Searching for Dark Matter
With Bubble Chambers

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First Bubble Chamber (Glaser, 1952)

1-cm diameter glass tube, filled with ether

Cosmic ray
In those days, if anybody had an idea, and people thought it was a good idea, then you could start working on it. You didn’t write proposals and that sort of stuff. Luis Alvarez
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Why Bubble Chambers Didn’t Last

- Bubble chamber image analysis throughput: ~ 1 million events per year by end of the 1960s.
- Bubbles take about 100 microseconds to grow to visible size.
- For comparison: LHC beams cross at a rate of 40 MHz, with ~ 10 interactions per crossing.

*Figure: Alvarez Nobel Prize Lecture, 1968.*
New Role: Lawn Ornaments?
WIMP Dark Matter Detector Wish List

• Large target mass (>1 ton for next generation)

• Low energy threshold. (~ 10 keV for standard WIMPs, lower for light WIMP models)

• Multiple target nuclei- test expected cross section dependences on atomic number and nuclear spin.

• Zero backgrounds from environmental radioactivity.

• Measure nuclear recoil energies.

• Measure nuclear recoil direction.
Bubble Chambers?

- Large target mass (>1 ton for next generation) ✔
- Low energy threshold. ✔
- Multiple target nuclei—test expected cross section dependences on atomic number and nuclear spin. ✔
- Zero backgrounds from environmental radioactivity. TBD.
- Measure nuclear recoil energies. By varying threshold
- Measure nuclear recoil direction. No
Coherence and Couplings

• WIMP interactions are coherent over target nucleus due to long wavelength

\[ \lambda = \frac{h}{m_X v_X} \approx 0.9 \text{ fm} \cdot \left( \frac{m_X}{100 \text{ GeV}} \right)^{-1} \left( \frac{v_X}{220 \text{ km/s}} \right)^{-1} \]

• For “spin-independent” couplings, this typically causes enhancement of cross section by \( A^2 \) (\( A = \text{atomic number} \)) due to summing over nucleons. Strongly favors detection on high-A targets (Germanium, Xenon,...).

• For “Spin-dependent” couplings, opposite spin pairs interfere with net coupling only to any remaining unpaired nucleon– either proton or neutron.

• We would like to have targets of varying \( A \) and spin (and form factors) to explore these dependences.
Unique contribution of bubble chambers to WIMP searches

- Capability to instrument a wide range of target nuclei with sensitivity to diverse WIMP-nucleon couplings. For example,
  - **Fluorine**: Best sensitivity to spin-dependent interactions.
  - **Iodine, Bromine, Xenon, Argon**: High-A targets to exploit \( A^2 \) dependence of spin-independent cross section.
  - **Hydrogen**: Enhanced sensitivity to low-mass particles.
- Very low backgrounds, due to unique discrimination mechanisms.
- Thresholds below 3 keV nuclear recoil energy.
- Lowest cost per ton of target mass.
Backgrounds from Radioactivity


- Detector materials contain trace radioisotopes from environment.

- “Primordial” Uranium and thorium at levels of $10^{-6} - 10^{-9}$ atoms/atom in most materials. Typically $>10^5$ ionizing events per day per kg of material.

- Cosmic rays muons and secondary neutrons. Reduced by going underground.

- Unstable isotopes produced in detector by cosmics rays.
Bubble Chamber Expansion/Compression Cycle

Pressure vs. Temperature diagram showing the states of matter (SOLID, LIQUID, GAS) and the expansion/compression cycle.
Bubble Nucleation by Radiation

(Seitz, “Thermal Spike Model”, 1957)

- Pressure inside bubble is equilibrium vapor pressure.
- At critical radius $R_c$, surface tension balances pressure.

$$R_c = \frac{2\sigma}{P_{vapor} - P_{external}}$$

- Bubbles bigger than the critical radius $R_c$ will grow; smaller bubbles will shrink to zero.
Energy Barrier to Bubble Nucleation

\[ E_{th} = 4\pi r_c^2 \left( \sigma - T \frac{\partial \sigma}{\partial T} \right) + \frac{4}{3} \pi r_c^3 \rho_v h \]

*Surface energy*  
*Latent heat*

Threshold energies in keV for CF$_3$I
Tuning the dE/dX Threshold for Bubble Nucleation

- The bubble chamber operator chooses a pressure and temperature, fixing the minimum size of bubbles that are allowed to grow against surface tension.
- This simultaneously determines minimum deposited energy and energy loss density (dE/dX) that will nucleate bubbles.
- Example below: superheated CF$_3$I at fixed temperature, two operating pressures.

