

SCIENTIFIC REPORT ON ESF-PESC EXPLORATORY WORKSHOP

"New phenomena in superfluidity and superconductivity"

1. Executive summary

The Workshop was convened by Prof. Giancarlo Strinati and the local organizer was Dr. Pierbiagio Pieri, both from the Department of Physics of the University of Camerino, Italy. The event was held in the D'Avack building at the University of Camerino on July 4-5, 2005.

It involved 20 speakers plus 8 additional participants, representing 7 European countries plus the U.S.A., Russia, and Japan.

Of the talks, 5 were experimental and 15 theoretical.

Representatives essentially from all world leading experimental groups attended the Workshop, thus feeding their latest results in the discussion. Elder scientists, who pioneered the main topics of discussion, were present together with young researchers working on the latest developments.

Discussion constituted a major part at the Workshop. To this end, each speaker was assigned 30 minutes for presentation and 15 additional minutes for questions and discussion.

There was also a round table at the end of the Workshop, which was led by eminent (2 experimental and 2 theoretical) scientists and where the participants summarized what they have agreed and what they still disagree on, as well as identified several aspects that need to be deepened in the future. Both the discussion time after each talk and the round-table discussion were quite dense and challenging, even beyond expectation.

Because the ESF representative, Prof. Louis Laurent, was unable to attend the Workshop, a shortened version of the ESF presentation was delivered by the convenor himself with the support of a Power-Point document provided by ESF.

Presentations were organized so as to cover a wide range of topics and disciplines in the field of the BCS-BEC crossover, with the purpose of stimulating cross fertilization among the different disciplines. To this end, specialists in atomic and optical physics, condensed matter, many-body effects, nuclear physics, and Quantum Monte Carlo simulations were all actively involved in the Workshop. This wide range of competences was especially noted in the course of the round-table discussion, where specialists in specific fields were asked to intervene at the appropriate time to convey their expertise in the discussion.

During the various discussions, the following topics were extensively explored and debated:

(i) Consensus has been eventually reached about the evidence of superfluidity in trapped Fermi gases through various probes, and especially by the recently detected presence by the MIT group of vortices on the BCS side of the crossover;

(ii) Measurements of collective excitations still remain puzzling (even though consensus has been lately reached between the experimental groups at Duke and Innsbruck on the values of the frequencies at the unitarity limit). What still remains to be settled is the agreement between the experimental data and the alternative theoretical calculations based, respectively, on Quantum Monte Carlo simulations and standard BCS mean-field theory;

(iii) The need to study the occurrence of the effects due to the composite nature of the bosons on the near BEC side of the crossover has been emphasized, on top of the well-known beyond-mean-field effects occurring for point-like bosons;

(iv) Extensive discussions have been made on the correct physical procedure for obtaining from the many-body diagrammatic structure in the zero-density limit the value $a_m=0.6a$ between the scattering lengths of the dimers (a_m) and of the fermions (a) which constitute the dimers themselves;

(v) The validity of the single-channel model has been settled to effectively describe the broad Fano-Feshbach resonances that are currently exploited to realize the BCS-BEC crossover experimentally;

(vi) The need to further explore the calibration of temperature across the BCS-BEC crossover and the related evolution of the jump of the specific heat at the critical temperature has been pointed out.

Abstracts and slides of the talks presented at the Workshop are available at the Workshop web page:

<http://fisica.unicam.it/nqs2005/workshop.php>

2. Scientific content of the event

Lately, it has been a very exciting time for the field of superfluidity and superconductivity, and in particular for the BCS-BEC crossover.

This topic was signaled as one of the ten "breakthroughs of the year" in the issue of Science of December 17, 2004, and has constituted the main focus of the present Workshop.

In this respect, the Workshop was particularly timely since it has been able to conjugate the banner year 2004 for ultracold condensate gases with the ongoing celebrations of the World Year of Physics 2005 to commemorate the Einstein's 1905 "*annus mirabilis*" (the name of Einstein occurring specifically in the acronym BEC standing for Bose-Einstein Condensate) .

This breakthrough was especially possible because a number of experimental groups around the world have recently performed extremely important experiments with trapped Fermi atoms (notably on the pairing gap, the condensate density, the specific heat, and the presence of vortices).

Even more numerous, theoreticians have rushed interpreting these experiments as well as suggesting new ways to catch the "smoking gun" of superfluidity in these neutral systems.

The systematic use of molecular Fano-Feshbach resonances has made it possible to induce fermions (which are prevented from condensing by the Pauli exclusion principle) to pair up into Cooper pairs (on the BCS side of the crossover) and into molecules (on the BEC side of the crossover), which can now condense similarly to bosons.

