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X-ray Spectroscopy of Highly Charged Ne-like Ions

N. Nakamura,[1] D. Kato, E. Nojikawa, F. J. Currell,[2] A. Ya Faenov,[3] T. A. Pikuz[3] and S. Ohtani[2]

Cold Trapped Ions Project, ICORP, JST, Axis Chofu 3F, 1-40-2 Fuda, Chofu, Tokyo 182-0024, Japan

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Abstract

X-ray spectra from Ne-like Xe, Cs and Ba have been observed with the Tokyo electron beam ion trap and a flat crystal spectrometer. For several $n = 3$ to 2 transitions in Ne-like Ba and Cs, wavelengths have been determined with an accuracy of about 200 ppm. The experimental wavelengths are compared with previous theoretical and experimental results. X-ray transitions in Ne-like Ba have also been used to measure the spatial distribution of X-ray radiation with a spherically bent crystal. The possibility to apply such techniques to diagnostics of an EBIT is discussed.

1. Introduction

Among highly charged ions the Ne-like sequence has been well investigated both theoretically [1–3] and experimentally [1,4,5] because of its closed shell. However the Ne-like sequence still contains interesting physics. Theoretical calculations by Kagawa *et al.* [2] showed that the order of excited levels changes between $(2p_{1/2})^{-1}(3s)_1$ and $(2p_{3/2})^{-1}(3d_{5/2})_1$ at the atomic number $Z \sim 55$. The wave functions of these states then strongly mix in this Z-region. As a result, the oscillator strength for the $2p^6 \rightarrow (2p_{1/2})^{-1}(3s)_1$ transition increases while that for the $2p^6 \rightarrow (2p_{3/2})^{-1}(3d_{5/2})_1$ transition decreases at $Z \sim 55$. Theoretical calculations by Zhang and Sampson [6] showed that the collision strengths for the electron impact excitation of these levels have similar Z-dependence. Systematic measurements of energy levels and excitation cross sections for $n = 3$ excited states will then be important to check the theoretical treatment for relativistic many body systems including strong mixing between levels.

2. Experimental setup

Ne-like ions were produced and trapped with the Tokyo electron beam ion trap (Tokyo-EBIT) [7–9]. A flat crystal spectrometer was used for wavelength measurements for $n = 3$ to 2 transitions in Ne-like Cs and Ba. The spectrometer consisted of a flat LiF(200) crystal ($2d = 4.0273$ Å) with an area of 100×50 mm^2 and a position sensitive proportional counter (PSPC). The crystal was placed 620 ~ 730 mm away from the center of the trap while the PSPC was placed at 460 ~ 740 mm away from the crystal. The effective volume of the PSPC was $100 \times 30 \times 4$ mm^3 and 4 atmospheric pressure of PR gas (90 % Ar + 10 % CH_4) was used. The spectrometer was operated in vacuo (~10^{-7} torr), and a Be-foil with a thickness of 50 μm separated the vacuum of the EBIT (~10^{-9} torr) and the spectrometer.

For observation of spatial distribution of X-ray radiation, a spherically bent crystal, placed in a FSSR-2D configuration [10,11] was used [12]. The spectrometer consisted of a spherically bent quartz crystal (orientation $2d = 6.67$ Å) with a radius of curvature of 186 mm and an X-ray CCD. The distance between the EBIT source and the crystal was 446 mm and the distance between the crystal and the CCD was 552 mm. With this configuration, it is possible to have a high resolution X-ray spectrum and spatial distribution along the electron beam simultaneously. The spectrometer was operated in a helium atmosphere to reduce absorption of the radiation.

3. Results and discussion

Fig. 1 shows the X-ray spectra from Ne-like Ba, Cs and Xe. The electron energies and currents at which the spectra were obtained are indicated in the figure. To determine the transition wavelengths for Ne-like Ba and Cs, the experimental wavelengths for the 3A, 3B, 3C and E2U lines in Ne-like Xe [4] have been used as references. Since the

