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Radiation linear energy transfer and drop size dependence of the low frequency signal from tiny superheated droplets

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ABSTRACT

The bubble nucleation in superheated tiny droplets of R-12 (CCl_2F_2, boiling point: $-29.8\ ^\circ C$) induced by neutrons and α-particles has been observed using condenser microphone as an acoustic sensor. The superheated droplets used in these experiments are of very small radii having distribution with main peak around 2–3 μm expanding until about 40 μm. The low frequency component of the acoustic shock wave released during bubble nucleation has been measured with condenser microphone and the analysis has been done using ROOT software. Pulses due to bubble nucleation have been recorded in the presence of ^{241}Am–Be neutron source (few keV to about 10 MeV) and ^{241}Am alpha-source (5.48 MeV with intensity 85.2%). The observables related to the power associated with bubble nucleation (P) and the area under the frequency spectrum of the signal (P_{Freq}) have been estimated for the α-particle and neutron induced events. It shows that the α-particle induced bubble nucleation signals are of lower intensity than those obtained from the neutron induced bubble nucleation signals. This phenomenon as observed with tiny droplets is opposite to that observed so far for the larger droplets.

1. Introduction

The superheated liquid is a metastable state of liquid and transits to the stable vapour state through the formation of a nucleus of vapour bubble. The vapour bubble subsequently expands to convert the liquid state to vapour state. A universally accepted complete theory of the mechanism of bubble nucleation is still unavailable. However, Seitz's phenomenological "thermal spike" model [1] provides a good description of the basic principles of the particle/radiation-induced bubble nucleation in a superheated liquid. According to this model, during the passage of an energetic particle through the liquid, a "thermal spike" [1] caused by the energy deposited in a highly localized region within the liquid is responsible for bubble nucleation. As a result, vapour embryos of different sizes are produced along the track of that particle. If the radius of the vapour embryo is larger than or equal to a certain critical radius (r_c), the vapour bubble becomes thermodynamically unstable and grows rapidly to visible size through evaporation of the superheated liquid. Otherwise it collapses back to the liquid state due to surface tension. Acoustic pulse generated during this process provides the signal of the passage of the particle, which can be recorded by acoustic sensors. Superheated droplet detector consisting of the droplets of superheated liquid is a promising neutron detector that has been using since 1979 [2]. Superheated droplet neutron dosimeter is used for measuring neutron dose equivalent in and around the radiotherapy beam and in patients in the presence of large background of photon flux (three to four orders of magnitude larger than neutrons) [3]. The threshold energy for such detector depends on temperature and pressure and the types of the sensitive liquid used in the detector. Thus the detector can be made insensitive to gamma rays while being sensitive to neutrons by varying the ambient temperature and pressure of the liquid. This property of the detector makes it a very useful tool in neutron dose measurement in a strong background of gamma rays.

The use of superheated droplets for measuring alpha-emitting actinides in environmental samples has been described and the alpha-detection efficiency was calculated for various alpha energies and for droplets diameter in the range of 2–10 μm [4]. The technique for measuring alpha activity using superheated emulsion in aqueous solutions was developed and the bubble nucleation rate for alpha induced events was measured for various alpha activities using superheated R-12 liquid droplets of total volume about 2 ml [5].

The superheated droplet detector is also used in cold dark matter WIMPs (Weakly Interacting Massive Particles) search experiments [6–8]. WIMP induced nuclear recoils are similar to neutron induced nuclear recoils. Alpha particle is the dominant

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backgrounds for dark matter search experiments using superheated liquids. It is observed that the acoustic signals generated by α-particle induced bubble nucleations have amplitude that are roughly a factor four higher than those due to neutron or WIMP induced nucleation events for droplets of radius about 100 μm of C_4F_{10} liquid [6]. The piezoelectric transducers were used to acquire the high frequency components (> 18 kHz) of the acoustic pulse generated during bubble nucleation. The similar result was observed with bubble chamber of CF_3I liquid instead of droplets and with piezo electric transducer [7]. The experiment with the active liquid, C_2ClF_5 having the droplets of radius ~30 μm with polymer as supporting matrix and electret microphone measuring the low frequency components, has also observed that the α-particle induced events are of larger amplitudes than the neutron induced events [8].

In the present work we have studied the effect of using droplets of smaller radii less than ~40 μm with the main peak around 2–3 μm and also the effect of recording the low frequency components of the pulses on bubble nucleation induced by α-particles and neutrons. In our earlier publications [9,10], the discrimination of neutron and γ-induced events for R-114 ($C_2Cl_2F_4$: b.p. 3.7 °C) and R-12 (CCl_2F_2; b. p. −29.8 °C) liquids has been described. In the literature [11], the power spectral density of acoustic signals generated by bubble nucleation due to neutron and gamma rays were studied with R-218 (C_3F_8; b.p. −36.65 °C) liquid droplets with diameter 70 ± 2 μm and a characteristic frequency pattern was observed at 200–400 kHz range only for neutrons. For the present experiments, we have fabricated detectors with R-12 as the sensitive liquid. The average value of droplet radii was about 21 ± 20 μm. Acoustic pulses arising from bubble nucleation events in the presence of ^{241}Am–Be neutron source and ^{241}Am alpha-source were recorded using condenser microphone. The condenser microphone records the information from the low frequency components (until about 20 kHz) of the pulse associated with a nucleation event. The analysis of acoustic signals has been carried out to understand the nucleation events due to α-particles and neutrons for such tiny droplets.

