# Absolute cross sections and decay rates for the triply excited $B^{2+}(2s2p^2\ ^2D)$ resonance in electron–metastable-ion collisions

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(Received 7 June 2001; published 7 February 2002)

Triply excited states of three-electron ions have been produced by resonant transfer excitation (RTE) in metastable two-electron-ion-beam–$H_2$ collisions. Measurements of the Auger-electron emission in the direction of the ion beam is used to determine the absolute cross sections for formation of the triply excited states and the branching ratios of the corresponding elastic and inelastic electron scattering channels. The results are compared to existing theoretical calculations of the Auger decay rates. Accurate measurements of the double differential cross sections are made on the bases of the known metastable ion beam fractions and known cross sections for RTE from the ground-state component of the beam. The system investigated is $B^{3+}(1s2s\ ^3S) + H_2$ leading to the $B^{2+}(2s2p^2\ ^2D)$ resonance that decays to $B^{3+}(1s2s\ ^3S)$, the elastic scattering channel and to $B^{3+}(1s2s\ ^1S)$ and $B^{3+}(1s2p\ ^3P)$, two inelastic scattering channels.

DOI: 10.1103/PhysRevA.65.032705 PACS number(s): 34.50.Fa, 32.80.Hd, 32.80.Dz

## I. INTRODUCTION

The excitation and decay dynamics of triply excited states have recently become the subject of intense experimental and theoretical interest. Studies of ions with an empty *K* shell provide new information on the correlated motion of a pair of electrons in the field of a nucleus. A number of transitions to states with an empty *K* shell were observed for Li I and Be II using the foil excitation technique [1–4]. The first observation of the transition to the $2s2p^2\ ^2D$ triply excited state from the $1s2s\ ^3S$ state was done for B and F Li-like ions [5,6]. A new interest in the subject arose and many publications appeared in a short period of time when the high-resolution photon-electron excitation method was introduced. Highly accurate measurements of the photoabsorbtion spectra have been made for transitions to various triply excited states [7–9]. The decay dynamics of the hollow lithium $2s^22p\ ^2P$ state into the different continua of the $Li^+$ ion has been studied experimentally. The first experimental determinations of partial photoionization cross sections for the lowest hollow lithium resonance ($2s^22p\ ^2P$ to $1s2s\ ^3S$, and $2s^22p\ ^2P$ to $1s2p\ ^3P$) were reported [10,11]. The photoexcitation of the ground state by a one-photon process is, however, limited to $^2P^o$ final states due to the dipole selection rules. Consequently, triply excited states with other configurations have received less attention and still pose experimental challenges. Absolute cross section measurements of the excitations to these hollow states, therefore, require different excitation techniques.

Simultaneous excitation of all three electrons from the ground state of $B^{2+}$ ions directly into the $2s2p^2\ ^2D$ state presents some experimental difficulties associated with small cross sections for the process. Alternatively, the excitation can be divided into two steps. First, one *K* shell vacancy is produced in the primary Li-like beam by stripping it in a foil, which leaves some ions in the metastable $1s2s\ ^3S$ state of $B^{3+}$. The fraction of $^3S$ ions in He-like $B^{3+}$ beams, produced in the foil, has been recently determined to high accuracy [12,13]. The transition to the triply excited $2s2p^2\ ^2D$ state is then induced in collisions of $B^{3+}(1s2s\ ^3S)$ with target gas by resonant transfer excitation (RTE). The use of ions which were initially *preexcited* to the $1s2s\ ^3S$ state, makes it possible to isolate processes contributing to the formation of the $2s2p^2\ ^2D$ state and thus, facilitates a critical comparison with recent theoretical results.

In the present paper the $B^{3+}(1s2s\ ^3S)$ metastable beam has been used to populate the triply excited $2s2p^2\ ^2D$ state of $B^{2+}$ in collisions with molecular hydrogen targets. The resonance was observed to decay back to the $B^{3+}(1s2s\ ^3S)$, the elastic scattering channel and to the $B^{3+}(1s2s\ ^3S)$ and $B^{3+}(1s2p\ ^3P)$, the two inelastic scattering channels, as shown in Fig. 1. Measurements of the Auger electron emission in the direction of the ion beam were used to determine the absolute cross sections for the formation of the $2s2p^2\ ^2D$ state and the branching ratios of the corresponding electron scattering channels. In particular, it was shown that the decay to the $1s2p\ ^3P$ state, known to contribute the most to the autoionization rates of other $2121'21''$ levels [14], does not dominate for $2s2p^2\ ^2D_j$ states. It was also

