Il Colle di Galileo

Breakdown of Ergodicity in Isolated Quantum Systems: From Glassiness to Localization

May 20 - July 12, 2019

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Abstract. We report on a workshop, held at GGI, in which researchers from several universities and research centers around the world met to discuss recent breakthroughs in our understanding of the approach to thermal equilibrium of quantum systems. The discussion spanned from the fundamental problems concerning the interplay of the foundations of thermodynamics and quantum mechanics, to the implications for quantum technologies, in particular for quantum computing.

Keywords. Complex Systems, Quantum Computation and Quantum Simulation, Entanglement, Equilibration, Foundations of Statistical Physics.

Quantum mechanics is now a century old, but its implications are still surprising us, in particular when the behavior of systems composed of many elementary objects (like fundamental particles or atoms) is considered. Thermodynamics is even older (the works of Carnot date to more than two centuries ago) but it is still a perfectly valid, unchallenged description of a *macroscopic system*, namely one in which the number of elementary components is very large. How does the system behavior change from a complex dynamic dominated by quantum mechanics to a coarse-grained, simpler one described by statistical mechanics and eventually thermodynamic equilibrium? Is it necessarily the fate of a sufficiently large, isolated system to reach thermodynamic equilibrium? Notice that this is a non-trivial question, since large classical mechanical systems (as exemplified by the theory surrounding the KAM theorem of Kolmogorv, Arnold, and Moser) equilibrate through a mechanism called *ergodicity*, which is taken as the basis of statistical mechanics.

Several experimental and theoretical physicists from all over the world met at GGI from May to July 2019 to discuss recent breakthroughs on this topic. They reviewed and discussed our novel understanding of the behavior of complex

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quantum systems and, in particular, which features of quantum mechanics stop the generic mechanisms of equilibration. Far from being of mere academic interest, this problem is at the core of a possible *quantum supremacy* of quantum technologies, especially of quantum computing on present-day computers. The importance of this question was testified by the participants at the workshop, whose range of expertise was unusual for a meeting on technical, theoretical and experimental Physics.

About 140 physicists took part in the workshops held over the course of eight weeks, while about 60 persons attended the main conference, which lasted a week. Participants came from the most diverse backgrounds: they included, for example, mathematical physicists *Michael Aizenman* (Princeton), *John Imbrie* (Virginia Tech), and *Simone Warzel* (TU Munich); professors of experimental Physics *Paola Cappellaro* (MIT) and *Edward Grant* (UBC Vancouver); and Dr. *Hartmut Neven*, Director of Engineering at Google and leader of the Google Quantum Artificial Intelligence Lab (there were indeed several participants from the Google QAI Lab). These different figures took interest and actively participated in the meeting, which consisted of several seminars per week as well as spontaneously organized lectures; the latter were usually the result of requests from younger participants, as the meeting also hosted about 30 registered students PhD and 25 postdoctoral researchers. The variety of the background of the scientists attending the meeting was recognized by the participants as one of a kind, with some of them (by their own admission) being exposed for the first time to all the various aspects of a topic so multi-faceted as the one discussed.

The meeting also hosted two longer-term visitors, supported by a grant of the Simons Foundation, namely Prof. S. Sondhi (Princeton) and Prof. M. Kardar (MIT), two widely recognized theoretical physicists who helped cement the interaction and mentor the students with their experience and hindsight.

Regarding the scientific results of the meeting, both theorists and experimentalists agreed on the possibility that quantum mechanics can indeed hinder thermalization in the presence of quenched disorder in the system. In this case, therefore, thermodynamics *does not provide* a valid description of the long-time behavior of the system. Ergodicity is *broken*. These ideas are the continuation of the lines of the work of Phil Anderson, one of the most prolific and widely recognized theoretical physicists of the second half of 20th century (his work on this topic earned him the Nobel Prize in Physics in 1973). Two of the organizers, Giorgio Parisi (Università La Sapienza) and Boris Altshuler (Columbia) were arguably among the people who contributed the most to the topic of ergodicity breaking in quantum mechanics with their works on spin glasses and Anderson localization, respectively.

The statement that quantum mechanics can hinder thermalization in several *typical* (i.e. non fine-tuned) systems has profound consequences on both fundamental and applied Physics. Examples discussed in the workshop included the dynamics of lattice gauge theories (discrete space versions of theories of interacting particles), quantum spin glasses (disordered coherent quantum systems), electrons in semiconductors, arrays of Josephson junctions, and, last but not least, quantum circuits. Implications ranged from a possible explanation of deviations from the theory of the results of heavy ion collision experiments, to the analysis of the performance of a quantum algorithm.

We were happy to see that GGI and INFN took the opportunity to be at the forefront of these research lines, even if the topic is not easily classifiable among those usually discussed at GGI meetings, given the multidisciplinarity of the subjects of this workshop .