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MARIE SKŁODOWSKA-CURIE ACTIONS

Individual Fellowship (IF)
Call: H2020-MSCA-IF-2015

PART B

"TACSS"

"Topological Aspect of Coherent Superconducting Spintronics"

This proposal is to be evaluated as:

Standard EF

Topological Aspects of Coherent Superconducting Spintronics (TACSS)

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Abstract

Majorana modes attracted utmost interests over the last decade. This is due to the decoherence-free opportunities these modes offer in term of quantum computation, in addition to their possible generation in actual experiments mixing superconducting and spin interactions. Nevertheless, these experiments inherently present difficulties in interpretations, as they require to take into account interfaces, boundaries and impurities. Therefore these usual experimental constraints have to be mixed with strong spin-orbit and spin-splitting interactions in superconductors, in order for the materials to reach their topological regime. At the moment there is no complete understanding of the phenomenologies associated to these extreme conditions.

During this project, entitled Topological Aspects of Coherent Superconducting Spintronics (TACSS), I aim at introducing and developing quasi-classic methodologies to deal with strong spin interactions in superconducting hetero-structures. Topological effects in superconductors with strong spin-orbit and spin-splitting effects will be derived and illustrated in the quasi-classic methodology. Also, a non-equilibrium description of superconducting spintronics will be developed, when charges and spins interact coherently. Finally, the developed methods will be applied to concrete experiments, ranging from material science to quantum state manipulation.

The project will fill a gap in material science, since it will especially focus on the difficulties to observe topological effects in experimentally accessible hetero-structures. In addition, the quasi-classic methods will be helpful for the mesoscopic physics community, discussing the spin interactions in quite generic terms. Finally, the time-dependent transport formalism will allow to design experiments in the emergent field of superconducting spintronics, when the charge and the spin influence each other in a coherent way.

Keywords: superconductivity ; mesoscopic ; spin-orbit ; spintronics ; Majorana modes ; magneto-electric ; hetero-structure ; quasi-classic transport ; gauge theory ; phase-space ;

Contents

List of participants

Participants	Short Name	Ac.	N.-Ac.	Country	Dept. / Division / Laboratory	Supervisor	Role of partner organisation
BENEFICIARY: Material Physics Center	MPC	✓		Spain	Electronic Properties at the Nanoscale Research Line (Mesoscopic Physics Group)	F. Sebastián BERGERET	Beneficiary. Host of most of main research activity. Provider of computing resources
PARTNER ORGANISATION: Rheinisch-Westfälische Technische Hochschule Aachen	RWTH	✓		Germany	Quantum Information Group	Fabien HASSLER	Host Secondment

1 Excellence

1.1 Quality, innovative aspects and credibility of the research

★ **Introduction** ★

The quest for Quantum Computers is a major driving force for the research in Physics, especially in Condensed Matter and Material Science, in charge of studying the exotic states of matter and interactions that could serve as basis for practical implementations. Recently, the so-called Topological Quantum Computation[1] has been proposed as a basis for robust, fault-tolerant, quantum computing. In this approach, qubits are encoded through the creation, manipulation and fusion of quasiparticles called anyons (a generalisation of the concept of bosons and fermions). The simplest form of anyons are called Majorana modes[2].

Majorana modes appear when superconductivity is induced on low dimensional materials with strong spin-orbit and spin-splitting interactions via proximity effect[3]. The practical realisation of these systems faces many important technical challenges, such as finding materials with strong enough spin interactions, creating superconducting heterostructures with high-quality interfaces, tuning the chemical potential to the topological sector, growing materials without impurities, etc. In addition, the topological aspects of these realistic solid state devices exhibiting Majorana modes are not completely understood. There are important open questions regarding the role of interactions, impurities and temperature on the topological phases.

There are thus great expectations to obtain theoretical tools able to combine the material dependent aspects of experimental setups with the fundamental perspectives in topological states of matter. The present project aims at developing such tools, and applying them to propose original experiments.

★ **State of the art** ★

Majorana modes are characterised by being identical to their own anti-particles, making them neither charged nor spin-polarised. So far, these quasiparticles have proven to be elusive, as they can only appear in systems with particle-hole symmetry, for example in a superconductor, but without neither spin rotation symmetry nor time reversal symmetry, and manifest as twins quasi-particles at the edge of low-dimensional structures. These conditions naturally appear in a bulk spinless p-wave superconductor. This long-thought state-of-matter has never been found in nature[4], but can be artificially induced through proximity effect (the physical phenomenon by which Cooper pairs propagate along a certain distance within certain types of materials when put in contact with a superconductors, thus also exhibiting superconductivity). In particular, Majorana modes are suspected to emerge at the interface between a superconductor and a topological insulator, *i.e.* an insulator with inverted conductance and valence bands[5]. Another way to break both the spin-rotation and the time-reversal symmetries is to associate strong spin-orbit and strong spin-splitting effects in a materials in the proximity with a superconductor. **The efficiency of the generation of Majorana modes through proximity effect is limited, in real life, by features inherent to the interfaces between the materials, such as roughness, mismatch defects, presence of impurities**, etc (see Fig.1).

Up to now, the **usual theoretical formalisms and methodologies applied to mesoscopic superconductivity have shown difficulties to deal with realistic features listed above**, even with the help of numerical methods. For instance the Bogoliubov-deGennes (a generalisation of the Schrödinger equation for superconductors) is pretty well designed to describe topological problems, but only from topological toy models in the clean limit, see Fig.1.b ; those are difficult to generalise for diffusive problems or to problems with spin-orbit interaction when neither spin nor momentum remains a good quantum number as in Fig.1.c. Another method is the microscopic Green function approach, which is difficult to generalise for interface and boundary problems since the Green functions consist in two-points correlators.

In contrast, **there is a transport formalism based on kinetic-like equations** (also called quasi-classic method) **that is very well adapted to the study of mesoscopic hybrid structures and out-of-equilibrium phenomena, and proved really helpful in the past**[6]. It consists in a systematic, low-

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[2] A. Kitaev, Physics-Uspekhi **44**, 131 (2001).

[3] X. Qi and S. Zhang, Rev. Mod. Phys. **83**, 1057 (2011). J. Alicea, Rep. Prog. Phys. **75**, 076501 (2012). C. W. J. Beenakker, Annu. Rev. Condens. Matter Phys. **4**, 113 (2013).

[4] see G. E. Volovik, Universe in a Helium Droplet (Oxford University Press, 2003) and references therein.

[5] L. Fu and C. L. Kane, Phys. Rev. Lett. **100**, 096407 (2008).

