Hungarian-German WE-Heraeus Seminar

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Goerlitz & HZDR Dresden

Book of Abstracts

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Statistical mechanics with nonadditive entropies –Concepts and applications

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Galileo's celebrated composition law for velocities is additive. Its generalization in special relativity is not. Why did Einstein violate that simple nice additivity? Because that was a small price to pay in order to achieve a more important goal, namely, to unify mechanics and electromagnetism through the Lorentz transformation of space-time. Analogously, the violation of additivity for entropic functionals is a small price to pay in order to achieve a more important goal, namely, to preserve the Legendre transformation structure of classical thermodynamics. The negation of additivity for a general physical entropic functional grounding a generalization of Boltzmann-Gibbs statistical mechanics is similar to the negation of the fifth postulate of Euclid, which led Riemann to the celebrated curved geometries, the mathematical basis for general relativity. I will elaborate on those concepts and illustrate, for some selected systems, how they can be very useful in handling complexity in physics and elsewhere. Bibliography at https://tsallis.cbpf.br/biblio.htm

2

Shedding new light on high energy density physics

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In this talk we will introduce recent developments in studying high enegy density physics with Exascale simulations. Specifically, we will focus on new capabilities of the PIConGPU simulation code and its use to study the interaction of high power lasers with solid density matter. In all of thse cases, the laser power irradiating the target exceeds values that drive relativistic electrons into the material, creating a situation were the material can even become relativistically transparent. We discuss several applictaions, from laser-driven compact particle accelerators to studying direct drive fusion to showcase where the use of high performance computing helps to shed new light on igh energy density physics.

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Laser ion acceleration using gold nanorods

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This work investigates how integrating gold nanorods into laser targets enhances laser-driven ion acceleration. By exploiting the localized surface plasmon resonance (LSPR) of gold nanorods, we improve the coupling of femtosecond Ti:Sapphire laser pulses to the target. Numerical simulations reveal that resonant plasmonic excitations in the nanorods substantially intensify local electromagnetic fields and field gradients, concentrating laser energy near the nanostructures. This enhanced energy deposition increases the maximum ion energies compared to conventional flat targets, enabling more efficient ion acceleration within the preplasma region. We analyze key mechanisms, including Coulomb explosion and plasmonic ponderomotive acceleration, and demonstrate that tailoring nanoparticle geometry and arrangement is critical for optimizing near-field enhancement. These results present a promising route to more compact and efficient ion sources, supporting future advances in laser-driven fusion.

4

Nonadditive entropies –From quantum-tunneling chemical reactions to cosmology

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The adoption of nonadditive entropies enables the generalization of Boltzmann-Gibbs (BG) statistical mechanics, one of the pillars of contemporary theoretical physics. It also leads to a generalization of the celebrated Central Limit Theorem in Theory of Probabilities. These facts constitute a rational basis to explain a myriad of complex phenomena that overcome the BG scenario. We will show illustrations in granular matter, cold atoms in dissipative optical lattices, high-energy collisions at LHC/CERN and elsewhere, quantum-tunneling chemical reactions, dissipative and conservative nonlinear dynamical systems, plasma, long-range-interacting Hamiltonian as well as overdamped many-body systems, black holes, neutrinos, dark matter, and related cosmological issues. Bibliography at https://tsallis.cbpf.br/biblio.htm

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Nanofusion review

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A review of our nanofusion project is given, comprising theoretical and experimental groups' contributions and fresh results.

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Estimating ionization degree and continuum lowering from ab initio path integral Monte Carlo simulations for warm dense hydrogen

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Warm dense matter (WDM), prevalent in astrophysical objects and crucial for inertial confinement fusion (ICF), presents significant challenges in characterizing fundamental properties such as ionization degree and continuum lowering. Experimental diagnostics of WDM, particularly for hydrogen due to its low scattering cross-section, are limited and often rely on model-dependent analyses, complicating the development and validation of equation of state (EOS) tables. *Ab initio* methods like path integral Monte Carlo (PIMC) offer exact simulations but do not inherently provide direct access to these quantities.
We introduce a method to extract ionization potential depression (IPD) and ionization degree from PIMC simulations using a chemical model based on Chihara decomposition, which separates bound and free electron contributions. By forward-fitting a chemically informed dynamic structure factor to the imaginary-time correlation function obtained from PIMC, we retrieve best-fit estimates for both IPD and ionization degree under well-defined thermodynamic conditions.
This approach enables the analysis of elastic and inelastic scattering components across a range of wave vectors, allowing us to assess the sensitivity of scattering signals to ionization and IPD. We find that sensitivity decreases at higher scattering angles, suggesting limitations in extracting these properties in non-collective regimes. By bridging exact simulations and chemical models, this method supports equation-of-state development and informs the design of future x-ray Thomson scattering experiments.

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HCON and the Noble Gases in the Outer Planets

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Giant planets consist primarily of the six most abundant elements of baryonic matter in the universe: H, He, O, C, N, Ne. In addition, the noble gas Ar is an important atmospheric trace element in the ice giants for inferrence of their rock content and interior structure. Observations of atnospheric composition, gravity field, magnetic field, and luminosity constrain interior models. We do that in order to learn about the deep interior composition and the behavior of warm dense matter, such as phase separation in H/He, H/O, or H/C-systems. The isotopes of H as well as dense solid C are of great interest in fusion experiments for civil energy production.

After a long period of poor constraints, the recent Jupiter observations with NASA's Juno spacecraft and the improvements in the H/He-Equation of state are meanwhile posing challenges for interior modelers. The standard view of adiabatic, i.e constant-entropy interiors requires revision, as stable layers, sub-adiababic or super-adiabatic, appear to be needed nearly everywhere now in Jupiter. Moroever, the long-standing faintness-problem of Uranus has converted into a brightness-problem of Neptune.
I will give an overview of current interior and evolution models of the Outer Planets and lay out directions for future progress. Key words here are double-diffusive convection and diamond rain.

Poster session / 8

Deep Learning with RESNET for High-Precision Laser Crater Data Processing

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RESNET (Residual Networks) is a deep learning architecture that has shown exceptional performance in image classification tasks. In this work, we apply a pre-trained RESNET model to classify and analyze laser crater data, leveraging its ability to capture complex patterns in high-dimensional datasets. The RESNET architecture provides a robust framework for improving the accuracy and speed of classification tasks, making it an ideal choice for the automated analysis of laser-induced craters and similar applications in material science.

