Nuclear Theory Group, Warsaw Univ. of Technology

- Piotr Magierski (Professor)
- Gabriel Wlazłowski (Assistant Professor)
- Janina Grineviciute (Postdoc)

*1 PhD, 2-3 undergraduate course students

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**My research projects**

1. Vortex-nucleus dynamics

2. Nuclear reactions (just started)

3. Cold atomic gases (in 2016?)
Dynamical phase imprint

Constant potential:  \( U_0 = 0.5 \) MeV

Time to make \( \pi \) difference:  \( T_\pi \sim 620 \) fm/c

0 to 0.1\( T_\pi \) : turn on the Uext

0.9\( T_\pi \) to \( T_\pi \) : turn off the Uext

\[
U_0 = U_0*(1.0 - \text{switch}_\text{function}(x - 27.0, 3.0, 2.0))
\]

\[
U_0*\text{switch}_\text{function}(x, 3.0, 2.0)
\]

Very Preliminary
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TDSLDA calculations for vortex-nucleus interaction

Kazuyuki Sekizawa

Faculty of Physics, Warsaw University of Technology

in collaboration with

G. Wlazłowski and P. Magierski
TDSLDA calculations for vortex-nucleus interaction

Outline

1. Introduction: Neutron star “glitches”

2. Methods and Results: TDSLDA & Vortex-nucleus interaction

3. Summary and Conclusion
1. Introduction:

Vortex-mediated neutron star “glitches”
NASA Conceptual Image Lab

"Gamma Rays in Pulsars"

by Walt Fener

http://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=10205
Pulsar: a rotating neutron star

Pulsar is one of the most accurate atomic clock

- First observation in 1968 (Crab pulsar)
- More than 2000 pulsars have been found
- Rotation period: a few ms - several seconds
- Spin-down: at most a few tens of ms per year
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Irregularities in their rotational frequency have been observed: the “glitches”
What is the “glitch”? 
What is the “glitch”?  

Glitch is a sudden spin-up of the rotational frequency
What is the “glitch”? 

Glitch is a sudden spin-up of the rotational frequency

Ex.) The Vela pulsar (PSR B0833-45)

- One of the most active glitching pulsars
- Period of pulsation: 89 ms
- Time between glitches: a few years
- $\Delta \Omega/\Omega \approx 10^{-6}$
- It repeats regularly

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Something must happen inside the neutron star!  

*MJD: Modified Julian Date
Where are glitches originated from?
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The “inner crust” of a neutron star is relevant to the glitches.
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Outer crust: Nuclei (Fe), electrons

\[ 0.3 - 0.6 \text{ km} \quad \rho < \rho_{\text{drip}} \]

\[ \rho_{\text{drip}} \approx 0.0014 \rho_0; \quad \text{Above } \rho_{\text{drip}} \text{ unbound neutrons exist outside nuclei} \]

\[ \rho_0 = 2.8 \times 10^{14} \text{ g/cm}^3 = 0.16 \text{ fm}^{-3}; \quad \text{Nuclear saturation density} \]
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- **Outer/inner core**
  - 9-12 km
  - $0.6 \rho_0 < \rho \leq 3.5 \rho_0$
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**Uniform nuclear matter:**  
\( n, p, e^-, \mu^- \)

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Hyperons?

Meson condensates?

Quark matter?
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**Inner crust**  
Nuclei, electrons, “dripped” neutrons  
0.5-0.8 km  \( \rho_{\text{drip}} \leq \rho \leq 0.6 \rho_0 \)

**Outer/inner core**  
9-12 km  \( 0.6 \rho_0 < \rho \leq 3-5 \rho_0 \)

Uniform nuclear matter:  
\( n, p, e^-, \mu^- \)

Hyperons?  
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Quark matter?
Structure of the inner crust
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A lattice of neutron-rich nuclei are immersed in a neutron superfluid
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Fig. 4 in N. Chamel and P. Haensel, Living Rev. Relativity 11, 10 (2008)
Structure of the inner crust

A lattice of neutron-rich nuclei are immersed in a neutron superfluid

Quantum vortices can exist!

