Nanoscale Science and Technology
Room 320 - Session NS-MoM

Frontiers in Nanoscale Electron, Ion, and Scanning Probes I

Moderators: Dr. Marek Kolmer, Ames National Laboratory, **Dr. Yongtao Liu**, ORNL

10:00am **NS-MoM-1 The Atomic Single-Electron Transistor***, **Dahlia Klein,*** University of Chicago **INVITED**

Electrons in solids owe their properties to the periodic potential landscapes they experience. Moiré lattices have given us powerful new ways to engineer such landscapes on nanometer scales, yet directly imaging them remains elusive. In this talk, I introduce the Atomic Single-Electron Transistor (SET), a scanning probe that uses a single atomic defect in a van der Waals material as an ultrasensitive, high-resolution potential sensor. Built upon the quantum twisting microscope (QTM) platform, this probe leverages the QTM's capability to form a pristine, scannable 2D interface between van der Waals heterostructures. Using the Atomic SET, we present the first direct images of the electrostatic potential in graphene aligned to hexagonal boron nitride. This potential exhibits approximate C6 symmetry, minimal dependence on carrier density, and a magnitude of ~60 mV even in the absence of carriers. Notably, this magnitude significantly exceeds theoretical predictions, suggesting that our current understanding may be incomplete. With ~1 nm spatial resolution and sensitivity to potentials generated by only a few millionths of an electron's charge, the Atomic SET opens a path to imaging charge order and thermodynamic properties across a wide range of quantum phenomena.

10:30am **NS-MoM-3 Local Spectroscopy Reveals Quantum Geometry of Magnetic Bloch States and Hyperorbits in Hofstadter Bands***, **Dengyu Yang,*** National Institute of Standards and Technology (NIST)/ University of Maryland, College Park*; Lisa Frammolino, Duarte de Sousa,* National Institute of Standards and Technology (NIST)*; Rishav Harsh, Keunhong Min,* National Institute of Standards and Technology (NIST)/ University of Maryland, College Park*; Young Jae Song, Sungmin Kim,* National Institute of Standards and Technology (NIST)*; Ian Mercer,* Penn State University*; Kenji Watanabe, Takashi Taniguchi,* NIMS (National Institute for Materials Science), Japan*; Jon-Paul Maria,* Penn State University*; Paul Haney, Joseph Stroscio,* National Institute of Standards and Technology (NIST)

When a two-dimensional electron system is subjected to both a periodic potential and a magnetic field, its spectrum reorganizes into Hofstadter minibands set by the rational magnetic flux per unit cell. While the resulting subband hierarchy has been widely studied, the semiclassical dynamics of magnetic Bloch states, described as hyperorbits and supporting the higher order fractal spectrum, has remained far less explored experimentally. Here we use ultra-low-temperature STM/STS, supported by band-structure calculations, to study Bernal bilayer graphene in an hBN moiré lattice. We directly resolve Hofstadter minibands across continued fraction fluxes of the form $1/(q_1+1/q_2)$, demonstrate q_1 subbands across moiré filling for $q_2 = 0$, and observe further q_2-fold energy splitting and minigap formation at higher-order fractions. The field evolution of these spectra near commensurate flux show branch connectivity and minigap evolution consistent with hyperorbit quantization of magnetic Bloch bands. Gate-dependent spectra track Chern-indexed gaps and reveal signatures consistent with interaction-driven flavor symmetry breaking. Theoretical calculations show the importance of the quantum geometry and Berry curvature of the electronic bands in determining the fine features of the energy spectrum. Our measurements show local spectroscopy of the magnetic Bloch states and the direct role of quantum geometry in Hofstadter physics.

10:45am **NS-MoM-4 Cryogenic STM Readout of High-Q MEMS Resonators for Superconducting Casimir-Force Measurements***, **Robbie Elbertse,** Minxing Xu, Ata Keşkekler,* Delft University of Technology, Netherlands*; Giuseppe Bimonte,* Università di Napoli Federico II, Italy*; Jinwon Lee, Sander Otte, Richard Norte,* Delft University of Technology, Netherlands

Scanning tunneling microscopy (STM) and micro-electromechanical systems (MEMS) have traditionally operated at vastly different length scales: one resolving atomic-scale structure, the other engineering collective motion in mesoscopic and macroscopic structures. Here we unite these regimes by using an STM junction as a minimally perturbative local actuator and detector for high-aspect-ratio MEMS resonators. Operating at cryogenic temperatures, we resolve acoustic modes of millimeter-scale, high-Q membranes without optical or capacitive readout, while maintaining local sensitivity to displacement and tip–sample interaction forces. The tunneling junction introduces negligible back-action and heating, enabling direct access to the intrinsic dynamics of microgram-scale oscillators. We demonstrate three complementary STM-based measurement modalities and show how they enable precision measurements of displacement, force, and pressure in cryogenic nanomechanical systems. We then apply this platform to the long-standing challenge of measuring changes in Casimir pressure across a superconducting transition, using a highly parallel on-chip membrane geometry. With verified micro-Pascal pressure resolution, this STM–MEMS approach provides a credible route toward studying fluctuation-induced forces in superconducting systems under conditions of alignment, stability, and sensitivity that have been difficult to access with conventional techniques.

