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Differential Cross Sections for Electron Capture from Argon by 6-MeV Protons*

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Differential cross sections for the capture of electrons from argon by 6-MeV protons have been measured as a function of the hydrogen-atom scattering angle between 0.02° and 0.14°. Cross sections were measured for capture from all shells and from the argon K shell alone. The differential cross section for K-shell capture does not agree with theoretical results obtained using either the Oppenheimer-Brinkman-Kramers approximation or a Born calculation which includes a contribution from the core-core interaction.

The capture of bound target electrons by fast point projectiles has been the subject of much theoretical study[1] but continues to stimulate considerable controversy. Whereas the Born approximation has been useful in describing ionization[2] and excitation[3] processes when the projectile velocity (v) is comparable to or exceeds that of the active target electron, it has not been totally successful in dealing with electron capture. For the former processes the potential between positive-charge centers does not contribute to the first Born amplitude, whereas in the case of electron capture this so-called core-core interaction may contribute importantly. Inclusion of this interaction is necessary to obtain detailed agreement between the Born theory and experiment for total electron capture by protons from hydrogen and helium.[4,5] However, if the nuclear charge of either projectile (Z_1) or target (Z_2) is large, the core term becomes the major contributor to the cross section and yields theoretical values far above experiment.[6] Indeed, for higher Z, the first Born cross sections calculated omitting the core term altogether [the Oppenheimer[7]-Brinkman-Kramers[8] (OBK) approximation] come closer to the experimental values.

Assessment of the success of the theory has been hampered by lack of data for capture from a specific target shell, and a lack of experimental differential electron-capture cross sections, $(d\sigma/d\Omega)_c$, as a function of the projectile scattering angle, θ. For example, Born calculations of $(d\sigma/d\Omega)_c$ are highly sensitive to the presence of the core term. Such experimental information is of special interest for higher-Z targets or projectiles since such cases emphasize effects of including this term in the calculation. In this paper we present results of experimental measurements of the differential cross section at small angles for the capture of argon K-shell electrons, $(d\sigma/d\Omega)_{cK}$, by protons at 6 MeV. At this energy the proton velocity is comparable to that of the target K-shell electron, and the K-capture cross section is near a maximum. Our results are in substantial disagreement with the calculations. In the experimental data there is no evidence for a zero in the differential cross section predicted by a Born calculation which includes the core term.[9] At somewhat larger angles the measured cross section decreases more slowly with angle than does the OBK calculation but follows the trend of the Born calculation.

The absence of experimental data on differential electron-capture cross sections is due largely to the extremely forward-peaked character of the angular distribution. For 6-MeV protons,

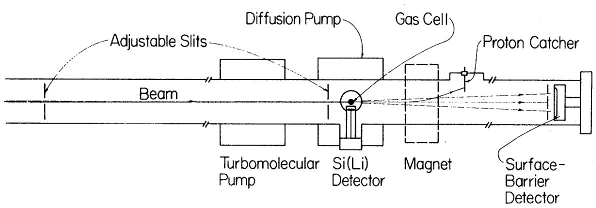

FIG. 1. Schematic of apparatus, not to scale.

more than half of the total cross section lies within a scattering angle of 0.03°, and thus very tight angular collimation is required. In Fig. 1, we show a schematic of our experimental arrangement. A proton beam was collimated and allowed to pass through a 1.5-cm-long gas cell containing Ar. Scattered hydrogen atoms then proceeded through an annular collimator and were detected in a surface-barrier detector while the remaining charged beam component was magnetically deflected onto a beam catcher. In order to obtain tight control of the angular resolution of the incident beam, we required that it pass square apertures separated by 5.6 m and adjusted to half widths of 0.25 mm (upstream) and 0.14 mm (downstream). The latter slit was located 15 cm before entrance to the gas cell. For angular resolution in the detection system, the surface-barrier detector was collimated by annuli with a ratio of inner to outer diameters ranging from 2.01/2.50 to 6.05/7.95 mm situated at a distance from the gas cell ranging from 0.65 to 3.36 m. To ensure proper alignment, the mount of the surface-barrier detector could be scanned laterally in both dimensions. Positioning of each annulus was performed on the beam by seeking axial symmetry in the scattering distribution. The center could be located reproducibly with an error less than 0.1 mm.

The gas cell was surrounded by an intermediate-pressure region that extended 5 cm along the beam and was evacuated by a 12-cm diffusion pump. Pressures between 50 and 200 mTorr were used in the target region; beam-line pressure remained below 8×10^{-6} Torr. At the higher cell pressures, some of the hydrogen atoms formed by capture in the gas cell were reionized by subsequent electron loss in further collisions. Since this destruction is not correlated with scattering angle, however, the only effect was to reduce the experimental detection efficiency for the neutrals. Determination of this efficiency, always greater than 0.67, was made by measuring neutral yields versus gas pressure and extrapolating to zero pressure. That this efficiency was not angle dependent was verified by spot checks taken at several angles and low gas pressure.

