Guest Editorial: Dynamics of Quantum Plasmas

M. Bonitz,[1, 2, *] A. D. Baczewski,[3] and T. Dornheim[4, 5]

[1] Institut für Theoretische Physik und Astrophysik, Christian-Albrechts-Universität zu Kiel, Leibnizstraße 15, 24098 Kiel, Germany
[2] KiNSIS, Christian-Albrechts-Universität zu Kiel, 24098 Kiel, Germany
[3] Center for Computing Research, Sandia National Laboratories, Albuquerque NM, USA
[4] Institute of Radiation Physics, Helmholtz-Zentrum Dresden-Rossendorf (HZDR), D-01328 Dresden, Germany
[5] Center for Advanced Systems Understanding (CASUS), Helmholtz-Zentrum Dresden-Rossendorf (HZDR), D-02826 Görlitz, Germany

The year 2025 had been designated by UNESCO as the International Year of Quantum Science and Technology. In 1925-27 quantum mechanics was developed by Schrödinger, Heisenberg, Bohr, Pauli, Dirac, Born, Fermi and many others. By now, quantum mechanics is the theoretical foundation of most fields of physics and chemistry, and it is the basis for modern nanotechnology. In plasma physics as well quantum effects play an important role. While this concerns in one way or the other nearly all areas of plasma physics, quantum effects are particularly prominent in dense plasmas and warm dense matter where they govern the dynamics of plasma electrons. The present special issue contains 19 original articles that cover quantum effects in dense plasmas, including inertial fusion. The papers are concerned with the equation of state, transport, optical properties and collective excitations, as well as various state of the art simulation methods.

I. INTRODUCTION

The year 2025 was designated by UNESCO as *The International Year of Quantum Science and Technology* to reflect on the dramatic progress that has been made in many areas of physics since the discovery of quantum mechanics in 1925-1927 by Heisenberg, Schrödinger, Born, Bohr, Pauli, Fermi, Dirac and many others. With the development of the mathematical framework of quantum mechanics, quantum concepts quickly became the fundamentals of modern physics – of the microworld of atoms, molecules, solids and liquids as well as of nuclear and elementary particle physics. But even at cosmic scales quantum physics is at the heart of many phenomena and processes, including the structure of planets and compact stars and the evolution of the early universe following the Big Bang, as imprinted in the Planckian nature of the cosmic microwave background radiation [1].

The year 2025 has also been the occasion to have a deeper look at quantum effects in plasmas and on their growing importance for the future of the field which has been the motivation of the present special issue. In plasmas, quantum effects arise primarily in the behavior of the lightest particles. Quantum effects of the plasma electrons are relevant either at sufficiently high density and/or low temperature where the degeneracy parameters $\chi > 1$ or $\Theta < 1$, for a definition, see Eqs. (1) and (2). This is the case in highly compressed plasmas, in warm dense matter (WDM), and high energy density plasmas (HEDP). At the same time, even in low-pressure plasmas where electrons are non-degenerate, quantum effects occur, for a recent review, see Ref. [2].

The articles in the present special issue are mostly concerned with WDM – a field on the border of plasma physics and condensed matter physics that has been of growing importance in recent years, e.g., [3–6]. Examples of WDM are the interior of the Earth [7], brown and white dwarf stars [8–10], giant planets, e.g., [11–16], and the outer crust of neutron stars [17, 18]. On the other hand, WDM is routinely produced via laser or ion beam compression or with Z-pinches, e.g. [19, 20]. The key experimental facilities include the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory [21, 22], the Z Pulsed Power Facility at Sandia National Laboratories [23, 24], the OMEGA Laser Facility at the Laboratory for Laser Energetics [25], the Linac Coherent Light Source (LCLS) at SLAC National Accelerator Laboratory [26–28], the European free-electron laser facilities FLASH and XFEL in Hamburg, Germany [29–31] and the Shenguang-II laser facility in Shanghai, China [32, 33].

The most important technological application of quantum plasmas is inertial confinement fusion [21–23]. In recent experiments at the NIF, major breakthroughs were achieved. For the first time the Lawson criterion for ignition was exceeded [34] and later a target gain greater than unity was reported [35]. In these experiments electronic quantum effects are expected to be crucial, primarily during the initial phase of the target implosion. Aside from dense plasmas, many condensed matter systems, such as the electron gas in metals or electron-hole plasmas in semiconductors or quantum materials, exhibit WDM behavior – if they are subject to strong excitation, e.g., by lasers or free electron lasers [36, 37].

* bonitz@physik.uni-kiel.de; Corresponding author

II. BACKGROUND

Quantum plasmas have evolved into an important subfield of plasma physics. Quantum effects are important in a broad variety of systems of current importance – from astrophysics to laboratory systems and technologically relevant plasmas, such as inertially confined fusion plasmas. Here we present a very short introduction to the relevant parameters and to the occurences of quantum plasmas that are useful in order to understand the articles of this special issue. For a broader overview, we refer to recent reviews [2, 38, 39] and the references cited therein.

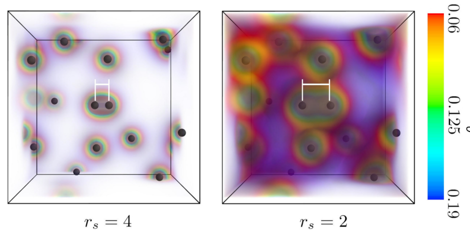

Figure 1. Illustration of one of the key quantum effects – the finite spatial extension of microparticles. Shown are *ab initio* path integral Monte Carlo results for the electronic density in the external field of a fixed snapshot of protons at the electronic Fermi temperature, $\Theta = 1$ [Eq. (1)]. We note the finite extension of the electron clouds around the protons even at low density ($r_s = 4$, cf. Eq. 6). The electrons would collapse into the proton, due to the Coulomb attraction, if classical mechanics would be valid. In the right panel, the density is increased by a factor 8 leading to pressure dissocation of molecules and to strong delocalization of the electrons shown by the bluish background color. Taken from Moldabekov *et al.* [40] with the permission of the authors; lincensed under a Creative Commons Attribution (CC BY 4.0).

Before proceeding, we briefly recall the peculiarities of quantum effects. It is important to realize that quantum plasmas differ qualitatively from classical plasmas. Therefore, they should not be seen as a "classical plasma with some quantum correction". Therefore, dedicated quantum methods are needed to theoretically describe of simulate quantum plasmas. An illustration of the essence of quantum behavior or electrons is presented in Fig.1: electrons are not point particles but exhibit a finite spatial extension (delocalization), and different electrons can overlap. The figure shows two snapshots from the simulation box of a fermionic path integral Monte Carlo simulation of hydrogen. In this parameter range the physical properties of the quantum plasma change drastically. In the left plot the plasma contains predominantly bound states: hydrogen atoms and molecules; one molecule is depicted in the center with two protons being approximately $1.4a_B$ apart. In the right panel, the density is increased by a factor of 8 and the temperature is increased by a factor of 4 [cf. the definitions (6) and (1)]. Correspondingly, the electron clouds of individual atoms start to overlap significantly, leading to a breakup of bound states and an increase of the degree of ionization. Physically, electrons are still weakly attached to protons, but there is a high electron density between the protons, shown by the blue background color.

