Electron-impact-excitation cross sections out of the $2\,^3S$ metastable level of helium at high energies

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In this paper we report experimental measurements of the electron-impact-excitation cross sections out of the $2\,^3S$ metastable level of helium into higher excited levels, with emphasis on measurements at high electron energies. The agreement between our metastable results and recent theoretical calculations is comparable to the agreement between experimental and theoretical values for excitation from the ground state.
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I. INTRODUCTION

In the last decade a number of experimental [1–4] and theoretical [5–9] results have been reported on electron-impact excitation out of the He($2\,^3S$) metastable level. There is, however, little agreement among the various results. At low electron energies ($<$20 eV), the different theoretical values for excitation into the $3\,^3L$ levels vary by over a factor of 10, with the experimental results lying at the higher end of this distribution. There are, nevertheless, some points of optimism. While differing in absolute magnitude, the energy dependence of the cross section values from the two independent experimental results of our group [1,3] have similar shapes to two of the most recent sets of theoretical results [8,9]. At high electron energies, all of the various theoretical values converge to within 10% of the Born values by 100 eV. In contrast, our previously reported experimental results are larger than the Born results by almost a factor of 2 at the highest energies at which measurements were made (500 eV).

To resolve the differences between experiment and theory, this Brief Report focuses on three issues. First, the largest source of uncertainty in the results of Ref. [1] comes from the uncertainty in the apparent cross sections for excitation from the ground state which are used for absolute calibration, as is explained in Sec. II. In order to improve upon this aspect of the experiment, we have remeasured these cross sections. Second, we have extended our measurements to higher electron energies in an attempt to enter the ''Born-Bethe regime.'' Third, we demonstrate that our apparatus yields the correct high-energy asymptotic behavior for cross section values.

The asymptotic limit of the high-energy cross sections is characteristic of the excitation process. For example, at high energies the cross section for electron excitation into an optically allowed level varies as $E^{-1}\ln E$, where E is the incident electron energy. For electron excitation into a spin-allowed but electric-dipole-forbidden level the cross section varies as $1/E$ at high energies. Thus the energy dependence of the electron excitation cross sections provides a signature for the electron excitation process.

II. APPARATUS AND DATA ACQUISITION

Our apparatus has been described in previous publications [1,10] and is only described briefly in this paper. A 1.6-keV helium ion beam is extracted from an rf-ion source. The focused ion beam is passed through a recirculating cesium vapor target, where it is partially neutralized, forming a beam of fast helium atoms. This near resonant charge transfer process [11] yields an atomic beam of 68% $2\,^3S$ atoms, 19% $2\,^1S$ atoms, and 13% $1\,^1S$ atoms [10]. After the remaining ions are swept out of the beam, the fast atomic beam is crossed at right angles by an electron beam of variable energy. The fluorescence from the excited atoms in the fast atomic beam is analyzed by a 1-nm narrow bandwidth interference filter, and is detected using a photomultiplier tube.

We measure the electron excitation cross sections out of the $2\,^3S$ level into the various higher levels as a function of the incident electron energy. Relative results are obtained by measuring the photon count rate at a given electron energy and dividing by the electron-beam current and neutral beam flux. The absolute calibration of these relative results is performed by comparing the metastable signal to the known ground-state excitation signal obtained by replacing the fast metastable beam target with a static ground-state gas target. The full procedure of the absolute calibration (see Ref. [1]) also involves measuring the electron-beam current and beam profile, the fast atomic beam flux and beam profile, the number density of the static gas target, and the photon emission rates from both targets. The *fundamental* result of our calibration procedure is the ratio of the metastable direct excitation cross section to the apparent cross section for excitation from the ground state at the same electron energies (see Table I). To place these ratio measurements on an absolute scale, we multiply the ratios by the ''known'' ground-state apparent excitation cross sections.

In our previous work we employed the ground-state cross sections results of Ref. [12] for our absolute calibration.

TABLE I. Measured ratio of the $2\,^3S\rightarrow n\,^3L$ metastable direct excitation cross section to that of the $1\,^1S\rightarrow n\,^3L$ ground-state apparent cross section at an electron energy of 27 eV.