Envelope
iron atoms

Outer crust
neutron rich nuclei, $e^-$

Inner crust
nuclear clusters, $n,e$

Solid crust

Mantle

Liquid core

Fig. 4 in N. Chamel and P. Haensel, Living Rev. Relativity 11, 10 (2008)
Scenario of the glitch
Scenario of the glitch

✓ Superfluid component is decoupled from normal one

\[ \Omega_{\text{super}} > \Omega_{\text{core}} \]

Neutron superfluid

Core
Scenario of the glitch

✓ Core must spin down due to the radiation processes

\[ \gamma, e^\pm \]

Core
 ✓ Neutron superfluid follows the spin-down by expelling vortices outward
The vortices are trapped by the lattice of nuclei.
Since $v_{\text{super}} > v_{\text{core}}$, the Magnus force exerts on the pinned vortices.
Scenario of the glitch

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- Catastrophic unpinning has been believed to be a cause of the glitches

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1. Core must spin down due to the radiation processes
2. Superfluid component expel vortices outwards, then pinning takes place
3. Pinning sites and the neutron superfluid are moving with different velocities
4. When a huge number of vortices unpinned, superfluid component spins down
5. The released angular momentum is transferred to crust, resulting in the glitch

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Vortex-nucleus interaction is a key quantity to understand the glitches
State-of-the-art study
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Binding energy was evaluated by axially symmetric HFB calculation
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\[ \Delta E = E_{\text{nucl}}^{\text{vor}} - E_{\text{unif}}^{\text{vor}} \]

- Cylinder: R=30 fm, h=40 fm
- Mesh: 0.25 fm
- Skyrme SLy4 & SkM*
- Pairing: DDDI (Ec=60 MeV)

State-of-the-art study

Binding energy was evaluated by axially symmetric HFB calculation

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2. Methods and Results:

3D TDSLDA calculations for vortex-nucleus dynamics
We assume a local form of the Kohn-Sham EDF in TDDFT.
We assume a local form of the Kohn-Sham EDF in TDDFT

- **TDSLDA equations:**

  \[
  i\hbar \frac{du_i(r)}{dt} = [h(r) - \mu]u_i(r) + \Delta(r)v_i(r)
  \]

  \[
  i\hbar \frac{dv_i(r)}{dt} = \Delta^*(r)u_i(r) - [h(r) - \mu]v_i(r)
  \]

  \(u_i(r), v_i(r)\): quasi-particle wave functions

  \(h(r)\): single-particle Hamiltonian

  \(\mu\): chemical potential
TDSLDA: *Time-Dependent Superfluid Local Density Approximation*

We assume a local form of the Kohn-Sham EDF in TDDFT

- **TDSLDA equations:**

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  i\hbar \frac{du_i(r)}{dt} = [h(r) - \mu]u_i(r) + \Delta(r)v_i(r) \\
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  \]

  \(u_i(r), v_i(r):\) quasi-particle wave functions \(h(r):\) single-particle Hamiltonian \(\mu: \) chemical potential

- **Local energy density functional:**

  \[
  \mathcal{E}(r) = \mathcal{E}_0(r) + g|\nu(r)|^2
  \]

  **Fayans EDF (FaNDF\(^0\)) w/o LS**
  
  Fayans and D. Zawischa, arXiv:nucl-th/0009034

  \[
  \mathcal{E}_0 = \mathcal{E}_{\text{kin}} + \mathcal{E}_{\text{vol}} + \mathcal{E}_{\text{surf}} + \mathcal{E}_{\text{Coul}} \\
  \mathcal{E}_{\text{vol}} = C_0 \left[ a_+^\rho \frac{\rho_+^2}{4} - \frac{1 - h_{1+}^\rho x_+^\rho}{4 + h_{2+}^\rho x_+^\rho} + a_-^\rho \frac{\rho_-^2}{4} - \frac{1 - h_{1-}^\rho x_+^\rho}{4 - h_{2-}^\rho x_+^\rho} \right]
  \]

  \[
  \mathcal{E}_{\text{surf}} = \frac{C_0}{4} \frac{a_+ r_0^2 (\nabla \rho_+)^2}{1 + h_+^s x_+^s + h_+^t r_0^2 (\nabla x_+)^2}
  \]

