デジタル・マテリアル研究チーム

Digital Materials Laboratory

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当研究チームは，物質中における複雑系のダイナミクスについて，計算機手法により研究を行う。さらに，様々な物理的手法を用いて得られた理論的予測を，単量子操作研究グループの他のチームと協力して検証する。当研究チームのメンバーがこれまでに携わった研究の例として，磁束ダイナミクスに関する集団輸送現象，超伝導デバイスによる量子コンピューティング，ナノ磁性およびスピントロニクス，バイオコンピューティング，多体系集団現象，量子現象を用いたバイオデバイスに関する研究などが挙げられる。

また，乱れた系，または低次元系における（量子化された磁束，電子，フォノン，粒界の）輸送現象に関する研究を行っている。これらの例には，幾何学的に制限された形状（薄膜，板状，極細線，極微ネットワークなど）や，多層膜，非周期性物質，準結晶，乱れた系などが含まれる。

物質における複雑系ダイナミクスに関するより深い理解は，他の研究分野の発展に貢献すると同時に自らも他分野との交流から寄与を受けている。

超伝導体を貫通する磁束線の振舞いの特性は，超伝導における解明されていない難問の１つである。これらの磁束線が超伝導体中の静止した渦糸（磁束量子）を通して運動するとき，「加負荷/無負荷」状態の周期的反復現象（loading-unloading cycles），「スティック/スリップ」型運動（stick-slip type motion），さらに砂粒やコロイド粒子など，他の媒質系でも見られる輸送現象に似た集団的「渋滞」状態（collective jamming）を呈する。

これまでに研究を行った課題には以下のものが含まれる。

（1）乱れた系における超伝導磁束量子のダイナミクス。

（2）非線形しきい値ダイナミクス，崩壊現象，なだれ現象，粉体系および超伝導系の不安定性。

（3）高温超伝導物質の磁気特性と温度特性。

（4）準結晶や他の非周期性物質系におけるフォノンおよび電子の輸送現象。

（5）音響干渉現象，フォノンの局在，および普遍的伝播における揺らぎ。

（6）スクイズドフォノンなどの固体中の量子揺らぎの制御。

（7）様々な系（超伝導線マイクロネットワークおよびジョセフソン接合マイクロアレイ（格子））における磁場中の電子の運動による量子干渉現象。

これらのミクロな系のいくつかは，まもなくナノスケールで展開されるようになると予想される。また，関連がないように見えるこれらの系のいくつかは，ある特殊な環境下において不安定性のしきい値に達すると，興味深い複雑系の非線形ダイナミクスを呈すると考えられる。

当研究チームは，本年度中に多くのプロジェクトに関わったが，簡潔にそのうち下記の幾つかの例について述べる。

1.　量子コンピューティング

量子情報技術の目標は，システムにおける量子状態の準備，操作，測定を含む量子状態の制御である。しかし，多くの量子ビットを集積し，任意に選択された量子ビットを結合することは，量子コンピューティング実現における大きな課題である。我々は，これらの問題を効率的に解決するためのジョゼフソン電荷量子ビットを使用する実現可能な実験的手法を提案した。この提案において任意の２つの電荷量子ビットが効果的に結合しているという意味で，この量子計算アーキテクチャーは集積性が良い。さらに重要なことは，ゲート操作により効率的な量子計算スキームを実現できたということである。

2.　時空間複雑系ダイナミクスに関する研究（特に磁束の運動制御，および粒子運動の制御について）

我々は超伝導中における磁束量子ダイナミクスに関する研究を続けており，特に我々が数年前に開拓し，現在多くの注目を集めているところの量子運動制御の新たな方法につて重点的をおき研究を行っている。

The “Digital Materials Laboratory” performs computational studies of complex dynamics in materials. We use physically-motivated numerical techniques to make theoretical predictions which can be tested experimentally, and we have often collaborated with experimental groups. We are currently working on several projects, including: collective transport in vortex dynamics, quantum computing in superconducting devices, nano-magnetism and spintronics, biologically-inspired computing, complex collective phenomena, etc. We are also working on “biologically-inspired devices using quanta”.

Our previous research has mainly focused on transport phenomena (of quantized magnetic flux or magnetic vortices, electrons, phonons, grains) in systems that have disorder and/or reduced dimensionality. Examples include confined geometries (e.g., films, slabs, micro-wires, micronetworks), multilayers, aperiodic, quasicrystalline, and dis-

ordered media.

A deeper understanding of complex dynamics in materials is now particularly well poised to contribute to advances in other disciplines and to benefit substantially from interactions with those disciplines.

The nature of the motion of penetrating magnetic flux lines is one of the major unsolved puzzles in superconductivity. As these flux lines move through stationary magnetic vortices in the superconductor, they exhibit loading-unloading cycles, "stick-slip" type motion, and collective "jamming" that resembles transport in other types of media: grains of sand and colloids.

Specific problems we have studied include: dynamics of superconducting vortices in disordered media; nonlinear threshold dynamics, collapse, avalanches, and instabilities in granular and superconducting systems; magnetic and thermal properties of high-TC materials; phonon and electron transport in quasicrystalline and other aperiodic systems; acoustic interference, phonon localization and universal transmission fluctuations; control of quantum fluctuations in solids, including squeezed phonons; and quantum interference due to electron motion in magnetic fields in a variety of systems (including superconducting wire micro-networks and Josephson junction micro-arrays). Several of these micro-systems will soon be developed at the nano-scale. Under certain circumstances, several of these apparently unrelated systems exhibit interesting complex nonlinear dynamics when driven to the threshold of instability.

During 2004, our team has been involved in many projects. For brevity, we will only highlight the following few examples. These fall in two general categories:

1. Quantum computing

2. Spatio-temporal complex dynamics, specially of vortices and particle-motion control. Also, particle-motion control.

A goal of quantum information technology is to control the quantum state of a system, including its preparation, manipulation, and measurement. However, scalability to many qubits and controlled connectivity between any selected qubits are two of the major stumbling blocks to achieve quantum computing (QC). We have proposed experimentally-realizable methods, using Josephson qubits, to efficiently solve these two central problems. The proposed QC architecture is *scalable* since any two charge qubits can be effectively coupled. More importantly, we formulate *efficient* and *realizable* quantum computing schemes to implement conditional gates.

We are continuing our studies of vortex dynamics in superconductors with particular emphasis on novel forms of vortex motion control, an area which we pioneered years ago and is now attracting considerable attention.

Research Subjects

1. Condensed matter physics; Computational physics; Complex systems
2. Quantum computing. Superconducting qubits
3. Vortex dynamics in superconductors

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