The MiniCLEAN Single-Phase Noble Liquid Dark Matter Experiment

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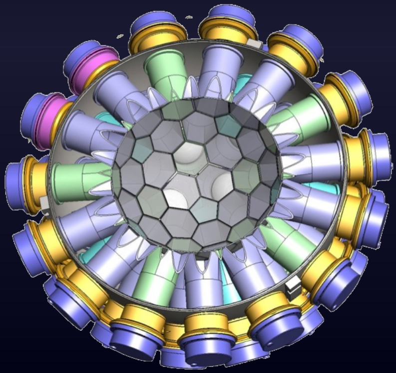
P-23 Weak Interactions Team
For the DEAP/CLEAN collaboration

LA-UR 11-00543

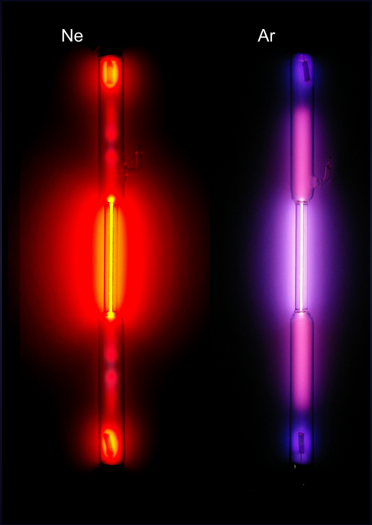
Indirect and Direct Detection of Dark Matter: Feb 10th 2011



Noble Liquid Targets

The noble liquids argon and neon offer:

- Copious scintillation light $\rightarrow$ low energy thresholds $\mathcal{O}(20\ \mathrm{keV_{ee}})$
- Scalability:
  - Relatively low cost $\rightarrow$ targets $\mathcal{O}(50\,T)$ feasible
  - Relatively high density $\rightarrow$ compact target and self-shielding against radioactive backgrounds
- Easy purification of radioactive contaminants [Harrison et al., 2007]



Noble Liquid Targets

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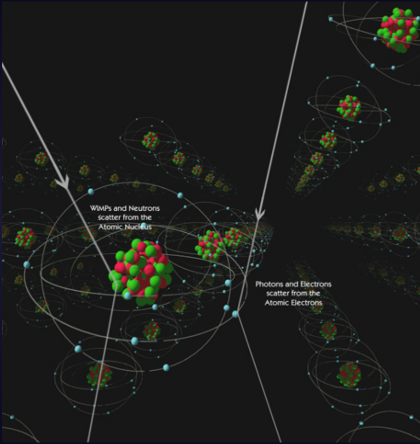
- ...which mitigates 1Bq/kg β decay rate due to ^{39}Ar present in atmospheric argon



Courtesy Michael Attisha

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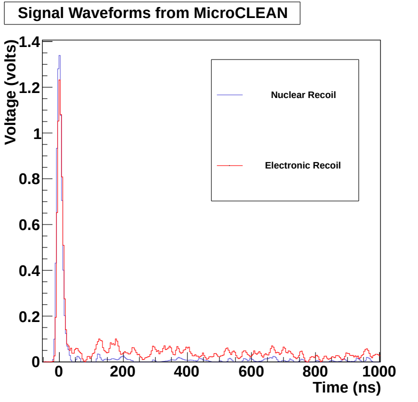
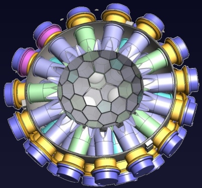
- Outstanding scintillation pulse shape discrimination (PSD) for separation of nuclear and electronic recoils....
- ...which mitigates 1Bq/kg β decay rate due to ^{39}Ar present in atmospheric argon
- Current PSD leakage measurements:
  - LAr: $< 4.8 \times 10^{-8}$ [Boulay et al., 2009]
  - LNe: $< 7 \times 10^{-3}$ [Nikkel et al., 2008]

