Energy dependence of the metastable fraction in $B^{3+}(1s^2\ ^1S,1s2s\ ^3S)$ beams produced in collisions with thin-foil and gas targets

M. Zamkov,[1] H. Aliabadi,[1] E. P. Benis,[1] P. Richard,[1] H. Tawara,[1] and T. J. M. Zouros[1,2]
[1]*James R. Macdonald Laboratory, Department of Physics, Kansas State University, Manhattan, Kansas 66506-2604*
[2]*Department of Physics, University of Crete, P.O. Box 2208, 71003 Heraklion, Crete, Greece*
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The fraction of metastable ions in $B^{3+}(1s^2\ ^1S,1s2s\ ^3S)$ beams produced in collisions with thin-foil and gas targets has been measured as a function of the incident energy in the range of 0.85–9 MeV. This was done by comparing the electron yield of doubly excited states formed in the collision of B^{3+} with hydrogen and helium targets. Significant differences were observed in the energy dependence of the metastable fraction between production in foil and gas targets. It was shown that the production of $1s2s\ ^3S$ metastable ions in a foil yields a constant fraction over the investigated energy range, unlike the fraction of metastable $1s2s\ ^3S$ ions produced in collisions with gas targets, which strongly depends on the incident beam energy. A theoretical study of the processes contributing to the formation of the ^3S metastable ions in collisions with foil and gas has been made. *K*-vacancy production in the ion-beam stripping process has been identified as a dominant mechanism and used to explain the observed difference in the energy dependence of the metastable fraction between production in collisions with gas and foil targets. A model is proposed for the calculation of the metastable fraction for He-like beams.

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INTRODUCTION

Experimental measurements of various collision cross sections for fast He-like ions require quantitative information on the fraction of ions in a long-lived $1s2s\ ^3S$ metastable state present in two-electron beams. The knowledge of this fraction is necessary for the absolute cross-section measurements of numerous processes including dielectronic recombination, transfer excitation, capture of the target electron, inelastic scattering, or recently discovered superelastic scattering of target electrons from highly charged metastable ions [1].

Several articles have investigated metastable ion-beam components, however, there are only a few experimental studies available so far that show the production-energy dependence of the metastable fraction of two-electron ions [2–4]. Terasawa *et al.* [2] measured the fraction of metastable ions in fast F^{7+} beams produced in carbon foils. This study is based on target-*K* x-ray production versus projectile ion charge state in a subsequent collision and relies on a large *K* shell to *K* shell vacancy-transfer cross section. This limits the method to nearly symmetric collision systems with an observable target x ray. The study revealed a relatively high, up to 30%, fraction of $1s2s\ ^3S$ ions in the emerging beams, which was not understood by theory. In Ref. [3] the fraction of metastable He $(1s2s\ ^3S)$ produced by electron capture of slow (25–90)-keV He^+ ions in H_2 gas was measured by photon-particle coincidence. The same study revealed that the conventional beam-attenuation technique [4], which is extensively used for the determination of the metastable fraction, substantially underestimates the metastable population of He-like beams. Until now, no experimental study of the energy dependence of the metastable fraction in two-electron ions produced in collisions of a primary beam with gas targets has been reported in the literature. Also no data are available on metastable ion production in a foil for low incident-ion energies. That creates a major problem in determining absolute cross sections for collisions with He-like ions, since theoretical calculations are very often unable to predict the correct fractions. Therefore, systematic experimental data are necessary to establish a benchmark for various absolute measurements in metastable He-like ion-atom collisions.

In the present work, we report the experimental measurement of the metastable $1s2s\ ^3S$-ion fraction in $B^{3+}(1s^2\ ^1S,1s2s\ ^3S)$ beams produced in both foil and gas targets. The metastable fraction has been studied over a wide range of beam energies, including a previously uninvestigated low-energy region. A significant difference in metastable fractions was observed for $1s2s\ ^3S$ ions produced in collision with foil and gas targets. The difference was found to depend strongly on the beam energy. We also present a theoretical study, which suggests that the dominant process contributing to the formation of the metastable ions is *K*-vacancy production. The model explains the observed difference in the energy dependence of metastable fractions between production in foils and gases. The model for the theoretical prediction of the metastable ^3S-ion fraction is proposed and is assumed to work for other He-like ions.

