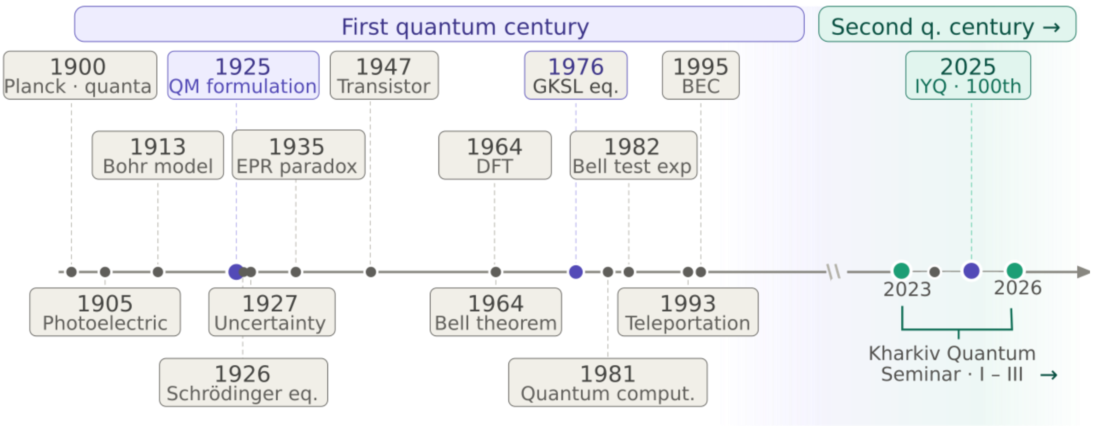
Opening the second quantum century with the Kharkiv Quantum Seminar



The idea of this Special Issue of the *Fizyka Nyzkykh Temperatur/Low Temperature Physics* journal emerged in 2025, the year which was proclaimed by the United Nations as the International Year of Quantum Science and Technology. The year was dedicated to the 100th anniversary of the formulation of quantum mechanics by Werner Heisenberg. In parallel to the realization of the idea with the Special Issue, as Guest Editors, we have just reached an important milestone this year — we celebrate the third anniversary of our Kharkiv Quantum Seminar.

The Kharkiv Quantum Seminar was established in 2023 as an initiative to support and advance Ukrainian science. During these three years, many outstanding researchers delivered their lectures on the forefront of modern quantum science. The aim of this Special Issue is therefore to bring together recent works by some of the speakers of our seminar, with contributions from the two organizers and their groups.

The time diagram on top of this preface shows a few milestones relevant for our Special Issue. While it is generally assumed that quantum mechanics was developed by 1925, arguably, it was born at the very beginning of the twentieth century. To reflect this, the timeline starts from Max Planck's quantum hypothesis of energy quantization, and the first quantum "century" may be viewed as beginning about 25 years before Heisenberg's complete formulation of quantum mechanics. Some other milestones on the timeline were chosen to indicate both the key quantum breakthroughs and those relevant for the content below.

In what follows, we review the contributions comprising this Special Issue, highlighting the directions of research they represent. With these, we would like to celebrate the beginning of the second quantum century, as the previous year symbolically marked the end of the first century.

A beautiful starter of the Special Issue is a tutorial (this article format has been accepted for the first time in the history of the *Fizyka Nyzkykh Temperatur/Low Temperature Physics* journal) by **Abhijit Sen, Sonali Panda, Mahima Arya, Subhajit Patra, Zizhan Zheng, and Denys I. Bondar** [1], where the authors give a timely introduction to reinforcement learning. This approach is viewed as one of the main methods in contemporary machine learning. Among the obvious advantages of this particular tutorial is its accessibility to readers without any previous experience in the field, requiring only basic knowledge in probability theory and quantum mechanics. It summarizes the main principles of classical reinforcement learning, then briefly introduces the basics of quantum computing and finally considers the quantum control task. The tutorial article also contains a set of practical problems with links to open-access Python codes.

