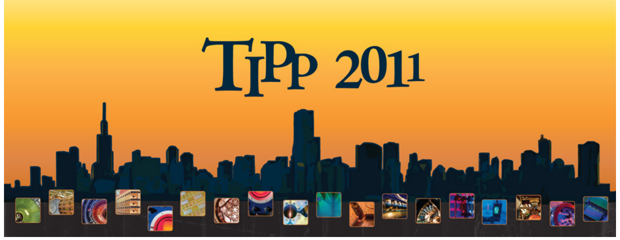

R&D for the Observation of Coherent Neutrino Scatter at a Nuclear Reactor with a Dual-Phase Argon Ionization Detector

Samuele Sangiorgio

on behalf of
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Lawrence Livermore
National Laboratory

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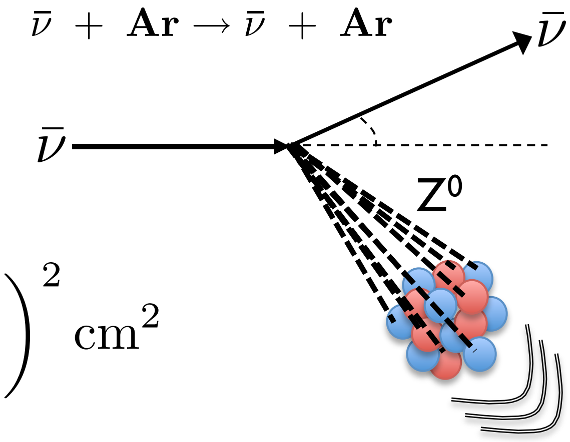
Predicted but hard to see

Coherent Neutrino Scattering (CNS) is a neutral current process where an incoming neutrino elastically scatters on a nucleus

- flavor blind
- predicted by the SM
- enhanced cross-section:

$$\sigma_{\rm cs} \simeq \frac{G^2 \boxed{N^2}}{4\pi} E_\nu^2$$

$$\simeq 0.42 \times 10^{-44} N^2 \left(\frac{E_\nu}{\rm MeV}\right)^2 {\rm cm}^2$$



$$\bar{\nu} + \mathbf{Ar} \rightarrow \bar{\nu} + \mathbf{Ar}$$

- low recoil energy:

$$\langle E_r \rangle = 716\ {\rm eV}\ \frac{(E_\nu/{\rm MeV})^2}{\boxed{A}}$$

Drukier and Stodolsky, PRD 30(11), 1984.

Where to look for Coherent ν Scattering

- Solar neutrinos
- Neutrino beams
- Supernovae
- Nuclear Reactors

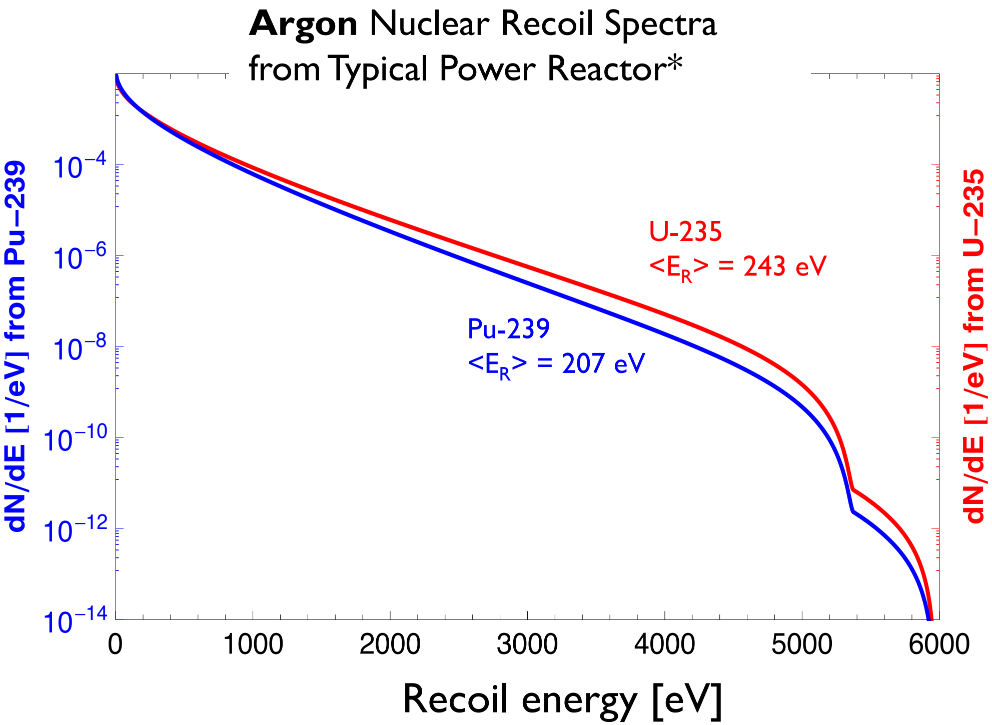
Coherence condition

$$\lambda_\nu >> R_{nucleus} \sim 1.25\ \mathrm{fm}\ A^{1/3}$$

Reactors are an attractive source of neutrinos for CNS investigation:

- High flux ($\Phi > 10^{12}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$)
- Energies up to ~10 MeV
- Allow for relative measurement when reactor is off for refueling

Average recoil energy of Ar from reactor neutrinos is ~ 240 eV !!



Argon Nuclear Recoil Spectra from Typical Power Reactor*

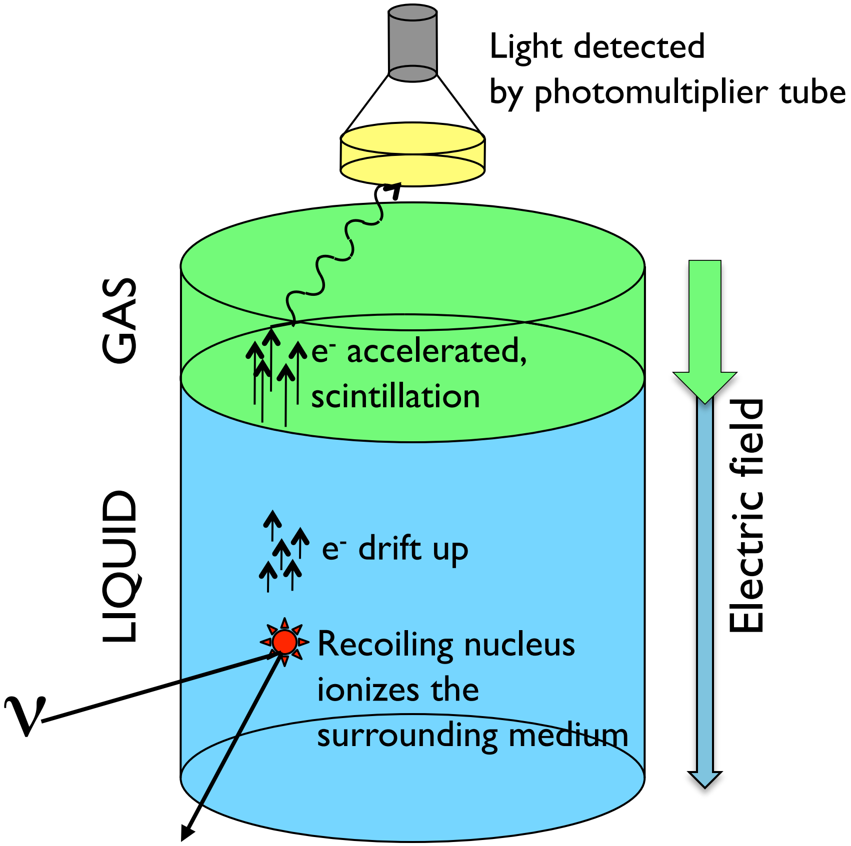
Hagmann & Bernstein, TNS 51(5) (2004)

(*) at ~ 25 m from a 3-GWt core with typical fuel composition

Dual-phase Noble-element Detectors

- Well known technology, extensively used for Dark Matter
- Good electron drift properties
- Large mass
- Low thresholds
- Scalability

  - Argon
  - Xenon



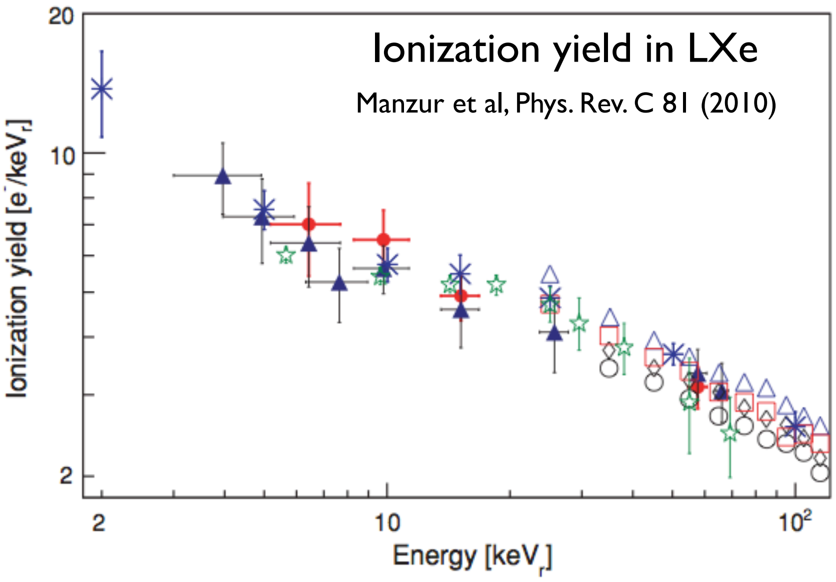
How many primary electrons are produced by a nuclear recoil?