To determine the metastable fraction a new accurate technique [5], based on the measurement of the relative Auger electron emission yields from the doubly excited $1s2l2l'$ states of B^{2+} formed in the collision of B^{3+} with the target, has been developed. In this method, the resulting metastable fraction is independent of the electron spectrometer constants and target pressure, which otherwise could be the source of a considerable experimental error. A new high-efficiency paracentric hemispherical spectrograph [6] has been used to analyze the Auger electrons emitted in the forward direction.

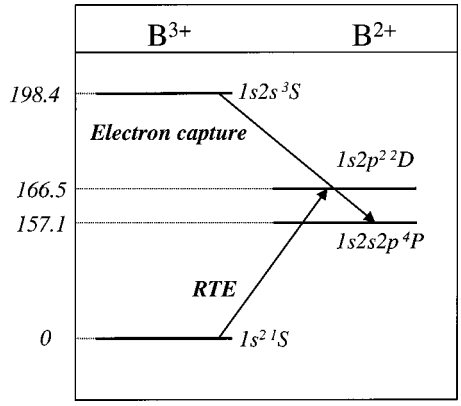

FIG. 1. Formation mechanisms of the doubly excited states of B^{2+} resulting from collisions of metastable B^{3+} $(1s^2\ ^1S, 1s2s\ ^3S)$ beams with gas targets.

COMPUTATION AND 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. Boron ions were produced either directly in the terminal of the tandem in the N_2 gas stripper or in 5 μg/cm^2 carbon foils, or were stripped after acceleration in a 5μg/cm^2 carbon-foil poststripper to achieve the desired charge state of +3. In any case, the produced B^{3+} beams were then focused into a 5-cm-long differentially pumped gas cell approximately 43 m from the tandem and 12 m from the foil poststripper. In this arrangement 99.99% of the metastable $1s2s\ ^3S$ ions (lifetime$\approx$100 ms [7]) produced at 4 MeV will reach the target. Formation of the $1s2s\ ^1S$ state (lifetime$\approx$9 μs [7]) is also possible by stripping. However, in the present method, the $1s2s\ ^1S$ state is negligible in the resulting $1s2s\ ^3S$ metastable fraction, assuming statistical population of the $1s2s\ ^1S$ and $1s2s\ ^3S$ states.

As a result of a collision of $B^{3+}(1s^2\ ^1S, 1s2s\ ^3S)$ ions with a target gas (H_2, He), doubly excited states of B^{2+} are formed, as shown in Fig. 1. Since the $1s2s2p\ ^4P$ state is produced by electron capture from the $1s2s\ ^3S$ metastable ions, its Auger decay can be used as an indication of a metastable component in the beam. The projectile ground-state component is evaluated from the electron yield of the $1s2p^2\ ^2D$ state, formed by resonant transfer excitation (RTE) from the ground-state ions. For the given collision parameters, the measured electron yields emitted at zero degrees from these two states are given by

$$Z(^4P) = N_m n \sigma_{\text{capture}} \xi_{^4P} \eta \Delta\Omega \frac{W_{^4P}(\theta)}{4\pi},$$

$$Z(^2D) = N_g n \sigma_{\text{RTE}} \xi_{^2D} \eta \Delta\Omega \frac{\Psi_{^2D}(\theta)}{4\pi}, \tag{1}$$

where N_g and N_m are the number of projectile ions in the ground and metastable states, respectively, at the final target area, n is the target number density, ξ is the Auger yield, η is the spectrometer efficiency, $\Delta\Omega$ is the effective solid angle. σ_{RTE} and σ_{capture} are the RTE and electron-capture cross sections for the formation of the ^2D and ^4P state, respectively. The $W(\theta)$ factors account for the angular distribution of the Auger electron emission. We assume that the emission from the ^4P state is isotropic and therefore set $W_{^4P}(\theta)=1$. For the RTE angular distribution $W_{^2D}(\theta)$ has been calculated according to Refs. [10,11].

