Potentiality of superheated emulsion detector for the study of Astrophysical reaction

V. Kumar[1,3], S. Sahoo[1,3], M. Das[1,3,*], and A. Mukherjee[2,3]
[1]*High Energy Nuclear and Particle Physics Division, Saha Institute of Nuclear Physics, Kolkata – 700064, INDIA*
[2]*Nuclear Physics Division, Saha Institute of Nuclear Physics, Kolkata – 700064, INDIA*
[3]*Homi Bhaba National Institute, Training School Complex, Anushakti Nagar, Mumbai 400094, India*
* email: mala.das@saha.ac.in

Introduction

Most of the elements in the periodic table are produced through the thermonuclear reactions inside the stars. Nuclei from helium to iron are synthesized in stars through fusion processes and nuclei above iron are produced in different capture reactions. Radiative capture reactions at low energies are very important to study from the nuclear astrophysical point of view. But these stellar reactions occur at very low energies and so the cross sections are very small, may be a few nano barns or pico barns or even less, thereby making the measurements very difficult in the laboratory. Measuring such low cross sections requires very efficient detector systems, apart from the other factors. New kinds of detectors are being developed recently to deal with the extremely low count rates in astrophysics experiments. The feasibility study of developing an unconventional detector using superheated liquid for the study of such reactions is investigated in this work.

One of the important capture reactions in nuclear astrophysics is the $^{12}C(p,\gamma)^{13}N$ reaction. While a study of this reaction is planned for the future, in this work we are exploring the possibility of studying this reaction by the superheated liquid technique. The target and detector will be superheated liquid, the liquid which is in liquid state above its normal boiling point. The main advantage of the new target-detector system is expected to be of higher density than the conventional gas targets. The proposed detector can be made insensitive to the gamma-rays, which allows detecting only the products of the nuclear reaction of interest. Giovene et al. [1] developed a bubble chamber to measure the very small cross sections of reaction for the time reversed capture process, namely the photodisintegration process.

In the present work, the projectile (protons) interacts with the target, the superheated liquid and the products of this reaction are nitrogen nucleus and gamma-rays. The target material is $C_2H_2F_4$ (R134a ;b.p. -26.3°C) which is the active material of the detector. It is very challenging because the projectile beam is coming from the vacuum and the detector is at atmospheric pressure. In the present work, we would like to explore the potentiality of R134a active superheated detector/target for the detection of the reaction product of the $^{12}C(p,\gamma)^{13}N$ reaction.

Kinetic energy of nitrogen nucleus

According to the nuclear reaction, the protons interact with the carbon nucleus and form the isotope of nitrogen. The nitrogen-nucleus will receive the kinetic energy and deposit that energy in the liquid.

Q value of the above reaction = 1.94 MeV. The excitation energy of N^{13} is calculated to be as 7.45 MeV. The projectile energy is 6 MeV and after passing through a window of few microns thick, the projectile energy is 5.51 MeV at the C.M. frame.

So the kinetic energy of N^{13} ~ 459 keV and that of proton is 5.97 MeV

This kinetic energy of nitrogen-nucleus will be used up in the bubble nucleation in superheated emulsion detector.

Possibilities of bubble nucleation

The superheated emulsion detector consists of the droplets of the superheated liquid suspended in a degassed gel matrix. The theory of bubble nucleation in a superheated liquid has been discussed by Seitz [2]. The bubbles are formed by the energy deposition of the energetic particles inside the liquid and during the process an acoustic signal is released that is detected by the acoustic sensors. To form a bubble of critical radius (R_c), the nucleus must have an energy E equal to or greater than certain threshold energy (E_{th}) such that the energy deposited by the particle over a path segment of length $2R_c$ (critical diameter) along the particle's track in the liquid satisfies the following condition:

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

Where: $\frac{dE}{dx}$ =stopping power of the liquid for the particle/nuclei, η_T= thermodynamic efficiency and E_c is the critical energy of bubble nucleation.

The bubble formation conditions can be summarized as follows:

Energy of the incident particle ≥ Critical energy and
The energy deposition over the effective length ($2R_c$) ≥ Critical energy.

If the projected range ≤ $2R_c$, $then\ E_{th} = \left(\frac{E_c}{\eta_T}\right)$
If projected range >$2R_c$, then $E_{th} > (\frac{E_c}{\eta_T})$

These conditions help to find the operating temperature and the sensitivity of the detector. We have calculated the variation of the critical energy and critical radius of the liquid with temperature and the energy deposition (LET ; linear energy transfer) of ^{13}N and ^1H in $C_2H_2F_4$. The condition of bubble formation has been verified for proton and nitrogen nuclei with the above mentioned kinetic energy in the liquid $C_2H_2F_4$ for the thermodynamic efficiency of 100%.

Sensitivity of detector

The detector is not sensitive at a single temperature for all particle/nuclei. The kinetic energy of the nitrogen nucleus is 459 keV and the projected range at this energy 1.84 µm in R134a. The maximum LET is 329E+02 keV/µm. The range is found to be larger than the 2Rc over an extended range of temperature range. By applying the 2nd condition of bubble formation, the sensitive temperature comes at T_{th} = 8.46 ºC for N^{13} nucleus and similarly for H^1, the threshold temperature is 32.81ºC. The result of the calculation is summarized in Fig.1

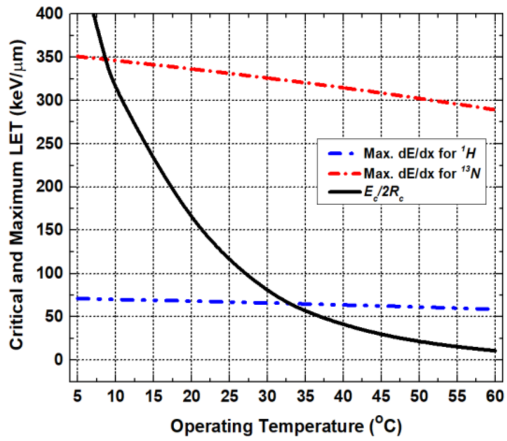

Fig.1. The threshold temperature of bubble nucleation for N^{13} and H^1 in $C_2H_2F_4$ superheated liquid.

It is already observed by S Sahoo et. al. [3] that R134a becomes sensitive to gamma-rays at and above 38.5±1.4ºC.

Conclusion

The R134a superheated liquid is sensitive to the reaction products, N-nucleus in the operating temperature of 8.46 ºC and above. The liquid becomes sensitive to protons at 32.81 ºC. Therefore, the detector shows the potentiality to study the above astrophysical reaction in the ambient temperature range of 8.46 ºC – 32.81 ºC where it is not sensitive to proton and gamma-rays.

References

[1] B. Di Giovine*et al., Nucl. Instrum. Meth.* A781, 96–104 (2015).

[2] F. Seitz, *Phys. Fluids*1, 2-13 (1958).

[3] S. Sahoo *et al. Nucl. Instrum. Meth.* A 931, 44-51(2019).