ionization at $T_e = 0.5 \text{ eV}$. Very sensitive to T_e	9
20. $Cs + e \rightarrow Cs^-$	$\beta n_{Cs} n_e$	very small	-	0	0	Requires photon emission or third body	11
21. $Cs^+ + e \rightarrow Cs$	$\alpha_1 n_{Cs} n_e$	$1.7 \times 10^{-19} \text{ cm}^2$	-	-	0	Radiative Recombination at $T_e = .13 \text{ eV}$	
22. $Cs_2^+ + e \rightarrow 2Cs$	$\alpha n_{Cs_2^+} n_e$	$\alpha = 2 \times 10^{-8} \text{ cm}^3/\text{sec}$	-	0	0	Requires molecular cesium ions	10,11,12,13,14
23. $Cs^+ + e \rightarrow Cs^{++} + 2e$	$n_{Cs^+} n_{e} \langle \sigma_2 v \rangle_e$	very small	+	-	0	Threshold at electron energy = 25eV	15

*Beam Energy = 1 keV. Numbers in parenthesis are rough estimates

** - = destroys, 0 = no effect, + = creates.

If $n_+ \approx n_e \gg n_{b-}$, the behavior of the plasma will be almost independent of the beam space charge. We know that in such a case $1/\tau_+ \approx C/L$, with $C = \sqrt{eT_e/M_i} = 1.2 \times 10^5 \sqrt{T_e}$ cm/sec the speed of sound for Cs^+ , and L a typical scale length.

Beam convergence or divergence will be neglected in determining plasma conditions.

The equations for dn_+/dt , dn_e/dt , and dn_{b-}/dt are quadratic in the three densities. There are still so many processes that the general solutions are not very useful. We start, therefore, by assuming that processes involving background plasma particles are negligible; the results can then be used to determine the accuracy of the assumption.

In equilibrium, Eq. (1) holds. The equation for n_+ is

$$\frac{dn_+}{dt} = J_0 n_{Cs} [\sigma_{00}^{(1)} + \sigma_{00}^{(2)}] + J_- n_{Cs} \sigma_{-0}^{(1)} - \frac{n_+}{\tau_+} \quad (2)$$

where σ 's are defined in Table 1. Only processes (1) - (13) have been considered, and small effects neglected. Process (7) is cancelled by the rapid reversion $D^+ + Cs \rightarrow D^0 + Cs^+$.

In equilibrium

$$n_+ = J_0 n_{Cs} \tau_+ \left[\sigma_{00}^{(1)} + \sigma_{00}^{(2)} + F \sigma_{-0}^{(1)} \right] \quad (3a)$$

$$= \frac{J_0 n_{Cs} L}{C} \left[\sigma_{00}^{(1)} + \sigma_{00}^{(2)} + F \sigma_{-0}^{(1)} \right] \quad (3b)$$

if $n_+ \gg n_{b-}$. Consider an example: $eJ_0 = 0.01$ A/cm², $L = 5$ cm, and $T_e = 1$ eV so $C = 1.2 \times 10^5$ cm/sec. The cross sections in Table 1 yield $n_+ = 260 n_{b-} = 5.2 \times 10^{11}$ cm⁻³ at a beam energy of 1 keV, so the assumption that $n_+ \gg n_{b-}$ is valid. As discussed above τ_e will adjust so that $n_e = n_+$.

Process (15), charge exchange on the background ions, effect n_+ by a relative amount of

$$\frac{F n_{+\sigma-+}^{(2)}}{n_{Cs} [\sigma_{00}^{(1)} + \sigma_{00}^{(2)} + F \sigma_{-0}^{(1)}]} = 1.2 \times 10^{-2} \quad (4a)$$

The relative effect on the negative beam is

$$\frac{n_{+\sigma-+}^{(2)}}{n_{Cs} \sigma_{-0}^{(2)}} = 5.4 \times 10^{-2} \quad (4b)$$

This process is thus unimportant for the assumed parameters. However, if higher plasma densities are obtained, e.g. due to $J_0 \geq 0.1 \text{ A/cm}^2$, charge exchange on cesium ions could become significant. The other processes among (14)-(18) are relatively negligible.

Ionization by electrons, process (19), is unfortunately very sensitive to T_e . At $T_e = 0.5 \text{ eV}$ it compares with the loss rate as

$$n_{Cs} L \langle \sigma v \rangle_e / C = 0.14$$

For $T_e \geq 0.6 \text{ eV}$, ionization becomes greater than the loss rate and, in the absence of other nonlinearities the plasma density will "exponentiate" until the cesium is "burned-out." Measurements in the lab suggest $T_e < 0.5 \text{ eV}$, but they are difficult to obtain to adequate accuracy. In addition, one anticipates that radiation and ionization losses will clamp electron temperature to very low values. Never-the-less, an accurate estimate of the energy balance is very difficult to obtain, so that it is difficult to be certain of the importance of electron ionization.

