Julien Garaud

Postdoctoral Researcher in Condensed Matter Theory

Department of Theoretical Physics,
KTH-Royal Institute of Technology
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Birth date May 23, 1982 **Citizenship** French

Education

2006–2010 **Ph.D. in Physics**, *Laboratoire de Mathémathiques et Physique Théorique (LMPT), Université François Rabelais*, Tours, France.
Superconducting Vortices in Weinberg–Salam theory. (Advisor: Pr. Mikhail Volkov)

2004–2006 **Master of Science**, *Université François Rabelais*, Tours.
Non-linear Phenomena. Research Training Period : Spinning Magnetic Monopoles.

2001–2004 **Bachelor of Science**, *Université François Rabelais*, Tours.

Academic positions

Research Positions

Since 09/2014 **Postdoctoral Researcher**, *KTH-Royal Institute of Technology*, Stockholm, Sweden .
Superconductivity, superfluidity, and topological defects (Advisor: Dr. Egor Babaev)

11/2010–08/2014 **Postdoctoral Researcher**, *University of Massachusetts*, Amherst MA, USA .
Topological defects in multi-component superconductors (Advisor: Dr. Egor Babaev)

Teaching Activities

2013 **Substitute teachings**, *KTH-Royal Institute of Technology*, Stockholm, Sweden.
Graduate level Condensed matter course (including developing full set of lecture notes).
See examples of my lecture notes at :
http://www.theophys.kth.se/~garaud/files/Lecture-notes/Lecture-notes-1.pdf
http://www.theophys.kth.se/~garaud/files/Lecture-notes/Lecture-notes-2.pdf

2011 **Substitute teachings**, *University of Massachusetts*, Amherst, MA.
Undergraduate Electricity and magnetism

2006–2010 **Teaching Assistant (Lectures and Labs)**, *Université François Rabelais*, Tours, France.
Undergraduate Mechanics, Electrodynamics, Fluid Mechanics, Electricity (total 290 h)

Scientific Activity

Online scientific profiles

[Google Scholar] http://scholar.google.com/citations?user=z2FrtfkAAAAJ&hl=en

[ArXiv] http://arxiv.org/a/garaud_j_1

Research coverage in general audience media

[i] Based on J. Carlström, **J. Garaud** and E. Babaev [15] :
Physicists Unveil New Kind of Superconductivity (2011) –
http://www.physorg.com/news/2011-10-physicists-unveil-theory-kind-superconductivity.html,
http://www.cryogenicsociety.org/15558/news/theory_for_type_15_superconductivity/,
http://physicsforme.wordpress.com/2011/10/24/a-new-kind-of-superconductivity/,
find more links here: http://www.theophys.kth.se/~garaud/news.html#nov2011

Publications

[1] D. F. Agterberg and **J. Garaud**
Checkerboard order in vortex cores from pair density wave superconductivity
Submitted to *Phys. Rev. Lett.* [cond-mat.supr-con] arXiv:1412.5101.

[2] **J. Garaud** and E. Babaev
Vortex chains due to nonpairwise interactions and field-induced phase transitions between states with different broken symmetry in superconductors with competing order parameters
*P*hys. Rev. B **91**, 014510 (2015). [cond-mat.supr-con] arXiv:1411.6656.

[3] **J. Garaud** and E. Babaev
Vortex matter in $\mathrm{U}(1) \times \mathrm{U}(1) \times \mathbb{Z}_2$ phase-separated superconducting condensates
Phys. Rev. B **90**, 214524 (2014). [cond-mat.supr-con] arXiv:1410.2985.

[4] D. F. Agterberg, E. Babaev and **J. Garaud**
Microscopic prediction of skyrmion lattice state in clean interface superconductors
Phys. Rev. B **90**, 064509 (2014). [*Kaleidoscope*] [cond-mat.supr-con] arXiv:1403.6655.

[5] **J. Garaud** and E. Babaev
Topological defects in mixtures of superconducting condensates with different charges
Phys. Rev. B **89**, 214507 (2014). [cond-mat.supr-con] arXiv:1403.3373.

[6] **J. Garaud** and E. Babaev
Domain walls and their experimental signatures in $s + is$ superconductors
Phys. Rev. Lett. **112**, 017003 (2014). [cond-mat.supr-con] arXiv:1308.3220.

[7] **J. Garaud**, K. Sellin, J. Jäykkä and E. Babaev
Skyrmions induced by dissipationless drag in $\mathrm{U}(1) \times \mathrm{U}(1)$ superconductors
Phys. Rev. B **89**, 104508 (2014). [cond-mat.supr-con] arXiv:1307.3211.

