RESEARCH STATEMENT

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I had my training in theoretical physics, with a focus on quantum and classical non-linear dynamics and statistical physics. My research employs a combination of analytical calculations and large-scale numerical simulations (Monte Carlo simulations, integration of ordinary and stochastic differential equations for molecular dynamics, matrix diagonalization). The main points of my research statement are based on transport in open quantum systems, and ferromagnetic behavior at the nanoscale:

1) Open quantum systems (i.e. systems that exchange matter and energy with an external environment) are at the center of many research areas in condensed matter physics, ranging from quantum computing, transport in mesoscopic systems to basic theoretical problems, such as the measurement problem in quantum mechanics. Using an effective non Hermitian Hamiltonian approach to open quantum systems, we recently demonstrated the occurrence of a Superradiance transition in a paradigmatic model for coherent quantum transport (transport through a sequence of potential barriers). This opens exciting research perspectives. Coherent quantum regime is very important in nanoscale applications and it has important consequences in basic energy problems: evidence of coherent energy transfer has been recently found in photosynthetic light-harvesting systems [1]. We recently have shown that superradiance can have an important role for the efficiency of energy transport in light-harvesting complexes. In the future I plan to investigate the consequences of the Superradiance transition in interacting many body systems. My aim is to focus on emergent properties of many body systems due to the interplay of openness and internal interaction. Emergent properties [2] arise from cooperative effects in many body interacting systems, therefore they belong to the system as a whole and not to its components. We experience the importance of emergent properties every day, examples of emergent properties is for instance life itself and consciousness.

2) In order to understand the ferromagnetic behavior on the nanoscale it is essential to analyze the time scale of magnetic relaxation. Indeed nanoscopic systems can have a ferromagnetic behavior, due to long magnetic relaxation times, even in cases when the system does not display a ferromagnetic phase transition in the thermodynamic limit [3]; viceversa nanosystems with a ferromagnetic phase transition in the thermodynamic limit, might not show ferromagnetic behavior due to finite size fluctuations. Recently we analyzed an ergodicity breaking energy threshold in anisotropic spin systems. We demonstrated that this threshold determines the anisotropic energy barrier in a wide class of spin systems, thus ruling the time scale of magnetic decay.

All the topics I mentioned (magnetism in nanoscale structures, microscopic theory of electronic transport and emergent phenomena in mesoscopic systems) are among the grand challenges in Condensed Matter Physics and in Basic Energy Science [4, 5]. In the next years many funding opportunities can be expected on these topics. In what follows, I give a brief description of my research interests. Note that below each section, I have listed my articles on the subject, while new research projects have no references.

1. I. OPEN QUANTUM SYSTEMS

The degree of opening affects the properties of a system in an highly non trivial manner. An example of this is the phenomenon of Superradiance: in a typical situation, we have a discrete quantum system coupled to an external environment characterized by a continuum of

states. When a system is weakly coupled to the external world, generically all states are similarly affected by the opening, but as the coupling increases, a sharp restructuring of the system occurs at a critical value of the coupling. Beyond this critical value, almost the entire decay width is shared by a few short-lived states, leaving all other (long-lived) states effectively decoupled from the external world. The segregation of decay widths beyond a critical coupling to the external world is referred to as the Superradiance transition, due to its analogy with Dicke Superradiance. Although Dicke Superradiance is associated with many-body systems, width segregation occurs also in the one-body case.

In order to study the effect of the opening on quantum systems, we use an approach based on an effective non-Hermitian Hamiltonian. This approach allows to consider arbitrary coupling strength between the system and the outside world. This approach was first formulated by Feshbach to study nuclear reactions. It was then analyzed by Weindenmuller [6]. Later V. Zelevinsky [7] and I. Rotter [8], showed how this theoretical framework allows a detailed analysis of the Superradiance transition in open quantum systems. Non Hermitian Hamiltonians have been already employed to study realistic open quantum systems, such as transport through quantum dots [9], superradiance in cold atoms [10] and nuclear physics [11].

1.1. **Statistical theory of transport and nuclear reactions.** In the past years I studied open quantum systems under the assumptions of Random Matrix Theory (RMT). We analyzed the interplay of intrinsic dynamics (chaotic or regular) and degree of opening of the system in determining statistical properties of transport in mesoscopic systems and statistical properties of nuclear reactions. The effect of Superradiance transition was also pointed out. Recently we suggested an explanation (our letter was accepted for publication in Phys. Rev. Lett.) for the deviations from Porter-Thomas distribution of neutron resonance width distribution, observed in recent experiments [12].

