Measurement of the Longitudinal Spin Diffusion Coefficient in Spin Polarized Atomic Hydrogen

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We report on the measurement of the longitudinal spin diffusion coefficient in doubly spin polarized atomic hydrogen. Measurements were made using pulsed nuclear magnetic resonance to probe the transport of magnetization between a sealed container and a large reservoir. Results are presented for densities between 1.4×10^{15} and 4.8×10^{16} cm^{-3} at temperatures between 246 and 470 mK in a magnetic field of 7.7 Tesla and are found to be in reasonable agreement with theoretical calculations by Lhuillier.

1. INTRODUCTION

Diffusion in a spin polarized quantum gas has been shown to differ from the case of a classical hard sphere gas as a result of identical particle exchange effects [1-4]. For the case of spin polarized atomic hydrogen, there have been both theoretical and experimental results reported in the literature [2,4-7]. In this paper we present a continuation and refinement of one of the experiments [4] as well as some additional results on the transition of the gas flow from a hydrodynamic into a Knudsen regime in a particular geometry.

The diffusion of atoms is measured using magnetic resonance as a probe of the transport of magnetization between two known volumes through a single cylindrical orifice. In the case where the spin transport equations can be linearized [2-5], the equation of motion for longitudinal magnetization P_z takes the form of a classical diffusion equation

$$\frac{\partial P_z}{\partial t} = D_o \nabla^2 P_z \tag{1}$$

where D_o is the self diffusion coefficient. Hence, an experiment which measures the longitudinal spin transport in the linear regime provides a direct measurement of the diffusion coefficient.

2. EXPERIMENTAL DESCRIPTION

The diffusion data was obtained by first filling the sample cell with atomic hydrogen at the chosen temperature. The experimental configuration has been described elsewhere [4]. The sample was then allowed to develop a high nuclear polarization by allowing for recombination to become T_1 limited [8]. The magnetization inside the volume enclosed by the resonator was then inverted using a 180° NMR pulse and the recovery of magnetization in the cavity was measured using a series of small tipping angle pulses. The 180° pulses were typically 20μsec long, followed by twenty, five degree probe pulses spaced in 50μsec intervals. The characteristic recovery time in the experiment is on the order of 100 msec and the entire experiment often lasted less than one second. Because this time is short when compared to both recombination times (10^3sec) and magnetic relaxation times (10^4sec), the

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recovery of magnetization in the cavity is governed by the diffusion of atoms through a small hole in the resonant cavity wall. If the scattering of atoms from the cell walls is purely specular, the recovery time is determined entirely by the resonator volume (0.7cm^3), the dimensions of the entrance hole (0.041cm diameter and 0.132cm long) and the diffusion coefficient D_o [9]. In this experiment it is useful to note that, since the recovery time is long compared to the spin wave lifetimes [4,5] and since the spins inside the resonator are "distinguishable" from the spins outside the cavity (they are "antiparallel"), there are no spin rotation effects which can alter the longitudinal spin diffusion through the channel.

3. DATA ANALYSIS

The initial amplitude of each free induction decay (FID) was first determined. Since these is finite "dead-time" after the RF pulse, the initial amplitudes were determined by extrapolation of the FID line shape (averaged over several FID's of the data set and fit separately to each individual FID) to the initial time. The result is a table of magnetization as a function of
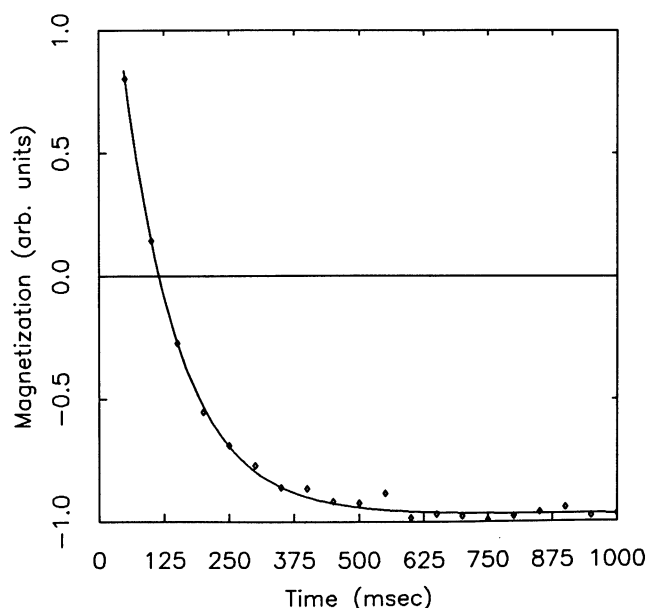

