A FORMATION PROCESS AND GROWTH MODEL FOR SUPERHEATED LIQUID BUBBLE CHAMBERS

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Dark matter is believed to be made of an unknown kind of particle. Its detection has been a challenge for more than 3 decades [1]. PICO is a direct dark matter search experiment that uses superheated liquid bubble chambers with different fluorocarbons as target liquids. The acoustic signal generated by the explosive phase transition caused by particles interacting with the target liquid is used for data analysis. A better understanding of the mechanisms that generate the acoustic signal provides better tools to discriminate amongst the particles that can create bubbles. Models of bubble formation and growth are a starting point to understand the mechanisms of the acoustic signal generation.

THE BUBBLE FORMATION MODEL

A model originally proposed by F. Seitz in 1956 is used to explain the bubble formation process [2]. The model quantifies the minimum amount of energy which needs to be deposited and the region in which this energy has to be deposited to form a bubble. The model also gives a prediction of the detector's response to different background particles which include neutrons and alphas. The vapour bubble equilibrium conditions are used by the model to quantify the above mentioned parameters. At equilibrium, the temperature inside and outside must be equal and using the assumption that the vapour has a constant isothermal compressibility, the pressure inside the bubble and the radius of the bubble are related by the following equations [3],

$$2\sigma = (p' - p'')r \tag{1}$$

$$p' = p_{sat} e^{\frac{-\rho'_{sat}}{\rho''}\left(\frac{p_{sat}-p''}{p_{sat}}\right)} \tag{2}$$

$$r = \frac{2\sigma}{(p_{sat} - p'')\left(1 - \frac{\rho'_{sat}}{\rho''}\right)} \tag{3}$$

where p is the pressure, r is the radius, ρ is the density, σ is the surface tension, $'$ represents inside the bubble and $''$ represents outside the bubble and the subscript *sat* denotes the property at saturation. The amount of heat that needs to be supplied to form a vapour bubble is the sum of the energy to vapourise the liquid, the work to create the volume and the energy to create the surface. This is represented by the following equation [3],

$$Q = 4\pi r^2\left(\frac{\sigma}{3} - T\frac{\partial\sigma}{\partial T} + \frac{m_s}{\rho' - \rho''}\rho'(h'_m - h''_m)\right) + \frac{4}{3}\pi r^3\rho'(h'_m - h''_m) \tag{4}$$

where T is the temperature, h_m is the enthalpy per unit mass and m_s is the mass per unit area. Having calculated the minimum energy necessary to form a bubble, simulations of particle tracks inside the detector can be performed to predict which particle interactions will produce a bubble. A Monte Carlo simulation program called TRIM [4] can simulate particle tracks and their interactions in different materials. As an example of a TRIM simulation, alpha and neutron tracks are analysed in C_3F_8 as the target liquid. An alpha particle will deposit its energy slowly at the beginning of the track and much more quickly at the end, i.e. the Bragg peak. For the neutron, however, the mean free path of interaction is very long compared to that of the alpha particle, and therefore the mechanism to create a bubble is different. The first interaction of the neutron will be with either a fluorine or a carbon and that atom will create the cascade that deposits the energy to form the bubble. The bubble volume with equilibrium radius, r, corresponds to a volume of liquid to be evaporated, $R = r(\rho'/\rho'')^{\frac{1}{3}}$. Once the particle tracks are generated, the volume R is scanned along the track where the sum of all energies is calculated; if this sum is greater than the minimum energy found in Eq. 4, a bubble is postulated to be formed. In a controlled environment where the flux and energy of particles are known, a prediction of bubble rates can be made. A graphic example of an alpha track and a neutron track from a fluorine cascade is shown in Fig. 1.

A problem with this method is that the track is considered static in time. However, the energy from interactions dissipates through phonons and therefore the scan should

SUMMARY

This paper presents a summary of an M.Sc. project on bubble formation and growth models in superheated liquid bubble chambers.

