

# Development of a Stark velocity filter for studying molecular ion - polar molecule reactions

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## 1. Introduction

Cold ion-molecule reactions play important roles in synthesis of molecules in dark interstellar clouds. In order to study the chemical evolution, the database of reaction rate coefficients of chemical reactions related to astrochemistry has been set up [1]. Recently, it was pointed out that the rate coefficients of molecular ion-polar molecule reactions are not sufficiently well known to understand the chemical evolution in dark interstellar clouds [2]. In this connection, we plan to perform measurements of cold ion-polar molecule reactions between sympathetically cooled molecular ions and cold polar molecules [3, 4]. As a first step, we have developed a Stark velocity filter to produce slow polar molecules. Then the characterization of the slow polar molecules of  $\text{ND}_3$ ,  $\text{CH}_2\text{O}$  and  $\text{CH}_3\text{CN}$  was performed by time-of-flight (TOF) measurements. Finally we measured the reaction rates between laser-excited  $\text{Ca}^+$  Coulomb crystals and the polar molecules.

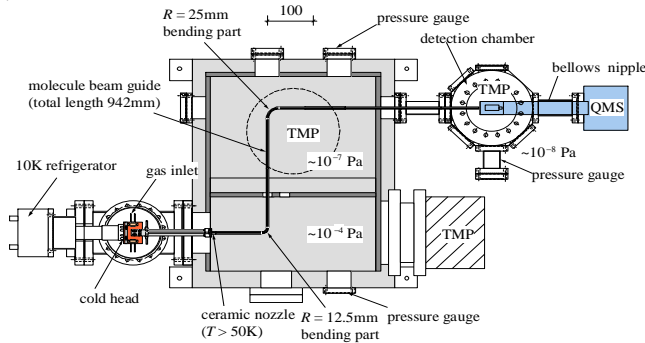


Figure 1. Experimental setup.

## 2. Experimental setup

Figure 1 shows a schematic drawing of our Stark velocity filter. The molecular beam guide consists of four stainless steel rods with a 2 mm diameter and the distance between the adjacent rods is 1 mm. The total length of the guide is 942 mm. The maximum absolute voltages applied to the electrodes are 3.0 kV.

The vacuum chamber enclosing the Stark velocity filter consists of three sections to compose of differential pumping system. The vacuum chamber was evacuated by three turbo molecular pumps backed by rotary pumps. The background pressures of the first and second vacuum chambers are kept to be about  $10^{-4}$

Pa and  $10^{-6}$  Pa. The base pressure of a detection vacuum chamber enclosing a cryogenic linear Paul trap is maintained to be less than  $10^{-8}$  Pa. From a gas inlet, the polar gas is loaded into a ceramic nozzle with an inner diameter of 1.5 mm. The gas nozzle can be cooled by a cryocooler in order to increase the intensity of slow polar molecules. The nozzle temperature is variable from room temperature to 50 K by simultaneously driving a cryocooler and a ceramic heater attached to the nozzle mount.

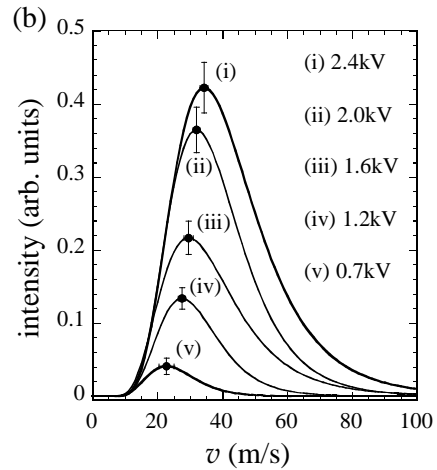
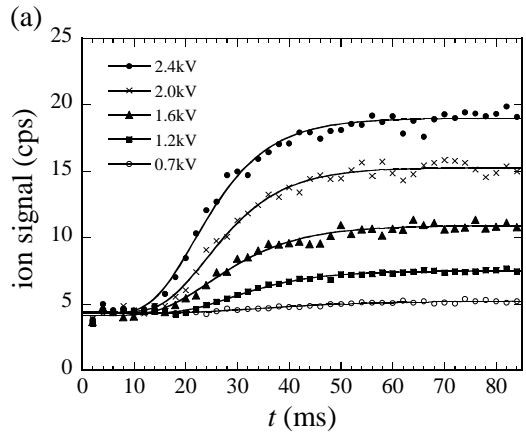


Figure 2. (a) TOF signals of slow  $\text{ND}_3$  molecules, (b) The velocity distributions derived from the TOF signals.

To begin with, we placed a quadrupole mass spectrometer (QMS) in front of the beam-guide exit to measure the TOF signals of slow polar molecules. Using a high voltage solid-state switch, the guide voltages of the Stark velocity filter were turned on at a high speed (10 ns / kV). Since the number density  $n$  of guided polar molecules is necessary information to

determine the reaction rate constants, we also determined  $n$  at the position of the ion trap by the following procedure. First, we leak the polar molecules into the detection vacuum chamber through a variable leak valve. Then we simultaneously measure the ion signal by the QMS and a pressure of the polar gas by an ionization pressure gauge. The pressure is corrected by multiplying the correction factor, which originates from the difference of the ionization cross sections between  $N_2$  and polar molecules. Finally, we obtain a correlation between the QMS signal and the number density of the polar molecules.

