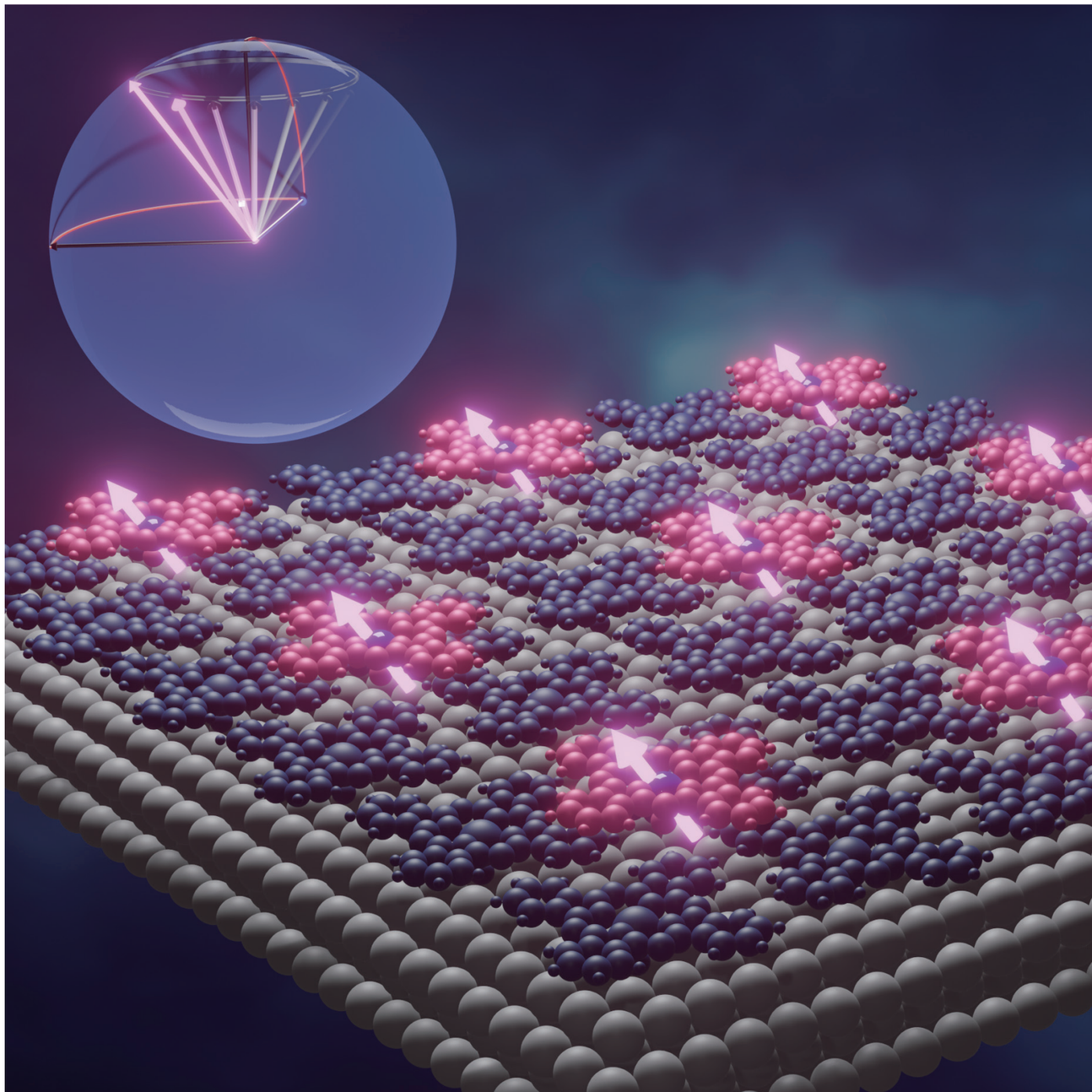
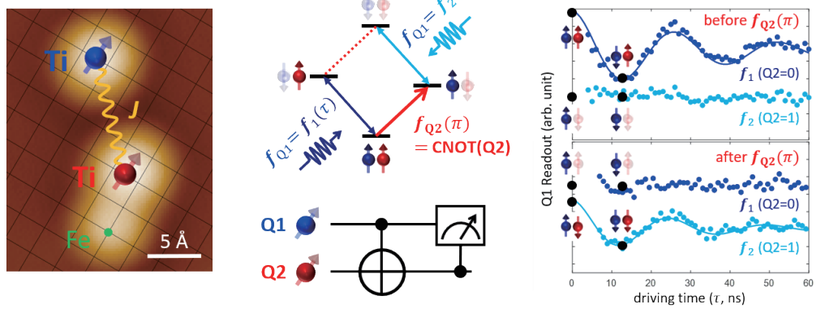
Table of Contents

Research Highlights



CNOT Gates

Two-qubit quantum gate using coupled spins on surface (teams : Phark, Bae, Wolf)



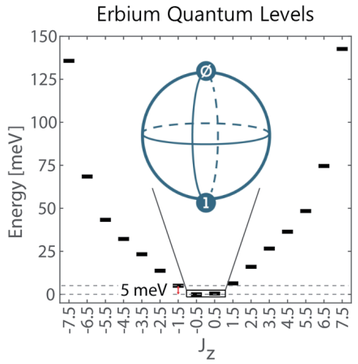
QNS teams Phark, Bae and Wolf, achieved a significant breakthrough in quantum computing. We demonstrated a two-qubit gate (controlled NOT; CNOT) using titanium (Ti) spins on a magnesium oxide surface. By manipulating atoms, we created a pair of atomic spin qubits that were weakly coupled to each other. Utilizing specialized equipment and techniques, we controlled and measured the qubits at the atomic scale, enabling multi-qubit operations. This work opens up possibilities for quantum applications based on bottom-up design of a robust qubit platform at the atomic scale.

Publication : *An atomic-scale multi-qubit platform, Y. Wang, Y. Chen, H. Bui, C. Wolf, M. Haze, C. Mier, J. Kim, DJ. Choi, C. P. Lutz, Y. Bae, S. Phark, A. Heinrich, Science 382, 87-92 (2023)*
DOI:10.1126/science.ade5050

Rare Earth Qubit

Surface-adsorbed rare earth qubit candidate (teams : Donati, Bae, Wolf)

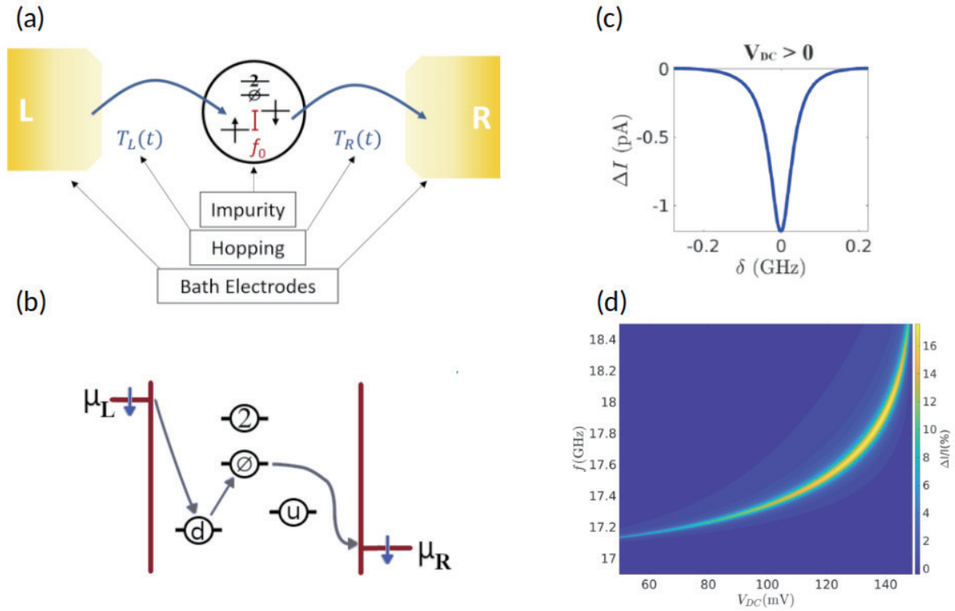
Our teams identified erbium (Er) and thulium (Tm) atoms on a magnesium oxide (MgO) surface as promising candidates for single-atom qubits. These lanthanide atoms exhibit a magnetic ground state suitable for quantum operations. Their well-shielded 4f electrons, located close to the atomic core, provide stability and minimize external disturbances, making them ideal for high-performance qubits. We have also achieved electron spin resonance transitions in a single Er atom by manipulating its interaction with an exchange-coupled Ti atom. This novel approach enables control of spin coherence in surface lanthanide atoms with minimal interference from the scanning probe tip. Our findings open new avenues for advancing quantum computing using these robust single-atom qubits.



Publication : *Erbium and thulium on MgO(100)/Ag(100) as candidates for single atom qubits, S. Reale, A. Singha, S. L. Ahmed, D. Krylov, L. Colazzo, C. Wolf, C. S. Casari, A. Barla, E. Fernandes, F. Patthey, M. Pivetta, S. Rusponi, H. Brune, and F. Donati, Phys. Rev. B 107, 045427 (2023)*
DOI: 10.1103/PhysRevB.107.045427

Quantum Simulation of ESR-STM

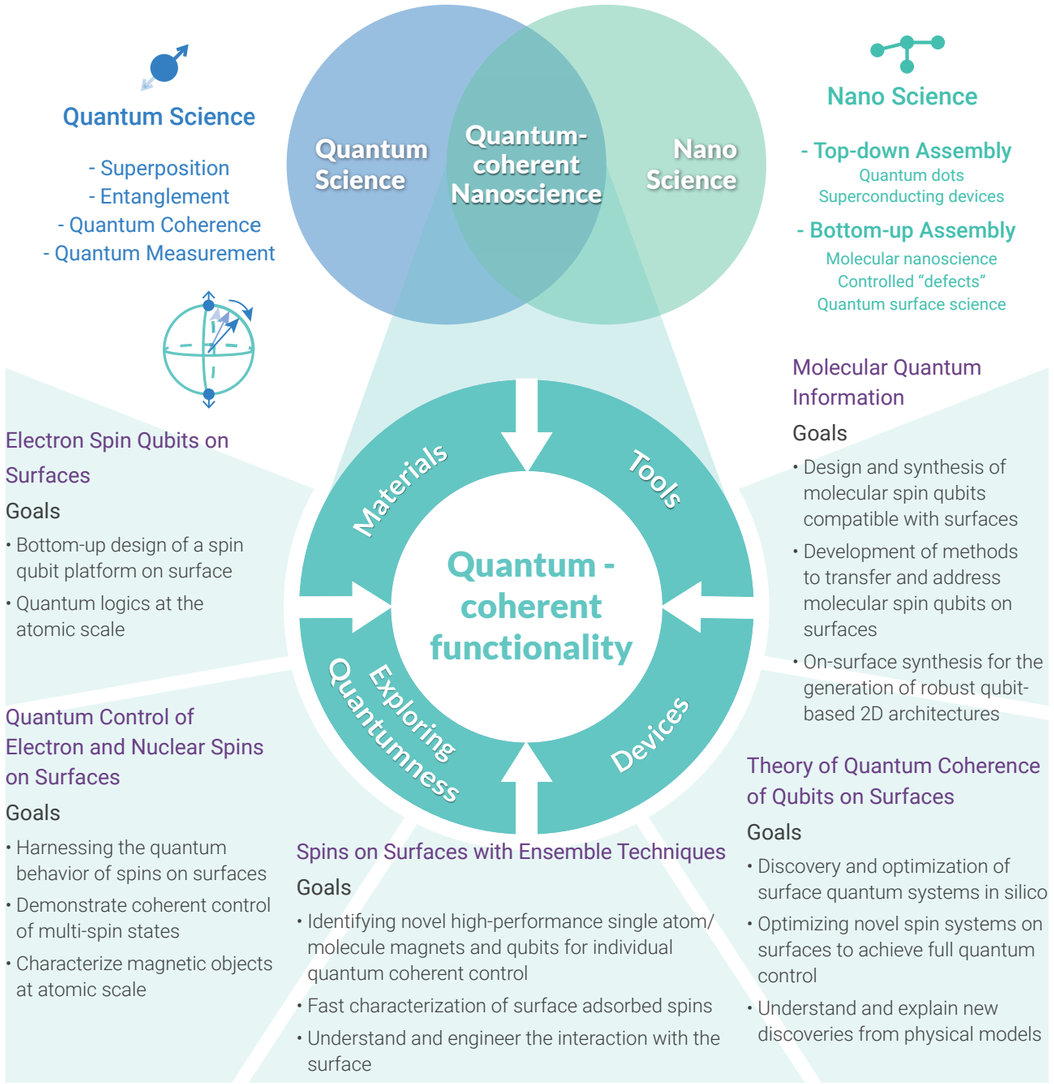
Explanation of experimental features found in ESR-STM (teams : Wolf)