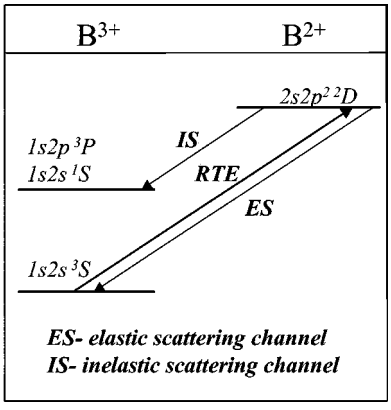


FIG. 1. The formation and decay energy diagram of the triply excited resonance $2s2p^2\ ^2D$ of $B^{2+}$, produced in collisions of the metastable $B^{3+}(1s2s\ ^3S)$ ions with an $H_2$ target.

 

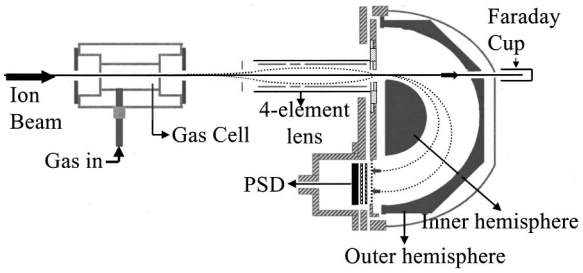


FIG. 2. Zero degree electron spectrometer with shown schematic of the gas cell, four-element lens, and hemispherical analyzer with a two-dimensional position sensitive detector labeled PSD.

demonstrated that the $2s2p^2\ ^2D$ state is populated primarily by RTE, and therefore, it was possible to extract the autoionization rates for the $2s2p^2\ ^2D_j$ to $1s2s\ ^3S$ decay channel from the measured cross sections. The results have been compared to the recent theoretical prediction of the perturbation ($1/Z$ expansion) method [14]. A very good agreement with theory has been observed for the measured decay branching ratio. However, the theoretical autoionization rate for the $2s2p^2\ ^2D$ to $1s2s\ ^3S$ decay compared to the experimental one was found to be higher by a factor of $1/0.61 = 1.64$.

## II. EXPERIMENTAL METHOD

The experiments were performed in the J. R. Macdonald Laboratory at Kansas State University, using the 7 MV EN tandem Van de Graaff accelerator. Primary beams of boron ions in the $2+$ charge state were produced in the accelerator terminal $N_2$ gas stripper and then poststripped in a 5 $\mu$g/cm$^2$ carbon foil to achieve the desired charge state of $3+$. After stripping, the $B^{3+}$ beams were focused into a 5 cm long differentially pumped gas cell, approximately 12 m downstream from the stripping foil [15]. In this arrangement 99.99% of the metastable $1s2s\ ^3S$ ions (lifetime$\approx$100 ms [14]) produced at 4 MeV will reach the target. Since knowledge of the fraction of metastable ions in incident $B^{3+}(1s2s\ ^3S,1s^2\ ^1S)$ beams is crucial for absolute cross section measurements, a newly developed technique has been used to determine the metastable population of the beam [12,13]. It is also important that only by stripping in the foil can we maximize the metastable fraction, which, in this case, equals 26–27 % [13], independent of the beam energy for the investigated range of ion energies. The target pressure was set at 20 mTorr to ensure the single collision regime. Auger electrons emitted in the forward direction from the $2s2p^2\ ^2D$ state have been detected with a new, high-efficiency zero degree Auger spectrograph [16,20], capable of analyzing Auger electrons in an energy bandwidth of about 20%, which significantly facilitates experimental measurements of low-intensity processes. The diagram of the experimental setup is shown in Fig. 2.