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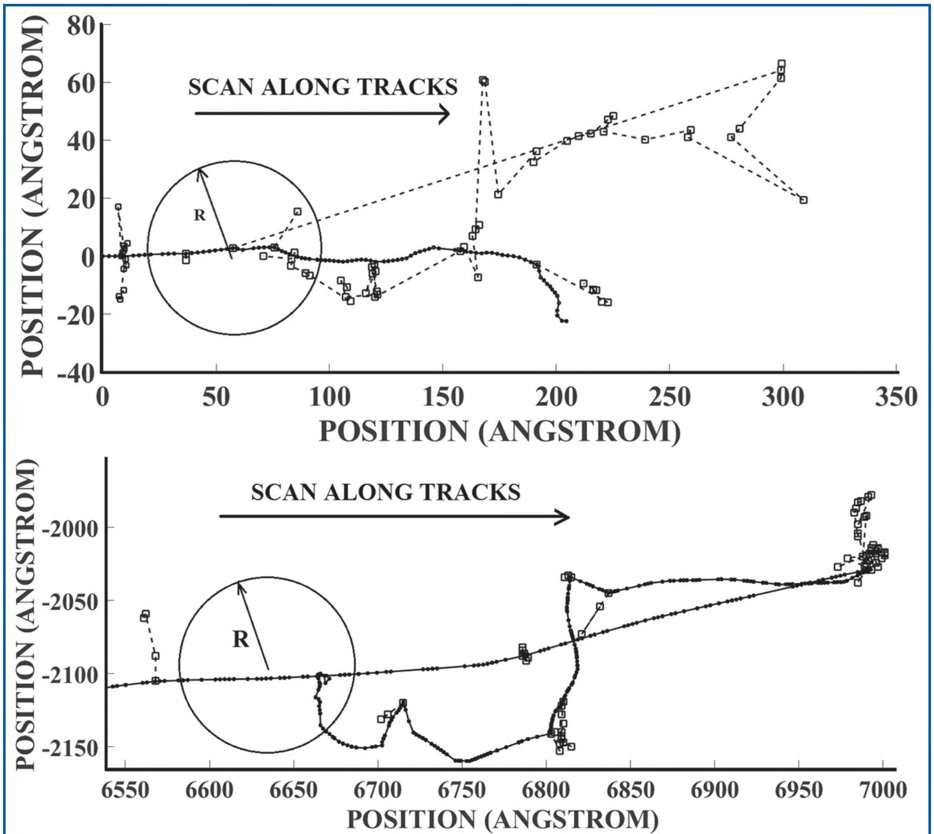

Fig. 1 Example particle tracks of an alpha and a fluorine cascade from a neutron, top plot, and an alpha, bottom plot. The solid lines are the particles and the square dashed lines are cascades. Note that for the alpha track there is a cascade cluster on the right hand side.

be performed in real time where phonon dissipation is allowed to occur. If an interaction occurred close to the edges of the time window, inside or outside, energy can flow in or out.

THE BUBBLE GROWTH MODEL

Equipped with the information about vapour bubbles, the bubble growth can now be investigated. As will be seen, bubble growth can be used as a tool to discriminate amongst particles that induced the bubble formation. Bubble growth is a two phase flow problem. For PICO's purposes, the vapour bubble interface position, velocity and acceleration need to be known. Two equations summarize the problem [5],

$$R\frac{d^2R}{dt^2}+\frac{3}{2}\left(\frac{dR}{dt}\right)^2=\frac{P'-P''}{\rho''}-\frac{2\sigma}{\rho''R}-\frac{4\mu}{\rho''R}\frac{dR}{dt} \qquad (5)$$

$$\frac{\partial T}{\partial t}+\frac{R^2}{r^2}\frac{dR}{dt}\nabla_s T=\alpha\nabla_s^2 T \qquad (6)$$

where R is the interface position, μ is the dynamic viscosity, α is a thermal diffusion constant and r is the position. These equations can be solved with the correct numerical model, grid space and boundary conditions. The expected solution should be of the form shown in Fig. 2 [4].

