Bhuvanesh Sundar

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Research interests

My interest is developing ideas for many-body quantum simulation with ultracold gases or noisy intermediate-scale quantum devices to solve problems in physics and engineering. I like to work in collaborative environments, and I actively collaborate with experimentalists. I motivate my research by the latest experiments for quantum simulation.

Education

Degree	Date of completion
Ph.D in Physics, Cornell University Thesis Title: Many-body physics using cold atoms Thesis supervisor: Erich J. Mueller	January 2017
Masters in Physics, Cornell University	January 2014
Bachelor of Technology in Engineering Physics **Minor degree in Computer Science**, Indian Institute of Technology, Delhi, India	May 2010

Work experience

- **Postdoctoral researcher** — February 2021 onwards
  JILA, Boulder
  Postdoctoral advisor: Ana Maria Rey
- **Postdoctoral researcher** — November 2019 to January 2021
  Institute for Quantum Optics and Quantum Information, Innsbruck
  Postdoctoral advisor: Peter Zoller
  - Variational quantum-classical algorithms for producing strongly correlated many-body states
  - Developing algorithms to probe many-body quantum systems
- **Postdoctoral researcher** — February 2017 to October 2019
  Rice University
  Postdoctoral advisor: Kaden R. A. Hazzard
  - Quantum simulation with ultracold gases
  - Developed a quantum algorithm for counting solutions of constraint satisfaction problems with applications in engineering
  - Developed and applied numerical methods - NLCE, TWA, ED, network analysis - for modeling and characterizing quantum systems in and out of equilibrium
- **Graduate research assistant** — August 2010 to January 2017
  Cornell University
  Graduate advisor: Erich J. Mueller
  - Quantum simulation of many-body physics with ultracold gases

Awards

- **ATOMS** travel grant for travel to the APS DAMOP conference, 2019.
- **ICAP** travel grant for travel to the ICAP conference, 2014.

Selected publications

1. *Proposal for measuring out-of-time-ordered correlators at finite temperature with coupled spin chains*, **B. Sundar**, A. Elben, L. Kh Joshi, and T. V. Zache, preprint available upon request.
2. *Quantum Variational Learning of the Entanglement Hamiltonian*, C. Kokail, **B. Sundar**, T. V. Zache, A. Elben, B. Vermersch, M. Dalmonte, R. v Bijnen and P. Zoller arXiv:**2105.04317**.
3. *Nonlinear dynamics in a synthetic momentum state*, F. A. An, **B. Sundar**, J. Hou, X.-W. Luo, E. J. Meier, C. Zhang, K. R. A. Hazzard and B. Gadway arXiv:**2105.04429**.
4. *Emergent complex quantum networks in continuous-variables non-Gaussian states*, M. Walschaers, N. Treps, **B. Sundar**, L. D. Carr, and V. Parigi, arXiv:**2012.15608**.
5. *Response of quantum spin networks to attacks*, **B. Sundar**, M. Walschaers, V Parigi and L. D. Carr, J. Phys. Complex. **2**, 035008 (2021).
6. *Proposal to measure out-of-time-ordered correlations using Bell states*, **B. Sundar**, arXiv:**2006.15093**.
7. *Spin-imbalanced ultracold Fermi gases in a two-dimensional array of tubes*, **B. Sundar**, J. A. Fry, M. C. Revelle, R. G. Hulet and K. R. A. Hazzard, Phys. Rev. A **102**, 033311 (2020).
8. *Cold atoms in optical lattices*, Invited Review; Chapters 2, 4 and 8 in "2D quantum metamaterials: Proceedings of the 2019 NIST workshop", Edited by Wiley P. Kirk, John N. Randall and James H. G. Owen.
9. *A quantum algorithm to count weighted ground states of classical spin Hamiltonians*, **B. Sundar**, R. Paredes, D. T. Damanik, L. Dueñas-Osorio, K. R. A. Hazzard, arXiv:**1908.01745**
10. *Analysis of continuous and discrete Wigner approximations for spin dynamics*, **B. Sundar**, K. C. Wang, and K. R. A. Hazzard, Phys. Rev. A **99**, 043627 (2019).
11. *Quantum dimer models emerging from large spin ultracold bosons*, **B. Sundar**, T. C. Rutkowski, E. J. Mueller, and M. J. Lawler, Phys. Rev. A **99**, 043623 (2019).
12. *Strings of ultracold molecules in a synthetic dimension*, **B. Sundar**, M. Thibodeau, Z. Wang, B. Gadway, and K. R. A. Hazard, Phys.Rev. A **99**, 013624 (2019).
13. *Complex-network description of thermal quantum states in the Ising spin chain*, **B. Sundar**, M. A. Valdez, L. D. Carr, and K. R. A. Hazzard, Phys. Rev. A **97**, 052320 (2018).
14. *Synthetic dimensions in ultracold molecules: Quantum strings and membranes*, **B. Sundar**, B. Gadway, and K. R. A. Hazzard, Sci. Rep. **8**, 3422 (2018).
15. *Quantum dynamics from a numerical linked cluster expansion*, I. G. White, **B. Sundar**, and K. R. A. Hazzard, arXiv **1710.07696**.