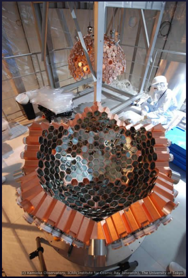


Single-Phase vs. Dual Phase Detectors

Single-phase (liquid only)

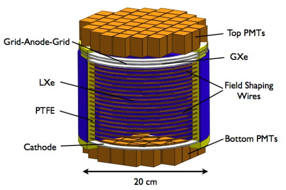


MiniCLEAN(LAr or LNe)

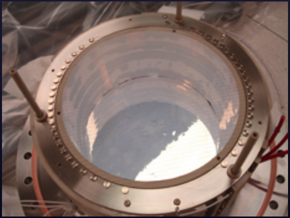


XMASS (LXe)

Dual-phase (gas over liquid)



XENON-10, also LUX, XENON-100 (LXe)



WARP, ArDM (LAr), also DARKSIDE (DAr)

Single-Phase vs. Dual Phase Detectors

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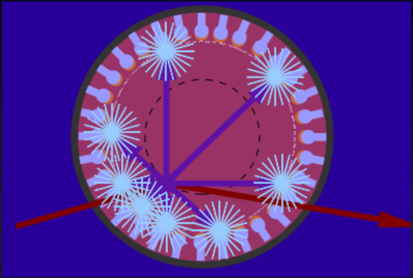
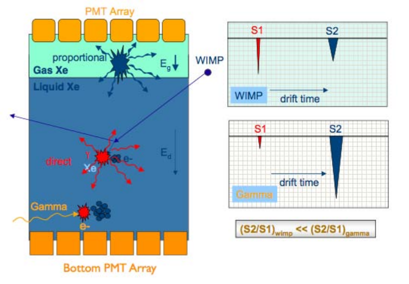


Dual-phase (gas over liquid)



Courtesy E. Aprile

- Interactions in target create ionized and excited states
- Recombination of ions and dexcitation create primary scintillation light (S1)

- Interactions in target create ionized and excited states.
- Recombination of some ions and dexcitation of states create primary scintillation light (S1)
- Remaining ions drifted in electric field of TPC
- Acceleration at gas/liquid interface creates proportional light (S2)

Single-Phase vs. Dual Phase Detectors

Single-phase (liquid only)

- Simple design with 4π photodetector coverage
  - Maximizes light collection (nearly 100% photocathode coverage possible)
- Multiple targets possible:
  - LHe, LNe, LAr, LKr, LXe
- Scintillation pulses are fast ($\tau_{\text{long}} \sim 1.5\ \mu$sec) $\rightarrow$ brief trigger window that minimizes ^{39}Ar pileup

Dual-phase (gas over liquid)

- TPC hits and drift times give good event localization: multiple hit rejection and good target fiducialization
  - Eliminates surface alpha decays

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DEAP/CLEAN choice:

- Simple design should scale well to tens of tons, gets better with size
  - Demonstrated light yield of 6.0 P.E./keV

    [Lippincott et al., 2010]
- LAr $\rightarrow$ good $\sigma_{\text{WIMP}}(A^2)$
- LNe $\rightarrow$ test $\sigma_{\text{WIMP}}(A^2)$, also ν physics

  [McKinsey and Coakley, 2005,

  Boulay et al., 2004, Horowitz et al., 2003]
- Reduced need for depleted argon, high calibration rates due to reduced pile-up.

DEAP/CLEAN: Single-Phase LAr and LNe Targets

Single phase design must demonstrate:

- Maximum limit for PSD for both argon and neon:
  - Determines need for depleted argon
  - Determines use/sensitivity for neon compared to argon
- 3D position reconstruction
- Ability to control surface α backgrounds via careful and radon-reduced assembly methods

MiniCLEAN is meant to demonstrate the above, followed closely by DEAP-3600.

