# Absolute differential cross sections for very-small-angle scattering of keV H and He atoms by $H_2$ and $N_2$

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Absolute differential cross sections for scattering of 0.5-, 1.5-, and 5.0-keV H and He atoms by $H_2$ and $N_2$ over the laboratory angular range 0.05°–0.5° are reported. Charged collision products are not detected, and no determination is made of the energy loss experienced by the scattered projectile. The measured cross sections therefore include both inelastic and elastic processes. The data are in excellent accord with previous measurements of these processes at larger angles. The data have been integrated over angle to permit comparison with other experimental data.

## I. INTRODUCTION

Studies of differential scattering in heavy-particle collisions give information which has been used previously to assess the validity of proposed interaction potentials for several systems.[1,2] Such studies also provide data required for modeling the behavior of physical processes in plasmas and planetary atmospheres. This paper reports the measurement of absolute cross sections for scattering of keV-energy, ground-state H and He atoms by $N_2$ and $H_2$ over a laboratory angular range of 0.05°–0.5°. The data have, in conjunction with analogous data obtained previously in this laboratory at larger angles, been integrated over angle to provide total scattering cross sections and to provide a basis for comparison with other experiments.

## II. APPARATUS AND EXPERIMENTAL METHOD

Figure 1 shows a schematic of the apparatus, which has been previously described in detail.[1–4] Ions emerging from an electron-impact source are accelerated to the desired energy and focused by an electrostatic lens. The resulting beam is momentum analyzed by a pair of confocal 60° sector magnets and passes through a charge-transfer cell (CTC), in which about 10% of the fast ions are converted into neutrals *via* charge transfer. The gas used in the CTC is helium in the case of a $He^+$ beam, and krypton in the case of a $H^+$ beam. Deflection plates DP1 remove ions remaining in the beam that emerges from the CTC.

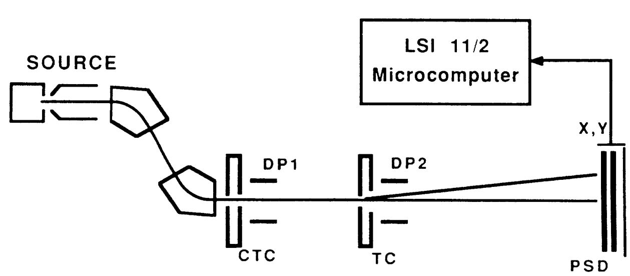


FIG. 1. Schematic of the apparatus.

A unique characteristic of this apparatus is the use of very small, widely separated, laser drilled apertures to provide a high degree of collimation. For this series of measurements, the exit aperture of the CTC and the entrance aperture of the target cell (TC) are 20 and 30 $\mu$m in diameter, respectively, and are separated by 49 cm. The neutral beam is thus collimated to less than 0.003° divergence. It is perhaps useful to note that apertures of this size are so small as to be virtually invisible to the naked eye, and that this degree of collimation is comparable to that provided by 0.25-cm apertures separated by 50 m. Such stringent constraints necessarily require high stability in the beam generation and transport system and result in rather tenuous beams—typically $\sim 10^3$ neutral particles per second.

The resonant nature of the $He^+$-He charge transfer, together with the tight collimation, ensure that essentially every helium atom entering the TC is in the ground state.[1] In the case of hydrogen the resonant $H^+$-H charge-transfer reaction cannot be readily used to produce a beam of ground-state atoms; nonetheless the near resonant $H^+$-Kr charge transfer and an electric field applied by DP1 to quench any 2*s* atoms *via* Stark mixing ensure that the hydrogen atoms are also predominantly in the ground state. The TC is 0.36 cm in length and has an exit aperture 300 $\mu$m in diameter. Gas pressure in the TC is maintained at a constant value between 1 and 10 mtorr. Deflection plates DP2 remove charged collision products from the beam.

Both primary and scattered atoms are detected by an axially located position sensitive detector (PSD), which has an active area 2.5 cm in diameter and is located 109 cm beyond the TC on the beam axis. The maximum observable scattering angle is thus about 0.7°. An LSI-11 microcomputer monitors the output of the PSD electronics and sorts the detected particles into a $90 \times 90$ array according to their arrival positions. The bin dimension of the array is chosen so that it corresponds to a distance on the PSD of either 274 or 68 $\mu$m, depending on the angular resolution desired.

For the thin target conditions used in this experiment, the differential cross section is related to the measured quantities by the expression

$$\frac{d\sigma(\theta)}{d\Omega}=\frac{\Delta S(\theta)}{SnL\,\Delta\Omega}\ , \qquad (1)$$

where $S$ is the primary beam flux, $\Delta S(\theta)$ is the flux scattered at laboratory angle $\theta$ into a solid angle $\Delta\Omega$, $L$ is the physical length of the cell, and $n$ is the number density in the TC obtained from a measurement of the gas pressure obtained using an MKS Baratron capacitance manometer.