16. *Lattice bosons with infinite range interactions*, **B. Sundar** and E. J. Mueller, Phys. Rev. A **94**, 033631 (2016).

17. *Proposal to directly observe the Kondo effect through enhanced photo-induced scattering of cold fermionic and bosonic atoms*, **B. Sundar** and E. J. Mueller, Phys. Rev. A **93**, 023635 (2016).

18. *Universal quantum computation with Majorana fermion edge modes through microwave spectroscopy of quasi-1D cold gases in optical lattices*, **B. Sundar** and E. J. Mueller, Phys. Rev. A **88**, 063632 (2013).

Invited talks

1. *Synthetic dimensions in ultracold gases*
AMO seminar at University of Michigan, Ann Arbor (2019).

2. *A quantum algorithm to count weighted ground states of classical spin Hamiltonians*
Cornell University Special Seminar (2019).

3. *A quantum algorithm to count weighted ground states of classical spin Hamiltonians*
Smalley-Curl Institute Postdoctoral Lunch Series, Rice University (2019).

4. *Synthetic dimensions in ultracold polar molecules: From topology to quantum strings*
University of Göttingen (2018).

5. *Synthetic dimensions in ultracold polar molecules: From topology to quantum strings*
Max Planck Institute for Complex Physical Systems, Dresden (2018).

6. *Synthetic dimensions in ultracold polar molecules: From topology to quantum strings*
Institute for Science and Technology, Austria (2018).

7. *The search for a spin-imbalanced superconducting phase*
Smalley-Curl Institute Postdoctoral Lunch Series, Rice University (2018).

8. *Synthetic dimensions in ultracold polar molecules*
Kang-Kuen Ni group seminar, Harvard University (2017).

9. *Universal quantum computation with Majorana fermions in cold atoms*
Electron Devices Seminar, Cornell University (2012).

Conference presentations and posters

1. *Protocol to measure the out-of-time-ordered correlator at finite temperature*
Oral presentation, APS DAMOP meeting (2021).

2. *Complexity in quantum spin networks*
Oral presentation, NetSci satellite workshop on Quantum Network Science (2020).
Poster presentation, APS DAMOP meeting (2021).

3. *Quantum speedup for weighted constrained counting problems*
Poster, NISQ workshop (2019),
Poster, APS DAMOP meeting (2019),
Poster, Smalley-Curl Institute summer colloquium, Rice University (2018).

4. *A complex network description of quantum systems*
Oral presentation, Smalley-Curl Institute Symposium, Rice University (2018).

5. *Synthetic dimensions in ultracold polar molecules*
Poster, Atomic Physics Gordan Research Conference (2019),
Poster, International conference on atomic physics (2018),
Oral presentation, Smalley-Curl Institute Colloquium, Rice University (2017).

