Annual PhD report - Second year

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XXXVIII cycle

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1 Research activity

I am a PhD student in Theoretical Physics and my research interests lie at the intersection between Quantum Field Theory, Statistical Mechanics and Condensed Matter Physics. In the following I describe in further detail the two different lines of research in which I worked this year.

- **Fractonic Gauge Theories**
  Recently, the interest in a new kind of quasiparticle, known as "fractons" , has been growing more and more. Fractons are exotic excitations of certain quantum phases of matter which are completely immobile in isolation, and whose low energy physics can be described by higher rank theories. The limited mobility property of fracton quasiparticles finds applications in many different contexts, including quantum information, spin liquids, elasticity, hydrodynamics, gravity and holography. In [1] we adopted a field theoretical approach to investigate the three dimensional action of a rank-2 symmetric tensor field invariant under the covariant fracton symmetry and with mass dimension equal to one. The theory appears as a non-topological higher rank generalization of the ordinary Chern-Simons model, depending only on the traceless part of the tensor gauge field. After defining a field strength, a rank-2 traceless "electric" field and a "magnetic" vector field were identified, in analogy with the standard Chern-Simons ones. Once matter is introduced, a Hall-like behaviour with fractonic features emerges. In particular, our model shows a Hall-like dipole current, together with a vectorial "flux-attachment" relation for dipoles. A gauge-fixing term was then introduced, from which propagators were computed and the counting of the degrees of freedom was performed. Finally, the energy-momentum tensor was shown to be conserved and the integrated energy density was proved to be zero, which reminds the topological nature of the standard Chern-Simons model. Remaining in this field of research we are currently investigating higher rank generalizations of 3D BF theory, focusing in particular on the case characterized by a rank-2 symmetric fractonic gauge field and a rank-2 gauge field without symmetries. Once matter is introduced, two different types of subdimensional particles emerge: fractons and lineons. Moreover, interestingly, we discovered that if one works partially on-shell on some particular solutions of the equations of motion then our theory can be exactly mapped to the low-energy effective field theory of the Rank-2 Toric Code, a quantum lattice model that has recently been extensively studied in condensed matter. We are also looking for connection between our theory and dipolar topological insulators, recently formulated in the condensed matter framework. Our work, that will be published soon, has been done in collaboration with A. Blasi, E. Bertolini, M. Carrega and N. Maggiore.

- **One-Dimensional Integrable Quantum Systems and Topological Frustration**
  Landau theory's implicit assumption that microscopic details cannot affect the global phases has been challenged only recently in systems such as antiferromagnetic quantum spin chains with an odd number of sites and periodic boundary conditions (*i.e.* subject to the so-called frustrated boundary conditions). Such systems have recently been of interest due to a very counterintuitive behavior: their properties are strikingly different from the ones characterizing the very same spin models, but in the absence of frustrated boundary conditions, even in the thermodynamic limit. In this context, the quantum phases exhibit a dependence on the boundary conditions. In [2], we showed that topological frustration modifies the zero temperature phase diagram of the XY chain in a transverse magnetic field by inducing new

boundary quantum phase transitions. Here, by boundary quantum phase transitions we mean non-analyticities in the ground state energy that are non-extensive in the number of particles. Such transitions are both of first and second order. Moreover, we came across the first case of second order boundary quantum phase transition characterized by a quartic dispersion relation. Our analytical results were supported by both analytical calculations and numerical investigations, and lay the foundation for understanding the phase diagram of frustrated model. In [3] we analyzed the effects of such frustration on a few-spin XY chain, with a particular focus on the strong even–odd effects induced in the ground-state energy. We then implemented a topologically frustrated quantum Ising chain on a quantum computer to show that our predictions are visible on current quantum hardware platforms. Finally, I contributed to the diagonalization and the phase diagram of the dimerized anisotropic XY chain analyzed in [4].

2 Publications

[1] E. Bertolini, A. Blasi, N. Maggiore and D. S. Shaikh, *Hall-like behaviour of higher rank Chern-Simons theory of fractons*, Submitted to Journal of High Energy Physics, [arXiv:2405.19446 [hep-th]].

[2] D. S. Shaikh, A. G. Catalano, F. Cavaliere, F. Franchini, M. Sassetti and N. T. Ziani, *Phase diagram of the topologically frustrated XY chain*, Eur. Phys. J. Plus 139 (2024) no.8, 743.

[3] De Filippi, F.R.; Mello, A.F.; Sacco Shaikh, D.; Sassetti, M.; Traverso Ziani, N.; Grossi, M. *Few-Body Precursors of Topological Frustration.* Symmetry 2024, 16, 1078.

[4] R. Grazi, D. Sacco Shaikh, M. Sassetti, N. Traverso Ziani and D. Ferraro, *Controlling energy storage crossing quantum phase transitions in an integrable spin quantum battery*, Submitted to Physical Review Letters, arXiv:2402.09169 [quant-ph].

3 Courses and exams

I attended the following courses:

- *Introduction to Black Holes*, Prof. S. Giusto (PhD course).
- *Foundations of Quantum Mechanics*, Prof. P. Solinas and Prof. N. Zanghì (PhD course).
- *Advanced Mathematical Methods for Physics*, Prof. S. Giusto (Master Degree course).

I am going to prepare the exams for the first two courses.