Interference between dielectronic and radiative recombination in electron - highly charged Bi collisions

Hirotugu Tobiyama¹, Hiroaki Nohara ¹, Anthony P Kavanagh², Nobuyuki Nakamura¹, Hirofumi Watanabe³, Hiroyuki A Sakaue⁴, Yueming Li⁵, Daiji Kato⁴, Fred J Currell², Chikashi Yamada⁶ and Shunsuke Ohtani¹

¹Inst. for Laser Science, The Univ. of Electro-Communications, Tokyo 182-8585, JAPAN
²Queen’s University Belfast, Belfast BT7 1NN, United Kingdom
³CREST, Japan Science and Technology Agency
⁴National Institute for Fusion Science, Toki, Gifu 509-5292, JAPAN
⁵Institute of Applied Physics and Computational Mathematics, P.O.Box 8009, Beijing 100088
⁶Dept. of Appl. Phys. and Chem., The Univ. of Electro-Communications, Tokyo, JAPAN

E-mail: nakamu@ils.uec.ac.jp

Abstract. Interference between radiative and dielectronic recombination in electron and highly charged Bi ion collisions has been studied by observing emitted x-rays with the Tokyo electron beam ion trap. The so-called Fano line shapes were fitted to the KLL DR resonant profiles observed as the enhancement of the x-ray counts. The shape parameters q have been determined similarly to the previous experiments for highly charged U [D A Knapp et al 1995 Phys. Rev. Lett. 74 54] and Hg ions [A J Gonzalez Martinez et al 2005 Phys. Rev. Lett. 94 20320]. The present results were compared to the previous results.

1. Introduction
Radiative recombination (RR) is non-resonant radiative electron capture by an ion, while dielectronic recombination (DR) is an indirect process which proceeds via doubly excited states produced resonantly by dielectronic electron capture:

RR: \( A^q^+ + e^- \rightarrow A^{(q-1)^+} + h\nu \),

DR: \( A^q^+ + e^- \rightarrow A^{(q-1)+**} \rightarrow A^{(q-1)^+} + h\nu \).

These two processes can interfere because they can have identical initial and final states. Their interference is generally weak because the cross section of RR is much smaller than that of DR. However, for highly charged heavy ions, since the RR cross section, which increases rapidly with the atomic number Z, becomes comparable to the DR cross section, which has less dependence on Z, the interference can be so significant that the asymmetric feature, the so-called Fano line shape [1], can be observed in the resonant structure. First observation of such interference was done with the electron beam ion trap (EBIT) at Lawrence Livermore National Laboratory [2] for the KLL DR resonance in highly charged U (Z = 92) ions. They observed the x-ray intensity
enhancement arising from the KLL DR resonance of He- to B-like U ions trapped in the EBIT and found the asymmetric profiles in the resonant structure. In the same way, the interference was also observed for highly charged Hg (Z = 80) ions with the Heidelberg EBIT [3]. Although the contributions for the different charge states were not clearly resolved, they successfully determined the shape parameters q for each resonant state by only including a narrow part of the RR line, chosen to include predominantly the contribution from only one or two charge states.

In this paper, we present observation of interference between radiative and dielectronic recombination in electron and highly charged Bi (Z = 83) ion collisions made by observing emitted x-rays with the Tokyo electron beam ion trap [4, 5]. Comparison with the previous measurements is presented.

2. Experiments
The experiments were performed using the Tokyo-EBIT. Bi was continuously injected from an effusion cell [6] into the EBIT. X-rays from the trapped Bi ions were observed with a solid state Ge detector which was located at 90° with respect to the electron beam. The electron energy was scanned from 53 to 55 keV in a triangle pattern with a scanning rate of about 5 ms/scan, which is fast enough to preserve the charge balance in the trap. The electron current was kept at 110 mA throughout the measurement.

3. Results and Discussion
Figure 1 shows the x-ray intensity integrated (integrated width is 2,500 eV) along the radiative recombination line corresponding to the L_12 (L shell with j = 1/2) vacancy as a function of electron energy. The structures appearing in the figure correspond to KL_12L_3 DR resonances for highly charged Bi ions. Although several charge states, i.e. He- to B-like ions, contribute to the structure, the contribution from only one or two charge states can be extracted by making the integration area for x-ray energy narrower as Gonzalez Martinez et al [3] performed. The example of the narrower integration is shown in Fig. 2, which was obtained by integrating with

**Figure 1.** Electron energy dependence of the observed intensity due to radiative recombination into L_12 vacancies, in the same way as is described in [3]. The energy scale has not been calibrated.

**Figure 2.** As Fig. 1 but with the integrated x-ray energy width narrowed to extract the contribution from Bi- and B-like ions as is described in [3]. Fano line shapes (convoluted with a Gaussian) fitted to the data are shown.
a width of 500 eV. The peak at lower electron energy corresponds to the KLL resonance of Be-like Bi and another peak at higher energy that of B-like Bi. As seen in the figure, these DR peaks show asymmetric features due to the interference effect. An asymmetric profile could perhaps arise from selective (diagonal) slicing procedure described in [3], used to generate Fig. 2. However it was confirmed analytically that the effect of this slicing procedure had a negligible effect on the $q$-values obtained from the present measurement. The $q$-values were determined by fitting two functions to the data shown in Fig. 2; each function is the convolution of a Gaussian distribution and a Fano profile. Resonant intensity, resonant energy, and $q$-value were used as free fitting parameters for each resonance during the fitting process while the natural width was fixed to the theoretical value for each resonance. One more free fitting parameter was used for the width of the Gaussian distribution used in the convolution corresponding to the EBIT’s electron beam energy width. The fitted result is shown in Fig. 2 and the obtained $q$-values were listed in Table 1 together with the previous results for Hg and U.

