Bubble nucleation in a superfluid ^{3}He–^{4}He mixture induced by acoustic wave

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We report the nucleation dynamics of bubbles induced by an acoustic wave pulse in ^{3}He–^{4}He liquid mixtures. The experiment was performed for the mixture with ^{3}He fixed concentrations of about 4% and 25% and the pure superfluid ^{4}He. When a pulse of 1 ms duration was applied to the mixture at the saturated vapor pressure, a spherical bubble was nucleated on the active area of a piezoelectric transducer. For the case of pure ^{4}He, not a spherically shaped bubble, but an irregularly shaped, larger one was observed. We took pictures with a high speed CCD camera of the bubble expansion and contraction motions after the nucleation. We also investigated the temperature dependence of the bubble nucleation by changing the acoustic wave power. The results show that the nucleation and growth dynamics of a cavitation bubble depend greatly on the ^{3}He concentration and temperature.

1. Introduction

The dynamics of a spherical bubble in a normal liquid has extensively been studied both theoretically [1,2] and experimentally [3,4]. Such a bubble can be produced by focusing a pulsed laser beam in normal liquids such as water and liquid nitrogen. For a bubble in liquid ^{4}He, a focused acoustic wave produced by a hemispherical piezoelectric transducer is used to generate a negative pressure in the small central part of the liquid bulk. The cavitation of bubbles is detected by light scattering [5,6]. Recently a visual observation of the boiling bubble nucleation in liquid ^{3}He was also reported [7]. In a liquid ^{3}He–^{4}He mixture, however, bubble nucleation has not been studied yet.

This paper reports the visual observation of the dynamics of a bubble cavitation generated by an acoustic wave pulse on the surface of a single-mode piezoelectric transducer immersed in a superfluid ^{3}He–^{4}He mixture.

There are several unique properties of superfluid mixtures propelling the study of bubble dynamics. Since the viscosity of a superfluid is considerably lower than that of an ordinary liquid, it is possible to observe a bubble motion at a large Reynolds number which is an important parameter in fluid dynamics. The viscosity in a liquid ^{3}He–^{4}He mixture can be varied over a wide range by changing the ^{3}He concentration and the temperature. Compared with a single-component liquid, the binary liquid mixture has one more attractive aspect. This is associated with the possible nucleation of the ^{3}He-concentrated phase from the supersaturated ^{3}He-dilute phase as a result of acoustic pulse. The growth kinetics of the ^{3}He-concentrated phase droplet in the ^{3}He-dilute phase has been studied in Refs. 8, 9. Thus the tensile strength of a liquid ^{3}He–^{4}He mixture can be manifested, depending on the conditions, in at least three ways as: boiling bubbles, cavitation bubbles, and the formation of ^{3}He-concentrated droplets.
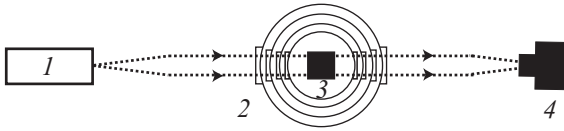
Fig. 1. A schematic of the experimental setup. Halogen light (*1*), cryostat (*2*), sample cell (*3*), CCD camera (*4*).

2. Experimental details

Figure 1 shows a schematic of the experimental setup. A ^{3}He–^{4}He dilution refrigerator is used for the experiment [10,11]. The inside of the cell can be observed through several infrared filters and infrared absorption glass from the outside. The cell has two $LiNbO_3$ transducers spaced about 10 mm apart and facing each other. The volume between the transducers is filled with the mixtures, ^{3}He concentration being either about 4% or 25%. The shadowgraph images were taken by a high-speed camera at 1000 fps [12]. The fundamental frequency of the transducer is 9.3 MHz, its diameter is 10 mm and that of the effective area is 4 mm. A com-
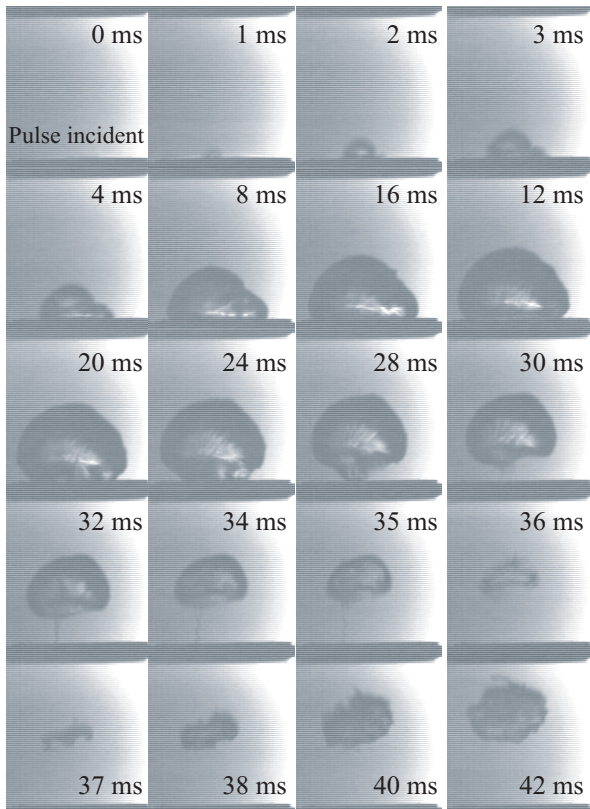

