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Hydrogen Neutral Fraction Determination in Polystyrene and Li Ablation Clouds for Pellet Charge Exchange Diagnostics of Fusion Plasmas

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The application of a diagnostic based on the pellet charge exchange (PCX) method using a compact neutral particle analyzer (CNPA) on Large Helical Device (LHD) for measurements of energy resolved neutral hydrogen fluxes from a polystyrene -$(C_8H_8)_n$- pellet ablation cloud was recently reported [1]. The estimation of the local distribution function $f_i(E)$ of fast protons entering the cloud using measured escaping atom energy spectra requires knowledge of both the fraction $F_0(E)$ of incident protons exiting the cloud as neutral atoms and the absorption depth $\tau(E,\rho)$ describing the loss of fast atoms in the plasma on their path from the cloud to CNPA [2].

Consider a monoenergetic flux $\Gamma_1(x,E)\big|_{x=0}$ [cm^{-2}s^{-1}] of fast protons H^+ of energy E entering the cold dense cloud surrounding an ablating solid pellet; x is the transversal distance across the cloud. The total hydrogen flux within the cloud will consist of H^0 and H^+ fractions $\Gamma_i(x,E) = F_i(x,E)\Gamma_1(0,E),\ i=0,\ 1$ due to the charge changing collisions with cloud particles. The conservation of the total number of hydrogen particles requires that the dimensionless non-negative functions $F_i(x,E),\ i=0,\ 1$ satisfy the condition $F_0(x,E) + F_1(x,E) = 1$. For the neutral fraction the boundary condition is $F_0(x,E)\big|_{x=0} = 0$. Densities $n_l(x)$ of the pellet cloud atomic and ionic species are expressed via the cloud density function $n_{\mathrm{cl}}(x)$ as $n_l(x) = \kappa_l n_{\mathrm{cl}}(x)$. The dimensionless non-negative proportionality coefficients κ_l obviously satisfy the condition $\sum_l \kappa_l = 1$. The electron density $n_e(x) = \kappa_e n_{\mathrm{cl}}(x)$ is obtained from the cloud plasma quasineutrality condition. Denote $\sigma_{1\to0}(E) = \sum_l \kappa_l \sigma_l^{1\to0}(E)$ the total effective cross-section of electron capture by H^+ and $\sigma_{0\to1}(E) = \sum_l \kappa_l \sigma_l^{0\to1}(E)$ the total effective cross-section of electron loss by H^0. The sums run over all possible electron capture and electron loss processes, respectively, and κ_l are the proportions of the corresponding target particles of the cloud. Let Ξ [cm^{-2}] be the line integral pellet ablation cloud density representing the number of target particles per cm^2 along the hydrogen path within the cloud: $\Xi(x) = \int_0^x n_{\mathrm{cl}}(\tilde{x})d\tilde{x}$. The rate equations $\dfrac{dF_0}{d\Xi} = \sigma_{1\to0}F_1 - \sigma_{0\to1}F_0$ and $\dfrac{dF_1}{d\Xi} = \sigma_{0\to1}F_0 - \sigma_{1\to0}F_1$ were solved in general form in [3]. The neutral fraction is $F_0(x,E) = F_0^\infty(E)\left(1 - e^{-(\sigma_{0\to1}(E)+\sigma_{1\to0}(E))\Xi(x)}\right) \xrightarrow{\Xi(x)\to\infty} F_0^\infty(E)$, where $F_0^\infty(E) = \sigma_{1\to0}(E)\big/\left(\sigma_{0\to1}(E)+\sigma_{1\to0}(E)\right)$ is the equilibrium value attained after a sufficient number of collisions. Thus, the proportions κ_l of cloud species and the cross-sections of relevant charge changing collision processes are needed to calculate the neutral fraction.

Four types of elementary processes, viz., charge exchange, ion impact ionization, electron impact ionization and neutral atom impact ionization, are listed below for two pellet materials.

$-(C_8H_8)_n-$ pellet cloud		Li pellet cloud	
Electron capture processes contributing to $\sigma_{1\to0}$			
$\underline{H}^+ + C^{q+} \to \underline{H}^0 + C^{(q+1)+}$, q = 0, …, 5	(1)	$\underline{H}^+ + Li^{q+} \to \underline{H}^0 + Li^{(q+1)+}$, q = 0, 1, 2	(9)
$\underline{H}^+ + H^0 \to \underline{H}^0 + H^+$	(2)		
Electron loss processes contributing to $\sigma_{0\to1}$			
$\underline{H}^0 + C^{q+} \to \underline{H}^+ + C^{(q-1)+}$, q = 1, …, 6	(3)	$\underline{H}^0 + Li^{q+} \to \underline{H}^+ + Li^{(q-1)+}$, q = 1, 2, 3	(10)
$\underline{H}^0 + C^{q+} \to \underline{H}^+ + C^{q+} + e^-$, q = 0, …, 6	(4)	$\underline{H}^0 + Li^{q+} \to \underline{H}^+ + Li^{q+} + e^-$, q = 0, 1, 2, 3	(11)
$\underline{H}^0 + H^+ \to \underline{H}^+ + H^0$	(5)	$\underline{H}^0 + e^- \to \underline{H}^+ + e^- + e^-$	(12)
$\underline{H}^0 + H^+ \to \underline{H}^+ + H^+ + e^-$	(6)		
$\underline{H}^0 + H^0 \to \underline{H}^+ + H^0 + e^-$	(7)	(fast hydrogen particles originating as	
$\underline{H}^0 + e^- \to \underline{H}^+ + e^- + e^-$	(8)	suprathermal ions from plasma are underlined)	

