Reactor neutrino spectrum

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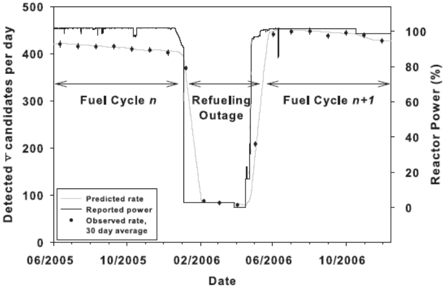
April 25, 2011

Motivation

- Accurate reactor ν oscillations experiments.
- Better sesitivities on ν magnetic search.
- Reactor monitoring.



SONGS: replacement of Pu was seen.

Most of the material based on arXiv:1101.2663v2 [hep-ex].

The Reactor's $\bar{\nu}_e$ and e^-

$$\mathrm{Spectrum(E)} = S_{\text{fission}} + S_{\text{n capture on } ^{238}\text{U}} + S_{\text{n capture on fission product}}$$

S_{fission}: fission of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu.

$S_{\text{n capture on } ^{238}\text{U}}$: $^{238}\text{U+n} \rightarrow {}^{239}\text{U} \underset{\beta\,(1.26\text{MeV})}{\longrightarrow} {}^{239}\text{Np} \underset{\beta}{\rightarrow} {}^{239}\text{Pu}$

$S_{\text{n capture on fission product}}$: e. g. ^{135}Xe+n.

The fissions

$$S_{\text{fission}}(t, E) = \sum_{k={}^{235}\text{U},\ {}^{238}\text{U},\ {}^{239}\text{Pu},\ {}^{241}\text{Pu}} \alpha_k(t) S_k(t, E)$$

α_k: fission rate, depend on abundance of isotope and neutrons.
S_k: $\bar{\nu}_e$ or e^- spectrum per fission.

$$S_k(t, E) = \sum_{fp=\text{fission product}} A_{fp}(t) S_{fp}(E)$$

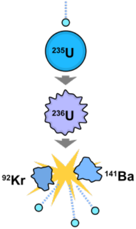
A_{fp}: activity of fp^{th} fission product, depend on neutrons.
S_{fp}: $\bar{\nu}_e$ or e^- spectrum of fp^{th} fission product.

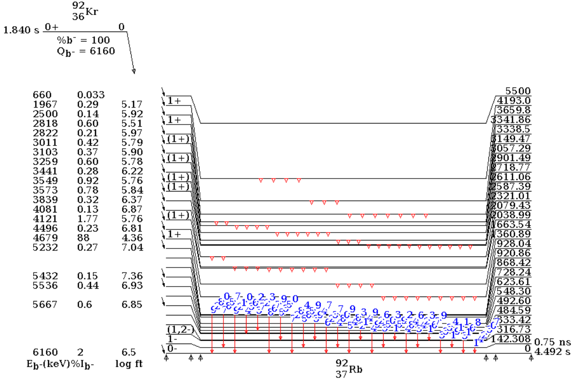
$$S_{fp} = \sum_{b=\text{decay branch}} BR_b S_b$$

BR_b: branching ratio of each decay branch.
S_b: $\bar{\nu}_e$ or e^- spectrum of each β-decay
Number of nuclei involve: 845 + unknown. Number of decay branch: >10000 + unknown.

The fissions

Example: A fission of ^{235}U into ^{92}Kr and ^{141}Ba, and β-decay branchs of ^{92}Kr





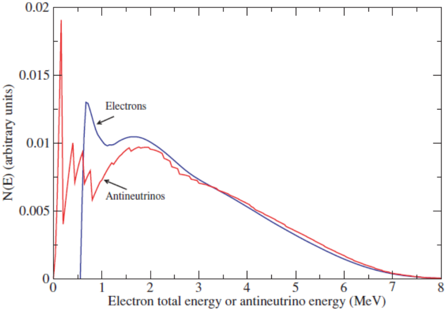
decay branchs

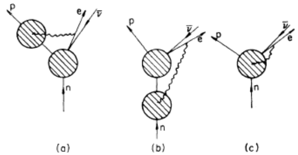
$$S_b \propto p_e E_e (E_0 - E_e)^2 \times F(Z, E_e) \times [\text{QEDcorrection}]$$

$F(Z, E_e)$: Fermi function, Coumlomb field attract outgoing e^-

$\rightarrow$ shift e^- spectrum toward left.

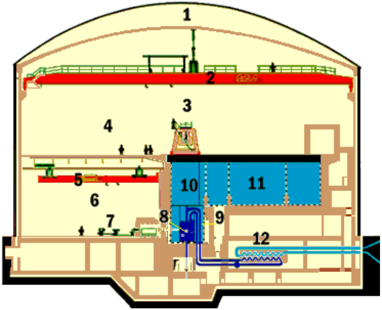
$\rightarrow$ create jigsaw at $\bar{\nu}_e$ spectrum.

