# Fraction of metastable $1s2s\,^3S$ ions in fast He-like beams ($Z=5-9$) produced in collisions with carbon foils

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Auger spectroscopy has been used to measure the fraction of metastable $1s2s\,^3S$ ions in fast He-like B, C, N, O, and F beams produced in collisions with thin carbon foils as a function of both the incident energy in the range of 0.5–2 MeV/$u$ and the foil thickness in the range of 1–5 $\mu$g/cm$^2$. The method used for determination of the metastable fraction is based on measurements of the electron emission from the doubly excited states of Li-like ions formed in collisions of primary beams with hydrogen and helium targets. Some differences were observed both in the energy dependence and the absolute value of metastable fractions for different beams. In particular, the metastable content in $C^{4+}$ ions produced in carbon foils was found to be significantly lower than that of other investigated beams. The observed deviation has been explained on the basis of $K$-vacancy sharing, which is known to have the highest probability for symmetric collisions. A model recently proposed for the calculation of the metastable fraction in He-like beams has been used to predict the metastable fraction for $B^{3+}$ ions leading to a good agreement with the experiment.

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## I. INTRODUCTION

Experimental measurements of various collision cross sections for He-like beams require quantitative information on the fraction of ions in the long-lived $1s2s\,^3S$ metastable state usually present in all two-electron beams. Knowledge of this fraction [1] is necessary for the absolute cross-section measurements of numerous processes, including dielectronic recombination [2], transfer excitation [3,4], capture of target electrons [5,6], and inelastic scattering or recently discovered superelastic scattering of target electrons from highly charged metastable ions [7].

A number of experimental techniques have been developed for the determination of the metastable fractions over the years [5,8–17] and several measurements of the metastable fraction for various He-like ions have been reported in the literature. However, there have been only a few experimental studies available so far that provide systematic information on the energy and foil thickness dependence of the metastable content in these beams [5,12,13]. Schiebel *et al.* [13] and Terasawa *et al.* [5] measured the fraction of metastable ions in fast $Si^{12+}$ and $F^{7+}$ beams, respectively, produced in thin carbon and gold foils. Their studies are based on target $K$ x-ray production vs projectile ion charge state in a subsequent collision and rely 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 yield. Studies revealed a relatively high (up to 30%) fraction of $1s2s\,^3S$ ions in the emerging beams. No adequate theoretical explanation has been provided for these high values. In Ref. [12] 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 study showed that the fraction of metastable ions was equal to 70% at lower energies. Another advancement has been made when a recently proposed technique [1] was used to measure the metastable fraction as a function of energy in $B^{3+}$ beams produced in collisions with both foil and gas targets. It was shown that the production of $1s2s\,^3S$ metastable $B^{3+}$ ions in a foil yields a constant fraction of 26 $\pm 6\%$ over the projectile energy range of 0.4–0.8 MeV/$u$, unlike the fraction of metastable $1s2s\,^3S$ ions produced in collisions with gas targets that strongly depends on the incident beam-energy. Based on the data available so far in the literature, other He-like beams have received less attention and metastable fractions have not yet been determined. Therefore, the goal of our investigation was to measure the metastable fraction for the He-like isoelectronic sequence, establishing a benchmark for various absolute measurements in metastable ion-atom collisions and revisiting the earlier proposed model of metastable ion formation [1].

In the present work, we report on the experimental measurement of the metastable $1s2s\,^3S$ ion fraction in He-like B, C, N, O, and F beams produced in collisions with carbon foils. The metastable fraction has been studied over a wide range of beam energies, using the recently developed technique [1], which is based on the measurements of the Auger electron emission from two Li-like doubly excited states ($1s2p^2\,^2D$ and $1s2s2p\,^4P$) formed in collisions of He-like beams with $H_2$ targets. In order to allow the direct comparison of measured metastable fractions for different ions, the metastable ion production energy was converted to the ratio of projectile velocity $V_p$ to the projectile $K$-shell electron

