DOUBLE BETA DECAY OF $^{150}$Nd WITH THE NEMO-3 EXPERIMENT

Outline

- Review of double beta decay theory/pheno.
- $^{150}$Nd in the NEMO-3 experiment
- Analysis Technique and preliminary results
- Summary

Summer Blot
IoP 2015 – Joint Particle, Astroparticle and Nuclear meeting
31 March, 2015
Double beta decay (2νββ)

- Nuclear decay which can occur if single beta decay is forbidden
  - *Daughter nuclei must have smaller mass than parent*
  - 35 naturally occurring isotopes capable of 2νββ
- Second order weak process
  - Half-lives \( \sim 10^{18} \) yrs
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What you detect

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ΣEe ≈ Q_{ββ}
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![Diagram showing nuclear decay and energy distribution](chart.png)
Neutrinoless double beta decay ($0\nu\beta\beta$)

- Beyond Standard Model process
- Violates lepton number conservation by 2 units
- Can be mediated in a number of ways: Majorana $\nu$, RHC…
  - If Majorana $\nu$, can provide neutrino mass measurement
- Half-life limits currently $>10^{25}$ yrs

\[ \frac{1}{T_{1/2}^{0\nu}(A,Z)} = \left|M_{0\nu}^{0\nu}(A,Z)\right|^2 \cdot G_{0\nu}^{0\nu}(Q_{\beta\beta},Z) \cdot \left\langle m_{\beta\beta} \right\rangle^2 \]

*Ideal isotope - want large $M_{0\nu}^{0\nu}$, and $G_{0\nu}^{0\nu}$ for shorter $T_{1/2}$*

*Large $Q_{\beta\beta}$ also helps with background suppression*

No missing energy $\rightarrow$ no neutrinos
Neodymium-150

- High $Q_{\beta\beta}$ and $Z$ → largest $G^{0\nu}$
- $M^{0\nu}$: 3.14 – 4.04
  - Large deformations due to high $Z$
- Natural abundance, 5.6%

With the NEMO-3 experiment

sources
- 60 mg/cm² foils
- 10 kg of $\beta\beta$ isotopes

tracker
- 6180 Geiger cells
- Vertex resolution: $\sigma_{x,y} \sim 3$ mm, $\sigma_z \sim 10$ mm

calorimeter
- 1940 optical modules
- Polystyrene scintillators
- $FWHM_{E} \sim 15% / \sqrt{E_{MeV}}$
- $\sigma_{t} \sim 250$ ps

$\gamma_1, 0.407$ MeV
$\gamma_2, 0.334$ MeV

$Q_{\beta\beta} = 3.37$ MeV

$^{150}$Nd $\rightarrow$ $^{150}$Sm

$^{150}$Nd

$^{150}$Sm

MeV
0.740
0.334
0.0
$^{150}$Nd
$^{150}$Sm

$0_{1^+}$
$2_{1^+}$
$0_{gs}^+$
$\gamma_1, 0.407$ MeV
$\gamma_2, 0.334$ MeV

$^{150}$Nd

$^{150}$Sm

NEMO-3 "camembert" (source top view)

36.5 g

S. Blot

IoP 2015
\[ ^{150}\text{Nd} \, 2\nu\beta\beta \text{ decay half-life} \]

- Select 2e\(^{-}\) events for optimal 2\nu\beta\beta/0\nu\beta\beta sensitivity
- Total exposure = 0.19 kg\cdot yr (\text{x2 increase} since [1])
- New 2\nu\beta\beta \, T_{1/2} under approval & compatible with published value:
  \[(9.11^{+0.25}_{-0.22} \, \text{(stat.)} \pm 0.63 \, \text{(syst.)}) \times 10^{18} \, \text{yrs}\]

\[ \Sigma E_{e} \]

\[ S/B = 2.9 \]
Background normalization

- Impurities in the foil can produce 2e events from a number of processes.
- Estimate the number of background events in the 2e channel using control channels which select different decay topologies.

**Diagram:**
- **Signal channel:** Single $\beta$ decay + $\gamma$, then $\gamma$ Compton scatters to produce second $e^-$. 
- **Control channel:** Single $\beta$ decay + $\gamma$, no Compton scatter.
Background normalization: $1e1\gamma$

- Many isotopes decay via single $\beta + \gamma$ emission
- Select events with $\beta + 1\gamma$ to measure background counting rate for each radionuclide
  - More sensitivity to different background contributions in control channels
Background estimation

- Use a total of 6 control channels to estimate background counting rates

- Define 1 signal channel (2e) for $2\nu\beta\beta$ measurement

- Perform a binned log-Likelihood fit on all $n$ channels simultaneously to obtain best estimate of both signal ($s$) and background ($b$) counting rates

$$\ln(L) = \sum_{i,n} \left( -s_{i,n} + \sum_j b_{i,n,j} \right) + d_{i,n} \ln \left( s_{i,n} + \sum_j b_{i,n,j} \right) - \ln(d_{i,n}!)$$