Fig. 1. Typical recovery curve for longitudinal magnetization in resonator volume after an inverting 180 degree pulse was applied at t = 0.

time. A typical recovery curve produced in this manner is shown in figure 1. These results were then fit to an exponential function form to obtain the recovery time. The recovery time is then corrected for the finite impedance presented by the flow channel in the resonator wall and the result used to evaluate the diffusion coefficient.

4. RESULTS

The results are summarized in figure 2. Over the temperature range of the experiment there are no discernible temperature dependences, in agreement with the theory [4]. As expected, the measurement has also been shown to be independent of initial polarization [4,7]. At higher densities ($n > 10^{16} cm^{-3}$) we find $D_o(n)$ inversely proportional to the density as expected for hydrodynamic flow (mean free path$<<$ sample cell dimensions). At the lower densities, we find $D_o(n)$ to be relatively constant with density as expected for the Knudsen regime (molecular diffusion).
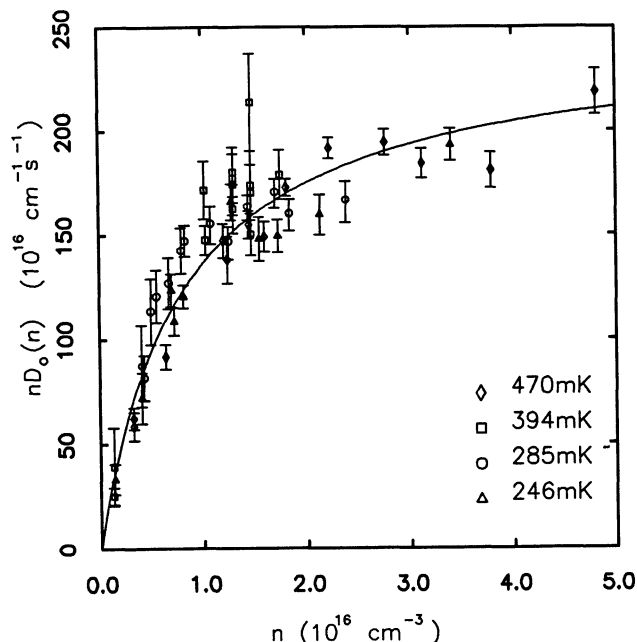

Fig. 2. Diffusion coefficient as a function of density, characterized by $nD_o(\infty) = 2.46 \times 10^{18} cm^{-3}$.

The results shown in figure 2 were fitted to a function of the form

$$D_o(n) = D_o(\infty)\left(\frac{n}{n_c + n}\right) \qquad (2)$$

where $D_o(\infty)$ is the asymptotic fully hydrodynamic diffusion coefficient and n_c is a crossover density from the effusive to the diffusive regimes. The particular value

of n_c is governed by the flow geometry as well as the nature of scattering at the walls of the flow channel. We find a value for $nD_o(\infty)$ of 2.46 x 10^{18} cm^{-1}sec-1 and a value of 7.826 x 10^{15} cm^{-3} for n_c. We prefer these results to our previously reported value because of an improved experimental technique which shortens the time scale of the entire experiment, as well as an improved analytic method. The present result is consistent with our previous data; however, this result emphasizes the slowness with which the transport crosses over from a diffusive into a hydrodynamic regime. This value for D_o is a factor of 1.6 larger than the results calculated by Lhuillier [2], 1.9 larger than the results of Birkholt et.al. [6] and 5 times larger than the value expected for a hard sphere gas described by the hydrogen s-wave scattering cross section 0.72Å.

Inspired by the striking results of Berkhout et.al. on the enhancement of capillary flow in this system [6], we are currently analyzing our data in an effort to corroborate their results. In particular the assumptions made in describing the effects of the finite flow channel dimensions depend on the nature of surface scattering and sticking probabilities [7]. If these effects are discernable in our data, this technique could have the advantage of being relatively immune to effects of recombination and nonuniform temperature distribution in the sample cell.

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