New Techniques
EXO, MOON, SuperNEMO

Andreas Piepke
for the EXO Collaboration
We know that neutrinos are massive. Oscillation observed with

• Solar and reactor neutrinos

• Atmospheric and accelerator neutrinos

• LSND and MiniBooNE → still unconfirmed, perhaps at this conference…

• We don’t know how neutrinos behave under charge conservation. Are neutrinos Dirac or Majorana particles?

• What is the absolute neutrino mass scale?

New generation double beta decay experiments will help answer these questions.
Decay rate translates into effective Majorana mass. Requires knowledge of nuclear physics quantities.

\[
(T_{1/2}^{0\nu})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_\nu \rangle^2
\]

\[
\langle m_\nu \rangle^2 = \left| \sum_i \eta U_{ei}^2 m_i \right|^2
\]

CP-phases can lead to cancellation. But how much? Replace masses by two possible choices of minimal mass \( m_1 \) or \( m_3 \) and add knowledge of mixing and mass splitting from oscillations.
The problem to be solved:

\[
\begin{align*}
  ^{76}\text{Ge} & : \ 5.8 \times 10^{28} \text{ y} \\
  ^{100}\text{Mo} & : \ 3.5 \times 10^{28} \text{ y} \\
  ^{136}\text{Xe} & : \ 4.8 \times 10^{28} \text{ y}
\end{align*}
\]

Rodin et al. PRC68 (2003)
Talk will cover SuperNEMO, MOON and EXO, all tracking calorimeters. I am a member of the EXO collaboration and will thus focus on this project.

Next generation experiments hope to actually observe neutrinoless double beta decay. The talk will focus on this decay mode.

$\beta\beta^{0\nu}$–decay: $A(Z,N) \rightarrow A(Z+2,N-2) + e^-$ has no easy to exploit experimental signature.

Given the interesting half lives of order $10^{27}$ to $10^{28}$ y, background reduction is THE problem to solve. Large source amount needed for reasonable decay rate.

Calorimetric detectors address this problem by carefully avoiding radioactivity of any kind and optimizing energy resolution. In many cases technical simplicity of the devices is a powerful advantage compared to more complex detectors.

Tracking calorimeters try to solve this problem by making background events more specific. EXO explores a novel method combining tracking with a true $\beta\beta$–tag. Such detectors are often technically complex which makes radioactivity control difficult. Energy resolution is not as good as for pure calorimeters. $\beta\beta^{2\nu}$–decay may become an irreducible background.
Decay modes distinguished by measurement of electron sum energy.

Left: expected spectra for 200 kg $^{136}$Xe in one year.

Right: leakage of $\beta\beta_{2\nu}$-events into $\beta\beta_{0\nu}$-analysis interval. $5.8^{\text{th}}$ power!

$\beta\beta_{2\nu}$: 40000 / year
$\beta\beta_{0\nu}$: 35 / year
MOON

- Tracking calorimeter. Source ≠ Detector
- Several tons of thin (20 mg/cm²) enriched Se or Mo foils
- Calorimetry through plastic scintillator σ=2-3% resolution
- Tracking through scintillating fibers or MWPC. Single/double track ID
- Perhaps dual purpose solar ν_e detector

Material supplied by

Hiro Ejiri
MOON : Majorana /Mo Observatory Of Neutrinos
Osaka, UW, FNAL, ICU, JINR, LANL, NIRS, Praha, Tokushima, UNC, VNIIEF.

1. Goal: $m_\nu \sim$ IH 30meV for ground and excited O+.
2. Detector \( \beta\beta \) source. Use one or two of \(^{100}\text{Mo}, \, ^{82}\text{Se}, \, ^{150}\text{Nd}\) with large \(Q > \) most RI .
3. \( \beta\beta \) tracking \( E_1, E_2, \Theta_{12} \) correlations to identify $\nu$-mass term.
4. Application to low-E solar $\nu$

**MOON detector**

Multi-layer PL plates: compact & active self-shields
Position /particle ID by PL fiber or MWPC chamber
Enriched isotopes by centrifugal separation.

**Sensitivity**

- 20-40 meV for \(^{100}\text{Mo}, \, ^{82}\text{Se}, \, ^{150}\text{Nd}\)
  with 5 year-ton and \(\sigma = 2-3 \%\) E-resolution.

