Flat cables for EXO-200

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outline

- **EXO-200 experiment**
  - the detector
  - low background requirements
  - cable design choice

- **flat cables for EXO-200**
  - material selection
  - details of cable design

- **flat cable fabrication and installation**
  - cable fabrication and handling
  - cable installation

- **outlook**
EXO-200

EXO-200 is a large double beta decay experiment employing 200 kg of liquid, enriched xenon (80% $^{136}$Xe) to look for neutrinoless double beta decay ($0\nu\beta\beta$) of $^{136}$Xe

how: double TPC detector with scintillation light readout
Double beta decay

Extremely rare decay of certain nuclei, where 2 neutrons decay into 2 protons: 

\[(A, Z) \rightarrow (A, Z-2) + 2e^- (+ 2\nu_e)\]

detectable in even-even nuclei when single $\beta$-decay is energetically forbidden

Double beta decay has not yet been observed for $^{136}$Xe (lifetime limit at $\sim 10^{22}$ y)
Neutrinoless double beta decay

Double $\beta$-decay without the emission of neutrinos (only 2 electrons)

0$\nu$$\beta$$\beta$ would appear, in the 2-electron energy spectrum as a peak at the endpoint energy of the decay.

Effective Majorana mass term

not allowed in the standard model (violates lepton conservation by 2)

possible only if neutrinos are their own antiparticles

$0\nu\beta\beta$ observable

- **event rate:** directly measured quantity
- **calculable phase space factor** (dependent on $Q$, $Z$)

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

- **nuclear matrix element (∼1-4)**
  - (calculated within particular nuclear models)

- **Majorana neutrino mass term**
  - (can be zero):

\[
\langle m_{\beta\beta} \rangle^2 = \left| \sum_i^N |U_{ei}|^2 e^{i\alpha_i} m_i \right|^2 \quad (\text{all } m_i \geq 0)
\]

In kinematic searches of neutrino mass in $\beta$-decay:

\[
\langle m_{\beta} \rangle^2 = \Sigma_i |U_{ei}|^2 m_i^2 > 0
\]
$0\nu\beta\beta$ effective neutrino mass

current $0\nu\beta\beta$ sensitivity

EXO-200 expected $0\nu\beta\beta$ sensitivity

$\Delta m^2_{23} < 0$

$\Delta m^2_{23} > 0$

99% CL (1 dof)

[Strumia and Vissani, hep-ph/0606054]
EXO-200 event rates

- current experimental limit on $0\nu\beta\beta$ of $^{136}$Xe is $10^{24}$ years

- $10^{25}$ years lifetime $\Rightarrow$ in 160 kg, 71 events/year (0.2 events/day)

- double beta decay events are essentially point events in LXe

- $\beta$ and $\gamma$ decays inside the detector are (the main) background

In particular:
- in LXe, virtually impossible to distinguish between single and double beta events (both point-like, within the $\sim$1 cm spatial resolution)
- $\gamma$ single site Compton scattering and total absorption events are also point-like

Some of these events will fall in the double beta energy bin!
**EXO-200 background suppression**

- locate the experiment underground (WIPP salt mine, New Mexico)

- passive, graded shielding around the detector (Pb, Cu, thermal fluid)

- selection of clean materials for TPC, thermal bath, cryostat, Pb shield

- maximize active volume in order to maximize event rate (finite supply of enriched xenon)

- selection of events in the data with various cuts (energy resolution, fiducial volume, double site events, radon decays, ...)

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muon flux at WIPP (~ 1600 m.w.e.):

$4.77 \times 10^{-3} \text{ m}^{-2} \text{ s}^{-1}$

$(3.10 \times 10^{-3} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1}, \sim 15 \text{ m}^{-2} \text{ h}^{-1})$

[Esch et al., NIM A 538 (2005) 516]
At WIPP (October 2007)
The EXO-200 detector

- Refrigeration and HFE feedthroughs
- Hermetic lead enclosure (25 cm, low activity Pb)
- Double, vacuum-insulated cryostat (low-background copper)
- Xe and TPC copper chamber
- Class 100 clean room

50 cm of ultra pure cryofluid, providing large thermal bath for uniform temperature (3M HFE-7000, hydrofluoroether C$_3$F$_7$OCH$_3$)
EXO-200 installation underground at WIPP

system ready for re-commissioning operations
EXO-200 background rates

Example and reference for EXO-200 background needs:
- the double cryostat is ~ 7 tons of copper
- $^{232}$Th and $^{238}$U intrinsic contamination is measured to be at most a few ppt (by weight)
- 1 ppt ($10^{-12}$) corresponds to a total $^{238}$U rate of $2 \times 10^6$ decays/y (compared to 0νββ 71 decays/y for $10^{25}$ years lifetime)

Naturally, not all U decays will generate single site events of the same energy inside the LXe ....... this depends on the distance from the active region.

