Laboratory Simulations of Molecular Hydrogen Formation in the Early Universe: A Progress Report

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Abstract.
During the epoch of protogalaxy and first star formation, H_2 is the main coolant of primordial gas for temperatures below $\sim 8,000$ K. The H_2 is formed via associative detachment (AD) of H^- and H. Uncertainties in the rate coefficient for this reaction have limited our understanding of protogalaxy formation during this epoch and of the characteristic masses and cooling times for the first stars. Recently we have carried out a series of laboratory measurements which remove these uncertainties. Here, we present the cosmological motivation for our work, describe the experimental approach, and point the reader to the relevant works where our AD results are reported and their cosmological implications explored.

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COSMOLOGICAL MOTIVATION

The importance of H_2 cooling in primordial gas was first proposed over 40 years ago [1]. This has subsequently been confirmed by numerical models of the formation of the first or Population III stars, demonstrating that H_2 is responsible for cooling the gas to temperatures of ~ 200 K [2, 3, 4].

Over the years a number of groups have studied the formation of H_2 by dust-free primordial chemistry (e.g., [5] and references therein). During the epoch of protogalaxy and first star formation, the dominant formation mechanism for H_2 is the associative detachment (AD) reaction [6]

$$\mathrm{H} + \mathrm{H}^- \rightarrow \mathrm{H}_2 + \mathrm{e}^-. \tag{1}$$

This process is the most fundamental anion-neutral interaction in physics and chemistry. However, theory and experiment have yet to converge in either the magnitude or energy dependence for this reaction. For temperatures below 10^4 K there is nearly a factor of 10 spread in the magnitude for the rate coefficient for this reaction [7, 8].

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This spread has major implications for models of protogalaxies and metal-free stars forming out of initially ionized gas, such as in H II regions formed by earlier Population III stars. For example, it limits our ability to predict whether or not a given protogalactic halo can cool and condense on a sufficiently short timescale before it is gravitationally disrupted through a collision with another protogalactic halo [7]. Also, initially ionized gas can form sufficient quantities of HD which can cool the gas down to the temperature of the cosmic microwave background (CMB), significantly below what H_2 cooling alone can achieve [9, 10, 11, 12, 13, 14]. In such gas, the dominant mechanism for forming HD is

$$\mathrm{H_2 + D^+ \to HD + H^+}. \tag{2}$$

However, the uncertainty in reaction 1 directly affects model predictions for the HD abundance and thereby the cooling rate of the gas [15]. For gas in free-fall, the resulting spread in the minimum temperature corresponds to a factor of 20 difference in the Jeans mass [16]. For shocked gas undergoing isobaric collapse, the time required to reach the CMB temperature can differ by up to a factor of two. This affects the likelihood that such gas will cool and collapse to form a star before undergoing another shock [15].

Previous experimental results for reaction 1 were performed at room temperature using a flowing afterglow apparatus and quoted factor of 2 accuracies [17, 18]. Recently, there has been a new flowing afterglow measurement at room temperature with a quoted 30% uncertainty [8]. However, none of these published afterglow results provide information on the energy or temperature dependence of the reaction, which limits their ability to benchmark theory.

Given the cosmological importance of reaction 1, we have developed an experimental method that is free of the systematics to which afterglows are prone. Specifically, we have designed and built a novel fast merged-beams apparatus in order to measure the energy dependence of the AD reaction. Our work here represents the first use of merged beams to study anion-neutral reactions.

EXPERIMENTAL APPROACH

Here we only briefly review the experimental apparatus and approach. A detailed description is given in [20]. We begin with a duoplasmatron ion source and extract the H^- to create a beam with an energy of $E_{H^-} = eU_s \sim 10$ keV ($U_s < 0$ V). The beam is then charge-to-mass selected using a Wien filter. This removes any other negative particles also extracted from the source. Standard electrostatic ion optics are used to direct the beam into an electrostatic spherical deflector which bends the beam 90°. This removes the direct line-of-sight from the ion source to the interaction region, thereby preventing neutrals and photons from making their way from the source directly into the interaction region. Subsequent ion optics focus and direct the beam into a floating cell biased to a potential $U_f = -1$ V to -281 V. The H^- decelerates as it enters the floating cell, where it is crossed with a laser beam which photodetaches $\sim 7.5\%$ of the H^-. This produces a neutral H beam with an energy of $E_H = e(U_s - U_f)$. Upon leaving the floating cell the H beam energy remains unchanged while the H^- beam energy returns to its initial value. The resulting self-merged H^- and H beams travel with a relative energy set by the floating cell potential. While laboratory energies are in the keV range, because the beams co-propagate, center-of-mass energies from the meV to keV range are achievable.

The beginning of the ~ 96 cm long interaction region is defined by a chopping electrode which is used to turn the anions on or off in the interaction region. The neutral beam is chopped by switching the laser on and off. In the interaction region the two ~ 10 keV beams interact to generate ~ 20 keV H_2. Standard beam chopping methods are used to extract the signal from the various beam-related backgrounds. Rotating wire beam profile monitors (BPMs) near the beginning and end of the interaction region are used to determine the overlap of the two beams and a geometric model was generated to extrapolate upstream and downstream of these BPMs and to interpolate in between. The end of the interaction region is defined by a quadrupole deflector which directs the H^- beam into a Faraday cup where the current is recorded.

The challenge for our experimental method is extracting the $\sim 10^2$ s^{-1} signal H_2 from the $\sim 10^{11}$ s^{-1} parent H beam. We do this by sending the neutrals into a gas cell of He where $\sim 5\%$ of each beam is converted into singly charged ions. At the end of the gas cell, the neutrals and ions enter a series of double-focusing 90° electrostatic analyzers [19]. A hole in the first deflector allows the neutrals to pass through and be collected in a neutral detector. The analyzers separate the ~ 20 keV H_2^+ ions from the ~ 10 keV H^+ ions and direct the H_2^+ onto a channel electron multiplier (CEM). The CEM counts are recorded as a function of time in the chopping pattern. Using the measured length of the gas cell and the He pressure in the cell in combination with the known cross section for stripping of H_2 allows us to convert the measured H_2^+ rate into an H_2 rate. Measuring all the relevant currents, beam shapes, energies, signal counts, and background rates, we can analyze our results offline to determine the absolute rate coefficient for this reaction.

ADDITIONAL INFORMATION

Our results for reaction 1 and their cosmological implications can be found in [16]. The analysis method and data collection are discussed thoroughly in [21]. We refer the reader to these references for more information.

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