Lawrence Livermore National Laboratory

Overview of Reactor Monitoring With Antineutrinos

Adam Bernstein

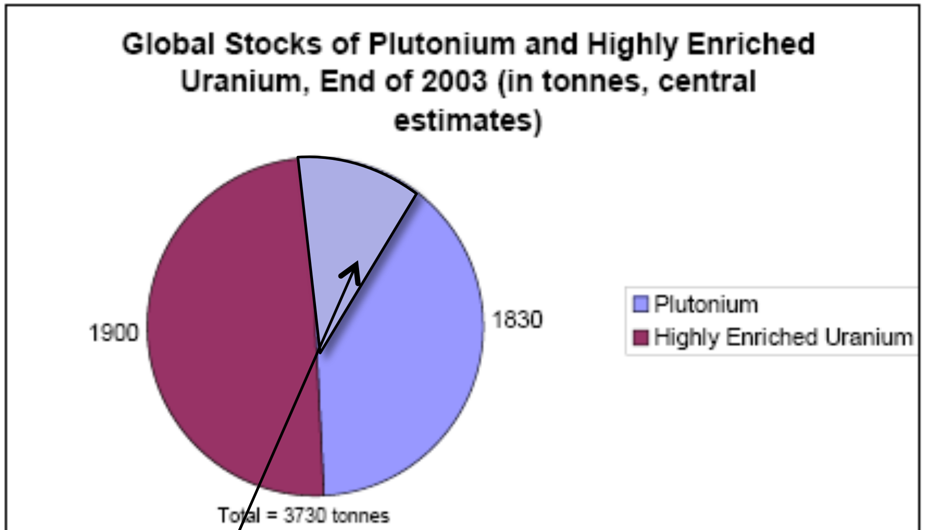
Group Leader, Advanced Detectors Group, Physics Division

Applied Antineutrino Physics Conference

Sendai, Japan,

Aug 3 2010

The Cold War – and civil nuclear reactors - have both generated large quantities of Plutonium and HEU



490 tons separated plutonium worldwide:
- **340 tons civil**
- **150 tons military**

Category	Plutonium (tonnes)	HEU (tonnes)
Civil	1675	175
Military	155	1725
Total	1830	1900

Estimates from http://www.isis-online.org

In units of Hiroshima strength fission weapons …

From HEU	~75,000
From separated Plutonium	~ 60,000
From all plutonium	~ 230,000
Total possible	~300,000

What is being done to monitor and reduce global stockpiles of nuclear materials and weapons ?

Historically and currently:

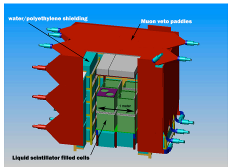
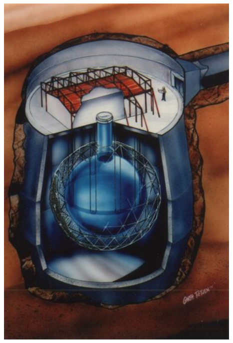
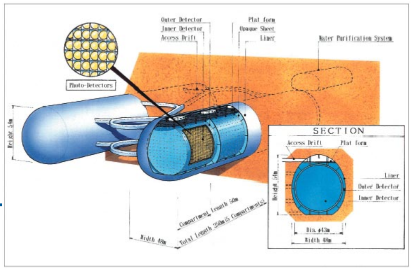
- Civil nuclear fuel cycle monitoring
- Weapons limits/dismantlement
- Military nuclear materials control and monitoring
- Domestic nuclear security in individual states
  - ‘ Homeland Security’
- National and International ‘Technical Means’

REDUCING NUCLEAR THREAT: Uranium container inventories help provide transparency in highly enriched uranium (HEU) processing. See pages 4 and 5 for more on NNSA's HEU Transparency Program.

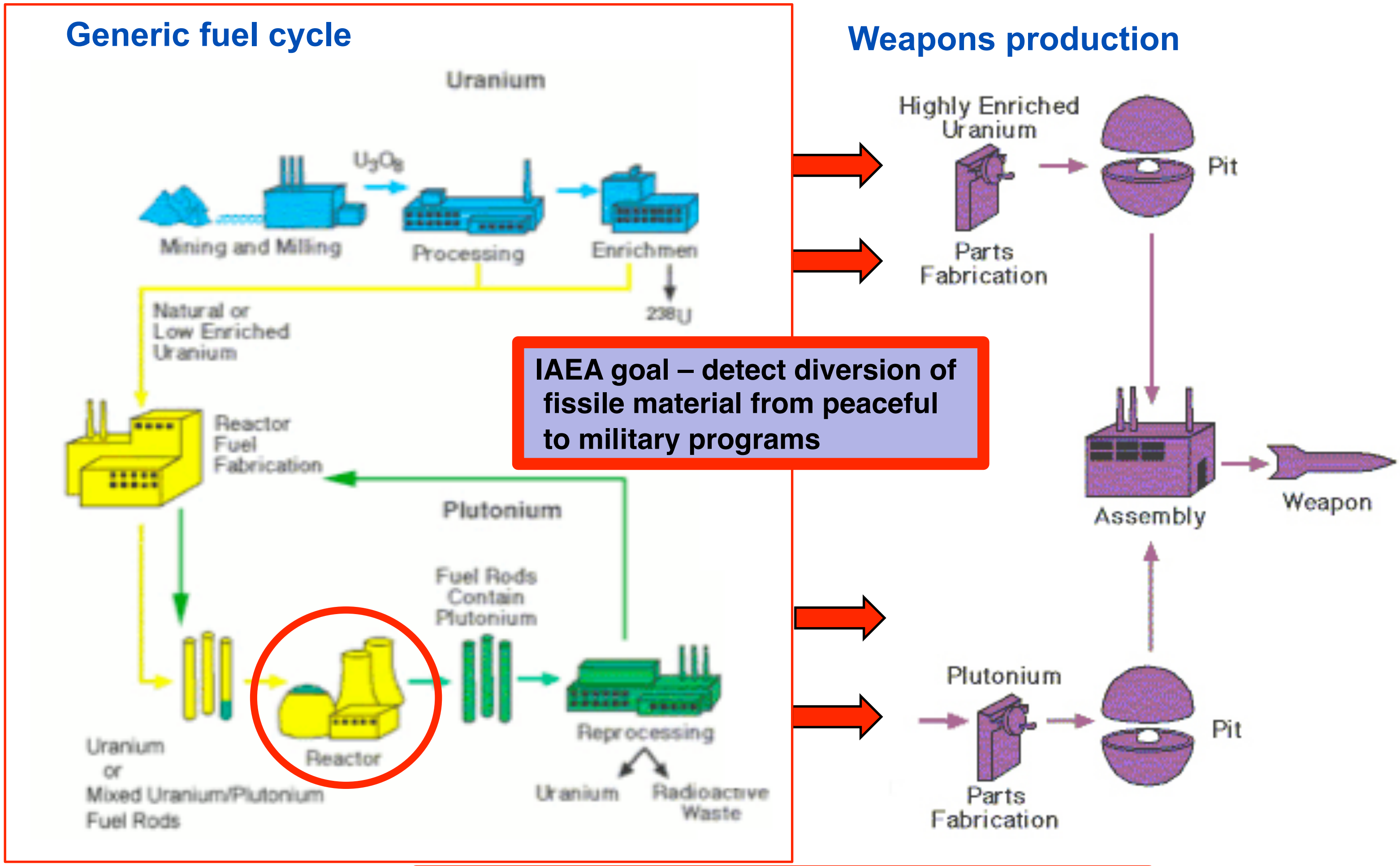
Considerable activity in the last two years

- Obama 2009 Prague speech – ‘the miracle year’ according to former US State and Def Secretaries Schultz and Perry
- First fully declassified US Nuclear Posture Review
- ‘New START’ Russia-US treaty
- 2010 Nuclear Security summit to secure vulnerable materials in 4 years (not gonna happen)