Processes (20), (21), and (23) are negligible. If the cesium ions were predominately Cs_2^+ , dissociative recombination, process (22), could be significant. Estimates in Appendix A indicate, however, that there is negligible Cs_2^+ present.

The processes which are important, therefore, are (1), (2), (11), (12), (15), and (19). To obtain the full equations for the cesium ion density and the negative beam density, set $n_e = n_+$, and define

$\sigma_+ = \sigma_{00}^{(1)} + \sigma_{00}^{(2)} \approx 1.4 \times 10^{-15} \text{ cm}^2$. Then, if $J_b = J_0 + J_-$,

$$\begin{aligned} \frac{dn_+}{dt} = & J_b n_{Cs} \sigma_+ - J_- n_{Cs} [\sigma_+ - \sigma_{-0}^{(1)}] \\ & - n_+ \left[\frac{1}{\tau_+} + n_{Cs} \langle \sigma v \rangle_e \right] - J_- n_+ \sigma_{-+}^{(2)} \end{aligned} \quad (5)$$

and

$$\frac{dJ_-}{dt} = n_{Cs} \sigma_{00}^{(1)} v_b [J_b - (1+F)J_-] - J_- n_+ \sigma_{-+}^{(2)} \quad (6)$$

In (6) we have used $\sigma_{00}^{(2)} = F\sigma_{00}^{(1)}$. It is interesting that to the accuracy of our knowledge $\sigma_+ \approx \sigma_{-0}^{(1)}$, so that the second term on the right side of Eq. (5) should be neglected.

If we define $n_+ = x$ and $J_- = y$, and neglect the second term in Eq. (5), these equations have the form

$$\frac{dx}{dt} = A - ax - bxy$$

$$\frac{dy}{dt} = B - cy - bxy$$

with all coefficients > 0 except (possibly) "a" if T_e is large. These have a classic nonlinear form which in principle can exhibit unlimited growth (until n_{Cs} is effected) or nonlinear oscillation. However, the nonlinear terms act to reduce x and y , so the equations will obviously be well behaved for $a > 0$.

To consider the nature of the equilibrium, note that the solutions x_0 and y_0 satisfy:

$$A - ax_0 - bx_0 y_0 = 0$$

and

$$B - cy_0 - bx_0 y_0 = 0$$

Let $x = x_0 + \delta x e^{st}$ and $y = y_0 + \delta y e^{st}$. Algebra yields

$$s = -\frac{1}{2} \left(\frac{A}{x_0} + \frac{B}{y_0} \right) \pm \sqrt{\frac{1}{4} \left(\frac{A}{x_0} - \frac{B}{y_0} \right)^2 + b^2 x_0 y_0}$$

As s is real there are no small scale oscillations about x_0, y_0 . However, if $s > 0$ the equilibrium is unstable and either unlimited ionization (until n_{Cs} is reduced) or a relaxation oscillation will occur. This will happen if

$$b^2 x_0^2 y_0^2 > AB.$$

To see the mechanism, suppose that electron ionization is so much stronger than ionization by the beam that we can set $A=0$. Then $dn_+/dt = 0$ when $y_0 = (-a)/b$, that is, when the beam density, n_{b-} , generates enough recombination with n_+ . However, a small decrease in n_{b-} will reduce recombination, which in turn permits n_+ to increase thus decreasing n_{b-} , etc.

To go further, the model must be improved by adding additional nonlinearity, such as the decrease in n_{Cs} . However, if that happens the charge exchange cell will cease to operate. Furthermore, the analysis would not be realistic in the absence of a good theory for T_e .

We conclude this part of the analysis, therefore, by noting that if an electron temperature much above 0.5 eV is generated the cesium will become highly ionized and the densities may become time dependent. In any event the charge exchange cell will cease to operate effectively.

PLASMA EFFECTS

We can now return to the effects discussed in the introduction.

(a) Space charge neutralization and ambipolar potentials

As the plasma density is large compared with the beam density, the radial electric field is $\sim T_e/L$. The cell length roughly equals the transverse dimensions, so the beam is bent thru an angle of order $T_e/E_b \leq 10^{-3}$ radian. Thus, in the absence of "anomalous" mechanisms the space charge potentials should not significantly effect the beam trajectories.

