ISS-RAD Fast Neutron Detector (FND)  
ACO On-Orbit Neutron Dose Equivalent and 
Energy Spectrum Analysis Status

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on behalf of the ISS-RAD science team

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Edward Semones  
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0. ISS-RAD Launch and Deployment

- ISS-RAD Arrived on Orbit!
- Launched in December 2015
- Deployed on ISS on 2/1/2016 in US Lab on Lab1O3, pointing forward
1. Introduction: Detection/Selection Mechanism: Boron-loaded Scintillator

- Neutrons deposit energy in plastic scintillator, some captured by $^{10}\text{B}$ atoms:

\[ \text{Incoming neutron} \rightarrow \text{scintillator} \]

Recoil centers

\[ \text{scint. photon} \]

\[ \text{scint. photon} \]

\[ \text{scint. photon} \]

\[ \text{scint. photon} \]

\[ \text{B}^{10} \rightarrow \text{B}^{11} \]

\[ \text{Li}^7 \]

\[ E_\alpha = 1.47 \text{ MeV} \]

\[ E_y = 0.48 \text{ MeV} \]

\[ E_{Li} = 0.84 \text{ MeV} \]

\[ \text{Recoil Pulse: sum of light signals produced during deceleration of neutrons} \]

\[ \text{Capture Pulse: light produced by neutron capture on boron} \]

- Measurements of recoil and capture photon signals and time-to-capture:
1. Introduction: Scintillation Light Creation/Propagation

- Example: End-to-end FND simulation (MCNP-PoliMi and FND signal processing algorithms) for monoenergetic neutron fields at PTB
- Spectral shape driven by number of high energy deposit neutron collisions off hydrogen
- Due to multiple scattering and scintillation light quenching in scintillator, even monoenergetic neutrons create broad distributions in FND recoil spectra.

![Graphs showing FND recoil spectra for different neutron energies: 250 keV, 500 keV, 1.2 MeV, 2.5 MeV, 5 MeV, 8 MeV, and 14.8 MeV.](image-url)
2. Analysis Methods

[Graphics modified from SwRI]
2. Analysis Variants to Extract Dose Equivalent and Neutron Energy Spectrum

- Different analysis methods depending on computational resource availability
- Dose equivalent (H*(10)) calculated with ICRP 74 conversion factors

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Computational Complexity</th>
<th>Output</th>
<th>Analysis Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) On-board (CZ)</td>
<td>Simple</td>
<td>Dose equivalent</td>
<td>- Conversion factors for each recoil amplitude bin; for fast on-board processing</td>
</tr>
<tr>
<td>b) Ground Light (CZ)</td>
<td>Moderate</td>
<td>Dose equivalent</td>
<td>- Background subtraction</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>- Conversion factors for each recoil amplitude bin</td>
</tr>
<tr>
<td>c) Ground Heavy (ML)</td>
<td>Complex</td>
<td>Flux and dose equivalent energy spectra</td>
<td>- Background subtraction</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Regularized unfolding into energy spectrum</td>
</tr>
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</table>

a) and b)

\[ \hat{A} x_{\text{ini}} = b_{\text{ini}}, \]

**Rescaling and regularization:**

\[ (\hat{A} w - \tilde{b})^T (\hat{A} w - \tilde{b}) + \tau \cdot (C w)^T C w = \min \]
Insert: Neutron Efficiencies

- Use exp efficiencies directly from Apr PTB 2015 data from 0.5 to 8 MeV
- For interpolated energies, use inverse square law fit of 0.5-8 MeV data (Cary Z.)
- Values depending on cuts in background subtraction and recoil/capture spectrum
Insert: Background/Chance Coincidence Subtraction

- Poisson time correlation between recoil and capture pulses for B10 capture event allow to subtract backgrounds (exponential process)
- Oversubtraction ensures all backgrounds subtracted; rejected neutron pairs recovered via efficiency correction
- Performed in both offline analyses

**Background fractions for ground test sources:**
* AmBe 40-50%
* Cf 80% (50-60% indirect radiation-only)
3. Ground Verification of Analysis Methods

graphics modified from SwRI
3. Ground Verification- PTB Source Runs

- **AmBe and Cf-254** source runs in **PTB** precision source bunker; corrections for effective depth and FND energy acceptance

