Cerium source
Beta Spectrum Modeling

Collaboration meeting

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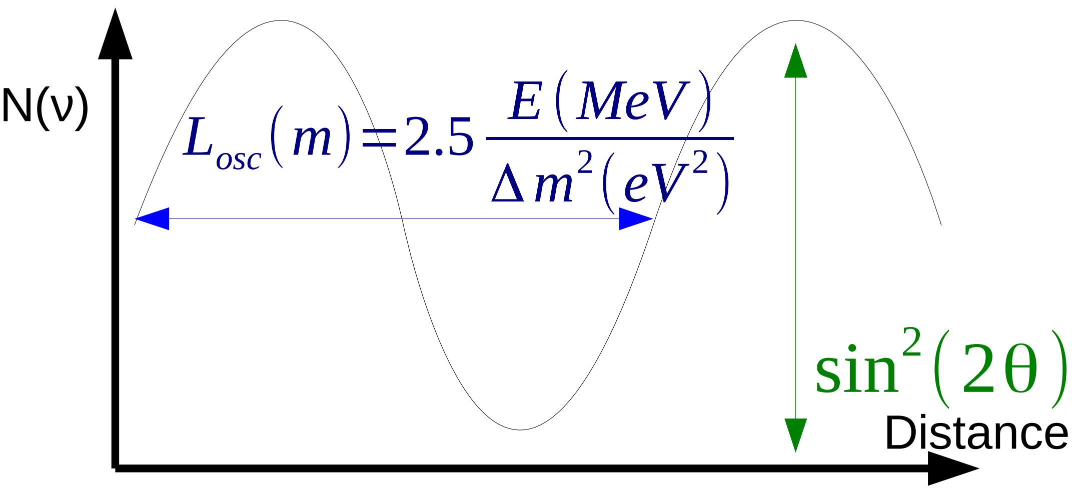
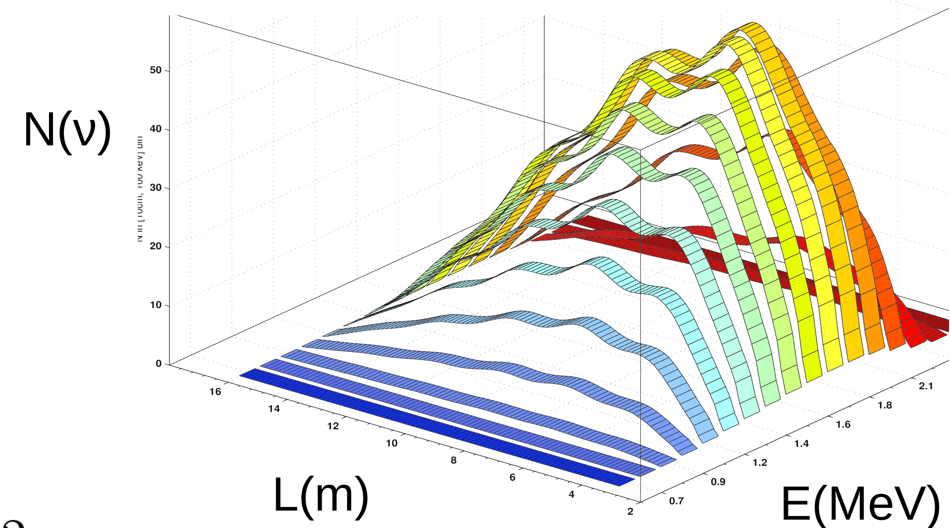
Outline

1. Beta spectrum modeling to probe into oscillations
2. The basis: Fermi Theory
3. Corrections to Fermi theory
4. Application
5. Model checking
6. Conclusion