Ionization Yield of Nuclear Recoils

- Nuclear recoils are less effective than electron recoils in producing ionization
- Experimental data for LXe for nuclear recoils down to 4 keV.

nuclear ionization quench factor

$$q(E_r) = \frac{N_{ion}(E_r, \text{nucleus})}{N_{ion}(E_r, \text{electron})}$$

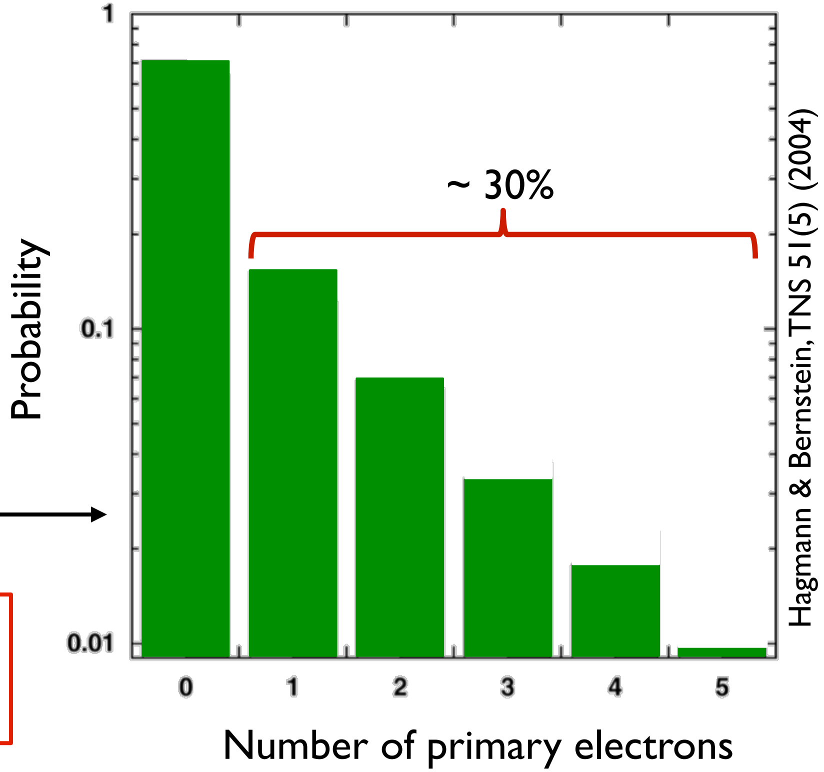


Ionization yield in LXe

Manzur et al, Phys. Rev. C 81 (2010)

- No data for Ar, only MonteCarlo

Simulated ionization spectrum from reactor neutrinos

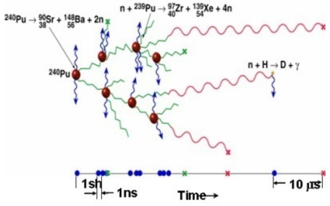


Hagmann & Bernstein, TNS 51(5) (2004)

We want to measure the ionization yield of nuclear recoils in LAr

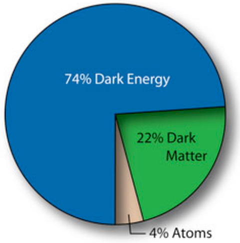
CNS and Dark Matter detectors

Coherent scatter detection



- Nuclear recoils < 5 keV
- Little to no S1 (primary) light
- Little or no overburden
- ~10 event per kg per day
- 10-20 kg active mass
- Modest purity: electron drift of 0.2-0.5 m
- Robust, easy to operate and to interpret
- Neutrino source can be turned off for various reactor designs

Dark Matter



- Nuclear recoils < few tens keV
- S1/S2 provides particle ID
- 100-5000 m.w.e. overburden
- ~1 event per 100 kg per month *
- Current generation is 100 kg or larger
- High purity Electron drift of 1-2 m
- Simplicity a secondary consideration
- No off switch for Dark Matter