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NONEQUILIBRIUM IN PRIMORDIAL QUARK-GLUON PLASMA

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Non-stationary breaking of thermal equilibrium is the dynamic pre-requirement for baryogenesis in primordial Universe – the other two Sakharov conditions are: existence of baryon conservation violating processes, and CP breaking allowing matter to grow more rapidly in abundance compared to antimatter. If there is quark-gluon plasma (QGP) nonequilibrium, a nonstationary behavior arises due to time dependence of the nonequilibrium properties. These arise naturally both, in an expending time dependent Universe, as well as in the laboratory formed exploding fireball of QGP. In the study of nonstationary condition we distinguish between two possible nonequilibrium features inherent to primordial quark-gluon plasma (QGP): i) The abundance (chemical) nonequilibrium and; ii) the momentum distribution (kinetic) nonequilibrium.

The Universe following on electroweak transformation at a temperature $T \simeq 125\,$GeV was dominated during the following $25\mu s$ by strongly interacting quarks and gluons forming a new state of matter, the color deconfined Quark-Gluon Plasma (QGP), hadronization at $T > 150\,$MeV formed material particles we are familiar with. In the laboratory environment QGP is formed in highly relativistic collisions of heaviest nuclei, with laboratory temperatures $T \simeq 0.5\,$GeV. For the strong QCD force the thermal reaction rates in QGP have been studied in depth in consideration of explosive disintegration of the dense matter fireball with QCD scale lifespan
$calO(10^{-22}$\,s). The following recent research builds upon our study of strangeness abundance

nonequilibrium in laboratory formed QGP and the lecture will review this matter in preparation of the more complex situation of interest to baryogenesis.

The expansion of the Universe is described by the Hubble parameter H which is many ({\it e.g.\/} 15-18) orders of magnitude slower compared to the microscopic reaction rates. Even so, we find that nonequilibrium of physical significance arises in the early Universe, similar to the laboratory formed QGP environment. Specifically, we show bottom quark abundance nonequilibrium near to hadronization of QGP. There is competition between strong force forming bottom pairs in fusion of gluons and lighter quarks, and weak interaction driving decay of bottom flavor. These two processes have nearly similar picosecond scale rate at$T \simeq 0.25$\,GeV, {\it i.e.} just above hadronization of the Universe.

The Higgs particle is in abundance nonequilibrium across the entire QGP domain: This is due to decay proceeding in a significant manner by a kinematically forbidden path $h(125\,\mathrm{GeV}) \rightarrow W^*W(2\cdot 80.4\,\mathrm{GeV}), Z^*Z(2\cdot 91.2\,\mathrm{GeV})$ (25.7 ± 2.5\% and 2.8 ± 0.3\% partial widths of $\Gamma_h = 3.7+1.9-1.4$\,MeV). Such decay is irreversible in a thermal bath, detailed balance is thus broken. This is so since collisions of real on-mass-shell gauge bosons cannot form Higgs and multiparticle back reaction occurs for each collision channel incoherently, while the decay of W^* and Z^* into a large multitude of physical channels is a coherent process assuring these virtual particles materialize with unit probability. We also discover that at $T < 25$\,GeV the Higgs momentum distribution is nonthermal. In this temperature range the abundance of 'heavy' particles Higgs couples to strongly via minimal Yukava coupling has diminished to be irrelevant while Higgs is too weakly coupled to light particles so once produced in $2 \rightarrow 1$ process it cannot scatter ($2 \rightarrow 2$ process). Hence the momentum distribution is what {\it e.g.\/} bottom pair fusion $b+\bar{b} \rightarrow h$ creates.

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Unraveling warm dense matter: from theory to experiment

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The rigorous description of warm dense matter (WDM)—an extreme state that is characterized by high densities, temperatures, and pressures—is of high importance for integrated radiation hydrodynamics simulations of inertial confinement fusion applications, in particular during the initial stage of the compression path. In addition, WDM conditions abound in a host of astro-physical objects such as giant planet interiors and white dwarf atmospheres. In the laboratory, WDM can be created using different techniques, but accurately diagnosing even basic parameters such as the density or temperature is difficult and usually relies on various model assumptions and approximations [1]. Very recently, we have shown that it is possible to extract a wealth of information such as the temperature [2] or degree of non-equilibrium [3] directly from x-ray Thomson scattering (XRTS) measurements without the need for any models or simulations. The combination of this new paradigm with highly accurate path integral Monte Carlo (PIMC) simulations [4] allows us to rigorously diagnose an experiment with spherically compressed beryllium carried out at the National Ignition Facility (NIF) [5], leading to a substantially lower estimate for the mass density (ρ = 22 ± 2 g/cc) compared to the Chihara model used in the original analysis (ρ = 34 ± 4 g/cc). Our work has important implications for radiation hydrodynamics simulations of implosion dynamics and equation-of-state measurements.

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N-photon amplitudes from the worldline formalism

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In this presentation, I introduce the worldline formalism and its application to off-shell N-photon amplitudes, initially in vacuum and later in a constant electromagnetic field. I then explore the current status of the off-shell four-photon amplitude, emphasizing its practical applications in quantum electrodynamics. Finally, I examine the low-energy limit of the N-photon amplitude in a constant electromagnetic field, introducing a closed formula analogous to the vacuum case that enhances our understanding of strong-field effects.

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Quantum Vacuum Nonlinearities in Strong Electromagnetic Fields

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The physical vacuum of a relativistic quantum field theory amounts to a non-trivial quantum state. It encodes information about the full particle content of the underlying microscopic theory in the form of virtual processes. If the theory features charged particles, the latter give rise to nonlinear effective couplings between electromagnetic fields that vanish in the formal limit of a vanishing Planck constant, but persist for a nonzero physical value. These couplings inherently modify Maxwell's linear theory of classical electrodynamics. However, for the field strengths reached by macroscopic electromagnetic fields currently available in the laboratory the quantum vacuum nonlinearities induced by Standard Model particles are parametrically suppressed relatively to the linear contribution by inverse powers of the electron mass and thus very small. Therefore, this fundamental tenet has remained experimentally challenging and is yet to be tested in the laboratory.

In my talk I will focus on quantum vacuum nonlinearities in strong electromagnetic fields arising from quantum electrodynamics (QED). On the one hand, I will highlight fundamental aspects of the Heisenberg-Euler effective action that supersedes the classical Maxwell action in governing the physics of strong macroscopic electromagnetic fields in the vacuum. On the other hand, I will outline the dark-field approach devised to measure the leading (weak-field, low-frequency) quantum vacuum nonlinearity in a dedicated experiment at the European X-ray Free Electron Laser (EuXFEL) within the Helmholtz International Beamline for Extreme Fields (HIBEF) Collaboration.