Understanding the mechanism that allows to drive and measure electron spin resonance (ESR) in the junction of a scanning tunneling microscope has been at the focus of studies from both angles, experiment and theory, since the first demonstration of ESR-STM in 2015. Whilst several models have been put forward, the theory team of QNS in close collaboration with the team of Nicolas Lorente (DIPC and CFM/Spain) started developing our own model. Now, after years of improving our understanding, we have put forward a comprehensive, microscopic and fully quantum-coherent model of how the modulation of the tunnel barrier by the applied radio-frequency voltage can drive ESR. In the latest iteration, our model includes a quantum impurity with arbitrarily large spins (S≥1/2) connected to two fermionic baths (representing the STM tip and substrate, Figure (a)). A periodic modulation of the hopping in the appropriate frequency range will then drive ESR (Figure (b)), which can be read by a spin-polarized electrode. The simulation is tailored to be as close to the experimental reality as possible, and it allows to calculate the true current (Figure (c),(d)) – the measured quantity in the experiment – which makes direct comparisons between theory and experiment relatively easy. Further, our model is able to calculate spectra in the long-time limit fast using Floquet theory whilst also allowing for short-time simulations (necessary to simulate, for example, quantum gates as in research highlight number). Our model is one of the most comprehensive descriptions of ESR in an STM to date and we anticipate that it will allow to simulate existing experiments and optimize control parameters to achieve the QNS vision of quantum-coherent control at the nanoscale.

Publication : *Many-body nonequilibrium effects in all-electric electron spin resonance, J. Reina-Gálvez, C. Wolf, N. Lorente, Phys. Rev. B 107, 235404 (2023)*
DOI:10.1103/PhysRevB.107.235404

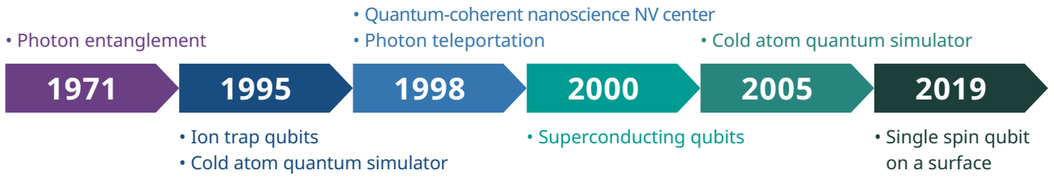
The Definition of Quantum Nanoscience



Timeline of relevant discoveries leading to quantum coherent nanoscience

Founders of Quantum Mechanics

"Gedankenexperimente" with individual quantum systems
- Schrödinger's cat (superposition)
- Einstein–Podolsky–Rosen (EPR) paper, spooky action at a distance (entanglement)
- Heisenberg's uncertainty principle (quantum measurement)

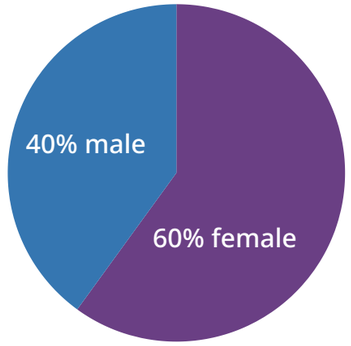


QNS at a Glance

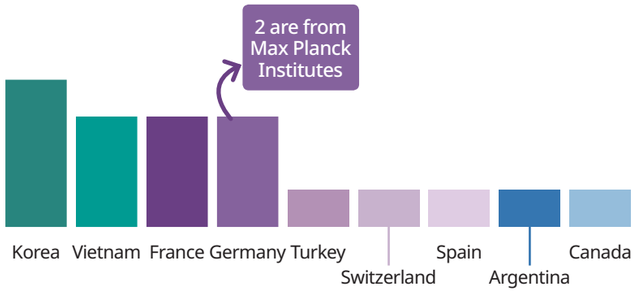
Personnel

Members Nationalities

Researchers Gender Distribution

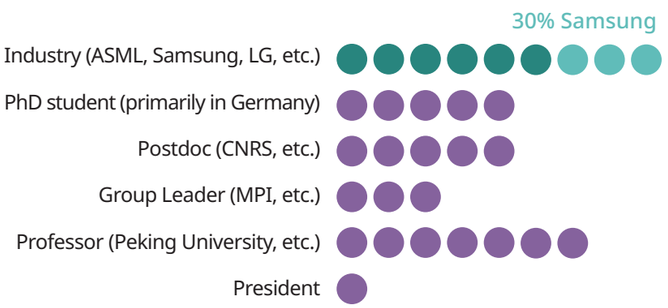


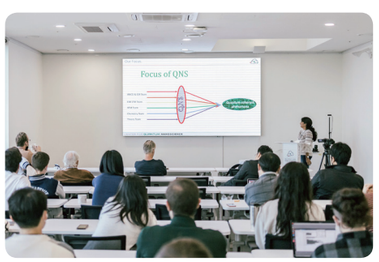
Where Students and Postdocs are Coming From



Researchers taking a break in the HUB

Alumni Placement

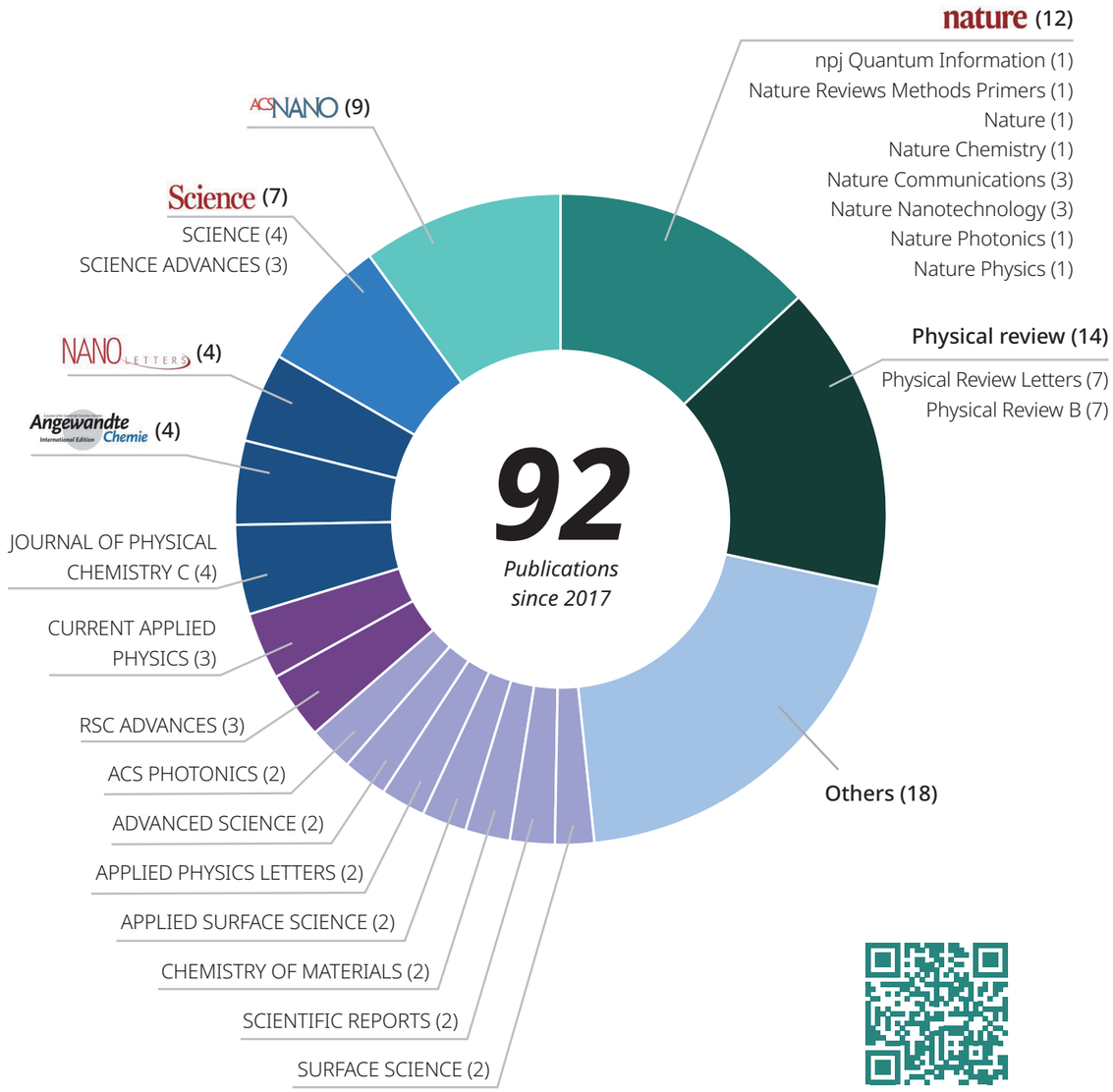




Alumni Meeting 2022 in Jupiter

Publications

QNS Publication Output



www.qns.science/publications/

Visitors and Events

Since 2017, QNS has held :

67 International events (conferences, workshops, symposia)

with over **3600** Korean & international attendees

Visitors by Nationality :

Europe	Asia	Americas	Australia
144	118	33	3

Professors from University of Basel with QNS PIs and Senior Scientists in Saturn seminar room

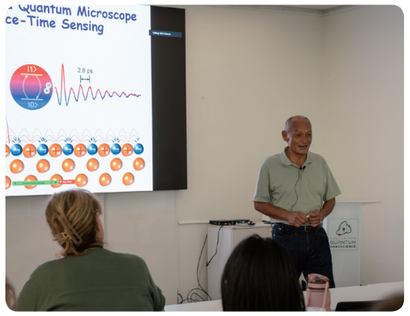
Visiting PhD student from University of Ottawa, Angéline Lafleur, with DJ Choi and Nicolas Lorente in the HUB

Colloquium Series

In the 1.5 years since the 5-year review, QNS has held 8 colloquia by various notable speakers including David Awschalom, Ali Yazdani, and Philip Kim who received the Ben Franklin Medal in Physics this year. Nearly 750 people attended these talks both in person and online.