This is a more complete scheme of atomic collision processes than that used in [1, 2] for the polystyrene cloud. In particular, the ionization of hydrogen atoms by C^{q+} ions has been taken into account, determining the high energy behaviour of $F_0(E)$. The simpler chemical and charge state composition of Li cloud with respect to that of polystyrene should be noted.

The experimental and theoretical data on reaction (1) for q = 0 is summarized in [4]; for q = 4 the experimental cross-section above 100 keV/a.m.u. may be found in [5]. For q = 5 theoretical estimations above 100 keV/a.m.u. are available [6, 7]. The required unknown cross-sections of (1) for q = 1, …, 5 in the energy range 1 keV/a.m.u – 1 MeV/a.m.u. have been calculated using the numerical codes ARSENY [8], CAPTURE [9], and continuum distorted wave (CDW) method [10-12]. The first order Coulomb-Born (CB1) approximation from [7] was also used for q = 5. For the intermediate energies a smooth interpolation has been used to join the calculated cross-section results.

The cross-sections of (2) and the inverse process (5), as well as (6), and the identical processes (8) and (12) were taken from [13]. The charge exchange (3) cross-sections were taken from [14]. They were corrected and extended to cover a broader energy range using the more recent source [15]. For the ion impact ionization (4) the data from [14] was used. It has been corrected and extended to lower energies using the well established scaling laws [16, 17]. For the cross-section of (7) an analytic formula has been used based on [18-20].

Among the processes involving Li ions, the cross-section of (9) for q = 0 may be found in [21]; for q = 1, 2 the cross-section has been calculated by the numerical code ARSENY [8] below 50 keV/a.m.u. and by CAPTURE [9] for higher energies. A smooth uniform polynomial approximation has been used to represent these two cross-sections. For the cross-sections of charge exchange processes (10) experimental data from [22, 23] and theoretical calculations [24] were used. The ion impact ionization (11) is thoroughly described in [25] for q = 3; for q = 1, 2 the cross-section has been calculated by the LOSS numerical code [26]. Finally, the neutral atom impact ionization cross-sections (4) and (11) for q = 0 were evaluated by using the Bohr model.

The resulting equilibrium neutral fractions are shown in Fig. 1 for different charge state distributions of the cloud ions. The presence of higher charge states tends to cause a nearly uniform decrease in $F_0^\infty(E)$ and does not alter the shape of the curve drastically. This resembles the helium neutral fraction behaviour in a Li cloud studied in [27].

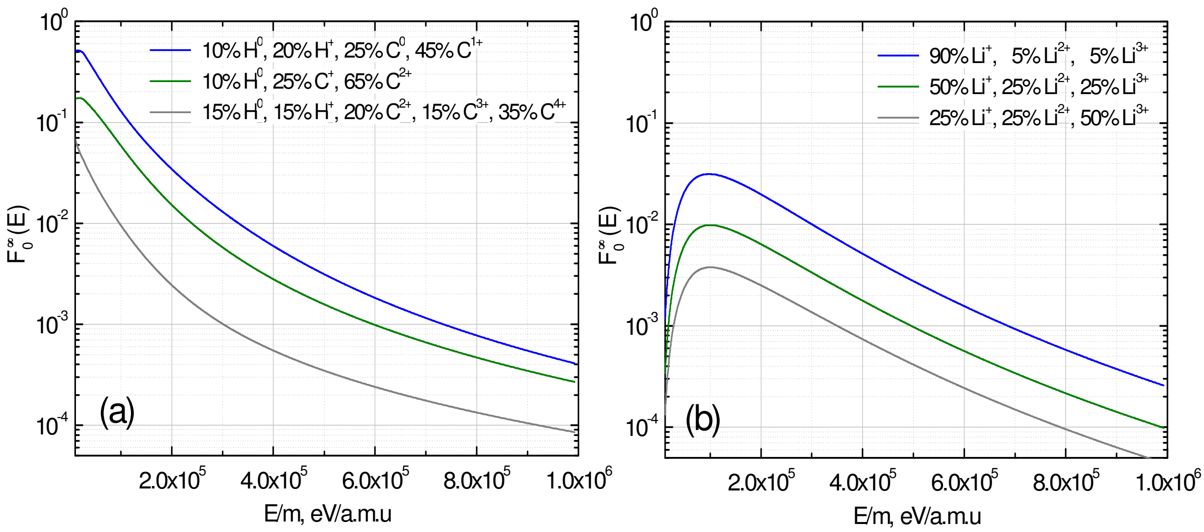

Fig. 1. Equilibrium neutral hydrogen fraction in -(C_8H_8)$_n$- (a) and Li (b) pellet clouds for different cloud ion abundances.