Fig. 2. Images of a sound-induced bubble on the surface of the piezoelectric transducer in a liquid ^{3}He–^{4}He mixture with the ^{3}He concentration of 4% at 300 mK. The applied voltage was 10.0 V and acoustic pulse duration was 1 ms. The frame width was 10 mm.

mercial RuO_2 resistance thermometer is placed in the cell and the pressure in it is monitored by a capacitive strain gauge.

3. Results and discussion

Figure 2 shows images of the bubble motion observed at 300 mK in the mixture with the ^{3}He concentration of about 4%. The duration of a acoustic wave pulse was 1 ms and the voltage applied to the transducer was about 10 V. Once the bubble was generated, it expanded explosively on the transducer surface within the time of 1–24 ms after the pulse was turned off. Then the bubble detached from the surface while contracting during 24–30 ms, collapsed with the upward jet flow at 30–36 ms, re-expanded, and ascended at 36–42 ms.

In the previous paper [13,14], we reported a liquid jet flow which pierced the center of the bubble in the ^{3}He-dilute phase at about 200 mK when the bubble detached from the transducer surface. From the flow patterns we proposed that the vortex ring was generated due to the jet flow. In the 4% ^{3}He mixture we also observed the liquid jet-like flow at 30–35 ms but we could not as clearly identify that the vortex ring had been formed at 36 ms in Fig. 2 as in the phase separated ^{3}He-dilute phase.

Figure 3 shows the images of the bubble motion observed at 680 mK in the 4% ^{3}He mixture. The acoustic pulse duration was 1 ms and the voltage applied to the transducer was about 6.14 V. The bubble showed similar behavior as in Fig. 2. Figure 4 shows the images of the bubble induced at 5.65 V voltage at 750 mK in the mixture with the ^{3}He concentration of 25%. The bubble ex-
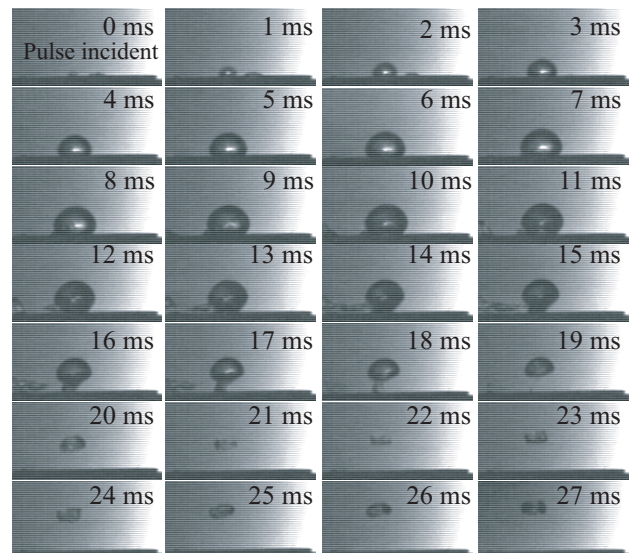

