Measuring β-Decay Energy Spectra

Update on Determination of β-energy spectral shapes in fission products affecting reactor decay heat, anti-neutrino flux, and addressing potential physics beyond the standard model
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**β-Energy Spectra**

Predicted $\beta^-$ Spectrum For Nuclear $\beta$-Decays

$$S(E) = NW(W^2 - 1)^{1/2}(W - W_0)^2 F(Z, W)C(Z, W)$$

Phase Space = $NE_e p_e E_\nu p_\nu$

Fermi Function

Shape Factor

**Shape Factors Can Be Much Larger or Smaller Than 1**

Often Shape Factors Are Not Reliably Predictable

Especially for First-Forbidden Non-Unique $\beta$ Decays

Abundantly Present in Fission Products

Sonzogni, Nino, McCutchan, PRC 98, 014323 (2018)

R.D. Evans, The Atomic Nucleus (1955)
Due to unknown nuclear matrix elements, predicting forbidden $\beta$ decays is challenging, therefore direct measurements of $\beta$ energy spectra, and ideally individual $\beta$ energy spectra, are needed.
β-Energy Spectra Impacts

Motivation to Measure β Energy Spectra

Reactor Antineutrino Spectra
Summation and Conversion method
Needed for accuracy and precision better than 5%, preferably 1%
Needed for antineutrino energy-spectral fine structure (on top of antineutrino oscillations)

Reactor Decay Heat
Needed for accuracy and precision of the β component of decay heat

Nuclear Structure
β-shape measurements, β-feeding intensities, and β-γ correlations can inform spin and parity assignments while they also help identify dominant nuclear matrix elements

Fundamental Weak Interaction Physics
(β-shape measurements precision needed better than 1%)

Beyond the Standard Model Physics
(β-shape measurements precision needed better than 1%)

What has been accomplished so far?

Set Up Detailed Simulations
   (Optical simulations still to be implemented)

Towards the Finalized Design of βSM Detector
   Power and Readout Boards (Components Ordered)
   Ordered Larger Volume Scintillators (Delivered)
   Ordered Photomultiplier Tubes (Delivered)
   Ordered Additional Electronic Parts (Ordered)
   Ordered Test and Calibration Sources (~10-100 nCi range) (Ordered)

   Constructed Prototype Connected with Beam Pipe
   Tested Vacuum of Prototype (Mid 10^{-7} torr)
   Used Sources to Test Light Collection, Readout, and Calibration
   Performed Various Source Measurements to Validate Simulations
   Hired Post-Doc with Start Date ~Jun 2023
Accurate and precise $\beta$ energy spectra measurements inform many areas physics research, both fundamental and applied, and should be pursued!

We at ORNL are working towards measuring important $\beta$ energy spectra for nuclear reactor based physics.
β-Spectrum Module (βSM)

Thank You for your Attention
Backup Slides
Pressure vs Time

Attachment (epoxied with torseal) of scintillator to beam pipe holds vacuum

Attachment of scintillator to beam pipe was mechanically stressed/tested
Knowing the individual $\beta$ energy spectra means knowledge of the antineutrino spectra due to the conservation of energy. But this is only for $\beta$ -decay level by level. This may be described as the energy sharing between leptons.

Due to unknown nuclear matrix elements and higher order corrections, the energy sharing between the $\beta$ and the antineutrino can not always be predicted. Direct $\beta$-energy measurements are needed to improve the summation method for the predicted reactor $\beta$ and antineutrino spectra to below the 5% level.

Improve the precision of both the summation and conversion method used to calculate the reactor antineutrino spectra.

Can the antineutrino endpoint steps be detected in new antineutrino detectors with good energy precision? Do screening exchange effects affect the antineutrino spectra near the end points? (Endpoint step?)

X. Mougeot, PRC 91, 055504 (2015)
β-Energy Spectra Measurements

Identifying First-Forbidden Unique from Allowed with Total Absorption Spectroscopy

Identification of individual β shape from complex β decays is possible

ORNL’s Modular Total Absorption Spectrometer (MTAS) is a very efficient β and γ-ray detector.

The MTAS detector can distinguish a first forbidden unique β decay and an allowed β decay

P. Shuai of ORNL and UTK, Phys. Rev. C 105, 054312

ORNL is redesigning the central detector in our MTAS array in order to more efficiently identify the β component from complex β decays.

We have approved beamtime for testing prototypes at Argonne National Laboratory.
β-Energy Spectra Measurements

Current State of β-Decay Energy Spectra Affairs

Extremely productive β spectral measurements performed from mid 50s until the mid 1970s. Research continues to this day with new precision instruments, but still with the same isotopes.

Why did this productive line of research slow down?

Most β-shape measurements are all near stability, most with low Q<sub>β</sub> nuclei and known spin changes.

X. Mougeot, PRC 91, 055504 (2015)

87Kr Integral β Spectrum
Wohn, et al., PRC 7, 160 (1973)

144Pr Integral β Spectrum + Fermi Plot

137Xe Ground state to ground state β spectrum
Al Kharusi, et al., PRL 124, 232502 (2020)
EXO-200 Collaboration
Identifying First-Forbidden Unique from Allowed with TAS:

Identification of $\beta$ shape from complex $\beta$ decays is possible. The MTAS detector can distinguish a first forbidden unique $\beta$ decay and an allowed $\beta$ decay.