[8] **J. Garaud**, E. Radu and M. S. Volkov
Stable Cosmic Vortons
Phys. Rev. Lett. **111**, 171602 (2013). [hep-th] arXiv:1303.3044.

[9] **J. Garaud**, J. Carlström, E. Babaev and M. Speight
Chiral $\mathbb{C}P^2$ skyrmions in three-band superconductors
Phys. Rev. B **87**, 014507 (2013). [*Editors' Suggestion*] [cond-mat.supr-con] arXiv:1211.4342.

[10] **J. Garaud**, D. F. Agterberg and E. Babaev
Vortex coalescence and type-1.5 superconductivity in Sr_2RuO_4
Phys. Rev. B **86**, 060513(R) (2012). [*Rapid Comm.*] [cond-mat.supr-con] arXiv:1207.6395.

[11] **J. Garaud** and E. Babaev
Skyrmionic state and stable half-quantum vortices in chiral p-wave superconductors
Phys. Rev. B **86**, 060514(R) (2012). [*Rapid Comm.*] [cond-mat.supr-con] arXiv:1201.2946.

[12] E. Babaev, J. Carlström, **J. Garaud**, M. Silaev and J. M. Speight
Type-1.5 superconductivity in multiband systems: magnetic response, broken symmetries and microscopic theory. A brief overview
Physica C **479**, 2–14 (2012). [cond-mat.supr-con] arXiv:1110.2744.

[13] J. Carlström, **J. Garaud** and E. Babaev
Length scales, collective modes, and type-1.5 regimes in three-band superconductors
Phys. Rev. B **84**, 134518 (2011). [cond-mat.supr-con] arXiv:1107.4279.

[14] **J. Garaud**, J. Carlström and E. Babaev
Topological solitons in three-band superconductors with broken time reversal symmetry
Phys. Rev. Lett. **107**, 197001 (2011). [cond-mat.supr-con] arXiv:1107.0995.

[15] J. Carlström, **J. Garaud** and E. Babaev
Semi-Meissner state and nonpairwise intervortex interactions in type-1.5 superconductors
Phys. Rev. B **84**, 134515 (2011). [cond-mat.supr-con] arXiv:1101.4599.

[16] **J. Garaud** and M. S. Volkov
Stability analysis of Superconducting Electroweak Strings
Nucl. Phys. B **839**, 310–340 (2010). [hep-th] arXiv:1005.3002.

[17] **J. Garaud** and M. S. Volkov
Superconducting non-Abelian vortices in Weinberg–Salam theory – electroweak thunderbolts
Nucl. Phys. B **826**, 174–216, (2010). [hep-th] arXiv:0906.2996.

[18] **J. Garaud** and M. S. Volkov
Stability analysis of the twisted superconducting semilocal strings
Nucl. Phys. B **799**, 430–455, (2008). [hep-th] arXiv:0712.3589.

Unpublished Works

[19] **J. Garaud**
Superconducting vortices in Weinberg–Salam theory, Ph.D. thesis (2010). [tel-00544753].
Laboratoire de Mathémathiques et Physique Théorique, Université de Tours.

[20] **J. Garaud**
Spinning magnetic monopoles, Master thesis (2006).
Laboratoire de Mathémathiques et Physique Théorique, Université de Tours.

Contribution to scientific libraries

[21] **J. Garaud** and A. W. Steiner
ode_bv_multishoot.h (included into O2scl), (2008).
A C++ abstract class template solver for Boundary Value Problems.
Included in the C++ scientific library O2scl (available at http://o2scl.sourceforge.net).
This is an advanced solver that I developed for boundary value Ordinary Differential Equations problems based on a multiple shooting scheme.

Other Professional activities

Referee **for *Physical Review Letters*, *Physical Review A*, *Physical Review B*, *Physical Review E*, and *Physics Letters A* .**

