# Technique for the determination of the $1s2s\,^3S$ metastable fraction in two-electron ion beams

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An experimental technique for the determination of the metastable $1s2s\,^3S$ fraction $f$ of two-electron ion beams is reported. The method utilizes the electron yields of the $1s2p^2\,^2D$ and $1s2s2p\,^4P$ doubly excited states, produced in collisions of two-electron ion beams with $H_2$ or He targets. The metastable beam fraction $f$ is determined in two successive measurements at the same beam energy but having different metastable fractions. The technique is applied to the case of $B^{3+}$ ions in collisions with $H_2$ targets. The results are in good agreement with those from our recent paper on similar metastable fraction measurements [M. Zamkov *et al.*, Phys. Rev. A **64**, 052702 (2001)]. The method can be safely applied in cases where the two different metastable fractions differ significantly.

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Several techniques can be found in the literature for determining the metastable fraction of multicharged ion beams, including the very popular ion beam attenuation [2], the beam-foil technique [3], photon-particle coincidence [4], normalization to the corresponding ground-state Auger spectra [5], metastable production modeling [6–8], and others [9]. Recently [1], we reported on the measurement of the $1s2s\,^3S$ metastable fraction in $B^{3+}(1s^2\,^1S, 1s2s\,^3S)$ beams produced in both thin foils and gas targets. The method was based on the measurement of the relative Auger electron yields from the $1s2p^2\,^2D$ and $1s2s2p\,^4P$ doubly excited states of $B^{2+}$, which are formed in collisions of $B^{3+}$ with $H_2$ gas targets. The advantage of the method is its simplicity, since it involves the measurements of the *relative* Auger electron yields, present in the same spectrum. Moreover, it can be easily applied to the ion-beam energy dependence study of the metastable fraction [1] and to the isoelectronic sequence investigation [10]. The weak point of the method is that it utilizes calculated cross sections for the production of $^2D$ and $^4P$ states. Thus, the accuracy of the method depends on the accuracy of the calculated cross sections. In addition, absolute cross-section measurements for processes related to the $^2D$ and $^4P$ states cannot be obtained with the previous method [1].

The need for a technique independent of any theoretical cross-section calculations, led us to investigate a different method for determining the two-electron beam $1s2s\,^3S$ metastable fraction. The quantitative information about the metastable beam fraction is indispensable for the absolute cross-section determination of all processes involved in two-electron ion-atom collisions, as, for example, the most recently investigated cases of superelastic electron scattering [11] and the production of Li-like hollow ionic states [12,13]. The method is based on the same principle as the one in our previous paper [1], i.e., on the distinct formation mechanisms of the $1s2p^2\,^2D$ and $1s2s2p\,^4P$ doubly excited states when $H_2$ or He targets are used. The population of the $^4P$ state is obtained through the $1s2s\,^3S$ metastable state via direct electron capture to the $2p$ state or via the process of nonresonant transfer and excitation (NTE) [14,15]. The $^2D$ state on the other hand, is formed from the $1s^2\,^1S$ ground state via resonant transfer and excitation (RTE) [16,17] or NTE and from the $1s2s\,^3S$ metastable state via NTE. However, the NTE contribution to the production of the $^2D$ state is much smaller than that from RTE when $H_2$ and He targets are used, especially for projectile energies near the RTE peak resonance or higher, and in these cases can be neglected. Consequently, in a collision involving a mixed state $(1s^2\,^1S, 1s2s\,^3S)$ two-electron ion beam colliding with $H_2$ or He targets, the Auger electron yields for the production of the $^2D$ and $^4P$ doubly excited states encrypt the information about the beam content.