In the following sections, we have presented nucleation principle, followed by the details of our experiment, droplet size measurement, analysis, results and discussion.

2. Nucleation principle

Radiation-induced bubble nucleation occurs by forming a vapour bubble of critical radius along the path of traversing particle through superheated liquid. To form a bubble of critical radius (r_c), the energy deposition (E_{dep}) by a charged particle along an effective path length (L_{eff}) within the superheated liquid must be greater than or equal to the critical minimum energy, $E_c(T, p)$ and can be expressed as

$$\int_0^{L_{eff}} \frac{dE}{dx} dx \geq E_c, \tag{1}$$

where dE/dx is the linear energy transfer (LET) of the particle. The critical minimum energy (E_c) can be calculated as the sum of the reversible works of bubble surface formation, evaporation of the liquid, expansion against pressure of the liquid and the irreversible works, such as energy lost by generation of the acoustic wave emission, by the action of viscous forces during bubble's growth, the thermal energy lost during the bubble expansion to its critical radius. The expression of E_c is [12,13],

$$E_c = -\frac{4\pi}{3} r_c^3 \left(p_v - p_0\right) + \frac{4\pi}{3} r_c^3 \rho_v h_l + 4\pi r_c^2 \left(\sigma - T\frac{d\sigma}{dT}\right) + W_{irr}, \tag{2}$$

where $\sigma(T)$ is the surface tension (liquid–vapour interfacial tension) of liquid at the temperature T, $p_v(T)$ is the equilibrium vapour pressure of superheated liquid at the temperature T, p_0 is the ambient pressure (pressure of the surroundings of the bubble), $\rho_v(T)$ is the density of the vapour and h_l is the latent heat of evaporation. The quantity ($p_v - p_0$) is called the "degree of superheat" of the liquid. The first term in Eq. (2) explains the reversible mechanical energy during expansion to a bubble of radius r_c against the pressure of the liquid. The second term represents the energy needed to evaporate the liquid to form a bubble of critical radius. The third term describes the work needed initially to create the liquid–vapour interface of vapour embryo while the last term, W_{irr}, is the irreversible works which has smaller contribution than other terms. The calculation of each of the terms of Eq. (2) for various freons at different temperatures, indicated that the first three terms provide more than 99% of the critical minimum energy [14]. The effective path length can be expressed using the relation,

$$L_{eff} = \frac{E_c}{\left(\frac{dE}{dx}\right)}, \tag{3}$$

and also in terms of the critical radius, $r_c(T, p)$ as

$$L_{eff} = a r_c, \tag{4}$$

where a is the nucleation parameter and r_c can be expressed as

$$r_c = \frac{2\sigma}{p_v - p_0}. \tag{5}$$

3. Present work

We performed two separate experiments with detectors made of superheated droplets of R-12, one in the presence of neutrons and the other in the presence of α-particles from ^{241}Am–Be (~111 GBq) neutron source and ^{241}Am (~30 Bq) α-source respectively at the temperature of 33.5 ± 0.5 °C. The detectors are not sensitive to gamma-rays emitted from the ^{241}Am–Be source at the experimental temperature. After irradiated by a source, the superheated emulsion has been replaced. The superheated emulsion used in both of the experiments were fabricated at the same time. The fabrication procedure has been discussed later in this section.

The schematic diagram of the experimental set up with α-source, ^{241}Am is shown in Fig. 1. The α-source was placed 1.5 cm above the top surface of the gel matrix. The same type of setup was used with the neutron source, ^{241}Am–Be, but in this case the source was kept at 1.4 m away from the detector. The dimension of the detector and alpha source position are shown in Fig. 2. In this

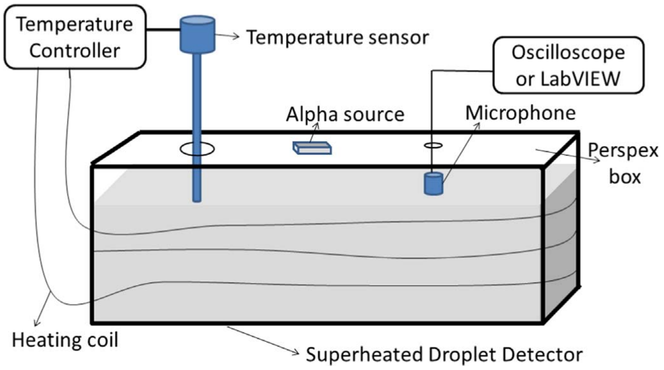

Fig. 1. Schematic diagram of experimental setup to measure the acoustic response of α-particle induced events in presence of ^{241}Am α-source.