Toward understanding the nuclear efficiency threshold of bubble chamber detectors

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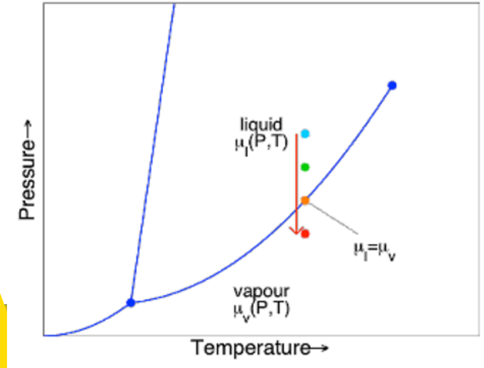
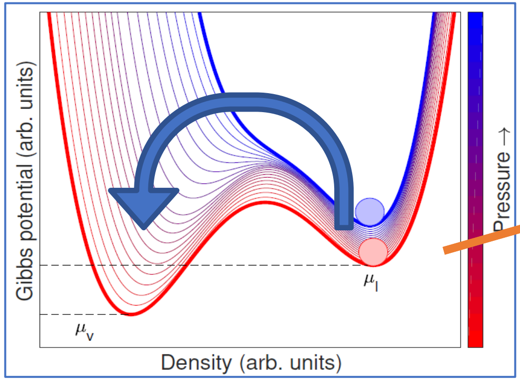
WNPPC 2022
February 2022

Bubble Chambers Overview

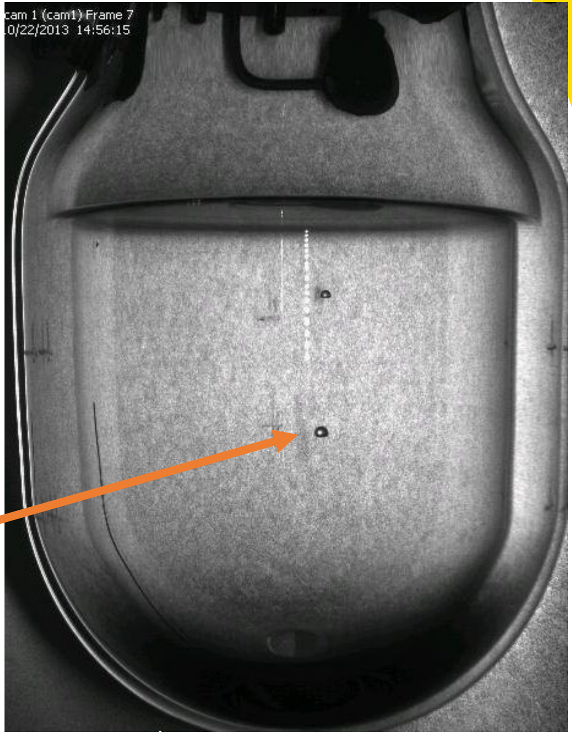
How does it work?

- Particles interact with target nuclei causes nuclear recoils (NR).
- A small deposition of energy causes a phase change in superheated fluid.
- Nucleation can be observed optically, acoustically, or barometrically.





PICO 2L [1]

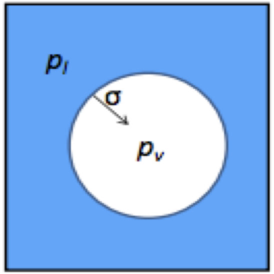


Current Physical Model

Current theory: the heat spike model

The latent heat of evaporation.

The Seitz model [2]: $E_{th} = \frac{4\pi}{3} R_c^3 \Delta p + \frac{4\pi}{3} R_c^3 \rho_v h_{lv} + \frac{4\pi}{3} R_c^3 \left(\sigma - T \frac{\partial \sigma}{\partial T} \right) + W_{irr}$



The work needed to form the bubble surface.

Combination of the free energy of surface and heat absorption from surrounding.

Irreversible work is small that we usually neglect.

- Δp : Pressure between bubble and liquid.
- ρ_v: Density of the bubble.
- σ: Surface tension.
- ΔH: Enthalpy change.
- T: Temperature.
- Where $R_c = \frac{2\sigma}{\Delta p}$, is called critical radius.