Testing for neutrinos oscillations





Independent squared mass differences Δm^2

➡ Different oscillation regimes: $\Delta m^2_{21} = 8 \times 10^{-5}\, eV^2$

$$\Delta m^2_{23} = 2 \times 10^{-3}\, eV^2$$

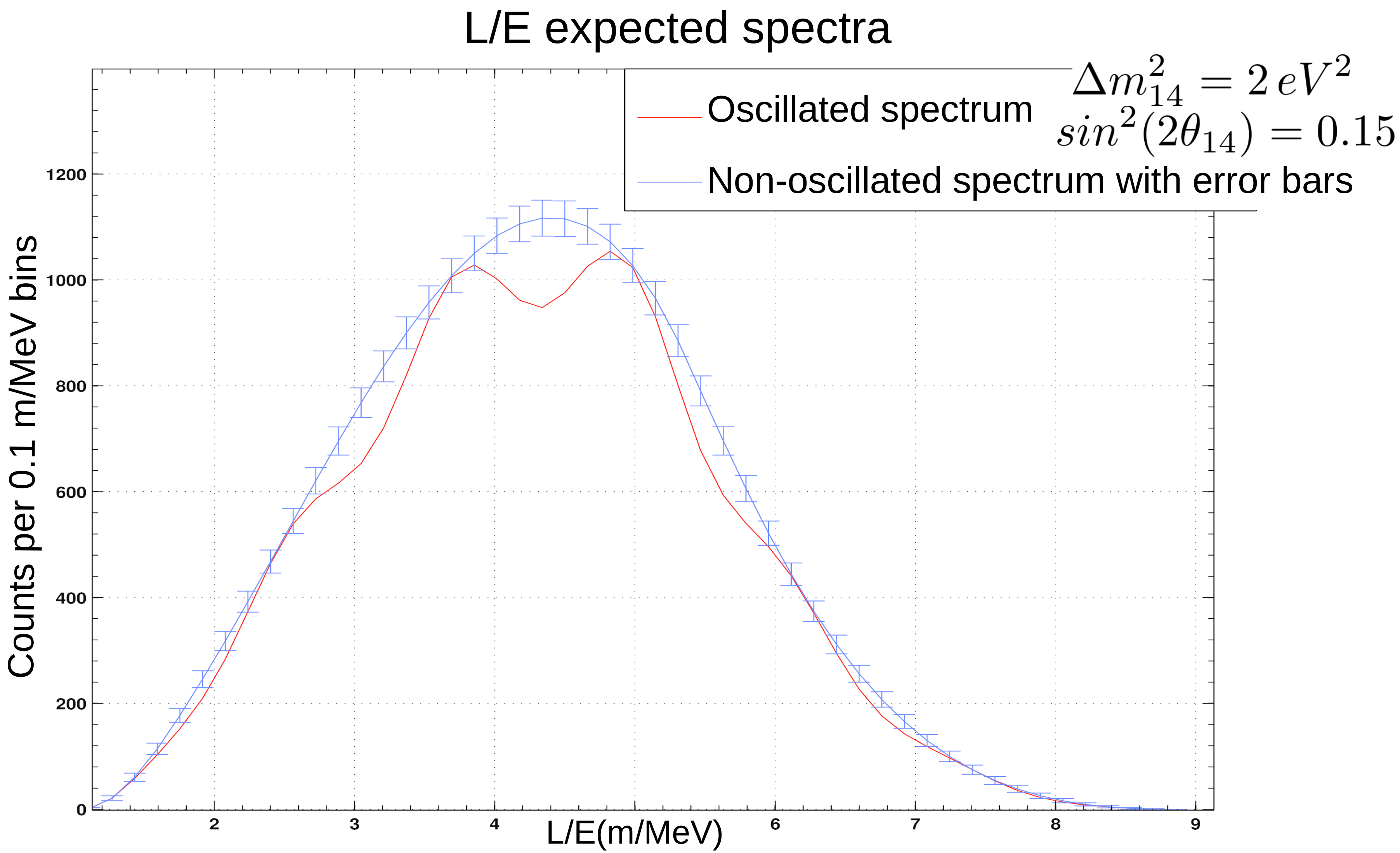
Oscillometry in the liquid scintillator detector

- Oscillation probability depends on L/E $\phi = \frac{c^3}{\hbar} \frac{\Delta m^2_{ij} L}{4E}$

➡ 2 ways for sterile ν oscillation detection

Oscillation detection methods:
- Spatial oscillation pattern
- Spectrum distortion

Utility of β spectrum modeling to search for oscillations



Precise spectrum prediction is necessary for neutrino oscillation pattern observation.

