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Spin-Polarized Deuterium: Stabilization in Magnetic Traps

J.M.V.A. KOELMAN, H.T.C. STOOF, B.J. VERHAAR and J.T.M. WALRAVEN*

Department of Physics, Eindhoven University of Technology,
5600 MB Eindhoven, The Netherlands.**

We report on a calculation of the spin-exchange two-body rate constants associated with the population dynamics of the hyperfine levels of atomic deuterium as a function of magnetic field in the Boltzmann zero temperature limit. We find that a gas of low field seeking deuterium atoms trapped in a static magnetic field minimum decays rapidly into an ultra stable gas of doubly spin-polarized deuterium.

INTRODUCTION

Among all fermionic species electron-spin polarized deuterium occupies a unique place. Having low mass and shallow short-ranged interaction potential, it is the most promising candidate for a degenerate nearly ideal Fermi gas. So far, spin-polarized deuterium has attracted relatively little attention of the experimentalists as this gas confined in ℓ-He lined cells was found to be much less stable than hydrogen [1].

In this contribution we show that spin-up polarized deuterium (D$\uparrow$) is especially suited for confinement in magnetic traps similar to those used for confining laser-cooled spin-polarized alkalies [2] and proposed [3] as confinement schemes for spin-up polarized hydrogen (H$\uparrow$). Magnetically trapped deuterium may well prove to be the purest experimental realization of the nearly ideal degenerate Fermi gas in which to a large extent density and temperature can be controlled independently. As such it is a most interesting model system enabling comparison with ab-initio theoretical results of any desired precision. This in contrast to dense, strongly interacting Fermi systems as nuclear matter, liquid ^{3}He and electron gases in metals.

D$\uparrow\ddagger$ SELECTION IN MAGNETIC TRAPS

We discuss the decay of D$\uparrow$, a mixture of the hyperfine states δ, ϵ and ζ (Fig.1), confined in a static minimum-B-field trap. The lifetimes of these trapped low field seekers are limited by inelastic two-body collisions. Considering the low values of the relevant temperatures and Fermi-Dirac statistics only low-energy s-wave scattering between atoms in anti-symmetrical spin states occurs. Using the notation $n_i (i= \delta,\epsilon,\zeta)$ for the densities of the trapped low-field-seekers and assuming the atoms formed in inelastic collision events to escape to a perfect adsorber outside the trapping region the decay of the trapped atoms is described by

$$\begin{aligned} \dot{n}_\delta &= -G_{\delta\zeta} n_\delta n_\zeta - G_{\delta\epsilon} n_\delta n_\epsilon \\ \dot{n}_\epsilon &= -G_{\epsilon\zeta} n_\epsilon n_\zeta - G_{\delta\epsilon} n_\delta n_\epsilon \\ \dot{n}_\zeta &= -G_{\epsilon\zeta} n_\epsilon n_\zeta - G_{\delta\zeta} n_\delta n_\zeta \end{aligned} \qquad (1)$$

with the effective decay rates G_i equal to the sum of all decay rates corresponding to collision processes in which i (= $\delta\epsilon$, $\delta\zeta$, $\epsilon\zeta$) is the initial spin state. A decay according to Eq.(1) yields a stable state in which only one hyperfine state is populated.

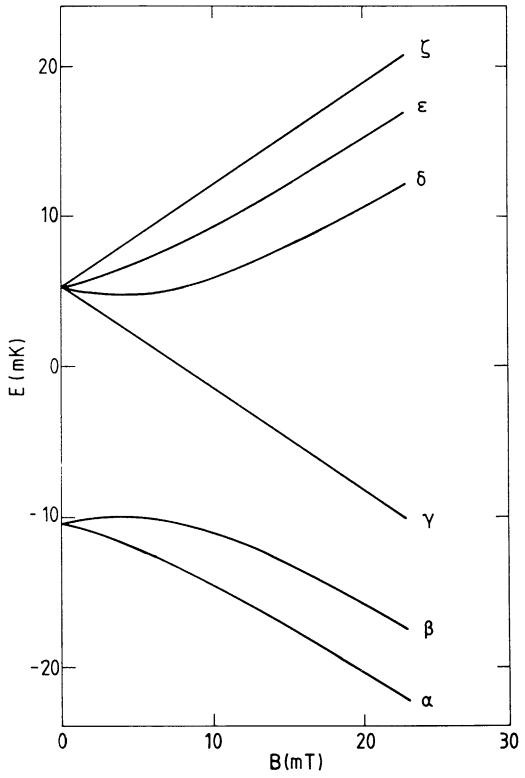

Fig. 1: Energies of the deuterium hyperfine states as a function of magnetic field.

At low magnetic fields ($B \lesssim 0.2$T) spin-exchange collisions dominate. The corresponding spin-exchange rates can be expressed in terms of t-matrix elements. Taking into account the low values of the relevant kinetic energies and the small hyperfine energy levels separations (Fig.1) we calculate these t-matrix elements assuming the initial as well as the final kinetic energies to be zero. In this way the decay rates G_i can be expressed in terms of the scattering lengths a_t

*Natuurkundig Laboratorium, Universiteit van Amsterdam, Valckenierstraat 65,
1018 XE Amsterdam, The Netherlands.
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and a_s for triplet and singlet potential scattering, respectively:

$$G_i = \sum_{f\neq i} G_{fi} = \pi(a_t-a_s)^2 \sum_{f\neq i} v_f \; |\langle f|P_t-P_s|i\rangle|^2 \quad (2)$$

in which $|i\rangle$ and $|f\rangle$ are normalized anti-symmetric two-body spin states, $P_t(P_s)$ is the projection operator on the triplet (singlet) spin state and v_f is the relative velocity of the two colliding atoms in the final spin state.