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velocity $v_K$. The most interesting result was the relatively low metastable ion fraction in $C^{4+}$ beams, approximately two and a half times lower than the metastable fraction in the other ion beams for which the metastable fraction is about 26%. Also, the production of $F^{7+}$ metastable ions was observed to be energy dependent for projectile velocities $V_p/v_K \leqslant 0.5$. Substantial progress has been achieved in the development of a model that can be used for theoretical estimates of the metastable fraction. The earlier proposed model [1] predicts the energy-dependent ratio of metastable fractions resulting from beam production in gas versus foils. In this work, it has been applied to the calculation of the metastable content in He-like $B^{3+}$ ions and the results were found to be in good agreement with the experiment.

The measurements were made with a single-stage hemispherical spectrograph, incorporating a hemispherical deflector analyzer, a large (40-mm-active-diameter) two-dimensional position-sensitive detector and a focusing/decelerating lens. The operation and performance of the spectrograph of zero degrees with respect to the beam direction has already been described in the literature [18–20].

## II. COMPUTATION AND EXPERIMENTAL METHOD

The experiments were performed at the J. R. Macdonald Laboratory at Kansas State University, using the 7 MV EN tandem Van de Graaff accelerator. He-like ions were produced either directly in the terminal of the tandem using 1–5 $\mu$g/cm$^2$ carbon foils, or after acceleration in a 5 $\mu$g/cm$^2$ carbon foil to achieve the desired charge state. In both cases, the ionic 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. The lifetime of the metastable $1s2s\,^3S$ state is fairly long compared to the time it takes the beam to travel to the gas cell. In the case of $F^{7+}$ $(1s2s\,^3S)$ ions that have the shortest lifetime ($\approx 0.28$ ms [21]), 99.9% of the initially metastable ions produced at 20 MeV will reach the target. Formation of the metastable $1s2s\,^1S$ state is also possible in foils. In any event, for $Z>5$, if we assume statistical population of $1s2s\,^1S$ and $1s2s\,^3S$ states, the fraction of the $1s2s\,^1S$ state in the beam at the target area will not exceed 1.5% and can be neglected. Moreover, the two doubly excited states $1s2p^2\,^2D$ and $1s2s2p\,^4P$ formed from ground and metastable components of the beam are not affected by the presence of $1s2s\,^1S$ ions.

The experimental technique used for the determination of the metastable fraction is described in Ref. [1]. It is based on measurements of the electron emission from the doubly excited states of Li-like ions, formed in collisions of metastable He-like ions with gas targets ($H_2$, He), as shown in Fig. 1. Since the $1s2s2p\,^4P$ state is produced only from the metastable $1s2s\,^3S$ component of the beam, its Auger decay intensity is proportional to the number of ions in the $1s2s\,^3S$ state. The projectile ground-state component can be assessed using the electron emission from the $1s2p^2\,^2D$ state, formed by resonant transfer excitation (RTE) [4] from the $1s^2\,^1S$ ground-state ions. The $1s2p^2\,^2D$ state may also be formed by a nonresonant transfer excitation (NTE) [3] from the $1s2s\,^3S$ state, however, the NTE cross section at the energies

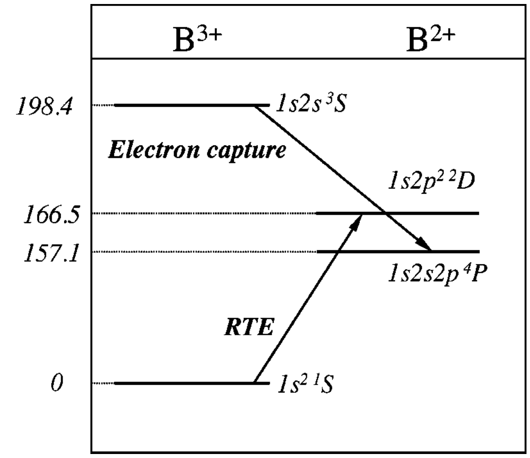


FIG. 1. Formation of the Li-like doubly excited states from ground and metastable components of He-like beam.