**Schedule** (tentative)

- 2006 Prototype MOON-1 without position
- 2006-2007 MOON-2 with position detector
- 2008 (Proposal)
MOON-1 Proto type
½ scale of MOON(1m × 1m)

Inside the ELEGANT V
Pb-Cu NaI shields since April 2005.

6-layers of PL 53×53×1cm³ Mo-Foil 160g @20mg/cm²×2

100Mo, 142 g
Plastic scintillator
Energy Resolution

$\sigma = 2.9 \pm 0.1 \% \ (6.8 \% \text{ in FWHM})$ at $Q=3.034$ MeV is just good for IH mass.

Compton-e in PL and Compton-$\gamma$ in NaI

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Compton-e in PL and Compton-$\gamma$ in NaI
SuperNEMO

• Tracking calorimeter. Source ≠ Detector
• ~100 kg of thin (50 mg/cm²) enriched Se or Nd foils
• Calorimetry through plastic scintillator or scintillating bar, σ≈2% resolution
• Tracking through Geiger cells. Single/double track ID

Material supplied by
Dominique Lalanne
NEMO 3 (Phase I)

100Mo
7.369 kg.y
219,000 ββ events
S/B = 40

(a) $E_{2e}$ (MeV)

(c) $E_e$ (MeV)

(b) $\cos(\theta)$

Number of events/0.05 MeV

Number of entries/0.03 MeV

NEMO 3 (Phase I)

100Mo
7.369 kg.y
219,000 ββ events
S/B = 40
SuperNEMO collaboration

NEMO collaboration + new labs ~ 60 physicists, 11 countries, 27 laboratories

- USA
  - MHC
  - INL (U. Texas)

- Marocco
  - Fes U.

- UK
  - UC London
  - U Manchester
  - IC London

- Finland
  - U. Jyvaskula

- France
  - CEN Bordeaux
  - IReS Strasbourg
  - LAL ORSAY
  - LPC Caen
  - LSCE Gif/Yvette

- Russia
  - JINR Dubna
  - INR Moscow
  - ITEP Moscow
  - Kurchatov Institute

- Ukraine
  - INR Kiev
  - ISMA Kharkov

- Slovakia
  - U. Bratislava

- Czech Republic
  - Charles U. Prague
  - CTU Prague

- Japan
  - U. Saga
  - U Osaka

- Spain
  - U. Valencia
  - U. Zaragoza
  - U. Autonoma Barcelona

- Marocco
  - Fes U.

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  - INR Kiev
  - ISMA Kharkov

- Slovakia
  - U. Bratislava

- Czech Republic
  - Charles U. Prague
  - CTU Prague

- Japan
  - U. Saga
  - U Osaka

- USA
  - MHC
  - INL (U. Texas)
SuperNEMO detector: possible design

For each module:
- Calorimeter: 300 to 1000 PMT’s (depending on the final design)
- Resolution (FWHM) at 3MeV = 4%
- Tracking: drift chamber (3000 cells in Geiger mode)
- Magnetic field: 25 gauss
- Source foil: 5 kg of enriched $^{150}$Nd or $^{82}$Se
- Water shield: 2kT of water for 20 modules

$\varepsilon(\beta\beta 0v) \sim 30\%$
SuperNEMO $\beta\beta$ source: $^{82}\text{Se}$, $^{150}\text{Nd}$

**Goal:**

$T_{1/2} > 10^{26}$ y  
$< m_\nu > \leq 50$ meV

**$^{82}\text{Se}$**

$Q_{\beta\beta} = 2.995$ MeV

Phase space factor $G_{0\nu} = 1.08 \times 10^{-25}$ y$^{-1}$eV$^{-2}$

Radiopurity requirements for the $\beta\beta$ source:

\[
\begin{align*}
2^{14}\text{Bi} & < 10 \mu\text{Bq/kg} \\
2^{08}\text{Tl} & < 2 \mu\text{Bq/kg} \\
\text{Radon} & < 2 \mu\text{Bq/m}^3
\end{align*}
\]

$T_{2\nu} = 9 \times 10^{19}$ y  
Expected background from $2\beta2\nu = 1.4$ evt/500kg.y in 200 keV  
(200 keV energy window at $Q_{\beta\beta}$)

Enrichment by ultracentrifugation

**$^{150}\text{Nd}$**

$Q_{\beta\beta} = 3.367$ MeV

Phase space factor $G_{0\nu} = 8.00 \times 10^{-25}$ y$^{-1}$eV$^{-2}$

Radiopurity requirements for the $\beta\beta$ source:

$2^{08}\text{Tl} < 2 \mu\text{Bq/kg}$

$T_{2\nu} = 9 \times 10^{18}$ y  
Expected background from $2\beta2\nu = 2.2$ evt/500kg.y in 200 keV  
(200 keV energy window at $Q_{\beta\beta}$)

Enrichment by laser

The best choice for phase space and background

Neutrino 2006
EXO
Enriched Xenon Observatory for double beta decay

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Physics Dept Stanford University, Stanford CA
Why $^{136}\text{Xe}$?