If there’s secular equilibrium, the rate is multiplied by the number of daughters; $^{214}$Bi has a 2447 keV γ ray, 1.57% branching ratio ($^{136}$Xe double beta Q-value is 2458 keV)

Cables are lightweight but very close to the center of the detector
the EXO-200 detector

HV (cathode)

TPC

cable conduits

electronics boxes

cables

Xe line (out)

Xe line (in)
flex cables on back of APD plane (copper on kapton, no glue)

teflon light reflectors

field shaping rings (copper)

x-y crossed wires, 60°

LAAPD plane (copper) and x-y wires (photo-etched phosphor bronze)

acrylic supports

Central HV plane (photo-etched phosphor bronze)

~40 cm
EXO-200 TPC and xenon vessel

- Xe vessel and detector made as light as possible to reduce radioactivity
- great effort in maximizing the fiducial volume

the cantilevered design was forced on us by the lack of vertical clearance at WIPP (top rather than side access would have been simpler)
the long (~8 feet) EXO-200 cables are routed through the copper legs and the cryostat vacuum space to the front-end electronics, too “hot” to be placed close to the detector.
**EXO-200 TPC**

- **APD plane** (copper)
- **cathode**
- **HV cable**
- **induction and collection wires**
- **HV connection**
- **copper TIG weld** (ceriated rod)
- **flex cable connections made here**
- **flex cable**
- **teflon insulator**
- **central APD substituted by teflon diffuser with optical fiber**
- **acrylic supports**
- **APD “spider”**
- **APD plane (copper)**
- **field shaping rings and resistor chain**
- **HV connection**

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EXO-200 cable design

a few possibilities were considered for the EXO-200 signal cables:

- individual, twisted pairs of insulated wires (e.g. kapton-coated)
- flat, flexible cables

the choice fell on flat cables for the following reasons:

- allow access and connections in the very limited space behind wires and APD plane (dictated by the need to maximize the active xenon)
- minimize mass (higher chance of low radioactivity)
- still allow for complicated routing into the legs
EXO-200 (transverse section)

- HV connection
- Flat cables routed through legs
- X,y wires and LAAPD plane
EXO-200 cathode, grid and anode

- Cu support ring
- Acrylic wire supports
- Pockets for flat cables
- Cathode (2 "bow ties")
- X-y crossed wires, 60°
EXO-200 copper APD plane

LAAPD plate (copper)

load LAAPDs in sockets
EXO-200 LAAPD connections ("pizza pies")

flat cable
"pizza pies"
(copper on kapton)
EXO-200 LAAPD contacts ("spider" springs)

LAAPD "spiders" act as holders and electrical contacts (photo-etched phosphor bronze, acrylic spacers, silicon bronze screws)
EXO-200 acrylic connectors

“Vee” and “Tee” cable supports (acrylic)
cables folded and connected with silicon-bronze screws (acrylic backing)
EXO-200 flat signal cables

flat cables routed through the legs

connection performed with silicon-bronze screws and spring-loaded phosphor bronze washers on acrylic backings
EXO-200 wire cables
EXO-200 backplane cable connections

- APD ‘spiders’
- Pizza ‘slices’ pigtails
- ‘dummy’ APDs
prototype detector
Materials qualification database

- Neutron Activation Analysis (NAA) - Alabama (MIT reactor)
- ICP-MS and GD-MS - INMS (Ottawa), commercial outfits
- Radon emanation - Laurentian (Sudbury)
- Gamma counting - Neuchâtel, Alabama
- Alpha counting - Alabama, Carleton, SLAC, Stanford
- Monte Carlo - Alabama, SLAC, Stanford, Maryland

