Direct Wavelength Measurement of the Visible M1 Transition in Ba^{7+} with a Novel Calibration Method

Naoki KIMURA[1,2], Ryunosuke KODAMA[3], Kento SUZUKI[3], Shimpei OISHI[3], Michiharu WADA[4], Kunihiro OKADA[1], Noriaki OHMAE[5,6], Hidetoshi KATORI[5,6,7] and Nobuyuki NAKAMURA[3]

[1]*Department of Physics, Sophia University, Tokyo 102-8554, Japan*
[2]*RIKEN Nishina Center, Saitama 351-0198, Japan*
[3]*Institute for Laser Science, The University of Electro-Communications, Tokyo 182-8585, Japan*
[4]*Wako Nuclear Science Center, Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK), Saitama 351-0198, Japan*
[5]*Quantum Metrology Laboratory, RIKEN, Saitama 351-0198, Japan*
[6]*RIKEN Center for Advanced Photonics, Saitama 351-0198, Japan*
[7]*Department of Applied Physics, The University of Tokyo, Tokyo 113-8656, Japan*

(Received 18 November 2018 / Accepted 30 November 2018)

We observed and directly measured the M1 transition between the two states of the fine structure splitting in the ground state of Ba^{7+} with a visible spectrometer coupled to a compact electron beam ion trap. To validate the measurement accuracy, we demonstrated a calibration method using Ar^{+} emissions from buffer gas. The wavenumber in vacuum was determined to be 23591.57 (15) cm^{-1}.

Keywords: visible spectroscopy, highly charged ion, electron beam ion trap, calibration

DOI: 10.1585/pfr.14.1201021

Visible transitions of highly charged ions (HCIs) have become attractive for various applications such as developments of next generation atomic clocks [1], studies of the solar corona [2], and plasma diagnoses for fusion reactors [3]. In recent years, visible spectra in various HCIs have been observed using electron beam ion traps (EBIT) by several research groups for the purpose of identifications of various transitions [4–8]. In this context, visible transitions in Ba plasma have been utilized since early times. For instance, the Ba plasma observation using the visible transitions emitted from singly charged Ba ions has been widely applied to study giant stars [9] and ionospheric plasma [10]. For highly charged Ba ions, several visible transitions have been identified so far [11, 12] after the first observation for Ba^{34+} [13].

We are developing a linear Paul trap combined with a microminiature EBIT [14], for use in the study of laser spectroscopy in cold HCI. We plan to demonstrate sympathetically cooled ion crystals with this instrument to confine HCIs to Lamb-Dicke regime [15]. Due to its relatively simple electron configuration, Ba^{7+} would be a good initial candidate for commissioning this instrument. The magnetic dipole (M1) transition ($^2P_{1/2}$ - $^2P_{3/2}$) between the two states of the fine structure splitting of the ground state in the visible region have a possibility for simplified Doppler-free spectroscopy using direct observation of laser-induced fluorescence (LIF). As the most abundant isotope, ^{138}Ba, has no hyperfine structure, the visible M1 transition can be used to maintain a closed optical cycle with only one laser. However, the theoretical Einstein A coefficient of this M1 transition is only 117 s^{-1} [16]. Thus, it is necessary to know the wavelength as accurately as possible in advance. In this letter, we report on the result of first direct measurement of the M1 transition of trapped Ba^{7+} in a compact EBIT using a novel calibration method.

The present experiment were performed using a visible light spectrometer (Jobin Yvon HR320) with a Peltier-cooled CCD (Andor iDus 416) connected to a compact electron beam ion trap, called CoBIT [17]. The details of our experimental setup and procedure were described in a previous paper [12]. As Ba atoms evaporate from the BaO cathode of CoBIT, Ba HCIs were easily trapped without any extra loading processes [12]. In order to calibrate the measurement, an Ar buffer gas was introduced to the vacuum chamber with a variable leak valve while trapping Ba HCIs.

Figure 1 shows a typical visible emission spectrum from Ba^{7+} and Ar^{+} in CoBIT. A Gaussian function was fitted to each observed peak. A linear background was assumed in the vicinity of each peak. Since grating type spectrometers generally have non-linearity for high precision measurement, a cubic polynomial equation is used for calibration formula between the wavenumber and the rela-

author's e-mail: naoki.kimura@riken.jp

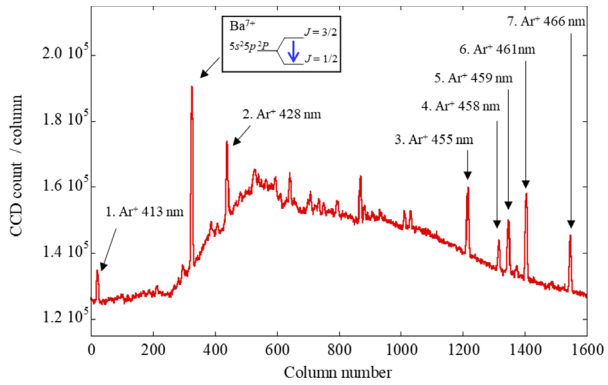

Fig. 1 Visible emission spectrum of Ba^{7+} and Ar^{+}. The electron beam energy was 90 eV. The collector current was 2.1 mA. The Ar gas pressure was 5×10^{-7} Pa (measured in the room temperature region of the CoBIT chamber).

