２６日ポスター４２番

ネマチックスピン状態にある ボース・アインシュタイン凝縮体における 非軸対称な量子渦

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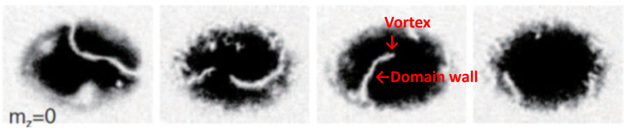
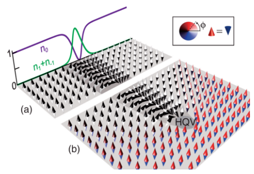
Hiromitsu Takeuchi, *An elliptic vortex in a nematic-spin Bose-Einstein condensate*, in preparation (2020)

Motivation

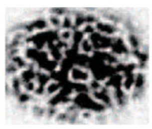
Quanched phase transition in a spin-1 Bose-Einstein condensate (BEC) of 23Na atoms (Seoul National Univ.)

Seji Kang, Sang Won Seo, HT, and Y. Shin PRL **122**, 095301 (2019)





A wall-vortex composite (schematic)



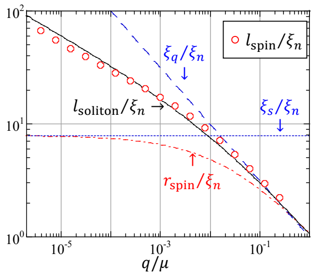
A non-equilibrium state

Vortex-wall *Plasma*

Analogue of QGP?

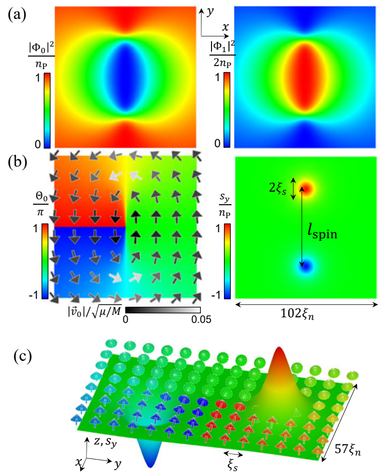
Analogue of quark confinement in binary BECs
D. T. Son and M. A. Stephanov, PRA **65**, 063621 (2002)

Numerical Result



Length scales

$$\xi_n = \frac{\hbar}{\sqrt{M\mu}}, \quad \xi_s = \frac{\hbar}{\sqrt{Mc_2 n}}, \quad \xi_q = \frac{\hbar}{\sqrt{Mq}}$$



Formulation

Energy functional of condensate wave function $\Phi_m\ (m=0,\pm1)$

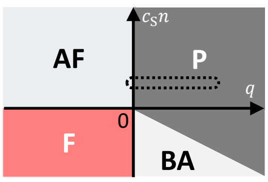
$$G(\boldsymbol{\Phi}) = \int d^3x \mathcal{G}$$

$$\mathcal{G} = \frac{\hbar^2}{2M}\sum_m |\nabla\Phi_m|^2 + \mathcal{U} \qquad \mathcal{U} = \frac{c_0}{2}n^2 + \frac{c_2}{2}\boldsymbol{s}^2 - (\mu-q)n - q|\Phi_z|^2 - ps_z$$

Particle density: $n = \sum_m |\Phi_m|^2 = \boldsymbol{\Phi}^* \cdot \boldsymbol{\Phi}$

Spin density: $\boldsymbol{s} = [s_x, s_y, s_z]^{\rm T} = i\boldsymbol{\Phi}\times\boldsymbol{\Phi}^*$

In the Cartesian coordinate $\boldsymbol{\Phi} = [\Phi_x,\Phi_y,\Phi_z]^{\rm T} = \left[\frac{-1}{\sqrt{2}}(\Phi_{+1}-\Phi_{-1}), \frac{-i}{\sqrt{2}}(\Phi_{+1}+\Phi_{-1}), \Phi_0\right]^{\rm T}$



図：スピノールBECの相図(bulk). 横軸qが2次ゼーマン効果，縦軸$c_S n$がスピン相互作用を表すパラメータ．点線の囲いはソウル国立大の実験の研究領域．

Normal (N) state ($\mu = 0$)	$\boldsymbol{\Phi} = \boldsymbol{0}, \boldsymbol{s} = s_z\hat{\boldsymbol{z}} + s_\perp\hat{\boldsymbol{r}}_\perp = 0$
Broken-axisymmetry (BA) state	$\Phi_x\Phi_y\Phi_z \neq 0, \boldsymbol{s} = s_\perp\hat{\boldsymbol{r}}_\perp$
Anti-ferromagnetic (AF) state	$\boldsymbol{\Phi} = \sqrt{n}e^{i\theta_G}\hat{\boldsymbol{r}}_\perp, \boldsymbol{s} = 0$

Nematic-spin order

The experiment @Soul $\frac{c_2}{c_0} = 0.0016$

Effective order parameter $\boldsymbol{\Phi} = \sqrt{n}e^{i\theta_G}\hat{\boldsymbol{d}}$

Pseudo-*director*: $\hat{\boldsymbol{d}} = [d_x, d_y, d_z]^{\rm T}$

Invariance under the operation:

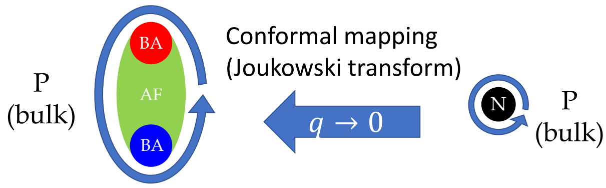
$$(\hat{\boldsymbol{d}}, \theta_G) \to (-\hat{\boldsymbol{d}}, \theta_G + \pi)$$

An elliptic vortex is realized in **P phase** $(c_0 \geq 0, \mu \geq q \geq 0, p = 0)$

$n = n_P$ and $\hat{\boldsymbol{d}} = \pm\hat{\boldsymbol{z}}$　$\Phi_0 = \sqrt{n}e^{i\Theta_0}, \Phi_{\pm1} = 0$

$$n_P = \frac{\mu}{c_0}$$

Schematic of a wall-vortex composite



Energy of an elliptic vortex

$$E_{\rm vortex} \approx U_{\rm core}(l_{\rm spin}) + U_{\rm hyd}(l_{\rm spin})$$

$U_{\rm core}(l_{\rm spin}) \sim \alpha_{\rm AF} l\left(1 + C_{\rm AF}\frac{l}{r_{\rm spin}}\right)$ → Effective elasticity of the wall

$U_{\rm hyd}(l_{\rm spin}) \sim \ln\frac{R}{l_{\rm spin}}$ → Hydrodynamic potential of an elliptic vortex

Summary

- ✓A vortex spontaneously breaks its axisymmetry leading to an elliptic vortex in antiferromagnetic spin-1 Bose-Einstein condensates of ^{23}Na atoms with small positive quadratic Zeeman effect.
- ✓The elliptic vortex has a planar singularity, considered the Joukowski transform of a conventional quantized vortex.
- ✓This structure is sustained by balancing the hydrodynamic potential and the elasticity of a soliton connecting two magnetized spots, which is experimentally observable by the in situ magnetization imaging.