# Resonance electron-impact excitation and polarization of the magnetic quadrupole line of neonlike $Ba^{46+}$ ions

Jun Jiang, Chen-Zhong Dong,* and Lu-You Xie
*College of Physics and Electronics Engineering, Northwest Normal University, Lanzhou 730070, China*

Jian-Guo Wang
*Institute of Applied Physics and Computational Mathematic, Beijing 100088, China*

(Received 9 May 2008; published 14 August 2008)

Detailed calculations have been carried out for the direct electron-impact excitation and resonant excitation cross sections from the ground state to the individual magnetic sublevels of $(2p_{3/2}^{-1}3s_{1/2})_2$ of highly charged ions of neonlike barium by using a fully relativistic distorted-wave method. The contributions of resonant excitations to the linear polarization of the magnetic quadrupole ($M2$) line $[(2p_{3/2}^{-1}3s_{1/2})_2\text{-}2p^6\ {}^1S_0]$ have been investigated systematically. It is found that the $4l5l'$, $4l6l'$, and $5l5l'$ resonances have significant depolarizing or enhancing effects on the linear polarization. These results agree very well with the experimental measurements by Takács *et al.* [Phys. Rev. A **54**, 1342 (1996)].

DOI: 10.1103/PhysRevA.78.022709 PACS number(s): 34.80.Dp

## I. INTRODUCTION

When the highly charged ions are excited by an electron beam or more generally by electrons with an anisotropic velocity distribution, the excited state populations for the magnetic sublevels may be in a nonstatistical way. Then, the radiation emitted from these unequally populated sublevels to a lower level may be strongly polarized. The degree of polarization depends on the extent of deviation from the statistical populations of excited magnetic sublevels. So the polarization of radiation can provide the information on both the excitation dynamics and incident electrons, based on which an important diagnostic tool has been developed to characterize the electron anisotropy in laboratory and astrophysical plasmas. This innovative diagnostic has been applied successfully to plasmas produced by lasers [1], vacuum sparks [2], $Z$ pinches [3,4], and solar plasmas [5,6].

The polarization of x-ray line emission from highly charged ions colliding with an electron beam has been the matter of numerous theoretical studies during the last two decades. Inal and Dubou [7] have calculated the polarization degrees for the heliumlike and lithiumlike iron ions with a nonrelativistic theory; Itikawa *et al.* [8] have calculated the polarization degree for the heliumlike Li, O, and $Z\rightarrow\infty$ ions; Reed and Chen [9] have investigated the relativistic effect on the polarization for several heavy heliumlike ions by using the fully relativistic program of Zhang [10]. Kai *et al.* [11–13] have investigated the heliumlike Be, C, O, Cl, Fe, Kr, Xe, and Cu ions by using Breit-Pauli $R$-matrix method. The theoretical polarization degrees have also been tested by a series of measurements. Henderson *et al.* [14] reported the first polarization measurement of the x-ray emission line of the highly charged heliumlike $Sc^{19+}$ ions. Other reported polarization measurements include hydrogenlike, heliumlike, and lithiumlike ions of $Ti^{21+}$, $Ar^{17}$, $Fe^{25+}$, $Fe^{23+}$, $Fe^{24+}$, $Ti^{19+}$, $Ti^{20+}$, $S^{13+}$, and $S^{14+}$ [15–21]. Except for some hydrogenlike ions [20,21], the calculations and measurements agree very well. Besides the polarization from the $K$-shell transitions by the direct electron-impact excitation process [22–27], there exist a few works on the x-ray line polarization produced by the resonant electron excitations. Inal and Dubau [29] utilized the semirelativistic method to calculate the resonance contribution for excitation from a $J=0$ state to any magnetic sublevel of heliumlike iron. Recently, the fully relativistic approach was described by Zhang [30] and it has also been used to study the resonance contributions to the cross section for the transitions between magnetic sublevels in highly charged heliumlike oxygen and iron and berylliumlike oxygen. At the aspect of experiment, the magnetic quadrupole line of neonlike ions was originally observed in neonlike iron created in solar corona [31] and has since been observed in several other neonlike systems in the laboratory Tokamak source [32] as well as in electron beam ion trap (EBIT) [28,33]. Especially, the polarization of the magnetic quadrupole transition in neonlike $Ba^{46+}$ ions was measured at various electron energies by Takács *et al.* [28], and a strong evidence for the existence of resonant excitation processes was found. However, so far, to our knowledge no theoretical calculations have been carried out to consider the resonant excitation contributions for this system.