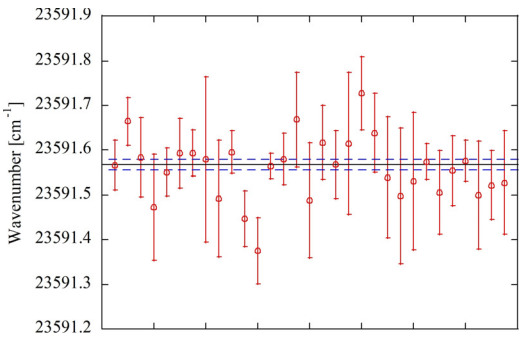

Fig. 2 Summary of the wavenumber measurements of $^2P_{1/2}$ - $^2P_{3/2}$ in Ba^{7+}. The black solid line is the average of this dataset. The blue dashed lines show the range of the standard error.

tive column number from the Ba^{7+} peak [5, 18]. We used 7 Ar^{+} peaks to determine the calibration function; the typical calibration resulted in a confidence interval (1σ) of 0.09 cm^{-1} for the Ba^{7+} peak position. In the Ba^{7+} peak, the full width at half maximum and the statistical error of the center were typically determined to be 8 cm^{-1} and 0.06 cm^{-1}, respectively. We repeated this measurement 31 times and obtained the dataset of measured values as shown in Fig. 2. The average and the standard error of this dataset are calculated as 23591.57 cm^{-1} and 0.01 cm^{-1}.

In order to estimate the systematic error in this calibration, we used Ar^{+} peaks as test cases. The wavenumber of each Ar peak ${}^{E}k^{i}$ was determined using other 6 Ar^{+} peaks with the same method as Ba^{7+} peak; here i is the identification number shown in Fig. 1. The results were compared with high precision literature values ${}^{L}k^{i}$ [19]. The differences ${}^{E}k^{i} - {}^{L}k^{i}$ are +0.14(2), −0.14(1), +0.07(3), +0.03(2), +0.01(1) in units of cm^{-1}, respectively for i = 2 to 5. In the case of Ba^{7+} peak, we can use 7 Ar^{+} peaks including the nearest Ar^{+} peak (i = 2) for calibration. As such the calibration error can be expected to be better than the test cases for the Ar^{+} peaks, we adopted the maximum difference in the tests, 0.14 cm^{-1} as the systematic error in the determination of the Ba^{7+} wavenumber.

In our previous experiments [8, 12], we utilized standard light sources placed outside CoBIT to obtain the reference lines for the wavelength calibration. Thus, the difference in the source position and the incident angle to the optical detection system could cause systematic uncertainties. In addition, since the reference lines and the objective lines were observed alternately, the thermal and mechanical drift could also cause systematic uncertainties. The total uncertainty caused by these factors was estimated to be typically 2 cm^{-1} from the reproducibility of the measurement. In our new calibration method, as the Ba^{7+} peak and the Ar^{+} calibration peaks emitted from the same point were simultaneously observed, these error factors were eliminated and the systematic error was derived from the validity of the cubic equation approximation in this calibration.

Table 1 Summary of the present work and the previous studies. The wavenumber k in vacuum of the fine structure splitting of the $5p\ ^2P$ in Ba^{7+} is given.

	Th. or Ex.	k [cm^{-1}]	Error
Safronova [16]	Theory	23605	
Churilov [20]	Experiment	23592	±1.5
This work	Experiment	23591.57	±0.15

In Table 1, the result of this measurement and previous studies are listed. The experimental value by Churilov [20] was indirectly obtained from the extreme ultra violet spectra in the laser produced plasma. The error in the present work is given by the sum of the standard error and the systematic error. The wavenumber measured in this work is in agreement with the previous studies, however the improved calibration technique has allowed for a greatly improved precision. For further improvement, we look for more calibration lines from other elements in this wavelength region.

This work is supported by RIKEN Pioneering Project Funding and Grant-in-Aid for JSPS Research Fellow (No.17J05087). We would like to thank Dr. Peter Schury for the proof reading of the manuscript.

[1] J.C. Berengut *et al.*, Phys. Rev. Lett. **105**, 120801 (2010).
[2] B. Edlén, Phys. Scr. **T8**, 5 (1984).
[3] Y. Ralchenko, Plasma Fusion Res. **8**, 2503024 (2013).
[4] P. Beiersdorfer *et al.*, Astrophys. J. **587**, 836 (2003).
[5] I. Draganić *et al.*, Phys. Rev. Lett. **91**, 183001 (2003).
[6] G. Brenner *et al.*, Astrophys. J. **703**, 63 (2009).
[7] A. Windberger *et al.*, Phys. Rev. Lett. **114**, 150801 (2015).
[8] S. Murata *et al.*, Phys. Rev. A **96**, 062506 (2017).
[9] R.D. McClure *et al.*, Astrophys. J. **352**, 709 (1980).
[10] E.M. Wescott *et al.*, J. Geophys. Res. **81**, 4495 (1976).
[11] J.R. Crespo López-Urrutia *et al.*, Phys. Scr. **T80B** (1999).
[12] J. Sakoda *et al.*, Phys. Scr. **T144**, 014011 (2011).
[13] C.A. Morgan *et al.*, Phys. Rev. Lett. **74**, 1716 (1995).
[14] N. Kimura *et al.*, RIKEN Accel. Prog. Rep. **50**, 202 (2017).
[15] K. Okada *et al.*, Hyper. Inter. **236**, 87 (2015).
[16] M.S. Safronova *et al.*, Phys. Rev. A **90**, 042513 (2014).
[17] N. Nakamura *et al.*, Rev. Sci. Instrum. **79**, 063104 (2008).
[18] S.T. Wollman *et al.*, Appl. Spec. **47**, 125 (1993).
[19] W. Whaling *et al.*, J. Quant. Spec. Rad. Trans. **53**, 1 (1995).
[20] S.S. Churilov *et al.*, J. Opt. Soc. Am. B **18**, 113 (2001).