DEAP/CLEAN detectors

picoCLEAN 2005

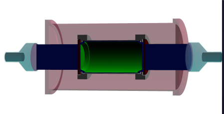
LNe scintillation, cryogenic PMT operation

DEAP-0 2005

LAr scintillation, LAr PSD

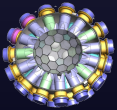
microCLEAN (4kg) 2006-present

LAr/LNe scintillation, PSD, NR quenching



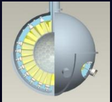
DEAP-1 (7kg) 2006-present

LAr PSD, optics R&D, background rejection



MiniCLEAN (500kg) 2012 -?

LAr/LNe WIMP search to $\mathcal{O}(10^{-45}\mathrm{cm}^2)$



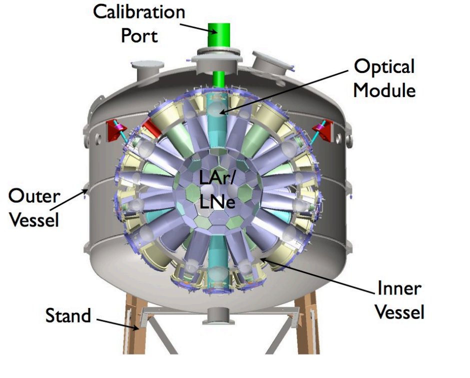
DEAP-3600 (3600kg) 2012-?

LAr/DAr WIMP search to $\mathcal{O}(10^{-46}\mathrm{cm}^2)$

MiniCLEAN: A Prototype LAr/LNe WIMP Search

MiniCLEAN is the first full DEAP/CLEAN prototype :

- The inner target volume of 500 kg (LAr) is surveilled by nearly 4π photodetector coverage
  - LAr $\rightarrow$ LNe target swap: "beam off" experiment with similar background
- Careful low background assembly procedures
- For single-phase, light collection is king:
  - PSD "resolution" $\propto e^{-N_{p.e.}}$ [Lippincott et al., 2008]
  - Energy and linear reconstructed position resolution $\propto 1/\sqrt{N_{p.e.}}$



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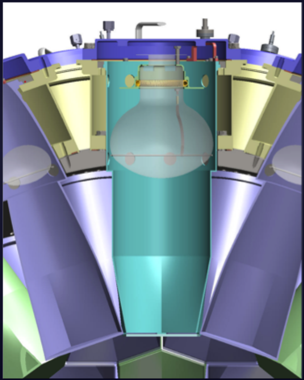

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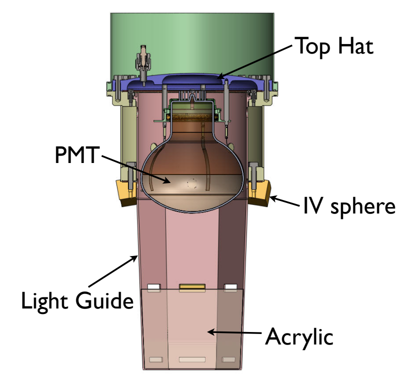
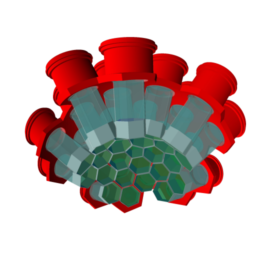
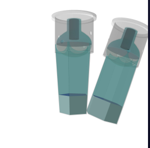


Detailed Simulation of the MiniCLEAN Detector

MiniCLEAN has been designed using a detailed Geant4/ROOT based simulation and analysis package called RAT, codeveloped with the SNO+ collaboration. RAT features:

- A simulation of the full detector geometry, including the water shield.
- Full treatment of photon transport, including scintillation, remission and PMT optics.
- Simulation of the front-end, trigger and DAQ electronics





