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Non-perturbative treatment of strongly-interacting fields: Insights from liquid theory

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HIGHLIGHTS

- We propose a new programme of solving the problem of strong interactions in field theory.
- The proposed approach is not perturbative and does not give divergences.
- We show the equivalence of Hamiltonians describing liquids and interacting fields.
- We show that Frenkel energy gap and massive Frenkel particles emerge as a result of interaction in the field.

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ABSTRACT

We outline a new programme of solving the problem of treating strong interactions in field theories. The programme does not involve perturbation theories and associated problems of divergences. We apply our recent idea of treating strongly interacting liquids to field theories by showing the equivalence of Hamiltonians of liquids and interacting fields. In this approach, the motion of the field results in the disappearance of $n-1$ transverse modes with frequency smaller than the Frenkel frequency ω_F, similar to the loss of two transverse modes in a liquid with frequency $\omega < \omega_F$. We illustrate the proposed programme with the calculation of the energy and propagator, and show that the results cannot be obtained in perturbation theory to any finite order. Importantly, the Frenkel energy gap $E_F = \hbar\omega_F$ and the associated massive Frenkel particle naturally appear in our consideration, the result that is relevant for current efforts to demonstrate a mass gap in interacting field theories such as Yang–Mills theory. Notably, our mechanism involves a

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physically sensible starting point in terms of real masses (frequencies) in the harmonic non-interacting field, in contrast to the Higgs effect involving the imaginary mass as a starting point. We further note that the longitudinal mode in our approach remains gapless, implying that both short-range and long-range forces with massive and massless particles naturally emerge and unify in a single interacting field, a result not hitherto anticipated. Finally, we comment on the relationship between our results and hydrodynamic description of the quark–gluon plasma.

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1. Introduction

The frontiers of modern physics are often said to lie in two directions where no adequate theoretical description exists: micro-world (particle physics, unified description of interactions and so on) and mega-world (cosmological problems). On the other hand, theoretical description of the familiar macro-world is considered to be largely complete. This is not quite the case: whereas solids and gases are well understood, the third state of the macro-world, the liquid state, presents serious theoretical problems. Surprising though it may seem, these problems are similar to those existing in the micro-world and mega-world from the point of view of physics and mathematics.

The main problem of theoretical description of liquids is the absence of a small parameter: contrary to solids and gases, kinetic and potential energy of atoms in the liquid are comparable in magnitude. As a result, it is impossible to develop a theory of real strongly interacting liquids by starting from the gas state and turning the interaction on. It is equally impossible to develop a first-principles theory of liquids by starting from the harmonic solid and introducing anharmonicity of interactions which increase the amplitude of vibrations leading to melting because the problem of the macroscopic number of bifurcations in the non-linear many-body system is not tractable. Since using the small parameter approach and perturbation theory is the main method of theoretical physics, the "gas" description of liquids has been most popular despite its inadequacy. Yet more than half a century ago J. Frenkel has proposed [1] a way to avoid infinitely complex mathematical problems involved in constructing a theory of liquids. He asserted that the motion of atoms in a liquid consists of almost harmonic oscillations as in the solid and fairly rare jumps of atoms between different adjacent equilibrium positions. The average time between these jumps is liquid relaxation time, τ. Calculating τ from first principles still remains an impossible task, but if we obtain τ from another experiment or computer simulation we are able to derive and explain most important liquid properties. In the last few years, we have used this approach to construct a thermodynamic theory of liquids in the wide range of parameters and explain excitation spectra and other physical properties of liquids [2–4]. Below we discuss how this approach can be applied to strong interactions in field theories and elementary particles.

In field theories, interactions are introduced to free field Hamiltonians to describe the processes of production of new particles, calculate their cross-sections as well as discuss interactions between different types of fundamental forces [5–7]. Problems related to divergences and infinities originating in perturbation theories of interactions have been raised at the early stages of development of field theories [8], stimulating new ideas, tour-de-force calculations as well as deeper philosophical issues [6]. The problem of divergences and divergent perturbation series remains profound and fundamental [9].

Notably, the treatment of interactions in field theories has been based on the premise that the only way of treating interaction terms is by using the perturbation theory (see, for example, p. 200 in Ref. [7]). The divergences arising in perturbation expansions are therefore viewed as a common necessity [5,6].

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