The metastable beam fraction, defined as the ratio of ions in the metastable $1s2s\ ^3S$ state to the total number of ions in the beam

$$F = \frac{N_m}{N_m + N_g} = \left(\frac{N_m}{N_g} + 1 \right)^{-1} \tag{2}$$

can now be expressed in terms of the electron emission from doubly excited states ^2D and ^4P, using Eq. (1) and incorporating the angular distribution factor $W_{^2D}(\theta)$ into the RTE cross section:

$$F = \left(\frac{Z(^2D)\sigma_{\text{capture}}\xi_{^4P}}{Z(^4P)\sigma_{\text{RTE}}\xi_{^2D}} + 1 \right)^{-1}. \tag{3}$$

Since for both the ^2D and ^4P states, the parameters n, η, and $\Delta\Omega$ from Eq. (1) are the same, they do not appear in the expression for the metastable fraction. This substantially reduces the absolute experimental error, since the effects of the target-pressure variation and the uncertainties in spectrometer efficiency, as well as in the experimental solid angle, are excluded. The Auger yields for $1s2s2p\ ^4P$ and $1s2p^2\ ^2D$ states were evaluated from the theoretical autoionization and fluorescence rates [8] and were found to be very close to unity. The RTE cross section for the $1s^2\ ^1S$ to $1s2p^2\ ^2D$ transition, used in Eq. (3), was calculated within the impulse approximation [9] using the resonant excitation-scattering cross section given in the *LS*-coupling scheme [10]. RTE cross sections have been previously measured and compared with theory [10–12], leading to fairly good agreement. To minimize the error due to the impulse approximation, which requires the projectile velocity to be much larger than the orbiting velocity of a target electron, the H_2 molecules with loosely bound electrons were chosen as a target. The results were also crosschecked by using a He target. The total electron-capture cross sections σ_{capture} to B^{3+} $(1s2s\ ^3S)$ metastable beam component resulting in the $1s2s2p\ ^4P$ state were obtained from the empirical scaling rule [13] and found to be in fair agreement. It was also compared to a scaling from the existing data for F^{7+} $(1s2s\ ^3S)$ [12].

The lifetime of the metastable ^4P state [8] is long compared to the time of flight of the ion in the gas cell, so the deexcitation behavior along the projectile trajectory should be taken into account. The fraction R of ions in the ^4P state that decay inside of the gas cell can be found by integrating over the gas cell, assuming the statistical distribution for all ^4P_J states,

$$R = \sum_j a_J \xi_{^4P,J} \left[1 - \frac{L_J}{L_{\text{cell}}} (1 - e^{L_{\text{cell}}/L_J}) \right]. \tag{4}$$

Here, L_{cell} is the length of the gas cell, L_J is the deexcitation length of an ion in the ^4P_J state given by $L_J = t_{^4P,J}\, V_p$, where $t_{^4P,J}$ is the lifetime of the ^4P_J state, V_p is the projectile velocity, $\xi_{^4P,J}$ is the Auger yield of the ^4P_J state, and $a_J = (2J+1)/\Sigma 2J+1$ is the statistical weight of the ^4P_J level.

According to Eq. (4), only ^4P electrons produced inside the gas cell should be included in the metastable fraction calculation. Therefore a small positive voltage (20–30 V) was applied to the gas cell to separate the ^4P electrons produced outside of it. The ratio R_0 of ^4P electrons produced inside the gas cell to those produced outside was found for a number of beam energies and then interpolated over the entire beam-energy range used in the experiment. It was found that only 9% of ions in the ^4P state at low beam energies and 7% at high beam energies decay in the gas cell. Finally, the electron yield $Z_{\text{cell}}(^4P)$ used in Eq. (5) is given by $Z_{\text{cell}}(^4P) = Z(^4P)R_0$.

