Experimental Determination of the Antineutrino Spectrum of the Fission Products of ^{238}U

Nils Haag

Chair for Experimental and Astroparticle Physics - E15
Technische Universität München

INT workshop - Seattle
Nov. 6th 2013

Content

- **Determination of the $\bar{\nu}_e$ spectrum of ^{238}U**
  - General idea
  - Experimental setup
  - Detector performance:
    - Gamma suppression
    - Response function
    - Energy calibration
  - Data analysis - Backgrounds
  - Results
- **Conclusion**

How to derive the reactor $\bar{\nu}_e$-spectra

Summation approach

- Compose S_{total} from single branches
- $\approx$ 845 nuclei, 10000 β-branches
- Knowledge of many parameters and β-spectra required
- Conversion to $\bar{\nu}$ (nearly) trivial ($E_{\bar{\nu}} \approx Q - E_{\beta}$)
- Quoted inaccuracies of order of 10 - 20 %

Conversion method

- Measure sum of β-spectra of the 4 fuel isotopes
- 3 of them already known (BILL, 1980's)
- ^{238}U only from summation method
- Conversion to $\bar{\nu}$ non-trivial

How to derive the reactor $\bar{\nu}_e$-spectra

Summation approach

- Compose S_{total} from single branches
- $\approx$ 845 nuclei, 10000 β-branches
- Knowledge of many parameters and β-spectra required
- Conversion to $\bar{\nu}$ (nearly) trivial ($E_{\bar{\nu}} \approx Q - E_\beta$)
- Quoted inaccuracies of order of 10 - 20 %

Conversion method

- Measure sum of β-spectra of the 4 fuel isotopes
- 3 of them already known (BILL, 1980's)
- ^{238}U only from summation method
- Conversion to $\bar{\nu}$ non-trivial

My work:

- Experimental determination of the $\bar{\nu}_e$-spectrum of the last missing contribution due to fission of ^{238}U
- Accuracy of $\sim 10\,\%$ at energies of $\sim 4\,\text{MeV}$

The ^{238}U experiment: Basic idea

- Measurements of β-spectra from two identical foils from natural uranium (0.7 % ^{235}U) in ...
  - ... thermal neutron beam: only fission of ^{235}U
  - ... fast neutron beam: mainly fission of ^{238}U

The ^{238}U experiment: Basic idea

- Measurements of β-spectra from two identical foils from natural uranium (0.7 % ^{235}U) in ...
  - ... thermal neutron beam: only fission of ^{235}U
  - ... fast neutron beam: mainly fission of ^{238}U

- Comparison of measured β-spectrum in thermal beam with BILL measurement of ^{235}U

  $\rightarrow$ Extraction of efficiency function

  $\rightarrow$ Test/cancel assumed detector response function

The ^{238}U experiment: Basic idea

- Measurements of β-spectra from two identical foils from natural uranium (0.7 % ^{235}U) in ...
  - ... thermal neutron beam: only fission of ^{235}U
  - ... fast neutron beam: mainly fission of ^{238}U

- Comparison of measured β-spectrum in thermal beam with BILL measurement of ^{235}U

  $\rightarrow$ Extraction of efficiency function

  $\rightarrow$ Test/cancel assumed detector response function

- γ-spectroscopy of irradiated foils:
  $\rightarrow$Determination of relative amount of fissions in both targets
  $\rightarrow$Absolute calibration of ^{238}U β-spectrum

The ^{238}U experiment: Basic idea

- Measurements of β-spectra from two identical foils from natural uranium (0.7 % ^{235}U) in ...
  - ... thermal neutron beam: only fission of ^{235}U
  - ... fast neutron beam: mainly fission of ^{238}U

- Comparison of measured β-spectrum in thermal beam with BILL measurement of ^{235}U

  $\rightarrow$ Extraction of efficiency function
  $\rightarrow$ Test/cancel assumed detector response function

- γ-spectroscopy of irradiated foils:
  $\rightarrow$Determination of relative amount of fissions in both targets
  $\rightarrow$Absolute calibration of ^{238}U β-spectrum

- Conversion into $\bar{\nu}_e$-spectrum

The ^{238}U experiment: Basic idea

- Measurements of β-spectra from two identical foils from natural uranium (0.7 % ^{235}U) in ...
  - ... thermal neutron beam: only fission of ^{235}U
  - ... fast neutron beam: mainly fission of ^{238}U

- Comparison of measured β-spectrum in thermal beam with BILL measurement of ^{235}U

  $\rightarrow$ Extraction of efficiency function
  $\rightarrow$ Test/cancel assumed detector response function

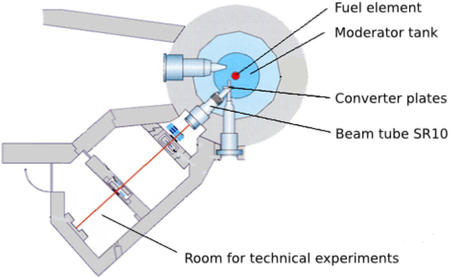
- γ-spectroscopy of irradiated foils:
  $\rightarrow$Determination of relative amount of fissions in both targets
  $\rightarrow$Absolute calibration of ^{238}U β-spectrum

- Conversion into $\bar{\nu}_e$-spectrum

$\Rightarrow$ Most systematical uncertainties vanish (unknown beam profile, fission rates ...)