Excited level	$Q_{\rm meta}^{\rm dir}/Q_{\rm gs}^{\rm app}$
$3\,^3S$	160 ± 35
$3\,^3P$	130 ± 30
$3\,^3D$	1500 ± 300
$4\,^3D$	550 ± 120

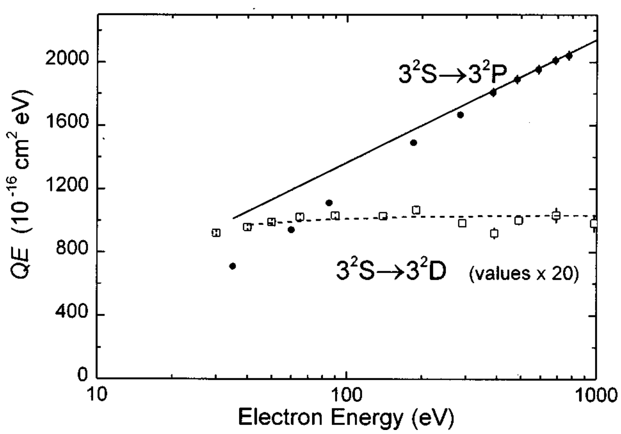

FIG. 1. Electron excitation of sodium. The relative experimental values have been normalized to the Born theoretical results at 775 eV. The solid line is the linear fit to the high-energy $3\,^2P$ data for determination of the $3\,^2S$–$3\,^2P$ oscillator strength. The dashed line is a Born calculation for the $3\,^2S$–$3\,^2D$ excitation cross section.

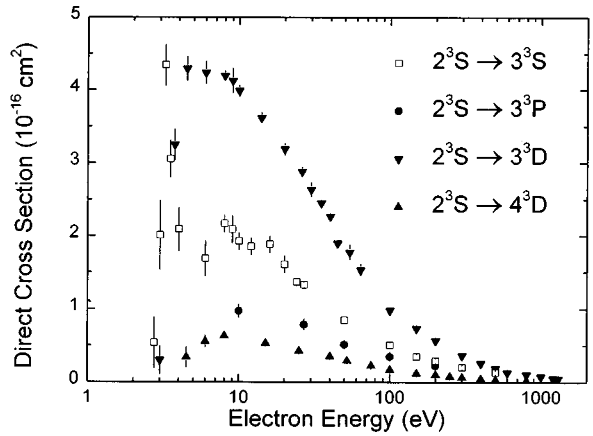

FIG. 2. Direct electron-impact excitation cross section for excitation out of the $2\,^3S$ metastable level of helium. The error bars are statistical only, and do not include the $\pm30\%$ uncertainty in the absolute calibration.

These results, however, were taken with a target density high enough that secondary pressure dependent effects may be important [13]; and the $n\,^1S$ results from this experiment are an average of 25% larger than the benchmark measurements of the same levels made by Van Zyl *et al.* [14]. Thus we have remeasured the relevant ground-state cross sections ourselves [15]. For the $3\,^3S$, $3\,^3P$, $3\,^3D$, and $4\,^3D$ levels we obtained peak apparent excitation cross sections (extrapolated to zero pressure), in units of $10^{-20}\,\mathrm{cm}^2$, of 86 ± 17, 59 ± 12, 19 ± 4, and 7.5 ± 1.5, respectively [15]. Our $n\,^1S$ cross sections measured at the same time agree to within 4% of the benchmark results of Ref. [14].

As a test of the operation of our apparatus we have examined the energy dependence of the cross sections for electron excitation out of the ground level of sodium into the $3\,^2P$ and $3\,^2D$ levels. Sodium provides a good test case since excitation out of the ground state of the alkalis is similar to excitation out of the metastable levels of helium [2], with similar excitation thresholds and cross-section magnitudes. In contrast to metastable helium, the sodium electron excitation cross sections are known with high accuracy [16], allowing us to verify the performance of our apparatus. This is especially important at high energies where the cross sections are small and the measurements are difficult due to the possibilities of secondary processes. The sodium results were obtained by replacing the fast metastable beam with a collimated, thermal-velocity sodium beam of similar size. Atoms excited by the electron beam were detected by the $3\,^2P \rightarrow 3\,^2S$ (589 nm) and $3\,^2D \rightarrow 3\,^2P$ (818 nm) emission lines using the same procedure employed for helium. Since we measure neither the sodium target density nor the detection efficiency of the optical detection system, our measurements give only *relative* electron excitation cross sections for the $3\,^2P$ and $3\,^2D$ levels as a function of the energy. Absolute results were obtained by normalizing to the Born theoretical values at an energy of 775 eV.