used in this study is expected to be negligible [22]. The expression for calculation of the metastable fraction [1] in terms of the electron emission yields $Z(^4P)$ and $Z(^2D)$ from the $1s2s2p\,^4P$ and $1s2p^2\,^2D$ states, respectively, is given by

$$F=\left[\frac{Z(^2D)\sigma_{capture}R}{Z_{cell}(^4P)\sigma_{RTE}\xi_{^2D}}+1\right]^{-1}, \qquad (1)$$

where $\sigma_{RTE}$ and $\sigma_{Capture}$ are the RTE and electron-capture cross sections for the formation of the $1s2p^2\,^2D$ and $1s2s2p\,^4P$ states, respectively, $\xi_{^2D}$ is the Auger yield for $1s2p^2\,^2D$ state and $R$ is the calculated fraction Ref. [1] of ions in the $^4P$ state that decay inside of the gas cell. The lifetime of the metastable $^4P$ state is long compared to the flight time of the ion in the gas cell, therefore the deexcitation behavior along the projectile trajectory should be taken into account. To separate $^4P$ electrons produced in the gas cell from those produced outside of it, a small positive voltage was applied to the cell. The Auger yields for $1s2s2p\,^4P$ and $1s2p^2\,^2D$ states were evaluated from theoretical autoionization and fluorescence rates [23] and found to be very close to unity. RTE cross sections for the $1s^2\,^1S$ to $1s2p^2\,^2D$ transition, used in Eq. (1), were calculated within the impulse approximation [24] using the resonant excitation-scattering cross section given in the $LS$-coupling scheme [25]. These cross sections have been previously measured and compared with theory [22,25,26], leading to a 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, $H_2$ or He gases with relatively loosely bound electrons were chosen as targets. The total electron capture cross sections $\sigma_{Capture}$ to He-like $(1s2s\,^3S)$ metastable beam component resulting in the $1s2s2p\,^4P$ state were obtained from the empirical scaling rule [27]. The uncertainties of measurements that arise from using Eq. (1) can be evaluated by taking the quadrature sum of the statistical (estimated at the 90% confidence level) and systematic uncertainties. The systematic uncertainty of the metastable fraction determination consists

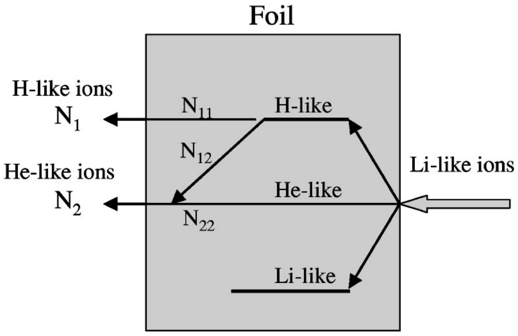


FIG. 2. Production of metastable ions in a foil from the incident Li-like beam.

