The Vortex Structure of a Neutron Star with CFL core

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Contents

Introduction

- It is widely accepted with high level of confiden-ce that inside a different phases of neutron star superfluid neutron vortex lattices exists.
- Due to their presence, rotational dynamics of NS can be explained` glitches, post-glitch relaxation, quasi-sinusoidal oscillations of angular velocity.
- In the dense core of NS there is a possibility of quark matter to exist in the 2 possible phases` 2SC and CFL

Introduction

- CFL phase was the stable in temperatures near the critical in the limit of weak interaction
- Quarks are forming condensate of Cooper pairs (diquarks) with J=0.
- In the work of *K. Iida, G. Baym, Phys. Rev., D66 , 014015, 2002* and *M. M. Forbes, A. R. Zhitnitsky, Phys. Rev., D65, 085009, 2002* one consider superfluid quark vortices due to violation of global $U(1)_B$ symmetry.

Introduction

- *A. P. Balachandran, S. Digal, T. Matsuura, Phys. Rev., D73, 074009, 2006* where find new semi-superfluid vortex filaments M_1 and M_2 with properties of both` superfluid and magnetic vortices.
- It was shown that two s-s vortices will repel each other *E.Nakano, M.Nitta, T.Matsuura, hep-ph/ 0708.4096, 2007.*

Introduction

- Kinetic energy of superfluid *U(1)*$_B$ vortex (line tension)

$$E_q = \rho \frac{\kappa_{\mathbf{B}}^2}{4\pi} \ln \frac{b}{\xi}$$

$\kappa_{\mathbf{B}} = 3\pi\hbar / m_B -$ is a quantum of circulation, *b*- outer radius of vortex.

Introduction

- Asymptotic expression of line tension of s-s vortex M_1

$$E_{1S} = \rho \frac{\kappa_1^2}{4\pi} \ln \frac{b}{\xi}$$

$\kappa_1^2 = \pi\hbar / m_b, \xi -$ correlation length of diquark pair

- for M_2

$$E_{2S} = \rho \frac{\kappa_1^2}{\pi} \ln \frac{b}{\xi}$$

- for canonical

$$E_M = \left(\frac{\Phi_0}{4\pi\lambda} \right)^2 \ln \frac{b}{\xi}$$

G-L equations

- for s-s vortices M_1

$$\lambda_q^2 \mathrm{rotrot}\vec{A} + \vec{A}\sin^2\alpha = \frac{\Phi_x \sin\alpha \nabla \vartheta}{2\pi} - \vec{A}^8 \sin\alpha \cos\alpha$$

$$\lambda_q^2 \mathrm{rotrot}\vec{A}^8 + \vec{A}^8 \cos^2\alpha = \frac{\Phi_x \cos\alpha \nabla \vartheta}{2\pi} - \vec{A}\sin\alpha \cos\alpha$$

where $\vec{A}$ and $\vec{A}^8$ are the vector potentials of magnetic and gluomagnetic fields, $\Phi_x = 2\pi\hbar c/q_x$

G-L equations

- after integrating by the contour that are passed by the boundary of quark core full flux of will be M_1

$$\Phi_M = 2\pi\hbar c / e = 2\Phi_0$$

where $\Phi_0 = 2 \cdot 10^{-7}\, gauss \cdot cm^2$ is a magnetic flux quantum.

- So, M_1 quantum is a twice as large as that of elementary one.

