UNIVERSITÀ DEGLI STUDI DI MILANO
DIPARTIMENTO DI FISICA
ALDO PONTREMOLI

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Report on the thesis:
"Collective properties of superfluid fermionic mixture in neutron star crust"

by Agata Marta Zdanowicz, M.Sc. Eng.

Dear members of the committee,

I have read with great interest the thesis submitted by Ms Zdanowicz, which deals with the very interesting topic of modelling the dynamics of impurities in a superfluid neutron star crust, and their interaction with superfluid neutron vortices. This is a topic very close to my heart, as I am mainly interested in studying such systems to model astrophysical phenomena such as pulsar glitches and continuous gravitational wave emission.

The kind of research described in this thesis, that applies state of the art computational tools, initially developed to describe laboratory systems, to astrophysical scenarios, is very timely. I am, in fact, chair of a recently funded COST Action, SCALES (CA24139) that aims to promote exactly the exchange of ideas between superfluid experimentalists, theorists and astrophysicists. The kind of work carried out by Ms Zdanowicz is exactly the sort of progress we would like to see in the Action.

The thesis is structured in 7 chapters. The first chapter is a very short summary, and the following two give a very well structured introduction to both the physical system, namely superfluids in neutron star interiors (chapter 2), and the methodology that is used in the thesis, density functional theory and the numerical W-BSk toolkit (chapter 3). This part is very clear and a useful summary for anybody who wishes to enter the field.

Chapter 4 presents the first results obtained by the candidate, and published in Physical Review X together with their collaborators. The main goal is the study of the effective mass of an impurity in a neutron star crust. This quantity has been previously calculated in different approximations, but in this thesis a full dynamical calculation with the W-BSk toolkit is presented. This allows to benchmark previous results with a new method free from assumptions, and also study dynamical dissipative phenomena such as vortex ring creation.

Chapter 5 pushes the methodology further. While in the previous chapter the effective mass was studied by slowly applying an electric field and extracting the mass, in chapter 5, which is based on results published by the candidate in Physical Review C, oscillations are studied. The results are first validated by comparing to those of chapter 4, and then extended to study additional mass parameters that describe the deformation of the impurity.

Chapter 6 finally presents new, and in my opinion incredibly interesting, results on the vortex impurity interaction, i.e. what is known as the pinning force. This interaction is thought to be at the basis of the phenomena of pulsar glitches, and the so-called timing noise in pulsars, but to date remained poorly explored, with only few approximate results available.

In this work, however, the candidate presents a host of results for the pinning force obtained with the W-BSk toolkit, and, what is notable compared to previous work, presents them for a variety of densities in the neutron star crust. This allows to map the force in detail and conclude that it remains repulsive at all densities, an issue that remained debated in previous static studies. Finally deformations of the impurity in this setup are studied. These results are not published but are of high impact, and I therefore believe that they can form the basis of significant publication.

I should note that the previous results are published in a first author paper by the candidate in Physical Review C (chapter 5) and, for chapter 4, in a publication in the high impact journal Physical Review X. No doubt a publication in a top tier international journal can be expected also for the results of chapter 6.

Overall the material is clearly presented and all relevant material given, I therefore have only a few question I would like the candidate to discuss during the defence:

1) In figure 4.8 and the discussion around it. What is the bare mass of the impurity here? I did not find what the A of the impurity is expected by models to be, only Z.

2) I was wondering if it would be possible to model the number of neutrons that are bound to the nucleus and which are free, and then extract the effective mass of the neutrons with this method.

3) Regarding the analysis of chapter 4 I was wondering if, possibly using oscillations as in chapter 5, one could expect to excite second sound, and compare the vortex nucleation threshold with the second sound speed, not only the sound speed.

4) At the end of chapter 5 the base of the neutron star crust is briefly mentioned. I wonder if the candidate could discuss more what the consequences of the obtained results would be for neutron star physics.

I stress that these are mostly curiosities and points for further discussion, that do not detract in any way from the high quality of the thesis.

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In summary, I believe the work presented in this thesis to be of high quality and to satisfy the legal requirements for the award of a PhD degree, and recommend the candidate proceed to the defence.

Kind regards

Milano, 23/03/2026

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