Combination of an Electron Spectrometer with an Ion Trap: first results for H^- + hν and H^- + H

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Abstract

A new instrument is under development which is able to guide and store anions and to detect simultaneously electrons using the superposition of suitable rf and magnetic fields. It is based on a modular design combining (i) an rf storage ion source with mass spectrometer, (ii) an octopole ion guide or alternatively a temperature variable 22PT (iii) an electron spectrometer based on magnetic adiabatic collimation, and (iv) an MCP detector. All modules are transparent in axial direction and, therefore, the ions can be exposed to a beam of photons or of neutrals, e.g. also an H-atom beam. This allows us to study photo detachment of electrons from trapped anions and the interaction of anions with neutrals. A first successful test has been the observation of the decay time of an H^- ensemble exposed to a 532 nm laser. At laser powers of a few mW, storage times are a few s in accordance with the known detachment cross section. Similar loss rates have been measured by exposing the H^- ions to a beam of H-atoms, i.e., via the formation of H_2 + e^- products. This contribution discusses the instrument and the ongoing activities, the measurement of absolute rate coefficients for H^- + H as a function of temperature. Long term objectives include to detect the emitted electrons with an electron multiplier detector, utilizing the guiding features of the magnetic bottle principle. The ultimate goal is the determination of the energy distribution of the electrons produced via photons or via associative detachment. Theoretical estimates, accounting for both the rf and the magnetic field, indicate a transmission probability of nearly 100 % and an energy resolution of better than 100 meV.

Keywords: ion traps, rf and magnetic fields, detecting electrons, anions, interstellar chemistry

Introduction

It is generally accepted, that ions and electrons play an important role in the chemistry of interstellar matter, and many related studies have been performed, mainly with cations. The recent detection of molecular anions in the interstellar medium [car06] has clearly indicated that there is more demand for laboratory studies of negative ion chemistry [mar10],[yan10]. Moreover, hydrogen atoms are the most abundant atomic species in the universe and collisions with H have a significant influence on the chemistry of interstellar clouds. Of special importance is the associative detachment (AD) reaction

$$H^- + H \rightarrow H_2 + e^- + 3.724\ \text{eV}. \qquad (1)$$

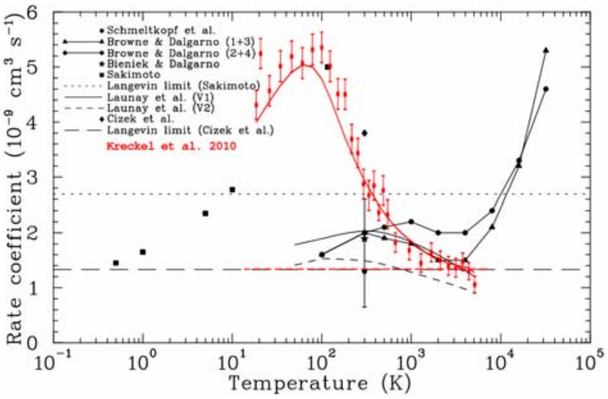

Fig. 1 Overview of theoretical and experimental rate coefficients for associative detachment in collisions of H^- and H. The plot is based on [glo06] and [kre10].

The role of this fundamental process in cooling of the primordial gas has been discussed recently [glo06]. It also has motivated the construction of a merged beam apparatus which has been used for determining the energy dependence of the cross-section for reaction (1) [kre10]. The present status of our knowledge is shown in Fig. 1.

Our aim is not only to verify these measurements with a complementary method and to extend the measurements towards lower temperatures, but also to measure the kinetic energy distribution of the detached electrons. The theory [ciz98] predicts that the major fraction of the exothermicity of reaction (1) produces $H_2(v,j)$ molecules with significant vibrational and rotational excitation. Energy conservation results in an electron energy distribution ranging from 0 to 1.5 eV. The planned experimental determination of this distribution will give us a better understanding of the AD process and will be a critical proof of the theory of AD [ciz98].

Experimental techniques

Our apparatus is based on the well established guided-ion-beam and ion-trapping technique [ger92]. We extend this technique by adding an electron spectrometer employing a magnetic adiabatic collimator [bea80]. Fig. 2 shows a schematic drawing of our apparatus. The H atom beam is produced in a microwave discharge source with variable beam temperature T = 10 – 300 K [bor08], [bor09]. H^- ions are produced in an electron impact storage ion source with H_2 as a precursor gas. After mass selection in an rf quadrupole (QMS), ions are captured in the rf octopole utilizing pulsed axial potential barriers. The H atom beam is passing through the octopole and interacts with H^- by AD reaction.

