01 Jan 1986

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Recommended Citation

M. W. Clark et al., "Electron Capture And Loss For 2.5-200-MeV 16S13++He Collisions," *Physical Review A*, vol. 33, no. 1, pp. 762 - 764, American Physical Society, Jan 1986.
The definitive version is available at https://doi.org/10.1103/PhysRevA.33.762

PHYSICAL REVIEW A VOLUME 33, NUMBER 1 JANUARY 1986

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Electron capture and loss for 2.5–200-MeV $_{16}S^{13+}$ + He collisions

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(Received 3 September 1985)

Electron-capture and -loss cross sections have been measured for highly charged ($q = 13+$) sulfur ions with energies 2.5–200 MeV colliding with helium. Electron capture varies by nearly six orders of magnitude over the energy range investigated, while electron loss varies by only about a factor of 2. The capture cross sections are in reasonable agreement with classical and empirical scaling rules, while the loss cross sections agree well with the plane-wave Born approximation.

The subject of electron capture and loss by ions in collisions with neutral target atoms has long been of fundamental and applied interest. Because of experimental limitations a given charge state can only be produced over a limited energy range and so, until recently, most measurements have been restricted to either the low-energy, low-charge-state regime or the high-energy, high-charge-state regime. With the development of the accel-decel technique for heavy ions, it has become possible to obtain high-charge-state ions at relatively low energies. This technique has been used successfully, for example, using the coupled MP tandem Van de Graaff accelerators at the Brookhaven National Laboratory.[1]

In this paper, measurements of single-electron-capture and -loss cross sections for 2.5–200-MeV $_{16}S^{13+}$ ions colliding with helium are reported. The capture cross sections vary by nearly six orders of magnitude over the energy range investigated while the electron-loss cross sections vary by only about a factor of 2 over the same energy range. We believe that this is the largest variation in energy investigated in this regime in a single experiment for a given charge-state ion.

Most theoretical studies of electron capture are restricted to fully stripped ions incident on atomic hydrogen. However, scaling rules applicable to different gas targets have been proposed, based on both theory[2] and on empirical observations.[3] In the present work v/v_0 varies from 1.8 to 15.9, where v is the velocity of the incident ion and v_0 is the Bohr velocity. This is generally considered to be the intermediate to high-energy regime for electron-capture collisions.

With regard to electron loss, v/v_e varies from 0.25 to 2.2 in the present measurements, where v_e is the velocity of the electron most likely to be lost from the projectile (the 2*s* electron in this case).[4] Classical theory[5] predicts that the energy dependence of the electron-loss cross section should exhibit a broad maximum with a peak value at an energy between $v = v_e$ and $2v_e$. The Born approximation[6] predicts the electron loss to be maximum at about $v/v_e = 1$ which corresponds to 1.3 MeV/amu or about 40 MeV for the present measurements with sulfur ions. Theoretical studies of electron loss are generally confined to loss of the single electron for hydrogenlike ions. However, Choi, Merzbacher, and Khandelwal[7] have calculated cross sections for L-subshell ionization of neutral atoms by structureless heavy ions using the plane-wave Born approximation (PWBA). In these calculations the spectator electrons serve only to reduce the effective nuclear charge and, hence, are accounted for by screening. The projectile single-electron-loss measurements reported here will be compared with these latter calculations.

A beam of S^{13+} ions was obtained from the tandem Van de Graaff at the Brookhaven National Laboratory. The beam was defined by two 1-mm-square apertures, one 7.5 and the other 2.5 m, upstream from the entrance aperture to the target gas cell. The gas cell was surrounded by three regions of differential pumping. All apertures were sufficiently small so that the detector used to detect the charge-changed ions was the limiting aperture after the target gas cell. Thus, all projectile ions scattered into ±0.12° of the incident beam direction were detected.

The target gas cell had a geometric length of 3.65 cm, defined by a 0.40-cm-diam entrance aperture and a 0.55-cm exit aperture. The theory for molecular flow[8] from a circular orifice was used to calculate end effects giving an effective gas cell length of 4.32 cm which was used in calculating the cross sections.