$i$: bins
$n$: channels
d: data
$s$: signal
$b$: bkg
Multivariate power with NEMO

- The ability to use both signal and background channels to estimate activities is a unique feature of NEMO-3
- Provides strong confidence in background model
  - Multiple observables to check data/MC agreement
- Important for $0\nu\beta\beta$ and other rare decay searches with very low statistics
  - Different kinematics help to distinguish between different underlying mechanisms

Multiple observables from 2e channel

- $E_{e\text{Max}}$
- $E_{e\text{Min}}$
- $\cos\theta_{ee}$
0νββ Status

- Using optimal background activities from LL fit for normalization
- No significant excess of data over expected background
- New limits for various underlying 0νββ mechanisms are under review by collaboration

- Limits set with $^{150}$Nd not competitive with current best 0νββ limits due to small exposure (0.19 kg-yr)
  \[ T_{1/2}(0\nu\beta\beta) > \sim 10^{22} \text{ yrs} \]
- Best limits from NEMO-3 come from $^{100}$Mo with 34.7 kg-yr exposure
  \[ T_{1/2}(0\nu\beta\beta) > 0.11 \times 10^{25} \text{ yrs} \]
  \[ m_{\beta\beta} < 0.33-0.87 \text{ eV} \]

Summary

- NEMO-3 investigated 7 isotopes, including 36.5g of $^{150}\text{Nd}$
- Using the full data set (~5 yrs) a new measurement of the $^{150}\text{Nd}$ 2$\nu\beta\beta$ decay $T_{\frac{1}{2}}$ to the ground state of $^{150}\text{Sm}$ – $x2$ more statistical precision
- No significant excess in $0\nu\beta\beta$ ROI observed $\rightarrow$ limits set
- Analysis technique employs a binned log-likelihood fit between signal and background channels
  - Good Data/MC agreement across all channels in multiple observables yields confidence in background model and overall modeling of nuclear decays and detector response
  - Promising for future tracker-calo $0\nu\beta\beta$ experiments like SuperNEMO
- Finalized background model opens doors for new interesting searches possible with $^{150}\text{Nd}$ (excited state decays, $0\nu4\beta$, …)
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Thank you! Questions?
BACKUP SLIDES
Systematic errors

- Systematic uncertainties considered for the $2\nu\beta\beta$ decay half-life to the ground state of $^{150}\text{Sm}$
- Dominated by 2e efficiency
- Large uncertainties on the background model have very little effect on the final half-life thanks to excellent background rejection in 2e$^-$ channel

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Systematic uncertainty (%)</th>
<th>Effect on $2\nu\beta\beta$ half-life (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2\nu\beta\beta$ efficiency</td>
<td>±5.50</td>
<td>±5.50</td>
</tr>
<tr>
<td>Thin foil simulation</td>
<td>±4.00</td>
<td>±4.00</td>
</tr>
<tr>
<td>Energy calibration</td>
<td>±1.20</td>
<td>±0.25</td>
</tr>
<tr>
<td>Enrichment factor</td>
<td>±0.50</td>
<td>±0.50</td>
</tr>
<tr>
<td>External bkgs.</td>
<td>±19.00</td>
<td>+0.20/−0.19</td>
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<tr>
<td>Radon bkgs.</td>
<td>±10.00</td>
<td>±0.02</td>
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<tr>
<td>Internal bkgs.</td>
<td>±33.39</td>
<td>+1.67/−1.68</td>
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<tr>
<td>Neighbouring foils</td>
<td>±25.00/-21.00</td>
<td>±0.24</td>
</tr>
<tr>
<td>Total</td>
<td>-</td>
<td>±7.03</td>
</tr>
</tbody>
</table>
Multivariate power with NEMO

Preliminary

• BiPo $T_{1/2} \sim 164 \, \mu s$

• NEMO-3 stores delayed hits up to $\sim 700 \mu s$

Control radon backgrounds with $\alpha$-tagging

Preliminary

- Data (487)
- $^{214}$Bi SWire In
- $^{214}$Bi SWire Out
- $^{214}$Bi SFoil In
- $^{214}$Bi SFoil Out
- $^{214}$Bi Mylar
- $^{214}$Bi Int
- total MC ($477 \pm 21$)

$\chi^2$/ndf = 47.16/33

$\alpha$ Range (cm)

$\alpha$ time ($\mu s$)

(Data - MC)

average $\alpha$ time delay ($\mu s$)
Multivariate power with NEMO

- Electron energy asymmetry larger for RHC than MM
- Different angular correlation
- Need NEMO-like detector to decipher between $0\nu\beta\beta$ processes