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Diagnostics of Charge Exchange Neutrals from Multi-Ion-Species NBI-Heated Plasmas on LHD

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Abstract

Fast ion kinetics and thermalization in neutral hydrogen beam heated hydrogen and noble gas target plasmas are studied on LHD heliotron by passive multi-chord and active radially scanning diagnostics of charge exchange (CX) neutral particles. In the passive method the natural creation of fast atoms within the plasma and their coming out to the periphery depend on the overall neutral balance. In active measurements the ionization / neutralization balance in an impurity pellet cloud is essential. The application of the relevant atomic elementary process data to the analysis of NPA measurements is described. The effect of the target plasma ion composition on pitch angle scattering intensity observed on energetic ion spectra is discussed.

Keywords:

charge exchange, pellet charge exchange, multi-component plasma, neutral particle analysis, fast ion distribution, particle beam, plasma heating, heliotron, Large Helical Device (LHD)

1. Introduction

The formation and evolution of suprathermal ion distribution function tail under the influence of the tangential hydrogen neutral beam injection (NBI) is studied on LHD by the neutral particle analysis (NPA) technique. The multidirectional passive analyzer [1] and active pellet charge exchange (PCX) diagnostics [2,3] are used. In this paper the emphasis is put on the application of the relevant atomic elementary process data to the analysis of these NPA measurements.

Calculating the fast ion distribution function from the energy resolved naturally occurring charge-exchange neutral particle flux requires the accurate modeling of the measured quantity [4], which assumes the knowledge of the type, density, and radial profiles of the charge-exchange centers.

In local PCX measurements a solid impurity pellet is injected in order to create an artificial localized target for the enhanced charge exchange process in the plasma. To obtain the local ion distribution function from the measured charge exchange atomic flux originating from the pellet cloud, one needs to know the energy dependent neutralization ratio for the fast ions entering the cloud. This is governed by the neutralization / ionization balance equations in the cloud [5].

The next section describes the elementary processes indispensable for the passive NPA data analysis in case of multi-component plasmas. Then, polystyrene pellet charge exchange measurements are considered and finally, the application of the CX cross-section data to the studies of Z_{eff} influence on fast ion spectra is discussed.

2. Interpretation of passive neutral fluxes

The formation of the flux of neutral atoms from a quasistationary plasma column and the attenuation of this flux on the way out to the periphery are determined by the three groups of elementary atomic processes, *viz.* charge exchange, recombination and ionization. The charge exchange process is of primal importance for calculating both the local source function of atoms in the plasma and the loss of atoms along the observation direction.

H^+ CX cross-sections [6] on He^0 and He^+ shown in Fig. 1 need to be taken into account in calculations of fast proton distributions resulting from neutral hydrogen beam injection into helium plasma. In studies of high-energy proton distributions in multi-species plasmas including Ne and Ar components the charge capture cross-sections by protons from the atoms and ions of these noble gases are required: $H^+ + Ne^{k+} \rightarrow H^0 +$

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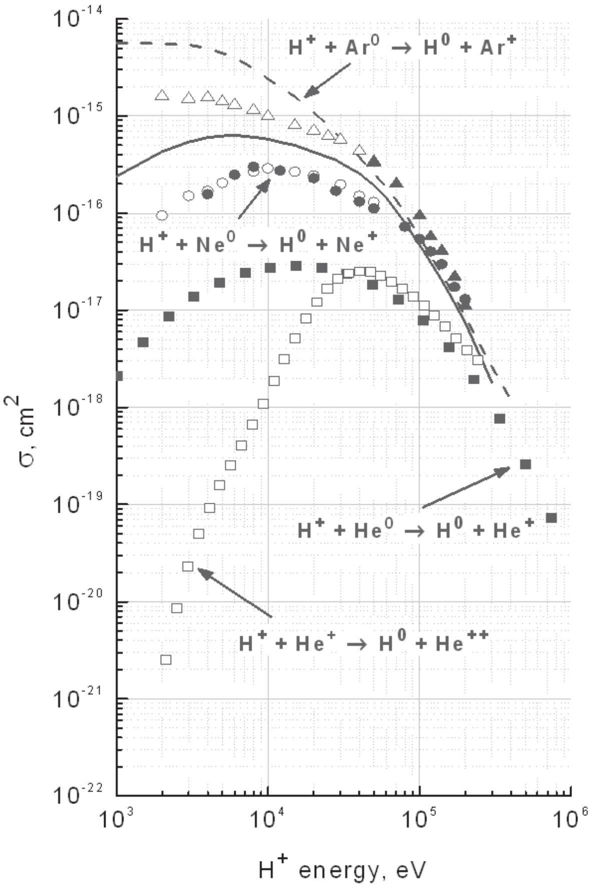