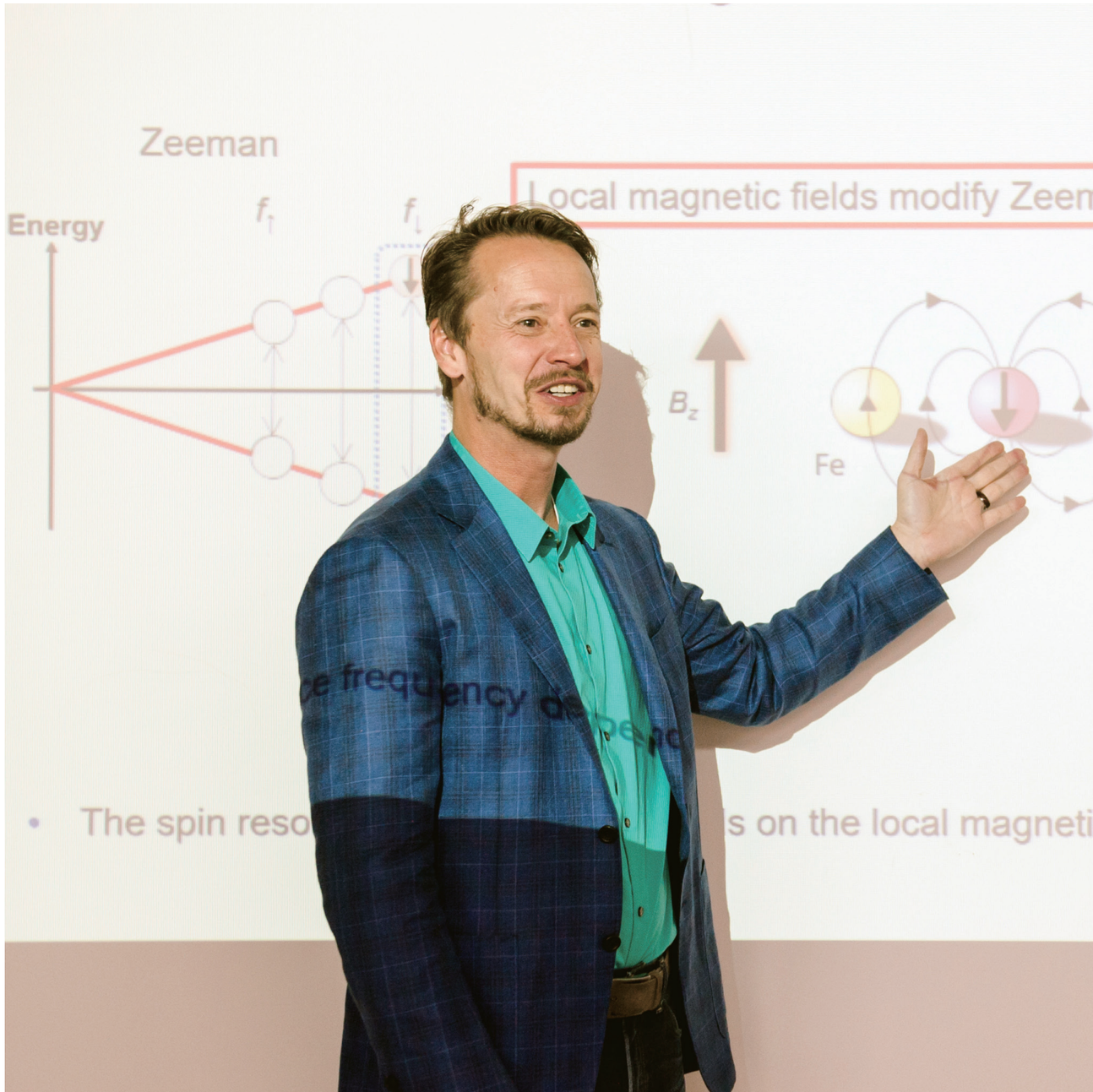
Harald Brune, December 2022

Philip Kim, May 2023



Wilson Ho, August 2023

Thought Leadership



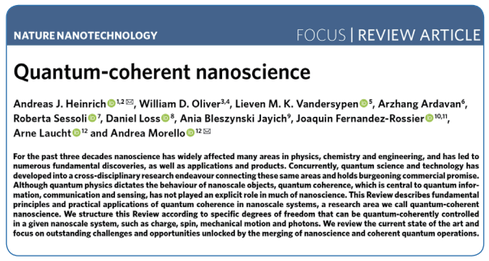
Field of Quantum Nanoscience

In 2018, Director Heinrich embarked on a mission to define the field of quantum nanoscience. It all began with a workshop, which has since evolved into something much greater. At that time, we established several milestones to be achieved by 2021 and beyond. As we reach 2023, our leadership in the field continues to flourish, exemplified by the upcoming second IBS Conference on Quantum Nanoscience, scheduled to take place at Ewha Womans University in Seoul.

2023

2nd IBS Conference on Quantum Nanoscience

2021


NATURE NANOTECHNOLOGY FOCUS | REVIEW ARTICLE

Quantum-coherent nanoscience

Andreas J. Heinrich, William D. Oliver, Lieven M. K. Vandersypen, Arzhang Ardavan, Roberta Sessoli, Daniel Loss, Ania Bleszynski Jayich, Joaquin Fernandez-Rossier, Arne Laucht and Andrea Morello

For the past three decades nanoscience has widely affected many areas in physics, chemistry and engineering, and has led to numerous fundamental discoveries, as well as applications and products. Concurrently, quantum science and technology has developed into a cross-disciplinary research endeavour connecting these same areas and holds burgeoning commercial promise. Although quantum physics dictates the behaviour of nanoscale objects, quantum coherence, which is central to quantum information, communication and sensing, has not played an explicit role in much of nanoscience. This Review describes fundamental principles and practical applications of quantum coherence in nanoscale systems, a research area we call quantum-coherent nanoscience. We structure this Review according to specific degrees of freedom that can be quantum-coherently controlled in a given nanoscale system, such as charge, spin, mechanical motion and photons. We review the current state of the art and focus on outstanding challenges and opportunities unlocked by the merging of nanoscience and coherent quantum operations.

Perspective Paper in Nature Nanotechnology

2019

1st IBS Conference on Quantum Nanoscience

2018

Workshop to Define Quantum Nanoscience

Spins on Surfaces

Director Heinrich was invited by the Deutsche Physikalische Gesellschaft (DPG) to organize a focus session on Spins on Surfaces. The session's remarkable attendance and engagement over the course of two days led the DPG to establish Spins on Surfaces as a regular topic for future conferences. This indicates the mainstream, ongoing relevance of spins on surfaces.

DPG

Rare Earth Single-Atom Magnets

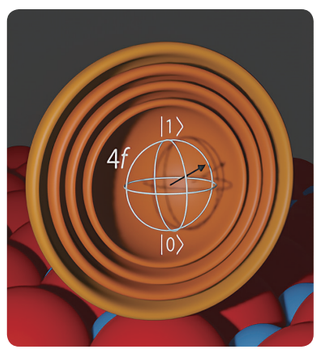
PI Fabio Donati has emerged as a prominent figure in the field of rare earth on surfaces. His investigations, initiated in 2014, resulted in the groundbreaking discovery of the first single-atom magnet, specifically holmium, in 2016. This milestone opened up new research avenues, highlighting the potential of rare earth atoms as single-atom bits.

Since joining QNS, Donati has continued to make substantial contributions to the field. His notable achievements include identifying the single-atom magnet with the largest anisotropy, which was published in both Nature Communications and Nano Letters in 2021. This finding showcased the exceptional magnetic stability of rare earth atoms and their potential as atomic-scale sources of magnetic fields.

Fabio Donati

Additionally, Donati devised a novel method, published in ACS Nano in 2021, for resolving the electronic configuration of these atoms with orbital sensitivity. This groundbreaking approach enables the anticipation of their performance in electric transport measurements and unveils emerging phenomena such as charge transfer and inter-atomic interactions.

One of Donati's remarkable accomplishments was the identification of the first single rare earth atom qubit candidate, as published in Physical Review B in 2023. This groundbreaking discovery lays the foundation for utilizing rare earth atoms as building blocks for quantum computing.



Through his visionary leadership and pioneering research, Fabio Donati has propelled the field of rare earth on surfaces to new heights. His significant contributions have enhanced our understanding of these systems and their potential applications, cementing his status as a leading figure in the field.

The figure illustrates the multi-orbital structure of a rare earth atom when situated on a surface. The 4f electrons, located near the atomic core, exhibit strong shielding against external perturbations, making these atoms promising candidates for high-performance qubits.

Image source : S. Reale et al.; Phys. Rev. B 107, 045427 (2023)

ESR-STM

QNS is currently the only group in the world capable of coherently controlling atoms and molecules on surfaces. QNS continues to generate interest and invites other groups to adopt the ESR-STM technique by sharing insights into the construction and usage of our instruments. For example, this review paper provides a detailed explanation of the design and construction of one of our ESR STMs named **Eve**:

Review Paper

Publication : Development of a scanning tunneling microscope for variable temperature electron spin resonance, J. Hwang, D. Krylov, R. Elbertse, S. Yoon, T. Ahn, J. Oh, L. Fang, W. Jang, F. Cho, A. Heinrich, Y. Bae, Rev. Sci. Instrum.1 September 2022; 93 (9): 093703. doi.org/10.1063/5.0096081

Online Tutorial

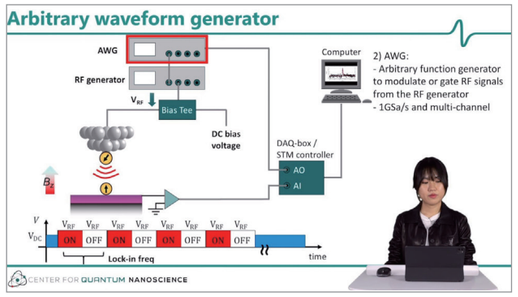
https://tutorial.qns.science/

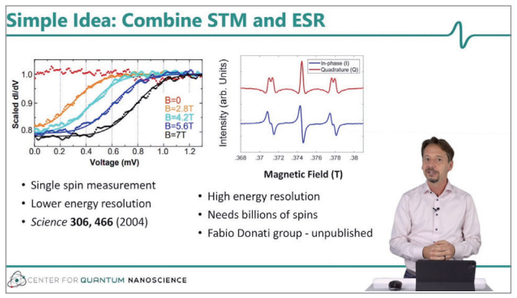
The ESR-STM Tutorial QNS developed during the pandemic has gained in following and importance with nearly one thousand subscribers currently.

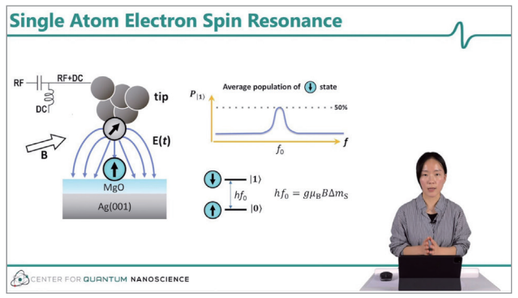
The dramatic growth in views of Section 1: "Prerequisites" indicate a growing interest in the concrete steps to building/retrofitting an ESR-STM setup.

Furthermore, the significant growth in Section 2: "Conducting Measurements" suggests that the tutorial is being used as a training tool, based on user and institutional feedback.

