SUPERFLUID DYNAMICS OF NUCLEAR SYSTEMS

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1. Project Purpose

The goal of the project is to understand the impact of pairing (pairing field dynamics in particular) on the outcome of nuclear reactions at low energies (at energies in the vicinity of the Coulomb barrier). The project is pioneering as the pairing dynamics has been barely studied in nuclear reactions. Only recently the development of TDSLDA allowed to get insight into the problem. As a second part of the project, we planned to investigate dynamics of quantum vortices in the dilute ultracold gases and nuclear matter forming the crust of neutron stars. The motivation comes from experiments on ultracold gases, where two vortex dipoles (vortex-antivortex pairs) have been collided in order to extract dissipative effects. Another motivation comes from the mysterious phenomenon of pulsar glitches - a feature of sudden increases in the spinning of neutron stars. The current understanding of the effect involves dynamics of quantized vortices as glitches result from a catastrophic release of pinned vorticity that suddenly changes the pulsation rate. Therefore the microscopic simulation of dynamics of vortices will provide the bridge between superfluid properties of nuclear matter and large-scale models of neutron stars.

2. Results

We have performed a detailed analysis of head-on collisions involving 90Zr and 96Zr nuclei at energies of the order of the Coulomb barrier. By varying the relative phase difference of pairing fields of two nuclei we have been able to investigate in detail the influence of the phase of Cooper pair condensate on nuclear dynamics. In order to ensure that the effects are not due to a particular form of nuclear energy density functional, we have used two functionals: SkM* and Sly4d, which have been constructed using different methodologies. The results which we have generated represent the most detailed numerical simulation data of pairing dynamics in nuclear collisions performed to date. We have extracted several quantities of paramount importance as a function of collision energies, pairing magnitude and relative phase difference. These observables are currently the subject of analysis:

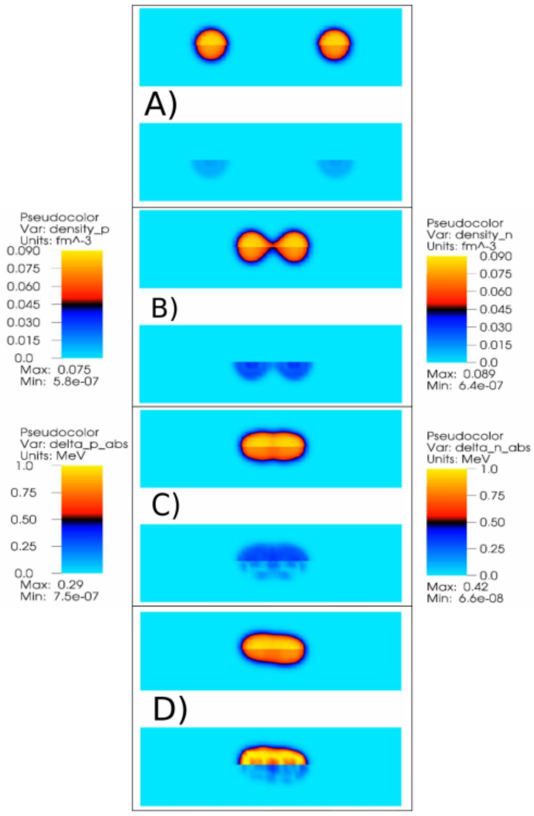

Fig 1. Snapshots from the nuclear collisions of ^{90}**Zr** + ^{90}**Zr** *are presented. Figure is made of four subfigures containing two panels, each of one containing two plots. Top(bottom) panel corresponds to the density(delta) profile. Upper(lower) plot on each panel shows the neutron (proton) distribution. On the side one can see a pseudocolor profile of the observables. Note that with time evolution (A - D) neutron pairing field appears. To the best of our knowledge this phenomenon has never been observed before.*

1) total kinetic energy of the fragments and total excitation energy,
2) time evolution of nuclear quadrupole and hexadecapole moments,
3) time evolution of neutron and proton pairing gap,
4) evolution of the flow energy (ie. part of the total energy due the currents).

Moreover, during the simulation processes we have detected new effects which are being analyzed now. The most intriguing one, which we have already started to investigate, is due to appearance of pairing in compound nucleus formed by two nuclei initially in normal state. Namely we have observed that neutron pairing field in 90Zr-90Zr have appeared during the collision as an oscillatory mode once the compound nucleus is formed. This effect resembles the celebrated **Higgs effect** (mode), where the initial symmetry is broken due to dynamics of many-body system. It is qualitatively new phenomenon in the context of nuclear physics. The investigation of collisions of other magic nuclei are currently being prepared. It will help us understand whether the effect of our simulations is generic.