The behavior of solid-state quantum devices is defined by the position and motion of charges in them. In particular, charge qubits, driven and probed via gate electrodes, are sensitive to changes in the position of the charges. As studied by **Seth Byard, Maksim Gomanko, and Sergey M. Frolov** [2], charge traps and defects surrounding mesoscopic quantum systems can contribute to the unintended charge dynamics. The authors report transport measurements of nanowire-based quantum dots. The measurements show fractional shifts in the stability diagrams, which present the current through the quantum dot as a function of left and right gate voltages. These diagrams demonstrated that the typical diagonal resonance lines were shifted by a fraction of the pattern's period, with this fraction close to the value of 1/3. While these shifts can be attributed to the fractional charge transport, as in the fractional quantum Hall regime, the authors present an alternative picture. There, the shifts are interpreted by possible capacitive coupling of the charge traps in the vicinity of the quantum system probed. Such concerns may illustratively relate to other layouts such as mesoscopic quantum Hall interferometers, provided there is sufficient volume of data accessible.

Understanding how a quantum system reaches thermal equilibrium when strongly coupled to its environment remains one of the central open problems in quantum thermodynamics, as standard weak-coupling assumptions fail to capture the interaction-induced operator content of the reduced equilibrium state. In this respect, **Gerard McCaul** [3] introduces the "quenched density" framework for deriving the Hamiltonian of mean force from the Feynman–Vernon influence functional, using the Hubbard–Stratonovich transformation to convert the imaginary-time path integral into a classical average over local propagators. The framework's conceptual contribution — cleanly separating the statistical properties of the bath from the algebraic structure of the system response — is a genuine advance in the formalism of strong-coupling thermodynamics.

An comprehensive study of pulse propagation simulated numerically using the Tkwant software package is given by **Prasoon Kumar, Thomas Kloss, and Xavier Waintal** [4]. The authors consider the Mach–Zehnder interferometer in the quantum Hall regime, built on a two-dimensional electron gas. The approach treats electron-electron interactions at the time-dependent mean-field level, which serves as the minimal description that properly restores gauge invariance and current conservation. The authors proceed in a stepwise manner, first characterizing the constituent elements of the device: a quasi-one-dimensional wire and a quantum point contact. This allows them to isolate the main effect of interactions, which is a renormalization of the pulse (plasmon) velocity consistent with Luttinger liquid theory, while the quantum point contacts are identified as sources of additional interaction-induced deviations. Most importantly for potential experimental realizations, the dynamical control of the interference pattern (encoded in the transient current plateau) turns out to be robust to the presence of interactions.

Can one of the main constituents of modern quantum technologies, a photon, travel with a superluminal velocity? While the information cannot be transferred faster than with the speed of light, not only subluminal but also superluminal velocities of light propagation are widely studied, considering phase, group, signal, and energy-transfer velocities. To a rectilinear free-space propagation of electromagnetic wavepackets, one can attribute a subluminal group velocity and a superluminal phase velocity, so that their product equals the speed of light squared. In his work, **Konstantin Y. Bliokh** [5] uses electromagnetic field theory, scalar wavepacket evolution, and quantum-mechanical formalism to describe the subluminal and superluminal propagation of free-space photons. These three approaches coherently paint a picture where the subluminal group velocity and superluminal phase velocity of photons represent an inherently consistent description of wave propagation.

Illumination of metallic needle tips by intense laser pulses allows addressing problems of attosecond physics and petahertz electronics. Using high-harmonic generation for free-standing metallic nanostructures results in only weak signals and suffers from other limitations. To overcome these, **Jonas Heimerl, Stefan Meier, Philip Popp, Timo Paschen, Lennart Seiffert, Felix López Hoffmann, Simon Wittigschlager, Daniel Lesko, Andreas Liehl, Alfred Leitenstorfer, Thomas Fennel, and Peter Hommelhoff** [6] developed two-color photoelectron modulation spectroscopy. In this technique, the bichromatic field is focused onto the needle, resulting in controllable electron emission. The paper reviews this efficient technique using intense femtosecond laser pulses and presents the electron trajectories and energy spectra, obtained experimentally and described theoretically, showing impressive mutual agreement. The carrier-envelope phase and the two-color relative phase are the knobs controlling the attosecond strong-field electron dynamics. The authors show how varying and optimizing the phases allows one to obtain rich information about the emitted electrons' trajectories and energy spectra.

