Elastic differential cross sections for small-angle scattering of 25-, 40-, and 60-keV protons by atomic hydrogen

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Elastic angular differential cross sections for small-angle scattering of protons by atomic hydrogen have been measured. The technique utilized unambigously distinguishes the elastically and inelastically scattered ions. The cross sections fall monotonically by 3 orders of magnitude in the angular range from 0.5 to 3.0 mrad, in the center-of-mass system. The experimental data obtained are in very good agreement with a multistate calculation and in fair agreement with both our Glauber-approximation and classical-trajectory Monte Carlo results.

INTRODUCTION

Angular differential cross section measurements offer the cleanest test for any theoretical approach of the scattering problem. The simplest collisional process in the one-electron system $H^+ + H(1s)$ is the elastic scattering of the incoming proton on the atomic-hydrogen target. The projectile ion is scattered by the target atom with no changes in the state of either the target atom or the incident ion. The theoretical treatment of that simple process is not fully understood at intermediate energies. The elastic scattering of protons by atomic hydrogen is also a difficult experimental problem. The necessity to distinguish elastically scattered ions from both the inelastically scattered ions and the unscattered ions requires high resolution in both energy loss and scattering angle. The University of Missouri—Rolla (UMR) ion-energy-loss spectrometer has the high resolution which makes the experiment possible. Preliminary results on the proton—atomic-hydrogen elastic differential cross sections have been presented by our group,[1,2] but this paper reports the first complete measurement of this elastic differential cross section in the intermediate-energy range.

EXPERIMENTAL METHOD

A description of the UMR ion-energy-loss spectrometer and the general method employed in ion-energy-loss spectrometry have been given in detail in Refs. 3—5. Both the high angular resolution of 120 μrad of the accelerator, with its relative angular position known to within 3.3×10^{-6} rad, and the accuracy of ±0.03 eV in determining the energy-loss scale, permit an unambiguous identification of the elastically scattered ions.

The apparatus is a linear accelerator-decelerator system. The accelerator section includes the ion source, extraction lens, velocity filter, beam focusing, steering, and profile monitoring elements. The decelerator contains the energy and beam detection analysis apparatus. The collision region and mass analyzer are located between the accelerator and decelerator section. The accelerator section and collision region are rotated as a unit about an axis that passes through the collision point, allowing the measurement of cross sections which are differential in both scattering angle and energy loss. Because of the complexity of the measurements and the magnitude of data required in order to get meaningful results, the data acquisition process is controlled by a minicomputer (Data General Nova 3/12).

In the collision between an incoming ion and a target atom, the scattered ion loses energy due to the recoil of the target atom even if no inelastic process is involved. This recoil-corrected energy loss is calculated and set during data acquisition by the controlling minicomputer. The measurement scattering angle, count time, and emergency and reset signals are also set and monitored. The transmitted ion current and scattering cell pressure for each measurement are channeled directly to the minicomputer, which corrects the measurement for scattering cell pressure deviations, instrument and residual caused background, and normal-incident beam drift. The angular distributions of the incident and elastically scattered beams are measured by recording the transmitted ion current while pivoting the apparatus about the scattering center. The scattering center lies within the geometrical center of a high-temperature reactive scattering cell. This high-temperature cell which is constructed on the basis of the furnace target technique[6] had a lifetime of approximately 340 h and excitation measurements indicated a dissociation fraction of the molecular hydrogen of over 95%.[7] The pressure in the scattering cell was measured with an MKS Baratron model 170 pressure meter and was maintained constant during a data acquisition run by a microcomputer based pressure controller using the analog signal from the pressure meter.[8]

To obtain absolute values for the differential cross section the product of the atomic-hydrogen target density n and the scattering region length l has to be known accurately. In our case it was not possible to measure the pressure in the scattering region directly and therefore we had to normalize our experimental data. This normalization was accomplished by measuring in the same data acquisition sequence not only the elastically scattered protons but also protons which have lost an energy corresponding to the excitation of the atomic-hydrogen target to its $n=2$ level. By integrating the $n=2$ differential excitation cross section with respect to angle we obtained a total cross section at each incident energy. These total cross sections were then set equal to the total cross sections reported by Park *et al.*,[4] which in turn were normalized to a Born-approximation calculation of Bates and Griffing[9] [$\sigma(n=2)=6.637\times10^{-17}$ cm^2] for 200-keV-proton impact excitation of atomic hydrogen to its $n=2$ level.

A consequence of the high-angular resolution is a low count rate which rapidly decreases with increasing scattering angles. This effect places a limit on the angle θ_{max}, at which a reasonable signal-to-noise ratio can be maintained. In addition, the detectable incident beam is smallest at the low-energy end of the operating range (20—200 keV) of the spectrometer. For elastic scattering at very small angles the overlap of the transmitted unscattered protons with those protons scattered through very small angles gives the limit for the smallest observable angle θ_{min}. The detailed procedure for obtaining the elastic differential cross section from the raw data is given in Ref. 3.