The state of interest, $2s2p^2\ ^2D$, is formed in collisions of the metastable $1s2s\ ^3S$ ions with hydrogen gas by RTE. It is a two-electron process where a weakly bound target $1s$ electron is transferred to a $2p$ orbital of the projectile and simultaneously excites the $1s$ projectile electron to a $2p$ state. The single differential RTE cross sections can be evaluated within the impulse approximation (IA) [17], the process, relating electron-ion cross sections to ion-atom scattering, also more recently referred to as the electron scattering model. The RTE cross section is given below:

$$\frac{d\sigma_{\mathrm{RTEA}}}{d\Omega} = \Omega_{\mathrm{RES}} \frac{J(Q)}{V_p + Q} \frac{W(\theta)}{4\pi}, \tag{1}$$

where $J(Q)$ is a Compton profile of the target, $V_p$ is the projectile velocity, $Q$ is the component of the target electron momentum in the direction of the beam, $\Omega_{\mathrm{RES}}$ is the resonant excitation-scattering cross section calculated using the LS-coupling scheme [18], and $W(\theta)$ is the angular distribution factor, which in case of the zero degree electron emission angle $\theta$ simply equals $2L+1$ [19]. Zero-degree RTE cross sections have been measured previously and compared with calculations using the electron scattering model [18,20,22], leading to a good agreement [21]. Therefore, by matching the theoretical RTE cross sections to the measured ones, the experimental determination of the autoionization rate that enters Eq. (1) as a factor is possible. To minimize the error due to the IA, which requires the projectile velocity to be much larger than the orbiting velocity of a target electron, $H_2$ molecules with slow loosely bound electrons were chosen as a target. In this case the uncertainty of measurements of the autoionization rate due to the possible error of predicted RTE cross sections is estimated to be less than 20% [18].

To obtain the RTE cross section from the Auger electron spectra, the measured electron yield from the $2s2p^2\ ^2D$ state has been normalized to the $1s2p^2\ ^2D$ line obtained in the same measurement. As discussed above, the cross section for the $1s2p^2\ ^2D$ to $1s^2\ ^1S$ transition can be accurately evaluated using Eq. (1) with Auger decay parameters obtained from Ref. [23]. It should also be corrected for the fraction of the metastable $1s2s\ ^3S$ ions in incident beams,

$$\left(\frac{d^2\sigma}{d\Omega\, dE}\right)^{2s2p^{2\,2}D}_{\mathrm{RTEA}} = \left(\frac{d^2\sigma}{d\Omega\, dE}\right)^{1s2p^2\ ^2D}_{\mathrm{RTEA}} \times \left(\frac{Y_{(2s2p^2\ ^2D)}}{Y_{(1s2p^2\ ^2D)}} \frac{[1-F(E)]}{F(E)}\right),$$

where $F(E)$ is the fraction of ions in the $1s2s\ ^3S$ state, $(d^2\sigma/d\Omega\, dE)^{1s2p^2\ ^2D}_{\mathrm{RTEA}}$ is the known cross section for the $1s2p^2\ ^2D$ to $1s^2\ ^1S$ transition, $Y_{(1s2p^2\ ^1D)}$ and $Y_{(2s2p^2\ ^1D)}$ are the measured electron yields for the $1s2p^2\ ^2D$ to $1s^2\ ^1S$ and $2s2p^2\ ^2D$ to $1s2s\ ^3S$ transitions, respectively.

## III. RESULTS

The Auger decay of the $2s2p^2\ ^2D$ state can result in different states of $B^{3+}$. Figure 3 shows two examples of Auger electron spectra obtained in the collision of 4.4 and 5.1 MeV $B^{3+}$ ions on $H_2$. The Auger electrons at 200.5 and 204.9 eV, emitted from the $2s2p^2\ ^2D$ state were observed. Using the recent calculation of the Auger energies for various decay channels from the $2s2p^2\ ^2D$ state [14] it was possible to

