Complex plasmas - a laboratory for selforganization

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This talk is devoted to unusual plasmas in which the Coulomb interaction energy between the charged particles exceeds their kinetic energy. These are ”nonideal” or ”strongly correlated” plasmas. Strong Coulomb correlations give rise to exciting selforganization effects including formation of liquids and crystals of charged particles and unusual collective and transport properties. While these correlation phenomena are beyond the scope of traditional plasma physics they are omnipresent in nature: they are observed in electrolytic solutions, dense astrophysical and laboratroy plasmas, ultracold ions and atomic gases in traps, electrons and excitons in quantum dots and even in the quark-gluon-plasma. This provides an interesting new link of plasma physics to other fields of physics.

Plasmas span a tremendous range of temperatures and densities – from the low densities observed in the ionosphere or in space plasmas to the huge densities in the core of white dwarf stars. Plasmas exist at even higher densities (such as in the interior of neutron stars or in heavy ion collision experiments) where nuclei and nucleons break up giving rise to the quark-gluon plasma, for an overview, see Fig. 1 and Ref. [1]. Plasma physics has always produced results that reached out into other fields. Examples are the explanation of the collective oscillations of the electron gas in metals or of the electron-hole plasma in semiconductors, e.g. [2]. A similar development occurs now in nonideal plasmas. These differ from conventional plasmas by strong Coulomb interaction, the energy of which exceeds the kinetic energy. The strength of the interaction energy is measured by the coupling parameter,

$$\Gamma = \frac{q^2}{4\pi\varepsilon_0 a_{ws} k_B T}, \tag{1}$$

where a_{ws} denotes the Wigner-Seitz radius (the maen interparticle distance). Despite the strongly different density and temperatures of different nonideal plasmas (Fig. 1), key properties of all nonideal plasmas follow universal trends. In fact, plasmas with the same value of Γ exhibit very similar behavior [1]. In other words, realizing a certain value of Γ in one plasma immediately allows for predictions for a broad range of other plasmas [3]. Strong correlations are typically observed at low temperatures (e.g. non-neutral plasmas such as ions in Penning or Paul traps) and/or high density (laser plasmas, plasmas in the core of planets or compact stars), cf. Eq. (1). An exception are complex plasmas where strong coupling can be easily achieved even at room temperature and very modest densities, cf. Fig. 1. The reason is the use of large particles (typically with a radius of several microns) that can collect very high charge (from tens to hundred thousand elementary charges) in a discharge environment.

These nonideal complex plasmas feature the strongest correlations reported so far, and experiments allow for an unprecedented precision and full single-particle resolution of the stationary and time-dependent many-particle behavior. Typical cooperative (selforganization) behavior arising from the strong Coulomb interaction is spatial ordering of particles into liquid-like and even crystalline arrangements as well as quite peculiar collective modes. While many of these properties of complex plasmas

