Simulation of Reactors for Antineutrino Experiments Using DRAGON.
\( n \rightarrow p + e^- + \bar{\nu}_e \)
A Long History of Reactor Neutrinos

A Particular Experiment:
The Double Chooz Collaboration:

APC Paris CNRS/IN2P3, CEA/DSM/IRFU, SPP, SPhN, SEDU, SIS, SENAC, IPHC Strasbourg, Subatech Nantes, ULB

INR RAS, IPC RAS, RRC Kurchatov

Aachen U., Hamburg U., MPIK Heidelberg, TU München, EKU Tübingen

HIT, Kobe U., Niigata U., Tohoku U., TGU, TIT, TMU

CIEMAT Madrid


Sussex U.

CBPF, UNICAMP
Measuring $\theta_{13}$:
The Most Complicated Formula:

$$
P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E}$$

$$
+ \frac{1}{2} \sin^2 \theta_{12} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{2E} \sin^2 \frac{\Delta m_{21}^2 L}{2E}$$

$$
- \left( \cos^4 \theta_{13} \sin^2 2\theta_{12} + \sin^2 \theta_{12} \sin^2 2\theta_{13} \cos \frac{\Delta m_{31}^2 L}{2E} \right) \sin^2 \frac{\Delta m_{21}^2 L}{4E}.
$$

Near

Survival Probability

Far

E=3MeV

$\sin^2 2\theta_{13} \sim 0.2$

$\Delta m_{31}^2 = 2.5 \times 10^{-5} \text{eV}^2$
And Really....

\[ P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E} \]

\[ E = 3\text{MeV} \]

\[ \sin^2 2\theta_{13} \sim 0.2 \]

\[ \Delta m_{31}^2 = 2.5 \times 10^{-5}\text{eV}^2 \]
T2K Lower Bound

Far Only

Far + Near

Reactor Systematics Dominate.

Double Chooz – sensitivity, no oscillations

$\sin^2(2\theta_{13})$
And It’s taking data....
T2K Lower Bound

Far Only

Far + Near

Reactor Systematics Dominate.

Double Chooz – sensitivity, no oscillations

\( \sin^2(2\theta_{13}) \)
A Few More Details on Reactor Anti-Neutrinos:

- $2 \times 10^{20}$ anti-neutrinos per s per GW$_{th}$
Simulating fission rates...
How do reactors work?
Fuel is arranged in assemblies.
The assemblies are inserted into the reactor vessel.
Enter the Dragon....

• Dragon is a 2D assembly code that directly solves the neutron transport equations (*Meaning it’s really fast*).

• We input detailed geometry and fuel compositions and then evolve the reactor in time.

• We then sum up the results of each assembly to get the total number of fissions in the core.

• Double Chooz is also doing these calculations with MURE (a MCNP based full core simulation).

G. Marleau @ Polytechnique Montreal
The Takahama Benchmark

JAERI-Tech 2000-071
(ORNL/TR-2001/01)
It is an amazing amount of work...

But Takahama is the most like Chooz.
There are three rods that were studied.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>PWR</th>
<th>Fuel Type</th>
<th>Ave. Bup (GWd/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF95</td>
<td>SF96</td>
<td>SF97</td>
<td>33.5</td>
</tr>
<tr>
<td>UO₂</td>
<td>UO₂-Gd₂O₃</td>
<td>UO₂</td>
<td>26.4</td>
</tr>
</tbody>
</table>

I am going to concentrate on SF97.
There are three rods that were studied.

They used both scanning techniques and destructive assays.
Where in the assembly is SF97?

It is located here near the edge.
This assembly was inserted into the Takahama reactor vessel.
Unique to Takahama is the detailed power history along the rod.

This is obtained by using the $^{148}\text{Nd}$ buildup coupled with simulations of the reactor (3% uncertainty).
With the detailed geometry and power history we are ready to simulate Takahama.
Understanding the performance....

After the three cycles a destructive chemical assay was performed. The uncertainties on the mass inventories is $\sim 0.3\%$.

DRAGON is performing well!
Understanding the performance....