[6] G. Eilenberger, Zeitschrift Für Phys. **214**, 195 (1968). A. I. Larkin and Y. N. Ovchinnikov, Sov. Phys. JETP **28**, 1200

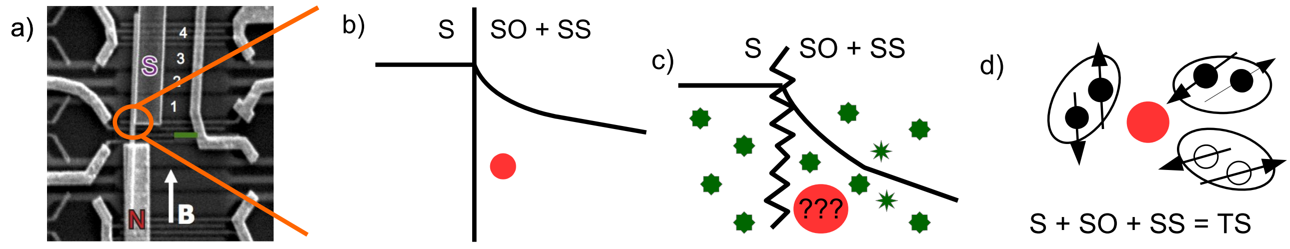

Figure 1: **a**) A real experiment using heterostructure between a normal (N) and a superconducting (S) metal. Actually, the normal region exhibits strong spin-orbit and spin-splitting effect (the Zeeman term induced by the magnetic B-field along the wire) **b**) The toy model of an interface leading to Majorana physics (localised at the interface, the red circle), which combines the property of S and both the effects of spin-orbit (SO) and spin-splitting (SS) interactions via proximity effect (the black line, representing the Cooper pair condensate penetrating the normal region). **c**) A realistic interface, when the materials contains impurities (lattice defect for instance, in green) and the interface is dirty. Then the emergence of Majorana modes is not completely understood. **d**) A sketch of the emergence of a Majorana mode in a fluid of Cooper pairs. In fact the spin (arrows) and charge (filled circle for electrons and empty circles for holes) pairing allows the emergence of a spin-less and charge-less quasi-particle (the Majorana mode, the red circle) as the emergent ground-state in a non trivial topological system with particle-hole symmetry (a superconductor). This non trivial topological superconductor (TS) combines the property of a S with strong SO plus SS effects.

energy expansion of the equation of motion for the quantum correlations in the phase-space. The associated transport equation is able to easily deal with realistic aspects of materials, such as impurities, boundaries and interfaces, with a fairly good accuracy for understanding and predicting experimental results. Recently, I generalised this method in order to deal with strong spin-orbit and weak spin-splitting effects when the spin is described as a gauge-redundant degree of freedom, in the same way as a charge is described in Maxwell electromagnetism[7]. In this formalism, the charge and spin degrees of freedom are thus treated on equal footing, and a gauge-covariant quasi-classic method can be developed. So far, this gauge-covariant quasi-classic method has been applied to intricate situations when the combination of spin-orbit and paramagnetic effects in superconducting bulk and heterostructures generates magneto-electric responses, present in both the ballistic and diffusive limits, and robust to the presence of impurities and interfaces[8].
Despite the gauge-covariant approach is ideally suited to deal with strong spin-orbit interaction in superconducting heterostructures, it is limited to weak spin-splitting effect. As such, it is unable to predict the appearance of the Majorana modes, since a weak spin-splitting effect is unable to completely break the spin rotation symmetry. Thus the topological sector of the spin and charge phenomenology is still outside the realm of the quasi-classic methodology and its convenient description of real interfaces and materials, and further work is required to understand the modern, topological aspects of condensed matter.
A significant step forward consists in generalising the transport formalism in order to include the non-trivial topology which emerges from the combination of strong spin-orbit *and* strong spin-splitting effects, when the latter leads to a robust chirality of the band, when the projection of the spin vector on the electronic momentum is locked. This would open the road to a **complete understanding of the interactions between charge and spin degrees of freedom, and to the emergence of the Majorana modes in systems with impurities, boundaries and interfaces**.

★ **Objectives** ★

This project aims at establishing a **complete picture of the interconnection between the charge and spin degrees of freedom in mesoscopic hetero-structures**, with their inherent impurities, interfaces, band-structure mismatch, and temperature difficulties taken into account. Several theoretical tools and methods will be developed in order to explore some key questions in topological problems, such as the emergence of Majorana modes in mesoscopic setups, or their robustness with respect to out-of-equilibrium

(1969). See also F. K. Wilhelm et *al.*, Superlattices Microstruct. **25**, 1251 (1999) and references therein for a review.
[7] F. Konschelle, Eur. Phys. J. B **87**, 119 (2014).
[8] F. Konschelle, I.V. Tokatly, and F.S. Bergeret, arXiv:1506.02977 (2015).

reservoirs, interfaces and impurities. These effects can be properly accounted for in a transport equation, once generalised to topological phenomenologies.

This generalisation **will provide a powerful theoretical tool for assisting in the key milestone of designing and realising a smoking-gun experiment to detect the Majorana modes in superconducting heterostructures**. In addition, the coupling between spin and charge will be addressed. Ultimately, these two degrees of freedom combine to generate some magneto-electric effects when an applied magnetic field generates a charge current and an electric field generates a spin current, or reciprocally a charge current generates magnetisation and a spin current generates a voltage drop. This provides an amazing versatility in the manipulation of the spin degree of freedom of the quasiparticles using circuits probes, and the associated phenomenology of dissipationless superconducting spintronics.

The ultimate goal of this project is to understand how the basic ingredients constituting mesoscopic hetero-structures, such as spin-orbit, spin-splitting, interfaces, impurities and boundaries, conspire to generate magneto-electric effects on the one side, and neutral topological Majorana modes on the other side.

★ Overview of the action ★

The present project guidelines are twofold:

<u>Work-package 1:</u> Development of **theoretical tools to describe the topological aspects of the quasi-classic transport formalism with strong spin-orbit and strong spin-splitting interactions in out-of-equilibrium superconductors**. The momentum-space topology associated to non-trivial band structure (for instance the appearance of a Dirac cone due to band inversion, or the complete spin-polarisation due to a strong spin-splitting effect) in systems with strong spin-orbit and strong spin-splitting effects will be included in a kinetic equation. In addition, the out-of-equilibrium phenomenologies will be included in the form of the standard Keldysh approach.

<u>Work-package 2:</u> **Applications of the developed methodologies to mesoscopic heterostructures, in order to understand both the Majorana modes and the magneto-electric phenomenologies**, in addition to the interconnections between these two sectors. For instance, one will focus on the thermal transport in systems with strong spin-orbit and strong spin-splitting effects, and its relation to the emergence of the neutral Majorana modes. This will constitute a first step towards the understanding of experimental results invoking Majorana modes. I will also study the spin and charge transport when these two degrees of freedom generates magneto-electric effects in superconducting spintronics heterostructures. Proposal for experiments in quantum simulation and quantum information will follow.

<u>Work-packages 3 and 4:</u> These two work-packages are dedicated to the organisation of a workshop about the topological aspects of superconductivity in San-Sebastián, and to the management of the project, respectively. In addition, I will develop a network of contacts with the european community of researchers on mesoscopic superconductivity thanks to visits at different laboratories and displacements to conferences over Europe, as part of Work-package 3.

★ Research methodology and approach ★

The chosen approach is to **develop quasi-classical methods when spin and charge degrees of freedom are treated on equal footing and when the topology of the band structure is taken into account**. The topological aspects of the band structure emerge from a combination of both strong spin-orbit and strong spin-splitting effects, which generate a chiral electronic gas at low energies. At the present time, these topological manifestations are understood only in the pure clean limit[9], and must be generalised to problems with impurities and interfaces. The quasi-classic methods will be generalised to include the associated Berry connection and the magnetic monopoles associated to the non-trivial topology of the band structure[10]. Then the different ballistic and diffusive limits can be addressed from the transport equation.

