Angular Differential Cross Sections for Excitation of Atomic Hydrogen by 25-, 50-, and 100-keV Protons

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Angular differential cross sections for the process $H^+ + H(1s) \rightarrow H^+(\theta) + H(n=2)$ are presented for 25-, 50-, and 100-keV protons incident on atomic hydrogen. The experimental results are in fair agreement with Glauber-approximation calculations.

The most basic ion-atom collision is the collision between a proton and atomic hydrogen. For this system, the excitation of the $n=2$ state of atomic hydrogen by proton impact is the least-complicated inelastic process. The initial- and final-state wave functions of the incident proton and the atomic-hydrogen target are well known. As a result, a comparison of the differential cross section for this process as determined from theory and experiment provides a meaningful test of the validity of the approximations employed to solve the general ion-atom scattering problem in this velocity range. Over forty-five theoretical studies on processes in the $H^+ + H$ collisional system have been undertaken. The primary calculative effort has focused on the determination of the total cross section for the $H(n=2)$ excitation. Because the impact-parameter treatment does not lend itself to the calculation of differential cross sections, the differential cross section has only been reported in a few cases.[1,2]

The lack of experimental results for $H^+ + H \rightarrow H^+(\theta) + H(n=2)$ is a testament to the difficulty of the measurement. Only four independent total-cross-section measurements are available[3-9] and of these only those of Park *et al.*[3,4] report results for incident proton energies greater than 35 keV. The only previously reported differential-cross-section measurement is the low-energy measurement of Houver, Fayteton, and Barat[10] at proton energies less than 2 keV. The present measurements are at the proton energies of 25, 50, and 100 keV corresponding to 1.0, 1.4, and 2.0 a.u. of velocity. In this proton-velocity range the theoretical models employed are much different than those which are applicable in the low-energy regime studied by Houver, Fayteton, and Barat.[10]

Measurements of the angular differential cross section for this fundamental ion-atom collisional process have been made by the method of angular-energy-loss spectrometry. The apparatus and general method employed in heavy-ion energy-loss spectrometry have been discussed elsewhere.[11-14] In the current experiment the apparatus has been considerably modified to permit precise rotation of the entire accelerator and associated apparatus about the collision point.[15] A dissociation furnace has been constructed which provides a target of atomic hydrogen. The target furnace has the general design of the furnace employed by Park *et al.*[3,4] with added features which permit varying the incident beam angle.

Protons scattered by the atomic-hydrogen target gas are decelerated, analyzed, detected, and recorded as a function of proton scattering angle and energy lost in the collision. Scattered protons which have excited the target atomic-hydrogen atoms to their $n=2$ states are identified by the inelastic energy transferred (10.2 eV) by the proton during the collision. Because the energy resolution of the incident beam was less than 1.2 eV, the 10.2-eV peak in the energy-loss spectrum is separated from the other features of the spectrum. In particular, it is separated from the peak at 12.08 eV corresponding to excitation of the $n=3$ state of atomic hydrogen and from the Lyman-α band of molecular hydrogen at 12.5 eV. Because the 10.2-eV peak is isolated, it is unnecessary to demonstrate that the target is entirely atomic hydrogen. However, the fraction of residual molecular hydrogen is small.

In laboratory coordinates, the angular resolution of the detection aperture was 37 μrad. The relative angular position of the accelerator is known to ±6.6 μrad. The angular distribution of the incident beam is shown in Fig. 1 in center-of-mass coordinates. This distribution was nearly independent of incident energy. Because the detected-proton count rate varied so strongly with scattering angle, the data were acquired using computer control to optimize the counting time during each measurement.[15]

The differential cross section was calculated using standard techniques from the measurement of the transmitted proton current as a function of energy loss and scattering angle and the known geometry of the apparatus. The immediate result