Nuclear security problems that antineutrino detectors might be able to address

Application	Scale	Status
1. IAEA *Safeguards* — Current Safeguards Regime — Plutonium Disposition — FMCT	**Near-field** → 5-1000 m **Detector Scale** → 1-100 tons	**Demonstrated with simple detectors (LLNL, Kurchatov)** 
2. Verification and Cooperative Monitoring • Confirm cessation of plutonium production - e.g. in North Korea, Iran	**Mid-Field** → 1– 10 km **Detector Scale** → 1-10 kiloton **Reactor Scale** → 10 MWT	**Detectors at this scale exist now** 
3. Remote Detection • Observe reactors and explosions across borders	**Far-Field** →10– 500 km **Detector Scale** → 1 Megaton (n.b. - *mass* not *yield*) **Reactor Scale** → 10 MWT	**Proposed for physics experiments** 

The International Atomic Energy Agency monitors the nuclear fuel cycle in 170 countries

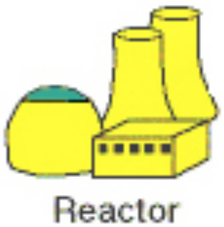


IAEA goal – detect diversion of fissile material from peaceful to military programs

Goal for antineutrinos measurements – track fissile inventories in operating reactors

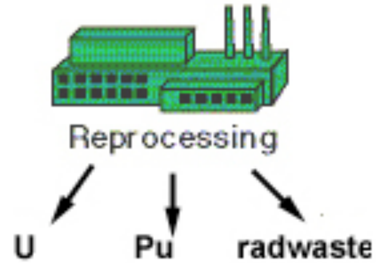
IAEA monitors about 220 reactors worldwide - without ever directly measuring core fuel inventories

(1-1.5 years)



(months to years)

(months)



(forever)

1. Check Input and Output **Declarations**
2. Verify with **Item Accountancy**
3. **Containment and Surveillance**

1 'Gross Defect' Detection
2. Cerenkov counters
3 Item Accountancy
4. Containment and Surveillance

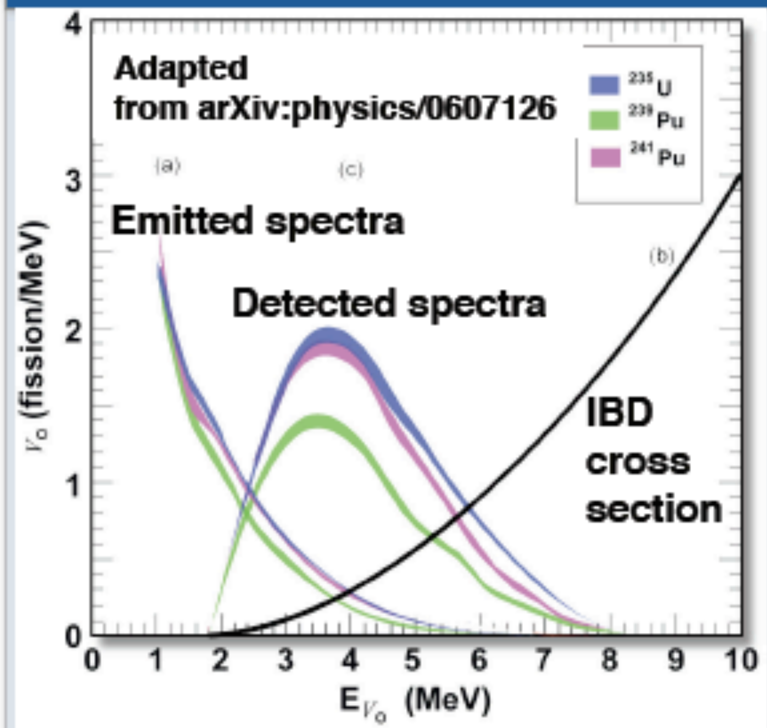
1 Check Declarations
2 Verify with **Bulk Accountancy**

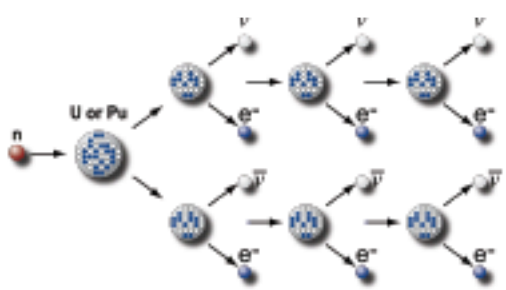
Operators Report Fuel Burnup and Power History

No Direct Pu Inventory Measurement - 'Bulk Accountancy' - is Made Unless and Until Fuel is Reprocessed

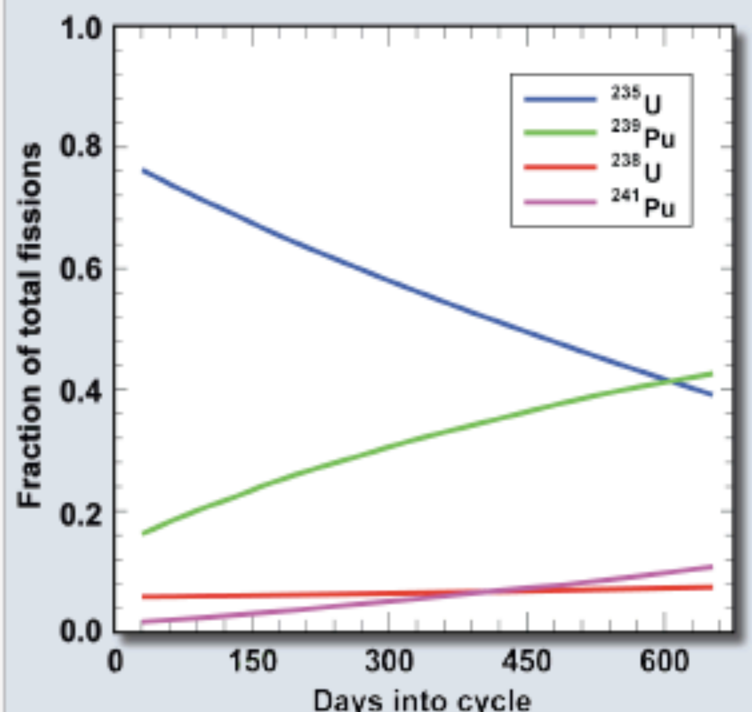
Antineutrinos encode information about fissile production and consumption in reactors through the 'burnup effect'