![Energy Thresholds Graph](image)

- dE/dX threshold at 15 psi and 65 psi
- CF$_3$I, T = 40°C
dE/dX Discrimination in 1960’s Bubble Chambers

Vapor Pressure – Operating Pressure (psi)

Gamma Insensitivity

Bubble nucleation probability for a gamma interaction in $C_3F_8$ or $CF_3I$
Prototype Dark Matter Detector at KICP, 2003

Diagram showing the setup of the detector with labeled parts:
- Pressure sensor
- Filter
- Gas
- Glycol
- Liquid
- Camera (1 of 2)
- Piston
Dirty Surfaces

Clean Surfaces
High Speed Bubble Chamber Movie
1000 frames/ second
$^{241}\text{Am-Be}$ neutron source
Demonstration of Continuously Sensitive Bubble Chamber

- Reinventing history-Glaser’s original “clean”, glass bubble chamber would remain sensitive for 10’s of seconds.
- Alvarez pioneered “dirty chambers” with metal surfaces: easy to build, but only sensitive for a few milliseconds.

Conventional Bubble Chamber

“Continuously Sensitive” Chamber

- Sensitive (1%)
- Insensitive (99%)

SLAC 1- meter hydrogen chamber

PICO-2L Chamber with CF$_3$I
Large Bubble Chamber WIMP Detector Cartoon

- Shielding Water @ 40 Deg C
- Glycol Hydraulic Fluid
- Water
- Fused Silica Inner Vessel
- $\text{CF}_3\text{I}$
- Stainless Steel Pressure Vessel
- PMTs (Water Cerenkov Muon Veto)
- High Speed Hydraulic Pressure Controller
2-Liter Chamber: PICO-2L
Large Chamber: PICO-60

STEEL PRESSURE VESSEL

INNER VESSEL ASSEMBLY
PICO-60 Chamber Testing at Fermilab
Alpha Decay Backgrounds

- Alpha particles and recoiling daughter nuclei can nucleate bubbles.

- The $^{238}\text{U}$ and $^{232}\text{Th}$ decay series include many alpha emitters, including radon ($^{222}\text{Rn}$) and its daughters, which are ubiquitous in the environment.
Alpha Backgrounds in 2006 COUPP Run at Fermilab

- High alpha background rate from radon dissolved in target fluid.
- Used pressure scanning to separate WIMPs/Alphas on basis of energy spectrum.

![Graph showing bubble count vs. pressure and energy threshold.](image)

- **Energy Threshold**: In KeV
- **Radon background**
- **Solid lines**: Expected WIMP response for $\sigma_{SD(p)} = 3$ pb
Imagine that we could photograph the bubble track with micron resolution a few microseconds after nucleation occurs, while bubbles are still just ~1 micron in diameter.

Video imaging of events on these time and distance scales impossible over the large required field of view: e.g. ~1 m³ of volume with ~1 micron resolution at a video rate of ~1 MHz.

**but**

Acoustic signal from alpha track is several times louder than recoil signal at high frequencies due to presence of multiple radiating bubbles.
• Bubble nucleation detected acoustically using piezoelectric microphones.
• Amplitude of acoustic signal differs for Alphas vs. Nuclear recoils.
• Distributions overlap at the ~10% level.
Acoustic Particle ID in Bubble Chambers

- Works much better in bubble chambers than in droplet detectors.
- >99.3% of alpha background rejected with 96% signal acceptance.
PICO-60 at SNOLAB, 2012
Anomalous Background Events

- Fluctuating rate of background events, from $\sim10$-100 counts per day.
- Non-uniform spatial distribution, with highest rates near top and walls of chamber.
- Highest rates during periods of temperature instability.
- Highest rates at beginning of bubble chamber expansion cycle.
- Anomalous acoustic amplitude distribution.
Space and Time Distribution of Recoil-Like Events

- Acoustically identified recoil-like events have anomalous spatial and time distributions.
- Correlation with temperature changes.
- This cannot be dark matter.
Acoustic Distribution

Calibration neutrons

Recoil-like background

20% excess acoustic power

Alpha background
Anomalous acoustic amplitude distribution of background

Nuclear recoil calibration events

Backgrounds

Acoustic Parameter
Expansion Time Dependence

- Probability of seeing a background event decreases the longer the chamber is expanded.
Something Floating in the Detector?

