Minimum WIMP-mass detectable by $C_2H_2F_4$ superheated liquid detector

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Introduction

The presence of dark matter (DM) is confirmed from several observational evidences such as galaxy rotation curves, gravitational lensing, cosmic microwave background and so on. Weakly interacting massive particles (WIMPs) [1] is considered as a most favorable DM candidates beyond the standard model of particle physics. World wide, several experiments are running to detect the WIMPs through various kinds of detector technologies. Direct detection of DM search experiments are looking for the signals produced via the elastic scattering of WIMPs with the target nuclei of the detector. There is no positive response yet from the current running experiments that are designed to sensitive to high mass WIMPS. Therefore, few future experiments are aimimg to explore low mass WIMPs region below 10 GeV.

WIMP search detectors should be free from all kinds of background paricles while running the experiments. The superheated liquid detector acts as a threshold detector [2], is suitable for the search of WIMPs with a better rejection of backgrounds. Flourine loaded superheated liquid detector like C_4F_{10}, CF_3I, C_2ClF_5 and so on have been used in many WIMPs search experiments. The presence of single unpaired proton in ^{19}F has driven the WIMPs search in spin-dependent sector.

In this paper, theoretically we have studied the minimum WIMP mass that would be sensitive to the $C_2H_2F_4$ (b.p -26.3 ^{0}C) superheated liquid detector. Here all the calculations are performed based on ^{19}F nuclei.

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Threshold energy and lowest WIMPs mass

To initiate bubble nucleation in the superheated liquid, the particle must have energy, E , equal to or greater than a certain threshold energy E_{th} with followed by the below given equation,

$$E_{dep}^{2R_c}(E = E_{th}) = \int_0^{2R_c} \left(\frac{dE}{dx}\right) dx = E_c/\eta_T \tag{1}$$

where $\frac{dE}{dx}$ is the stopping power of the recoil nuclei, η_T is the thermodynamic efficiency, $2R_c$ is the critical diameter and E_c is the minimum critical energy required for bubble nucleation and is given by [3]

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

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

If at any given temperature and pressure, the range (R) of the particle at energy $E = E_c/\eta_T$ satisfies $R(E = E_c/\eta_T) \leq 2R_c$, then we have $E_{th} = E_c/\eta_T$. On the other case, if $R(E_c/\eta_T) > 2R_c$, then E_{th} will be larger than E_c/η_T and is determined by the Eq.1. For an ideal case $\eta_T = 1$ [4], where E_{th} will be equal to E_c. But from experiments [5], it is seen that the E_{th} become closer to E_c values at $\eta_T = 50\%$. So 50% and the ideal case, 100% values of η_T are considered for threshold energy calculation.

For a given target material, the condition $E_{R,max} \geq E_{R,th}$ implies that the target element is insensitive to WIMP mass below a certain value and is given by,

$$m_{\chi,lowest} = m_A \left[\left(\frac{2m_A v_{esc}^2}{E_{R,th}} \right)^{1/2} - 1 \right]^{-1} \quad (3)$$

Where, m_A is the target nucleus mass and v_{esc} is the escape speed. v_{esc} value 540 kms^{-1} is considered for the calculations.

Results and Discussions

We have calculated the E_c value (Eq.2) using the thermodynamic values from the "NIST" database and also the ranges of the ^{19}F nuclei in $C_2H_2F_4$ liquid is calculated using "SRIM" software package. The threshold energies of ^{19}F recoiling nuclei require for bubble nucleation in $C_2H_2F_4$ liquid using Eq.1 is calculated which are listed in Table I.

T (^{0}C)	E_c (keV)	$2R_c$ (nm)	Ranges ($E = E_c$) (nm)	η_T(50%) $E_{R,th}$ (keV)	η_T(100%) $E_{R,th}$ (keV)
35	1.92	34.32	10.37	3.84	1.92
40	1.08	26.72	6.92	2.16	1.08
45	0.61	20.78	4.94	1.22	0.61
50	0.34	16.10	3.82	0.68	0.34
55	0.19	12.40	3.18	0.38	0.19
60	0.10	9.46	2.82	0.20	0.10

TABLE I: Threshold energies of ^{19}F nuclei for bubble nucleation in $C_2H_2F_4$ superheated liquid at different temperatures.

From Table I, it is seen that at $\eta_T = 100\%$, the $E_{R,th}$ will be equal to E_c at the corresponding temperature. With the help of $E_{R,th}$ value, we can calculate the lowest WIMP mass by using Eq.3 that will be sensitive to the $C_2H_2F_4$ liquid detector.

From Fig.1, we see that $C_2H_2F_4$ liquid detector will be sensitive to WIMP mass below 5 GeV operating at 35^{0}C temperature with presence of ^{19}F nuclei whereas at 60^{0}C operating temperature detector will be sensitive to WIMPs mass below 1 GeV. With 100% thermodynamic efficiency, detector will be sensitive to 540 MeV WIMPs mass at 60^{0}C temperature. At higher temperatures, detector will be sensitive to background gamma-rays thus requires proper shielding and discrimination techniques.

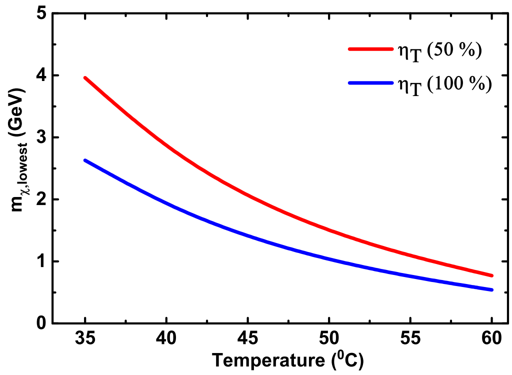

FIG. 1: Lowest WIMP mass as a function of $C_2H_2F_4$ liquid temperature.

Conclusions

$C_2H_2F_4$ liquid detector can be serve as a good detector in the search of WIMP mass below 5 GeV and the detector would be sensitive to sub-GeV WIMP mass while operated at 60^{0}C temperature.

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