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Spectroscopy of Highly Charged Ions with an Electron Beam Ion Trap
電子ビームイオントラップによる多価電離イオンの分光測定

NAKAMURA Nobuyuki, SAKAUE Hiroyuki A., KATO Daiji, and MURAKAMI Izumi
中村信行，坂上裕之，加藤太治，村上泉

Institute for Laser Science, The University of Electro-Communications
1-5-1 Chofugaoka, Chofu, Tokyo 182-8585, Japan
電気通信大学レーザー新世代研究センター 〒182-8585 調布市調布ヶ丘1-5-1

We present spectra of highly charged heavy ions obtained with an electron beam ion trap (EBIT). In particular, we focus on tungsten spectra, which is important for the diagnostics of the ITER plasma. Many previously-unreported lines have been observed and identified.

1. Introduction

An electron beam ion trap (EBIT) [1] is a powerful device to obtain the atomic data of highly charged ions needed for understanding and controlling high temperature plasmas, such as fusion plasmas and the solar corona. It can trap highly charged ions interacting with a monoenergetic electron beam for many hours. It is thus regarded as a well-defined simple plasma consisting of unidirectional monoenergetic electrons and trapped ions with a narrow charge state distribution. Consequently the EBIT plasma is an unique and ideal source for high resolution spectroscopic studies of highly charged ions. Spectra from an EBIT are useful to survey and identify previously unreported lines, and also to provide benchmark for plasma models. An EBIT can also be used as a device to study the interactions of electrons with highly charged ions. Such spectroscopic and collisional data can be obtained for ions over wide ranges of charge state and atomic number; any ion of any element can practically be studied. Interaction energy between ions and electrons can also be varied over a wide range, such as 100 eV to more than 100 keV.

2. Electron Beam Ion Trap (EBIT)

An EBIT [1] was developed at the Lawrence Livermore National Laboratory based on the principle of an electron beam ion source (EBIS) [2] developed at Joint Institute for Nuclear Research in Dubna. An EBIT consists of a Penning-like ion trap and a high-energy, high-density electron beam going through the trap. Its main components are an electron gun, a drift tube (ion trap), an electron collector, and a superconducting magnet. The drift tube is composed of three (or more) successive cylindrical electrodes where a well potential is applied for trapping ions axially. Radial ion trap is achieved by the combination of the strong axial magnetic field produced by the magnet and the space charge potential of the high density electron beam compressed by the magnetic field. Highly charged ions are produced by successive electron impact ionization of the trapped ions. Emission of highly charged ions excited by the electron beam can be studied spectroscopically through a slit opened at the middle of the drift tube. Since the trapped ions are produced and excited by an (quasi-)monoenergetic electron beam, an EBIT has following advantages over plasma sources. (1) A narrow charge state distribution can be obtained with a dominant charge state controlled by the electron energy. (2) Electron energy dependent emission processes, such as resonant excitation, can be studied. (3) There is no Doppler shift and less Doppler broadening. (4) Polarization of radiation excited by a unidirectional electron beam can be studied. We have developed a high-energy EBIT called the Tokyo-EBIT [3] in 1995 and a compact low-energy EBIT called CoBIT [4] in 2007. The former can be operated with electron energies of 1 to 200 keV, and the latter can be operated with electron energies of 0.1 to 2 keV. The complementary use of them enables spectroscopic studies of tungsten ions with a wide range of charge state.

An element of interest is usually introduced through the slit on the drift tube as a molecular beam. Not only rare gases and molecular gases, compounds which have a relatively high vapor pressure can also be used. For example, for producing tungsten ions, tungsten hexacarbonyl ($W(CO)_6$) are used respectively.

We have several spectrometers for a wide wavelength range: a crystal spectrometer for the x-ray range, a grazing-incidence flat-field grating spectrometer for the EUV to soft x-ray range, and a Czerny-Turner spectrometer for the visible range.

3. Tungsten Spectra

Tungsten is considered to be the main impurity in the ITER plasma, and thus spectroscopic data of tungsten ions are necessary to diagnose and control the high temperature plasma in ITER [5]. In particular, there is strong demand for emission lines in the visible range in the diagnostics of the edge plasmas [6]. Since efficient optical components, such as mirrors, lenses, optical fibers, etc., are available, efficient and effective diagnostics can be expected with the visible range. Until recently, however, only one visible emission line [7] has been reported for tungsten ions with a charge state higher than two. Survey and identification of previously unreported visible lines of tungsten ions are thus in strong demand. An EBIT is a suitable device for such a purpose. As an example, tungsten spectra obtained with CoBIT are shown in Fig. 1. As seen in the figure, observed lines revealed strong dependence on electron energy, i.e., they appeared at a certain threshold energy and their intensity became weak when the energy was further increased. This strong dependence reflects the charge distribution in the trap. For example, after the electron energy was changed from 630 eV to 675 eV, production of W^{23+} became available because the ionization energy of W^{22+} is 643 eV [8]. The lines at around 409 and 432 nm, appeared at 675 eV, are thus considered to be emission lines from W^{23+}. When the energy was further increased to 725 eV, which is higher than the ionization energy of W^{23+} (690 eV), the intensity of these lines became small because the number of W^{23+} was decreased due to further ionization, and the line from W^{24+} appeared at around 419 nm. The validity of such identification based on the appearance energy has been confirmed through several previous experiments [9]. Consequently, the lines indicated by arrows in the figure are assigned to be the transition of tungsten ions shown in each spectrum. Since transitions between different electronic configurations in highly charged heavy ions should fall in shorter wavelength range, such as EUV and x-ray, transitions in the visible range can be assigned as M1 transitions between fine structure levels. The detailed identification of the fine structure levels should be done through comparison with theoretical calculations. Although it is rather difficult to calculate fine structure splitting precisely for many electron heavy ions, some lines in Fig. 1 have been identified through the comparison with detail calculations [10]. Survey of previously unreported lines is also possible with plasma sources, but observation of spectra excited by a mono-energetic electron beam in an EBIT is quite useful for the identification of the responsible charge state as shown here.

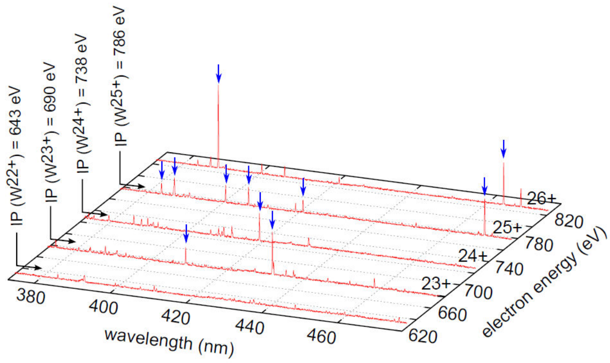

Fig.1. Visible spectra of highly charged tungsten ions observed with CoBIT. IP(W^{q+}) represents the ionization potential of W^{q+}.

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