ics—1976, AIP Conference Proceedings No. 33, edited by P. D. Barnes, R. A. Eisenstein, and L. S. Kisslinger (American Institute of Physics, New York, 1976).
[4]N. S. Craigie and C. Wilkin, Nucl. Phys. B14, 477 (1969); V. M. Kolybasov and N. Ya. Smorodinskaya, Yad. Fiz. 17, 1211 (1973) [Sov. J. Nucl. Phys. 17, 630 (1973)]; G. W. Barry, Ann. Phys. (N.Y.) 73, 482 (1972).
[5]S. A. Gurvitz and A. S. Rinat, Phys. Lett. 60B, 405 (1976).
[6]R. G. Arnold *et al.*, Phys. Rev. Lett. 35, 776 (1975).
[7]J. C. Alder *et al.*, Phys. Rev. C 6, 2010 (1972).
[8]E. T. Boschitz *et al.*, Phys. Rev. C 6, 457 (1972).
[9]E. Coleman, R. M. Heinz, O. E. Overseth, and D. E. Pellet, Phys. Rev. 164, 1655 (1967).
[10]L. Dubal *et al.*, Phys. Rev. D 9, 597 (1974).
[11]B. E. Bonner *et al.*, to be published.
[12]M. L. Evans *et al.*, Phys. Rev. Lett. 36, 497 (1976); G. Glass *et al.*, Phys. Rev. D 15, 36 (1977).
[13]C. Richard-Serre *et al.*, Nucl. Phys. B20, 413 (1970).
[14]K. Kuroda, A. Michalowicz, and M. Poulet, Nucl. Phys. 88, 33 (1966).
[15]P. C. Gugelot, J. Källne, and P. U. Renberg, Phys. Scr. 10, 252 (1974).
[16]N. E. Booth *et al.*, Phys. Rev. D 4, 1261 (1971).
[17]J. Banaigs *et al.*, Nucl. Phys. B23, 596 (1970).
[18]G. Igo *et al.*, Nucl. Phys. A195, 33 (1972).

Absolute Cross Sections for 2*s*-2*p* Excitation of C^{3+} by Electron Impact

P. O. Taylor,[a] D. Gregory, and G. H. Dunn[b]
Joint Institute for Laboratory Astrophysics, University of Colorado and National Bureau of Standards, Boulder, Colorado 80309

and

R. A. Phaneuf[c] and D. H. Crandall
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830
(Received 19 August 1977)

Absolute cross sections have been measured for excitation of the $2s\,^2S_{1/2}$-$2p\,^2P_{1/2,3/2}$ resonance doublet in Li-like C^{3+} by electron impact for energies ranging from below threshold (8.0 eV) to 530 eV. The measurements agree with recent unpublished Coulomb-Born and close-coupling calculations over the entire range of electron energies.

Electron-impact excitation processes for multiply charged ions are of considerable interest for the diagnostics and modeling of solar, astrophysical,[1] and high-temperature laboratory plasmas. In fusion reactors,[2-4] for example, the presence of multiply charged impurity ions can severely limit plasma heating, lead to instabilities, and cause significant energy losses in the form of line radiation. In all cases absolute cross sections or rate coefficients are needed to infer concentrations and radiation balance. Experimental measurements of cross sections for electron-impact excitation of ions have dealt primarily with singly charged ions. Experimental and theoretical results have been reviewed in recent articles by Dolder and Peart[5] and by Seaton.[1] Bradbury *et al.*[6] reported preliminary measurement for excitation of $N^{4+}(2s\text{-}2p)$ and found results averaging about 2.5 times higher than theory. Phaneuf, Taylor, and Dunn[7] measured cross sections for excitation of the 479.7-nm line of Hg^{2+}. However, results reported here are considered to be the first definitive results for a multiply charged ion.

Ions with lithiumlike structure are frequently observed in the plasmas mentioned. The 2*s*-2*p* transitions are strong and at relatively convenient wavelengths. Consequently, much of the excitation-rate-coefficient work has been for such ions.[8,9] Furthermore, since there are only three electrons in all, and only one valence electron, theoretical study and calculations of the cross sections are quite tractable.[1,10,11]

There remains the need for definitive experimental data on the cross sections for these ions. Measurements[12] on the first member of the sequence, Be^+, are uniformly displaced by about 18% from the most elaborate calculations[13] (five-state close coupling merged into CBX II at higher energies), and the source of the difficulty has not been identified. Known uncertainties in this case total to only about ±8%; so a discrepancy actually exists.

