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Iso-nuclear tungsten dielectronic recombination rates for use in magnetically-confined fusion plasmas

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Under the auspices of the IAEA Atomic and Molecular Data Center and the Korean Atomic Energy Research Institute, our assembled group of authors has reviewed the current state of dielectronic recombination (DR) rate coefficients for various ion stages of tungsten (W). Subsequent recommendations were based upon available experimental data, first-principle calculations carried out in support of this paper and from available recombination data within existing atomic databases. If a recommendation was possible, data were compiled, evaluated and fitted to a functional form with associated uncertainty information retained, where available. This paper also considers the variation of the W fractional abundance due to the underlying atomic data when employing different data sets.

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Contents

1. Introduction

Tungsten (symbol W, nuclear charge $Z = 74$) has been chosen as one of the plasma-facing materials in the divertor, a region of high predicted heat load in the ITER tokamak currently under construction in Cadarache, France. In preparation, other large-scale tokamak experiments such as JET have also adopted tungsten within their configuration in order to provide insight to projected ITER operational plasma conditions. Tungsten has several appealing characteristics as a plasma-facing material which include good heat conductivity, a high melting temperature, resistance to erosion and low affinity for tritium [1]. However, as a plasma impurity even highly charged tungsten ions in the core region of the tokamak may not be fully stripped of electrons and consequently radiation will constitute an important energy loss mechanism [2,3]. Therefore, characterization of this problem requires accurate collisional and radiative data for many ion stages and remains an issue of the utmost importance for the fusion community.

In magnetically-confined fusion the ionization balance is dominated by several competing electron-impact driven processes. On one hand we have direct ionization/excitation-autoionization and on the other we have recombination. Recombination may occur by either radiative recombination (RR) and/or dielectronic recombination (DR).

Tungsten, for many of the considered charge states, under ITER conditions of interest is a complicated many-electron problem; for example, in the temperature range of 3–5 keV, typical of the core plasma temperature in present experiments it is expected that nickel-like W^{46+} will be the most dominant abundant charge state. Alternatively in the temperature range of 15–20 keV (representative of ITER core conditions) neon-like W^{64+} is expected to be the most abundant ion stage. Owing to the large number of intermediate Rydberg states involved in many of the Tungsten DR ion stages, it can be very computationally intensive to calculate certain ion stages using perturbative distorted-wave methods and therefore our review sometimes includes DR results from simpler empirical or semi-empirical models.

For plasma modeling of magnetically-confined plasmas valuable impurity influx data can be expressed in terms of effective rate coefficients for ionization and recombination from which the radiative power loss for each charge state may be calculated (assuming a Maxwellian plasma). These data are sufficient to calculate the collisional-ionization equilibrium and, in conjunction with a model inclusive of impurity source terms and impurity transport, to simulate the profile of an impurity charge state distribution for a given background plasma. This ultimately allows us to simulate the impurity effects on the radiative power balance. In general, effective rate coefficients are functions of electron temperature and density, but under certain low density conditions the coronal approximation may be appropriate.

In our following discussions and presentation of tables, we shall be referring to the following original sources. These are a mixture of semi-empirical formulae such as the Burgess General Formula through to distorted-wave methods as implemented within the HULLAC, FAC and AUTOSTRUCTURE codes, as well as selected *R*-matrix calculations. Distorted-wave methods provide the bulk of new calculations carried out in preparation of this paper.

The first comprehensive set of recombination rate coefficients for tungsten (and many other impurity ions) in fusion plasma DR was developed in 1976 at Princeton and Livermore [2,4]. These rate coefficients for dielectronic recombination were based on the Burgess general formula [5]. An average-ion model [4], was used as the basis for the computed rate coefficients, but the data that were published are derived quantities: average charge $\langle Z \rangle$, squared charge $\langle Z^2 \rangle$, and radiative cooling rates as a function of electron temperature in a low density plasma. The rate coefficients themselves became widely used in fusion plasma modeling through the ADPAK set of subroutines that were included in the Multi-Ion Species Transport (MIST) code [6] and in several other transport codes; therefore the rate coefficients described originally in [4] are often called the **ADPAK** rates. In [4] the authors estimate their rate coefficients to be uncertain by a factor of 2–4, and especially uncertain for high-*Z* impurities.

A detailed comparison with EUV emissions in ASDEX-U pointed to problems with the ADPAK rates for tungsten. As expressed in [7]: