Abstracts, NS166: *Emerging Quantum Technologies*

Heike Riel (overview talk): *Computing – From Bits to Qubits*

Classical computers which represent information as bits have evolved over many years in an unprecedented way and became ubiquitous in our life. Today these classical technologies based on miniaturization are reaching their limits and new computing paradigms are in quest to reduce power consumption and increase the performance of computation. Two new computing paradigms are emerging as driving force in computation, first neuromorphic computing or technologies mimicking the brain to accelerate computing workloads for artificial intelligence (AI) and quantum computing to solve relevant problems that are intractable to classical computer. Quantum computing systems are built from the bottom up and are reaching the limits of what can be classically simulated. The entire quantum computing stack is developed starting from the qubit and quantum processor technology, control electronics to software, algorithms, to applications for quantum computing. Significant advances have been recently achieved that enabled to scale superconducting qubits to a 127-qubit processor and increase quality and speed to improve the performance of quantum computation. In this presentation an overview of our activities in the field of new computing paradigms of AI hardware technologies and quantum computing is given.

Michelle Simmons: *Engineering Qubits in Silicon with Atomic Precision*

The realisation of a large-scale error corrected quantum computer relies on our ability to reproducibly manufacture qubits that are fast, highly coherent, controllable and stable. The promise of achieving this in a highly manufacturable platform such as silicon requires a deep understanding of the materials issues that impact device operation. In this talk I will demonstrate our progress to engineer every aspect of device behaviour in atomic qubits in silicon. This will cover the use of atomic precision lithography to achieve fast, controllable exchange coupling [1], fast, high fidelity qubit initialisation and read-out [2]; low noise all epitaxial gates allowing for highly stable qubits [3]; and qubit control [4] that provide a deep understanding of the impact of the solid-state environment [5] on qubit designs and operation. I will also discuss our latest results in [6] analogue quantum simulation.

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[2] D. Keith, M. G. House, M. B. Donnelly, T. F. Watson, B. Weber, M. Y. Simmons, “Microsecond Spin Qubit Readout with a Strong-Response Single Electron Transistor”, Physical Review X 9, 041003 (2019); D. Keith, S. K. Gorman, L. Kranz, Y. He, J. G. Keizer, M. A. Broome, M. Y. Simmons, “Benchmarking high fidelity single-shot readout of semiconductor qubits”, New Journal of Physics 21, 063011 (2019).

[3] L. Kranz S. K. Gorman B. Thorgrimsson Y. He D. Keith J. G. Keizer M. Y. Simmons, “Exploiting a Single-Crystal Environment to Minimize the Charge Noise on Qubits in Silicon”, Advanced Materials 32, 2003361 (2020).

[4] L. Fricke, S.J. Hile, L. Kranz, Y. Chung, Y. He, P. Pakkiam, J.G. Keizer, M.G. House and M.Y. Simmons, “Coherent spin control of a precision placed donor bound electron qubit in silicon”, Nature Communications 12, 3323 (2021).

[5] M. Koch, J.G. Keizer, P. Pakkiam, D. Keith, M.G. House, E. Peretz, and M.Y. Simmons, “Spin read-out in atomic qubits in an all-epitaxial three

Charles Marcus: *Topological Superconductivity in Epitaxial Hybrid Materials*

This talk will examine phase control in hybrid semiconductor superconductor materials, including frustration in periodic arrays, phase bias in planar Josephson junctions, and fluxoid quantization in full-shell nanowires. When phase can induce topological superconductivity is discussed and demonstrated.

Qi-Kun Xue: *From topological insulators to quantum anomalous Hall effect*

The quantum Hall effect (QHE), a quantized version of the Hall effect [1], was observed in two-dimensional (2D) electron systems under magnetic field more than 40 years ago [2, 3]. The quantum anomalous Hall (QAH) effect refers to a quantized version of the anomalous Hall effect [4], which doesn't require an external magnetic field. It had been predicted to occur in "2D graphite" with broken time reversal invariance [5], and more recently in 2D magnetic topological insulators [6, 7]. It was first experimentally observed in thin films of magnetically doped $(Bi,Sb)_2Te_3$ topological insulator in 2013 [8]. In this talk, the history and recent progress in the study of QAH effect are presented.

