Novel sound phenomena in superfluid helium in aerogel and other impure superfluids

Peter Brusov [a,1], Paul Brusov [b], Gavin Lawes [c], Jeevak Parpia [c], Chong Lee [d], Akira Matsubara [e], Osamu Ishikawa [f]

[a] *Low temperature laboratory, Physical Research Institute, Rostov-on-Don, 344090, Russia*
[b] *Department of Physics and Applied Physics, Strathclyde University, Glasgow, G4 0NG , UK*
[c] *Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca 14853, NY, USA*
[d] *Physics Dept., Hannam University, Daedukgu, Taejon, Korea*
[e] *Dept. of Physics, Graduate School of Science, Kyoto University, Kyoto, Japan*
[f] *Graduate School of Science, Osaka City University, Sugimoto 3-3-138, Sumiyoshi-ku, Osaka, Japan*

Abstract

Impure superfluids exhibit very unusual properties including unexpected acoustic features. We calculate the coupling between temperature and pressure oscillations for impure superfluids and for superfluid He in aerogel and show that the coupling between first and second sound modes is governed either by $c\frac{\partial\rho}{\partial c}$ (c is impurity concentration) or by $\sigma\rho_a\rho_s$ (ρ_a is aerogel density), rather than by the thermal expansion coefficient $\frac{\partial\rho}{\partial T}$, which is enormously small in pure superfluids. This replacement plays a fundamental role in sound phenomena. It leads "to the existence of such phenomena as the slow ""pressure"" waves and fast ""temperature"" " waves and modifies significantly all sound conversion phenomena.

Key words: "superfluids;impurity;aerogel;sound"

1. Enhancement of the coupling between sound modes in impure superfluids

For a great deal of time, the only impurities in He II studied experimentally were dissolved ^{3}He atoms. In the last decade new techniques for producing impure superfluids with unique properties have been developed and these new systems have been studied intensively. This new class of systems include superfluid helium confined to aerogel (Cornell, Lancaster, Manchester, Northwestern), He II with different impurities (D_2, N_2, Ne, Kr) (Cornell), superfluids in Vycor "glasses, and watergel - a frozen water ""lattice"" in HeII (Chernogolovka). These " systems exhibit very unusual properties including unexpected acoustic features. We discuss the sound properties of these systems and show that sound phenomena in impure superfluids are modified from those in pure superfluids[1]. " A bulk superfluid supports two sound modes; first sound which is ordinary sound " corresponding to pressure (density) oscillations at constant entropy density and second sound, representing temperature (entropy) oscillations. These modes turn out to be decoupled via smallness of the thermal expansion coefficient $\frac{\partial\rho}{\partial T}$. We calculate the coupling between temperature and pressure oscillations for impure superfluids (including ^{3}He -^{4}He mixtures) and for superfluid He in aerogel. To study coupling of sounds in impuried superfluids we suppose that impurities participate just in normal moving and add to the system of hydrodynamic equations the continuity equation for impurities. To analyze the sound conversion phenomena in He in aerogel we use the modification of hydrodynamic equations introduced for this case by McKenna et. al.

[1] Email : pnb1983@yahoo.com

[2].We replace $\rho_n \to \rho_n + rho_a = \rho_{na}$ and add the extra restoring force P_a due to the aerogel. We show that the coupling between these two sound modes is governed either by $c\frac{\partial\rho}{\partial c}$ (c is impurity concentration) or by $\sigma\rho_a\rho_s$ (ρ_a is aerogel density), rather than by $\frac{\partial\rho}{\partial T}$. This replacement plays a fundamental role in sound phenomena in impure superfluids and in superfluids in aerogel. It enhances the coupling between two sound modes and decreases the threshold values for nonlinear processes as compared to homogeneous superfluids. It leads to the existence of such phenomena as the slow mode and heat pulse propagation with the velocity of first sound observed in superfluids in aerogel. This means that it is possible to observe in impure superfluids such unusual sound phenomena as slow pressure (density) oscillations and fast temperature (entropy) oscillations. Sound conversion, which has been observed in pure superfluids only by shock waves should be observed at moderate sound amplitude in impure superfluids. Also, Cerenkov emission of second sound by first sound (which never been observed in pure superfluids) could be observed in impure superfluids. Some unexplained phenomena observed in superfluid He in aerogel, namely a slow pressure mode with all other attributes of thermal waves[3]. as well as fast thermal waves[4]can be understood in terms of the increased coupling between pressure and temperature oscillations.Pressure oscillations only propagate with a speed u_1, while thermal oscillations propagate with a speed u_2. Exciting pressure oscillations causes temperature oscillations in the vicinity of the transducer. If these oscillations have a low frequency, corresponding to the speed of second sound, thermal waves can propagate, while pressure oscillations cannot. These thermal oscillations in turn generate pressure oscillations at the receiving transducer. This is observed in He in aerogel (but not in pure superfluids) because of the significant increasing in coupling between pressure and temperature oscillations. Fast thermal waves can be understood with a similar argument

2. Change the nature of first and second sounds

Let us show that the presence of impurities changes even the nature of first and second sounds.In pure superfluids, for first sound $v_n \approx v_s$, while for second sound $j = \rho_n v_n + \rho_s v_s = 0$, if one neglects the thermal expansion coefficient β. To the first order in β approximate one finds:

$$j = \frac{\beta\rho}{s\rho_n}\frac{u_1^2 u_2^2}{u_1^2 - u_2^2} v_s \tag{1}$$

so the mass flow in impure superfluids is non-zero in second sound because of the replacement of β by $\sigma\rho_s\rho_n$ (or $c\partial\rho/\partial T$).For first sound

$$v_n = v_s\left(1 + \frac{\beta\rho}{\rho_s s}\frac{u_1^2 u_2^2}{u_1^2 - u_2^2}\right). \tag{2}$$

so $v_n \neq v_s$ in impure superfluids. For example [5] , in ^{3}He-^{4}He mixtures at c=0.2 for the wide temperature region for first sound

$$v_n = (1.2 - 1.5)v_s \tag{3}$$

and for second sound

$$v_n = -(0.6 - 0.8)\frac{\rho_s}{\rho_n}v_s. \tag{4}$$

This means that in impure superfluids 1) normal and superfluid components in first sound don't longer move coherently, 2) mass flow in second sound is nonzero and could be significant. The enhanced coupling between first and second sound changes the nature of the modes. Just three processes are allowed by conservation laws, two of them for conversion of first sound into second sound (parametric decay of first sound and Cerenkov emission of second sound by first sound) and just one for conversion of second sound into first sound (transformation of two second sounds into first sound).Cerenkov emission of second sound by first sound never been observed even in pure superfluids, while parametric decay of first sound and transformation of two second sounds into first sound have been observed in pure HeII by shock waves. We have shown that increased coupling of sounds in impure superfluids decreases the threshold of all nonlinear processes and leads to possibility of observation of sound conversion at moderate pressure (temperature) amplitude in opposite to case of pure superfluids, where shock waves were used. Cerenkov emission could be observe in impure superfluids.

References

[1] Peter Brusov, *et al.*, Phys. Rev. B Rapid Commun., **63**, 14507 (2001).

[2] M. J. McKenna, *et al.*, Phys. Rev. Letts. **66**, 1878 (1991).

[3] A. Golov, D. A. Geller and J. M. Parpia, Phys. Rev. Letts. **82**, 3492 (1999).

[4] N. Mulders, *et al.*, Phys. Rev. Letts. **67**, 695 (1991).

[5] B.Eselson, *et al.*, Usp. Fiz. Nauk**112**,591(1974).