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Electron capture at very small scattering angles from atomic hydrogen by 25–125-keV protons

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Differential cross sections for electron capture in collisions between protons and hydrogen atoms have been experimentally determined for incident proton energies of 25, 60, and 125 keV in the center-of-mass scattering-angle range of 0–3 mrad. The experimental results compare more favorably with the results of both a multistate and a two-state calculation than with the results of a continuum distorted-wave-approximation calculation. There is no evidence of a Jackson-Schiff-type minimum.

The study of the mechanism of electron capture in collisions of protons with hydrogen atoms has been the subject of a vast amount of atomic collision literature. (See Refs. 1–18 and references therein.) In the intermediate range of relative collision velocity $0.8 \leq v \leq 2.5$ a.u., a thorough understanding of this mechanism has been thwarted by the lack of experimentally determined cross sections which are differential in angle. The only published experimentally derived information relating to the angular distribution of charge-exchange products for this collision system is contained in the work of Everhart and coworkers[16,17] and Bayfield.[18] In the region of very-small-angle scattering where the value of the total cross section is determined, there is virtually no experimentally derived data. Hence, the virtues of a given approximation method or theoretical model can only be judged in relationship to the results of other theories for the angular dependence or by the agreement of the theoretically and experimentally predicted total cross section.

A reasonably good test of an approximation method or theoretical model is provided by the comparison of the calculated results for both the *total* cross section and the *differential* cross section for the process under investigation with the corresponding experimentally determined cross sections. The lack of experimentally determined differential cross sections for electron capture in the intermediate velocity range for the proton–atomic-hydrogen collision system has prompted the work reported in this Communication.

The present experiment involves a measurement of the angular dependence of electron capture into all bound states of hydrogen in the collision

$$H^+ + H \rightarrow H(\theta) + H^+ \ .$$

These measurements were made in the differential ion-energy-loss spectrometer laboratory at the University of Missouri-Rolla. Recently, the apparatus in this laboratory has been modified[19] so that angular distributions of fast-atom products of ion-atom collisions may be studied for very small scattering angles.

The basic apparatus used for the present experimental investigation has been described in the literature.[19–23] The additions to this apparatus which enabled the present measurement consist of a fast-atom detector and the electronics necessary for converting the current output of the electron multiplier in the fast-atom detector into digital information suitable for acquistion by the NOVA minicomputer which controls the data-acquistion process.

In the present experiment an incident beam of protons is focused on the center of a tubular coaxial tungsten furnace which has been especially constructed for measurements differential in the laboratory scattering angle.[22,23] Hydrogen molecular gas entering this furnace is thermally dissociated to provide the atomic-hydrogen target. The ion beam exiting the target furnace is directed via an analyzing magnet to a decelerating column for ion-energy-loss determination. The fast-atom detector with appropriate solid-angle-defining slits is mounted on the zero-degree port of the analyzing magnet. The angular resolution of the apparatus is 120 μrad in the laboratory system.

Because the detection efficiency of the scattered neutral particle detector for hydrogen atoms has not been measured, the present results have been normalized to the value of the total cross section for electron capture into all bound states reported in Ref. 24.

The hydrogen-atom target chamber is similar in construction to several other target chambers which are described in the literature.[25,26] A comparison of the operating characteristics of these other target chambers, both at other laboratories and at this laboratory, with those of the present design is consistent with the conclusion that the dissociation frac-

tion of the present hydrogen-atom target chamber is greater than 95%.

A procedure for unraveling the "true" differential cross section from the "apparent" differential cross section (the latter includes the inherent integration over the acceptance angle of the detector) has been developed at this laboratory and is described in Refs. 20–23. This procedure has been used in the analysis of the present measured angular distributions to obtain the "true" differential cross section. For the present work the difference between the "true" and the "apparent" differential cross sections is small. In fact, at laboratory scattering angles larger than 0.6 mrad these two differential cross sections are essentially equal.

