Measured electron-impact ionization of Be-like ions: B^+, C^{2+}, N^{3+}, and O^{4+}

R. A. Falk,* G. Stefani,† R. Camilloni,† and G. H. Dunn‡
Joint Institute for Laboratory Astrophysics, University of Colorado and National Bureau of Standards, Boulder, Colorado 80309

R. A. Phaneuf, D. C. Gregory, and D. H. Crandall
Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830
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Electron-impact-ionization cross sections have been measured from threshold to about 20 times threshold for Be-like ions B^+, C^{2+}, N^{3+}, and O^{4+} with the use of the crossed-beams technique. The ion beams consist of mixtures of ions in the $2s^2\,{}^1S$ ground state and the $2s2p\,{}^3P_{0,1,2}$ metastable states. For B^+ and C^{2+} the metastable fractions could be changed, allowing estimates of ground-state cross sections, while for N^{3+} and O^{4+} the metastables appear to dominate the beams and the fractions could not be changed. The measured cross sections are compared with a variety of predictions. Distorted-wave calculations compare most favorably, but discrepancies up to 40% are found. The metastable-state—ground-state mixture complicates the comparisons for these beam experiments and is probably an issue for all environments where light ($Z \le 15$) Be-like ions occur.

I. INTRODUCTION

The electron-impact ionization of ions is of fundamental importance in understanding plasmas and is difficult to predict from first principles. Ionization can proceed directly by

$$e^- + X^{+q} \to X^{+(q+k)} + (k+1)e^- \quad (1)$$

or through intermediate states, such as

$$e^- + X^{+q} \to (X^{+q})^* + e^- \to X^{+(q+k)} + (k+1)e^- \;. \quad (2)$$

The present study will detect only single ionization events ($k=1$). Most theoretical calculations predict only single ionization via process (1), but process (2) is known to be important in particular cases and is currently being included in some predictions.

Usually the ground state of ions is predominant in their physical environments, but in some cases excited states of ions are important. For Be-like ions the lowest excited states $2s2p\,{}^3P_{0,1,2}$ are metastable; they lie near in energy to the ground state $2s^2\,{}^1S_0$; and they are favored over the ground state by a 9 to 1 ratio of statistical weights. For B^+ through O^{4+} the lifetimes of these metastables are supposed to vary from about 1 sec to a few milliseconds,[1] which is long compared to typical atomic states and even to lifetimes of these ions in most laboratory and astrophysical environments. Thus, for Be-like ions metastable states may predominate. Predicted ionization cross sections are significantly higher (+50% roughly at peak) for the metastable- versus ground-state ions.[2] Figure 1 shows the schematic relationship of energy levels important to the present study and gives specific transition energies[3] for each of the ions to be considered. In every case the threshold energy for direct ejection of the $2p$ electron from the $2s2p\,{}^3P$ metastable ions is the lowest, followed by direct ejection of one of the $2s$ electrons of the $2s^2\,{}^1S$ ground-state ions, and then by that for direct ejection of the $2s$ electron from metastable ions. These thresholds are designated, respectively, by m, g, and m' in subsequent figures.

II. EXPERIMENTAL TECHNIQUE

The measurements were made using the crossed—charged-beams technique.[4,5] The specific apparatus for the B^+ measurements[6,7] and the C^{2+}, N^{3+}, and O^{4+} measurements[8,9] have been described before. In both setups, a well-defined ion beam, accelerated through

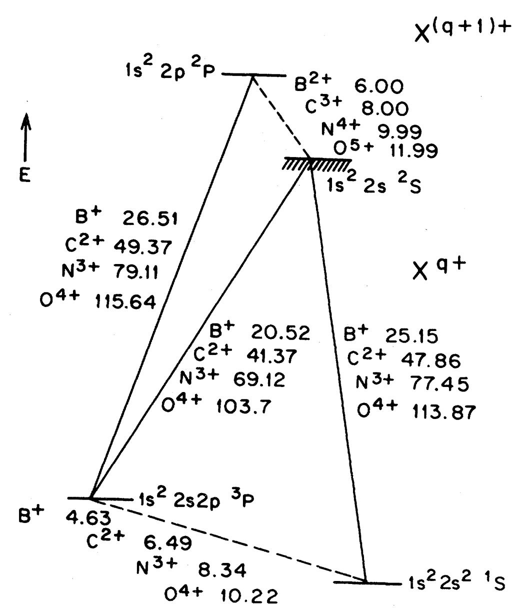

FIG. 1. Partial Grotrian diagram of the Be-like ions and their next higher charge state (Li-like). Solid lines connecting states indicate possible ionization paths with the threshold energies (eV) for each species indicated. Relative positions of the states are roughly to scale.