The experimental single differential cross section $d\sigma/d\Omega$ (or SDCS) can be obtained from the doubly differential cross-section spectrum after integrating over the energy range of the corresponding peak and is given by

$$\frac{d\sigma}{d\Omega} = \frac{N_e}{N_I n l \Delta\Omega T \eta}, \tag{1}$$

where $N_e$ is the raw electrons counts, $N_I$ the number of ions collected during the measurement, $n$ the target density, $l$ the target length, $\Delta\Omega$ the spectrograph solid angle, $T$ the spectrograph transmission, and $\eta$ the spectrograph overall efficiency. In the case of a mixed beam of undetermined metastable fraction, Eq. (1) describes the normalized electron yields $Z$ for the $^2D$ and $^4P$ states, rather than the absolute cross sections. Thus, for each case the yield may be written as

$$Z(^2D) = \frac{N_e(^2D)}{N_g n l \Delta\Omega T \eta}\frac{N_g}{N_I} = \frac{d\sigma(^2D)}{d\Omega}\frac{N_g}{N_I}, \tag{2}$$

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$$Z(^4P)=\frac{RN_e(^4P)}{N_m nl\Delta\Omega T\eta}\frac{N_m}{N_I}=\frac{d\sigma(^4P)}{d\Omega}\frac{N_m}{RN_I}, \tag{3}$$

where $N_g$ and $N_m$ are the number of ions in the $^1S$ ground and $^3S$ metastable states, respectively. $R$ is the lifetime correction factor for the electron yield of the $^4P$ state [1,9], since it is a long-lived state decaying not only along the gas target length, but throughout the path to the exit of the analyzer. Defining the metastable fraction $f$ as

$$f\equiv\frac{N_m}{N_m+N_g}=\frac{N_m}{N_I} \tag{4}$$

and replacing it in Eqs. (2) and (3), gives

$$Z(^2D)=\frac{d\sigma(^2D)}{d\Omega}(1-f), \tag{5}$$

$$Z(^4P)=\frac{d\sigma(^4P)}{d\Omega}\frac{1}{R}f. \tag{6}$$

The proposed method is based on two different metastable fraction measurements at the same beam energy. The metastable beam fraction depends on both the target type (gas or foil) and the collision energy [1]. Consequently, by utilizing two different target types at the same beam energy, two different metastable fraction beams may be obtained. Denoting by the indices 1 and 2 the two different measurements, Eqs. (5) and (6) are reduced to the following system of equations:

$$Z_1(^2D)=\frac{d\sigma(^2D)}{d\Omega}(1-f_1), \tag{7}$$

$$Z_2(^2D)=\frac{d\sigma(^2D)}{d\Omega}(1-f_2), \tag{8}$$

$$Z_1(^4P)=\frac{d\sigma(^4P)}{d\Omega}\frac{1}{R}f_1, \tag{9}$$

$$Z_2(^4P)=\frac{d\sigma(^4P)}{d\Omega}\frac{1}{R}f_2. \tag{10}$$

The above system is exactly solved giving the two different fractions as

$$f_1=Z_1(^4P)\frac{Z_1(^2D)-Z_2(^2D)}{Z_1(^2D)Z_2(^4P)-Z_2(^2D)Z_1(^4P)}, \tag{11}$$

$$f_2=Z_2(^4P)\frac{Z_1(^2D)-Z_2(^2D)}{Z_1(^2D)Z_2(^4P)-Z_2(^2D)Z_1(^4P)}. \tag{12}$$

Note that, the same projectile energy ensures that the SDCSs for producing the two states remain the same, resulting in their cancellation in Eqs. (11) and (12). At the same time, the lifetime correction factor $R$ for the $^4P$ state is also canceled, thus eliminating a very important correction factor. The $^4P$ lifetime correction was unavoidable in the works of Zamkov *et al.* [1] and Lee *et al.* [9], resulting in significant additional uncertainties. Consequently, the proposed method has the advantage of utilizing only *relative* Auger electron yields to obtain the metastable fraction, avoiding thus any further theoretical assumptions or experimental corrections.