- **Dose verifications:**
  * Extract reference dose from PTB normalization for 0.5 to 8 MeV energy range
  * True rate: **0.708** μSv/min AmBe, **0.495** μSv/min Cf (sensitivity to chance coincidences)
  * Online: **0.673** μSv/min AmBe, **1.091** μSv/min Cf
  * Offline light: **0.696** μSv/min AmBe, **0.537** μSv/min Cf

- **Spectral verification** (Offline heavy)
  * Subtraction of PTB room return data to compare to ISO spectra
  * **AmBe**: unfolding results **within 10%** of ISO AmBe in all bins

* **Cf**: **within 26%**: possibly due to rapid decrease of spectrum in energy range (factor 30), vs AmBe and Orbital < 3
- Test unfold of artificial combination sample of 5 monoenergetic sources within 30% on non-empty bins
4. Orbital Raw Data

graphics modified from SwRI
4. Exemplary Raw Orbit Data

- Shown below: 24 hour slice from 7/1/16 with largest SAA pass to date
- Shown are single/raw PMT and pulse-pair-discriminated rates
- Discriminated rate increases by factor 30-40 inside SAA compare to magnetically unshielded areas outside of SAA
4. Exemplary Raw Orbit Data

- ISS altitude mostly constant/ within 1% since ACO start (411 km)
- Fraction of available data >5% in about 1/3 of ACO period- correction investigations to be performed
- Rework of ground analysis software in ROOT (R. Rios) largely improved data quality and handling
5. ACO Dose and Spectral Analysis, Status

graphics modified from SwRI
5.1 Dose Equivalent Rate Variation vs. Time

- Analysis Comparison: Online, offline light and offline heavy: H*(10) dose equivalent rates, daily averages
- Current implementations of online algorithm factor of ~2 above offline heavy, offline light ~0.5

Increase likely due to charged particle environment change (online algorithm does not have background subtraction)
Insert: Longitude/Latitude Binning

- SAA selection: use cuts: lon in [-90;10]; lat < 10 && FND singles rate derivative cut
- To determine rigidity per data point, use 2015 lookup table from NASA LaRC with cuts for sufficient optimize statistics: high lat <3 GV, low lat >=11 GV
- To be cleaned up...

Graphic from NASA Langley Research Center
5.2 Energy Spectrum Unfolding Results

- Offline Heavy energy flux spectrum and dose equivalent results in [0.2;0.87) MeV vs time, full ACO period

<table>
<thead>
<tr>
<th>Isotropic Absolute Flux [n/cm^2/s]</th>
<th>Orbit-averaged</th>
</tr>
</thead>
</table>

\[
\text{Total avg flux} = 4.0 \pm 0.1 \text{ n/cm}^2\text{s} \\
\text{Total avg } H^*(10) \text{ dose eq. rate} = 5.6 \pm 0.2 \mu\text{Sv/hr}
\]
5. Dose Equivalent Results ACO Period Totals/Averages

- Offline heavy: Neutron flux energy distributions in [0.2;0.87) MeV

<table>
<thead>
<tr>
<th>Total Avg.</th>
<th>Flux [c/cm^2/s]</th>
<th>H*(10) dose eq. rate [μSv/hr]</th>
</tr>
</thead>
<tbody>
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<td>Integral</td>
<td>4.0</td>
<td>5.6</td>
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<tr>
<td>Low Lat</td>
<td>2.1</td>
<td>3.0</td>
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<tr>
<td>High Lat.</td>
<td>6.2</td>
<td>8.6</td>
</tr>
<tr>
<td>SAA</td>
<td>17.9</td>
<td>24.9</td>
</tr>
</tbody>
</table>
5.2 Energy Spectrum Unfolding Results, Variations vs. Time and Lat/Long Comparison

- Magnetic Shielding/SAA Comparison: Offline Heavy H*(10) dose equivalent rates and flux in [0.2;0.87) MeV, daily averages
- Flat over 6 months

