Effects of Magnetic Field and Rotation on $^3P_2$ Superfluidity in Neutron Stars

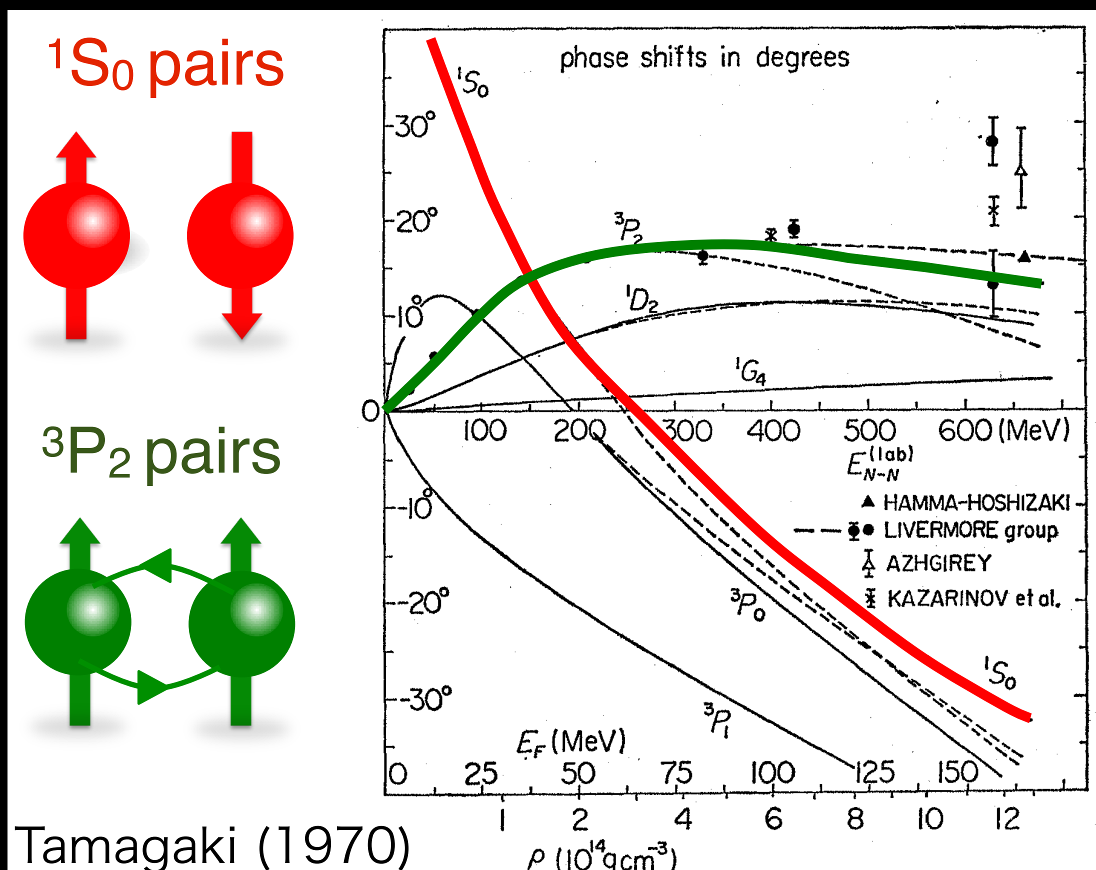
Kota Masuda (U. Tokyo / RIKEN)
with Muneto Nitta (Keio Univ.)