- PICO bubbles chambers contain repeatedly stressed mechanical parts (steel and quartz) in contact with fluids → generation and transportation of particulates?

Convection stirring up particulates?
Looking for Dust with Microscopes

- Liquids passed through teflon filters with 200 nm pore size.
- Studied using optical and electron microscopy, X-ray fluorescence, Alpha spectroscopy, mass spectroscopy at PNNL and University of Alberta.
- Result: majority of contamination from quartz and stainless steel materials used in chamber construction.

- PICO-60 sample:
  - 7 µg quartz particles
  - 240 µg stainless steel and iron oxide
X-Ray Fluorescence Under the Microscope

Draw a box around something interesting

A spectrum appears...
Optimization of Cuts

• Combined cuts on position, expansion time and acoustic amplitude yield background free region.
• Monte Carlo methods used to estimate sensitivity.

A background free region (~50% of exposure) by cutting on AP, expansion time, and Z
Improved Cleaning Procedures for 2016-2017 Run

- Spray jet cleaning with high purity, hot detergent system.
- Measurements of fluid particle counts for quality control.
Most Recent PICO Result: PICO-60 2017 Run

- Aggressive cleaning to remove Inner Vessel particulate contamination.
- 52 kg of $\text{C}_3\text{F}_8$ target liquid (46 kg fiducial)
- 1167 kg-day efficiency-corrected exposure.
- 3.3 keV threshold (14 degrees C, 30 psi)
- 106 single bubble events passing basic data quality and optical fiducial volume cuts.
PICO-60 2017 Acoustic Analysis

- Two parameter acoustic analysis:
  - Acoustic Power (AP)
  - Neutral Network score
- Blind analysis- first time for PICO.
- Zero WIMP candidates passing acoustic cuts!
PICO-60 Incipient Neutron Background

- Three multiple scatters observed, no singles.
- Marginally compatible with background model expectation (0.96 multiple, 0.25 single)
PICO 60 WIMP - Proton Exclusion

The 90% C.L. limit on the SD WIMP-proton cross section from PICO-60 C₃F₈ blue, along with limits from PICO-60 CF3I (red), PICO-2L (purple), PICASSO (green), SIMPLE (orange), PandaX-II (cyan), IceCube (dashed and dotted pink), and SuperK (dashed and dotted black)

PICO-40L: A ”Right Side Up” Bubble Chamber without Water

• New design concept eliminates water buffer layer from chambers.
  • Water/target liquid interface traps contamination.
  • Water coating of particulates suspected to play a role in bubble nucleation mechanism.
• Larger pressure vessel increases separation between radioactive construction materials and fiducial voluum.
• Goal: background-free 15 ton-day physics run.
• To be commissioned in Summer 2018.
PICO-40L Under Construction
PICO-500

- PICO-500 proposal approved in 2017 by Canada Foundation for Innovation (CFI).
- Detector final design is underway, with many concepts tested in PICO-40L.
Progress of PICASSO/COUPP/ PICO Program

50 GeV WIMP constraints

- PICASSO (1 L SDD)
- ZEPLIN-I
- PICASSO (4.5 L SDD)
- XENON10
- XENON100
- LUX
- PICO-2L run-1
- PICO-2L run-2
- PICO-500
- PICO-60 C$_3$F$_8$
- PICO-40L

SD WIMP-proton/neutron 90% C.L. cross section [cm$^2$]


- WIMP-proton
- WIMP-neutron
Backup slides
Nuclear Recoil Signal from WIMPs-Ingredients