Fig. 1 Lower: experimental cross-sections of electron capture by H^+ from He^0 (solid squares) and from He^+ (open squares) [6]; middle: experimental (open and solid circles) [13,14] and theoretical (solid line) [7,8] H^+/Ne^0 CX cross-sections; upper: experimental (open and solid triangles) [13,14] and theoretical (dashed line) [7,8] H^+/Ar^0 CX cross-sections.

$Ne^{(k+1)+}$ and $H^+ + Ar^{l+} \rightarrow H^0 + Ar^{(l+1)+}$. The experimental data on these cross-sections is not abundant. However, various theoretical estimations exist, among which historically the first one is the approximation suggested by Oppenheimer, Brinkman and Kramers based on the quantum perturbation theory. This so-called OBK approximation, *e.g.* monograph [7], allows one to obtain an analytic expression for the charge transfer probability amplitude. More profound theoretical models and scaling laws exist, *e.g.* [8,9].

The authors of [10] propose a treatment of the charge state distribution in neon plasma involving their upgraded code [11]. When fast ion distributions are of interest, it is enough to know the high energy behaviour of the charge exchange cross-sections for σE-correction of the neutral particle energy spectra, while the absolute values of the cross-sections are not required. The asymptotics of the charge capture cross-sections at high energies is thoroughly discussed in [12].

As an example of the analytical and empirical behaviour at typical suprathermal energies, Fig. 1 illustrates the experimental H^+/Ne^0 and H^+/Ar^0 CX cross-sections [13,14] shown by circles in comparison with Gryzinski's theoretical model estimations [7,8] shown by solid curves.

3. Pellet charge exchange

In order to calculate the local ion distribution function from the time and energy resolved atomic flux $\Gamma^{(PCX)}(E, \boldsymbol{r}(t))$, besides the knowledge of the geometry of experiments, one needs to have the information about the energy dependent dimensionless factor $F_0(E)$ [2]. This factor determines the fraction of particles that enter the pellet ablation cloud as ions and exit as neutral atoms.

As it was shown in [15] and [5],

$$F_0(E) = 1/(1 + \sigma_{0\rightarrow 1}/\sigma_{1\rightarrow 0}),$$

where $\sigma_{1\rightarrow 0}$ and $\sigma_{0\rightarrow 1}$ are hydrogen neutralization and ionization cross-sections in the cloud respectively.

Figure 2 shows $F_0(E)$ calculated in [5] for a polystyrene $(-C_8H_8-)_n$ pellet ablation cloud. The cloud was assumed to consist of 25 % C^{1+}, 25 % C^{2+} and 50 % H^0. The relevant elementary atomic processes involving carbon in this case are as follows:

$$H^+ + C^{1+} \rightarrow H^0 + C^{2+};$$

$$H^+ + C^{2+} \rightarrow H^0 + C^{3+};$$

$$H^0 + C^{1+} \rightarrow H^+ + C^0;$$

$$H^0 + C^{2+} \rightarrow H^+ + C^{1+}.$$

The possible recombination processes and the electron impact ionization processes are neglected. The cross-sections of hydrogen ionization by charge exchange with C^{1+} and C^{2+} ions are given in [16]. The H^+/H^0 CX cross-section is very well known. The cross-sections of the electron capture by protons from C^{1+}

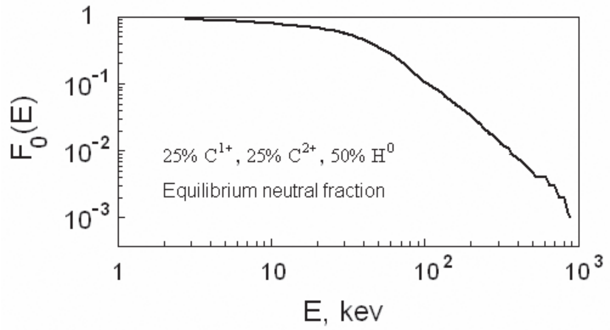

Fig. 2 Estimation of the equilibrium neutral fraction energy dependence for a polystyrene $(-C_8H_8-)_n$ pellet ablation cloud [5].