In the present work, a computationally fast and accurate fully relativistic distorted-wave program has been developed, based on Zhang's method [10,30] and the Grasp92 [34], Ratip [35], and REIE [36] packages, for calculating the specific magnetic sublevel excitations including both the direct and resonance excitation contributions. As an example, the electron-impact excitation processes of neonlike $Ba^{46+}$ ions are studied systematically, and the polarization degree of the magnetic quadrupole line is obtained and compared with the experimental measurements [28]. In Sec. II, we first provide a short description of the theoretical method and computational procedure. In Sec. III, the electron-impact excitation cross sections and the corresponding polarization are analyzed. Finally, a few conclusions about resonance excitation contributions to the electron-impact excitations are summarized in Sec. IV.

*Corresponding author; dongcz@nwnu.edu.cn

 

## II. THEORETICAL METHOD

In the isolated resonance approximation, the resonant excitation contributions can be added to the direct excitation contribution, thus, the electron-impact excitation cross section of the target ion from $\beta_i J_i M_i$ to $\beta_f J_f M_f$ can be written as [30]

$$\sigma_{\varepsilon_i}(\beta_i J_i M_i - \beta_f J_f M_f) = \sigma^{\mathrm{dir}}_{\varepsilon_i}(\beta_i J_i M_i - \beta_f J_f M_f) + \sigma^{\mathrm{res}}_{\varepsilon_i}(\beta_i J_i M_i - \beta_f J_f M_f) \qquad (1)$$

in which the subscripts $i$ and $f$ refer to the initial and final states, while $\varepsilon_i$ is the impact electron energy in Rydberg, $\beta$ represents all additional quantum numbers required to specify the initial and final states of the target ion in addition to its total angular momentum $J$ and $z$ component $M$, $\sigma^{\mathrm{dir}}_{\varepsilon_i}(\beta_i J_i M_i - \beta_f J_f M_f)$ and $\sigma^{\mathrm{res}}_{\varepsilon_i}(\beta_i J_i M_i - \beta_f J_f M_f)$ are the direct and resonant excitation cross sections from the given initial magnetic sublevel $M_i$ to the final magnetic sublevel $M_f$, respectively. It is convenient to choose the $z$ axis to be in the direction of the motion of the impact electron. Then the $z$ component of the impact electron orbital angular momentum is zero, namely $m_{l_i}=0$. In this case the direct electron-impact excitation cross section is written as [10]

$$\begin{aligned}\sigma^{\mathrm{dir}}_{\varepsilon_i}&(\beta_i J_i M_i - \beta_f J_f M_f)\\ &= \frac{2\pi a_0^2}{k_i^2} \sum_{\substack{l_i,l_i',j_i,j_i'\\ m_{si},l_f,j_f,m_f}} \sum_{J,J',M} (i)^{l_i-l_i'}[(2l_i+1)(2l_i'+1)]^{1/2}\\ &\quad\times \exp[i(\delta_{\kappa_i}-\delta_{\kappa_i'})] C\left(l_i \tfrac{1}{2} m_{l_i} m_{si}; j_i m_i\right) C\left(l_i' \tfrac{1}{2} m_{l_i'} m_{si}; j_i' m_i\right)\\ &\quad\times C(J_i j_i M_i m_i; JM) C(J_i j_i' M_i m_i; J'M) C(J_f j_f M_f m_f; JM)\\ &\quad\times C(J_f j_f M_f m_f; J'M) R(\gamma_i,\gamma_f) R(\gamma_i',\gamma_f'),\end{aligned} \qquad (2)$$

where $a_0$ is the Bohr radius, $C$'s are Clebsch-Gordan coefficients, $R$'s are the collision matrix elements, $\gamma_i = \varepsilon_i l_i j_i \beta_i J_i JM$ and $\gamma_f = \varepsilon_f l_f j_f \beta_f J_f JM$, $J$ and $M$ are the quantum numbers corresponding to the total angular momentum of the impact system, target ion plus free electron, and its $z$ component, respectively, $m_{s_i}$, $l_i$, $j_i$, $m_{l_i}$, and $m_i$ are the spin, orbital angular momentum, total angular momentum, and its $z$ component quantum numbers, respectively, for the incident electron $e_i$. $\delta_{\kappa_i}$ is the phase factor for the continuum electron. $\kappa$ is the relativistic quantum number, which is related to the orbital and total angular momentum $l$ and $j$. It turns out that the $R(\gamma_i,\gamma_f)$ are independent of $M$. $k_i$ is the relativistic wave number of the incident electron

$$k_i^2 = \varepsilon_i\left(1 + \frac{\alpha^2 \varepsilon_i}{4}\right), \qquad (3)$$

and $\alpha$ is the fine-structure constant.