In addition, I will further generalise these concepts to out-of-equilibrium situations following standard Keldysh approach[11]. This second step will have applications in the emerging field of superconducting spintronics, where one aims at manipulating the spin degree of freedom using mesoscopic circuitry. When realised

[9] D. Xiao, M.-C. Chang, and Q. Niu, Rev. Mod. Phys. **82**, 48 (2009). X. Qi and S. Zhang, Rev. Mod. Phys. **83**, 1057 (2011).

[10] G. Sundaram and Q. Niu, Phys. Rev. B 59, 14915 (1999). C. H. Wong and Y. Tserkovnyak, Phys. Rev. B **84**, 115209 (2011).C. Wickles and W. Belzig, Phys. Rev. B **88**, 045308 (2013).

[11] A. Kamenev, in *Nanoscopic Quantum Transport, Les Houches Summer School* (Springer, 2004), arXiv:cond-mat/0412296.

coherently and without dissipation, these manipulations are of interest for quantum simulation and quantum information.

★ **Originality and innovative aspects of the research programme** ★

Once developed, **the quasi-classic model will illustrate the interconnection between the charge and spin degrees of freedom when spin-orbit and spin-splitting interactions are present in realistic materials with impurities, interfaces and boundaries**. This achievement allows understanding of the essential questions of how and why these interactions lead to magneto-electric effects in some situations, and to charge-less and spin-less quasi-particles (Majorana modes) in others.

The new quasi-classic methodology will open the road to dealing with topological aspects in materials with impurities, interfaces and temperature effects duly undertaken. It will offer a description of mesoscopic setups complementary to the widely used Bogoliubov-deGennes (also called scattering or Landauer-Büttiker) formalism.

Applications will range from fundamental perspectives in condensed matter to quantum information and quantum engineering realisations. Especially, the development of the time-dependent transport formalism allows to understand the manipulation of the spin degrees of freedom via the coherent and dissipationless charge flow in superconductors, developing the emerging field of coherent superconducting spintronics.

At a longer term perspective than the present project, I would like to develop a **complete and novel theoretical scheme for dealing with spin and charge interactions in mesoscopic heterostructures**, including the description of topological, dynamical and coherent phenomenologies in realistic devices. This scheme could be for instance in the form of a versatile software available as a tool for the mesoscopic physics community ranging from material science perspectives to quantum information applications. This project constitutes a proof-of-principle for such larger, more ambitious goal.

1.2 Clarity and quality of transfer of knowledge/training for the development of the researcher in light of the research objectives

As a theoretician, my main concern is not really about the location of the laboratory, but about how to acquire skills and methods in order to treat and understand novel problems. For this, I need to be able to interact with the best specialists in the fields which concern my research. Taking this into accounts, **F.S. Bergeret is best suited as a supervisor of the present project**, as he masters all the methodologies about transport in superconducting hetero-structures, and keeps a world-wide network of collaborators (on both theoretical and experimental sides) which are at the vanguard of the field. For instance his knowledges about out-of-equilibrium superconductivity, quasi-classic methods, superconducting spintronics effects, thermal effects in superconductors among other skills will greatly help developing the gauge-covariant quasi-classic methods towards non-equilibrium phenomenologies in superconductors with strong spin-orbit interactions. Especially, **he is well acquainted with designing and describing experiments mixing magnetic and superconducting devices**, and so his help will be particularly appreciated when making proposals for verification of the novel effects discovered during this project.

In return, **my experience about topological phenomena** in superconductors and their relations to topological quantum computation acquired over the last few years at RWTH Aachen (Germany) **will profit to F.S. Bergeret**. The present project will open the road to **active collaborations** between the Mesoscopic Physics group in San-Sebastián and the Institute for Quantum Information in Aachen.

The topological aspects of the quasi-classic formalism will be developed with the help of F. Hassler in Aachen, whose knowledges about Majorana fermions will be particularly appreciated for both F.S. Bergeret and I. In return, F. Hassler will learn quasi-classic methods from the experiences of F.S. Bergeret and mine.

1.3 Quality of the supervision and the hosting arrangements

★ **Qualification and experience of the supervisor** ★

F. Sebastián Bergeret (FSB) is Scientific Researcher appointed by the Spanish National Research Council (CSIC), and integrated the Material Physics Center in San-Sebastián on 2009, at which he is head of the Mesoscopic Physics Group, coordinating the activity of currently 3 postdoc researchers, 1 PhD student and

3 associate members. His scientific expertise and research interest are the transport phenomena at the nanoscale emerging from combination of magnetic and superconducting effects. **He achieved world-wide visibility** within the specialised community **after introducing the notion of triplet correlations in superconducting heterostructures** 15 years ago, and since then continues in vanguard of this field. He is author of more than 65 publications, including one Review of Modern Physics, 12 Physical Review Letters, one Nature Physics and one Nature Communication, which have gathered more than 2200 citations (WoS, Sept. 2015). Several of his publications reflect his experience in the topics related to this proposal as[12].

FSB scientific work is characterised by an **intense collaboration with both theoretical and experimental groups** in order to maximise the impact of the research carried on by him and his group. His network of collaborators includes, in the experimental side, Francesco Giazotto (Scuola Normale Superiore, Pisa, Italy), Mark Blamire and Jason Robinson (Cambridge University, UK), Teun Klapwijk (Delft University, The Netherlands), Jan Aarts (Leiden Univesity, The Netherlands), Marco Aprili (Université Paris Sud, France), Felix Casanova and Luis Hueso (CIC Nanogune, San-Sebastián) Jagadeesh Moodera (MIT, USA), Samuel Bader and Samuel Jiang (Argonne National Laboratory, USA); and in the theoretical side Ilya Tokatly (University of the Basque Country, Spain), Tero Heikkilä (University of Jyväskylä, Finland), Alfredo Lévy-Yéyati and Juan Carlos Cuevas (Universidad Autónoma de Madrid, Spain), Anatoly Volkov (Ruhr-Universität Bochum, Germany). The possibility of interacting with such network for developing collaborations is one of the reasons why working under FSB supervision was chosen.

★ Hosting arrangements ★

The Material Physics Center (MPC) Foundation was created in 2009 for managing the joint center established by the Spanish National Research Council (CSIC) and the University of the Basque Country (UPV). The center shows the long term commitment of the institutions for stabilising a community of specialists in materials sciences. The MPC headquarters are integrated in the Ibaeta Campus at San-Sebastián, within walking distance to other institutions focused into different aspects of materials sciences, such as the CIC Nanogune, the Donostia International Physics Centre (DIPC), POLYMAT, and the Materials Science and Chemistry Departments of the UPV. Altogether, **this community offers a rather unique and thrilling environment**, **focused exclusively into material science and with very high visibility within the global research community**. This gives researchers the opportunity to interact with many world-class scientists, which often leads to collaboration and career opportunities. As an example of the quality of the research performed in synergic collaboration with institutions from the environment in San-Sebastián, in the period 2008-2012 the researchers of the MPC collaborating with the DIPC produced 776 publications, from which 23% appear among the 10% of most cited in the area of Physics and Astronomy (data collected from Scopus for the SCImago Institutions Ranking).

