Oak Ridge National Laboratory

Measuring β-Decay Energy Spectra

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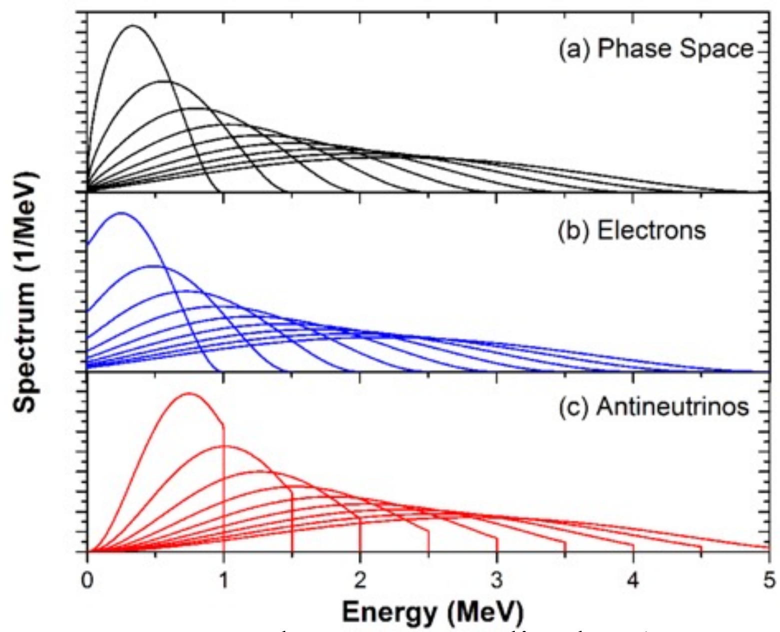
β-Energy Spectra Measurements

Predicted β⁻ Spectrum For Nuclear β-Decays

$$S(E) = \underbrace{NW(W^2 - 1)^{1/2}(W - W_0)^2}_{\text{Phase Space}} F(Z,W)C(Z,W)$$

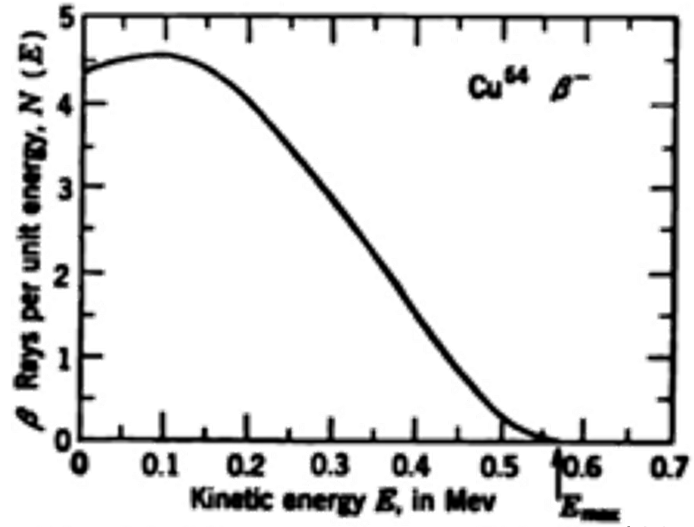
Fermi Function

Shape Factor

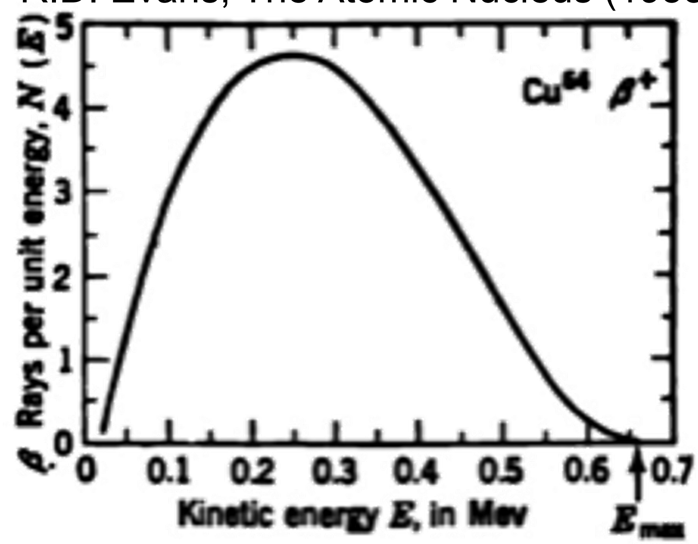


Each curve normalized to 1

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



R.D. Evans, The Atomic Nucleus (1955)



β-Energy Spectra Measurements

Many Motivations to Measure β Energy Spectra

Reactor Antineutrino Spectra
Summation and Conversion method
(Needed for accuracy and precision better than about 5%, preferably 1%)

Reactor Decay Heat
(Needed for accuracy and precision better than a few %)

Nuclear Structure
(β-shape measurements 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%)

A. Glick-Magid, *et al.*, Physics Letters **B 767** (2017) 285–288
O. Naviliat-Cuncic and M. Gonzalez-Alonso, Ann. Phys. 525, No 8-9, 600-619 (2013)

β-Energy Spectra Measurements

Motivations:

Reactor Antineutrino Spectra

Knowing the individual β energy spectra means knowledge of the antineutrino spectra due to the conservation of energy. But this is only for β -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 β and the antineutrino can not always be predicted. Direct β-energy measurements are needed to improve the summation method for the predicted reactor β 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?)