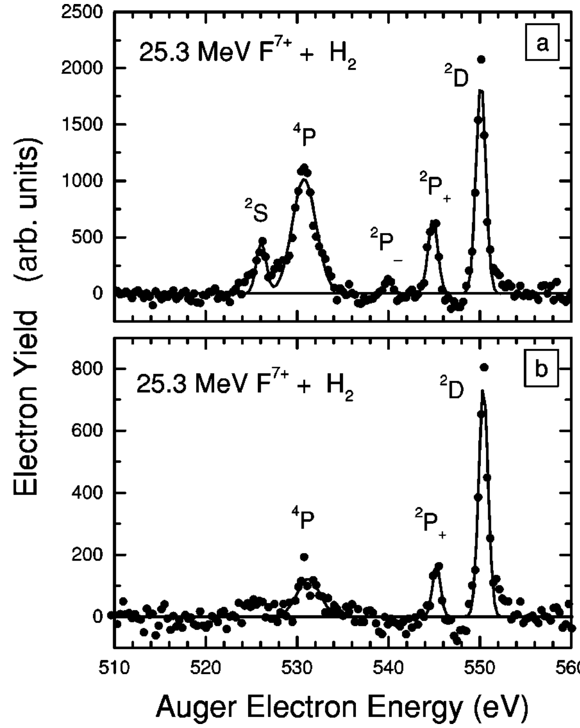


FIG. 3. Zero-degree Auger electron spectra measured for 25.3 MeV $F^{7+}$ on $H_2$ collisions. $F^{7+}$ $(1s^2\ ^1S, 1s2s\ ^3S)$ beams were produced in carbon foils at two different metastable production energies of (a) 25.3 and (b) 3.3 MeV, respectively.

primarily of energy-dependent uncertainties of the RTE [22] and electron capture [27] cross sections and is expected not to exceed 30%.

Since the dominant mechanism contributing to the formation of the $1s2s\ ^3S$ state in collisions of fast ionic beams with foil targets has been identified [1], theoretical estimates of the metastable fraction in He-like ions can be made. It has been recently demonstrated [1] that the formation of the metastable $1s2s\ ^3S$ ions in collisions with both solid and gas targets is proportional to the production of $K$-shell vacancies in the primary beams [1]. This result gives rise to a model illustrated in Fig. 2, where the formation of the $1s2s\ ^3S$ state from Li-like incident beams in the foil is shown. Upon entering the foil, primary beams will end up in various charge states, as shown. According to the study mentioned above, only H-like ions with a 1s electron will substantially contribute to the formation of the $1s2s\ ^3S$ state. Li-like ions initially ionized to the He-like charge state are known to be dominantly in the ground state [1]. As shown in Fig. 2, the emerging He-like ion beam will consist of two parts: (i) one part is $N_{22}$, which is the fraction of Li-like ions initially ionized to the He-like charge state (these ions have a small fraction $F_2$ of the metastable $1s2s\ ^3S$ state), (ii) the other part is $N_{12}$, which is formed from H-like ions in the foil that subsequently undergo an electron capture as they exit the foil (these ions have a fraction $F_1$ of the metastable $1s2s\ ^3S$ state). The metastable $1s2s\ ^3S$ ion fraction $F$ is defined as the ratio of metastable ions to the total number of He-like ions in the beam after passing through the foil and can be expressed as

$$F = \frac{N_{metastable}}{N_{metastable} + N_{ground}} = \frac{F_1 N_{12} + F_2 N_{22}}{N_{12} + N_{22}},$$

$$\simeq \frac{N_{12} F_1}{N_2}. \tag{2}$$

Since $F_2$ is small ($<1.5\%$, [1]), it has been neglected in the last step. $N_2$ is the fraction of He-like charge state in the emerging beam [28]. $N_{12}$ can be expressed as

$$N_{12} = \frac{N_1 N_2'}{N_1'}, \tag{3}$$

where $N_1$ is the He-like charge state fraction [28]. $N_1'$ and $N_2'$ are the H- and He-like charge state fractions, respectively, produced from a primary H-like beam. The metastable $1s2s\ ^3S$ ion fraction can thus be expressed as

$$F = \frac{N_1 N_2'}{N_2 N_1'} F_1. \tag{4}$$

$F_1$ can be determined experimentally as will be discussed in the following section.

## III. RESULTS

### A. Experimentally measured metastable fraction

Measurements of the metastable fraction for He-like B, C, N, O, and F beams will be discussed first. In order to increase the range of metastable ion production energies, beams were produced both inside the tandem terminal using 1–5 $\mu g/cm^2$ foils and after the tandem in 5 $\mu g/cm^2$ carbon foils. In the first case the metastable ion production energy differs from the final energy of the beam, at which the doubly excited states are formed, by a factor of $q+1$, where $q$ is the ionic charge state. In the second case, both the metastable ion production energy and the final beam energy are the same. Figure 3 shows two examples of Auger electron spectra obtained in the collision of 25.3 MeV $F^{7+}$ ions on $H_2$. Although the final energies of these two beams are the same, the metastable ions were produced in two different ways as