  \(\Delta(r) = -\frac{d\mathcal{E}(r)}{d\nu^*(r)} = -g\nu(r)\) \(\Delta(r):\) local pairing field \(\nu(r):\) anomalous density
We can efficiently work with the local pairing field
**Problem:** \( \nu(r_1, r_2) \) and thus \( \Delta(r_1, r_2) \) diverge when \( r_1 = r_2 \)

\[
\nu(r_1, r_2) = \sum_i v_i^*(r_1) u_i(r_2) \propto \frac{1}{|r_1 - r_2|}
\]
Regularization for zero-range pairing interaction

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**Prescription:**

\[
\Delta(r) = -g \nu_{\text{reg}}(r) = -g_{\text{eff}}(r) \nu_c(r)
\]

\[
\frac{1}{g_{\text{eff}}(r)} = \frac{1}{g} - \frac{mk_c(r)}{2\pi^2\hbar^2} \left[ 1 - \frac{k_F(r)}{2k_c(r)} \ln \frac{k_c(r) + k_F(r)}{k_c(r) - k_F(r)} \right] - \frac{ml_c(r)}{2\pi^2\hbar^2} \left[ 1 - \frac{k_F(r)}{2l_c(r)} \ln \frac{k_F(r) + l_c(r)}{k_F(r) - l_c(r)} \right]
\]

\[
\nu_c(r) = \sum_{E_i \leq E_c} v_i^*(r) u_i(r)
\]

\((l_c \leq k_F \leq k_c)\) \quad \text{\(E_c\) : a cutoff energy}

Regularization for zero-range pairing interaction

We can efficiently work with the local pairing field

**Problem:** $\nu(r_1, r_2)$ and thus $\Delta(r_1, r_2)$ diverge when $r_1 = r_2$

$$\nu(r_1, r_2) = \sum_i \nu_i^e(r_1) u_i(r_2) \propto \frac{1}{|r_1 - r_2|}$$

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$$\Delta(r) = -g \nu_{\text{reg}}(r) = -g_{\text{eff}}(r) \nu_c(r)$$

$$\frac{1}{g_{\text{eff}}(r)} = \frac{1}{g} - \frac{mk_c(r)}{2\pi^2\hbar^2} \left[ 1 - \frac{k_F(r)}{2k_c(r)} \ln \frac{k_c(r) + k_F(r)}{k_c(r) - k_F(r)} \right]$$

$$- \frac{m l_c(r)}{2\pi^2\hbar^2} \left[ 1 - \frac{k_F(r)}{2l_c(r)} \ln \frac{k_F(r) + l_c(r)}{k_F(r) - l_c(r)} \right]$$

$l_c \leq k_F \leq k_c$

$E_c$: a cutoff energy

**Example:** $^{110}\text{Sn}$, Woods-Saxon

We can efficiently work with the local pairing field

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**Example:** \( ^{110}\text{Sn}, \text{Woods-Saxon} \)

**Homogeneous neutron matter**

We use our own 3D TDSLDA code written in CUDA C with MPI
Computational settings

We use our own 3D TDSLDA code written in CUDA C with MPI

- EDF: Fayans EDF (FaNDF$^0$) w/o LS
- 3D uniform lattice: 50x50x40
- Mesh spacing: 1.5 fm
- $dt\sim0.054$ fm/c
- $E_e=75$ MeV (Nwf$_n$: 32,665, Nwf$_p$: 13,967)
- Time-evolution: split-operator w/ predictor corrector
- Derivatives: Fourier transformation
- Periodic boundary condition
- Each CUDA core is responsible for each grid point
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- Physical situation
  - $N: 2633.4 \quad \Rightarrow \quad \rho_n \sim 0.016 \text{ fm}^{-3}, \quad k_F \sim 0.78 \text{ fm}^{-1}$
  - $Z: 50$ (Sn)
Computational settings

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- **Some details**
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- **Physical situation**
  - $N$: 2633.4  \( \rho_n \sim 0.016$ fm$^{-3}$, $k_F \sim 0.78$ fm$^{-1}$
  - $Z$: 50 (Sn)

- **Performance**
  - Ex: 48 nodes (192 GPUs) on HA-PACS
    -> 28 hours for 10,000 fm/c time-evolution
We dynamically generate an initial configuration starting from a uniform system.
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- Adiabatic switching

\[ H(t) = s(t)H_1 + [1 - s(t)]H_0 \]

\( s(t) \): a smooth switch function [0, 1]