A. Hayes, *et al.*, PRL 112, 202501 (2014)
L. Hayen, *et al.*, PRC 99, 031301(R) (2019)
L. Hayen, *et al.*, PRC 100, 054323 (2019)
X. Mougeot, PRC 91, 055504 (2015)

β-Energy Spectra Measurements

Due to challenges in predicting forbidden β decays, direct measurements of the β energy spectra are needed.

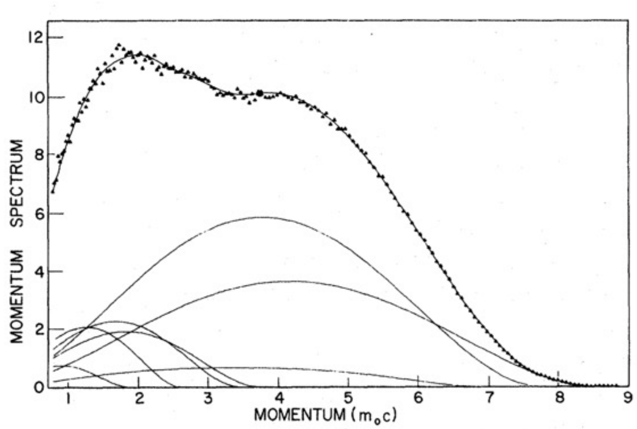
β-Energy Spectra Measurements

Current State of β-Decay Energy Spectra Affairs

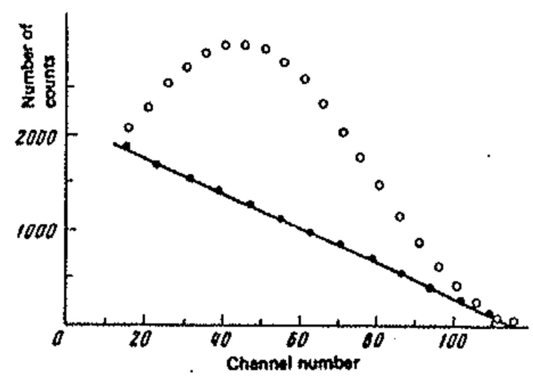
Extremely productive β spectral measurements performed from mid 50s until the mid 1970s.
Research continues to this day with new precision instruments, but still with the same isotopes.

Why did this productive line of research slow down?

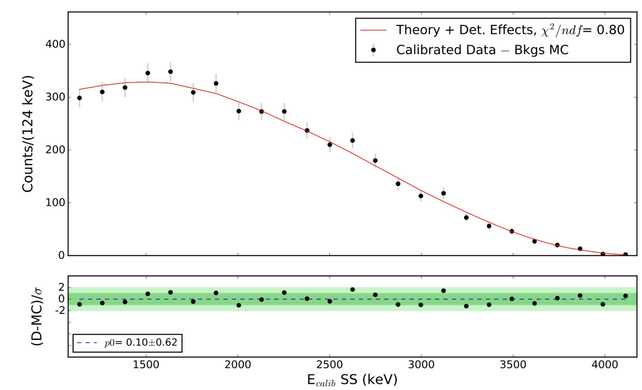
Most β-shape measurements are all near stability, most with low Q_β nuclei and known spin changes.
X. Mougeot, PRC 91, 055504 (2015)



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



^{144}Pr Integral β Spectrum + Fermi Plot
Borovoi, *et al.*, SJNP 32(5) (1980)



^{137}Xe Ground state to
ground state β spectrum
Al Kharusi, *et al.*, PRL 124, 232502 (2020)
EXO-200 Collaboration

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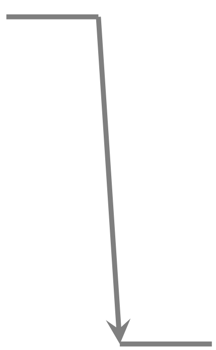
β-Energy Spectra Measurements

Current State of β-decay energy spectra affairs

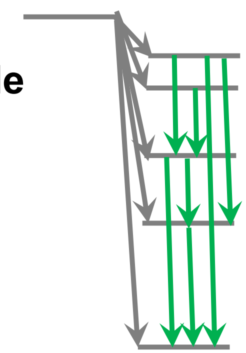
β energy spectra have been measured with magnetic spectrometers + ancillary detectors, silicon detectors, organic and inorganic scintillators, ionization chambers…
All detectors have advantages, disadvantages, and unique experimental challenges and opportunities.



Simple

Experimental challenges with β-energy measurements include

Beta detector challenges
Electron back scattering
Bremsstrahlung
Low efficiency requiring high activity sources



Complex

but most limiting effect is dealing with
Complicated Decay Patterns
Need to isolate the βs level by level, otherwise measurements are inconclusive.

