NASA LAW, October 25-28, 2010, Gatlinburg

Molecular Hydrogen Formation in the Early Universe: New Implications From Laboratory Measurements

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ABSTRACT

We have performed the first energy-resolved measurement of the associative detachment (AD) reaction $H^- + H \rightarrow H_2 + e^-$. This reaction is the dominant formation pathway for H_2 during the epoch of first star formation in the early universe. Despite being the most fundamental anion-neutral chemical reaction, experiment and theory have failed to converge in both magnitude and energy dependence. The uncertainty in this rate coefficient severely limits our understanding of the formation of the first stars and protogalaxies.

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1. Introduction

H_2 cooling of primordial clouds in the early universe led to the formation of protogalaxies and the first stars, commonly called Population III stars. H_2 is formed during this epoch via the associative detachment (AD) reaction

$$\mathrm{H}^- + \mathrm{H} \rightarrow \mathrm{H}_2^- \rightarrow \mathrm{H}_2 + \mathrm{e}^- . \quad (1)$$

Utilizing a novel merged-beams apparatus that we have developed at Columbia University, we have performed absolute measurements for this reaction. Our work is the first energy-resolved experimental study for this reaction and has been published in Kreckel et al. (2010) and Bruhns et al. (2010).

Prior to our work, there was nearly an order-of-magnitude uncertainty in the rate coefficient for this AD reaction Glover et al. (2006). This uncertainty severely limited our ability to model protogalaxies and metal-free stars forming from initially ionized gas, such as in ionized regions (i.e., H II regions) created by earlier Population III stars (Glover et al. 2006; Glover & Abel 2008; Kreckel et al. 2010). These uncertainties have been greatly reduced by our new experimental results with their uncertainty of ±24%.

2. Experiment

Using a duoplasmatron ion source we create a 10 keV H^- beam which is steered through a floating cell of potential U_f. Inside the floating cell the H^- beam crosses a 1.4 kW, 975 nm diode laser which photodetaches ∼7.4% of the anions, creating an H beam of ∼10 keV. In this way we are able to create merged H^- and H beams. The energy of any H_2 formed is essentially the sum of the H^- and H energies or ∼20 keV. The relative energy E_r between the beams is set by varying U_f. Beam collimation is provided by two circular 5-mm-diameter apertures separated by 280 cm, with one located before the photodetachment chamber and the other after.

The beginning of the interaction region is determined by a "chopper" electrode which can deflect and thereby turn the H^- beam on and off. The H beam is chopped by switching the laser on and off. Chopping both beams out of phase allows us to extract the signal generated in the interaction region from various backgrounds. The end of the interaction region is set by a quadrupole deflector which directs the H^- beam into a Faraday cup. The remaining neutrals enter a He gas cell where about 5% of the H_2 and H are stripped generating H_2^+ and H^+. After this cell the neutrals and ions enter an electrostatic energy analyzer. The analyzer is set to transmit the ∼20 keV H_2^+ ions and discriminate against

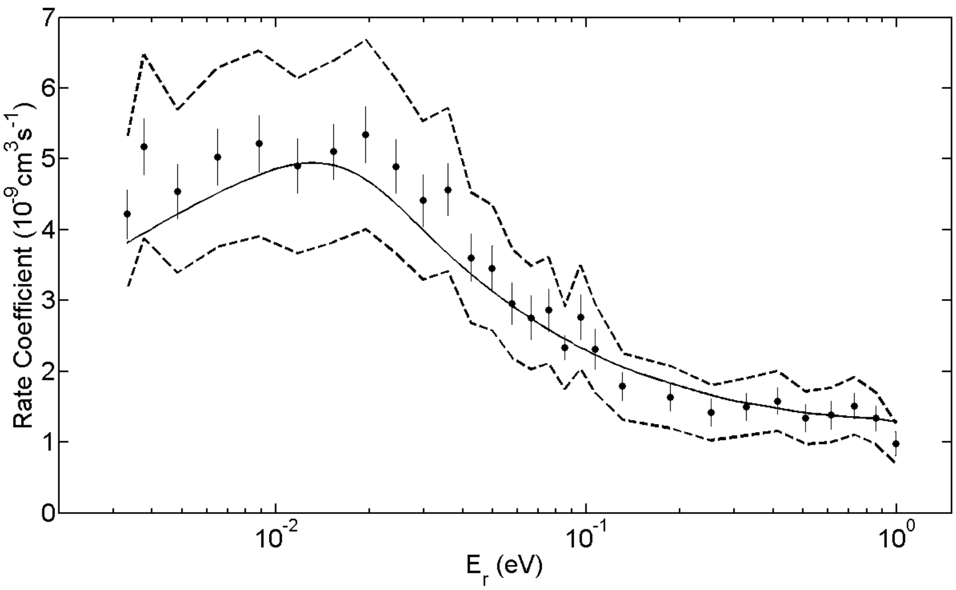

Fig. 1.— Our measured rate coefficient for reaction (1) from Kreckel et al. (2010). The circles show our measurements, the error bars are the 1σ statistical uncertainty, and the dashed lines are the $\pm 1\sigma$ total experimental uncertainty. The solid line is the theory of Čížek et al. (1998).

the $\sim$10 keV H^+. The transmitted H_2^+ ions are directed onto and counted with a channel electron multiplier.

3. Results

Experimentally, we measure the cross section $\sigma_{\rm AD}$ for reaction (1) times the relative velocity $v_{\rm r}$ between the H^- and H beams convolved with the velocity spread of the experiment. This gives a rate coefficient. Our results as a function of $E_{\rm r}$ are shown in Fig. 1. We find excellent agreement with the theory of Čížek et al. (1998). This is discussed in greater detail in Kreckel et al. (2010) and Bruhns et al. (2010).

To examine the effect of our AD data on primordial star formation, we simulated primordial gas evolving within an initially ionized protogalactic halo Kreckel et al. (2010). Using our results and error bars, the simluations found the uncertainty in the characteristic Population III mass is reduced from more than a factor of twenty to around a factor of two. As a result we are significantly closer to the point where remaining uncertainties in models for protogalaxy and first star formation tell us something about the cosmology and not about the underlying chemistry.

This was supported in part by the NSF Divisions of Astronomical Sciences and Chemistry.

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