The MPC Foundation offers full integration to its scientific staff, providing the appropriate working conditions and state-of-the-art infrastructure (the MPC headquarters were inaugurated in 2010), granting access to every scientific event taking place locally (workshops, courses, etc). Both MPC and DIPC have allocated budgets which fund the mobility both of staff and guests researchers, with the aim of promoting networking and collaborative work. **This center actively encourages researchers to develop their own agenda of workshops and conferences**, providing staff, facilities and economical support for their development. **MPC is committed to help researchers to develop and consolidate their careers**. A project manager (Francisco Lopez-Gejo) is full-time employed for designing, together with the supervisors, a plan of mentoring and provides support in the preparation of proposals. Among all the possibilities for career development, it should be noted that both **CSIC and UPV** (joint partners of the centre) **offer both tenure track permanent positions in a regular basis**.

[12] F. S. Bergeret, A. F. Volkov, and K. B. Efetov, Phys. Rev. Lett. **86**, 3140 (2001). F. S. Bergeret, A. F. Volkov, and K. B. Efetov, Rev. Mod. Phys. **77**, 1321 (2005). F. S. Bergeret and I. V. Tokatly, Phys. Rev. Lett. **110**, 117003 (2013). A. Ozaeta, P. Virtanen, F. S. Bergeret, and T. T. Heikkilä, Phys. Rev. Lett. **112**, 057001 (2014). E. Villamor et al., Phys. Rev. B **91**, 020403 (2015). F. Konschelle, I. V. Tokatly, and F. S. Bergeret, arXiv:1506.02977 (2015).

1.4 Capacity of the researcher to reach and re-enforce a position of professional maturity in research

During the last few years, I have developed quasi-classic tools to deal with strong spin-orbit and spin-splitting interactions in superconductors. It has been a long road venturing from the methodology of the high-energy physics to the statistical quantum-field theory of superconductivity, finally successful (Ref.7). These methods are now available for exploration of the intriguing physics of spin and charge mixing in coherent structures, a far simpler problem than the development of novel methodologies. For this project I will thus benefit from the experience I acquired previously in the field of quasi-classic and transport formalisms. **It will allow me to publish more** than during my last few years of research, **a crucial point to get a permanent position**.

Of particular interest for my future career will be to learn how to deal with time-dependent problems. This tool is required to work on quantum information problems, when dynamics describes the interactions of the quantum system with designed or unwanted reservoirs. Since part of the project aims at developing versatile tools to take into account topological effects, I will get acquainted with this emerging field. In addition, I will develop the attractive topic of superconducting spintronics, **allowing me to become a leading expert in this field** at the international level.

To develop a network for future collaborations is an other key point for a career in fundamental research. The opportunities in San-Sebastián are promising to that respect (the list of F.S Bergeret's collaborators can be found in section 1.3). During the two-years period, **I will supervise some master and PhD students** in collaboration with F.S. Bergeret and his group, and I will thus acquire some experiences required for applications as an assistant professor. **This project thus offers me serious possibilities and required skills in order to get a permanent position** somewhere in Europe, including locally at MPC or its partners CSIC and DIPC.

2 Impact

2.1 Enhancing research- and innovation-related skills and working conditions to realise the potential of individuals and to provide new career perspectives

This project will let me become and expert on the topological and out-of-equilibrium aspects of superconductivity, with a broad scope of potential skills ranging from fundamental condensed matter to applications in the fields of quantum information and spintronics. These advanced skills are complementary to those which I already have, and indeed allow me **to position myself as one of the few experts bridging between two important theoretical modelling disciplines**. The joint use of these formalisms multiplies its power and applicability, and therefore allows me to achieve a vanguard position, with many opportunities for collaborating with the groups developing applications. This position provides me also with research objectives which overlap, but do not compete directly with those of my collaborators, thus leaving space for developing an independent career and, eventually, **establishing a long-term project that will let me lead a research group**.

Most of the stable research jobs in Europe are conditioned to a tenure track. **The international visibility of this research** thanks to the MPC environment and the collaboration network of F.S. Bergeret (see section 1.3) will multiply the possibility of collaborating during the project, thus boosting the output, which will be key for my tenure track.

The benefices for the research community and the society of knowledge will be important as well. The project has been designed with the aim of maximising the connection between my research and the activities in which it is relevant, and the impact on them. Despite containing mainly fundamental studies, the project aims to contribute to the development of Quantum Computation, which is one of the long term objectives set by the European Commission in the H2020 agenda. A whole scientific community which takes part in this research is facing now important technical challenges, due to the difficulty of finding suitable materials and interfacing them, in order to obtain and manipulate exotic physical phenomena (such as the Majorana modes). This community will benefit from a computational tool which will allow to understand better, orientate and optimise the experimental realisations.

2.2 Effectiveness of the proposed measures for communication and results dissemination

★ Communication and public engagement strategy of the action ★

The research groups at MPC maintain a deep commitment with the outreach of scientific research, and the attraction of young students towards the scientific careers. Most of these commitments are channelled through the collaborations with the Donostia International Physics Center (DIPC), from which many researchers, including supervisor F.S Bergeret, are Associated Members. Researchers, with the support of DIPC staff, design and develop an intensive agenda of outreach activities, including wide public divulgative lectures, visits from secondary schools and presence in media and social networks. Specific activities of this type, focused in the activity and its outcome, will be scheduled along the two years of duration.

An event of special interest will be the Frontiers of Condensed Matter Summer school for postgraduate students, which take place annually alternating between Les Houches and San-Sebastián. This School is jointly organised by the Materials Physics Center CFM-CSIC (Spain), the École Doctorale de Physique de Grenoble (France), the Casimir Research School Delft-Leiden (Netherlands), and the École Doctorale de Physique et d'Astrophysique (PHAST), Lyon (France), and F.S. Bergeret is Member of the Organising Committee. Special dedicated seminars focused in the topic of this project will be scheduled in the schools taking place the years in which the project will be executed.

★ Dissemination of the research results ★

The outcome of this research will be published in high-profile international peer-reviewed journals. I am aiming for at least 4 articles in high-profile journals along the project. All published work will be given open-access rights, and available on internationally known platforms as arXiv.org and hal.archives-ouvertes.fr. They will also be available through my personal web-page[13] and social networks on my Twitter account.

Dissemination of results will also be done through participation into specialised conferences and workshops, in order to identify possible opportunities for collaboration.

★ Exploitation of results and intellectual property rights ★

The outcome of the project will be monitored in a continuous basis in order to ensure proper protection of the Intellectual Property, taking the guidelines of the European IPR Helpdesk as working basis (who will be contacted if necessary). The ER, supervisor, and a Project & Innovation Manager will jointly asses the potential for exploitation and design the best procedure for avoiding conflicting paths between the protection of knowledge and the dissemination of scientific results. In the particular case of software (the most relevant outcome of the project), exploitation will be designed in an open access basis. Any collaboration, including secondment will be object to an IP agreement detailing the terms of the joint exploitation of results.