**History: Daily Average Isotopic H*(10) Rate [μSv/hr]**

**History: Daily Average Isotropic Absolute Flux [n/cm^2/s]**
5.3 Comparing ACO to Simulated Data, Status
5.3 Spectral Comparison to Simulation

- Comparison to Oltaris (HZETRN-based) simulated data: Simple, forward-only, ray-by-ray simulation
- Ray-trace of material in US lab with latest US lab shield configuration file
- Attempt to match solar conditions: same sunspot number period matched
- Underestimation expected

Graphics from NASA Langley Research Center
5.3 Spectral Comparison to Simulation

- Spectral comparison to offline heavy: Neutron fluence totals/averages
- Simulation factor 3-4 below unfolded results- simulation fidelity being increased
5.4 Comparing ACO to Other Experimental Measurements, Status
5.4.1 Comparison to Other Neutron Dose Equivalent Measurements

- NASA IV-TEPC:
  * Sensitive to neutrons and heavy ions
  * IV-TEPC located in US Lab from Mar 8 through Apr 5 2016
  * NASA TP-2013-217375 finds Mars surface effective dose from GCR heavy ions **factor 5 larger** than neutron contribution
  * Dose eq calculated for LET > 5, 10, 15 keV/mum
    (He peak at ~0.8 keV/mum) with
    ICRP 60 quality factors

<table>
<thead>
<tr>
<th>Dose Equivalent Rate [µSv/day, µSv/hr]</th>
<th>ISS-RAD FND, 0.2-8.75 MeV, ACO</th>
<th>IV-TEPC (LET &gt; X keV/mum)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>134 +/- 4.8*, 5.6 +/- 0.2*</td>
<td>506.4, 21.1 (5)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>465.6, 19.4 (10)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>448.8, 18.7 (15)</td>
</tr>
</tbody>
</table>
5.4.2 Comparisons to Prior Spectral Measurements

- Bubble detectors, M. Smith et al (US lab data)
- Summed Space Bubble Detector Spectrometer data from ISS-20/21 (Oct 2009) to ISS-45/46 (Jan 2016)
- Dose equivalent difference consistent with different energy acceptance range
- 27% higher than FND data for bin [0.6;2) MeV; uncertainties of other overlapping bins low
5.4.2 Comparisons to Prior Spectral Measurements

- Mass of ISS changed by factor 4+ between 2001 and 2016 (90 to 420 tons)
- Significant increase of mass in vicinity of US Lab (20% effect on neutron flux estimated in Ruymen et al, Rad Meas 43 47ff, 2007)
5.4.2 Comparisons to Prior Spectral Measurements

- Bonner ball spheres: H. Koshiishi et al (2007), data taken in 20C

<table>
<thead>
<tr>
<th>Instrument</th>
<th>ISS-RAD FND, 0.2-8.75 MeV, ACO</th>
<th>SBDS</th>
<th>IV-TEPC (LET &gt; X keV/mum)</th>
<th>Bonner Ball 2001</th>
</tr>
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<tbody>
<tr>
<td>Dose Equivalent Rate [µSv/day, µSv/hr]</td>
<td>134 ± 4.8*, 5.6 ± 0.2*</td>
<td>2016: 152 + 60 – 43, 6.3 + 2.5 - 1.8</td>
<td>506.4, 21.1 (5)</td>
<td>69.6, 2.9 (LAB1P1)</td>
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<tr>
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<td></td>
<td>2009-2016 avg.: 149 + 40 - 22, 6.2 + 1.7 - 0.9</td>
<td>465.6, 19.4 (10)</td>
<td>465.6, 19.4 (10)</td>
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<td></td>
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<td></td>
<td>448.8, 18.7 (15)</td>
<td>88.8, 3.7 (LAB1D3)</td>
</tr>
</tbody>
</table>
5.4.2 Comparisons to Prior Spectral Measurements

- Bonner ball collected time/lat-long resolved data
- High energy SAA close at high energy, orbit-averaged larger discrepancy
- Material difference could account for 20% total flux difference
- BBND relocation: Up to 50% different flux -> significance of local mass environment/distribution
- Further study: Energy-dependent discrepancies potentially due to interplay of different production & scatter cross sections

![Isotropic Differential Flux Comparison](image)