The technique was applied to $B^{3+}$ ions. The experiments were performed in the J. R. Macdonald Laboratory at Kansas State University, using the 7-MV EN tandem van de Graaff accelerator. The $B^{3+}$ beams were produced either inside the accelerator terminal, after colliding the initial $B^-$ beam with $N_2$ gas targets or thin (5 $\mu$g/cm$^2$) carbon foils, or outside the accelerator terminal, after colliding the incident $B^{2+}$ beam with Ar gas targets or thin carbon foils. The first process will be referred to as ''electron stripping'' while the second process as ''electron poststripping,'' or simply ''stripping'' and ''poststripping,'' respectively. The $B^{3+}$ ions, were magnetically selected and focused in a 5-cm-long differentially pumped gas cell to be collided with $H_2$ gas targets. The electron emission spectra were obtained at zero degrees with respect to the beam axis with a single-stage high-efficiency hemispherical spectrograph utilizing a focusing/decelerating lens system and a large position sensitive detector. A full width at half maximum resolution of 0.3% in the projectile rest frame was attained by decelerating the electrons by a factor of $F=4$. The experimental setup along with the spectrograph operation and performance has been described to some extent [18–20]. All spectra were recorded at the same tuning energy and deceleration factor ($F=4$). They were normalized to the same target pressure and ion charge collected at the Faraday Cup placed right after the spectrograph. High statistics data were accumulated to minimize the uncertainties. Single collision conditions were ensured by using a $H_2$ target pressure of 20 mTorr.

The gas cell was located at approximately 43 m away from the accelerator, and 12 m from the electron poststripper. Since the lifetime of the metastable $B^{3+}(1s2s\,^3S)$ state is about 100 ms [21], the reduction of the metastable component along the beamline path is negligible for both production locations. Formation of the metastable $B^{3+}(1s2s\,^1S)$ state is also possible. Assuming statistical population, a production ratio of $N_{1_S}/N_{3_S}=1/3$ is established. Moreover, the $B^{3+}(1s2s\,^1S)$ state lifetime is about 9 $\mu$s [21], allowing for a beam reduction by 15% in the case of electron poststripping and 45% in the case of electron stripping, at a beam energy of 4 MeV. The existence of the $1s2s\,^1S$ metastable component does not affect the technique, since the $^1S$ state can populate neither the $^4P$ state, due to spin conservation considerations nor the $^2D$, as RTE is energetically not allowed and NTE is negligible. However, redefining the corrected $1s2s\,^3S$ metastable fraction as

$$f_{corr}\equiv\frac{N_{3S}}{N_g+N_{3S}+N_{1S}} \tag{13}$$

and using Eq. (4) and the ratio $N_{1S}/N_{3S}$, the measured $1s2s\,^3S$ metastable fraction $f$ should be corrected as