A detailed description of the data acquisition and analysis technique has been presented by Nitz *et al.*[1] and only a brief review will be provided here. Discrimination between counts due to scattering from the target gas and counts arising from other sources (such as scattering from the background gas, scattering from edges of apertures, and dark counts) is accomplished by taking two data sets, one with gas in the target cell and one without. The scattered flux $\Delta S(\theta)$ is obtained by organizing the $90\times 90$ data arrays into concentric rings and subtracting the gas-out data from the gas-in data.

The experimental uncertainty in the number of counts at a particular angle is primarily statistical, varying between 1% at 0.05° and 10% at 0.5°. Angular uncertainties arise from the finite width of the primary neutral beam, the discrete nature of the analysis rings, and electronic noise in the detector's position encoding circuits, and yield a combined uncertainty of about 0.015° when a bin dimension of 68 $\mu$m is used.

## III. RESULTS AND DISCUSSION

Differential cross sections have been determined at energies of 0.5, 1.5, and 5.0 keV and the results are presented in Figs. 2–5 together with the earlier data of Newman *et al.*[3,4] These independent absolute measurements agree satisfactorily in the regions of overlap. The cross sections generally decrease smoothly with increasing scattering angle except for an undulation seen in several cases in the vicinity of 0.1°. Similar structure was observed in earlier He–rare-gas measurements by Nitz *et al.*[1] and Gao *et al.*[2] Quantum-mechanical calculations of scattering from the steeply rising, lower repulsive wall of an atom-atom interaction potential[1,2] also show this structure, which Beier[5] has discussed in analogy to optical diffraction from a disc.

The effect of the finite angular resolution of the apparatus has previously[3,4] been estimated by calculating the convolution of theoretical atom-atom cross sections with an apparatus function that accounts for the discrete analysis rings, the physical beam size, and the inherent PSD position-finding uncertainty. The convolved cross

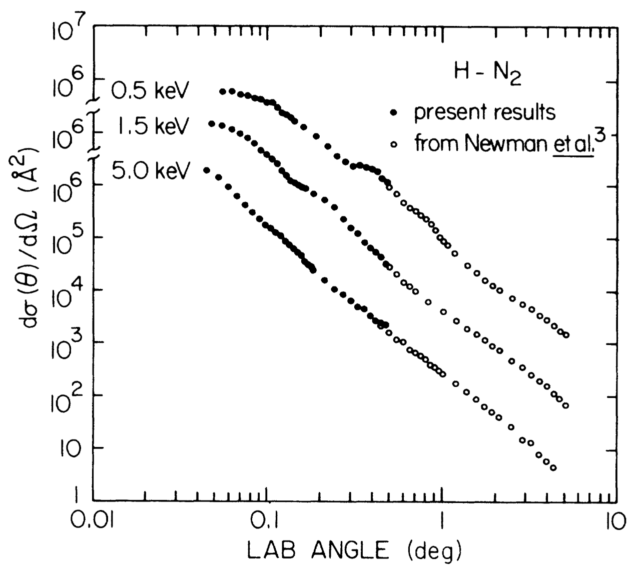


FIG. 3. Differential cross sections for H-$N_2$ scattering at projectile energies of 0.5, 1.5, and 5.0 keV.

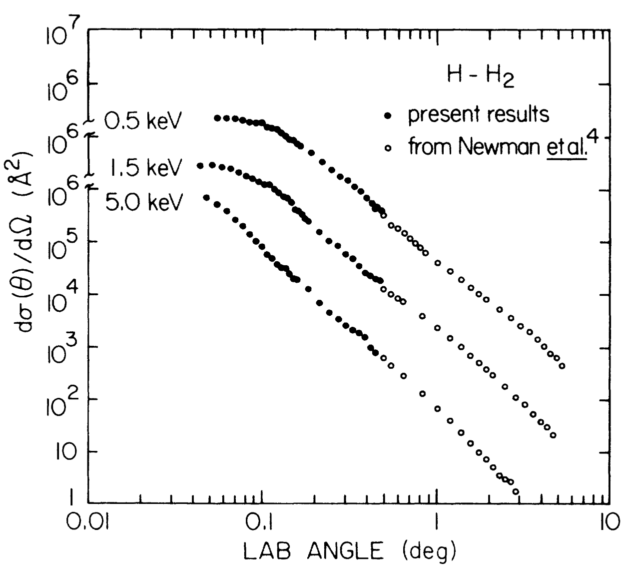


FIG. 2. Differential cross sections for H-$H_2$ scattering at projectile energies of 0.5, 1.5, and 5.0 keV.