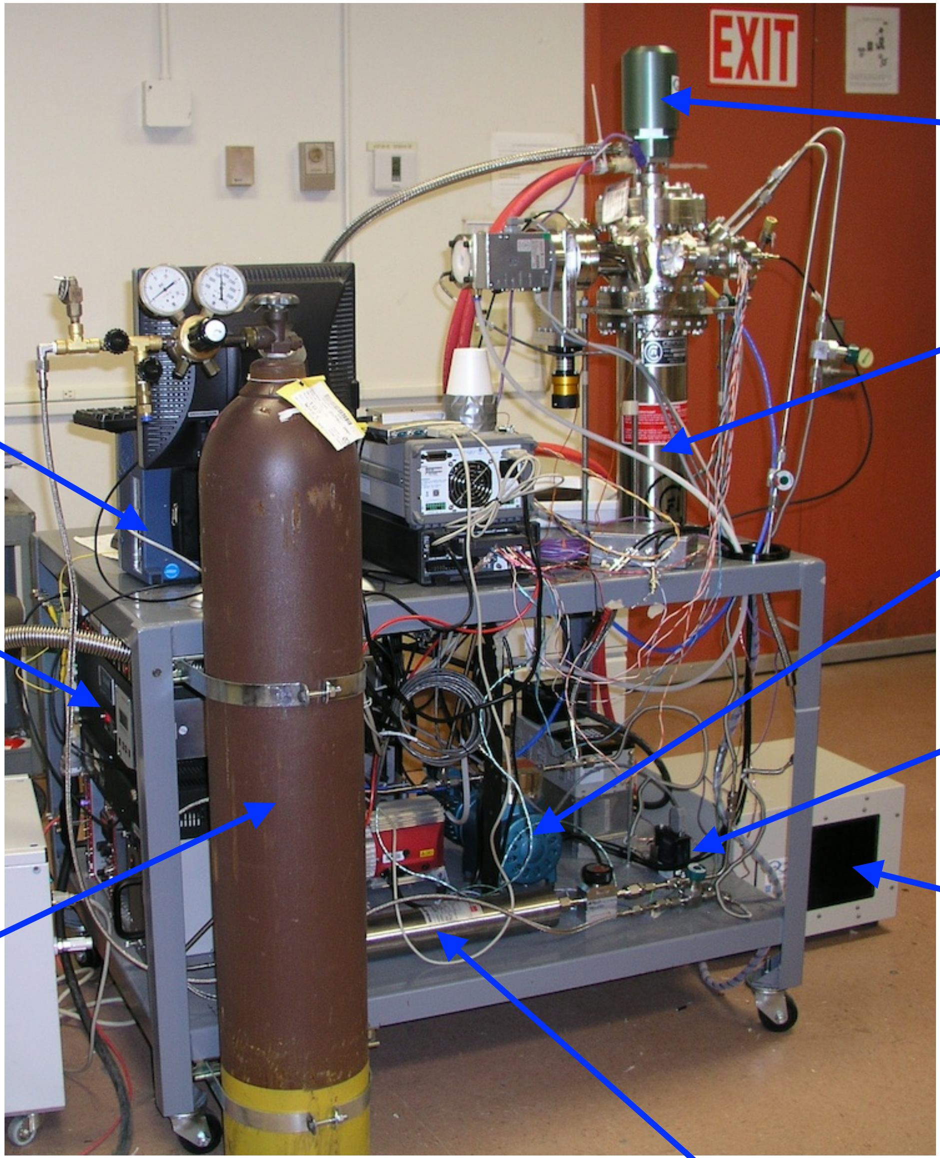
Unique to monitoring

Unique to dark matter

(*) assume σ = 1e-45 cm^2 for a100-GeV WIMP on Xe

Dual-phase Ar Ionization Detector

Compact and movable design



cryocooler head

cryogenic dewar

DAQ

Slow control

circulation pump

flow control

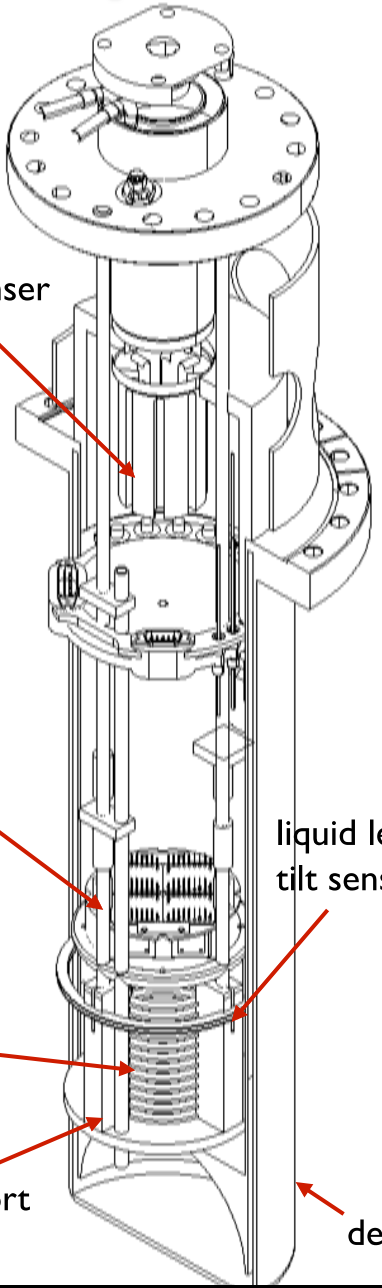
cryocooler cooling system

Argon gas

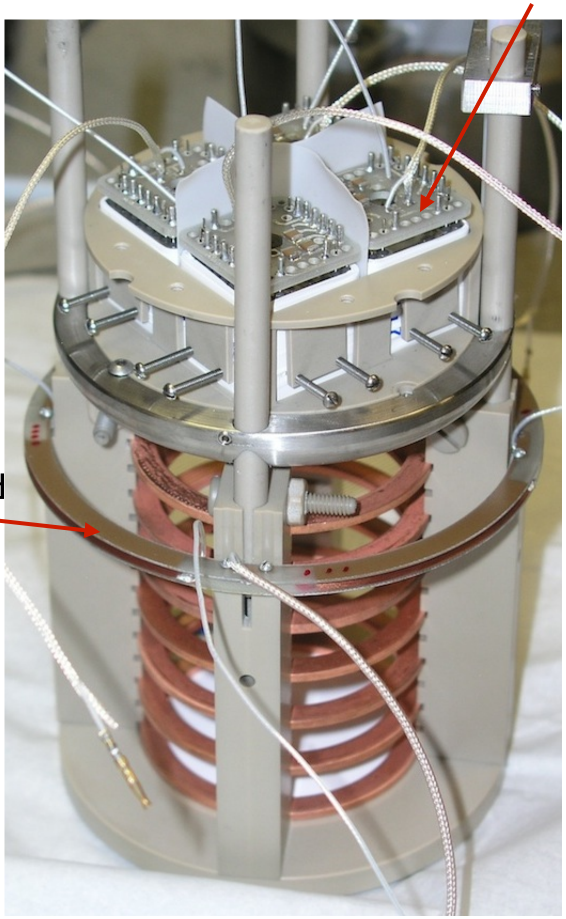
gas purifier

Dual-phase Ar Detector Guts

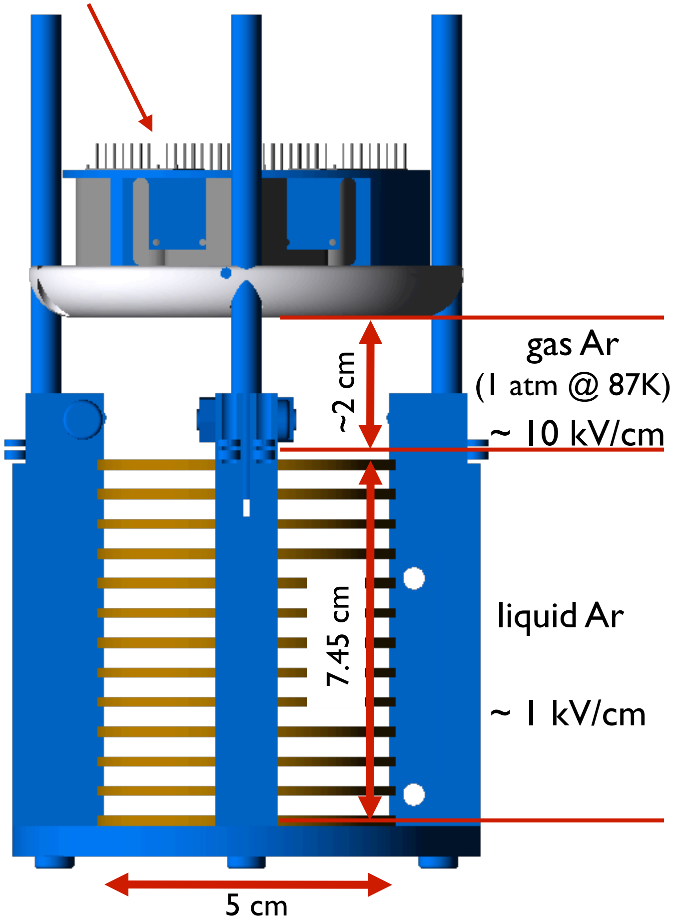
- In-situ Liquid Ar production w/ cryocooler
- Primary region volume: ~ 200 g LAr
- TPB as a wavelength shifter



liquid level and tilt sensor

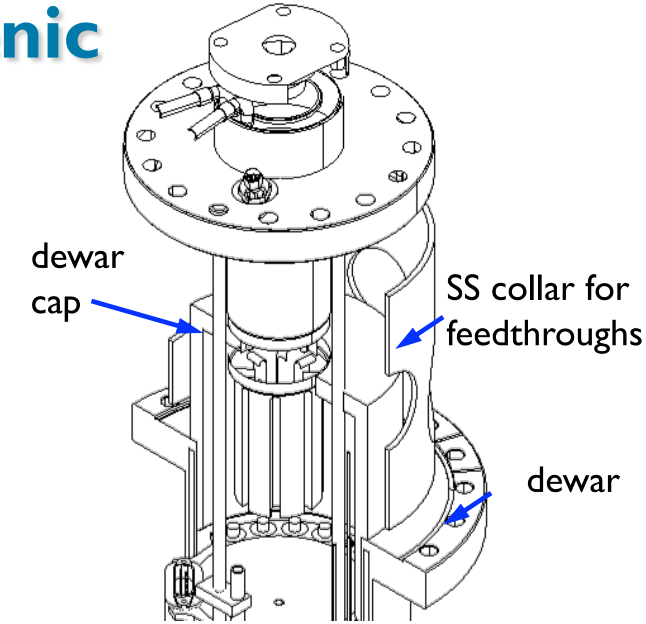


4x Hamamatsu R8520-06-MOD 1” PMTs for LAr operation



Dual-phase Ar Detector Cryogenic

- Automatic cool-down and liquefaction in less than ~ 20 h
- Temperature stability ± 0.05 K
- Continuous purification of Ar 2-3 times per day
- Low-power cryocooler with variable cooling power

