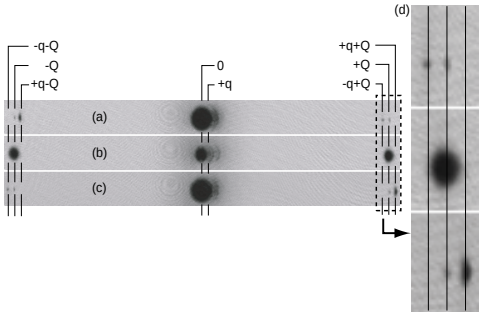
Experimental observation of the Bogoliubov transformation for a Bose-Einstein condensed gas

The pioneering paper by Bogoliubov in 1947 was the starting point for a microscopic theory of superfluidity [1]. Bogoliubov found the non-perturbative solution for a weakly interacting gas of bosons. The main step in the diagonalization of the Hamiltonian is the famous Bogoliubov transformation, which expresses the elementary excitations (or quasi-particles) with momentum q in terms of the free particle states with momentum +q and –q. For small momenta, the quasiparticles are a superposition of +q and -q momentum states of free particles.

Following the theoretical suggestion in ref. [2] we observed such superposition states by first optically imprinting phonons with wavevector q into a Bose-Einstein condensate and probing their momentum distribution using Bragg spectroscopy with a high momentum transfer. By combining both momentum and frequency selectivity, we were able to "directly photograph" the Bogoliubov transformation [3].



Momentum distribution of a condensate with phonons. After imprinting +q phonons into the condensate, momentum analysis via Bragg spectroscopy transfers a momentum ±Q (two photon recoil) to the atoms. Absorption images after 40 ms time of flight in (a), (b), and (c) show the condensate in the center and outcoupled atoms to the right and left for probe frequencies of 94, 100, and 107 kHz, respectively. The small clouds to the right of the condensate are phonons which were converted to free particles. The size of the images is 25 x 2.2 mm. (d) The outlined region in (a) - (c) on the right is magnified, and clearly shows outcoupled atoms with momenta Q±q, implying that phonons with wavevector $q/\hbar$ have both +q and -q free particle momentum components.

1. N.N. Bogoliubov, *On the theory of superfluidity*, J. Phys. (USSR) **11**, 23 (1947).
2. A. Brunello, F. Dalfovo, L. Pitaevskii, and S. Stringari, *How to Measure the Bogoliubov Quasiparticle Amplitudes in a Trapped Condensate*, Phys. Rev. Lett. **85**, 4422 (2000).
3. J.M. Vogels, K. Xu, C. Raman, J.R. Abo-Shaeer, and W. Ketterle, *Experimental observation of the Bogoliubov transformation for a Bose-Einstein condensed gas*, Phys. Rev. Lett. **88**, 060402 (2002).