In Figs. 1–3 the experimentally determined differential cross sections for electron capture in collisions of protons with hydrogen atoms are presented for incident proton velocities of 1, 1.55, and 2.24 a.u. (25, 60, and 125 keV). The experimental results which are for capture into all bound states of hydrogen are compared with the theoretical results for capture into the ground state calculated in the two-state, two-center atomic expansion method (TSAE),[27–29]

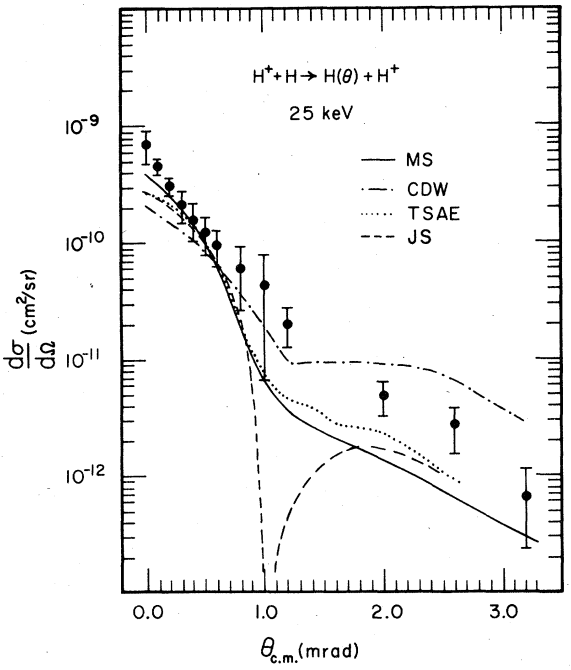

FIG. 1. Differential cross sections for electron capture in collisions between 25-keV incident protons and hydrogen atoms. Closed circles are the experimental results with error bars of one standard deviation. The solid line is the result of the MS calculation; the dot-dash-dot line is the result of the CDW calculation; the dotted line is the result of the TSAE calculation; and the dashed line is the result of a Jackson-Schiff calculation.

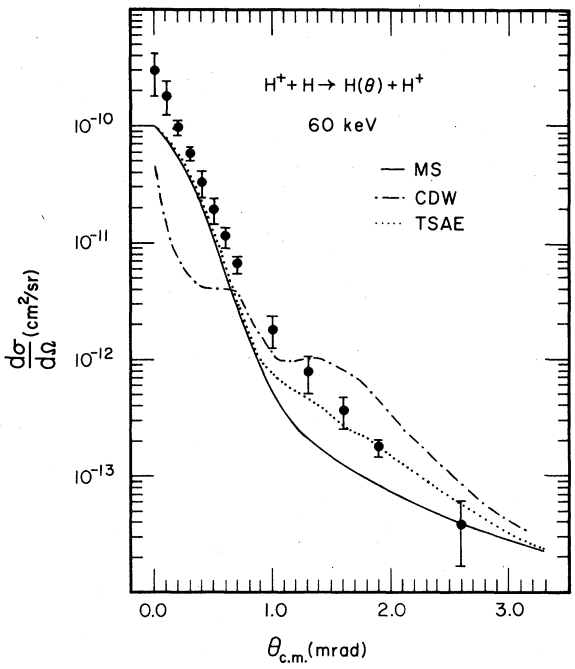

FIG. 2. Differential cross sections for electron capture in collisions between 60-keV incident protons and hydrogen atoms. For the legend see Fig. 1.

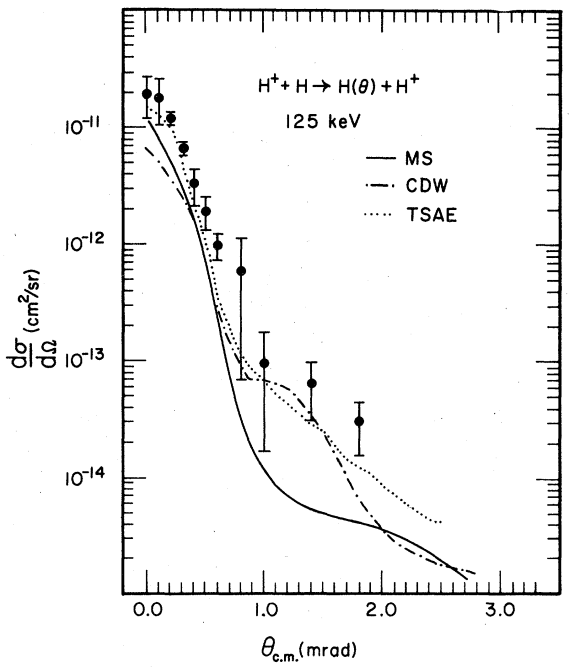

FIG. 3. Differential cross sections for electron capture in collisions between 125-keV incident protons and hydrogen atoms. For the legend see Fig. 1.

the continuum distorted-wave approximation (CDW),[30–32] and the multistate two-center, coupled-state approximation (MS).[5–7] All three calculations were formulated in the impact parameter approximation using the eikonal approximation to obtain the reported differential cross sections.