熱場の量子論とその応用, 3rd Sep., 2014

$^3P_2$ Superfluidity in Neutron Stars

Nuclear physics

$\rho_0 < \rho$: $^3P_2$ペアに強い引力

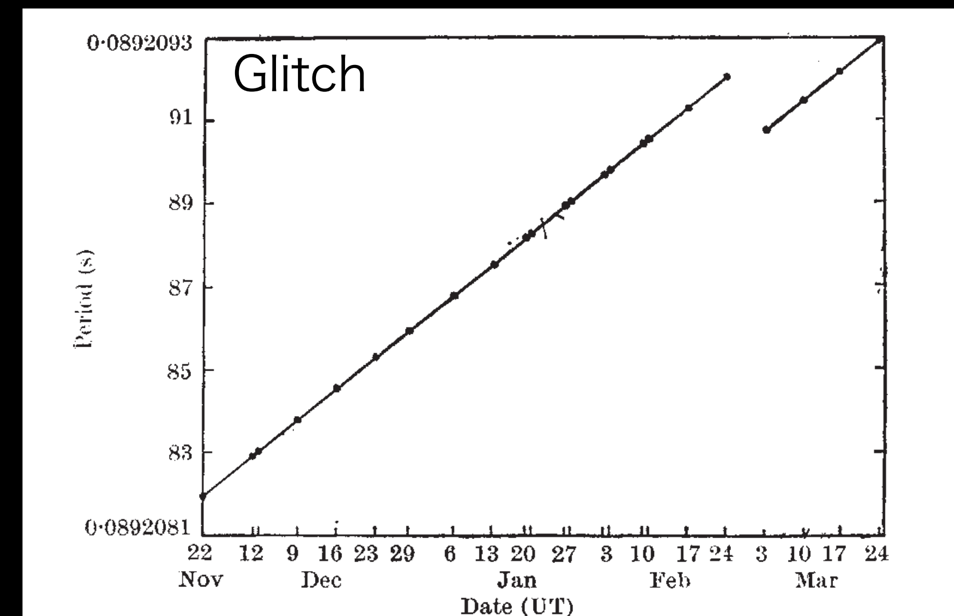


Tamagaki (1970)

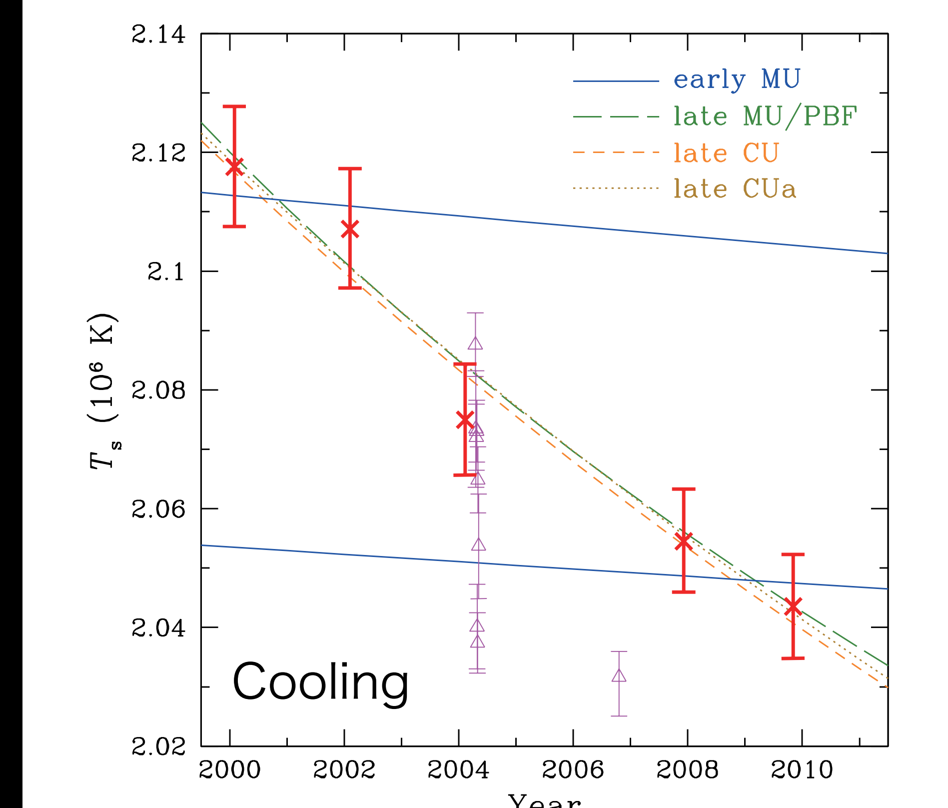
Key Questions

- NS内で$^3P_2$の基底状態は？
- 観測量への影響は？

Astrophysics (NS)



