Gamma background rejection with superheated liquid detector for dark matter search

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Introduction

Superheated liquid detector is presently being used in direct detection of cold dark matter (CDM) experiments [1] which are searching for the most promising candidates, Weakly Interacting Massive Particles (WIMPs). The superheated liquids, C_4F_{10} (b.p.- 1.7 °C), CF_3I (b.p. -21.8 °C), C_3F_8 (b.p. -36.8 °C) etc. are used for such experiments. The WIMPs are expected to produce the nuclear recoils similar to neutrons during passing through detector, and in both cases it is the recoiling nucleus that triggers the bubble nucleation event.

According to Seitz's "thermal spike" model [2], if the energy deposited by a particle within a certain effective path length ($L_{\rm eff}$) of superheated liquid becomes greater than a certain threshold energy ($E_{\rm c}$), the vapour bubble grows, eventually converting the superheated liquid into the vapour phase and can be expressed as, $\int_0^{L_{\rm eff}} \frac{dE}{dx} dx \geq E_c$, where dE/dx is the linear energy transfer (LET) of the particle. If the radius of vapour bubble is less than critical radius ($r_{\rm c}$), it collapses back to the liquid state. $L_{\rm eff}$ can be expressed as, $L_{\rm eff} = br_{\rm c} = b\frac{2\sigma(T)}{(p_{\rm v}-p_0)}$, where σ(T) is the surface tension of liquid at the temperature T, $p_{\rm v}$ is the equilibrium vapour pressure of superheated liquid and p_0 is the ambient pressure, b is called nucleation parameter. The threshold energy ($E_{\rm c}$) needed to form a vapour bubble of $r_{\rm c}$ is,

$$E_{\rm c} = -\frac{4\pi}{3}r_{\rm c}^3(p_{\rm v}-p_0) + \frac{4\pi}{3}r_{\rm c}^3\rho_{\rm v}h_{\rm lv} + 4\pi r_{\rm c}^2\left[\sigma - T\frac{d\sigma}{dT}\right] + W_{\rm irr}, \quad (1)$$

where $\rho_{\rm v}$ is the density of the vapour and $h_{\rm lv}$ is the latent heat of evaporation. The first term in Eq. 1 explains the reversible mechanical energy during expansion to a bubble of radius $r_{\rm c}$ against the pressure of the liquid. The second term represents the energy needed to evaporate the liquid during formation of the 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 $W_{\rm irr}$, is the irreversible works which has smaller contribution than other terms.

In order to detect the WIMP induced nuclear recoils with lower energy, the detector must have a relatively low threshold energy. At the low value of threshold energy, detectors also become sensitive to γ-ray induced nucleation events. Thus the ability to effectively distinguish between γ-ray and nuclear recoil induced nucleation event is an important requirement for the use of such detectors in WIMP CDM search experiments. To understand the response of superheated liquid detector to various particles, one has to take recourse to simulation. The aim of the present work is to study gamma rejection probability of C_3F_8. The nucleation probability due to γ-ray has been studied at different operating temperature of the detector and hence at different threshold energies using GEANT4.95 simulation toolkit.

Present Work

The spherical shaped superheated liquid detector of C_3F_8 with radius 7.0 cm was cre-

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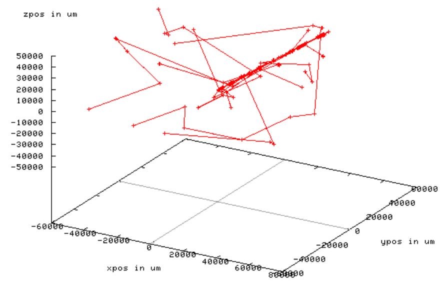

FIG. 1: Tracks of particles in case of 100 γ-ray of energy 662 keV in a spherical detector of radius 7.0 cm. The momentum was only in x direction.

ated in simulation for simplicity. The interactions of γ-ray of energies, namely, 60 keV, 662 keV, 1.46 MeV having initial positions at the center of the detector were studied at 22 °C. Tracks of particles are shown in Fig. 1, while the interactions of γ-ray are presented in Table I. The nucleation probability due to γ-ray has been studied with 10000 γ-ray of 662 keV. The simulation was performed for detector temperature 1 °- 45 °C and compared with the experimental results. The LET of γ-ray and the secondary electrons and positrons along its track was obtained from simulation. The probability of bubble nucleation has been calculated for each temperature for different values of nucleation parameter (b) and plotted as a function of threshold energy (shown in Fig. 2). For a particular nucleation parameter (b) and a particular threshold energy (E_c), the probability of bubble nucleation (P_B) due to γ-ray is defined as,

TABLE I: Interactions of γ-ray within the detector having C_3F_8 of density 1.33 gm.cm^{-3}.

Radius (cm)	Energy (MeV)	Compton scattering (%)	Photo-electric effect (%)	Conversion (%)	Rayleigh scattering (%)
7.0	0.060	73.80	18.45	0.0	7.75
	0.662	93.41	6.59	0.0	0.0
	1.460	92.31	6.15	0.0	1.54

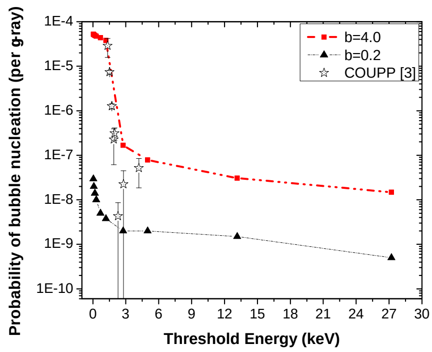

FIG. 2: Probability of bubble nucleation in C_3F_8 as a function of threshold energy.

$$P_B = \frac{\text{No. of interactions with LET} \geq \frac{E_c}{br_c}}{\text{Total number of interactions} \times N_\gamma}, \quad (2)$$

where N_γ is the number of gamma rays.

Results and discussions

It is observed that at 15 °C and 30 psi ($E_c \approx 2.7$ keV), the nucleation probability due to γ-ray is about 1.68×10^{-7} per γ-ray for b=4.0. From Fig. 2, it is observed that C_3F_8 has a good capability to reject γ-ray induced nucleation events at low threshold energy.

Acknowledgments

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References

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