References
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[2] K. von Klitzing, G. Dorda, M. Pepper, Phys. Rev. Lett. **45**, 494 (1980).
[3] D. C. Tsui, H. L. Stormer, A. C. Gossard, Phys. Rev. Lett. **48**, 1559 (1982).
[4] E. H. Hall, Philos. Mag. **12**, 157 (1881).
[5] F. D. M. Haldane, Phys. Rev. Lett. **61**, 2015 (1988).
[6] M. Z. Hasan, C. L. Kane, Rev. Mod. Phys. **82**, 3045 (2010).
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Masahito Ueda (overview talk): *Information thermodynamics*

Information thermodynamics incorporates quantum measurement into thermodynamics, thereby enabling one to evaluate the cost of measurement and that of information erasure in information processing of thermodynamics [1]. The total cost of measurement and information erasure resolves the paradox of Maxwell's demon. Information thermodynamics also unifies the modern fluctuation theorem with information theory [2], leading to a rather unexpected consequence that the inclusion of the factor 1/N! in the thermodynamic entropy introduced by Gibbs (the Gibbs paradox) is equivalent to the validity of the fluctuation theorem with absolute irreversibility for gas mixing [3].

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Jukka Pekola: *Quantum thermodynamics experiments in superconducting circuits*

I will describe experiments on superconducting quantum circuits combined with an ultrasensitive calorimeter. The heart of the calorimeter is a thermometer capable of measuring local temperature down to microsecond time scales. Experiments on quantum limited heat transport, heat valves and refrigerators based on superconducting qubits will be presented. A detector with noise down to that dictated by the fluctuation-dissipation theorem gives a possibility for continuous wideband single microwave photon detection.

Alexia Auffèves: *Quantum technologies need a quantum energy initiative*

Quantum technologies are currently the object of high expectations from governments and private companies, as they hold the promise to shape safer and faster ways to extract, exchange, and treat information. However, despite its major potential impact for industry and society, the question of their energetic footprint has remained in a blind spot of current deployment strategies. In this Perspective, I argue that quantum technologies must urgently plan for the creation and structuration of a transverse quantum energy initiative, connecting quantum thermodynamics, quantum information science, quantum physics, and engineering. Such an initiative is the only path towards energy-efficient, sustainable quantum technologies, and to possibly bring out an energetic quantum advantage.

Elisabeth Giacobino (overview): *Quantum optics: from the first achievements to quantum technologies*

This talk will present the first achievements in experimental quantum optics, with the realization of squeezed light and quantum correlated beams for continuous variables, and the generation of single photons, and twin and entangled photons, leading to groundbreaking results in basic quantum physics as well as in applications. Then it will show the impressive progress in the development of novel quantum optical systems allowing for the demonstration of more fundamental properties of quantum mechanics and major advances in quantum measurement, communication, simulation and computing.

Alain Aspect: *Quantum non-locality: fruitful intuitions for quantum technologies*

Einstein's conclusion that quantum mechanics is not complete was based on a local realist worldview. After Bell's theorem and subsequent experiments, one must renounce local realism. I will argue that non-local quantum images can yield fruitful intuitions.

Anton Zeilinger: *From Curiosity about Quantum Foundations to the Roots of Quantum Technology*

Early experiments on quantum foundations were motivated essentially by curiosity. There was no awareness that this opened up the avenue to quantum information. The experiments I will discuss go from neutron interferometry via three-photon entanglement, and entanglement swapping to recent path identity results based on a seminal and long overlooked paper by Wang, Zou, and Mandel. I will also argue that experiments on the foundations continue to be a fascinating field.