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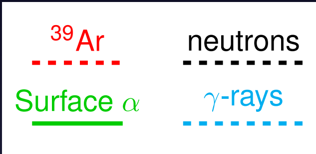
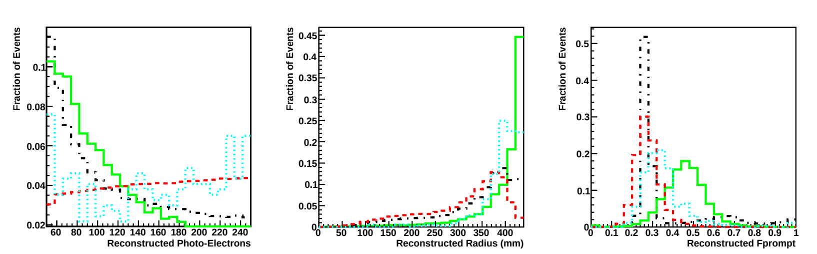
- The ability to generate backgrounds from beginning(particle interactions) to end (output of DAQ)
- Simulation of important backgrounds (unit normalized and before most cuts) →
- Production of reconstructed variables that define R.O.I:



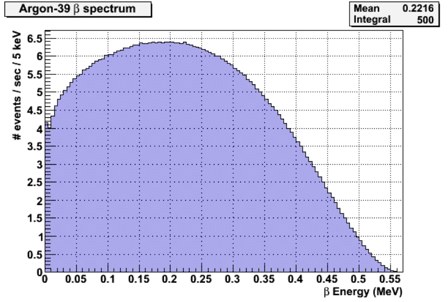


Recoil Energy | Event Position | PSD Variable

Energy Reconstruction in MiniCLEAN

Detector designed for maximum light collection and for single PE counting at low energies which improves all observables. We project an effective light yield of >= 6 PE /keV

- Calibrate using “free”, constant ^{39}Ar beta decay spectrum
- Cross check with:
  - Monoenergetic: ^{83m}Kr spikes [Lippincott et al., 2010]
  - Compton spectra: external γ sources such as ^{57}Co, ^{22}Na



The β energy spectrum of the ^{39}Ar decay

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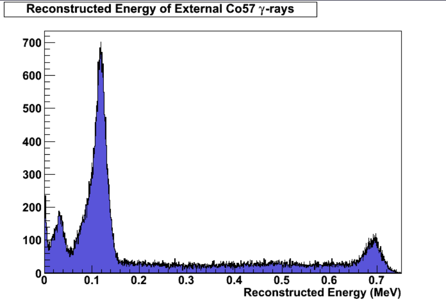

Simulated reconstructed energy of ^{57}Co γ-rays in MiniCLEAN

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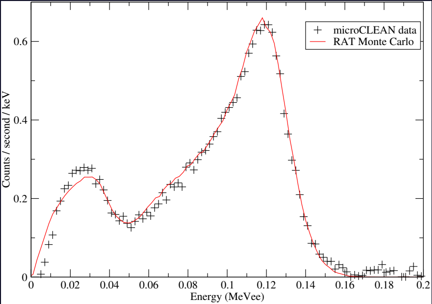
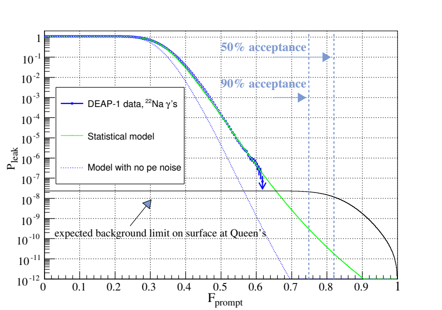


Data and Simulation of ^{57}Co γ-rays in MicroCLEAN

Pulse Shape Discrimination (PSD) In MiniCLEAN

- DEAP-1 [Boulay et al., 2009] has already established PSD rejection of 4.7×10^{-8} for $25\mathrm{keV_{ee}} < \mathrm{E} < 86\mathrm{keV_{ee}}$
- MiniCLEAN needs to demonstrate $\sim 10^{-9}$ for $20\mathrm{keV_{ee}} < \mathrm{E} < 40\mathrm{keV_{ee}}$ for zero electron recoil background. With our projected light yield and the DEAP-1 noise model, we project $\sim 1 \times 10^{-10}$, for a threshold of 75 P.E.
- PSD statistic: F_{prompt}: % of light detected in first 100 ns of pulse.
- Smarter handling of time dependence may do better job with PSD and:
  - Reject surface α events
  - Reject multiple or inelastic neutron scatters