This particular solution was calculated for superheated water. The simulation starts at the equilibrium radius with a temperature disturbance of varying magnitude. The interface position as a function of time is shown in the bottom curves of Fig. 2. These curves show two important parts of the bubble growth, a degenerate growth at the end, and a non-degenerate growth near the beginning. The non-degenerate part can be made clearer with the interface velocity shown in the top curves in Fig. 2. The magnitude of the initial temperature disturbance gives rise to substantially different bubble growth. That's the key to particle discrimination. Suppose that an alpha deposits most of its energy very quickly in the Bragg peak which is localised, whilst the neutron deposits its energy through a cascade which is slower and less localised, shouldn't this translate to different initial temperature disturbances for bubble growth? If so, this is why bubble growth can be used as a tool for particle discrimination. However, there is one more important part of bubble growth, the interface acceleration as shown in the top curves of Fig. 3 [4].

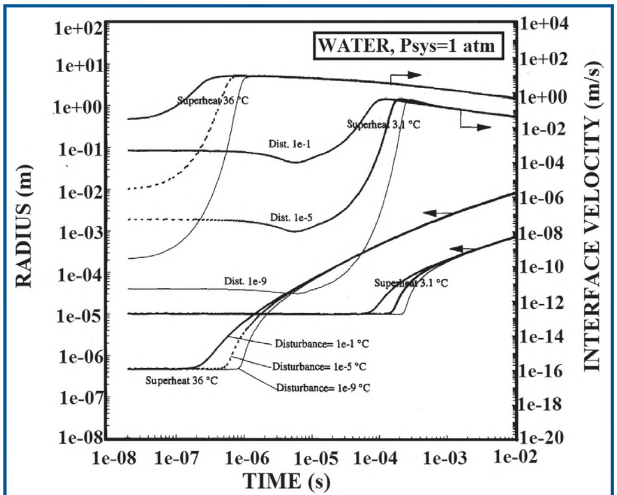

Fig. 2 Expected solution to the coupled differential equations (5) and (6) for different initial temperature disturbances. This solution is for superheated water at 1 atmosphere and shows the interface velocity, $\frac{dR}{dt}$ (top plots), and the interface position, R (bottom plots). Arrows point to the correct axis.

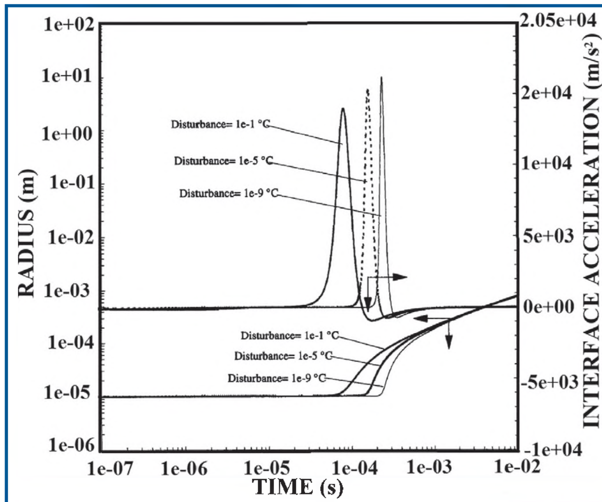

Fig. 3 Expected solution for the interface acceleration, $\frac{d^2R}{dt^2}$, of the coupled differential equations (5) and (6) for different initial temperature disturbances. Arrows point to the correct axis.

The interface acceleration is responsible for the acoustic shock, which is responsible for the acoustic signal. Therefore, by working backwards from the registered acoustic signal to the acoustic shock and to the disturbance, a prediction of which type of particle that caused the bubble can be made.

CONCLUSION

The bubble formation model can be improved to better understand the detector response and to be able to translate the deposited energy into an initial disturbance for the bubble growth model. The bubble growth model has to be completed for C_3F_8 and confirm the effects obtained for water [5].

REFERENCES

1. L. Bergström, “Dark Matter Candidates”, *New J. Phys*., **11**, 105006 (2009).
2. F. Seitz, “On the Theory of Bubble Chambers”, *The Physics of Fluids*, **Vol. 1** No. 1 (1958).
3. J.W. Gibbs, “On the Equilibrium of Heterogeneous Substances”, Connecticut Academy (1874).
4. J. Ziegler *et al.,* “Transport of Ions in Matter”, *Nucl. Inst. Methods*, **B268**, 1818-1823 (2010).
5. H.S. Lee and H. Merte, “Spherical vapour bubble growth in uniformly superheated liquids”, *Int. J. Heat Mass Transfer*, **39**(12): 2427-2447 (1996).