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a potential of a few kV (1 kV for B^+ and 10 kV for C^{2+}, N^{3+}, and O^{4+}), is crossed with a magnetically confined electron beam.[10] After the interaction with the electron beam, the primary ions of charge q and the product ions of charge $q+1$ are separated in a 45° parallel-plate electrostatic analyzer. A guarded Faraday cup collects the primary ions and another biased Faraday cup collects the electrons. The product ions are detected by an electron multiplier operated in a pulse counting mode. The electron beam is chopped, allowing a pair of gated scalers to separately count background counts and signal plus background. For C^{2+}, N^{3+}, and O^{4+} targets the products were detected using a channel electron multiplier which has near unit counting efficiency for these fast ions.[8,11] For the B^+ measurements a 20-stage focused dynode multiplier with a large sensitive area, but less than unit efficiency, was used. In this latter case, the absolute cross section was measured at a benchmark energy of 398 eV by using the multiplier as a biased Faraday cup and measuring product ion current with a calibrated vibrating reed electrometer. All other B^+ measurements were then normalized to the value at this energy (a measurement at the benchmark being included in each measurement sequence).

For the B^+ measurements the energy spread in the interaction volume is about 0.5 eV (Ref. 7), while for the C^{2+}, N^{3+}, and O^{4+} cases this is about 2 eV.[9] The difference derives from higher fringe fields in the interaction volume due to electrostatic deflectors needed to compensate for the deflection of the ion beam by the electron-beam-confining magnetic field.

The B^+ ions were formed in a commercial hot-cathode-discharge source[12] fed by BF_3 gas. The multiply charged ions were formed in a Penning ion gauge source (ORNL-PIG) (Ref. 13) using as source gases: CO mixed with Xe to produce C^{2+}, N_2 to produce N^{3+}, and O_2 mixed with Xe to produce O^{4+}. Typical ion currents were 10^{-7} A.

In the case of B^+, and less reliably for C^{2+}, the metastable fractions in the beams were varied by adjusting discharge conditions, but efforts to do this for N^{3+} and O^{4+} were not successful. For B^+ it has been previously demonstrated that the metastable content of a beam can depend on both discharge conditions and feed gas species.[14] For the multicharged ions, assuming sequential ionization as the primary formation mechanism in the source, the Be-like ion will be produced principally by ionization of ions with one less charge. Thus, it is reasonable that the metastable fraction for the highly charged ions might be fairly independent of variations in gas feed or discharge parameters. In fact, the ratio might be supposed to be that of the statistical weights, implying 90% metastables. For the ions investigated here the shortest metastable lifetime[1] is a few milliseconds (O^{4+}), which is long compared to ion confinement time in the source and compared to the few microsecond transport time from the source to the beams interaction point. Note, however, that for more highly charged ions the decay of the metastable states is faster and their relative population may be decreased. For example, for Al^{9+} the decay time becomes a few microseconds,[1] which is comparable to transport times in the present experiments.

For cases where the metastable fraction can be significantly varied and where cross sections can be measured at some energies between the thresholds for metastable- and ground-state ionization, the ground-state cross section can be directly inferred. The measured cross section σ for the mixed-state beam can be related to the ground-state cross section σ_g and the metastable-state cross section σ_* above and below the ground-state threshold energy E_g^{th} by

$$\sigma(E_b)=f\sigma_*(E_b) \tag{3}$$

and

$$\sigma(E_a)=(1-f)\sigma_g(E_a)+f\sigma_*(E_a)\ , \tag{4}$$

where f is the metastable fraction and $E_b<E_g^{\text{th}}<E_a$.

If the metastable fraction can be changed then a second set of Eqs. (3) and (4) can be obtained with a σ' and f'. Solving these four equations yields

$$\sigma_g(E_a)=\frac{\sigma(E_a)-\kappa\sigma'(E_a)}{1-\kappa}\ , \tag{5}$$

where

$$\kappa=\frac{\sigma(E_b)}{\sigma'(E_b)}=\frac{f}{f'}\ . \tag{6}$$

Equation (5) defines a procedure for extracting σ_g from two sets of raw data with different metastable fractions. Neither f nor σ_* can be determined by this method.

Related methods have been used before to obtain ground-state cross sections from measurements with different metastable fractions (see Ref. 15 for one example).

The sensitivity of the procedure described here depends on significant metastable fraction change and precise cross-section measurements. In the present B^+ data these requirements could be met. The metastable fraction could be reliably changed by changing voltages applied to the discharge. For the C^{2+} case the change in the metastable content produced by changing discharge current and gas flow was smaller than in the B^+ case and could not be reproduced definitively by simply setting source parameters to predetermined values.

III. RESULTS

Table I presents measured cross sections for all of the species studied. These data are for mixed ground- and metastable-state ion beams. At the end of Table I, we list an average cross-section value measured below the thresholds for ionization out of the metastable states. This value should be zero and a nonzero value is evidence for two-beam modulation of background.[5,7,8] For both of the B^+ data sets, a small but statistically significant signal is found below threshold. The B^+ data given in Table I have been corrected by subtracting this residual value for all measured cross sections as has been done previously.[8] For the C^{2+}, N^{3+}, and O^{4+} cases the measured cross sections below threshold are given but have not been subtracted from the data because the values are not statistically different from zero. It should be noted here that the B^+ data, for which the spurious below-threshold signal occurred, was acquired with a different apparatus [Joint Institute of Laboratory Astrophysics (JILA)] from the other data [Oak Ridge National Laboratory (ORNL)] but that similar background problems have been encountered previously for both sets of apparatus.[7,8]

TABLE I. Measured cross sections for electron-impact ionization of Be-like ions. For B^{+} the below-threshold measured values have been subtracted from the cross-section values given in the table. Numbers in parentheses are counting statistics (67% confidence level) and numbers preceded by ± are reproducibility as determined from standard deviation of the mean of four or more separate repeated measurements. Cross sections without uncertainty designated have the same statistics as indicated for sample cases.

