Bubble Chamber Calibrations

E. Dahl, for PICO Collaboration
Outline

• Bubble Chamber Thermodynamics
• Nuclear Recoil Calibrations
  – Charged Pions
  – Low-energy neutrons
  – High-energy neutrons
• Electron Recoil Calibrations
  – When is an ER not just an ER?
• Scintillating bubbles...
Bubble Chamber Basics

- Superheated Target – CF$_3$I, C$_3$F$_8$, ...
- Particle interactions nucleate bubbles
- Cameras and acoustic sensors capture bubbles
- Chamber recompresses after each event
Bubble Chamber Basics

• For interactions in this talk, response is **BINARY** – bubble/no-bubble
  – By the time we *hear* a bubble, it’s drawn 1 MeV from the fluid
  – By the time we *see* it, it’s drawn 10 PeV
Bubble Chamber Thermodynamics

• Reaching the superheated state

Superheated Liquid
Bubble Chamber Thermodynamics

• Consider the *equilibrium* state with a bubble:

\[ T_l = T_b \text{ (thermal equilibrium)} \]
\[ \mu_l = \mu_b \text{ (chemical equilibrium)} \]

\[ P_b \approx P_{vap} \]
\[ P_b - P_l = P_s = 2\sigma / r_c \text{ (mechanical equilibrium)} \]

Note, this is an *unstable* equilibrium
Bubble Chamber Thermodynamics

• What does it take to produce critical bubble?

\[
E_T = 4\pi r_c^2 \left( \sigma - T \left( \frac{\partial \sigma}{\partial T} \right)_\mu \right) + \frac{4\pi}{3} r_c^3 \rho_b (h_b - h_l) - \frac{4\pi}{3} r_c^3 (P_b - P_l)
\]

1.53 keV
1.81 keV
-0.15 keV

= 3.19 keV total

Surface energy, Bulk energy, Reversible Work
Bubble Chamber Thermodynamics

• What does it take to produce critical bubble?
  – Energy (heat) deposition $> E_T$
  – In a volume $< r_c$

• 0th order, dream scenario:
  – Nuclear recoils with $E_r > E_T$ make bubbles
  – Electron recoils don’t make bubbles
• Nuclear recoils not all $< r_c$, definitely not $<< r_c$
• Not all electronic stopping converted to local heating (Inverse Lindhard effect)
Nuclear Recoil Efficiency – Definition

• For each target fluid, need to measure set of probabilities

\[ P_X(E_r | E_T) \]

that a recoil of energy \( E_r \) and species \( X \) makes a bubble in a chamber at \textit{thermodynamic} threshold \( E_T \)

• Assumptions:
  – \( P_X \) monotonic in \( E_r, E_T \)
  – \( P_X = 0 \) for \( E_r < E_T \)
  – \( P_{\text{high-A}} > P_{\text{low-A}} \) at fixed \( E_r, E_T \)
Nuclear Recoil Calibrations: Challenges

• Threshold detector!

\[ \text{Bubble Rate} = \int dE_r \ P(E_r) \times R(E_r) \]

- Cannot determine efficiency with single recoil spectrum
- High-energy recoils wash out sensitivity near threshold
Nuclear Recoil Calibrations: Challenges

• Threshold detector!

• 1k bubbles / day max
  – Tagged scattering requires complete tagging (no wasted bubbles)

• Multiple nuclei with different kinematics
Nuclear Recoil Calibrations: Advantages!

• No electron sensitivity!
  – No shielding necessary with $^9\text{Be}(\gamma,n)$ sources
  – Can work with charged beams directly (e.g. $\pi^-$ scattering)

• Excellent 3-D position reconstruction
  – Take advantage of multiple scattering
The CIRTE Experiment


12 GeV $\pi^-$

$E_r = (p\theta)^2 / 2M_N$

13.5 keV $^{127}$I recoil = 4.7 mrad scatter

0.7 mrad resolution (multiple Coulomb scattering and pixel size)
Silicon Pixel Telescope at the Fermilab Test Beam Facility
Silicon Pixel Telescope + Bubble Chamber
bath to minimize the material traversed by the pion beam are tube has inner diameter of 10 mm. Beam tubes in the water

including the relative timing of the telescope trigger and acoustic signal, as well as solid targets of quartz, graphite, Teflon or crystalline iodine. Data taken in a test run in December 2011 with no target, target empty data set was taken. In addition, data were taken for selected runs with one of three targets.

naturally the result of inelastic interactions. Figure 1 shows an example scattering event. The pion beam is in the upstream direction. The camera image is not to scale but the test sample is 6 mrad), including the vertical extent of the pixel planes. Because the uncertainty on the location of the point of closest approach of the two components, with an associated scattering angle, we require the uncertainty on the location of the point of closest approach (upstream track) to be less than 2.1 mm in the horizontal direction and less than 0.9 mm in the vertical direction. The combined event acceptance of these timing and spatial cuts is 0.958 ± 0.011.

The telescope triggers, bubbles forming outside of the region covered by the telescope planes, multiple bubble events and ber triggers, bubbles forming outside of the region covered by the telescope planes, multiple bubble events and primary losses due to premature bubble chamber dead times. We were dead for the remainder of the beam spill, allowing pressures and associated data to be recorded and the chamber created a bubble chamber trigger, causing the video image to be turned on.

Expanding to the superheated state 22 seconds before the arrival of the beam, allowing time for pressure and temperature transients to dissipate after expansion. The observed number of pion tracks (4), and to meet in space to within 0.5 mm. To exclude pions that passed through little or no CF3I, we perform a full simulation of the number of scatters in the target-full data set to the number in the target-empty data set normalized to the standard Gaussian approximation for MCS [15].