The ^{238}U experiment: Experimental site

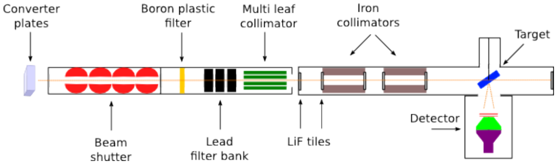
Experimental site: Scientific neutron source Heinz Maier-Leibnitz FRM II

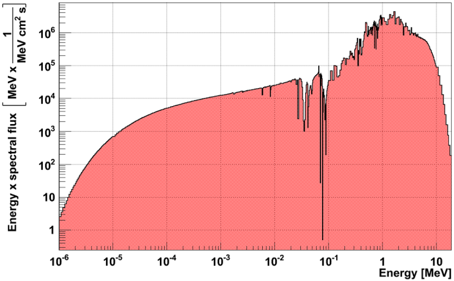


The converter facility at SR10

- Removable converter plates of 500 g ^{235}U in thermal neutron cloud
- Thermal and fast neutron beam available

The ^{238}U experiment: Neutron spectrum

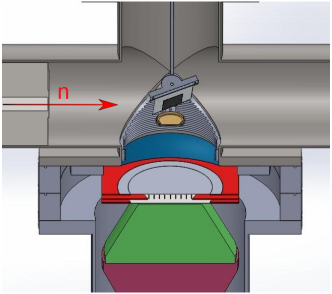




The ^{238}U experiment: The detector

Detector setup

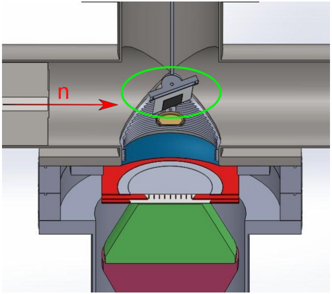
- Spectroscopic module of plastic scintillator and photomultiplier
- Multiwire Chamber for suppression of gamma-induced events

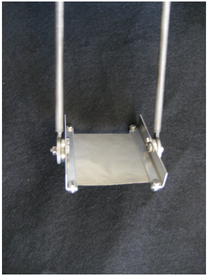


The ^{238}U experiment: The detector

Detector setup

- Spectroscopic module of plastic scintillator and photomultiplier
- Multiwire Chamber for suppression of gamma-induced events





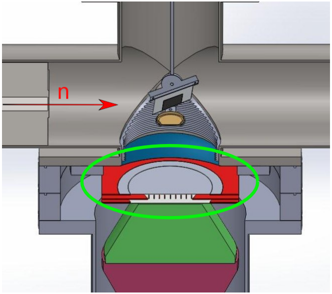
- **Target** from natural uranium:

  99.3 % ^{238}U
  0.7 % ^{235}U

- 25 μm thickness
- Between Ni foils

Detector setup

- Spectroscopic module of plastic scintillator and photomultiplier
- Multiwire Chamber for suppression of gamma-induced events

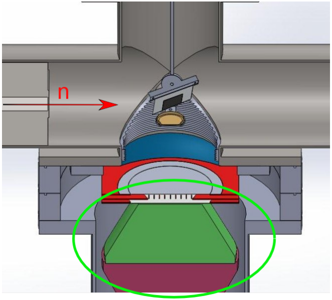


- **MWC**:
  γ- suppression
- 25 Au-coated W-wires
- Counting gas: CF_4

The ^{238}U experiment: The detector

Detector setup

- Spectroscopic module of plastic scintillator and photomultiplier
- Multiwire Chamber for suppression of gamma-induced events



- **Scintillator** and **PM** for β-spectroscopy
- 6.5 cm thick plastic scintillator (13 MeV)
- Truncated cone for optimal electron detection

The ^{238}U experiment - the experimental setup

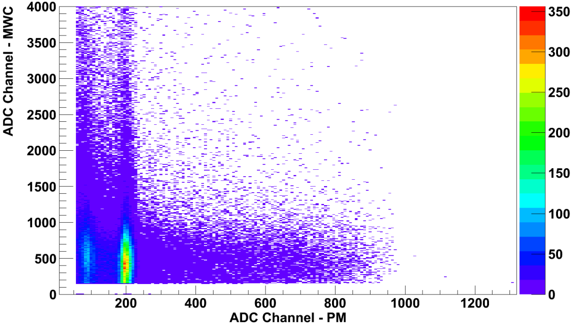
The ^{238}U experiment - the experimental setup