RESULTS AND DISCUSSION

The experimental and theoretical differential cross sections for elastic scattering of 25-, 40-, and 60-keV protons by atomic hydrogen are shown in Figs. 1—3. The shape of the displayed experimental data shows the typical features of differential cross sections at these intermediate energies. Firstly, they are highly peaked at small scattering angles, which means the scattering is almost all in the forward direction. Secondly, in the center-of-mass system they fall

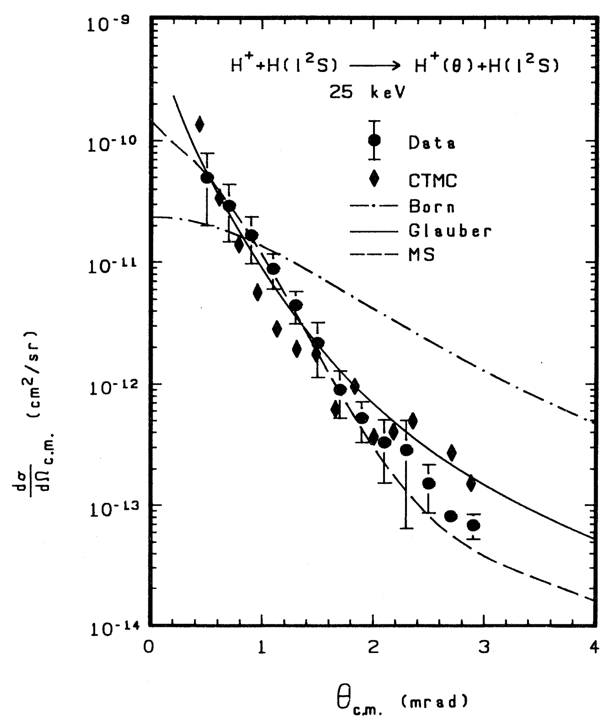

FIG. 1. Comparison of the experimental and theoretical angular differential cross sections at a laboratory collision energy of 25 keV for the elastic scattering of protons from atomic hydrogen, in the center-of-mass frame. For discussion see text. The error bars represent one standard deviation from the mean.

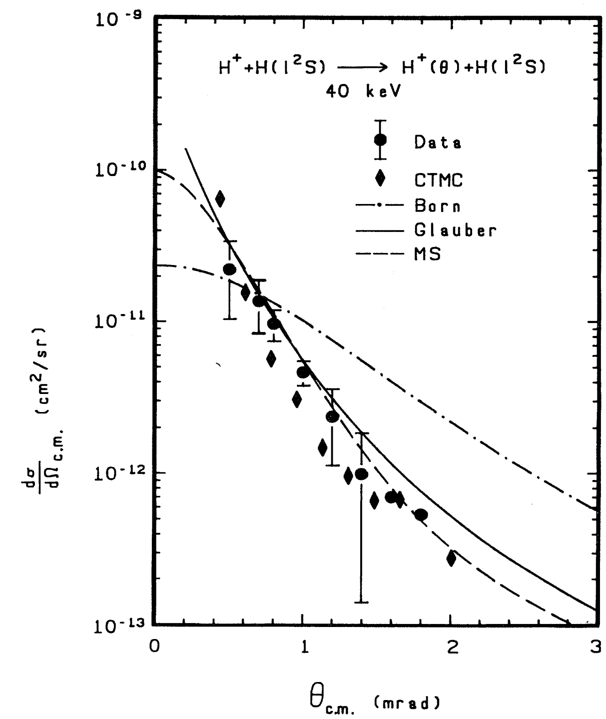

FIG. 2. Same as Fig. 1 for a laboratory collision energy of 40 keV.

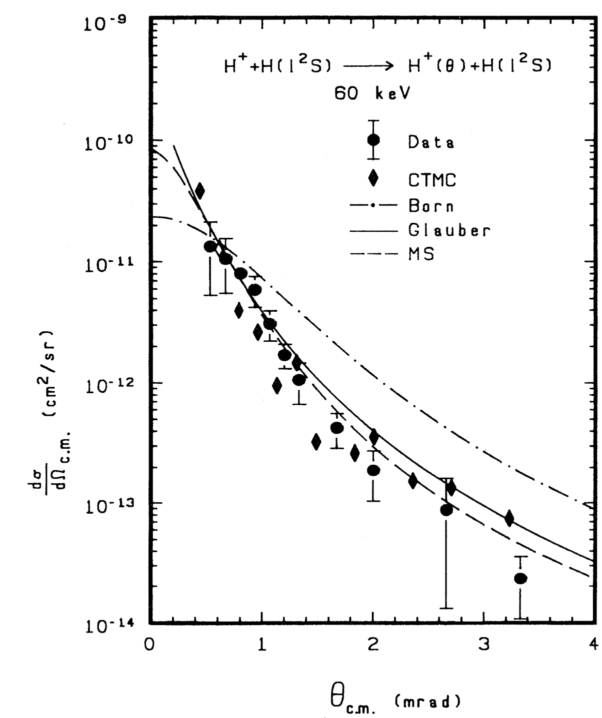

FIG. 3. Same as Fig. 1 for a laboratory collision energy of 60 keV.