The differential cross section for total charge exchange, $(d\sigma/d\Omega)_c$, was obtained from the total number of scattered neutrals, N_h, normalized to the number of Ar K x rays, N_x, observed in a Si(Li) detector viewing the interaction region. In order to convert the ratio N_h/N_x to $(d\sigma/d\Omega)_c$ on an absolute scale one must know both the absolute cross section for production of Ar K x rays by 6-MeV protons, σ_x, and the absolute efficiency for detection of Ar x rays produced along the entire interaction region. In view of the large uncertainties attending the calculation of this efficency for our large-solid-angle geometry, we have chosen instead to place our values for $(d\sigma/d\Omega)_c$ on an absolute scale by requiring that our integrated total cross section agree with that given by Macdonald *et al.*[10]

The capture of electrons from the argon K shell was identified by detecting the scattered hydrogen atoms in delayed coincidence with Ar K x rays. The technique is described by Macdonald, Cocke, and Eidson.[11] If the experimental angular collimation is perfect, the differential cross section for capture from the K shell, $(d\sigma/d\Omega)_{cK}$, is related to the number of coincidences, N_c, by $(d\sigma/d\Omega)_{cK}=(N_c\sigma_x)/(N_x\Delta\Omega)$, where $\Delta\Omega$ is the solid angle subtended by the collimator of the surface-barrier detector. The coincidence data were analyzed using the time spectrum of coincident x-ray and neutral events, and correction for random coincidences was made in the usual way. A typical count rate for the neutrals was 4 kHz; for coincidences, 2×10^{-2} Hz. Because of the finite angular resolution in the experiment the following correction was included in the data reduction. If the true $d\sigma/d\Omega$ is assumed to vary smoothly as $1/\theta^n$ over the angular region accepted for a given detector position, it can be shown that $(d\sigma/d\Omega)_{\theta=\theta_0}=(\Delta\sigma/\Delta\Omega)F$, where θ_0 is the average angle weighted by $1/\theta^n$, $\Delta\sigma$ is the observed cross section in the solid angle $\Delta\Omega$, and F is a form factor obtained by numerically integrating over the acceptance region defined by the collimators. In our case F was found to differ from unity by less than 1% in all cases. Empirically, $n=2$ was found appropriate to our data, although the analysis is not very sensitive to this choice. Details are described by Randall *et al.*[12]

The resulting differential cross sections plotted versus θ_0 are shown in Fig. 2. Absolute scale error is estimated at 20%; relative error bars

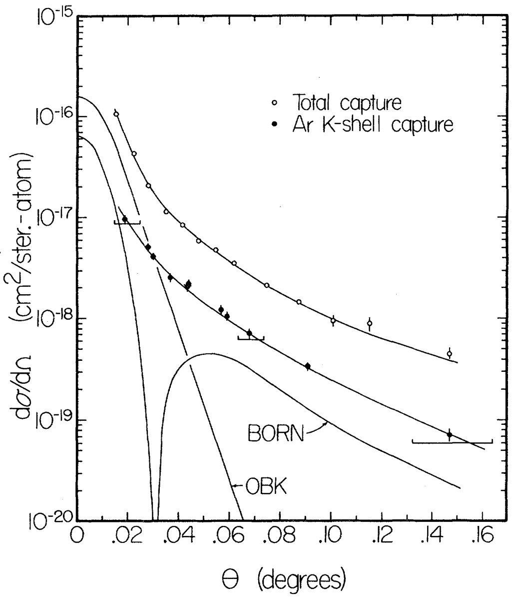

FIG. 2. Differential cross sections for capture of electrons from argon by 6-MeV protons. The representative horizontal bars indicate widths at half-maximum of the finite-angular-resolution functions for those data points. The Born curve is from Ref. 9 and includes the core-core interaction scaled to a strength which gives asymptotic charge neutrality to the target. The OBK curve, a Born calculation which excludes the core-core interaction, is taken from Ref. 9. A proton in a classical collision at an impact parameter of 3×10^{-10} cm, approximately one argon K-shell radius, would be scattered through an angle of 0.084°.

are shown in the figure. For $\theta \gtrsim 0.03°$, $(d\sigma/d\Omega)_{cK}$ is approximately 25% of $(d\sigma/d\Omega)_c$, independent of θ. The ratio of total cross sections, σ_{cK}/σ_c, was found to be (15± 0.9)% in Ref. 11. Thus capture of L-shell electrons, the major contribution to $(d\sigma/d\Omega)_c$, is preferentially enhanced over that of K-shell electrons for $\theta \gtrsim 0.03°$. We verified this result in an independent experiment by measuring the ratio N_c/N_h using open circular collimators of varying small radii on the surface-barrier detector.

