Lecture 10.1: Calibration of the LUNA II Accelerator

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Plan For Today

1. In-Class Survey

2. Final Calibration Lecture
   - Overview
   - Resonances
   - Carbon Capture
   - Combined Energy Calibration

3. Homework Reports
To what extent, in any undergraduate or graduate class, have you covered the topics of Statistics, Error Propagation, Curve Fitting, or the Feldman-Cousins Method? Take a few minutes to e-mail me the answer.
LUNA II Beam Energy Calibration

Basic Information
- Experiment: Laboratory for Underground Nuclear Astrophysics II (LUNA II) accelerator
- The larger of the DIANA accelerators will be similar but with higher beam intensity.
- Instrument Calibrated: Accelerator proton energy ($E_p$).
- Standard 1: Nuclear capture resonances
- Standard 2: Nuclear capture $\gamma$ emissions from $^{12}$C

Source

Experiment Overview

- Goal is to understand nuclear capture (fusion) at low energies (130 keV - 400 keV).
- Accelerator capable of 400 kV accelerates protons or $\alpha$ particles into nuclear targets
- At these energies, the cross sections $\sigma(E)$ vary strongly as a function of energy
- Need to know the energy of our beam protons $E_p$
- We know the total voltage of the accelerator $V$ to high precision
What is an eV?
Calibration Procedure

Goals

- An eV is defined as the energy required to accelerate an elementary charge across a potential of 1 volt.
- Nominally, accelerating a proton across a potential of $x \text{ V}$ would imbue it with kinetic energy $x \text{ eV}$
- The calibration measures the different between the nominal expectation and reality using two standards.

Setup

- Thin disks of C, Mg, and Na are affixed to a cooled backing.
- Target is placed in front of a high purity Germanium (HP-Ge) detector that will detect $\gamma$ rays from calibration runs.
LN$_2$ cooled Cu tube

cold trap
target

beam

Turbo pump
collimator

window
target chamber

HP-Ge detector
Resonances

Notation Convention

In nuclear physics, capture reactions are written in the form Target(projectile, ejected particle)Recoiling Nucleus. For example $^{25}\text{Mg}(p, \gamma)^{26}\text{Al}$ is equivalent $p + ^{25}\text{Mg} \rightarrow ^{26}\text{Al} + \gamma$.

- Choose narrow resonances with $\gamma$ emissions
- An increase in $\gamma$ flux indicates $E_p$ is at the known resonance

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$E_R$/keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{23}\text{Na}(p, \gamma)^{24}\text{Mg}$</td>
<td>$308.75 \pm 0.06$</td>
</tr>
<tr>
<td>$^{25}\text{Mg}(p, \gamma)^{26}\text{Al}$</td>
<td>$316.11 \pm 0.11$</td>
</tr>
<tr>
<td>$^{26}\text{Mg}(p, \gamma)^{27}\text{Al}$</td>
<td>$338.30 \pm 0.10$</td>
</tr>
<tr>
<td>$^{25}\text{Mg}(p, \gamma)^{26}\text{Al}$</td>
<td>$389.24 \pm 0.11$</td>
</tr>
</tbody>
</table>

Four are used:
Procedure

- Calculate the “Lewis” effect, which is a shift of the peak in accelerators with very narrow beam energy distributions caused by the fact that the distribution is not Gaussian.
- Tune accelerator voltage to find peak count of $\gamma$ rays with $E_\gamma > 2.8$ MeV.
- Deconvolve Lewis effect to obtain the location of the resonance peak in accelerator energy $E_{ACC} = V \times 1\frac{\text{keV}}{\text{kV}}$.
- Calculate the shift $\Delta \equiv E_{ACC} - E_p$, where $E_p$ is determined by finding the resonance.
- Repeat for other resonances and find linear relationship $\Delta = mV + b$. 
Resonance Results