H. Koshiishi et al, Rad. Meas. 42 (2007), 1510ff

- ISS-RAD FND Lab 103 2016
- BBND Lab 1P1 2001
- BBND Lab 1D3 2001

BBND Ratios to ISS-RAD: Isotropic Differential Flux
5.5 Comparisons to ISS-RAD CPD Charged Particle Dose Equivalent

- CPD charged particle dose equivalent with estimated/expected Q factor ~500 μSv/day (see C. Zeitlin’s ISS-RAD talk)

- FND energy acceptance possibly accounts for ~50% of total neutron dose equivalent contribution (see L. Heilbronn et al, LSSR 7 90 ff (2015))

  -> total neutron dose equivalent ~250 μSv/day, would correspond to 30% of total dose equivalent (Mars surface ~10%)
6. Forward Work

graphics modified from SwRI
6. Forward Work/Systematic Studies

- Accounting for data unavailability (scaling, 2D-interpolation, uncertainty (SAA))
- Estimate sample impurities (protons) from exp data (TRIUMF) and simulation (GEANT)
- Calculate 3D efficiency from ISS-RAD EM experimental data (PTB 2015)
- Calculate full systematic uncertainties from unfolding (boundary effects etc)
- Potential improvement on low energy resolution through software update (pending)

- Call for additional neutron experimental data for ISS!

-> Publish data.
Backup
B: Orbital Peculiarities
B: Introduction
Outline:

1. Introduction: Basic Interpretation of FND Data

2. Orbital Data Analysis Methods (Online, Offline Light, Offline Heavy)

3. Ground Verification of Analysis Methods

4. Raw Orbital Data

5. ACO Analysis, Status

6. Forward Work

graphics modified from SwRI
1. Introduction: Response Spectrum Shape

- ‘Monoenergetic’ neutron calibration ($\Delta E < 5\%$) at PTB, Germany:

Data taking setup

FND on beam axis/in forward scattered field at 2.5m from target
1. Introduction: Response Spectrum Shape

- Filtered ADC spectrum in response to monoenergetic neutron fields (after background subtraction):
1. Introduction: Scintillation Light Creation/Propagation: Light Function Formalism

- Shape of response spectra dominated by:

  a) **Multiple scattering** of neutron with scintillator material nuclei: multiple pulses of scintillation light per neutron

  b) **Scintillation light quenching** (ionization quenching - Birk's law): nonlinear amount of collected scintillation light per interaction depending on energy deposit & scattering target

**Even monoenergetic neutrons create broad distribution in light deposit/FND recoil spectra.**

- Approach describing scintillation light generation in multiple scattering: Light function formalism

**Literature:**
Neutron recoils on...

V.V. Verbinski et al, NIM 65 (1968) 8 ff
B: Analysis Methods
2.a On-Orbit Analysis (Cary Z.)

- Conversion factors for each recoil bin amplitude to dose equivalent (H*(10))
- Factors derived from:
  * Fit of PTB recoil spectra means with power law
  * Fit PTB efficiency with inverse second order parameterization
  * Multiply recoil and efficiency fit with ICRP dose conversion factors in each recoil bin
2.b) Offline Light Analysis (Cary Z.)

- Fit of PTB background-subtracted recoil spectra means with power law
- Fit PTB efficiency with inverse second order parameterization
- Multiply recoil and efficiency fit with ICRP dose conversion factors in each recoil bin
2.c) Offline Heavy (Martin L.): Regularized SVD Unfolding

- Uncertainties on data distributions and response matrix
  => use regularized, singular vertex decomposition-based unfolding algorithm (ROOT: TSVDUnfold)

- **Advantages:**
  * correct treatment of uncertainty-equipped input quantities (detector response matrix, input distribution)
  * full uncertainty propagation; fast

- **Limitations (found small):**
  * ‘strength’ of regularization described by free parameter, needs to be determined from characteristics of orbit data, simulation and ground test data (systematic uncertainty)
  * dependence on input distribution

General problem formulation:

\[ \hat{A} x^{ini} = b^{ini}, \quad \sum_{i=1}^{n_b} \left( \sum_{j=1}^{n_x} (\hat{A}_{ij} x_j - b_i)^2 \right) = \text{min} \]