Invited talks

Mar. 2014 **Probing unconventional superconducting states with topological defects**, *LPS*, Orsay.
Feb. 2014 **Domain-walls and Skyrmions in multi-component superconductors**, *LMPT*, Tours.
Apr. 2013 **Topological defects in multi-component superconductors**, *GREMAN*, Tours.
Apr. 2013 **Topological defects in multi-component superconductors**, *LPTMC*, Paris.
Mar. 2013 **Topological solitons in superconductors with BTRS**, *LPS*, Orsay.
Dec. 2012 **Skyrmions in multi-component superconductors**, *LOMA*, Bordeaux.
Oct. 2012 **Topological solitons in multi-component superconductors**, *KTH*, Stockholm.
Apr. 2012 **Topological solitons in superconductors with BTRS**, *UMass*, Amherst.
Sep. 2011 **Ground-states in multi-component superconductors**, *LMPT*, Tours.
Apr. 2011 **Non-pairwise interactions in type–1.5 superconductors**, *UMass*, Amherst.
Oct. 2010 **Superconducting vortices in electroweak theory**, *KTH*, Stockholm.
Aug. 2010 **Superconducting electroweak vortices**, Oldenburg.
Nov. 2006 **Spinning magnetic monopoles and vortices**, *MAPMO*, Orléans.

Contributed talks

Sep. 2015 **Vortex matter in nanostructured superconductors (VORTEX IX)**, Rhodes.
TBA

Jun. 2014 **New Horizon of Strongly Correlated Physics (NHSCP2014)**, *ISSP*, Tokyo.
Topological defects and their experimental signature in s+is superconductors

Sep. 2013 **Vortex matter in nanostructured superconductors (VORTEX VIII)**, Rhodes.
Topological excitations in $s + is$ superconductors and their experimental signatures

Aug. 2013 **Workshop Superconductivity: the Second Century**, Nordita, Stockholm.
Topological excitations in $s + is$ superconductors

Mar. 2013 **March meeting of the APS**, Baltimore, MD.
Chiral $\mathbb{C}P^2$ skyrmions in three-band superconductors and layered superconducting structures

Dec. 2012 **Quantized flux in tightly knotted and linked systems**, *Newton Institute*, Cambridge.
$\mathbb{C}P^2$ baby-skyrmions in three-component superconductors (talk and poster)

Mar. 2012 **March meeting of the APS**, Boston, MA.
Topological solitons in three-band superconductors with broken time reversal symmetry

Sep. 2011 **Vortex matter in nanostructured superconductors (VORTEX VII)**, Rhodes.
Magnetic response of multi-component type-II and type-1.5 superconductors (poster)

Mar. 2011 **March meeting of the APS**, Dallas, TX.
Ground states of multi-band type-I and type-1.5 superconductors and interlaced type-I/type-II layered superconducting structures in external magnetic field

Nov. 2008 **Workshop knots and vortons III**, *LMPT*, Tours.
Superconducting vortices in electroweak theory

May 2007 **Workshop knots and vortons II**, *LMPT*, Tours.
Stability of superconducting semilocal vortices

Scientific and technical skills

General mathematical expertise

Modelisation and numerical simulations of complex systems – Linear/non-linear Partial Differential Equations – Finite elements – Finite differences – Optimization – Monte Carlo simulations – Parallel tempering

Computer skills

Scientific Progr. : C/C++, FreeFem++.
Libraries : FreeFem++, Boost, FFTW, Qt4.
Devel. : autotools, svn.
OS : Linux, Mac OS X.
Other : TEX, LATEX, html/css, Doxygen.

System Progr. : bash, perl, sbatch, qsub.
Parallelism : MPI.
Vizualization : Gnuplot, VTK, Paraview, Qt4.
Software : Mathematica, Maple.

Spoken languages

French **Mother tongue**
English **Fluent**
Spanish **Basic knowledge**

Last update : 14/02/2015

Recent research interest

I am interested in various aspects of superconductivity, cold atomic systems and magnetism. I am in particular interested in the physical properties and observability of various kind of topological defects that may be created during phase transitions occurring therein. Associated with broken symmetries, topological defects are ubiquitous in physics, as they arise in a very broad context including early universe cosmology, particle physics, solid state, condensed matter physics and more. They are believed to drive certain phase transitions in many physical system, as for example vortices in superfluids and superconductor, dislocation in liquid crystals, domain-walls or skyrmions in magnets, and much more. During my earlier works, as Ph.D. student in high-energy physics, dealt with vortex solutions of the Weinberg–Salam theory of electroweak interactions, that may have been produced during early universe phase transitions.

After graduating four years ago, I have been working in the fields of superconductivity and cold atomic systems. I have been interested there, in studying topological defects and their observational properties in systems with multiple broken symmetries, such as multi-component superfluids, exotic superconducting states and more. These are typically modelled by multiple order parameters or order parameters with multiple components. Due to the existence of multiple length-scales and higher broken symmetries, the subtle interplay between multiple these order parameters or their components yields a very rich physics that is typically absent in single-component systems. The resulting properties may in general help to probe the underlying physics, as for example pairing mechanisms of new or unconventional materials.