	B^{+}			C^{2+}		N^{3+}		O^{4+}	
	Low metastables	High metastables		Low metastables	High metastables				
Energy (eV)	σ (10^{-18} cm^2)	σ (10^{-18} cm^2)	Energy (eV)	σ (10^{-18} cm^2)	σ (10^{-18} cm^2)	Energy (eV)	σ (10^{-18} cm^2)	Energy (eV)	σ (10^{-18} cm^2)
21.1	0.40(0.25)	1.04(0.20)	40.2	+0.31(0.22)		67.0	0.04(0.03)	104	0.09(0.06)
22.2	1.35	1.86	41.2	0.56	1.15(0.18)	68.6	0.24(0.04)	109	0.37(0.05)
23.1	2.89	5.10	42.0	0.86		70.1	0.49(0.04)	113	0.48(0.06)
24.2	5.19	7.86	43.1	1.21±0.12	1.82	72.9	0.75(0.03)	118	0.79(0.05)
25.3	6.53	10.4	44.0	1.57(0.22)		74.4	0.98(0.04)	128	1.08(0.07)
26.3	9.84	14.2	45.3	2.44	2.87	75.6	1.08(0.03)	143	1.61(0.05)
27.3	13.0	18.1	47.1		3.26	78.2	1.37(0.04)	167	2.20(0.08)
28.4	16.9(0.26)	22.5(0.20)	47.8	2.88±0.08		79.7	1.60(0.03)	194	2.54(0.07)
29.4	20.9	25.9	50.4	4.20	4.75(0.14)	82.7	1.91(0.05)	240	2.81(0.04)
30.5	24.3	28.6	53.0	5.25(0.13)	5.96	91.3	3.00(0.05)	288	2.93(0.03)
31.5	27.0	32.0	54.7	5.69		115	3.91(0.05)	338	2.88(0.03)
32.5	29.2(0.27)	33.8±0.4	56.0	6.19	7.20	142	4.52(0.03)	387	2.87(0.03)
33.5	32.3	37.2	57.5	6.79		197	5.00(0.02)	485	2.66(0.02)
34.6		37.4	59.3	7.21(0.11)	8.18(0.16)	245	5.12(0.02)	520	2.67(0.03)
35.6	36.5	39.5	60.9	7.91		288	5.28(0.04)	544	2.60(0.04)
38.3	41.3		70.7	9.68		328	5.08(0.02)	570	2.67(0.03)
42.5	46.6	52.3	75.6	10.19		337	5.05(0.02)	584	2.70(0.02)
46.8	48.6±0.3	53.2±0.4	85.4	10.98		347	4.98(0.02)	604	2.65(0.03)
52.5	52.2	57.8	95.3	11.44		357	4.93(0.02)	634	2.71(0.03)
63.0	54.8	60.5	110	12.06		367	4.87(0.02)	663	2.60(0.05)
73.4	56.8±0.5	60.0	127	12.21		377	4.86(0.02)	693	2.59(0.05)
83.5	56.5±0.3	59.4	146	11.90±0.10	12.65(0.06)	387	4.82(0.04)	783	2.38(0.02)
94	55.0±0.2	59.1±0.2	159	11.91		396	4.77(0.02)	980	2.04(0.03)
103	54.4	59.4	182	11.61		406	4.76(0.02)	1177	1.87(0.03)
144	51.2	53.5	216	11.30		416	4.70(0.02)	1475	1.46(0.02)
195	47.4	49.1	282	10.36		426	4.68(0.02)		
246	42.1	43.3	341	9.12		436	4.63(0.02)		
297	39.0	39.7	392	8.92		446	4.61(0.02)		
347	35.3	35.6	418	8.12		455	4.58(0.02)		
398	32.1±0.4	32.0±0.4	493	7.73±0.30		470	4.46(0.02)		
						490	4.41(0.02)		
						510	4.36(0.02)		
						584	4.22(0.03)		
						683	4.08(0.03)		
						782	3.70(0.03)		
						880	3.57(0.03)		
						980	3.15(0.03)		
						1079	3.12(0.03)		
						1178	2.86(0.03)		
						1326	2.59(0.03)		
						1476	2.32(0.03)		
a	+0.27±0.10	+1.14±0.16	a	+0.08±0.07	+0.01±0.19	a	0.00±0.03	a	−0.05±0.03

[a]Below threshold.