*but: Experimental uncertainties* \( \Delta b \neq 0 \)

\[ \sum_{i=1}^{n_b} \left( \frac{\sum_{j=1}^{n_x} \hat{A}_{ij} x_j - b_i}{\Delta b_i} \right)^2 = \text{min}, \quad (\hat{A} x - b)^T (B^{-1})(\hat{A} x - b) = \text{min} \]

Rescaling and regularization:

\[ (\hat{A} w - \hat{b})^T (\hat{A} w - \hat{b}) + \tau \cdot (C w)^T C w = \text{min} \]

regularization parameter: chosen from rank of response matrix/problem

-> need response matrix for given recoil channel number and chosen neutron energy binning
2.c) Unfolding Neutron Energy Binning

- Neutron energy binning:
  * low and high limits: approach from detector side:
    @ **lower limit: 200 keV** (electronics lower pulse cutoff/arming threshold)
    @ **upper limit: 8.5 MeV** (corresponding pulses start to saturate 12-bit ADC)
  * bin width:
    @ Low energy challenge:
      $ Unfolding requires unique response matrix rows- recoil spectrum of neighboring energy bins should ‘peak’ in different recoil bins $ FND orbit data histograms hardcoded to 512 channel width (29 bins)
      $ Light function nonlinearity: first recoil bin contains most of all < 1 MeV neutrons; 1.59 MeV centered in second bin $ Unfolding algorithm reacts positively to similar neutron energy bin size
    @ Choose high energy bin widths following detector resolution (from light fct cal.)

<table>
<thead>
<tr>
<th>Lower Lim</th>
<th>Center</th>
<th>Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>0.664</td>
<td>0.927</td>
</tr>
<tr>
<td>1.127</td>
<td>1.59</td>
<td>0.927</td>
</tr>
<tr>
<td>2.054</td>
<td>2.403</td>
<td>0.698</td>
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<tr>
<td>2.752</td>
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<td>0.698</td>
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<td>6.5</td>
<td>1.5</td>
</tr>
<tr>
<td>7.25</td>
<td>8</td>
<td>1.5</td>
</tr>
</tbody>
</table>

recoil binning-driven

energy resolution-driven
2.c) Response Matrix Assembly

- Unable to reproduce experimental PTB datasets with sufficient accuracy through MCNP-based simulation
- Create response matrix instead by ‘scaling’ available experimental monoenergetic distributions
- All bin centers straddled by available experimental data; assumption is that spectra change continuously with energy (supported by simulation results): Along MCNP-calibrated light function,
  a) scale down experimental distribution for higher energy
  b) scale up exp distribution from lower energy
  c) average

![Scaled Recoil Spectra Scan from Experimental Neutron Energies](image1)

![Neutron Light Conversion Functions](image2)
2.c) Response Matrix Assembly

- Response matrix and row slices from scaled experimental distributions

Reconstructed Yields from Created Neutrons

FND Response Matrix

Reconstructed Yields from All Created Neutrons
- 0.66 MeV
- 1.59 MeV
- 2.40 MeV
- 3.10 MeV
- 3.91 MeV
- 5.00 MeV
- 6.50 MeV
- 8.00 MeV

Created Neutron Energy [MeV]

Reconstructed Channel Number

Yields

10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}

0 2000 4000 6000 8000 10000 12000 14000

Recoil Channel Number

0 2000 4000 6000 8000 10000 12000 14000

Created Neutron Energy [MeV]

Reconstructed Channel Number

Yields

0 2000 4000 6000 8000 10000 12000 14000

0 2000 4000 6000 8000 10000 12000 14000

0 2000 4000 6000 8000 10000 12000 14000

0 2000 4000 6000 8000 10000 12000 14000
2.c) Response Matrix Assembly

- Can choose ‘input spectrum’ freely: weighting of columns of response matrix relative to each other
- Choose ‘input spectrum’ close to expected truth: Koshiishi et al, published 2007 (data from 2001);