Our measured cross sections for sodium (corrected for cascades) are shown in Fig. 1, in which we plot the product of the direct cross section multiplied by the energy as a function of the incident electron energy on a log scale (a Bethe plot). For excitation into an optically allowed level the Bethe plot is expected to be linear at high energies. As can be seen in Fig. 1, this is the case for electron excitation into the $3\,^2P$ level. The slope of the Bethe plot in the high energy limit is related to the oscillator strength of the transition [17]. The Na($3\,^2S \rightarrow 3\,^2P$) oscillator strength obtained from our Bethe plot is 1.06 ± 0.11, which agrees well with the known value of 0.98 [18]. For excitation into a spin allowed but optically forbidden level such as the Na($3\,^2D$) level, the Bethe plot is expected to be a horizontal line at high energies, which is indeed what we observe. The excellent agreement of the oscillator strength obtained using the Bethe plot of our measured $3\,^2P$ values with the accepted value, combined with the zero slope obtained for the $3\,^2D$ data, gives us confidence that we are able to make accurate measurements at high energies with our apparatus.

III. RESULTS AND DISCUSSION

Figure 2 shows our measured helium excitation cross sections as a function of the incident electron energy. Table II lists values of the four excitation cross sections we have

TABLE II. Direct electron-impact excitation cross sections, in units of $10^{-16}\,\mathrm{cm}^2$. Values marked with a ⊗ have an uncertainty of $\pm40\%$, and all other values have a total uncertainty of $\pm33\%$.

Energy (eV)	Direct cross section $(10^{-16}\,\mathrm{cm}^2)$ $2\,^3S \rightarrow 3\,^3S$	$2\,^3S \rightarrow 3\,^3P$	$2\,^3S \rightarrow 3\,^3D$	$2\,^3S \rightarrow 4\,^3D$
10	1.93	0.97	3.98	0.60
27	1.33	0.79	2.82	0.42
50	0.84	0.52	1.83	0.31
100	0.51	0.35	0.98	0.17
200	0.29	0.23⊗	0.57	0.10
300	0.20		0.36	0.065
500	0.13		0.19	0.029⊗
800			0.10	0.016⊗
1000			0.074⊗	
1300			0.048⊗	

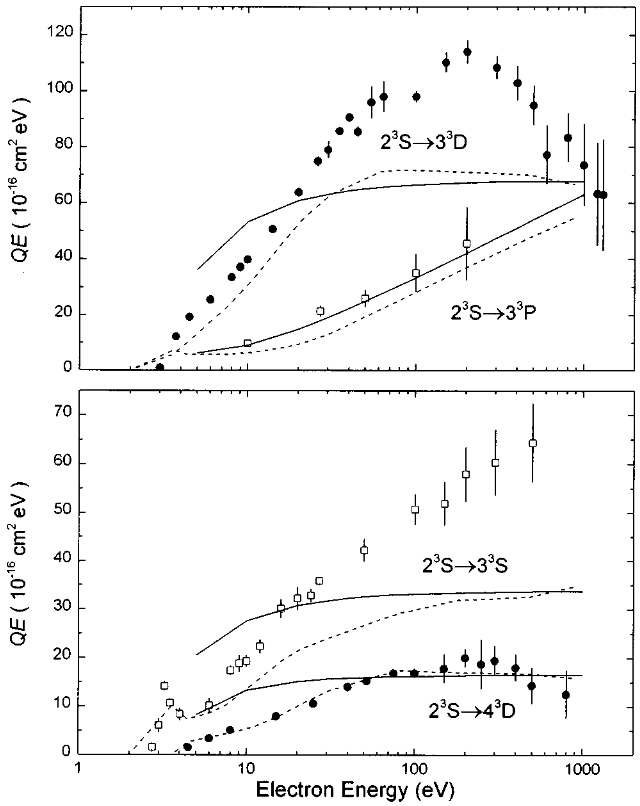

FIG. 3. Bethe plot of experimental and theoretical data. Solid lines are the Born calculations of Ref. [22], and dashed lines are the CCC results of Ref. [8]. The error bars include only the statistical uncertainty.

studied at selected energies. Due to the reduction in cascades from the use of a fast beam target [1], excitation into higher-lying levels which cascade down into the level of interest contribute much less than 10% of measured signal. Since the exact value of the cascade correction is sensitive to the experimental conditions under which the data were taken, the direct cross-section results in this paper have already been fully corrected for cascades [1,19].