6. *Quantum dimer models emerging in ultracold Mott insulating Bose gases with a large spin*
   Oral presentation, APS March Meeting (2017),
   Poster, APS DAMOP meeting (2017).

7. *Quantum phases of bosons with long range interactions in an optical lattice*
   Poster, ARO-AFOSR MURI program meeting, University of Chicago (2016),
   Poster, EPIQM summer school, Cornell University (2016),
   Poster, APS DAMOP meeting (2016).

8. *Simulating the Kondo effect in cold atoms using photo-induced scattering*
   Oral presentation, APS DAMOP meeting (2015).
   Poster, International conference on atomic physics (2014).

9. *Microwave probes of Majorana fermions*
   Poster, Symposium on Novel Topological Quantum Matter, UT Dallas (2013).

Other conferences, summer schools, and meetings

1. Quantum network science workshop, Army Research Office — May 2019
2. 2D quantum metamaterials workshop, Zyvex Labs and NIST — April 2018
3. MURI meeting at the University of Chicago — September 2016
4. Emergent Phenomena in Quantum Materials summer school, Cornell University — June 2016
5. International Conference on Atomic Physics summer school — June 2014

Teaching experience

1. Grader for Quantum information processing — Fall 2016
2. Waves and thermodynamics — Fall 2016
3. Basic quantum mechanics — Spring 2016
4. Waves and thermodynamics — Fall 2015
5. Graduate quantum mechanics — Fall 2013
6. Thermodynamics ad statistical mechanics — Fall 2011
7. Waves, optics and quantum physics — Spring 2011
8. Mechanics-1 — Fall 2010

Skills

- Proficient in Mathematica, MATLAB, Python, C, C++
- Experienced with numerical Monte Carlo, DMRG, variational optimization, cluster expansions, mean field methods, semiclassical methods

Professional organizations

Member of the American Physical Society — August 2012 to present

Service and Leadership

- Session chair for "Dynamics of ultracold atoms in optical lattices", APS DAMOP meeting 2021.
- Refereed over 40 articles for Phys. Rev. A, Phys. Rev. B, Phys. Rev. Lett., Nature Materials, European Physics Journal D, and Entropy.
- Taught a workshop on using Wolfram Mathematica to undergraduate physicists at Cornell University.

Brief summary of research

1. **Learning the entanglement Hamiltonian.** We propose a classical-quantum variational method to learn the entanglement Hamiltonian and the entanglement spectrum of a subsystem in a quantum many-body system. We do this by time-evolving the subsystem with a family of deformed Hamiltonians, and optimizing for the constancy of the subsystem under time evolution.
2. **Measuring the out-of-time-ordered correlations.** We proposed a feasible protocol to measure the out-of-time-ordered correlation for a class of Hamiltonians, by measuring local correlations between two systems that are evolved after initially being entangled in the thermofield double state. Our method allows one to measure the spreading information in finite temperature systems. We implement our method on a trapped ion platform.
3. **A quantum algorithm for counting minima.** In a multi-disciplinary collaboration with Leonardo Duenas-Osorio (civil engineer) and David Damanik (mathematician), we designed a quantum approximate optimization algorithm that lets us sample the ground states of a classical Hamiltonian with a given weight function. We used this to solve weighted counting problems, and considered counting edge covers on a graph with weights as an example. We showed that our algorithm has a sub-quadratic quantum speedup over the best available classical algorithm. We implemented this algorithm for small problem instances on IBMQ and with trapped ions in Norbert Linke's experiment (see below).
4. **Variational quantum optimization with trapped ions.** In an ongoing collaboration with Kaden Hazzard and Norbert Linke, we designed and implemented the above quantum algorithm (developed with Leonardo Duenas-Osorio and David Damanik) as well as another variational quantum optimization algorithm for maxcut with a digital quantum circuit in Norbert Linke's trapped ion experiment. We observed one of the first instances of an improvement in the experimental results as the variational circuit's depth increased from $p = 1$ to $p = 3$.
5. **Interacting Fermi gas on a 2D lattice.** In collaboration with Randall Hulet and Kaden Hazzard, we simulated experiments in Hulet's lab on an attractively interacting spin-imbalanced Fermi gas in a two dimensional array of tubes, and numerically found density profiles and phases consistent with experimental measurements. Our calculations indicate that the Fulde-Ferrel-Larkin-Ovchhinnikov phase is present in some regions of the trap ini the experiment.
6. **Analysis of Truncated Wigner Approximations.** We compared the performance of the continuous and discrete truncated Wigner approximations (which are semiclassical methods) for spin dynamics in a quenched Ising or XXZ system, against exact solutions. We were able to gain general insights into the shortcomings of the approximations - they predominantly suppress correlation along one spin direction.