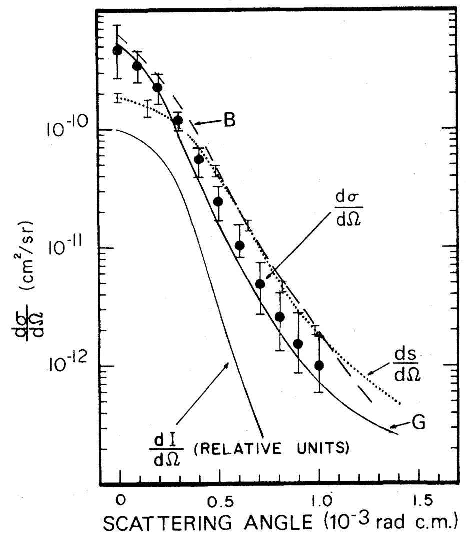

FIG. 1. Angular differential cross sections for 50-keV (laboratory energy) proton excitation of atomic hydrogen to the $n=2$ state. $d\sigma/d\Omega$, derived angular differential cross section; $ds/d\Omega$, raw data; $dI/d\Omega$, incident-beam angular distribution; G, Glauber theory, Franco and Thomas, Refs. 1 and 2; B, first Born approximation, Franco and Thomas, Refs. 1 and 2. The cross sections and scattering angles are given in center-of-mass coordinates.

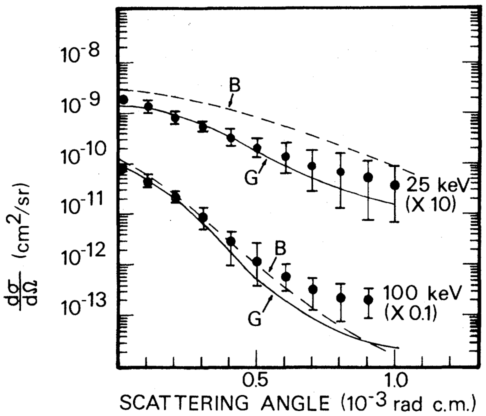

FIG. 2. Angular differential cross sections for 25- and 100-keV (laboratory energy) proton excitation of atomic hydrogen to the $n=2$ state. Closed circles, experimental angular differential cross sections; G, Glauber theory, Franco and Thomas, Refs. 1 and 2; B, first Born approximation, Franco and Thomas, Refs. 1 and 2. The cross sections and scattering angles are given in center-of-mass coordinates.

of the measurement is an apparent differential cross section,

$$ds/d\Omega = I(\theta)/(nplI_{0f}\,\Delta\Omega)\,, \tag{1}$$

where $I(\theta)$ is the proton current at the scattering angle θ scattered into the detector solid angle $\Delta\Omega$, I_{0f} is the total elastic proton current exiting the collision target furnace, n is Loschmidt's number, p is the pressure in Torr, and l is the target length.

$ds/d\Omega$ is related to the "true" differential cross section, $d\sigma/d\Omega$, through a quadruple integral which incorporates the geometry of the apparatus and the angular distribution of the incident beam.[15] Because of the high angular resolution of the apparatus, $ds/d\Omega$ and $d\sigma/d\Omega$ are not greatly different. This suggested the technique successfully applied to extract the "true" differential cross section from the measured apparent results.[15] The "true" angular differential cross section is assumed to have the form

$$d\sigma(\theta)/d\Omega = f(\theta)\,ds(\theta)/d\Omega\,, \tag{2}$$

where $f(\theta)$ is a slowly varying function of θ, which can be accurately approximated by a truncated Taylor-series expansion. Substitution of this expression into the integral expression noted above leads to a series of linear, independent, coupled, algebraic equations which are solved by standard numerical methods to yield $f(\theta)$ at each measurement angle. Knowledge of $f(\theta)$ gives $d\sigma(\theta)/d\Omega$ by Eq. (2).

The data shown are obtained in the manner described above from the observed proton-current measurements using the derived relationship between the proton current, the geometry, and the differential cross section. While the effect of this procedure on the values quoted is larger for protons on atomic hydrogen than for any other case we have studied, it is still relatively small. Figure 1 shows both the apparent and "true" differential cross sections for 50-keV proton excitation of atomic hydrogen to the $n=2$ state. The general agreement between experiment and available theory is unchanged by the mathematical operations on the data. However, as would be expected, $d\sigma/d\Omega$ is more sharply peaked in the forward direction than $ds/d\Omega$.