The primary analysis output is the bubble nucleation fraction as a function of time, where $N_{\text{bub}}/N_{\text{emp}}$, is shown as the points in Fig. 2.

Each pion track is fitted for an upstream and downstream direction. The combined event acceptance of these timing and spatial cuts is 0.958 ± 0.011.

The next step is to associate a bubble with a unique track using both time and space correlations. The timing requirement for correlating a track with a bubble is $t<120$ ms. The bubble locations are reconstructed using standard COUPP techniques [1], and 3-D point of closest approach of the two components, with an associated scattering angle, we require the uncertainty on the location of the point of closest approach (upstream track) to be less than 2.1 mm in the horizontal direction and less than 0.9 mm in the vertical direction. The combined event acceptance of these timing and spatial cuts is 0.958 ± 0.011.

The angular smearing correction is made to the MCS from the absent CF3I by convolution with $r_{\text{emp}} f_{\text{tot}}$, and therefore cancels in the final ratio, $r_{\text{bub}}$. The number of tracks creating multiple hits $N_{\text{multi}}$, and therefore cancels in the final ratio, $r_{\text{bub}}$. The primary analysis output is the bubble nucleation fraction as a function of time, where $N_{\text{bub}}/N_{\text{emp}}$, is shown as the points in Fig. 2.
CIRTE Results

- At $E_T=13.6$ keV, $P_{l-127}$ consistent with step-function at $E_r=16.8$ keV
Neutron Calibrations

• Mono-energetic low-energy neutrons
  – $^{51}\text{V}(\text{p},\text{n})\ ^{51}\text{Cr}$
    • Many very sharp (∼0.25 keV) resonances
    • Neutrons from 4.8 to 119 keV
  – $^{9}\text{Be}(\gamma,\text{n})$
    • $^{88}\text{Y}$, $^{207}\text{Bi}$, $^{124}\text{Sb}$

Phys. Rev. 100, 167 (1955)
Neutron Calibrations

• Data on- and off- Fluorine resonances

ENDF (and thus Geant4, MCNP) gets these resonances \textit{wrong} (has them as isotropic)

Fixed in:
A. Robinson
PRC 89, 032801 (2014)
• No carbon turn-on, apparent fluorine turn-on...
Absolute Normalization of $^{51}$V(p,n) Data

• Two $^3$He counters recording neutron exposure in superheated state
  – 1 fixed position below $^{51}$V target
  – 1 in various positions to measure angular distribution of emitted neutrons
  – Simulation must reproduce relative rates in 2 $^3$He counters to include data

• Measure $^{51}$Cr in target (27.7 day, 320-keV $\gamma$)

• Absolute neutron flux known to 7%-11%, depending on neutron energy
AmBe in PICO-2L

• High-multiplicity events measure sensitivity to low-energy recoils
  – e.g. neutron stays in fluorine resonance for many few-keV scatters

\[ C_3F_8 \]
Throw it all together

- Fit to piece-wise linear efficiency curves
  - ‘kinks’ fixed at 0%, 20%, 50%, 80%, 100%
  - Energy of kinks floats (10 free parameters)

- For WIMP limit, use most pessimistic efficiency consistent with calibration data at 1-sigma
  - Depends on WIMP mass, interaction
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“Electron Recoils”

- Many gamma energies, several generations of detectors
"Electron Recoils"

- But why are $C_3F_8$ and $CF_3I$ so different?

E. Dahl, 9/25/15, KICP
Anomaly Discovered

Gamma Rejection

C₃F₈ gets CF₃I
gamma sensitivity???
Anomaly Verified

Anomalous sensitivity Reproduced at Northwestern...

E. Dahl, 9/25/15, KICP
A common thread

• The $\text{C}_3\text{F}_8$ chambers with high gamma sensitivity all had potential for high-Z contaminants
  
  — Tungsten residue from a thoriated welding rod test in the Northwestern chamber...

• Are we seeing Auger cascades in high-Z nuclei?
A test for Tungsten

• $^{207}\text{Bi}$ source
  – 73-85 keV: 74% BR <- Photoabsorption candidate
  – 570 keV: 98%
  – 1064 keV: 75%

• If W-photoabsorption is culprit, 2mm lead will cut rate by order of magnitude…
A test for Tungsten

- If W-photoabsorption is culprit, 2mm lead will cut rate by order of magnitude...
Bubble Nucleation by Auger Cascades

• Auger cascades can lead to 10+ sub-keV electrons from the parent atom
• Vastly different track topology than you get from single high-energy electron

• Compton Scatters and νe-→νe can leave inner shell vacancies, unlike ³H decays.
  – Thomas-Imel says this shouldn’t matter in xenon below 10 keVee, but worth checking...
A Scintillating Xenon Bubble Chamber

- All the perks of a bubble chamber
  - ER insensitivity
  - Easy 3D recon (no E-field req’d)
- With scintillation light for energy scale

E. Dahl, 9/25/15, KICP
A Scintillating Xenon Bubble Chamber

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A Scintillating Xenon Bubble Chamber

• Possible new tool for calibrations
  – “Inverse Lindhard” measurement
  – Photoneutrons without shielding (S1 only)
  – Other ideas?

3 weeks ago
Summary

• Nuclear Recoils
  – Nucleation probability determined by
    • Pion scattering
    • Mono-energetic neutrons with absolute rate calibration
    • Bubble multiplicity
  – Close to thermodynamic limit when tracks are small

• Electron Recoils
  – Not all electron recoils are equal
  – Auger cascades give much higher bubble nucleation probability than beta’s or valence Compton scatters