H. Koshiishi et al, Rad. Meas. 42 (2007), 1510ff
B: Light Calibration
2. Light Function Calibration - Flowchart

- Goal: Extract continuous light function describing scintillator behavior to freely choose energy binning
- For each experimental monoenergetic data sample, start from first principles:

a) Create energy deposit files

a.1) Generate MCNP-PoliMi energy deposits per neutron-target interaction vs. time, for experimental energies

a.2) ‘Time-connect’ independent MCNP source events for respective Poisson-distributed event rate

b) Light function calibration

b.1) Convert energy deposits to light yield with light function

b.3) Simulate light collection and pulse digitization in FND PMT and electronics

b.2) Apply resolution (scintillator, PMT, pulse processing electronics)

b.5) Apply FND FPGA pulse pair selection logics

b.4) Convert to channelnumber values using photon calibration results

Fill recoil spectrum

for each energy deposit (~5M per energy)

b.6) Apply chance coincidence subtraction, scale factor (efficiency not part of optimization, just product)

Check match to experimental data

Adjust light function and resolution

optimization loop for each energy sample

Create recoil spectra

Check against experimental spectra

Goal: Extract continuous light function describing scintillator behavior to freely choose energy binning
2.a.1 Generation of Neutron Energy Deposits: MCNP-PoliMi

- Use MCNP-PoliMi package:
  * MCNP limitations for neutron propagation and fission/inelastic scattering simulation:
    @ only returns total energy deposition of each neutron in target volume for conversion to light
    @ photon and neutron productions in fission/inelastic collision events not correlated in time/energy/multiplicity

  * PoliMi package writes out each interaction of single neutrons and photons
    @ time correlation within each single history, resolution in 100 ps
    => energy-to-light conversion possible on per-interaction-basis

  @ elastic, (n,\gamma) and (n,n') interactions accurately modeled/propagated

  * Generations of 1e+08 n per experimental energy in bias cone around FND

Model started by A. Bahadori (SRAG)
2.a.2 ‘Time-connect’ Neutron Energy Deposits from MCNP-PoliMi

- Output of PoliMi: ASCII file containing interactions of neutrons and photons with target material:

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</tbody>
</table>

- Limitation in PoliMi: no transport of non-neutron/photon decay products of capture/fission reactions -> manually distribute recoil energy among decay products & convert to light

- To create realistic succession of neutron events in scintillator: ‘time-connect’ PoliMi events to experimental flux (30-310 /s/cm\(^2\)):

<table>
<thead>
<tr>
<th>History</th>
<th>Particle Type</th>
<th>Interaction</th>
<th>ZAID</th>
<th>Energy Deposited [MeV]</th>
<th>Absolute Time [μs]</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>1</td>
<td>-99</td>
<td>6000</td>
<td>0.3258</td>
<td>200.9430278347747105272</td>
</tr>
<tr>
<td>15</td>
<td>1</td>
<td>-1</td>
<td>6000</td>
<td>1.223006</td>
<td>200.9446278347747067983</td>
</tr>
<tr>
<td>15</td>
<td>1</td>
<td>-99</td>
<td>1001</td>
<td>1.19312</td>
<td>200.9471278347747045245</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>-1</td>
<td>6000</td>
<td>1.153535</td>
<td>249.6897651601931613641</td>
</tr>
<tr>
<td>21</td>
<td>1</td>
<td>-99</td>
<td>6000</td>
<td>2.070328</td>
<td>258.0006369570315882811</td>
</tr>
<tr>
<td>35</td>
<td>1</td>
<td>-99</td>
<td>6000</td>
<td>0.027568</td>
<td>372.9355042009522662738</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>~15 min</td>
</tr>
</tbody>
</table>
2.b.1 Convert Energy Deposit to Light- Function Parameterization

- Fit to Verbinski data parameterized as: 2\textsuperscript{nd} order polynomial at low deposited energy; \sqrt{\text{const}+E^2} at high energy
- Change 5 parameters to optimize match with experimental data

\[ L(x_{ED}) = \begin{cases} 
ax_{ED} + bx_{ED}^2 & \text{for } x < g \\
\frac{c + d \sqrt{e^2 + f^2 x_{ED}^2}}{2} & \text{for } x \geq g, \text{ where } a = \frac{df^2g}{\sqrt{e^2 + f^2 g^2}} - 2bg \]