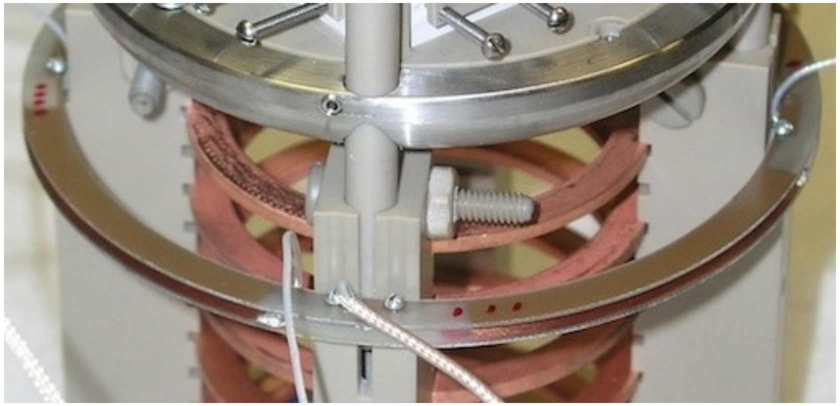


dewar cap

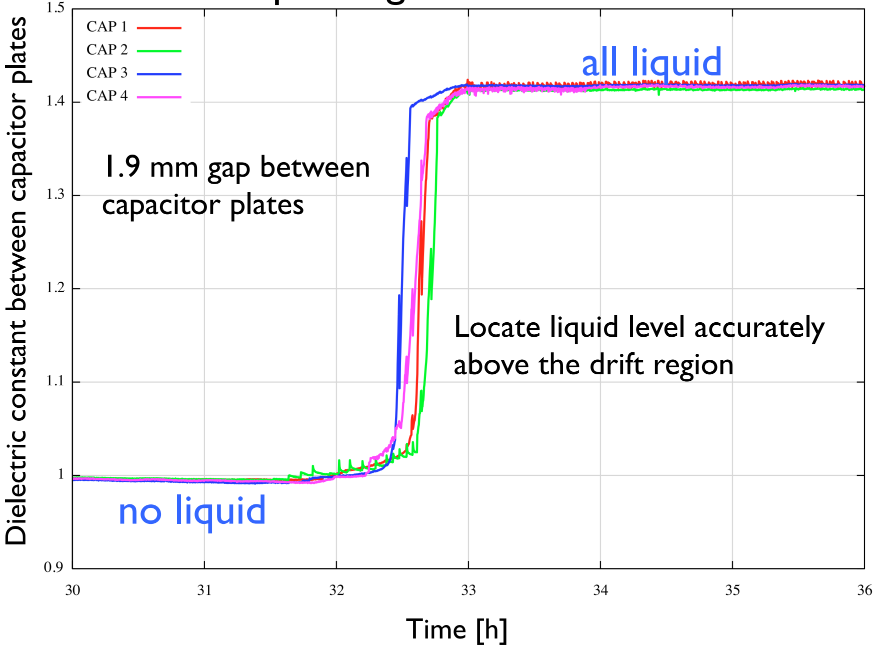
SS collar for feedthroughs

dewar

- Sensitive liquid level tilt sensor



Liquid Argon tilt and level sensor



1.9 mm gap between capacitor plates

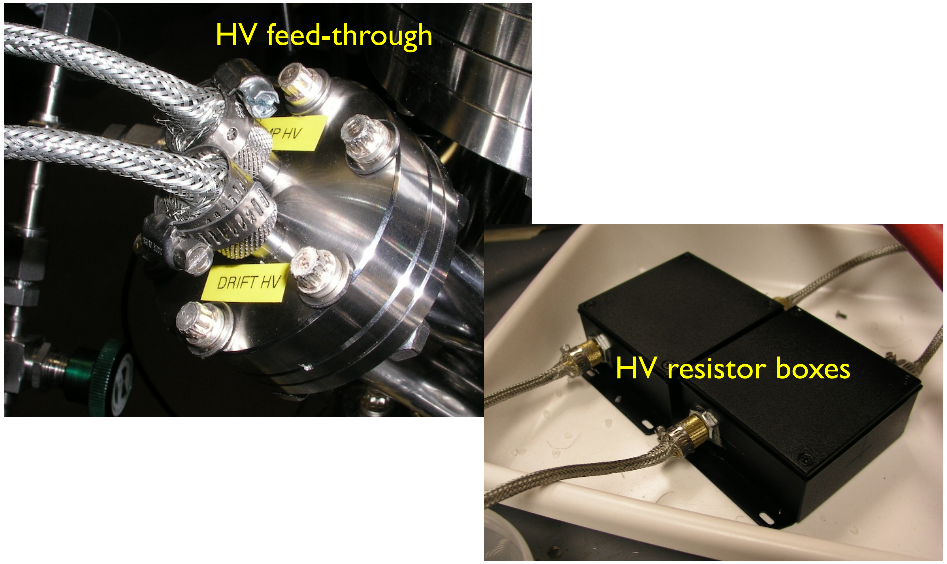
Locate liquid level accurately above the drift region

Dual-phase Ar Detector High Voltage

- Gas Argon has poor dielectric properties
- Needs careful design of feed-throughs that are reliable and compatible with high-vacuum requirements
- Current setup needs 30 kV max. Future designs may require >100 kV

Present design:

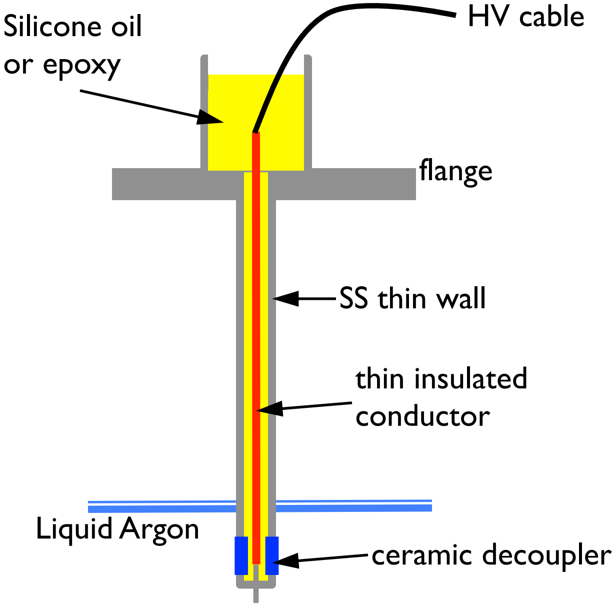
- Feed the HV cable directly in to the cryostat space using a quick-disconnect coupling (o-ring seal)



Pros: easy to setup
Cons: feed-through not UHV compatible; not scalable; high heat load

Proposed design:

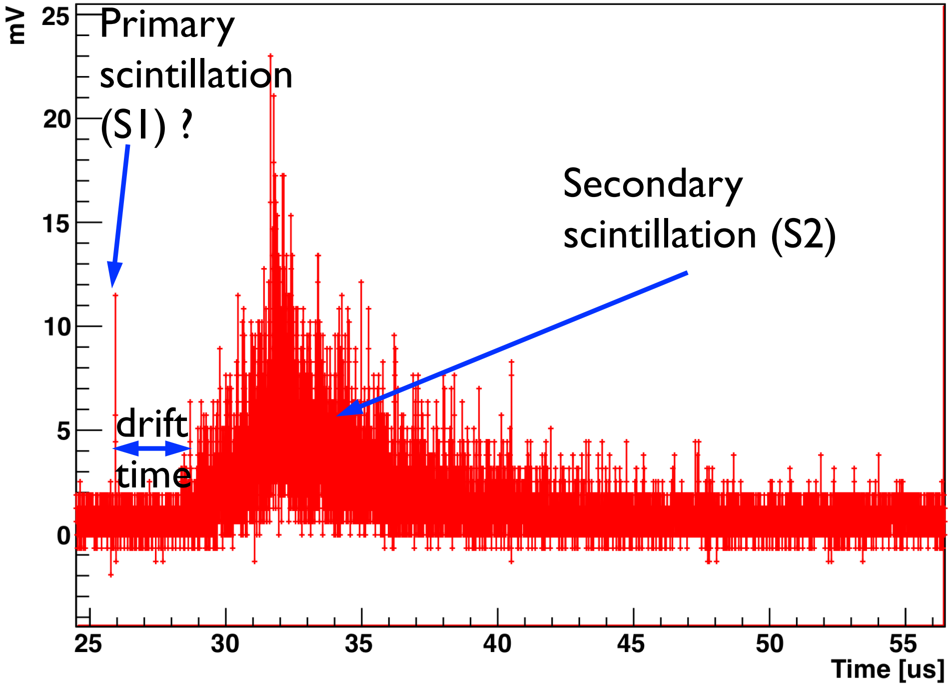
- Bring feed-through in the liquid



Pros: UHV-compatible
Cons: bulkier and semi-rigid

First light!

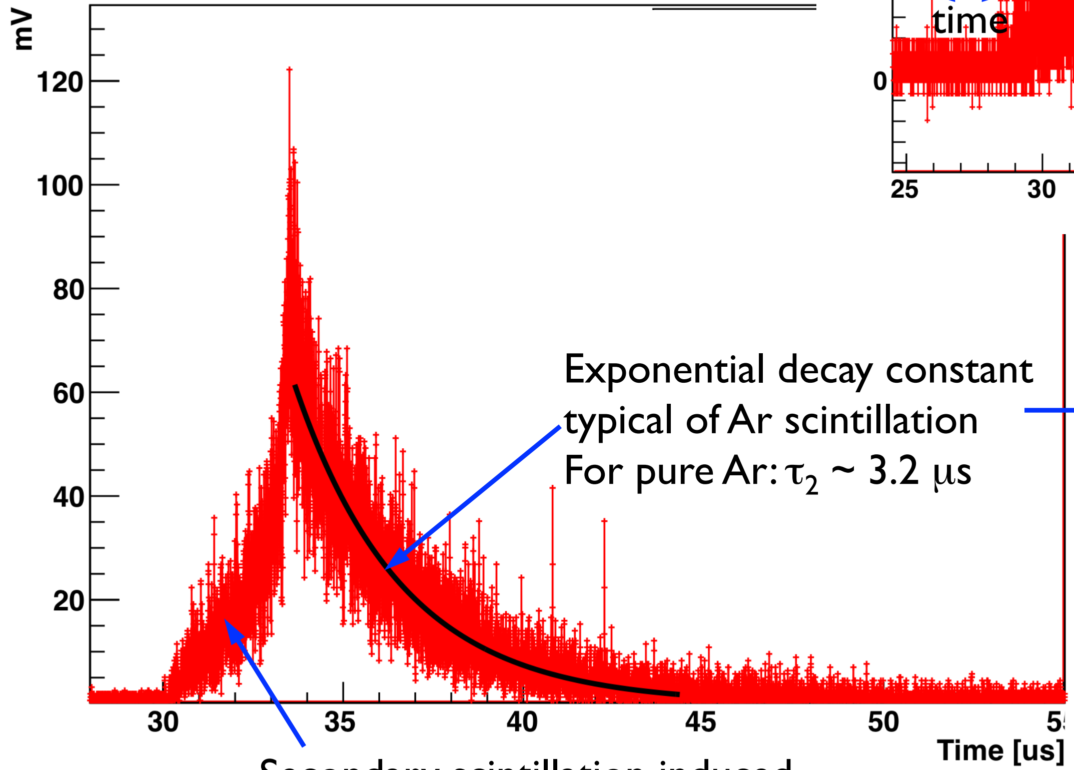
- Only a single 1” PMT
- Poor light collection efficiency
- No Ar recirculation
- Low E fields (~ 4 kv/cm in gas)
- External γ source