$^{238}\text{U} \rightarrow ^{239}\text{Pu} \rightarrow ^{240}\text{Pu} \rightarrow ^{241}\text{Pu} \rightarrow \ldots \rightarrow ^{244}\text{Cm}$

This is discussed nicely in Djurcic, Detwiler et al.
$^{235}$U highly correlate to the power variation.
$^{239}\text{Pu}$ is dominated by other things.
Using SONGs Data to Verify Reactor Models:

San Onofre Nuclear Generating Station

SONGs reactor: 3.438 GWth output

SONGs detector: 0.64 ton liquid scintillator doped with Gd

Data from LLNL and Sandia NL

DPF 2011
In the End.

• Dragon is a 2D assembly code that directly solves the neutron transport equations (*Meaning it’s really fast*).

• We performed the Takahama benchmark and it is performing as well as the standard reactor modeling codes.

• You can get it yourself: http://www.polymtl.ca/nucleaire/DRAGON/en/index.php
And Just In Case....
The Other half of your prediction...the Spectra

\[ S_{\text{tot}}(E) = \sum_{k=^{235}\text{U}, ^{238}\text{U}, ^{239}\text{Pu}, ^{241}\text{Pu}} \alpha_k \times S_k(E) \]

Number of Fissions per Isotope

Anti-neutrino spectra from the Isotopes
Where did the spectra come from?

The beta spectrum of $^{235}\text{U}$, $^{239}\text{Pu}$ and $^{241}\text{Pu}$ were measured using a spectrometer.

Now you use energy conservation to extract the neutrino spectrum.
Updating the Extraction....
Is this evidence for sterile neutrinos?

The blue line is a fit to a 4th neutrino state with a mass splitting of $>1\text{ eV}^2$. 
Not to be confused with Bugey-3 in 1995

Nuclear Physics B 434, 503-532, 1995
and these measurements are tricky...

Bugey in 1984

13.6m

18.3m


Fig. 2. (a) Positron energy spectrum measured at position 1 (reactor OFF subtracted). The data points with dashed error bars show the reactor OFF spectrum. The error bars are statistical. The expected positron energy spectrum is shown as a shaded band delimited by the point-to-point errors. (b) Ditto at position 2.
The Electronics:

- Signal + HV on one cable.
- Frontend cards shape pulses, corrects baseline and integrates charge.
- Analog Trigger triggers on photoelectron equivalent.
- 500MHz Caen digitizers record pulses.
- Subset of PMTs sent to second system to record muon events.
Single Photo-Electron Data:

channel = 53, trigger_id = 46

Amplitude: $<\text{IPE}> \sim 8\text{ADC counts}$
Charge: $<\text{IPE}> \sim 60\ \text{DUQ}$ (integrated ADCx2ns)

Charge

PRELIMINARY

PRELIMINARY
Inner Detector Muon Event

DC Preliminary
Inner Veto Muon Event

DC Preliminary

Lindley Winslow
And then there were three:

Daya Bay
IRENO
DOUBLE

arXiv:hep-ex/0701029v1
arXiv:1003.1391v1
arXiv:hep-ex/0606025v4

DPF 2011

Lindley Winslow
The Three Experiments:

<table>
<thead>
<tr>
<th></th>
<th>Double Chooz</th>
<th>Daya Bay</th>
<th>RENO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor Cores</td>
<td>2 Cores</td>
<td>6 Cores</td>
<td>6 Cores</td>
</tr>
<tr>
<td>Total Power</td>
<td>8.54 GW</td>
<td>11.6 GW†</td>
<td>16.4 GW</td>
</tr>
<tr>
<td>Target Mass</td>
<td>8.24 tons</td>
<td>20 tons</td>
<td>15 tons</td>
</tr>
<tr>
<td>Near Distance</td>
<td>400m</td>
<td>300-500m†</td>
<td>290m</td>
</tr>
<tr>
<td>Near Overburden</td>
<td>115 m.w.e</td>
<td>~100 m.w.e†</td>
<td>130 m.w.e</td>
</tr>
<tr>
<td>Far Distance</td>
<td>1.05km</td>
<td>1.6-1.9km</td>
<td>1.4km</td>
</tr>
<tr>
<td>Far Overburden</td>
<td>300 m.w.e.</td>
<td>350 m.w.e</td>
<td>460 m.w.e.</td>
</tr>
<tr>
<td>Events per Day</td>
<td>425/43</td>
<td>1600/400†</td>
<td>5000/100</td>
</tr>
</tbody>
</table>

† Daya Bay will increase to 17.4GW in 2011, has two near sites, and uses multiple detectors per site.
Why the two detectors?