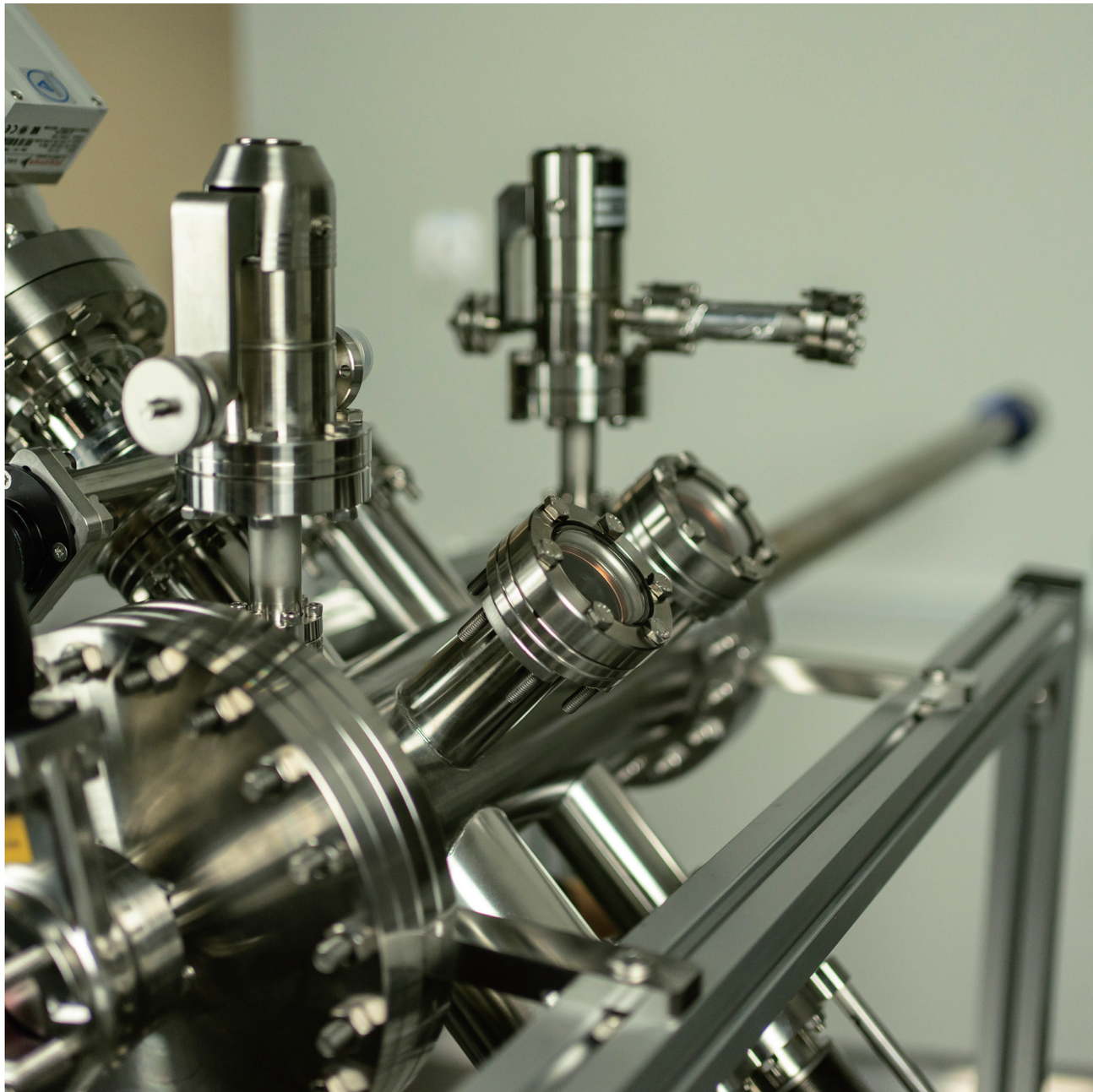
Tutorial Section	Percentage of Views (%)	
	DEC' 21	JUNE' 23
Introduction	46%	18%
Section 1. Prerequisites	27%	**47%**
Section 2. Conducting Measurements	17%	**24%**
Section 3. Theory of ESR-STM	10%	11%





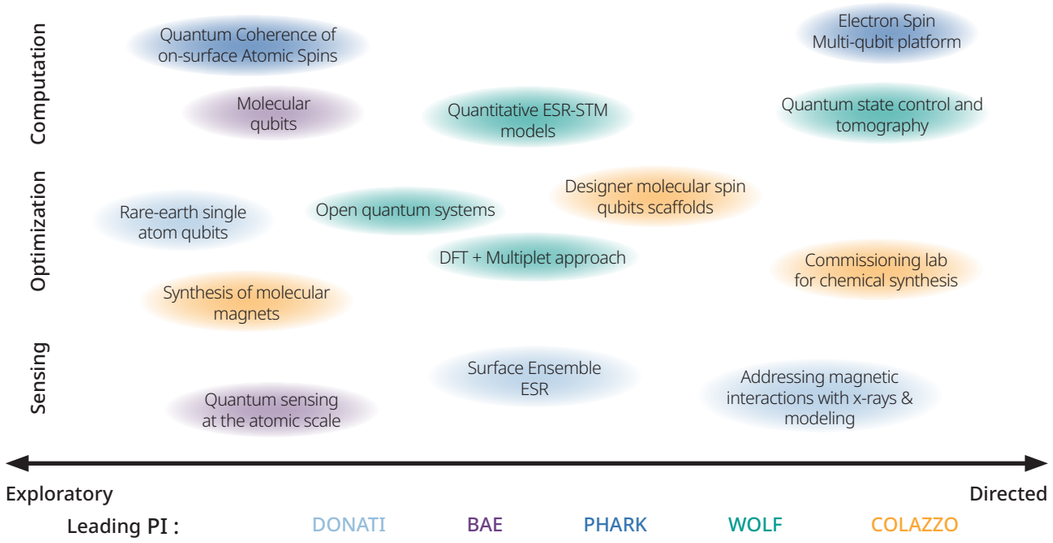


Scientific Updates



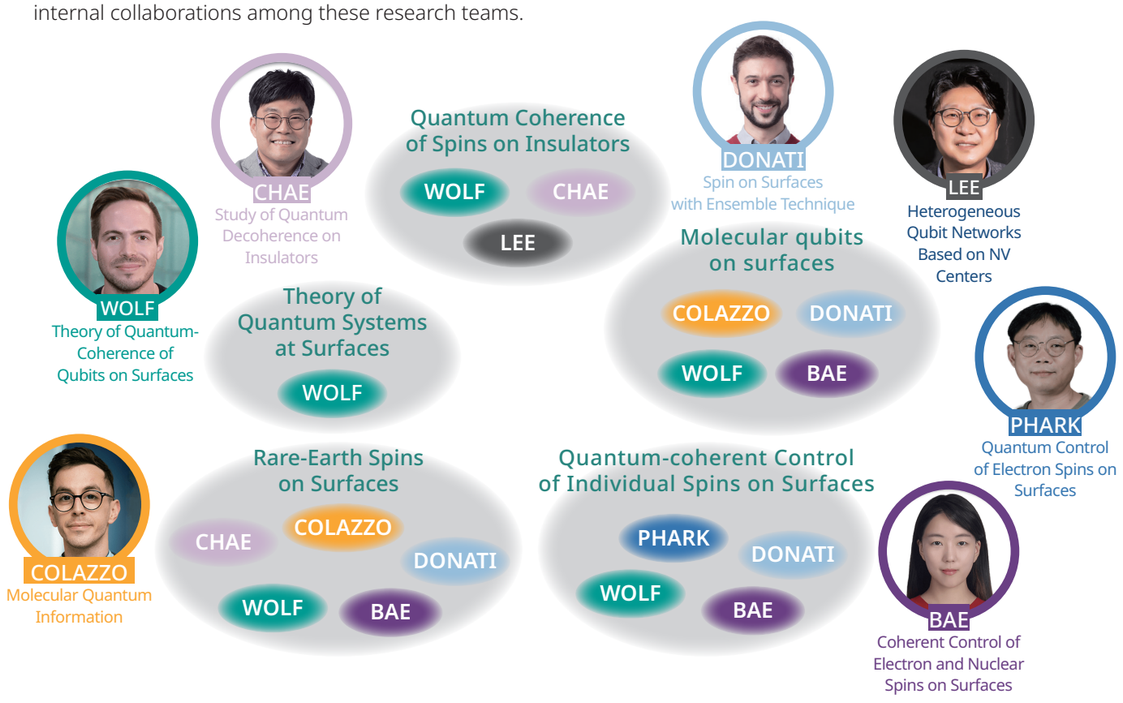
Scope of Projects

QNS's current scientific work primarily revolves around quantum sensing and quantum computation. The following plot showcases our endeavors in basic science, illustrating the balance between exploratory and directed approaches towards making new discoveries.



Collaborative Structure of QNS

Many visitors remark about how intensively collaborative QNS is. This is a visualization of our dynamic internal collaborations among these research teams.



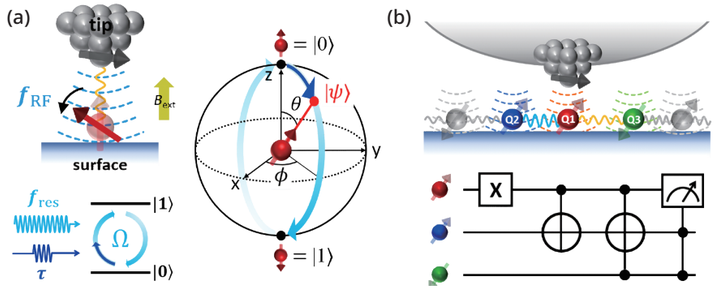
Research Updates by Group

Electron Spin Qubits on Surfaces

PI Soo-hyon PHARK

(left to right) Valeria Sheina, Hong Bui, Soo-hyon Phark, Chau Bui, Thanh Truong

In the past 18 months, our research group has achieved significant progress in driving electron spin resonance (ESR) of multi-spin systems on a surface. We successfully implemented pulsed-ESR functionality to study atomic scale spin structures at multiple frequencies. Combined with precise atom-by-atom position control, we constructed a platform for electron spin multi-qubits on a surface. Our recent breakthrough includes the demonstration of fundamental quantum logic gates using coupled titanium (Ti) atomic spins on an MgO surface. These gates, including coherent control of a single qubit and controlled NOT (CNOT) and Toffoli (CCNOT) gates involving multiple qubits, have been accepted for publication in Science. We have also achieved universal quantum control of individual spin qubits on a surface, enabling precise manipulation of superposition states in all directions in space. Our work has been published in NPJ Quantum Information. Additionally, we overcame limitations in the scanning tunneling microscope (STM) geometry to control remote spins outside the tunneling junction, which provides a protocol for constructing on-surface multi-qubit systems.



Spin qubit platform on surface at the atomic scale

(a) Quantum coherent control of an on-surface single spin qubit using electron spin resonance (ESR) in scanning tunneling microscope (STM)

(b) Multiple qubits crafted atom-by-atom on surface and multi-qubit quantum gates

Publication list to date :

2023
- S. Phark, H. T. Bui, A. Ferrón, J. Fernández-Rossier, J. Reina-Gálvez, C. Wolf, Y. Wang, K. Yang, A. J. Heinrich, & C. P. Lutz, "Electric-Field-Driven Spin Resonance by On-Surface Exchange Coupling to a Single-Atom Magnet", Advanced Science.10,1002.
- Y. Wang, Y. Chen, H. T. Bui, C. Wolf, M. Haze, C. Mier, J. Kim, D.-J. Choi, C. P. Lutz, Y. Bae, S. Phark, A. J. Heinrich, "An electron-spin qubit platform crafted atom-by-atom on a surface", Science.
- Y. Wang, M. Haze, H. T. Bui, W.-H. Soe, H. Aubin, A. Ardavan, A. J. Heinrich, S. Phark, "Universal quantum control of an atomic spin qubit on a surface", NPJ Quantum Inf. 9, 48.

2022
- X. Zhang, C. Wolf, Y. Wang, H. Aubin, T. Bilgeri, P. Willke, A. J. Heinrich, T. Choi, "Electron spin resonance of single iron phthalocyanine molecules and role of their non-localized spins in magnetic interactions", Nature Chemistry 14, 59–65.