The determination of $\tau(E,\rho)$ includes an accurate calculation of the total stopping cross section σ_{loss} of escaping H^0 [28] and the Jacobian $Q^-(\rho)$ reflecting the measurement geometry [29]. Fig. 2 illustrates the attenuation factor calculated for plasma Z_{eff} = 1.5 for H^0 fluxes originating from different radial locations:

$$A(E,\rho) = \exp\left(\int_\rho^1 n_e(\tilde{\rho})\sigma_{loss}(E,\tilde{\rho})\,Q^-(\tilde{\rho})d\tilde{\rho}\right).$$

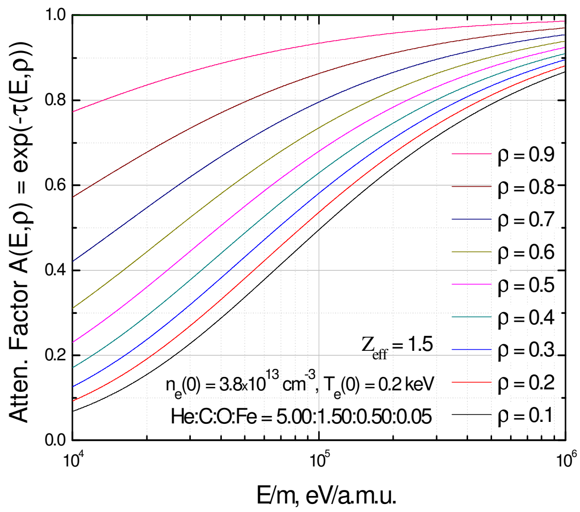

Fig. 2. Neutral hydrogen flux attenuation factor in plasma.

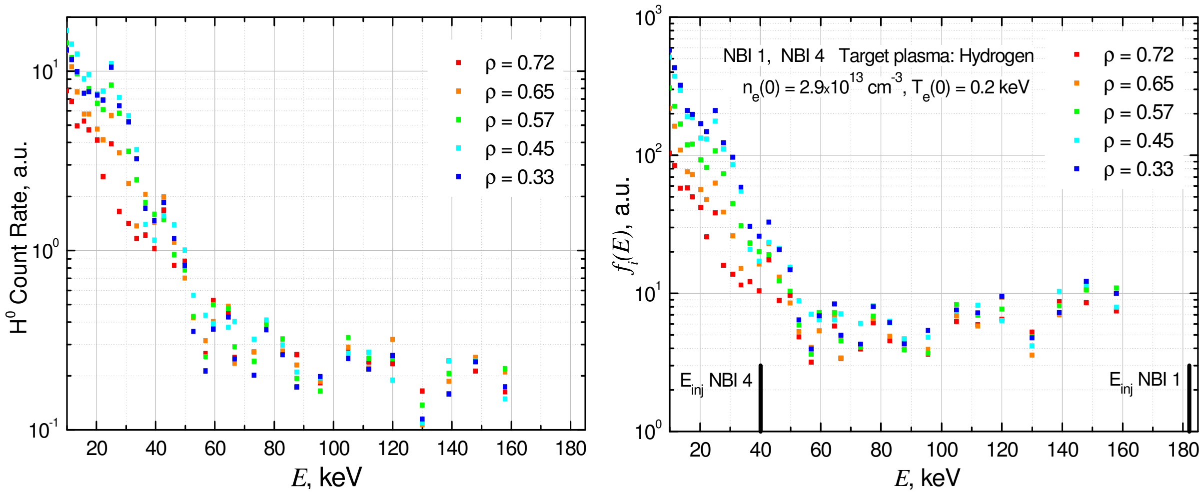

Fig. 3. PCX neutral particle spectra (left) measured by CNPA at LHD R_{ax} = 3.60 m and reconstructed radially resolved tangential and perpendicular NBI- induced proton energy distributions (right).

The obtained functions $F_0^{\infty}(E)$ and $A(E,\rho)$ represent, respectively, the classical probability of an incident proton "neutralization" in the pellet cloud and the Poisson exponent giving the resulting H^0 atom "survival" probability. These probablities enter multiplicatively into the probablity density function for PCX neutral particle kinetic energy. Thus, the developed scheme is to be applied for the calculation of $f_i(E)$. Fig. 3 shows $f_i(E)$ reconstruction from CNPA data measured in PCX experiments on LHD from high collisionality $NBI_{\parallel}$ and $NBI_{\perp}$ heated hydrogen plasma.

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