Detector Performance

The coincidence

Coincidence matrix

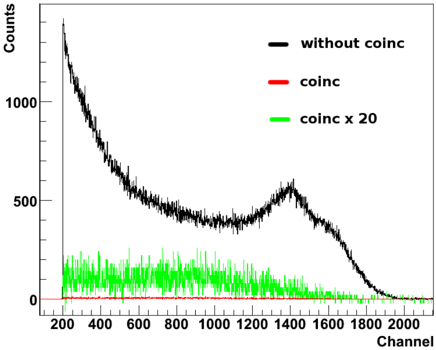
- Assign PM and MWC signal event-by-event
- Possibility to introduce offline cuts
- Time resolved: Check for time dependencies (nothing unexpected observed)



Detector performance: γ-suppression

Coincidence between PM and MWC

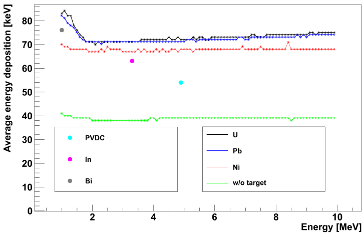
- ^{60}Co source outside detector pot
- Without coincidence: Compton-edges of γ-lines
- Coincidence: Background suppression of $\gtrsim 99.5\,\%$

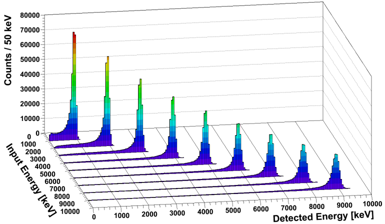


Detector performance: Response function

Monoenergetic β line is affected by:

- Energy deposition in material between target and detectors
- Backscattering and bremsstrahlungs losses at scintillator
- Scattering off the detector housing
- Gaussian broadening: photon statistics in spectroscopic module





- Simulations cross-checked with Bi-calibration measurements

Detector performance: Energy calibration

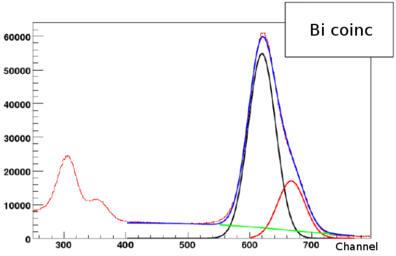
Energy calibration

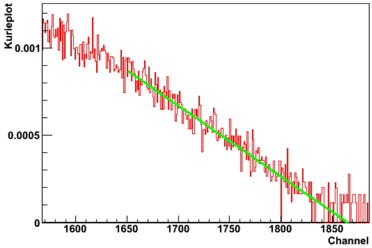
^{207}Bi: Lines of internal conversion at 1 MeV

^{116}In β-decay: Q-value at 3.3 MeV

^{38}Cl β-decay: Q-value at 4.9 MeV

- Spectroscopic module: FWHM: 8 % at 1 MeV

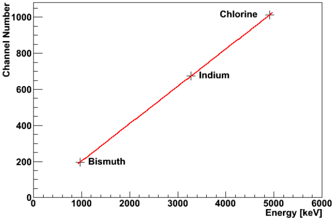


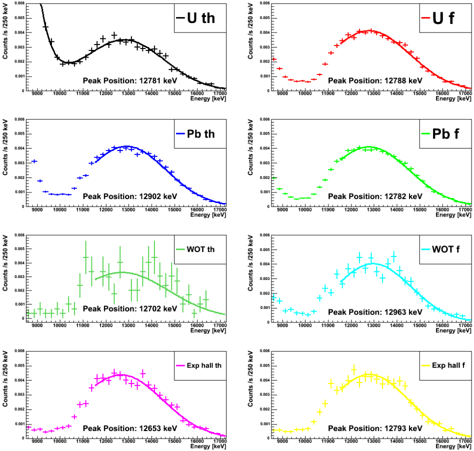


Detector performance: Energy calibration II + Stability

Final calibration

- Calibration linear
- Cross-check by μ peak at 13 MeV





- Energy + Rate stability check

Data Analysis

Data analysis: Background

Background sources:

- Gammas from fission
- Target-independent, diffuse BG
- Target-dependent background:
  - Conversion of gammas from the beam
  - Electrons, mainly from ^{28}Al
  - Capture of scattered neutrons
- Neutron capture on H-atoms in scintillator
- ^{235}U fission in fast beam

BG handling:

- In decay: β and γ's
- Check with simulation:
  - Use calculated fission spectra
  - Add 2 gammas to every decay
- Influence cancelled by:
  - Small solid angle (2 %)
  - Efficiency for γ detection
  - Normalisation to BILL
- Remaining BG: O(10^{-3})

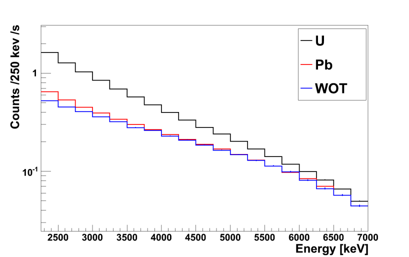
Data analysis: Background

Background sources:

- Gammas from fission
- Target-independent, diffuse BG
- Target-dependent background:
  - Conversion of gammas from the beam
  - Electrons, mainly from ^{28}Al
  - Capture of scattered neutrons
- Neutron capture on H-atoms in scintillator
- ^{235}U fission in fast beam

BG handling:

- Measurement without target
- Dummy measurements (Pb + Ni)



- Cross check with detector simulations

Data analysis: Background

Background sources:

- Gammas from fission
- Target-independent, diffuse BG
- Target-dependent background:
  - Conversion of gammas from the beam
  - Electrons, mainly from ^{28}Al
  - Capture of scattered neutrons
- Neutron capture on H-atoms in scintillator
- ^{235}U fission in fast beam

BG handling:

- Gamma line at 2.2 MeV
- Neutrons from fission: No dummy measurement possible
- Small but indeterminable
- Lower threshold for β-spectrum: 2.25 MeV

Data analysis: Background

Background sources:

- Gammas from fission
- Target-independent, diffuse BG
- Target-dependent background:
  - Conversion of gammas from the beam
  - Electrons, mainly from ^{28}Al
  - Capture of scattered neutrons
- Neutron capture on H-atoms in scintillator
- ^{235}U fission in fast beam

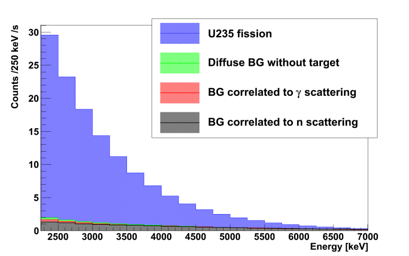
BG handling:

- Thermal beam: ^{235}U fissions
- Fast beam: ^{235}U and ^{238}U
- Analytical determination of ^{235}U fissions in fast beam (σ_f and neutron spectrum known)

Data analysis: β-spectra

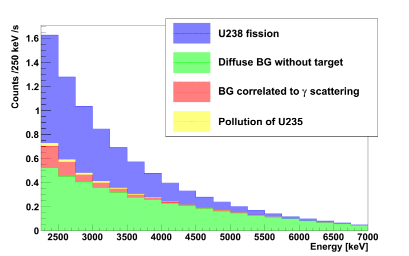
^{235}U β-spectrum

- Signal to BG ratio:
  $\approx$ 6.5 at 4 MeV
  $\gtrsim$ 1 up to 6.5 MeV
- Thermal beam BG:
  mostly scattered neutrons



^{238}U β-spectrum

- Signal to BG ratio:
  $\approx$ 0.7 at 4 MeV
  $\gtrsim$ 1 up to 3.5 MeV
- Main fast beam BG:
  diffuse (target-independent)
- Lower threshold: 2.25 MeV



Data analysis: Normalisation to BILL

Precise:

$$\underbrace{\frac{MyU5}{BILLU5 \otimes resp}}_{\text{Normalisation function NF}} = \frac{MyU8}{TrueU8 \otimes resp}$$

$$\Rightarrow TrueU8 \otimes resp = MyU8 \cdot \frac{BILLU5 \otimes resp}{MyU5}$$

$\Rightarrow$ Absolute calibration of ^{235}U by comparison to BILL

- Apply NF to MyU8
- But: De-convolution of TrueU8 and response function necessary

Data analysis: Normalisation to BILL

Precise:

$$\underbrace{\frac{MyU5}{BILLU5 \otimes resp}}_{\text{Normalisation function NF}} = \frac{MyU8}{TrueU8 \otimes resp}$$

$$\Rightarrow TrueU8 \otimes resp = MyU8 \cdot \frac{BILLU5 \otimes resp}{MyU5}$$

$\Rightarrow$ Absolute calibration of ^{235}U by comparison to BILL

- Apply NF to MyU8
- But: De-convolution of TrueU8 and response function necessary

$\rightarrow$ Make an easy approximation

Data analysis: Normalisation to BILL II

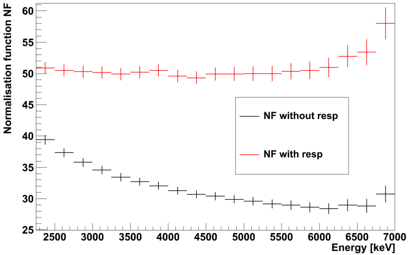
Approximation:

- Neglect bin-to-bin correlations in response function:

$$\frac{MyU5}{BILLU5 \cdot resp} = \frac{MyU8}{TrueU8 \cdot resp}$$

$$\Rightarrow TrueU8 = MyU8 \cdot \underbrace{\frac{BILLU5}{MyU5}}_{1/NF}$$

- Final result differs from precise calculation by $< 2\,\%$
- Corrected for this small effect