2021
- P. Willke, T. Bilgeri, X. Zhang, Y. Wang, C. Wolf, H. Aubin, A. J. Heinrich, T. Choi, "Coherent Spin Control of Single Molecules on a Surface", ACS Nano 15, 17959–17965.
- H. J. Kim, Y. H. Choi, D. Lee, I. H. Lee, B. K. Choi, S. Phark, Y. J. Chang, "Enhanced passive thermal stealth properties of VO2 thin films via gradient W doping", Appl. Surf. Sci. 561, 30.
- S. Kwon, D. Y. Jeong, W.-S. Chae, K. Noh, P. Devi, L. Colazzo, Y. You, T. Choi, D.-W. Kim, "Electronic structures and optical characteristics of fluorescent pyrazinoquinoxaline assemblies and Au interfaces", Scientific Reports 11, 16978.
- A. Singha, P. Willke, T. Bilgeri, X. Zhang, H. Brune, F. Donati, A. Heinrich, T. Choi, "Engineering atomic-scale magnetic fields by dysprosium

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- K. Yang, S. Phark, Y. Bae, T. Esat, P. Willke, A. Ardavan, A. J. Heinrich, C. P. Lutz, "Probing resonating valence bond states in artificial uantum magnets", Nat. Commun. 12, 993.

2020 - X. Zhang, P. Willke, A. Singha, C. Wolf, T. Esat, M. Choi, A. J. Heinrich, T. Choi, "Probing Magnetism in Artificial Metal–Organic Complexes Using Electronic Spin Relaxometry", Phys. Chem. Lett. 25, 441.

2019 - K. Yang, W. Paul, S. Phark, P. Willke, Y. Bae, T. Choi, T. Esat, A. Ardavan, A. J. Heinrich, C. P. Lutz, "Coherent spin manipulation of individual atoms on a surface", Science, 366, 509-512.
- P. Willke, A. Singha, X. Zhang, T. Esat, C. P. Lutz, A. J. Heinrich, T. Choi, "Tuning Single-Atom Electron Spin Resonance in a Vector Magnetic Field", Nano Letters, 19, 8201-8206.

2017 - J. A. Fischer, L. M. Sandratskii, S. Phark, D. Sander, S. Parkin, "Atomic structure governed diversity of exchange-driven spin helices in Fe nanoislands: Experiment and theory", Phys, Rev. B 96, 140407.
- T. Choi, C. P. Lutz, A. J. Heinrich, "Studies of Magnetic Dipolar Interaction of Individual Atoms Using ESR-STM", Curr. Appl. Phys. 17, 1513.
- S. Phark, D. Sander, "Spin-polarized scanning tunneling spectroscopy with quantitative insights into magnetic properties", Nano Convergence 4, 8.
- T. Choi, W. Paul, S. Rolf-Pissarczyk, A. J. Macdonald, F. D. Natterer, K. Yang, P. Willke, S. Baumann, A. Ardavan, C. P. Lutz. A. J. Heinrich, "Atomic-scale sensing of the magnetic dipolar field from single atoms", Nat. Nanotechnol. 12, 420.

Quantum Control of Electron and Nuclear Spins on Surfaces

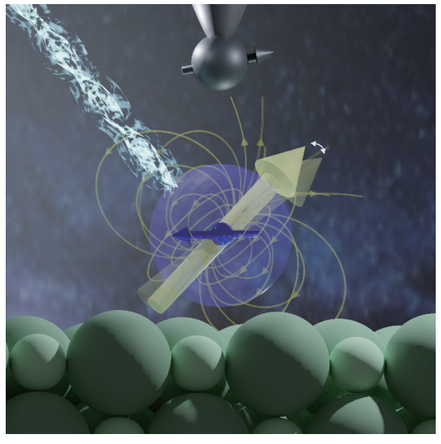
PI Yujeong BAE

(left to right) Jeongmin Oh, Kyungju Noh, Jinkyung Kim, Yujeong Bae, Dmitriy Borodin, Piotr Kot, Jiyoon Hwang

Our team has achieved success in demonstrating the coherent manipulation of electron spins on surfaces, further enhancing the spin coherence time remains essential for advancing the surface qubit platform. We focus on enhancing spin coherence for advanced surface qubits, exploring materials like nuclear spins and lanthanide atoms for better quantum coherence. In 2022, we identified the anisotropic hyperfine interactions of single atoms on a surface, which allows us to determine the electronic ground state with high precision. As the next step, we aim to characterize the lifetime and coherence time of the nuclear spin and demonstrate the coherent control of nuclear spins on surfaces.

Lanthanide atoms like Er and Tm are promising qubit candidates. With team Donati, we determined Er's magnetic properties on MgO/Ag(100), achieving ESR observation via a Ti-Er dimer, even with the STM tip over the Ti atom. This marks the first-ever ESR demonstration of 4f-electron spins.

Since the 5-year review, we've engaged international collaborators from esteemed institutions like Ohio State University, TU Delft, EPFL, Nanogune, Politecnico di Milano, DIPC, and Forschungszentrum Jülich.



Development of a scanning tunnel microscope for variable temperature electron spin resonance, 093703 (2022)

Publication list to date :

2023 - Yujeong Bae and Andreas J. Heinrich, "Roadmap on Technologies for NanoMRI: An Atomic Sensor on Surfaces".
- Yu Wang, Yi Chen, Hong T. Bui, Christoph Wolf, Masahiro Haze, Cristina Mier, Jinkyung Kim, Deung-jang Choi, Christopher P. Lutz, Yujeong Bae*, Soo-hyon Phark, Andreas J. Heinrich, "An electron-spin qubit platform crafted atom-by-atom on a surface", arxiv.org/abs/2108.09880.
- Y. Bae, A. J. Heinrich, "Roadmap on Technologies for NanoMRI: An Atomic Sensor on Surfaces".
- Y. Wang, Y. Chen, H. T. Bui, C. Wolf, M. Haze, C. Mier, J. Kim, DJ Choi, C. P. Lutz, Y. Bae, S. Phark, A. J. Heinrich, "An electron-spin qubit platform crafted atom-by-atom on a surface", Science.
- K. Noh, L. Colazzo, C. Urdaniz, J. Lee, D. Krylov, P. Devi, A. Doll, A. J. Heinrich, C. Wolf, F. Donati, Y. Bae, "Template-directed 2D nano patterning of S=1/2 molecular spins", Nanoscal Horiz.

2022 - J. Kim, K. Noh, Y. Chen, F. Donati, A. J. Heinrich, C. Wolf, Y. Bae, "Anisotropic hyperfine interaction of surface-adsorbed single atoms", Nano Lett. 22, 9766.
- J. Hwang, D. Krylov, R. Elbertse, S. Yoon, T. Ahn, J. Oh, L. Fang, W. Jang, F. H. Cho, A. J. Heinrich, Y. Bae, "Development of a scanning tunneling microscope for variable temperature electron spin resonance", Rev. Sci. Instrum. 93, 093703.
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2021 - J. Kim, W. Jang, T. H. Bui, DJ Choi, C. Wolf, F. Delgado, Y. Chen, D. Krylov, S. Lee, S. Yoon, C. P. Lutz, A. J. Heinrich, Y. Bae, "Spin resonance amplitude and frequency of a single atom on a surface in a vector magnetic field", Phys. Rev. B 104, 174408. Selected as Editors' Suggestion.
- C. Mier, J. Hwang, J. Kim, Y. Bae, F. Nabeshima, Y. Imai, A. Maeda, N. Lorente, A. J. Heinrich, DJ Choi, "Atomic manipulation of in-gap states in the β-Bi2Pd superconductor", Phys. Rev. B 104, 045406.
- K. Yang, S. Phark, Y. Bae, T. Esat, P. Willke, A. Ardavan, A. J. Heinrich, C. P. Lutz, "Probing resonating valence bond states in artificial quantum magnets", Nat. Commun. 12, 993.

2019 - K. Yang, W. Paul, S. Phark, P. Willke, Y. Bae, T. Choi, T. Esat, A. Ardavan, A. J. Heinrich, C. P. Lutz, "Coherent spin manipulation of individual atoms on a surface", Science 366, 509.
- P. Willke, K. Yang, Y. Bae, A. J. Heinrich, C. P. Lutz, "Magnetic Resonance Imaging of Single Atoms", Nat. Phys. 15, 1005.
- K. Yang, W. Paul, F. D. Natterer, J. L. Lado, Y. Bae, P. Willke, T. Choi, A. Ferrón, J. Fernández-Rossier, A. J. Heinrich, C. P. Lutz, "Tuning the exchange bias on a single atom from 1 mT to 10 T", Phys. Rev. Lett. 122, 227203. Physics, Editors' Suggestion.

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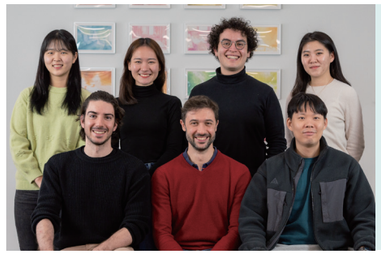
- P. Willke, Y. Bae, K. Yang, J. L. Lado, A. Ferrón, T. Choi, A. Ardavan, J. Fernández-Rossier, A. J. Heinrich, C. P. Lutz, "Hyperfine Interaction of Individual Atoms on a Surface", Science 362, 336.
- P. Willke, Y. Bae, T. Choi, "Electron Spin Resonance on Individual Atoms on Surfaces", Physics and high technology, Korean Physical Society.
- P. Willke, W. P. Paul, F. D. Natterer, K. Yang, Y. Bae, T. Choi, J. Fernández-Rossier, A. J. Heinrich, C. P. Lutz, "Probing Quantum Coherence in Single-Atom Electron Spin Resonance", Sci. Adv. 4, eaaq1543.

2017 - K. Yang, Y.Bae, W. Paul, F. D. Natterer, P. Willke, J. L. Lado, A. Ferrón, T. Choi, J. Fernández-Rossier, A. J. Heinrich, C. P. Lutz, "Engineering "Engineering the eigenstates of coupled spin-1/2 atoms on a surface", Phys. Rev. Lett. 119, 227206.

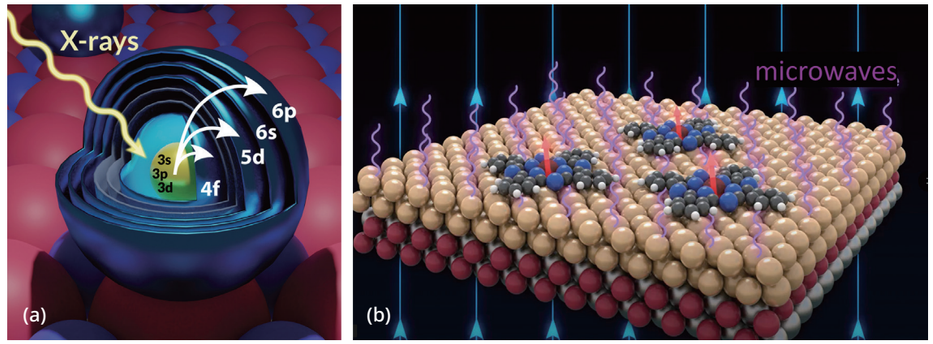


Spins on Surfaces with Ensemble Techniques

PI Fabio DONATI

(left to right) Jinju Lee, Stefano Reale, Soyoung Oh, Fabio Donati, Massine Kelai, Franklin Cho, Yewon Kim

The ensemble measurement team has made remarkable progress by employing X-ray absorption spectroscopy (XAS) and electron spin resonance (ESR). In collaboration with EPFL and the theory team led by Christoph Wolf, we identified lanthanide atoms on the surface with potential for quantum coherence. Our work was published in Physical Review B. Collaborating with the Eve team, led by Yujeong Bae, we discovered an innovative method to induce ESR transitions using an exchange-coupled Ti atom, opening new avenues for spin dynamics. With Peter Liljeroth's group, we identified anti-ferromagnetic interactions in a 2D metal-organic framework coupled to a superconductor. We developed an in-house surface ensemble ESR setup, enabling the detection of ultra-thin molecular layers through ESR measurements. Additionally, we obtained surface resonators for investigating the spin and coherence properties of surface-adsorbed mono-layers and sub-monolayers of molecules.