Continuity requirements for 1\textsuperscript{st} and 2\textsuperscript{nd} derivative
2.b.2 Apply Resolution- Implementation

- Single-point implementation of all experimental resolution contributions:
  * light production/quenching/reflections in plastic,
  * light coupling scintillator to PMT
  * PMT photon detection
  * electronic noise (PMT/amplifier) etc
- Optimize 3 parameters to match experimental data

\[
\frac{\Delta L}{L} = \left( \alpha^2 + \frac{\beta^2}{L} + \frac{\gamma^2}{L^2} \right)^{1/2}
\]
2.b.3 Light Collection/Pulse Digitization (see Michael V.’s talk)

- Convert light yields to corresponding **electronics signal pulses** via Gaussian function sampled by 33 MHz clock; area normalized to light yield
- Two filters create **bipolar signals** for peak detection and ‘**moving average (sum)**’ for signal height
- Time width of Gaussian chosen to match experimental signal processing pulse width (full width ~390 ns)

![Pulse Processing Time Series](image)
2.4 Light to Channelnumber Conversion: Photon Calibration

- Inputs: experimental photon source and MCNP-simulated energy deposit spectra
- Perform global fit of conversion function parameters: create channelnumber spectra from generated deposited energy spectra

\[ N_{\text{Exp. Gamma}}(x_{\text{CHN}}) = N_{\text{Exp. Bg}}(x_{\text{CHN}}) + \int R(x_{\text{CHN}}, x_{\text{ED}}) N_{\text{Sim. MC}}(x_{\text{ED}}) \, dx_{\text{ED}} \]

\[ R(x_{\text{CHN}}, x_{\text{ED}}) = e \]

Channelnumber-to-light yield conversion:

\[ ED(x_{\text{CHN}}) = \begin{cases} a + bx_{\text{CHN}}^c & \text{for } x < e \\ d + bx_{\text{CHN}} & \text{for } x \geq e, \text{ where } d = a + be^c - be \end{cases} \]

Continuity requirement
2.b.4 Light to Channelnumber Conversion: Photon Calibration

- Result: Low light yield region prefers nonlinear (power law) shape (also seen in other literature):

**FND Channelnumber to Light Yield Conversion**

Global red. chisq. = 695 / 490 = 1.42
Red. chisq. for single plots:
- Co-57: 27/31 = 0.86
- Ba-133: 63 / 35 = 1.80
- Na-22 a): 53 / 32 = 1.67
- Cs-137: 108 / 70 = 1.54
- Mn-54: 69 / 80 = 0.86
- Co-60: 211 / 160 = 1.32
- Na-22 b): 164 / 100 = 1.64
2. b. 5 FND Pulse Pair Selection (see Michael V.'s talk)

- Apply same selection as FND FPGA
- Algorithm considers three latest detected pulse amplitudes (moving averages) and time intervals between them (zero crossing of bipolar signal)

- Pulse selection logics: accept A, B as pulse pair:

  I) \( SH_B \) in capture signal window \&\&
  II) \( \Delta t_{AB} \) in capture time window \&\&
  III) \( \Delta t_{AB} < \Delta t_{BC} \) \| \( SH_C \) outside of capture signal window \| \( \Delta t_{BC} \) outside of capture time window }
2. Preliminary Calibration Results - Recoil Spectra Match

- Deviations for low channel numbers at mid to high energies - further analysis to be done to identify missing process/incorrect treatment of neutron interactions; resolution to be adjusted as well

![Graphs showing recoil spectra distribution for different energies](image_url)
B: Isotropic Source Term Correction
B: Offline Light Spectrum Extraction Study
2c) Direct Mapping/Conversion Spectral Match Test

- Created ‘truth’ distributions from ISO for AmBe and Cf sources:
  - apply detector resolution, direct mapping binning and energy range selection (0.5-8 MeV)
  - Cf ISO binning mostly too wide for smearing to have effect;

<table>
<thead>
<tr>
<th>ISO AmBe and Cf Neutron Spectra, Binnings &amp; FND Resolution</th>
</tr>
</thead>
</table>

- Original AmBe and Cf ISO raw neutron spectra, showing distributions for AmBe and Cf sources.