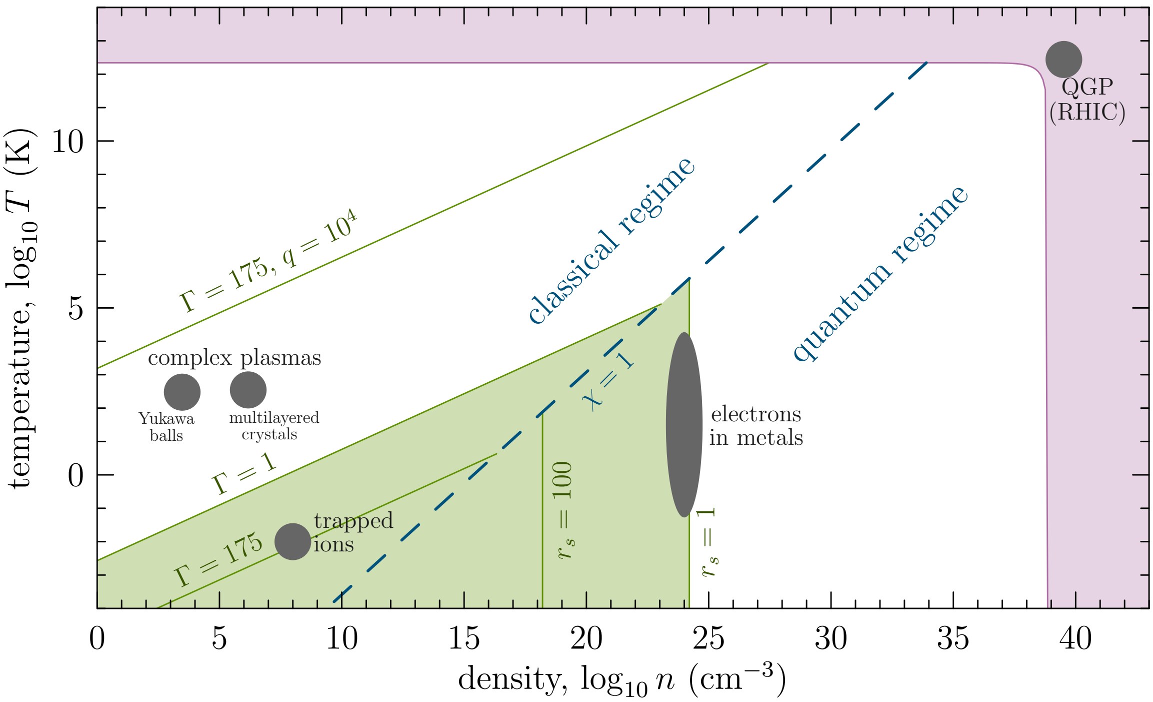

Fig. 1: Density-temperature range of nonideal plasmas. Nonideality effects are important in the shaded (green) area, (below the line $\Gamma = 1$ and left from the line $r_s = 1$) and lead to spatial selforganization phenomena such as formation of liquid-like and solid structures. Coulomb crystallization is observed for $\Gamma > 175$. Complex plasmas allow to realize crystallization requirements at room temperature due to the high charge on the particles. Here, Γ is the classical coupling parameter, Eq. (1), and r_s the quantum coupling parameter [3]. The outer layer of extreme temperatures and densities corresponds to the range where the quark-gluon-plasma (QGP) is expected to exist which represents an example of a weakly nonideal plasma (with color Coulomb interaction). From Ref. [1].

have been topic of recents reviews and text books, here we sketch some new developments related to the influence of a magnetic field. Then the plasma properties (assuming for simplicity a single plasma component embedded into a neutralizing background) are governed by a second dimensionless parameter, the ratio of the cyclotron frequency to the plasma frequency,

$$\beta = \frac{\omega_c}{\omega_p} \tag{2}$$

describing the ratio of magnetic field and Coulomb interaction effects. For $\beta \gtrsim 1$ a complex plasma will be strongly magnetized leading to drastically changed properties. An example are the transport properties such as conductivity, heat conductivity or mobility. In Fig. 2 we show the behavior of the diffusion coefficient of a nonideal plasma (one-component plasma model) as function of β for different values of the coupling parameter. First we observe that diffusion perpendicular to the magnetic field direction decreases both with β and Γ. For small Γ the familiar quadratic decrease with B is recovered. Interestingly, for large magnetic field, $\beta > 1$, the decrease resembles Bohm diffusion ($D \sim 1/\beta$). It is interesting to consider also the diffusion coefficient in field direction which is constant in conventional high-temperature plasmas. However, in nonideal plasmas, a reduction with β is observed as well [4]. This is explained by selforganization phenomena. Due to Coulomb interaction the particle motions perpendicular and parallel to the field become coupled, and the field dependence of $D_\perp$ affects the behavior of parallel diffusion.

