The nuclear efficiency of bubble chamber detectors

Xiang(Alex) Li
Supervisor: Prof. Marie-Cécile Piro
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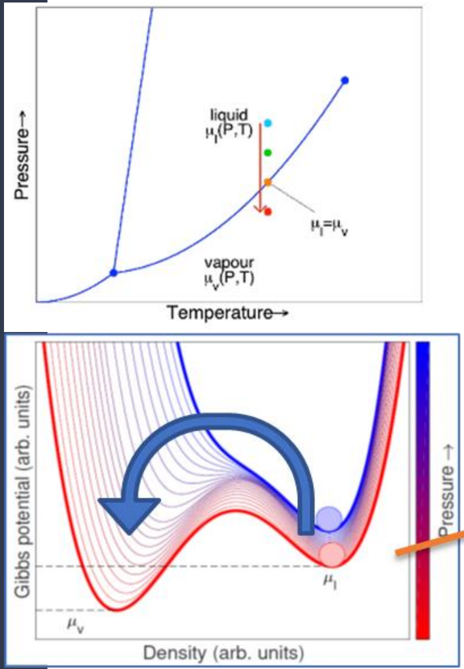
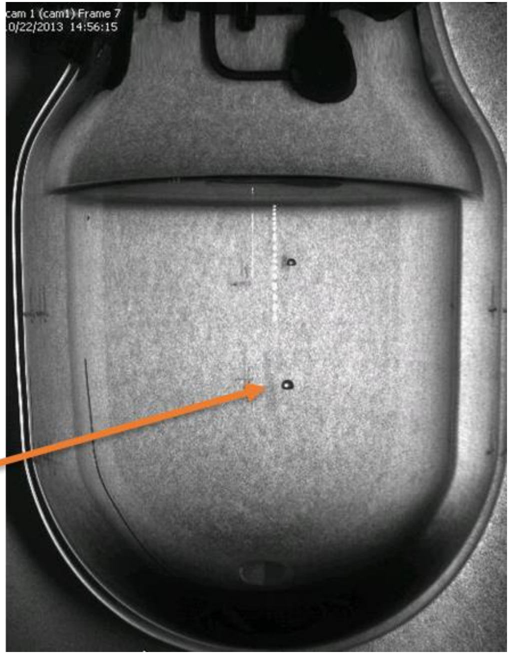
Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

UNIVERSITY OF ALBERTA

Overview

- 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.
- Detect WIMPs, coherent neutrino.





¶ [Amole, C. et al. (2020, January 15).]

The Seitz Model

The latent heat of evaporation.

¶ Seitz (1958)

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

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.
- ρv: Density of the bubble.
- σ: Surface tension.
- ΔH: Enthalpy change.
- T: Temperature.
- Where $R_c = 2\sigma/\Delta p$, is called critical radius.

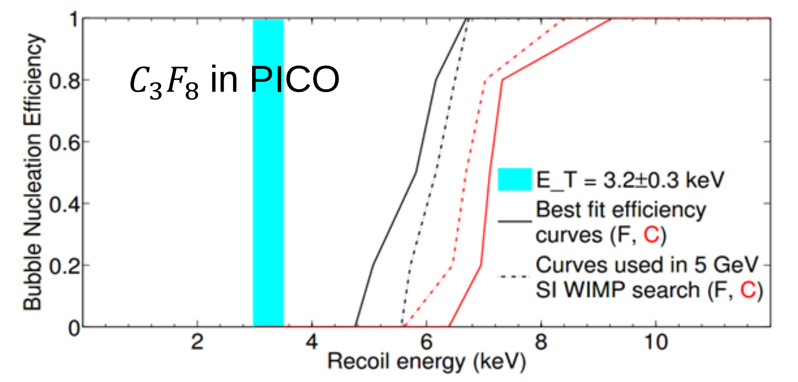
Condition for phase transition:

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

- l_c: The critical length or track length.
- Where $l_c = bR_c$

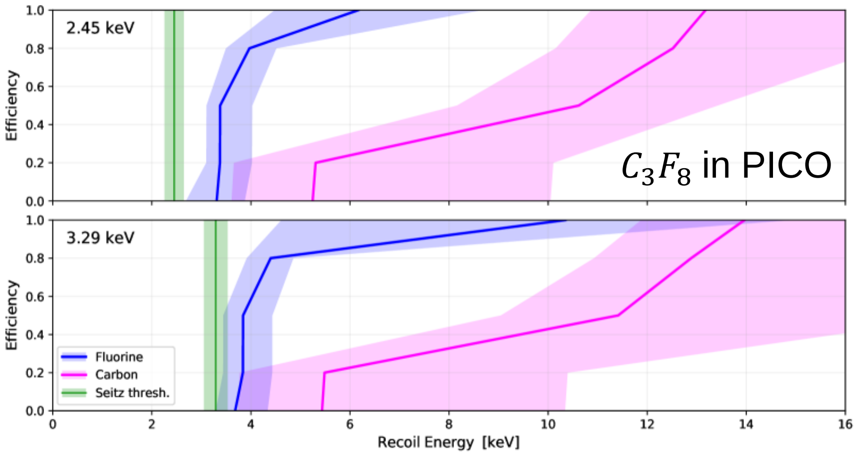
b is a value obtained experimentally

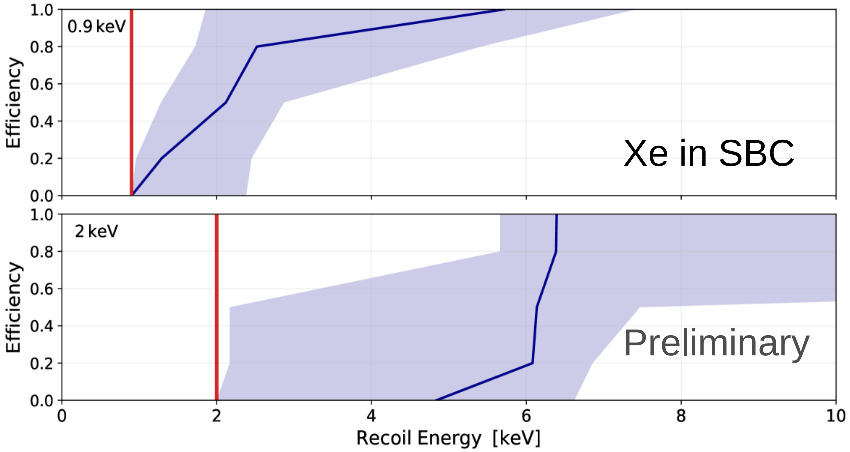
Experimental Discrepancy



¶ Amole, C et al. (2015)

¶ Durnford, D., & Piro, M.-C. (2022).





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).

Methods:

- Molecular dynamic.
  - Study the bubble formation and growth.
- SRIM Monte Carlo simulation.
  - Study the energy transfer.

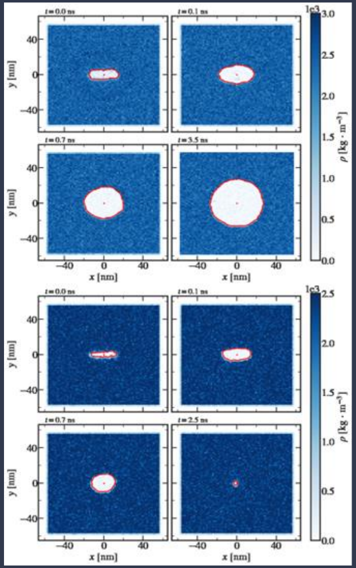
Molecular Dynamic (MD)

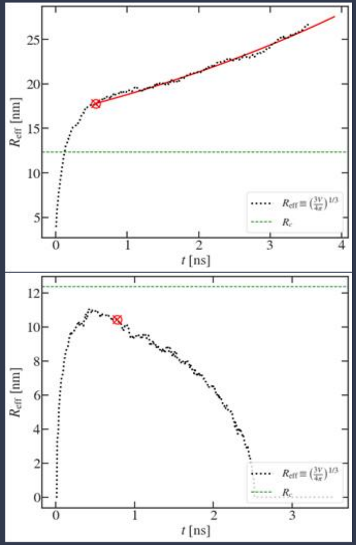
— ¶ LAMMPS

$E_{th} = 0.9\ keV, T = -43°C, P = 25\ psia$ LXe.