Fermi modeling of Beta spectrum

$$n \rightarrow p + e^- + \bar{\nu}$$

- From Fermi's Theory, β spectrum:

$$N(W) = KpW(W - W_0)^2 F(Z,W) C(Z,W)$$

  - $W = \frac{E}{m_e}$ Reduced electron energy W_0: maximal energy $\frac{Q_\beta}{m_e} + 1$
  - F: Fermi function: influence of Coulomb field from point-like nucleus
  - C: Shape factor from nature of the transition (phase space factor) and small corrections

Transition categorized according to:

- Branching ratio, Q_β
- Change in nucleus state $\Delta\pi, \Delta I$
- Ratio between weak axial and vector currents

Parity change	ΔI = 0	1	2
No	Allowed	Allowed	2nd forbidden
Yes	1st forbidden	1st forbidden	1st forbidden

Cerium Source

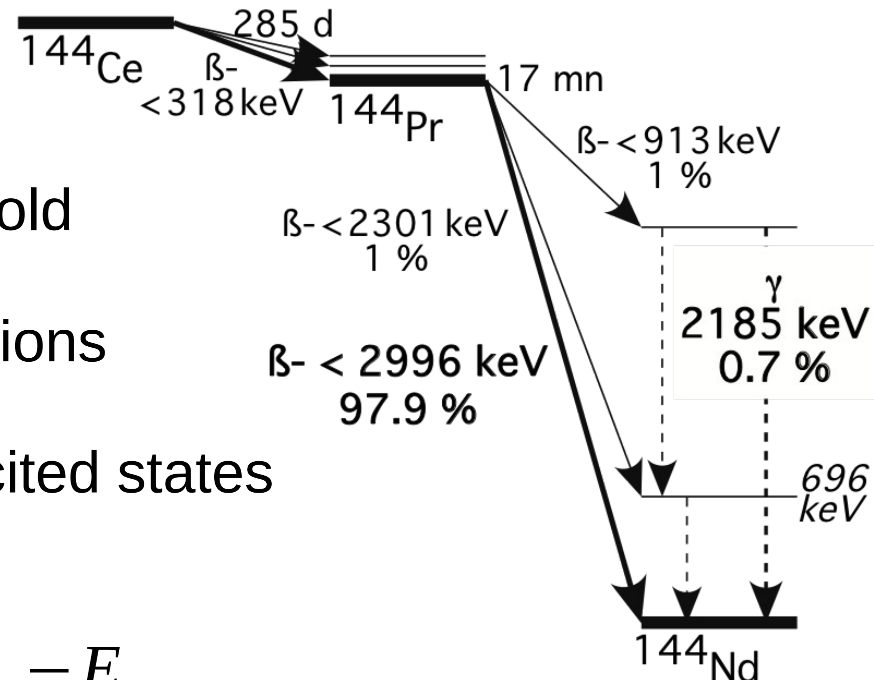
- beta decay pair 144Ce-144Pr

→ Two transitions from Praseodymium above IBD $\bar{\nu}_e + p \rightarrow e^+ + n$ threshold

→ Nine allowed or 1st forbidden transitions

→ Three negligible transitions from excited states

- Theoretical conversion procedure by energy conservation: symmetry $E_\nu \approx E_0 - E_e$



144Ce-144Pr decay scheme

For using with spectroscopic measurements, eight major 144Pr transitions are modeled.
Cerium is taken into account (possible impurity even if chemical purification of 144Pr is attempted)