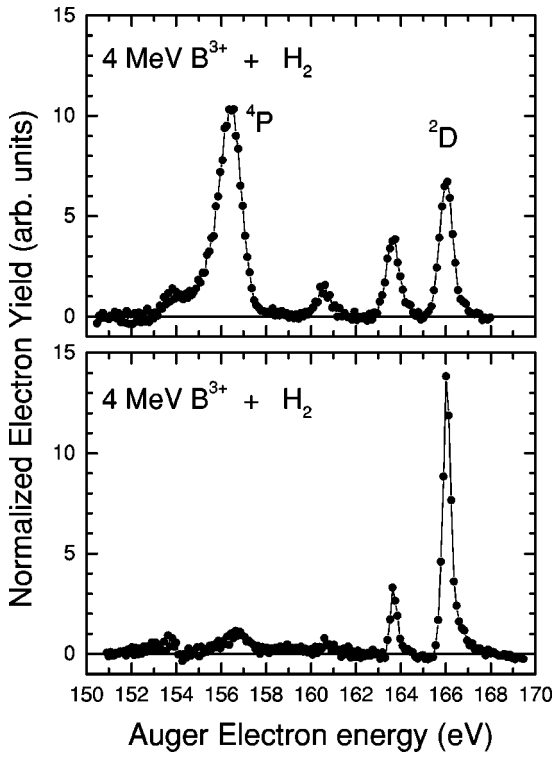


FIG. 1. Experimental data for the collision system of 4 MeV $B^{3+}+H_2$. The presence of the $^4P$ peak, predominantly produced by a $2p$ electron capture to the $1s2s\,^3S$ ion core, implies a significant metastable component. [*Top*] The $B^{3+}$ beam was produced after colliding the incident $B^{2+}$ beam in thin carbon foils. [*Bottom*] The $B^{3+}$ beam was produced directly from the tandem accelerator, after colliding the initial $B^-$ beam with $N_2$ gas targets inside the accelerator terminal. As can be seen, this process leads to a significantly diminished $^4P$ peak implying an almost pure ground-state beam.

$$f_{corr}=f\frac{1}{1+\frac{\lambda}{3}f}\simeq f-\frac{\lambda}{3}f^2, \tag{14}$$

where $\lambda$ is the fraction of the $^1S$ beam component reaching the gas cell. For moderate ($<50\%$) metastable beam fractions, the above correction does not exceed the value of 10%, and is neglected in this work, as it is well within the statistical uncertainties.

In Fig. 1 the Auger spectra for the 4 MeV $B^{3+}+H_2$ collision system are shown. The spectra were energy calibrated, transformed to the projectile frame and background subtracted by applying a polynomial fit, adequate for the background shape. The presence of the enhanced $^4P$ peak in Fig. 1 (top) implies a significant metastable component for that case, a fact that was expected, since the later $B^{3+}$ beam was produced after poststripping $B^{2+}$ ion beams in 5-$\mu$g/cm$^2$ carbon foils [1]. Similarly, the much reduced $^4P$ peak present in the spectrum in Fig. 1 (bottom), implies that the $B^{3+}$ beam is almost totally in the ground state. In this case, the $B^{3+}$ beam was produced directly from the tandem accelerator, after gas stripping. A $B^{3+}$ beam of about 100 pA was produced this way, which even though of very low intensity was more than adequate for the highly efficient measurement offered by the spectrograph. The normalized yields for the $^4P$ and $^2D$ states were obtained after integrating the corresponding peaks for each case. The metastable fractions were

TABLE I. Summary of the different metastable fraction $B^{3+}$ beams along with their production processes. In the case of poststripping the collision energy is the same as the final beam energy, while in the case of stripping, the collision energy differs from the final beam energy by a factor of $(q+1)$, where $q$ is the incident ion charge. One should recall that the errors in the results of Ref. [1] include the uncertainty from the calculated cross sections.

| Stripping method | Incident ion | Stripping energy (MeV) | Final energy (MeV) | Fraction (this work) (%) | Fraction (Ref. [1]) (%) |
|---|---|---|---|---|---|
| Gas stripping | $B^-$ | 1 | 4 | $3\pm1$ | $1\pm1$ |
| Foil post stripping | $B^{2+}$ | 4 | 4 | $28\pm8$ | $26\pm8$ |
| Gas post stripping | $B^{2+}$ | 4.5 | 4.5 | $18\pm5$ | $16\pm5$ |
| Foil post stripping | $B^{2+}$ | 4.5 | 4.5 | $42\pm10$ | $26\pm8$ |

