Characterisation of superheated droplet detector for low mass dark matter search

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Introduction

The astronomical observation and the large scale structure of the universe confirm the concept of the dark matter (DM). Weakly Interacting Massive Particles (WIMPs) are the most promising DM candidates. Direct detection of DM experiments are looking for the signature of nuclear recoils that expected to be produced by the interaction of WIMPs with that of the detector nuclei in a reduced background environment. The use of superheated droplet detector (SDD) in the search of rare events (WIMPs) in DM experiments has been established a promising technology, as threshold of the detector can be controlled by changing the operating temperature and/or pressure.

The available experimental results are in the higher WIMP mass region [1] but now it needs to be explored in the low mass WIMP region. In order to make the detector to be sensitive to low mass WIMP, the detector should operate at very low threshold where it becomes sensitive to the gamma rays. The threshold energy of superheated droplet detector decreases with the increase of the operating temperature. The WIMP induced nuclear recoils are similar to the neutron induced nuclear recoils. Therefore, it is important to discriminate between the nuclear recoils and gamma induced events while operating the detector at low threshold (below 1 keV). At a low threshold regime the low mass target nuclei will be sensitive to the low mass WIMP region.

Principle of bubble nucleation

According to the Seitz's thermal spike model [2], the energetic radiation deposits energy inside the superheated liquid and microbubbles are formed. The microbubbles grow very fast and form vapour buuble when it attains the critical size of radius R_c. The minimum energy required to form a critical size microbubble is known as threshold energy (E_c) of the bubble nucleation and is given by Eq. (1),

$$\begin{aligned} E_c &= 4\pi R_c^2\left(\sigma - T\frac{\partial\sigma}{\partial T}\right) + \frac{4\pi}{3}R_c^3\rho_v\left(h_v - h_l\right) \\ &\quad -\frac{4\pi}{3}R_c^3\left(P_v - P_l\right) \end{aligned} \tag{1}$$

where, $\sigma(T)$ is the liquid-vapour interfacial tension at temperature T, $P_v(T)$ is the vapour pressure and $P_l(T)$ is the pressure of the liquid. Also $\rho_v(T)$ is the vapour bubble density, $h_v(T)$ and $h_l(T)$ are the specific enthalpies of vapour bubble and liquid respectively.

Experimental method

$C_2H_2F_4$ (b.p. -26.3 °C) superheated droplet detector has been fabricated at the laboratory with three different rotation frequencies 400 rpm; 20 min (A), 900 rpm; 5 min (B) and 1400 rpm; 5 min (C) of the stirrer's. The detector was irradiated with ^{241}Am-Be and ^{137}Cs sources separately at an operating temperature of 37°C and 45°C. The detector was immersed in a water bath and the bath temperature was controlled by a temperature controller. The acoustic signals released during the bubble nucleation process were converted to electrical signal using the condenser microphone and the data were recorded in Labview.

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Results and Discussion

The measured radius distributions have a sharp peak around 20 μm bin, 60 μm bin and 10 μm bin in case of A, B and C respectively, which are shown in Fig. 1.

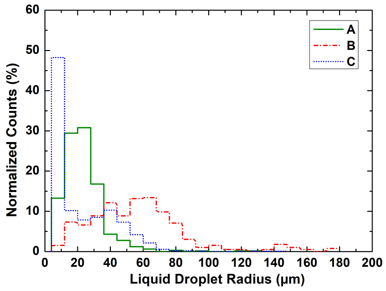

FIG. 1: Distribution of radius of droplets of $C_2H_2F_4$ liquid used in the experiment.

The power of the signal is proportional to the energy released during the bubble formation process. The power spectrum of the pulses for neutron induced events at 37°C and gamma induced events at 45°C for three cases A, B and C are shown in Fig. 2, Fig. 3 and Fig. 4.

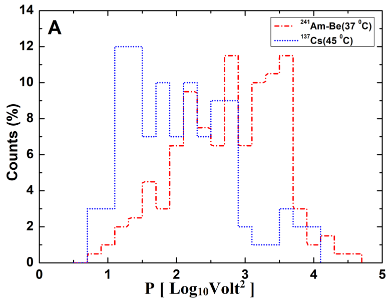

FIG. 2: Power distribution for neutron and gamma-ray induced events for case A.

The result shows that neutron induced events are of higher power values than that of the gamma induced events in case of A and C while almost overlapped in case of B. For neutron induced recoils, the energy deposition is more localized than that of the electrons originating from gamma rays. As a result, the neutron induced pulses are of comparatively higher value of power. Gamma-ray induced events are due to the partial deposition of energy in the smaller droplet by electrons but both full energy deposition and partially energy deposition by electrons for larger droplets. Therefore, we observed larger gamma ray induced pulses in case of C, and only smaller pulses for other two cases.

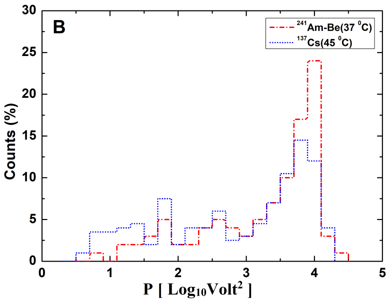

FIG. 3: Power distribution for neutron and gamma-ray induced events for case B.

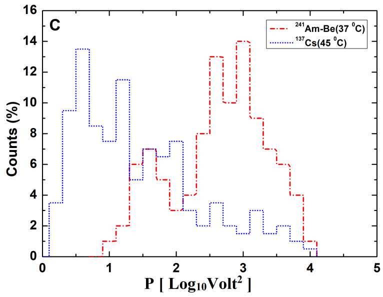

FIG. 4: Power distribution for neutron and gamma-ray induced events for case C.

Conclusion

The present experiment demonstrates that the nuclear recoil events can be separarted from the gamma ray induced events in case of smaller droplets for DM search experiment while operated at low threshold.

References

[1] PICO collaboration, Physical Review Letters 118, 251301(2017).
[2] F. Seitz, The physics of fluids 1, 2(1958).