Poster session / 13

Pauli blocking in Tetraquarks

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In the light of the recent discoveries at CMS regarding the $X(6900)$ and other all-charm tetraquark candidates we will discuss the internal structure of the all-charm tetraquarks and the impact of

the Pauli blocking on the possible substructures of exotic hadrons and the mass spectrum of the fully-heavy tetraquarks. We will provide our proposition of the structure of the tetraquark and the explanation of the atypical quantum numbers of the resonances found in the di-J/ψ mass spectrum.

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Soft and hard interactions in high multiplicity PP collisions at LHC energies

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The transverse momentum spectra and their multiplicity dependence serve as key tools for extracting parameters to be compared with theoretical models. Over the past decade, the scientific community has extensively studied the possibility of a system analogous to quark-gluon plasma, predicted in heavy nuclei collisions, also existing in collisions involving light nuclei and protons. We have reanalysed the data published by the ALICE Collaboration at the LHC. We present the dependence of the mean transverse momenta obtained in the soft and soft+hard (mixed) parts. Finally, we also discuss possible refinements of the analyses concerning the use of statistical parameters of higher order, aimed at a more detailed way of comparing the models with data.

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Response of materials to external perturbations under extreme conditions

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The exchange-correlation (XC) functional is essential in Kohn-Sham density functional theory (KS-DFT), while the kinetic energy functional is key in orbital-free DFT. We analyze these functionals by observing how materials respond to external perturbations [1-6]. Our new method computes the static XC kernel across any level of Jacob's ladder without functional derivatives, allowing us to explore XC kernels from local density approximations to hybrid functionals. This has led to the identification of parameters of hybrid functionals under high-pressure conditions. Currently, we are applying this approach to XC kernels in linear response time-dependent DFT to study the X-ray Thomson scattering spectrum of materials, collaborating closely with experimental teams [7-9]. This contribution highlights our methodological advancements and their applications under various conditions, from ambient to extreme, using high-power lasers.

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Matter at high energy densities: planetary interiors and inertial confinement fusion

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We apply large-scale molecular dynamics simulations based on density functional theory (DFT-MD) to infer the high-pressure phase diagram of hydrogen-helium and H-C-N-O mixtures. Of particular interest is the nonmetal-to-metal transition in dense fluid hydrogen that occurs at few megabars (metallization). Furthermore, demixing of hydrogen and helium is predicted at about the same extreme conditions which leads to helium rain in the deep interior of gas giant planets like Jupiter and Saturn. We calculate the corresponding equation of state data and transport properties like electrical and thermal conductivity and discuss the impact of our results on the interior, evolution, and magnetic field of giant planets like Jupiter and Saturn (H-He), Uranus and Neptune (H-C-N-O mixtures). Furthermore, we consider higher temperatures relevant for stellar astrophysics and inertial confinement fusion scenarios. We calculate EOS data and construct conductivity models that are applicable for a wide range of densities and temperatures.

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Producing high brilliance gamma rays via Compton scattering in flying focus regime

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Some of the highest-energy photon beams produced experimentally rely on a fundamental quantum electrodynamics process: nonlinear Compton scattering between laser photons and ultra-relativistic electrons. We discuss how the energy lost by electrons and the yield of emitted photons in this process can be substantially increased by replacing a stationary-focus laser pulse with an equal-energy flying-focus pulse. The moving focal point of a flying focus forms an intensity peak that can travel at any velocity, independent of the laser group velocity, over distances much longer than a Rayleigh range [1]. This enables co-propagation of ultra-relativistic particles with the laser focus, so that they stay in the region of peak field intensity for prolonged interaction times [2,3]. The advantages of the flying focus are a result of operating in the quantum regime of the interaction, where the energy loss and photon yield scale more favorably with the interaction time than the laser intensity. Analytic estimates and simulations show that GeV-scale electrons colliding with 1-10 J laser pulses can increase up to five times the yield of 1-20 MeV photons using a flying focus pulse, laying the foundation for producing the brightest laboratory gamma source in this energy range [4].
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Primordial black-hole formation and heavy r-process element synthesis from the cosmological QCD transition

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We review the role of primordial black holes (PBHs) for illuminating the dark ages of the cosmological evolution and as dark matter candidates. We elucidate the role of phase transitions for primordial black hole formation in the early Universe and focus our attention to the cosmological QCD phase transition within a recent microscopical model.We explore the impact of physics beyond the Standard Model on the cosmic equation of state and the probability distribution for the formation of primordial black holes which serve as dark matter (DM) candidates. We argue that besides primordial black holes also droplet-like quark-gluon plasma inhomogeneities may become gravitationally stabilized for a sufficiently long epoch to distill baryon number and form nuclear matter droplets which upon their evaporation may enrich the cosmos locally with heavy r-process elements already in the early Universe.

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Transport in ultra-dense plasmas in neutron stars and white dwarfs in magnetic fields

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I will review recent work on electrical and thermal conductivity and the electrical and thermal Hall effect in electron-ion plasmas relevant to hot neutron stars, white dwarfs, and binary neutron star mergers, focusing on densities found in the outer crusts of neutron stars and the interiors of white dwarfs. We consider plasma consisting of a single species of ions, which could be either iron ^{56}Fe or carbon ^{12}C nuclei. The temperature range explored is from the melting temperature of the solid $T \sim 10^9 - 10^{11}$ K. This covers both degenerate and non-degenerate electron regimes. The impact of magnetic fields on electrical and thermal conductivity is analyzed, showing anisotropy in low-density regions and the presence of the electrical and thermal Hall effect. The transition from a degenerate to non-degenerate regime is characterized by a minimum ratio of conductivities.

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Verifying TDDFT with Ultrahigh Resolution X-ray Thomson Scattering Measurements

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The dynamic structure factor (DSF) of a system provides a wealth of information on its properties, such as its temperature, density and on electron correlations. The state-of-the-art approach to calculating the DSF is using time-dependent density functional theory (TDDFT), which provides an in-principle exact calculation of the full electronic response of the system in an ionic environment. The DSF can also be directly measured in experiment via x-ray Thomson scattering (XRTS), but it is convolved with the source-and-instrument function (SIF) of the setup. The rigorous benchmarking of TDDFT with experiment is challenging due to (a) the need to precisely know experimental conditions, and (b) the SIF needs to be carefully handled as it otherwise obscures features in the DSF. Here, we present results from a novel ultrahigh resolution setup at the European XFEL. The SIF of this setup is sufficiently narrow that its broadening of the measured DSF is negligible. We have used this setup to benchmark TDDFT-predicted DSFs in ambient conditions for simple metallic Al and single crystal semiconducting Si. Once the experimental geometry is accounted for, we find TDDFT produces accurate DSFs over a range of scattering vectors. We conclude by considering applications of ultrahigh resolution spectroscopy to broader experimental scenarios.