A. Parameters and occurrence of quantum plasmas

The basic parameters of dense quantum plasmas and warm dense matter are[41–45]: the electron degeneracy parameters

$$\Theta = \frac{k_B T}{E_F}\,, \tag{1}$$

$$\chi = n\Lambda^3, \tag{2}$$

that contain characteristic length and energy scales – the thermal de Broglie wavelength, and the Fermi energy of electrons (in 3D), respectively:

$$\Lambda = \frac{h}{\sqrt{2\pi m k_B T}}\,, \tag{3}$$

$$E_F = \frac{\hbar^2}{2m}(3\pi^2 n)^{2/3} = k_B T_F\,, \tag{4}$$

where n and T are the free electron density and temperature. Quantum degeneracy effects of the ions are important only in plasmas that are very strongly compressed, e.g. [2, 46]. The reason is that the degeneracy parameter of the ions is a factor $(mT/m_i T_i)^{3/2}$ smaller than the one of the electrons. The second important parameter in dense plasmas is the classical coupling parameter of ions

$$\Gamma_i = \frac{Q_i^2}{a_i k_B T_i}\,, \tag{5}$$

where Q_i is the ion charge, and a_i is the mean interionic distance. Further, the Brueckner parameter of electrons (quantum coupling parameter in the low-temperature limit) is

$$r_s = \frac{a}{a_B}, \qquad a_B = \frac{\hbar^2 \epsilon_b}{m_r Q_i e}, \tag{6}$$

where $a = (4/3\pi n)^{-1/3}$ denotes the mean distance between two electrons, a_B is the Bohr radius, $m_r = m m_i/(m + m_i)$ is the reduced mass, and ϵ_b is the background dielectric constant. For hydrogen plasmas, $m_r \approx m$, $\epsilon_b = 1$, and $a_B = 0.529177$Å. Alternatively, the coupling strength in the degenerate limit is defined by

$$\Gamma_q^2 = \frac{(\hbar\omega_{pl})^2}{E_F^2} = r_s \cdot \frac{16}{9\pi}\left(\frac{12}{\pi}\right)^{1/3} \approx 0.88 \cdot r_s\,, \tag{7}$$

where the plasma frequency is defined in Eq. (9) below. An interpolation between the classical and strongly degenerate limits is possible with the modified coupling parameter

$$\Gamma = \frac{e^2/a}{\left[(k_BT)^2 + E_F^2\right]^{1/2}} = \frac{e^2}{ak_BT}\frac{1}{(1+\Theta^{-2})^{1/2}}\,. \qquad (8)$$

In parts of the literature, in particular, papers using quantum hydrodynamic (QHD) models, the coupling parameter Γ_q is denoted H and occasionally misinterpreted as a measure of quantum diffraction effects, e.g., Sec. III B and Ref. [47].

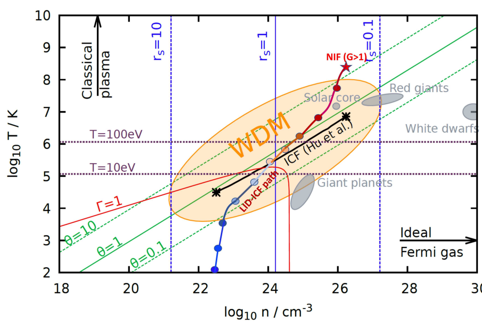

Figure 2. Density-temperature plane around the warm dense matter (WDM) regime with a few relevant examples. Electronic *quantum effects* are observed for $\Theta \lesssim 1$, cf. Eq. (1). Strong coupling of the electrons is observed inside the line $\Gamma = 1$, Eq. (8). Note that the values of Θ and r_s refer to jellium (electrons in fully ionized hydrogen). The density-temperature path of the D-T shell for laser-indirect-drive (LID) ICF is added to illustrate that the in-flight shell conditions are mostly in the quantum strongly coupled regime before reaching ignition with fusion gain larger than one on the National Ignition Facility; the colors demonstrate the temperature increase; for more details, see Ref. [2]. Adapted from Ref. [39]; licensed under a Creative Commons Attribution (CC BY NC ND) license.

The relevance of quantum effects in plasmas is indicated in Fig. 2. Quantum effects are important below the green line $\Theta = 1$ which applies to many astrophysical objects such as giant planets or white dwarf stars. At high temperatures the plasma behaves as an ideal classical gas, whereas, at high density, electrons exhibit ideal Fermi gas behavior. At the same time, Coulomb coupling effects are strong inside the line $\Gamma = 1$, cf. Eq. (8). Interestingly, the recent successful inertial fusion experiments at the NIF went right through the strong coupling and quantum plasma ranges, during their initial compression phase. Fig. 1 shows *ab initio* path integral Monte Carlo results for the electronic density of hydrogen for two relevant density at $\Theta = 1$ [40]. These results nicely illustrate the quantum delocalization of the electrons even for the lower density ($r_s = 4$, left panel), whereas classical electrons would simply collapse into the protons due to the Coulomb attraction.

B. Dynamic properties

While quantum effects in plasmas in thermal equilibrium have been subject of a recent review article [2], the present special issue concentrates on dynamic properties. This comprises frequency-dependent phenomena, both in equilibrium and nonequilibrium, as well as nonequilibrium relaxation processes. Dynamic processes are characterized by the relevant intrinsic frequencies of the plasma and the associated time scales. The central eigenfrequency is the plasma frequency

$$\omega_{pl} = \sqrt{\frac{4\pi ne^2}{m}}\,, \qquad (9)$$

describing collective modes in the limit of large wave length. Excitations on smaller scales (larger wave number q) exhibit larger frequencies which in the collisionless limit (random phase approximation, RPA) has positive quadratic and quartic contributions

$$\frac{\omega^2(q)}{\omega_p^2} = 1 + \frac{\langle v^2\rangle}{\omega_p^2}q^2 + \left\{\frac{\left(\Delta v^2\right)^2}{\omega_p^2} + \frac{\hbar^2}{4m^2}\right\}\frac{q^4}{\omega_p^2}\,, \qquad (10)$$

that depend on density and temperature, for details, see Ref. [48]. If the plasma is strongly correlated, the dispersion may become non-monotonic, eventually forming a roton-like minimum [49]. In addition to the electronic plasmon there is also a well pronounced mode at lower frequencies – the ion acoustic mode. Its linear dispersion is governed by the ion sound speed which depends on the plasma properties and is a sensitive experimental diagnostic.