Corrections to Fermi Theory

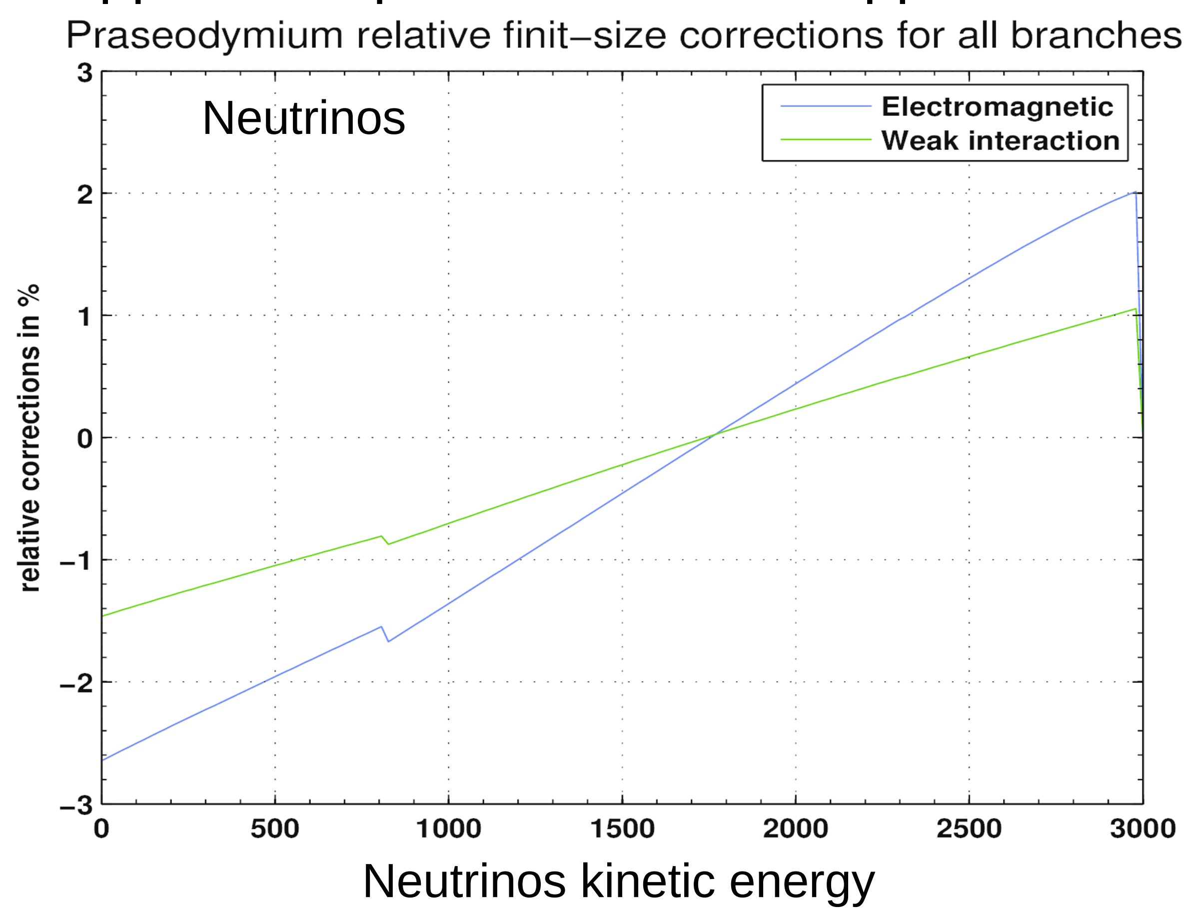
Fermi Theory accounts only for point-like nucleus Coulomb field.

Various corrective possible corrective terms with order of magnitude of 1%.

