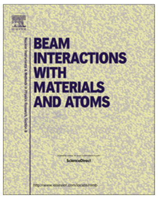
Nuclear Instruments and Methods in Physics Research B xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb



Visible spectra of highly charged holmium ions observed with a compact electron beam ion trap

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ARTICLE INFO

Article history:
Received 15 November 2016
Received in revised form 8 March 2017
Accepted 26 March 2017
Available online xxxx

Keywords:
Highly charged ions
EBIT
Visible spectra

ABSTRACT

We present visible spectra of highly charged holmium ions, which is a potential candidate ion for constructing a precise atomic clock. A compact electron beam ion trap is used for producing and trapping holmium ions. By observing electron energy dependence of the spectra, the charge state is assigned for each emission line. We also present theoretical transition frequency and amplitude obtained with two different methods.

1. Introduction

Recently, an optical clock utilizing transitions in highly charged ions has been proposed as a potential candidate for an accurate and stable clock that has an excellent sensitivity to a possible fine structure constant variation [1–3]. Dzuba et al. [4] have proposed to use Ho^{14+}, whose ground state configuration is $4f^6 5s$, and predicted several optical transitions useful for cooling and observation. However, the uncertainty in the predicted transition energy between states of different configurations is estimated to be large as 10,000 cm^{-1}, which corresponds to several tens of percent for the transitions in the optical range. This is in contrast to the situation for one valence electron ions, such as Ag-like ions, where the agreement with experiments reaches 1% or even less [5]. The large uncertainty in Ho^{14+} is due to dense and complex fine structure levels arising from the half occupied $4f$ subshell. It is thus important to determine the transition wavelength experimentally for designing and constructing the clock with Ho^{14+}.

In this paper, we present visible spectra of highly charged holmium ions observed with an electron beam ion trap (EBIT). We used a compact EBIT, called CoBIT [6], which is a useful device for observation and identification of previously-unreported transitions in highly charged ions. Several transitions of Ho^{14+} have been observed in the visible range. We also present theoretical calculations of transition frequency and amplitude.

2. Experiment

The present experimental setup was essentially the same as that used in our previous studies, where the visible emission lines of tungsten ions were observed [7–9]. Briefly, a compact electron beam ion trap, called CoBIT [6], was used for producing highly charged holmium ions. Holmium was injected into CoBIT as a vapor by using an effusion cell [10] operated at 900–950 °C. The emission excited by the electron beam was observed with a commercial Czerny-Turner type of visible spectrometer (Jobin

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http://dx.doi.org/10.1016/j.nimb.2017.03.135
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Please cite this article in press as: T. Nakajima et al., Visible spectra of highly charged holmium ions observed with a compact electron beam ion trap, Nucl. Instr. Meth. B (2017), http://dx.doi.org/10.1016/j.nimb.2017.03.135

Yvon HR-320) with a focal length of 320 mm. For the spectra shown in this paper, a 300 g/mm grating blazed at 500 nm was used. The diffracted light was detected with a liquid-nitrogen-cooled back-illuminated CCD (Princeton Instruments Spec-10:400B LN), operated at −115 °C. The wavelength was calibrated using emission lines from several standard lamps placed outside CoBIT. Emission in the extreme ultraviolet (EUV) range was also observed to help the identification of visible lines. A grazing-incidence flat-field spectrometer [11] consisting of a 1200 g/mm concave grating (Hitachi 001-0660) and a Peltier-cooled back-illuminated CCD (Roper PIXIS-XO: 400B) was used.

3. Theory

Theoretical calculations of the energy levels and transition probabilities for I-like Ho^{14+} were performed using relativistic Hartree–Fock method (COWAN code) [12–14] and a version of the configuration interaction method (CI) for many-valence-electron atoms [4,15]. Both approaches are not totally *ab initio*. They rely on some fitting parameters, especially for the energy difference between states of different configurations. Thus, in the absence of experimental data the fitting cannot be done and theoretical uncertainties for the energies are large. Large uncertainties in the energies strongly affect the transition probabilities (e.g., dipole probabilities are $\sim \Delta E^3$, where ΔE is the transition energy). They also affect the amplitudes of the electric dipole (E1) transitions. These amplitudes are zero in the single-configuration approximation for the $5s - 4f$ transition which cannot occur as an E1 transition. The transitions become non-zero when mixing with appropriate configurations are included. This mixing, when treated perturbatively, is inversely proportional to the energy interval between the states of different configurations, i.e. is sensitive to the uncertainties in the energies. On the other hand, the amplitudes of the magnetic dipole (M1) transitions between states of the same configuration are not sensitive to the energies and are considered to be stable in the calculations.