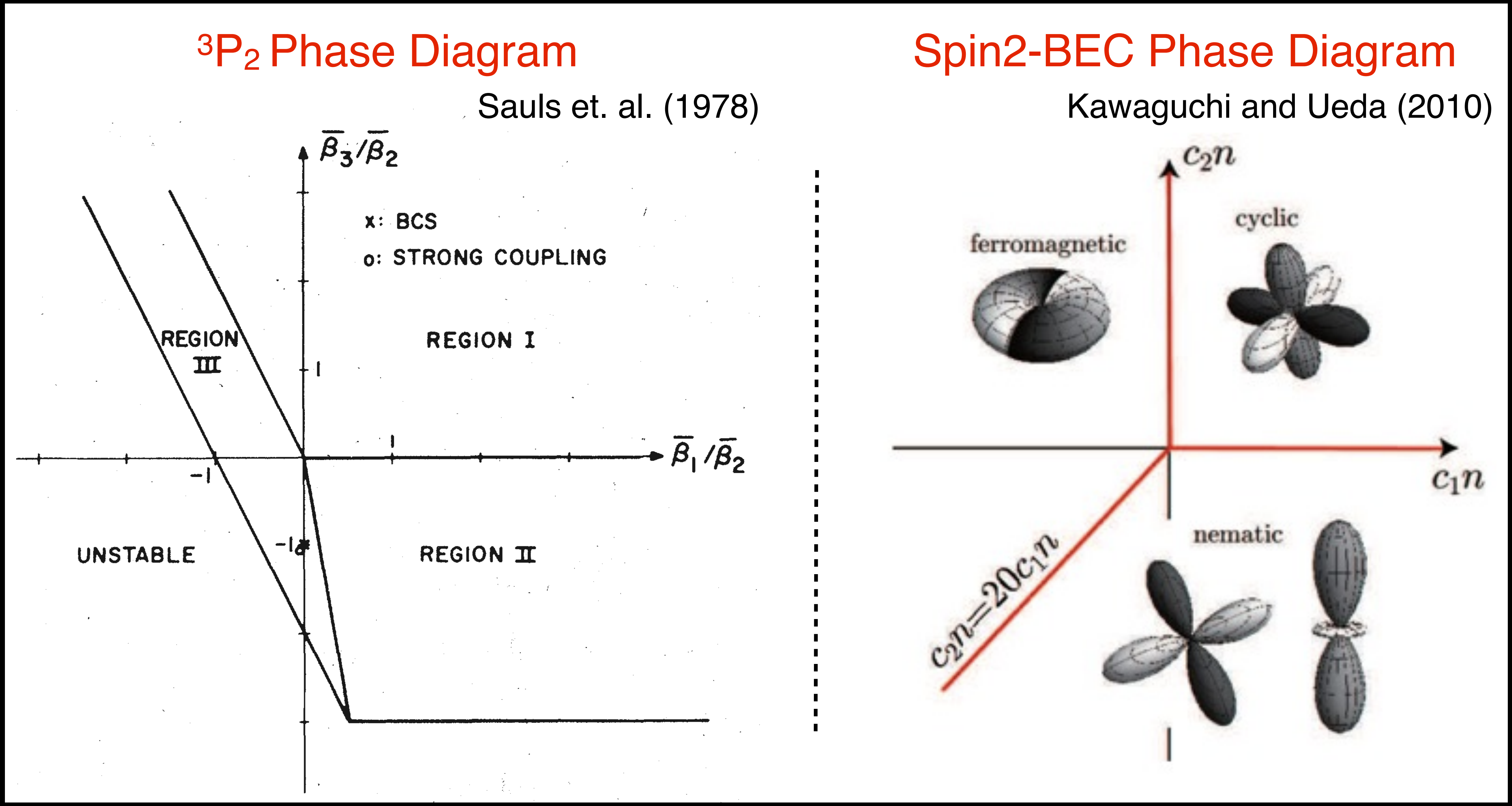
Reichley et.al. (1969)



Heinke et.al. (2010)

Method

Ginzburg-Landau Free Energy Density (4次):



4次の範囲で基底状態は縮退している

$^3P_2$ 運動項、磁場、回転 ⟶ どの状態が選ばれる？

Main Results

Phase	$\tilde{M}$	G/H	6th
Uniaxial	$[U(1) \times S^4]/\mathbb{Z}_2$	$U(1) \times S^2/\mathbb{Z}_2$	✔

Main Results

Phase	$\tilde{M}$	G/H	6th	B-field	gradient	$^3P_2$
Uniaxial	$[U(1) \times S^4]/\mathbb{Z}_2$	$U(1) \times S^2/\mathbb{Z}_2$	✔		✔	
Dihedral-2		$U(1) \times SO(3)/D_2$		✔		✔
Biaxial		$[U(1) \times SO(3)]/D_4$		✔		

