# MA 36: Focus Session: Ising Superconductivity in Monolayer Transition Metal Dichalcogenides (joint session TT/HL/MA)

Superconducting monolayer transition metal dichalcogenides (TMDs) like $NbSe_2$, $TaS_2$, and gated $WSe_2$ or $MoS_2$, have attracted lot of interest in recent years. On the one hand Ising spin-orbit coupling pins the electron's spin out of plane, and hence is responsible for critical in-plane magnetic fields by far exceeding the Pauli limit. On the other hand, while the underlying pairing mechanism is still under debate, recent experiments provide strong evidence for its unconventional, multiband, nature. The Focus Session will feature experimental and theoretical advances on the superconductivity in monolayer TMDs, with focus on universal features, a possible Luttinger-Kohn mechanism, a nodal or even chiral nature of the gap functions, and their phase diagram.

Organizers: Milena Grifoni (Universität Regensburg), Julian Siegl (Universität Regensburg)

Time: Thursday 9:30–12:45 Location: H36

**Topical Talk** MA 36.1 Thu 9:30 H36

**Evidence of Unconventional Superconductivity in Monolayer and Bulk van der Waals Material $TaS_2$** — •Somesh Chandra Ganguli[1], Viliam Vano[1,2], Yuxiao Ding[1], Maryam Khosravian[1], Jose Lado[1], and Peter Liljeroth[1] — [1]Department of Applied Physics, Aalto University FI-00076 Aalto, Finland — [2]Joseph Henry Laboratories and Department of Physics, Princeton University, Princeton, NJ, USA

Unconventional superconductors are at the forefront of modern quantum materials' research. Even though unconventional superconductivity has been discovered in a large number of bulk systems, intrinsic unconventional superconductivity in the monolayer limit has remained elusive.

In our work, we demonstrate the evidence of nodal f-wave superconductivity in monolayer 1H-$TaS_2$. We also observe the emergence of many-body excitations potentially associated to its unconventional pairing mechanism. Furthermore, the nodal f-wave superconducting state in the pristine monolayer 1H-$TaS_2$ is driven to a conventional gapped s-wave state by the inclusion of non-magnetic disorder. I will also briefly describe our recent results on bulk layered superconductor 6R-$TaS_2$ where alternating metallic and Mott insulating layers gives rise to unconventional superconductivity.

Our results demonstrate the emergence of unconventional superconductivity in van der Waals (vdW) materials and therefore opens possibilities to create designer unconventional superconductivity in vdW heterostructures.

**Topical Talk** MA 36.2 Thu 10:00 H36

**Signatures of Unconventional Superconductivity in Transition Metal Dichalcogenides** — •Miguel Ugeda — Donostia International Physics Center, San Sebastián, Spain

Lowering the dimensionality of a material is an effective strategy to boost electronic correlations that fail to be captured by conventional pictures. In this arena, two-dimensional (2D) materials provide an ideal platform for the exploration of quantum collective phenomena arising from such strong interactions due to their simple synthesis and modelling. In this talk, I will review the rich physics that emerges in the family of transition metal dichalcogenide (TMD) metals in the superconducting state in the 2D limit. While many of these TMD metals exhibit superconductivity in both the bulk form down to the monolayer, the latter limit stores exciting surprises beyond the BCS frameworks that have been revealed in the last years. I will focus on our $NbSe_2$, the most representative TMD superconductor, where I will describe our recent STM/STS experiments. Lastly, I will briefly describe our current efforts to induce unconventional superconductivity in more complex TMD heterostructures.

**Topical Talk** MA 36.3 Thu 10:30 H36

**Friedel Oscillations and Chiral Superconductivity in Monolayer $NbSe_2$** — •Magdalena Marganska[1,2], Julian Siegl[1], Anton Bleibaum[1], Marcin Kurpas[3], Wen Wan[4], John Schliemann[1], Miguel M. Ugeda[4,5], and Milena Grifoni[1] — [1]Institute for Theoretical Physics, University of Regensburg, 93 053 Regensburg — [2]Institute for Theoretical Physics, Wrocław University of Science and Technology, Wyb. Wyspiańskiego 27, 50-370 Wrocław, Poland — [3]Institute of Physics, University of Silesia in Katowice, 41-500 Chorzów, Poland — [4]Donostia International Physics Center, Paseo Manuel de Lardizábal 4, 20018 San Sebastián, Spain — [5]Ikerbasque, Basque Foundation for Science, Bilbao 48013, Spain

In 1965 Kohn and Luttinger proposed a mechanism for superconductivity, based on the electronic Coulomb interaction alone. The screening effects, which cause Friedel oscillations of charge density around impurities, modulate also the interaction between moving electrons. If it has attractive regions, superconductivity can arise by exploiting them. This mechanism, negligible in 3D metals, can become much stronger in 2D electronic systems. In a monolayer of $NbSe_2$ the screening is further suppressed, due to the multi-orbital nature of the electronic band at the Fermi level. We show how this, and the presence of K/K' Fermi surfaces, leads to superconducting pairing. The dominant gap solution at $T = 0$ has the chiral p+ip symmetry. It evolves with increasing temperature, turning from fully chiral at T=0 to a nematic solution with p-like symmetry close to the critical temperature. Our results are also consistent with our tunneling spectroscopy measurements in $NbSe_2$.