The differential cross sections obtained at a fixed incident proton energy and energy loss are relative. They are normalized by equating the total cross section, obtained by numerically integrating the differential cross section, to the total cross section reported by Park *et al.*[3] The error bars shown in Figs. 1 and 2 represent random errors. Systematic errors which might arise from the data-analysis scheme discussed above are not included; however, the random error shown does include differences in the analyzed results from various sets of data.

Figure 2 shows the Glauber and first–Born-approximation calculations[1,2] as well as the average data for the differential cross sections for excitation of atomic hydrogen to the $n=2$ state by 25- and 100-keV protons. Note that the results at 25 keV have been multiplied by 10 and the results at 100 keV have been divided by 10 in order to plot results on the same curve. The theoretical calculations were provided by Thomas[2] who provided data at the specific energies and angles required for a detailed comparison of experiment and theory. At 25 keV, the first–Born-approximation calculations lie above the measurements at all angles. This is not unexpected because the total cross sections obtained for the excitation of the $n=2$ state also lie above the total-cross-section measurement at 25 keV. The results at 50 keV are shown in Fig. 1. At 50 keV first–Born-approximation calculation provides results which are higher than the experimental differential cross sections; however, the difference is not as large as at 25 keV. The first–Born-approximation calculation of the differential cross section at 100 keV is more sharply peaked and falls faster than the data; however, the agreement is surprisingly good. At this energy the first–Born-approximation calculation of the total cross section provides good agreement with the experimental results.

The Glauber calculation[1,2] appears to give good agreement with the measured differential cross section at all three proton energies. The Glauber calculation of the differential cross section gives a result at 25 keV that is in very good agreement near the origin and has more slope at the larger scattering angles. At 100 keV the Glauber calculation yields a differential cross section which is a little more sharply peaked and falls more rapidly over the entire angular range. The data and theory are in good agreement over the entire angular range at 50 keV.

The measurements of angular differential cross sections provide a better test of the theoretical models than do total–cross-section measurements. In the earlier study which provided total–cross-section measurements as a function of proton impact energy, the Glauber approximation was found to provide unexpectedly good agreement.[3,4] In this study the same approximation is shown to provide unexpectedly good agreement with respect to the angular dependence. At most scattering angles, the Glauber calculations give differential cross sections that lie within the error bars of the experimental results for 25-, 50-, and 100-keV protons. In the scattering-angle range covered by this experiment, it appears that at least for a structureless projectile, the Glauber approximation provides an adequate description for the differential cross section with respect to both absolute magnitude and angular dependence.

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[1]V. Franco and B. K. Thomas, Phys. Rev. A 4, 945 (1971).

[2]B. K. Thomas, private communication.

[3]J. T. Park, J. E. Aldag, J. M. George, and J. L. Peacher, Phys. Rev. A 14, 608 (1976).

[4]J. T. Park, J. E. Aldag, and J. M. George, Phys. Rev. Lett. 34, 1253 (1975).

[5]J. T. Morgan, J. Geddes, and H. B. Gilbody, J. Phys. B 6, 2118 (1976).

[6]T. Kondow, R. J. Girnius, Y. P. Chong, and W. L. Fite, Phys. Rev. A 10, 1167 (1974).

[7]Y. P. Chong and W. L. Fite, Phys. Rev. A 16, 933 (1977).

[8]R. F. Stebbings, R. A. Young, C. L. Oxley, and H. Ehrhardt, Phys. Rev. 138, A1312 (1965).

[9]R. A. Young, R. F. Stebbings, and J. W. McGowan, Phys. Rev. 171, 85 (1968).

[10]J. C. Houver, J. Fayteton, and M. Barat, J. Phys. B 7, 1358 (1974).

[11]J. T. Park and F. D. Schowengerdt, Rev. Sci. Instrum. 40, 753 (1969).

[12]J. T. Park and F. D. Schowengerdt, Phys. Rev. 185, 152 (1969).

[13]G. W. York, Jr., J. T. Park, J. J. Miskinis, D. H. Crandall, and V. Pol, Rev. Sci. Instrum. 43, 230 (1972).

[14]J. T. Park, in *Collision Spectroscopy*, edited by R. G. Cooks (Plenum, New York, 1978), pp. 19–90.

[15]J. T. Park, J. L. Peacher, J. M. George, and J. E. Aldag, Phys. Rev. A (to be published).