For initially randomly orientated target ions, the case of interest here, one can average over initial magnetic sublevels $M_i$ of the target ion and obtain the cross section for excitation to a specific final magnetic sublevel $M_f$,

$$\sigma^{\mathrm{dir}}_{\varepsilon_i}(\beta_i J_i - \beta_f J_f M_f) = \frac{1}{2J_i+1} \sum_{M_i} \sigma^{\mathrm{dir}}_{\varepsilon_i}(\beta_i J_i M_i - \beta_f J_f M_f). \qquad (4)$$

The resonance contribution is treated as a two-step process, i.e., electron capture by an $N$-electron ion to form a doubly excited state $k$ of an $(N+1)$-electron ion followed by autoionization to the final level of the transition [30],

$$\sigma^{\mathrm{res}}_{\varepsilon_i}(\beta_i J_i M_i - \beta_f J_f M_f) = \sum_k \sigma^{\mathrm{cap}}(\beta_i J_i M_i - \beta_k J_k M_k) \times B(\beta_k J_k M_k - \beta_f J_f M_f), \qquad (5)$$

where $\sigma^{\mathrm{cap}}$ is the capture cross section and $B$ is the branching ratio, which is given by

$$B(\beta_k J_k M_k - \beta_f J_f M_f) = \frac{A^a(\beta_k J_k M_k - \beta_f J_f M_f)}{\sum_m A^a(k-m) + \sum_{m'} A^r(k-m')}. \qquad (6)$$

In Eq. (6) the autoionization rate $A^a(k-m)$ and radiation rate $A^r(k-m')$ can use the values for the autoionization and radiation rates between levels [30].

The capture cross section for unpolarized electrons is given by [30]

$$\sigma^{\mathrm{cap}}_{\varepsilon_i}(\beta_i J_i M_i - \beta_k J_k M_k) = S^{\mathrm{cap}}(\beta_i J_i M_i - \beta_k J_k M_k)\,\delta(\varepsilon_i - \varepsilon_{ik}), \qquad (7)$$

where

$$\begin{aligned}S^{\mathrm{cap}}&(\beta_i J_i M_i - \beta_k J_k M_k)\\ &= \frac{2\pi a_0^2}{k_i^2} \sum_{\substack{l_i,l_i',j_i,j_i'\\ m_{si}}} (i)^{l_i-l_i'}[(2l_i+1)(2l_i'+1)]^{1/2}\\ &\quad\times \exp[i(\delta_{\kappa_i}-\delta_{\kappa_i'})] C\left(l_i \tfrac{1}{2} 0 m_{si}; j_i m_i\right) C\left(l_i' \tfrac{1}{2} 0 m_{si}; j_i' m_i\right)\\ &\quad\times C(J_i j_i M_i m_i; J_k M_k)\\ &\quad\times C(J_i j_i' M_i m_i; J_k M_k) R(\gamma_k,\gamma_i) R(\gamma_k',\gamma_i').\end{aligned} \qquad (8)$$

Now we consider the autoionization process. Of course this is closely related to the inverse transition for electron capture. But in this case the ejected electron need not be moving in the $z$ direction. So the autoionization rate between magnetic sublevels is [30]

$$\begin{aligned}A^a&(\beta_k J_k M_k - \beta_f J_f M_f)\\ &= \frac{2}{\hbar} \sum_{l_f,j_f,m_f} |C(J_f j_f M_f m_f; J_k M_k) R(\gamma_k,\gamma_f)|^2.\end{aligned} \qquad (9)$$

In order to fit the experimental results, we replace the energy $\delta$ function with a Gaussian profile. The dielectronic resonance excitation strength, which is the integral of resonant excitation cross section over the natural width of resonance, can be written as

TABLE I. The direct electron-impact excitation cross sections ($cm^2$) from the ground state $2p^6$ $J=0$ to the specific magnetic sublevels $M_f$ of the level $2p_{3/2}^{-1}3s_{1/2}$ $J=2$ of neonlike $Ba^{46+}$ ions.

| $\varepsilon_i$ (eV) | $M_f=0$ | $M_f=\pm 1$ | $M_f=\pm 2$ | Total | Zhang [38] |
|---|---|---|---|---|---|
| 4823 | $1.66\times 10^{-23}$ | $1.57\times 10^{-23}$ | $1.28\times 10^{-23}$ | $7.36\times 10^{-23}$ | $7.10\times 10^{-23}$ |
| 5848 | $1.26\times 10^{-23}$ | $1.16\times 10^{-23}$ | $8.67\times 10^{-24}$ | $5.32\times 10^{-23}$ | $4.97\times 10^{-23}$ |
| 7768 | $7.62\times 10^{-24}$ | $7.00\times 10^{-24}$ | $5.13\times 10^{-24}$ | $3.19\times 10^{-23}$ | $2.82\times 10^{-23}$ |
| 11288 | $4.89\times 10^{-24}$ | $4.47\times 10^{-24}$ | $3.23\times 10^{-24}$ | $2.03\times 10^{-23}$ | $1.24\times 10^{-23}$ |

$$S^{\mathrm{res}}(\beta_iJ_iM_i-\beta_fJ_fM_f)=S^{\mathrm{cap}}(\beta_iJ_iM_i-\beta_kJ_kM_k)\times B(\beta_kJ_kM_k-\beta_fJ_fM_f). \quad (10)$$