Produced and Detected Antineutrino Spectra





Change in Fission Rates with Time

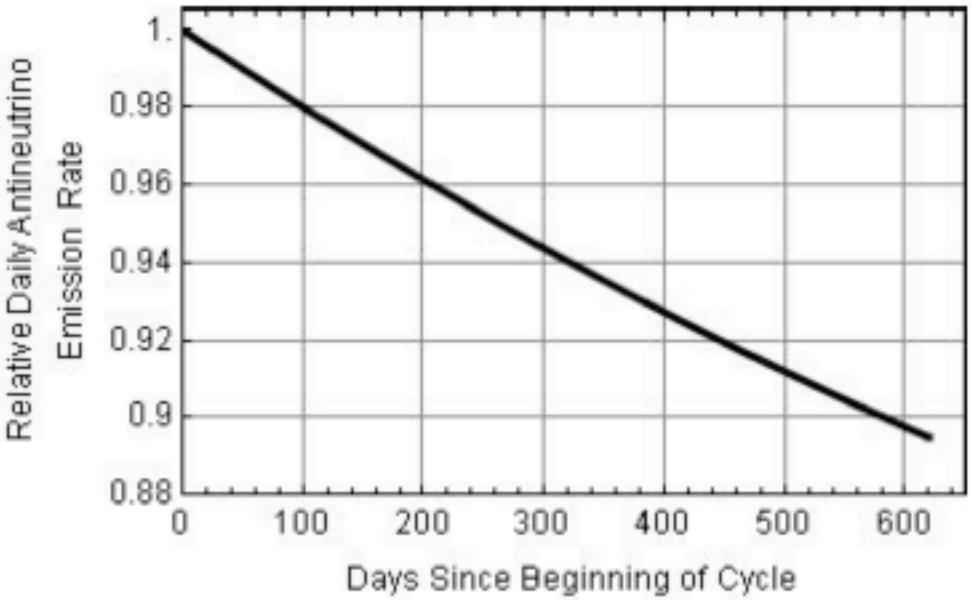


Isotopic evolution of a representative PLWR fuel cycle

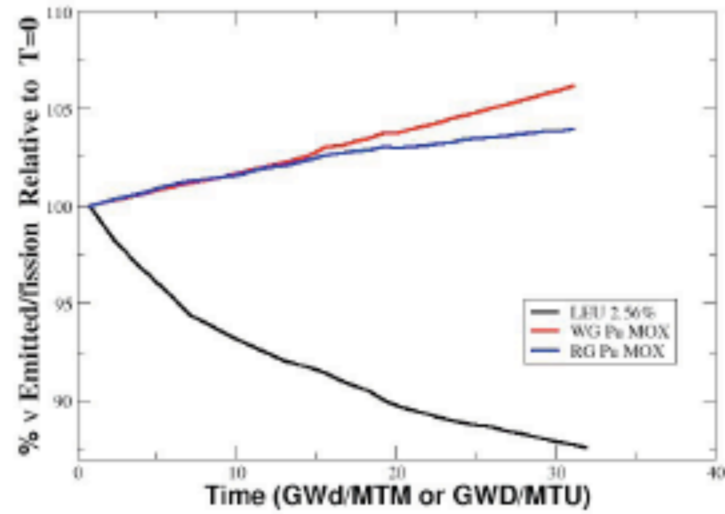
Rate example: 400-4000 events per day
25-m standoff
3-GWt reactor
1 ton detector

Result: antineutrino rate changes even at constant reactor power changes depend on fuel and reactor type

Typical commercial reactor with Low Enriched U



Reactor with initial 5% Pu content+ unenriched U



Simulation/Plot from Anna Hayes, LANL

$$N_{\bar{\nu}} = \gamma \cdot (1 + k(t)) \cdot P_{th}(t)$$

First order: ~10%
Varying contributions from Pu/U isotopes → $k(t)$

Zeroth order: reactor power → $P_{th}(t)$

Some common methods of antineutrino detection

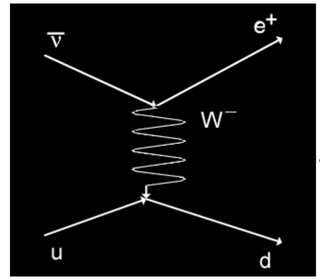
1.Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$

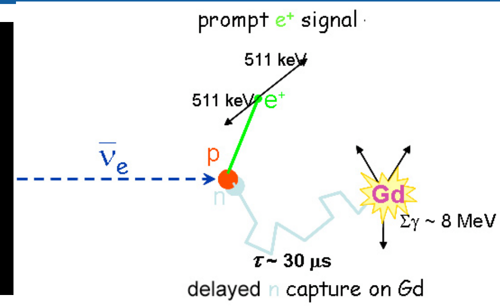
The gold standard for antineutrino detection

A robust time-coincident signal

'*good old inverse beta*' - Petr Vogel

Neutrinos *are not* a background for this process

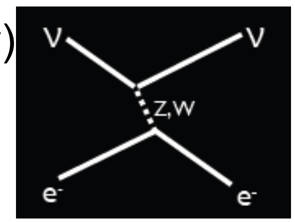




2.Antineutrino-electron scattering

(~100x **smaller** cross section than inverse beta decay)

$$\sigma \sim 10^{-44}\,\mathrm{cm}^2 \, \frac{E_\nu(\mathrm{MeV})}{10\,\mathrm{MeV}}$$



Neutrinos *are* a background for this process

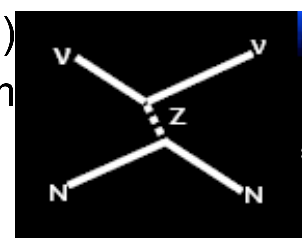
3.Coherent antineutrino-nucleus scattering

$$\sigma_{\mathrm{coh.}} \approx 0.4 \times 10^{-44}\,\mathrm{cm}^2 N^2 E_\nu(\mathrm{MeV})^2$$

(100-1000x **larger** cross section than inverse beta decay)

But - a very weak signal (10s-100s of eV nuclear recoils)