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1.2. **Superradiance and transport through nanosystems.** One might ask whether in a realistic situation the coupling to the external environment can be increased up to the point where a Superradiance transition occurs. In order to address this problem I have investigated electron transport through a finite one dimensional sequence of square potential barriers, which is a paradigmatic model in solid state physics. This potential profile appears in real applications, such as semiconductor superlattices, arrays of quantum dots, and electron transport in molecular systems, and has been widely discussed in the literature. Using the effective non-Hermitian Hamiltonian approach, we have shown that the Superradiance transition (also called the Dicke effect in the mesoscopic community) occurs already in this simple model as the coupling to the external world is increased by adjusting the widths or heights of the external potential barriers. We have also demonstrated that the Superradiance transition strongly affects resonance structure and transmission. For instance, maximum transmission is obtained at the Superradiance transition point. The analysis has been extended to multidimensional systems and to branched-circuit systems, which are very relevant to information technology.

4. *A. Ziletti, F. Borgonovi,* ***G.L. Celardo*** *, F.M. Izrailev, L. Kaplan and V.G. Zelevinsky, arXiv:1109.1575v1.*

3. *S.Sorathia, F.M.Izrailev, V.G.Zelevinsky,* ***G.L.Celardo*** *, arXiv:1107.2371.*

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1.3. Quantum coherence in photosyntetic systems. The amount of energy humans use annually is delivered to Earth by the Sun in one hour! It could be of fundamental importance to use solar energy in an effective way. Natural photosynthetic systems are already able to capture and store solar energy. Most photosynthetic systems are composed by Antenna complexes, which capture photons from the sun, and a reaction center where the energy collected by the Antenna complexes is transformed in chemical energy. Antenna complexes are able to transfer excitations to the reaction center with an efficiency of more then 95%. For a long time It was thought that energy transfer in Antenna complexes occurs through classical processes, a kind of random walk of the excited electron to the reaction center. Surprisingly, evidence of coherent quantum energy transfer has been recently found in photosynthetic light-harvesting systems [1]. What really surprises researchers is how long coherence is in complex biological systems can last at temperatures between $77K$ - $293K$. Recently we investigated the relevance of long lasting quantum coherence for the efficiency of energy transport at room temperature in Fenna-Matthews-Olson photosynthetic complexes. The dissipation due to the coupling of the complex to a reaction center has been analyzed using an effective non Hermitian Hamiltonian. We showed that as the coupling to the reaction center is varied the maximum efficiency in energy transport is achieved at the superradiance transition, signaled by a segregation of the imaginary parts of the eigenvalues of the effective non Hermitian Hamiltonian. This approach allows to study different coupling schemes to the reaction center. We show that maximal efficiency at room temperature is sensitive to the way we couple the system to the reaction center.

1. **G.L.Celardo** , F. Borgonovi, V.I. Tsifrinovich, M. Merkli and G.P. Berman, arXiv:1111.5443.

1.4. Superradiance in many body systems. So far, my research on open systems has primarily addressed transport properties in one body problems. What will be the effect of Superradiance on the transport properties of many body systems? For instance in Dicke Superradiance, the intensity of radiation of N non interacting atoms goes as N^2, due to a collective cooperative phenomenon. I am particularly interested in new emergent phenomena that might arise from the interplay of internal interaction and degree of opening. Usually emergent phenomena are studied as a consequences of complex interaction between the many components of a system, and the effect of changing the degree of opening is largely neglected. For this reason there are many interesting questions which need to be answered about the effect of opening on many body quantum systems, such as the effect of the degree of opening on decoherence and entanglement of specific many-body subspaces. For instance in [14] the presence of superdecoherent and sub-decoherent subspaces have been pointed out in a simple model of quantum computer interacting with a phononic bath.

2. II. ERGODICITY BREAKING AND MAGNETIC DECAY IN NANOSYSTEMS

From a theoretical point of view the problem of magnetization decay in nanosystems is difficult to treat: nanoscopic systems are too big to be solved by brute force calculation and too small to be tackled by statistical mechanics at the equilibrium. Indeed, the problem of magnetization decay is a typical example of out of equilibrium phenomenon, which is the decay out of a metastable state. On the other hand, magnetism at the nanoscale has also important consequences in the technology of memory and information processing devices. The quest for improving magneto-storage density calls for the realization of smaller and smaller magnetic units. Understanding the time scale of magnetic relaxation is essential to use nanoscopic devices in information technology, i.e. nanoscopic memory units.