The convoluted resonance cross section is

$$\sigma_{\varepsilon_i}^{\mathrm{res}}(\beta_iJ_iM_i-\beta_fJ_fM_f)=\sum_k\frac{S^{\mathrm{res}}(\beta_iJ_iM_i-\beta_fJ_fM_f)}{\sqrt{2\pi}\Gamma}\times\exp\left(-\frac{(\varepsilon_i-\varepsilon_{ik})^2}{2\Gamma^2}\right). \quad (11)$$

In order to compare with the experimental results [28] directly, we choose the width $\Gamma$ as 5 eV which is the uncertainty of the electron beam energy in the experiment [28].

The polarization degree of the radiation emitted without detecting the scattered electron is then defined by

$$P=\frac{I_{\parallel}-I_{\perp}}{I_{\parallel}+I_{\perp}}, \quad (12)$$

where $I_{\parallel}$ and $I_{\perp}$ are the intensities of photons with electric vectors parallel and perpendicular to the electron beam direction, respectively. If we assume that electron-impact excitation is the dominant mechanism for populating the upper magnetic sublevel, the linear polarization degree for radiation from the $J=2$ to the $J=0$ line is [7]

$$P=\frac{\sigma_2-\sigma_1}{\sigma_2+\sigma_1}, \quad (13)$$

where $\sigma_2$ and $\sigma_1$ are the electron-impact excitation cross sections from the ground state to the $M_f=2$ and $M_f=1$ magnetic sublevels, respectively.

### III. RESULTS AND DISCUSSIONS

The resonant excitation process for the magnetic sublevels of the magnetic quadrupole line of neonlike $Ba^{46+}$ ions can be characterized as

$$\begin{aligned}e^-(\varepsilon_il_ij_i)+\mathrm{Ba}^{46+}(2p^6;J=0,M_i=0)&\\ \rightarrow \mathrm{Ba}^{45+}(2p^5nln'l';J_kM_k)&\\ \rightarrow \mathrm{Ba}^{46+}(2p^53s;J=2,M_f)&\\ +e^-(\varepsilon_fl_fj_f).&\end{aligned}$$

In the calculations, the contributions from the double excited states $4l5l'$, $4l6l'$, and $5l5l'$ are included. They give the dominant contribution over the energy range calculated by theory and observed by experiments [28,36].

In the calculations of the initial- and final-state wave functions for target, besides the configurations of the $2s^22p^6$ and $2s^22p^53s$, we have also considered the configuration interactions among the $2s^22p^53p$, $2s^22p^53d$, $2s2p^53s$, $2s2p^53p$, and $2s2p^53d$, in which 37 levels are included totally. The continuum wave function is generated by the component COWF of Ratip package [37] by solving the coupled Dirac equation in which the exchange effect between the bound and free electron are considered. Since continuum orbitals cannot reach asymptotic sinusoidal behavior quickly, especially for those with low energy and high quantum numbers, some direct transition matrix elements depend on the larger $r$ behavior of continuum orbitals. So it is necessary to calculate the continuum radial functions to the very large $r$, and contain its contribution to transition matrix elements. In this work, the largest $r$ is chosen as 190 a.u.

To our knowledge there are no other theoretical results of electron-impact excitation cross sections available to the magnetic sublevels of neonlike $Ba^{46+}$ ions with which we can compare. However we can make comparisons with some experimental and theoretical results to the fine-structure levels. In Table I some direct impact excitation cross sections resolved to magnetic sublevels are shown and compared with the available theoretical results [38]. From the table we can find that a variational trend agrees very well for the two theoretical calculations. But our results are a little larger than those of Zhang *et al.* [38]. Although we do not know the details of their calculation, the deviation, we think, may come from the different radial integral range. If we choose 70 a.u. as the integral range, the total cross sections are $7.12\times 10^{-23}$ $cm^2$, $5.02\times 10^{-23}$ $cm^2$, $2.90\times 10^{-23}$ $cm^2$, and $1.29\times 10^{-23}$ $cm^2$ for the incident energy 4824 eV, 5848 eV, 7768 eV, and 11 288 eV, respectively. These results agree with those of Zhang *et al.* very well. So we think that the results of Zhang *et al.* may not be convergent. In Table II our results are compared with some measurements and other calculations. No obvious discrepancy is found for the considered states.