The below-threshold signal in the B^{+} data was not systematically investigated in part because it is so small. However, detailed diagnostics on similar problems have been performed for other measurements with the same apparatus (see Ref. 7—thesis of Rogers). Such spurious signals can arise due to pressure modulation from beam switching or from modulation of position and/or shape of one beam by the space charge of the other. For the present experiment, with an electron beam switching frequency of 2 kHz, the pressure modulation should be of the order of 10^{-12} Torr and shifted by $-\pi/2$ in phase relative to the beam modulation. Thus, it is estimated that the pressure modulation does not cause the spurious below-threshold signal in the B^{+} data. In the present case a good candidate for the cause of the spurious signal is the modulation of the position of the background B^{2+} ions at the detector due to space charge of the electron beam. Since the detector sensitivity does vary across its surface, such position modulation of the background ions could change the measured background slightly as the electron beam is switched on and off. This spurious modulated background could then appear as a postive or negative signal depending on details of ion beam focusing and position. On the basis of the present below-threshold measurements (Fig. 2), previous experience,[7,8] and the fact that the electron density increases by only about a factor of 2 from 20 to 300 eV—the background modulation effect is believed to be fairly independent of collision energy and reasonably constant for a given set of ion beam tuning parameters. Thus, within a given data set, simple subtraction of the measured below-threshold signal from each above-threshold measurement was selected as the appropriate correction to the data with corresponding increase in uncertainties as discussed below.

A. B^+ results

Figure 2 shows measured cross sections (points) and extracted ground-state cross sections (solid curve) for B^+. Estimating uncertainties is complicated by the residual signal below threshold. The measured cross sections for both "high" and "low" metastable data sets are shown for 16–20 eV in the inset of Fig. 2. For energies near threshold, the background subtraction applied should be reliable. At higher energies the uncertainty is greater due to the assumption that this background was constant. For the error bars shown at 36 and 94 eV, uncertainties of $\pm 0.6\times 10^{-18}$ cm^2 and $\pm 1.2\times 10^{-18}$ cm^2, respectively, have been included for this correction. The remaining relative uncertainty in the B^+ data is primarily due to counting statistics. As seen from Table I the reproducibility (typically $\pm 0.4\times 10^{-18}$ cm^2 given as $\pm$ values) and counting statistics (typically $\pm 0.3\times 10^{-18}$ given in parentheses) are representative of relative uncertainties (as discussed in Ref. 7) and are less than 1% of the peak cross section value.

The value of κ [Eq. (6)] determined from the ratio of the "low metastable" to "high metastable" measurements at the five lowest energies is 0.57 ± 0.06. The "best" single determination of κ is probably from the data at 23.1 eV which give $\kappa = 0.56$. Using $\kappa = 0.57$ in Eq. (5) and the pairs of data points in Table I, values of σ_g were obtained on a point by point basis and are approximated by the smooth, solid curve on Fig. 2. The relative uncertainties traced through Eq. (5) sum to about $\pm 9\%$ at standard confidence level (67% confidence level). Additional abso-

