DIPOLAR DECAY OF MAGNETICALLY TRAPPED ATOMIC DEUTERIUM GAS

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ABSTRACT

We have calculated the magnetic dipolar spin relaxation limited stability of magnetically trapped doubly spin-polarized atomic deuterium gas for temperatures small in comparison with the electronic Zeeman splitting. In the degeneracy regime ($T \ll T_F$) we typically find lifetimes of some hours.

I. INTRODUCTION

In magnetically trapped doubly spin-polarized hydrogen (H↑↑) and deuterium (D↑↑) gases, the Bose and Fermi-character respectively, profoundly affects the dipolar relaxation limited stability of the samples. In magnetically trapped H↑↑ two-body dipolar relaxation rates are predicted [1] to be fast and, to lowest order, independent of temperature. In D↑↑, however, as a direct consequence of the Pauli exclusion principle acting between fermions in the same internal state, the relaxation rates are expected [2] to decrease dramatically with decreasing temperature. In Ref.2 we showed that a minimum-B-field trap similar to those used for confining laser-cooled spin-polarized alkalis [3] and spin-polarized hydrogen atoms [4] can be used to study doubly spin-polarized deuterium. The hyperfine population dynamics associated with fast two-body spin-exchange collision processes between deuterium atoms in low-B-field seeking hyperfine states (D↑), almost inevitably leads to a gas of D↑↑ atoms. Applying an evaporative cooling scheme similar to that proposed for H↑↑ [5] to trapped D↑↑ atoms, will ultimately lead to an extremely stable ultra- cold gas. Therefore, magnetically trapped deuterium gas offers a unique possibility for the experimental observation of degenerate quantum behavior under conditions in which to a large extent density and temperature can be controlled independently.

In Ref.2 only some preliminary results on the stability of a gas of D↑↑-atoms against dipolar relaxation processes were presented. These results were restricted to the Boltzmann regime, i.e. to temperatures well above the Fermi temperature T_F. Here we present a more general theory which also applies to the degeneracy regime ($T \ll T_F$) and the cross-over regime ($T \simeq T_F$). The results are given in the form of a simple closed expression which, in the relevant regimes, describes the temperature and magnetic field dependence of the effective decay rates within a few percent. This expression also determines the dipolar decay rates of magnetically trapped fermionic alkali atoms.

II. DIPOLAR DECAY

Spin depolarization due to the magnetic dipole-dipole interaction is the dominant loss mechanism for magnetically trapped D↑↑ gas [3]. Taking into account only the electron-electron part of the dipolar interaction, which by far dominates over the electron-deuteron and deuteron-deuteron contributions, we find that only a limited set of hyperfine transitions are allowed. Denoting the one atom hyperfine states α, β, γ, δ, ϵ, and ζ in order of increasing energy, so that the trapped doubly-polarized state is denoted by ζ, we find that at B-fields exceeding a few tens of milli-Teslas two colliding ζ-state atoms only allow for hyperfine transitions to α-state atoms. The two-body relaxation processes which are allowed for, can be denoted as: $\zeta\zeta\rightarrow\zeta\alpha$ and $\zeta\zeta\rightarrow\alpha\alpha$. Assuming the ζ-state atoms formed in the above dipolar relaxation events to have acquired enough energy to escape from the trap and stick to a wall outside the trap region, and the α-state atoms which are repelled from the minimum-B-field trap also to stick to an adsorbing wall, we find for the decay of the ζ-atom gas

$$\frac{d}{dt} n = -2 n^2 \left(G_{\zeta\zeta\rightarrow\zeta\alpha} + G_{\zeta\zeta\rightarrow\alpha\alpha}\right) , \qquad (1)$$

with n denoting the ζ-atom density. At B-fields of a few milli-Tesla and lower, electronic dipolar relaxation processes involving final states with ϵ-atoms ($\zeta\zeta\rightarrow\zeta\epsilon$, $\zeta\zeta\rightarrow\epsilon\epsilon$ and $\zeta\zeta\rightarrow\epsilon\alpha$) become competitive. We do not take into account this B-field regime because, as will be shown below, this regime is of less interest for purposes of D-atom trapping.

At B-fields exceeding a few tens of milli-Teslas the hyperfine energy splitting between the ζ- and α-state is dominated by the electronic Zeeman energy and much larger than typical kinetic energies (ranging from milli-Kelvins to micro-Kelvins). This considerably facilitates the calculation of the rates. Within the PWBA-scheme, which thanks to the Pauli exclusion principle should be an excellent approximation at low temperatures, and assuming the velocity distribution function to be isotropic, we find

$$G_{\zeta\zeta\rightarrow\zeta\alpha} = \frac{2\sqrt{2}}{15\pi} \gamma B^{-1/2} E_k , \qquad (2)$$

and

$$G_{\zeta\zeta\rightarrow\alpha\alpha} = \sqrt{2}\, G_{\zeta\zeta\rightarrow\zeta\alpha} , \qquad (3)$$

with E_k denoting the average kinetic energy per atom, and the parameter $\gamma \equiv (m\,\mu_e)^{3/2} (\mu_o\mu_e/\hbar^2)^2$ which when the deuterium atom mass is substituted for m takes the value $\gamma = 8.3\times10^{-14}\mathrm{cm}^3\mathrm{s}^{-1}\mathrm{T}^{1/2}\mathrm{K}^{-1}$.