- Reasonable Q-value of $2457.8 \pm 0.4$ keV based on recent high precision mass measurement at FSU. M. Redshaw, J. McDaniel, E. Wingfield and E. G. Myers, to be submitted to Phys. Rev.
- Active detection medium in both liquid and gaseous phase. Suited for charge collection plus high yield UV scintillator ($@ 3 \text{kV/cm} \sim 25 \text{ph/keV,} \sim 50 \text{e/keV, anti-correlated}$).
- Isotope $^{136}\text{Xe}$ has reasonable natural abundance 8.9%.
- Noble gas, isotopic enrichment by ultra centrifugation cost effective. No chemistry needed.
- Xenon can be re-purified during operation and moved to different detector.

Ionization potentials:
- Xe: 12.130 eV
- Ba$^+$: 5.212 eV
- Ba$^{++}$: 10.004 eV

$\rightarrow \beta\beta$–decay product atom remains charged $\rightarrow$ opens possibility of Ba removal and final state tagging through Ba single ion detection

$^1$ XENON Collaboration data
EXO Road Map

• Goal: build 1 to 10 ton high resolution tracking TPC using enriched $^{136}\text{Xe}$. Equip with Ba-final state tagging. → This should result in extremely small if not zero random background. Envisaged sensitivity 10 meV, covers mass range allowed for inverted hierarchy.

  ▪ Active R&D program under way. Explores the technical feasibility in phased approach.

  ▪ Detect decay and vertex in TPC using liquid Xenon

  ▪ Extract Ba ion using a charged probe. Transfer into ion trap, use laser pumping to identify single ion.

  ▪ Research on a high pressure gas TPC and in situ detection of Ba in the Xenon gas is being pursued too.
EXO Technical Preparation

Build and operate a smaller scale TPC to demonstrate that required energy resolution and background can be achieved. Demonstrate feasibility of large scale enrichment of $^{136}$Xe.

We are building detector using 200 kg enriched Xe (at hand), to be installed at WIPP, New Mexico 2006/2007. Will demonstrate background and energy resolution.

Ba extraction, transfer and single ion detection being developed in the lab in parallel.

After successful completion of these parallel research thrusts preparation of full proposal. In this plan proof of principle does not require the funding of a very costly large experiment up front.
The roadmap to the background free discovery of Majorana neutrinos and the neutrino mass scale

Gain practice with Ba trapping and spectroscopy in Xe and other gases

Gain practice with Ba grabbing and release

Build a fully functional ion grab, transfer, trap, spectroscopy cell

Design & build a large size, low background prototype LXe $0\nu\beta\beta$ detector

Measure $2\nu\beta\beta$ in $^{136}$Xe, gain operational experience, reach the best $0\nu\beta\beta$ sensitivity

Design and build a large, ton scale experiment with Ba tagging

Learn about physics and economics of Xe enrichment on a grand scale

Enrich a large amount of Xe (200 kg)

Improve the energy resolution in LXe
EXO-200

Scientific goals:

1) Measurement of yet unobserved $\beta \beta_{2\nu}$ decay of $^{136}\text{Xe}$. Task: $T_{1/2} > 10^{22}$ y, \(~67 \text{ dcs / (d 100 kg)}\). Important background for EXO.

2) Test of the Heidelberg evidence for $\beta \beta_{0\nu}$ decay.

Expectation for $^{136}\text{Xe}$ [Ge $\pm 3\sigma$ range (0.7-4.2)\cdot10^{25}$ y]:

- $T_{1/2} = (0.58–3.5)\cdot10^{25}$ y [Rodin et al. PRC68 (03) RQRPA] 7-43 dcs / (y 100 kg)
- = (0.66–4.0)\cdot10^{25}$ y [Staudt et al. EPL13 (90) QRPA]
- = (0.48–2.9)\cdot10^{25}$ y [Caurier et al. NPA654 (99) SM]

Approach:

Achieve good resolution by utilizing both ionization and scintillation and the fact that both are anti-correlated. Resolution (extrapolated from 570 keV to 2460 keV) achieved in the lab: $1.6\% @ Q_{\beta \beta}$.