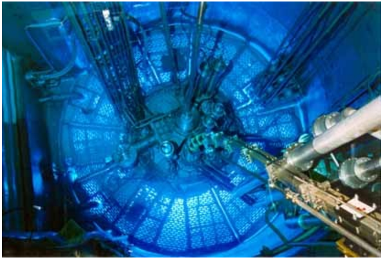




Convert e^- spectrum to $\bar{\nu}_e$ spectrum: old way

e^- spectrum of ^{235}U, ^{239}Pu, ^{241}Pu are measured at ILL(Institut Laue-Langevin) High-Flux reactor by neutron bombardment on ^{235}U, ^{239}Pu, ^{241}Pu thin foil.





Convert e^- spectrum to $\bar{\nu}_e$ spectrum: old way

$$S_k \qquad \sum_{b=\text{virtual decay branch}} \qquad BR_b S_b$$

Cut e^- spectrum into n-bin, the highest E bin must come from largest branch(one branch), assume constant Z

$\rightarrow$ fit the last bin with SINGLE branch e^- spectrum

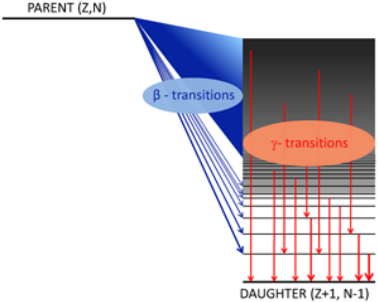
$\rightarrow$ subtract that spectrum from measured e^- spectrum

$\rightarrow$ fit the last bin after subtraction.

Z dependent of Fermi function affect jigsaw structure of low Energy $\bar{\nu}_e$ spectrum.

Add all the fission product and β-branch

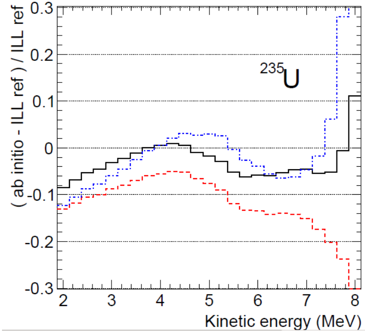
A near complete data available at ENSDF(Evaluated Nuclear Structure Data File).
However ...



E_0 and branching ratio was measured by γ spectrum, and γ could "lost" in measurement $\rightarrow$ assign larger E_0
$\rightarrow$ Pandemonium Effect(Hardy, 1977)
Using Total Absorption Gamma Spectrometer(TAGS).

Compare with Measured e^- spectrum

Calculate e^- spectrum - ILL Measured spectrum:

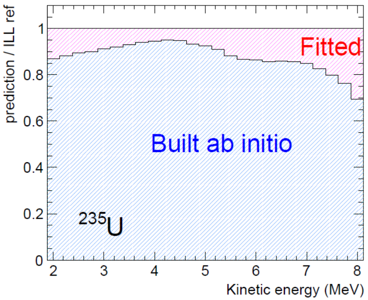


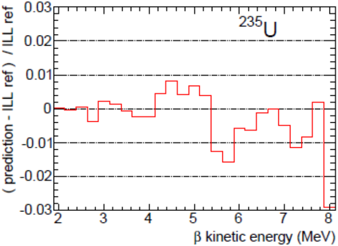
ENSDF only, replace some with Pandemonium-corrected data, add in JENDL(Japanese Evaluated Nuclear Data Library) and model.

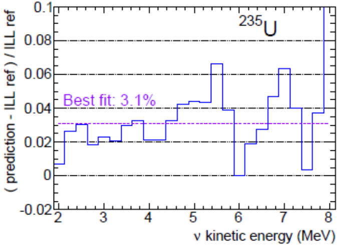
±10%

Another way

Add everythings in ENSDF and Pandemonium-corrected data, and fit remaining as "old way".







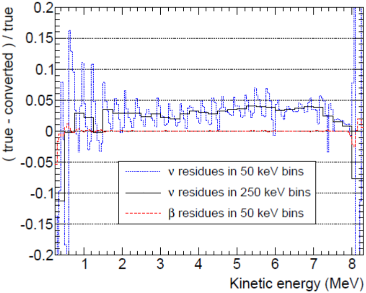
The remaning are fitted with 5 virtual branches with Z=46.

e^- spectrum $\pm 1\%$

$\bar{\nu}_e$ spectrum shift +3%

Cross check on the method

Use ENSDF only to generated $\bar{\nu}_e$ and e^-, then convert generated-e^- spectrum to $\bar{\nu}_e$ with old way.