(b) Stripping

The discussion of plasma generation included stripping, which was shown to be unimportant as long as electron ionization of plasma was negligible

(c) Charge Exchange

For total beam currents $> 0.1 \text{ A/cm}^2$, the production of Cs^+ may be strong enough to limit beam current by the process $\text{D}^- + \text{Cs}^+ \rightarrow \text{D}^0 + \text{Cs}$.

(d) Effects on the Charge-exchange medium

Effects on the vapor density should be negligible. Post¹⁶, however, has pointed out that as the energy of the first excited state of cesium is $E_{\text{ex}} = 2.44 \text{ eV}$ below ionization (the ground state is $E_0 = 3.89 \text{ eV}$), the cross section for $\text{D} + \text{Cs}^* \rightarrow \text{D}^- + \text{Cs}^+$ should be $\approx (3.89 + .75)/(2.44 + .75) = 1.9$ larger than for unexcited cesium. (Here 0.75 eV is the D^- binding energy.) Thus, if there is a large density of excited cesium the production of D^- could be enhanced.

We can make a rough estimate of the excited state density, in which excitation is balanced by radiative decay. Thus, scaling excitation to ionization we estimate

$$\frac{n_{\text{Cs}^*}}{n_{\text{Cs}}} \sim n_e \langle \sigma v \rangle_{\text{ioniz}} \tau_{\text{decay}} e^{-E_{\text{ex}}/kT_e} e^{-E_0/kT_e}$$

Because the state is resonant, $\tau_{\text{decay}} \leq L^2/C\ell$, with ℓ the mean-free-path for the light in the cesium vapor. The absorption length¹⁷ is about $1.3 \times 10^{12}/n_{\text{Cs}}$ so that $\tau_{\text{decay}} = L^2 n_{\text{Cs}} / 1.3 \times 10^{12} C$ and

$$\begin{aligned} \frac{n_{\text{Cs}^*}}{n_{\text{Cs}}} &\sim \frac{L^2 n_{\text{Cs}} n_e \langle \sigma v \rangle_{\text{ioniz}}}{1.3 \times 10^{12} C} e^{-E_{\text{ex}}/kT_e} e^{-E_0/kT_e} \\ &\approx 1 \times 10^{-5} \text{ at } T_e = 0.5 \text{ eV.} \end{aligned}$$

We conclude that the contribution to D^- formation from charge-exchange on excited states is negligible.

CONCLUSION

It follows from the above analyses that the effect of plasma in a cesium charge-exchange cell is negligible unless $T_e > 0.5$ eV. An energy analysis was not performed, but radiation from excited states, ionization, and energy transport to walls will probably maintain $T_e < 0.5$ eV. Experimental observations, although not definitive, support this conclusion.

If beam currents become of order 0.1 A/cm^2 , however, the negative ion destroying process $D^- + Cs^+ \rightarrow D + Cs$ will become important; from Eq. (14b) we estimate that $(n_{+}\sigma_{-+}^{(2)})/(n_{Cs}\sigma_{-0}^{(2)}) \approx 0.54$. Thus, at high current densities in the cesium cell it will be necessary to take active steps to destroy Cs^+ . Possibilities include the use of geometry to minimize transport distances to walls or the use of some impurity which would generate a large recombination coefficient for Cs^+ . In addition, recent measurements of the D^- formation cross-section¹⁹ indicate that it increases as the beam energy is lowered to 0.5 keV. The cesium plasma density will decrease at lower beam energies, thus reducing the magnitude of the problem. Because of the uncertainties in the present estimates measurements will be required to determine when the Cs^+ density becomes large enough to be important.

APPENDIX A. Cs_2^+ density

The primary mechanism for forming Cs_2^+ ions is $\text{Cs}^+ + 2\text{Cs} \rightarrow \text{Cs}_2^+ + \text{Cs}$.

The rate equation is thus

$$\frac{dn_{\text{Cs}_2^+}}{dt} = K C_a n_{\text{Cs}}^2 - \frac{C_2 n_{\text{Cs}_2^+}}{L}$$

where C_a is the cesium atomic velocity and C_2 that of the Cs_2^+ . Loeb¹⁷ estimates $K \approx 7 \times 10^{-33} \text{ cm}^5$. In equilibrium

$$\frac{n_{\text{Cs}_2^+}}{n_{\text{Cs}}^+} = \left(L \frac{C_a}{C_2} \right) (K n_{\text{Cs}}^2)$$

The term $L C_a / C_2$ is $\lesssim 10 \text{ cm}$. At $n_{\text{Cs}} = 2 \times 10^{14} \text{ cm}^{-3}$, $n_{\text{Cs}_2^+} / n_{\text{Cs}}^+ \lesssim 3 \times 10^{-4}$.

We conclude that molecular ions may be neglected.

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