- Nucleus finite-size effects
- Atomic electrons effects (screening)
- Radiative QED corrections
- “Weak magnetism” effect
- Recoils and mass effects

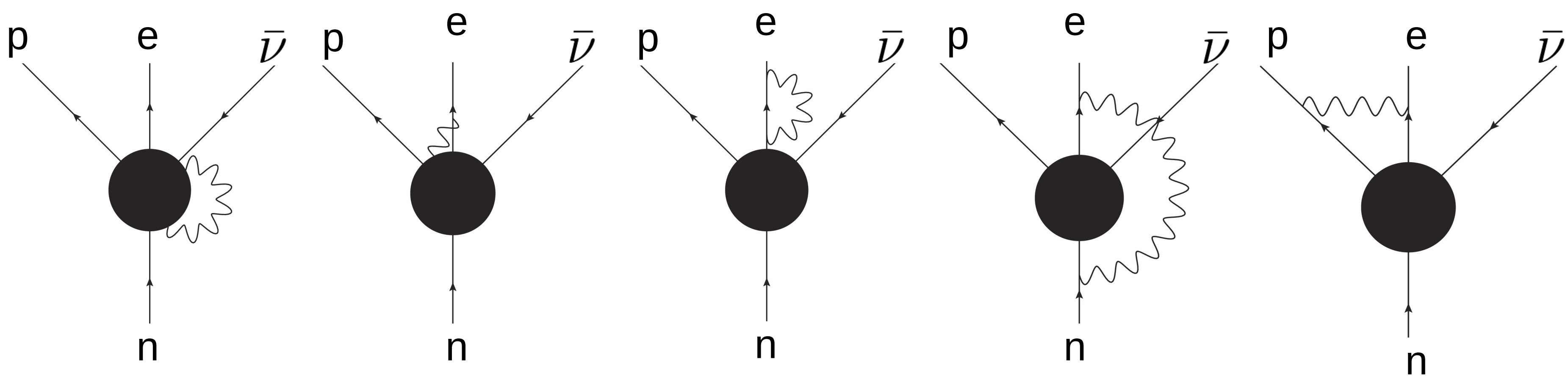
Finite-size corrections

- Electromagnetic effect: correction to Fermi function
  - Uniformly charged sphere, as opposed to point-like Fermi's approach
  - Large term
  - Small error (<10^{-5})



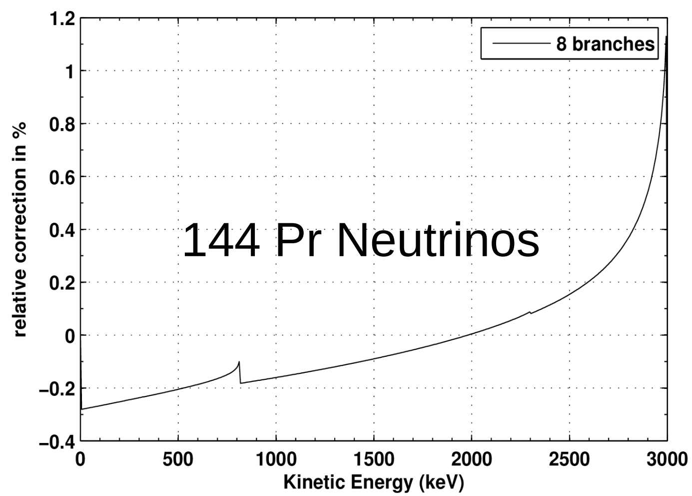
- Weak interaction analogous:
  - Smaller term
  - Depends on transition vector/axial type
  - Stronger uncertainty (<0.05)

Radiative corrections

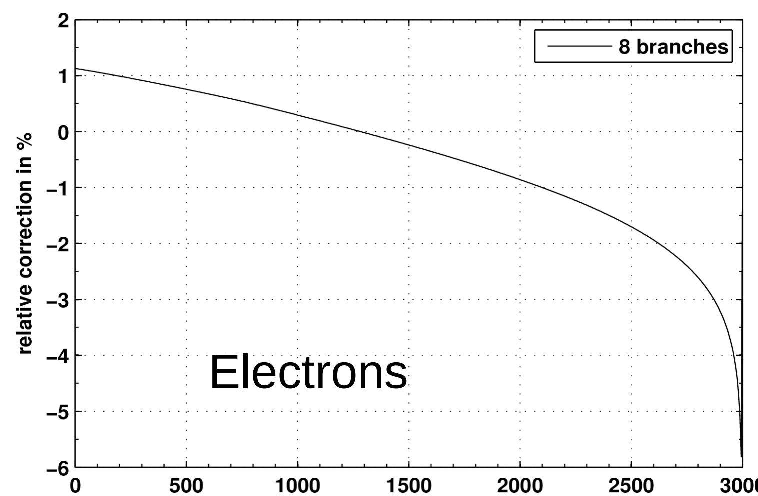


Feynman diagrams for 1st order corrections

- Emission of real and virtual photons
- First order $\alpha^n Z^{n-1}$ for terms which affect spectrum shape
- Smaller for neutrinos than for electrons