Condition for phase transition:

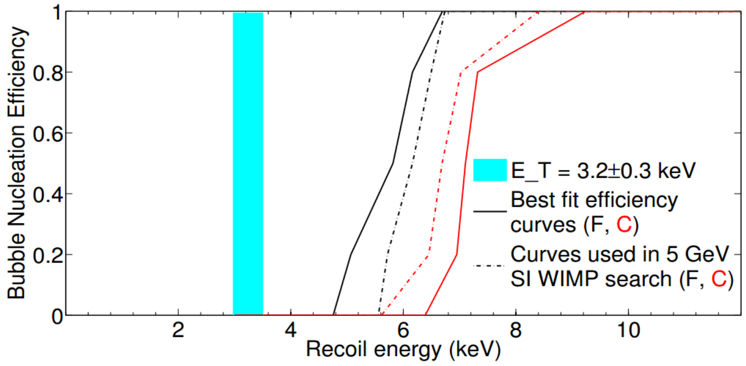
$$E_{\mathrm{dep}} = \int_0^{l_c} \frac{\mathrm{d}E}{\mathrm{d}x}\,\mathrm{d}x \geqslant E_{th}$$

- l_c: The critical length or track length.
- Where $l_c = \mathrm{bR_c}$
- b is a value obtained experimentally.

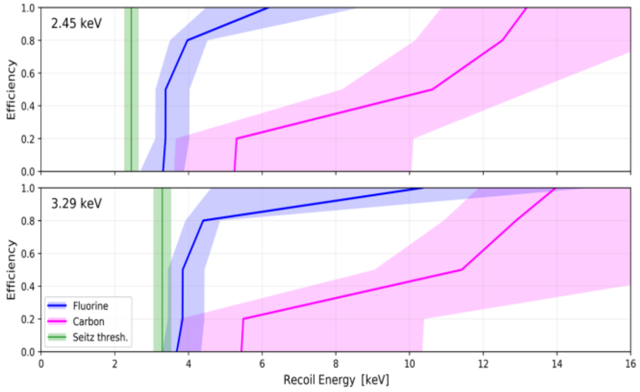
Current Physical Model

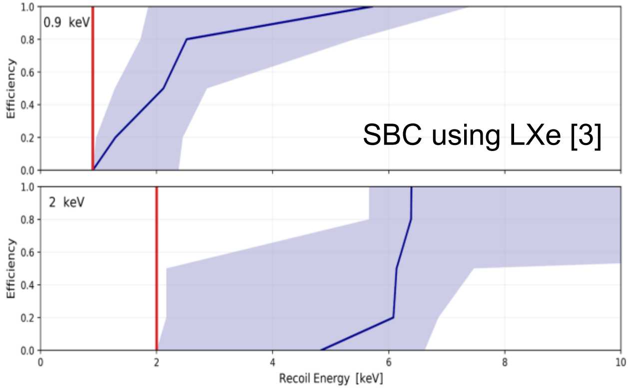
Experimental discrepancy:

PICO-2L C_3F_8 [4]



PICO-60 using C_3F_8[3]





- It's well known that the threshold for nucleation deviates from the predicted Seitz threshold. (PICO-2L, PICO-60, SBC, etc.)
- Recent new fitting results [3]:
  → See Daniel Durnford's talk

Objectives

Goals:

- Understand why the response is not a step function.
- Explore why the response is delayed and what factors cause the efficiency curve pattern.
- Establish a theory/model that one can extrapolate to other recoil threshold energies (in the range from 1 – 200 keV).

Study methods:

- Molecular dynamic (MD) to study the bubble formation and growth in microscopic scale.
- SRIM Monte Carlo simulation to study the energy transfer (depth penetration, losses, etc.).