$E_{dep} = 2\ keV$

$E_{dep} = 1\ keV$



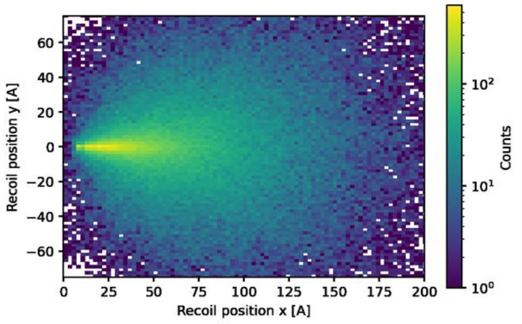


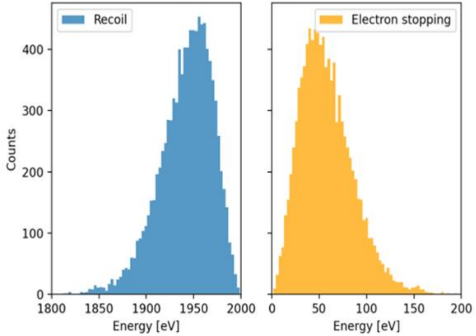
¶ Thompson A. P. et al. (2022)

Monte Carlo (MC)

— ¶¶ SRIM

$E_{NR} = 2\ keV$

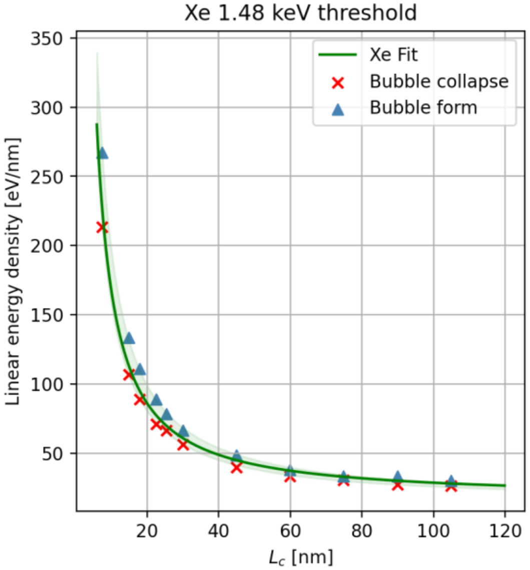


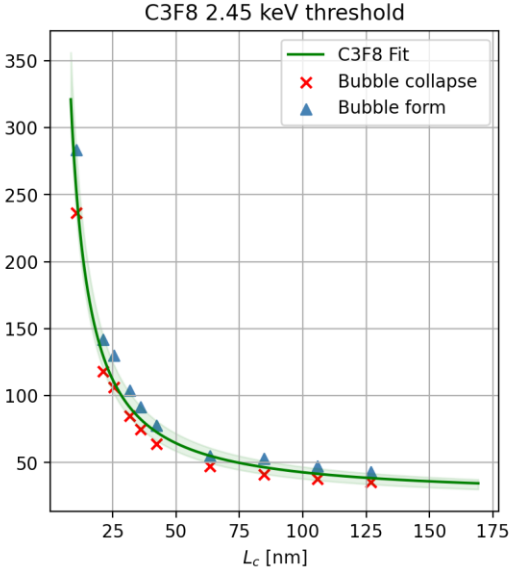


¶ ¶ Ziegler, J. et al. (2010)

