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A novel merged beam apparatus to study the cosmic origins of organic chemistry

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ABSTRACT

Reactions of atomic carbon with molecular ions play a critical role for gas phase molecular formation in interstellar clouds. These interactions are the first links in the chain of chemical reactions leading to the synthesis of complex organic species. Much of our knowledge of this process is through spectroscopic observations and theoretical models. However, our understanding of this chemistry is constrained by uncertainties in the underlying reaction rate coefficients. Data from quantum calculations are limited to reactions involving three or fewer atoms. Meanwhile, previous experimental studies have been hampered by the difficulty in generating a sufficiently intense and well characterized neutral carbon beam. To address these issues and to study these reactions experimentally, we are building a novel laboratory device which does not suffer from such limitations.

1. Introduction

The cosmic pathway towards life is thought to begin in molecular clouds when atomic carbon is fixed into molecules (Herbst 1995). These reactions initiate not only the formation of organic molecules in the cosmos, but also provide some of the first threads knitting atoms and molecules into solid material. Such processes are critical for the eventual formation of

planets and may determine a major component of the organic chemistry that is present on their young surfaces.

Space-based observations of molecular lines are used extensively to understand the molecular universe and its role in the chemical pathway towards life. Interpreting spectral observations from these facilities requires the use of sophisticated astrochemical models (Wakelam et al. 2006; Woodall et al. 2007). However, our chemical understanding of the universe is limited to a large degree by uncertainties in the atomic and molecular data used in the astrochemical models.

To address these astrochemical needs we are constructing a novel device to study gas-phase chemical reactions involving neutral atomic C and molecular ions. Our understanding for these reactions is extremely poor. Experimentally this is because of the difficulty in producing a sufficiently intense and well characterized beam of carbon atoms (Savić et al. 2005). Theoretically this is because fully quantum mechanical calculations of chemical reactions for molecular systems with four or more atoms are still not yet computationally feasible (Bettens & Collins 1998).

The initial steps in the carbon chemistry of molecular clouds begin with reactions involving C and C^+. For our proof-of-principle measurement, we propose to study the reaction

$$C + H_3^+ \rightarrow CH^+ + H_2. \quad (1)$$

H_3^+ is ubiquitous in both diffuse and dense molecular clouds (Geballe 2006; McCall 2006), thereby making reaction 1 one of the first steps towards organic chemistry in molecular clouds (e.g., van Dishoeck 1998). No measurements for this reaction exist at temperatures relevant for molecular clouds; and the uncertainty in the rate coefficient is at least a factor of 5 (see Figure 1).

2. Apparatus Description

Using a negative ion sputter source, we will produce a 30 keV C^- beam. We will cross a 2 kW diode laser at 808 nm with the C^- beam at an angle of 2.7° (similar to the arrangement of Kreckel et al. 2010a). The resulting ∼21 cm overlap length will convert ∼10% of the C^- beam into a ground term $C(^3P_J)$ beam. The population of the J levels will mimic that of molecular clouds. The C^- beam will then be electrostatically removed, leaving behind a pure neutral C beam.

We will use a duoplasmatron source to generate a 7.5 keV beam of H_3^+. Initial studies will be carried out using this hot H_3^+ ion source. Future upgrades will replace this with a

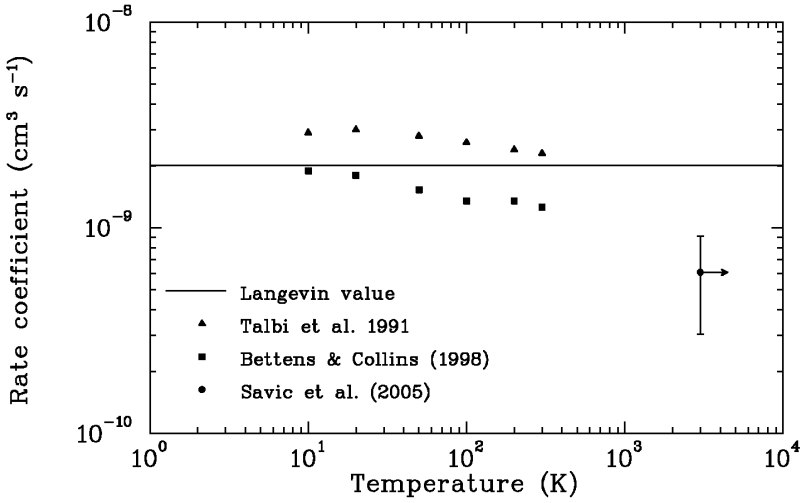

Fig. 1.— Rate coefficients for the reaction 1 showing the Langevin value and the classical trajectory theoretical results of Talbi et al. (1991) and Bettens & Collins (1998). The experimental result from Savić et al. (2005) on D_3^+ has been scaled by the reduced masses of the C/H_3^+ and C/D_3^+ systems.

cold molecular ion source. The H_3^+ beam will be merged electrostatically with the C beam for an interaction length of ∼1 m. Because the beams will co-propagate, we will be able to achieve the low relative collision energies required to study collisions at molecular cloud temperatures.

Chemical reactions will occur throughout the interaction length. Using low density beams and low background pressures ensures that multiple collisions have an insignificant effect on the measured reactions. As a result of using fast beams, the angular spread of the reaction products will be strongly compressed in the forward direction, allowing their 4π detection on a small surface with standard detector technology.

The end of the interaction region will be determined by the first in a series of parallel electrostatic plates, together called a chicane. The first set will be used to demerge the H_3^+ from the heavier C and CH^+ beams. The H_3^+ will be directed into a Faraday cup. The chicane will remerge the CH^+ beam with the C beam. Both beams will then be directed into an electrostatic energy analyzer (similar to that described in Kreckel et al. 2010b). The neutrals will pass through the analyzer and be collected in a calibrated neutral particle current detector. The CH^+ will be directed into a channel electron multiplier with a detection efficiency of nearly 100%. Reactions between the 7.5 keV H_3^+ and 30 keV C will produce 32.5 keV CH^+. Stripping of C off the background gas will produce 30 keV C^+. The energy analyzer will allow us to select against this background, so that it does not swamp the desired

CH^+ signal. Standard beam chopping techniques will be used to collect data and extract the signal from the background.

3. Conclusion

We are developing a unique instrument for studying chemical reactions with atomic C, which will not suffer from the limitations of previous experimental methods. Measuring all the relevant currents, beam shapes, energies, signal counts, and background rates will enable us to determine absolute cross sections. Our innovative apparatus will provide important laboratory data for interpreting molecular cloud spectra in the visible, infrared, and radio regions of the spectrum.

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