論文内容の要旨

論文題目: Phase structure and low-energy excitations in spinor Bose-Einstein condensates

(スピノール・ボース・アインシュタイン凝縮体における相構造及び低エネルギー励起)

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We study the phase structure and low-energy excitations in spin-1 and spin-2 Bose-Einstein condensates (BECs). We demonstrate that the spinor BEC of ultracold atomic gases represents highly nontrivial phenomena and provides a venue to understand essence of condensates with internal degrees of freedom such as superfluid ^{3}He, high-T_C superconductivity, and color superconductivity in quantum chromodynamics.

By using the Gross-Pitaevskii analysis, we first show the possible phase structure of spin-1 and spin-2 BECs in the presence or absence of the quadratic Zeeman effect. In the second place, based on the Bogoliubov theory, we take into account the effect of quantum fluctuations and seek the Bogoliubov excitation modes and Lee-Huang-Yang corrections to the ground-state energy, pressure, sound velocity, and quantum depletion. We investigate the Bogoliubov theory for all the phases of spin-1 and spin-2 BECs that can be realized experimentally.

We then focus on the massless Bogoliubov modes and try to relate them to Nambu-Goldstone (NG) modes. We examine relationships between the number of symmetry generators that are spontaneously broken and that of NG modes in spin-1 and spin-2 BECs in light of rules discussed in nuclear physics. It is found that in a spin-2 nematic phase there are special Bogoliubov modes that have gapless linear dispersion relations but do not belong to the ordinary NG modes.

We show that such residual massless modes in the nematic phase are quasi-NG modes, which play a prominent role in high energy physics but have been elusive experimentally. Emergence of the quasi-NG modes originates from the fact that the symmetry of the nematic phase is larger than that of the Hamiltonian. When they appear, the conventional order parameter manifold should be enlarged. Consequently, topological defects that are stable within the conventional order parameter manifold become unstable and decay by emitting the quasi-NG modes. Contrary to conventional wisdom, however, we show that the topological defects are stabilized by quantum fluctuations that make the quasi-NG modes massive, thereby suppressing their emission.