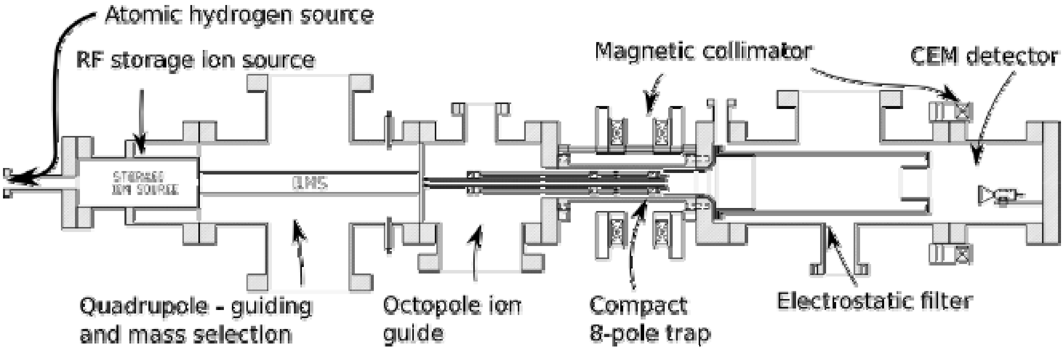

Fig. 2 Combination of a Guided Ion Beam instrument with a MAC Electron Spectrometer. The H^- ions are produced in the storage ion source. A quadrupole transfers the ions into an octopole ion guide where they can be trapped between the indicated electrostatic barriers. Superimposed to this trapping region is a magnetic field shown in Fig. 3.

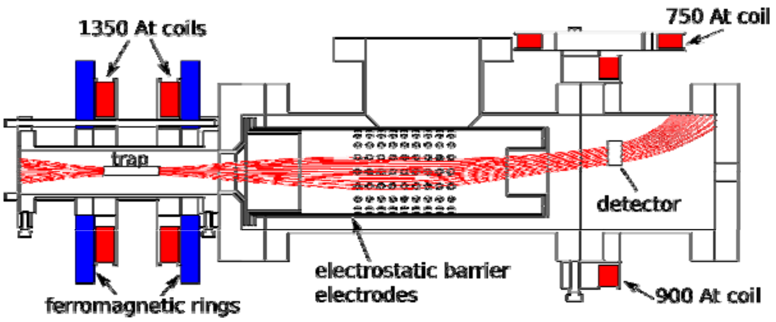

Fig. 3 The design of magnetic adiabatic collimator. Solenoid coils are displayed in red, ferromagnetic rings in blue. Magnetic field lines going through the trap were calculated using FEniCS [log10].

Electrons produced in the AD with random velocity direction are guided out of the octopole using an axial magnetic field. Their energy is analyzed with a so-called MAC-E-Filter (Magnetic Adiabatic Collimation combined with an Electrostatic Filter). This type of spectrometer was first proposed in [bea80] and has been described in [lob85] and [pic92]. It is based on adiabatic invariance of magnetic momentum ($E_{\perp}/B$) in slowly varying magnetic field. Our actual construction is shown in Fig. 3. Two solenoids are producing a magnetic guiding field in the trap. Two ferromagnetic rings surrounding these solenoids enhance the intensity and homogeneity of the field inside the trap and shield the magnetic field outside. This arrangement converts 97 % of the energy associated with radial motion ($E_{\perp}$) into axial motion, creating a collimated beam of electrons. This beam is filtered by a variable electrostatic retarding potential barrier, i.e., only electrons with energy above a selected barrier are detected by the off-axis channeltron electron multiplier.

Results and discussion

The design of the apparatus was verified by numerical simulations. The configuration of coils and ferromagnetic rings producing the desired shape of magnetic field was designed using femm [mee10] and FEniCS [log10] software. The theoretical estimates for the resolution of the MAC-E filter were verified by simulating trajectories of electrons in the calculated electromagnetic field [rou09]. We checked the calculations of magnetic field by measuring the axial magnetic field using a Hall probe. The results which are presented in [rou10], demonstrate a good agreement of the measured field with numerical calculations.

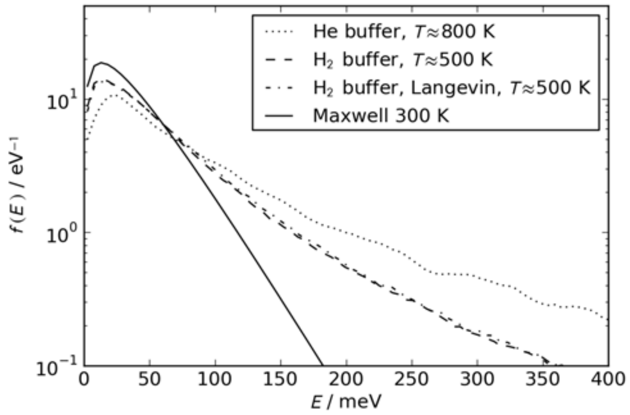

Fig. 4 Calculated energy distributions of H^- ions the octopole for He and H_2 buffer gas at 300 K. The dash-dotted line show a calculation including small angle Langevin scattering.

