Communication: Mapping water collisions for interstellar space conditions

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We report a joint experimental and theoretical study that directly tests the quality of the potential energy surfaces used to calculate energy changing cross sections of water in collision with helium and molecular hydrogen, at conditions relevant for astrophysics. Fully state-to-state differential cross sections are measured for H2O–He and H2O–H2 collisions at 429 and 575 cm−1 collision energy, respectively. We compare these differential cross sections with theoretical ones for H2O+H2 derived from state-of-the-art potential energy surfaces [P. Valiron et al., J. Chem. Phys. 129, 134306 (2008)] and quantum scattering calculations. This detailed comparison forms a stringent test of the validity of astrophysics calculations for energy changing rates in water. The agreement between theory and experiment is striking for most of the state-to-state differential cross sections measured. © 2010 American Institute of Physics. [doi:10.1063/1.3475517]

Interpretation of the molecular rotational spectra delivered by Earth and space-borne telescopes is a complex process requiring knowledge of molecular state-to-state collisional excitation rates over a broad range of temperatures and transitions. Because these rates for energy changing (inelastic) collisions are not usually known experimentally,1,2 astronomical models rely predominantly on theoretical estimates that require accurate intermolecular potential energy surfaces (PESs). Water is the most abundant polyatomic molecule in the Galaxy. Detailed knowledge of the energy transfer rates and mechanisms for water is critical in many astrophysical applications, including line transfer, thermal balance of interstellar clouds, and the occurrence of astrophysical masers.3

Our work is designed to test the PES describing the interaction of H2O with H2 and He, which are the dominant colliders in most astronomical environments. A stringent test of the accuracy of a PES is its ability to predict state-to-state differential cross sections (DCSs), which are sensitive probes of those regions of the interaction potential that govern energy transfer. In media with little ionization, water molecules collide with H2 molecules in one of the lowest rotational states, or with He atoms, at collision energies in the range from a few cm−1 to a few hundreds of cm−1.3,4 In our laboratory, we collide H2O with >90% in its lowest rotational state with H2 or He at collision energies of 575 and 429 cm−1, respectively.

Previous experiments by Buck and co-workers5 measured partially state-resolved DCSs for He+H2O scattering. Nesbitt and co-workers6 reported state-selective integral cross section measurements for H2O+argon scattering. Cappeletti and co-workers7,8 measured total integral cross sections for H2O+ rare gas scattering. Our specific goal here is to determine the angular distribution in the center of mass frame of the nascent excited H2O state flux created by scattering the ground state H2O by H2 or He. Such a measurement is now possible using the velocity map imaging (VMI) method9,10.

The experimental procedure and VMI apparatus is described in Fig. 1 and is similar to that of Ref. 10. Full details of the apparatus11 and the nascent water laser ionization detection method12 will be given in forthcoming publications. In short, molecular beams of water and H2 or He are crossed at 90°, where H2O and H2 are prepared predominately in their lowest possible rotational states. Collisions produce nascent H2O in higher rotational states. State selective ionization under velocity mapping conditions produces an image of the nascent final state three-dimensional velocity distribution. A typical raw image is shown in Fig. 2(a). Experimental conditions are optimized to minimize the formation of water clusters. Our experiment detects water monomers; if water clusters arise from scattering water, the location and size of the Newton sphere (Fig. 2) will be quite different from that of a monomer collision because of the different kinematics and the dynamics of the cluster dissociation. The images shown in Fig. 2 display no evidence of cluster contributions. We assume that clusters do not affect the results of this study.

In Fig. 2, the rotational quantum states of H2O are labeled JJK, where J is the total rotational angular momentum, and K is a projection of J on the a and c rotation axis. The nuclear spin statistics of two identical hydrogen atoms results in two forms of H2O, ortho (Ka+Kc = odd), and para (Ka+Kc = even), and two forms of H2, para (J=even) and ortho (J=odd). Inelastic collisions conserve

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externally cooled by cold N2 gas to a temperature of 170 K in order to anneal an iron oxide catalyst at 20 K and was then expanded through a pulsed valve.