Analytic PSD Model Showing Extrapolation to 10^{-10}

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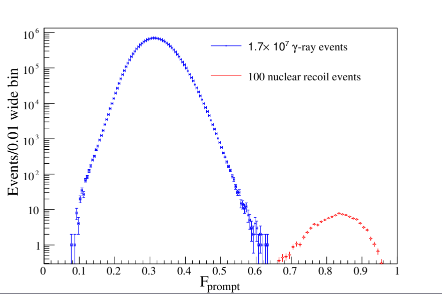
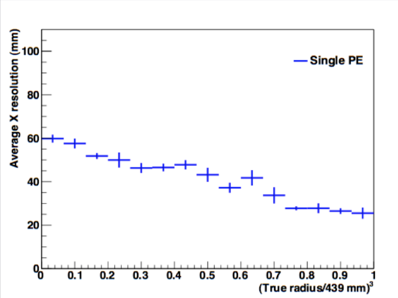


Electron/Nuclear Recoil Data from DEAP-1

3D Position Reconstruction in MiniCLEAN

Rely on 3D position reconstruction to suppress surface α decays at edge of sensitive volume.

- Using likelihood fit with full optical modeling for reconstruction
- Our simulations predict a position resolution of better than 5 cm at the edge of the detector where it matters most.
- Uniform ^{39}Ar will expose any bias and/or non-uniformity
- External γ sources will produce more localized events at the edge of the detector as a cross check.

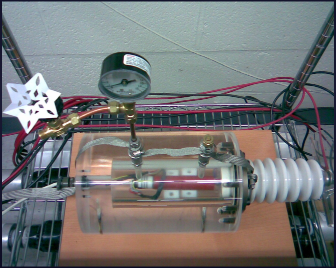


Linear Position Resolution of Simulated 20 keV β events in MiniCLEAN

Neutron Background Rejection in MiniCLEAN

Neutron induced nuclear recoils constitute most dangerous background for WIMP search. Dominated by (α, n) from PMT glass.

- Study events using a miniature pulsed D-D neutron generator from Schlumberger
  - Produces monoenergetic $\sim$ 2.4 MeV neutrons.
  - Trigger detector off driving pulse $\rightarrow$ reduce accidental backgrounds

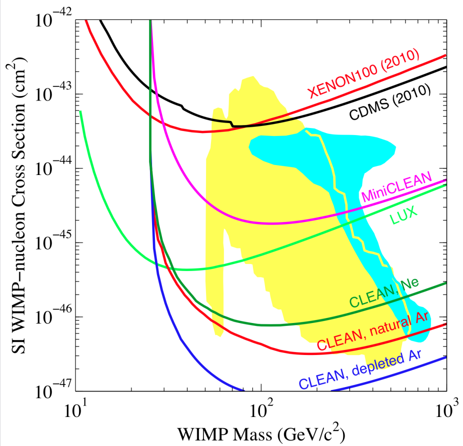


- Further explore background using tagged neutron sources:
  - AmBe
  - U/Th doped borosilicate $\rightarrow$mimics PMT neutron background

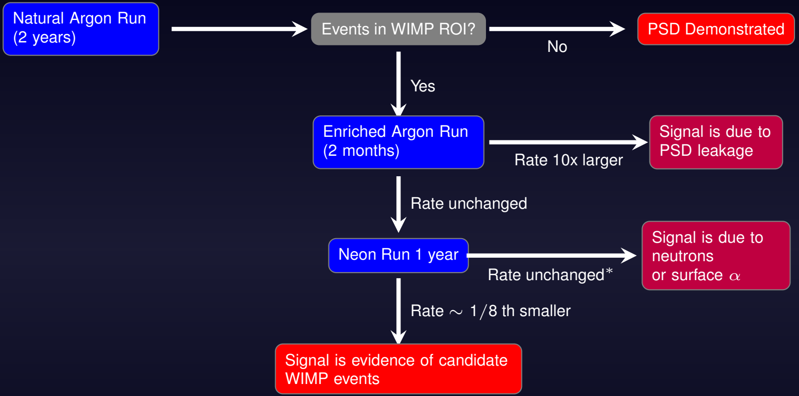
Complete neutron calibration essential to understanding neutron background and energy response.