Molecular Dynamic

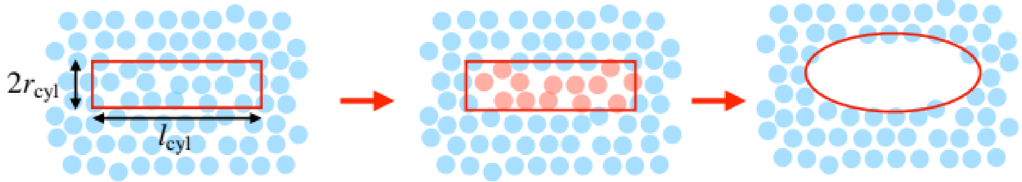
Molecular dynamic simulation in LAMMPS [5]:

- In LAMMPS, the molecular or atoms are interacting with each other by the Lennard-Jones potential.

$$u_{\mathrm{LJ}}(r) = 4\epsilon\left[\left(\frac{\sigma}{r}\right)^{12} - \left(\frac{\sigma}{r}\right)^{6}\right]$$

- σ: size of the atom/molecular.
- ϵ: minimum potential energy.
- r: distance.

- An incoming particle deposits energy that is simulated by rescaling energy inside a cylinder.
- The resulting bubble will either grow or collapse depending on the Seitz energy threshold or energy density dE/dx.

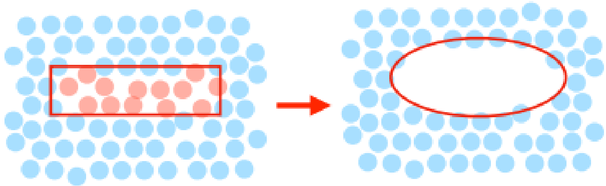


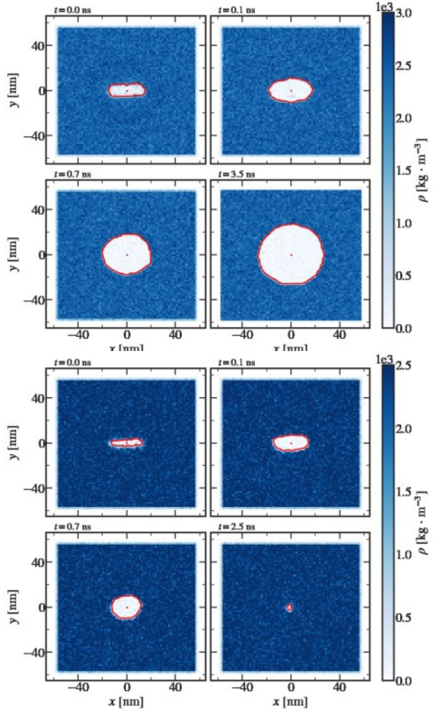
$$l_{\mathrm{cyl}} = l_c = \mathrm{bR_c}$$

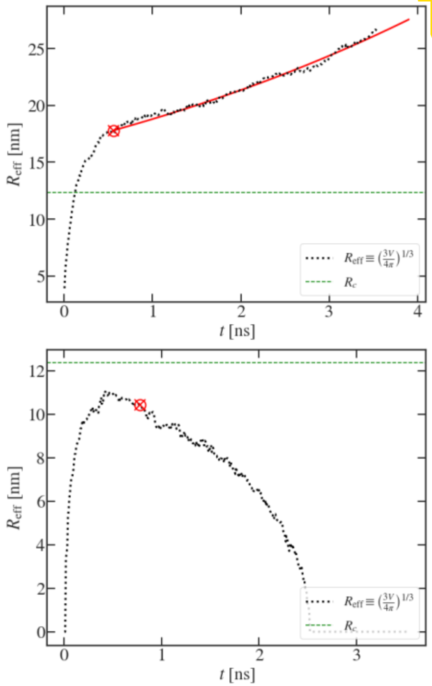
Molecular Dynamic

Molecular dynamic simulation in LAMMPS [5]:

- $E_{th} = 0.9$ keV, $T = -43$ °C,
  p $= 25\ psia$.
- 2 keV and 1 keV energy deposition in liquid xenon as an example
- The red fitting curve represents the bubble growth expansion described by Rayleigh-Plesset-Zwick equation