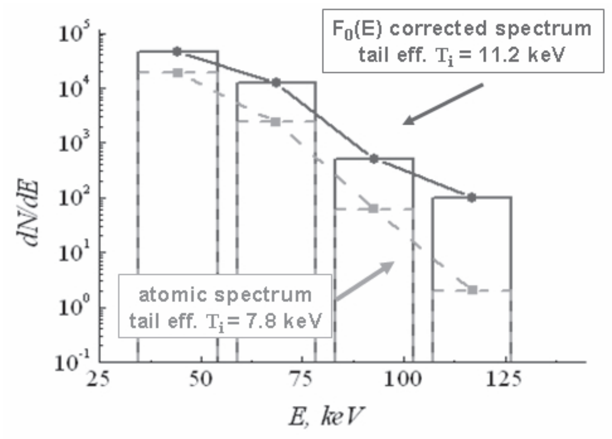

Fig. 3 Orthogonally measured PCX spectrum obtained by digital processing of natural diamond detector signals [3]. Target plasma $R_{ax} = 3.53$ m, $\beta = 0.20$ %, $B = 2.856$ T, $n_e = 1.5 \times 10^{13}$ cm^{-3}, tangential NBI heating (175 keV, 4 MW NBI #1, 150 keV, 1 MW NBI #2).

and C^{2+} ions were calculated in [5] using Oppenheimer-Brinkman-Kramers scaling not applicable at lower energies $E < 10$ keV.

Figure 3 shows both raw and $F_0(E)$ corrected PCX pitch angle scattered particle spectra measured orthogonally from tangential NBI heated hydrogen plasma [3].

4. CX spectra from multi-species plasmas

The influence of the target plasma Z_{eff} on the intensity of the pitch angle scattering of NBI-produced fast ions has been studied. A substantial enhancement of the pitch angle scattering of fast ions from tangential NBI has been observed for plasmas with higher Z ion species in comparison with hydrogen plasma. The asymptotic behaviour of H^+/Ne^{k+} and H^+/Ar^{l+} charge exchange cross-sections at high energies [7] was used for σE-correction of the measured neutral particle spectra.

Figure 4 shows the energetic proton distributions along three viewing directions from $n_e = 0.4 \times 10^{13}$ cm^{-3}, central $T_e = 2$ keV target plasmas. Fig. 4 (a) refers to 131 keV hydrogen NBI into hydrogen ($Z = 1$) plasma; Fig. 4 (b) 132 keV hydrogen NBI into neon ($Z = 10$) plasma and in Fig. 4 (c) 135 keV hydrogen NBI into Ar ($Z = 18$) / He ($Z = 2$) mixture plasma.

Figure 5 shows the corresponding contour plots of H^+ energy and pitch angle distributions in the axes $E_\perp, E_\parallel$ for these three target plasma ion compositions respectively. The sectorial gaps are due to the fact that the measurements are made along several discrete directions [1]. It can be seen that the angular diffusion of energetic protons is very sensitive to the background plasma ion composition in similar discharges. The in-