May be interesting for reactor monitoring out to a few km



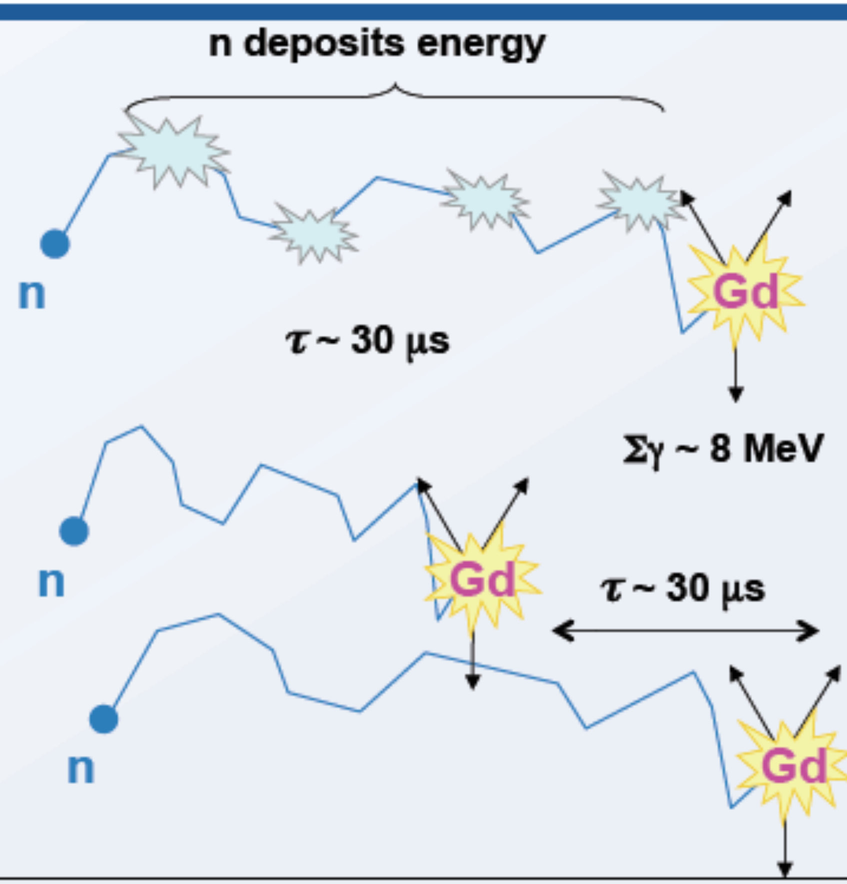
Enhanced by square of neutron number

Neutrinos *are* a background for this process

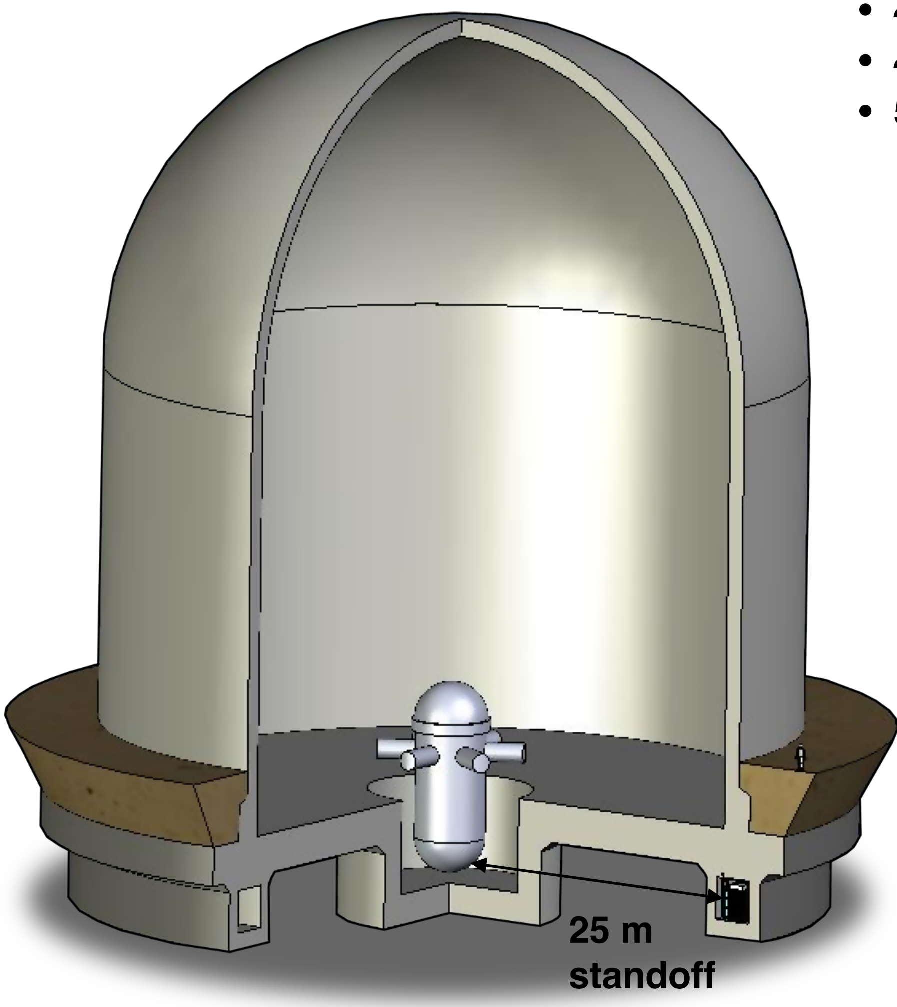
The signal: inverse beta decay

- **Positron**
  - **Immediate**
  - **1- 8 MeV (incl 511 keV γs)**
- **Neutron**
  - **Delayed (τ = 28 µs for Gd)**

An important background: cosmogenic neutrons

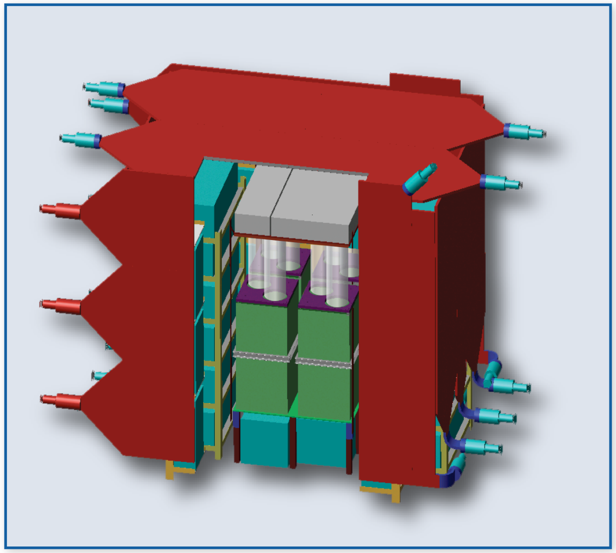


Example: the SONGS1 detector at the San Onofre Nuclear Generating Station



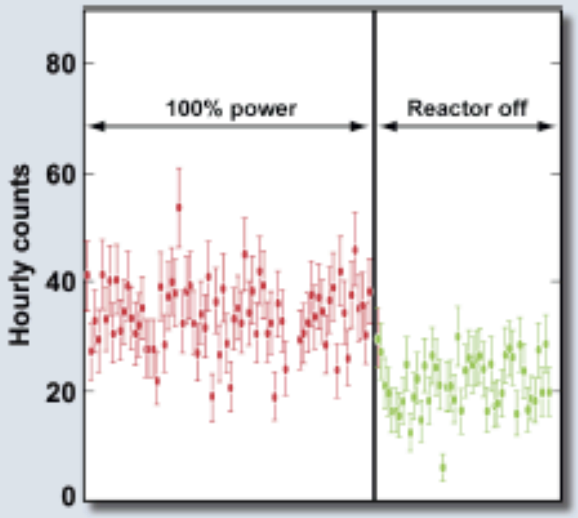
- ~ 10^{17} antineutrinos/m^2/sec 25-m standoff
- ~ 6,000 events/ton/day -perfect detector
- 500-1000 events/ton/day - simple detector

0.64 tons Gd scintillator
Water/polyethylene shield
Plastic muon veto
2.5 meters on a side,

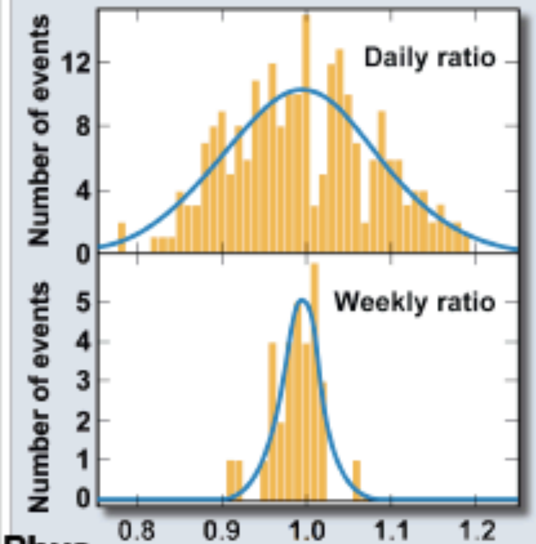


What reactor safeguards information do antineutrino measurements provide ?

Determine reactor on/off status within 5 hours with 99.9% C.L.

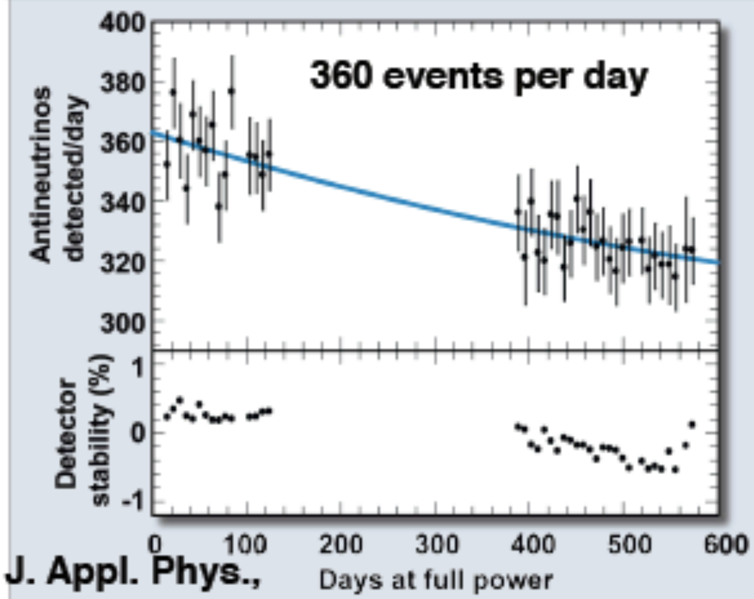


Measure thermal power 3% (relative), one week



J. Appl. Phys., 103, 2008.

2000 events per day would give 95% CL detection of 70 kg Pu removal



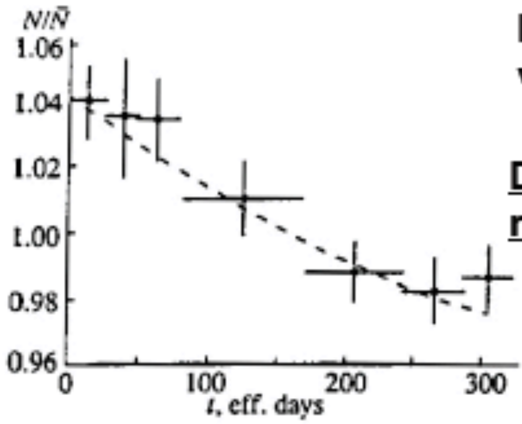
J. Appl. Phys., 105, 2009.

