Longitudinal spin diffusion in a nondegenerate trapped $^{87}$Rb gas

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Longitudinal spin diffusion of two pseudo-spin domains is studied in a trapped $^{87}$Rb sample above quantum degeneracy, and the effect of the degree of coherence in the domain wall on the dynamics of the system is investigated. Coherence in a domain wall leads to transverse-spin-mediated longitudinal spin diffusion that is slower than classical predictions, as well as altering the domains’ oscillation frequency. The system also shows an instability in the longitudinal spin dynamics as the longitudinal and transverse spin components couple, and a conversion of longitudinal spin to transverse spin is observed, resulting in an increase in the total amount of coherence in the system.

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The development of ultracold trapped atomic systems of fermions and bosons has opened up new paths of study for transport phenomena. In particular, theoretical and experimental studies of spin transport have been of recent interest in a number of systems including strongly interacting degenerate Fermi gases near unitary [1,2], dilute noncondensed bosonic gases close to quantum degeneracy [3,4], and ultracold gases in optical lattices [5,6].

In this regime, spin diffusion is not a purely dissipative process but rather a coherent effect dominated by the identical spin rotation effect (ISRE), in which symmetrization of the two-body wave function in binary collisions between identical particles leads to coherent exchange interactions when the thermal de Broglie wavelength is larger than the two-body interaction length [10]. In this regime, spin diffusion is not a purely dissipative process but rather a coherent effect dominated by the ISRE. Examples of such collective behavior include spin waves [4], spin self-rephasing [11], and non-conservation of transverse spin [12].

Diffusion is also strongly modified by quantum effects, leading to, for example, nonlinear and anisotropic spin diffusion [3,13] and universal spin dynamics [1]. Near unitarity, experiments on two spin domains in a strongly interacting Fermi gas showed reversal of spin currents [13], where atoms underwent trap oscillations but the spin domains bounced off each other, resulting in quantum-limited spin diffusion. Also in unitary Fermi gases, further quantum modifications to diffusive timescales were observed [1,2]. In [6], patterned spin textures were used to study diffusion in various geometries, showing diffusive behavior in one dimension (1D), but large departures from classical transport in two dimensions.

In the nondegenerate case of a 1D two-domain spin structure studied here, quantum modifications to diffusion appear as a decrease in the oscillation rate of spin domains in a harmonic potential and an increase in the longitudinal spin diffusion time, through coupling to the transverse spin. This effect shows sensitivity to the degree of coherence present in the domain wall between spin domains, which highlights the quantum mechanical nature of the dynamics more clearly. In this work we demonstrate the alteration of longitudinal spin diffusion timescales depending on the initial amount of the coherence in the domain wall and also report observation of a longitudinal spin instability, which leads to an increase in the total amount of coherence present in the system.

The mechanism for coherent atom-atom scattering is the ISRE, where exchange scattering between indistinguishable particles with different spin orientations leads to precession of each atom’s spin about their combined spin. The theoretical description of spin dynamics in nondegenerate quantum systems was developed using semiclassical kinetic theory [13]. We adopt the notation of [17] and describe the time evolution of the spin density distribution, $\sigma(p,z,t)$, with a 1D quantum Boltzmann equation that includes the ISRE via a spin-torque term:

$$\partial_t \sigma(p,z,t) + \partial_0 \sigma(p,z,t) - \hat{\Omega} \times \sigma(p,z,t) = \frac{\partial \sigma}{\partial t}\big|_{1D},$$  \hspace{1cm} (1)

where $\partial_0 = \frac{p}{m} \partial_z - \frac{\partial U_{\text{int}}}{\partial \hat{s}} \frac{p}{m}$ and $\hat{\Omega} = (U_{\text{int}} \hat{u}_\parallel + g\hat{S})/\hbar$. The mean-field interaction strength for two scattering particles with $s$-wave scattering length $a$ and mass $m$ is $g = \frac{a \hbar^2}{m}$, and $\hat{u}_\parallel$ is the longitudinal unit vector on the Bloch sphere. The experimentally observable qua-
tity is the spin $\vec{S}(z, t) = \int dp \vec{σ}(p, z, t)/2\pi\hbar$. $\vec{S}$ contains the longitudinal spin $S_\parallel$ and the transverse spin $S_\perp$, with magnitude $S_{\perp}$ (i.e. the spin coherence) and phase angle $\phi$. $U_{\text{ext}}$ and $U_{\text{diff}}$ are the trapping potential and differential potential experienced between the two states (due to differential mean-field and Zeeman shifts).

