

POLATOM ESF Research Networking Programme:

Common perspectives for cold atoms, semiconductor polaritons and nanoscience

***Report on the short term visit of Andrea Perali to the Physics Department
of the University of Antwerp, Belgium***

Visiting researcher: Andrea Perali, Physics Unit of the School of Pharmacy, University of Camerino, Italy.

Host researcher: Arkady Shanenko, Physics Department, University of Antwerp, Belgium.

Title of the project work: Atypical BCS-BEC crossover phenomena driven by quantum-size effects in quasi-1D and quasi-2D fermionic condensates

Period of the visit: from the 13-th of May to the 20-th of May 2012.

Reference number: [4844](#)

1. Purpose of the visit:

As illustrated in the submitted project, the purposes of the visit were: *i)* the theoretical and numerical investigation of the signatures of shape resonances and BCS-BEC crossover phenomena in ultracold fermionic systems confined in traps with reduced dimensionality, as cigar-shape or pancake-shape traps. The approach to evaluate the physical quantities of interest for the characterization of the superfluid state of the system (gap parameters, chemical potential, correlation lengths) is based on the numerical solution of the Bogoliubov-de Gennes equations. As shown below, this purpose anticipated in the submitted project has been carried out during the visit in Antwerp. *ii)* Regarding the second purpose, the analysis on how to extend the t-matrix diagrammatic approach to the case of many-subband fermionic systems, we started to discuss it during the visit, in order to set the theory and the self-consistent equations, together with physical considerations on the relevant quantities to be valuated, but the writing of the code has been postponed, because in the last weeks we received the referee reports on our first paper on the BCS-BEC crossover induced by quantum-size effects submitted to Physical Review Letters and we decided to work together to perform the numerical calculations and the theoretical analysis which have been necessary to overcome the referees' criticisms and to improve our manuscript for the resubmission. *iii)* The last purpose of my visit reported in the project was the presentation of a seminar on the pseudogap and the BCS-BEC crossover, and indeed I gave it, together with interesting discussions on this topic, as illustrated below. *iv)[new]* Moreover, some weeks before leaving for Antwerp, an additional purpose has been given to my visit: to act as a member of the commission for the defense of the Ph. D. thesis of Y. Chen on "Superconductivity in Nanofilms and Nanocylinders", and this useful and interesting task took me some working time before and during the visit.

2. Description of the work carried out during the visit:

Part of the work during my visit consisted on the detailed analysis of the two referee reports we recently got for our first paper on this topic submitted to Physical Review Letters. In particular, to overcome the criticisms of the referees it has been necessary to perform the following actions: *i)* Running new calculations of the ground state properties ($T=0$) of the superfluid phase, as the pair wave function and the excitation gaps within the Bogoliubov-de Gennes approach and preparing corresponding figures for the new version of our paper. Other numerical results have been generated to show the robustness of our ultraviolet regularization of the contact potential, considering a different regularization with an energy cutoff and analyzing the quantitative differences in the physical quantities in few relevant cases. *ii)* Detailed analysis of the experimental set up which is at present used to confine fermions in quasi-1D geometries (Hulet group experiment) and which experimental probes available can be suitable to detect the signatures of the atypical BCS-BEC crossover predicted in our paper. *iii)* Including the changes in the manuscript, writing the resubmission letter for the Editor of PRL and the reply for the referees. Besides the work for our paper, I have presented a department seminar entitled “Pseudogap in ultracold Fermi gases: comparison with experiments and Quantum Monte Carlo results and insights for the pseudogap phase of cuprates”. In the second slide of my seminar the ESF POLATOM grant supporting my visit has been explicitly acknowledged, reporting all the information of the research network and the reference number of my grant. Finally, another task completed during my visit has been the reading and the writing of the report on the Ph.D. thesis of the student Yajiang Chen entitled “Superconductivity in Nanofilms and Nanocylinders”, of which Arkady Shanenko and Francois Peeters are the supervisors. I was nominated in the board of the commission for the defence of the Chen’s thesis. Interesting discussions with Francois Peeters, Jacque Tempere and Serghei Klimin of the Physics Department of the University of Antwerp on the pseudogap and pair fluctuations in ultracold fermions have been also conducted during my stay.

3. Description of the main results obtained:

The results obtained during my stay in Antwerp have been: *i)* The main conclusions on the BCS-BEC crossover induced by quantum-size effects, previously obtained by a combined analysis of the mean field critical temperature and the correlation length of the pairs, are now confirmed by the new numerical calculations using the ground state pair wave-function and gap parameters ($T=0$), as required by one of the referees. *ii)* We repeated the calculations of relevant superfluid properties using a different regularization scheme for the contact potential from the one considered in our paper, showing that the main conclusions of our work do not depend on the particular regularization adopted. *iii)* The analysis of the experimental papers recently published; we can confirm that the trap geometry considered in our work can be easily experimentally realized and that our theoretical predictions can be tested by the widely used radio-frequency spectroscopy (even momentum and radial resolved) experiments. Moreover, the seminar permitted to spread the knowledge of the physics of ultracold atoms between the many members of the Physics Department of University of Antwerp who attended it. On the other hand, my participation to the commission for the Ph.D.

thesis of Y. Chen permitted to me to increase my expertise on the physics of superconducting nanostructures with different geometrical configurations.

4. Future collaboration with host institution:

i) Writing a long paper with new results and extended connections to experiments on the (atypical) BCS-BEC crossover in ultracold fermions, trapped in quantum confined quasi-1D geometries. We are planning to submit the long paper to Physical Review A; *ii)* Working on the quasi-1D fermionic system under rotation, investigating the physical properties of the vortex state; *iii)* Organize conferences and workshops on quantum size effects and crossover phenomena in multicomponent superconductors and superfluids; *iv)* Exchange of students, both at the Master or Ph.D. level; *v)* Looking for opportunities to participate together to European calls (Marie Curie; Strep projects; etc.).

5. Projected publications / articles resulting or to result from the grant (ESF must be acknowledged in publications resulting from the grantee's work in relation with the grant):

Title: Atypical BCS-BEC crossover induced by quantum-size effects.

Authors: A. A. Shanenko, M. D. Croitoru, A. V. Vagov, V. M. Axt, A. Perali, F. M. Peeters.

Archive: arXiv: 1203.3325

Submitted to Physical Review Letters.

The explicit acknowledgements to the ESF POLATOM is going to be inserted in the new version of the above reported manuscript which we are going to resubmit soon to PRL.

We plan to prepare and write a second long paper on the BCS-BEC crossover in nano-structured fermionic systems, and submit it to Physical Review A, again citing EFS POLATOM for support.

6. Other comments:

Our collaboration on ultracold atoms and superfluid or superconducting nanostructures will continue at least for other two years, because of the several ideas, projects and events we plan to work on and organize together. Therefore, we are going to submit again applications for short-term visits in both Universities of Camerino and Antwerp. Long-term visit applications would be also possible, as well as the visit of other researchers of the condensed matter groups involved in the planned research activities.

In conclusions we really appreciate the aims of the POLATOM ESF Network and its usefulness in empowering collaborations between European researchers and institutions in order to fulfill complex projects and to establish long term network collaborations. Therefore, we thank a lot and we are indebted to the POLATOM ESF Network for the financial support of the visit of Andrea Perali (University of Camerino) to Arkady Shanenko (University of Antwerpen).

Yours sinerely,

Andrea Perali

Camerino, 22/05/2012

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