Results from Lawrence Livermore/Sandia National Labs Joint Deployment at San Onofre

Since Neutrino 2008 , IAEA has published an Experts White Paper on antineutrino detection and issued a request to its Member States for further R&D on reactor monitoring

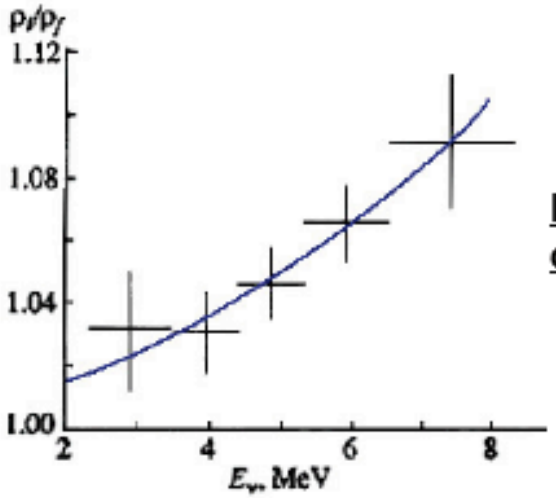
Mother Russia

First theoretical and experimental demonstrations were performed by 1970s → 1980s Mikaelyan Klimov, others @ Kurchatov



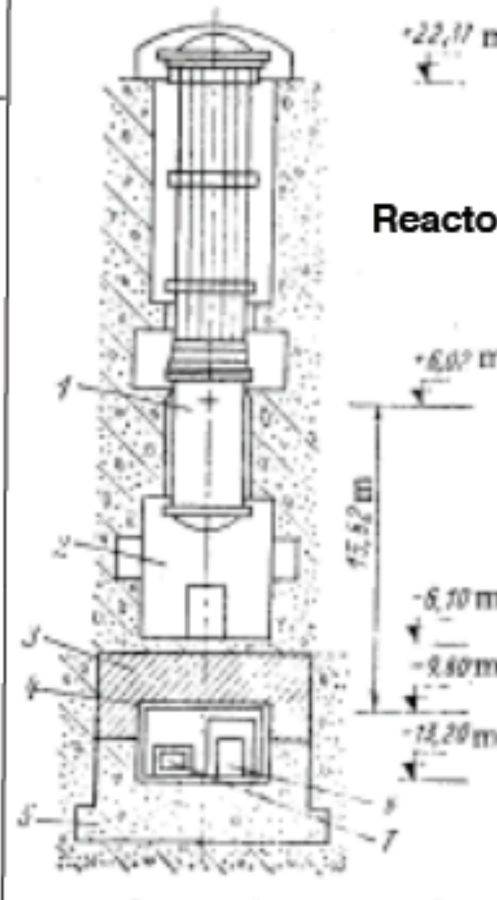
Relative antineutrino rate versus cycle day

<u>Demonstrates change in rate throughout cycle</u>



Ratio of beginning and end of cycle spectra:

<u>Demonstrates spectral hardening due to Plutonium ingrowth.</u>



Reactor

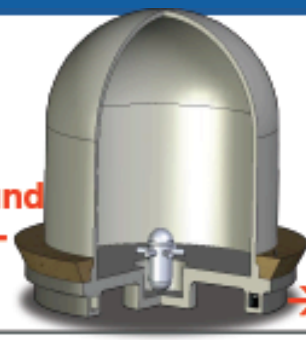
Detector(s)
18 m below reactor

The AAP community has been working on safeguards optimization since an IAEA Experts Meeting in 2008

LLNL/SNL, Brazil, Japan

+ More deployment locations
+ Less intrusive
+ Maybe easier to install
+ Requested by IAEA

Above ground detectors ←



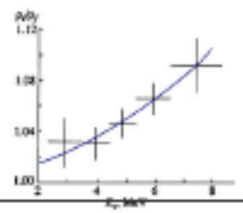
→ 10-20 mwe overburden

+ More sensitive safeguards measurements
+ lower background, more forgiving design space

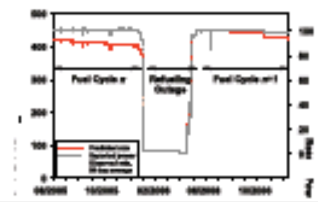
France

Spectrally resolving detectors ←

+ Reduce or eliminate dependence on operator declarations



→ Rate-based detectors



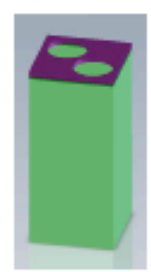
+ Simpler to construct
+ Probably less expensive
+ Possibly easier to interpret

U Hawaii/NGIA

Directional detectors ←

+ may aid with standoff discovery of reactors
+ may aid with background rejection
+ Complex or impossible to design

→ Non-directional detectors



+ Proven technology
+ Less complex

Taiwan, Sandia Natl. Lab, U of Chicago, LLNL

Coherent Neutrino Nuclear Scatter Detectors

ABOVE GROUND DETECTORS

San Onofre, Kaska, Angra

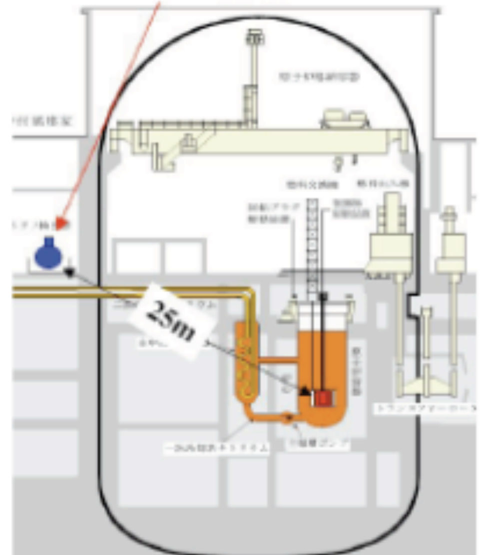
Above ground detectors

Japanese Effort: Kaska

(Tohoku U., Tokyo Tech, TMU, Niigata U., Kobe U., TGU, Hiroshima Tech, MEU, KEK)

•FIRST Trial of Neutrino Detection from **Joyo Fast Research Reactor** with Gd loaded liquid scintillator (2006 ~ 2007).

- **Pth=140MW**
- **Frequent ON/OFF**
- **L~25m**

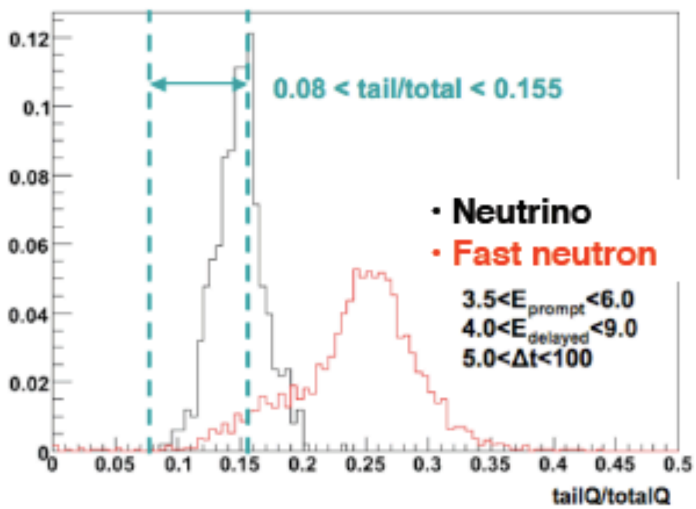


•KASKA detector prototype 2x3x2.5m, 0.7t, **above ground**.

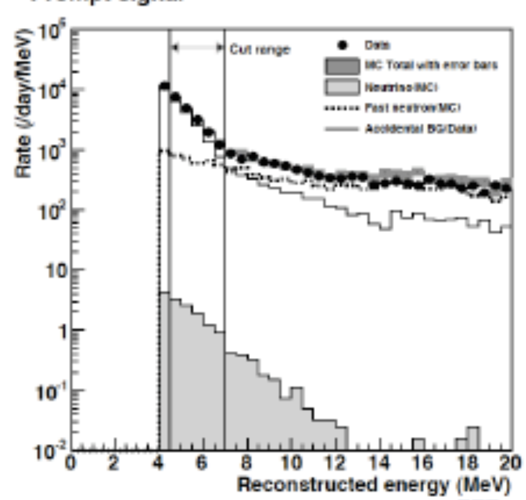
•The most sever BKG is **fast neutron**.

=> Need to improve the detector.