With these considerations included, the metastable beam fraction is given by

$$F = \left(\frac{Z(^2D)\sigma_{\text{capture}} R}{Z_{\text{cell}}(^4P)\sigma_{\text{RTE}}\xi_{^2D}} + 1 \right)^{-1}. \tag{5}$$

RESULTS

A. Production of metastable ions in N_2 gas

The B^{3+} ions were produced in the accelerator terminal in collisions of the incident B^- ions with nitrogen gas. Since the positive ions are then accelerated, the production energy of B^{3+} is less than the ultimate beam energy by a factor of 4, which is due to the charge change of the stripped ions. Figure 2 shows two examples of Auger electron spectra obtained in the collision of 5.1- and 7.1-MeV B^{3+} ions on H_2. The corresponding metastable ions were produced in an N_2 gas at the collision energies of 1.27 and 1.77 MeV, respectively. The Auger electrons at 157.0 and 166.5 eV attributed to the $1s2s2p\ ^4P$ to $1s^2\ ^1S$ and the $1s2p^2\ ^2D$ to $1s^2\ ^1S$ Auger decay were observed. In Fig. 2(a), which shows the spectrum taken at the metastable production energy of 1.27 MeV, the intensity of the ^4P Auger line is significantly smaller than that of the ^2D line, even though the electron capture that contributes to the formation of the ^4P has a larger cross section than RTE at this beam energy. This fact can be interpreted in terms of a very small fraction of metastable ^3S ions in the incident beam, which is in agreement with calculations using Eq. (5) that gives a value of only 3%. In contrast, as presented below, the Auger spectrum measured for the same collision and production energies, but produced in the foil [see Fig. 3(b)], which has a much more intense ^4P line, results in a metastable fraction of 26%. In Fig. 2(b), which shows the spectrum taken with gas stripping at the higher metastable-ion-production energy, the intensity of the ^4P line has increased relative to the intensity of the ^2D line, thus the metastable fraction grows with increasing metastable-ion-production energy. The energy dependence of the metastable fraction produced in the gas is shown by circles in Fig. 4. Very few (<1%) metastable ions are produced by gas stripping if the production energy is lower than 1 MeV. The metastable fraction increases with the energy reaching saturation when the B^- projectile velocity is near the B^{4+} $1s$ electron orbital velocity. These observations demonstrate that nearly pure ground-state two-electron ion beams can be produced.

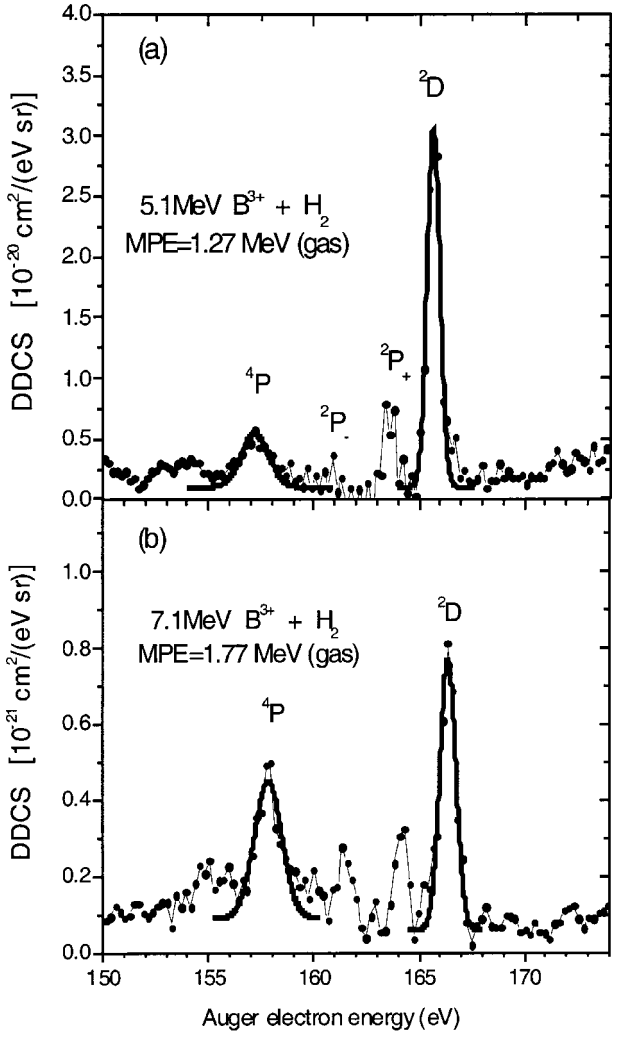

FIG. 2. 0° Auger spectra measured for $B^{3+}+H_2$ collisions at the projectile energies of 5.1 and 7.1 MeV. The B^{3+} ($1s^2\ ^1S$,$1s2s\ ^3S$) beam was obtained in collision of primary B with nitrogen gas at the metastable production energies (MPE) of 1.27 and 1.77 MeV, respectively.