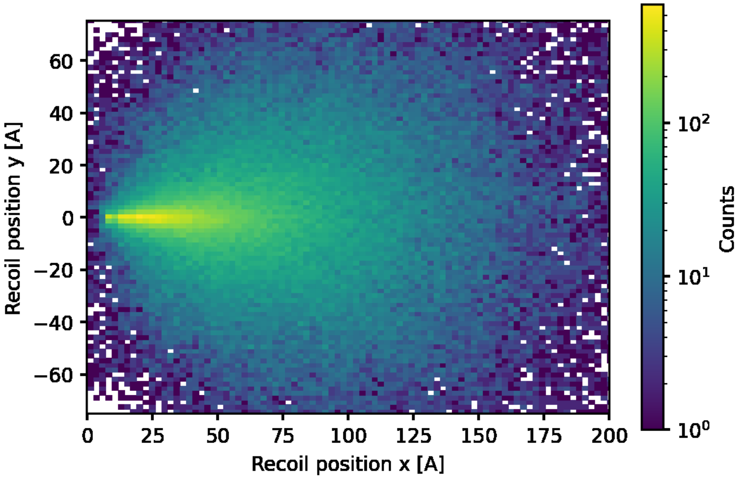


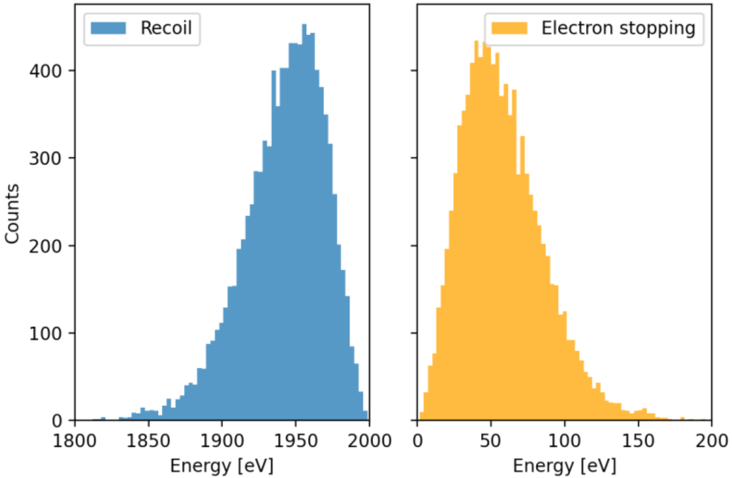


Monte Carlo

Monte Carlo simulation in SRIM [6]:

- Able to track how much energy of nuclear recoil is transferred into energy in heat spike.
- The graphs below show the 2 keV nuclear recoil events in liquid xenon.