With all the advances in experimental and theoretical research methodology, there are still many open questions in modern condensed matter physics. In particular, the question of magnetism in RuO_2 remains a central and actively debated issue in the context of altermagnetism. **Diana Csontosová, Kyo-Hoon Ahn, and Jan Kuneš** [7] approach this problem using a three-orbital Hubbard model treated within the Hartree-Fock approximation followed by the random phase approximation (RPA). A key methodological finding is that the non-interacting spin susceptibility provides a poor proxy for the full RPA result, underlining the importance of the multi-band nature of the problem. Throughout the studied parameter range, the leading instability is found to lie in the spin channel, confirming that spin susceptibility is the dominant response. In the stoichiometric system without spin-orbit coupling, commensurate altermagnetic order is identified as the leading instability at sufficiently low temperatures, whereas in other regimes, incommensurate wave vectors emerge. The authors analyze how the band splitting induced by the staggered Weiss field differs fundamentally between altermagnets and antiferromagnets: in antiferromagnets, splitting occurs only near band crossings, while in altermagnets isolated bands can be spin-split when the corresponding Bloch states exhibit site polarization.

Development of nanoscale superconductivity for quantum technologies is significantly based on understanding the properties of type-II superconductors. The values of the magnetic field between the critical ones result in penetration of the Abrikosov vortices and the mixed state, which exhibits a nonlinear upturn in the current-voltage characteristics. The enhancement of the vortex pinning is needed for improving the current-carrying characteristics. With such motivation, **Anton Pokusinskyi, Clemens Schmid, Thomas Hauet, and Oleksandr Dobrovolskiy** [8] theoretically study how, with increasing current density, vortices appear, vortex rivers are formed, eventually resulting in the formation of normal domains. For different topologies of defects (linearly-extended, grain-boundary, and L-shaped), the current-voltage curves and the order-parameter spatial distribution are calculated by solving numerically the Ginzburg–Landau equation. The obtained evolution of the order parameter and the respective current-voltage characteristics are analyzed in relation to the experimentally accessible dynamics regimes in superconducting thin films.

As for exotic quantum systems, **Oleksandr V. Marchukov, Neelam Shukla, Jeremy Armstrong, Bastien Humbert, Jan Arlt, and Artem G. Volosniev** [9] study collective excitations in atomic Bose-Einstein condensates governed by a generalized Gross–Pitaevskii equation with an arbitrary power-law nonlinearity. A key result of the paper is analytical: in the Thomas–Fermi (strongly interacting) regime, the frequency of the scissors mode turns out to be universal, i.e., independent of the specific form of the nonlinearity. This is because the scissors mode is a pure shear mode that does not probe the compressibility of the system, which is the quantity sensitive to nonlinearity. To go beyond this analytical result, the authors perform numerical simulations focusing on the experimentally relevant Lee–Huang–Yang liquid, where the nonlinearity differs from the standard mean-field case. They uncover pronounced finite-size effects in the approach to the Thomas–Fermi limit, which should be observable in current cold-atom experiments. Importantly, the scissors mode frequency remains clearly identifiable even under strong quenches, facilitating its experimental observation in trapped atomic gases of neutral atoms.

Lanthanide-based molecular nanomagnets have strong magnetic anisotropy and slow magnetization relaxation, which makes them important for applications in quantum technologies. As one important property of lanthanide-based single-ion magnets, at low temperatures they display a regime of coherent quantum tunneling of magnetization. This is studied by specialists in this field, **Ana Arauzo, Elena Bartolomé, Javier Luzón, Silvia Melnic, Sergiu Shova, and Juan Bartolomé** [10], for the holmium-based antiferromagnetic chains. The authors report on the synthesis, structural and magnetothermal characterization of such polymeric complexes at low temperature. It was demonstrated by studying magnetic properties that the low-temperature behavior is defined by strongly anisotropic non-Kramers holmium ions, which can be described as antiferromagnetically coupled atoms in an Ising-like chain. These studies demonstrate that magnetic measurements at sub-Kelvin temperatures allow studying quantum phenomena which otherwise could be overlooked.

The contribution by **John P. Perdew** [11] presents a concise conceptual perspective on the role of spontaneous symmetry breaking in approximate density functional theory (DFT) for treating strongly correlated systems. The author argues that a “proper” approximate exchange-correlation functional — one that accurately describes normal correlation — can effectively capture the energetic effects of strong correlation through spontaneous symmetry breaking. By invoking the Levy constrained search, the work demonstrates that the energy obtained from a fully symmetry-broken solution serves as a rigorous lower bound (often close) to the exact ground-state energy. The manuscript also discusses the importance of proper self-interaction corrections, provides illustrative examples, and offers a time-centered physical interpretation of symmetry breaking.