Build tracking liquid Xe TPC with 1 cm spatial resolution. Allows to discriminate gamma background from electron signal. Background reduction by MC: depending on proximity and type reduction factor 5-50. Initially no Ba tagging.

Please see poster #14 by Jesse Wodin and Andrea Pocar
Ionization alone:

$$\sigma(E)/E = 3.8\% @ 570 \text{ keV}$$
or

$$\beta \text{ or } Q$$

Ionization & Scintillation:

$$\sigma(E)/E = 3.0\% @ 570 \text{ keV}$$
or

$$\beta \text{ or } Q$$

(a factor of 2 better than the Gotthard TPC)

E. Conti et al. Phys. Rev. B (68) 054201

EXO-200 will collect 3-4 times as much scintillation as ionization further improvement possible

Drift Field [kV/cm]

<table>
<thead>
<tr>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>10</td>
<td>12</td>
<td>14</td>
<td></td>
</tr>
</tbody>
</table>

Ionization Signal

Correlated Signal

Compilation of Xe resolution results

EXO ioniz + scint
EXO ioniz only

Energy resolution improvement in LXe
Massive effort on material radioactivity qualification

- NAA\(^a\)
- Low background $\gamma$-spectroscopy\(^b\)
- $\alpha$-counting\(^c\)
- Radon counting\(^d\)
- GD-MS and ICP-MS\(^e\)

Th/U Sensitivity
Teflon (TPC): <0.3 ppt or 1 and 4 $\mu$Bq/kg
Cu (TPC): <0.8 ppt

Online database for collaborators at present includes > 230 entries

MC simulation of backgrounds
Alabama & Stanford / SLAC

\(^a\) Alabama using MIT reactor
\(^b\) Neuchatel, Alabama
\(^c\) Alabama, SLAC, Carleton
\(^d\) Laurentian
\(^e\) Canadian Inst. Standards
25 cm Pb

5 cm Cu cryostat

50 cm cryogenic fluid HFE-7000

Thin walled Cu TPC

EXO-200
What’s inside the vessel (besides 200 kg enriched Xe)?

Mechanical supports and cable/Xe conduits

- 2x259 large area (1.6cm active diameter) unmounted APDs
- 228.6mm
- 186.2mm
- 170.8mm
- Inductive and charge collecting wire planes
- Cathode grid
EXO-200 installation at HEPL (Stanford campus)

- 7 ft thick concrete roof
- EXO-200 clearooms
- Pre-assembly soft clean room
- Lead cradle
- HFE storage dewar
EXO-200 schedule

- May, 2006: Pb cradle installation complete
- Jun, 2006: Cryostat installed
- Jul, 2006: First full cooldown
- Oct, 2006: End tests at Stanford
- Nov, 2006: Dismounting complete
- Nov, 2006: Lower first module at WIPP
- Dec, 2006: Lower last load (Pb arches) at WIPP
Assumptions:
1) 200 kg of Xe enriched to 80% in 136
2) $\sigma(E)/E = 1.4\%$ obtained in EXO R&D, Conti et al Phys Rev B 68 (2003) 054201
3) Low but finite radioactive background:
   20 events/year in the $\pm 2\sigma$ interval centered around the 2.46 MeV endpoint
4) Negligible background from $2\nu\beta\beta$ ($T_{1/2} > 1 \cdot 10^{22}$yr R.Bernabei et al. measurement)

### EXO-200 Majorana mass sensitivity

<table>
<thead>
<tr>
<th>Case</th>
<th>Mass (ton)</th>
<th>Eff. (%)</th>
<th>Run Time (yr)</th>
<th>$\sigma_E/E @ 2.5\text{MeV}$ (%)</th>
<th>Radioactive Background (events)</th>
<th>$T_{1/2}^{0\nu}$ (yr, 90%CL)</th>
<th>Majorana mass (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXO-200</td>
<td>0.2</td>
<td>70</td>
<td>2</td>
<td>1.6*</td>
<td>40</td>
<td>$6.4 \times 10^{25}$</td>
<td>0.27†</td>
</tr>
</tbody>
</table>

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**What if the Heidelberg signal is due to $\beta\beta 0\nu$–decay?**