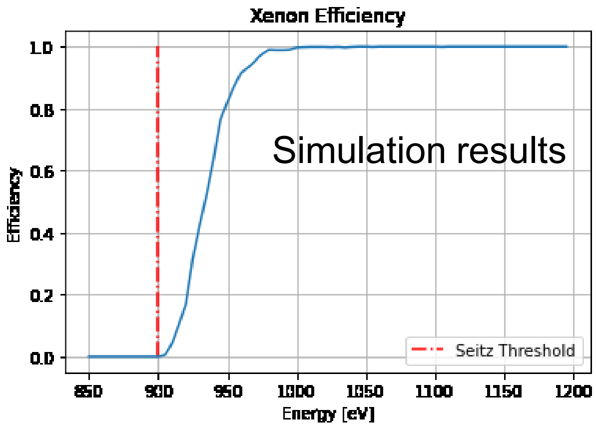


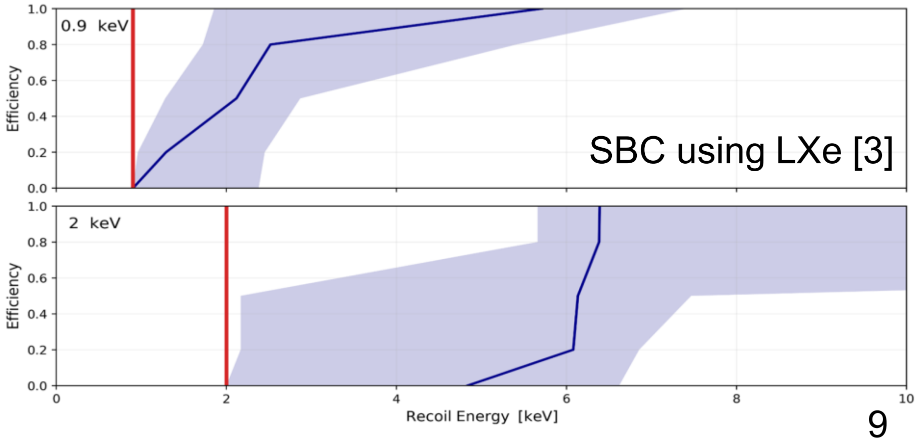


Reproduce Efficiency Curve

Method 1

- We are using SRIM to study the bubble nucleation efficiency.
- Nuclear recoil energy contributes to the heat spike.
- Electron stopping does not contribute to heat spike.
- The assumption is that if the energy is larger than the Seitz threshold, the bubble can form.

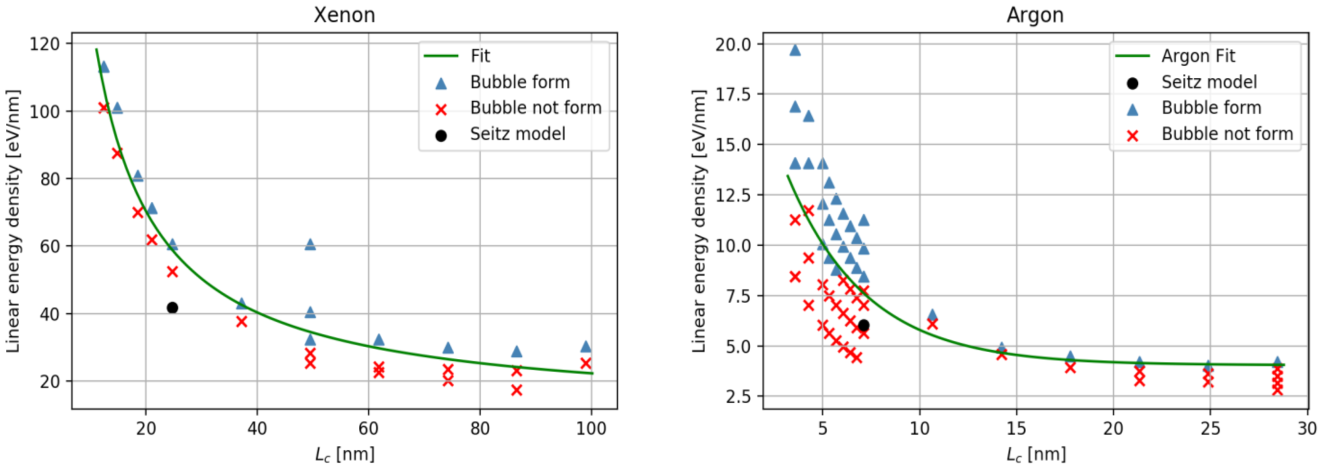




Linear Energy Density

Bubble formation with respect to the track length in MD

- The fit function represents the separation between the bubble formed and not formed.
- The l_c is the length of energy deposition defined manually in MD simulation.



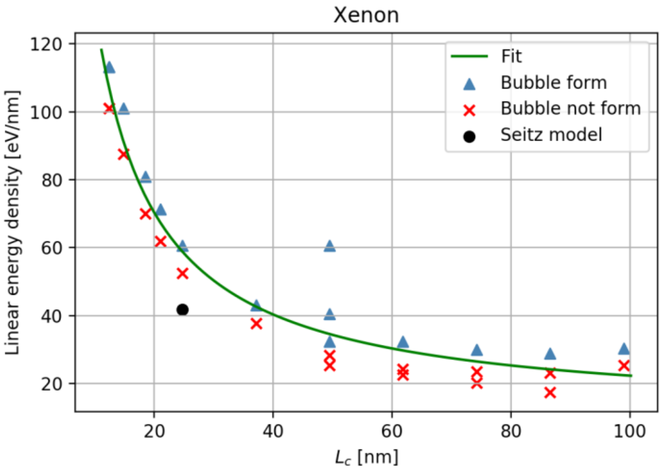
Fitting function: $f(x) = \frac{a}{x^2} + \frac{b}{x} + c$