From the theory side, collective plasma properties follow from the dynamic structure factor $S(q,\omega)$ or the dielectric function, $\epsilon(q,\omega)$. Closely related to the dielectric properties are transport and optical properties, e.g. [6, 39, 50]. These quantities, for warm dense matter and inertial fusion applications, are in the focus of many of the papers in this issue.

Another group of dynamic properties is related to nonequilibrium quantum plasmas that are excited e.g. by laser pulses. There is a large variety of relaxation, dissipation and thermalization processes that drive the plasma back into thermal equilibrium. This is topic of high current interest in dense quantum plasmas [6] and is subject of several contributions in this special issue.

III. SUMMARY OF AREAS COVERED

This special issue comprises a total of 19 papers, including 17 original papers devoted to a variety of topics that we discuss in more detail below. In addition, there is a review article by V. Karasiev *et al.* [51], cf. Sec. III G, and an article devoted to the memory of Dr Fernando Haas [52], cf. Sec. III B.

A. Numerical Methods, Verification and Validation in Plasma Physics

In this topical area there are three original papers.

1. The first is by Roden *et al.*, "Thermalization of optically excited Fermi systems: Electron–electron collisions in solid metals" [53]. It derives an expression for the full Boltzmann collision integral in the random-k approximation and then compares it to various relaxation-time approaches in the context of the thermalization of a degenerate plasma subsequent to femtosecond excitation. The authors report that a constant relaxation time works well for electrons close to the Fermi energy, but the importance of capturing energy-dependent relaxation plays an important role at higher energies.

2. The second article in this topic is by Kononov *et al.*, "Real-time time-dependent density functional theory for high-energy density physics" [54]. It is both a review of the theoretical formalism underlying real-time TDDFT and a tutorial that describes many of the practical computational details for calculating three different response properties relevant to HED plasmas. These details will be useful to practitioners learning to run real-time calculations.

3. The third paper is by Padilla-Gomez *et al.*, "Quantum kinetic modeling of KEEN waves in a warm-dense regime" [55] and is devoted to application of quantum kinetic theory to KEEN waves. The authors present solutions of the quantum Vlasov equation demonstrating that quantum diffraction weakens electron trapping.

B. Quantum Hydrodynamics

Quantum Hydrodynamics (QHD) has emerged as a theoretical approach to quantum plasmas following the paper by Manfredi and Haas [56]. QHD is independent from first-principles methods [38] that are discussed in the other sections of this editorial. The main idea of QHD is to extend classical hydrodynamics to the quantum domain where the focus lies mainly on linear and nonlinear oscillations and waves, for a recent discussion, see [44].

1. The article by Manfredi *et al.*, "Obituary: Fernando Haas (1970–2024)" [52] is devoted to the scientific legacy of Fernando Haas who introduced, together with G. Manfredi, the concept of quantum hydrodynamics into plasma physics [56]. The authors discuss the scientific achievements of F. Haas and also share personal recollections underlining, both, his scientific rigor and remarkable personality.

2. The paper by Sarkar *et al.*, "Ion-acoustic wave propagation with Bohm quantum potential near and at supercritical values in degenerate plasmas" [47] studies nonlinear waves in relativistic degenerate electron-positron-ion plasmas thought to exist in white dwarf stars.

C. Inertially Confined Plasmas, Dense Plasmas, Equations of State

This topical area comprises 9 original articles that are devoted to theory and simulation of the equation of state, collective and transport properties of dense quantum plasmas. Of particular interest is the broad variety of concepts and approaches that are highly complementary. Many of the results reported are of methodological relevance for inertial confinement fusion.

1. The article by Gawne *et al.*, "Spectral deconvolution without the deconvolution: Extracting temperature from x-ray Thomson scattering spectra without the source-and-instrument function" [57] explores a new approach for the model-free interpretation of X-ray Thomson scattering (XRTS) experiments in the imaginary-time domain [58, 59] that eliminates the need for explicit knowledge of the source-and-instrument function of the experimental set-up. This is achieved by combining measurements at multiple scattering angles and confirmed on the basis of extensive ray-tracing simulations.

2. The paper by Röpke, "The virial expansion of plasma properties: Benchmarks for numerical results" [60] is devoted to analytical low-density expansion of thermodynamic functions, dielectric function and conductivity. The author derives analytical benchmarks for the uniform electron gas and for hydrogen and compares them to recent fermionic path integral Monte Carlo (PIMC) results of Dornheim *et al.* [5] and Filinov *et al.* [61].

3. The paper by Böhme *et al.*, "Correlation function metrology for warm dense matter: Recent developments and practical guidelines" [62] gives a practical hands-on recipe for the model-free interpretation of XRTS experiments using the recent imaginary-time Laplace transform method [58, 59]. As a practical example, they consider a recent XRTS measurement on optically heated diamond [63].

4. The article by Ebeling and Röpke, "On the foundation of the quantum statistics of thermal plasmas from Planck and Unsöld to recent developments" [64] gives an introduction into quantum statistics with an overview on the ionization equilibrium in hydrogen and helium. It discusses quantum statistical results and compares to PIMC simulation data.

5. Kononov *et al.*, "Nonlinear effects in light-ion stopping powers within real-time time-dependent density functional theory" [65] compares the results of real-time TDDFT calculations to effective charge models for low-Z stopping in warm dense matter. It examines nonlinear effects near and below the Bragg peak, finding that even proton stopping powers can show subtle and complex deviations from linear-response theory.

6. The paper by White *et al.*, "Quantum fluctuations in dense plasma simulations " [66] describes an excited states molecular dynamics (ESMD) model that accounts for transitions among different excited electronic configurations among pseudoatoms. Fluctuations among configurations with finite lifetimes are shown to impact predictions of various observables in steady-state plasmas.

7. The paper by Kählert, "Structural and dynamic properties of dense hydrogen plasmas from semiclassical molecular dynamics simulations" [67] uses the improved Kelbg potential [68, 69] to compute, among others, the plasmon dispersion and ion-acoustic mode for dense hydrogen. Comparison to first principles simulations confirms the high accuracy of the method.

8. Sharma *et al.*, "Mixed stochastic-deterministic density functional theoretic decomposition of Kubo–Greenwood conductivities in the projector augmented wave formalism" [70] applies the recently developed and highly efficient mDFT formalism to the calculation of optical conductivities for low-Z warm dense matter. Both Kubo-Greenwood and real-time mDFT calculations are compared to results from the traditional (and less efficient) Kohn-Sham formulations.

9. Tolias *et al.*, "Exact series expansion for even frequency moments of the dynamic structure factor" [71] presents explicit expressions for the even frequency moments in terms of odd frequency moments of the dynamic structure factor. The latter can be evaluated from the sum rules, and the new relations thus provide a systematic pathway towards the characterization of all frequency moments.