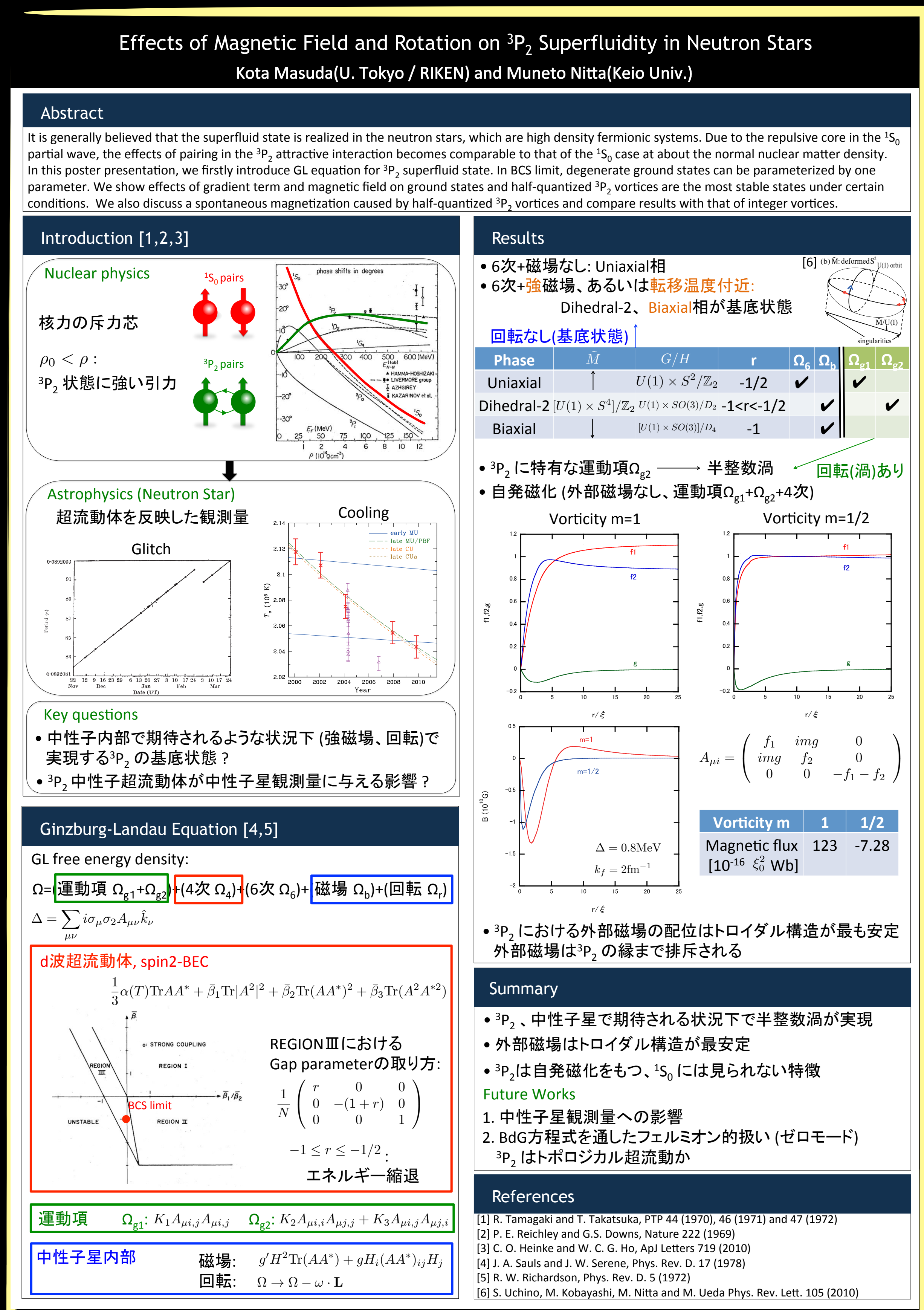
Dihedral-2, Biaxal相で非自明なトポロジカル欠陥

↓

強磁場、転移温度付近、$^3P_2$ 運動項

⟶ 半整数量子渦の実現

トロイダル磁場の安定化



Effects of Magnetic Field and Rotation on $^3P_2$ Superfluidity in Neutron Stars

Kota Masuda(U. Tokyo / RIKEN) and Muneto Nitta(Keio Univ.)

Abstract

It is generally believed that the superfluid state is realized in the neutron stars, which are high density fermionic systems. Due to the repulsive core in the $^1S_0$ partial wave, the effects of pairing in the $^3P_2$ attractive interaction becomes comparable to that of the $^1S_0$ case at about the normal nuclear matter density. In this poster presentation, we firstly introduce GL equation for $^3P_2$ superfluid state. In BCS limit, degenerate ground states can be parameterized by one parameter. We show effects of gradient term and magnetic field on ground states and half-quantized $^3P_2$ vortices are the most stable states under certain conditions. We also discuss a spontaneous magnetization caused by half-quantized $^3P_2$ vortices and compare results with that of integer vortices.