Primary scintillation (S1) ?

drift time

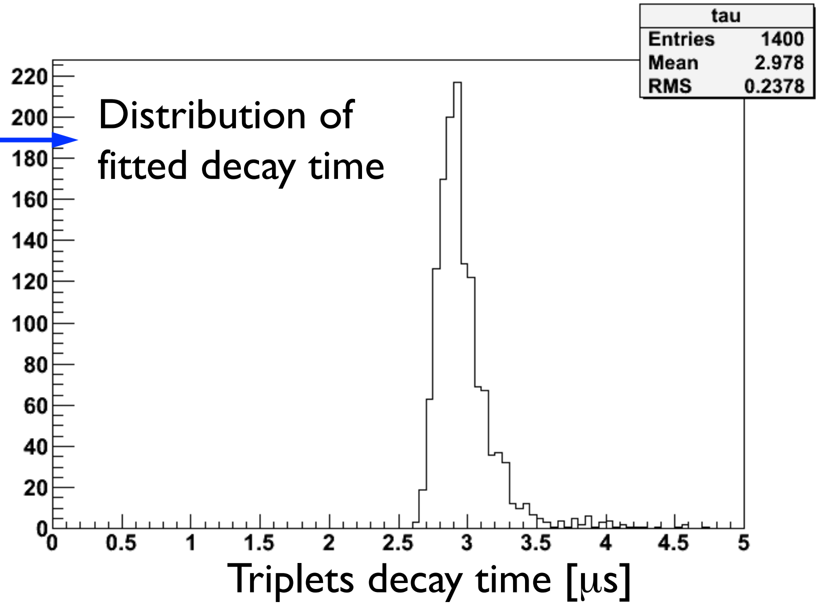
Secondary scintillation (S2)



Exponential decay constant typical of Ar scintillation

For pure Ar: τ_2 ~ 3.2 μs

Secondary scintillation induced by electrons accelerated in gas

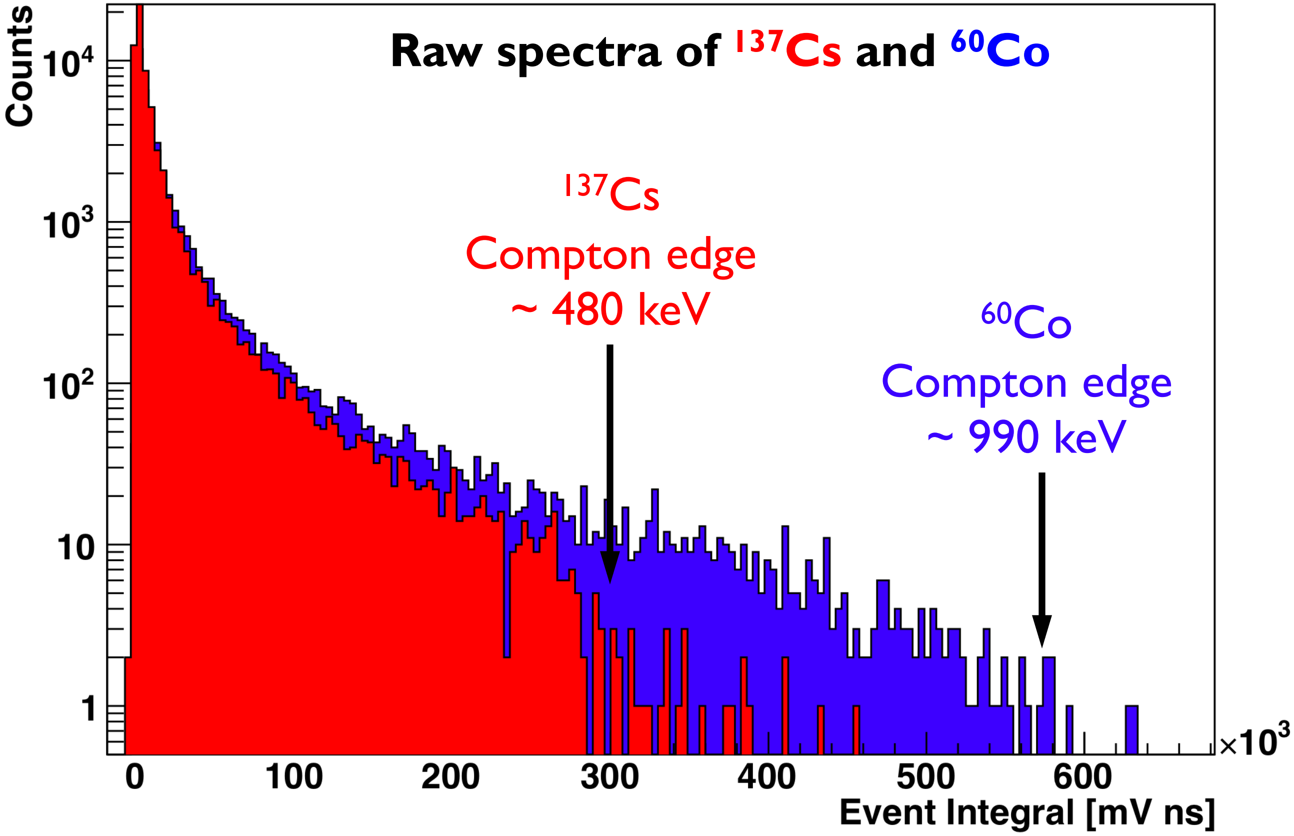


Distribution of fitted decay time

First light!

- Only a single 1" PMT
- Poor light collection efficiency
- No Ar recirculation
- Low E fields (~ 4 kv/cm in gas)
- External γ source

Proportionality of light output with energy



Detector calibration with ^{37}Ar

Provides low-energy uniform calibration throughout the whole detector volume

Decay scheme

100% electron capture

$t_{1/2}$ = 35.04 d

Q(gs) = 813.5 keV

Decay radiation

K-electron capture 2.82 keV (90.2%)

L-electron capture 0.27 keV (8.9%)

M-electron capture 0.02 keV (0.9%)

Isotope production

Produced by neutron irradiation of ^{nat}Ar at a nuclear reactor

^{37}Ar signal in a proportional Argon counter

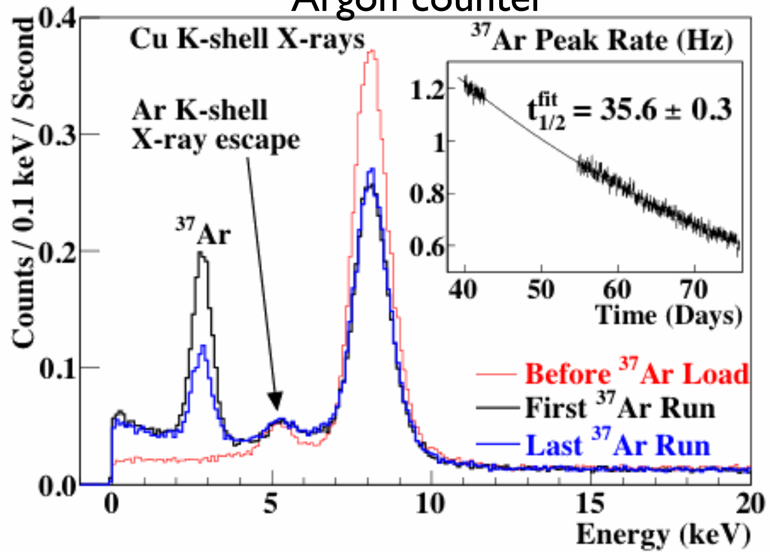


Fig. 4. Proportional counter energy spectra. When the counter was loaded with the ^{37}Ar sample, the ^{241}Am calibration source was re-oriented resulting in a change in the intensity of the Cu K-shell X-ray peak. Inset shows the half-life decay of the ^{37}Ar peak intensity.