D. Radiation: Emission, Absorption, Transport

1. The original article by Preising and Redmer, "Electronic opacities of Jupiter's and Saturn's interior from ab initio simulations" [72] presents the electronic opacity for two prototypical gas giant planets based on a combination of the Kubo-Greenwood formula with *ab initio* DFT simulations. These results are important for the understanding of, e.g., thermal evolution and thus help to refine planetary models.

E. Basic Plasma Phenomena, Waves, Instabilities

1. Bakri *et al.*, "Wave–particle interactions in a spin polarized plasma" [73] analyzes a spin-Vlasov-Poisson-Landau-Lifshitz model in which itinerant electrons and fixed ions interact through Coulomb and magnetic exchange interactions. A magnon-electron resonance is identified, through which damping or instability of the attendant spin wave can occur.

2. Pagiazitis *et al.*, "Path integral molecular dynamics: A high-fidelity approach to quantum dynamics of electrons" [74] studies the weakly coupled non-degenerate uniform electron gas using ring-polymer molecular dynamics to account for quantum diffraction. Benchmark data for the equation of state and diffusivity are reported along the quantum-classical crossover and a microscopic mechanism by which binary collisions are softened by quantum effects is corroborated.

F. Plasma-Based Accelerators, Beams, Radiation Generation

The article by Ming Zi *et al.*, "Quantum stochasticity effects on angular distributions in electron-beam collision with laser pulse" [75] presents quantum electrodynamics particle-in-cell simulations of a laser-wakefield accelerated electron beam interacting with an ultra intense laser field. The study reveals three distinct manifestations of quantum stochasticity effects, including double-peak positron distributions.

G. Review Article

The paper by Karasiev *et al.*, "Thermal exchange-correlation functionals: Capturing quantum electron behavior in warm, dense plasmas" [51] presents a comprehensive review of cutting-edge developments in density functional theory simulations. It is devoted to thermal exchange–correlation (XC) functionals that are explicitly designed for simulations of warm dense quantum plasmas. The authors highlight the importance of consistent XC functionals that take into account thermal XC and spatial inhomogeneity on the same level of sophistication. The review provides clear instructions for current practitioners and outlines a pathway upwards on Jacob's ladder of functional approximations [76] for future developments.

IV. CONCLUSIONS AND OUTLOOK

The present special issue presents an overview on quantum plasmas with a focus on dynamic properties and nonequilibrium effects. It demonstrates the diversity of applications and questions as well as of theoretical and simulation concepts. Most of the articles are devoted to dense quantum plasmas and warm dense matter since this field has attracted particular attention, primarily, due to the impressive recent progress in inertial confinement fusion. At the same time, many questions regarding the properties and relaxation behavior of dense quantum plasmas are still poorly understood or cannot yet be accurately predicted. This requires further strong research efforts both, in experiment and simulation, in particular, to resolve rapid processes. We hope that readers will obtain an excellent overview and that this special issue will stimulate further research in the field of quantum plasmas.

ACKNOWLEDGMENTS

We thank the authors who contributed excellent papers to this special issue. We are also grateful to the editorial team of Physics of Plasmas, in particular Mike Mauel and Igor Kaganovich who welcomed and sharpened our concept for this special issue, and Megan Moore, and Debora Cruz, who assisted us with handling the manuscripts.
This work has been supported by the Deutsche Forschungsgemeinschaft via grants BO1366/13-2, BO1366/16-1 and DO2670/1-1.

This work has received funding from the European Research Council (ERC) under the European Union's Horizon 2022 research and innovation programme (Grant agreement No. 101076233, "PREXTREME"). Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the European Research Council Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

ADB acknowledges support from Sandia National Laboratories' Laboratory Directed Research and Development (LDRD) Projects No. 218456 and 233196 and the US Department of Energy Science Campaign 1. This work was performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science.

This article has been co-authored by an employee of National Technology & Engineering Solutions of Sandia, LLC under Contract No. DE-NA0003525 with the U.S. Department of Energy (DOE). The employees own all right, title and interest in and to the article and are solely responsible for its contents. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this article or allow others to do so, for United States Government purposes. The DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan.

---

[1] R. Durrer, *The Cosmic Microwave Background*, 2nd ed. (Cambridge University Press, 2020).
[2] M. Bonitz, K. Hanno, K. Daniels, C. Makait, P. Hamann, J. Vorberger, Z. Moldabekov, S. X. Hu, V. Karasiev, D. Kraus, H. Kersten, J.-P. Joost, P. Ludwig, and T. Dornheim, Quantum effects in plasmas, Phys. Plasmas (2026).
[3] F. Graziani, M. P. Desjarlais, R. Redmer, and S. B. Trickey, *Frontiers and Challenges in Warm Dense Matter* (Springer, 2014).
[4] V. E. Fortov, *Extreme States of Matter (High Energy Density Physics, Second Edition)* (Springer, Heidelberg, 2016).
[5] T. Dornheim, S. Groth, and M. Bonitz, The uniform electron gas at warm dense matter conditions, Phys. Rep. **744**, 1 (2018).
[6] J. Vorberger, F. Graziani, D. Riley, A. D. Baczewski, I. Baraffe, M. Bethkenhagen, S. Blouin, M. P. Böhme, M. Bonitz, M. Bussmann, A. Casner, W. Cayzac, P. Celliers, G. Chabrier, N. Chamel, D. Chapman, M. Chen, J. Clerouin, G. Collins, F. Coppari, T. Döppner, T. Dornheim, L. B. Fletcher, D. O. Gericke, S. Glenzer, A. F. Goncharov, G. Gregori, S. Hamel, S. B. Hansen, N. J. Hartley, S. Hu, O. A. Hurricane, V. V. Karasiev, J. J. Kas, B. Kettle, T. Kluge, M. D. Knudson, A. Kononov, Z. Konopkova, D. Kraus, A. Kritcher, S. Malko, G. Massacrier, B. Militzer, Z. A. Moldabekov, M. S. Murillo, B. Nagler, N. Nettelmann, P. Neumayer, B. K. Ofori-Okai, I. I. Oleynik, M. Preising, A. Pribram-Jones, T. Ramazanov, A. Ravasio, R. Redmer, B. Rethfeld, A. P. Robinson, G. Röpke, F. Soubiran, C. E. Starrett, G. Steinle-Neumann, P. A. Sterne, S. Tanaka, A. P. Thompson, S. B. Trickey, T. Vinci, S. M. Vinko, L. Wang, A. J. White, T. G. White, U. Zastrau, E. Zurek, and P. Tolias, Roadmap for warm dense matter physics, Plasma Phys. Control. Fusion **68**, 073501 (2026).