The average kinetic energy per atom depends on the precise form of the single-particle velocity distribution function. At low kinetic

energies the dipolar interaction is much more effective for elastic collisions ($\zeta\zeta \rightarrow \zeta\zeta$) than for inelastic ones ($\zeta\zeta \rightarrow \zeta\alpha$ and $\zeta\zeta \rightarrow \alpha\alpha$), as the energy released in a inelastic transition reduces the overlap between initial and final states. As a result, the velocity distribution may be assumed to be in thermal equilibrium and given by the Fermi-Dirac distribution. The mean free particle energy for a Fermi-Dirac distribution can be parametrized in temperature units as

$$E_k(n,T) \simeq \left[\left(\frac{3}{5}T_F\right)^{1.7} + \left(\frac{3}{2}T\right)^{1.7}\right]^{1/1.7} \qquad (4)$$

This reduces in the Boltzmann limit ($T \gg T_F$) and in the degeneracy limit ($T \ll T_F$) to the well-known expressions $^3/_2T$ and $^3/_5T_F$, respectively. In the cross-over regime ($T \simeq T_F$) Eq.4 is accurate within 2%.

III. IMPLICATIONS FOR MAGNETICALLY TRAPPED D↑↑

An important feature of the above results is that the fermionic character of the deuterium atoms manifests itself in the relaxation rates as a proportionality to the mean kinetic energy of the atoms (Eq.2) so that the stability grows with decreasing temperature. This is not so for hydrogen atoms which behave like bosons. The same analysis applied to bosons in essence yields an equation similar to Eq.(2) but with E_k replaced by the Zeeman energy $\mu_e B$, yielding relaxation rates independent of temperature.

Another aspect of the above described decay worth to mention here is that, with exception of the Boltzmann($T \gg T_F$)-regime, the relaxation rates not only depend on the magnetic field strength and temperature but via a dependence on T_F also on atom density. For instance, in the degeneracy limit ($T \ll T_F$), the relaxation rates are proportional to $n^{2/3}$ yielding a decay $dn/dt \sim n^{8/3}$. This behavior makes it possible to determine the trapped gas temperature, and more specifically to signal degeneracy, simply by monitoring the trapped atom density.

Using the above equations we find for the characteristic decay rate $\Gamma_{dip} \equiv -n^{-1}dn/dt$:

$$\Gamma_{dip} \simeq \frac{4\sqrt{2}}{15\pi}(1+\sqrt{2})\,\gamma\, n\, B^{-1/2}\left[\left(\frac{3}{5}T_F\right)^{1.7} + \left(\frac{3}{2}T\right)^{1.7}\right]^{1/1.7}. \qquad (5)$$

with a relative error not exceeding a few percent for B>0.03T. For B= 0.1 T the above analysis is applicable up to temperatures of a few tens of milli-Kelvins. At $n = 10^{14}cm^{-3}$ and T= 10 mK we find $\Gamma_{dip} \simeq 0.1\ s^{-1}$. At the same density and magnetic field but for $T = T_F \simeq 39\ \mu K$ Eq.(14) yields $\Gamma_{dip} \simeq 5\times10^{-4}s^{-1}$, while for $T \ll T_F$ the decay rate reaches its minimum value $\Gamma_{dip} \simeq 2\times10^{-4}s^{-1}$.

At fields below a few tens of milli-Teslas the decay rates no longer scale as $B^{-1/2}$, not only because the hyperfine level splitting is no longer dominated by the Zeeman term, but also because at these fields the electronic dipolar relaxation channels $\zeta\zeta \rightarrow \zeta\epsilon$, $\zeta\zeta \rightarrow \epsilon\epsilon$, and

ζζ→εα open up. For purposes of creating stable D-atom gases, this low B-field region is of less interest: as the decay rates increase with lowering B-fields, regions with low B-values must be avoided in an optimum minimum-B-field trap for D-atoms.

The above equations not only apply to the case of D↑↑, but also to any doubly spin-polarized fermionic alkali atom gas, provided the relevant kinetic energies are small in comparison with the Zeeman level separation. As the relaxation rates depend on the atomic mass m as $\sim m^{3/2}$, the alkalis are more unstable against dipolar relaxation than deuterium. Hence, even without taking into account decay due to resonance recombination, which is absent in D↑↑ [3] but effective in magnetically trapped doubly spin-polarized alkalis [6], deuterium is more stable than the alkalis.

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