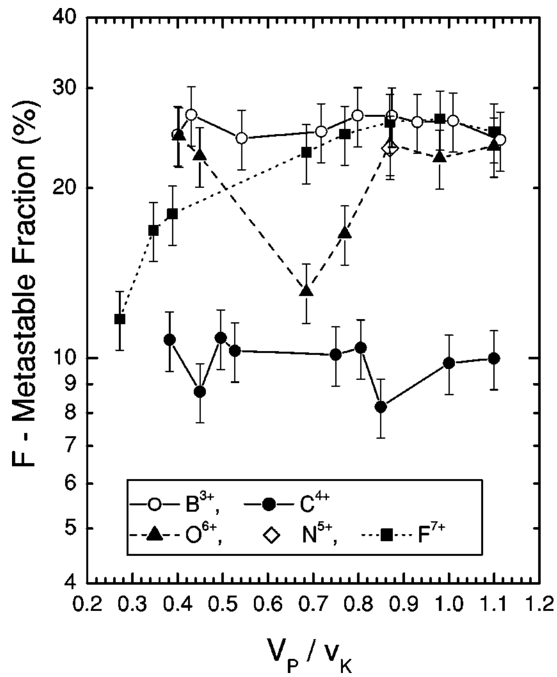


FIG. 4. The metastable fraction $F$ in He-like B, C, N, O, F beams vs the projectile velocity in units of projectile $K$-shell electron velocity. The error bars correspond to the statistical uncertainty and are plotted at the 90% confidence level. Lines are drawn to guide the eye.

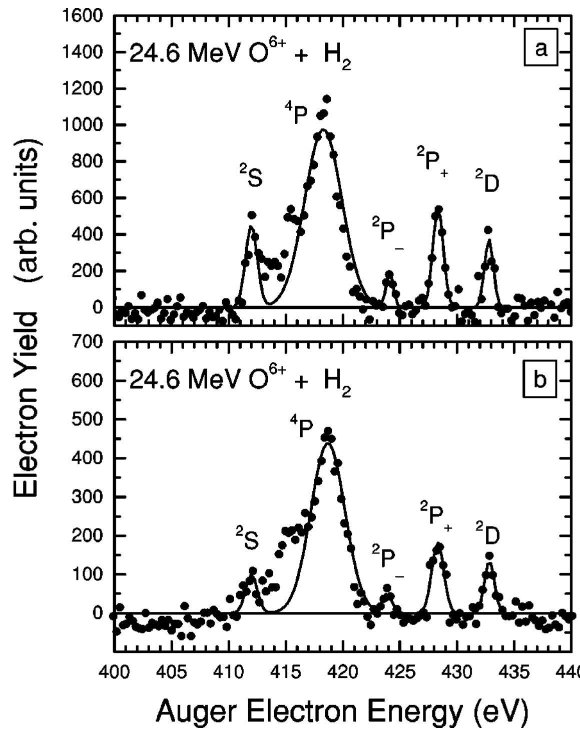


FIG. 5. Zero-degree Auger electron spectra measured for 24.6 MeV $O^{6+}$ on $H_2$ collisions. $O^{6+}$ $(1s^2\,{}^1S, 1s2s\,{}^3S)$ beams were produced in carbon foils at two different metastable production energies of (a) 24.6 and (b) 3.5 MeV, respectively.

described above, i.e., at 25.3 MeV [Fig. 3(a)] and at 25.3/8 = 3.3 MeV [Fig. 3(b)]. That gives us an opportunity to compare metastable fractions at two different production energies regardless of the electron capture or RTE cross sections entering Eq. (1). In Fig. 3(a) the intensity ratio of the $1s2s2p\,{}^4P$ peak formed from the $1s2s\,{}^3S$ metastable state component to the $1s2p^2\,{}^2D$ peak formed from the ground-state component is higher than in Fig. 3(b). This indicates a greater fraction of metastable ions in the $F^{7+}$ beams produced at 25.3 MeV.