**15 min. break**

**Topical Talk** MA 36.4 Thu 11:15 H36

**Unconventional Pairing in Ising Superconductors** — •Andreas Kreisel[1], Subhojit Roy[2,3,4], Brian M. Andersen[1], and Shantanu Mukherjee[2,3,4] — [1]Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark — [2]Department of Physics, Indian Institute of Technology Madras, Chennai, 600036, India — [3]Center for Atomistic Modelling and Materials Design, IIT Madras, Chennai 600036, India — [4]Quantum Centers in Diamond and Emergent Materials (QCenDiem)-Group, IIT Madras, Chennai, 600036 India

Ising spin orbit coupling arises in materials with non-centrosymmetric crystal structure in conjunction of an in-plane mirror symmetry and is realized in some two dimension transition metal dichalcogenides. Example materials are monolayer $NbSe_2$, $MoS_2$, $TaS_2$, and $PbTe_2$, where signatures of unconventional superconductivity are found in contrast to their three dimensional bulk counterparts. In this talk, I present a microscopic formalism to calculate the superconducting instability from a momentum-dependent spin- and charge-fluctuation-mediated pairing interaction in presence of spin orbit coupling that induces a spin splitting. This pairing is then applied to the electronic structure of transition metal dichalcogenides. We provide a quantitative measure of the mixing between the even- and odd-parity superconducting states which varies with Coulomb interaction. The pairing scenario from spin fluctuations together with the mixing of the odd-parity superconducting state gives rise to an enhancement of the critical magnetic field.

**Topical Talk** MA 36.5 Thu 11:45 H36

**High-Field Study of Ising Superconductivity in TMDs** — •Oleksandr Zheliuk[1,2], Xiaoli Peng[3], Andrew Ammerlaan[1,2], Puhua Wan[3], Yulia Kreminska[3], Steffen Wiedmann[1,2], Uli Zeitler[1,2], and Jianting Ye[3] — [1]High Field Magnet Laboratory (HFML-EMFL), Radboud University, Toernooiveld 7, Nijmegen 6525 ED, The Netherlands — [2]Radboud University, Institute for Molecules and Materials, Nijmegen 6525 AJ, The Netherlands — [3]Zernike Institute for Advanced Materials, University of Groningen, 9747 AG Groningen, The Netherlands

Semiconducting transition metal dichalcogenides are known for their strong spin-orbit coupling, the possibility of hosting a variety of quantum phases such as two-dimensional superconductivity with upper critical fields that by far bypasses the Pauli limit, Josephson coupled states, and high mobility electron gasses accessed in electric double-layer transistor (EDLT) configuration. Despite its well-established electronic structure, the dome-shaped superconducting phase diagram where the critical temperature $T_c$ can be modulated by carrier concentration is yet to be understood. This talk will sharpen the understanding of the electronic structure of the electron-doped $MoS_2$, covering recent insights into superconductivity in $MoS_2$ probed via the multivalley transport phenomena accessed in high magnetic field.

MA 36.6 Thu 12:15 H36

**Unconventional Pairing in Ising Superconductors: Application to Monolayer $NbSe_2$** — •Subhojit Roy[1], Andreas Kreisel[2], Brian Andersen[3], and Shantanu Mukherjee[4] — [1]Indian Instititute of Technology Madras, Chennai, 600036, India — [2]Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark — [3]Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark — [4]Indian Instititute of Technology Madras, Chennai, 600036, India

The presence of a non-centrosymmetric crystal structure and in-plane mirror symmetry allows an Ising spin-orbit coupling to form in some two-dimensional materials, where a nontrivial nature of the superconducting state is currently being explored. In this study(1), we develop a microscopic formalism for Ising superconductors that captures the superconducting instability arising from a momentum-dependent spin- and charge-fluctuation-mediated pairing interaction. We apply our pairing model to the electronic structure of monolayer $NbSe_2$, where first-principles calculations reveal the presence of strong paramagnetic fluctuations. Our calculations provide a quantitative measure of the mixing between the even- and odd-parity superconducting states and its variation with Coulomb interaction. Further, numerical analysis in the presence of an external Zeeman field reveals the role of Ising spin-orbit coupling and mixing of odd-parity superconducting state in influencing the low-temperature enhancement of the critical magnetic field.

[1] S. Roy et al., 2D Mater. 12 015004 (2025).

MA 36.7 Thu 12:30 H36

**Emergence of Unconventional Superconductivity and Doped Mott Physics in 6R-$TaS_2$** — •Yuxiao Ding[1], Amritroop Achari[2], Jonas Bekaert[3], Jose Lado[1], Rahul R. Nair[2], Peter Liljeroth[1], and Somesh C. Ganguli[1] — [1]Aalto University, Finland — [2]University of Manchester, UK — [3]University of Antwerp, Belgium

Discovery of Unconventional superconductivity in van der Waals (vdW) materials have brought about a paradigm shift in modern condensed matter research for their tunability and potential application in quantum computing. Among these, most prevalent are 4Hb-$TaS_2$ and 6R-$TaS_2$. They comprise of alternating Mott insulating and metallic layers and give rise to exotic quantum states such as topological superconductivity, anomalous Hall effect potentially associated with hidden magnetism etc. We have studied, using low temperature STM/STS, the newly discovered vdW superconductor 6R-$TaS_2$. For the 1T phase, a doped Mott phase was observed with potential charge order occurring due to hybridisation between 1T and underlying 1H layer. We also observe Kondo sites in the half-filled regime, which unlike 4Hb-$TaS_2$, were more robust under the application of tip-induced electric field. This indicates significantly different interlayer interactions in these two systems. We also observe evidence of unconventional superconductivity in the 1H phase, indicated by the presence of V-shaped superconducting gap and many-body excitations. Our results pave a new direction in understanding the role of interplay between magnetism and superconductivity in layered unconventional superconductors.