Projected MiniCLEAN Performance

- After two years of running with a 150 kg natural ("atmospheric") argon target (fiducial) , we project sensitivity to the spin independent WIMP-nucleon scattering cross section of $2 \times 10^{-45} \mathrm{cm}^2$ at 90% C.L., assuming a MSSM WIMP of 100 GeV/c^2 in mass
- Follow with 2 month dedicated PSD run using an "enriched" argon target, containing 10x more ^{39}Ar.
- Further explore backgrounds and prepare for CLEAN ν-program using a LNe target for 1 year.



Exploration of Signal and Backgrounds in MiniCLEAN



* work is ongoing towards full understanding of neutron propagation in neon, including neutron scattering measurements @ TUNL and LANL

Projected MiniCLEAN schedule

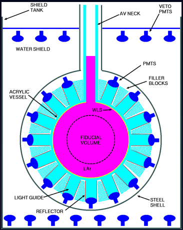
Construction of the detector components is ongoing.

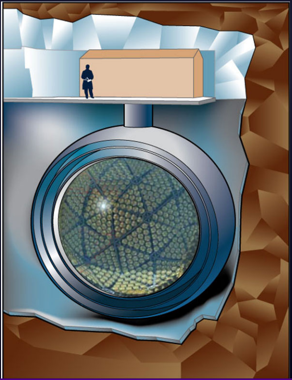
- Experimental infrastructure at SNOLAB (2 km underground) **ready now**
- Outer vacuum vessel complete
- Inner cryogenic vessel fabrication in progress now, complete summer 2011
- Commissioning and start of 2 year LAr run begins in early 2012



Next phases of DEAP/CLEAN Program

- DEAP-3600: 3600 kg of LAr. All acrylic (Mini-SNO) design excludes a neon target, but provides increased neutron shielding.
  - @SNOLAB in 2012
- CLEAN (10-100 T):
  - WIMP reach with neon: $1 \times 10^{-46}\ \mathrm{cm}^2$
  - WIMP reach with natural argon: $7 \times 10^{-47}\ \mathrm{cm}^2$
  - WIMP reach with depleted argon: $2 \times 10^{-47}\ \mathrm{cm}^2$
  - Measure p-p solar ν flux to 1%





Conclusions

MiniCLEAN:

- Observes the scintillation light from liquid argon or neon targets
- Will push the frontiers of PSD($\sim 10^{-10}$ leakage), allowing the use of natural argon
- Will provide fully competitive WIMP sensitivity ($\sigma_{\mathrm{SI}} \sim 2 \times 10^{-45} \mathrm{cm}^2$)
- Will test the single phase noble liquid design which holds promise of providing a path to multi-ton scale WIMP experiments

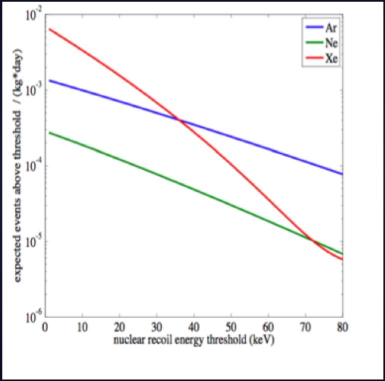
Thanks for your attention! Questions?

Extra Slides

Detector Materials For Direct WIMP Searches

Larger A^2, high radiopurity, low energy thresholds and cost are concerns

- Noble liquids and germanium are popular choices.
- Argon has lower A^2 and higher energy thresholds, but both facts partially cancel out due to the greater kinetic energy imparted upon the argon nucleus during a WIMP interaction –> exponential energy spectrum has more gentle decay constant.
- The same holds for neon.



