Simulation of threshold of superheated liquid detector for dark matter search

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Introduction

Dark Matter search is one of the interesting and important unsolved problems in Astroparticle Physics. Weakly Interacting Massive Particles (WIMPs) are the most promising cold dark matter candidates. PICO is one of the currently running dark matter direct search experiments at SNOLab, Sudbury Canada. PICO uses bubble chamber with superheated liquid for the search for dark matter. WIMPs are extremely difficult to detect, as they have an interaction cross section of the order of picobarn. Thus it becomes necessary to identify the unwanted backgrounds of neutrons, alpha particles and gamma photons in the dark matter search experiment [1].

The principle of operation of the bubble chamber is based on the 'thermal spike' model of Seitz. If the energy deposited within a certain critical length (L_c) is greater than the critical energy E_c for nucleation, then vapour bubble is formed in the superheated liquid. If the energy deposited is less than this minimum value, then nucleation does not take place. This potential barrier E_c is given by Gibbs' equation,

$$E_c = \frac{16\pi}{3}\frac{\sigma(T)^3}{(p_v(T)-p_0)^2} \tag{1}$$

Here, $p_v(T)$ is the equilibrium vapour pressure of the superheated liquid, p_0 is the ambient pressure, and $\sigma(T)$ is the surface tension at temperature T. This energy E_c will form a vapour bubble of critical radius r_c, where

$$r_c = \frac{2\sigma(T)}{p_v(T)-p_0} \tag{2}$$

If the bubble radius is less than r_c, it collapses back to the liquid state. L_c can be expressed as $L_c = kr_c$, where k is called the nucleation parameter. If dE/dx is the LET in the liquid, then for nucleation to occur, we must have $dE/dx \geq E_c/kr_c$.

Direct search experiments are aiming to run at low threshold energy of the detector. However, at lower thresholds, the sensitivity to gamma rays is greatly increased. Hence it is necessary to understand the response of the superheated liquid detector to gamma rays in order to separate the nucleation events induced by gamma rays and WIMPs. In the present work, the nucleation probability due to gamma rays in superheated C_4F_{10} (boiling point ~ -1.7 ^oC) has been studied. The response was studied at different temperatures of the detector using the simulation toolkit GEANT4.

Present Work

Two different geometries of the detector were chosen for the simulation. The first one was a spherical bubble chamber of radius 7.0 cm filled with superheated C_4F_{10}. Such a bubble chamber is used in the PICO experiment. The gamma photons were incident randomly on the detector with uniform momentum distribution. Fig. 1 shows the track of a gamma photon in the bubble chamber and fig. 2 shows the positions in the bubble chamber at which interaction took place. The second geometry that was chosen was a cylindrical Superheated Drop Detector with radius 1.75 cm and height 5.0 cm. There were four independent detectors with 5000 drops of radii 41 µm, 100 µm, 300 µm and 500 µm respectively and superheated droplets of C_4F_{10} were suspended in visco-elastic gel matrix. Drop radius of 41 µm finds application in most SDD experiments and radius of 100 µm was used in the PICASSO experiment. The co-ordinate system was chosen such that the origin was at the centre of the cylinder and the long axis of the cylinder was along the z-axis. The gamma source was placed along the x-axis, 1.0 cm away from the detector wall. The momentum of incoming gamma photons was taken to be randomly distributed in this case. The simulation was done for several temperatures between 10^{o}C and 70^{o}C for both the detector geometries, with 10^5 incident gamma photons. The energy for the gamma photons was chosen to be 662 keV which is the photon peak of ^{137}Cs.The LET of gamma photons and the secondary electrons and positrons created along the track was obtained from simulation. The bubble nucleation probability at a particular temperature and a given value of k is given by

$$P = \frac{\text{No.of interactions with LET} \geq E_c/kr_c}{\text{Total number of interactions} \times N} \qquad (3)$$

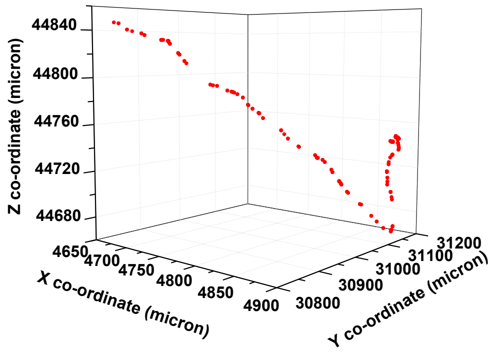

Fig. 1: Track of a 662 keV gamma photon in the spherical bubble chamber of radius 7.0 cm

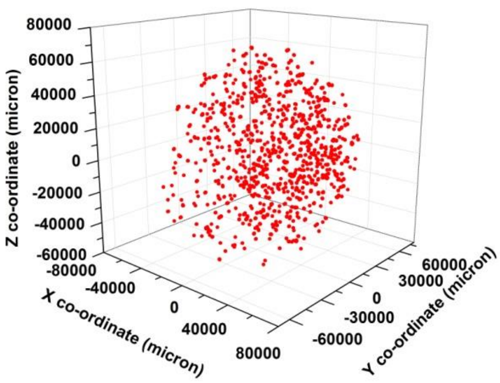

Fig. 2: Interaction positions in the bubble chamber

where N is the number of incident gamma photons. The bubble nucleation probabilities in the SDD with drop radius of 100 µm, obtained from simulation was compared with the experimental data, which showed that an approximate value of k could be equal to 0.12. Fig. 3 shows the nucleation probabilities at different values of the threshold energy for nucleation and different detector settings for k = 0.12.

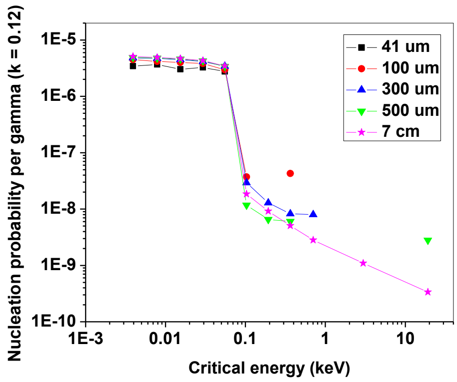

Fig. 3: Probability of bubble nucleation per gamma photon in superheated C_4F_{10} as a function of critical energy for nucleation. Probabilities for all detector settings have been shown.

Discussions

From fig. 3 it can be seen that at a 3 keV threshold energy (temperature ~ 20 ^{o}C) in the 7.0 cm bubble chamber of superheated C_4F_{10}, the nucleation probability is around 1.1 x 10^{-9} per gamma photon. In the SDD with drop radius 100 µm, the probability is obtained to be zero from the simulation. Thus, around 3 keV thresholds, in the region of WIMP search operating temperatures, it has a good capability of rejecting the nucleation events induced by gamma rays.

References

[1] S. Archambault, *et al.*, *New J. Phys.* 13 (2011), **043006**.