Fig. 3. Images of a sound-induced bubble on the surface of the piezoelectric transducer in a liquid ^{3}He–^{4}He mixture with the ^{3}He concentration of about 4% at 680 mK. The applied voltage was 6.14 V and acoustic wave pulse duration was 1 ms. The frame width was 10 mm.
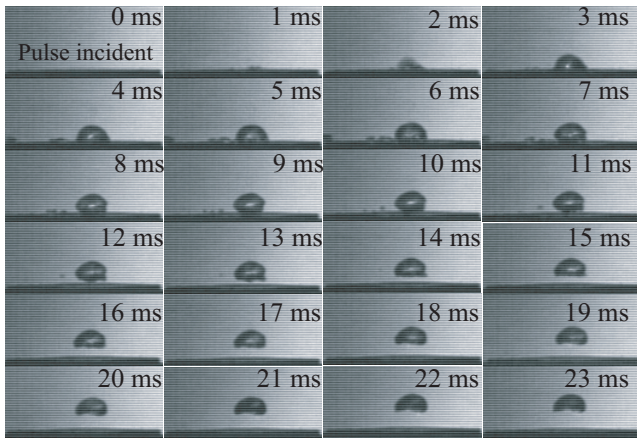
Fig. 4. Images of a sound-induced bubble on the surface of the piezoelectric transducer in a liquid ^{3}He–^{4}He mixture with the ^{3}He concentration of 25% at 750 mK. The applied voltage was 5.65 V and acoustic wave pulse duration was 1 ms. The frame width was 10 mm.

Fig. 6. The threshold times pulse width for the bubble nucleation. The pulse duration was 1 ms for ^{3}He–^{4}He mixtures and 5 ms for the pure superfluid ^{4}He.

perienced a small expansion and ascended without contraction. Figures 3 and 4 show that the collapse time for the bubble in Fig. 4 was longer than that in Fig. 3; this difference seems to depend on the ^{3}He concentration.

The temperature dependence of the bubble nucleation threshold in the 4% and 25% mixtures is plotted in Fig. 5. The temperature range varies from 150 mK to 850 mK in the 4% mixture, and from 500 mK to 800 mK in the 25% mixture. For the 25% mixture, data points are terminated at around 500 mK, since the mixture experiences phase separation below that temperature.

For both mixtures, the threshold voltage increased gradually as the temperature decreased. For the 4% mixture, the voltage at the minimum temperature was 2.5 times larger than that at the highest temperature. The same tendency was observed for the 25% mixture. This appears to be thermally activated type of nucleation, but at the mo-
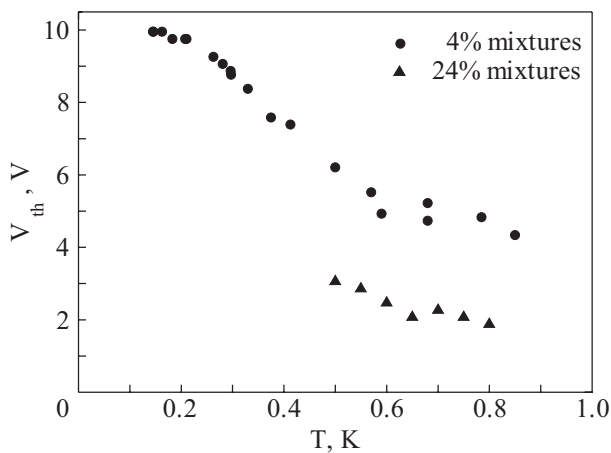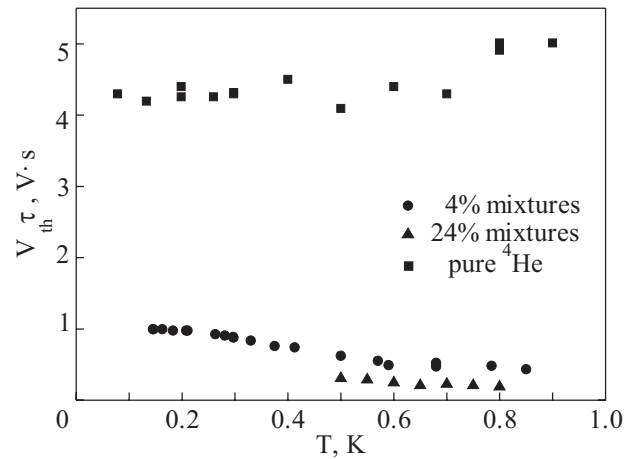
ment, it is difficult to estimate the activation energy, since the experimental data are insufficient. As the temperature goes down, the viscosity of both mixtures increases with the Fermi degeneracy. It would be interesting to investigate how the viscosity affects the nucleation in a mixture in the lowest temperature region.

Another interesting feature is that the threshold voltage goes down as the ^{3}He concentration increases. ^{3}He does make it easier for the bubble to be nucleated. This is consistent with the concentration dependence of the surface tension of the mixture.