3 Implementation

3.1 Overall coherence and effectiveness of the work plan

The work plan has been structured into two main blocks of activities (work-packages, WP). Additional WPs take care of management and dissemination issues. The project aims at ambitious goals, and therefore implies some risk-taking. In order to control this risk, several milestones have been set. These are points at which decisions will be taken in order to ensure that progress and achievement of goals is achieved. The output of the project is structured as a set of deliverables (D).

★ WP-1: Theoretical tools and methodology of the quasi-classical formalism ★

This work-package (WP) is dedicated to the generalisation of the quasi-classic methods to describe the time-dependent and topological aspects of the spin interactions in superconducting materials. One ambitions to understand the topological aspects associated to a strong spin-splitting effect.

The first milestone of this project will be to understand how to generate some effective topological actions using the quasi-classic methods. Once obtained, such a topological field theory may help classifying the new topological phases and observables appearing in bulk and/or mesoscopic heterostructures. The topological field theory and its applications to real materials, and the effects of temperature, boundaries and impurities on the topological phases will be addressed.

[13] Hyper-links should work on the PDF version. They can be found on my personal web-page: http://fraschelle.free.fr as well.

D-1.1 (month 1-4/6): **Effective topological field theory in superconductors with spin interactions**: the goal is to obtain a low-energy topological field theory of superconductivity using a gradient expansion. To analyse the conditions for the generation of the topological effective field theory, and to establish the proper form of it will be the important aspects of this task. This task ends with the deliverable D-1.1 in the form of a publication.

Milestone (M-1) takes place after month 4. If I realise D-1.1 can not be achieved within a few months, I will re-order the project to focus on D-1.2 and WP-2. See also section 3.2.

D-1.2 (month 4/6-10/12): **Time dependent quasi-classic transport theory of superconductors heterostructures with spin interactions**: This task aims at generalising the gauge-covariant transport equations already established (see Ref.7) to non-equilibrium problems, in order to deal with spin-interactions in superconductors. This task will provide the deliverable D-1.2 in the form of a publication given the details of the methods, and some immediate examples to be further discussed in D-2.3.

★ **WP-2: Applications on topological aspects of superconductivity** ★

The second part of the project focuses in understanding the phenomenologies associated to spin and charges in real materials. Two important lines will be followed. On the one side I will understand the spintronics effects in superconducting systems when spin and charge degrees of freedom interact coherently. On the other side I will study the generation of Majorana modes, a charge-less and spin-less quasi-particle emerging from the topological sector of spin and charge interactions in superconductors, and how to detect them in realistic situations. An accurate description of mesoscopic setups with strong paramagnetic and/or spin-orbit interactions will be developed. In addition, proposals of experimental verifications will follow, and collaborations with experimentalists will influence future axis of research.

This work-package is divided in tasks as follow, each of them resulting in at least one publication.

D-2.1 (month 10/12-14/16): **Thermal Hall effect in topological superconductors**: since the Majorana fermions are charge- and spin-less particle, they lead only to a so-called thermal Hall effect (*i.e.* Righi-Leduc effect), when current of energy and temperature gradient are related like the charge current and electric field in a Hall bar. This task will explore such phenomenology in superconductors, and results in the deliverable D-2.1 in the form of at least one publication dealing with both thermal Hall and its quantum version (characterised by edge states and thermal conductance quantisation).

D-2.2 (month 14/16-20): **London momentum and Majorana modes**: Once obtained a correct description of the thermal Hall effect and understood its connection to the gravitational anomaly, one can study the possible modification of the London momentum. Under a thermal Hall effect, one naively expects to find some modifications of the generation of a magnetic field by the precession of a macroscopic piece of topological superconductor. This task ends with the deliverable D-2.2 in the form of a publication.

At this point the second milestone (M-2) of the project will be reached. The project can be oriented differently depending on the outcome of D-2.2. See also section 3.2.

D-2.3 (month 20-24): **Superconducting spintronics**: This task is dedicated to the charge-full and spin-full sector of the phenomenology, when magneto-electric effects arise in superconducting heterostructures. It is an emerging field at the present time, and the project will contribute to the basis towards a global understanding of the mutual interactions between charge and spin. A few examples and proposals will follow. This task will result in one or several deliverables D-2.3 in the form of a publication each.

D-2.4 (month 20-24): The final part of the project is to understand how the neutral Majorana modes emerge from a system full of spin and charge interactions. This will help understanding the emergence of topological phenomenology in superconductors and its relation to quantum state protection.

★ **WP-3: Result dissemination and communication** ★

The third work-package will consist in the organisation of a work-shop on the topological aspects of superconductivity. This work-shop (planed in the last trimester of the project at the DIPC in San-Sebastián) aims at inviting a few specialists of the spin effects in superconducting heterostructures. Both experimentalists and theoreticians will discuss about the progress done along the few years of the project, and on the emerging perspectives which are difficult to foreseen at the present time.

In addition, I will participate to a few conferences every year during the project, especially to some workshops and specialised conferences about mesoscopic superconductivity and topological phases. See also section 2.2. Moreover, I will co-supervise the formation of a PhD student in San-Sebastián, in collaboration with F.S.

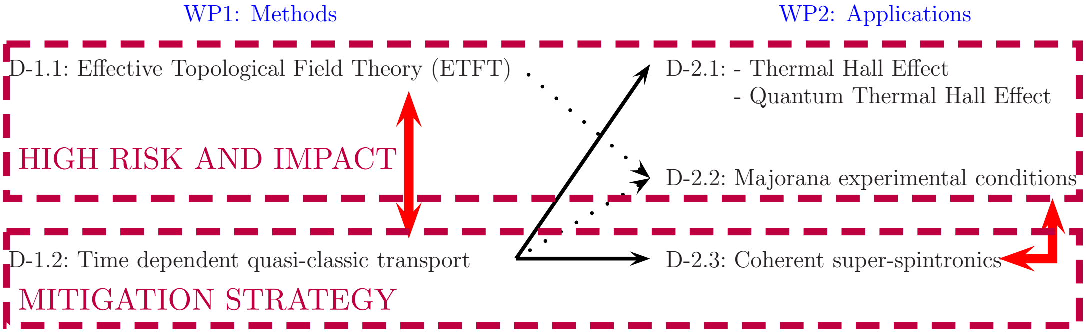

Figure 2: Logical interconnections between the different deliverables of WP-1 and WP-2. The red arrows mark the milestone, when the project might be re-order or adapted to effectiveness.

Bergeret. See also section 1.4.
Finally, I will move to the different laboratories around Europe in order to keep contact with a network of experimentalists and to present my results and progresses along the project. See also section 1.3.
D-3.1: Organisation of a workshop and publication of its book of abstracts, on the Scienceconf platform.
D-3.2: Displacements for visiting senior researchers, and collaborations.
D-3.3: Displacement to workshops, seminars and conferences over Europe.
D-3.3: Supervision of PhD thesis by a student, co-supervised with F.S. Bergeret.

★ **WP-4: Management** ★

The last work-package will be devoted to the management of the project, meetings organisation and monitoring with students and supervisor. The deliverables are the first year management report (D-4.1), second year management report (D-4.2) and website(s) update (D-4.3).