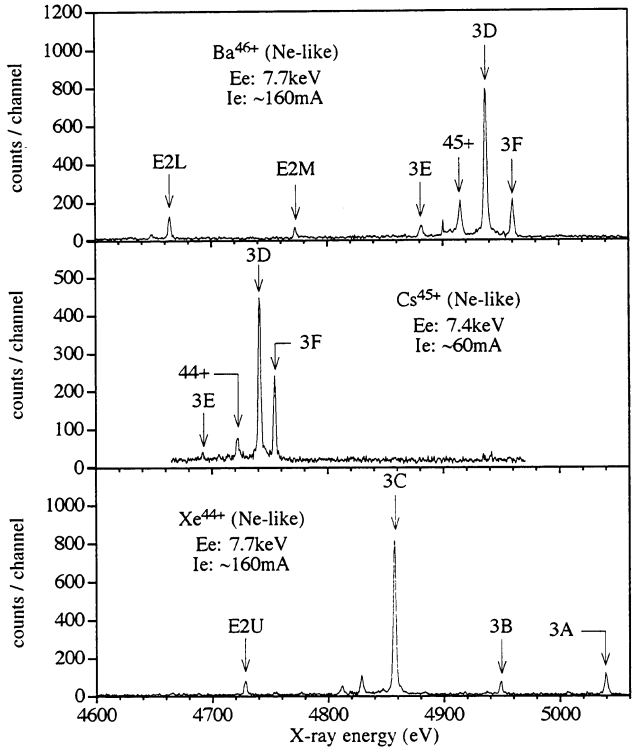

Fig. 1 X-ray spectra from Ne-like Ba, Cs and Xe. the notations used by Beiersdorfer *et al.* [4] are indicated in the figure. Ee and Ie represent the electron energies and the currents, respectively, at which the spectra were obtained.

[1]E-mail: nakamura@hci.jst.go.jp.
[2]Permanent address: University of Electro-Communications, Chofu, Tokyo 182-8585, Japan.
[3]Permanent address: Multicharged Ions Spectra Data Center, VNIIFTRI, Moscow region, 141570, Russia.

radiation source was regarded as an entrance slit for the spectrometer, the source position should not be moved during the measurement. Therefore the same values for the EBIT parameters were used for both the objective ions (Ba or Cs) and the reference (Xe). To remove the uncertainty arising from the drift of the electronics and so on, the measurements of the objective ions and the reference were performed alternately.

In Table I present experimental results are listed together with previous experimental and theoretical results. The uncertainties in the present experiments were estimated from the quadrature sum of four contributions: the statistical errors for the reference (Xe) and the objective lines (Ba or Cs), the uncertainties in the reference, and the uncertainties arising from the nonlinear positional response of the detector. Among them the last two contributions were dominant. As for the previous results, it is noted that the wavelengths which have a similar value are listed in the same row regardless of the assignments in the original papers. Among the three theoretical values the values by Aglitskii *et al.* [1] show best agreement with the present experimental results.

Fig. 2 shows an X-ray spectrum obtained with the spherically bent crystal spectrometer. The horizontal axis corresponds to the spectral dispersion, i.e. transition energy, while the vertical axis corresponds to the spatial distribution of the radiation. The trap region of the Tokyo-EBIT consists of five cylindrical electrodes [12]. Negative potential was applied only to the middle electrode with respect to the other electrodes to obtain the spectrum shown in Fig. 2(a). Thus the trap potential shape was a "u-shaped" potential, and the ion distribution was not flat. On the other hand, negative potential was applied to the three central electrodes to obtain the spectrum shown in Fig. 2(b). Thus the trap potential shape was a "flat" potential, and the ion distribution was flat. For the "u-shaped" potential, since the ions become more concentrated in the central region of the trap as the temperature of the ions reduces, we can get information about the temperature of the observed ions. Assuming that the ion density is proportional to $\exp(-qV(z)/kT)$, the ion temperature for the trapped Ne-like Ba ions has been estimated to be 7.5 ± 3.5 keV. The uncertainty was estimated from the statistics, the uncertainty in the determination of the absolute position, and spatial resolution of the spectrometer. Since the axial trap potential V_{trap} was about 380 V for the "u-shaped" trap, T/qV_{trap} is about 0.4. Although the present result is consistent with the results obtained by Schneider *et al.* [13], the temperature obtained from the present measurement is much higher than that obtained by Beiersdorfer *et al.* [14,15] and by Adler *et al.* [16]. One of possible reasons for the higher temperature is that no coolant was injected in the present measurement. The larger axial trap potential and the larger magnetic field than the previous experiments can also result in higher temperature.