Almost all current measurements are of simple beta decays with strong feedings to one or two levels, long half lives, and easily producible in large quantities, *i.e.* near stability

Need to access and measure complicated β-decay patterns, for example fission products.

β-Energy Spectra Measurements

What is needed to extract β energy spectra from complex decay patterns?

In order to extract individual β decays from complex β decay patterns the following is needed:

High efficiency β detector
High efficiency γ detector
Ability to separate βs from γs
High statistics will help
Energy precision preferred but not necessarily required
(β shapes are wide smooth functions)

Several of these are usually mutually exclusive requirements

Needed Measurements

Individual Complex β -Decays of fission products – Ongoing
Individual β energy spectra for each level in complex β -decays
Integral β measurements for each fuel type

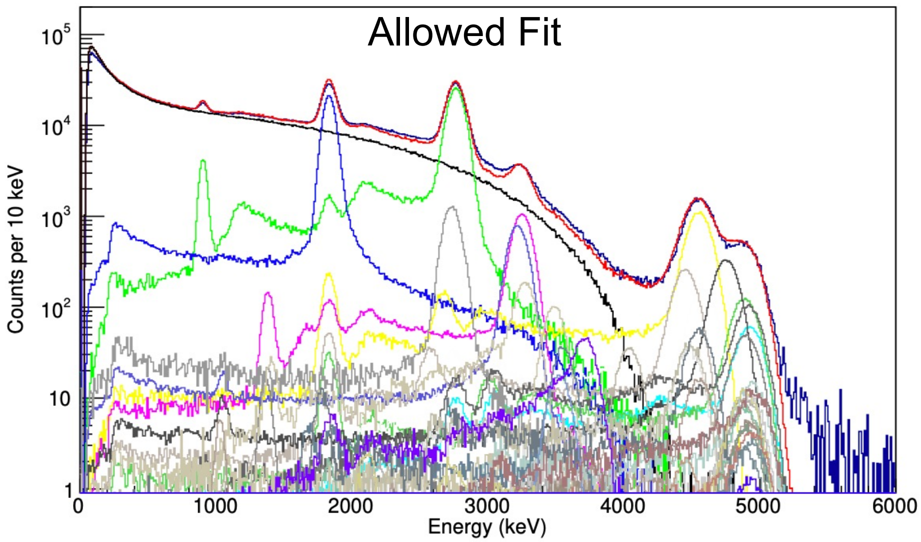
Integral γ measurements for each fuel type

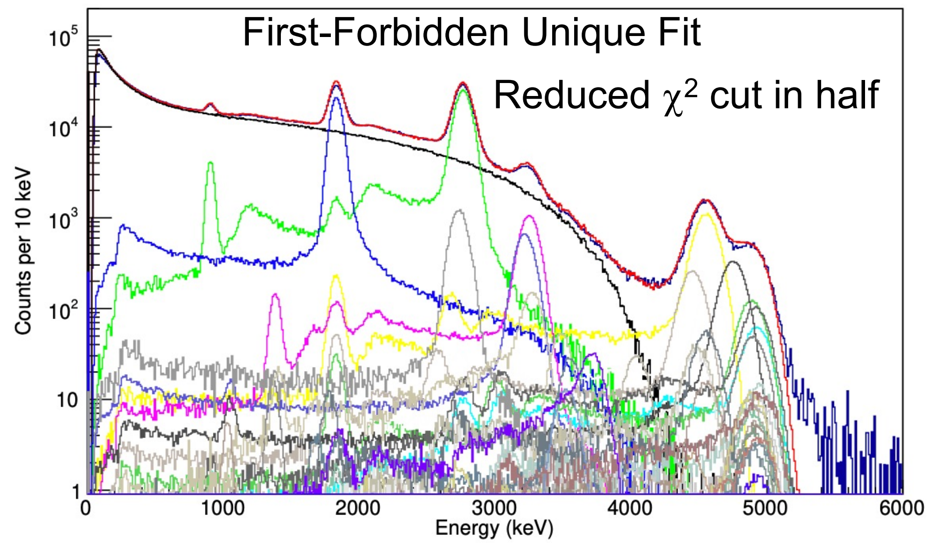
Verifying integral beta measurements in several ways is the best possible
Kopeikin versus Schreckenbach

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, in preparation

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

Accurate and precise β energy spectra measurements from individual β decays level by level informs many areas physics research, both fundamental and applied and should be pursued!

We at ORNL are working on separating the β energy spectra level by level.

β-Energy Spectra Measurements

Using Total Absorption Spectroscopy to Perform Aggregate Nuclear Fuel β and γ Measurements

Measuring aggregate γ and β spectra by fuel component would give further information on reactor antineutrinos and decay heat by fuel type.

Needed:

Source of Various Nuclear Fuels

HIFR at ORNL is a good source of single nuclear fuels
(^{233}U, ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu + others)

Detector Demands

High beta efficiency
High gamma efficiency
High neutron efficiency
Or ideally all three at once.

Good energy resolution if possible
Handle high rates if possible
(Oh, is that all?)

Total Absorption Spectroscopy is an excellent option.

β-Energy Spectra Measurements

Thank You for your Attention

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