4. Results and discussion

Fig. 1 shows experimental spectra obtained with electron energies of 260–490 eV. Note that the electron energy was just determined from the potential difference between the electron gun and the middle electrode at the ion trap. The actual interaction energy should be slightly different from the indicated values mainly due to the space charge potential of the electron beam. The electron beam current was 7 mA and the data acquisition time was 30 min for each spectrum. No efficiency correction was applied so that intensity cannot be compared.

The charge state that should be assigned to each observed line can be determined from the electron energy dependence. For example, the prominent lines at around 480 nm and 550 nm in the spectrum obtained at 490 eV can be assigned to Cd-like Ho^{19+} because it appeared when the electron energy exceeded the ionization energy of In-like Ho^{18+} (439 eV [16]) and dominated when the energy was further increased. In the same manner, the emission lines of Xe-like Ho^{13+} to In-like Ho^{18+} can also be assigned from the energy dependence as indicated in the figure. The charge state assignment was also confirmed by the time of flight analysis of ions extracted from the trap [9] and also by the EUV spectra obtained at the same time with the visible spectra.

The energy level structure of higher charge states is rather simple. For example, Cd-like Ho^{19+} has a ground state configuration of [Kr]$4d^{10}4f^2$ with 13 fine structure levels within an energy range of about 15 eV. The energy levels of the first excited configuration, [Kr]$4d^{10}4f5s$, lie above 45 eV, so that they are well separated from the ground state. Thus, the visible emission lines that have been assigned to Cd-like Ho^{19+} are considered to be the M1 transitions between fine structure levels in the ground state configuration similarly to the M1 transitions observed for Cd-like W^{26+} [7,17].

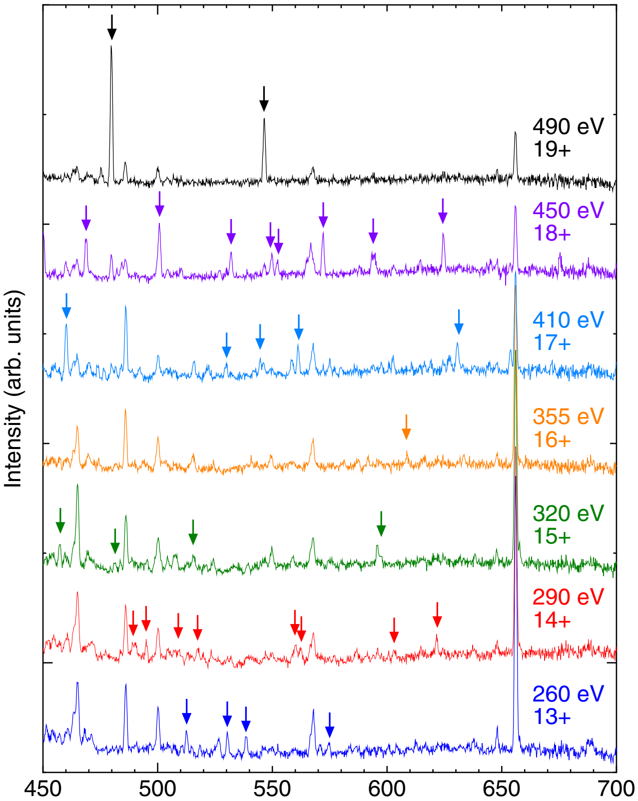

Fig. 1. Spectra of highly charged holmium ions obtained with a compact electron beam ion trap. The values indicated on the right are the electron beam energy and the dominant charge state for each energy. The emission lines assigned to the dominant charge state are indicated by the arrows.

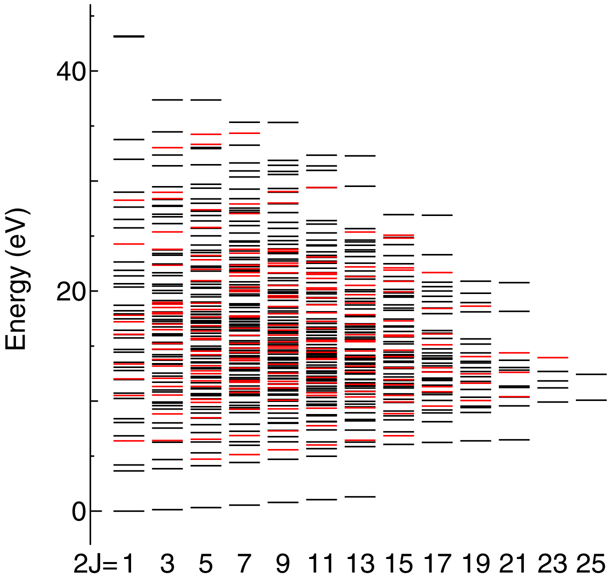

Fig. 2. Energy levels of the ground configuration ([Kr]$4f^65s$) (black) and the first excited configuration ([Kr]$4f^55s^2$) (red) of I-like Ho^{14+} calculated with the flexible atomic code [18]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)