Noble Liquid Properties I

Properties of argon:

- Boils at 87K
- Atomic mass (A) is 40
- Density is 1.4g/cc
- Cost is $\sim$ \$2K/ton
- Unstable istopes: ^{39}Ar
  - Produces background rate of 1Bq/kg
- Excellent PSD:
  - Leakage is better than 1 electronic recoil event out of every 16.7 million events

Properties of neon:

- Boils at 27K
- Atomic Mass (A) is 20
- Density is 1.4g/cc
- Cost is $\sim$\$90K/ton
- Unstable isotopes: none
- Weaker PSD:
  - Leakage is better than than 1 electronic recoil event out of every 1434 events
- Simple filtration with activated carbon

Noble liquid properties

Liquified Noble Gases: Basic Properties

Dense and homogeneous
Do not attach electrons, heavier noble gases give high electron mobility
Easy to purify (especially lighter noble gases)
Inert, not flammable, very good dielectrics
Bright scintillators

	Liquid density (g/cc)	Boiling point at 1 bar (K)	Electron mobility (cm^2/Vs)	Scintillation wavelength (nm)	Scintillation yield (photons/MeV)	Long-lived radioactive isotopes	Triplet molecule lifetime (μs)
LHe	0.145	4.2	low	80	19,000	none	13,000,000
LNe	1.2	27.1	low	78	30,000	none	15
LAr	1.4	87.3	400	125	40,000	^{39}Ar, ^{42}Ar	1.6
LKr	2.4	120	1200	150	25,000	^{81}Kr, ^{85}Kr	0.09
LXe	3.0	165	2200	175	42,000	^{136}Xe	0.03

Dan McKinsey (Yale)

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Surface α decays

Arise due to U / Th decay chains: often via contamination from radon and its daughters. Mainly an issue on front face of optical cassettes, clean assembly goal: 1 α/m^2/day (equivalent to SNO NCDs) leading to 367 recoil nuclei into the argon per year.

- Decays in acrylic:
  - Nuclear recoil into acrylic, α into TPB and/or argon. Some prompt light from TPB with a range of energies in argon.
- Decays in TPB and on surface:
  - Nuclear recoil into TPB, alpha into argon: high energy event out of energy ROI
  - α into TPB, Nuclear recoil into argon: low energy, mainly prompt.
- Decays in argon:
  - See both, α produces high energy event.

Surface α decays: Position Reconstruction

Expect 8 recoiling nuclei to fall within energy region of interest. Reject the remainder using position reconstruction. Resolution projected to be 4cm at threshold. Fiducial volume cut at r=29.5cm reduces this to 0.03 events/year. Does not assume any PSD cuts.

Hamamatsu R5912-MOD02

Special tube developed to maintain acceptable QE at low temps.

- Platinum underlay on photocathode to reduce space-charge build-up at low temperatures
- This reduces photon transmission but helps QE when cold.
- Also has 14 dynodes versus 10 in R5912.
- QE: 22% $\rightarrow$ 16% @ 390nm @ room temp
- QE@27K $\sim$ 70% of that at room temp [Nikkel et al., 2007]
- Immersion eliminates trouble of windows, more reliable detector, less light loss

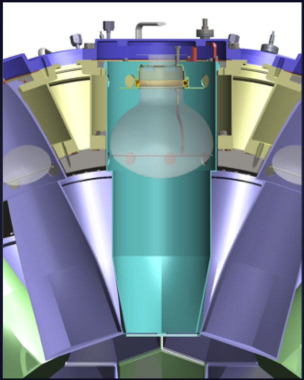
^{39}Ar Spike for PSD demonstration

End of run spike with $\sim$ 10x more ^{39}Ar than natural argon best choice, exact topology and backgrounds as WIMP search.