In Fig. 1 the cross sections from the ground state $2p^6$ $J=0$ to the magnetic sublevels of the level $2p^53s$ $J=2$ are displayed, and both the direct and resonant excitations from the $4l5l'$, $4l6l'$, and $5l5l'$ are included. The resonance structures can be clearly identified from the figure. For the energy ranging from 5 keV to 5.2 keV, the $4l5l'$ resonance dominates the indirect contribution and the cross section enhances more than 2 times compared with the direct excitation. In the EBIT experiment [33], it was found that the emission of $M2$ is enhanced by more than 50% in the same energy range due to resonance excitation. However, in Ref. [28], the $4l6l'$ and

TABLE II. Theoretical and experimental direct electron-impact excitation cross sections ($10^{-21}$ cm$^2$) from the ground state $2p^6$ $J=0$ of neonlike $Ba^{46+}$.

| | $\varepsilon_i$=5.69 keV | | | | $\varepsilon_i$=8.20 keV | | | |
|---|---|---|---|---|---|---|---|---|
| Up level | This work | Reed [39] | Ivanov [40] | Experiment [41] | This work | Reed [39] | Ivanov [40] | Experiment [41] |
| $(2p_{3/2}^{-1}3p_{3/2})_0$ | 1.25 | 1.13 | | | 0.99 | 0.84 | | |
| $(2p_{1/2}^{-1}3p_{1/2})_0$ | 0.89 | 0.79 | | | 0.70 | 0.58 | | |
| $(2p_{1/2}^{-1}3s_{1/2})_0$ | 0.75 | 0.68 | | | 0.61 | 0.52 | | |
| Sum $J=0$ | 2.89 | 2.60 | 2.48 | $2.50\pm0.35$ | 2.30 | 1.95 | 1.83 | $2.27\pm0.32$ |
| $(2p_{3/2}^{-1}3d_{5/2})_1$ | 3.63 | 3.55 | 3.20 | $3.98\pm0.56$ | 3.54 | 3.23 | 2.87 | $3.30\pm0.46$ |
| $(2p_{1/2}^{-1}3d_{3/2})_1$ | 2.12 | 2.00 | 1.78 | $2.12\pm0.30$ | 2.06 | 1.82 | 1.64 | $1.82\pm0.25$ |

$5l5l'$ contributions were thought too small to be seen in a plot of total line intensity, but both of them were observed in the high-resolution polarization measurement. From the present work we can see that the contributions of the $5l5l'$ and $4l6l'$ are really very small, but the contributions of the $5l5l'$ are larger than those of the $4l6l'$. The dielectronic resonance excitation strength of the given doubly excited states which have large contributions on the resonance excitation are given in Table III.

In Fig. 2 the present calculated polarization degrees of the $M2$ line are compared with the existing measurements of Takács *et al.* [28]. The present results are shifted to the left 130 eV for considering the space charge effects in the experiment [28]. If only the direct impact excitations are considered in our calculations, the negative polarization degree increases from 10% to 13% smoothly with increasing of electron energy, which agrees with the experiment of Takács *et al.* [28] very well. The averaged polarization degree of $-12\%\pm10\%$ also agrees with the assumption of $-5\%\pm10\%$ by Beiersdorfer *et al.* [33] at the considered energy range. For the energy from 5.3 keV to 5.6 keV, where the $4l6l'$ resonance series is dominant, the change of polarization is relatively small because of relatively small resonance excitation contributions. However, when the energy is larger than 5.6 keV, the effects of the $5l5l'$ resonance excitation on the polarization are very obvious. There are two peaks with the obvious decreasing of negative polarization for the energy close to 5.8 keV, and one of them was measured by Takács *et al.* [28]. For the energy near 5.75 keV, the negative polarizations were increased to −26%, which was not measured by experiment because of the limited energy points. Comparing with the Takács *et al.* [28] calculations with the cascade scheme, we can find that the cascade effects may play a relatively small role.

For the energy ranging from 4.9 keV to 5.3 keV, where the contribution of the double excited states $4l5l'$ is dominant, the negative polarization degree is largely enhanced to −22% at the energy near 5 keV, and at the energy near 5.1 keV the polarization degrees decrease strongly, which agrees with the experiments excellently. However, in this

