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Mechanisms of Non-Thermal Desorption from Molecular Ices: Photon- and Electron-Induced Processes

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1. Introduction

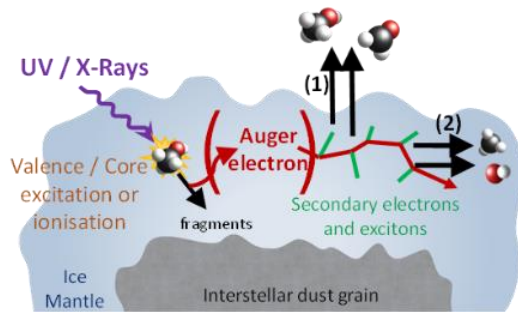


Figure 1: Scheme of processes taking place in the ice after photon absorption.

In the coldest regions (10 K – 100 K) of the interstellar medium, where stars and planets are formed, molecular matter exists mainly in the solid phase, forming ices on the surface of dust grains. Although thermal desorption at these temperatures is negligible, several molecules have been detected in the gas phase in a variety of cold environments such as dark cores [1], photo-dominated regions (PDRs) [2] and protoplanetary disks [3]. It is widely

accepted that non-thermal desorption mechanisms must be considered to explain the observations. These mechanisms include photodesorption, cosmic ray sputtering [4], and desorption induced by exothermic reactions [5]. Photodesorption has been widely studied, especially UV-induced desorption and, more recently, X-ray-induced desorption. However, most of the experimental data is not quantitative and, when yields are available, there are discrepancies in the literature regarding the efficiency of the process. A detailed description of the photodesorption mechanisms also requires the study of electron-induced desorption. Secondary low-energy electrons will be created in the ice when the UV photon energy is above the ionization threshold, and in the case of X-rays the decay of the core-excited or ionized state is mainly through Auger emission for light elements. The systems we have studied previously include CO, N₂ [6], CH₃OH [7], CH₃CN [8], and HCOOH [9] both as pure ices and in mixtures with water. **Our approach, covering a wide energy range and comparing photon- and electron-based irradiations, allows us to determine the main physical properties that drive the induced desorption and chemistry in the ice.** This talk will focus on the most recent and complete set of results obtained on ammonia NH₃ ices, comparing the inner- and valence-shell excitation regions.

2. Methods

Two setups were used for the experiments: the SPICES setup of the LERMA group, and the E/SOLID setup housed at ISMO. In both systems NH₃ ices are formed by cryogenic deposition (50-100 molecular layers), and the desorption of neutral species is measured by mass spectrometry. Thermal desorption experiments (TPD) were used to calibrate the desorption signal, the ice thickness and for the analysis of the processed ice layers. The SPICES setup was coupled to two SOLEIL synchrotron beamlines: (i) DESIRS, valence-shell range (5-12 eV), and (ii) SEXTANTS, core-shell range (395-420 eV, N 1s edge). The ice composition changes are followed in situ by FT-RAIRS during UV irradiation or by photo-absorption during X-ray irradiation. The twin electron irradiation experiments were performed using the E/SOLID setup, in the low energy range as well as at 385 eV, in order to mimic the secondary Auger electrons thought to be major vectors of chemical changes and desorption in X-ray irradiations at the N-K edge. Desorption yields were determined as a function of irradiation energy (spectroscopic study) or at fixed energy as a function of the accumulated dose received by the ice (kinetics study).

3. Results

Quantitative desorption yields, in molecules per incident photon, were determined. In the UV and X-ray energy range the main molecules detected in the gas phase during irradiation are NH_3 and N_2 . **In both cases, desorption of NH_3 mostly follows the ice photo-absorption profile (Figure 2), with some discrepancies in the soft X-ray energy range associated with the nature of the resonances below the N 1s ionization energy.** The mechanisms leading to desorption after photon absorption will be discussed, including the role of Auger electrons created in the ice after X-ray absorption [11], as well as the effects of different parameters such as photon flux, ice morphology and irradiation temperature.

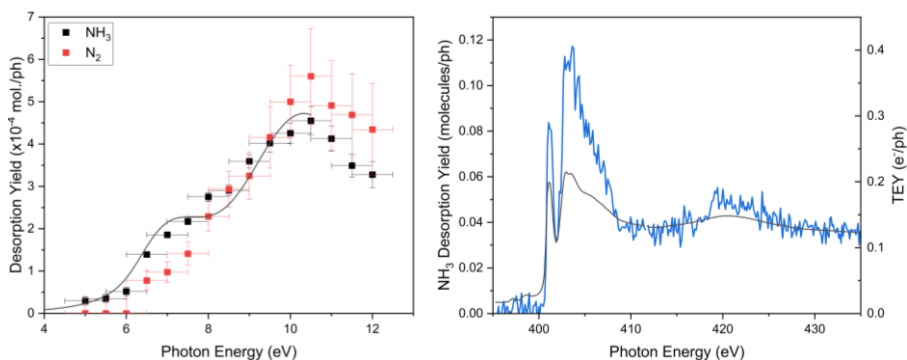


Figure 2: Photodesorption yields determined from pure NH_3 ices. Left: UV-induced photodesorption. The solid line is the photon absorbance [10] convoluted with the photon spectral profile (FWHM=1eV). Right: X-ray induced desorption near the N 1s edge. The black line is the Total Electron Yield (TEY, photo-absorption).

The desorption-relevant depth, i.e., the number of molecular layers involved in the desorption process, is a key property dependent on the energy transfer mechanisms involved. This depth is needed to estimate desorption yields per absorbed photon and quantitatively compare them to the electron-induced desorption yields. To determine it, we have measured the photon- and electron-induced desorption yield of NH_3 as a function of the ice thickness (at fixed irradiation energy). The desorption-relevant depth varies significantly for each type of irradiation and energy. This is illustrated together with the incident particle penetration depths in Figure 3.

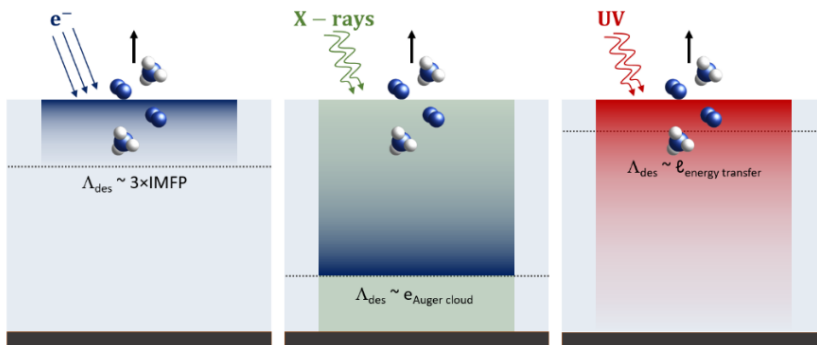


Figure 3: Representation of the relevant depth for the different non-thermal desorption processes studied (dotted lines). The penetration depth of the primary particles is also shown (colored areas).

4. Conclusions and perspectives

The magnitude of the desorption yields depends strongly on the energy domain of the initial excitation/ionization (valence- or core-shell). The comparison between photon and electron-induced desorption requires knowing the desorption-relevant depth for each process, especially when multiple-step chemical processes are at play.

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