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Spin Changing Collisions of Hydrogen

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ABSTRACT

We discuss spin changing collisions of hydrogen atoms. Employing a fully quantal theory we calculate and present new collision data. We discuss the respective roles of spin exchange and long range magnetic interactions in collisonal redistribution of sub-level populations. The calculated atomic data is needed for accurate modeling of 21 cm line emission/absorption by primordial hydrogen in the early universe.

1. Introduction

The 21 cm line of atomic hydrogen was first observed by Ewen & Purcell (1951) in 1951. This discovery hastened the development of radio astronomy (Stephan 1999) and observation of the 1420 Mhz transition in interstellar hydrogen allowed the first maps of large scale structures, obscured in the visible bands, in our galactic neighborhood. A new generation of radio observatories, such as the LOFAR array (LOFAR 2006), the proposed Square Kilometer Array (SKA 2006) as well as possible future lunar based arrays, promise capabilities that will allow ”transformational” observations of the early universe. By detection of the red shifted 21 cm line from environments at and before the epoch of re-ionization, such instruments could provide unprecedented information on primordial matter density fluctuations and provide insight into the nature of dark matter. Loeb & Zaldarriaga (2004) recently proposed application of 21 cm tomography (Madau et al. 1997) of the dark age universe. Accurate modeling of emission and/or absorption of the 21 cm line in primordial hydrogen depends crucially on the values of spin exchange collision rates. In this abstract we present the results of a multichannel collision theory using state-of-the-art molecular potentials to calculate the spin exchange rate coefficients. We discuss the respective roles of spin exchange and long range magnetic interactions in collisonal redistribution of sub-level populations. Atomic units are used throughout, unless otherwise stated.

2. Discussion

The internal states of the atoms are represented by the kets, $|f_a m_a f_b m_b>$ where $f_a m_a$ are hyperfine quantum numbers of atom A, and $f_b m_b$ that of atom B. We consider a transition from state $|j> \equiv |f_a m_a f_b m_b>$ to $|i> \equiv |f'_a m'_a f'_b m'_b>$, the cross section is given by

$$\begin{aligned} \sigma(j \rightarrow i) &= \frac{\pi}{2k_j^2} \sum_L (2L+1) \, |T_{[ij]}(L) + (-1)^L T_{[\tilde{i}j]}(L)|^2 \\ T_{[ij]}(L) &\equiv \delta_{[ij]} - S_{[ij]}(L) \end{aligned} \qquad (1)$$

where $k_j^2/2\mu$ is the kinetic energy in the entrance channel, μ is the reduced mass, $S_{[ij]}$ is the S-matrix and the notation $\tilde{i}$ implies that if $i = \{f_b m_b f_a m_a\}$ then $\tilde{i} = \{f_a m_a f_b m_b\}$. The cross sections defined in Eq. (1) take into account the quantum symmetry of two identical bosons (hydrogen atoms). A detailed discussion of the theory and calculations was given elsewhere (Zygelman 2005), here we present the effective rate coefficients for a hydrogen atom to undergo an $F = 1$ to $F = 0$ hyperfine transition as a function of collision temperature. The rates are tabulated in Table 1. For higher temperatures we recommend the rates tabulated by Allison & Dalgarno (1969) multiplied by a factor of 4/3 (Zygelman 2005).

Using these rates, as well as radiation induced transition frequencies, one can model the spin temperature T_s (Purcell & Field 1956) of the hydrogen gas. It is an essential parameter that determines, in part, the observed brightness temperature. The former is defined by the relation

$$\frac{N_{F=1}}{N_{F=0}} = 3 \exp(-\Delta E / k T_s), \qquad (2)$$

and implicitly assumes that the $F = 1$ sub-levels are equally populated. In a discussion of processes that populate the magnetic sub-levels (Zygelman 2005), we pointed out that collisions do not necessarily bring those populations into statistical equilibrium. This conclusion follows from selection rules for spin exchange, that two hydrogen atoms must conserve the sum of the two spin components along the quantization axis. Collisional relaxation of the gas requires, in addition to spin exchange, the dipolar spin relaxation (Zygelman 2005) mechanism. The rates for the latter process where estimated to have values that are a factor 10^{-4} smaller than spin exchange rates. For conditions that existed in the dark age universe, we conclude that dipolar spin relaxation processes do not play a role. This could allow a scenario where the hydrogen could acquire distinct sub-level spin temperatures. Full understanding of the kinetic processes that bring the hydrogen gas into equilibrium will require knowledge of all hyperfine level collision transition rates in addition to elastic scattering rates. We are presently pursuing a program that involves an accurate calculation of all state-state collision rates for a range of collision temperatures.

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Table 1: Rate coefficient $\kappa(1-0)$ for the effective $F = 1 \rightarrow F = 0$ collision induced spin changing transition as a function of temperature. The rates are expressed in units of $cm^3\ s^{-1}$

$T(K)$	$\kappa(1-0)$
1	1.38×10^{-13}
2	1.43×10^{-13}
4	2.71×10^{-13}
6	6.60×10^{-13}
8	1.47×10^{-12}
10	2.88×10^{-12}
15	9.10×10^{-12}
20	1.78×10^{-11}
25	2.73×10^{-11}
30	3.67×10^{-11}
40	5.38×10^{-11}
50	6.86×10^{-11}
60	8.14×10^{-11}
70	9.25×10^{-11}
80	1.02×10^{-11}
90	1.11×10^{-10}
100	1.19×10^{-10}
200	1.75×10^{-10}
300	2.09×10^{-10}

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