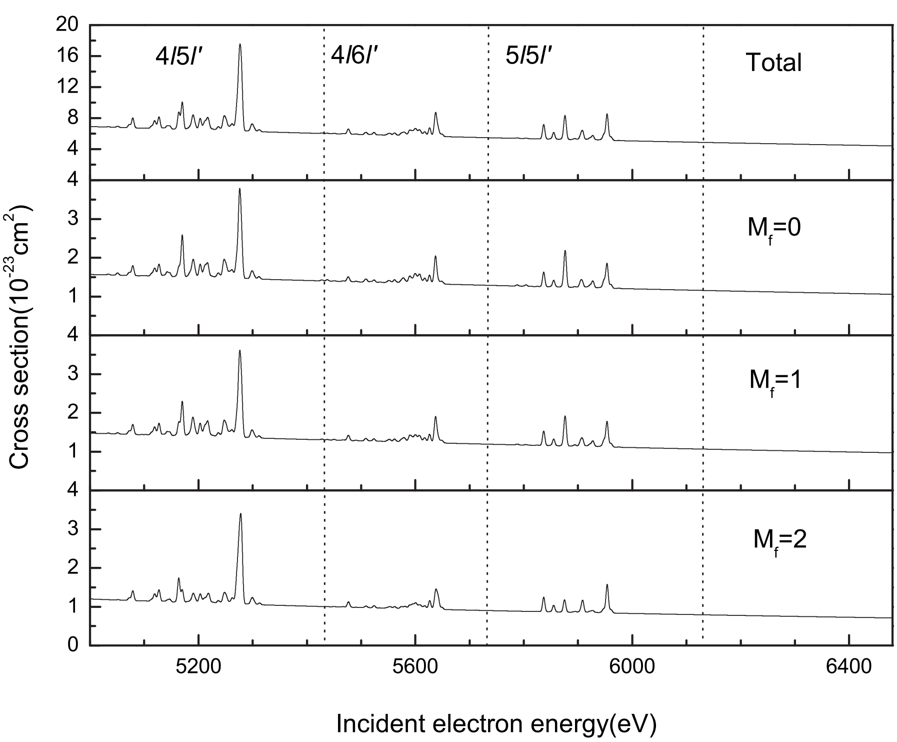


FIG. 1. The electron-impact excitation cross sections of neonlike $Ba^{46+}$ from the ground state $2p^6$ $J=0$ to the specific magnetic sublevels $M_f$ of the level $2p_{3/2}^{-1}3s_{1/2}$ $J=2$ as a function of the incident electron energy.

TABLE III. The dielectronic resonance excitation strength for the $M2$ line $[2p^6\,{}^1S_0-(2p_{3/2}^{-1}3s_{1/2})_2]$ of neonlike $Ba^{46+}$.

| Doubly excited state | Resonance energy ($10^3$ eV) | Total $S^{res}$ ($10^{-22}$ cm$^2$ eV) |
|---|---|---|
| $4l5l'$ | | |
| $[(2p_{3/2}^{-1}4p_{3/2})_0 5s_{1/2}]_{1/2}$ | 5.17 | 10.14 |
| $[(2p_{3/2}^{-1}4f_{7/2})_5 5d_{5/2}]_{9/2}$ | 5.27 | 4.91 |
| $[(2p_{3/2}^{-1}4f_{5/2})_2 5d_{5/2}]_{7/2}$ | 5.28 | 17.80 |
| $[(2p_{3/2}^{-1}4f_{7/2})_3 5d_{5/2}]_{9/2}$ | 5.28 | 9.02 |
| $4l6l'$ | | |
| $[(2p_{3/2}^{-1}4f_{5/2})_3 6d_{5/2}]_{7/2}$ | 5.64 | 5.15 |
| $[(2p_{3/2}^{-1}4f_{7/2})_4 6d_{5/2}]_{9/2}$ | 5.64 | 2.57 |
| $5l5l'$ | | |
| $[(2p_{3/2}^{-1}5s_{1/2})_2 5p_{3/2}]_{1/2}$ | 5.84 | 5.49 |
| $[2p_{3/2}^{-1}(5p_{3/2}^2)_0]_{3/2}$ | 5.88 | 4.72 |
| $[(2p_{3/2}^{-1}5d_{5/2})_1 5f_{5/2}]_{7/2}$ | 5.95 | 5.40 |
| $[(2p_{3/2}^{-1}5d_{5/2})_1 5f_{5/2}]_{9/2}$ | 5.95 | 4.44 |

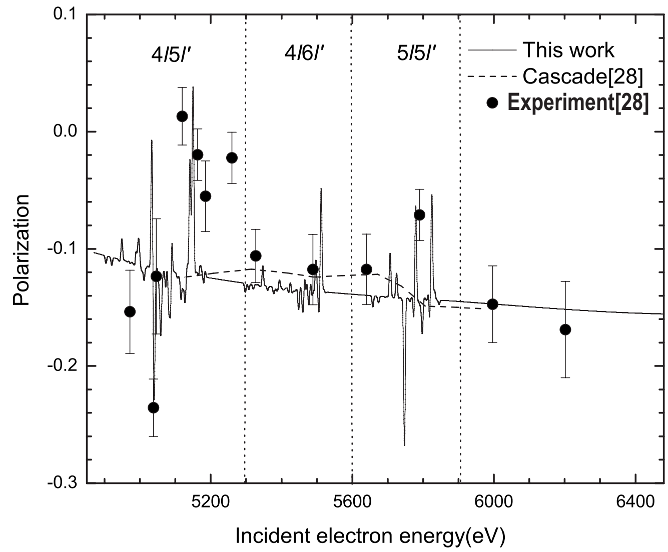


FIG. 2. Linear polarization degree of neonlike $Ba^{46+}$ $M2$ line $(2p_{3/2}^{-1}3s_{1/2})_2 \rightarrow 2p^6$ $J=0$ as a function of the incident electron energy. Solid line represents the present work; dashed lines represent the Takács *et al.* [28] calculations which considered the cascade scheme. The experimental data from Takács *et al.* [28] are given as solid circles.