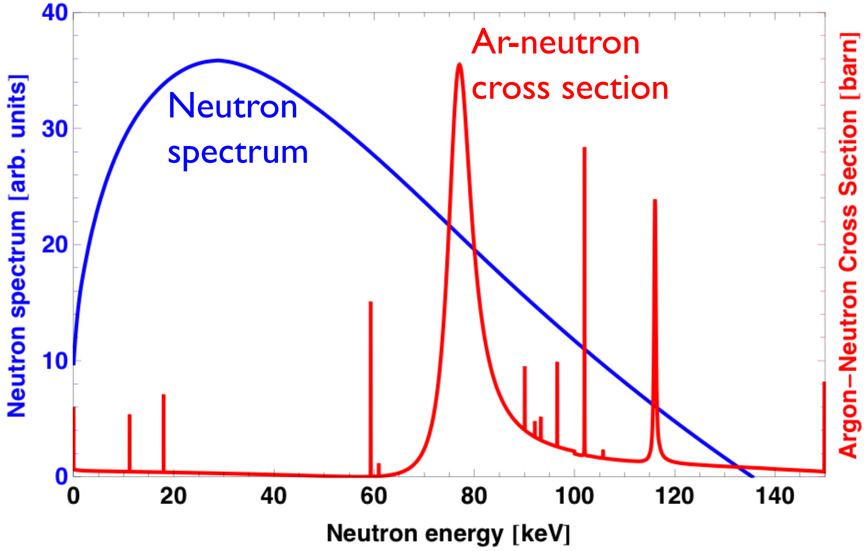
C.E. Aalseth, et al. submitted to Nucl. Instru. Meth. A

Ionization Yield Measurement using Neutrons

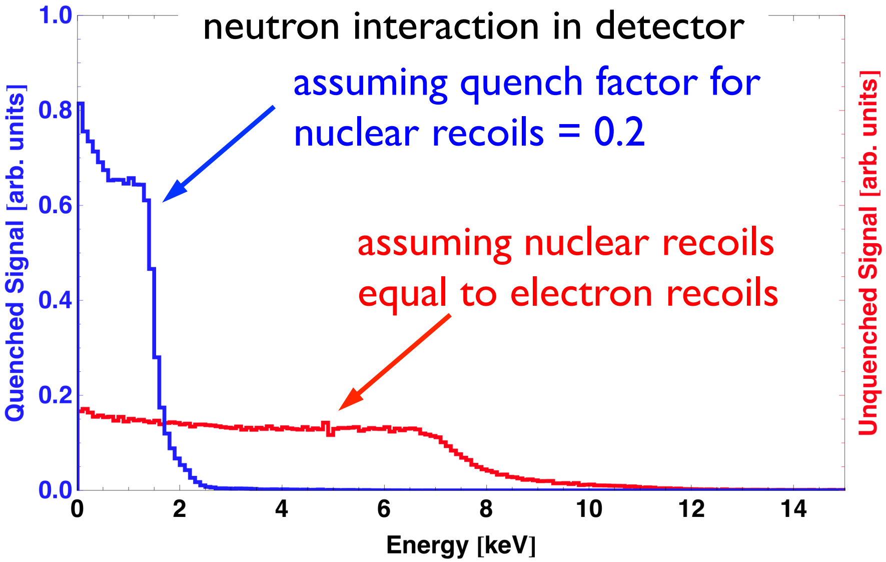
Using a1.93MeV proton accelerator, neutrons are generated up to an energy of 135 keV through the ^{7}Li(p,n)^{7}Be reaction.

The neutrons interact primarily within the 80 keV resonance of ^{40}Ar, **producing recoils with an energy of up to ~8 keV.**

$$T_{\mathrm{Ar}}^{\mathrm{MAX}} = \frac{4mM}{(m+M)^2} E_n$$

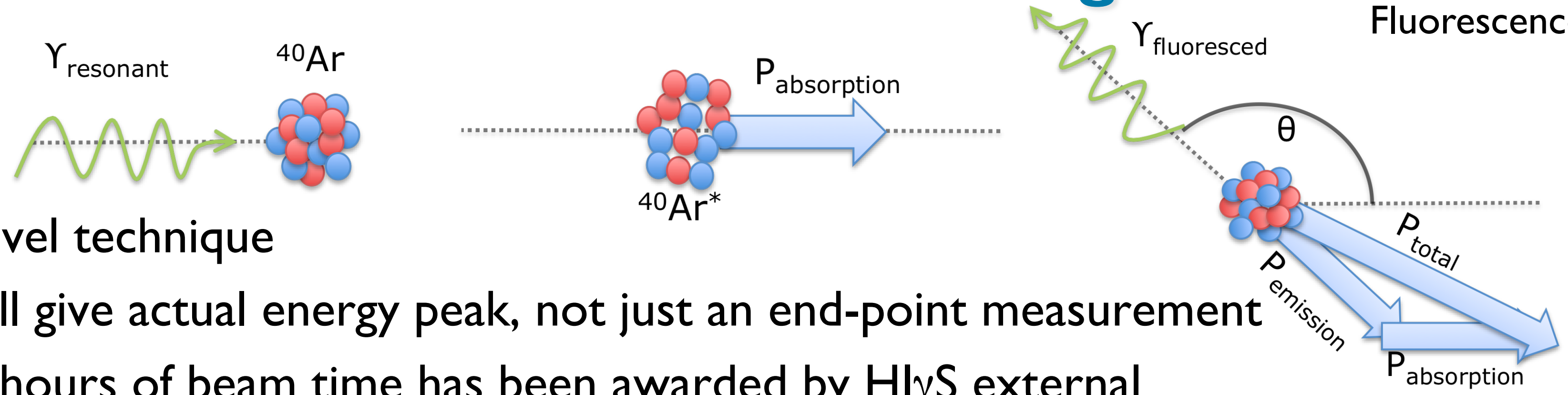


- End point measurement
- Backgrounds
  - – gamma from ^{7}Li(p,p’)^{7}Li
  - – gammas from neutron capture
  - – measured by running the proton beam below the neutron-generating threshold and below the 80 keV resonance
- Full simulation ongoing


Simulated spectrum from neutron interaction in detector

Ionization Yield Measurement using NRF

Nuclear
Resonance
Fluorescence



- Novel technique
- Will give actual energy peak, not just an end-point measurement
- 60 hours of beam time has been awarded by HIγS external Program Advisory Committee
- Allow to investigate **sub-keV recoil energies**

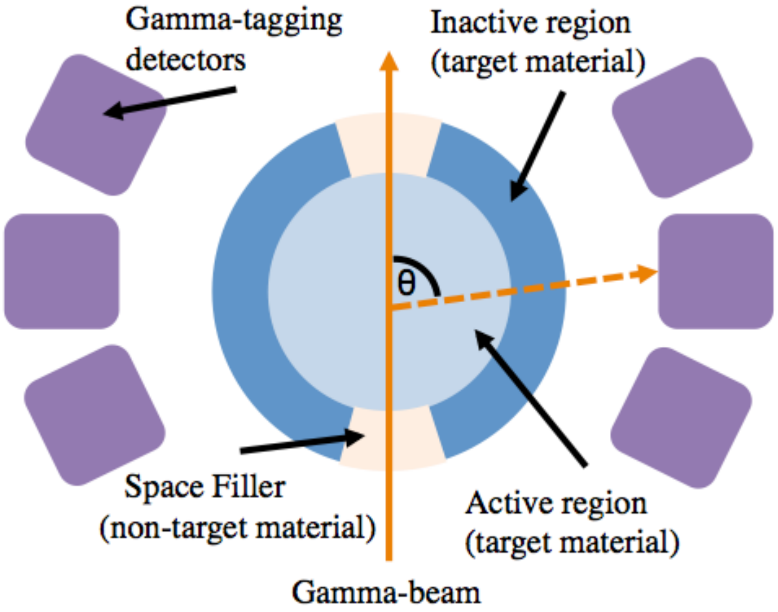
Recoil energy

Angle of fluorescence

$$E_{\mathrm{NR}} = \frac{2(E_r \sin(\theta/2))^2}{Mc^2}$$

Resonance energy
(for Ar: 4.8 MeV & 9.8 MeV)

Argon mass



arXiv:1105.5156

A 10kg Detector for Reactor Monitoring

- Performed preliminary design study for a 10-kg liquid/gas Argon detector
- Stringent technical requirements
  - small footprint
  - movable
  - modular design for installation in hard-to-get locations
  - limited electrical power
  - very limited network access for remote control and operation
  - limited time access for operators
  - no ready access to liquid cryogens
  - shallow depth → shielding
  - safety
  - limited air circulation and no air conditioning
  - harsh environment: dust, humidity, noise, vibrations