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What is the Quark-Gluon Plasma made of?

Author: Berndt Mueller[1]

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My lecture will first survey our current theoretical understanding of the internal structure of the quark-gluon plasma as it is created in relativistic heavy-ion collisions based on insights from thermal perturbation theory, lattice gauge theory, and holography. I will then discuss how this structure can be experimentally probed and review what data from RHIC and LHC have told us about “what the QGP is made of”. The talk will conclude with an outlook on future directions of investigation.

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Experimental platforms for measurements of warm dense matter at the European XFEL

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“If you can measure it, it is not warm dense matter and if you can compute it, it is not warm dense matter” has long been an unofficial definition of the peculiar state of matter between condensed matter and hot plasma. It is present in the interior of large planets, small stars and transiently in inertial confinement fusion concepts. Due to immense developments in theoretical methods, computational capabilities, and new experimental infrastructures, this definition has now become outdated. Especially, hard X-ray free electron lasers (XFELs) have proven as a revolutionary tool to advance our understanding from numerical interpolations through a basically unknown regime to an era of precision measurements that can benchmark atomistic simulations and macroscopic models with highest resolution in space and time. In this talk, recent progress at the HED instrument of the European XFEL in measuring WDM will be presented. Chiefly, two experimental platforms to make high-resolution spectroscopic measurements will be described, as well as some initial results and important considerations for experimental design. This talk uses data from HED proposals 3777, 6656, and 8040, and I am indebted to all collaborators who participated in these experiments.

Poster session / **23**

Image reconstruction with proton computed tomography

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One of the most successful treatments in cancer therapy is proton therapy, with radiation planning being a key element. Photon CT is commonly used for this purpose; however, it does not provide sufficiently accurate information about the range of protons. Therefore, proton CT imaging is more favorable for radiation planning. Due to the Coulomb scattering of protons, it is important to calculate the Relative Stopping Power at the voxel level (thus, appropriate handling of trajectories is also required), for which several algorithms have been developed. The aim of my research is to test, further develop, and optimize a software package using the Richardson-Lucy algorithm developed in the Bergen Proton-CT Collaboration.

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Multiphoton Pair Production in the Collision of Circularly Polarized Waves

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Particle production by strong electric fields is the poster child for what happens when quantum electrodynamics is pushed to the extreme.

In this talk, we focus on the production of electron-positron pairs in two counterpropagating, circularly polarized electromagnetic fields. Using the Wigner formalism, we compute the corresponding correlation functions numerically and display the results as high-resolution momentum maps. Through spectroscopic analysis, we identify the polarization and kinematic signatures of the incident fields in the final positron distribution. Based on these findings, we present an intuitive model of helicity transfer in multiphoton pair production.

Publications
[1] C. Kohlfürst, Phys. Rev. D 110 (2024), L111903.

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Ab Initio Predict Phase Separation of Planetary Ices and Explain the Unusual Magnetic Fields of Uranus and Neptune

Author: Burkhard Militzer[None]

This talk will review of results from experiments and computer simulations of planetary ices in the regime of warm dense matter. Large quantities of these ices are assumed to by stored in the mantles of Uranus and Nepune. Both planets have unusual, nondipolar magnetic fields. Existing observation and models for the interior structures of these ice giant planets are discussed before results from recent computer simulations are presented that predict mixtures of H2O, CH4 and NH3 to phase separate under the pressure-temperature condition in the interiors of Uranus and Neptune [1], which implies that their icy mantles have two separate fluid layers: an upper H2O-dominated layer and stably stratified mixture of hydrocarbons below. The magnetic fields of Uranus and Neptune are primarily generated in the upper layer, which is convective and electrically conducting. Because this layer is comparatively thin, it gives rise to the generation of disordered magnetic fields, which offers an explanation for why the Voyager 2 spacecraft measured these two ice giant planets to have nondipolar magnetic fields, while strong dipolar fields had been expected. The lower mantle layer is predicted to be stably stratified. A signature of the stratification can be detected in normal modes, which lends support to placing a Doppler imager on a future space mission to Uranus.

[1] B. Militzer, "Phase Separation of Planetary Ices Explains Nondipolar Magnetic Fields of Uranus and Neptune", PNAS (2024) DOI: 10.1073/pnas.240398112.

Poster session / 26

One-particle spectral function of Jellium from Path-integral Monte Carlo simulations

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Path-integral Monte Carlo (PIMC) simulations are a powerful tool for investigating the properties of dense plasmas in equilibrium, capable of providing exact solutions to the quantum many-body problem. However, being formulated in the imaginary-time domain, these methods only give direct access to imaginary-time correlation functions from which spectral information may be inferred. Carrying out this additional step for the density-density correlation function has e.g. led to the first ab-initio characterization of the dynamic structure factor for the warm dense uniform electron gas [1].

PIMC simulations involving open trajectories as realized by the worm algorithm [2] additionally permit the computation of the one-particle Green's function, the most fundamental object of many-body perturbation theory. Here we present our first results for the one-particle spectral function $A(k, \omega)$.

[1] Dornheim et al., Phys. Rev. Lett. 121, 255001 (2018)
[2] Boninsegni et al., Phys. Rev. E 74, 036701 (2006)

27

Effect of Landau damping modes and resurrection of bound states on thermodynamics of fluctuations

Author: Biplab Mahato[1]

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The Nambu-Jona-Lasinio (NJL) model is a widely used chiral effective field theory of QCD. We use the NJL type model to describe mesons, diquarks, and baryons, with the latter treated as a quark-diquark pair. Going beyond the mean field level, we discuss Landau damping modes and reappearance of bound states beyond the Mott dissociation temperature at non-zero momentum relative to the medium. Finally, we describe the effect of these two phenomena on thermodynamics using the generalized Beth-Uhlenbeck approach.