Our starting point in this research was the discovery of an ergodicity breaking energy threshold in isolated anisotropic spin systems. We called this threshold Topological Non-connectivity Threshold (TNT), see also Ref.s [15]. Below this threshold the system, when isolated, is non ergodic, which is: it cannot explore the available constant energy surface, since the available phase space is separated in at least two disconnected regions, characterized by a different sign of the magnetization. We have also demonstrated that in case of long range interaction among

the spins, the disconnected energy portion determined by the TNT remains finite, even in the thermodynamic limit. This fact shows that we can have a many body system which is not ergodic in a relevant part of its spectrum, even in presence of non linear dynamics and for large number of particles.

On the other hand for nanoscale structures, the TNT has important consequences both for short and long range interacting spins. When the system is in contact with an heat bath, this threshold represents an effective energy barrier for magnetic reversal, so that for average thermal energy below the TNT, the relaxation times depends exponentially on this energy barrier. Our analysis showed that for long range interaction this energy barrier grows as some power of the volume of the particle. This remarkably contrast with the behavior of short range interacting systems, where the energy barrier is proportional to the cross-sectional particle area, rather than to its volume. Long range interaction among the spins could thus induce stable ferromagnetic behavior in nanoscopic systems at room temperature.

Note that in many realistic situations one needs to go beyond nearest neighbor coupling, taking into account the long range nature of the interaction [16] . It is the case, for instance, of the dipolar interaction in 3–d systems, or of the so–called RKKY (Ruderman-Kittel-Kasuya-Yosida) interaction. In particular, the latter might be responsible for the ferromagnetic behavior of Diluted Magnetic Semiconductors (DMS) [17] and Diluted Magnetic Oxides (DMO) [18], promising materials for the realization of spintronics devices.

9. *F. Borgonovi,* **G.L.Celardo**, *"Enhancement of magnetic anisotropy barrier in long range interacting spin systems", cond-mat/1106.0148.*

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3. III. QUANTUM INFORMATION

Building a "useful" quantum computer is still a great theoretical and experimental challenge. The problems involved are numerous and pertain to all aspects of quantum computation: initial state preparation, evolution, and the final state read–out, which produces the output of the computation. We have analyzed a solid state model of quantum computation, and we showed how it is possible to reduce the errors that appear during the dynamical evolution of the system. Furthermore, we also considered the effect of external errors, modeled as random unitary perturbations on the evolution of the system. We showed that a modified quantum algorithm is more stable with respect to external unitary perturbations.

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4. IV. CHAOS AND THERMALIZATION

It is well known that in spite of dynamical disorder (high sensitivity of individual trajectories to initial conditions), chaotic systems display good statistical order (weak dependence of statistical properties on initial conditions). On this basis, it is possible to give a statistical description even of small systems, which lie outside the realm of statistical mechanics. It is also natural to ask whether well known methods of statistical mechanics apply in the case of small chaotic

systems. We demonstrated that single particle level occupation numbers can be described using standard statistical mechanical distributions (Bose-Einstein or Fermi-Dirac), even for small isolated systems. This means that a chaotic interaction can play the role of an internal heat bath.

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5. V. CONTROLLING ION CHANNEL DYNAMICS (BIOPHYSICS)

Ion channels are macromolecular "pores" in cell membranes, through which various ionic substances are allowed to pass. To a large degree, ion channels determine the properties of excitable cells in nerve and muscle tissue, and are at the center of intense studies in biophysics. Ion channels possess several metastable states, which can be modeled as local minima of a certain potential profile. Transitions between metastable states are thermally activated, and are also influenced by the electrical potential difference between the internal and external parts of the cell. When the potential difference between the interior and exterior of the cell is modified, the potential profile also changes, thus leading to a redistribution of the ion channel over different metastable states. It has been pointed out in [19] that applying a time dependent external potential can induce a focusing of the ion channel on a single metastable state. Preliminary experimental verification of this has been presented in [20]. It is still unclear what conditions are needed to focus the ion channel on one state or another. The purpose of this project is to understand the form of the time dependent external potential needed to focus the ion channel on a desired metastable state, and to demonstrate this control experimentally.

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