MD summary

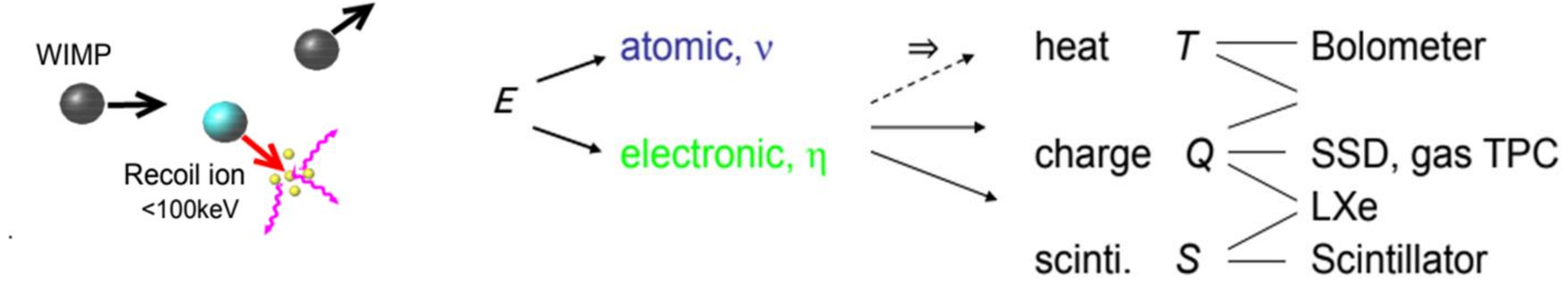
Bubble nucleation depending on the linear energy density and the track length





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

Energy Transfer



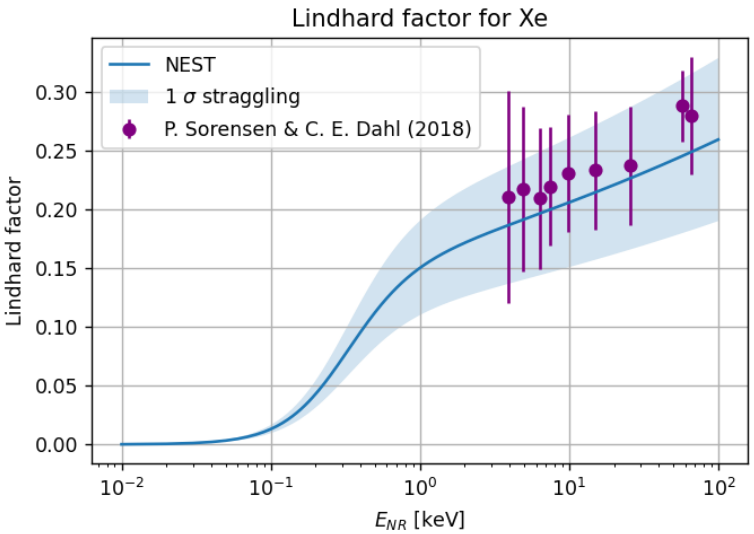
Fraction of electronic and nuclear (atomic) energy is called Lindhard factor (quenching factor):

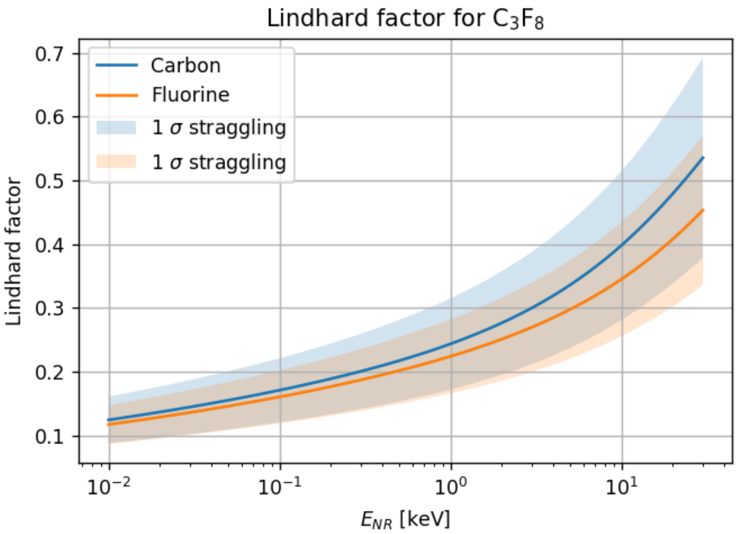
$$L = \frac{E_e}{E_{nr}}$$

$$L = \frac{kg(\epsilon)}{1+kg(\epsilon)} \quad \begin{cases} \epsilon = 11.5\,(E_0/\mathrm{keV})\,Z^{-7/3} \\ k = 0.133 Z^{2/3} A^{-1/2} \\ g(\epsilon) = 3\epsilon^{0.15} + 0.7\epsilon^{0.6} + \epsilon \end{cases}$$