Yoshihisa Yamamoto: *Single photon coherent Ising machine*

In this talk we will review the recent progress in coherent Ising machines (CIM). The CIM is an optical parametric oscillator (OPO) network based special purpose computer for Ising model and related optimization problems. The Ising cost function is mapped to the OPO network loss landscape by dissipative coupling rather than the energy landscape by Hamiltonian coupling, which allows an upward search by gain in contrast to a standard downward search by cooling. We will discuss a new operation mode of CIM with extremely weak excitation and nonlinear measurement feedback. To our surprise, the product of time-to-solution and energy-to-solution becomes minimum and the sampling efficiency of optimum and sub-optimum solutions is maximum at an extremely weak excitation level of one (average) photon per site.

Atac Imamoglu: *Strongly correlated electrons in atomically thin semiconductors*

Twisted bilayers of two dimensional semiconductors have emerged as a new paradigm for exploration of strongly correlated electron systems. In this talk, I will describe experiments revealing signatures of kinetic magnetism in hole-doped Mott state of electrons in a triangular lattice.

Mikhail Lukin (overview talk): *Programmable quantum systems for simulations, sensing and computing*

A broad effort is currently under way to build quantum machines that may be capable of outperforming the existing classical counterparts in executing useful tasks in areas ranging from computation and communication to sensing and metrology. Practical realization of such systems and exploration of their potential capabilities and limitations are among the central challenges in the new field of quantum science and engineering. In this talk, we will describe several examples of recent work towards these goals. These include realization of programmable systems composed of hundreds of quantum bits and their use for scientific applications such as studying new forms of quantum matter, solving complex computational problems and developing new approaches to optical atomic clocks, as well recent advances in controlling solid-state spin impurities for quantum sensing, aimed towards magnetic resonance imaging of individual molecules and novel approaches to biomedical diagnostics. Current challenges and new opportunities will be discussed.

Jun Ye: *Clock based on quantum matter*

Precise control of quantum states of matter, including engineered interactions and correlations between quantum particles, is revolutionizing the performance of atomic clocks and metrology. The confluence of quantum science and precision measurement provides opportunities to explore emerging phenomena and test fundamental physics. Recent advances include a measurement of the gravitational time dilation over a sub-millimeter spatial separation.

Jörg Wrachtrup: *Precision measurements of correlated electron materials*

Spins in wide band gap semiconductors are a leading contender in various areas of quantum technology. Most notably they have been established as a novel tool for nanoscale sensing, major hardware for long distance quantum entanglement, as well as small scale quantum registers for quantum computing. I will present the use of spins in in those areas [1,2,3]. Specifically, I will discuss quantum sensing with spins to investigate magnetism in 2D materials including the investigation domain patterns [4] and Moiré structures in twisted 2D layers [5]. Here the nitrogen vacancy center in diamond is used to probe and image electronic magnetism in mono- and multilayers of materials like CrBr3. By using dedicated measurements strategies based on quantum algorithms one can enhance the performance of those quantum sensors to achieve better signal quality and improve the spectral resolution in those measurements [6].

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[2] N. Morioka et al. Nature Com. 2516 (2020)
[3] N. Chejanovsky et al. Nature Mat. 20, 1079 (2021)
[4] Qi-Chao Sun et al. Nature Com. 12, 1989 (2021)
[5] T. Son et al. Science 374, 1140 (2021)
[6] V. Vorobyov et al., njp Quantum Information 7, 124 (2021)

Paola Cappellaro: *Practical quantum advantage in sensing*

Quantum sensors exploit the strong sensitivity of quantum systems to external disturbances to measure various signals in their environment with high precision. Nitrogen Vacancy color centers in diamond have in particular emerged as exquisite probes of magnetic fields. These quantum sensors have the potential to be a revolutionary tool in material science, quantum information processing, and bioimaging. However, the same strong coupling to the environment also limits their sensitivity due to its decohering effects. Error correction strategies, including quantum error correction codes, robust many-body quantum phases, and dynamical decoupling, can help in fighting decoherence, but they incur the risk of also canceling the coupling to the signal to be measured.