7. **Quantum complex networks.** In collaboration with Lincoln Carr and Kaden Hazzard, we investigated the network structure of correlations between spins in an Ising chain using network analysis tools. We found that quantum correlations typically form a complex network even in this simple system, and the network structure varied across the phase diagram, mirroring the complexity of the underlying system.

   In two other ongoing collaborations with Lincoln Carr and Valentina Parigi, we investigate the robustness of complex quantum networks to network attacks. We find that complex quantum networks are more robust to these attacks than regular quantum netwoks.

8. **Synthetic dimensions.** In collaboration with Bryce Gadway and Kaden Hazzard, we proposed to simulate fully controllable single-particle Hamiltonians in experiment using the internal rotational states of ultracold polar molecules as a large synthetic dimension extending up to potentially hundreds of sites. We coupled the synthetic states via microwave driving. We found that dipole interactions drive the system to undergo a dimensional collapse and form a fluctuating quantum string which spontaneously breaks translational symmetry in the synthetic direction.

   In another ongoing collaboration with with Bryce Gadway, Kaden Hazzard, and Chuanwei Zhang, we simulate an experiment with interacting bosonic ^{87}Rb atoms in a synthetic lattice created from momentum states. We investigate the onset of self-trapping in this gas, and matched the experimental observations with numerical calculations.

9. **Numerical linked cluster expansion.** We developed tools to extend the numerical linked cluster expansion method to calculate dynamics of on-site observables and pair correlations in non-equilibrium systems. Our method applies to any lattice model, and is often five to ten orders of magnitude faster than other methods such as exact diagonalization.

10. **Quantum dimer models.** In collaboration with Erich Mueller and Michael Lawler, we proposed an experiment to produce a quantum dimer model using ultracold atoms with large hyperfine spin in a deep optical lattice. The atoms have spin-dependent interactions produced by an optical Feshbach resonance. We proposed using photoassociation to observe correlations in the ground state of the quantum dimer model.

11. **Supersolid bosons in an optical cavity.** We modeled an experiment in Prof. Tilman Esslinger's group with bosons trapped in a transversely pumped single mode optical cavity, and calculated the many-body phase diagram. The atoms experience effective infinite range interactions mediated by the cavity. We found the atoms arrange in a superfluid, supersolid, charge density wave or Mott insulator in different regions of the phase diagram, in good agreement with the experiments.

12. **Kondo physics.** We proposed an experiment to observe the Kondo effect by scattering an ultracold Fermi gas with a Bose gas. The fermions and bosons have spin-dependent interactions produced by an optical Feshbach resonance. We calculated the momentum transferred in a scattering experiment, and showed that it has a logarithmic temperature dependence, analogous to the resistivity of alloys with magnetic impurities.

13. **Quantum computation with Majorana fermions.** We described how microwave spectroscopy of spin-orbit coupled cold fermions in quasi-1D traps can be used to detect, manipulate, and entangle exotic nonlocal qubits associated with Majorana edge modes. We devised protocols to perform universal quantum computation with the qubits encoded in the edge modes.