[7] A. Hausoel, M. Karolak, E. Sasioglu, A. Lichtenstein, K. Held, A. Katanin, A. Toschi, and G. Sangiovanni, Local magnetic moments in iron and nickel at ambient and Earth's core conditions, Nat. Communications **8**, 16062 (2017).
[8] D. Saumon, W. B. Hubbard, G. Chabrier, and H. M. van Horn, The role of the molecular-metallic transition of hydrogen in the evolution of Jupiter, Saturn, and brown dwarfs, Astrophys. J. **391**, 827 (1992).
[9] G. Chabrier, Quantum effects in dense Coulumbic matter - Application to the cooling of white dwarfs, Astrophys. J. **414**, 695 (1993).
[10] G. Chabrier, P. Brassard, G. Fontaine, and D. Saumon, Cooling Sequences and Color-Magnitude Diagrams for Cool White Dwarfs with Hydrogen Atmospheres, Astrophys. J. **543**, 216 (2000).
[11] M. Schlanges, M. Bonitz, and A. Tschttschjan, Plasma Phase Transition in Fluid Hydrogen-Helium Mixtures, Contributions to Plasma Physics **35**, 109 (1995).
[12] V. Bezkrovniy, V. S. Filinov, D. Kremp, M. Bonitz, M. Schlanges, W. D. Kraeft, P. R. Levashov, and V. E. Fortov, Monte Carlo results for the hydrogen Hugoniot, Phys. Rev. E **70**, 057401 (2004).
[13] J. Vorberger, I. Tamblyn, B. Militzer, and S. A. Bonev, Hydrogen-helium mixtures in the interiors of giant planets, Phys. Rev. B **75**, 024206 (2007).
[14] B. Militzer, W. B. Hubbard, J. Vorberger, I. Tamblyn, and S. A. Bonev, A Massive Core in Jupiter Predicted from First-Principles Simulations, Astrophys. J. Lett. **688**, L45 (2008).
[15] R. Redmer, T. R. Mattsson, N. Nettelmann, and M. French, The phase diagram of water and the magnetic fields of Uranus and Neptune, Icarus **211**, 798 (2011).
[16] N. Nettelmann, R. Püstow, and R. Redmer, Saturn layered structure and homogeneous evolution models with different EOSs, Icarus **225**, 548 (2013).
[17] P. Haensel, A. Y. Potekhin, and D. Yakovlev, *Neutron Stars 1: Equation of State and Structure* (New York: Springer, 2006).
[18] J. Daligault and S. Gupta, Electron-Ion Scattering in Dense Multi-Component Plasmas: Application to the Outer Crust of an Accreting Neutron Star, Astrophys. J. **703**, 994 (2009).
[19] K. Falk, Experimental methods for warm dense matter research, High Power Laser Science and Engineering **6**, e59 (2018).
[20] D. B. Sinars, M. A. Sweeney, C. S. Alexander, D. J. Ampleford, T. Ao, J. P. Apruzese, C. Aragon, D. J. Armstrong, K. N. Austin, T. J. Awe, A. D. Baczewski, J. E. Bailey, K. L. Baker, C. R. Ball, H. T. Barclay, S. Beatty, K. Beckwith, K. S. Bell, J. Benage, J. F., N. L. Bennett, K. Blaha, D. E. Bliss, J. J. Boerner, C. J. Bourdon, B. A. Branch, J. L. Brown, E. M. Campbell, R. B. Campbell, D. G. Chacon, G. A. Chandler, K. Chandler, P. J. Christenson, M. D. Christison, E. B. Christner, I. Clay, R. C., K. R. Cochrane, A. P. Colombo, B. M. Cook, C. A. Coverdale, M. E. Cuneo, J. S. Custer, A. Dasgupta, J.-P. Davis, M. P. Desjarlais, I. Dolan, D. H., J. D. Douglass, G. S. Dunham, S. Duwal, A. D. Edens, M. J. Edwards, E. G. Evstatiev, B. G. Farfan, J. R. Fein, E. S. Field, J. A. Fisher, T. M. Flanagan, D. G. Flicker, M. D. Furnish, B. R. Galloway, P. D. Gard, T. A. Gardiner, M. Geissel, J. L. Giuliani, M. E. Glinsky, M. R. Gomez, T. Gomez, G. P. Grim, K. D. Hahn, T. A. Haill, N. D. Hamlin, J. H. Hammer, S. B. Hansen, H. L. Hanshaw, E. C. Harding, A. J. Harvey-Thompson, D. Headley, M. C. Herrmann, M. H. Hess, C. Highstrete, O. A. Hurricane, B. T. Hutsel, C. A. Jennings, O. M. Johns, D. Johnson, M. D. Johnston, B. M. Jones, M. C. Jones, P. A. Jones, P. E. Kalita, R. J. Kamm, J. W. Kellogg, M. L. Kiefer, M. W. Kimmel, P. F. Knapp, M. D. Knudson, A. Kreft, G. R. Laity, P. W. Lake, D. C. Lamppa, W. L. Langston, J. S. Lash, K. R. LeChien, J. J. Leckbee, R. J. Leeper, G. T. Leifeste, R. W. Lemke, W. Lewis, S. A. Lewis, G. P. Loisel, Q. M. Looker, A. J. Lopez, D. J. Lucero, S. A. MacLaren, R. J. Magyar, M. A. Mangan, M. R. Martin, T. R. Mattsson, M. K. Matzen, A. J. Maurer, M. G. Mazarakis, R. D. McBride, H. S. McLean, C. A. McCoy, G. R. McKee, J. L. McKenney, A. R. Miles, J. A. Mills, M. D. Mitchell, N. W. Moore, C. E. Myers, T. Nagayama, G. Natoni, A. C. Owen, S. Patel, K. J. Peterson, T. D. Pointon, J. L. Porter, A. J. Porwitzky, S. Radovich, K. S. Raman, P. K. Rambo, W. D. Reinhart, G. K. Robertson, G. A. Rochau, S. Root, D. V. Rose, D. C. Rovang, C. L. Ruiz, D. E. Ruiz, D. Sandoval, M. E. Savage, M. E. Sceiford, M. A. Schaeuble, P. F. Schmit, M. S. Schollmeier, J. Schwarz, C. T. Seagle, A. B. Sefkow, D. B. Seidel, G. A. Shipley, J. Shores, L. Shulenburger, S. C. Simpson, S. A. Slutz, I. C. Smith, C. S. Speas, P. E. Specht, M. J. Speir, D. C. Spencer, P. T. Springer, A. M. Steiner, B. S. Stoltzfus, W. A. Stygar, J. Ward Thornhill, J. A. Torres, J. P. Townsend, C. Tyler, R. A. Vesey, P. E. Wakeland, T. J. Webb, E. A. Weinbrecht, M. R. Weis, D. R. Welch, J. L. Wise, M. Wu, D. A. Yager-Elorriaga, A. Yu, and E. P. Yu, Review of pulsed power-driven high energy density physics research on Z at Sandia, Physics of Plasmas **27**, 070501 (2020).
[21] E. I. Moses, R. N. Boyd, B. A. Remington, C. J. Keane, and R. Al-Ayat, The National Ignition Facility: Ushering in a new age for high energy density science, Phys. Plasmas **16**, 041006 (2009).
[22] O. A. Hurricane, D. A. Callahan, D. T. Casey, E. L. Dewald, T. R. Dittrich, T. Döppner, S. Haan, D. E. Hinkel, L. F. Berzak Hopkins, O. Jones, A. L. Kritcher, S. Le Pape, T. Ma, A. G. MacPhee, J. L. Milovich, J. Moody, A. Pak, H.-S. Park, P. K. Patel, J. E. Ralph, H. F. Robey, J. S. Ross, J. D. Salmonson, B. K. Spears, P. T. Springer, R. Tommasini, F. Albert, L. R. Benedetti, R. Bionta, E. Bond, D. K. Bradley, J. Caggiano, P. M. Celliers, C. Cerjan, J. A. Church, R. Dylla-Spears, D. Edgell, M. J. Edwards, D. Fittinghoff, M. A. Barrios Garcia, A. Hamza, R. Hatarik, H. Herrmann, M. Hohenberger, D. Hoover, J. L. Kline, G. Kyrala, B. Kozioziemski, G. Grim, J. E. Field, J. Frenje, N. Izumi, M. Gatu Johnson, S. F. Khan, J. Knauer, T. Kohut, O. Landen, F. Merrill, P. Michel, A. Moore, S. R. Nagel, A. Nikroo, T. Parham, R. R. Rygg, D. Sayre, M. Schneider, D. Shaughnessy, D. Strozzi, R. P. J. Town, D. Turnbull, P. Volegov, A. Wan, K. Widmann, C. Wilde, and C. Yeamans, Inertially confined fusion plasmas dominated by alpha-particle self-heating, Nat. Phys. **12**, 800 (2016).
[23] M. K. Matzen, M. A. Sweeney, R. G. Adams, J. R. Asay, J. E. Bailey, G. R. Bennett, D. E. Bliss, D. D. Bloomquist, T. A. Brunner, R. B. Campbell, G. A. Chandler, C. A. Coverdale, M. E. Cuneo, J.-P. Davis, C. Deeney, M. P. Desjarlais, G. L. Donovan, C. J. Garasi, T. A. Haill, C. A. Hall, D. L. Hanson, M. J. Hurst,