Here I will show recent advances in tackling this challenge, including exploiting and improving control and the use of ancillary systems, that achieve an advantageous compromise between noise and signal cancellation. These strategies can not only improve the sensitivity of quantum sensors, but also yield new applications, via the transduction of biological signals of interest into quantum perturbations or the frequency up/down-conversion of signals of interest.

Jian-Wei Pan (overview talk): *Dream or Reality? Quantum Communication: the Past, Present and Future*

In this talk, I will give an overview on the 40 years' long history of quantum communications and show how this field has evolved from a pure theoretical idea into an emerging technology. The privacy and security underpin human dignity and is one of the most important human rights. However, every advance in classical cryptography has been defeated by advances in cracking. In 1984, Charles Bennett and Gilles Brassard theoretically ended the encryption-decryption battle by inventing quantum cryptography. However, there are major challenges to turn this idea into practically secure and large-scale quantum communications. I will discuss the experimental efforts to close security loopholes in the quantum key distribution using realistic devices, and go to long distance practically useful at a global scale. One possible solution for large-scale quantum communication is quantum repeater. After 20 years of development, quantum repeaters enable quantum communication at a distance of 500 km. More effectively, by developing a quantum science satellite Miciusand exploiting the negligible decoherence and photon loss in the out space, practically secure quantum cryptography, entanglement distribution, and quantum teleportation have been achieved over thousand-kilometer scale. The systematic technologies developed in quantum communications are also widely applicable for other optical quantum information processing tasks, especially the demonstrations of quantum computational advantage with up to hundreds of photons.

In future, it is foreseen to establish a global quantum communication network and quantum internet with metropolitan quantum communication network, inter-city quantum communication connected by quantum repeaters, and long-distance quantum communication with quantum satellites including the quantum constellation and GEO quantum satellite. Moreover, a GEO satellites carring a ultra-precise optical clock also provides new platform for the study of quantum metrology such as precise timing information sharing, and can even provide the possibility of new probes for fundamental physics.

Artur Ekert: *Privacy for the paranoid ones - a quantum path towards the ultimate limits of secrecy*

Among those who make a living from the science of secrecy, worry and paranoia are just signs of professionalism. Can we protect our secrets against those who wield superior technological powers? Can we trust those who provide us with tools for protection? Can we even trust ourselves, our own freedom of choice? Recent developments in quantum cryptography show that some of these questions can be addressed and discussed in precise and operational terms, suggesting that privacy is indeed possible under surprisingly weak assumptions. I will provide an overview of how quantum entanglement, after playing a significant role in the development of the foundations of quantum mechanics, became a new physical resource for all those who seek the ultimate limits of
secrecy.

Nicolas Gisin: *From Bell non-locality to quantum comm-unication and back to network non-locality*

Quantum information science emerged from studies on the foundations of quantum physics. I'll illustrate this, starting from Bell inequalities all the way to commercial Quantum Key Distribution and Quantum Random Number Generator chips. But the story doesn't stop here. Quantum information science, in turn, feeds back into the foundations, asking questions like, e.g., "how does non-locality manifest in quantum networks".

Steve Girvin (overview talk): *Quantum Computation, Error Correction, and Simulation with Superconducting Qubits and Bosonic Modes*

This talk will present an overview of systems comprised of both qubits and oscillators. Such hybrid platforms offer powerful architectures with novel gates and instruction sets for quantum computation and hardware-efficient quantum error correction now going beyond the break-even point. In addition, recent experiments on quantum simulations of physical models containing bosons show that these can be vastly more efficient on platforms containing bosonic modes.

John Martinis: *System testing of a quantum computer*

In order to specify a quantum computer technology, it is important to describe not just the qubit type and architecture, but qubit errors. This is because qubits are fundamentally error-prone, and computational power can only occur if the errors are small enough, roughly 2%. I will describe how the quantum supremacy experiment from Google was able to measure system error rates, and that these errors can be described in a simple probabilistic manner.