Switch on-off various effects

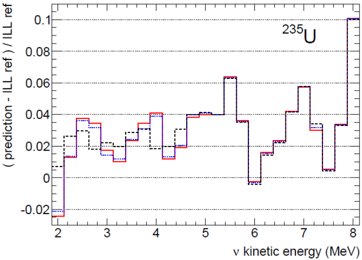
→ +3% below 4 MeV from QED correction.

→ +3% above 4 MeV from using correct Z

("old way" use constant Z to fit all virtual branches)

Error

Activities was simulated by MCNP(Monte-Carlo N-Particle transport code) for Reactor Evolution.

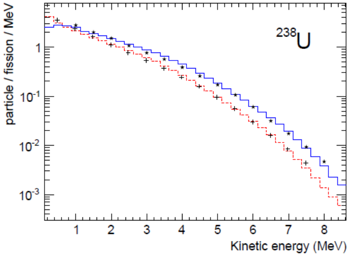


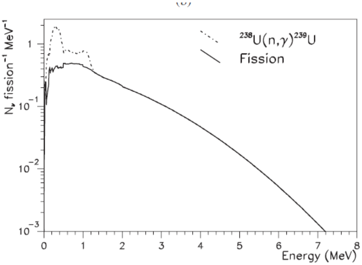
after 12h, after 36h, accumulate.

Time variation affect $\pm 1\%$.

Total error for ^{235}U, ^{239}Pu, ^{241}Pu $<$ 4% at 2-5 meV.

No measured e^- spectrum exist for ^{238}U.

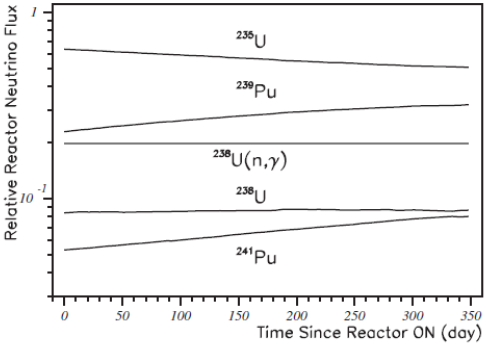




Using ENSDF, Pandemonium-corrected, JENDL and model.
Compare with [Vogel, 1981](different nuclear database) $\pm$10%.

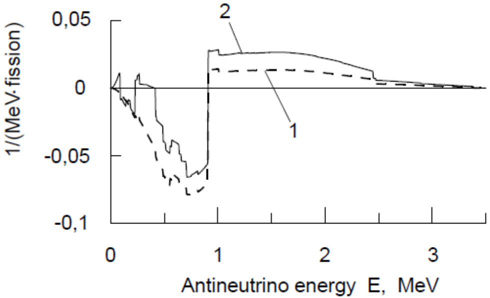
$$^{238}\mathrm{U+n} \rightarrow {}^{239}\mathrm{U} \xrightarrow[\beta(1.26\mathrm{MeV})]{} {}^{239}\mathrm{Np} \xrightarrow[\beta(0.71\mathrm{MeV})]{} {}^{239}\mathrm{Pu}$$

Time evolution



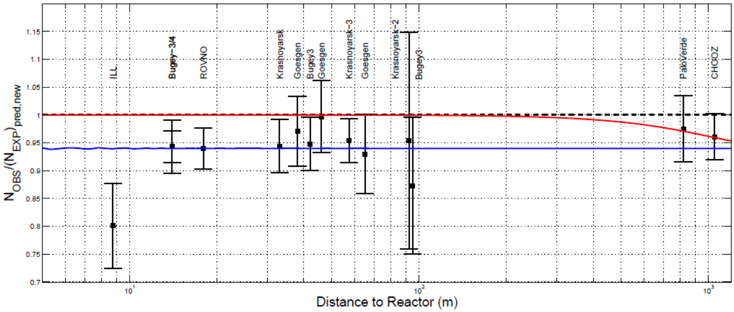
n capture on fission product

Mainly on ^{135}Xe, very strong n-absorber.
^{135}Xe $\rightarrow$ ^{135}Cs.
or ^{135}Xe + n $\rightarrow$ ^{136}Xe(stable)



The effect is minor.
[Kipeikin, 2004]

Impact of $+3\%$



Average $\mathrm{N_{obs}/N_{pred}}$ = 0.937±0.027(used to 0.979±0.029).
$\rightarrow$ a sterile neutrino?

Conclusion

- $\pm\sim$1% on e^- spectrum of ^{235}U, ^{239}Pu, ^{241}Pu.
- $\pm\sim$10% on new/old calculation on ^{238}U's $\bar{\nu}_e$.
- $+$ 3% shift above 2 MeV.
- $<$ 2 MeV spectrum uncheck.