3.2 Appropriateness of the management structure and procedures

★ **Project organisation and management structure** ★

This project does not have a complex structure, as I will be in charge of developing all the activities myself. I will work independently although under the direct supervision of Sebastian Bergeret, which is committed to provide continuous feedback in a daily basis if necessary.
Collaborations will be developed with Fabian Hassler at RWTH-Aachen (Germany), especially for the topological aspects of the quasi-classic formalism.
My work will benefit from interaction with Ilya V. Tokatly (CIC Nanogune, San Sebastian, Spain) and other members of the Mesoscopic Physics group (Vitaly Golovach and Dario Bercioux).
I will also participate in the supervision of a PhD student during part of his training.

★ **Risks that might endanger reaching project objectives** ★

This project has ambitious goals and therefore takes some high risk paths, but has also been designed to have mitigation paths through which success is granted. This will be done smoothly since the project contains several independent parts, as discussed in Fig.2.
The project requires a methodology extension of the quasi-classic formalism, which may takes longer times than announced above. So the first milestone M-1 of the project aims to asses if the progress rate is correct, or would require excessive efforts. If then I understand why generalising quasi-classic formalism to topology requires more time than suggested in the project schedule, I will focus on spintronics effects, and to develop a time-dependent approach for the gauge-covariant transport formalism, as discussed in D-1.2.
If difficulties arise in the establishment of a complete formalism, I will focus on adiabatic time dependency in a first step, or in harmonic approximation, which already present some interesting aspects of the non-equilibrium problems, but are drastically simplifying hypothesis. Eventually, one can discuss systems at zero-temperature as a simplifying hypothesis as well: in that case the time dependency combines well with the gauge-covariance. In any case it will be interesting for me to understand how to deal with the Keldysh approach, a methodology F.S. Bergeret masters. I am confident that the experiences acquired over the years

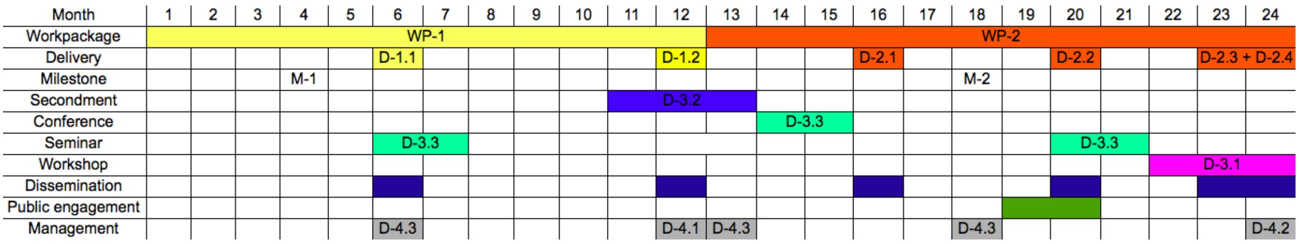

Figure 3: Gantt chart of the project.

in the Mesoscopic Physics Group in San-Sebastián will suffice to generalise all these knowledges toward a gauge-covariant transport formalism.
As for the applications of the methodologies, I put a second milestone on D-2.2 since its implementation may reveal difficult as well. There as well, I aim at acquiring new skills for me and my future career, as understanding how to deal with thermal effects in heterostructures. This might take other forms than a publication proposing a detection scheme for Majorana fermions, as *e.g.* a review on thermal effect, a review on quasi-classic formalism, or a close collaboration with an experimental team working on this subject, for instance the Pisa group led by F. Giazotto.
The above discussion is summed-up in Fig.2, showing how the project can be re-adapted to reach effectiveness. The Gantt chart is on Fig.3.

3.3 Appropriateness of the institutional environment

The activity carried on in this project is theoretical work. The researcher will therefore require appropriate office space and access to computing facilities. In response to these needs MPC will provide office space in its headquarters, which is a modern building (operational since 2010), with capacity for hosting up to 120 people under optimal conditions (currently 96 people are hosted). The computing needs will be covered by granting access and computing time to the High-Performance Computing cluster hosted at MPC headquarters.
Another important factor in the context of this project is networking. To this respect, MPC offers a rather singular environment, with the proximity to CIC Nanogune, Polymat and DIPC. As an example, DICP (F.S. Bergeret is Associate Member to DIPC) hosted 95 short-term visits and 54 long-term visits only in 2014, including 7 Nobel Laureates and Distinguished Scholars.

3.4 Competences, experience and complementarity of the participating and institutional commitment

The Mesoscopic Physics group in San-Sebastián is world leading in the field of the interaction between superconducting and spin properties, and so it is the most appropriate choice for developing the scheme of superconducting spintronics. In addition F.S. Bergeret experiences in theoretical methods and collaborations with experimental teams (see section 1.3) will emulate international visibility of the project.
The Institute for Quantum Information in Aachen is one of the most experienced in Europe in the field of Topological Quantum Computation. Collaborating with this institute will stimulate the present project. Especially, F. Hassler is an expert on statistical properties of Majorana modes in superconductors, and his collaboration to this project is well appreciated.
A successful collaboration between the two laboratories goes hand to hand with a successful project dealing with these two phenomena.

4 Curriculum Vitae

François Konschelle

Born on September, 30 1983
French nationality
Single, no child

Contact:
14 route de Béhobie
64700 Hendaye, France
Email: f.konschelle@gmail.com
Website: fraschelle.free.fr

Research interests: Superconductivity - Coherence effects - Quantum to classical transition - Topological effects in mesoscopic devices - Nanomechanical systems - Quantum information

Main achievements: Fluctuations at the normal to inhomogeneous superconducting phase transition - Proximity effect between superconductors and spin-textured systems - Electromotive effects in superconductors - Decoherence in Majorana qubits - Gauge description of the transport equations of superconductivity - Magneto-electric effect in Josephson systems

★ **Research experiences** ★

Since Dec. 2014 Post doctoral activities on gauge-covariant transport formalism of superconductivity in the Mesoscopic Physics group, at the Material Physics Center, San-Sebastián (Spain), supervised by F. Sebastián Bergeret and Ilya V. Tokatly.

Feb. 2012 - Dec. 2014 Post doctoral activities on hybrid superconducting devices including topological properties of superconductivity and quantum information in the Institute for Quantum Information, at Aachen University (Germany), supervised by Fabian Haasler.

Nov. 2009 - Nov. 2011 Post doctoral activities on nano-mechanical systems at Kavli Institute of Nanoscience in Delft (The Netherlands), supervised by Yaroslav M. Blanter.

Sept. 2006 - Oct. 2009 Ph. D. in condensed matter theory on superconductivity and magnetism at CPMOH, University of Bordeaux (France), supervised by Alexandre Buzdin and Jérôme Cayssol.

April to July 2006 Training period in soft matter theory at CPMOH, University of Bordeaux (France), supervised by Aloïs Würger.

★ **Teaching experiences** ★

2012 - 2013 Tutorials in *Mesoscopic physics and quantum information* for master students at RWTH University of Aachen. About 10 hours.

2006 - 2008 Teaching in *Methodological aspects of experimental sciences* for bachelor students at University of Bordeaux. About 30 hours a year.

2004 - 2007 Tutoring in general physics for undergraduate students at University of Bordeaux. About 60 hours a year.

★ Supervision of graduate students ★

Spring 2014 1 Master Student (F. Ihno-Stamm) at the Institute for Quantum Information, at Aachen University (Germany), in collaboration with Fabian Haasler.