In the reaction experiment, the QMS was replaced by the cryogenic linear Paul trap in which a  $Ca^+$  Coulomb crystal was produced by the laser cooling technique [4]. A laser-induced fluorescence (LIF) image from  $Ca^+$  ions was observed by a cooled CCD camera at a right angle to the trap axis. The number of the  $Ca^+$  ions was determined by a size a fluorescence image of a  $Ca^+$  Coulomb crystal.

| molecule | $v_p$ (m/s) | $T_p$ (K) | $n$ ( $cm^{-3}$ )                  |
|----------|-------------|-----------|------------------------------------|
| $ND_3$   | 23 ~ 40     | 1 ~ 4     | $3 \times 10^4 \sim 9 \times 10^5$ |
| $CH_2O$  | 23 ~ 32     | 2 ~ 4     | $9 \times 10^4 \sim 1 \times 10^6$ |
| $CH_3CN$ | 23 ~ 34     | 3 ~ 6     | $5 \times 10^3 \sim 1 \times 10^5$ |

Table 1. A summary of TOF measurements of slow polar molecules by the Stark velocity filter.

### 3. Results

We have successfully produced slow polar molecules of  $ND_3$ ,  $CH_2O$  and  $CH_3CN$  with a peak velocity of lower than 40 m/s. Examples of TOF signals of slow  $ND_3$  molecules are shown in Fig. 2 (a). The time differentiation of the time-distribution signals gives us the velocity distributions, where the Gompertz function was used to reproduce the experimental growth signals [5]. Fig.2 (b) shows the velocity distributions derived from the TOF signals. In the measurement, the guide voltage ( $V_g$ ) was systematically changed from  $\pm 0.7$  kV to  $\pm 2.4$  kV. At  $V_g = \pm 0.7$  kV, the most probable velocity was 23(2) m/s, which corresponds to a thermal energy of only 1.2 K. The same measurements were performed for  $CH_3CN$  and  $CH_2O$  molecules. A summary of the measurements was given in Table 1.

Finally, we have performed reaction-rate measurements between a  $Ca^+$  Coulomb crystal and slow polar molecules. Fig. 3 (a) shows a decay curve of the number of  $Ca^+$  ions in the Coulomb crystal as a function of the irradiation time of slow  $CH_3CN$  molecules. Fig.3 (b) shows a decay curve caused by the laser-induced reactions between  $Ca^+$  and background gases (mainly hydrogen molecules). The

results indicate that both the reaction rates are same within the errors.

The details of the reaction experiments and the discussions will be presented at the oral presentation.

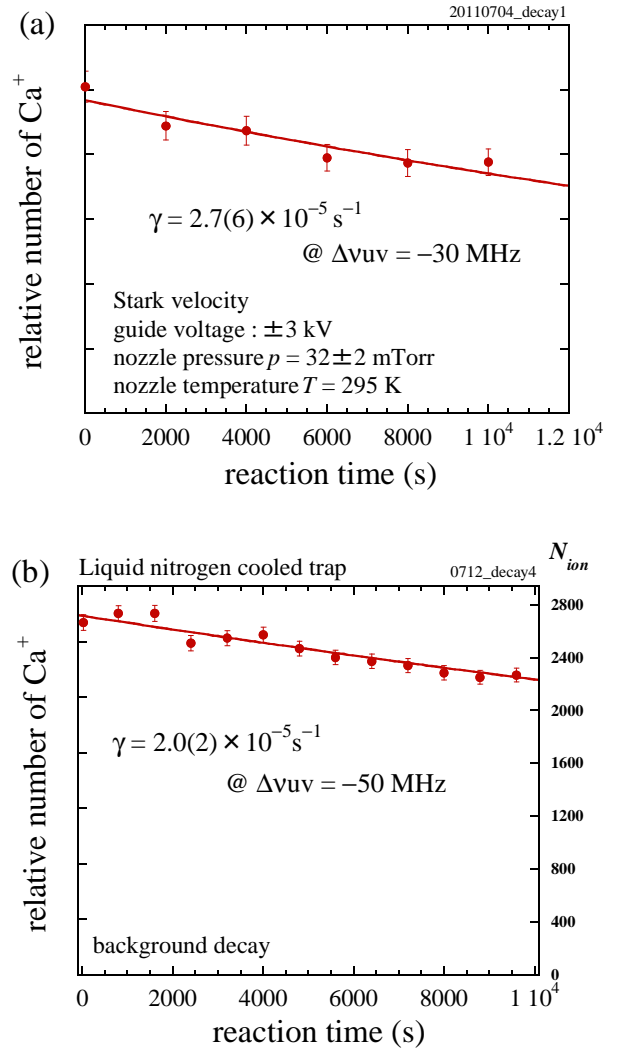


Figure 3. Reaction-rate measurement between a  $Ca^+$  Coulomb crystal and slow  $CH_3CN$ .

### References

- [1] J. Woodall et al.: *A&A* **466**, 1197 (2007).
- [2] V. Wakelam et al.: *A&A* **451**, 551 (2006).
- [3] S. Willitsch et al.: *Phys. Rev. Lett.* **100**, 043203 (2008).
- [4] N. Kimura et al.: *Phys. Rev.* **A83**, 033422 (2010).
- [5] M. T. Bell et al.: *Faraday Discuss* **142**, 73 (2009).