Using Eq.(2) in the case of spin-exchange relaxation in atomic hydrogen with $a_t=1.34a_0$ and $a_s=0.32a_0$ we reproduce the values of the H+H spin-exchange relaxation rates obtained with a coupled channel calculation [4] within a few percent up to magnetic field strengths of 0.1 Tesla. For atomic deuterium we find $a_t=-6.8a_0$ and $a_s=13.0a_0$ and obtain the values of the spin-exchange decay rates displayed in Fig.2.

As mentioned before a decay described by Eqs.(1) yields a stable state consisting of one single hyperfine component. Which hyperfine state will survive depends on the relative magnitudes of the decay rates G_i as well as on the initial fractional populations. In fact the effective $\delta\epsilon$-rate dominates over both competitive rates yielding a preferential decay of δ- and ϵ-atoms. Hence, equal initial populations of the low field seeking states will lead to a trapped gas of ζ-atoms (doubly spin-polarized deuterium). At fields $20mT\lesssim B\lesssim 100mT$ a fraction of ζ-atoms equal to 12-14% remains trapped. Actually these are worst case results. Taking into account that low field seeking atoms formed in inelastic spin-exchange events may well be trapped, we find much larger surviving fractions.

MAGNETICALLY TRAPPED D↑↑

The trapped ζ-atom gas will be ultra long lived as in the zero temperature limit two body collisions can be ruled out due to the Pauli principle. For low nonzero temperatures the dominant two body relaxation is due to inelastic electronic dipolar collisions with odd initial angular momentum quantum number. Using plane-wave Born expressions [5] we find the corresponding rate to be proportional to the relative collision energy and hence to diminish as $\sim T$ when the temperature is lowered. Notice that this energy dependence favours relaxation of fast atoms leading to a self-cooling contribution associated with relaxation which is absent in the hydrogen case. For density $10^{14}cm^{-3}$ and temperatures approximately equal to the corresponding Fermi temperature $T_f\simeq 39\mu K$ we estimate the lifetime due to dipolar relaxation to be several hours. Under similar conditions the lifetime of H↑↑ is a few seconds [4].

Interestingly enough, though the thermalization rate also vanishes in the low temperature limit we found that the system still achieves thermal equilibrium on a timescale substantially smaller than the dipolar lifetime of D↑↑. In fact, due to elastic dipolar collisions in the limit $T\to 0$ the ratio of the thermalization rate to the relaxation rate increases as $1/\sqrt{T}$. This in contrast to the case of H↑↑ where in the zero-temperature limit this ratio vanishes. This shows the possibility to use an evaporative cooling scheme similar to those described in Ref.3 as an efficient means for cooling the trapped D↑↑ gas down to the degeneracy regime.

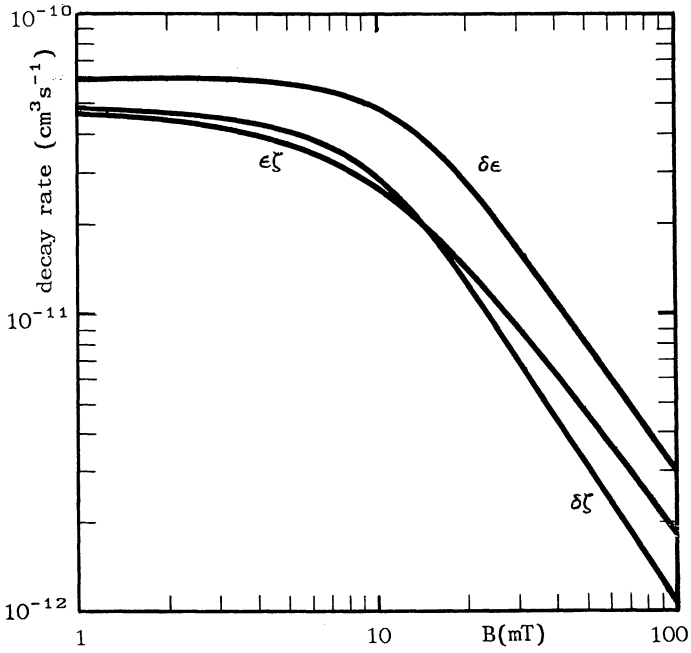

Fig. 2: The effective spin-exchange decay rates $G_i(i=\delta\epsilon,\ \delta\zeta,\ \epsilon\zeta)$ as defined in Eq.(2).

CONCLUSION

We have shown that a gas of low field seeking deuterium atoms trapped in a static magnetic field minimum decays rapidly into a gas of doubly-spin-polarized atomic deuterium whose stability grows with decreasing temperature. Evaporative cooling applied to such a system ultimately leads to an ultra-stable state. D↑↑ is not only likely to be the most stable B-field trappable spin-polarized system (including the alkalies), but may also be cooled well into the degeneracy regime.

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