11:00am **NS-MoM-5 Andreev Reflection and Electronic Reconstruction in Proximate Contacts to Superconductors***, **Petro Maksymovych,*** Clemson University*; Sang Yong Song,* Daegu Gyeongbuk Institute of Science and Technology, Republic of Korea*; Wonhee Ko,* University of Tennessee Knoxville*; Chengyun Hua, Gabor Halasz, Jiaqiang Yan, Benjamin Lawrie,* Oak Ridge National Laboratory, USA*; Jose Lado,* Aalto University, Finland

The transition from tunneling to contact is a crossover from exponentially decaying wavefunction overlap to coherent electronic hybridization between two conductors, and can be generally expected to produce phenomena distinct from both the tunneling and strong-coupling limits. Using the layered unconventional superconductor FeSe as a model system, we demonstrate that traversing this crossover with a scanning tunneling microscope enables both spectroscopic fingerprinting of the superconducting order parameter and nanoscale manipulation of individual vortex lines.

In the tunneling regime, Tunneling Andreev Reflection (TAR) spectroscopy exploits the exponential sensitivity of the excess decay rate to Andreev reflection, separating Andreev and quasiparticle currents through the additivity of their excess decay rates. Transport simulations show how higher-order scattering processes and the competition between Andreev and quasiparticle channels shape the decay rate spectra as coupling strength increases, distinguishing s-wave, d-wave, and sign-changing order parameters in ways inaccessible to conventional conductance-based methods [1].

At weak physical contact, the STM junction becomes a tunable vortex pinning potential. Tip-induced strain locally suppresses the larger of FeSe's two superconducting gaps while leaving the smaller gap intact, replicating the gap structure observed at twin boundaries and wrinkles. This strain-induced inclusion deflects individual vortex lines with forces of 1–5 pN, orders of magnitude larger than previously achieved in conventional superconductors, and the vortex line deformation grows logarithmically with contact conductance, consistent with an anisotropic inclusion model. Tip geometry further sets the deformation strength, providing a tunable handle even within dense vortex lattices [2].

Together, these results establish the tunneling-to-contact window as a powerful probe of quantum states, opening new pathways for studying exotic superconductors, vortex-bound electronic states, and nanoscale magnetism.

Research sponsored in part by Division of Materials Science and Engineering, Basic Energy Sciences, Office of Science, US DOE at the Oak Ridge National Laboratory, and, at Clemson University by the State of South Carolina through funding for the Battelle Savannah River Alliance Workforce Development Program.

[1] Maksymovych et al., Fingerprinting superconductors by disentangling Andreev and quasiparticle currents across tunable tunnel junctions, arXiv:2601.20798v1

[2] Song et al. Nanoscale (2026), 10.1039/D5NR04204F.

11:15am **NS-MoM-6 Probing Unconventional Superconductivity by Atomically Resolved Multi-Particle Tunneling Spectroscopy***, **Wonhee Ko,*** University of Tennessee, Knoxville

Unconventional superconductivity is central to emerging quantum technologies, including dissipationless electronics and topological quantum computing. Still, identifying the nature of unconventional superconducting states remains challenging because few experimental techniques can directly probe the superconducting order parameter. Here, we use scanning tunneling microscopy (STM) to perform multi-particle tunneling spectroscopy in atomic resolution and reveal the nature of unconventional superconductivity across a range of material systems. Multi-particle tunneling processes involving Cooper pairs—most notably Andreev reflection and Josephson tunneling—provide direct spectroscopic access to superconductivity [1,2]. With atomic-scale spatial resolution, STM further uncovers local variations in these tunneling spectra, offering insight into the symmetry of the superconducting order parameter. Applying these techniques to Fe-based chalcogenides and epitaxial two-dimensional superconductors, we have identified clear signatures of unconventional superconductivity in both classes of materials [3,4].

[1] W. Ko, E. Dumitrescu, and P. Maksymovych, *Phys. Rev. Res.* **3** 033248 (2021)

[2] W. Ko, J. L. Lado, and P. Maksymovych, *Nano Lett.* **22** 4042 (2022)

[3] W. Ko, S. Y. Song, J. Yan, J. L. Lado, and P. Maksymovych, *Nano Lett.* **23** 8310 (2023)

[4] P. Maksymovych, S. Y. Song, B. Lawrie, W. Ko, and J. L. Lado, *arXiv:2601.20798*

11:30am **NS-MoM-7 Optical Properties of Single Molecules Explored with sub-nm Precision*, Anna Roslawska,*** Max Planck Institute for Solid State Research, Germany **INVITED**

Light-matter interaction is essential for mechanisms such as luminescence, photosynthesis, and energy harvesting, defining the emission characteristics of molecular systems and governing the conversion of energy between photons and electrons. While these processes are intensively studied and employed, little is known about their dependence on atomic-scale properties since reaching such precision in optics is extremely demanding. This challenge is nowadays overcome thanks to the combination of optical spectroscopy approaches with scanning probe microscopy, which profit from the extreme field enhancement provided by the tip that enables atomic-scale optics. In my talk, I will discuss how this approach can be applied to probe optical properties of individual phthalocyanine [1-3] and chlorophyll molecules.

1. A. Rosławska, T. Neuman, B. Doppagne, A. Borisov, M. Romeo, F. Scheurer, J. Aizpurua, G. Schull, Phys. Rev. X, 12, 011012, 2022.

2. K. Kaiser, S. Jiang, M. Romeo, F. Scheurer, G. Schull, A. Rosławska, Phys. Rev. Lett. 133, 156902, 2024.

3. A. Rosławska, K. Kaiser, M. Romeo, E. Devaux, F. Scheurer, S. Berciaud, T. Neuman, G. Schull, Nat. Nanotechnol., 19, 738-743, 2024.

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