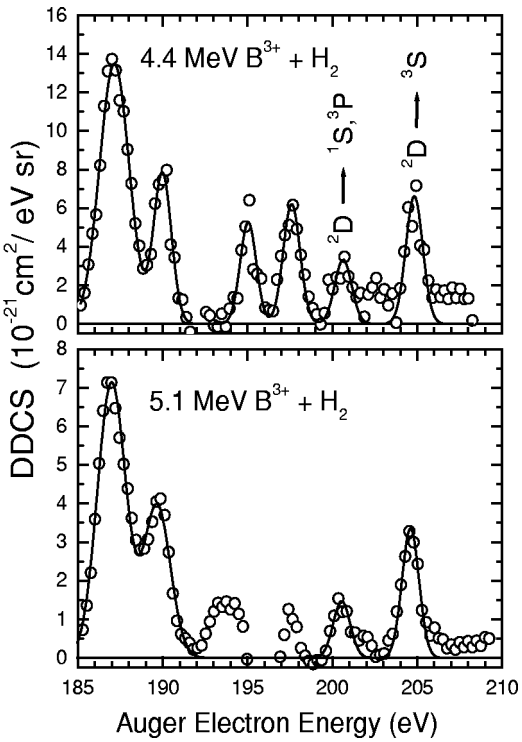


FIG. 3. 0° Auger projectile electron spectra measured for $B^{3+}+H_2$ collisions at two projectile energies of 4.4 and 5.1 MeV are presented. Auger electron peaks at 200.5 and 204.9 eV are attributed to the $1s2p\ ^3P$, $1s2s\ ^3S$ and to the $1s2s\ ^3S$ Auger decay channels from the $2s2p^2\ ^2D$ state, respectively. The bold lines are the Gaussian fits to the two Auger electron peaks.

identify the observed transitions. The more pronounced peak at 204.9 eV was attributed to the $1s2s\ ^3S$ elastic Auger decay channel. The peak at 200.5 eV consists of the two unresolved $1s2p\ ^3P$ and $1s2s\ ^1S$ inelastic Auger decay channels. The separation in Auger energy between these two states is approximately 0.15 eV, which makes the task of measuring individual cross sections extremely difficult. However, their combined contribution is measurable and can be used to estimate the branching ratio for the $1s2s\ ^3S$ decay channel providing another test of theory. No evidence of the Auger electrons corresponding to $1s2p\ ^1P$ Auger decay was observed, which is consistent with the available theoretical predictions estimating that the contribution of this decay channel to the total autoionization rate is negligible for ions with $Z<10$. Since the Auger decay channels for the $2s2p^2\ ^2D$ state are limited to the ones described above, the unambiguous identification of the relaxation for this state has been made.

The absolute differential cross sections for the $1s2s\ ^3S$ to $2s2p^2\ ^2D$ excitation followed by the more pronounced decay to the $1s2s\ ^3S$ state were obtained from the Auger spectra by using Eq. (1). To confirm the resonant behavior of the $1s2s\ ^3S$ to $2s2p^2\ ^2D$ transition measurements have been taken at six collision energies in the range of 2–7 MeV. The fraction of $B^{3+}$ ions in the metastable $1s2s\ ^3S$ state for this energy region, as discussed above, equals approximately 26.5%. Figure 4 shows the resulting single differential cross section (SDC) for the transition versus the projectile energy.

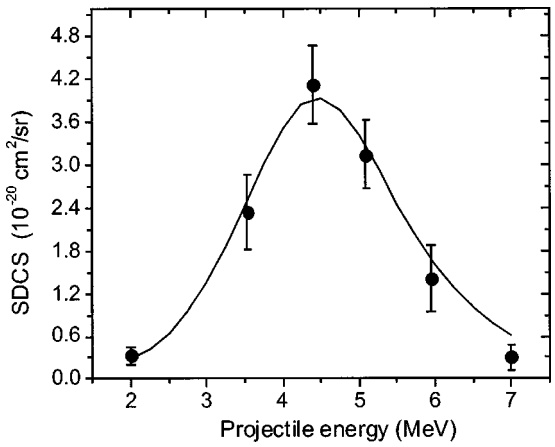


FIG. 4. Measurements of single differential cross sections for the $1s2s\ ^3S$ to $2s2p^2\ ^2D$ excitation followed by the Auger decay to the $1s2s\ ^3S$ state as a function of projectile energy. The theoretical single differential cross section, calculated using the available autoionization rates [14], was multiplied by a factor of 0.61 to fit the experimental data. Error bars represent the statistical error.

For comparison, the zero-degree RTE cross section calculated within IA using the autoionization rate from Ref. [14] is given. Theory was found to best fit the experimentally observed Compton profile of the transition, if scaled by a factor of 0.61. In addition, the theoretical RTE cross section integrated over projectile energies has been compared to the integrated experimental SDC and found to match the latter if multiplied by a factor of 0.59, which is close to the factor obtained by fitting the theory to the experimental data, indicating that the contribution to the formation of the triply excited state is limited to RTE only and the theoretical description of the target Compton profile is correct. Nevertheless, the resulting difference between measured and predicted differential cross sections exceeds the absolute experimental error of 25% calculated by taking the quadrature sum of the statistical and absolute uncertainties. Since the technique used for the calculation of RTE cross sections is known to be accurate for collisions of fast ions with hydrogen targets, the observed discrepancy between theory and experiment is expected to arise mainly from the two theoretical decay parameters used in the calculation; the total autoionization rate and the relative Auger rate for the particular decay channel. Due to the negligibly small radiative decay probability [14] for the $2s2p^2\ ^2D$ state, the relative Auger rate for a particular channel is equal to the branching ratio for this channel and can be obtained directly from the experimental data. The branching ratio for the $1s2s\ ^3S$ Auger decay branch from the $2s2p^2\ ^2D$ state is defined as the ratio of Auger decay intensity for the $1s2s\ ^3S$ state to the total Auger decay intensity and according to the identification of all decay channels from the $2s2p^2\ ^2D$ state, can be given as