(implement a ability of n/γ pulse shape discrimination(PSD) , optimized BKG rejection)



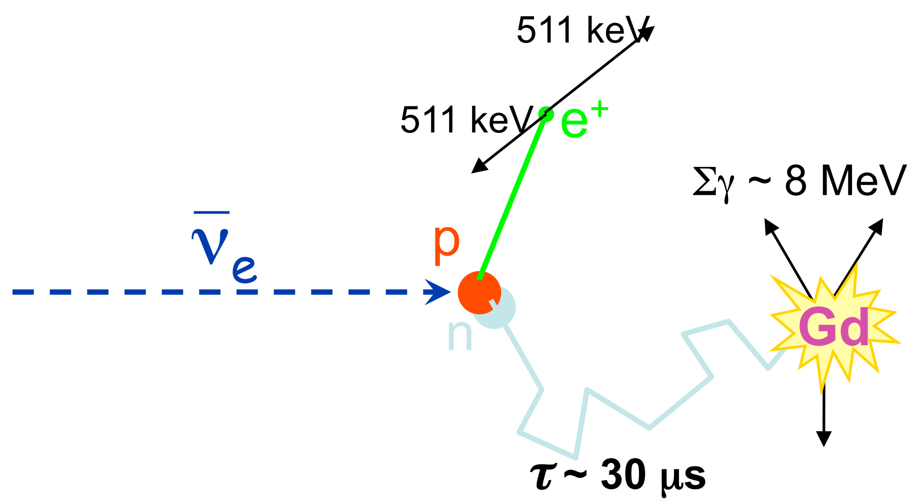
Prompt signal



Water Cerenkov antineutrino detectors ? LLNL and SuperK have shown we can tag neutrons in water (next, EGADS)

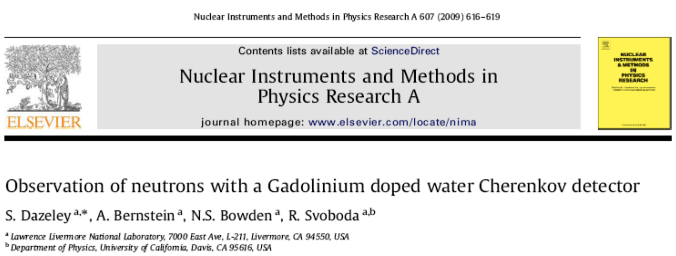
Use Gd to detect the neutron, as in liquid scintillator
Gd-doped water (Bernstein, 1999)
GdCl3 (Beacom & Vagins, 2003)

$$\nu_e + p = e^+ + n$$



The same prompt e+ signal + n capture on Gd as LSCINT But - 100x less light output

March 2009 : LLNL/SNL demonstration with a 250 kg Gd-doped water detector



Nuclear Instruments and Methods in Physics Research A 607 (2009) 616–619
Contents lists available at ScienceDirect
Nuclear Instruments and Methods in Physics Research A
journal homepage: www.elsevier.com/locate/nima

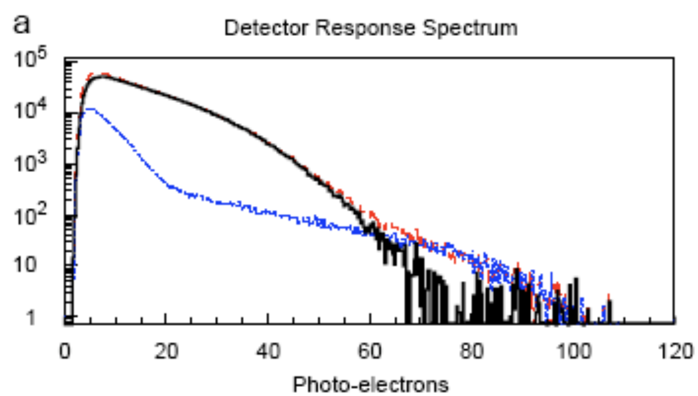
Observation of neutrons with a Gadolinium doped water Cherenkov detector

S. Dazeley [a,*], A. Bernstein [a], N.S. Bowden [a], R. Svoboda [a,b]
[a] Lawrence Livermore National Laboratory, 7000 East Ave, L-211, Livermore, CA 94550, USA
[b] Department of Physics, University of California, Davis, CA 95616, USA

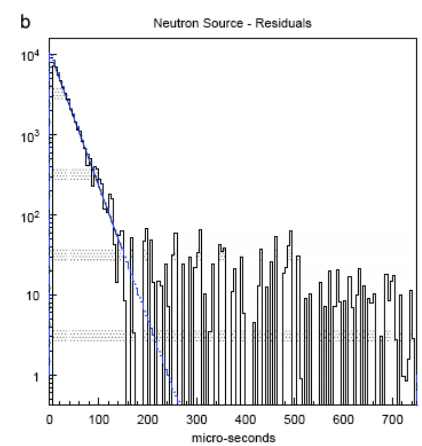
May 2009 - study of neutron tagging with a cell lowered into SuperK

Astroparticle Physics
Volume 31, Issue 4, May 2009, Pages 320-328
doi:10.1016/j.astropartphys.2009.03.002 | How to Cite or Link Using DOI

First study of neutron tagging with a water Cherenkov detector



Neutron energy spectrum
black = neutron source
blue = background



Inter-event time spectrum
With τ 28 μs

Gd doped water detector deployment in the US

Features:

Indifferently sensitive to: positrons thermal neutrons, gammas… no discrimination

But

Insensitive to an important class of background – fast neutrons

e+ positron

n thermal neutron

n ~~fast neutron~~

LLNL/SNL effort, March 2010

PMT installation in water tank

Shield and detector shipped in a standard 20 ft. container

Installed at SONGS reactor in Southern California

Testing in a country under IAEA safeguards - The Brazilian ANGRA water detector roject

- Central detector : ~ 2.00m x 1.60m x 1.40m
- Target volume: 1.36m x 0.98m x 0.90m ~1 ton
- Water + 0.1% Gd viewed by 40 8” PMT’s
- External Shield: borated polyethylene;
- Muon veto: extruded plastic scintillator strips;

EXPECTED RATES AT THE DETECTOR

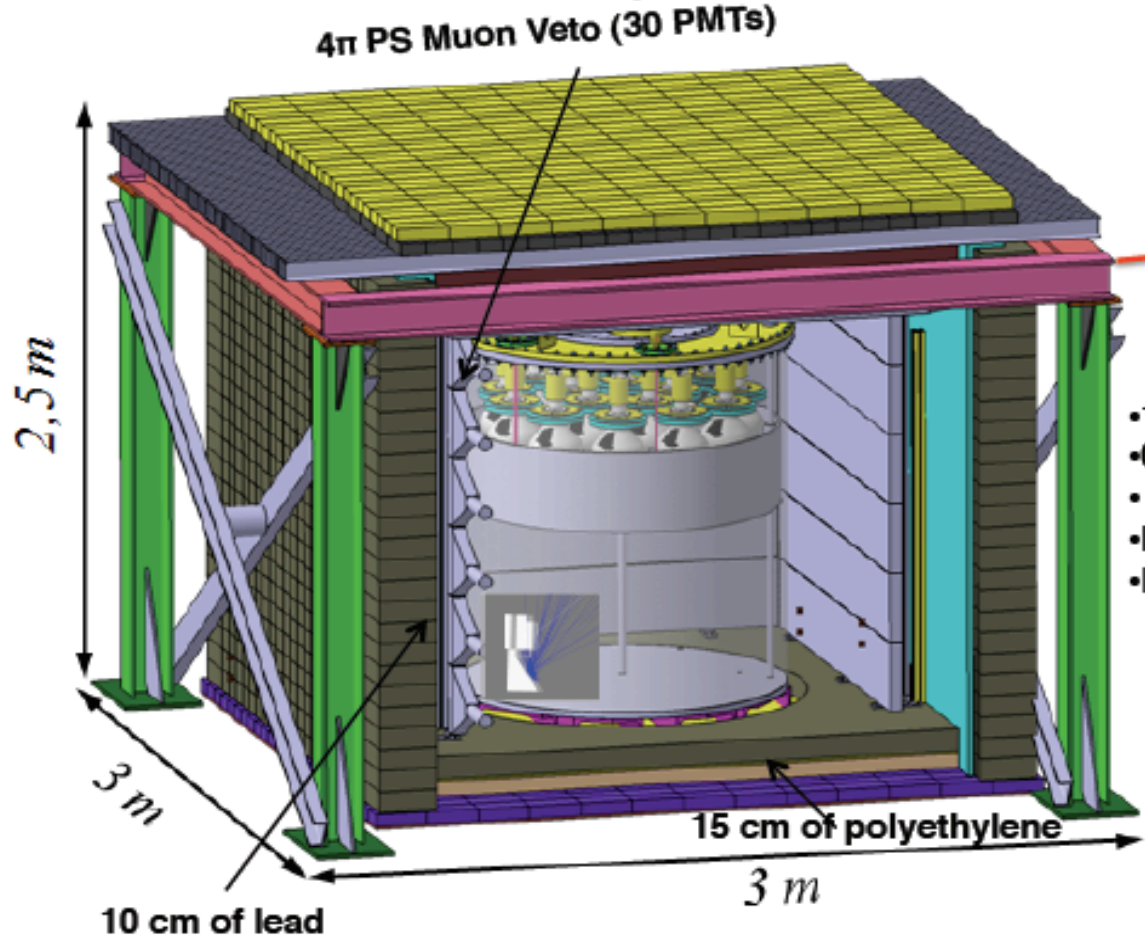
- Neutrino interactions: 4,400/day (~ 0.05 Hz)
- Neutrino signal: ~ 1.000 events/day (~ 0.01 H
- Muon rate at target: ~ 350 Hz
- Neutron background rate: ~ 4 Hz (with 30cm polyethylene shielding) ⇒ background rate has to be reduced by a factor at least ~10^4