The less sophisticated theoretical predictions are expected to be more reliable for the higher-Z members of the Li sequence, since effects due to coupling to other excited levels should be of lesser importance as Z increases. The energy of the 2*p* level varies as $Z+1$, whereas the energies of higher-n levels vary roughly as $(Z+1)^{1.8}$. For

C^{3+} the $2p$ and $3s$ levels are 8.0 and 37.5 eV, respectively, above the $2s$ ground state. Experimentally, on the other hand, as Z increases the situation becomes progressively more difficult for two reasons. First, the wavelengths of the $2s$-$2p$ transition shift to the vacuum ultraviolet, making absolute optical calibration more difficult and somewhat less accurate. Second, the problem of producing multiply charged ion beams of sufficient intensity at low enough energies to allow collection of a reasonable fraction of the emitted-photon flux imposes a further constraint.

In this Letter we report measurements of absolute cross sections for electron-impact excitation of the unresolved $2s\,^2S_{1/2}$-$2p_{1/2,3/2}$ resonance doublet (154.8, 155.1 nm) in C^{3+} for electron energies ranging from below threshold at 8.0 to 530 eV.

The general experimental method has been discussed in detail in previous reports,[14-16] and will be only briefly outlined here, along with details specific to the present investigation. A mass-to-charge analyzed beam of 29-keV C^{3+} ions was produced in the cold-cathode Penning discharge source of the "ORNL PIG" heavy-ion facility.[17] The beam was collimated and intersected at right angles with a magnetically confined electron beam of energy variable from 5 to 530 eV in a region where the ambient pressure was less than 1.3×10^{-7} Pa (1×10^{-9} Torr). Resonance 155-nm photons emitted into a cone along the third orthogonal axis were detected by a solar-blind photomultiplier. To separate the electron/ion signal from the much larger background photon flux, an on-line computer was utilized to chop both beams and to gate the counters and current integrators from which the signals were derived and reduced. Ion currents were typically 0.1–0.2 μA (particle) and electron currents ranged from 0.1 mA at 10 eV to 4 mA at 530 eV.

The absolute cross section just above threshold (10.2 eV) was determined by detecting the photon flux into an $f/2.8$ aperture using a solar-blind photomultiplier whose quantum efficiency at 155 nm was measured both prior to and immediately following the measurement by direct comparison to a standard vuv (vacuum ultraviolet) photodiode[18] calibrated by the National Bureau of Standards (NBS). There are no other lines from C^{+3} at this electron energy; so further light dispersion was not necessary. The variation in sensitivity across the photocathode surface was measured by moving a small spot over the surface. The sensitivity for detecting an excited $2p$ level was evaluated throughout the relevant space by numerical integration, including the effects of beam overlap, surface variation of quantum efficiency, finite lifetime of the moving ions, solid-angle variation, and anisotropy of the radiation[11] using methods similar to those described previously.[14,19] Low signal-count rates of 0.5 sec^{-1} compared to a background of 50 sec^{-1} necessitated 30 hours integration time to achieve 8% statistics (90% confidence level) on the cross section at the 10.2-eV absolute data point.

For cross-section measurements in the region from 6–530 eV, an aluminized quartz cylinder (light pipe) was inserted between the photocathode and the interaction volume to increase the photon-collection solid angle. Further, either a BaF_2 or sapphire window served as a cutoff filter for background photons with wavelengths below 135 nm. The resultant detector had a peak spectral response at 155 nm, and a pass-band width (full width at half-maximum) of about 40 nm. As before, to distinguish the emissions of C^{+3}, no further light dispersion was necessary. These measures roughly doubled the signal-to-background ratio, while increasing the photon-collection efficiency at 155 nm by a factor of 2, thereby reducing the time required to achieve comparable statistical precision on the relative cross section by a factor of 4.

The usual systematic checks were performed and established the independence of the experimental cross sections on beam current, modulation frequency, and background gas pressure. Corrections were made for the effects of space-charge depression and spiraling in the magnetically confined electron beam using empirical formulas determined during previous work.[14,16] The high ion velocity contributes about 1.3 eV to the interaction energy, and in addition to space charge and contact potentials, there is a further energy shift (about 1 eV) and spreading due to field penetration from ion-deflector plates used to compensate for bending of the ions in the magnetic field confining the electron beam.

