Review report on PhD thesis by Šimon Midlik: Quantum fluid dynamics and quantum turbulence probed using micro- and nano-resonators

I read dissertation thesis by Šimon Midlik: Quantum fluid dynamics and quantum turbulence probed using micro- and nano-resonators, including attached preprints of published articles with a great interest.

Turbulence is still an object of the active research and investigation for experimental and theoretical physicists, as the turbulence overlaps and joins two physics worlds – classical and quantum. In our "classical" world we deal with turbulence on everyday base: mostly it is a turbulent behavior of atmosphere and water (liquids), etc. Elucidating and understanding of the dynamic of the classical (and quantum) turbulence, the physical origin of its generation, its time evolution and decay, etc., this allows us to make the efficient steps to eliminate a negative influence of the turbulent processes. Obviously, the research in turbulence has significant impact on society and enormous applications in everyday life.

As the turbulence overlaps two physical worlds: classical and quantum and this is just quantum world allowing us to investigate and to understand more fundamental underlying physics: physics of the quantum world – world of the quantum turbulence. The quantum turbulence is a unique macroscopic phenomenon manifested only in two quantum fluids, i.e. the superfluid 4He and superfluid 3He (there is also possibility to generate vortices in BEC of ultra-cold gases, however, in reduced geometry).

Thesis by Šimon Midlik is focused on experimental investigation of the quantum turbulence in superfluid 4He and superfluid 3He. He used, I could say, not only traditional measuring methods like the second sound technique, but author also introduced novel techniques based on mechanical resonators (quartz tuning forks, vibrating wires), but specially MEMS and NEMS. Physical motivation of an application of these (later mentioned) devices is that, being very sensitive, they can detect very tiny amount of the vortices (energy), in ideal case – only one vortex, and this gives us possibility of the energy dissipation in single vortex – the dissipation in quantum regime. I should stress that I appreciate this innovation, namely as these devices are fabricated in house (CEITEC – nano Research Infrastructure). As it comes to new knowledge on the quantum turbulence presented in thesis I would like to select, according to my opinion, two the most important ones. The first outcome is an experimental evidence of the presence of two distinct types of turbulent flows at all temperatures in He II. These two flows have different dynamical properties and coupling character of the possible turbulent structures – classical vortices and quantized vortices. At higher temperature the quasi-classical or Kolmogorov type of quantum turbulence with the coupled motion of normal and superfluid components dominates. On the other hand, the ultra-quantum or Vinen type of quantum turbulence consisting of a chaotic bundle of quantized vortices becomes crucial at very low temperatures. As a consequence, there is temperature crossover between these regimes – and this is characterized by introducing a new quantum length scale l_Q, which marks the onset of the quantum character of the flow, where quantization of circulation becomes essential. This parameter is introduced by the author. The second result is an experimental evidence about possibility to attach stably a single quantum vortex to a MEMS/NEMS wire in superfluid 3He-B, and to detect additional losses caused by the vortex. Although this experiment was performed in collaboration with Helsinki

ULT laboratory, I appreciate this result as it opens new possibilities of the study of single vortex dynamics – the dynamics on the quantum level.

To summarize: all scientific results presented in thesis are new, innovative and extend our knowledge on dynamics of classical and quantum fluids, in particular quantum turbulence in superfluid He-II and in superfluid 3He-B, and they are applicable in other fields of physics.

Presented thesis is written in English. From a formal point of view, thesis is clearly and very well written, however there are minor misprints and some formal mistakes (e.g. references to the equations in text should be in brackets; text in some pages is out of bounds, etc.). I appreciate reasonable graphical documentation including many graphs presenting the measured dependencies, based on which physical interpretations and conclusions were made.

Final part of thesis consists of preprints of the selected scientific articles of the author. There are six preprints of articles: APL 1x, PNAS 1x, Phys Rev. B 2x, JLTP 2x. It is worth to note, that results of the thesis had been presented by the applicant as an invited talk on recent conference EMP User meeting 2022 held in High Tatras, Slovakia, and the EMP User meeting 2023 held in Lancaster. This also demonstrates the eligibility of the applicant for independent work.

Although many of in thesis presented results have already been published in articles and therefore, they already passed a review process, I have a few, rather general questions to the applicant related to the results presented in thesis:

- My first question is related to basic physics of superfluid 4He and superfluid 3He: in Fig. 1.4 on the page 10 you show the dispersion curves for both superfluids. Later on you discuss the process of the Andreev reflection in superfluid 3He. But looking on the dispersion curve of the superfluid He-II, I am asking a simple question: can process similar to the Andreev reflection also exist in superfluid He-II? Could you discuss this question more general?

- Paragraph 1.2.3 Mutual friction: "Mutual friction originates from the scattering of normal component on the quantized vortex core and is acting to align the of the components to be parallel." , and later (page 21): In the two-fluid regime, mutual friction allows both-way energy transfer between components, as schematically shown in Figure 1.9. … ". My question is: how do you imagine the energy transfer between these components? Can you describe such process?

- Page 36, Figure 2.1. (right) Excellent scaled dependence of the normal component drag coefficient as a function of the Donnelly number measured for various temperatures using different devices. What physics is behind these scaled curves, what did they say to us?

- Page 52: " …., the existence of the two-level energy systems or surface effects especially important for low dimensional devices." As it comes to two-level energy systems in low dimensional devices – could you give/provide some specific examples?

- Chapter 4.3 Vacuum properties: Your NEMS (as many others) demonstrates Duffing-type nonlinearity. In your case "positive" i.e. the frequency of the "jump" increases with rising excitations. However, there are NEMS (and MEMS) having opposite behaviour. What do you think what is the physical origin of this Duffing behaviour?

In conclusion, I would like to say that the dissertation thesis by Šimon Midlik: **“**Quantum fluid dynamics and quantum turbulence probed using micro- and nano-resonators” has a high scientific level, scientific results presented in the thesis are new and they extended our knowledge on quantum turbulence. Results have been published in internationally accepted scientific journals and there are sufficient numbers of scientific citations on them. I checked scientific outputs of the applicant in scientific database WoS: the applicant is a co-author of 9 scientific articles: APL 1x, Phys Rev. B 2x, JLTP 3x, Rev. Sci. Instr., etc. and has more than 40 citations. For a student just finishing his PhD study - it seems to be an excellent starting point for his scientific carrier demonstrating his ability of the independent scientific work.

Finally, I declare that thesis by Šimon Midlik: Quantum fluid dynamics and quantum turbulence probed using micro- and nano-resonators” satisfies all requirements for the dissertation thesis required by the law, I recommend this thesis to be defended and after successful defense I support the nomination of Šimon Midlik for the academic degree “philosophiae doctor” - PhD.

Košice, August 18th, 2023 RNDr. Peter Skyba, DrSc.