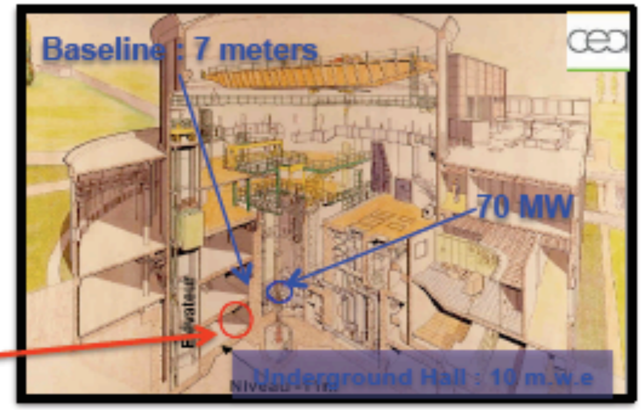
Start of data taking expected by spring 2011.

NEUTRINOS ANGRA Project

Spectral detectors

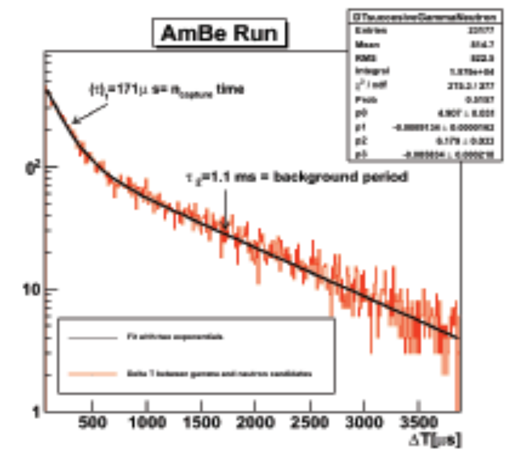
The Nucifer Experiment





Osiris Research Reactor
CEA-Saclay (1000 ν/d)

- 16 x 8' PMTs
- 0.8 m³ Gd-LS (0.5%)
- reflective Teflon walls
- Double containment
- Low fire hazard design

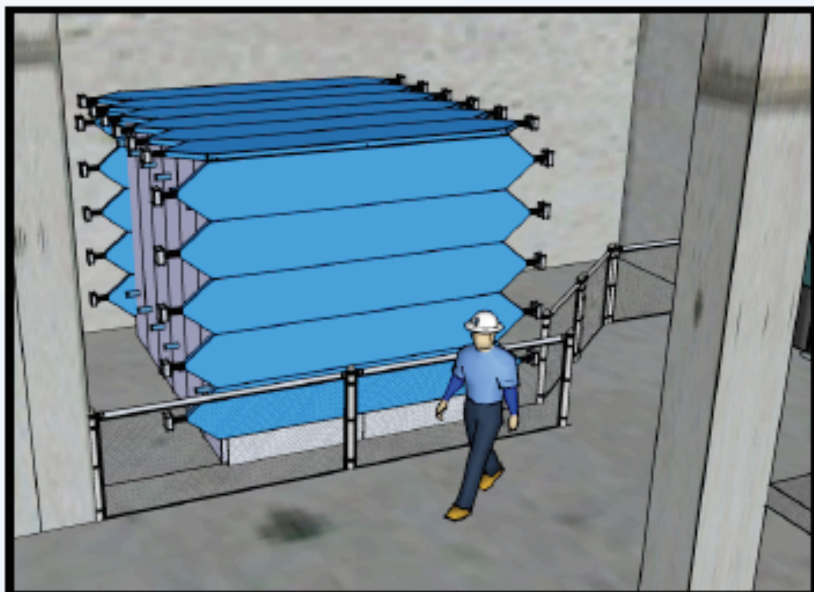


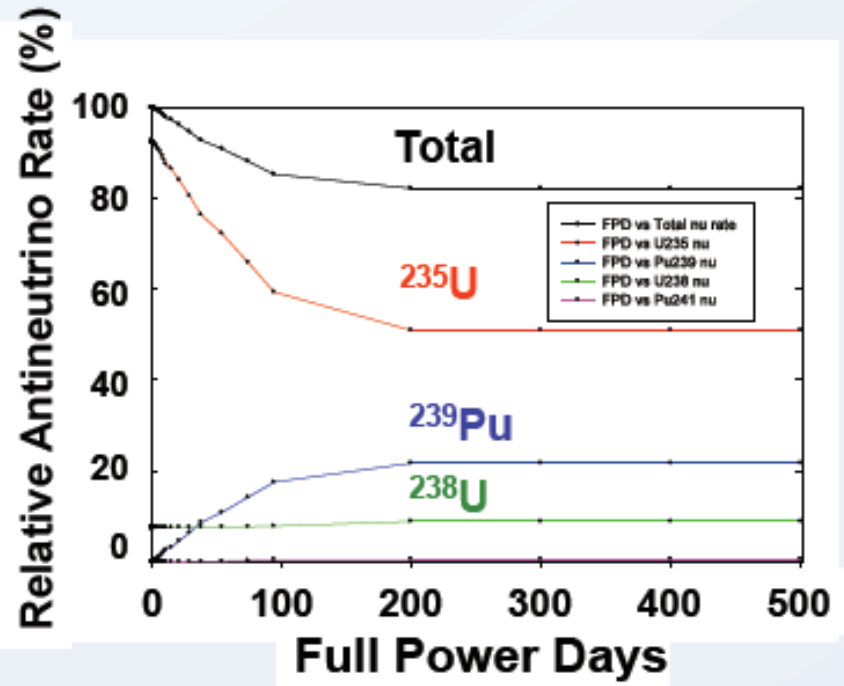
- Sensitivity for 16 days run : 60kg of Pu diverted (75% confidence level, 4% fake alert)
- First neutrinos @ Osiris CEA-Saclay (11/2010)

Subatech cea

Measuring burnup at different reactor types
LLNL/SNL CANDU Deployment - late 2010

- 75m from the core of a CANDU6 online refueled reactor
- Liquid Scintillator Detector, ~10x as efficient per m^2 as "SONGS1"
- Will measure fuel evolution from fresh startup to equilibrium