B. Jones, M. D. Knudson, R. J. Leeper, R. W. Lemke, M. G. Mazarakis, D. H. McDaniel, T. A. Mehlhorn, T. J. Nash, C. L. Olson, J. L. Porter, P. K. Rambo, S. E. Rosenthal, G. A. Rochau, L. E. Ruggles, C. L. Ruiz, T. W. L. Sanford, J. F. Seamen, D. B. Sinars, S. A. Slutz, I. C. Smith, K. W. Struve, W. A. Stygar, R. A. Vesey, E. A. Weinbrecht, D. F. Wenger, and E. P. Yu, Pulsed-power-driven High Energy Density Phys. and inertial confinement fusion research, Phys. Plasmas **12**, 055503 (2005).

[24] M. D. Knudson, M. P. Desjarlais, A. Becker, R. W. Lemke, K. R. Cochrane, M. E. Savage, D. E. Bliss, T. R. Mattsson, and R. Redmer, Direct observation of an abrupt insulator-to-metal transition in dense liquid deuterium, Science **348**, 1455 (2015).

[25] R. Nora, W. Theobald, R. Betti, F. Marshall, D. Michel, W. Seka, B. Yaakobi, M. Lafon, C. Stoeckl, J. Delettrez, A. Solodov, A. Casner, C. Reverdin, X. Ribeyre, A. Vallet, J. Peebles, F. Beg, and M. Wei, Gigabar Spherical Shock Generation on the OMEGA Laser, Phys. Rev. Lett. **114**, 045001 (2015).

[26] P. Sperling, E. Gamboa, H. Lee, H. Chung, E. Galtier, Y. Omarbakiyeva, H. Reinholz, G. Röpke, U. Zastrau, J. Hastings, L. Fletcher, and S. Glenzer, Free-Electron X-Ray Laser Measurements of Collisional-Damped Plasmons in Isochorically Heated Warm Dense Matter, Phys. Rev. Lett. **115**, 115001 (2015).

[27] S. H. Glenzer, L. B. Fletcher, E. Galtier, B. Nagler, R. Alonso-Mori, B. Barbrel, S. B. Brown, D. A. Chapman, Z. Chen, C. B. Curry, F. Fiuza, E. Gamboa, M. Gauthier, D. O. Gericke, A. Gleason, S. Goede, E. Granados, P. Heimann, J. Kim, D. Kraus, M. J. MacDonald, A. J. Mackinnon, R. Mishra, A. Ravasio, C. Roedel, P. Sperling, W. Schumaker, Y. Y. Tsui, J. Vorberger, U Zastrau, A. Fry, W. E. White, J. B. Hasting, and H. J. Lee, Matter under extreme conditions experiments at the Linac Coherent Light Source, J. Phys. B **49**, 092001 (2016).

[28] C. Bostedt, S. Boutet, D. M. Fritz, Z. Huang, H. J. Lee, H. T. Lemke, A. Robert, W. F. Schlotter, J. J. Turner, and G. J. Williams, Linac Coherent Light Source: The first five years, Rev. Mod. Phys. **88**, 015007 (2016).

[29] U. Zastrau, P. Sperling, M. Harmand, A. Becker, T. Bornath, R. Bredow, S. Dziarzhytski, T. Fennel, L. Fletcher, E. Förster, S. Göde, G. Gregori, V. Hilbert, D. Hochhaus, B. Holst, T. Laarmann, H. Lee, T. Ma, J. Mithen, R. Mitzner, C. Murphy, M. Nakatsutsumi, P. Neumayer, A. Przystawik, S. Roling, M. Schulz, B. Siemer, S. Skruszewicz, J. Tiggesbäumker, S. Toleikis, T. Tschentscher, T. White, M. Wöstmann, H. Zacharias, T. Döppner, S. Glenzer, and R. Redmer, Resolving Ultrafast Heating of Dense Cryogenic Hydrogen, Phys. Rev. Lett. **112**, 105002 (2014).

[30] T. Tschentscher, C. Bressler, J. Grünert, A. Madsen, A. P. Mancuso, M. Meyer, A. Scherz, H. Sinn, and U. Zastrau, Photon Beam Transport and Scientific Instruments at the European XFEL, Appl. Sci. **7**, 592 (2017).