The uncertainties are calculated by taking the quadrature sum of the statistical and absolute uncertainties, each estimated at the 90% confidence level. The absolute uncertainty of the metastable fraction determination according to Eq. (5) consists primarily of energy-dependent uncertainties of the RTE and electron-capture cross sections and is expected not to exceed 20%. Since the RTE cross sections become small for H_2 targets at high beam energies, a He target was used in place of H_2. This facilitates the measurement of resonant ^2D lines since the Compton profile of a helium target is broader than that of hydrogen [14].

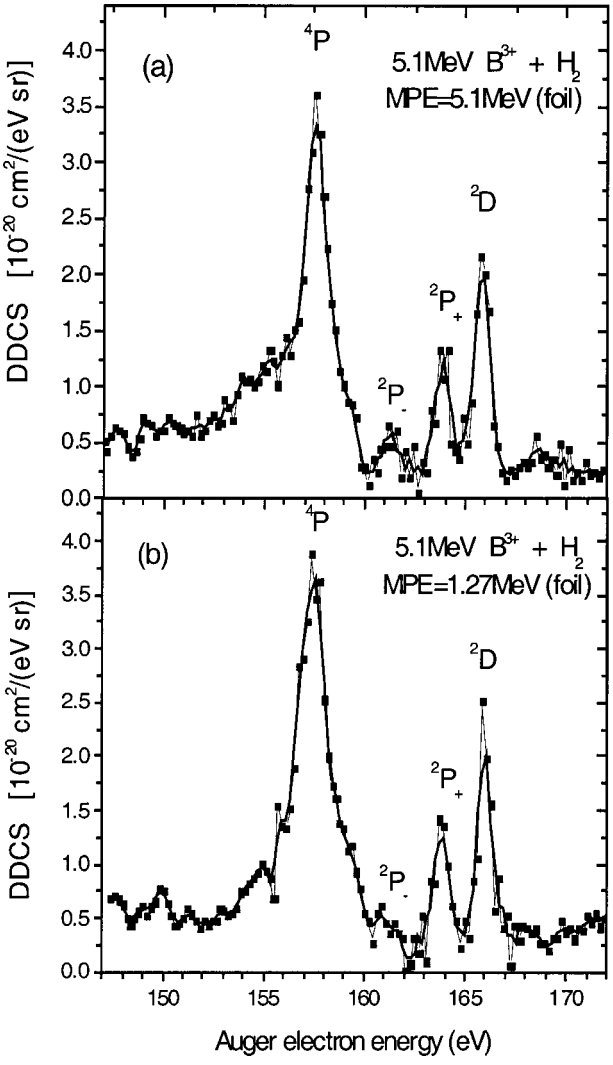

FIG. 3. 0° Auger spectra measured for 5.1-MeV $B^{3+}+H_2$ collisions. The B^{3+} ($1s^2\ ^1S$,$1s2s\ ^3S$) beams were produced in a carbon foil at two different MPE of 5.1 and 1.27 MeV, respectively.

B. Production of metastable ions in foils

B^{3+} beams were produced in a foil in two different ways: one by stripping the ion beam inside of the tandem at the terminal and the other by stripping the ion beam in a foil after the tandem. By using this method it was possible to produce B^{3+} ions at two different metastable beam production energies with the same final beam energy, which gives the advantage of measuring the relative metastable fraction at two production energies, independent of the electron capture or RTE cross sections. Figure 3 shows two examples of Auger electron spectra obtained in the collision of 5.1-MeV B^{3+} ions on H_2. These spectra were obtained with two beams that were produced in different ways with production energies of 5.1 and 1.27 MeV. The ratio of the intensities of ^4P to ^2D lines in the spectra does not change much from the lower to the higher energies; consequently, the metastable fractions are also approximately the same. Further measurements over the metastable-ion-production energy range of 1–8.5 MeV have also led to the determination of a constant fraction of about 26%. These results are plotted as squares in Fig. 4 along with the metastable fraction resulting from the gas stripping.