The ensemble-averaging techniques used by the team to investigate the magnetic and quantum coherent properties of surface adsorbed atoms or molecules

(a) Orbital-selective X-ray magnetic circular dichroism **(b)** Surface-ensemble electron spin resonance

Publication list to date :

2023 • S. Reale, A. Singha, S. L. Ahmed, D. Krylov, L. Colazzo, C. Wolf, C. S. Casari, A. Barla, E. Fernandes, F. Patthey, M. Pivetta, S. Rusponi, H. Brune, and F. Donati, "Erbium and thulium on MgO(100)/Ag(100) as candidates for single atom qubits", Phys. Rev. B 107, 045427.

• K. Noh, L. Colazzo, C. Urdaniz, J. Lee, D. Krylov, P. Devi, A. Doll, A. J. Heinrich, C. Wolf, F. Donati and Y. Bae, "Template-directed 2D nanopatterning of S = 1/2 molecular spins", Nanoscale Horiz. 8, 624.

2022 • J. Kim, K. Noh, Y. Chen, F. Donati, A. J. Heinrich, C. Wolf, and Y. Bae, "Anisotropic Hyperfine Interaction of Surface-Adsorbed Single Atoms", Nano Letters 22, 9766.

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• F. Donati, M. Pivetta, C. Wolf, A. Singha, C. Wäckerlin, R. Baltic, E. Fernandes, J.-G. de Groot, S. L. Ahmed, L. Persichetti, C. Nistor, J. Dreiser, A. Barla, P. Gambardella, H. Brune, and S. Rusponi, "Correlation between Electronic Configuration and Magnetic Stability in Dysprosium Single Atom Magnets", Nano Letters 21, 8266.

• A. Singha, D. Sostina, C. Wolf, S. L. Ahmed, D. Krylov, L. Colazzo, P. Gargiani, S. Agrestini, W.-S. Noh, J.-H. Park, M. Pivetta, S. Rusponi, H. Brune, A. J. Heinrich, A. Barla, and F. Donati, "Mapping Orbital-Resolved Magnetism in Single Lanthanide Atoms", ACS Nano, 15, 16162.

• A. Singha, P. Willke, T. Bilgeri, X. Zhang, H. Brune, F. Donati, A. J. Heinrich, and T. Choi, "Engineering atomic-scale magnetic fields by dysprosium single atom magnets", Nature Commun., 12, 4179.

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2019 • M. Studniarek, C. Wäckerlin, A. Singha, R. Baltic, K. Diller, F. Donati, S. Rusponi, H. Brune, Y. Lan, S. Klyatskaya, M. Ruben, A. P. Seitsonen, and J. Dreiser, "Understanding the Superior Stability of Single-Molecule Magnets on an Oxide Film", Adv. Sci. 6, 1901736.

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2018 • A. Singha, F. Donati, F. D. Natterer, C. Wäckerlin, S. Stavric, Z. S. Popovic, Z. Sljivancanin, F. Patthey, and H. Brune, "Spin Excitations in a 4f-3d Heterodimer on MgO", Phys. Rev. Lett. 121, 257202.

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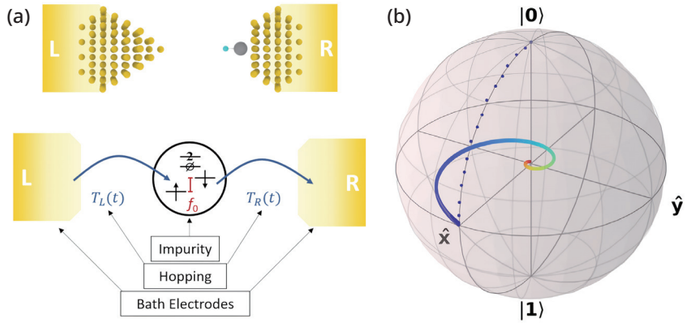
Theory of Quantum Coherence of Qubits on Surfaces

PI Christoph WOLF

(left to right) Jose Galvez, Curie Lee, Christoph Wolf, Corina Urdaniz, Boyeon Kang, Jisoo Yu

The theory team has made remarkable progress in developing our approach for calculating the current through a quantum impurity out of equilibrium. Our work has been accepted for publication in Physical Review B. We conducted simulations for coupled spin-1/2 systems, characterizing parameters related to driving and decoherence. We are developing algorithms to create and measure maximally entangled states in surface-based spin-1/2 systems. Our "Global Hub" program has attracted collaborations with researchers from esteemed institutions, establishing our expertise in quantum-coherent surface spin systems. We have active collaborations in Density Functional Theory (DFT) and DFT-based calculations of magnetic multiplets.



From quantum transport to quantum logic operations

(a) Model used to describe transport through a quantum impurity under radio-frequency driving, representing the situation of a localized spin in an ESR-STM junction

(b) Quantum logic operation–here a square-root-of-not gate–shown on the Bloch sphere. This operation creates a superposition state (also known as Bell state), which are unique to quantum information and have no classical equivalent

Publication list to date :

2023 • Y. Wang, Y. Chen, H. T. Bui, C. Wolf, M. Haze, C. Mier, J. Kim, D.-J. Choi, C. P. Lutz, Y. Bae, S. Phark, A. J. Heinrich, "An electron-spin qubit platform crafted atom-by-atom on a surface", Science.

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• Phark, S., Bui, H. T., Ferrón, A., Fernández-Rossier, J., Reina-Gálvez, J., Wolf, C., Wang, Y., Yang, K., Heinrich, A. J., & Lutz, C. P. Electric-field-driven Spin Resonance by On-surface Exchange Coupling to a Single-atom Magnet. Advanced Science.

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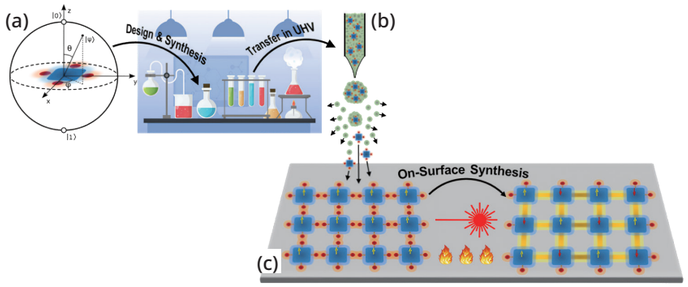
2019
- Gálvez, J. R., Wolf, C., Delgado, F., & Lorente, N. A cotunneling mechanism for all-electrical Electron Spin Resonance of single adsorbed atoms. Physical Review B, 100(3), 35411.

IBS Young Scientist Fellowship
On-surface Chemistry

PI Luciano COLAZZO

(left to right) Serim Jeon, Lukas Spree, Dasom Choi, Luciano Colazzo, Young Woo Kim, Caroline Hommel

The chemistry team has made impressive strides in synthetic chemistry. We synthesized unique molecules, including $ErPc_2$, not previously studied by other research groups. We produced isotopically pure FePc molecules with a nonzero nuclear spin, studied via scanning tunneling microscopy (STM). YPc_2 molecules played a vital role as stable test spins for the surface ensemble ESR team led by Fabio Donati. Our general chemistry lab has expanded and is equipped with cutting-edge tools. We have published papers on STM experiments, electrospray deposition for STM sample preparation, fabrication of highly ordered arrays, and template-directed 2D nanopatterning of molecular spins.



Workflow for creating highly ordered structures of molecular qubit candidates on surfaces

Publication list to date :

2023
- S. Reale, A. Singha, S. L. Ahmed, D. Krylov, L. Colazzo, C. Wolf, C. S. Casari, A. Barla, E. Fernandes, F. Patthey, M. Pivetta, S. Rusponi, H. Brune, and F. Donati, "Erbium and thulium on MgO(100)/Ag(100) as candidates for single atom qubits", Phys. Rev. B 107, 045427.
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Who We Are

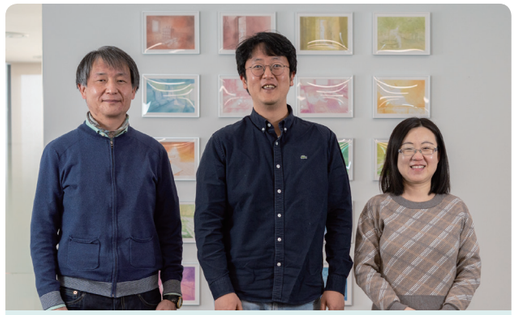
QNS Teams

PIs

(left to right) Yujeong Bae, Luciano Colazzo, Andreas Heinrich, Christoph Wolf, Fabio Donati, Soo-hyon Phark

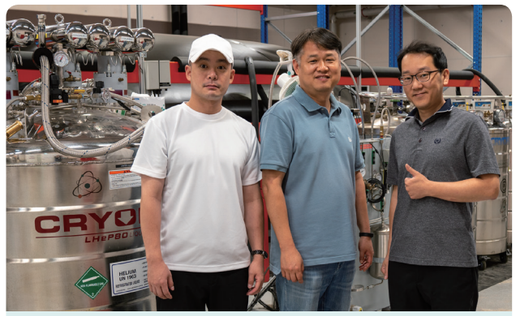
Postdocs

(left to right) Franklin Cho, Massine Kelai, Piotr Kot, Jose Galvez, Lukas Spree, Valeria Sheina, Corina Urdaniz, Caroline Hommel, Dmitriy Borodin, Alexina Ollier



Senior Scientists

(left to right) We-hyo Soe, Wonjun Jang, Lei Fang



Engineering Team

(left to right) Soonhyeong Lee, Sangwon Yoon, Minsu Seo

Students

(left to right) Hong Bui, Dasom Choi, Stefano Reale, Jeongmin Oh, Soyoung Oh, Jisoo Yu, Curie Lee

Operations Team

(left to right) Jiho Han, Hyein Lee, Mina Lee, Heejung Shin, Kyojong Lee, Hyewon Kyung, Jihee Min, Michelle Randall, Jaehee Lee, Sunny Kim

People Highlights

Wonjun Jang

"QNS was the best choice for me."

Wonjun Jang left Korea University to join QNS as a postdoc when our center was founded. After completing his postdoc, he secured a coveted role at Samsung Advanced Institute of Technology. However, due to his preference for the research environment and opportunities at QNS, he decided to return.

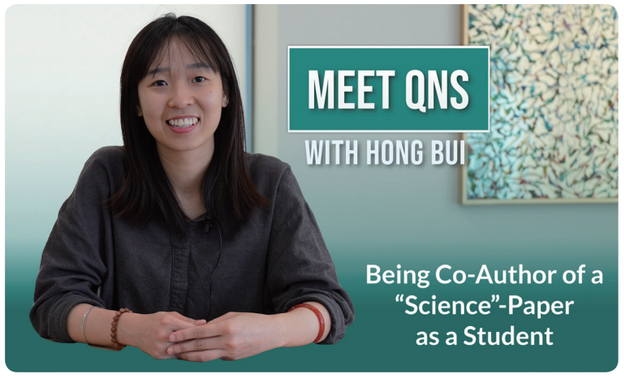
Watch on YouTube

Dmitriy Borodin

"A successful scientist never stops learning."

After winning the prestigious Otto-Hahn Medal, Dmitriy "Dima" Borodin entrusted his career to QNS and relocated to Korea for his postdoc.

Watch on YouTube



Hong Bui

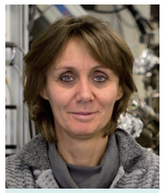
"By doing science you explore something new every day."

Hailing from Vietnam, Hong firmly believes that it was her destiny to pursue her PhD at QNS. While destiny may have played a role, it was her unwavering commitment to learning and diligent work that have now resulted in her Science paper publication before graduation!

Watch on YouTube

Advisory Board

QNS would not be possible without the generous support and lasting contributions of Ewha Womens University and the Institute for Basic Science. We would also like to thank our advisory board members for their input and encouragement.