図1. Crossed-beam VMI apparatus. Pulsed molecular beam expansions of pure H2 or He and H2O in Ar are skinned and crossed at 90°. Newly formed rotationally excited H2O is state selectively ionized by a pulsed laser operating around 248 nm. The H2O+ ions are projected by a VMI lens to a two-dimensional imaging detector monitored by a charge coupled device (CCD) camera. Normal H2 was converted to para-H2 using an iron oxide catalyst at 20 K and was then expanded through a pulsed valve externally cooled by cold N2 gas to a temperature of 170 K in order to decrease the population of H2(J=1).

Images collected with the H2O and H2 or He beam separated in time were subtracted from images collected in optimal time overlap for background correction. A set of background-corrected images is shown in Fig. 2. These images are density maps of nascent H2O; conversion to the desired flux map is carried out using the IMSIM software procedure, which reproduces a simulated density image in quantitative agreement with the raw images. The derived flux angular distributions (DCSs, dσ/dΩ) for the selected images are shown as black lines in the panels of Fig. 3.

An important experimental observation is that for the same final states at nearly the same collision energy, water scatters much more strongly in the forward direction (defined in Fig. 2) due to collisions with H2 compared to He. Changing the H2 supersonic beam conditions (using para-H2 versus normal-H2 and cooling the H2 nozzle assembly from ~330 to 170 K), we find that the scattering remains strongly in the forward direction. Forward scattering is thus favored for all rotational states of H2. Hence, an important difference between H2 and He is indicated in our differential measurements, even when scattering is for the most part by para-H2(J=0), which is often assumed to behave similarly to He.

The experimental data are compared here with DCS predictions from a fully quantum analysis using the most recent and advanced PES for the nonreactive systems H2O+He (Ref. 16) and H2O+H2. Few such calculations exist in literature. For the H2O+H2 case, a full nine-dimensional PES (including all inter- and intramolecular degrees of freedom) was obtained from Ref. 18. This nine-dimensional PES was averaged over the vibrational ground state wave functions of H2O and H2, yielding a five-dimensional rigid-body PES. This latter PES has been used to calculate many energy changing cross sections and rates relevant for astrophysics, making it all the more important to perform the present evaluation. The H2O–He PES was derived from the PES of Hodges et al. using their routines as input to our fitting scheme, which is similar to the original scheme of Green et al.

The scattering S-matrices needed for computing DCSs for both H2O–H2 and H2O–He were calculated by employing the close coupling formalism implemented in the MOLSCAT program. For H2 with J=1,2, the DCS calculation made use of an algorithm derived from the original DCS formulas. Inelastic cross sections of interest were converged to 1%. For the specific angles 90°, 135°, and 180° in the DCS plotted in Fig. 3, the lower left diagonal arrow shows the propagation direction of the ionization laser beam. Backscattered images of inelastically scattered H2O in the indicated final JKa state for collisions with para-H2 and He.
the $\text{H}_2$–$\text{H}_2$ collision (rotational temperature of $\text{para-}\text{H}_2 \approx 220$ K), we averaged the theoretical DCS over a rotational distribution in the $\text{H}_2$ beam of 61% $\text{H}_2(J=0)$, 10% $\text{H}_2(J=1)$, and 29% $\text{H}_2(J=2)$, as measured experimentally using $(2+1)$ Resonance Enhanced Multi-Photon Ionization (REMPI) of $\text{H}_2$ around 200 nm. Collisions resulting in $\text{H}_2(J)$ changing cross sections were both measured [using $2+1$ REMPI of $\text{H}_2(J=1,2)$ at $\approx 200$ nm] and calculated to be negligible. Comparisons of the experimental and fully quantum calculated DCSs plotted in Fig. 3 show remarkably good agreement for both the $\text{H}_2$–$\text{H}_2$ and the $\text{H}_2$–$\text{para-H}_2$ systems. We have not smoothed any possible quantum oscillations appearing in the theoretical DCS. Some remnants of the oscillations averaged over the experimental resolution may be visible at the experimental level.