- Small trigger window in single phase experiment makes this possible
- Collect second electron recoil sample in 10th of the time
- Simple analysis: 0 events after cuts in spike $\rightarrow$ no ^{39}Ar background
- Better analysis: fold spike sample in with WIMP data set, include known ^{39}Ar decay rate as a prior

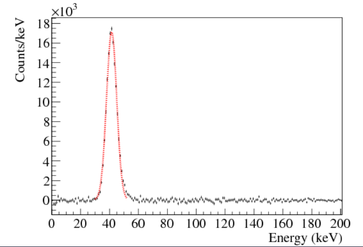
Radon Free Detector Assembly

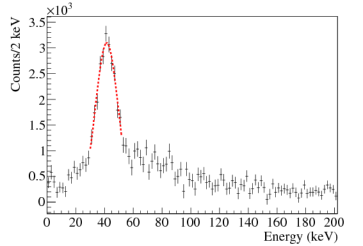
Radon daughter plate-out on surface of lightguides poses possible background. Mitigate background during construction by cutting front layer of acrylic (exposed fresh layer) and then quickly moving WLS plate into vacuum glovebox. Remainder of assembly of optical cassette and cassette insertion done under vacuum in glovebox. Goal is 1 α decay $/m^2$/day. This is similar to what was achieved in the SNO NCDs.



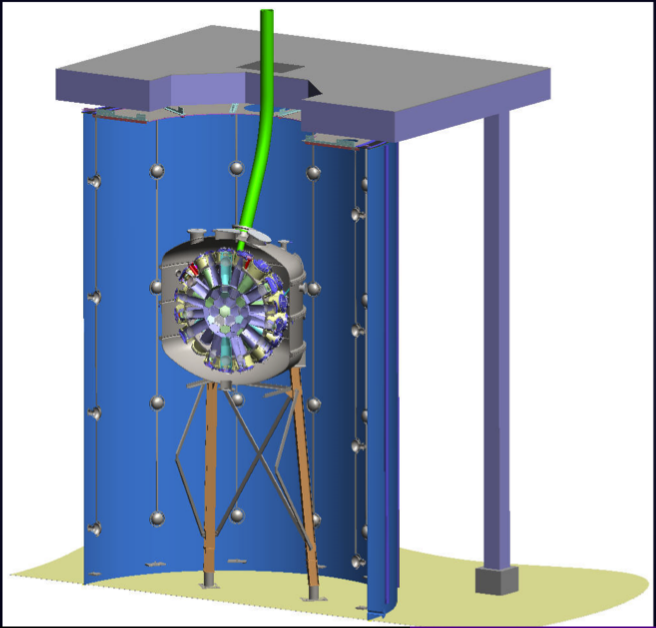
Energy Calibration with ^{83m}Kr spikes

- Key energy calibration in MiniCLEAN involves spiking the detector with ^{83m}Kr, produced by the decay of ^{83}Rb in charcoal trap.
- ^{83m}Kr half-life is 1.83 hours, allowing short spiking runs
- Decay produces two conversion electrons with energy sum of 41.4 keV (monoenergetic)
- Demonstrated in MicroCLEAN [Lippincott et al., 2010]





MiniCLEAN engineering details



Solar ν physics with CLEAN

Majority ($\sim$91%) of ν flux from sun is via the p-p process. Standard solar model predicts the flux to 1%. Energies below 423 keV. Signal is low energy electron recoils from neutrino-electron scattering.

- Need zero electronic recoil backgrounds: rules out everything but LHe, LNe.
- Need large self-shielding mass, to get backgrounds down and statistical error to < 1%.
- Need to understand systematics to <1%

Also sensitive to SN ν via coherent neutrino-nucleus scattering: 4 events/ton of LNe for SN @ 10kpc.

- See [McKinsey and Coakley, 2005, Boulay et al., 2004, Horowitz et al., 2003] for more details

Calibration with ^{39}Ar

Natural 1Bq/kg ^{39}Ar decays useful for:

- Single PE calibration via single photons in long triplet tail
- Energy calibration via known β spectrum
- Detector Stability
- Position reconstruction calibration (uniform background)
- Detector Health (via measurement of triplet lifetime)

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