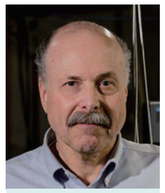


Roberta Sessoli

Professor of General and Inorganic Chemistry 'Ugo Schiff', University of Florence

Awards

- 2019 RSC Centenary Prize for world-leading research on molecular magnetism
- 2015 Lecoq de Boisbaudran Award from the European Rare Earths Society

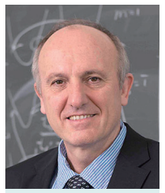


David Awschalom

Professor in Molecular Engineering, University of Chicago

Awards

- 2005 Oliver E. Buckley Prize by the American Physical Society
- 2005 Agilent Europhysics Prize by the European Physical Society



Daniel Loss

Professor of Theoretical Physics, University of Basel

Awards

- 2017 King Faisal International Prize in Science (Physics)
- 2010 Marcel Benoist Prize

Yonuk Chong

Director of the Quantum Information Research Support Center
Professor in Nano Engineering, Sung Kyun Kwan University (SKKU)

Don Eigler

American physicist & retired IBM Research Fellow

Awards

- 2010 Kavli Prize
- 1993 IBM Fellow

William Jo

Director of New and Renewable Energy Research Center
Professor of Physics, Ewha Womans University

Andrea Morello

Scientia Professor of Quantum Engineering, University of New South Wales

Awards

- 2019 Walter Boas Medal
- 2011 Eureka Prize for Scientific Research

Franz J. Giessibl

Professor of Physics, University of Regensburg

Awards

- 2016 Foresight Institute Feynman Prize in Nanotechnology
- 2014 Joseph F. Keithley Award For Advances in Measurement Science of the American Physical Society

Ying Jiang

Boya Distinguished Professor, Peking University

Awards

- 2020 Zhongguancun Award to Outstanding Young Scientists, Beijing Government
- 2019 Outstanding Research Award (1st class), Ministry of Education of China

Women in Science

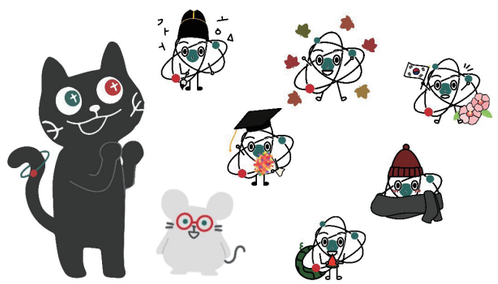
The QNS Women in Science Program, led by PI Yujeong Bae since its establishment in 2022, focuses on addressing the gender gap in STEM (science, technology, engineering, and mathematics), particularly in physics. Its primary objective is to promote gender equality, foster an inclusive platform for female scientists, and create a robust network where women in the field can establish meaningful connections. Being located on the campus of Ewha Womans University, QNS benefits from a vibrant community of female students and professors, offering an ideal environment for networking and collaborative opportunities. Having successfully organized seven gatherings, including the privilege of talking with esteemed female scientists, QNS remains committed to nurturing the professional development of our researchers and contributing to the global advancement towards gender equality in STEM.

QNS Women in Science

Career talk with 5 female Professors from different Universities

Student Ambassador Program

In 2022, QNS hosted a Student Ambassador Program. The goal was to promote our basic research in a more easily digestible way, especially to Korean University students. We selected ten students from different universities and disciplines to create and promote social media content for QNS.



Student Ambassador creations for QNS

QNS Student Ambassadors 2022

Awards

Year	Name	Award Name	Awarder
2023	Andreas Heinrich	Humboldt Research Award	Alexander von Humboldt Foundation
2023	Dmitriy Borodin	Otto-Hahn Medal and Otto-Hahn Award 2023	Max Planck Society
2023	Dasom Choi	Best Poster Awards	Korean Physics Society
2022	Lukas Spree	Feodor Lynen Scholarship	Alexander-Von-Humboldt Foundation
2022	Lukas Spree	SCF-DCC Best Poster Prize of ECMM2022	European Institute of Molecular Magnetism
2022	Juyoung Park	LG Display Scholarship (LGenius)	LG Display
2022	Do Thi Nga	Excellent Presentation in Applied Physics Field	Korean Physics Society
2022	Curie Lee	Undergraduate Presentation Participation Award	Korean Physics Society
2021	Andreas Heinrich	Heinrich Rohrer Medal (Grand Medal)	Japan Society of Vacuum and Surface Science
2021	Andreas Heinrich	Karl Friedrich Bonhoeffer Award Lecture	Max Planck Institute for Biophysical Chemistry
2021	Luciano Colazzo	Young Scientist Fellowship (YSF)	Institute for Basic Science (IBS)
2021	Do Thi Nga	Best Oral Presentation	Korean Physics Society
2021	Jinkyung Kim	Best Poster Award	Korean Physics Society
2021	Do Thi Nga	Excellent Presentation in Applied Physics Field	Korean Physics Society
2021	Jinkyung Kim	Outstanding Presentation Award	Korean Physics Society
2021	Juyoung Park	Outstanding Presentation Award	Korean Physics Society
2021	Juyoung Park	Outstanding Presentation Award	Korean Physics Society
2021	Jiyoon Hwang	Best Poster Presentation Award	ICAMD2021
2021	Shinjae Nam	Best Thesis Prize	Ewha Woman's University Physics Department
2020	Yujeong Bae	Asian Office of Aerospace Research and Development	
2020	Philip Willke	Emmy Noether Programme	Deutsche Forschungsgemeinschaft (DFG)
2020	Philip Willke	Gerhardt Ertl Young Investigator Award	The journal Surface Science through Elsevier Scientific Publishing
2020	Safa Ahmed	Marie Skłodowska-Curie COFUND program	Quantum Science and Technologies at the European Campus (QUSTEC)
2020	Daria Sostina	Marie Skłodowska-Curie COFUND program	Quantum Science and Technologies at the European Campus (QUSTEC)
2020	Do Thi Nga	Best Oral Presentation	Korean Physics Society
2020	Jinkyung Kim	Outstanding Presentation Award	Korean Physics Society
2020	Jinkyung Kim	Outstanding Poster Award	Korean Physics Society
2019	Do Thi Nga	Best Oral Presentation	Korean Physics Society
2018	Andreas Heinrich	2018 Feynman Prize in Nanotechnology	Foresight Institute
2018	Andreas Heinrich	Joseph F. Keithley Award 2018 For Advances in Measurement Science	American Physical Society (APS)
2018	Andreas Heinrich on behalf of QNS	2018 Excellent National R&D Performance	Korean Ministry of Science and ICT
2018	Andreas Heinrich on behalf of QNS	2018 Performance Evaluation Award by the Minister	Korean Ministry of Science and ICT
2018	Fabio Donati	Max Auwärter Award 2018	Austrian Physical Society
2018	Philip Willke	Feodor Lynen Scholarship	Alexander-von-Humboldt Foundation
2018	Wonjun Jang	Young Vacuum Scientist Award	Korean Vacuum Society

5 Year Review Results

Highest Possible Rating

QNS was reviewed by a panel comprised of domestic and internationally leading researchers. We were relieved and proud to receive the top rating of '**Outstanding**'.

How we improved since then

Since the review, we have consistently pushed ourselves by conducting clear-eyed assessments and swiftly implementing improvements. Our engagement with the Korean scientific community has grown even stronger, as evidenced by our participation in several events and growing collaborations. Since the 5-year review, QNS has hosted two major events for the Korean National Research Foundation, as well as numerous visits by our domestic colleagues, along with several joint workshops.

What's still to do

While we are always overflowing with aspirations, we have identified one significant need as our top priority. QNS instruments and techniques are at the cutting edge of science, requiring considerable time and effort for our students and postdocs to master them. To address this, we are implementing the following developments:

1. Student Training Program

We have established a mandatory course for students, serving as a boot camp to enhance their comprehension and proficiency in our field's state-of-the-art knowledge and skills. This course was delivered for the first time in Summer 2023.

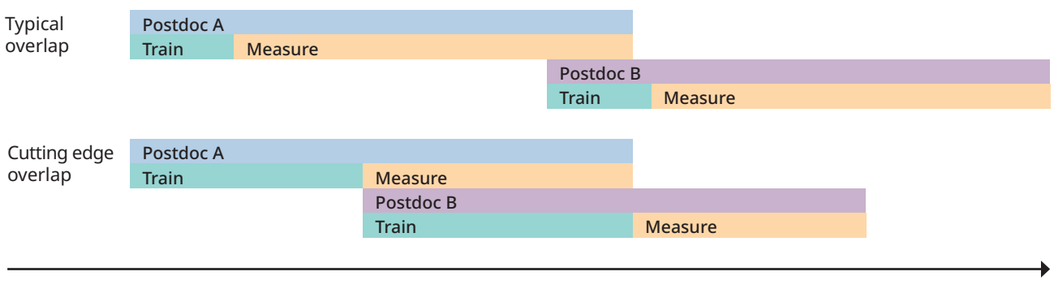
QNS Newcomer Course — 2023

Day (10-12 AM)	Course	Lecturer
2023/06/28 (Wed)	Theory of spins on surface: Introduction	Christoph
2023/07/04 (Tue)	Theory of spins on surface: spin states and excitations	Christoph
2023/07/06 (Thu)	Molecules on surface 1	Luciano
2023/07/07 (Fri)	Molecules on surface 2	Luciano
2023/07/12 (Wed)	Advanced theory: Coherent processes and quantum coherence	Christoph
2023/07/13 (Thu)	Vacuum technology: vacuum pumps and gauges, and backing	We-Hyo
2023/07/14 (Fri)	Sample preparation and atom/molecule deposition	We-Hyo
2023/07/18 (Tue)	Advanced theory: open quantum systems and transport formalism	Christoph
2023/07/19 (Wed)	LT-STM: DAQ, preamplifier, lock-in technique and STS	We-Hyo
2023/07/20 (Thu)	SP-STM: tip fabrication, spin-dependent trnsport/tunneling	We-Hyo
2023/07/21 (Fri)	ESR-STM: AWG, RF generator, measurement schemes	We-Hyo
2023/07/26 (Wed)	Advanced theory: quantum bits and gates	Christoph
2023/07/27 (Thu)	Ensemble electron spin resonance	Franklin
2023/07/28 (Fri)	X-ray adsorption spectroscopy	Fabio

2. Increasing Postdoc Overlap

Our objective is to extend the overlap duration of postdocs from several months to at least 1 year. By doing so, we can provide adequate training time while maximizing our measurement capacity.

Naturally, it is important to note that in order to achieve this, overall postdoc labor costs will increase and recruiting efforts will be intensified.



Example of the enhanced postdoc overlap required for our cutting edge instruments and techniques

Feedback from Recent Visitors

The following is a smattering of unattributed feedback we have received from senior visitors in 2023. This includes translations.

Team Spirit is definitely the most fascinating culture here at QNS.

Our recent achievement would not have been possible without the commendable hospitality and scientific transparency of QNS, so I'd like to take the opportunity to thank all of you very much for letting us learn from you!

Your people are very serious in pushing their science forward and they are sweet. My previous visit seems to be 4 years ago and during these days the institute has stabilized its expertise and your colleagues have obtained confidence in their science. It was quite impressive.

With the combination of professional expertise, Korean work ethic and the type of open discourse I experienced at QNS, which is probably new in intensity for Korean society, you are creating something new that promises to bring both the country and science in general forward. It will be very difficult for Germany to keep up with the pace. I'm curious to see whether we'll be able to turn things around again and master the challenges we're facing again.

Public Outreach and Science Communication Activities

SPIN ART

QNS firmly believes in enhancing public understanding of quantum nanoscience as a way of reciprocating the support received from Korean taxpayers in funding IBS. To achieve this goal, QNS organizes several long-term public outreach programs. Here are the main projects aimed at engaging with the Korean public.