Giving valuable insight on the (unconventional) broken symmetries and phase transitions, the topological defects I have been studying, as for example vortices, domain-walls, skyrmions, etc, may be used as observable markers that signal multiple broken symmetries related to unconventional states of superconductors, superfluids, ultra-cold atoms, magnets and more.

Brief summary of recent results

- Prediction of a field-induced charge density wave order originating in competing pair density wave and d-wave superconducting states [1]. This order provides strong evidence for pair density wave order in the pseudogap phase of the cuprates.
- Investigation of magnetization properties of superconducting systems with competing order parameters [2, 3]. That is, superconductors with phase separation driven by intercomponent density-density interaction. We demonstrate there, that multi-body intervortex interactions can be strongly non-pairwise.
- Prediction of unconventional magnetic response in interface superconductors with a strong Rashba spin-orbit coupling [4]. We demonstrate microscopically that in the clean limit interface superconductors, such as $SrTiO_3/LaAlO_3$, are ideal candidates to observe defects characterized by homotopy invariants of $S^2 \to S^2$ maps, in addition to those of $S^1 \to S^1$ maps.
- Identification of topological properties of flux-carrying topological defects in mixtures of charged condensates that have different (commensurate) electric charges [5]. Such situation is expected to appear for example in liquid metallic deuterium.
- Prediction of experimental signatures of domain wall structures in superconductors with broken time-reversal symmetry originating in $s+is$ gap structure [6]. This could apply in particular to $Ba_{1-x}K_xFe_2As_2$ at certain doping. We discuss experimental set-ups to stabilize domain walls and measure their influence on the magnetization processes.
- Discovery of stable vortons within Witten model [8]. These are vortex loops stabilize against collapse by permanent currents along the vortex line. These objects potentially apply to various condensed matter physics systems but also to early universe cosmology or high density QCD.
- Prediction of a new phase in $U(1) \times U(1)$ superconductors with interspecies dissipationless drag [7]. The dissipationless current interaction renders vortices unstable in favour of skyrmions whose long-range interaction substantially modifies magnetization processes.
- Explanation of vortex coalescence in Sr_2RuO_4 [10]. We argued that observed vortex coalescence in Sr_2RuO_4 can be explained by non-monotonic interactions originating in multiband nature of Sr_2RuO_4 .

These predictions received recently strong experimental support from μSR measurements in Phys. Rev. B 89, 094504 (2014).

- Prediction of skyrmionic state in chiral p-wave superconductors [11].
- Discovery of new kind of stable topological solitons in three-component superconductors with spontaneously Broken Time-Reversal Symmetry [14, 9]. These flux carrying topological defects, characterized by $\mathbb{C}P^2$ topological invariants are skyrmions. Their formation could signal BTRS, for example in some iron based superconductors, as well as in Josephson-coupled bi-layers of $s_\pm$ and ordinary s-wave superconductor.
- Findings of a new kind of collective mode in three-band superconductors with broken time reversal symmetry [13]. This collective mode is associated with mixed phase-density collective excitations. Thus it is different from the Legget's mode.
- Finding new kind of multibody intervortex forces in multiband superconductors [15].

Details of academic works

Ph.D. thesis – Defended September 29, 2010

Title *Superconducting vortices in Weinberg–Salam theory*

Supervisor Professor M. S. Volkov

Referees Prof. C. Bachas, Prof. M. Shaposhnikov, Prof. P. Sutcliffe.

Jury Prof. C. Bachas, Dr. M. Chernodub, Dr. P. Grandclément, Prof. A. Niemi, Prof. M. Shaposhnikov, Prof. M. S. Volkov.

Abstract This dissertation provides a detailed analysis and a subsequent discussion of the stability properties of new vortex-like solutions of the bosonic sector of the electroweak theory. The new solutions are current carrying generalizations of embedded Abrikosov–Nielsen–Olesen vortices. Such vortices carry an electric current whose typical scale is the *billion* of Ampères.

http://tel.archives-ouvertes.fr/tel-00544753/fr/ (in French)

Master thesis – Defended June 26, 2006

Title *Spinning magnetic monopoles*

Supervisor Professor M. S. Volkov

Abstract This dissertation discuss the possibility to construct generalizations of the 't Hooft–Polyakov magnetic monopole, in Yang–Mills–Higgs theory. Static axially symmetric deformations are considered.