Another type of reaction which we have started to investigate are collisions: 90/92/94/96Zr+124Sn, where the discrepancy have been observed between experimental and theoretical energies at which merging (capture) occurs. According to our hypothesis, part of this effect is due to pairing dynamics. In order to quantify this conjecture we have generated initial configurations of nuclei. We plan to continue these studies.

Concerning vortex dynamics, we have performed a series of collisions of vortex dipoles (vortex-antivortex) pairs. The study has been inspired by experiments performed by LENS group at University of Florence. The idea is to quantify the dissipative effects by measuring the distance between vortex and antivortex after the collision and thus estimate the loss of collision energy due to dissipation. The collision between vortex dipoles is accompanied by the exchange of vortex (antivortex) between colliding pairs. As a result the dissipative effects due to phonon excitations and vortex core excitations are possible. In our simulations we have focused on extraction of the vortex core excitation, which is believed to play a significant role in BCS limit (contrary to BEC limit where this dissipative channel is absent). The results that we have generated indicate that dissipative effects are significantly suppressed as compared to experimental results. We attribute these discrepancies to two effects. First, in our approach based on TDSLDA framework the effects originated from two-body collisions are absent and, second, the experimental results are performed at finite temperature (about 0.3*Tc) whereas our framework is designated to describe T=0 evolution. These results may become extremely useful to quantify the range of validity of TDSLDA approach. We have performed several studies for various "dipole moments" of colliding pairs both in the unitary regime as well as in the BCS limit. These results are currently under investigation and will help us to construct a model of vortex core excitation.

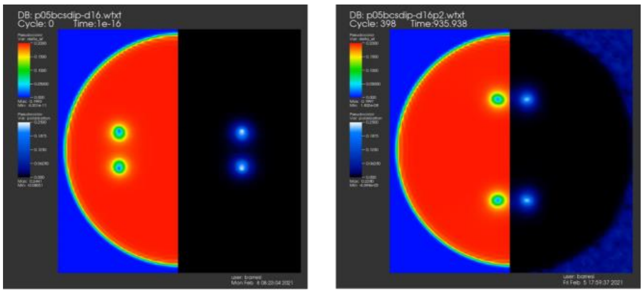

Fig 1. Snapshot from the quadrupole collision in polarized BCS are presented. a) Vortex phases are imprinted with a 16 lattice units distance in a trapped BCS with relative polarization of 0.5%; left half shows Delta normalized with Fermi energy, right half shows the relative polarization. Spin-up particles are localized in the vortex cores, which have an initial relative polarization of 24.4%. b) After the collision, relative polarization in the core has decreased by 1.6%: spin-up particles have escaped the vortices in the collision process.

3. Roles of the MCRP and its significance

The usage of the Cygnus computer allowed us to obtain several important results which were listed above. In particular, the role of Cygnus supercomputer was significant in studies of collisions of Zr-isotopes and vortex dipole collisions. Unfortunately due to very high occupancy of the machine during the Fall 2020 we were unable to accomplish tasks related to vortex dynamics in neutron stars. For this reason we were also unable to use the whole allocation that we asked for in our proposal (we have reported this problem in several emails sent to the system administrators). The problem has been eventually resolved at the beginning of 2021, however, this delay is reflected in the absence of results concerning neutron stars.

4. Future plan

The results obtained withing this allocation allowed us to identify several interesting phenomena which are worth of further investigation. These include the following problems:

- Investigation of dynamic excitation of Higgs mode in nucleus-nucleus collision of magic nuclei
- Investigation of the contribution of pairing excitation modes to extra push energy needed to explain discrepancy between experimental and to-date theoretical results obtained within TDHF approach.
- Role of dissipative effects in Kelvin waves generation, in particular those generated due to Donnelly-Glaberson instability.

The study of these effects are planned to be continued.

5. Publications and conference presentations

(1) Journal papers

One paper is under process of review for PRL.

At least two more papers reporting nuclear collisions and vortex dipole collisions are currently under preparation.

(2) Presentations

Due to Covid the number of presentations have been limited.

The result were presented during one seminar in June 2020 at Warsaw University of Technology by Piotr Magierski

In July 19-21, 2021 the workshop at ECT* (Trento, Italy): **Nuclear Physics Meets Condensed Matter** is organized where the results will be reported by Piotr Magierski

Also on July 5, 2021 one of the members of the project (Gabriel Wlazłowski) organizes the mini-symposium PASC21:"**Time Dependent Superfluid Density Functional Theory and Supercomputing: Latest Developments and Challenges**", where three members of the project: Kazuyuki Sekizawa, Gabriel Wlazłowski and Piotr Magierski will also report results obtained using Cygnus.

(3) Others

Supercomputer	Use	Allocated resources*	
		Initial resources	Additional resources
Cygnus	Yes/~~No~~	97 810	------------ -
Oakforest-PACS	~~Yes~~/No	-------------	------------ -
*in units of node-hour product			