[31] U. Zastrau, K. Appel, C. Baehtz, O. Baehr, L. Batchelor, A. Berghäuser, M. Banjafar, E. Brambrink, V. Cerantola, T. E. Cowan, H. Damker, S. Dietrich, S. Di Dio Cafiso, J. Dreyer, H.-O. Engel, T. Feldmann, S. Findeisen, M. Foese, D. Fulla-Marsa, S. Göde, M. Hassan, J. Hauser, T. Herrmannsdörfer, H. Höppner, J. Kaa, P. Kaever, K. Knöfel, Z. Konôpková, A. Laso García, H.-P. Liermann, J. Mainberger, M. Makita, E.-C. Martens, E. E. McBride, D. Möller, M. Nakatsutsumi, A. Pelka, C. Plueckthun, C. Prescher, T. R. Preston, M. Röper, A. Schmidt, W. Seidel, J.-P. Schwinkendorf, M. O. Schoelmerich, U. Schramm, A. Schropp, C. Strohm, K. Sukharnikov, P. Talkovski, I. Thorpe, M. Toncian, T. Toncian, L. Wollenweber, S. Yamamoto, and T. Tschentscher, The High Energy Density Scientific Instrument at the European XFEL, Journal of Synchrotron Radiation **28**, 1393 (2021).

[32] J. Zhu, J. Zhu, X. Li, B. Zhu, W. Ma, X. Lu, W. Fan, Z. Liu, S. Zhou, G. Xu, and et al., Status and development of high-power laser facilities at the nlhplp, High Power Laser Science and Engineering **6**, e55 (2018).

[33] N.-Y. Shi, J.-H. Liang, C. Mo, D. Wu, H. Liu, Y. Dai, X.-H. Yuan, Z. Zhang, and J. Zhang, First-principles estimation of plasma jet properties from x-ray thomson scattering spectrum in the double-cone ignition scheme, Nuclear Fusion **65**, 106038 (2025).

[34] H. Abu-Shawareb, R. Acree, P. Adams, J. Adams, B. Addis, R. Aden, P. Adrian, B. B. Afeyan, M. Aggleton, L. Aghaian, and A. Aguirre (Indirect Drive ICF Collaboration), Lawson Criterion for Ignition Exceeded in an Inertial Fusion Experiment, Phys. Rev. Lett. **129**, 075001 (2022).

[35] H. Abu-Shawareb, R. Acree, P. Adams, J. Adams, B. Addis, R. Aden, P. Adrian, B. B. Afeyan, M. Aggleton, L. Aghaian, and A. Aguirre (The Indirect Drive ICF Collaboration), Achievement of Target Gain Larger than Unity in an Inertial Fusion Experiment, Phys. Rev. Lett. **132**, 065102 (2024).

[36] R. Ernstorfer, M. Harb, C. T. Hebeisen, G. Sciaini, T. Dartigalongue, and R. J. D. Miller, The Formation of Warm Dense Matter: Experimental Evidence for Electronic Bond Hardening in Gold, Science **323**, 1033 (2009).

[37] L. Waldecker, R. Bertoni, R. Ernstorfer, and J. Vorberger, Electron-Phonon Coupling and Energy Flow in a Simple Metal beyond the Two-Temperature Approximation, Phys. Rev. X **6**, 021003 (2016).

[38] M. Bonitz, T. Dornheim, Z. A. Moldabekov, S. Zhang, P. Hamann, H. Kählert, A. Filinov, K. Ramakrishna, and J. Vorberger, Ab initio simulation of warm dense matter, Physics of Plasmas **27**, 042710 (2020), https://doi.org/10.1063/1.5143225.

[39] M. Bonitz, J. Vorberger, M. Bethkenhagen, M. Böhme, D. Ceperley, A. Filinov, T. Gawne, F. Graziani, G. Gregori, P. Hamann, S. Hansen, M. Holzmann, S. Hu, H. Kählert, V. Karasiev, U. Kleinschmidt, L. Kordts, C. Makait, B. Militzer, Z. Moldabekov, C. Pierleoni, M. Preising, K. Ramakrishna, R. Redmer, S. Schwalbe, P. Svensson, and T. Dornheim, Toward First-principles based simulations of dense hydrogen, Phys. Plasmas **31**, 110501 (2024).

[40] Z. Moldabekov, S. Schwalbe, M. P. Böhme, J. Vorberger, X. Shao, M. Pavanello, F. R. Graziani, and T. Dornheim, Bound-State Breaking and the Importance of Thermal Exchange–Correlation Effects in Warm Dense Hydrogen, Journal of Chemical Theory and Computation **20**, 68 (2024).

[41] S. Ichimaru, Strongly coupled plasmas: high-density classical plasmas and degenerate electron liquids, Rev. Mod. Phys. **54**, 1017 (1982).