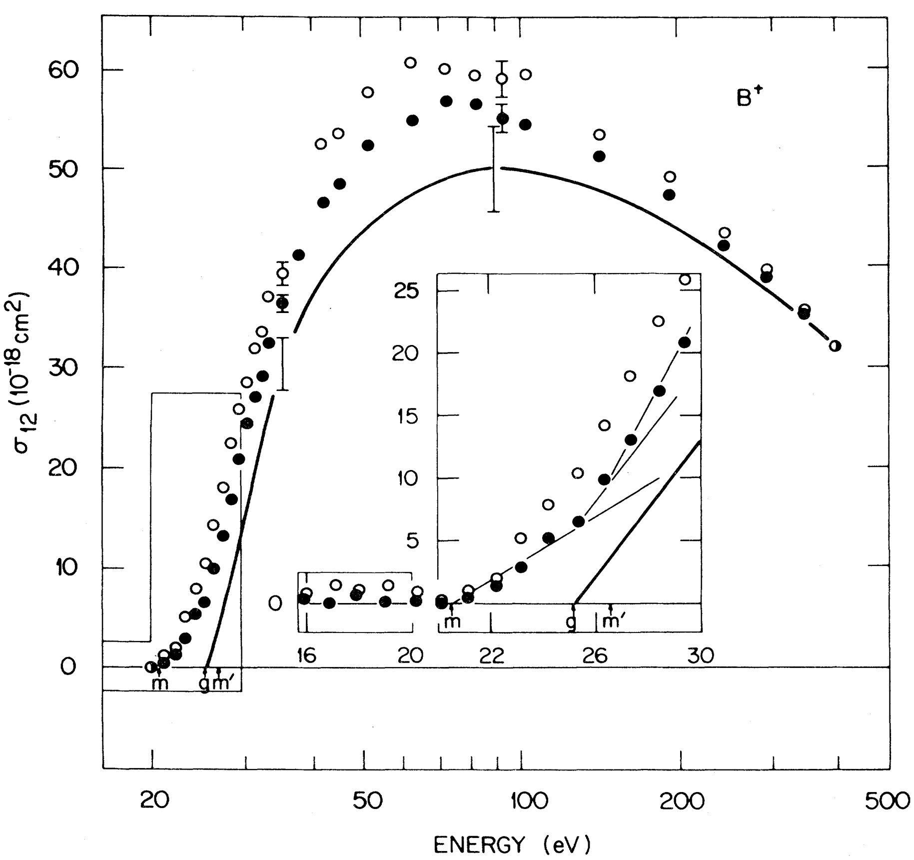

FIG. 2. Electron-impact ionization of B^+. Solid points are low metastable data and open circles are high metastable. Solid curve is the deduced experimental ground-state cross section. Inset shows the near-threshold region expanded including the 16–20 eV region where the nonzero measured cross sections were determined and then subtracted from each data set. Arrows indicate threshold energies for removal of metastable (m and m') and ground-state (g) outer electrons. Uncertainties due to counting statistics are roughly the size of data points. Total relative uncertainties are shown on the data points at 36 and 95 eV and the total absolute uncertainties in the deduced ground-state cross sections are shown on the solid curve at 36 and 95 eV.

lute uncertainty in the original data is about $\pm 5\%$ (the same as in Ref. 7). Thus the total absolute uncertainty in the derived ground-state cross section, taken as the quadrature sum of relative and absolute components, is about $\pm 10.5\%$ (at standard confidence level).

Referring again to the inset of Fig. 2, the near-threshold data in greater detail, we note that, in the energy region 20.5 to 25.2 eV, only direct ionization of the $2p$ electron of the $2s2p\ ^3P$ is possible, and the data clearly indicate that these ions are present in the beam. Even if only metastable-state ions were present a new threshold should occur for ionization of the $2s$ electron at 26.5 eV. The data (with statistical precision about the size of the symbols and with energy resolution about 0.5 eV) suggest three slopes as indicated by the three fine lines drawn through the low metastable data set on the inset of Fig. 2. These three slopes are then representing the onset of ionization of the $2p$ electron of the $2s2p\ ^3P$ states beginning at m, of one of the $2s^2$ electrons of the $2s^2\ ^1S$ ground state beginning at g, and of the $2s$ electron of the $2s2p\ ^3P$ states beginning at m'. A reliable estimate of the ground-state cross section can be obtained only because of the ability to change the metastable fraction and invoke Eqs. (5) and (6). A rough estimate based on the thresholds observed is that for the low metastable conditions roughly 50% of the incident ions are in the metastable states. Then for the high metastable case the percentage of metastables would be close to 90%.

Figure 3 presents a comparison of the extracted ground-state cross section for B^+ with theoretical predictions in the form of scaled cross sections. The Lotz prediction[16] (chain curve) is based on the single parameter form of the Lotz formula which is recommended for ions with $q \geq 4$ but which has been previously found to be just as reliable as the multiparameter formula[9] (as it is in this case). The Younger distorted-wave—exchange prediction[2] is based on fitting parameters for the isoelectronic sequence obtained from detailed calculations on more highly charged members of the sequence. The derived experimental results agree better with the Younger prediction near threshold, but better with the Lotz formula at the high energies emphasized by the scaling in Fig. 3. The experimental cross sections are least reliable at high energies because of the corrections required by the false signals below threshold, but the larger uncertainty allowed does not encompass either prediction. The calculations do not include indirect effects (inner-shell excitation autoionization), which have been assumed to be fairly small for B^+, but which could cause a discrepancy between the calculations and experiment of the type shown in Fig. 3. However, in order to reconcile experiment and theory the total excitation-autoionization contribution would need to be 20% or so at the highest energies, which seems unlikely.

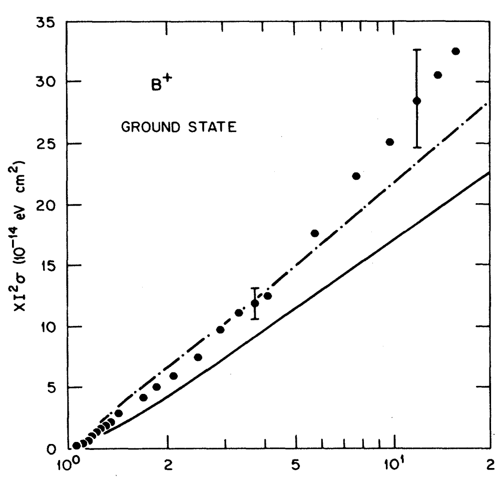

FIG. 3. Product $XI^2\sigma$ plotted vs X (energy in threshold units) for B^+, where I is the ionization potential and σ is the ground-state ionization cross section. Solid curve is from distorted-wave results of Younger (Ref. 2); chain curve is Lotz prediction (Ref. 16) and data points are deduced from present measurements. Error bars are estimates of total uncertainty at standard confidence level.