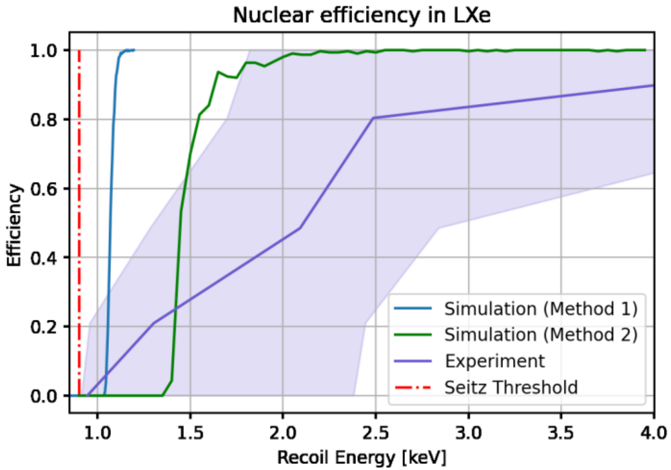
Reproduce Efficiency Curve

Method 2

- Assuming the linear energy density larger than the fitting curve the bubble will form.
- Results compared with nucleation efficiency for SBC using LXe [3].

  → See Daniel Durnford's slides.





Conclusion

Summary:

- We perform molecular dynamics and Monte Carlo simulation to study the nucleation efficiency discrepancy between the Seitz's model and experimental result.
- The preliminary are promising and seems to better reproduce the experimental data.

Next step:

- Use other gas species (Ar, C_3F_8, etc.)
- Explore how to simulate multi-compounds atoms in molecular dynamics.
- Generalize the result to construct a real physics model to explain the discrepancy observed between the experimental results and the current Seitz model.

Thank you for your attention!

[1] Amole, C. (2020, January 15). *Dark matter search with bubble chambers*. News. Retrieved February 10, 2022, from https://news.fnal.gov/2016/07/dark-matter-search-bubble-chambers/
[2] F. Seitz, On the theory of the bubble chamber, Phys. Fluids 1 (1958) 2.
[3] Durnford, D., & Piro, M.-C. (2022). Nucleation efficiency of nuclear recoils in Bubble Chambers. *Journal of Instrumentation*, *17*(01). https://doi.org/10.1088/1748-0221/17/01/c01030
[4] Amole, C et al. (PICO Collaboration), Phys. Rev. Lett. 114, 231302 (2015)
[5] *LAMMPS molecular dynamics simulator*. (n.d.). Retrieved February 10, 2022, from https://www.lammps.org/
[6] Ziegler , J. (n.d.). *Interactions of ions with matter*. SRIM & TRIM. Retrieved February 10, 2022, from http://www.srim.org/

Backup

Bubble expansion can be described by the equation ¶ :

$$\frac{\mathrm{d}R}{\mathrm{d}t} = -\left[\frac{A^2\sqrt{t-t_s}}{B} + \frac{2\nu_1}{R}\right] + \sqrt{A^2 - \frac{2\gamma}{\rho_1 R} + \left(\frac{2\nu_1}{R} + \frac{A^2\sqrt{t-t_s}}{B}\right)^2}$$

A — speed of expansion in the linear growth phase [m/s]
B — characteristic rate of expansion in the thermal growth phase [m/s^2]
ν_1— Kinematic viscosity [m2/s]
γ — Surface tension [N/m]
ρ_l— Fluid density [kg/m3]
The initial condition is provided by the existing (MD) simulations.

¶ T. Kozynets, S. Fallows and C. Krauss, "Modeling emission of acoustic energy during bubble expansion in PICO bubble chambers", *Physical Review D*, vol. 100, no. 5, 2019. Available: 10.1103/physrevd.100.052001.

Backup

The linear energy density as function of track length is fit with:

$$f(x) = \frac{a}{x^2} + \frac{b}{x} + c$$

Where $a = 16.88$ eV/nm, $b = 79.41$ eV/nm, $c = 13.40$ eV/nm.

x is defined as l_c/R_c, where $R_c = 12.36$ nm.