**Table 1.** Shape parameter $q$ obtained in the present measurements (Bi) and the previous measurements (Hg [3], U [2]).

| charge state | level | $q_{\text{Hg}(80)}$ | $q_{\text{Bi}(83)}$ | $q_{\text{U}(92)}$ |
|--------------|-------|----------------------|----------------------|----------------------|
| Be           | $(1s^2s^22p_{1/2}2p_{3/2})_{J=3/2}$ | 6.7(0.6) | 5.2(0.4) | 4.8(0.4) |
| Be           | $(1s^2s^22p_{1/2}2p_{3/2})_{J=5/2}$ | 18.2(6.6) | 16.1(1.8) | NA |
| B            | $(1s^2s^22p_{1/2}2p_{3/2})_{J=1}$ | 5.1(0.3) | 5.4(0.4) | 2.9(0.2) |
| B            | $(1s^2s^22p_{1/2}2p_{3/2})_{J=2}$ | 10(1) | 14.7(3.5) | NA |

The error presented in table 1 for our measurement is just that given by the weighted least squares fitting procedure. It means that the systematic errors arising from the existence of small peaks and the uncertainties in the theoretical widths are not included. Furthermore, it is rather difficult to find the most favorable fitting result. Thus the actual uncertainty is considered to be larger than the error listed in the table, but it is difficult to estimate the value quantitatively. Considering this a large discrepancy is not found between the Bi and Hg results. It may be a matter of course, because the difference in the atomic number is only 3 between Bi and Hg. In comparison with the U results, rather large discrepancies can be found; $q$-values seem to be smaller than those for Hg and Bi. This may imply the strong interference for the higher-$Z$ element. However, it is noted that the $q$-values for U were obtained with charge-unresolved data, which is similar to Fig. 1 in this paper, so that the systematic error might be larger than the values listed in the table. In order to study the $Z$-dependence of the interference effect, more systematic studies with different $Z$ will be needed.

DR processes and thus interference effects can be observed not only with emitted x-rays but also with extracted ions [7]. The extracted ion measurements have the following advantage compared to the x-ray measurements:

1. the ion measurements have higher efficiency because the total (extraction and transport) efficiency is an order of 10% while the observation solid angle for x-ray measurements is usually less than 0.1%,
2. the charge state of extracted ions can be clearly separated by an analyzing magnet.

In addition to the above, there is an essential difference between these methods; the ion measurements give an integrated cross section whereas the x-ray measurements give a differential cross section. Observation with extracted ions is on going and will be published elsewhere.
In summary, we studied interference between radiative and dielectronic recombination in the collisions between electrons and highly charged Bi ($Z = 83$) ions through x-ray observation using the Tokyo EBIT. The shape parameters $q$ obtained from the present measurements were very close to those obtained for Hg ($Z = 80$) by the Heidelberg group, but slightly larger than those obtained for U ($Z = 92$) by the Lawrence Livermore group. This may imply that the interference effect is larger for the higher-$Z$ element although more systematic studies including extracted ion measurements are needed to understand the $Z$-dependence.

Acknowledgments
This work was supported by the Matsuo Foundation and the JSPS program under the Japan-UK Research Cooperative Program, and partially supported by the CREST program, “Creation of Ultrafast Ultralow Power, Super-performance Nanodevices and Systems” in the Japan Science and Technology Agency. APK and FJC also acknowledge generous support from the Royal Society which made their participation in this experimental program possible.

4. References
[1] Fano U 1961 Phys. Rev. 124 1866
[2] Knapp D A, Beiersdorfer P, Chen M H, Scofield J H and Schneider D 1994 Phys. Rev. Lett. 74 54
[3] González Martínez A J, Crespo López-Urrutia J R, Braun J, Brenner G, Bruhns H, Lapierre A, Mironov V, Soria Orts R, Tawara H, M. Trinczek M, J. Ulrich J and J. H. Scofield J H 2005 Phys. Rev. Lett. 94 203201
[4] Currell F J, Asada J, Ishii K, Minoh A, Motohashi K, Nakamura N, Nishizawa K, Ohtani S, Okazaki K, Sakurai M, Shiraiishi H, Tsurubuchi S and Watanabe H 1996 J. Phys. Soc. Japan 65 3186
[5] Nakamura N, Asada J, Currell F J, Fukami T, Hirayama T, Kato D, Motohashi K, Nojikawa E, Ohtani S, Okazaki K, Sakurai M, Shimizu H, Tada N, Tsurubuchi S and Watanabe H 1998 Rev. Sci. Instrum. 69 694
[6] Yamada C, Nagata K, Nakamura N, Ohtani S, Tahahashi S, Tobiyaama T, Tona M, Sakurai M, Kavanagh A P and Currell F J 2006 Rev. Sci. Instrum. 77 066110
[7] Nakamura N, Tobiyaama H, Nohara H, Kato D, Watanabe H, Currell F J and Ohtani S 2006 Rad. Phys. Chem. in press