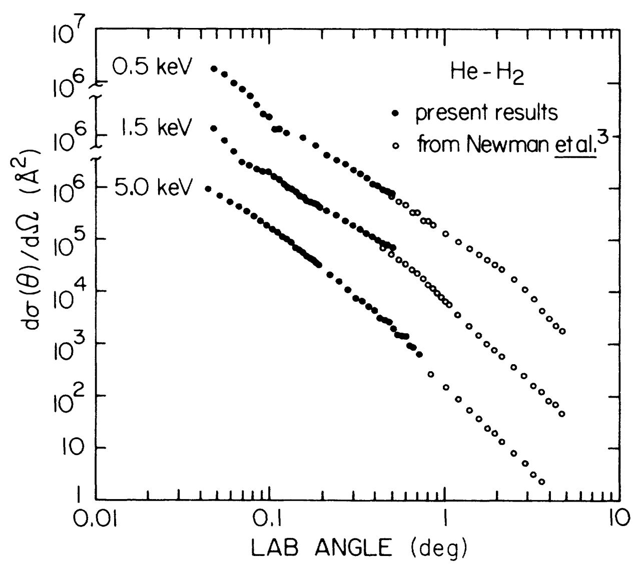


FIG. 4. Differential cross sections for He-$H_2$ scattering at projectile energies of 0.5, 1.5, and 5.0 keV.

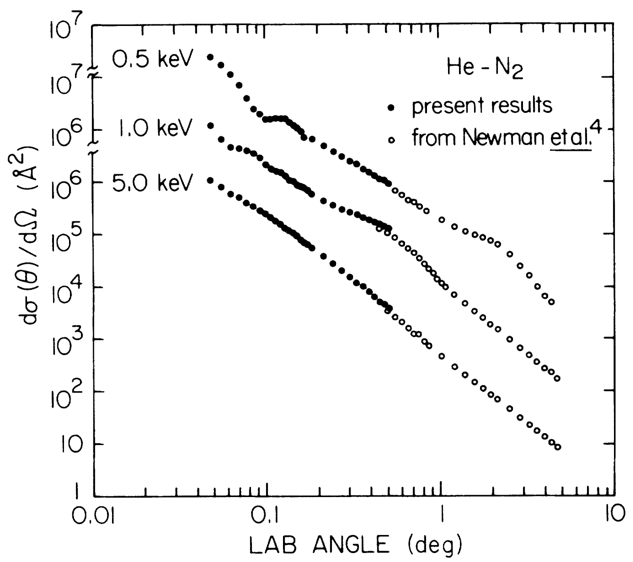


FIG. 5. Differential cross sections for He-$N_2$ scattering at projectile energies of 0.5, 1.5, and 5.0 keV.

sections differed from those without convolution only where the cross sections were changing rapidly (for example, near the diffraction undulation), and even then the differences were very small. The present atom-molecule cross sections are very similar in shape to the atom-atom data, except that the diffraction undulations are less pronounced in the present work, and it is concluded that apparatus effects do not significantly degrade the resolution of the present cross sections.

Table I shows integral cross sections obtained by integrating the differential cross sections over angle, where use has been made of the data of Newman *et al.*[3,4] In order to perform the integration at large angles ($5° < \theta \le 180°$), the differential cross sections were extended to their large-angle limit using a linear extrapolation of the experimental results on a log-log plot. This procedure is empirically justified by calculations performed in this laboratory of differential cross sections for scattering by a screened Coulomb potential, and has proved useful in similar circumstances.[3,4]

In order to extrapolate the differential cross sections to smaller angles (0°–0.05°), use is made of the expression (independent of interaction potential) of Mason *et al.*[6]

$$\sigma(\phi) \approx \sigma(0)\exp[-\tfrac{1}{2}\sigma(0)k\phi^2] , \qquad (2)$$

where $\sigma(0)$ is the differential cross section at zero scattering angle and the scattering angle $\phi$ and wave number $k$ are expressed in the center-of-mass frame. This function has been fitted to the experimental data for H projectile scattering over the laboratory angular range 0.05°–0.1° [using $\sigma(0)$ as an adjustable parameter] and then integrated over the angular range 0°–0.05°. This procedure has not been carried out for the He projectile scattering data because the diffraction undulation precludes fitting the Mason *et al.* function to the data over a sufficient range of angles.

The uncertainties in Table I were obtained by combining systematic effects (such as uncertainties in target thickness, primary beam flux, and detector calibration) together with uncertainties arising from the extrapolation procedures. The relative contribution of scattering at angles below 0.05° increases with energy and at high energies leads to a considerable uncertainty in the total ($0° \le \theta \le 180°$) cross section. Contributions to the total cross section from scattering at angles greater than 5° are typically less than 5% because of the very rapid fall in the differential cross section with increasing angle. In consequence, even generous estimates of the uncertainties in the extrapolation lead to very small contributions to the overall uncertainty.