- WIMP spectrum in a detector is obtained by convolution of monoenergetic detector response with modeled dark matter velocity distribution.
- Standard dark matter density is 0.3 GeV/cm$^3$

Response to single velocity component

$$E_{\text{max}} = \frac{2m^2 m_N}{(m_\chi + m_N)^2} V^2 \chi$$

Energy Spectrum for WIMP recoils on Germanium

- $M = 50$ GeV
- $\sigma_{Wn} = 10^{-45}$ cm$^2$
- $100$ GeV
- $200$ GeV
- $500$ GeV
Construction of Sensitivity Plots

- Often in this field backgrounds cannot be accurately modeled and subtracted.
- For any possible WIMP mass, the data allow a maximum possible signal amplitude,
- Excluded region in Mass * Cross Section plane is the envelope of these amplitudes.
- Figures below illustrate trivial case where spectrum is known with high statistical accuracy. Other techniques have been developed for the case of a sparse spectrum.

Assume local WIMP density 0.3 GeV/cm$^3$

![Graphs showing event rate versus energy and WIMP mass versus cross section.](image-url)
Background Discrimination: Possible Observables

- Pulse shape differences in scintillation light in noble liquids or crystals. DarkSide, DEAP, KIMS, DAMA.

- Ratio of ionization to scintillation in liquid noble gases. LUX, LZ, Xenon, PANDA-X

- Ratio of ionization or scintillation to total deposited heat energy in cryogenic calorimeter. CDMS, EDELWEISS, CRESST.

- Efficiency for bubble formation in superheated liquids. COUPP, PICO, PICASSO, SIMPLE.

- Annual modulation in spectrum due to motion of Earth around the Sun. DAMA

- Track ion charge density in gas drift chamber. Daily modulation in direction of ion tracks. DMTPC, DRIFT
Possible Mechanism for Generating Events-Equipped Alpha Emitters

- When an alpha decay occurs in liquid, alpha particle and daughter nucleus recoil contribute about equally to amplitude of acoustic signal \( \rightarrow \) alpha decay acoustic amplitude approximately 2 \( \times \) nuclear recoil from a neutron or WIMP.

- If the alpha-emitting isotope is embedded in solid material <10 microns thick, alpha particle can escape to make a bubble, but nuclear recoil is hidden in the solid. Acoustic amplitude similar to nuclear recoil.

- Ongoing R&D: We are attempting to demonstrate suppressed acoustic signal from alpha activity in particulates with test chambers at Northwestern, Queen’s University.
PICO-60 2013-2014 Physics Run

- Detector began operating in April ‘13. First physics data in June.
- Target: 37 kg CF$_3$I. Optimal for sensitivity to spin-independent WIMP-nucleon couplings.
- High live time fraction, growing to >90% by end of run.
- 5000 kg-days “WIMP exposure” from June ‘13 to May ’14.
- Several different operating modes explored: fixed threshold points (temperature, pressure), threshold scans from 7 keV to 30 keV.
- Extensive neutron calibration data.
- Run was ended in May ’14 to allow inspection of detector and fluids for particulate contamination.
Nucleon Coupling Limits

Consider spin-dependent coupling to proton and neutron

See Tovey for details:
Spin-Independent WIMP Scattering Limits from PICO-60 2013-2014 Run
The Future

• PICO-60 2016-2017 Run
  – Switch from CF$_3$I to C$_3$F$_8$ target to enhance spin-dependent sensitivity.
  – New techniques to reduce particulate load, including semi-continuous filtration of liquids during the run.
  – Potential for 2 orders of magnitude improvement in sensitivity, depending on resulting backgrounds.

• R&D: Development of single-fluid bubble chamber design.
  – Eliminate the water/target liquid interface where “dirt” accumulates.
  – Could be the basis for future experiment with ton-scale target mass- our long term goal.
2017 PICO Result: Factor of 17 Improvement in Spin-Dependent Sensitivity
Spin-independent Limits

- Iodine (high Z) is good for heavy WIMPs.
- Fluorine target gives better sensitivity to lighter WIMPs.
- 3.3 keV nuclear recoil threshold—still high compared to what has been achieved with cryogenic detectors, CCDs and liquid xenon/argon.