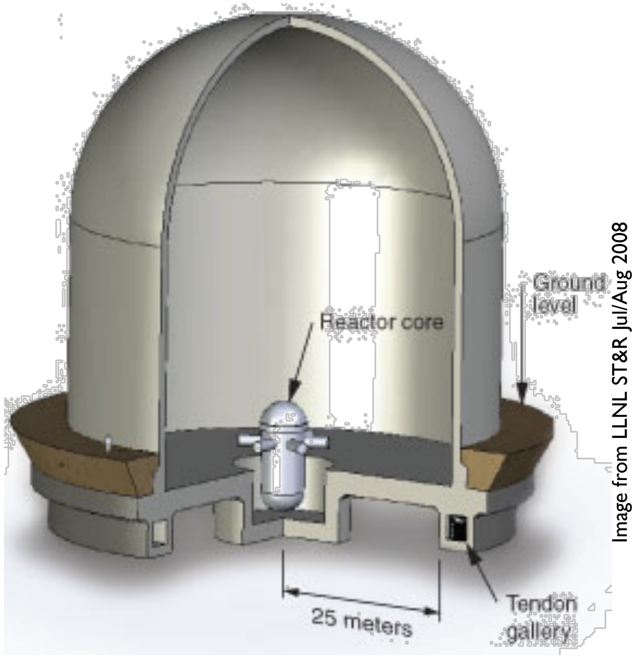


Image from LLNL ST&R Jul/Aug 2008
https://www.llnl.gov/str/JulAug08/bernstein.html

- Assuming 100% efficiency in detecting single primary electrons, we expect to see ~ 170 events/day (for ν flux of $6x10^{12}$ cm^{-2} s^{-1})
- If signal follows reactor outages, we have confirmation of signal

→ first observation ever of CNS !

Conclusions

- Dual-phase noble-element detectors -the technology that is successfully being used for Dark Matter- could be extended to detected Coherent Neutrino Scattering
- We are developing a LAr detector that will be sensitive to nuclear recoils in a currently inaccessible energy range
- Measurement of the nuclear ionization yield is critical and we have plans for
  - Neutron measurement at 8 keV recoils
  - Novel NRF technique to probe sub-keV nuclear recoils
- Upon successful deployment of the small prototype, we will develop a larger detector to search for CNS at a nuclear power plant.

Backup slides

Backgrounds

- All processes that produce a small number (1-5) of primary electrons in the active region:

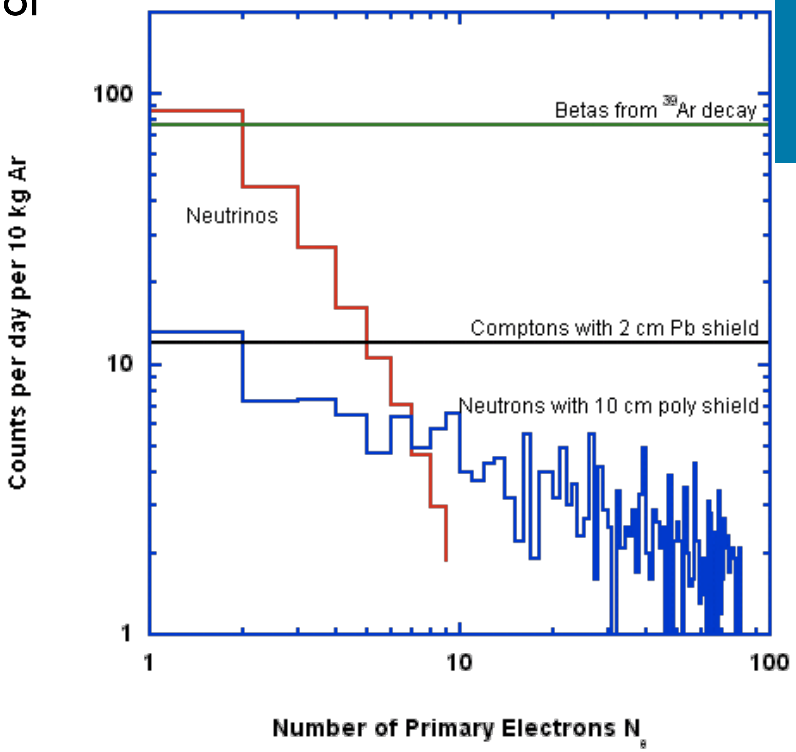
10 kg Ar, 25 m standoff, 3.4 GWt Signal:
<250 eV> nuclear recoil energies for <4 MeV> neutrino energies
→ after quenching: 1-10 free e-
→ **~200 per day** (1 or more liquid e-)

radioactive backgrounds

Background type	counts/ dy/10 kg
Dominant: ^{39}Ar (sim.; depleted Ar reduces 20x)	1000
Internal gammas: (measured, XENON10):	~ 50 per day @ 3 keVee; but ~1 Hz of single liquid electrons
External U/Th/K : (sim., after2 cm Pb shield)	~ 100
External neutrons: (sim. @ 20 mwe, after 10 cm borated poly shield):	~ 32

Monte Carlo Simulation

C. Hagmann, IEEE Trans.Nucl.Sci. 51 (2004)



Shield: Inner: 2cm Lead
Outer: 10cm borated polyethylene

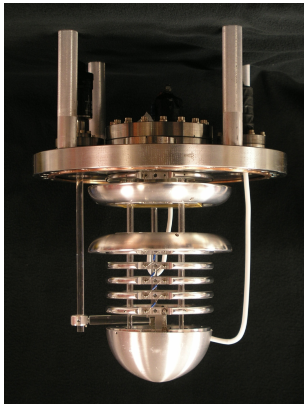
Rates in plot simulated@ 20 mwe

spontaneous single-electron signals

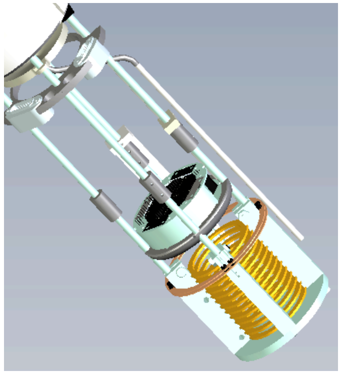
- field emission of electrons
- emission from surface of liquid
- others?

fiducialization of active volume and good discrimination between events with 1 and 2 primary electrons

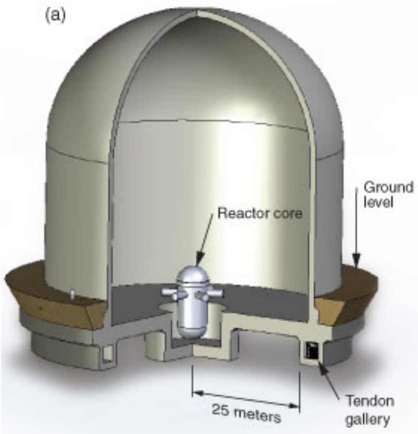
Experimental Program - Overview



- Single-phase detector
  - Understand the gaseous region of the proposed dual-phase detectors
  - Kazkaz et al, NIM A 621, 2010



- Small (~200 g) dual-phase detector
  - Study the ionization yield of nuclear recoils in liquid argon
  - Develop an understanding of dual-phase detector design and operation



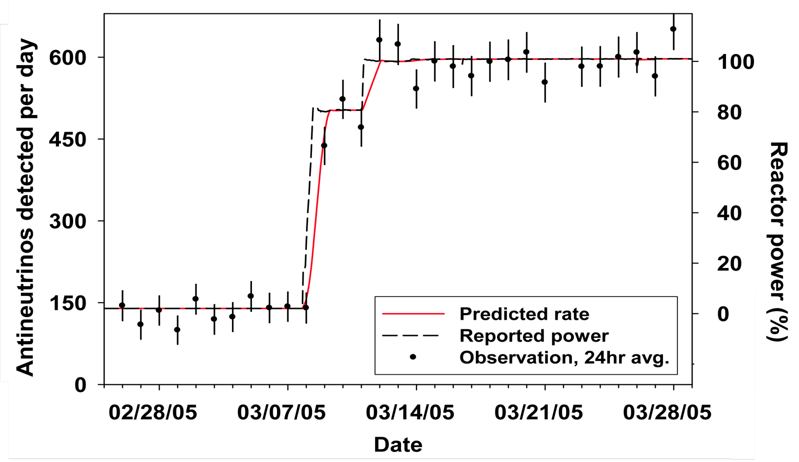
- Large (10 kg) dual-phase detector
  - Deployment at a reactor
  - Look for variation of CNS signal due to outages
  - Detection of CNS!

Detector for Reactor Monitoring

- To be sited at a nuclear power plant (e.g., the San Onofre Nuclear Generating Station)
- Assuming 100% efficiency in detecting single primary electrons, we expect to see ~ 170 events/day (for ν flux of 6×10^{12} cm^{-2} s^{-1})
- If signal follows reactor outages, as it has been done with Gd-doped liquid-scintillators, we have confirmation of signal

→ first observation ever of CNS !