- Translated to fiducial energy range, demonstrating resolution differences.

- Direct mapping/conversion spectral match test results for AmBe and Cf sources in various energy ranges.

- FND ‘Truth’, energy range 0.5-8 MeV, showing binning and energy range selection effects.

- Neutron energy resolution graph showing energy dependence on neutron energy (MeV).
2c) Direct Mapping/Conversion Spectral Match Test

- Scale ‘truth’ histograms with PTB reported (adjusted) neutron flux
- Comparison with GAS analysis results statistics-limited to <~ 5 MeV (only spotty shadow cone and background subtraction data at higher chn bins):
  @ Expected: Low energy spectrum overestimated, medium/high energy spectrum underestimated
  @ AmBe spectrum shows structure in ISO-truth, not reflected in DBM spectrum: deviations +45% to -41%;
  @ Cf spectrum closer (statistics limited): overestimate at low bins ~22%, medium energy bins large uncertainties, in part consistent;
- Conclusion: Direct Mapping/Conversion analysis method by design shows limitations in reproducing neutron energy spectra.

Lack of exp data
B: MCNP Neutron Cross Sections
4.1a Simulation of Neutron Energy Deposits: MCNP-PoliMi

- for all materials use ENDF-VII library at 300 K, assembled in 2005; max energy 20 MeV, 500-3500 energies depending on material
4.1a Simulation of Neutron Energy Deposits: MCNP-PoliMi

- for all materials use ENDF-VII library at 300 K, assembled in 2005; max energy 20 MeV, 500-3500 energies depending on material

![Neutron Energy Deposits Diagram](C(n,ngamma)C, C(n, gamma)C, C(n, alpha)Be, C(n, n'3alpha))
B: Photon Calibration Nonlinearities
6) Low Energy Nonlinear Light Output in Literature

Energy deposit -> Light Yield -> Channelnumber

FND Channelnumber to Energy Deposit Conversion

FND Fit Result


Assumed linear

Literature c)

FND Fit Result: 
A ~ C^1.02

Literature a)

http://iopscience.iop.org/0031-9155/59/16/4621/article
http://pasj.asj.or.jp/v63/sp3/63s303/63s303-frame.html
http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4696573
4. Scintillation Light Creation/Propagation: Light Function Formalism

MCNP-PoliMi Scintillator Simulations

Exp. Recoil of 8 MeV Monoenergetic

Number of Interactions per Neutron with B-10 Capture
B: Misc Auxiliary Analysis Items
2) Neutron Efficiency Results, ADC Saturation

- Efficiencies from PTB datasets: Rel. uncertainties 2-3%;

![Graph showing neutron efficiencies vs. incident neutron energy]  

- ADC saturation for high pulse heights

![Histogram showing 'Clipping' above channel number ~15k: ADC value reported smaller than actual pulse height]  

'Clipping' above channel number ~15k: ADC value reported smaller than actual pulse height.
2) Preliminary Fit Result to Capture Pulse Distributions

- Experimental data not corrected for beam background/room return
2) Preliminary Simulation Result for Delta \( t \) Capture Distribution

- Experimental data not corrected for beam background/room return

![Histograms of Delta \( t \) for different neutron energies](image-url)
B2) Test: AmBe vs. Distance, Extraction of Absorption Depth

- To be able to approximate FND as point detector
- fit doubles rates with shifted inverse squares:
  \[ f(d) = [0] + [1] \times \frac{1}{(d + [2])} \]
* only fit >=20cm data to avoid geometry issues (point source approximation);
* fit results:
  @ [0]: background rate 0.5 ± 0.07 Hz;
  @ [2]: effective absorption depth of RAD = 7.2 ± 0.5 cm
* deduce distance from JSC source to expose FND to roughly 50 μSv/hr for reference (neglecting room scattering, probably ~20%):
  @ JSC calibration 5/21/14: source strength 2.380e+05 Hz;
  @ with ICRP74 AmBe conversion factor 391 pSv*cm² per n:
  -> distance from absorption center to source = 23.1 cm;
  -> distance from side of FND stack to source = 15.9 cm.

red chisq. of fit = 5.52/4 = 1.38