Goals:
  a) select adequate materials for EXO-200 construction
  b) qualify adequate cleaning procedures for components prior to installation
  c) feed data into full simulation of EXO-200 background

[EXO collaboration; D. Leonard et al., NIMA 591, 490 (2008)]

> 330 entries
substrate selection

substrates procured from two companies, Nippon Steel and DuPont

_Nippon Steel Espanex:_
- glue-less 18 µm copper on 25 µm kapton (2 rolls)
- glue-less 15 µm copper on 40 µm kapton (1 roll)
- glue-less 18 µm copper on 50 µm liquid crystal (1 roll)

_DuPont Pyralux:_
- glue-less 18 µm copper on 25 µm kapton (1 roll)

material of choice:
Nippon Steel Espanex MC18-25-00CEM, lot G5L03-23L2
### raw substrate qualification

<table>
<thead>
<tr>
<th>#</th>
<th>Material</th>
<th>Method</th>
<th>K conc. $(10^{-9} \text{ g/g})$</th>
<th>Th conc. $(10^{-12} \text{ g/g})$</th>
<th>U conc. $(10^{-12} \text{ g/g})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td><em>Photo-etching: Cu on polyimide substrate</em></td>
<td>ICP-MS</td>
<td>–</td>
<td>$&lt; 3$ $(&lt; 0.05 \text{ pg/cm}^2)$</td>
<td>$19 \pm 2$ $(0.30 \pm 0.03 \text{ pg/cm}^2)$</td>
</tr>
<tr>
<td></td>
<td>Cu coating Nippon Steel Chemical Co., Espanex flat cable MC18-50-00CEM,</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Polyimide thickness: 50 µm, Cu thickness: 18 µm</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>102</td>
<td>Polyimide substrate Nippon Steel Chemical Co., Espanex flat cable MC18-25-00 CEM, lot 65605-11R1. Polyimide thickness: 25µm, Cu thickness: 18 µm</td>
<td>NAA</td>
<td>$&lt; 299$</td>
<td>$&lt; 1600$</td>
<td>$&lt; 1500$</td>
</tr>
<tr>
<td></td>
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<td></td>
</tr>
<tr>
<td>103</td>
<td>Cu coating Nippon Steel Chemical Co., Espanex flat cable MC18-25-00 CEM, lot 65605-11R1. Polyimide thickness: 25µm, Cu thickness: 18 µm</td>
<td>ICP-MS</td>
<td>–</td>
<td>$69 \pm 3$ $(1.1 \pm 0.05 \text{ pg/cm}^2)$</td>
<td>$100 \pm 3$ $(1.6 \pm 0.04 \text{ pg/cm}^2)$</td>
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<tr>
<td>104</td>
<td>Polyimide substrate, Nippon Steel Chemical Co., Espanex flat cable, MC15-40-00 VEG. Polyimide thickness: 40µm, Cu thickness: 15µm</td>
<td>NAA</td>
<td>$107 \pm 12$</td>
<td>$&lt; 450$</td>