Uncertainties other than those associated with the absolute radiometric calibration come from uncertainties in the anisotropy-correction factor, the form factor, the electron–path-length correction, uncollected beam currents, ion velocity, finite–excited-state–lifetime correction, beam-current measurement accuracy, and possible impurities in the ion beam. These uncertainties add in quadrature to ±5% at "good confidence level" (GCL), believed roughly equivalent to the 90%

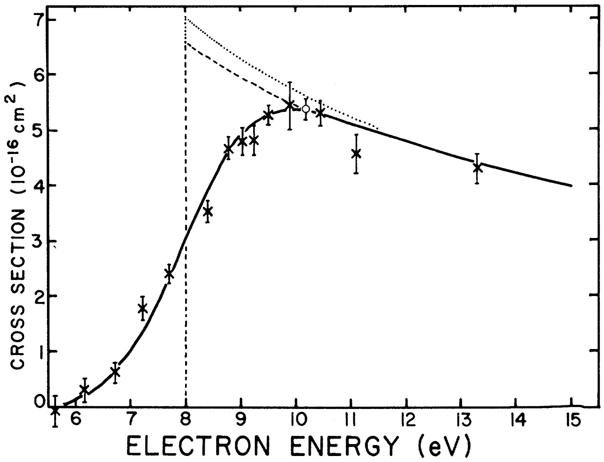

FIG. 1. Cross section vs electron energy for $e + C^{3+}(2\,^2S_{1/2}) \rightarrow e + C^{3+}(2\,^2P_{1/2,3/2})$. Open circle is an absolute measurement. Crosses are measured relative to the open circle. The dashed curve: two-state close-coupling (Ref. 10). Dotted curve: unitarized Coulomb-Born with exchange (Ref. 10). Solid curve: "expected" cross section (see text) resulting from convolution of electron energy distribution with the two-state close-coupling calculation. Bars represent statistical uncertainties at 90% confidence level. There are additional systematic uncertainties totaling ±17% at "good confidence level" (see text).

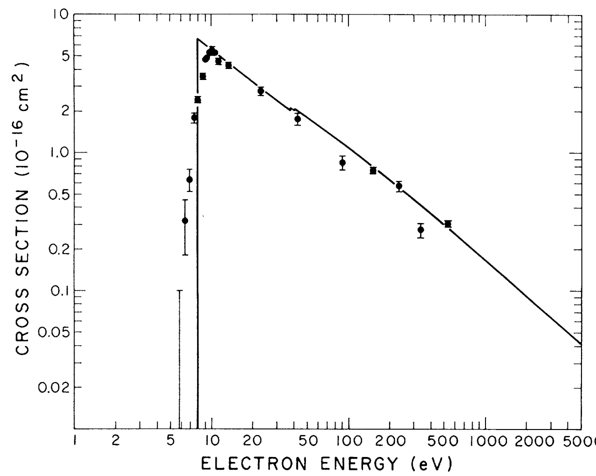

FIG. 2. Cross section vs electron energy for emission of 155-nm radiation from $e + C^{3+}(2\,^2S_{1/2}) \rightarrow h\nu$(155 nm). Solid curve is theory from Ref. 10, and is plotted from coefficients in Table II of Ref. 10. Curve includes close-coupling calculation estimates for $2s$-$2p$, and unitarized Coulomb-Born with exchange calculation estimates for $2s$-$3s$ and $2s$-$2d$ cascade contributions. Bars represent statistical uncertainties at 90% level. There are additional systematic uncertainties totaling ±17% at "good confidence level" (see text).

confidence level on statistical uncertainties. Uncertainties in the absolute radiometric calibration stem from temperature effects, geometry, time stability of the reference standard, transfer between detector and reference standard, and the accuracy of the transfer standard. These all sum in quadrature to give an uncertainty in the radiometric calibration of ±16.3% (GCL), a quantity which is dominated by the ±15% (GCL) uncertainty in the accuracy of the NBS-calibrated standard photodiode used for a transfer standard. Total systematic uncertainties sum in quadature to give ±17% (GCL).

Results of the measurements and comparisons with relevant theories are shown in Figs. 1 and 2. The open circle in Fig. 1 represents the absolute measurement at 10.2 eV. As described above, the points shown by crosses were measured relative to this point. The dashed curve in Fig. 1 shows the two-state close-coupling calculations of Magee *et al.*[10] The dotted curve is the unitarized Coulomb-Born with exchange calculation of Magee *et al.*[10] The solid curve is a convolution of the electron-energy distribution used in the experiment with the close-coupling calculation, and thus is what is "expected" of a measurement using our beam if the theory is correct. Bars on the points represent the statistical uncertainties at 90% confidence level (about 1.7 standard deviations) and do not include the systematic uncertainty discussed above. Figure 2 shows all the data over a broader energy range, and the solid curve is plotted from coefficients in Table II of Ref. 10. The curve includes close-coupling estimates for $2s$-$2p$, and unitarized Coulomb-Born with exchange calculation estimates for $2s$-$3s$ and $2s$-$3d$ cascade contributing transitions.

The agreement between the measurements and convoluted close-coupling calculations shown in Fig. 1 is extremely good. A similar conclusion can be drawn from Fig. 2 concerning the measurements and the composite theoretical prediction.