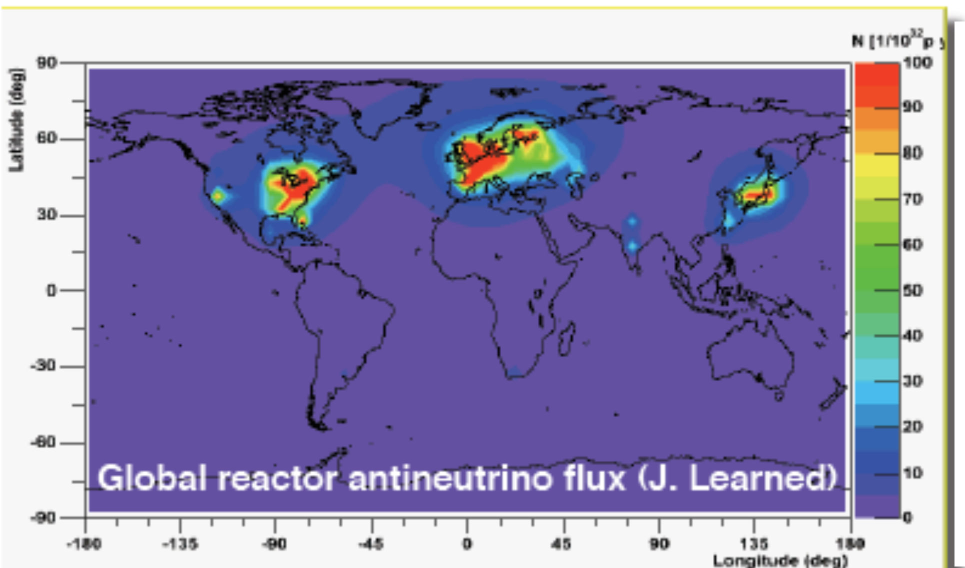




http://arxiv.org/abs/0908.4338

Just how hard is it to find a small remote reactor ?

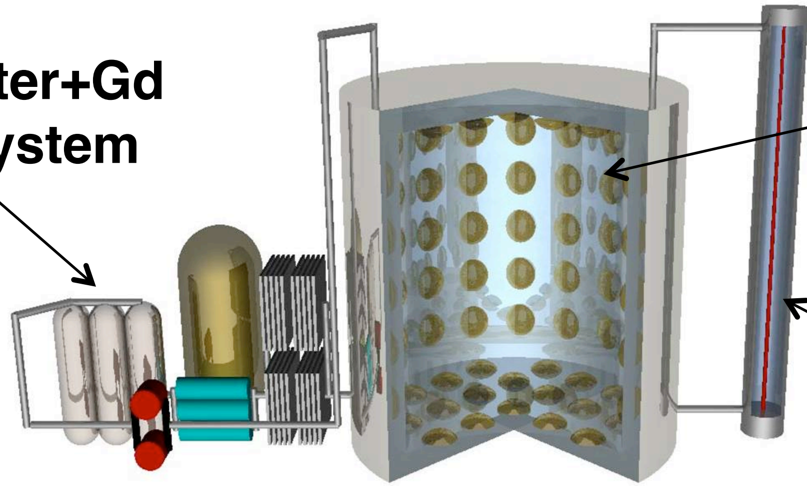
Goal	Required event rate	Standoff for indicated detector mass	
10 MWt reactor		10 kiloton	1 Megaton
25% est. of total power	16 per year	~40 km	~400 km
Required bg rate relative to KamLAND	only valid in purple (reactor free) regions in the plot	10	100



Mediumand long term prospects for demonstration of large scale Gd-doped water detectors

Selective Water+Gd Filtration System

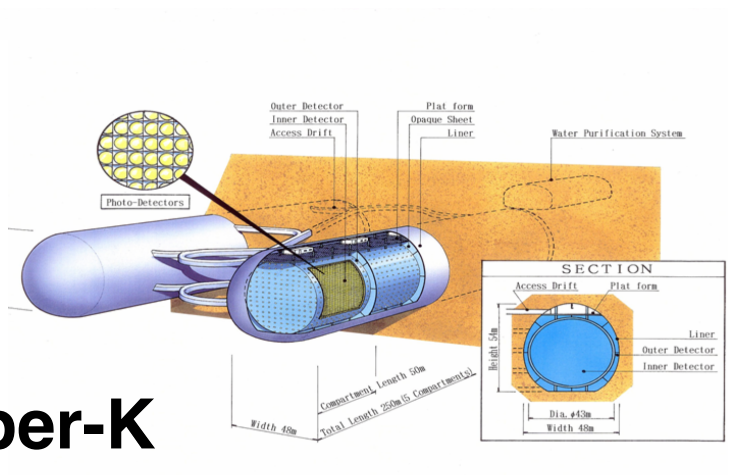
[graphic by A. Kibayashi]



200 ton (6.5 m X 6.5 m) water tank (SUS304)

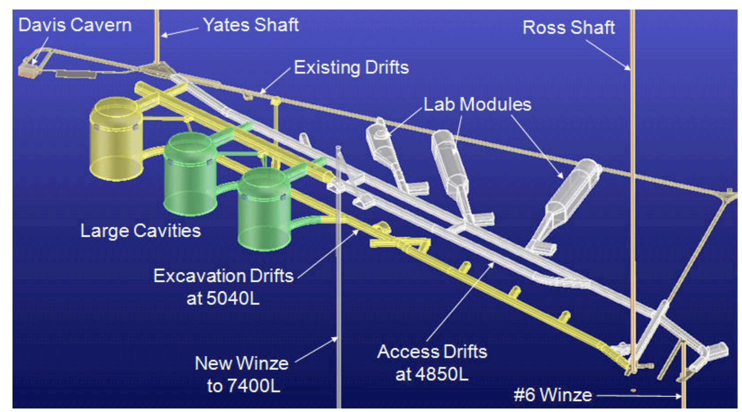
Transparency Measurement

Medium-term – the 200 ton EGADS experiment at the Kamioka mine



Hyper-K

LBNE@ DUSEL



Long term Japanese and American Megaton array programs – 10-20 years

Since this is Applied Antineutrino Physics, technology development should not be our only focus

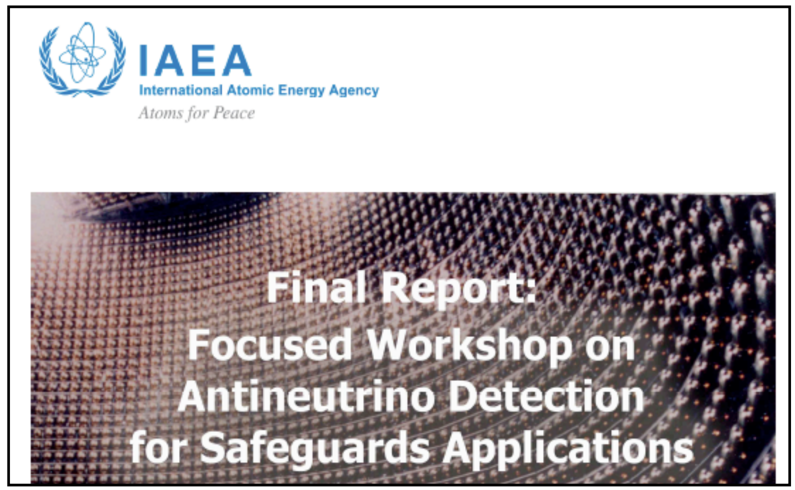
- **Better understanding of IAEA needs**
  - Find out how are safeguards done at most PWRs and BWRs
  - How can antineutrino detection complement the current reactor safeguards regime ?
  - Study of diversion scenarios (see Bernstein talk later today)
  - Formal interactions with the IAEA through Member State Support Programs

→

Result of 2008 Experts Meeting at IAEA HQ:

Interest in application for:

- **Shipper-receiver differences,**
- **Bulk Process/ Online Refuel Reactor Verification**
- **Research reactor power**
- **Safeguards by Design, Integrated Safeguards**
- **Aboveground Detection**



Summary and conclusions

- Safeguards and physics experiments have demonstrated practical unattended and nonintrusive monitoring of reactors with cubic meter scale detectors - e.g. SONGS, Rovno expts.
- Key measurements of safeguards interest are:
  1. Operational status in hours
  2. Relative thermal power in weeks
  3. Burnup/fissile content constraints in weeks to months

- AAP community must continue to optimize among cost complexity and sensivity
  - US Brazil, Canadian, French Japanese, Taiwanese and Russian efforts are underway – see their talks
- I did not mention important topics
  - Reactor simulations to improve connection between fissile content and antineutrino rate
  - Neutrino Directionailty (see John Learned talk)
  - Argon and Ge coherent scatter (see Reyna and Wong talks for Ge)
- Long Range monitoring – Megaton scale devices, water only, not forbidden by physics, significant advances in background rejection required