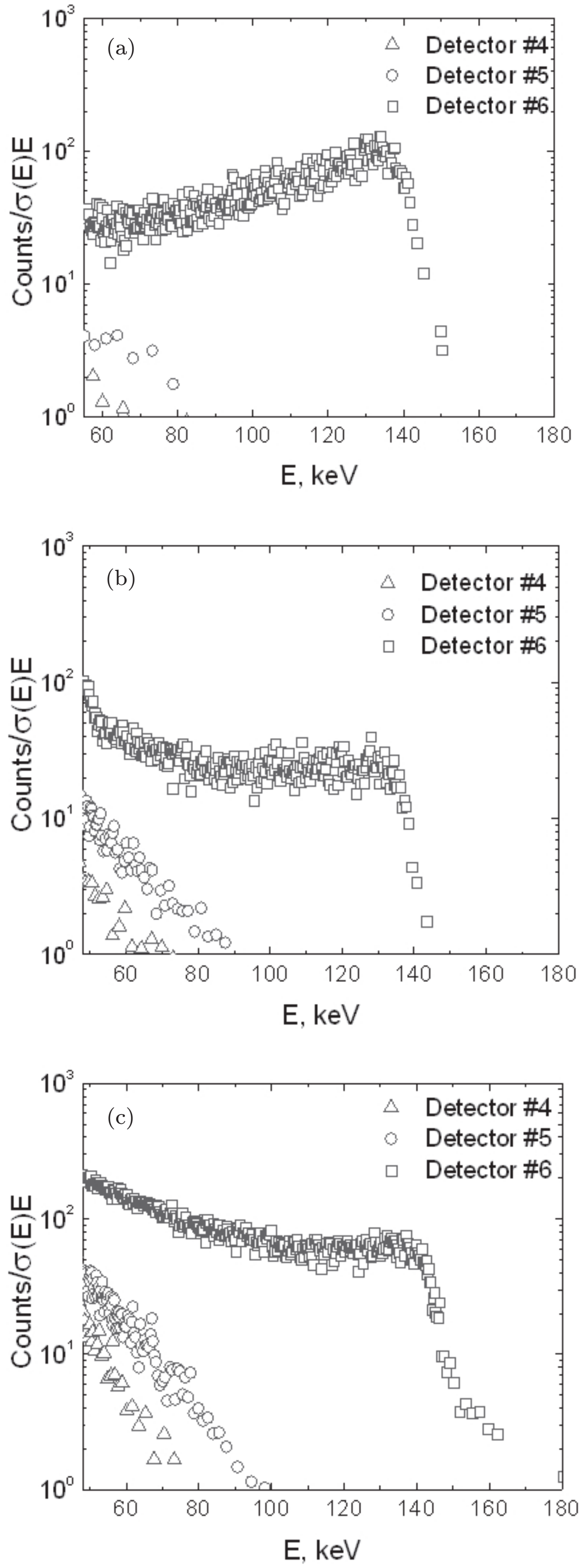

Fig. 4 H^+ energy distributions $f(E, \theta)$ along three directions from H, Ne and Ar / He target plasmas.

terpretation is that the Legendre operator describing the angular spread on the right hand side of the Fokker-Planck equation contains the term proportional to Z_{eff}, which is responsible for the ion contribution to the pitch

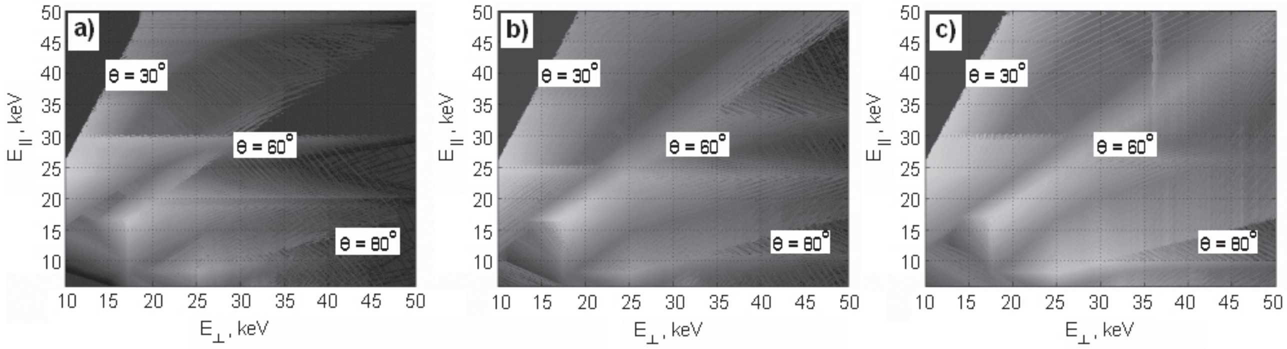

Fig. 5 Contour plots of the H^+ energy distributions $f(E_{\perp}, E_{||})$ from H, Ne and Ar / He target plasmas.

angle scattering. The value $Z_{eff} = \frac{1}{n_e}\sum_i Z_i^2 n_i$ strongly depends on the target plasma ion species.

5. Summary

The analysis of neutral particle measurements from multi-ion-species plasmas requires the the overall neutral balance modeling and reliable experimental data on the charge exchange cross-sections. However, in studies of suprathermal distribution tails it is enough to know the asymptotic behaviour of the cross-sections at high energies.

Active charge exchange measurements with impurity pellets require the knowledge of the cloud charge state composition and the relevant cross-sections.

The enhancement of the pitch angle scattering of beam ions in plasmas with higher effective charge has been observed and interpreted in terms of Fokker-Planck equation for energetic ions.

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