Central value $T_{1/2}^{0\nu} (\text{Ge}) = 1.2^{+3}_{-0.5} \cdot 10^{25}$, ($\pm 3\sigma$) (PL B 586 (04))

In 200 kg EXO, 2 yr:

- Worst case (RQRPA, upper limit) 19 events on top of 40 events bkgd $\rightarrow 2.6 \sigma$
- Best case (NSM, lower limit) 159 events on top of 40 bkgd $\rightarrow 11.2 \sigma$
Barium Grabber

Three techniques being tested in parallel at Stanford:

**Cryo tip:** - thin layer of Xe-ice formed on surface of a metal
  - Ba ion is electrostatically attracted to the ice surface
  - ice is thawed at the entrance of the trap and Ba ion is released

  *Challenge: control the ice thickness to ~100 atomic layers*
  → Close to a solution

**FE tip:** - use very sharp STM tip to grab ion, Ba ion lands near the very tip
  - strong positive bias field emits the ion in the trap

  *Challenge: maintain tips sharp in LXe*
  → Field emission microscope being commissioned, to be installed soon

**RIS tip:** - tip is a ~200 μm fiber with semitransparent metallization at end
  - Ba ion is attracted to metallization and neutralized
  - A desorption laser pulse evaporates the Ba in the trap
  - A second pulse (2 specific wavelengths) resonantly ionizes the Ba when it is still ~100 μm from the fiber tip

  *Challenge: The lasers are expensive*
  → Each step demonstrated and known to work with high efficiency

Typical radius ~10 nm
Grabber tip transfer system being built at the Univ of Neuchatel. To be installed on the Stanford linear trap in 2006.
Ba single Ion Detection

Linear Paul (RFQ) Traps

- Radial confinement from AC potential across rods.
- Axial confinement from DC potentials across rod segments.

Please see poster #20 by Matt Green and Bjorn Flatt
High loading efficiency for incoming ions observed.

Ions that loaded at one end will travel to the other.

Ions can be manipulated by changing the DC potential configuration.

Please see poster #20 by Matt Green and Bjorn Flatt
Stanford Linear Trap

6/14/2006
Ion signal as a function of time as ions are loaded and unloaded from the linear trap. The quantized structure demonstrates our ability to detect single atoms in a buffer gas with high S/N.

Please see poster #20 by Matt Green and Bjorn Flatt
Histogram of ion fluorescence signal. With a 5 sec integration the signal from 1 ion is distinguishable from background at the 8.7σ level.

Please see poster #20 by Matt Green and Bjorn Flatt
EXO neutrino effective mass sensitivity

Assumptions:
1) 80% enrichment in 136
2) Intrinsic low background + Ba tagging eliminate all radioactive background
3) Energy res only used to separate the 0ν from 2ν modes: Select 0ν events in a ±2σ interval centered around the 2.46 MeV endpoint
4) Use for 2νββ T_{1/2} > 1·10^{22} yr (Bernabei et al. measurement)

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<th>Mass (ton)</th>
<th>Eff. (%)</th>
<th>Run Time (yr)</th>
<th>E/E@2.5MeV (%)</th>
<th>2νββ Background (events)</th>
<th>T_{1/2}^{0ν} (yr, 90%CL)</th>
<th>Majorana mass (meV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conservative</td>
<td>1</td>
<td>70</td>
<td>5</td>
<td>1.6*</td>
<td>0.5 (use 1)</td>
<td>2×10^{27}</td>
<td>50</td>
</tr>
<tr>
<td>Aggressive</td>
<td>10</td>
<td>70</td>
<td>10</td>
<td>1†</td>
<td>0.7 (use 1)</td>
<td>4.1×10^{28}</td>
<td>11</td>
</tr>
</tbody>
</table>

* s(E)/E = 1.4% obtained in EXO R&D, Conti et al Phys Rev B 68 (2003) 054201
† s(E)/E = 1.0% considered as an aggressive but realistic guess with large light collection area
# Courier et al. Nucl Phys A 654 (1999) 973c
Conclusion

The next generation $\beta\beta$-experiments hope to observe this decay.

Unambiguous evidence will be important for making a clear case that Neutrinos are Majorana particles.

To achieve this we will need experiments using different methods and different nuclides. In case of success this would give some handle on the matrix element calculations and their spread.

This goal requires both high resolution calorimetric and tracking detectors.

Several large tracking detectors are being prepared. We hope that they will help provide this unambiguous evidence utilizing their high diagnostic power.

Stay tuned! First data will come soon.