B. C^{2+} results

Figure 4 shows the data for ionization of C^{2+} ions. Again, for these measurements, the metastable fraction was changed, but in this case the change was small and could not always be reproduced. The problem with false signals below threshold was not apparent in this C^{2+} data. Most of the data which were acquired with high metastable conditions (open circles) are near threshold. The near-threshold data were used to derive a value for $\kappa = 0.70 \pm 0.15$ (approximate uncertainty) which together with the individual data pairs gives deduced ground-state cross sections of 5.0×10^{-18} cm^2 at 59 eV and 10.2×10^{-18} cm^2 at 145 eV shown by the stars in Fig. 4. The uncertainty (at standard confidence) in these deduced ground-state cross sections is roughly $\pm 20\%$, dominated by uncertainty in κ which can only be roughly estimated from the four lowest-energy cross-section pairs.

Figure 4 includes the crossed-beams data (open triangles) of Woodruff *et al.*[17] which are in excellent overall agreement with present results. The good agreement in measured cross-section magnitude suggests that the metastable fraction is about the same in the two experiments. However, detailed examination of the data near threshold (inset of Fig. 4) suggests that the C^{2+} beams of Woodruff *et al.* contained fewer metastables than beams in the present measurements, so that the two experiments are not as consistent as they appear at first glance. The small difference in measured cross sections which should be found if the metastable fractions are somewhat different, would likely be smaller than the combined absolute uncertainties of the data of each experiment (about $\pm 6\%$ for each of the experiments at the peak of the cross section).

Not shown in Fig. 4 are results from ion trap experiments for ionization of C^{2+} by Hamdan *et al.*[18] Those cross sections are somewhat lower than present measurements (about 10.5×10^{-18} cm^2 at the peak), but with $\pm 25\%$ uncertainties, so that no inconsistency with present results or metastable fractions can be inferred.

The slopes in the present data associated with the various thresholds (inset of Fig. 4) are less distinct for this C^{2+} case than for the B^+ results. The energy spread in the electron beam is about ± 2 eV for the ORNL apparatus,[9] which is consistent with the near-threshold

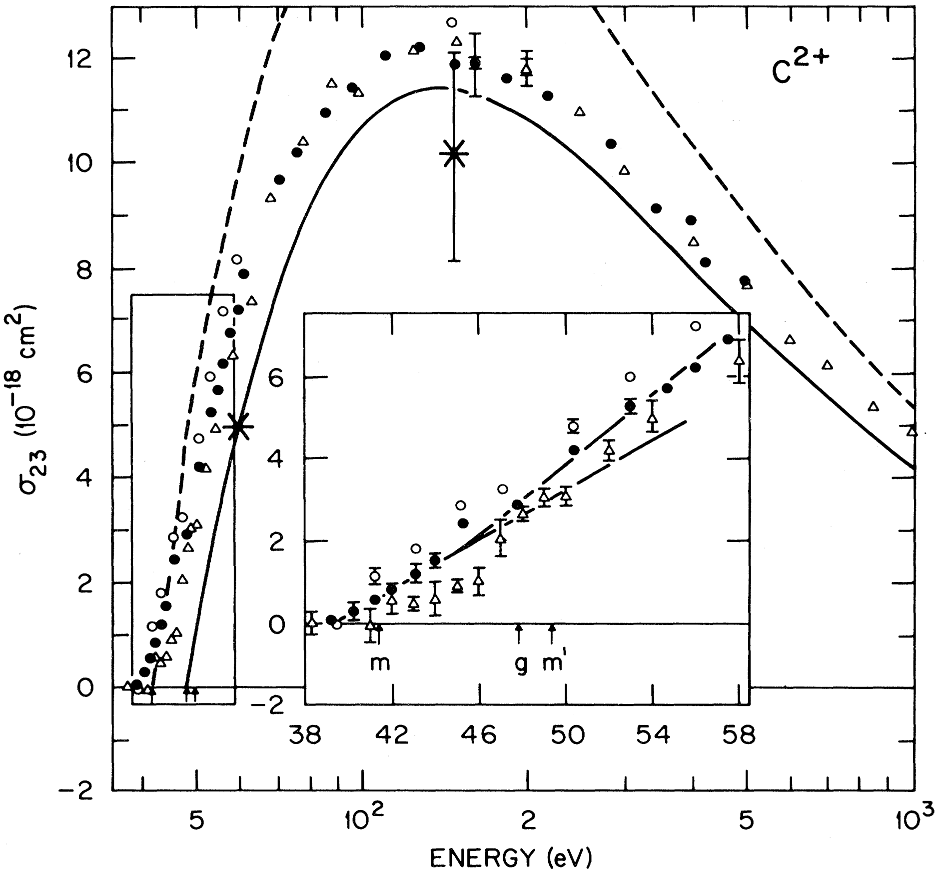

FIG. 4. Electron-impact ionization of C^{2+}. Solid points are present measurements with low metastables; open circles are present measurements with high metastables; open triangles are measurements of Woodruff *et al.* (Ref. 17); stars are ground-state cross sections deduced from present measurements. Curves are distorted-wave calculations by Younger (Ref. 2) for $2s^2\,{}^1S_0$ ground-state ions (solid curve) and for the $2s2p\,{}^3P$ metastable ions (dashed curve). Error bars are relative uncertainties at standard confidence except outer bars on data near 200 eV are typical total uncertainties. Lines through the low metastable data in the inset simply indicate change of slope in the data.