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$E_R$/keV</th>
<th>$V$/kV</th>
<th>$\Delta$/keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{23}\text{Na}(p, \gamma)^{24}\text{Mg}$</td>
<td>308.75 ± 0.06</td>
<td>311.24</td>
<td>2.49 ± 0.06</td>
</tr>
<tr>
<td>$^{25}\text{Mg}(p, \gamma)^{26}\text{Al}$</td>
<td>316.11 ± 0.11</td>
<td>318.83</td>
<td>2.65 ± 0.11</td>
</tr>
<tr>
<td>$^{26}\text{Mg}(p, \gamma)^{27}\text{Al}$</td>
<td>338.30 ± 0.10</td>
<td>340.80</td>
<td>2.50 ± 0.10</td>
</tr>
<tr>
<td>$^{25}\text{Mg}(p, \gamma)^{26}\text{Al}$</td>
<td>389.24 ± 0.11</td>
<td>392.17</td>
<td>2.93 ± 0.11</td>
</tr>
</tbody>
</table>

Limitations and Next Steps

- These resonances only provide calibration for a few specific points.
- No calibration for beam energy below 308.75 keV.
- Next, we turn to a non-resonant nuclear capture for lower energies and a continuous spectrum.


\[ p + ^{12}\text{C} \rightarrow ^{13}\text{N} + \gamma \]

**Advantages**

- Enables energy measurements over a continuous spectrum 
  \( E_p = 100 - 400 \text{ keV} \)
- The relationship between \( E_p \) and \( E_\gamma \) is well understood
- “Accurate calibration lines from \( \gamma \)-ray sources can be found in the literature for this energy range.”
- “…the results are not influenced by any C-deposition on the target during the runs.”

**Deconvolution**

- The spectrum of \( \gamma \) rays is convoluted with several other uncertainties and effects before reaching the detector.
- Need to deconvolve all of these and fit to extract \( E_\gamma \).
Shape Distorting Factors

Physical Effects

- As the protons traverse the thick target, they lose energy, decreasing the cross section $\sigma(E_p)$
- Stopping power of the target is also a function of energy $dE/dx(E_p)$
- $\gamma$ spectrum is slightly distorted by the recoil of $^{13}$N nucleus.
- Asymmetry in the peak shape due to the relatively large solid angle of the detector at a distance of 39 mm

Detector Effects

- Detector bin width $\delta E_\gamma$.
- Detector efficiency $\varepsilon(E_\gamma)$.
- The detector energy resolution $\Delta E_\gamma = 3$ keV.
Both plots show the simulated $\gamma$ spectrum at $E_p$. The open points show the $\gamma$ spectrum after accounting for the recoil of $^{13}$N nucleus, the asymmetry due to the large solid angle of the detector, and $\delta E_\gamma$ (detector bin width). The solid points show the spectrum after accounting for the detector energy resolution.
Figure: Relevant section of the $\gamma$ ray spectrum near the capture line of $^{12}\text{C}(p, \gamma)^{13}\text{N}$ at $E_p = 350$ keV: The solid curve through the data points represents a fit to the data accounting for all detector and physical spectral distortion effects, including $dE/dx(E_p)$, $\varepsilon(E_\gamma)$, and $\sigma(E_p)$. The fit is in good agreement with data $\chi^2 = 1.1$, allowing us to extract $E_p$. 
Combined Energy Calibration
The shift $\Delta$ is plotted vs. the voltage $V$ of the accelerator. The solid line assumes a linear dependence of $\Delta$ from $V$ ($\Delta = mV + b$) and the dashed lines represent the uncertainty band around $\Delta$. 
Shift and Finding $E_p$

We define

$$\Delta \equiv V \cdot 1 \frac{\text{keV}}{\text{kV}} - E_p = mV + b$$

and we want to know $E_p$ for a given $V$.

$$\Rightarrow E_p = (1 - m)V - b$$

The fit to the previous slide yields

$$m = (0.0067 \pm 0.0002) \frac{\text{keV}}{\text{kV}}$$

and

$$b = (0.41 \pm 0.05) \text{ keV}$$
Homework Report Format

- Each student will have 10 min. for presentation + 5 min. for questions
- Ideally, all will be in PDF format from one laptop
- Will have a break after 3 or 4 presentations