[1] Mahato B., Blaschke D., Ebert D. arxiv:2409.10507

28

Density Functionals and EoS for heavy-ion collisions, neutron stars, mergers and supernovae

Authors: David Blaschke[None]; Gerd Röpke[1]; Oleksii Ivanytskyi[2]

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We present a novel relativistic density functional approach for QCD matter, which can be motivated by a nonlocal medium-screened confining interaction among quarks. The approach suggests a phenomenological confining mechanism equivalent to suppressing excitations of quark quasiparticles by their large self-energies already at the mean-field level. Chirally symmetric form of the functional provides spontaneous breaking and dynamical restoration of chiral symmetry of QCD and allows representing the approach as a chiral quark model with self-consistently derived medium-dependent

couplings. Hadrons are systematically introduced to the approach as color-singlet (anti)quark correlations with the corresponding quantum numbers. The approach explains the chemical freeze-out of the fireball created in relativistic collisions of heavy ions (HIC) via the Mott dissociation of hadrons. Supplemented with the repulsive vector-isoscalar, vector-isovector and attractive diquark pairing interactions, the density functional is applied for modeling neutron stars (NS) and constructing equation of state for supernova explosions and mergers of NS. It is shown that color superconductivity drives trajectories of evolution of the QCD matter in these dynamical processes toward the high temperatures typical for HIC.

Poster session / 29

Electrical conductivity of a warm neutron star crust in magnetic fields: Neutron-drip regime

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We compute the anisotropic electrical conductivity tensor of the inner crust of a compact star at nonzero temperature by extending a previous work on the conductivity of the outer crust. The physical scenarios, where such crust is formed, involve protoneutron stars born in supernova explosions, binary neutron star mergers, and accreting neutron stars. The temperature-density range studied covers the transition from a semidegenerate to a highly degenerate electron gas and assumes that the nuclei form a liquid, i.e., the temperature is above the melting temperature of the lattice of nuclei. The electronic transition probabilities include (i) the screening of electron-ion interaction in the hard-thermal-loop approximation for the QED plasma, (ii) the correlations of the ionic component in a one-component plasma, and (iii) finite nuclear size effects. The conductivity tensor is obtained from the Boltzmann kinetic equation in relaxation time approximation accounting for the anisotropy introduced by a magnetic field. The sensitivity of the results towards the matter composition of the inner crust is explored by using several compositions of the inner crust, which were obtained using different nuclear interactions and methods of solving the many-body problem. The standard deviations of relaxation time and components of the conductivity tensor from the average are below $\leq 10\%$ except close to crust-core transition, where nonspherical nuclear structures are expected. Our results can be used in dissipative magnetohydrodynamics simulations of warm compact stars.

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Thermodynamical string fragmentation and QGP-like effects in jets

Authors: Antonio Ortiz Velasquez[None]; Robert Vertesi[1]

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It has been proposed to search for thermal and collective properties arising from parton-fragmentation processes by examining high jet charged-constituent multiplicities (N_{j,ch}) in proton-proton (pp) collisions [1]. Initial studies that tested this proposal using the PYTHIA 8 event generator with the

Monash tune, incorporating multiparton interactions (MPI) and the MPI-based colour reconnection (CR) model, did not reveal any strangeness enhancement, nor provide conclusive evidence for the presence of radial flow. In this contribution, we expand upon the proposed Monte Carlo study by eliminating selection biases associated with triggering on charged particle multiplicities. We disable MPI to focus exclusively on jet fragments. We analyse pp collisions at $\sqrt{s}$=13 TeV simulated with PYTHIA 8, exploring different implementations of the generator: thermodynamical string fragmentation and the standard Lund fragmentation model, considering various CR models. Surprisingly, the thermodynamical string fragmentation model predicts a hint of strangeness enhancement in jets. Additionally, the light-flavor baryon-to-meson ratios as a function of j_T exhibit similarities across all PYTHIA 8 implementations, and hint at radial flow-like effects. In contrast, the ratio of heavy-flavor hadrons (Lambda_c/D^0) at low j_T as a function of N_{j,ch} shows a similar trend to that observed as a function of charged-particle multiplicity in soft data, suggesting that colour string junctions may play an important role in jet development [2].

[1] A. Baty, P. Gardner, W. Li, PRC107 (2023) 064908,
[2] R. V., A. O., arXiv:2408.06340

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Energetic Particle Acceleration and Modulation in the Heliosphere: The Role of ICMEs and Planetary Magnetospheres

Author: Zsofia Bebesi[1]

[1] *HUN-REN Wigner Research Centre for Physics*

Interplanetary Coronal Mass Ejections (ICMEs) are critical drivers of energetic particle dynamics across the heliosphere, influencing both solar energetic particle (SEP) acceleration at ICME-driven shocks and the modulation of galactic cosmic rays (GCRs), resulting in observable Forbush decreases. The interaction of these heliospheric transients with planetary magnetospheres provides a unique laboratory for studying acceleration and transport processes in complex plasma environments.
Saturn's magnetosphere, while internally dynamic, allows for the penetration of heliospheric energetic particles such as SEPs and GCRs. Observations from the Cassini mission have shown that these particles can access the outer and middle magnetosphere, enabling indirect solar wind monitoring and revealing ICME-induced variations such as Forbush decreases and SEP-driven transient radiation belts.
In contrast, Jupiter's much stronger and rapidly rotating magnetosphere presents a fundamentally different scenario. External solar particles - particularly SEPs - encounter significant barriers to entry due to the planet's intense magnetic field and dense, internally sourced plasma environment, limiting direct SEP penetration into the inner magnetosphere. Instead, Jupiter sustains its own high-efficiency particle acceleration processes, including wave–particle interactions and rotationally driven transport. These mechanisms energize particles to MeV and, in some cases, relativistic energies, producing radiation belts and current systems that effectively mask or override signatures of heliospheric transients.
By examining different aspects of these planetary magnetospheres, we gain deeper insights into the physics of energetic particle acceleration and transport.
These findings have implications not only for understanding space plasma dynamics but also for analogous processes in astrophysical and laboratory settings.

