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Editorial: Current research on spin glasses

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Editorial on the Research Topic
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Overview

Fifty years after the discovery of phase transition-like behavior in random-dilute magnetic alloys, the spin-glass state is still not fully understood. Interpreting spin-glass behavior is of practical importance for understanding cooperative behavior in random systems, and fundamental interest for insight into complexity that occurs across multiple times and spatial scales. In recent years, great strides have been made towards clarifying the spin-glass problem utilizing novel experimental techniques, detailed simulations of microscopic models, and analytical analyses of mean-field and scaling theories.

Our goal for this Research Topic was to gather recent developments in the general area of spin-glass-like behavior into a review that can guide future progress. Specifically, we have assembled a range of recent studies from diverse disciplines to provide up-to-date insight into the behavior of complex systems. The volume contains a series of papers that can provide readily accessible (open access) content from top researchers in the field. We briefly summarize the papers in this Research Topic.

Experimental papers

The experimental papers in this Research Topic clearly show that even 50 years after the discovery of the spin glass state, much about the state is not understood and spin glasses remain a rich environment for discovery. Some of the main issues that come up in these papers include the exact experimental nature of the 3D phase transition, probing the large finite-size effects and time dependencies associated with crossing the Lower Critical Dimension of the phase transition, as well as investigations, in the spin glass phase, of the myriad of interesting time dependencies including memory, rejuvenation and temperature chaos.

In this Research Topic, Pradham et al. provide the first comparative study (on the same sample) of a variety of techniques (FC, ZFC, AC, onset of remanence) as a function of

magnetic field and temperature, that in the past have been used to determine the spin glass transition temperature. Kenning et al. have used ultra-high sensitivity DC SQUID magnetometry to probe close to the transition temperature elucidating for the first time, the strong time, temperature and magnetic field dependencies of the Thermal Remanent Magnetization (TRM) observed in this region.

He and Orbach present an array of results, first exploring the growth of a coherence length scale obtained from waiting time effect data, found from SQUID magnetometry, and compare this data directly with the growth of the 4-spin correlations as observed by the Janus simulations. They then present a theory relating the nonlinear magnetic field terms tothe effective waiting time and finally they report results on several other spin glass effects including temperature chaos, memory and rejuvenation.

Zhai and Orbach probe the time dependencies observed in spin glass thin films as a function of layer thickness, probing through the lower critical dimension. They compare the data with data found in large scale simulations and both neutron and muon spin scattering and provide analysis in terms of correlated growth in-plane and out-of-plane.

Well below the spin glass phase transition temperature, many time-dependent effects have been observed. Freedberg and Dahlberg explore both memory and rejuvenation and their experimental signatures as observed with in-phase and out-of-phase susceptibility and DC magnetization techniques.

Harrison discusses transport measurements in spin glasses, in particular Universal Conductance Fluctuations, to probe the spin glass state as a function of frequency and temperature.

Theoretical/computational papers

Theoretical developments that were originally spawned by the discovery of glassy behavior in disordered spin systems have, of course, expanded way beyond the confines of real materials. Mean field replica theory (honored with the Physics Nobel prize for G. Parisi in 2021) has inspired myriad of uses, not only in physics but also in computer sciences, engineering, as well as laying the foundations to machine learning (honored with the Physics Nobel prize for J. Hopfield in 2024). However, its applicability to actual magnetic materials in finite dimensions, specifically to the Edwards-Anderson lattice spin glass model, remains a widely discussed issue. It is its very glassy nature, entailing slow equilibration and the need of extensive disorder averaging, that is also the obstacle to provide conclusive insights with

simulations of low-temperature behavior in and out of equilibrium. In turn, these challenges have driven many fruitful designs of ever more ingenious mathematical concepts, computational techniques, and algorithms, some of which we showcase in this Research Topic.

The complexities of bringing traditional Monte Carlo techniques, so well-honed for ordinary materials, to bare on the thermodynamic behavior of magnetic glasses is exemplified in the review by Münster and Weigel, concerning the application of cluster algorithms to expedite equilibration near the phase transition. Similarly, Hukushima and Krauth explore the evolution of Markov chains to establish empirical as well as rigorous bounds on mixing and equilibration for the Edwards-Anderson model in 3d, in light of some recent algorithmic breakthroughs for structural glasses such as the hard-sphere model.

The breadth that the spin glass paradigm has taken on since its inception is demonstrated by Lanthier et al., who study the application of tensor networks to reduce the complexity, without or with only minimal loss of accuracy, in sparsely connected mean-field spin glasses with general p-spin coupling terms, which proves effective beyond expectations near the zero-temperature SAT/UNSAT transition. This has been an exceedingly fruitful area of research at the interface of spin glass theory and combinatorial optimization problems in computer science, such as SATisfiability. A similar reduction in complexity is employed by Boettcher to heuristically search for ground states of the Edwards-Anderson model, which is an (NP-)hard optimization problem deep in the UNSAT regime, to measure the energy cost of domain wall excitations in dimensions d = 3, …,8. Finally, Newman and Stein take a mathematically rigorous approach to such droplet excitations that are central to an understanding of the nature of ground states in the Edwards-Anderson model, showing that the relevance of replica theory to finite dimensional glasses is equivalent to the presence of certain critical droplets in the infinite lattice.

Dedication: in memory of Paolo Sibani

The guest editors would like to dedicate our work on this Research Topic to our dear friend and fellow scientist Paolo Sibani. Until his sudden passing, Paolo was a co-editor on this Research Topic. Paolo felt that this type of spin glass Research Topic, which includes both experimental and theoretical/computational papers and expresses the current state of the field, was both timely and necessary. In his work on this Research Topic Paolo brought the same

joy and enthusiasm that he brought to life and everything he worked on. His friendship will be greatly missed!

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