Michel Devoret: *Error correction of a logical qubit*

The accuracy of logical operations on quantum bits (qubits) must be improved for quantum computers to surpass classical ones in useful tasks. To that effect, quantum information needs to be made robust to noise that affects the underlying physical system. Rather than suppressing noise, quantum error correction aims at preventing it from causing logical errors. This approach derives from the reasonable assumption that noise is local: it does not act in a coordinated way on different parts of the physical system. Therefore, if a logical qubit is encoded non-locally, it is possible, during a limited time, to detect and correct noise-induced evolution before it corrupts the encoded information. We present an experiment based on superconducting cavities and a transmon artificial atom – the latter employed here as an ancillary non-linear element [1] – that implements autonomous error correction, incorporating novel operations [2] and feedback control based on reinforcement learning [3]. Recently, we have stabilized in real-time a logical qubit manifold spanned by Gottesman-Kitaev-Preskill grid states, reaching a correction efficiency such that the lifetime of the encoded information was prolonged by a factor of two beyond the lifetime of the physical qubits composing our system.

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Peter Zoller (overview talk): *Programmable Quantum Simulators with Atoms and Ions*

Quantum simulation aims at `solving' complex quantum many-body problems efficiently and with controlled errors on quantum devices. Here we discuss quantum simulation from the perspective of programmable analog quantum simulators, as realized in present cold atom and ion experiments, where the unique features are scalability to large particle numbers and programmability. The focus of this talk is to report work from a theory-experiment collaboration with a programmable trapped ion platform with up to fifty qubits/spins, with the goal to develop and demonstrate a toolbox of quantum protocols, addressing questions from fundamental quantum science to application as quantum technology. Examples include variational quantum algorithms preparing many-body ground states, and measurement protocols revealing the entanglement structure of the many-body wavefunction, e.g. as tomography of the entanglement Hamiltonian. In addition, we demonstrate `optimal' quantum metrology with variational quantum circuits, where quantum simulators act as `programmable quantum sensors'. Finally, we address the problem of verification of quantum simulators via Hamiltonian and Liouvillian learning as an experimental protocol, i.e. we `learn' the operator structure of both the many-body Hamiltonian and Lindbladian characterizing (Markovian) decoherence.

Chris Monroe: *Quantum Computing with Atoms*

Trapped atomic ions are a leading physical platform for quantum computers, featuring qubits with essentially infinite idle coherence times and the highest purity quantum gate operations. Such atomic clock qubits are controlled with laser beams, allowing densely-connected and reconfigurable universal gate sets. The path to scale involves concrete architectural paths based on well-established protocols, from shuttling ions between QPU cores to modular photonic interconnects between multiple QPUs. Full-stack ion trap quantum computers have thus moved away from the physics of qubits and gates and toward the engineering of optical control signals, quantum gate compilation for algorithms, and software-defined error mitigation and correction. I will summarize the state-of-the-art in these quantum computers in both academic and industrial settings, and summarize how they are being used for both scientific and commercial applications.

Immanuel Bloch: *Large Scale Quantum Simulations using Ultracold Atoms in Optical Lattices*

40 years ago, Richard Feynman outlined his vision of a quantum simulator for carrying out complex calculations of physical problems. Today, his dream has become a reality and a highly active field of resarch across different platforms ranging from ultracold atoms and ions, to superconducting qubits and photons. In my talk, I will outline how ultracold atoms in optical lattices played a vital contribution in starting this vibrant and interdisciplinary research field 20 years ago and now allow probing and controlling of quantum phases in- and out-of-equilibrium with fundamentally new tools and single particle resolution. Novel (hidden) order parameters, entanglement properties, full counting statistics or topological features can now be measured routinely and provide deep new insight into the world of correlated quantum matter. I will introduce measurement and control techniques and discuss a few highlight applications from the field of 1) strongly correlated quantum systems, 2) topological quantum matter and 3) out-of equilibrium dynamics in quantum many-body systems and provide an outlook for future challenges and opportunities in this system.

