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Symmetric Mass Generation: Challenging Equilibrium Effective Theories and Extending Kibble–Zurek Dynamics

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Understanding the origin of mass has been a central theme in modern physics. In the Standard Model, spontaneous symmetry breaking provides the dominant paradigm, with the Higgs mechanism for bosons and Yukawa-type couplings for fermions [1]. Symmetric mass generation (SMG) presents a fundamentally different scenario in which fermions acquire a mass gap while all symmetries remain intact [2−5]. This places SMG transitions outside the Landau–Ginzburg–Wilson (LGW) framework, akin to deconfined quantum critical points but with fermionic degrees of freedom playing the central role [6,7].

Studies on the equilibrium criticality of SMG transitions remain relatively few, and their nonequilibrium dynamics are even less explored. In this work [8], the authors present an important study of the SMG transition in a bilayer honeycomb lattice model [5]. Using unbiased determinant quantum Monte Carlo (DQMC) simulations [9−12], they achieve two major contributions: (i) an unambiguous identification and high-precision characterization of the equilibrium criticality for the SMG transition in the bilayer honeycomb lattice model, and (ii) the first generalization of the Kibble–Zurek mechanism (KZM) [13,14] and finite-time scaling (FTS) [15−21] to the SMG transition. These findings deepen our understanding of quantum criticality and nonequilibrium phenomena.

Equilibrium Criticality of the SMG Transition in Bilayer Honeycomb Lattice

A key contribution of this work is the definitive resolution of a controversy surrounding the bilayer honeycomb lattice model. Previous variational Monte Carlo (VMC) studies suggested the existence of an SMG transition, but the reliability of the VMC approach is limited by the choice of the trial wavefunction. Moreover, mean-field analyses of this model have identified a possible exciton condensation order, leaving the true nature of the transition an open question [5].

Through large-scale, unbiased DQMC simulations, the authors provide compelling evidence for a direct SMG transition. By carefully analyzing the single-particle energy gap, they locate the critical point at $J_c = 2.584(4)$ and conclusively rule out exciton condensation and other symmetry-breaking orders. This resolves the controversy and establishes the bilayer honeycomb lattice model as a clean platform for studying SMG physics.

Equally important is the determination of the critical exponents. The authors extract the correlation-length exponent $\nu = 1.025(59)$ and the fermion anomalous dimension $\eta = 0.11(2)$. Notably, these values deviate from prior VMC estimates, suggesting that further theoretical investigations are needed to fully understand the critical properties of this transition.

Nonequilibrium Critical Dynamics of the SMG Transition in Bilayer Honeycomb Lattice

A further important contribution of this work lies in its extension to nonequilibrium critical dynamics. The KZM provides a general framework for describing driven critical dynamics. While its historical formulation is closely tied to topological defect production in symmetry-breaking transitions, the underlying origin of Kibble–Zurek scaling more broadly follows from critical slowing down and the loss of adiabaticity induced by external driving [13,14]. Nevertheless, for the SMG transition—which lacks both symmetry breaking and ordinary topological defects—it is not immediately obvious how to formulate a concrete FTS theory [15−21].

The authors address this question by studying the driven dynamics of the SMG transition, establishing a generalized FTS framework and exploring the physical meaning of the resulting driving-induced length scale. They argue that this length scale may be associated with fractionalized excitations and emergent gauge fields—the fundamental degrees of freedom in the field-theoretic description of SMG. In this way, their work provides a dynamic probe of fractionalization, offering a new window into a hidden aspect of quantum criticality beyond the LGW framework.

Conclusion

This work is significant on multiple levels. First, it provides a reliable characterization of the SMG criticality in this specific model, helping to resolve the controversy surrounding its phase diagram. Second, it establishes a generalized nonequilibrium scaling theory for the SMG transition, demonstrating that the KZM and FTS can be extended to a new class of quantum critical points where conventional order parameters are absent. Third, the findings have practical relevance: SMG has been invoked to explain exotic phenomena in nickelate superconductors and bilayer graphene, and this work provides a theoretical framework for interpreting future experiments in these systems.

Moreover, the study opens up several exciting directions. The novel critical exponents demand a new analytical field theory for SMG transitions. The nonequilibrium framework can be extended to other deconfined quantum critical points. And the predictions of generalized FTS also await further experimental verification in other platforms.

In summary, the authors have made an important contribution to the study of SMG transitions. By bridging equilibrium criticality and nonequilibrium dynamics, they have not only resolved a controversy surrounding the bilayer honeycomb lattice model but also extended the reach of the KZM and FTS to the SMG transition. This work deepens our understanding of mass generation and quantum criticality, while offering a new perspective for exploring exotic quantum

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dynamics beyond the LGW paradigm.

Note Added

It is worth noting that independent concurrent studies by He, You, and Xu have also investigated the equilibrium criticality of this same model [22,23], reporting equilibrium results consistent with those presented here, which offers further cross-validation of the numerical observations.

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