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学位（専攻分野）	博士（理学）
学 位 記 番 号	総研大甲第 2654 号
学位授与の日付	2026 年 3 月 24 日
学位授与の要件	高エネルギー加速器科学研究科　素粒子原子核専攻 学位規則第６条第１項該当
学 位 論 文 題 目	Numerical studies on real time evolution in quantum systems - Quantum decoherence and the beginning of the universe
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博士論文の要旨

氏　　名：山森　直幸

論文題目：Numerical studies on real time evolution in quantum systems
- Quantum decoherence and the beginning of the universe

Real-time dynamics in quantum systems can be described in two standard frameworks: the Schrödinger picture and the Feynman path integral. These two formulations are equivalent, but the path integral approach is better suited to describing systems with many degrees of freedom, such as QFT. Moreover, in numerical studies, the former entails a computational cost comparable to Hamiltonian diagonalization and thus grows exponentially with system size, whereas the latter can be evaluated using Monte Carlo methods with potentially polynomial scaling. However, the main obstacle to numerically simulating theories formulated in the path integral formalism is the sign problem associated with a highly oscillatory phase factor. In this work, we carry out numerical studies of real-time dynamics in quantum decoherence and superstring theory within the path integral formalism. To address the sign problem, we employ the Lefschetz thimble method (LTM) and the Complex Langevin method (CLM), depending on the context.

Decoherence is the environment-induced suppression of quantum coherence, manifested as the decay of off-diagonal components of a reduced density matrix. It plays a central role in the emergence of classical behavior from quantum dynamics. In theoretical studies, decoherence has often been investigated using the Caldeira–Leggett model. It has also been shown that treating the system and the environment together within the real-time path integral formalism enables a first-principles computation of the reduced density matrix. For typical initial conditions, the action is quadratic. After discretization, therefore the path integral becomes a finite-dimensional multivariate Gaussian integral. The relevant saddle point is complex and is obtained by solving a linear system whose coefficient matrix is very large but sparse. The remaining integration along the associated Lefschetz thimble can then be performed analytically. This provides an alternative to master-equation approaches, which are typically derived under additional assumptions such as the Born and Markov approximations or a high-temperature approximation.

Motivated by experimental progress on decoherence in increasingly large and complex systems, including mesoscopic objects such as massive molecules, we extend this path integral strategy to a three-dimensional cubic lattice model with nearest-neighbor interactions. Working entirely at the level of the action, we separate the degrees of freedom into center-of-mass (CM) and relative coordinates, treating the CM sector as an analogue of the distinguished system and the relative modes as an effective environment. This setup enables controlled scaling studies of how coherence depends on physical parameters. Our numerical results show a clear suppression of off-diagonal components in the reduced density matrix. Decoherence becomes faster as the system size parameter N is decreased, the interaction/pinning strength c is increased, or the temperature is raised.

On the superstring-theory side, we study the IKKT matrix model. This model is a nonperturbative formulation of superstring theory and can be obtained by dimensionally reducing ten-dimensional $\mathcal{N} = 1$ supersymmetric SU(N) Yang–Mills theory to zero dimensions. Space-time does not exist a priori, but emerges dynamically from the matrix degrees of freedom. Since the corresponding path integral has a complex weight, we employ the Complex Langevin method (CLM) to address the sign problem. Recent CLM studies have indicated that the Lorentzian and Euclidean models can be related by a Wick rotation. In that case, the emergent space-time becomes complex. To forbid this Wick rotation, we introduce a Lorentz invariant mass term with coefficient γ. For $\gamma > 0$, typical classical solutions exhibit an expanding space-time. However, the dimensionality of space-time is not determined at the classical level and is instead selected by quantum effects.

In CLM simulations, when the Dirac operator develops a zero mode, a singular drift problem arises. To control this, we introduce a quadratic fermionic mass deformation with coefficient m_{f}. These mass terms break SUSY, so we take the $\gamma \to 0$ and $m_{\mathrm{f}} \to 0$ limits after the large-N limit to recover the original IKKT model. As m_{f} is decreased, SUSY effects become more important, but the singular drift problem also becomes more severe. To enhance the effects of SUSY while keeping the complex Langevin method working, we additionally suppress bosonic fluctuations by introducing an anisotropy in the Lorentz invariant mass term with parameter ξ.

Another basic issue is that, due to the noncompactness of Lorentz symmetry, the partition function is divergent. A conventional regularization introduces a cutoff that breaks Lorentz symmetry, but the associated Lorentz symmetry breaking artifact remains even in the limit where the cutoff is removed. Following previous work, we gauge-fix Lorentz symmetry from the beginning. Within this framework, our CLM results show an expanding behavior in which three spatial directions grow while the remaining ones stay small, leading to an emergent (3+1)-dimensional expanding space-time.

（別紙 Separate Sheet）

Results of the Doctoral Thesis Defense

博士論文審査結果

Name in Full
氏　　名　山森　直幸

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論文題目
Numerical studies on real time evolution in quantum systems
- Quantum decoherence and the beginning of the universe

山森氏の博士論文では、量子系の実時間発展に関する数値的な研究の成果がまとめられている。特に、量子デコヒーレンスや宇宙の始まりなどに対して、ファインマンの経路積分法に基づいて行った研究について、これまでに氏が行ってきた研究が丁寧に解説されている。

量子デコヒーレンスの研究においては、ファインマン・ヴェルノン流に環境系を先に積分してしまうことをせずに、対象系と環境系もまとめて経路積分で扱っている。これにより、問題を巨大な一次方程式系の計算に帰着し、従来のマルコフ近似や高温近似などの制限を超えて、縮約密度行列の実時間発展を正確に計算している。この手法を大規模な分子系に応用した研究では、個々の原子の相対運動を「環境」と定義し、分子重心の運動に与える影響を解析した。その結果、重心運動の量子デコヒーレンスに関する性質を定量的に明らかにし、新たなスケーリング則を発見することに成功した。

また、宇宙の始まりの研究においては、超弦理論の非摂動的定式化として提案された IKKT 行列模型の数値シミュレーションを行っている。この計算は「符号問題」という技術的制約のため極めて難しいと考えられているが、山森氏は近年大きな発展を遂げた複素ランジュバン法と呼ばれる方法を駆使することでこの課題に取り組み、計算を完遂した。その結果、超弦理論が予言する(9+1)次元の時空から、我々の宇宙に対応する(3+1)次元の膨張時空が出現することを示唆する興味深い結果を得た。なお、この計算を遂行するにあたり、IKKT 行列模型が持つローレンツ対称性を「ゲージ固定」することが必須であったが、こうした模型の定義に関わる基礎的な研究においても、山森氏は共同研究者として重要な役割を果たした。その結果をまとめた論文は Physical Review Letters に掲載され、国際的に高く評価されている。

これらの内容は高い学術的価値が認められ、明快な英語で書かれている。以上より、博士論文の内容として必要な水準を遥かに超えるものであることを評価認定し、審査委員会は全会一致で山森氏の博士論文審査を合格と判定した。