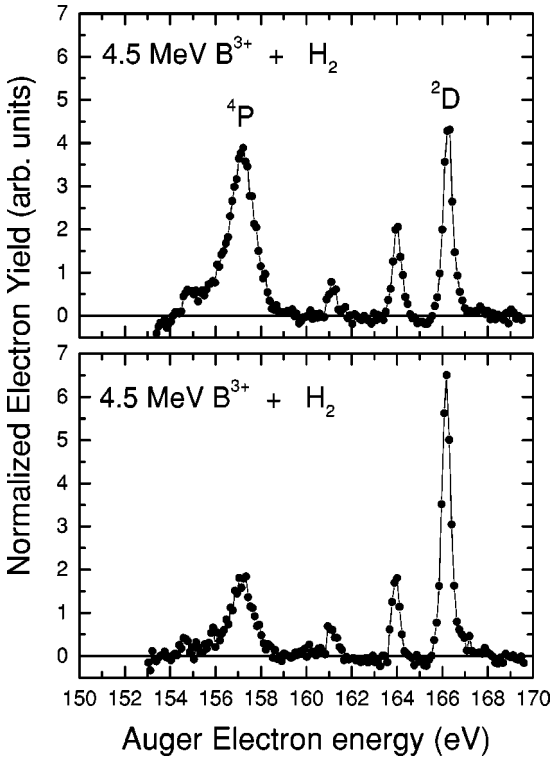


FIG. 2. Experimental data for the collision system of 4.5 MeV $B^{3+}+H_2$. [*Top*] The $B^{3+}$ beam was produced by foil poststripping as in Fig. 1. [*Bottom*] The $B^{3+}$ beam was produced by poststripping in Ar gas targets. The metastable fraction in the gas poststripping case is seen to be much larger than when produced by gas stripping in the accelerator terminal at much lower stripping energy as shown in Fig. 1 (bottom).

determined according to Eqs. (11) and (12). The results, presented in Table I, show a very good agreement with the results from our previous method [1], indicating that in the referenced method, the RTE and capture cross sections can be very well used for the metastable determination to within an uncertainty of 30%.

The accuracy of the method was also investigated, as large error bars are expected in cases where the two fractions differ by small amounts. Indeed, Eqs. (11) and (12), are mainly governed by the $Z_1(^2D)$-$Z_2(^2D)$ term. Small differences in the metastable fraction result in small differences in the $^2$D RTE state yield, thus enhancing the absolute uncertainties. In order to verify this, the previous set of measurements were repeated, after producing the low metastable fraction $B^{3+}$ beam by poststripping in Ar gas targets. The essential difference between the latter case and the case where the $B^{3+}$ beam was obtained by gas stripping (inside the accelerator terminal), is the higher stripping energy. A larger metastable fraction was obtained in this way, which is clearly seen from the enhanced $^4P$ peak in Fig. 2 (bottom). The results of this second set of measurements are also presented in Table I. It is seen that the new metastable fraction values agree with the previous measurements within the statistical uncertainties. However, the absolute uncertainty is expected to be larger in the later case since the $Z_1(^2D)$-$Z_2(^2D)$ term is smaller.

In an effort to test the method at its extreme, the experiment was repeated utilizing 20-MeV $F^{7+}$ beams, for which metastable fraction measurements have been reported [22]. Beams with different metastable fractions were obtained by foil stripping and by foil poststripping. The difference in the normalized $^2D$ yields was less than 1%, indicating a very small difference in the metastable fractions, resulting in huge uncertainties. The above tests showed that the technique can be safely applied only in cases where the produced metastable fractions are significantly different ($>50\%$).

Our conclusions are summarized as follows. The relative electron yields of the $1s2p^2\,^2D$ and $1s2s2p\,^4P$ doubly excited states, produced in collisions of two-electron ion beams with $H_2$ or He targets, have been used to determine the metastable $1s2s\,^3S$ content of two-electron beams. Our experimental technique utilizes the above electron yields, measured in two separate and distinct measurements at the same collision energy but of two quite different metastable fractions, to determine the $1s2s\,^3S$ metastable beam component. The technique was applied to the case of $B^{3+}$ ions colliding with $H_2$ targets and the results were in good agreement with previous results from our recent paper on similar metastable fraction measurements [1]. The method can be safely applied to cases where significantly different ($>50\%$) metastable fractions can be produced by utilizing different ion-beam preparation procedures.

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