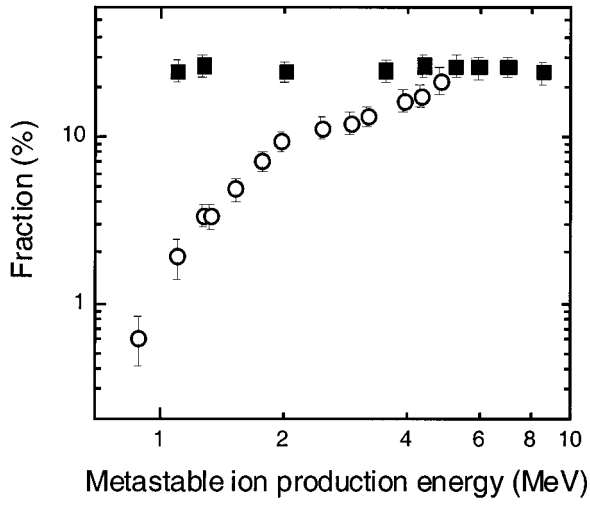

FIG. 4. The metastable fraction $F=B^{3+}(1s2s\ ^3S)/B^{3+}(1s^2\ ^1S,1s2s\ ^3S)$ versus the stripping energy. Circles, the metastable fraction of the ionic beam produced in N_2 gas; squares, the metastable fraction of the ionic beam produced in carbon foils. The error bars correspond to the statistical uncertainty and are plotted at the 90% confidence level.

C. Mechanisms involved in the production of the metastable ions in gas and foil

In order to simplify the theoretical study of the processes contributing to the formation of the metastable B^{3+} ions, the incident beam was assumed to be B^{2+}. To validate this assumption, the production of $B^{3+}(1s2s\ ^3S)$ ions in foils obtained from both B^{2+} and B^- incident beams was experimentally shown to be the same. In our model it was possible to isolate two processes that may contribute to the formation of the ^3S state in B^{3+} beams. The first mechanism to be discussed is the ionization of the B^{2+} K-shell electron resulting in a $1s2s\ ^3S$ state of B^{3+}. Its contribution can be evaluated, assuming that the B^{3+} ions in the ground state are produced by the ionization of the $2s$ electron in B^{2+}. Using the K- and L-shell vacancy production cross sections, estimated by scaling the plane-wave Bohr approximation calculation for H^++H collisions [15], it was demonstrated that the metastable fraction calculated within this model is only 1.5–2 % for the energy range where the maximum is expected. Since this value is significantly lower than the metastable fraction measured in the experiment, the above suggested mechanism is thus shown to have a negligible contribution to the formation of the metastable ions. To confirm this result experimentally, the fractions of metastable ions produced by stripping B^{3+} and B^{2+} incident beams were compared and found to be equal within the experimental error.

The second process, contributing to the formation of the ^3S state, is the K-vacancy production in $B^{3+}(1s^2)$ ions followed by subsequent electron capture. In this model the metastable ^3S ion fractions resulting from collisions with the solid and gas targets are given by

$$F_{\text{foil}}=\frac{n\sigma^{\text{foil}}_{1s2s\ ^3S}N_1}{n\sigma^{\text{foil}}_{\text{total}}N_1+N_0}, \tag{6}$$

$$F_{\text{gas}}=\frac{n\sigma^{\text{gas}}_{1s2s\ ^3S}M_1}{n\sigma^{\text{gas}}_{\text{total}}M_1+M_0}, \tag{7}$$

where n is the target number density, N_1 and N_0 are the fractions of ions with one and zero K-shell vacancies produced in a foil, and M_1 and M_0 are the fractions of ions with one and zero K-shell vacancies produced in gas. $\sigma^{\text{foil}}_{1s2s\ ^3S}$ and $\sigma^{\text{gas}}_{1s2s\ ^3S}$ are the electron-capture cross sections resulting in the $1s2s\ ^3S$ state. $\sigma^{\text{gas}}_{\text{total}}$ and $\sigma^{\text{foil}}_{\text{total}}$ are the total electron-capture cross sections. If we assume the electron-capture cross sections to be approximately equal for both gas and solid targets, then the ratio of the metastable fraction produced in gas to the measured fraction produced in a foil can be expressed in terms of the B^{4+} charge-state-production cross sections for solid and gas targets as shown below

