§22. Calculation of Low-Z Impurity Pellet Induced Charge Exchange Neutral Particle Fluxes

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The highest priority task in nuclear fusion reactor physics is to obtain an experimentally proven description of the local ion distribution function and its temporal evolution. This information would then serve as a basis for fusion reaction rate calculation and all subsequent physical and engineering issues, such as reactor power, plasma evolution towards ignition, estimation of neutron fluxes, etc.

In the local active diagnostic method, referred to as Pellet Charge eXchange (PCX), an ablating solid impurity pellet cloud is used as a dense target for electron capture by fast ions. Energy- and time-resolved measurements of the resulting neutral hydrogen and helium fluxes can be used to study local fast ion energy distributions in the plasma.

The estimation of the local distribution function $f_i(E)$ of fast ions entering the cloud requires knowledge of both the fraction $F_0(E)$ of incident ions exiting the cloud as neutral atoms and the attenuation factor $A(E,\rho)$ describing the loss of fast atoms in the plasma. These functions enter multiplicatively into the probability density for escaping neutral particle kinetic energy. A general calculation scheme has been developed and realized as a FORTRAN code, which is to be applied for the calculation of $f_i(E)$ from PCX experimental results obtained with low-Z impurity pellets.

Proportions of cloud species and the knowledge of cross-sections of relevant charge changing atomic collision processes in a wide energy range are needed to calculate the neutral fraction. The equilibrium neutral hydrogen fraction [1] attained after a sufficiently large number of collisions is

$$F_0^\infty(E) = \sigma_{1\to0}(E) \big/ \left(\sigma_{0\to1}(E) + \sigma_{1\to0}(E)\right), \qquad (1)$$

where $\sigma_{1\to0}(E)$ and $\sigma_{0\to1}(E)$ are the total effective cross-section of electron capture by H^+ and the total effective cross-section of electron loss by H^0 correspondingly. Neutral helium fraction can be calculated in an analogous way by solving the corresponding electron capture and electron loss rate equations as shown in [1].

One-electron charge exchange and ion impact ionization reactions for hydrogen are as follows.

$$H^+ + A^{q+} \to H^0 + A^{(q+1)+}, \quad q = 0,\ldots,(Z-1)$$
$$H^0 + A^{q+} \to H^+ + A^{(q-1)+}, \quad q = 1,\ldots,Z$$
$$H^0 + A^{q+} \to H^+ + A^{q+} + e^-, \quad q = 1,\ldots,Z$$

In case of helium particle measurements one-electron charge exchange and ion impact ionization reactions are

$$He^+ + A^{q+} \to He^0 + A^{(q+1)+}, \quad q = 0,\ldots,(Z-1)$$
$$He^{2+} + A^{q+} \to He^+ + A^{(q+1)+}, \quad q = 0,\ldots,(Z-1)$$
$$He^0 + A^{q+} \to He^+ + A^{(q-1)+}, \quad q = 1,\ldots,Z$$
$$He^+ + A^{q+} \to He^{2+} + A^{(q-1)+}, \quad q = 1,\ldots,Z$$
$$He^0 + A^{q+} \to He^+ + A^{q+} + e^-, \quad q = 1,\ldots,Z$$
$$He^+ + A^{q+} \to He^{2+} + A^{q+} + e^-, \quad q = 1,\ldots,Z$$

A designates the chemical symbol of the impurity and *Z* its nuclear charge number.

The corresponding cross-sections for Li, Be, B, C, and Ne impurities may be found in an extensive report [2, 3] consisting of two parts covering charge exchange and ion impact ionization respectively. Cross-section σ, [cm^2] as a function of specific energy $\mathcal{E} = E/m$ [keV/a.m.u.] is expressed for all reactions by the following formula

$$\sigma(\mathcal{E}) = \exp\left(\sum_{i=0}^{15} \alpha_i T_i(\xi)\right), \qquad (2)$$

where

$$\xi = 2\left(\frac{\ln\mathcal{E} - \ln\mathcal{E}_{\min}}{\ln\mathcal{E}_{\max} - \ln\mathcal{E}_{\min}}\right)^\gamma - 1 \qquad (3)$$

and $T_i(\xi)$ is the *i*th degree Chebyshev polynomial of the first kind. The 19 parameters required to calculate the cross-section for each reaction are $\mathcal{E}_{min}$ - lower limit of the approximating formula applicability range, $\mathcal{E}_{max}$ - upper limit of the approximating formula applicability range, γ - index of power in the nonlinear variable change formula and α_i - coefficients of $T_i(\xi)$.

The neutral flux attenuation in the plasma column enters multiplicatively in the form of Poisson exponent determined by $\lambda_{\rm mfp}(E, \rho)$, i.e. the local mean free path of a neutral atom with respect to all electron loss reactions $H^0 \to H^+$ or $He^0 \to He^+$, $He^0 \to He^{2+}$. From the practical viewpoint it can be calculated as

$$\lambda_{mfp}^{-1}(E,\rho) = n_e(\rho)\sigma_{loss}(E,\rho) \qquad (4)$$

using a suitable approximating formula for the total neutral hydrogen or helium stopping cross section $\sigma_{loss}(E,\rho)$ in magnetically confined plasma in the presence of certain impurity species. Practical formulas for hydrogen total stopping cross-section were developed in [4]. The determination of the attenuation factor $A(E,\rho)$ also includes an accurate calculation of the Jacobian $Q^-(\rho)$ reflecting the measurement geometry [5]. The ensuing formula is

$$A(E,\rho) = \exp\left(\int_\rho^1 n_e(\tilde\rho)\sigma_{loss}(E,\tilde\rho)\, Q^-(\tilde\rho)\, d\tilde\rho\right). \qquad (5)$$

The calculation scheme described above has been applied to the analysis of PCX experimental data on LHD with polystyrene pellets (TESPEL).

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3) I.Yu. Tolstikhina, P.R. Goncharov, *et al.*, NIFS-DATA Research Report, Part II (to be published).
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