Matthias Steffen: *From Error Mitigation to Error Correction: A Continuous Path*

How do we deal with errors in quantum mechanics? We trade resources measured in the form of complexity, number of qubits, and runtime for reduced impact of errors. Quantum Error Correction (QEC) generally trades number of qubits and runtime along with classical processing (syndrome matching) to reduce effective errors rates. Owing to the significant overhead associated with planar QEC codes, practical error correction still requires major technical advances likely requiring years of further study. On the other hand, quantum error mitigation trades runtime as measured by the number of quantum circuit executions for reduced errors when measuring expectation values. Simulations suggest that noise free estimates of 100 qubit circuits at depth 100 are realizable with physical error rates at 1e-4, repetition rates of 1kHz, and a total runtime of a day. This significantly raises the prospects for potential quantum advantage well before fault-tolerant quantum computing. In this talk we will discuss the current status of error mitigation including results with up 50 qubits.

Rainer Blatt: *Quantum Computation and Quantum Simulation with Trapped Ca+ Ions*

The state-of-the-art of the Innsbruck trapped-ion quantum computer [1] is briefly reviewed. We present an overview on the available quantum toolbox and discuss the scalability of the approach.
With up to 50 fully controlled ion qubits we perform quantum simulations investigating quantum transport [2] and emerging hydrodynamics features [3]. Employing the quantum toolbox for entanglement-enhanced Ramsey interferometry, we find optimal parameters for quantum metrology [4]. Quantum computers can be protected from noise by encoding the logical quantum information redundantly into multiple qubits using error-correcting codes. Manipulating logical quantum states by imperfect operations requires that all operations on the quantum register obey a fault-tolerant circuit design to avoid spreading uncontrolled errors. We demonstrate a fault-tolerant universal set of gates on two logical qubits in the trapped-ion quantum computer [5].

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[3] M. K. Joshi et al., Science **376**, 720 (2022)
[4] C. D. Marciniak et al., Nature **603**, 604 (2022)
[5] L. Postler et al., Nature **605**, 675 (2022)

John Preskill (overview talk): *Making predictions in a quantum world*

I will review an experimentally feasible procedure for converting a quantum state into a succinct classical description of the state, its classical shadow. Classical shadows can be applied to predict efficiently many properties of interest, including expectation values of local observables and few-body correlation functions. Efficient classical machine learning algorithms using classical shadows can address quantum many-body problems such as classifying quantum phases of matter. I will also explain how experiments that exploit quantum memory can learn properties of a quantum system far more efficiently than conventional experiments.

David DiVincenzo: *Transmon platform for quantum computing challenged by chaotic fluctuations*

Our work looks at the transmon array as a many body (boson lattice) system, asking what attributes of the many body phase influence the usability of this array for gate-based quantum computing. Many body localization is desirable.

Ref: Christoph Berke, Evangelos Varvelis, Simon Trebst, Alex Altland, and David P. DiVincenzo, “Transmon platform for quantum computing challenged by chaotic fluctuations,” arXiv:2012.05923, Nature Communications 13, 2495 (2022).

Krysta Svore: *Quantum at Scale*

While quantum computation has long been promised, and new scenarios and problems for it to tackle are being explored, at the moment we are short on scale. To define and understand the requirements of scale requires also knowing the needs of the problems to be solved. And then, together with those requirements, working to define the desiderata of the system architecture. I’ll describe what’s needed to scale as we know it today, and the quantum and classical technologies we believe will take us there.

Ignacio Cirac: *Quantum Information Theory and Many-body Physics*

In this talk I will review some of the connections between these two research areas. In particular, on who local dynamics in many body systems can be described in terms of quantum circuits and cellular automata, as well as tensor networks.