G-L equations

- for M_2`

$$\lambda_q^2 \mathrm{rotrot}\vec{A} + \vec{A}\sin^2\alpha = \frac{2\Phi_x \sin\alpha \nabla\vartheta}{2\pi} - \vec{A}^8 \sin\alpha\cos\alpha$$

$$\lambda_q^2 \mathrm{rotrot}\vec{A} + \vec{A}\sin^2\alpha = \frac{2\Phi_x \sin\alpha \nabla\vartheta}{2\pi} - \vec{A}^8 \sin\alpha\cos\alpha$$

and flux $4\Phi_0$

Vortices in the quark core

- Critical angular velocity for $U(1)_B$

$$\omega_{c1}^{B} = \frac{3\hbar}{2m_B R_q^2} \ln \frac{R_q}{\xi}$$

- for M_1

$$\omega'_{c1} = \frac{\hbar}{2m_B R_q^2} \ln \frac{R_q}{\xi}$$

- and M_2

$$\omega''_{c1} = \frac{\hbar}{m_B R_q^2} \ln \frac{R_q}{\xi}$$

Vortices in the quark core

- In hadronic phase neutron vortices start to appear when

$$\omega > \omega_{c1}^{n} = (\hbar / 2m_B R_n^2 \ln(R_n / \xi_n)$$

- For hadronic core with $R_n = 5 \cdot 10^5 cm$ and neutron coherence length $\xi_n = 3.1 \cdot 10^{-12} cm$`

$$\omega_{c1}^{n} = 5 \cdot 10^{-14} \sec^{-1}$$

Vortices in the quark core

- For s-s vortices $R_q = 10^5 cm$ so

$$\omega'_{c1} = 1.3 \cdot 10^{-12}$$

- Density of M_1-s is equal $n_\nu = 10^3 \omega.$

Vortices in the quark core

- In transition region each neutron vortex is joining with M_1 s-s vortex in the core because their quanta of circulation and their number densities are equal.
- Meanwhile chemical potential will be continuous at the border

Proton vortices in the hadronic phase

- Due to entrainment current density will be

$$\vec{j} = \frac{e}{m_1}\left(\rho_{11}\vec{v}_1 + \rho_{12}\vec{v}_2\right)$$

- Maxwell equation

$$rot\vec{H} = \frac{4\pi}{c}\frac{e}{m_1}\rho_{12}\vec{v}_2$$

- Presence of unentrained superfluid protons ensures:

$$rot\vec{B} = \frac{4\pi}{c}\frac{e}{m_1}\left(\rho_{11}\vec{v}_1 + \rho_{12}\vec{v}_2\right)$$

Proton vortices in the hadronic phase

- Near neutron vortex

$$H(r) = \frac{\Phi_1}{2\pi\lambda^2} \ln \frac{b}{r}$$

where

$$\Phi_1 = \frac{m_1 \rho_{12}}{m_2 \rho_{11}} \Phi_0 = \frac{m_1}{m_2} k \Phi_0$$

- Proton vortices arise within a circle of radius δ_n where $H(r) = H_{c1}$

$$H_{c1} = \frac{\Phi_0}{4\pi\lambda^2} \ln \frac{\lambda}{\xi_1} \qquad \delta_n = b\left(\frac{\lambda}{\xi_1}\right)^{\frac{1}{3|k|}} = 10^{-5}\,cm$$

Proton vortices in the hadronic phase

- Mean induction

$$B = \frac{k\Phi_0}{4\pi\lambda^2}\left(\frac{\lambda}{\xi_1}\right)^{-\frac{2}{3k}}$$

see. D.M Sedrakyan, K.M. Shahabsyan, Sov. Phys. Usp. 34(7), 1991.

- Due to conservation of magnetic flux proton vortex clusters create around initial s-s vortex M_1 new s-s vortices with radius $\lambda = 10^{-11} cm$.
- Two proton vortices with flux Φ_0 coalesce at the border with one M_1 .

Conclusions

- The Ginzburg Landau equations for semi-superfluid vortices in the CFL phase quark core were derived
- Asymptotic energy values and critical angular velocities for s-s. vortices are calculated
- It was shown that inside the rotating star core, lattice of s-s. vortices appears with smallest magnetic flux quantum
- While hadronic phase consist of stable lattice of neutron vortices.

Conclusions

- Magnetic field generated in hadronic phase penetrates into quark core through newly created s-s M_1 vortices.