<table>
<thead>
<tr>
<th></th>
<th>Chooz</th>
<th>Double Chooz</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reactor</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>v flux and spectrum</td>
<td>1.9%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Reactor Power</td>
<td>0.7-2%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td><strong>Detector</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solid Angle</td>
<td>0.3%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Target Mass</td>
<td>0.3%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Density</td>
<td>0.3%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>H/C and Gd ratio</td>
<td>1.2%</td>
<td>&lt;0.2%</td>
</tr>
<tr>
<td>Spatial Effects</td>
<td>1.0%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Live time</td>
<td>-</td>
<td>&lt;0.2%</td>
</tr>
<tr>
<td><strong>Analysis</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>From 3-7 cuts.</td>
<td>1.5%</td>
<td>0.2-0.3%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>2.7%</td>
<td>&lt;0.6%</td>
</tr>
</tbody>
</table>
The Estimated Background Rates:

<table>
<thead>
<tr>
<th>Detector</th>
<th>Site</th>
<th>Background</th>
<th>Accidental Materials</th>
<th>PMTs</th>
<th>Fast n</th>
<th>Correlated μ-Capture</th>
<th>(^9\text{Li})</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHOOZ</td>
<td>Rate ((d^{-1}))</td>
<td>0.42 ± 0.05 (\text{(stat)}) ± 0.1 (\text{(sys)})</td>
<td>1.6%</td>
<td></td>
<td></td>
<td></td>
<td>0.6 ± 0.4</td>
</tr>
<tr>
<td>(24 (\nu/d))</td>
<td>Rate ((d^{-1}))</td>
<td>1.01 (\text{(stat)}) ± 0.1 (\text{(sys)})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Far</td>
<td>bkg/(\nu)</td>
<td>1.6%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Systematics</td>
<td>0.2%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Double Chooz</td>
<td>Rate ((d^{-1}))</td>
<td>(0.5 \pm 0.3) (\pm 0.8) (\pm 0.2)</td>
<td>(&lt;0.1) (%)</td>
<td>1.5%</td>
<td>0.2%</td>
<td>(&lt;0.1) (%)</td>
<td>1.4 ± 0.5</td>
</tr>
<tr>
<td>(69 (\nu/d))</td>
<td>Far</td>
<td>bkg/(\nu)</td>
<td>0.7%</td>
<td></td>
<td></td>
<td>(&lt;0.1) (%)</td>
<td>1.4%</td>
</tr>
<tr>
<td></td>
<td>Systematics</td>
<td>(&lt;0.1) (%)</td>
<td>(&lt;0.1) (%)</td>
<td></td>
<td></td>
<td>(&lt;0.1) (%)</td>
<td>0.7%</td>
</tr>
<tr>
<td>Double Chooz</td>
<td>Rate ((d^{-1}))</td>
<td>(5 \pm 3) (\pm 9) (\pm 1.3)</td>
<td>0.4</td>
<td></td>
<td></td>
<td>(&lt;0.1) (%)</td>
<td>9 ± 5</td>
</tr>
<tr>
<td>(1012 (\nu/d))</td>
<td>Near</td>
<td>bkg/(\nu)</td>
<td>0.5%</td>
<td></td>
<td></td>
<td>(&lt;0.1) (%)</td>
<td>1%</td>
</tr>
<tr>
<td></td>
<td>Systematics</td>
<td>(&lt;0.1) (%)</td>
<td>(&lt;0.1) (%)</td>
<td></td>
<td></td>
<td>(&lt;0.1) (%)</td>
<td>0.2%</td>
</tr>
</tbody>
</table>

arXiv:hep-ex/0606025v4