We dynamically generate an initial configuration starting from a uniform system

- **Adiabatic switching**

  \[ H(t) = s(t)H_1 + [1 - s(t)]H_0 \]
  
  \[ s(t): a \text{ smooth switch function } [0, 1] \]

- **Quantum friction**

  \[ i\hbar \dot{\Psi}(t) = (H(t) + U_{\text{qf}}(t))\Psi(t) \]

  \[ \dot{E} = \langle \Psi(t) | H(t) \dot{\Psi}(t) \rangle + \frac{2}{\hbar} \text{Im} \left[ \langle \Psi(t) | H(t)U_{\text{qf}}(t)\Psi(t) \rangle \right] \leq 0 \]

  \[ U_{\text{qf}}(t) \propto -2\text{Im} \langle \Psi(t) | H(t) \Psi(t) \rangle = -\hbar \nabla \cdot j(t) = \hbar \dot{\rho}(t) \]

  *\( U_{\text{qf}} \) removes any irrotational currents

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- **What we do in practice:**

Uniform system \(\rightarrow\) +Tube \(\rightarrow\) +HO \(\rightarrow\) +Coulomb \(\rightarrow\) -HO \(\Rightarrow\) Put it to a static solver w/o Coulomb

Initial state generation: Impurity at the center

Neutron density

Proton density
The prepared initial states

I. “separated” configuration

II. “pinned” configuration
How to extract the force
We measure the force exerts on the impurity by an external potential.
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- Idea:
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- Idea: The nucleus should be at rest for $F_{\text{ext}} = -F$

- Dynamical construction of the $F_{\text{ext}}$

\[ F_{\text{ext}}(t + \Delta t) = F_{\text{ext}}(t) - \alpha V(t) \]

$V(t)$: cm velocity of the nucleus
$\alpha$: a small constant
How to extract the force

We measure the force exerts on the impurity by an external potential

- **Idea:** The nucleus should be at rest for $F_{\text{ext}} = -F$

- **Dynamical construction of the $F_{\text{ext}}$**

\[
F_{\text{ext}}(t + \Delta t) = F_{\text{ext}}(t) - \alpha (V(t) - V_{\text{drag}})
\]

*We slowly drag the nucleus with constant velocity*
How to extract the force

We measure the force exerts on the impurity by an external potential

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- **Dynamical construction of the $F_{\text{ext}}$**

  $$F_{\text{ext}}(t + \Delta t) = F_{\text{ext}}(t) - \alpha (V(t) - V_{\text{drag}})$$

  *We slowly drag the nucleus with constant velocity*

- **Corresponding external potential for protons**

  $$V_{\text{ext}}^{(p)} = -\frac{1}{Z} F_{\text{ext}}(t) \cdot r$$

  *a constant slope uniform along z-direction*
Vortex-nucleus dynamics I: from “separated” configuration
The extracted force

We find “repulsive” nature of the vortex-nucleus interaction

Force and \( R \) vs. time

*Green line: averaged over 50 measurements (540 fm/c)

\( F_c \): positive for repulsive
\( F_t \): positive for anti-clockwise

*Dragging along x-axis

TDSLDA calculations for vortex-nucleus interaction

Fri., Jan. 8, 2016
Vortex-nucleus dynamics II: from “pinned” configuration
The extracted force

We find “repulsive” nature of the vortex-nucleus interaction

Force and $R$ vs. time

$F_c$: positive for repulsive  
$F_t$: positive for anti-clockwise

*Green line: averaged over 50 measurements (540 fm/c)
- To determine the force per unit length when the vortex line bends

\[ \mathbf{f} \propto \int f(r) \mathbf{r} \times dl \]

- To examine density dependence of the interaction
Summary and Conclusion

Summary

✓ The vortex-nucleus interaction is the essential quantity to understand the glitches.

✓ We are conducting microscopic, dynamical simulations with TDSLDA.

✓ Our simulation is providing qualitatively new things:

  ➢ The first, three-dimensional, microscopic, dynamical simulation for the vortex-nucleus interaction with a new force extraction technique
  
  ➢ The “bending” mode of the vortex line
  
  ➢ The “repulsive” nature of the interaction (at least for $\rho \sim 0.1\rho_0$)
Summary and Conclusion

Our simulation will provide significant impact on glitch studies!

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