energy range, there are also some sharp decreases of the negative polarization in the experiment, but could not be reproduced by our calculations. In order to explain the discrepancies between the experiments and the present calculations, the other processes, such as the elastic collision, inner-shell ionization of sodiumlike $Ba^{45+}$ ions, the radiative recombination (RR) of fluorinelike $Ba^{47+}$ ions and the dielectron recombination (DR) of fluorinelike $Ba^{47+}$ ions, should be considered. After a preliminary estimate, it can be concluded that the contributions of the elastic collision, inner-shell ionization of sodiumlike $Ba^{45+}$ ions and the RR of fluorinelike $Ba^{47+}$ ions are too small to explain the present sharp discrepancies in the energy range of 4.9 keV to 5.3 keV. But it is noted that the DR process of fluorinelike $Ba^{47+}$ ions may be one of the main factors which lead to the discrepancies between the experiments and present calculations and some detailed calculations will be done in future works.

## IV. CONCLUSION

Detailed calculations have been carried out for the direct electron-impact excitation and the $4l5l'$, $4l6l'$, and $5l5l'$ resonant excitation cross sections from the ground state to the individual magnetic sublevels of the fine-structure level $(2p_{3/2}^{-1}3s_{1/2})_2$ of the highly charged neonlike $Ba^{46+}$ ions by using a fully relativistic distorted-wave method and our developed program. The polarization of the magnetic quadrupole line has been investigated systematically. Our results show that the $4l5l'$ resonant series have larger contributions on the electron-impact excitation cross sections which are enhanced more than 2 times compared with the direct excitation in the energy range of 5 keV to 5.2 keV. The polarization changes from −22% to 4% in this energy range, but there are still some sharp decreases of polarization in the experiment, which could not be reproduced by our calculations. Perhaps it is due to the DR process of fluorinelike $Ba^{47+}$ ions. However, the $4l6l'$ and $5l5l'$ resonant series have small contributions to the excitation cross sections, but they make the polarization of the $M2$ line change evidently. Our calculations are found to be in good agreement with the experimental results in the same energy range.


## ACKNOWLEDGMENTS

This work has been supported by the National Natural Science Foundation of China (Grants No. 10434100 and 10774122), the China/Ireland Science and Technology Collaboration Research Fund (Contract No. CI-2004-07), the Specialized Research Fund for the Doctoral Program of Higher Education of China (Grant No. 20070736001) and the Foundation of Northwest Normal University (Grant No. NWNU-KJCXGC-03-21).



[1] J. C. Kieffer, J. P. Matte, M. Chaker, Y. Beaudoin, C. Y. Chien, S. Coe, G. Mourou, J. Dubau, and M. K. Inal, Phys. Rev. E **48**, 4648 (1993).

[2] R. Beier, C. Bachmann, and R. Burhenn, J. Phys. D **14**, 643 (1981).

[3] A. S. Shlyaptseva, S. B. Hansen, V. L. Kantsyrev, B. S. Bauer, D. A. Fedin, N. Ouart, S. A. Kazantsev, A. G. Petrashen, and U. I. Safronova, Rev. Sci. Instrum. **72**, 1241 (2001).

