Localization of spin mixing dynamics in a spin-1 Bose-Einstein condensate

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We propose to localize spin mixing dynamics in a spin-1 Bose-Einstein condensate by a temporal modulation of spin exchange interaction, which is tunable with optical Feshbach resonance. Adopting techniques from coherent control, we demonstrate the localization/freezing of spin mixing dynamics, and the suppression of the intrinsic dynamic instability and spontaneous spin domain formation in a ferromagnetically interacting condensate of ^{87}Rb atoms. This work points to a promising scheme for investigating the weak magnetic spin dipole interaction, which is usually masked by the more dominant spin exchange interaction.

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Dynamic localization is ubiquitous in nonlinear systems, both for classical dynamics as in an inverted pendulum with a rapidly modulating pivot [1] or an ion in a Paul trap [2], and for quantum dynamics like a one- or two-dimensional soliton in a Bose-Einstein condensate (BEC) when the attractive interaction strength is rapidly modulated [3–6]. It is often used to stabilize a dynamically unstable system.

Spin mixing dynamics of a spin-1 atomic condensate are dynamically unstable [7] when the spin exchange interaction is ferromagnetic, *i.e.*, favoring a ground state with all atomic spins aligned. When confined spatially, the unstable dynamics is known to cause formation of spin domain structures [8, 9]. For many applications of spinor condensates, from quantum simulation to precision measurement [10], it is desirable that spin domain formation is suppressed. In addition, atomic spin dipolar interactions, although weak when compared to typical spin exchange interactions, induce intricate spin textures that are difficult to probe when masked by spin domain structures. Thus the suppressing/freezing of the undesirable dynamics from spin exchange interaction is also important for investigating the effect of dipolar interaction [11, 12].

Compared to conventional magnets in solid states, a spin-1 BEC has one unsurpassed advantage: its spin exchange interaction between individual atoms can be precisely tuned through optical (as well as magnetic) Feshbach resonances [13–19]. By adjusting the two s-wave scattering lengths a_0 and a_2 of two colliding spin-1 atoms via optical means, the spin exchange interaction strength, characterized by $c_2 = 4\pi\hbar^2(a_2-a_0)/3M$ with M the mass of the atom, is tunable. Analogous to an inverted rigid pendulum with a rapidly oscillating pivot, a fast temporal modulation of the spin exchange interaction can localize the spin mixing dynamics, equivalent to a suppressing/nulling of the spin exchange interaction.

This study is devoted to a theoretical investigation of spin dynamics in a spin-1 BEC under the temporal modulation of the spin exchange interaction. As an application, we illustrate the suppression of the dynamic instability and the resulting prevention of spin domain formation in a condensate with ferromagnetic interaction. The proposed scheme to control the spin exchange interaction will potentially provide a substantial improvement to the accuracy of several envisaged magnetometer setups and to enable cleaner detections of dipolar effects.

For both spin-1 atoms ^{87}Rb and ^{23}Na, popular experimental choices, their spin-independent interaction strength, characterized by $c_0 = 4\pi\hbar^2(2a_2 + a_0)/3M$, is two to three orders of magnitude larger than $|c_2|$ [20–22]. This ensures the validity of single spatial mode approximation (SMA) [23–27] when the number of atoms is small and the magnetic field is low. The spin degrees of freedom and the spatial degrees of freedom become separated within the SMA. This allows one focus on the most interesting spin dynamics free from density dependent interactions.

Within the mean field framework, the spin dynamics of a spin-1 condensate under the SMA is described by [28]

$$\begin{aligned} \dot{\rho}_0 &= \frac{2c}{\hbar}\rho_0\sqrt{(1-\rho_0)^2-m^2}\sin\theta, \qquad (1)\\ \dot{\theta} &= \frac{2c}{\hbar}\left[(1-2\rho_0)+\frac{(1-\rho_0)(1-2\rho_0)-m^2}{\sqrt{(1-\rho_0)^2-m^2}}\cos\theta\right], \end{aligned}$$

where ρ_i $(i=+,0,-)$ is the fractional population of component $|i\rangle$, $(\sum_i \rho_i = 1)$, $m = \rho_+ - \rho_-$ is the magnetization in a spin-1 Bose condensate, a conserved quantity. θ is the relative phase [28]. $\phi(\vec{r})$ is a unit normalized spatial mode function under the SMA determined from a scalar Gross-Pitaevskii equation with an s-wave scattering length of a_2. As before, the effective spin exchange interaction is given by $c(t) = c_2(t)N\int d\vec{r}|\phi(\vec{r})|^4$, albeit the time dependence, with N the total number of trapped atoms. Although the system dynamics (1) does not con-