<td>$&lt; 900$</td>
</tr>
<tr>
<td>105</td>
<td>Cu coating, Nippon Steel Chemical Co., Espanex flat cable MC15-40-00 VEG</td>
<td>ICP-MS</td>
<td>–</td>
<td>$135 \pm 6$ $(1.8 \pm 0.07 \text{ pg/cm}^2)$</td>
<td>$67 \pm 5$ $(0.9 \pm 0.06 \text{ pg/cm}^2)$</td>
</tr>
<tr>
<td>106</td>
<td>Nippon Steel Chemical Co., Espanex flat cable MC15-40-000VEG. $^{60}$Co: $&lt; 0.18 \text{ mBq/kg}$</td>
<td>Ge</td>
<td>$880 \pm 120$</td>
<td>$&lt; 250$</td>
<td>$121 \pm 32$</td>
</tr>
<tr>
<td>107</td>
<td>Nippon Steel Chemical Co., Espanex flat cable, and MC18-25-00CEM, lot G5L03-23L2. $^{60}$Co: $&lt; 0.6 \text{ mBq/kg}$, $^{137}$Cs: $&lt; 1.3 \text{ mBq/kg}$</td>
<td>Ge</td>
<td>$&lt; 146$</td>
<td>$&lt; 260$</td>
<td>$&lt; 46$</td>
</tr>
<tr>
<td>108</td>
<td>Polyimide substrate, Nippon Steel Chemical Co., Espanex flat cable, G5L03-23L2. $^{60}$Co: $&lt; 0.6 \text{ mBq/kg}$</td>
<td>ICP-MS</td>
<td>$390 \pm 110$ $(1.4 \pm 0.4 \text{ ng/cm}^2)$</td>
<td>$50 \pm 17$ $(0.54 \pm 0.06 \text{ pg/cm}^2)$</td>
<td>$450 \pm 170$ $(1.6 \pm 0.6 \text{ pg/cm}^2)$</td>
</tr>
<tr>
<td>109</td>
<td>Cu coating, Nippon Steel Chemical Co., Espanex flat cable, G5L03-23L2. $^{60}$Co: $&lt; 0.6 \text{ mBq/kg}$</td>
<td>ICP-MS</td>
<td>$94 \pm 19$ $(1.5 \pm 0.3 \text{ ng/cm}^2)$</td>
<td>$34 \pm 6$ $(0.55 \pm 0.09 \text{ pg/cm}^2)$</td>
<td>$41 \pm 6$ $(0.66 \pm 0.1 \text{ pg/cm}^2)$</td>
</tr>
<tr>
<td>110</td>
<td>Nippon Steel, Espanex flat cable, MC15-40-00 VEG. Etched by Basic Electronics. $^{60}$Co: $&lt; 0.56 \text{ mBq/kg}$, $^{137}$Cs: $&lt; 0.63 \text{ mBq/kg}$</td>
<td>Ge</td>
<td>$&lt; 160$</td>
<td>$&lt; 40$</td>
<td>$&lt; 97$</td>
</tr>
<tr>
<td>111</td>
<td>Polyimide substrate Nippon Steel Espanex flat cable MC15-40-000VEG. $^{60}$Co: $&lt; 0.6 \text{ mBq/kg}$</td>
<td>ICP-MS</td>
<td>$229 \pm 71$ $(1.3 \pm 0.4 \text{ ng/cm}^2)$</td>
<td>$317 \pm 4$ $(1.8 \pm 0.02 \text{ pg/cm}^2)$</td>
<td>$3880 \pm 120$ $(22 \pm 0.7 \text{ pg/cm}^2)$</td>
</tr>
<tr>
<td>112</td>
<td>Cu coating Nippon Steel Espanex flat cable, MC15-40-000VEG. Etched by Basic Electronics</td>
<td>ICP-MS</td>
<td>$105 \pm 23$ $(1.4 \pm 0.3 \text{ ng/cm}^2)$</td>
<td>$45 \pm 4$ $(0.6 \pm 0.05 \text{ pg/cm}^2)$</td>
<td>$1720 \pm 23$ $(23 \pm 0.3 \text{ pg/cm}^2)$</td>
</tr>
</tbody>
</table>

