Quantum Materials Research Group

Balázs Újfalussy, Ivan Contini Abilio, Annamária Kiss, Nóra Kucska, András Lászlóffy, Krisztián Palotás, Karlo Penc, Levente Rózsa, Levente Vitos, Dániel Vörös

Quantum spin glasses.

Quantum spin glasses are a fascinating class of materials where interactions between spins are so frustrated that no simple magnetic order can form. Understanding the nature of these materials is a challenging problem. Unlike regular magnets, spin glasses feature randomly arranged spins that freeze into unpredictable orientations at low temperatures causing a unique energy landscape with numerous local minima. Spin glass systems display a phase transition characterized by the breaking of a complex symmetry known as replica symmetry. The order parameters are defined as the overlaps between different replicas. Unlike conventional magnets, the transition in spin glasses is typically not sharp, which complicates the experimental observation of both the glass transition and the associated glassy properties. Consequently, there is a significant need for theoretical studies of spin glass models. Spin glasses are scientifically relevant not only in condensed matter physics but also in interdisciplinary fields. They provide insights into neural networks, optimization problems, and even economics. The mathematical techniques developed to understand spin glasses have found correspondence with problems in computer science, such as the study of algorithmic complexity and information theory.

Classical spin glasses have been investigated extensively, and much progress has been achieved through the exact solution of mean-field models such as the famous classical Sherrington-Kirkpatrick (SK) model which is an Ising model with long-range frustrated ferromagnetic (which align spins in the same direction) and antiferromagnetic (which align spins in opposite directions) couplings. The simplest possible extension that adds quantum-mechanical aspects to the SK model is the inclusion of a transverse magnetic field, which adds additional layers of complexity. By combining the advanced continuous-time quantum Monte Carlo numerical technique with the sophisticated mathematical method of replica symmetry breaking we construct a numerically exact solution to this model [1].

Our study reveals the complete phase diagram of the model with a quantum glass phase at low temperatures and transverse fields, which is shown in Figure 1.A. Both thermal and quantum fluctuations melt the glass phase leading to the emergence of the paramagnetic phase. The quantum spin glass features non-trivial spin dynamics which we are able to compute with great detail. We determine the dynamical response of the spins, as well as their static response functions. We also extracted the distribution of the order parameters that characterizes how spins are correlated in the spin glass phase. Importantly, we derive the precise form of the dynamical response function which reflects the presence of abundant low-energy excitations. We find that the low-energy part of the response function is highly insensitive to the value of the transverse magnetic field in the glassy phase (Figure 1.B). This property is compared to the results with experimental measurements performed on the rare-earth compound $LiHo_xY_{1-x}F_4$ in a transverse field, which is believed to undergo a quantum spin glass transition [2]. We find an excellent agreement between our mean-field results and the experimental data., highlighted in Figure 1.B.

In summary, we advance the theoretical understanding of quantum spin glasses, bridging the gap between theoretical models and experimental results. Our work provides a general framework for solving other mean-field quantum glass models such as electron glasses and quantum Heisenberg spin glasses.

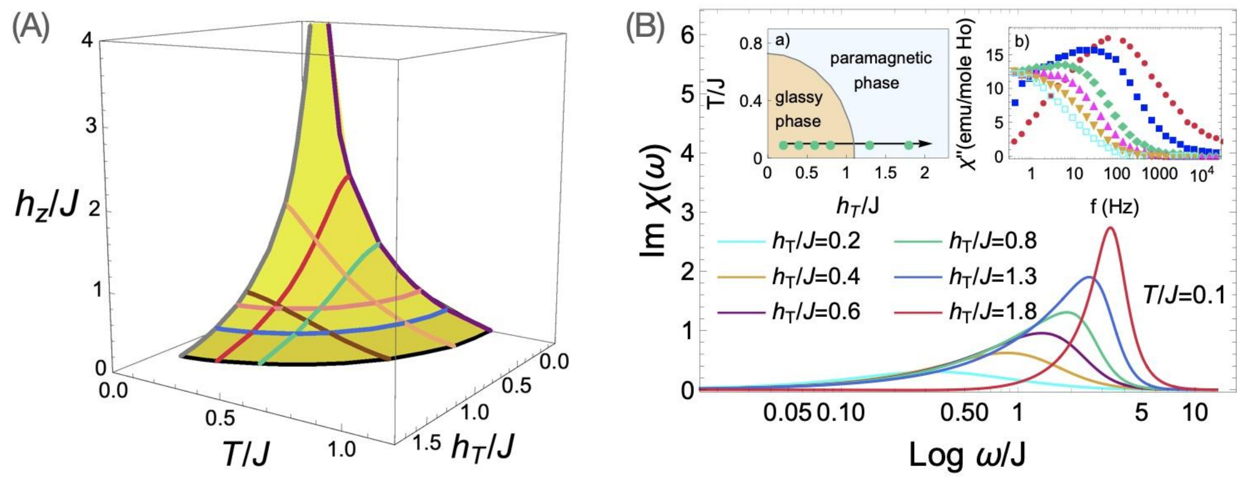

Figure 1. (A) Phase diagram in terms of the temperature T, transverse field h_T, and on-site disorder h_z, measured in units of the interaction strength J. (B) Comparison between the calculated dynamical susceptibility (main panel) and a.c. susceptibility measurements [2] (panel b)) moving from the spin glass phase to the paramagnetic phase as indicated in panel a) by varying the value of the transverse magnetic field.

References:

[1] A. Kiss, G. Zaránd and I. Lovas, *Complete replica solution for the transverse field Sherrington-Kirkpatrick spin glass model with continuous-time quantum Monte Carlo method*, Phys. Rev. B 109, 024431 (2024) https://doi.org/10.1103/PhysRevB.109.024431

[2] C. Ancona-Torres, D. M. Silevitch, G. Aeppli, T. F. Rosenbaum, *Quantum and classical glass transition in $LiHo_xY_{1-x}F_4$*, Phys. Rev. Lett. 101, 057201 (2008) https://doi.org/10.1103/PhysRevLett.101.057201