The beam emerging from the target gas cell passed through a set of parallel electrostatic deflector plates, followed by a 4-m drift region to allow sufficient spatial separation of the charge-state components. The charge-changed components ($q-1$ and $q+1$) were detected using solid-state detectors and the non-charge-changed component was measured in a Faraday cup. The gas cell pressure was measured using a capacitance manometer. Cross sections were obtained from a straight line fit to the measured particle yields as a function of gas pressure (target thickness). Data were obtained under single collision conditions as established by the linearity of the measured yields with gas pressure. Primary beam attenuation was generally less than a few percent, except for the lowest beam energies, and the differential pumping ensured that the beam line gas thickness was less than 2% of that of the target.

Relative uncertainties in the measurements are generally $< \pm 10\%$. Systematic uncertainties are estimated to be ±4% in the determination of the target gas pressure, ±10% in the calculation of the effective gas cell length, ±5% for possible beam loss in the collimators, and ±3% due to gas impurities. Combining these, the total systematic uncertainty is estimated to be ±12%. (For 2.5 MeV the charge exchange in the beam line and the low beam current increased the systematic uncertainty in the data at that energy to ±40%.) The absolute uncertainty can be obtained by combining the relative uncertainty assigned to each cross section with the systematic uncertainty.

The measured single-electron-capture and -loss cross sections are shown in Fig. 1(a). The capture cross sections decrease rapidly with the incident projectile energy while the loss cross sections show relatively little energy dependence over the energy range investigated. The rate of decrease for the capture cross sections increases with energy as shown in Fig. 1(b) and no single exponential function of the form $\sigma = \sigma_0 E^{\alpha}$ can be used to describe the energy dependence over the entire energy range (E is the projectile energy in MeV/amu). However, if only the cross-section values obtained at energies between 0.5 and 1 MeV/amu are considered, an exponential function with $\alpha = -3.5 \pm 0.1$ can be fitted to the data, while for cross sections above 2.5 MeV/amu this becomes $\alpha = -4.1 \pm 0.2$, thereby illustrating how the energy dependence steepens with projectile energy.

Born-approximation calculations[9] for fully stripped ions incident on atomic hydrogen targets predict that the electron-capture cross-section energy dependence should increase over the present projectile energy range, reaching an asymptotic high-energy limit of $E^{-5.5}$ (2nd Born) or E^{-6} (1st Born). While the present measurements do not test the high-energy limit, the results are not inconsistent with these predictions of the Born approximation.

Various scaling rules have been used in an attempt to extend theoretical work to partially stripped ions and targets

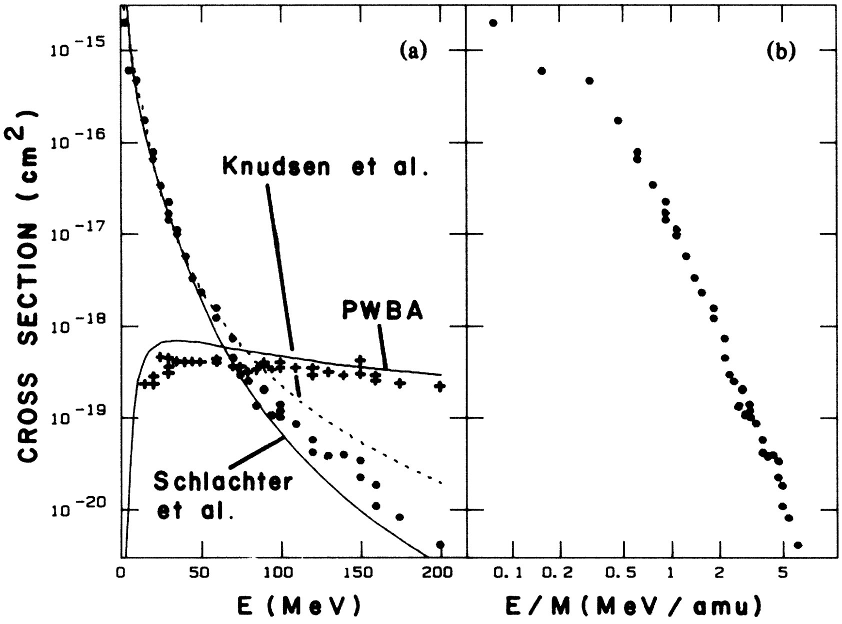

FIG. 1. (a) Electron-capture (●) and -loss (+) cross sections for 2.5–200-MeV $_{16}S^{13+}$ + He collisions. The dashed curve labeled Knudsen *et al.* is the classical scaling rule of Ref. 2 for electron capture while the solid curved labeled Schlachter *et al.* is the empirical scaling rule of Ref. 3. The PWBA curve is the electron-loss prediction obtained from Ref. 7. Relative uncertainties are generally smaller than the size of the data points. Systematic uncertainties are discussed in the text. (b) Electron-capture data of part (a) plotted on a log-log scale to show the increasing projectile energy dependence of these cross sections.