Data analysis: Normalisation to BILL II

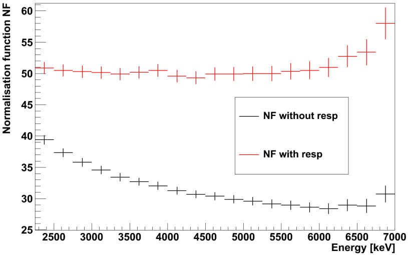
Approximation:

- Neglect bin-to-bin correlations in response function:

$$\frac{MyU5}{BILLU5 \cdot resp} = \frac{MyU8}{TrueU8 \cdot resp}$$

$$\Rightarrow TrueU8 = MyU8 \cdot \underbrace{\frac{BILLU5}{MyU5}}_{1/NF}$$

- Final result differs from precise calculation by $< 2\,\%$
- Corrected for this small effect

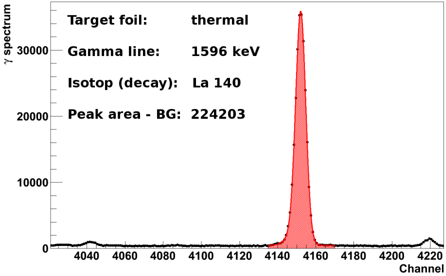


- With response: NF flat
  $\rightarrow$ Good understanding of detector
- Approximation fine because of shape of spectrum
  (exp $\otimes$ gauss = exp)
- Benefit: No knowledge of resp needed to re-evaluate

Absolute calibration

Absolute calibration of ^{238}U

- γ-spectroscopy of the two irradiated foils
- Screen both foils 5 times each in ~ 2 weeks
- Measure peak areas of selected lines
- Solve Bateman equations (trivial)
  $\Rightarrow N_f(\mathrm{th}) = (44.4 \pm 0.3) \cdot N_f(\mathrm{fast})$



Now the β-spectrum of the fission products of ^{238}U is ready

The U238 β - spectrum

Energy [keV]	$N_\beta \left[\frac{betas}{fission \cdot MeV}\right]$	stat. err. [%]	norm. err. [%]	norm. err. BILL [%]
2250 - 2500	1.032	3.2	2.1	1.7
2500 - 2750	$8.302 \cdot 10^{-1}$	3.0	2.1	1.7
2750 - 3000	$6.922 \cdot 10^{-1}$	2.4	2.1	1.7
3000 - 3250	$5.698 \cdot 10^{-1}$	2.3	2.1	1.7
3250 - 3500	$4.533 \cdot 10^{-1}$	2.4	2.1	1.7
3500 - 3750	$3.740 \cdot 10^{-1}$	2.4	2.1	1.7
3750 - 4000	$2.807 \cdot 10^{-1}$	2.7	2.1	1.7
4000 - 4250	$2.279 \cdot 10^{-1}$	2.9	2.1	1.7
4250 - 4500	$1.725 \cdot 10^{-1}$	3.5	2.1	1.8
4500 - 4750	$1.343 \cdot 10^{-1}$	3.9	2.1	1.8
4750 - 5000	$1.084 \cdot 10^{-1}$	4.5	2.1	1.8
5000 - 5250	$7.891 \cdot 10^{-2}$	5.5	2.1	1.8
5250 - 5500	$5.831 \cdot 10^{-2}$	6.8	2.1	1.8
5500 - 5750	$4.137 \cdot 10^{-2}$	9.7	2.1	1.8
5750 - 6000	$2.909 \cdot 10^{-2}$	11.7	2.1	1.8
6000 - 6250	$2.765 \cdot 10^{-2}$	11.1	2.1	1.8
6250 - 6500	$2.248 \cdot 10^{-2}$	12.7	2.1	1.8
6500 - 6750	$1.296 \cdot 10^{-2}$	18.9	2.1	1.9
6750 - 7000	$7.078 \cdot 10^{-3}$	28.1	2.1	1.9

Conversion into $\bar{\nu}_e$-spectrum

Hypothetical branch approach not feasible (statistics), but:

- Weak interaction: Similarity of e^- and $\bar{\nu}_e$
- Differences: Mass of e^- and e.m. corrections
- Shift of electron spectrum by 511 keV + E_{corr} ($E_{corr} \in [0, 100]$ keV):

$$N_\nu(E_\nu) = N_e(E_{kin} + 511\, keV + E_{corr}) \cdot k_e(E_{kin})$$

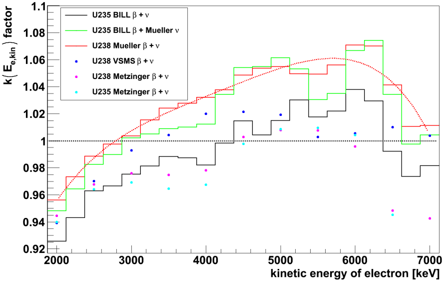
Conversion into $\bar{\nu}_e$-spectrum

Hypothetical branch approach not feasible (statistics), but:

- Weak interaction: Similarity of e^- and $\bar{\nu}_e$
- Differences: Mass of e^- and e.m. corrections
- Shift of electron spectrum by 511 keV + E_{corr} ($E_{corr} \in [0, 100]$ keV):

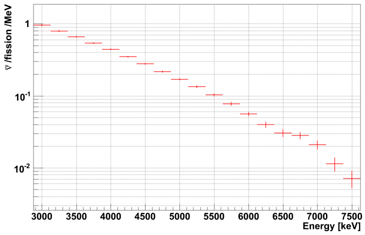
$$N_\nu(E_\nu) = N_e(E_{kin} + 511\,keV + E_{corr}) \cdot k_e(E_{kin})$$

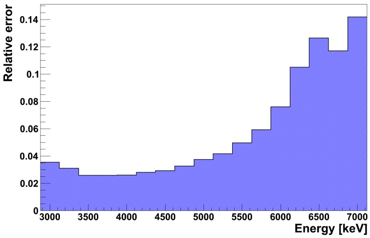
- $(1-k) \lesssim 5\,\%$
- Determination of k from former meas. and calc.
- Error on correction k: $\sim 2\,\%$

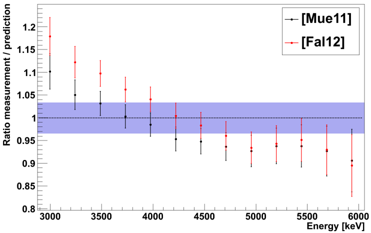


The final $\bar{\nu}_e$-spectrum

Antineutrino spectrum of the fission products of ^{238}U:







- Total relative error $\sim 6\,\%$ at $4\,\mathrm{MeV}$ (regime interesting for current experiments)
- Spectral distortions of $\sim 10\,\%$

The U8 spectrum

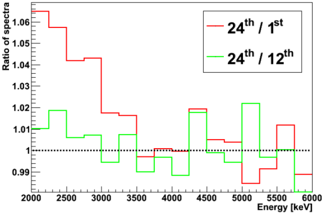
Energy [keV]	$N_{\bar{\nu}}$ $\left[\frac{\bar{\nu}}{fission \cdot MeV}\right]$	error [%]	norm. error [%]
3000	$9.586 \cdot 10^{-1}$	3.5	3.3
3250	$7.952 \cdot 10^{-1}$	3.1	3.3
3500	$6.603 \cdot 10^{-1}$	2.6	3.3
3750	$5.406 \cdot 10^{-1}$	2.6	3.3
4000	$4.433 \cdot 10^{-1}$	2.6	3.3
4250	$3.498 \cdot 10^{-1}$	2.8	3.3
4500	$2.787 \cdot 10^{-1}$	2.9	3.3
4750	$2.171 \cdot 10^{-1}$	3.3	3.3
5000	$1.700 \cdot 10^{-1}$	3.7	3.4
5250	$1.341 \cdot 10^{-1}$	4.1	3.4
5500	$1.032 \cdot 10^{-1}$	5.0	3.4
5750	$7.737 \cdot 10^{-2}$	5.9	3.4
6000	$5.618 \cdot 10^{-2}$	7.6	3.4
6250	$3.973 \cdot 10^{-2}$	10.6	3.4
6500	$3.048 \cdot 10^{-2}$	12.6	3.4
6750	$2.805 \cdot 10^{-2}$	11.7	3.4
7000	$2.093 \cdot 10^{-2}$	14.1	3.4
7250	$1.139 \cdot 10^{-2}$	21.9	3.4
7500	$7.132 \cdot 10^{-3}$	30.0	3.4

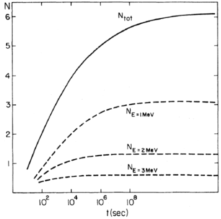
Table 5.2: *The $\bar{\nu}$ - spectrum of the fission products of ^{238}U. The energies given represent the center of the 250 keV wide bins. The error quoted in the third column is the combined inaccuracy of all error sources, apart from the global absolute normalisation uncertainty which is quoted in the last column.*

Remark on radioactive equilibrium

$$FinalU8 = MyU8 \cdot \frac{BILLU5}{MyU5}$$

- Data from the first 11 hours of irradiation not used
- Used data:
  - 42 hours in fast neutron beam (^{238}U)
  - 16 hours in thermal beam (^{235}U)
  - Off-equilibrium effects of BILL and MyU5 nearly cancel
- Consider effects in ^{238}U

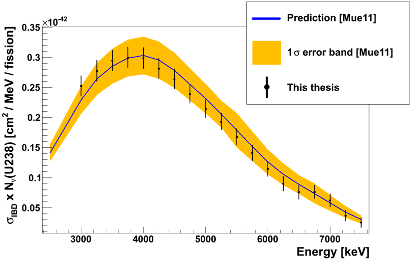




Measured mean cross section per fission

- Important for reactor experiments:

  Product of spectrum and cross section inverse beta decay (IBD)



Mean cross section (IBD) per fission:

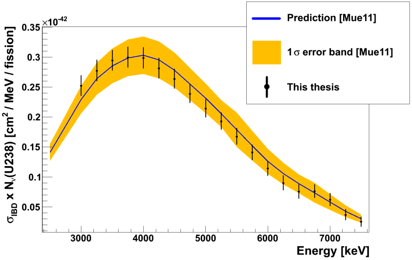
$$< \sigma_{f,U238} >_{red} = \int_{2.875\ MeV}^{7.625\ MeV} S_{U238}(E) \cdot \sigma_{IBD} dE$$

$$\frac{<\sigma_{f,U238}>_{red}(This\ thesis)}{<\sigma_{f,U238}>_{red}([Mue11])} = 0.97 \pm 0.08(pred.) \pm 0.03(exp.)$$

Measured mean cross section per fission

- Important for reactor experiments:

  Product of spectrum and cross section inverse beta decay (IBD)



Mean cross section (IBD) per fission:

$$< \sigma_{f,U238} >_{red} = \int_{2.875\ MeV}^{7.625\ MeV} S_{U238}(E) \cdot \sigma_{IBD} dE$$

$$\frac{<\sigma_{f,U238}>_{red}(This\ thesis)}{<\sigma_{f,U238}>_{red}([Mue11])} = 0.97 \pm 0.08(pred.) \pm 0.03(exp.)$$

- Theoretical predictions confirmed and accuracy enhanced
  $\rightarrow$ Slight spectral distortion revealed

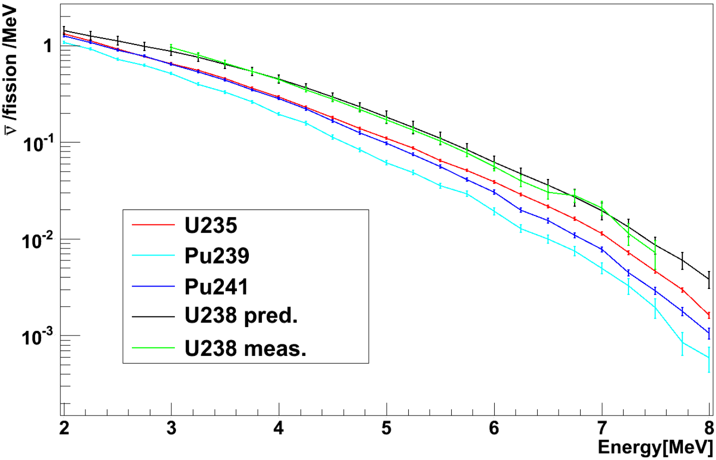
Conclusion

- ^{238}U $\bar{\nu}_e$-spectrum only from calculations (10 % contribution)
  $\Rightarrow$ ^{238}U experiment: γ-suppressing β-spectroscope
- Overall error $\leq 7\,\% \pm 3\,\%$ (norm.) up to 6 MeV
  $\rightarrow$ Accuracy significantly enhanced
- Calculations confirmed with slight spectral distortion
- Fully correlated to BILL U235 spectrum!

Conclusion

- ^{238}U $\bar{\nu}_e$-spectrum only from calculations (10 % contribution)
  $\Rightarrow$ ^{238}U experiment: γ-suppressing β-spectroscope
- Overall error $\leq 7\,\% \pm 3\,\%$ (norm.) up to 6 MeV
  $\rightarrow$ Accuracy significantly enhanced
- Calculations confirmed with slight spectral distortion
- Fully correlated to BILL U235 spectrum!
- Thesis submitted for publication $\rightarrow$ online next week
- Paper in preparation $\rightarrow$ will appear this year

Reactor $\bar{\nu}_e$ spectra now complete



Contact

Nils Haag

Chair for Experimental and Astroparticle Physics - E15
Technische Universität München

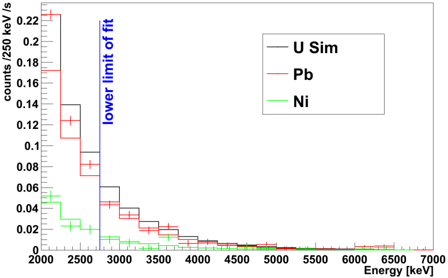
E-Mail: nils.haag@ph.tum.de
Tel: 089 289 12524

Backup

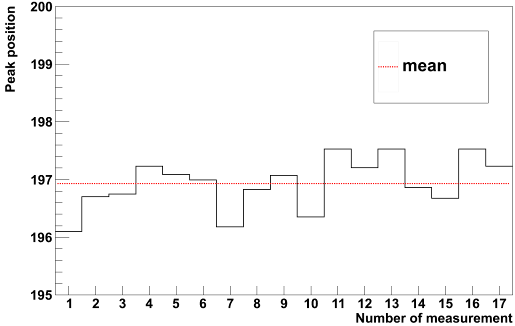
Data Analysis: Target-dependent background