The reason why Bohm diffusion is recovered in a nonideal plasma can be traced to collective modes excited in these systems. It is, therefore, interesting to analyze the plasmon spectrum of a complex plasma. Due to the strong coupling, traditional approaches based on the Vlasov dielectric function fail. Instead there exist alternative analytical approaches that derive from condensed matter theory, most

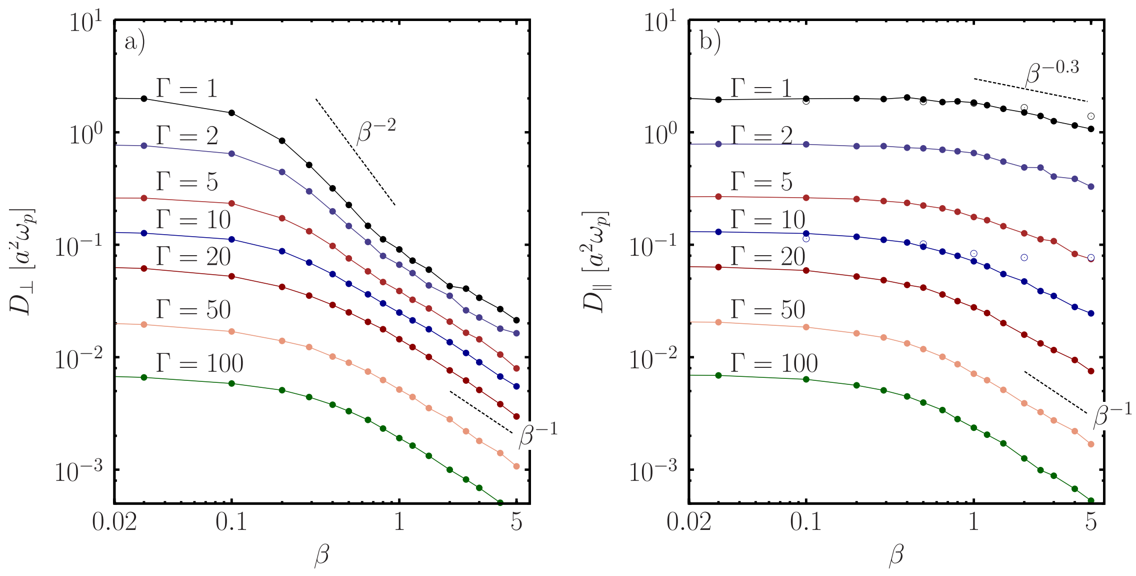

Fig. 2: Diffusion coefficient in a nonideal plasmas as a function of magnetic field strength. Left (right) panel shows the diffusion coefficient perpendicular (parallel) to the field for different coupling strengths Γ. The dimensionless magnetic field strength is given by $\beta = \omega_c/\omega_p$. From Ref. [4].

notably, the computation of phonon spectra for crystals or the quasi-localized charge approximation (QLCA) by Kalman and Golden, for the liquid state, which generally agree well with simulations. Here we show results from first-principle molecular dynamics simulations [5] which are exact, up to (small) computational noise. Fig. 3 depicts the plasmon spectrum of a two-dimensional strongly correlated in a liquid state, as it can be realized in dusty plasmas. The upper plot shows the spectrum for a weak magnetic field and contains two modes. The first is the (magneto-)plasmon which, however, has a quite unusual wave number dispersion strongly differing from high-temperature plasmas and reflecting correlation effects. Note that there is a second low-frequency mode – a shear mode – which is due to strong correlations and was predicted QLCA and confirmed by experiments. There is substantial damping (Landau damping and collisional damping). The lower two plots show the change of the spectrum when the magnetic field is increased. Evidently the field strongly reduces the damping and flattens the dispersion (middle plot). Furthermore, the magnetice field gives rise to additional high-frequency modes that appear to be equally spaced and resemble Bernstein modes of high-temperature plasmas. In contrast to the latter which occur at multiples of the cyclotron frequency, here the frequency spacing is different, and the frequency of the n-the harmonic is $\omega_n = n\sqrt{(\omega_c^2 + 2\omega_E^2)}$. This frequency is the geometric mean of the cyclotron frequency and the Einstein frequency which corresponds to the mean oscillation frequency of a particle in the frozen eінvironment of all the others, thus reflecting the correlations of the nonideal plasma.

These results are of importance for strongly correlated and strongly magnetized plasmas that are expected to exist e.g. in the outer layers of neutron stars where β may reach values on the order of $1 \ldots 10^3$. Current experiments with dusty plasmas using superconducting magnets reach only values $\beta \ll 1$ due to the large size of the particles. Recently a novel method has been proposed how to reach values of $\beta \sim 1 \ldots 10$ [6] that will allow to experimentally investigate stronlgy magnetized nonideal plasmas in the near future.