other than atomic hydrogen. In Fig. 1(a) two scaling laws are compared with the present results. Knudsen, Haugen, and Hvelpund[2] have obtained a scaling law based on the classical model of Bohr and Lindhard,[5] combined with the statistical, first-order, Lenz-Jensen atomic model. They derive a universal scaling law for electron-capture sections with reduced parameters $\tilde{\sigma}=\sigma_c Z_2^{2/3}/q$ and $\tilde{E}=E/(Z_2^{16/21}q^{4/7})$, where σ_c is the measured electron-capture cross section, E is the projectile energy in keV/amu, q is the projectile charge state, and Z_2 is the atomic number of the target. Schlachter *et al.*[3] have found an empirical scaling rule for electron-capture cross sections based on the best fit to a wide range of experimental measurements. In this case the reduced parameters $\tilde{\sigma}=\sigma_c Z_2^{1.8}/q^{0.5}$ and $\tilde{E}=E/(Z_2^{1.25}q^{0.7})$ were used. Considering the broad range of parameters embodied in both of these scaling rules, the agreement with the present measurements is considered to be quite good.

The measured single-electron-loss cross sections shown in Fig. 1(a) exhibit the broad maximum predicted by classical theory[5] and the Born approximation.[6] The maximum value is at an energy of about 1 MeV/amu which corresponds to $v/v_e \sim 0.9$ (see Ref. 4) in good agreement with the general predictions of both theories.

The theoretical curve for electron loss shown in the figure is based on the plane-wave–Born-approximation (PWBA) calculations of Choi *et al.*[7] In these calculations the L_1-subshell ionization cross sections are expressed in terms of a parameter $\theta_{L1}=4I_{L1}/(Z_L^2 R_\infty)$, where I_{L1} is the actual L_1 binding energy, Z_L is the "screened" nuclear charge, and R_∞ is the Rydberg constant. Thus, θ_{L1} is the ratio of the actual to the screened L_1 binding energy. Since the actual and the screened binding energies are equal for lithiumlike ions,[10] θ_{L1} must be unity. The tables of Choi *et al.*[7] include values for θ_{L1} only up to 0.78 and so these tables were extended to $\theta_{L1}=1$. The results of these calculations[11] give the curve labeled PWBA in Fig. 1(a). The agreement between theory and experiment is good with the theory being about 25% higher than the data for all but the lowest energies investigated. The calculated contribution of K-shell ionization to single-electron loss for the present case is negligible.

In summary, the single-electron-capture cross sections for 2.5–200-MeV $S^{13+}+He$ collisions vary by nearly six orders of magnitude while the loss cross sections vary by only about a factor of 2. The capture cross sections agree reasonably well with the classical model of Knudsen *et al.*[2] and the empirical scaling rule of Schlachter *et al.*[3] The loss cross sections are predicted satisfactorily by the plane-wave–Born-approximation calculations of Choi *et al.*[7] It should be noted that in the present work the experimental determination of the ionization cross sections does not require a knowledge of Auger or fluorescence yields. Furthermore, at least for lithiumlike ions, effects due to multiple ionization or ionization accompanied by excitation are negligible. Also, the use of hydrogenic wave functions to calculate the ionization cross sections in Ref. 7 is expected to be a much better approximation for the present case than for inner-shell ionization of neutral atoms. Thus, these measurements for electron loss may provide the most rigorous test to date of the PWBA theory for ionization.[10]

This work was supported in part by the U.S. Department of Energy, Division of Chemical Sciences, the Science of Engineering Research Council, Great Britain, and the U.S. Department of Energy, Office of Magnetic Fusion Energy. The authors would like to acknowledge very helpful discussions with Professor Eugen Merzbacher.

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