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Craters produced by high energy femtosecond single laser pulses in UDMA polymer embedded with plasmonic gold nanorods

Author: Ágnes Nagyné Szokol[1]

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The role of localized surface plasmon resonance in the laser induced nanoplasmonic fusion is receiving more and more attention [1, 2, 3]. In this work the studies of craters created by high energy femtosecond laser pulses in urethane dimethacrylate (UDMA) - triethylene glycol dimethacrylate (TEGDMA) polymers embedded with plasmonic gold nanoparticles will be presented. A comparison will be done with the same polymer but without gold nanorods. The morphology of the craters was investigated by white light interferometry and the changes of the structure were examined by Raman spectroscopy. Laser irradiations executed with different intensities showed prominent changes in morphology with special regard to the volume of the craters in the presence of gold nanorods [4]. The irradiations carried out by different pulse lengths with intensities in the range of 1018 W/cm2 brought new structures.
Authors:
Ágnes Nagyné Szokol, Roman Holomb, Nour Jalal Abdulameer, Márk Aladi, Miklós Kedves, Béla Ráczkevi, Péter Rácz, Attila Bonyár, Melinda Szalóki, Alexandra Borók, Norbert Kroó, Tamás Biró, Miklós Veres

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[2] Kroó, N., Csernai, L.P., Papp, I. et al. Indication of p + 11B reaction in Laser Induced Nanofusion experiment. Sci Rep 14, 30087 (2024). https://doi.org/10.1038/s41598-024-80070-5
[3] István Rigó, Judit Kámán, et al. Raman spectroscopic characterization of crater walls formed upon single-shot high energy femtosecond laser irradiation of dimethacrylate polymer doped with plasmonic gold nanorods. https://arxiv.org/abs/2210.00619v2
[4] Nagyné Szokol, Á., Kámán, J., Holomb, R. et al. Morphology studies on craters created by femtosecond laser irradiation in UDMA polymer targets embedded with plasmonic gold nanorods. Eur. Phys. J. Spec. Top. (2025). https://doi.org/10.1140/epjs/s11734-025-01599-8

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Laser Induced p+11B Fusion by Resonant Nanorod Antenna Array

Author: Laszlo P. Csernai[1]

[1] *University of Bergen*

The NanoPlasmonic Laser Induced Fusion Energy (NAPLIFE) project by simultaneous ignition of the whole target, aims to avoid instabilities and pre-detonation. Fusion by regulating the laser light absorption via resonant nanorod antennas implanted into hydrogen rich polymer targets. This is the only project using this method, up to now. Boron-nitride (BN) was added to UDMA-TEGDMA polymer. Theoretical considerations and first verification experiments are presented. Our experiments with resonant nanoantennas accelerated protons up to 225 keV energy were accelerated. These protons led to p + 11B fusion, indicated by the sharp drop of observed backward proton emission numbers at the 150 keV resonance energy of the reaction. The generation of alpha particles was verified.

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Analytic continuation of path integral Monte Carlo data for the strongly coupled electron liquid

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Co-authors: Alex Benedix-Robies [2]; Jan Vorberger [3]; Michael Friedlander [4]; Michael Hecht [5]; Nicholas Barnfield [6]; Phil-Alexander Hofmann [2]; Tim Hoheisel [7]; Tobias Dornheim

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Path integral Monte Carlo (PIMC) simulations are one of the few methods which can describe the many body effects of strongly coupled quantum systems. However, PIMC simulations yield imaginary time correlation functions (ITCF) that must be analytically continuated back to real time to extract dynamic information about the system. In this talk, we present three recent works that have successfully conducted analytically continuation for the finite temperature electron liquid. Each work uses a different approach: Bryan's maximum entropy method [https://arxiv.org/pdf/2503.20433], dual Newton optimization with entropic regularization [https://arxiv.org/abs/2501.01869], and PyLIT' s regression method [submission in progress]. These works have explored data-driven Bayesian priors, resampling methods, non-linear grid spacing, new regularization terms, and different regularization weight selection procedures.

Since the analytic continuation amounts to an inverse Laplace transform of a function with poles, then, in theory the same information is present in either representation. However, in practice the inversion is difficult. Here, we also present investigations that have observes the same phenomena in both the imaginary and real time. We focus on observing a repeated roton (i.e. double roton) structure [submission in progress], differentiating which pair potential was used in PIMC simulation [https://arxiv.org/abs/2504.00737], and the satisfaction of sum rules [https://arxiv.org/pdf/2503.20433]. Note that there are no constraints enforcing these phenomena in the analytic continuation tools. For these three phenomena, we have find good agreement between real time and imaginary time representations.

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Exact results for WDM from many-body theory and simulations

Author: Gerd Röpke[1]

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The analytical approach to the theory of dense plasmas can be given within the framework of the formalism of Green's functions.While in general approximations have to be performed, exact results can be derived in limiting cases. They serve as a benchmark for numerical simulations such as DFT or PIMC simulations and can be used to derive interpolation formulas.
As an example, we consider the equation of state, the electrical conductivity and the ionization potential depression.
From the Green's function approach, the medium corrections of a few-body system embedded in a dense plasma are obtained in a systematic way. Of particular interest is the Mott effect, which describes the dissolution of bound states with increasing density.

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High-Intensity Laser Experiments on Nanoplasmonic Ion Acceleration and Fusion

Authors: Imene Benabdelghani[1]; Márk Aladi[1]; Tamás Sándor Biró[1]; Miklós Ákos Kedves[1]

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High-intensity femtosecond laser irradiation of plasmonic nanostructured polymer targets, including boron-containing thin foils, has been investigated to explore resonant plasmonic field enhancement for improving the efficiency of laser-driven ion acceleration and aneutronic fusion. Experiments conducted at the Wigner Research Centre for Physics and ELI-ALPS aimed to demonstrate enhanced proton/ion energies and increased p-B fusion yield via plasmonic effects. Comprehensive diagnostics utilizing Thomson parabola spectrometry, CR-39 track detectors, and alpha particle detectors were employed to simultaneously characterize the accelerated ion spectra and fusion-generated alpha particles, confirming plasmon-assisted fusion reactions. These results contribute to the development of compact laser-driven fusion sources for potential applications in fusion energy and medical research, while also establishing a versatile platform for investigating plasmonics in strong-field physics.

Poster session / 37

Synchrotron radiation extension for PIConGPU

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The poster presents an extension for the Particle-in-Cell (PIC) simulation code, incorporating Quantum Electrodynamic Synchrotron Radiation effect to enhance the simulation of plasma phenomena. PIConGPU, a highly scalable and open-source 3D PIC code, is employed to model complex interactions in plasma physics. The implemented algorithm approximates radiation by calculating photon emission probabilities using theoretical framework of synchrotron radiation. Later the extended PIC code is used to predict the X-ray radiation created by an accelerated electron bunch in Laser Wakefield Accelerator. This work aims to provide a comprehensive toolkit for simulating and analyzing high-energy plasma interactions, contributing to advancements in small electron accelerators.

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A possible role of Primordial Black Holes in the Early Universe?