behavior and is about equal to the separation of the *g* and *m'* thresholds. The suggestion of the near-threshold data is that the metastable fraction is higher for the C^{2+} case than for B^+. An estimate based on the threshold data is 65% metastables for the low metastable case and about 90% for the high metastable case. The near-threshold results of Woodruff *et al.* would then suggest a lower metastable fraction (say 40% roughly) in their ion beam. The ions in the present case were formed in the ORNL-PIG source which is a magnetically confined discharge designed to produce highly charged ions and which produces roughly equal intensities of C^{3+} and C^{2+}. The duoplasmastron used by Woodruff *et al.* was operated to optimize C^{2+} production but the plasma was probably cooler and less ionized than in the ORNL-PIG. It is reasonable to suppose that the metastable fractions could be as different in the two sources as implied by the near-threshold data.

Also shown in Fig. 4 are Younger's distorted-wave—exchange predictions of ionization of C^{2+} for the ground state (solid curve) and for the metastables (dashed curve). Within the uncertainties introduced by mixed metastable and ground-state beam components, there is no discrepancy with Younger's predictions. The distorted-wave—exchange predictions for the ground state by Moores[19] and by Jakubowicz and Moores[20] are not shown in Fig. 4, but are little different from Younger's. Lotz predictions[16] are close to Younger's for the metastables but higher for the ground state (and consequently, in slightly poorer agreement with experiment for the ground state).

C. N^{3+} and O^{4+} results

For N^{3+} and O^{4+} the metastable fraction could not be significantly changed. Figures 5 and 6 show the observed cross sections (solid points) compared to distorted-wave calculations by Younger.[2] Younger discusses the metastable question and provides cross sections for both the ground (solid curve) and metastable (dashed curves) initial states. Considering the energy spread and relative uncertainty of the measurements, the near-threshold experimental measurements are consistent with Younger's calculations for 100% metastable fraction. However, 90%

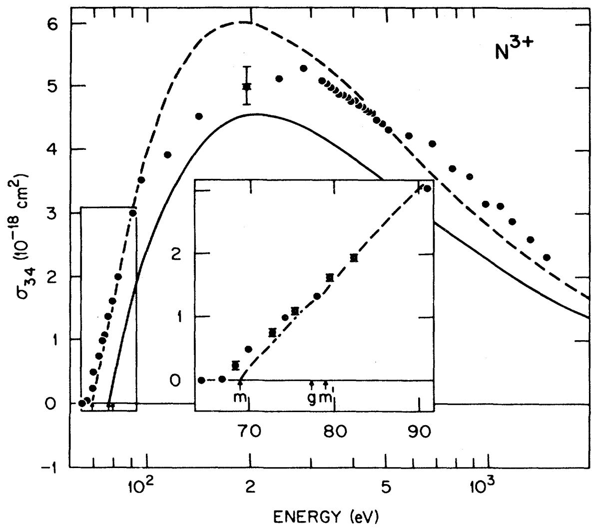

FIG. 5. Electron-impact ionization of N^{3+}. Present data (solid points) compared with distorted-wave calculations of Younger (Ref. 2) for $2s^2\,{}^1S$ ground-state ions (solid curve) and for $2s2p\,{}^3P$ metastables (dashed curve). Error bars are as in Fig. 4.

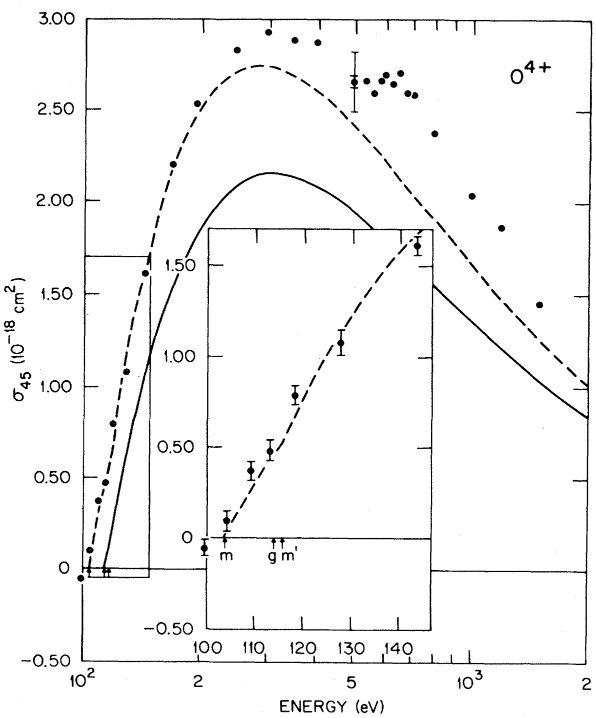

FIG. 6. Electron-impact ionization of O^{4+}. Present data (solid points) compared with distorted-wave calculations of Younger (Ref. 2) for $2s^2\,{}^1S$ ground-state ions (solid curve) and for $2s2p\,{}^3P$ metastables (dashed curve). Error bars are as in Fig. 4.