We create a two-domain structure of “up-down” pseudo-spin states in a nondegenerate gas of $^{87}$Rb atoms trapped in an external harmonic potential and observe the relaxation to equilibrium. The trap is axisymmetric, with trapping frequencies of $2\pi \times (6.7, 260, 260)$ Hz. Due to rapid averaging from the high radial frequency, any dynamics can be treated effectively as one-dimensional.

The pseudo-spin doublet here consists of two magnetically trapped hyperfine ground states of $^{87}$Rb ($\vert 1 \rangle \equiv \vert 1, -1 \rangle$ and $\vert 2 \rangle \equiv \vert 2, 1 \rangle$), coupled via a two-photon microwave transition. (See [20, 21] for a detailed description of the apparatus.)

We use optical patterning and microwave pulse techniques to prepare the two spin domains (see Fig. 1a). A magnetically trapped $^{87}$Rb sample is evaporatively cooled to just above quantum degeneracy (temperature $T \sim 650$ nK and peak density $n \sim 2.6 \times 10^{13}$ cm$^{-3}$). Initially in state $\vert 1 \rangle$, atoms are transferred to $\vert 2 \rangle$ by a microwave $\pi$-pulse with Rabi frequency $\Omega_{\text{Rb}} = 3.4$ kHz, except where they are illuminated with an off-resonant, partially masked laser beam that creates an optical step potential on top of the trapping potential. The Bloch sphere representation of the spin doublet is shown for the preparation sequence in Fig. 1(a). This procedure creates domains of spin up and down separated by a helical domain wall in which the spin vector is coherently twisted, while remaining fully polarized.

The longitudinal spin projection is measured by directly measuring the number of atoms in states $\vert 1 \rangle$ and $\vert 2 \rangle$ using absorption imaging, which measures the atomic density distribution. The images of each state are divided into equally spaced axial bins, and the local population difference between the two states is given by $S_{\parallel}(z) = \frac{N_{1}(z)}{N_{2}} - \frac{N_{2}(z)}{N_{1}}$ with $N_{\text{tot}} = \sum_{z} N_{i}(z)$, summed over all axial bins. Ramsey-type experiments are used to measure the transverse spin component, in which a $\pi/2$-pulse rotates the transverse spin component $S_{\perp}$ into longitudinal spin $S_{\parallel}$. We normalize the transverse spin component by the magnitude of a fully coherent sample, $c(z, t) \equiv S_{\perp}(z, t)/S_{\perp}^{\text{max}}$, and the total coherence in the sample is $c_{\text{tot}}(t) \equiv \int c(z, t) dz$.

Figure 2 shows the typical time evolution of the two-domain spin structure. The longitudinal spin component $S_{\parallel}$ exhibits oscillations of the spin domains as well as diffusion of the longitudinal spin gradient, which damps the oscillations. These measurements reveal that the longitudinal domains persist for much longer than expected for classical longitudinal diffusion times $\sim 25$ ms for similar conditions [17] and oscillate much slower than trapping oscillations (Fig. 2b). The presence of a coherent domain wall has a stabilizing effect, which agrees with theoretical predictions and previous experiments in spin-polarized gases [12, 22–24]. We study this effect in more detail by controllably tuning the amount of initial coherence in the domain wall.