$$B(^3S)=\frac{Y(^3S)}{Y(^3P)+Y(^1S)+Y(^3S)},$$

where $Y$ is the measured electron emission from the particu-

TABLE I. Measured and calculated autoionization rates, branching ratios, and widths for the $2s2p^2\ ^2D$ state of $B^{2+}$ followed by Auger decay to the $1s2s\ ^3S$ state are presented.

| | Present data | Theory [1] |
|---|---|---|
| Autoionization rate ($s^{-1}$) | $34.8\pm8.5\times10^{13}$ | $57\pm10^{13}$ |
| Width $\Gamma_A$ (eV) | $0.23\pm0.6$ | 0.38 |
| Branching ratio for $1s2s\ ^3S$ decay channel | $62\pm8\%$ | 57% |

lar state. The resulting branching ratio is independent of the electron spectrometer constants, metastable population of the beam or the target pressure, and the formation mechanism of the $2s2p^2\ ^2D$ state. Therefore, the absolute error for this measurement is limited to only the statistical error. Since the branching ratio, $B(^3S)$, does not depend on the beam energy, it is possible to reduce the statistical error of the measurement by using the experimental data taken at the resonant energy of 4.4 MeV. Finally, the branching ratio for the $1s2s\ ^3S$ decay channel from the $2s2p^2\ ^2D$ state was found to be $62\pm8\%$, where the absolute error is the statistical uncertainty of the measurement estimated at the 90% confidence level. The branching ratio obtained from the theoretical Auger rates [14] is 57%, which is in good agreement with our results presented in Table I.

We can now conclude that the difference between measured and predicted absolute cross sections arises from the remaining theoretical parameter used in calculation of the RTE cross sections, namely, the autoionization rate. Theoretical and experimental autoionization rates are compared in Table I.

## IV. CONCLUSION

The triply excited $2s2p^2\ ^2D$ state of $B^{2+}$ Li-like ions has been populated by RTE, in collisions of metastable $B^{3+}(1s2s\ ^3S)$ ion beams with hydrogen targets. The decay of the resonance was investigated using the zero-degree Auger projectile spectroscopy. Experimental data have been used to determine the absolute cross sections for the formation of the $2s2p^2\ ^2D$ state and the branching ratios of the corresponding elastic $(1s2s\ ^3S)$ and the inelastic $(1s2s\ ^1S,1s2p\ ^3P)$ electron scattering channels. In particular, absolute single and double differential cross sections for the $1s2s\ ^3S$ to $2s2p^2\ ^2D$ resonant excitation were obtained as a function of the collision energy. Since the observed resonant behavior of this transition suggests only the RTE contribution to the formation of the $2s2p^2\ ^2D$ state, we were able to obtain the autoionization rate for the elastic decay channel from the $2s2p^2\ ^2D$ state as well as the branching ratio for the $2s2p^2\ ^2D$ to $1s2s\ ^3S$ main decay branch. The data have been used to critically test the predictions of the perturbation ($1/Z$ expansion) method [14]. A very good agreement with theory has been observed for the measured decay branching ratio, however, the absolute value of the theoretical autoionization rate for the $2s2p^2\ ^2D$ to $1s2s\ ^3S$ decay was found to be higher than the experimental result by a factor of $1/0.61=1.64$, which is well outside the experimental error bars.

## ACKNOWLEDGMENT

This work was supported by the Division of Chemical Sciences, Geosciences and Biosciences, Office of Basic Energy Sciences, Office of Sciences, U.S. Department of Energy.