[4] A. S. Shlyaptseva, V. L. Kantsyrev, N. Ouart, D. Fedin, S. Hamasha, and S. Hansen, Proc. SPIE **5196**, 16 (2003).
[5] E. Haug, Sol. Phys. **61**, 129 (1979).
[6] E. Haug, Sol. Phys. **71**, 77 (1981).
[7] M. K. Inal and J. Dubau, J. Phys. B **20**, 4221 (1987).
[8] Y. Itikawa, R. Srivastava, and K. Sakimoto, Phys. Rev. A **44**, 7195 (1991).
[9] K. J. Reed and M. H. Chen, Phys. Rev. A **48**, 3644 (1993).
[10] H. L. Zhang, D. H. Sampson, and R. E. H. Clark, Phys. Rev. A **41**, 198 (1990).
[11] T. Kai, S. Nakazaki, and K. A. Berrington, Nucl. Instrum. Methods Phys. Res. B **235**, 249 (2005).
[12] T. Kai, S. Nakazaki, T. Kawamura, H. Nishimura, and K. Mima, Phys. Rev. A **75**, 012703 (2007).
[13] T. Kai, S. Nakazaki, T. Kawamura, H. Nishimura, and K. Mima, Phys. Rev. A **75**, 062710 (2007).
[14] J. R. Henderson, P. Beiersdorfer, C. L. Bennett, S. Chantrenne, D. A. Knapp, R. E. Marrs, M. B. Schneider, K. L. Wong, G. A. Doschek, J. F. Seely, C. M. Brown, R. E. LaVilla, J. Dubau, and M. A. Levine, Phys. Rev. Lett. **65**, 705 (1990).
[15] P. Beiersdorfer, D. A. Vogel, K. J. Reed, V. Decaux, J. H. Scofield, K. Widmann, G. Hölzer, E. Förster, O. Wehrhan, D. W. Savin, and L. Schweikhard, Phys. Rev. A **53**, 3974 (1996).
[16] P. Beiersdorfer, J. Crespo Lóez-Urrutia, V. Decaux, K. Widmann, and P. Neill, Rev. Sci. Instrum. **68**, 1073 (1997).
[17] A. S. Shlyaptseva, R. C. Mancini, P. Neil, and P. Beiersdorfer, Rev. Sci. Instrum. **68**, 1095 (1997).
[18] P. Beiersdorfer, G. Brown, S. Utter, P. Neill, K. J. Reed, A. J. Smith, and R. S. Thoe, Phys. Rev. A **60**, 4156 (1999).
[19] D. L. Robbins, A. Ya. Faenov, T. A. Pikuz, H. Chen, P. Beiersdorfer, M. J. May, J. Dunn, K. J. Reed, and A. J. Smith, Phys. Rev. A **70**, 022715 (2004).
[20] N. Nakamura, D. Kato, N. Miura, T. Nakahara, and S. Ohtani, Phys. Rev. A **63**, 024501 (2001).
[21] D. L. Robbins, P. Beiersdorfer, A. Ya. Faenov, T. A. Pikuz, D. B. Thorn, H. Chen, K. J. Reed, A. J. Smith, K. R. Boyce, G. V. Brown, R. L. Kelley, C. A. Kilbourne, and F. S. Porter, Phys. Rev. A **74**, 022713 (2006).
[22] Y. Itikawa, R. Srivastava, and K. Sakimoto, Phys. Rev. A **44**, 7195 (1991).
[23] M. K. Inal and J. Dubau, J. Phys. B **22**, 329 (1989).
[24] A. S. Shlyaptseva, I. E. Golovkin, and U. I. Safronova, J. Quant. Spectrosc. Radiat. Transf. **56**, 157 (1996).
[25] A. S. Shlyaptseva, R. C. Mancini, P. Neill, P. Beiersdorfer, J. R. Crespo López-Urrutia, and K. Widmann, Phys. Rev. A **57**, 888 (1998).
[26] M. H. Chen and J. H. Scofield, Phys. Rev. A **52**, 2057 (1995).
[27] P. Hakel, R. C. Mancini, C. Harris, P. Neill, P. Beiersdorfer, G. Csanak, and H. L. Zhang, Phys. Rev. A **76**, 012716 (2007).
[28] E. Takács, E. S. Meyer, J. D. Gillaspy, J. R. Roberts, C. T. Chantler, L. T. Hudson, R. D. Deslattes, C. M. Brown, J. M. Laming, J. Dubau, and M. K. Inal, Phys. Rev. A **54**, 1342 (1996).
[29] M. K. Inal and J. Dubau, Phys. Rev. A **47**, 4794 (1993).
[30] H. L. Zhang and D. H. Sampson, Phys. Rev. A **66**, 042704 (2002).
[31] M. Loulergue and H. Nussbaumer, Astron. Astrophys. **24**, 209 (1973).
[32] M. Klapisch *et al.*, Phys. Lett. **69**, 34 (1978).
[33] P. Beiersdorfer, A. L. Osterheld, M. H. Chen, J. R. Henderson, D. A. Knapp, M. A. Levine, R. E. Marrs, K. J. Reed, M. B. Schneider, and D. A. Vogel, Phys. Rev. Lett. **65**, 1995 (1990).
[34] F. A. Parpia, C. F. Fischer, and I. P. Grant, Comput. Phys. Commun. **94**, 249 (1996).
[35] S. Fritzsche *et al.*, Nucl. Instrum. Methods Phys. Res. B **205**, 93 (2003).
[36] J. Jiang, C. Z. Dong, L. Y. Xie, J. G. Wang, J. Yan, and S. Fritzsche, Chin. Phys. Lett. **24**, 691 (2007).
[37] S. Fritzsche, J. Electron Spectrosc. Relat. Phenom. **114–116**, 1155 (2001).
[38] H. L. Zhang and D. H. Sampson, At. Data Nucl. Data Tables **43**, 1 (1989).
[39] K. J. Reed, Phys. Rev. A **37**, 1791 (1988).
[40] L. N. Ivanov, E. P. Ivanova, and L. V. Knight, Phys. Rev. A **48**, 4365 (1993).
[41] R. E. Marrs, M. A. Levine, D. A. Knapp, and J. R. Henderson, Phys. Rev. Lett. **60**, 1715 (1988).