The Bethe plots of our data in Fig. 3 show that, except for the $3\,^3P$ level, at electron energies as high as 1000 eV the helium cross sections do not have the expected Born-Bethe asymptotic behavior. This is in sharp contrast to sodium, where the high energy Born-Bethe limit is reached by 300 eV (see Fig. 1). Instead of having a constant value of QE at high energies as expected for excitation into dipole-forbidden levels, the $3\,^3D$ and $4\,^3D$ levels have a maximum at 200 eV. We find the cross sections for excitation out of the $2\,^3S$ level into the $3\,^3D$ and $4\,^3D$ levels to have *exactly* the same energy dependence, but differ by a factor of 6 in magnitude. The Bethe plot of the $3\,^3S$ level is also expected to be flat at high energies, but is observed to be increasing to an energy of at least 500 eV. Since the Bethe plot for excitation into an optically allowed level is expected to be linear at high energies, one might at first think that the $3\,^3S$ data have not been sufficiently corrected for cascades. However, the $3\,^3S$ level's sole source of cascades are from n^3P ($n \geqslant 3$) levels, which all have lifetimes much longer than that of the $3\,^3S$ level. Due to the motion of the atoms in the fast beam, these long-lived $n\,^3P$ levels decay into the $3\,^3S$ level *after* the atoms have left the optical system's viewing region, and thus do not contribute to the measured signal. Since we obtain the expected flat curve for excitation of the Na($3\,^2D$) level, we also do not believe that an experimental artifact is responsible for the unexpected behavior.

The $3\,^3P$ level does demonstrate the expected Born-Bethe behavior of a dipole-allowed transition. We have also observed this low onset of Born-Bethe behavior for dipole-allowed processes in the excitation of metastable argon [20]. As a first-order test of the absolute calibration, we can extract an oscillator strength for the $2\,^3S-3\,^3P$ transition from the Bethe plot of the data. The derived value of 0.059 ± 0.007 (statistical uncertainty only) agrees well with the accepted value of 0.064 [21].

Lagus *et al.* [1] compared their measured cross section for excitation out of the $2\,^3S$ level with seven sets of theoretical values. Since then, a number of more recent theoretical calculations have also been published. Figure 3 includes, in addition to our experimental measurements, theoretical values based on both the convergent-close-coupling (CCC) method [8] and the Born approximation [22]. Our $3\,^3P$ and $4\,^3D$ cross sections agree well with the theoretical results, while the $3\,^3S$ and $3\,^3D$ cross sections are still substantially larger than the theoretical values at high energies. It is interesting to note that for the two $n\,^3D$ levels both the CCC results and our experimental measurements have a peak in the value of QE (at 100 eV for the CCC results, and 200 eV for our results). We also note that compared to the Born values, the Bethe plot of the CCC theoretical values for the $3\,^3S$ level is not flat, but is still increasing well above 100 eV. This is similar to the slow approach to Born-like behavior seen in our experimental data.

On average, the experimental data for the four levels is a factor of 1.4 times larger than the CCC theoretical values [8]. Calculations of the $3\,^3S$, $3\,^3P$, and $3\,^3D$ cross sections by the method of R matrix with pseudostates (RMPS) have been reported for energies below 20 eV [9], and we find a similar constant multiple difference of 1.35 between our results and those calculations. Combining the $\pm 30\%$ uncertainty in the absolute calibration with the statistical uncertainty, the error bars of the experimental data overlap with the theoretical results.

To place these results in perspective, let us consider how the theoretical calculations compare with experimental data for excitation from the *ground state* of He. For excitation into the $n\,^3L$ levels, the CCC cross sections of Fursa and Bray from 30 to 500 eV [23] are lower than the ''experimental'' values of Ref. [24], on average, by a factor of about 1.3 for the $3\,^3S$ and $3\,^3P$ levels, with a slightly larger discrepancy for the $3\,^3D$ level. The RMPS calculations, which cover energies up to 40 eV, again give $3\,^3L$ cross sections smaller than the experimental values [24], but generally within the limit of the experimental uncertainty. Thus we see the same level of agreement between theory and experiment for excitation out of the ground level and out of the $2\,^3S$ metastable level [25].

IV. CONCLUSIONS

Compared to Na, the onset of Born-like behavior is at a much higher energy for excitation into dipole-forbidden levels from the He($2\,^3S$) level. This point is relevant to measurements where the difficulty in performing an independent absolute calibration necessitates the use of Born-Bethe calculations to place the measurements on an absolute scale. Our results indicate that this normalization technique is not always practical for excitation out of metastable levels, since the cross-section values are very small (and subject to large uncertainties) at energies where the Born-Bethe approximation would hold.

In summary we have measured the electron excitation cross sections out of the $2\,^3S$ metastable level of helium into four higher levels. It is especially interesting that the excitation cross sections out of the $2\,^3S$ level of helium and into the $3\,^3D$ and $4\,^3D$ levels have very similar energy dependences at high energies but very different magnitudes. Our measurements differ from the CCC and RMPS theoretical calculations by an amount that is similar to the disagreement between measured ground-state cross sections and the corresponding CCC and RMPS values.

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