

Formation of Molecular Hydrogen on Dust Grains



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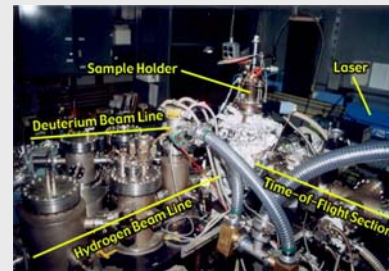
<http://physics.syr.edu/research/astro>

We thank NASA APRA Program and the Italian Ministry for Education and Research for financial support



•Left: a diagram of our laboratory astrophysics experiment. Surrounding the central chamber in the figure (clockwise from the 9 o'clock position) are the ultra-high vacuum pumps, the time-of-flight line, and the hydrogen and deuterium atomic beamlines. The central chamber contains the interstellar dust analogue sample mounted at the end of a cold stage rotatable in the plane of the diagram.

•Right: The photograph shows the central chamber, the atomic beamlines used for dosing the cold sample with H and D atoms, and the time-of-flight section to measure the time of flight of HD molecules that form on the surface. In the background is the final stage of a UV laser, to be utilized for measuring the ro-vibrational state of HD molecules coming off the surface by laser-ionizing them.



Molecular hydrogen is the most abundant molecule in the Universe. It acts as a coolant in the gravitational collapse of a cloud in the formation of a protostar, and enters, whether in neutral or ionized form, most reaction schemes for the formation of other molecules.

H₂ is continuously destroyed by UV photons, thus an efficient formation route must be available. Since gas-phase reaction pathways cannot provide H₂ in sufficient quantities to justify observations, it is believed that H₂ forms on dust grains.

Our group was the first to actually measure in the laboratory the formation of H₂ on dust grain analogues in simulated ISM conditions (Pirronello et al., ApJ 475, L69; 483, L131).

Purpose of Experiments: to obtain detailed information on the processes of H₂ formation and ejection from the dust grain into the gas phase in a variety of ISM environments

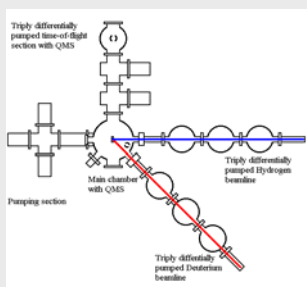
Experimental conditions: low sample temperature (5-30 K), low background pressure (10⁻¹⁰ torr), low flux of gas-phase atoms (10¹² atoms/cm²/sec)

Information extracted from data: H₂ formation yield, reaction rate, reaction kinetics, energetics of reaction steps, translational energy of ejected molecules.

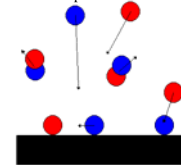
Theoretical approach: use of rate equations and the Master Equation to extrapolate experimental results to the ISM

Measuring Methods

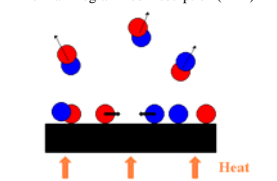
To simulate the flux of atomic hydrogen colliding with dust grains in the interstellar medium, we send atomic hydrogen (blue in figures) and deuterium (red) gas through the beamlines to impinge on the surface of the sample. The atomic beamlines provide a collimated flow of hydrogen or deuterium atoms from two radiofrequency dissociation sources. The careful measurement of the intensity of the beams and of the time of exposure gives the quantity of reactants available. To simulate gas-surface processes in ISM conditions, the flux has to be as low as possible. The sample, a dust grain analogue (an amorphous silicate, carbonaceous material or ice mixture), is cooled to typical interstellar grain temperatures (10-30 Kelvin) and below using liquid helium, and is maintained in ultra-high vacuum conditions (10⁻¹⁰ torr).



Irradiation phase



Thermal Programmed Desorption (TPD)



Some H₂ molecules may form quickly during the irradiation stage because of the fast diffusion of H atoms on the surface. The energy released in the reaction ejects some of the molecules back into the gas phase. In our measurements, this fast reaction accounts for a small fraction of the total molecular hydrogen yield (above left). After the sample has been exposed to the atomic gases, we heat it up (above right). The increase in temperature makes hydrogen and deuterium atoms diffuse and react forming molecules that are ejected from the surface (the Thermal Programmed Desorption experiment). In our experiments, most molecules come off during this phase of the experiments.