SONGS antineutrino detector
inverse β decay on liquid scintillator



N. S. Bowden, Journal of Physics: Conference Series, **136** (2008).

from nrc.gov

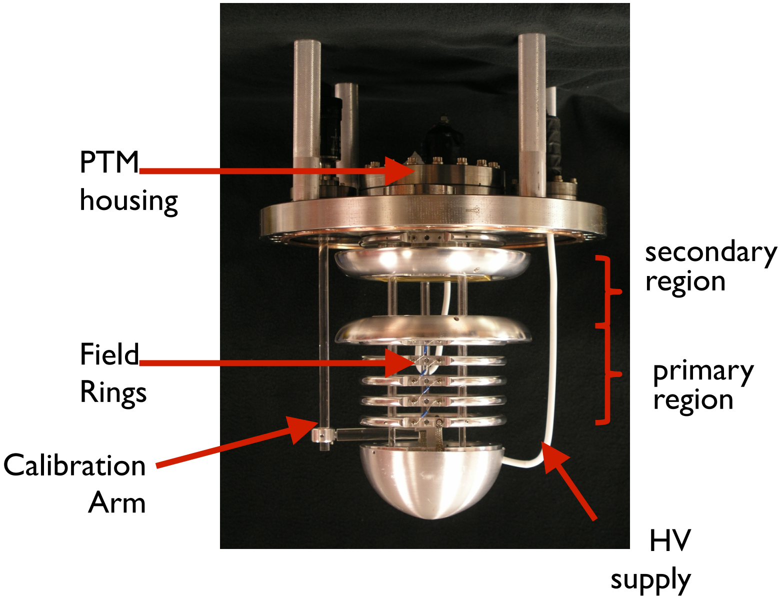
Single-phase Detector

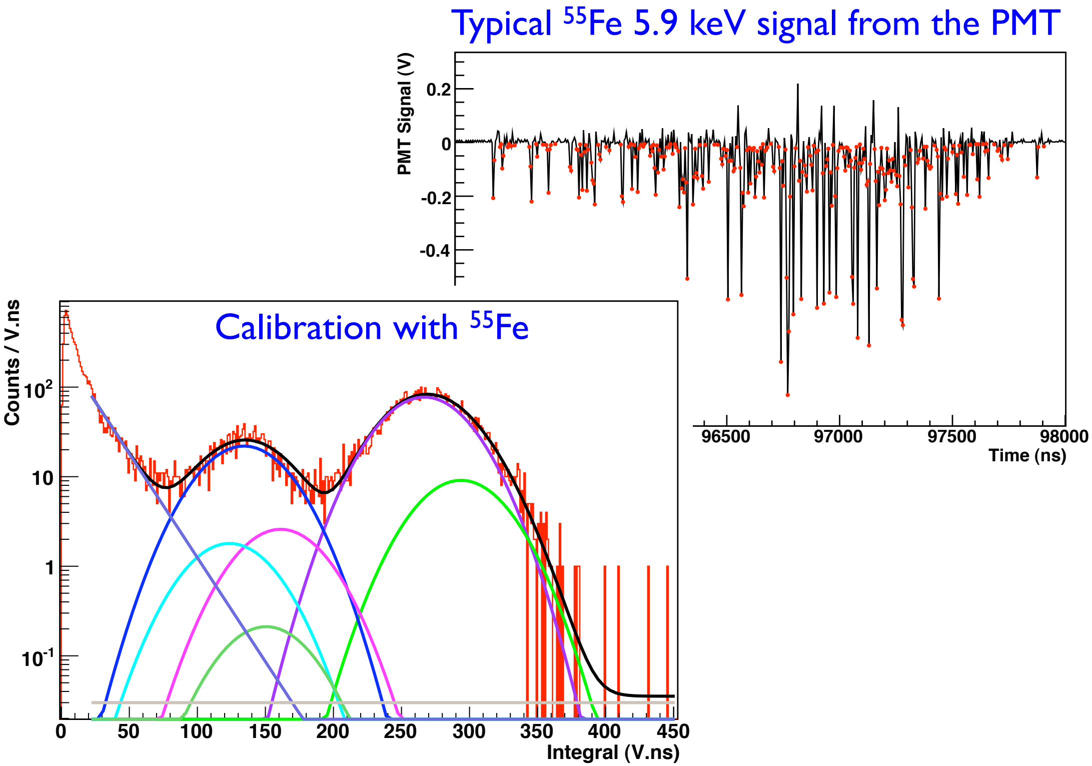
- Understand detector systematics
- Develop the data acquisition and analysis tools
- Specs:
  - 400 Torr Ar / 6 Torr N_2
  - continuous gas purification
  - 0.333 kV/cm drift region
  - 2 kV/cm gain region
  - ^{55}Fe source (5.9 keV X-ray)

- More ongoing:
  - Fiducialization studies
  - Secondary scintillation at high gas density
  - Understand pulse shape

    → K. Kazkaz N01-5

More in Kazkaz et al, NIM A 621, 2010




Typical ^{55}Fe 5.9 keV signal from the PMT

Calibration with ^{55}Fe

General dual-phase detector design

Noble elements are used
for their drift properties

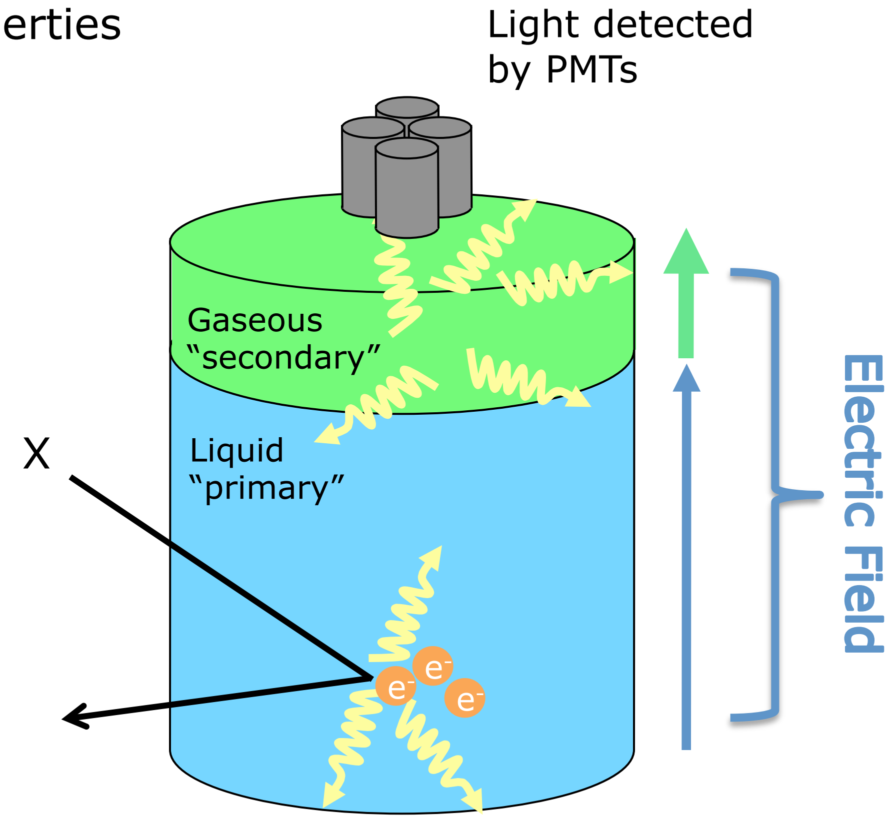
Time

e^- drifted through the gas producing secondary scintillation (S2) (~3 μs)

e^- drift up, through the liquid and into gas (few μs)

Recoiling nucleus ionizes surrounding medium and prompt scintillation(S1) produced (1-1000 ns)

A particle scatters off a nucleus



Noble Gases Properties

	He	Ne	Ar	Kr	Xe
Atomic number	2	10	18	36	54
Boiling point [K]	4	27	87	119	165
Liquid phase density [g/cm^3]	0.145	1.2	1.4	2.4	3.06
Radioactive isotopes			^{39}Ar	^{85}Kr	^{136}Xe ?
Price [$/ft^3]	50	2500	20	25000	
Scintillation light [nm]		80	128	147	178
Electron drift velocity in liquid @ 1 kV/cm [mm/μs]			2.1 [ref 1]	~ 2.7 [ref 2]	~ 2 [ref 2]
Ionization energy (liquid) [eV]	25.5	21.5	23.7 [ref 3]	20.5 [ref 3]	16.4 [ref 3]

[1] Walkowiak, NIM A 449 (2000) 288
[2] Yoshino et al, Phys Rev A 14 (1976)
[3] Takahashi et al, J. Phys. C 7 (1974) 230