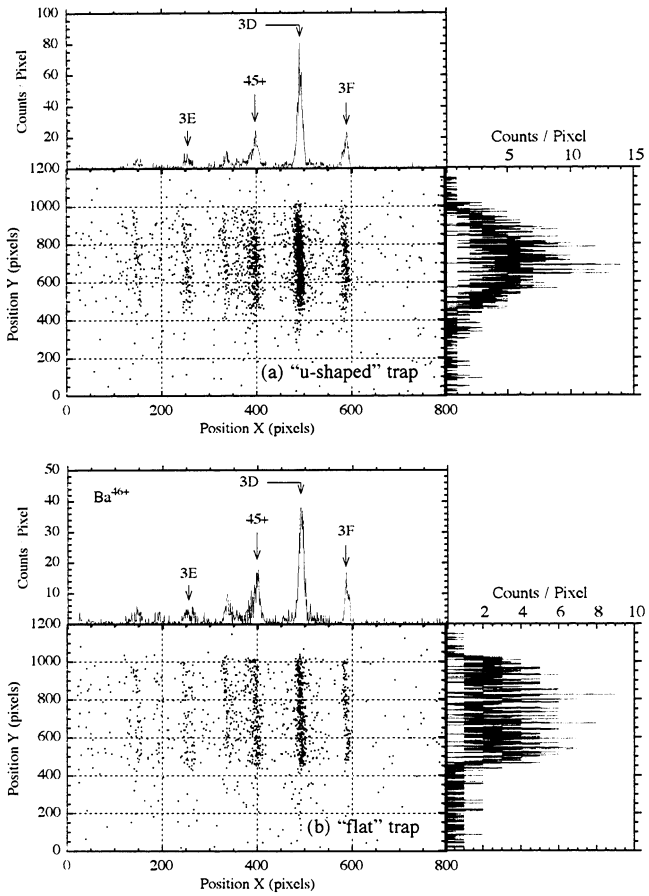

Fig. 2. Two dimensional X-ray spectra of Ne-like Ba obtained with the spherically bent crystal. The integrated images for the vertical direction represent X-ray spectra obtained by the crystal dispersion. The integrated images for the horizontal direction represent spatial distributions of the radiation. (a) The "u-shaped" potential was applied to the drift tubes. (b) The "flat" potential was applied to the drift tubes.

Table I. *Wavelengths of several n=3 to 2 transitions in Ne-like Ba and Cs. All values are given in Å. The numbers in the parentheses represent the experimental uncertainties, e.g. 2.6582(7) represents 2.6582±0.0007*

Element	Line*	Present (Expt)	Aglitskii[a] (Expt)	Aglitkii[a] (Theor)	Quinet[b] (Theor)	Zhang[c] (Theor)
Ba	E2L	2.6582(7)			2.6589	2.6557
	E2M	2.5978(5)			2.5977	2.5940
	3E	2.5396(4)	2.5396	2.5394	2.5409	2.5357
	3D	2.5110(3)	2.5125	2.5106	2.5121	2.5063
	3F	2.4995(4)	2.5005	2.4993	2.5012	2.4945
Cs	3E	2.6424(7)	2.6439†	2.6430	2.6447	2.6394
	3D	2.6149(6)	2.6162†	2.6147	2.6166	2.6101
	3F	2.6078(6)	2.6196†	2.6075	2.6093	2.6028

[a] Reference [1].
[b] Reference [3].
[c] Reference [6].
* The notations used by Beiersdorfer *et al.* [4] are used.
† Smoothed experimental values obtained by the least square method from the experimental values for other experiments.

4. Conclusion

X-ray spectra from Ne-like Xe, Cs and Ba were observed with a flat crystal spectrometer. The wavelengths for the several $n = 3$ to 2 transitions in Ne-like Cs and Ba were determined and compared with the previous experimental and theoretical results. By using a spherically bent crystal spectrometer, spatially resolved X-ray spectra from an EBIT was obtained with high spectral resolution and high luminosity. This scheme is considered to be very useful in the diagnosis of EBIT source parameters, such as the temperature of the trapped ions.

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