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The cosmic X-ray background radiation has been almost completely resolved into discrete objects, mainly from the growth of massive black holes in the universe. However, a few years ago, evidence for a new population of black holes from the early universe emerged from the correlation of fluctuations in the X-ray and infrared backgrounds. Similarly, quasars have been discovered with astonishingly massive black holes already formed shortly after the Big Bang. The detection of gravitational waves from the merger of pairs of very heavy, apparently non-rotating stellar black holes presents another puzzle. Recently, using the micro-lensing effect and distance determination with the ESA satellite GAIA, about 20 black holes in our galaxy have been discovered with masses that cannot be generated by stellar processes. In the past few months, the discovery of several galaxies that formed very early in the universe with the James Webb Space Telescope has been surprising, seeming to contradict the classical expectations of cosmology. These phenomena might be explained by a contribution of primordial black holes that formed immediately after the Big Bang to the dark matter.

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The effect of extra dimensions on astrophysical observables

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Kaluza and Klein proposed a theory with a compactified extra dimension,
which may appear in high-energy phenomena, such as nuclear reactions,
strong gravitational effects, or in the presence of superdense matter.
In this work, I show how astrophysical observables will be modified in
the presence of extra compactified dimensions.

The interior of a compact star is modelled as a multidimensional interacting degenerate Fermi gas, embedded in a static, spherically symmetric spacetime with extra compactified spatial dimensions. The equation of state of this extreme medium is given and compared to the standard models of superdense matter. The modification of the mass-radius relation of compact stars is calculated and compared to realistic star models and astrophysical observation data. The interaction strength has been determined for this extraordinary matter. Constraints on the size of the extra dimension have been estimated based on pulsar measurements [1-3].

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Poster session / 40

Higher order density functionals for hybrid neutron stars

Author: Oliver Heymer[1]

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This work extends the thermodynamics of a chirally symmetric confining energy density functional approach for quark matter to higher-order Taylor expansion in the quark bilinears, which goes beyond the standard current-current form [1] and encodes confining effects inn the medium dependence of the Taylor expansion coefficients [2]. These higher
order interaction terms allow for a softness of quark matter at the deconfinement transition to entail a strong first-order with large latent heat but simultaneously a sufficient stiffening at higher densities to describe massive hybrid neutron stars with color superconducting quark matter cores. We introduce nonlocality of the quark currents inspired by generalized gradient approximations in electronic structure theory; the extended functional optimizes predictive accuracy for inhomogeneous systems [3]. We discuss the solutions of the Tolman-Oppenheimer Volkoff equation in comparison with multi-messenger observations of pulsars.

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Can rotation solve the Hubble Puzzle?

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The discrepancy between low and high redshift Hubble constant H_0 measurements is the highest significance tension within the concordance Lambda cold dark matter paradigm. If not due to unknown systematics, the Hubble Puzzle suggests a lack of understanding of the universe's expansion history despite the otherwise spectacular success of the theory. We show that a Gödel inspired slowly rotating dark-fluid variant of the concordance model resolves this tension with an angular velocity today $_0 \simeq 2 \times 10^{-3}\,\mathrm{Gyr}^{-1}$. Curiously, this is close to the maximal rotation, avoiding closed time-like loops with a tangential velocity less than the speed of light at the horizon.

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HIGH FIELD NANOPLSMONICS HELPING NUCLEAR FUSION

Author: Norbert Kroo[1]

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Surface plasmon polaritons are the light of the nanoworld, with a broad spectrum of special properties. These properties open the field for a high number of applications, both in the fields of low and high intensities In the present work localized plasmons (LSPP) have been resonantly excited by ultrashort (n.10fs) , high intensity (up to n.1018 W/cm2) pulses of Ti:Sa lasers on gold nanoparticles, implanted into a transparent polymer. The laser shots created craters in the studied samples. The volume of these craters is presented as the function of the exciting laser intensity for the samples with (significantly larger) and without resonant gold nanoparticles. The difference is explained by the creation of deuterium in the nanoparticle seeded sample, detected with Raman and LIBS spectroscopy. These data indicate significant energy production by nuclear trasmutation (hydrogen to deuterium), clearly proving the decisive role of the unique properties of the LSPP-s. BN seeded samples have also been studied, where the p11B reaction has been observed by Thompson parabola measurements and by detecting α particles in CN39 films. Some results of mass spectrometry measurements are also presented, confirming some results of the observations mentioned above

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Ab Initio Predict Phase Separation of Planetary Ices and Explain the Unusual Magnetic Fields of Uranus and Neptune

Author: Burkhard Militzer[1]

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This talk will review of results from experiments and computer simulations of planetary ices in the regime of warm dense matter. Large quantities of these ices are assumed to by stored in the mantles of Uranus and Nepune. Both planets have unusual, nondipolar magnetic fields. Existing observation and models for the interior structures of these ice giant planets are discussed before results from recent computer simulations are presented that predict mixtures of H2O, CH4 and NH3 to phase separate under the pressure-temperature condition in the interiors of Uranus and Neptune [1], which implies that their icy mantles have two separate fluid layers: an upper H2O-dominated layer and stably stratified mixture of hydrocarbons below. The magnetic fields of Uranus and Neptune are primarily generated in the upper layer, which is convective and electrically conducting. Because this layer is comparatively thin, it gives rise to the generation of disordered magnetic fields, which offers an explanation for why the Voyager 2 spacecraft measured these two ice giant planets to have nondipolar magnetic fields, while strong dipolar fields had been expected. The lower mantle layer is predicted to be stably stratified. A signature of the stratification can be detected in normal modes, which lends support to placing a Doppler imager on a future space mission to Uranus.

[1] B. Militzer, “Phase Separation of Planetary Ices Explains Nondipolar Magnetic Fields of Uranus and Neptune”, PNAS (2024) DOI: 10.1073/pnas.240398112.

Interior structure of Uranus with four layers: 1) hydrogen (light blue), 2) water (dark blue), 3) hydrocarbons (red), and 4) rocky core (yellow). The planet has a disordered magnetic field that originates primarily from its water layer.