2012 - 2014 2 PhDs (C. Ohm and J. Ulrich) at the Institute for Quantum Information, at Aachen University (Germany), in collaboration with Fabian Haasler.

2009 - 2011 2 PhDs (G. Labadze and M. Dukalski) at the Kavli Institute of Nanoscience in Delft (The Netherlands), in collaboration with Yaroslav M. Blanter

★ Institutional responsibilities ★

Since Dec. 2014 Organiser of Journal Clubs, at the Material Physics Center, San-Sebastián (Spain)

2012 - 2014 Organiser of Journal Clubs, at the Institute for Quantum Information, at Aachen University (Germany)

2009 - 2011 Organiser of Journal Club and Organiser of experimental/theoretical collaborative meetings, at the Kavli Institute of Nanoscience in Delft (The Netherlands)

2007 - 2009 Member of the Laboratory Council, elected member to represent non-permanent members, at CPMOH (now LOMA), University of Bordeaux (France)

★ Memberships of scientific societies ★

2008 - present Member of the SFP (Société Française de Physique - French Physical Society)

2012 - 2013 Member of the DPG (Deutsche Physikalische Gesellschaft - German Physical Society)

2008 - present Member of the EPS (European Physical Society)

★ List of publications ★

9 publications in peer-reviewed journals, 1 peer-reviewed proceeding.
Total number of citations: 80
h-index: 5

Research-ID profile available at:
http://www.researcherid.com/rid/D-3804-2014

Google Scholar profile available at:
http://scholar.google.com/citations?user=54SvhF8AAAAJ

Articles (in chronological order)

1. *Anomalous fluctuation regimes at FFLO transition.* **François Konschelle**, Jérôme Cayssol and Alexandre I. Buzdin. Europhys. Lett. 71, 67001 (2007) or arXiv:cond-mat/0612387. Cited 14 times.

2. *Non-sinusoidal current-phase relation in strongly ferromagnetic and moderately disordered SFS junctions.* **François Konschelle**, Jérôme Cayssol and Alexandre I. Buzdin. Phys. Rev. B 78, 134505 (2008) or arXiv:0807.2560. Cited 16 times.

3. *Magnetic moment manipulation by a Josephson current.* **François Konschelle** and Alexandre I. Buzdin. Phys. Rev. Lett. 102, 017001 (2009) or arXiv:0810.4286. Cited 21 times.

4. *Oscillations of magnetisation and conductivity in anisotropic Fulde-Ferrell-Larkin-Ovchinnikov superconductors.* **François Konschelle**, Jérôme Cayssol and Alexandre I. Buzdin. Phys. Rev. B 79, 224526 (2009) or arXiv:0902.2298. Cited 1 time.

5. *Long-ranged singlet proximity effect in ferromagnetic nanowires.* **François Konschelle**, Jérôme Cayssol and Alexandre I. Buzdin. Phys. Rev. B 82, 180509 (R) (2010) or arXiv:1009.3181. Cited 6 times.

6. *Self-sustained oscillations of a torsional SQUID resonator induced by Lorentz-force feedback.* Samir Etaki, **François Konschelle**, Yaroslav M. Blanter, H. Yamaguchi and Herre van der Zant. Nature Comm. 4, 1803 (2013). Cited 8 times.

7. *Effects of nonequilibrium noise on a quantum memory encoded in Majorana zero modes.* **François Konschelle** and Fabian Hassler. Phys. Rev. B 88, 075431 (2013) or arXiv:1306.2519. Cited 11 times.

8. *Transport equations for superconductors in the presence of spin interaction.* **François Konschelle**. Eur. Phys. J. B 87, 119 (2014) or arXiv:1403.1797. Cited 2 times.

9. *Electromotive interference in a mechanically oscillating superconductor: Generalized Josephson relations and self-sustained oscillations of a torsional SQUID.* **François Konschelle** and Yaroslav M. Blanter. Europhysics Letters 109, 68004 (2015) or arXiv:1110.1357.

Note that the break in publications of three years between 2010 and 2013 corresponds to the delay taken in submitting the articles number 6 and 9 (for instance publication 9 was available on the arXiv in the late 2011, but has been accepted for publication only in late 2014 and published in early 2015, due to a succession delays during both the referee and rewriting processes), as well as the change of projects from superconducting/ferromagnet proximity effect (during my thesis, publications 1-5) to nanomechanical systems (publications 6 and 9) in Delft (Netherlands), and to Majorana fermions (publication 7) in Aachen (Germany) before returning to magnetic interactions in superconducting systems with spin-orbit interaction (publication 8 and the two preprints below), which I want to develop in this project.
Despite my publication list is quite short, I am the first (or corresponding) author on all publications, and all works have been done in small collaborations (only two co-authors at maximum in all publications), except for the experimental publication 6 for which I provided theoretical support only.
All my publications are available on the open-access arXiv server.

Preprints

1. *Magneto-electric coupling in a two-dimensional ballistic Josephson junction with in-plane magnetic texture.* **François Konschelle**. arXiv:1408.4533.

2. *Theory of the spin-galvanic effect and the anomalous phase-shift φ_0 in superconductors and Josephson junctions with intrinsic spin-orbit coupling.* **François Konschelle**, Ilya V. Tokatly and F. Sebastián Bergeret. arXiv:1506.02977.

Proceedings

- *Superconducting fluctuations near the FFLO phase.* François Konschelle, Jérôme Cayssol and Alexandre I. Buzdin. J. Phys.: Conf. Ser. 150, 052121 (2009) or hal-00319673 [CNRS preprint server]. Cited 1 time

The proceeding is available on the HAL-CNRS server, with a full list of publications, at:
http://hal.archives-ouvertes.fr/aut/konschelle/

Selected Talks to Conferences

- *Electromotive interferences in nanomechanically oscillating superconductors.* Superconductivity session of the French Physical Society (SFP: Société française de physique). Bordeaux, France (2011).

- *Effects of nonequilibrium noise on a quantum memory encoded in Majorana zero modes.* Collective mode session of the French Physical Society (SFP: Société française de physique). Marseille, France (2013).

- *Effects of nonequilibrium noise on a quantum memory encoded in Majorana zero modes.* Condensed Matter in Paris 2014. Paris, France (2014)

Selected poster sessions

- *Electromotive interferences in nanomechanically oscillating superconductors.* GDR de Physique Mésoscopique, annual meeting. Aussois, France (2012).

- *Environmentally induced memory decay in Majorana fermion qubit.* Deutsche Physikalische Gesellshaft Frühjahrstagung, Regensburg, Deutschland (2013).

- *Effects of nonequilibrium noise on a quantum memory encoded in Majorana zero modes.* Frontiers in Quantum Engineered Devices conference. Obergurgl, Austria (2013). – GDR Information Quantique, Fondements & Applications (IQFA), annual meeting. Paris, France (2013). – GDR de Physique Mésoscopique, annual meeting. Aussois, France (2013).

- *Magneto-electric coupling in a two-dimensional ballistic Josephson junction with in-plane magnetic texture.* Condensed Matter in Paris 2014. Paris, France (2014)

Thesis

- *Supraconductivité en présence de forts effets paramagnétique et spin-orbite.* François Konschelle - Ph.D. advisors : Jérôme Cayssol and Alexandre I. Buzdin (2009). tel-00517920 [CNRS thesis server] (in french).