The more striking results are observed in the time evolution of the transverse spin component. Fig. 2c) shows the spatiotemporal evolution of the amplitude of the transverse spin (coherence) extracted from Ramsey spectroscopy measurements (Fig. 2d-e)). There is a rapid rise in Ramsey fringe contrast within the longitudinal spin domains, where the initial fringe amplitude is small (Fig. 2c)), which shows the spread of coherence toward the edges of the atomic cloud.

Spreading of the coherence could result from diffusion of the transverse spin, but the total transverse spin mag-
nitude in the gas increases (Fig. 1(d)). This increase implies the appearance of coherence near the edges of the cloud is not due to spin diffusion, but rather is due to conversion of longitudinal spin into transverse spin as a result of an instability in the longitudinal spin current. This effect has been observed in spin-polarized gas systems \cite{22,23} and was described as an experimental manifestation of the Castaing instability \cite{12}. Although the trapped atomic system possesses different experimental parameters than spin-polarized gases, the physics governing the phenomenon is similar \cite{25-27}. As discussed in \cite{25}, if the transverse spin is confined in the domain wall region, it dephases and the gradient in $S_{||}$ decays via ordinary longitudinal diffusion, since the kinetic equation decouples for longitudinal and transverse spin components \cite{28}. However, if the ISRE is large enough (i.e. large Leggett-Rice parameter), the longitudinal spin current becomes unstable, a coupling between longitudinal and transverse spin dynamics occurs, and the $S_{||}$ gradient decays via transverse diffusion across the coherent domain wall. Thus transverse-spin-mediation of longitudinal diffusion increases the timescale for longitudinal diffusion to be comparable with slower transverse diffusion times, which are are slower due to coherent spin interactions that are absent from longitudinal spin dynamics.

To study the effect of initial coherence in the domain wall on dynamics of the two-domain structure, we initialize domain walls with different $S_{||}$ and observe their evolution toward equilibrium. Coherence is controlled via the same off-resonant laser used to prepare the spin domains. A short light pulse creates a nonuniform differential atomic potential, whose inhomogeneity induces rapid dephasing of the transverse spin component in the domain wall. The degree of coherence is controlled by the pulse length (up to 0.6 ms), and we characterize the initial coherence in the domain wall via Ramsey spectroscopy. This forced dephasing procedure can reduce the initial coherence by over 70%. The coherence is normalized to the maximum coherence, $S_{||}^{\text{max}}$, measured by transferring the entire ensemble into a fully polarized superposition of the two states with a $\pi/2$-pulse in the absence of any inhomogeneities.

Figure 3(a) shows the longitudinal time evolution for different initial degrees of coherence. This data suggests that both the frequency of the longitudinal spin domain oscillation as well as the longitudinal spin diffusion rate decrease as the coherence is increased in the domain wall. The dynamics for a two-domain structure is dominated by the dipole mode, which we isolate via the dipole moment of the spin distribution, $\langle zS_{||}(z,t)\rangle$, where $\langle \cdot \rangle_n$ denotes a density-weighted average to compensate for low signal-to-noise ratio at the edges of the distribution. Figure 3(b) shows the evolution of spin-dipole moments for the three coherences shown in Fig. 3(a). The frequency $f$ and damping rate $\Gamma$ of the longitudinal oscillations are then extracted from these moments.

We repeat the experiment for different initial amounts of coherence, $c_{\text{init}}$; calculate the time-dependent dipole moment; and extract $f$ and $\Gamma$ from decaying sinusoidal fits to these oscillations. The results are summarized in Fig. 3(c) and (d). Both $\Gamma$ and $f$ decrease as $c_{\text{init}}$ increases, showing the stabilizing effect of a coherent domain wall. The oscillation frequency is primarily controlled by two competing factors: oscillation in the trapping potential and mean-field-induced spin rotation. In the incoherent limit, the oscillation frequency approaches the trapping frequency, as the system approaches a mixture of two distinguishable classical ideal gases that diffuse according to classic Boltzmann theory. The large $c_{\text{init}}$ limit entrains longitudinal diffusion with slower transverse diffusion.