3 orders of magnitude in the observed angular range from 0.5 to 3.0 mrad. With increasing projectile velocity (from 1 a.u. for 25-keV protons to 1.55 a.u. for 60-keV protons) the differential cross sections decrease in magnitude over the whole range of angular scattering.

A trial measurement of the proton-molecular hydrogen elastic differential cross section was made. The measured elastic differential cross section for an H_2 target is very similar in shape and in magnitude to the elastic differential cross section for an atomic-hydrogen target. Because at all angles where comparisons were made the difference in the cross sections was less than a factor of 3, a 5% H_2 contamination in the target would have less than a 10% effect on the measured elastic differential cross section.

The error bars shown represent only the rms statistical errors. As discussed in detail in Ref. 3 the systematic errors arising from both the measurement technique and the data-analysis program should have only a minor effect on the curve shape and the magnitude of the data. Moreover, the curve shape of the differential cross section would be unaffected by systematic errors induced by the data-analysis program.

Various theoretical calculations were carried out in order to compare with the experimental data. These are also shown in Figs. 1—3. The Born-approximation calculation,[9] as expected, is not in agreement with the experimental data. In general, the Born results have the wrong curve shape and they are larger than the experimental results in magnitude over the observed scattering angle range except at the very small scattering angles where the Born results cross over the experimental results. The agreement between the experimental data and the Born results obviously improves as the incident proton energy increases.

We also carried out a full Glauber-approximation calculation[10] using the techniques developed by Thomas and Gerjouy.[11] This Glauber-approximation calculation compares more favorably with the experimental data particularly at small scattering angles. However, at the larger scattering angles the Glauber approximation results are greater in magnitude than the experimental data and they indicate a slightly different curve shape. Of course, the Glauber-approximation diverges at the scattering angle of 0° (Ref. 10) and thus is not expected to follow the experimental data at extremely small scattering angles. In comparison the Glauber-approximation results for proton—atomic-hydrogen elastic scattering do not provide as impressive an agreement with experiment as do the Glauber results for the proton excitation of the atomic-hydrogen target to its $n=2$ level.[12] The poorer agreement of the Glauber-approximation with the experimental data in the case of the elastic scattering may be due to the fact that this approximation does not adequately account for the effect of the electron capture and ionization channels. However, considering the simplicity of the Glauber-approximation calculation, the theoretical results for the differential elastic cross sections of proton—atomic-hydrogen scattering are in remarkably good agreement with the experimental measurements.

Our classical trajectory Monte Carlo (CTMC) calculation is in fair agreement with the experimental data.[13,14] The curve shape of the CTMC results are fair except again for the extremely small scattering angles near 0° where the CTMC results tend to diverge. In general the magnitude of the CTMC results are lower than the experimental data. The CTMC calculation suffers from the same problem as the experiment; namely, the differential cross section falls orders of magnitude over a very small range of scattering angles. This means that a very large number of trajectories are required in the CTMC calculation to obtain reliable results for the larger scattering angles. For scattering angles $\theta_{\text{c.m.}}$ greater than 2 mrad the CTMC data points have a tendency to converge to or even to cross over the experimental results. However, the CTMC calculation is a three-body calculation and thus it contains the effect of the other scattering channels on the elastic scattering. The CTMC method treats consistently the three reactions, excitation, electron capture, and elastic scattering, and cross sections are produced simultaneously. Except for classical mechanics and the use of a microcanonical ensemble for the ground-state hydrogen atom, there are no other approximations. The Coulomb potentials are exact and the dynamics of the collision process is done exactly. This may account for the good overall agreement of the CTMC results with the experimental data.

A sophisticated multistate (MS) calculation by Shakeshaft is available for proton-hydrogen atom scattering using a scaled hydrogenic basis set.[15] Thirty-five basis functions, centered about each proton, were included in the expansion of the electron wave function. The use of a scaled hydrogenic basis set allows one to include the ionization channel as well as the excitation and electron capture channels. By applying a procedure discussed by Wilets and Wallace,[16] differential cross sections can be obtained from the transition amplitudes calculated by Shakeshaft.[15] The results for the elastic scattering of protons from hydrogen atoms using the procedure mentioned above are given by Wadehra and Shakeshaft.[17] These multistate results (also shown in Figs. 1—3) are in very good agreement with the experimental data over the whole observed angular scattering range both in magnitude and curve shape.

In conclusion this paper shows that there are only minor discrepancies, with the exception of the Born approximation, between the experiment and the various theories for the elastic proton—atomic-hydrogen scattering in the intermediate-energy range. However, for this particular scattering process additional data at larger scattering angles are needed for a complete test of the theories. Also experiments at lower collision energies are important for a full understanding of the proton—atomic-hydrogen scattering process.

ACKNOWLEDGMENTS

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