On the web

Pedagogical activity on the Stack Exchange - Physics Q&A website,
http://physics.stackexchange.com/users/16689/

Short blogging activities on Twitter,
https://twitter.com/FraSchelle

5 Capacity of the Participating Organisations

Beneficiary	
General Description	The Material Physics Center is a Research Association created for managing the joint research center established by the Spanish Council for Research (CSIC) and the University of the Basque Country (UPV/EHU). All three institutions (CSIC, UPV/EHU and MPC) provide funding for the operations of the center. The aim of the joint initiative is to focus, coordinate and rationalise the investment of resources by the funding bodies in the area of Materials Sciences. The MPC has received the status of Centre of Excellence by the Basque Country Government (BERC). Currently, the centre hosts 96 people, including 55 researchers (36 permanent, 19 temporary/visiting), 27 PhD students and 11 technical, management and administrative support staff.
Role and Commitment of key persons (supervisor)	Javier Aizpurua - Director of Material Physics Center (legal signatory of research contract) - will be actively monitoring the evolution of the research contract and verifying that F. Konschelle has access to all the resources required for his research. F.S. Bergeret - Head of the Mesoscopic Physics Group (Supervisor) - is specialist in the field of transport properties of nanostructures, and in particular those containing superconducting and magnetic materials. He will be directly supervising both technical and management tasks of the project. F.S. Bergeret is committed to produce high-quality, high-impact research together with his group. He actively coordinated the activities of the group and the intensive agenda of international collaborations which boost the impact of the research and provide the group members with opportunities to establish collaborations and develop their careers. Francisco Lopez - Project & Innovation Manager at MPC - will be providing support for the management of the project, as well as advice about career opportunities for F. Konschelle.
Key Research Facilities, Infrastructure and Equipment	Material Physics Center headquarters is located in the Ibaeta Campus at San Sebastian, which also concentrates several related Departments (Chemistry, Materials Sciences) of the University of the Basque Country, technological centers such as CIC Nanogune and Polymat, and singular institutions such as the European Theoretical Spectroscopy Facility (ETSF) and the Donostia International Physics Center (DIPC). All together, this constitutes a thrilling environment for research in Materials Science. It is expected that F. Konschelle will require office space and access to the high-performance-computing center, which will be duly provided.
Independent research premises?	The HO will guarantee within the work contract that the researcher (F. Konschelle) will be given full autonomy, and will be granted access to all the facilities required for the development of his research plan. The use of these facilities will be provided free of charge.
Previous Involvement in Research and Training Programmes	F.S. Bergeret has been involved in the following projects: 2012-2015 Principal Investigator of the Project "Transport Properties of Hybrid Nanostructures: Superconductors, Ferromagnets and Normal Metals", awarded by the Spanish Ministry of Science and Innovation. 2010 Principal Investigator of the Project "Transport Theory of Superconducting Nanostructures" , awarded by the Spanish National Research Council. Budget: EUR 30,000. F.S. Bergeret has supervised in the past the training of A. Verso (postdoctoral stay), A. Ozaeta (PhD studies).
Current involvement in Research and Training Programmes	F.S. Bergeret is currently involved in the following projects: 2015-2018: Principal Investigator of the Project "Spin Transport in hybrid structures: metals, superconductors, semiconductors, graphene and topological insulators", awarded by the Spanish Ministry of Economy and Competitiveness. Budget: EUR 150,000. He currently has one PhD student and three Post-docs under supervision.
Relevant Publications and/or research / innovation products	F. S. Bergeret, A. F. Volkov, and K. B. Efetov, Rev. Mod. Phys. **77**, 1321 (2005). F. S. Bergeret and I. V. Tokatly, Phys. Rev. Lett. **110**, 117003 (2013). A. Ozaeta, P. Virtanen, F. S. Bergeret, and T. T. Heikkilä, Phys. Rev. Lett. **112**, 057001 (2014). E. Villamor et al., Phys. Rev. B **91**, 020403 (2015). F. Konschelle, I. V. Tokatly, and F. S. Bergeret, arXiv:1506.02977 (2015).

Partner Organisation	
General description	The JARA-Institute for Quantum Information (IQI) is a joint initiative of the RWTH-Aachen University and the Peter-Grünberg Institute at Forschungszentrum Jülich in Germany. It is divided in several groups, whose research range from fundamental aspects of quantum computation (Quantum Fault-Tolerance and Error Correction group, lead by B. Terhal and Quantum Many-Body Systems, Entanglement and Complexity group, lead by N. Schuch) to their realisations in condensed matter systems (activities on Spin-Qubits, Superconducting Qubits and Cavities, and Majorana Qubits and Non-Abelian Anyons, lead by D. DiVincenzo and F. Hassler) as well as experimental applications (Quantum Technology group, lead by H. Bluhm and L. Schreiber). It consists of 6 permanent members, 20 students and post-docs and 2 management and administrative support staff. It publishes about twenty publications per year.
Key Persons and Expertise (supervisor)	Fabian Hassler (FH) is Junior Professor at IQI since 09/2011. He has 35 publications and H-factor 14. He is world-wide known for his introduction of methods to detect and control Majorana modes in superconducting heterostructures, especially their braiding properties. His research activities focus on Quantum Information, Mesoscopic physics and Atomic, molecular and optical physics.
Key Research facilities, infrastructure and equipment	Fabian Hassler will provide essential knowledge about the topological aspect of Majorana modes. This knowledge transfer will be vital for a successful completion of WP2.
Previous and Current Involvement in Research and Training Programmes	In his short time at RWTH Aachen University, Fabian Hassler has supervised 2 PhD students (Christoph Ohm, expected year of graduation 2015, and Jascha Ulrich, expected year of graduation 2016), 3 master's students, and 8 bachelor's students. He is the principal investigator of the project "Josephson junction arrays of topological superconductors as quantum simulators" funded by the Deutsche Forschungsgesellschaft with a volume of EUR 170,000 over 3 years (2015-2018).
Relevant Publications and/or research/innovation product	*Anyonic interferometry without anyons: How a flux qubit can read out a topological qubit* - F. Hassler, A. R. Akhmerov, C.-Y. Hou, and C. W. J. Beenakker, New J. Phys. **12**, 7 (2010). *The top-transmon: a hybrid superconducting qubit for parity-protected quantum computation* - F. Hassler, A. R. Akhmerov, and C. W. J. Beenakker, New J. Phys. **13**, 095004 (2011). *Coulomb-assisted braiding of Majorana fermions in a Josephson junction array* - B. van Heck, A. R. Akhmerov, F. Hassler, M. Burrello, and C. W. J. Beenakker, New J. Phys. **14**, 035019 (2011).

6 Ethical Issues

Any ethical or security issue is expected in this project of theoretical fundamental physics.

END PAGE

MARIE SKŁODOWSKA-CURIE ACTIONS

Individual Fellowship (IF)
Call: H2020-MSCA-IF-2015

PART B

"TACSS"

"Topological Aspect of Coherent Superconducting Spintronics"

This proposal is to be evaluated as:

Standard EF