One may infer that well within the ±17% (GCL) systematic uncertainties, theory is fully capable of predicting the cross section for excitation of the $2s$-$2p$ transition of a highly charged Li-like ion. As already noted, one can draw a similar conclusion[12] for that magnitude of agreement for the singly charged member of the isoelectronic series (Be^+); except in that case there is a nearly uniform 18% displacement of the theory from the measurements.

Calculations using the effective–Gaunt-factor estimator formula[20] with a threshold effective Gaunt factor of 0.2 (generally quite good for *singly* charged ions) yields a threshold cross section of only 2.1×10^{-16} cm^2. This is a factor of 3 less than the threshold value measured here and verifies that, with multiply charged ions, one should estimate using much larger effective Gaunt factors.

The authors are grateful to W. D. Robb, J. B. Mann, and R. J. W. Henry for communicating their theoretical results prior to publication. We also wish to thank J. Hale for assistance with the ORNL PIG source. This work was supported in part by the U. S. Energy Research and Development Administration.

[a]Present address: Center for Astrophysics, 60 Garden Street, Cambridge, Mass. 02138.

[b]Staff Member, Quantum Physics Division, National Bureau of Standards.

[c]Work performed while a Research Associate with the Joint Institute for Laboratory Astrophysics.

[1]M. J. Seaton, Adv. Mol. Phys. 11, 83 (1975).

[2]C. F. Barnett, in *Proceedings of the Ninth International Conference on the Physics of Electronic and Atomic Collisions, Seattle, Washington, 1975,* edited by J. S. Risley and R. GeBalle (Univ. of Washington Press, Seattle, 1976), p. 846.

[3]E. Hinnov, Phys. Rev. A 14, 1533 (1976).

[4]C. Breton, C. DeMichelis, and M. Mattioli, Nucl. Fusion 16, 891 (1976).

[5]K. T. Dolder and B. Peart, Rep. Prog. Phys. 39, 693 (1976).

[6]J. N. Bradbury, T. E. Sharp, B. Mass, and R. N. Varney, Nucl. Instrum. Methods 110, 75 (1973).

[7]R. A. Phaneuf, P. O. Taylor, and G. H. Dunn, Phys. Rev. A 14, 2021 (1976).

[8]H. J. Kunze, Space Sci. Rev. 13, 565 (1972).

[9]G. N. Hadad and R. W. P. McWhirter, J. Phys. 6, 715 (1973).

[10]N. H. Magee, Jr., J. B. Mann, A. L. Merts, and W. D. Robb, Los Alamos Scientific Laboratory Report No. LA-6691-MS, April 1977 (unpublished).

[11]J. N. Gau and R. J. W. Henry, Phys. Rev. A 16, 986 (1977).

[12]P. O. Taylor, R. A. Phaneuf, and G. H. Dunn, private communication.

[13]M. A. Hayes, D. W. Norcross, S. B. Mann, and W. D. Robb, to be published.

[14]P. O. Taylor and G. H. Dunn, Phys. Rev. A 8, 2304 (1973).

[15]P. O. Taylor, Ph.D. thesis, University of Colorado, 1972 (unpublished).

[16]P. O. Taylor, K. T. Dolder, W. E. Kaupilla, and G. H. Dunn, Rev. Sci. Instrum. 45, 538 (1974).

[17]M. L. Mallory and D. H. Crandall, IEEE Trans. Nucl. Sci. 23, 1069 (1976).

[18]L. R. Canfield, R. G. Johnston, and R. P. Madden, Appl. Opt. 12, 1611 (1973).

[19]D. H. Crandall, R. A. Phaneuf, and G. H. Dunn, Phys. Rev. A 11, 1223 (1975).

[20]H. van Regemorter, Astrophys. J. 157, 473 (1969).

State-Resolved Rotational Excitation in HD + HD Collisions

W. Ronald Gentry
Chemical Dynamics Laboratory, Department of Chemistry, University of Minnesota, Minneapolis, Minnesota 55455

and

Clayton F. Giese
Tate Laboratory of Physics, School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455
(Received 26 September 1977)

A novel pulsed–moleuclar-beam technique has been used to measure differential cross sections for state-resolved rotational transitions in HD+HD collisions. Inelastic transition probabilities are reported for the rotation-energy–level transitions $J_AJ_B=00\rightarrow J_A'J_B'=(10,01)$, 11, and (20,02) at a center-of-mass scattering angle at 90° and at several collision energies. A brief description of the apparatus is provided.

The processes of vibrational- and rotational-energy transfer in molecular collisions are relevant to virtually all dynamic phenomena in the gas phase. These processes are especially important in some areas of great current interest —most notably in understanding the internal dynamics of gas-phase infrared lasers and the chemical and physical effects which the laser radiation induces in gas-phase targets. In recent years, considerable effort has been devoted to using molecular-beam techniques to investigate energy transfer in single bimolecular collisions,