$$\frac{F_{\text{gas}}}{F_{\text{foil}}}=\frac{\sigma^{\text{gas}}_{1s2s\ ^3S}}{\sigma^{\text{foil}}_{1s2s\ ^3S}}\frac{n\sigma^{\text{foil}}_{\text{total}}N_1+N_0}{n\sigma^{\text{gas}}_{\text{total}}M_1+M_0}\frac{M_1}{N_1}\approx\frac{M_1}{N_1}. \tag{8}$$

Here $n\sigma^{\text{foil}}_{\text{total}}N_0+N_1\approx n\sigma^{\text{gas}}_{\text{total}}M_0+M_1$ is the total B^{3+} projectile flux. This approximate equation states that the measured difference in the energy dependence of the metastable fraction between production in foil and gas is primarily due to the difference in the K-vacancy production leading to $B(1s^{-1})$ ions in these two media. To support this conclusion the ratios from the left- and right-hand side of Eq. (8) were compared and are plotted in Fig. 5 versus the metastable-ion-production energy. The charge-state fractions M_1 and N_1 for the gas and foil stripping were obtained from Refs. [16,17]. The graph reveals the apparent correlation between these ratios, which suggests that the proposed mechanism contains the dominant contribution to the production of the $1s2s\ ^3S$ metastable state.

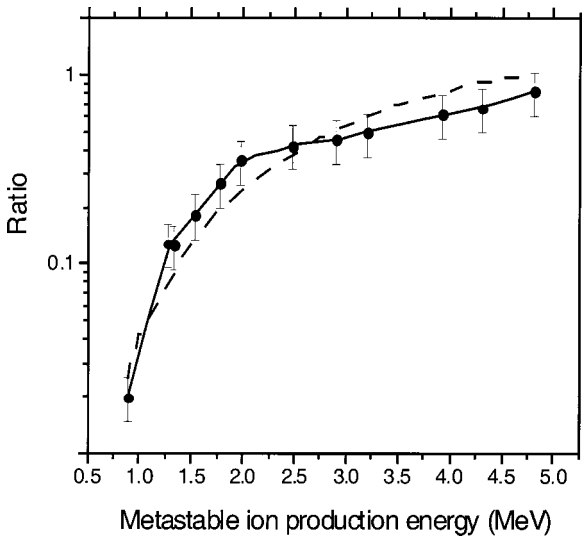

FIG. 5. The comparison of predicted and observed ratios of the metastable fraction produced in gas to the metastable fraction produced in a foil. Circles, experimentally observed ratio of metastable fractions, $F_{\text{gas}}/F_{\text{foil}}$. Dashed line, the ratio predicted by the proposed model, M_1/N_1.

CONCLUSION

The metastable ion fraction in $B^{3+}(1s^2\ ^1S,1s2s\ ^3S)$ beams, produced in collisions with foil and gas targets has been measured as a function of the metastable-ion-production energy in the range of 0.85–9 MeV. This was done by using a highly accurate technique, based on the measurement of the Auger electron emission from the doubly excited states formed in collision of B^{3+} with the H_2 and He targets. The Auger electrons emitted in the forward direction were detected with the new paracentric hemispherical spectrograph. The most striking observation is the significant difference in the energy dependence of the metastable fraction between production in collisions with solid and gas targets. The observed fraction of metastable ions produced in the foil does not vary with the stripping energy, while the fraction of metastable ions resulting from the gas stripping monotonically rises with the stripping energy. It was demonstrated that the dominant production mechanism of the metastable ^3S ions in both solid and gas targets is the K-shell vacancy production in B^{3+} beams, followed by subsequent electron capture. A theoretical model has been proposed for the calculation of the metastable fraction for He-like beams. This model has also been used to explain the difference in the energy dependence of the metastable fraction between production in collisions with solid and gas targets. Further systematic investigations of the production mechanisms and projectile Z dependence of the metastable fraction are planned.

ACKNOWLEDGMENTS

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