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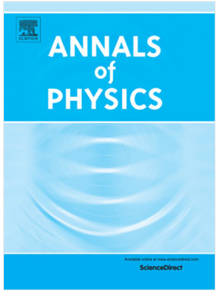

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Polar-core spin vortex of quasi-2D ferromagnetic spin-1 condensate in a flat-bottomed optical trap with a weak magnetic field

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Motivated by the recent experiments realized in a flat-bottomed optical trap [Science 347, 167 (2015); Nat. Commun. 6, 6162 (2015)], we study the ground state of polar-core spin vortex of quasi-2D ferromagnetic spin-1 condensate in a finite-size homogeneous trap with a weak magnetic field. The exact spatial distribution of local spin is obtained with a variational method. Unlike the fully-magnetized planar spin texture with a zero-spin core, which was schematically demonstrated in previous studies for the ideal polar-core spin vortex in a homogeneous trap with infinitely large boundary, some plateaus and two-cores structure emerge in the distribution curves of spin magnitude in the polar-core spin vortex we obtained for the larger effective spin-dependent interaction. More importantly, the spin values of the plateaus are not 1 as expected in the fully-magnetized spin texture, except for the sufficiently large spin-dependent interaction and the weak-magnetic-field limit. We attribute the decrease of spin value to the effect of finite size of the system. The spin values of the plateaus can be controlled by the quadratic Zeeman energy q of the weak magnetic field, which decreases with the increase of q.

I. INTRODUCTION

Recently, a flat-bottomed optical trap was realized to study the dynamics of quasi-two-dimensional (quasi-2D) scalar Bose-Einstein condensates [1, 2]. For the condensed atoms trapped in the bottom, the trap is homogeneous and the condensate have an uniform number density. Comparing with the harmonic trap in the most earlier experiments, the homogeneous trap provides a more suitable tool for studying the magnetic properties of spinor condensates [3–10]. The reason is that the spin-independent (i.e., density-density) interaction of the most spinor condensates is much larger than the spin-dependent (i.e., spin-spin) interaction [6–8], thus for spinor condensates in a homogeneous trap, the spin-independent interaction would enhance the uniform number density and the spin configuration of spinor condensates will be determined by the spin-dependent interaction.

A scalar condensate can host only one type of vortex, that is, a U(1) vortex or a gauge vortex. There are no atoms in the core of vortex [11]. However, a spinor condensate can host a much richer variety of vortices. Atoms are allowed to stay in the core of spin vortices [12, 13], which is because there are more than one hyperfine components in spinor condensates and one or more components may occupy the vortex core of the other components to reduce the density-density interaction energy [7, 8].

Polar-core vortex [14–17] of ferromagnetic spin-1 condensate is just such a spin vortex, whose core is filled by the $m_F = 0$ atoms. There is a mass flow of $m_F = 1$ component around the vortex and an equal but opposite flow of $m_F = -1$ component around the vortex. This gives rise to a net spin flow, but no net mass flow. The polar-core vortex was first observed by Berkeley group in the quenching experiment of ferromagnetic spin-1 ^{87}Rb condensate from an initial polar state [15]. Much attention has been focused on the quenching dynamics and the short and long time dynamical behaviors have been studied extensively [7, 8, 18–23].

Despite the relevance of polar-core vortex to a wide variety of interesting physical processes, a comprehensive study of their ground-state properties is lacking. In most of previous studies, the polar-core spin vortex is schematically demonstrated as a fully-magnetized spin texture in $x - y$ plane with a zero-local-spin core at the center of condensate [7, 8, 22]. This demonstration is suitable for the ideal polar-core vortex in a homogeneous trap with infinitely large boundary.

In this paper, we study the ground-state properties of polar-core spin vortex in a quasi-2D ferromagnetic spin-1 condensate trapped in a finite-size flat-bottomed optical trap with a weak homogeneous magnetic field. We pay special attention to the effect of finite size of the system. The exact spatial distribution of local spin is obtained with a variational method. Some plateaus and two-cores structure are observed in the distribution curves of spin magnitude for the larger effective spin-dependent interaction, which is proportional to both the bare spin-dependent interaction and the radius of the homogeneous trap. The spin magnitudes of the plateaus are not 1 as expected in the fully-magnetized spin texture, except for the sufficiently large spin-dependent interaction and the weak-magnetic-field limit. The spin magnitude of the plateaus can be controlled by the quadratic Zeeman energy of the weak homogeneous magnetic field, which decreases with the growth of the quadratic Zeeman energy.

The polar-core spin vortex in a finite-size flat-bottomed optical trap we considered in this paper shares the same features with that in a harmonic trap [24–27], such as the core size is proportional to the spin healing length, and the ferromagnetic order parameter is singular at the vortex core [26]. Some different properties arise