metastable fractions would not give distinguishably different cross-section shapes. It was recognized in the initial measurements for N^{3+} and O^{4+} that the metastable fraction was high,[21] and it was then roughly estimated at 50%. However, the subsequent work by Younger provides sufficiently reliable near-threshold comparison to suggest a higher metastable fraction. For N^{3+} the measured peak cross-section value is closer to the calculated ground-state cross section, but for O^{4+} the measured cross section is higher than even the 100% metastable calculated case. A reasonable estimate for the metastable fraction in the present N^{3+} and O^{4+} beams is 90%.

Because of the previous observations of excitation-autoionization contributions to total ionization in Li-like ions,[22] this contribution was deliberately searched for in the N^{3+} (around 400 eV) and O^{4+} (around 550 eV). Figure 6 clearly shows a small feature which enhances the O^{4+} cross section by about 10% near 550 eV, but no structure is found in the N^{3+} data (Fig. 5). The scaled Coulomb-Born approach has been applied by Sampson and Golden[23] for Be-like ions for which $Z/N \geq 2$ (N equals the number of bound electrons) including excitation of a 1s electron followed by autoionization. For O^{4+} they predict that an excitation-autoionization feature should occur at 543 eV and add about 5% to the cross section for initial ground-state ions and about 7% for metastable ions. The total cross section for ionization of O^{4+} predicted by Sampson and Golden is about 25% below present measurements.

Sampson and Golden do not provide predictions for N^{3+}, but their predictions for more highly charged Be-like ions give the relative excitation-autoionization contribution as nearly the same for all cases. Thus it is surprising that no feature was found near 400 eV in the N^{3+} experiment to within a precision of about $\pm 0.5\%$. The slope of the N^{3+} experimental data near this energy is different from the predictions (Fig. 5), however, suggesting some enhancement of the cross sections. With respect to the excitation-autoionization feature, the comparison of O^{4+} and N^{3+} data with predictions is similar to the case for Na-like ions Al^{2+} and Mg^{+} (Ref. 9). It is possible that the excitation-autoionization enhancement for N^{3+} (and for Mg^{+}) is complicated by formation of recombination resonances—double autoionization[24] which could spread the total enhancement of the ionization cross section to lower energies and obscure the distinct excitation features normally expected.[25]

IV. DISCUSSION

The present measurements were carried through with high accuracy with the intent of providing tests of theoretical predictions. Accurate comparisons with theory are compromised by metastable populations of the target beams which could change during measurements and which were difficult to assess. Ground-state cross sections have been extracted, but with increased uncertainties due to the extraction process. We have often quoted uncertainties at the 90% confidence level but such confidence cannot reasonably be assessed for any of the individual cross sections given here in view of population uncertainties.

Table II presents comparison of peak cross sections obtained from the present experiments, the best semiempirical representation (Lotz), and representative quantum cal-

TABLE II. Comparisons of peak cross sections in units of 10^{-18} cm^2 for ionization of Be-like ions (approximate energy at which the cross section peaks is also given). Lotz (Ref. 16) and Younger (Ref. 2) are calculated values. Total uncertainties, given in parentheses, are estimated at standard confidence level.

	B^+ (70 eV)			C^{2+} (130 eV)		
	Lotz	Younger	Expt.	Lotz	Younger	Expt.
Ground state	52.3	38.7	50.0 (11%)	14.5	11.4	10.2 (20%)
Metastable states	62.3	67.3	60.0[a] (6%)	16.4	16.3	13.0[a] (6%)
	N^{3+} (210 eV)			O^{4+} (300 eV)		
Ground state	5.51	4.53		2.55	2.15	
Metastable states	6.10	6.00	5.2[a] (6%)	2.77	2.74	2.9[a] (6%)

[a]These values are the measurements marked high metastable, which are estimated to be for roughly 90% metastable ions.

culations (Younger). The level of agreement is reasonable, but cannot be asserted to be good. For these peak values of the cross sections the experiment does not confirm any improvement of quantum results over semiempirical values nor any improvement of predictions with increasing ionic charge.

The data clearly indicate a high metastable content in the incident ion beams. Estimates that Be-like ions will be found in the statistical ratio (90%) in metastable states versus the ground state seem appropriate except in environments where collision times are longer than the metastable lifetimes. Thus except for highly charged ions and particularly low-density environments (e.g., interstellar medium) the metastable states of Be-like ions are likely to dominate.

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*Present address: Ball Research Corp., Boulder, Colorado 80439.

†Permanent address: Laboratorio Metodologie Avanzate Inorganiche, Consiglio Nazionale delle Ricerche, Rome, Italy.

‡Quantum Physics Division, National Bureau of Standards, Boulder, Colorado 80309.

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