PACS numbers: **03.75.–b**, 05.70.Fh, 64.60.Ht
DOI: 10.1070/PU2008v051n06ABEH006544
DOI: 10.3367/UFNr.0178.200806h.0633

Formation kinetics of the Bose condensate and long-range order

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The rapidly developing area of research related to ultracold gases has opened up the unique possibility of studying the formation kinetics of a Bose condensate and long-range order. The isolation of a gas from the walls in magnetic and electric traps and the possibility of observing the intrinsic real-time evolution of the system are the decisive factors in this case. Although the first theoretical papers in this field appeared in the early 1990s, it was not until 2007 that the first experimental research on the time evolution of long-range order was reported in the literature [1 – 2]. A vigorous study of this phenomenon was pursued between these dates, and this report is concerned with the analysis of the data and existing notions in this area.

The capability of rapid cooling by cutting off the Maxwellian tails enables studying the evolution starting from the points in time when all correlation properties of a gas are purely classical and there is not the slightest trace of a condensate. In this case, the kinetics proceed with conservation of the total energy and the number of particles in the system. As it turns out, the evolution comprises four stages.

During the first stage, which is described by the Boltzmann equation, a particle flux forms in the energy space, directed towards lower energies. When the particles that constitute the condensate in equilibrium occur in the energy range where the kinetic energy is lower than the interparticle interaction energy, the formation of collective correlations sets in and the kinetic equation is no loner valid (the number of particles that fall into this energy range, which is commonly termed the coherence interval, is comparable with the total number of particles). But even before this, the evolution goes through a stage during which all occupation numbers of individual modes become much greater than unity. As shown in Refs [3, 4], the system is then adequately described by the classical Bose field, which obeys the nonlinear Schrödinger equation in the form of the Gross – Pitaevskii equation. The solution of this equation leads to an important result: in the coherence interval, the fluctuations of density are suppressed and the single-particle density matrix depends only on phase fluctuations. At this stage, a special quasicondensate state emerges, which is equivalent to the genuine condensate in local properties, but has no long-range order. An instantaneous picture of the gas actually demonstrates the division of the system into finite-size quasicondensate domains. Each domain has a specific phase in the absence of phase correlation between different domains.

This picture underlay the prediction that the evolution during the third stage should be accompanied by the emergence of a vorticity structure. This prediction was borne out by the direct numerical solution of the nonlinear Schrödinger equation [5], which demonstrated the emergence of a vorticity ball and its temporal evolution.

The final stage is characterized by the damping of nonequilibrium regular-phase fluctuations and the relaxation of the vorticity structure. This occurs with an increase of quasicondensate domains in size, which is effectively equivalent to an increase in the density-matrix decay distance, thereby determining the evolution of the long-range order scale [3, 4] (see also Ref. [6]). The long-range order settling time τ_L increases with the domain size L: $\tau_L \sim L^n$, where $n = 1-2$, depending on parameter ratios.

The report presents a comparison with the theory and a comprehensive analysis of the experimental results found in Refs [1, 2], especially of the temporal evolution of long-range order formation [1]. The analysis relies on the theory elaborated for the analog of the Hanbury – Brown – Twiss effect for particles in the 'two sources, one detector' setup in the evolution of a nonequilibrium system involving a classical-to-quantum transformation of correlations [7]. Experimental data are qualitatively and quantitatively compared with theoretical predictions.

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PACS numbers: 05.30.Fk, **71.10.–w**, 74.20.Fg
DOI: 10.1070/PU2008v051n06ABEH006548
DOI: 10.3367/UFNr.0178.200806i.0633

Superfluid Fermi liquid in a unitary regime

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1. Introduction

When choosing the subject of my presentation at this session dedicated to the 100th anniversary of the birth of Landau, I wanted to speak about something that would have surprised Landau. I believe that the recently prepared physical object — a universal superfluid Fermi liquid — meets this requirement in the best way possible.

As is well known, Landau did not regard the microscopic theory of fluids as a problem worth being occupied with. I quote a well-known passage from *Statistical Physics* [1]: "In contrast to gases and solids, liquids do not permit calculating the thermodynamic quantities or at least their temperature dependences in the general form. The reason lies with the strong interaction between the molecules of a liquid and, at the same time, the absence of the smallness of oscillations, which imparts simplicity to the thermal motion in solids. Because of the high intensity of molecular interaction, the knowledge of a specific interaction law, which is different for different liquids, becomes significant for calculating thermodynamic quantities."

This statement is perfectly correct for all liquids existing in nature. However, progress in experimental techniques has recently enabled preparing liquids with properties independent of any quantities that characterize the interaction. This situation emerges because the interatomic interaction in these bodies is, in a sense, infinitely strong. The case in point is ultracold gases near the so-called Feshbach resonances.