¶ Hitachi (2017)

Linhard factor





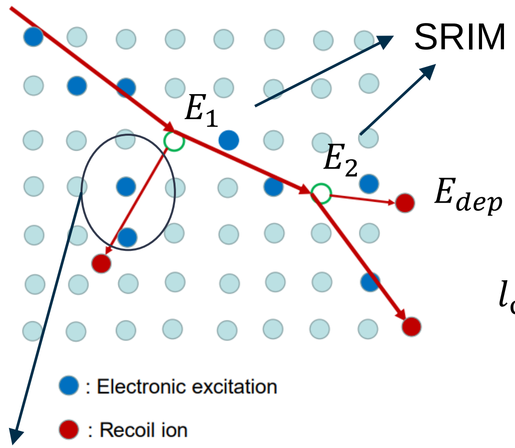
Xe is used ¶NEST package to calculate the Linhard factor.

¶ Szydagis, M, Et al. (2017)

MC+MD with Linhard factor correction

Monte Carlo in SRIM:

Collision cascades



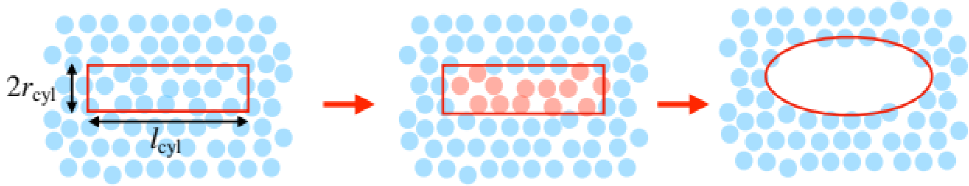
$$E_{1,elec} = E_1 \cdot L(E_1)$$

$$E_{dep} = \sum_i (1 - L(E_i))E_i$$

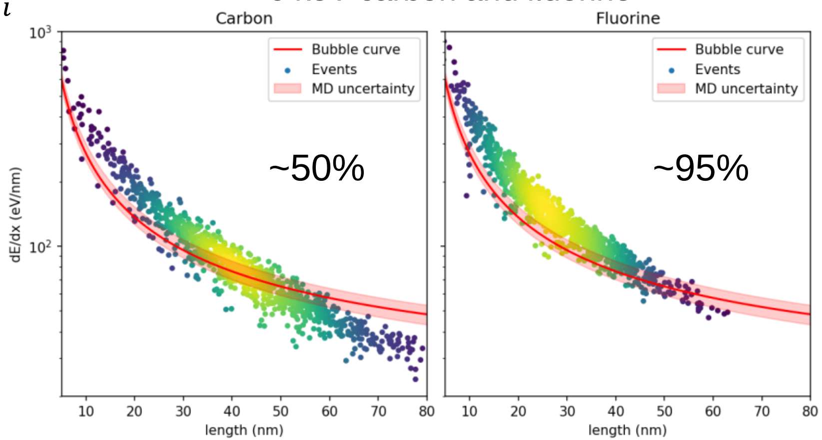
$$l_{\text{cyl}} = l_c = \text{bR}_\text{c}$$

¶ Hitachi (2017)