This is a "frontier research", that will have most probably implications for high-temperature superconductivity, nuclear physics, and possibly other fields too. So far, this constitutes mostly "basic research", but (even unpredicted) applications may follow in the future.

European research groups had a prominent role in this field over the past years, with major contributions both in theory and experiments. In this respect, the present Workshop has contributed strengthening the European leadership in this novel and important field of Physics, laying at the same time the ground for possible future collaborations among the participants.

3. Assessment of the results and contribution to the future direction of the field

Now that vortices have been detected on the BCS side of the crossover, so that there are no longer serious doubts that the Fermi gas has entered the superfluid phase, it has been agreed that it will be important and timely to reconsider previous measurements on different aspects of the BCS-BEC crossover in trapped Fermi gases.

In particular, it will be important to extend those measurements to wider ranges of the experimental parameters (especially coupling and temperature) as well to improve their precision.

The Josephson effect has further been signaled as the definite proof of the occurrence of superfluidity in trapped Fermi gases, very much like as it occurs in conventional superconductors.

Preliminary measurements have been presented exploiting the density imbalance between the two fermionic species coupled by pairing effects. This will certainly constitute an important research topic in the near future, with various experimental groups preparing to explore its consequences in trapped Fermi atoms. Close connections with the by-layer systems realized with semiconducting materials have also been emphasized at the Workshop.

Along similar lines, imbalance due to differences in the atomic masses have also been indicated as a topic of definite interest in the near future.

The agreed universality features related to the broad Fano-Feshbach resonances have stimulated discussion on the possible connection of the BCS-BEC crossover in trapped Fermi gases with high- T_c materials. In particular, the radio-frequency spectroscopy measurements, which have already suggested the occurrence of a pseudo-gap above the critical temperature in trapped Fermi gases, could specifically highlight this connection with high- T_c materials. In this respect, the importance to further refine and extend these measurements has been pointed out at the Workshop.

Again in connection with alternative physical systems (like He3), the importance of exploring symmetries of the gap parameter different from s-wave (in particular the p-wave symmetry) has been evidenced at the Workshop.

Finally, it is realized that a close connection between the physics of trapped Fermi atoms and condensed-matter systems can be established when the Fermi atoms are trapped in optical lattices. In particular, artificial condensed-matter systems can be generated in this way by introducing only those degrees of freedom that are believed to be essential for the expected physics. Ongoing progresses along these lines have been discussed at the Workshop, together with the wide range of future manipulations (like magnetic effects, the role of controlled disorder, etc.).

4. Final programme

Monday, July 4, 2005

- 08:30-08:45 **Welcome** to the participants
- 08:45-09:00 **Presentation of the ESF**
- 09:00-09:45 **F. Chevy**
Expansion of an ultra-cold Fermi gas in the BEC-BCS crossover regime
- 09:45-10:30 **A. Turlapov**
Dynamics and thermodynamics of a strongly-interacting Fermi gas
- 10:30-11:00 Coffe break
- 11:00-11:45 **G. Bruun**
Viscosity and Thermal Relaxation for a resonantly interacting Fermi gas
- 11:45-12:30 **H. Stoof**
Dressed Feshbach molecules in the BEC-BCS crossover
- 12:30-14:15 Lunch
- 14:15-15:00 **M. Greiner**
Fermi Condensates
- 15:00-15:45 **M. Zwierlein**
Vortices and Superfluidity in Strongly Interacting Fermi Gases
- 15:45-16:30 **R. Combescot**
Collective mode frequencies of a trapped Fermi gas in the BEC-unitarity crossover
- 16:30-17:00 Coffee break
- 17:00-17:45 **P. Pieri**
BCS-BEC crossover with ultracold Fermi atoms
- 17:45-18:30 **M. Kagan**
Composite fermions and quartets in ultracold gases and in high- T_c superconductors
- 18:30-19:15 **C. Mora**
BEC-BCS crossover and four-body problem in a quasi-one-dimensional cold fermion gas
- 19:15-20:00 **S. Kokkelmans**
Self-consistent description of BCS-BEC crossover including two scattering poles