[42] S. Ichimaru, H. Iyetomi, and S. Tanaka, Statistical

physics of dense plasmas: Thermodynamics, transport coefficients and dynamic correlations, Physics Reports **149**, 91 (1987).
[43] M. Bonitz, *Quantum Kinetic Theory*, 2nd ed. (Springer, Cham, 2016).
[44] M. Bonitz, Z. A. Moldabekov, and T. S. Ramazanov, Quantum hydrodynamics for plasmas—Quo vadis?, Physics of Plasmas **26**, 090601 (2019).
[45] Ott, Torben, Thomsen, Hauke, Abraham, Jan Willem, Dornheim, Tobias, and Bonitz, Michael, Recent progress in the theory and simulation of strongly correlated plasmas: phase transitions, transport, quantum, and magnetic field effects, Eur. Phys. J. D **72**, 84 (2018).
[46] M. Bonitz, V. S. Filinov, V. E. Fortov, P. R. Levashov, and H. Fehske, Crystallization in Two-Component Coulomb Systems, Phys. Rev. Lett. **95**, 235006 (2005).
[47] M. M. Sarkar, S. Barua, and M. G. Hafez, Ion-acoustic wave propagation with bohm quantum potential near and at supercritical values in degenerate plasmas, Physics of Plasmas **32**, 072703 (2025).
[48] P. Hamann, T. Dornheim, J. Vorberger, Z. Moldabekov, and M. Bonitz, *Ab initio* results for the plasmon dispersion and damping of the warm dense electron gas, Contrib. Plasma Phys. **60**, e202000147 (2020).
[49] T. Dornheim, S. Groth, J. Vorberger, and M. Bonitz, Ab initio Path Integral Monte Carlo Results for the Dynamic Structure Factor of Correlated Electrons: From the Electron Liquid to Warm Dense Matter, Phys. Rev. Lett. **121**, 255001 (2018).
[50] P. Hamann, T. Dornheim, J. Vorberger, Z. Moldabekov, and M. Bonitz, Dynamic Properties of the warm dense Electron gas: an *ab initio* path integral Monte Carlo approach, Phys. Rev. B **102**, 125150 (2020).
[51] V. V. Karasiev, S. X. Hu, K. P. Hilleke, A. A. Ellaboudy, D. I. Mihaylov, and S. B. Trickey, Thermal exchange-correlation density functionals for warm dense matter, Physics of Plasmas **33**, 030501 (2026), review Article.
[52] G. Manfredi, A. Bret, G. Brodin, I. Kourakis, M. Marklund, J. T. Mendonça, and H. Terças, Obituary: Fernando Haas (1970–2024), Physics of Plasmas **32**, 102104 (2025).
[53] S. Roden, C. Seibel, T. Held, M. Uehlein, S. T. Weber, and B. Rethfeld, Thermalization of optically excited Fermi systems: Electron–electron collisions in solid metals, Physics of Plasmas **33**, 053906 (2026).
[54] A. Kononov, M. Nguyen, and A. D. Baczewski, Real-time time-dependent density functional theory for high-energy density physics, Physics of Plasmas **33**, 043905 (2026).
[55] F. A. Padilla-Gomez, S. Gong, M. S. Murillo, F. R. Graziani, and A. J. Christlieb, Quantum kinetic modeling of KEEN waves in a warm-dense regime, Physics of Plasmas **33**, 043902 (2026).
[56] G. Manfredi and F. Haas, Self-consistent fluid model for a quantum electron gas, Phys. Rev. B **64**, 075316 (2001).
[57] T. Gawne, A. Kononov, A. D. Baczewski, H. M. Bellenbaum, M. P. Böhme, Z. A. Moldabekov, T. R. Preston, S. Schwalbe, J. Vorberger, and T. Dornheim, Spectral deconvolution without the deconvolution: Extracting temperature from x-ray thomson scattering spectra without the source-and-instrument function, Physics of Plasmas **33**, 052705 (2026).
[58] T. Dornheim, M. Böhme, D. Kraus, T. Döppner, T. R. Preston, Z. A. Moldabekov, and J. Vorberger, Accurate temperature diagnostics for matter under extreme conditions, Nature Communications **13**, 7911 (2022).
[59] T. Gawne, J. Vorberger, Z. Moldabekov, H. Bellenbaum, and T. Dornheim, Model-free interpretation of X-ray Thomson scattering measurements (2026).
[60] G. Röpke, The virial expansion of plasma properties: Benchmarks for numerical results, Physics of Plasmas **33**, 052703 (2026).
[61] A. Filinov and M. Bonitz, The equation of state of partially ionized hydrogen and deuterium plasma revisited, Phys. Rev. E **108**, 055212 (2023).
[62] M. P. Böhme, W. M. Martin, H. M. Bellenbaum, B. M., V. J., S. Schwalbe, Z. A. Moldabekov, T. Gawne, B. Hamel, S. andAguilar-Solis, A. Sharma, F. R. Graziani, T. Döppner, S. H. Glenzer, T. Dornheim, and D. T. Bishel, Correlation function metrology for warm dense matter: Recent developments and practical guidelines, Physics of Plasmas **33**, 042701 (2026).
[63] W. M. Martin, J. Nilsen, L. B. Fletcher, M. J. MacDonald, L. Andersen, A. Arnott, H. Bellenbaum, M. Böhme, N. Boiadjieva, N. Czapla, T. E. Cowan, T. Döppner, G. Dyer, R. N. Ettelbrick, R. Falcone, S. Faubel, E. Galtier, A. Laso Garcia, T. Gawne, L. Hancock, P. Hart, N. J. Hartley, M. L. Herbert, X. Huang, G. Jain, K. D. Kabelitz, D. Khaghani, D. Kraus, H. J. Lee, P. Li, Y. Lu, M. Mettry-Yassa, P. McGehee, B. Nagler, J. Rips, S. Schumacher, E. R. Toro, T. Toncian, X. Xia, A. Gleason, and S. H. Glenzer, Characterizing laser-heated polymer foams with simultaneous x-ray fluorescence spectroscopy and thomson scattering at the matter in extreme conditions endstation at lcls, Physics of Plasmas **32**, 072701 (2025).
[64] W. Ebeling and G. Röpke, On the foundation of the quantum statistics of thermal plasmas from planck and unsöld to recent developments, Physics of Plasmas **33**, 032705 (2026).
[65] A. Kononov, T. W. Hentschel, S. B. Hansen, and A. D. Baczewski, Nonlinear effects in light-ion stopping powers within real-time time-dependent density functional theory, Physics of Plasmas **33**, 032704 (2026).
[66] J. White, C. Johnson, K. Davis, H. TranTran, C. Fontes, and C. Starret, Quantum fluctuations in dense plasma simulations, Physics of Plasmas **33**, 032701 (2026).
[67] H. Kählert, Structural and dynamic properties of dense hydrogen plasmas from semi-classical molecular dynamics simulations, Physics of Plasmas **33**, 022701 (2026).
[68] A. Filinov, M. Bonitz, and W. Ebeling, Improved Kelbg potential for correlated Coulomb systems, J. Phys. A: Math. Gen. **36**, 5957 (2003).
[69] A. V. Filinov, V. O. Golubnychiy, M. Bonitz, W. Ebeling, and J. W. Dufty, Temperature-dependent quantum pair potentials and their application to dense partially ionized hydrogen plasmas, Phys. Rev. E **70**, 046411 (2004).
[70] V. Sharma, L. A. Collins, and A. J. White, Mixed stochastic-deterministic density functional theoretic decomposition of Kubo–Greenwood conductivities in the projector augmented wave formalism, Physics of Plasmas **33**, 012704 (2026).
[71] P. Tolias, J. Vorberger, and T. Dornheim, Exact series expansion for even frequency moments of the dynamic structure factor, Physics of Plasmas **32**, 082704 (2025).
[72] M. Preising and R. Redmer, Electronic opacities of jupiter's and saturn's interior from ab initio simulations, Physics of Plasmas **33**, 053301 (2026).
[73] B. Bakri, N. Crouseilles, P.-A. Hervieux, and G. Man-

fredi, Wave–particle interactions in a spin polarized plasma, Physics of Plasmas **33**, 022111 (2026).

[74] I. Pagiazitis, N. R. Shaffer, and S. X. Hu, Path integral molecular dynamics: A high-fidelity approach to quantum dynamics of electrons, Physics of Plasmas **33**, 012117 (2026).

[75] M. Zi, Y.-Y. Ma, X.-H. Yang, G.-B. Zhang, J.-X. Liu, T. Wu, Y. Deng, and F.-Q. Shao, Quantum stochasticity effects on angular distributions in electron-beam collision with laser pulse, Physics of Plasmas **32**, 103101 (2025).

[76] J. P. Perdew and K. Schmidt, Jacob's ladder of density functional approximations for the exchange-correlation energy, AIP Conf. Proc. **577**, 1 (2001).