Further measurements at other production energies revealed that the metastable fraction increases with metastable ion production energy and reaches the maximum value of approximately 26% as shown in Fig. 4. As mentioned above the metastable ion production energy has been converted to the ratio of the corresponding projectile velocity to the $K$-shell electron velocity. The metastable fraction measured for $O^{6+}$ ions, shown by solid triangles in Fig. 4, attains the same maximum value of 26% in the beam at $V_p/v_K = 1$. However, the energy dependence of the metastable fraction in these ions is different from that of $F^{7+}$ at lower velocities $V_p$. Two electron spectra resulting from the collision of 24.6 MeV $O^{6+}$ on $H_2$ are shown in Fig 5. Metastable ion production energies are 24.6 MeV and 24.6/7 = 3.5 MeV, respectively. Since intensity ratios of $1s2s2p\,{}^4P$ to $1s2p^2\,{}^2D$ peaks are approximately equal in both spectra, the two beams have approximately the same fraction of metastable $1s2s\,{}^3S$ ions. Measurements at other energies also revealed a constant metastable fraction of about 26% with a small "dip" around $V_p/v_K = 0.65$. The presence of this "dip" could possibly be due to the competition between the two processes, described in Sec. II, involved in the production of the $1s2s\,{}^3S$ state: the production of ions incident on the foil and the single-electron capture to the $1s2s\,{}^3S$ state. The cross section for the first process increases as a function of the projectile velocity, whereas, the electron capture decreases with increasing projectile velocity. Thus, the resulting probability for the metastable ion production may have a minimum.

Only one measurement was taken for He-like $N^{5+}$ beams due to ion source limitations. The experimental data point was measured for the projectile velocity $V_p/v_K = 0.87$, which is close to the expected maximum value of the metastable fraction. The fraction was found to be 24%. This result, shown in Fig. 4, is consistent with fractions for $B^{3+}$ (taken from Ref. [1]), $O^{6+}$, and $F^{7+}$ ions.

### B. Influence of *K*-vacancy sharing

A significant deviation from the metastable fraction of He-like ions discussed above was observed for $C^{4+}$ beams, where the fraction of metastable $1s2s\,{}^3S$ ions turned out to be relatively lower. These measurements show that $C^{4+}$ beams produced in a foil contain only 10% of ions in the $1s2s\,{}^3S$ state (Fig. 4) independent of the production energy within the investigated range. The observed difference between metastable fractions for $C^{4+}$ and other He-like ions can be understood if $K$-vacancy sharing between the projectile and the target is taken into account. The $K$-vacancy transfer probability in near-symmetric collisions ($C^{4+}$ on carbon foil) is known to be close to 1/2 [29]. In this case, the $K$

TABLE I. Metastable fraction in $B^{3+}$ beams obtained experimentally [1] and within the proposed model calculation.

| Metastable ion production energy (MeV) | Metastable fraction (%) | |
|---|---|---|
| | Experiment | Calculation |
| 3.5 | 26±6 | 33.8 |
| 5.1 | 26±6 | 23.4 |

vacancy in an incident metastable $C^{4+}$ ion will be transferred to the target atom, leaving approximately half of the projectile ions in the ground state, which is consistent with the observed metastable fraction. Since the *K*-vacancy transfer probability for other He-like beams is about one order of magnitude smaller than that for $C^{4+}$ ions, the reduction of corresponding metastable fractions is negligible.

### C. Model calculation of the metastable fraction

In order to test the accuracy of the model calculation, based on Eq. (4), additional measurements were performed for the $B^{3+}$ ions. All three parameters entering Eq. (2) were determined experimentally. Charge fraction $N_{12}$ was obtained using Eq. (3), where the parameters were determined by means of the magnetic separation of the required charge state from $B^{2+}$ and $B^{4+}$ beams incident on the thin carbon foil. The remaining parameter $F_1$ is the fraction of He-like ions in the $1s2s\,^3S$ state, formed from H-like beams. Experimentally, $F_1$ was determined by measuring the metastable fraction in $B^{3+}$ ions produced in a carbon foil from $B^{4+}$ incident beams, using Eq. (1) as explained in Sec. II. Combining these two results, the fraction of $1s2s\,^3S$ ions in the beam was calculated using Eq. (4). Measurements for the model calculation were performed at two different ion energies. The calculated fractions are compared to the existing experimental data for $B^{3+}$. The results are shown in Table I. The discrepancy between the measured and calculated fractions is within the error arising from measurements of charge state fractions entering Eq. (3).