Efficiency of the H + H → H₂ reaction

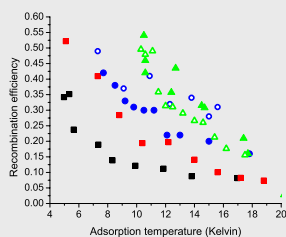
The recombination efficiency is calculated from the ratio of the HD yield divided by the theoretical maximum yield assuming a perfectly efficient formation process. In other words:

Let *H* and *D* represent the total number of hydrogen and deuterium atoms on the surface. The maximum number of molecules that can form on the surface is

$$\frac{H+D}{2} \text{ Assuming a perfectly efficient reaction, a fraction } \frac{2 \cdot H \cdot D}{(H+D)^2} \text{ of the total will be HD molecules.}$$

The recombination efficiency is therefore given by

$$R = \frac{\text{measured HD yield}}{\frac{H+D}{2}} = \frac{\text{measured HD yield}}{\frac{H+D}{2}} = \frac{H \cdot D}{(H+D)^2}$$

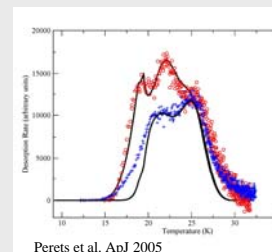


Left: measurements of recombination efficiency on polycrystalline olivine (black), amorphous carbon (red), high density (blue) and low density (green) amorphous water ice (Vidali et al., 2004). Measurements of recombination efficiency on amorphous silicates (Mg,Fe₂SiO₄) - kindly provided by J.Brucato (Astronomical Observatory of Naples) - and the study of the correlation of molecule formation efficiency with surface morphology are under way.

Mechanisms of the H + H → H₂ reaction

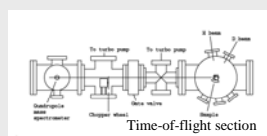
Figure at right shows desorption of HD from amorphous water ice. In one experiment, HD molecules are deposited and then desorbed from the ice. In the other, H and D atoms are deposited, a heat pulse is applied and the reaction products are recorded. If H and D atoms diffused rapidly and formed HD, then the desorption trace would be the same as the one when HD is deposited molecularly. This is not what we observe. Rather, a heat pulse is necessary to initiate the steps of the reaction, leading to a signature that is different from the mere desorption of molecules already present on the surface. In these experiments, it is crucial to use a low atom flux and short irradiation times - to mimic ISM conditions, or otherwise an H atom landing on the surface could make just a few hops and react with a D atom, making HD almost instantaneously and without the need of a heat pulse - (Vidali et al., 2005).

HD desorption rate from a high density amorphous water ice as a function of the sample temperature. The integrated rate gives the total amount of HD produced in the surface reaction. The position and size of peaks give the energetics of the reaction. The solid lines are the results of simulations (Perets et al., 2005).



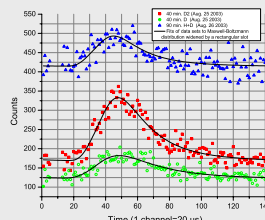
Translational Energy of Molecules

The formation of H₂ on grains releases ~4.5 eV. The kinetic energy of H₂ molecules is collisionally redistributed to the cloud, while the ro-vibrationally energy is re-adsorbed and lost to the cloud. Here we present results on the measurement of the kinetic energy of H₂ coming off amorphous ice.



HD formation and desorption from amorphous ice:
 $f(t)dt \sim t^{-4} e^{-mL^2/2kTt^2} dt$ $E_{kinetic} = 2kT$
 T ~ 16 - 22 K

A similar result was obtained by Hornekaer et al., Science (2003) also on amorphous ice → most molecules stay on surface (probably due to surface morphology - amorphous ice with porous structure)



•Roser et al. ApJ 596 L55 (2003); Vidali et al. J.Geophys.Res. 106 (2004)

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