Nanoscience in Middle Schools

3,300	3,300+	1,000+	660
Middle schools receive the resources every semester	Students learned this curriculum in their schools	Teachers downloaded the resources	Students learned this curriculum directly from QNS

2019~ongoing | *https://qns.science/nanokomik-en/*

QNS has developed an engaging and interactive nanoscience curriculum for Korean middle school students. This curriculum is designed to be taught both in person and online. Every semester, QNS distributes the curriculum to all 3,300 middle schools across Korea, enabling thousands of students to learn and benefit from it in their schools.

In addition, QNS offers direct instruction of this curriculum through the online course called 'Nanokomik at QNS.' During every school break, 110 students from various regions of Korea participate in this course, allowing them to deepen their understanding of science and actively engage with QNS. The most engaged student is rewarded with a visit to QNS as an incentive.

◀ Students doing hands-on experiments in the nanoscience curriculum

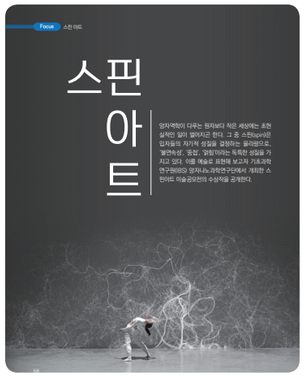
Art Contest

2019, 2021, 2024	750	12	3
Years of QNS Art Contests	Participants	Winners	Art exhibitions of winning pieces

2019~ongoing | *https://qns.science/art-en/*

QNS regularly organizes art contests aimed at educating artists about the fundamental concepts in our field. The participating artists then express these concepts in their unique artistic styles, making them more accessible to the general public. Art serves as a powerful medium for engaging with non-scientists and can be showcased through art exhibitions, events, and social media platforms. These contests not only raise awareness of QNS but also contribute to making quantum nanoscience more comprehensible for Korean society.

Art contest exhibition at QNS



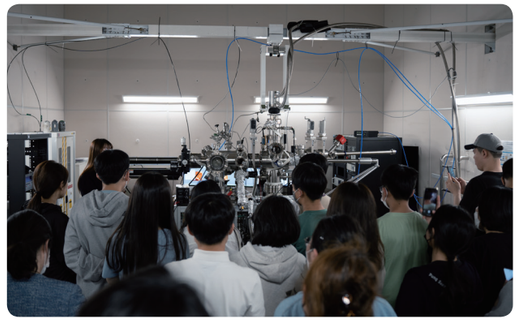
Art contest featured in a magazine

Open Lab

- 2023 QNS Open Lab with a 'Quantum Entanglement' magic show
- 500 students, teachers, and parents applied to visit for only 100 available spots
- This event motivated several students to wish to study at QNS one day

Welcome Remarks

Magic Show



Lab Tour

Student Participants

Scientific and Policy Events

QNS often receives requests to host events for embassies and other organizations such as the Korean National Research Fund (NRF). These have included the:

- **US-Korea Quantum Initiative Symposium** a bilateral funding review of the US Air Force and Korean NRF
- **Nobel Memorial Tour** with a delegation from several Swedish Universities
- **Swiss-Korean Open Dialogue - Preparing for the Age of Quantum** a bilateral meeting that took place at QNS organized by the Swiss Embassy and Korean NRF

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Federal Department of Economic Affairs, Education and Research EAER

State Secretariat for Education, Research and Innovation SERI
International Relations

Bern, 6 June 2023

Dear Director Heinrich, Dear Andreas,

I would like to express my sincere gratitude to you for hosting the Dialogue on Quantum which took place on 18 May 2023 at EWHA University. The Swiss delegation welcomed the direct exchange with their Korean counterparts to learn about ongoing activities in the field of quantum science and technology on both sides and possibilities to further develop their collaboration. I was delighted to gain such valuable insights directly from our stakeholders and to witness the strong interest and openness from both countries to intensify future cooperation.

Quantum science and technology is a promising area of research that has the potential to revolutionize the world as we know it and could lead to breakthrough in many areas. However, there are still many open questions and challenges in that field that require our brightest minds to work together. Both our countries exhibit great capabilities and strengths in this field and I am assured that we can complement and benefit each other.

I am convinced that the Swiss-Korean bilateral cooperation will continue to flourish and look forward to seeing many joint initiatives in the future.

Yours sincerely

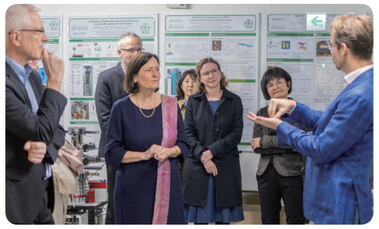
State Secretariat for Education,
Research and Innovation SERI

Jacques Ducrest
Ambassador
Head of the International Relations Division

Mr. Andreas HEINRICH
Director of IBS Center for Quantum Nanoscience
EWHA Womans University
Seoul

Lab tour with Swiss Federal Councilor Guy Parmelin and President of ETH Board Michael Hengartner among others

US-Korea Quantum Symposium 2022



Lab tour with DFG (The Deutsche Forschungsgemeinschaft) President

We were not only very impressed by your scientific work, but also by the facilities and the organization of your multinational team. Thank you very much for giving us this deep insight into the work of the QNS.

Die Präsidentin

Professorin Dr. Katja Becker

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Seodaemun-gu
03760 Seoul
Republic of Korea

9. Mai 2023

Lieber Herr Heinrich,

auf diesem Wege möchte ich mich bei Ihnen noch einmal herzlich für den Empfang unserer Delegation beim Center for Quantum Nanoscience bedanken.

Der Besuch bei Ihnen hat uns das Potenzial der bilateralen Zusammenarbeit r Weise vor Augen geführt. Nicht uch die *facilities* sowie die ns sehr beeindruckt. Haben n Einblick in die Arbeit des QNS

ejeon haben wir sehr produktive der Zusammenarbeit zwischen t der IBS-Geschäftsstelle haben von internationalen Förderungen

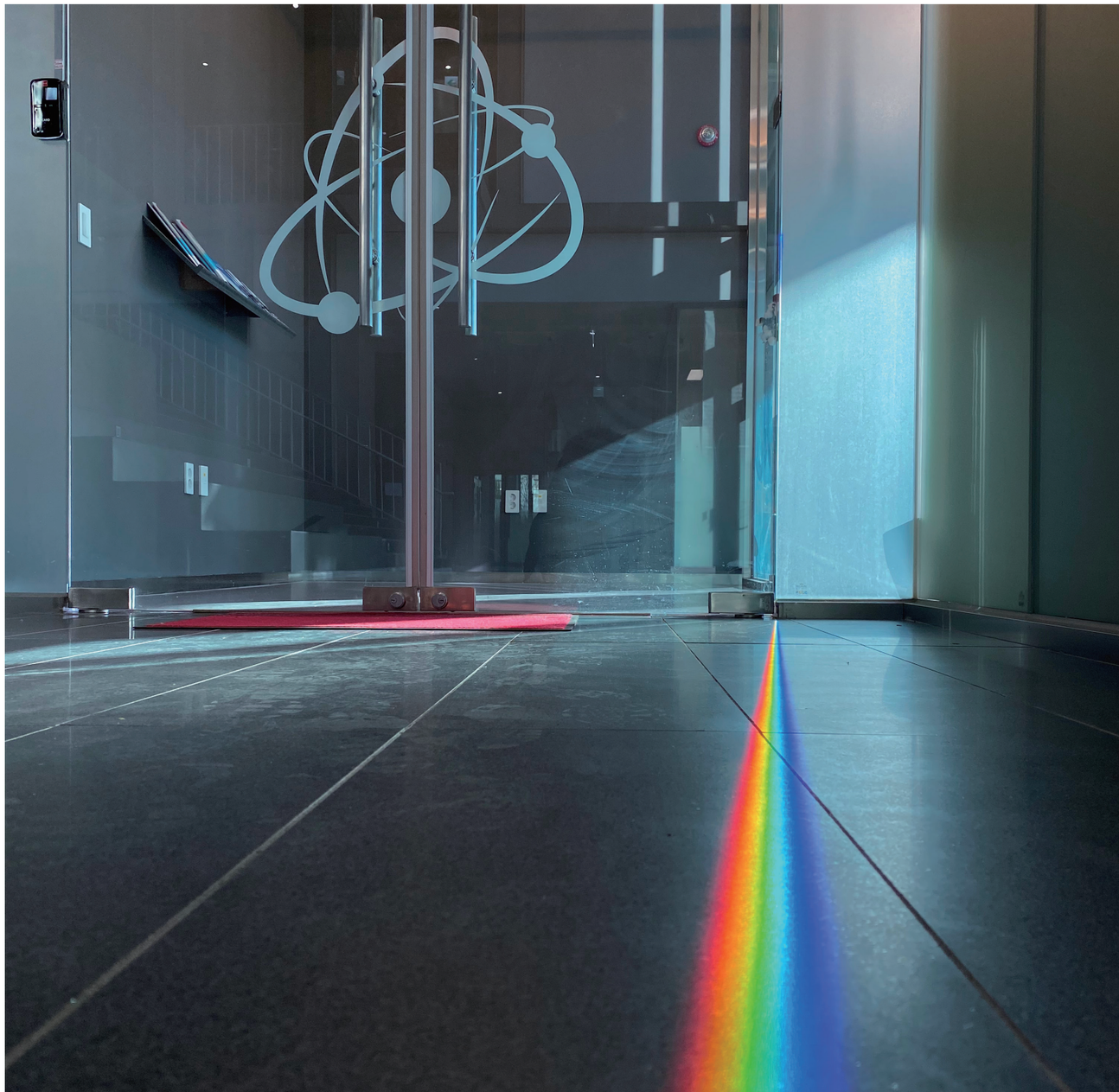
Nun hoffen wir, dass unserer Gespräche in Korea rasch und nachhaltig Früchte tragen und wir in Zukunft erneut Gelegenheit für ein Treffen mit Ihnen haben werden.

Mit freundlichen Grüßen

Katja Becker

DFG

What's Next



IBS Conference on Quantum Nanoscience

ICQNS 2023

Bringing the quantum nanoscience community together

IBS Conference on Quantum Nanoscience

Speakers

Ying Jiang
Peking University

Andrea Morello
University of New South Wales

Harry Anderson
University of Oxford

Danna Freedman
Massachusetts Institute of Technology

Seigo Tarucha
RIKEN

Andreas Heinrich
Center for Quantum Nanoscience

Lisanne Sellies
University of Regensburg

Ania Jayich
University of California, Santa Barbara

Guido Burkard
University of Konstanz

Yujeong Bae
Center for Quantum Nanoscience

Rupert Huber
University of Regensburg

Mark Hogg
University of Basel

Junho Suh
POSTECH

Yonuk Chong
Sungkyunkwan University (SKKU)

10-13 October 2023

Ewha Womans University
Seoul, South Korea

Sessions

Session 1:
Spin qubits in color centers and dopants

Session 2:
Quantum nanophotonics

Session 3:
Quantum control in molecular qubits

Session 4:
Quantum surface science

Session 5:
Quantum limits of mechanical motion

Session 6:
Spin qubits in quantum dots

ICQNS 2023

www.icqns2023.org

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CENTER FOR QUANTUM NANOSCIENCE

Come with your challenge, we have the tools and people to make it happen together

QNS Collaborative Fellowship

Submissions Open:
October 2023

Introduction to the fellowship

QNS's Collaborative Fellowship offers a unique opportunity for highly qualified researchers in quantum coherent nanoscience. Fellows can apply their creativity to develop ideas that can be realized using QNS's world class microscopic and spectroscopic instrumentation.

Fellows will be paired with a member of QNS's senior scientific staff in order to combine ideas with know-how and technical expertise. If appropriate, theory analysis and modeling can become part of the collaboration as well.

Proposed projects must aim to result in tangible outcomes such as a co-authored, peer reviewed publication.

Learn more about submission guidelines, review processes, example case studies, and important deadlines all at:

www.qnsfellowship.science

@QNSscience

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