For the sake of comparisons between He and $\text{para-H}_2$ scattering, we also show computed DCSs for scattering between water and $\text{para-H}_2$ using the $\text{H}_2 J=0,2$ rotor states in the channel basis as before, but considering only $J=0$ initial and final states. In this calculation, the coupled channel propagation used for computation of the $S$ matrix elements includes a full description of molecular $\text{H}_2$, including its anisotropy, but the partial wave sum used for construction of the DCS from the $S$ matrix elements is identical to that for $\text{H}_2$–$\text{H}_2$ collisions. The results are shown as blue lines in the left panels of Fig. 3. In this case, the DCS structure becomes very different from the results that include an average over the experimental rotational state distribution. The strong forward scattering disappears and the overall structure becomes qualitatively similar to scattering of $\text{H}_2$–$\text{H}_2$ by He. Very similar results were obtained when only $J=0$ was included in the $\text{H}_2$ rotor basis, that is, when $\text{H}_2$ was treated as an atom in the scattering calculation. Apparently the most important difference between scattering by He and by $\text{H}_2 (J=0)$ is the different shape of the potential; in particular, the well is deeper for $\text{H}_2$. While no attempt is given here to compare absolute values of cross sections, the computed DCSs for He and for $\text{H}_2 (J=0\rightarrow0)$ show strong similarities at the energies studied, away from the resonance regimes.

$\text{H}_2$–$\text{H}_2$ scattering is thus quite sensitive to the initial rotational state of the $\text{H}_2$, even though most collisions result in no change in its rotational state. Ignoring this dependence and treating all $\text{H}_2$ molecules as $J=0$ molecules or as atoms can introduce important errors. The common procedure of estimating rates for $\text{para-H}_2$ collisions with those from simpler He calculations should thus be applied with caution.

Differences in the scattering of water by $\text{para-H}_2$ and normal-$\text{H}_2$ have been found in pressure broadening experiments and simulations at $50 < T < 200$ K. The present experiments, however, did not detect a qualitative change in the DCS changes in $\text{H}_2$ beam conditions. In our experiment, it is not possible to produce a beam of pure $\text{para-H}_2(J=0)$. Even at the nozzle temperature of 170 K, the expected population ratio of $\text{para-H}_2(J=0)$ to $\text{para-H}_2(J=2)$ is still 4.3:1. Replacing normal-$\text{H}_2$ by $\text{para-H}_2$ at this temperature in our apparatus produced beams with measured $\text{H}_2$ populations in $J>0$ states of 28%, and the observed images had quite similar angular distributions to those observed under other beam conditions. It is likely that this state distribution was not pure enough to reveal the He-like DCS predicted by the calculation. These experimental indications are qualitative for the present apparatus configuration because the reliability of the signal in the forward scattering region suffers from wide beam angles and background subtraction uncertainty. Improved experiments with more narrow beams and a higher accuracy in the forward scattering region, and more detailed comparisons with scattering by the other rare gases as well as by $\text{D}_2$ (whose spin statistics are inverted with respect to $\text{H}_2$) are under way. Lower collision energies will also be studied using a smaller molecular beam crossing angle.

In summary, experiments are now possible that provide sensitive information in the form of state-to-state differential cross sections for collisions of $\text{H}_2$O with $\text{H}_2$, He, and other species under conditions relevant to those of interstellar space. Although the center-of-mass energy tested here is somewhat higher than the usual energies found in interstellar matter, the shape of the PES has been thoroughly tested, setting great confidence in the calculating scheme that we used to obtain the PES. The measured and calculated properties for the most part agree quite well, giving confidence in the quality of the PESs describing the $\text{H}_2$–$\text{H}_2$, $\text{H}_2$–$\text{He}$ interactions. The PESs for $\text{H}_2$O interaction with $\text{He}$ and $\text{H}_2$ in general appear to pass the experimental DCS test with flying colors. Our results point out the differences between collisions of water with helium and with cold $\text{para-H}_2$, and suggest similarities in the shape of the DCS for all initial $\text{H}_2(J)$ states.

Various tests at lower collision energies, including $\text{H}_2$–$\text{H}_2$O cluster spectroscopy, and scattering experiments testing the resonance or elastic regimes should be undertaken in parallel with more global tests such as pressure broadening or virial coefficient measurements. All these tests
comparing theory with experiment help assess the validity of the H$_2$O–H$_2$ PES of paramount importance to understanding the abundance and role of water in the interstellar matter.

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