The work by **Joaquim Telles de Miranda, Maxim Khodas, and Alex Levchenko** [12] demonstrates a productive, unified approach to explaining the nonreciprocity of various transport properties in a fairly broad class of Rashba superconductors. The authors note that, at first glance, the magnetochiral asymmetry and the superconducting diode effect have little in common, other than the obligatory violation of spatial-inversion and time-reversal symmetry. In particular, the latter is an intrinsic thermodynamic equilibrium property of a superconductor and manifests itself in the nonreciprocity of critical currents, while the magnetochiral asymmetry is a nonlinear dissipative transport effect arising in a resistive state. However, the description of both phenomena is based on the same higher-order Lifshitz invariants. Therefore, the authors suggest that in Rashba superconductors, along with the magnetochiral asymmetry, the superconducting diode effect should also be observed, which remains to be verified experimentally.

On the methodology side, **Denys I. Bondar and Ole Steuernagel** [13] suggest a paper on symplectic split-operator propagators based on tridiagonal representations of multimode bosonic Hilbert spaces, with applications to optomechanical and Bose–Hubbard Hamiltonians. The manuscript addresses an insightful computational problem and proposes a potentially useful approach for working with structured bosonic systems. A unique feature of this work is the employment of tools from number theory — combinatorial number systems and, in particular, the Skolem polynomials — that lie well outside the standard toolkit of most practicing quantum physicists. To the best of our knowledge, this may be among the first applications of the Skolem polynomials in quantum physics. The introduced method makes it possible to numerically describe systems with much larger numbers of basis states than available to date.

Ideologically related to the above study, **Roman Ovsiannikov, Kurt Jacobs, Andrii G. Sotnikov, and Denys I. Bondar** [14] present a fast, memory-efficient, and unitarity-preserving numerical method for simulating the time-dependent closed Tavis–Cummings model, in which a multilevel spin system — motivated by nitrogen-vacancy center ensembles — interacts with a cavity mode beyond the rotating-wave approximation. The key algorithmic insight is that, while the Tavis–Cummings Hamiltonian is not tridiagonal in the natural product basis, it can be decomposed into a diagonal time-dependent part and two terms that become tridiagonal under different basis orderings. Crucially, switching between these orderings requires only a permutation of the coefficient vector (a simple reindexing rather than a matrix multiplication), making the basis change computationally negligible. The authors benchmark their method against the established QuTiP solver and demonstrate a clear computational advantage for larger system sizes, while maintaining near-unitary evolution over long simulation runs.

This year we have the golden jubilee (fiftieth anniversary) of the Gorini–Kossakowski–Sudarshan–Lindblad (GKSL) equation, which is the main working tool to describe open quantum systems nowadays. Particularly, this equation is often used to describe driven-dissipative two- and multi-level systems, known as qubits and qudits, respectively. The equation essentially implies several approximations and transformations. **O. A. Ilinskaya, O. V. Ivakhnenko, A. I. Ryzhov, O. Yu. Kitsenko, and S. N. Shevchenko** [15] systematically present the derivation and the application of the GKSL equation, making an accent on the choice of the bases for both the solution and presentation of the result. The authors consider diabatic, stationary, adiabatic, superadiabatic, and Floquet bases. For both qubit and qudit systems, the authors solve the GKSL equation for the dynamics and stationary solutions, and demonstrate different pictures in different bases, which extends the quantum toolbox for controlling the occupation of systems' states.

We would like to conclude this overview article by thanking our colleagues who participated in our Kharkiv Quantum Seminar and those who contributed to this Special Issue. It is gratifying that the authors of this issue live and work in very different countries, including Ukraine, Austria, Brazil, Czechia, Denmark, France, Germany, India, Israel, Japan, Moldova, Romania, Spain, Taiwan, the United Kingdom, and the United States of America. Let us continue to further develop internationally entangled quantum science for the prosperity of democratic values. In turn, together with all the participants of the Kharkiv Quantum Seminar, we are happy to further "impress you".

The Guest Editors acknowledge financial support of the IMPRESS-U grant (provided by the U.S. National Academy of Sciences and the Office of Naval Research).

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