We also examined the bubble nucleation in pure superfluid ^{4}He (see Fig. 7). In order to induce an inception of bubbles in the superfluid ^{4}He, larger acoustic power and longer duration of a pulse were required. The duration of the pulse applied to the transducer was 5 times as longer. To compare the threshold of nucleation in the mixture, we plotted a threshold voltage multiplied by the pulse width as a function of temperature in Fig. 6. It can easily be seen how difficult it was to nucleate the bubble in pure ^{4}He. In
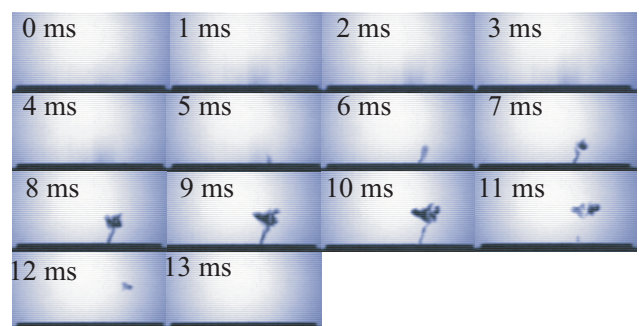

Fig. 5. Threshold of the bubble nucleation with an acoustic pulse. The pulse duration was 1 ms in ^{3}He–^{4}He mixtures.

Fig. 7. Bubble nucleation in superfluid ^{4}He. The applied voltage was 8.5 V at $T = 140$ mK. Acoustic pulse duration was 5 ms. The frame width was 10 mm.

contrast to mixtures, the threshold voltage in the superfluid ^{4}He is almost constant within the whole temperature range.

These distinctions can be understood as follows. First, the tensile strength of liquid ^{4}He against bubble nucleation is noticeably larger than that of liquid ^{3}He. The numerical estimates [15] for zero temperature yield approximately –9 bar for ^{4}He and –3 bar for ^{3}He, respectively. Thus one can expect that the threshold for the bubble nucleation decreases gradually with the growth of the ^{3}He concentration.

The growth of the nucleation threshold voltage in mixtures with decreasing the temperature is likely to be associated with the energy dissipation effect due to the presence of viscosity which grows as the temperature lowers. In superfluid ^{4}He the effect of energy dissipation and viscosity plays, apparently, negligible role and thus the temperature influences the nucleation conditions insignificantly.

Note that the similar temperature behavior of the nucleation threshold voltage is observed in the experiments where the negative pressure is produced by focusing an acoustic wave in the liquid bulk. In spite of the different sound frequency of about 1 MHz the cavitation threshold voltage was approximately temperature-independent in superfluid ^{4}He. In its turn, in normal liquid ^{3}He the threshold voltage is smaller and temperature-dependent, increasing at lower temperatures. For details, see Review 16. Therein one can also find the discussion of such temperature dependences from the point of possibility for the thermal-quantum crossover in the nucleation mechanism.

In addition, the bubble dynamics in superfluid ^{4}He is quite different from that in liquid ^{3}He–^{4}He mixtures. Figure 7 shows images of the observation in the pure superfluid ^{4}He at an amplitude of 8.5 V and 5 ms duration at 140 mK. It turned out that we did not succeed in producing bubbles of the spherical shape in pure ^{4}He. The string-like shape was initially seen at the corner of the active area of the transducer at 5 ms. Next, this tip expanded at 7–10 ms. Obviously, as compared with the bubbles observed in the mixture, it behaved quite differently. When higher voltage was applied to the transducer, the size of the bubble became larger and the shape proved to be highly irregular with an ill-defined surface [13].

4. Conclusions

We observed a single bubble nucleation by acoustic waves in a liquid ^{3}He–^{4}He mixture at the ^{3}He concentration of about 4% and 25%. The shape of the bubble was quite different in the mixtures and pure superfluid ^{4}He. The dynamics of the nucleated bubble became temperature and ^{3}He concentration dependent. In particular, the concentration affected the difference in collapse time of the bubble. We also investigated the temperature dependence of the bubble nucleation threshold. In the superfluid mixture the threshold became smaller as the temperature increased. While, in the superfluid ^{4}He the nucleation threshold was almost temperature-independent. The introduction of ^{3}He impurity facilitates the nucleation of bubbles. The results demonstrate distinctly that ^{3}He impurity in superfluid ^{4}He plays a significant role both in the nucleation of a bubble and in its dynamics.

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