The shapes of the differential cross sections predicted by the MS calculation[7] shown in Figs. 1–3 are in reasonably good agreement with the shapes of the experimentally determined cross sections. However, a multiplicative factor of 1.2 (to account for a $1/n^3$ excited-state population) does not bring the theoretical and experimental results into confluence. The differences in both shape and magnitude between the MS results and the experimental results could be explained by the use of an insufficient basis set in the calculation, the influence of capture into excited states, or a combination thereof.

Two multistate two-center, coupled-state calculations have been reported by Shakeshaft: the first using a 12-state Sturmian basis set[5] and the second using a 35-state scaled hydrogenic basis set.[7] Unfortunately, the electron-capture differential cross sections from the second calculation are not yet available; hence the effect of the size of the basis set on the angular distribution cannot be assessed.

While the total cross section for capture into $H(2s)$ has been well established experimentally,[11–15] the only measurement of the angular distribution of the probability for electron capture into $H(2s)$ remains that reported by Bayfield.[18] He observed a dramatic shift in the angular distribution toward smaller scattering angles as the incident energy increased from 6 to 30 keV. At the highest energies there is an off-zero maximum in the angular distribution of the probability centered near 3.5 mrad in the center of mass. Such an angular distribution would contribute to the observed differences between the present experimental results and the MS results. However, the magnitude of the probability is too small (of order 0.05) to account for the observed differences.

The results of the TSAE calculation of Lin[29] are in good agreement with the results of both the present work and the MS calculation. This agreement shown in Figs. 1–3 and the agreement obtained between TSAE results and experimental results for collisions of protons with helium atoms[19] demonstrate the utility of the TSAE calculation in the range of intermediate incident velocities.

The results of the CDW calculation[4] compare less favorably than the MS and the TSAE results with the present experimentally determined differential cross sections. For angles greater than approximately 1.0 mrad the CDW results overestimate the experimental results for all but the highest energy. For angles less than approximately 0.6 mrad the CDW results underestimate the experimental results more than the results of either the TSAE or the MS calculation. The worst overall agreement between the results of the CDW calculation and the present experiment is obtained at 60 keV as shown in Fig. 2.

The structure in the differential cross sections predicted by the CDW approximation is not observed in the MS or TSAE approximation results, nor is there any evidence for such structure in the experimentally determined differential cross sections.

An explanation for the observed "discrepancy" between the CDW and the experimentally determined differential cross sections cannot be offered at the present time. However, it should be pointed out that, when the total cross sections obtained in the CDW approximation for capture into the $n = 1$, 2, and 3 states are added together, the resulting total cross section is in good agreement with the experimentally accepted result for capture into all states in the intermediate velocity range. (See Ref. 4, Fig. 7.)

The results of a Jackson-Schiff (JS) calculation[33] of the differential cross section for electron capture are shown in Fig. 1. A computer simulation of the present experiment demonstrated that, although the Jackson-Schiff minimum could not be resolved, the presence of the minimum shown in Fig. 1 would be detected by a significant decrease of two orders of magnitude in the differential cross section in an interval from 0.9 to 1.8 mrad. While the total cross section predicted by the JS model is in reasonably good agreement with the experimentally accepted result,[33] the nonphysical Jackson-Schiff minimum, a mathematical artifact of the calculated angular distribution,[6] which is not observed in the present experimental results, indicates the weakness of this approximation.

Previous experimental investigations[34,35] of other collision systems have also failed to detect the minimum predicted by calculations[36] equivalent to the Jackson-Schiff calculation.

The experimentally determined differential cross sections reported in this Communication provide new, previously unobtainable data that are necessary for forming a more complete understanding of the electron-capture process in the fundamental atomic collision of a proton with a hydrogen atom in the intermediate incident velocity region. The discrepancies between theoretical and experimental results illustrated by the present work clearly indicate the direction for future work.

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