In fast neutron beam:

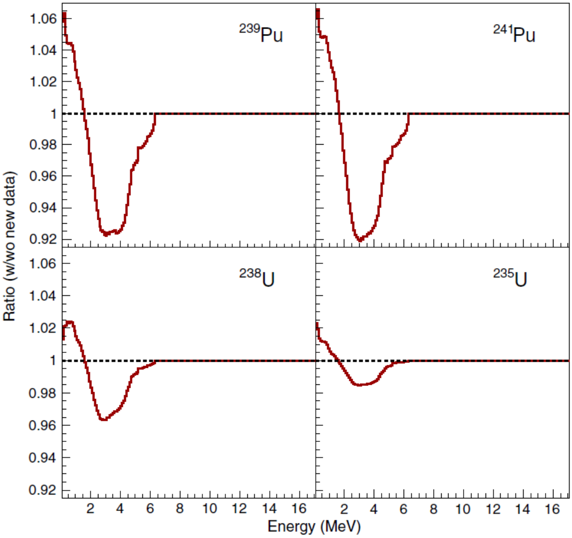
- Dummy target measurements: Lead and Nickel
- Analyse residual BG (after subtraction of diffuse BG)
- Simulate signal from gammas (beam) and electrons (Al - decay)
- Simulation reproduces data for gammas (fit area)
  $\rightarrow$ correctly predicts BG with U target
- Total BG to be corrected for: Only few % at 4 MeV



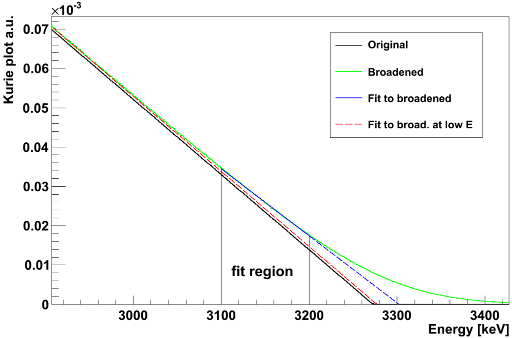
Stability of Bi peak



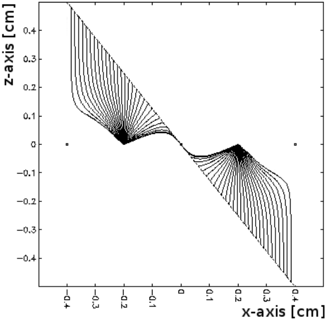
Impact of new pandemonium isotopes

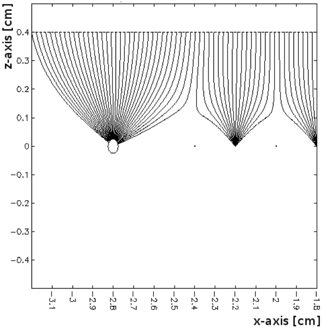


Impact of gaussian broadening on Kurie plots

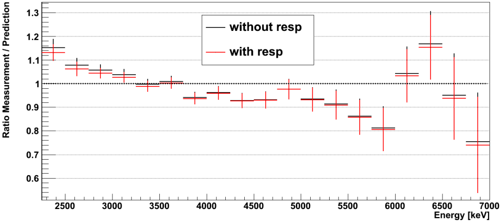


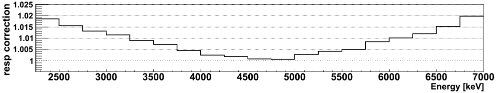
Garfield simulaiton of MWC



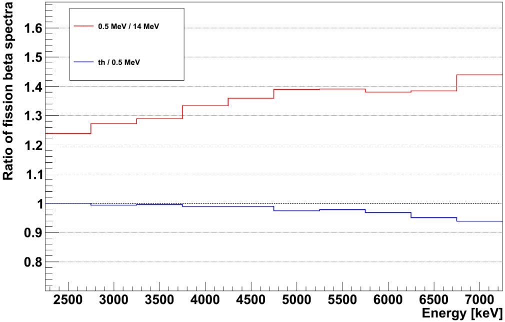


Comparison of final result with and w/o response in NF

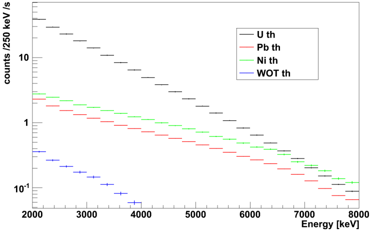


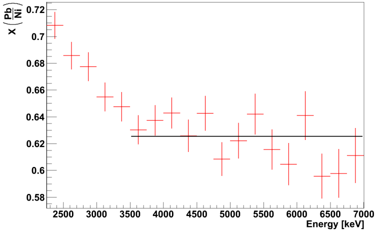


No problem with neutron spectrum



Thermal Beam





No problem with decay correlated gammas