Tuesday, July 5, 2005

- 09:15-10:00 **G. Shlyapnikov**
Diatomic molecules in Fermi Gases
- 10:00-10:45 **G. Astrakharchik**
Momentum distribution and condensate fraction of a Fermi gas in the BCS-BEC crossover
- 10:45-11:15 Coffee break
- 11:15-12:00 **C. Castellani**
Strongly Correlated Superconductivity and Pseudogap Phase in multi-band systems close to Mott transition
- 12:00-12:45 **K. Goral**
BCS-BEC crossover in ultracold gases of 40K
- 12:45-14:30 Lunch
- 14:30-15:15 **F. Pistolesi**
Superharmonic Josephson relation at $0-\pi$ -junction transition
- 15:15-16:00 **P. Schuck**
Fermion-Boson scattering in a Fermion-Boson environment
- 16:00-16:45 **M. Urban**
Two-fluid dynamics of a superfluid Fermi gas at finite temperature
- 16:45-17:15 Coffee break
- 17:15-18:00 **M. Szymanska**
BEC of composite bosons in semiconductor microstructures
- 18:00-18:45 **A. Hamilton**
Bilayer Quantum Hall Systems: From spontaneously broken symmetries to excitonic superfluidity
- 18:45-20:00 **Round Table**
Emerging Opportunities for Experiments and New Focuses for Theory
Chairmen: R. Grimm, M. Inguscio, L. Pitaevskii, G. Shlyapnikov

5. Final list of participants

Alexander Altmeyer
e-mail: alexander.altmeyer@uibk.ac.at
Innsbruck University, Institute of Experimental Physics
Universitaet Innsbruck
Institut fuer Experimentalphysik
Technikerstrasse 25/4
A 6020 Innsbruck, Austria
Tel: +435125076345
Fax: +435125072921

Dr. Grigory Astrakharchik
e-mail: astra@science.unitn.it
Dipartimento di Fisica, Università di Trento
Via Sommarive, 38050 Povo (TN), Italy
Tel: +390461881633
Fax: +390461882014

Dr. Georg M. Bruun
e-mail: bruun@nbi.dk
NORDITA, Blegdamsvej 17
2100 København Denmark
Tel: +45 3532 5432
Fax: +45 3538 9157

Prof. Claudio Castellani
e-mail: claudio.castellani@roma1.infn.it
Dipartimento di Fisica Università La Sapienza
P.le A.Moro, 2 00185 Roma, Italy
Tel: +390649914292
Fax: +39064957697

Dr. Frederic Chevy
e-mail: chevy@lkb.ens.fr
Département de physique de l'Ecole Normale Supérieure
Laboratoire Kastler Brossel
24 rue Lhomond, 75231, Paris, France
Tel: +33 1 44 32 33 07
Fax: +33 1 44 32 00 76

Prof. Roland Combescot
e-mail: combesco@lps.ens.fr
Laboratoire de Physique Statistique Ecole Normale Supérieure
24 rue Lhomond 75231 Paris Cedex 05, France
Tel : 33 1 44 32 35 00
Fax: 33 1 44 32 34 33

Dr. Krzysztof Goral
e-mail: Krzysztof.Goral@physics.ox.ac.uk
Clarendon Laboratory
Department of Physics
University of Oxford
Parks Road Oxford OX1 3PU United Kingdom
Tel: +44 1865 272 276
Fax: +44 1865 272 400

Dr. Markus Greiner
e-mail: markus.greiner@colorado.edu
JILA, University of Colorado
440 UCB Boulder, CO 80309-0440, USA
Tel: +1 303 492 5735
Fax: +1 303 492 4876

Prof. Rudolf Grimm
e-mail: rudi@ultracold.at
Institute of Experimental Physics
University of Innsbruck, 6020 Innsbruck, Austria
Institute of Quantum Optics and Quantum Information (IQOQI)
Austrian Academy of Sciences, 6020 Innsbruck, Austria
Tel.: ++43 (0)512 507 6300
Fax: ++43 (0)512 507 2921

Prof. Alex Hamilton
e-mail: alex.hamilton@unsw.edu.au
Cavendish Laboratory, Madingley Road,
Cambridge CB3 0HE, United Kingdom
Tel: +44 880625566

Prof. Massimo Inguscio
e-mail: inguscio@lens.unifi.it
Università di Firenze
Dipartimento di Fisica
Via Nello Carrara 1, 50019 Sesto Fiorentino, Italy
Tel: +390554572483
Fax: +390554572451

Prof. Maxim Yu. Kagan
e-mail: kagan@kapitza.ras.ru
P.L.Kapitza Institute for Physical Problems,
Ul. Kosygina 2, Moscow 119334, Russia
Tel: +7 095 137 79 85
Fax: +7 095 938 20 30

Dr. Servaas Kokkelmans
e-mail: s.kokkelmans@tue.nl
Department of Physics
Eindhoven University of Technology
P.O.Box 513 5600 MB Eindhoven The Netherlands
Tel: +31 40 247 3357
Fax: +31 40 245 6050

Prof. Kathryn Levin
e-mail: levin@jfi.uchicago.edu
James Franck Institute
University of Chicago
5640 Ellis Ave Chicago
Ill 60637 USA
Tel: +1 773 702 7186
Fax: +1 773 834 0471