No other differential measurements of these processes have apparently been carried out, although a number of investigators have investigated collisions of H and He with $H_2$ and $N_2$ at these energies. The measurements are of two types. Some involve the detection of energetic ions created in processes such as stripping[7–9]

$$H + N_2 \to H^+ + N_2 + e^- , \qquad (3)$$

while others involve the attenuation of a highly collimat-

TABLE I. Summary of cross sections for H-$H_2$, H-$N_2$, He-$H_2$, and He-$N_2$ neutral scattering.

| Process | Cross section (Å$^2$) $0° \le \theta \le 0.05°$ (Extrapolation) | $0.05° \le \theta \le 5.0°$ (Expt. data) | $5.0° \le \theta \le 180°$ (Extrapolation) | $0° \le \theta \le 180°$ (Total) |
|---|---|---|---|---|
| H(0.5 keV)-$H_2$ | 0.53±0.02 | 7.17±0.36 | 0.20±0.03 | 7.9±0.4 |
| H(1.5 keV)-$H_2$ | 0.64±0.06 | 4.25±0.21 | 0.05±0.01 | 4.9±0.3 |
| H(5.0 keV)-$H_2$ | 1.8±0.5 | 2.90±0.15 | 0.01 | 4.7±0.7 |
| H(0.5 keV)-$N_2$ | 1.5±0.1 | 15.4±0.8 | 1.0±0.2 | 17.9±1.0 |
| H(1.5 keV)-$N_2$ | 4.3±0.6 | 13.1±0.6 | 0.5±0.08 | 17.9±1.2 |
| H(5.0 keV)-$N_2$ | 7.6±2.2 | 7.06±0.35 | 0.12±0.02 | 14.8±2.6 |
| He(0.5 keV)-$H_2$ | | 14.7±0.7 | 0.5±0.08 | |
| He(1.5 keV)-$H_2$ | | 10.1±0.5 | 0.1±0.02 | |
| He(5.0 keV)-$H_2$ | | 6.04±0.30 | 0.01 | |
| He(0.5 keV)-$N_2$ | | 19.6±1.0 | 0.9±0.1 | |
| He(1.5 keV)-$N_2$ | | 15.2±0.8 | 0.6±0.1 | |
| He(5.0 keV)-$N_2$ | | 10.1±0.5 | 0.3±0.04 | |

TABLE II. Comparison of cross sections for H projectile neutral scattering, fast-ion formation, and H-beam attenuation measurements. Present experimental results are shown in the neutral column. The minimum detector angle for attenuation measurements was 0.12°, and neutral cross sections (experimental results and extrapolations) are accordingly integrated from 0.12° to 180°.

| | Cross section (Å$^2$) | | | |
|---|---|---|---|---|
| Process | Neutral | Fast ion | Sum | Attenuation |
| H(0.5 keV)-$H_2$ | 5.4 | 0.1[a] | 5.5 | 4.3[b] |
| H(1.5 keV)-$H_2$ | 2.6 | 0.6[a] | 3.2 | 3.1[b] |
| H(5.0 keV)-$H_2$ | 1.1 | 1.2[c] | 2.3 | 2.3[b] |
| H(0.5 keV)-$N_2$ | 11.7 | 0.7[a] | 12.4 | 12.0[b] |
| H(1.5 keV)-$N_2$ | 6.9 | 1.6[a] | 8.5 | 9.0[b] |
| H(5.0 keV)-$N_2$ | 3.1 | 3.0[c] | 6.1 | 6.4[b] |

[a]References 7 and 8.
[b]Reference 10.
[c]References 8 and 9.

ed beam of H or He as it passes through a cell containing the target gas.[10] This attenuation arises both from collisions leading to energetic ions and from neutral scattering outside some minimum scattering angle $\theta_{min}$. It is instructive to compare these earlier measurements to the present work in the case of H projectiles, as a reasonably complete set of cross sections is available, as shown in Table II. The attenuation cross sections are those measured by Belyaev and Leonas;[10] in their work the minimum scattering angle $\theta_{min}$ was 0.12°. The "neutral" cross sections were accordingly obtained by integrating the present differential cross sections from 0.12° to 180°. The "fast-ion" production cross sections are those of Van Zyl *et al.*,[7] Smith *et al.*,[8] and Stier and Barnett.[9] The terms in the "sum" column are obtained by adding those in the neutral and fast-ion columns, and are seen to be in generally good agreement with the "attenuation" values.

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