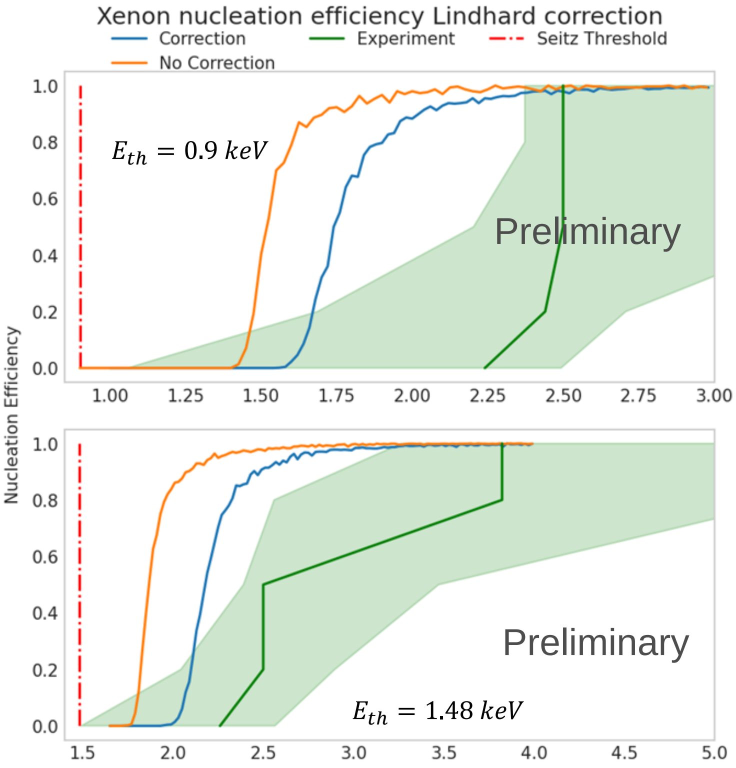
Molecular dynamics in LAMMPS:

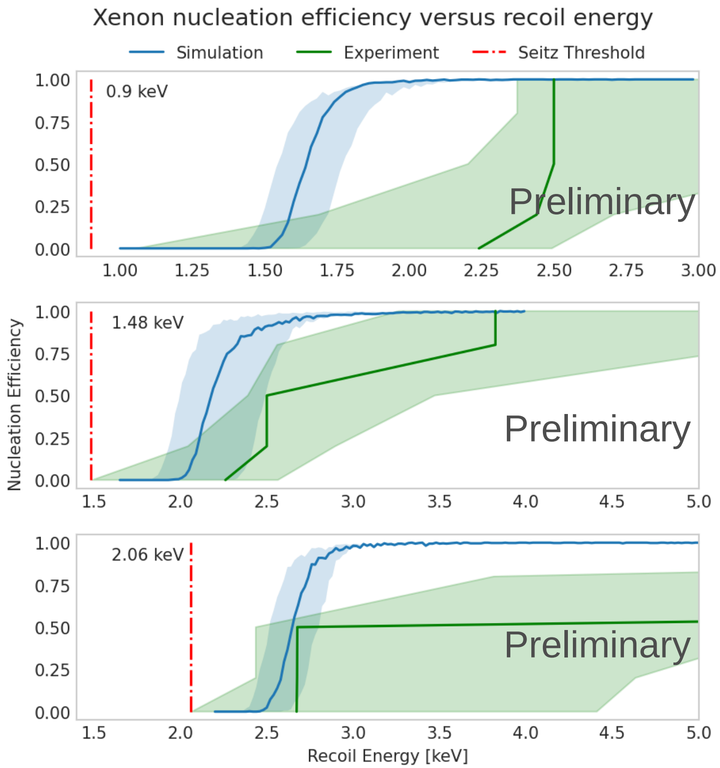


6 keV carbon and fluorine

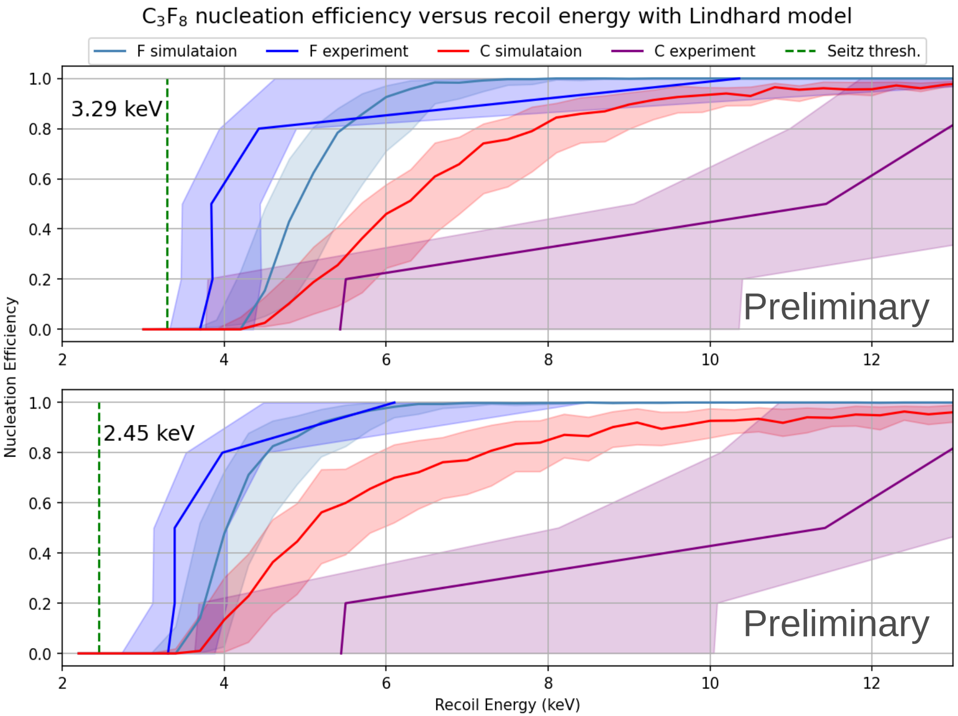


Xenon results





C_3F_8 results



Conclusion

Summary:

- Lindhard model has been used to model bubble nucleation efficiency for bubble chamber detectors.
- Xe and C_3F_8 results have been compared with experimental data.

Next:

- Compare and interpret the fit theoretically obtained with bubble forms and collapse.
- Determine Lindhard factor from the bubble nucleation efficiency curve.
- Present method can be used to estimate the exclusion limit.

Thank you for your attention!

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Arthur B. McDonald
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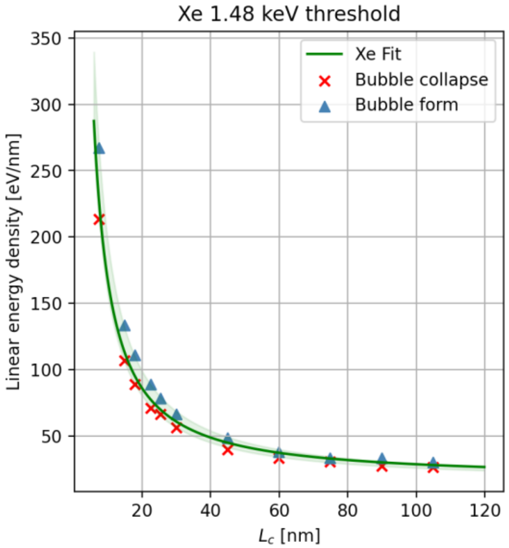
Back up

Systematic:

- Region between bubble form and collapse.
- k-value for compound is usually between 0.1 ~ 0.2.

Statistics:

- Fluctuation in energy transfer.



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$$\Omega_L^2 = \frac{\mathcal{L}}{14}\gamma\left\{\left(\frac{\gamma^{1/2}}{C_A E_c^{1/2}} - \frac{7}{4}\right)^2 + \frac{7}{16}\right\}$$

$$C_A = 2/3\left\{E_{1c}^{-1/2} + \frac{1}{2}\gamma^{1/2}E_c^{-1/2}\right\}$$

$$E_{1c} \cong M_1^3(M_1+M_2)^{-2}Z^{4/3}Z_1^{-1/3}\cdot 500\mathrm{eV}$$

$$E_{2c} \cong (M_1+M_2)^2 M_1^{-1} Z_2 \cdot 125\mathrm{eV}$$

Where $Z^{2/3} = Z_1^{2/3} + Z_2^{2/3}$

$E_c = \gamma E_{2c}$ and $\gamma = 4A_1A_2/(A_1+A_2)^2$

Backup

- 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.

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 (2019)