Dr. Christophe Mora
e-mail: mora@thphy.uni-duesseldorf.de
Institut fuer Theoretische Physik
Heinrich-Heine Universitaet
Universitaetsstr 1 D-40225 Duesseldorf, Germany
Tel: +49 211 81 14285
Fax: +49 211 81 15630

Prof. Philippe Nozieres
e-mail: nozieres@ill.fr
Institut Laue Langevin
BP 156 F-38042 GRENOBLE cédex France
Tel: +33 04 76 20 71 11
Fax: +33 04 76 88 24 16

Dr. Yoji Ohashi
e-mail: yohashi@sakura.cc.tsukuba.ac.jp
University of Tsukuba (Physics department)
1-1-1 Ten-nou-dai
305 Tsukuba, Ibaraki, Japan
Tel: +81 298 53 4275
Fax +81 298 53 4492

Dr. Pierbiagio Pieri
e-mail: pierbiagio.pieri@unicam.it
Dipartimento di Fisica
Universita' di Camerino
Via Madonna delle carceri 9
62032 Camerino (MC) Italy
Tel: +39 0737 402534
Fax: +39 0737 402853

Dr. Fabio Pistolesi
e-mail: pistoles@grenoble.cnrs.fr
Laboratoire de Physique et Modélisation des Milieux Condensés, CNRS-UJF
LPM2C- Maison des Magistères - C.N.R.S. 25, avenue des Martyrs
B.P. 166 - 38042 GRENOBLE Cedex France
Tel: +33 4 76 88 74 96
Fax: +33 4 76 88 79 83

Prof. Lev Pitaevskiy
e-mail: lev@science.unitn.it
Dipartimento di Fisica, Università di Trento
Via Sommarive, 38050 Povo (TN), Italy
Tel: +390461881544
Fax: +390461882014

Prof. Peter Schuck
e-mail: schuck@ipno.in2p3.fr
Groupe de Physique Theorique
Institut de Physique Nucleaire
91406 Orsay Cedex, France
Tel: +33 1 69 15 79 29
Fax: +33 1 69 15 77 48

Prof. Gora Shlyapnikov
e-mail: shlyapn@ipno.in2p3.fr
Laboratoire de Physique Theorique et Modeles Statistique
Universite Paris-Sud XI
Bat. 100, 91405 Orsay Cedex France
Tel: +33 1 69 15 79 46
Institute phone: +33 1 69 15 73 49
Fax: +33 1 69 15 65 25

Prof. Henk T.C. Stoof
e-mail: H.T.C.Stoof@phys.uu.nl
Utrecht University
Department of Physics and Astronomy
Institute for Theoretical Physics
Leuvenlaan 4, 3584 CE Utrecht, The Netherlands
Tel: +31 30 2531871
Fax: +31 30 2535937

Prof. Giancarlo C. Strinati
e-mail: giancarlo.strinati@unicam.it
Dipartimento di Fisica
Università di Camerino
Via Madonna delle carceri 9
62032 Camerino (MC) Italy
Tel: +39 0737 402541
Fax: +39 0737 402853

Dr. Marzena H. Szymanska
e-mail: mhs24@hermes.cam.ac.uk
Theory of Condensed Matter, Cavendish Laboratory
Cambridge University
Cambridge, United Kingdom
Tel: +44 1223 33 74 61
Fax: +44 1223 33 73 56

Dr. Andrey Turlapov
e-mail: Andrey.Turlapov@phy.duke.edu
Duke University
Department of Physics
107 Physics Building
Box 90305 Durham NC 27708, USA
Tel: +1 919 660 2516
Fax: +1 919 660 2525

Dr. Michael Urban
e-mail: urban@ipno.in2p3.fr
Institut de Physique Nucléaire
Batiment 100 A
15 rue Georges Clémenceau
F-91406 Orsay cedex, France
Tel: +33 1 69 15 62 47
Fax: +33 1 69 15 77 48

Martin Zwierlein
e-mail: zwierlei@mit.edu
Massachusetts Institute of Technology
Room 26-265
77 Massachusetts Avenue
Cambridge MA 02139 USA
Tel: +1 617 253 6677

6. Statistical information on participants

Age:

26-30: 4
31-35: 9
36-40: 3
41-45: 3
46-50: 0
51-55: 3
55-60: 3
60-65: 1
65-70: 0
70-75: 2

Gender:

M: 26

F: 2

Country of original Research Institution:

Austria: 2

Denmark: 1

France: 7

Germany: 1

Japan: 1

Italy: 6

Netherlands: 2

Russia: 1

United Kingdom: 3

USA: 4