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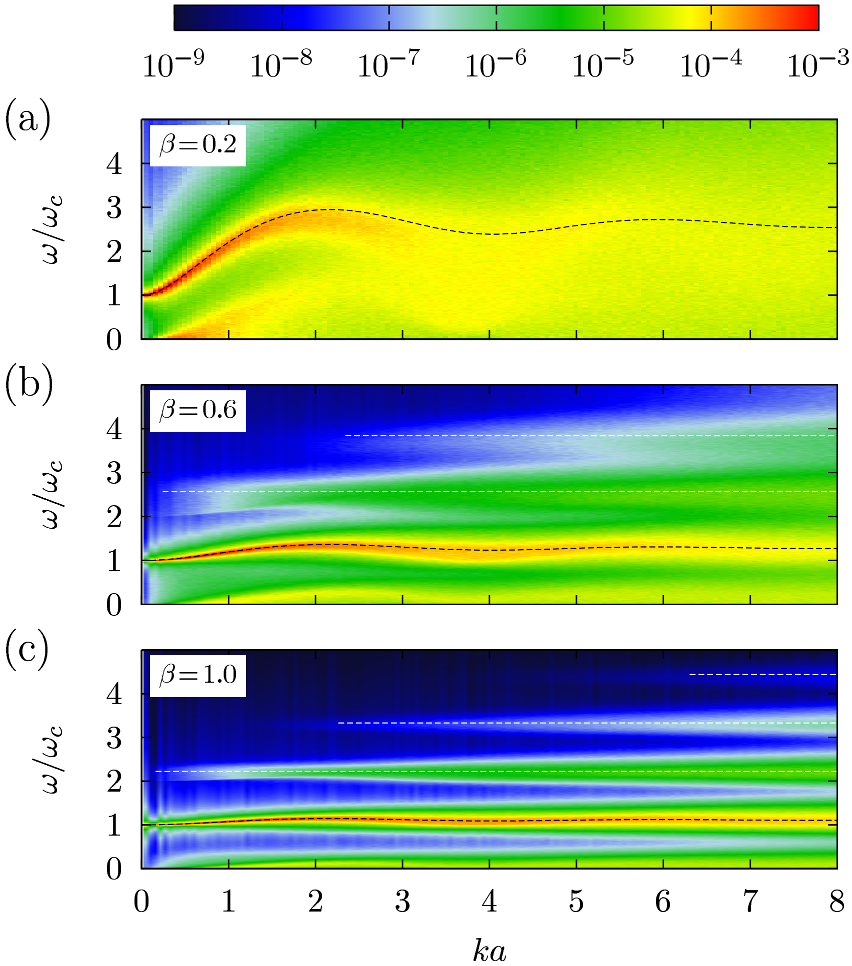

Fig. 3: Collective plasma oscillations in a nonideal two-dimensional one-component plasma with statically screened interaction, $\kappa = 2$, and $\Gamma = 200$ for three different magnetic field strengths β. The upper figure shows the magnetoplasmon and magnetoshear mode, whereas the lower ones contain additional modes – "dressed" Bernstein modes. First-principle molecular dynamics simulation results (color) and QLCA dispersion (black dashed line) [5].

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References

[1] M. Bonitz, C. Henning, and D. Block, Reports Progr. Phys. **73**, 066501 (2010)

[2] "Introduction to Complex Plasmas", M. Bonitz, N. Horing, and P. Ludwig (eds.), Springer, Berlin (2010)

[3] For completeness, we mention that in quantum plasmas there exists a second parameter, $r_s = a_{ws}/a_B$, where a_B is the Bohr radius. In multicomponent plasmas the situation is even more complex, for details and further references, see Ref. [2].

[4] T. Ott, and M. Bonitz, Phys. Rev. Lett. **107**, 135003 (2011)

[5] M. Bonitz, Z. Donko, T. Ott, H. Kählert, and P. Hartmann, Phys. Rev. Lett. **105**, 055002 (2010)

[6] H. Kählert, J. Carstensen, M. Bonitz, H. Löwen, F. Greiner, and A. Piel, submitted for publication