Introduction [1,2,3]

Nuclear physics

核力の斥力芯

$\rho_0 < \rho$:

$^3P_2$ 状態に強い引力

$^1S_0$ pairs

$^3P_2$ pairs

Astrophysics (Neutron Star)

超流動体を反映した観測量

Glitch

Cooling

Key questions

- 中性子内部で期待されるような状況下 (強磁場、回転)で実現する$^3P_2$ の基底状態？
- $^3P_2$ 中性子超流動体が中性子星観測量に与える影響？

Ginzburg-Landau Equation [4,5]

GL free energy density:

Ω=(運動項 $\Omega_{g1}+\Omega_{g2}$)+(4次 Ω_4)+(6次 Ω_6)+(磁場 Ω_b)+(回転 Ω_r)

$$\Delta = \sum_{\mu\nu} i\sigma_\mu \sigma_2 A_{\mu\nu}\hat{k}_\nu$$

d波超流動体, spin2-BEC

$$\frac{1}{3}\alpha(T)\mathrm{Tr}AA^* + \bar{\beta}_1\mathrm{Tr}|A^2|^2 + \bar{\beta}_2\mathrm{Tr}(AA^*)^2 + \bar{\beta}_3\mathrm{Tr}(A^2A^{*2})$$

STRONG COUPLING / REGION I / REGION II / REGION III / UNSTABLE / BCS limit

REGIONⅢにおける
Gap parameterの取り方:

$$\frac{1}{N}\begin{pmatrix} r & 0 & 0 \\ 0 & -(1+r) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$-1 \le r \le -1/2$:
エネルギー縮退

運動項 Ω_{g1}: $K_1 A_{\mu i,j}A_{\mu i,j}$ Ω_{g2}: $K_2 A_{\mu i,i}A_{\mu j,j} + K_3 A_{\mu i,j}A_{\mu j,i}$

中性子星内部 磁場: $g'H^2\mathrm{Tr}(AA^*) + gH_i(AA^*)_{ij}H_j$
回転: $\Omega \to \Omega - \omega\cdot\mathbf{L}$

Results

- 6次+磁場なし: Uniaxial相
- 6次+強磁場、あるいは転移温度付近:
  Dihedral-2、Biaxial相が基底状態

[6] (b) $\tilde{M}$: deformed S^2, U(1) orbit, $\tilde{M}$/U(1), singularities

回転なし(基底状態)

Phase	$\tilde{M}$	G/H	r	Ω_6	Ω_b	Ω_{g1}	Ω_{g2}
Uniaxial	↑	$U(1)\times S^2/\mathbb{Z}_2$	-1/2	✔		✔	
Dihedral-2	$[U(1)\times S^4]/\mathbb{Z}_2$	$U(1)\times SO(3)/D_2$	-1<r<-1/2		✔		✔
Biaxial	↓	$[U(1)\times SO(3)]/D_4$	-1		✔		

- $^3P_2$ に特有な運動項Ω_{g2} ⟶ 半整数渦 回転(渦)あり
- 自発磁化 (外部磁場なし、運動項$\Omega_{g1}+\Omega_{g2}$+4次)

Vorticity m=1 Vorticity m=1/2

$\Delta = 0.8\mathrm{MeV}$, $k_f = 2\mathrm{fm}^{-1}$

$$A_{\mu i} = \begin{pmatrix} f_1 & img & 0 \\ img & f_2 & 0 \\ 0 & 0 & -f_1-f_2 \end{pmatrix}$$

Vorticity m	1	1/2
Magnetic flux [10^{-16} ξ_0^2 Wb]	123	-7.28

- $^3P_2$ における外部磁場の配位はトロイダル構造が最も安定
  外部磁場は$^3P_2$ の縁まで排斥される

Summary

- $^3P_2$ 、中性子星で期待される状況下で半整数渦が実現
- 外部磁場はトロイダル構造が最安定
- $^3P_2$は自発磁化をもつ、$^1S_0$ には見られない特徴

Future Works

1. 中性子星観測量への影響
2. BdG方程式を通したフェルミオン的扱い (ゼロモード)
   $^3P_2$ はトポロジカル超流動か

References

[1] R. Tamagaki and T. Takatsuka, PTP 44 (1970), 46 (1971) and 47 (1972)
[2] P. E. Reichley and G.S. Downs, Nature 222 (1969)
[3] C. O. Heinke and W. C. G. Ho, ApJ Letters 719 (2010)
[4] J. A. Sauls and J. W. Serene, Phys. Rev. D. 17 (1978)
[5] R. W. Richardson, Phys. Rev. D. 5 (1972)
[6] S. Uchino, M. Kobayashi, M. Nitta and M. Ueda Phys. Rev. Lett. 105 (2010)

ご意見、議論
お願いします!

ありがとうございました