The somewhat surprising result that the ratio between K-shell and total capture is nearly angle independent for larger angles demands that we assess the importance of the capture of L-shell electrons accompanied by ionization of the K-shell in the same collision, since this two-step process would be experimentally indistinguishable from the direct K-shell capture. The differential cross section for the two-step process is the product of the probability for K-shell ionization and $(d\sigma/d\Omega)_c$. The semiclassical-Coulomb-approximation (SCA) calculation,[13] which enjoys considerable experimental support for low projectile-target charge ratio,[14] predicts a maximum of 0.7% for this probability at small impact parameter b. While the association of a given b with a particular value of θ is not clearly justified (the Bohr parameter[15] $\chi = 2Z_1Z_2e^2/\hbar v = 2.3$ for 6-MeV p on Ar, thus diffraction effects may be important), the impact-parameter formalism should nevertheless be reliable for the calculation of probabilities, since the de Broglie wavelength of the projectile is much less than the Ar K-shell radius. Because the *maximum* SCA probability is so much smaller than the observed cross section ratio of 25%, we think it is improbable that the two-step process can contribute importantly to $(d\sigma/d\Omega)_{cK}$.

The OBK calculation clearly overestimates the cross section at small angles and underestimates it at large angles. A Born calculation which includes the full core term produces a value of σ_{cK} some 320 times the experimental cross section of (15.8 ± 0.9) b. Since this result is so violently inconsistent with the total-cross-section data, we choose to compare, in Fig. 2, our values of $(d\sigma/d\Omega)_{cK}$ with the predictions of a Born calculation which includes the core-core interaction scaled to a strength which gives asymptotic charge neutrality to the target.[9] The latter calculation gives $\sigma_{cK} = 14.8$ b, in adequate agreement with experiment. The zero which is predicted to appear near 0.03° and which results from cancelation between OBK and core amplitudes does not appear in the data, however. Both theoretical curves in Fig. 2 are for 1s-1s charge transfer only. The addition of capture to all states through $n=3$ raises the curves by 16%, independent of θ. The zero in the Born curve is not removed.

We interpret the lack of agreement for small angles as an indication of fundamental inadequacies in the theory. As discussed by several authors,[4,16] there are fundamental objections to inclusion of the core term in the first Born calculation. Our data lend experimental support to this point, but show further that the omission of the core term entirely leads to an incorrect angular distribution. We point out that the presence of L- and M-shell electrons might modify substantially the angular distribution which one would obtain for capture from the isolated K shell, and both experimental and theoretical investigation of this point would clearly be of interest. Our results nevertheless suggest that it is difficult at present to place a great deal of confidence in the details of electron-capture calculations based on the first Born approximation even though correct total cross sections have been calculated.

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Ultraviolet Radiation Produced in Near-Threshold Ar + Ar Atomic Collisions*

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First measurements are reported of the near-threshold behavior of the vacuum-ultraviolet emission cross section for Ar + Ar atomic collisions. The experimentally observed threshold is 18 ± 2 eV. The absolute emission cross section is presented for center-of-mass energies from threshold to 150 eV. The monitored radiation results from the decay of the lowest excited resonance state of the Ar atom and individual substate contributions are determined over most of the energy range investigated.

Measurements of the absolute ultraviolet emission cross section for Ar + Ar collisions have been made from near threshold to 150 eV center-of-mass energy. These measurements represent the first experiment in which the emitted uv radiation is spectrally dispersed in the low-energy region. The bulk of the observed radiation is shown to emanate from the lowest excited state of the Ar atom, which forms a quartet of levels from the $3p^5 4s$ configuration. Two of these levels are metastable and two decay optically. Photons from the decaying levels, at wavelengths of 104.8 and 106.7 nm, have been observed with absolutely calibrated detectors that collect radiation emitted at 90° relative to the neutral-atomic-beam axis. No attempt has been made to distinguish direct collisional excitation of these levels from reactions feeding these levels via cascading processes.

The monoenergetic beam of Ar atoms is formed by near-resonant charge transfer of suitably prepared Ar^+ ions.[1] The ion source, of electron-impact type, is operated at electron energies below the threshold for excited-state ion formation. The charge-transfer species H_2 is employed for neutralizing Ar^+ ions to ensure that the product neutral Ar atoms are in their ground electronic states at the lower collision energies. Thus for the $Ar^+ + H_2$ reaction, sufficient energy in the center-of-mass system (11.6 eV) to excite a