Poster session / 45

Hybrid Nuclear Matter EOS with Color Superconducting Quark Phase: Bayesian Constraints from Observations

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We perform a Bayesian analysis of the equation of state (EOS) constraints using recent observational data, including pulsar masses, radii, and tidal deformabilities. Our focus is on a class of hybrid neutron star EOS that incorporates color superconducting quark matter, based on a recently developed nonlocal chiral quark model. The nuclear matter phase is described using a relativistic density functional approach within the DD2 class, while the phase transition between nuclear and quark matter is described using a Maxwell construction.
Our analysis identifies a region within the two-dimensional parameter space, defined by the vector meson coupling and scalar diquark coupling, where the observational constraints are met with the highest probability (90% of the maximum). We present the overlap of this region with those where other properties are fulfilled:
1. Strong phase transition that produces a third family of compact stars.
2. Maximum mass of hybrid neutron star exceeds that of the purely nucleonic star.
3. Onset mass for quark deconfinement below one solar mass.

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Dynamically assisted tunneling in the impulse regime

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We study the enhancement of tunneling through a potential barrier by a time-dependent electric field with special emphasis on pulse-shaped vector potentials. In addition to the known effects of preacceleration and potential deformation already present in the adiabatic regime, as well as energy mixing in analogy to the Franz-Keldysh effect in the nonadiabatic (impulse) regime, the pulse can enhance tunneling by "pushing"part of the wave function out of the rear end of the barrier. These findings could be relevant for nuclear fusion or applications in condensed matter an atomic physics.

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Advancement of high intensity laser driven particle accelerators to application readiness

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Improved control of high intensity laser beam parameters on target recently enabled
proton energies beyond 100 MeV, dose-controlled sample irradiation experiments, and
the demonstration of seeded FEL light.
This presentation focuses on the chain of developments at the Petawatt laser DRACO at Helmholtz-Center Dresden-Rossendorf that enabled the first dose controlled systematic irradiation of tumors in mice [1] with laser accelerated protons. Details on acceleration mechanisms and strategies to increase stability and energy will be discussed [2] as well as beam transport by means of a dedicated pulsed solenoid beamline to a secondary target together with online metrology and dosimetry. In parallel, improved control of interaction parameters together with different types of targets operated close to relativistic induced transparency enabled the exploitation of acceleration mechanisms surpassing target normal sheath acceleration [3,4]. Here proton energies well beyond 100 MeV could be reached at repetition rate compatible laser parameters.
With improved LWFA parameters, in particular spectral charge density and beam divergence, a dedicated beamline operated by Synchrotron Soleil at HZDR enabled the first observation of seeded FEL

light from a laser plasma electron accelerator [5]. Strategies to develop this source to the EUV range, of interest for probing of plasma densities relevant for ion acceleration, will be discussed.

References:
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Properties of non-cryogenic DTs and their relevance for fusion

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In inertial confinement fusion, pure deuterium-tritium (DT) is usually used as a fusion fuel. In their paper, S. Y. Guskov et al. [Plasma Phys. Rep. 37, 1020 (2011)] instead propose using low-Z compounds that contain DT and are non-cryogenic at room temperature. They suggest that these fuels can be ignited for $\varrho_{DT} R > 0.35$ g/cm^2 and $kT_e > 14$ keV, i.e., parameters that are more stringent but still in the same order of magnitude as those for DT. In deriving these results, Guskov et al. assume that ionic and electronic temperatures are equal and consider only electronic stopping power. Here, we show that at temperatures greater than 10 keV, ionic stopping power is not negligible compared to the electronic one. We demonstrate that this necessarily leads to higher ionic than electronic temperatures. Both factors facilitate ignition, showing that non-cryogenic DT compounds are more versatile than previously known. In addition, we find that heavy beryllium borohydride ignites more easily than heavy beryllium hydride, the best-performing fuel found by Guskov et al. Our results are based on an analytical model that incorporates a detailed stopping power analysis, as well as on numerical simulations using an improved version of the community hydro code MULTI-IFE. Alleviating the constraints and costs of cryogenic technology and the fact that non-cryogenic DT fuels are solids at room temperature opens up new design options for fusion targets with Q >100. The discussion presented here generalizes the analysis of fuels for energy production.

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Monte-Carlo Event Generation in XRTS Analysis

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X-ray Thomson scattering (XRTS) is a powerful diagnostic technique for probing matter under extreme conditions, such as those generated by high-intensity laser interactions in the High-Energy Density (HED) regime. Facilities like the HIBEF endstation at the European XFEL enable such experiments, offering unprecedented access to strongly coupled plasmas and warm dense matter. The interpretation of XRTS spectra typically relies on theoretical models for the dynamic structure factor, derived from linear response theory or time-dependent density functional theory (TDDFT), which are directly linked to the measured differential scattering cross section.

In this talk, we explore a novel approach to XRTS data analysis based on Monte Carlo event generation, a technique widely employed in particle physics for simulating collision events and detector responses. By generating synthetic scattering events consistent with theoretical models and instrumental resolution, we demonstrate how this method can provide an event-level perspective on detector signals, offering enhanced insight into fluctuation phenomena, background contributions, and the full statistical character of the measurement. This approach opens new pathways for interpreting complex XRTS data in regimes dominated by strong fields, non-equilibrium dynamics, and plasma collective effects.

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Warm dense matter at the HIBEF

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The Helmholtz International Beamline for Extreme Fields (HIBEF) at the High Energy Density (HED) instrument of the European XFEL combines high-intensity fs-pulse lasers, and high energy ns-pulse lasers, with hard x-rays having exceptional spectral brilliance. This enables a wide spectrum of research into HED physics, strong-field QED, warm dense matter (WDM) and new high pressure phases of materials. This talk will provide an overview of the first 5 years of operation of HED/HIBEF, and highlight some of the outstanding results, including first direct measurement of the liquid structure of carbon, resonant probing of WDM heating by imaging bound-bound transitions in single high charge states, and a new mechanism of cylindrical ablative compression to 10x solid density using J-class short pulse lasers versus kJ-class ns-pulse shock compression.

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Resolving Warm Dense Aluminum with First-Principles and Machine-Learned MD Simulations

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Understanding warm dense matter relies on accurate theoretical input to interpret experimental observables such as X-ray Thomson scattering spectra. In this work, we perform density functional theory molecular dynamics simulations of aluminum to compute the static ion structure factor across a range of density-temperature conditions. To efficiently explore a finer grid, we train a neural network potential and run machine-learned molecular dynamics simulations. The resulting structure factors are used within a Bayesian inference framework to identify the most probable thermodynamic conditions realized in the experiment. Based on these conditions, we compute the electron dynamic structure factor using time-dependent density functional theory. This hybrid approach—combining ab initio simulations with machine learning and statistical inference—provides precise diagnostic support for interpreting scattering data and offers a robust framework for benchmarking theoretical models of warm dense matter.