[1] R. Bruch, G. Paul, and J. Andra, Phys. Rev. A **12**, 1808 (1975).
[2] M. Rødbro, R. Bruch, and P. Bisgaard, J. Phys. B **12**, 2413 (1979).
[3] M. Agentoft, T. Andersen, and K. T. Chung, J. Phys. B **17**, L433 (1984).
[4] S. Mannervik, R. T. Short, D. Sonnek, E. Träbert, G. Moller, V. Lodwig, P. H. Heckmann, J. H. Blanke, and K. Brand, Phys. Rev. A **39**, 3964 (1989).
[5] E. P. Benis, T. J. M. Zouros, P. A. Zavodszky, H. Aliabadi, and P. Richard, in XXI ICPEAC, Sendai, Japan, 1999, edited by Y. Tikawa, K. Okuno, H. Tanaka, A. Yagashita, and M. Matsuzawa (1999), p. 5.
[6] P. A. Zavodszky, H. Aliabadi, P. Richard, M. W. Gealy, and C. P. Bhalla, in *Proceedings of the APR99 Meeting of the American Physical Society*, edited by Barrett H. Ripin (AIP, Woodbury, NY, 1999), Vol. 44, No. 1, Pt. I, p. 408.
[7] L. M. Kiernan, E. T. Kennedy, J.-P. Mosnier, J. T. Costello, and B. F. Sonntag, Phys. Rev. Lett. **72**, 2359 (1994).
[8] L. M. Kiernan, M.-K. Lee, B. F. Sonntag, P. Sladezek, P. Zimmerman, E. T. Kennedy, J.-P. Mosnier, and J. T. Costello, J. Phys. B **28**, L161 (1995).
[9] Y. Azuma, S. Hasegawa, F. Koike, T. Nagata, E. Shigemasa, A. Yagishita, and I. A. Sellin, Phys. Rev. Lett. **74**, 3768 (1995).
[10] L. Journel, D. Cubaynes, J.-M. Bizau, S. Al Moussalami, B. Rouvellou, F. J. Wuilleumier, L. VoKy, P. Faucher, and A. Hibbert, Phys. Rev. Lett. **76**, 30 (1996).
[11] S. Diehl, D. Cubaynes, J.-M. Bizau, L. Journel, B. Rouvellou, S. Al Moussalami, F. J. Wuilleumier, E. T. Kennedy, N. Berrah, C. Blanchard, T. J. Morgan, J. Bozek, A. S. Schlachter, L. VoKy, P. Faucher, and A. Hibbert, Phys. Rev. Lett. **76**, 3915 (1996).
[12] M. Zamkov, H. Aliabadi, E. P. Benis, T. Gray, P. Richard, H. Tawara, and T. J. M. Zouros, in *Proceedings of the 16th International Conference on the Application of Accelerators in Research and Industry*, edited by Jerone L. Duggan, AIP Conf. Proc. No. 576 (AIP, Melville, 2001), p. 179.
[13] M. Zamkov, H. Aliabadi, E. P. Benis, P. Richard, H. Tawara, and T. J. M. Zouros, Phys. Rev. A **64**, 15 (2001).
[14] U. I. Safronova and R. Bruch, Phys. Scr. **57**, 519 (1998).
[15] T. W. Tunnell, C. Can, and C. P. Bhalla, IEEE Trans. Nucl. Sci. **NS-26**, 1124 (1979).
[16] E. P. Benis, K. Zaharakis, M. M. Voultsidou, T. J. M. Zouros, M. Stockli, P. Richard, and S. Hagmann, Nucl. Instrum. Meth-

ods Phys. Res. B **146**, 120 (1998).
[17] D. Brandt, Phys. Rev. A **27**, 1314 (1983).
[18] T. J. M. Zouros, C. P. Bhalla, D. H. Lee, and P. Richard, Phys. Rev. A **42**, 678 (1990).
[19] B. Cleff and W. Mehlhorn, J. Phys. B **7**, 593 (1974).
[20] C. P. Bhalla, Phys. Rev. Lett. **64**, 1103 (1990).
[21] D. H. Lee, P. Richard, T. J. M. Zouros, J. M. Saunders, J. L. Shinpaugh, and H. Hidmi, Phys. Rev. A **41**, 4816 (1990).
[22] E. P. Benis, T. J. M. Zouros, and P. Richard, Nucl. Instrum. Methods Phys. Res. B **154**, 276 (1999).
[23] M. H. Chen, B. Crasemann, and H. Mark, Phys. Rev. A **27**, 544 (1983).