Confining H^- ions in an octopole trap has also some issues due to their low mass. We intend to cool the ions by buffer gas cooling. For efficient cooling, the masses of ions and buffer gas should be similar. In order to prevent heating by collisions in the rf field, the buffer gas particles should ideally have slightly lower mass than ions. Therefore we intend to use molecular hydrogen for cooling – the lightest gas that does not react with H^-. Energy distributions of ions in an octopole with H_2 and He buffer gasses calculated by particle simulation are shown in Fig. 4. It can be seen that the heavier helium buffer gas causes more rf heating and is less efficient in cooling. The influence of small angle Langevin scattering [nan95] was also calculated. The graph in Fig. 4 shows the result for small angle collision with a rather high cutoff parameter of 9 as defined by [nan95]. No significant influence of small angle collisions was observed. The mean energy of ions cooled by H_2 at 300 K is 0.07 eV, which corresponds to temperature $T \sim 500$ K. The mean energy in collisions with 50 K atomic hydrogen beam is then below 0.08 eV. This energy is small compared to the total energy released during the collision and we expect, that the basic structure of electron spectrum calculated by [ciz98] for collisions at 0.01 eV will be retained. Moreover, the cold effusive beam can be used to increase the collision rate of ions in the field free region, which will decrease this rf heating effect.

Currently we perform test measurements using the CEB-22PT apparatus [bor08], which combines a cold effusive beam of atomic hydrogen with a 22-pole ion trap. This instrument will be used for measurement of the rate coefficient as a function of temperature. Fig. 5 shows the loss of H^- caused by photodetachment. A diode pumped solid state green laser (532 nm, 3-5 mW) has been used to detach the electrons. The results are in qualitative agreement with the theoretical cross section. A quantitative analysis requires determination of the effective overlap between the ion cloud and the laser beam. The electrons produced by the laser have a well defined kinetic energy. Therefore, they are ideal for testing and calibrating the electron spectrometer.

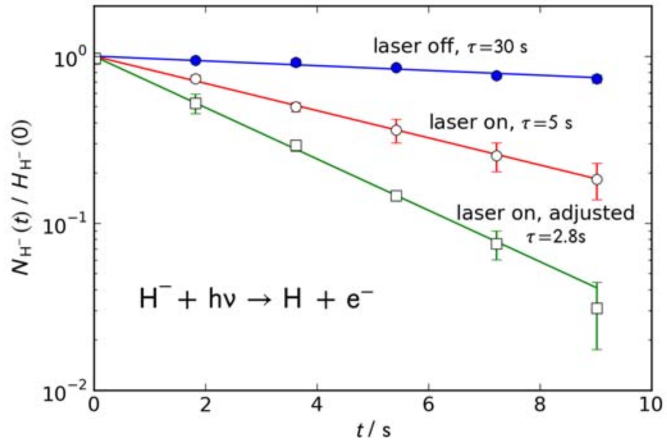

Fig. 5 Loss of H^- ions via photodetachment and reactions. The loss with a storage time of 30 s has been due to minor impurities in the trap; improvement of the vacuum leads to much longer times. A diode pumped solid state green laser (532 nm, 3-5 mW) has been used to detach the electrons. .

First measurements with the hydrogen atom beam were also performed. Fig. 6 shows the kinetics with the discharge switched OFF (no H atoms) and two measurements with the discharge switched ON. The results show that, without H atoms, the ions are trapped for long times – no loss is visible in the 10 s time frame. The measurements with the discharge ON were performed 20 minutes apart in order to verify stability of the H atom beam. The results agree with each other within the statistical error for the measurements. The stability of the H atom beam is crucial for measurement of AD rate coefficient as a function of temperature.

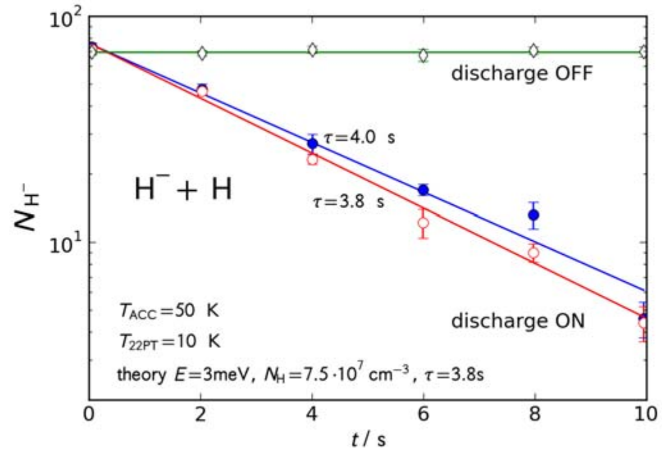

Fig. 6 Reaction of H^- with H atoms. Test of the reproducibility and the stability of the H atom beam. The collision temperature 30 K corresponds to a mean collision energy of 3/2 kT = 4 meV

Conclusions

We presented the design of a versatile instrument that will be primarily operated as an octopole ion trap with an electron spectrometer. Alternatively, the arrangement can be used as an guided ion beam instrument. For detecting product ions, the electron spectrometer can be replaced by a quadrupole mass spectrometer. The first results for H^- photodetachment and associative detachment measured in a CEB-22PT apparatus illustrate the potential of the technique.

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