### D. Foil thickness considerations

The proposed model implies a correlation between the foil thickness and the fraction of metastable ions in emerging beams. Therefore, several different foil thicknesses were used in measuring the fraction of $1s2s\,^3S$ ions in 13.3 MeV $C^{4+}$ beams. Since the incident-beam energy does not change in this test, the error arising from uncertainties in RTE and electron capture cross sections is eliminated. The results are shown in Fig. 6 along with the fraction of metastable ions formed in $N_2$ gas. There is only a small difference in the metastable ion fractions of beams produced in 2 and 5 $\mu$g/cm$^2$ foils. However, the fraction decreases when a 1 $\mu$g/cm$^2$ foil is used and it is even lower in the case of a $N_2$ gas. The result is consistent with the fact that, according to the model, the metastable fraction is proportional to the production of H-like $C^{5+}$ ions, which in turn is reduced for thin foils or gases. Finally, since the experimental study of the metastable fraction has been done using 5 $\mu$g/cm$^2$ foils, the results are not expected to vary with small changes in foil thickness.

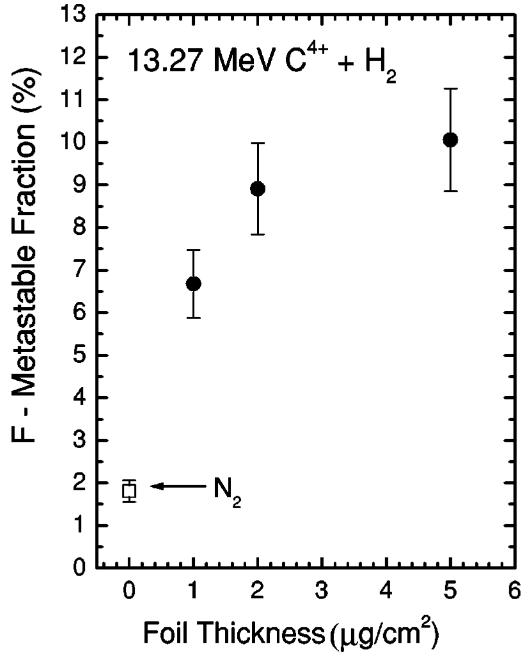


FIG. 6. The metastable fraction $F$ in 13.27 MeV $C^{4+}$ beams as a function of foil thickness. The error bars correspond to the statistical uncertainty and are plotted at the 90% confidence level.

## IV. CONCLUSIONS

High-resolution Auger projectile spectroscopy has been used to measure the fraction of metastable $1s2s\,^3S$ ions in fast He-like B, C, N, O, and F beams produced in collisions with C foils and $N_2$ gas targets as a function of both the incident energy in the range of 0.5 to 2 MeV/$u$ and the foil thickness in the range of 1–5 $\mu$g/cm$^2$. The method used for the determination of the metastable fraction is based on measurements of the electron emission from the doubly excited states of Li-like ions formed in the collision of primary beams with hydrogen and helium targets [1]. Some differences were observed both in the energy dependence and the absolute value of metastable fractions for different elements. In particular, the metastable content in $C^{4+}$ beams produced in carbon foils was found to be significantly lower than that of the other investigated beams. The observed deviation has been explained by *K*-vacancy sharing, which is known to have the highest probability for symmetric collisions. A model recently proposed [1] for the calculation of the metastable ion beam content has been modified and tested for $B^{3+}$ leading to a satisfactory agreement with recent experimental data.

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