[EXO collaboration; D. Leonard et al., NIMA 591, 490 (2008)]
flat cable production process

production proceeds as follows:

1. generate CAD drawing of desired trace pattern and contour (shape)
2. produce mask film (artwork) with desired pattern
3. drill holes (pattern and alignment) on raw sheet
4. apply photoresist on raw sheet
5. align artwork on top (Cu side) of raw sheet
6. expose photoresist
7. develop photoresist
8. etch (exposed parts harden and are NOT etched away, i.e negative artwork)
9. strip remaining photoresist off
10. 2 DI water rinses
11. isopropanol rinse
12. apply coverlayer (long cables only)
13. cut by hand
14. plasma etch (oxygen, CF₄ - small cables only)
15. place in double ziplok bag
etchant options

<table>
<thead>
<tr>
<th>Etchant</th>
<th>Etching temperature (°C)</th>
<th>Etch rate (μm/min)</th>
<th>Undercut</th>
<th>Dissolved copper capacity</th>
<th>Regeneration and metal recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cupric chloride (CuCl₂)</td>
<td>50–54</td>
<td>25–50</td>
<td>Low</td>
<td>120–140</td>
<td>Copper recovery and regeneration</td>
</tr>
<tr>
<td>Ferric chloride (FeCl₃)</td>
<td>43–49</td>
<td>25–50</td>
<td>Low</td>
<td>40–60</td>
<td>Regeneration</td>
</tr>
<tr>
<td>Alkaline etchants</td>
<td>43–55</td>
<td>30–60</td>
<td>Lower</td>
<td>140–170</td>
<td>Copper recovery and regeneration</td>
</tr>
<tr>
<td>Hydrogen peroxide/sulphuric acid (H₂O₂ + H₂SO₄)</td>
<td>43–55</td>
<td>Variable</td>
<td>Low</td>
<td>50–90</td>
<td>Copper recovery</td>
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<tr>
<td>Ammonium persulphate [(NH₄)₂ S₂ O₈]</td>
<td>38–55</td>
<td>7</td>
<td>High</td>
<td>40–55</td>
<td>Copper recovery</td>
</tr>
<tr>
<td>Chromic-sulphuric acid [CrO₃ + H₂SO₄]</td>
<td>26–33</td>
<td>Variable</td>
<td>Lower</td>
<td>50–60</td>
<td>Not available</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Etchant</th>
<th>Corrosiveness</th>
<th>Neutralisation and disposal problems</th>
<th>Toxicity</th>
<th>Operational cost*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cupric chloride (CuCl₂)</td>
<td>High</td>
<td>Low</td>
<td>Medium</td>
<td>Low</td>
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<tr>
<td>Ferric chloride (FeCl₃)</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Alkaline etchants</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
</tr>
</tbody>
</table>

* Include disposal cost.

[O. Cakir, J. Mat. Process. Technol. 175, 63 (2006)]

etching reaction: \( \text{CuCl}_2 + \text{Cu} \rightarrow 2\text{CuCl} \)  
(cupric) \hspace{1cm} (cuprous)

regenerating reaction: \( \text{NaClO}_3 + 6\text{HCl} \rightarrow 6\text{Cl}^- + \text{NaCl} + 3\text{H}_2\text{O} \)

\( \text{CuCl} + \text{Cl}^- ! \rightarrow !\text{CuCl}_2 \)
qualification of etching process

production bid included a test production for us to qualify radiologically

we worked with two firms:
  - Basic Electronics
  - Flexible Circuit Technologies (FlexCTech)

etching process was different: one used ferric chloride (FeCl$_3$), the other cupric chloride (CuCl$_2$)

we tested samples from both companies, and both etching process added surface contamination:
  - supply our own chemicals (successfully tested, but too expensive)
  - require DI water and other clean practices
  - clean at Stanford (tested and developed procedure)
EXO-200 flat signal cable

flat cable production performed with Flexible Circuit Technologies, at A-Flex and Pacific Image facilities in Southern California

Cutting panels, drilling
Wet chemistry (etching)
Plasma cleaning (small parts)
Cover layer, final cutting

Two people for 4 weeks on site!
- handling with gloves
- clean surfaces, tools (alcohol)
- new, clean containers
- cover parts
- use DI water
- rinse with high grade alcohol
- plasma etch small parts
- bag parts
applying photoresist

exposing long cables

developer
touch-up

etch

etched parts

photoresist stripper
the etching process
wipe down, roll up, bag

hand cut!
flat cable installation

once back at Stanford:

1. clean each cable (small and long) as follows
   - acetone bath and delicate wipe
   - ethanol bath and delicate wipe
   - several HCl (6% and 3%) baths, with DI water rinse in between and after, checking pH of rinse water
   - final ethanol bath

2. install small cables

3. epoxy pot long cables in cryostat flanges

4. install long cables in legs, TPC in chamber and connect
EXO-200 small wire cables installed on both halves of the TPC
EXO-200 induction (y) wire fan-out
EXO-200 flat signal cable assembly

cleaning and patching
EXO-200 flat signal cable assembly

rolling

rolling

gluing
EXO-200 flat signal cable feedthroughs

After rolling, the flat cables are sealed in potted with a special cryogenic epoxy feedthrough flanges welded on the inner cryostat door.

Cables are first glued to acrylic fixtures, then glued to copper flanges with thin copper lips and controlled epoxy profile.

We succeeded in producing leak-tight feedthroughs and thermally cycling them several times.
EXO-200 flat signal cable feedthroughs
final mounting alignment on the cryostat doors
The End

thanks to:
the EXO collaboration
SLAC