We compare these measurements with transport theory by numerically simulating Eqn. 11 (see \cite{21} for details). The shaded regions in Fig. 3(c) and (d) represent one-sigma confidence bands from Monte Carlo simulations of Eqn. 11 including statistical fluctuations in density, temperature, and domain wall size, as well as a systematic density calibration uncertainty. The data agrees well with theoretical predictions. Discrepancies in $f$ at low co-
and normalizing by the number of axial bins. For all the coherence across the cloud for each time step from top to bottom $c_{\text{init}} = S_z \big/ S_{\text{max}}$, with a representative decaying sinusoidal fit to (iii) $c_{\text{init}} = 0.28$. (c) Damping rate and (d) oscillation frequency of the dipole moment for different initial coherences. Error bars correspond to fitting uncertainties for dipole moment oscillations and initial coherence measurements, and the shaded band is the result of numerical simulations of Eqn. 1 (see text).

Figure 4(a) shows the total coherence $S_z$ for different initial coherences in the domain wall, from top to bottom $c_{\text{init}} = 0.71, 0.51, 0.30$ respectively in the cloud center. (b) Time evolution of the coherence in different spatial regions, denoted by $z = (0, 0.3, 0.6) \times w_{\text{axial}}$ [dotted lines in (i)]. The dashed box indicates a change in sampling rate to measure both the fast initial rise of coherence and longer relaxation to equilibrium. (c) Time evolution of total ensemble coherence for initial coherences shown in (a).

Coherence is likely due to challenges in fitting oscillations in a critically damped regime where the quality factor drops. Overdamping should occur for $c_{\text{init}} < 0.2$, but it is experimentally challenging to reduce the coherence to this level without altering the longitudinal spin domains. The effect of the spin instability can be seen more clearly in the transverse spin dynamics (Fig. 4). The time evolution of $S_z(z,t)$ for two-domain structures with different initial amounts of coherence in the domain wall is shown in Fig. 4(a). The rise and spread of coherence for different $c_{\text{init}}$ shows similar spatial behavior, but the transverse spin persists longer when there is more coherence in the domain wall initially. Figure 4(b) shows the evolution of coherence in different regions of the cloud for the high $c_{\text{init}}$ preparation (Fig. 4(b)(i)).

Figure 4(c) shows the total coherence of the ensemble, $C_{\text{tot}}(t)$, for different $c_{\text{init}}$, which is calculated by summing the coherence across the cloud for each time step and normalizing by the number of axial bins. For all initializations there is an initial rapid rise of the coherence followed by a gradual decrease, but with different timescales for different $c_{\text{init}}$. The maximum amount of total coherence created across the cloud depends on the initial amount of coherence in the system, and the time to reach maximum coherence also increases as $c_{\text{init}}$ increases. These results highlight the transverse source of enhanced lifetimes of longitudinal spin domains with coherent domain walls. The presence of coherence in the spin domain wall links diffusion timescales and increases longitudinal diffusion times to be as long as transverse diffusion times.

In conclusion, our results reveal the stabilizing effect of coherence in a domain wall, leading to an increase in longitudinal domain lifetimes. These effects are explained by coupling between longitudinal and transverse spin dynamics, which induces transverse-channel-mediated longitudinal spin diffusion. While not a direct measure of anisotropic diffusion, alteration of diffusive timescales by adjusting only the longitudinal-transverse spin coupling (via the coherence) is strongly suggestive of anisotropic diffusion. There also is an accompanying rise in the total amount of coherence, which indicates a conversion of longitudinal spin into transverse spin as a result of an instability in the longitudinal spin dynamics. Longer longitudinal domain lifetimes result from more coherence in the domain walls, and suppression of this instability leads to even longer longitudinal diffusion times. Our ex-
Experimental results show good agreement with numerical simulations of the quantum Boltzmann equation and emphasize the importance of quantum effects in spin transport in trapped ultracold bosonic systems, even above quantum degeneracy.

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