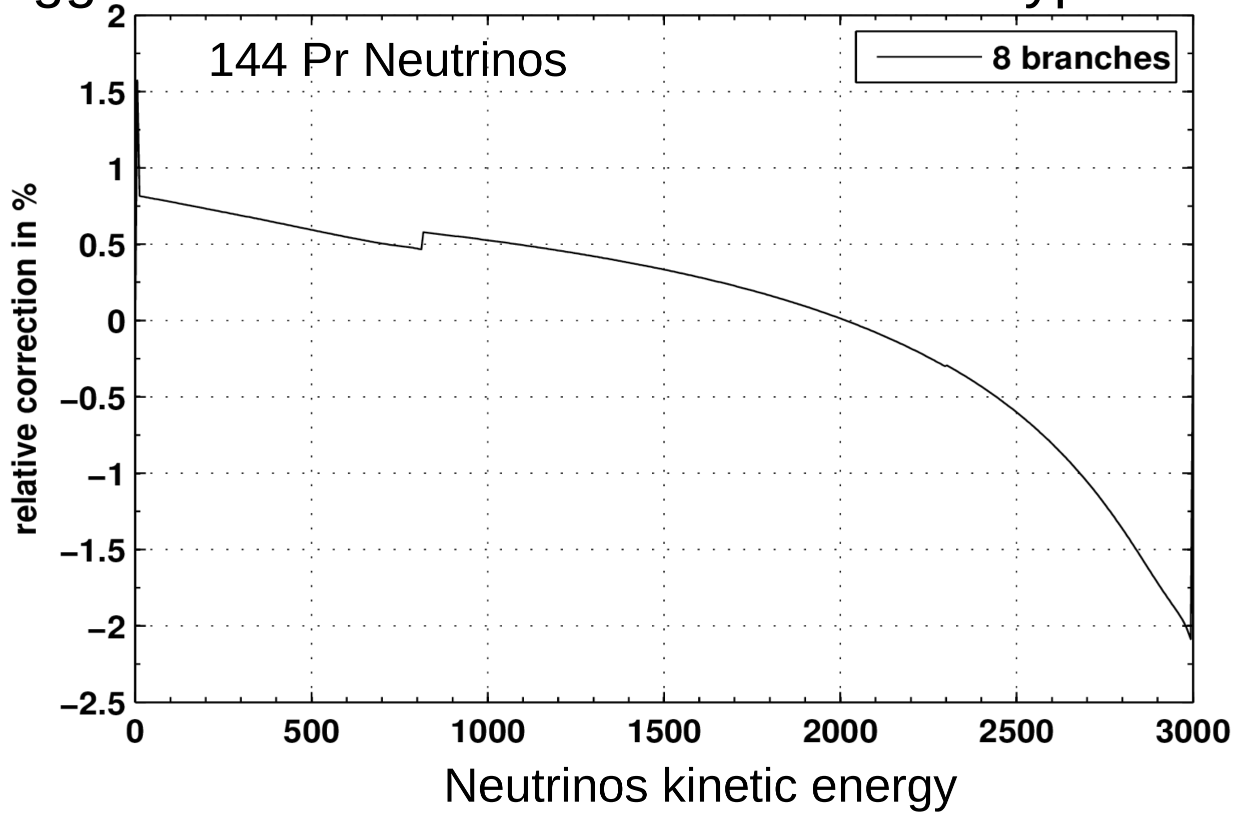
Neutrino kinetic energy



Electron kinetic energy

Screening effect

- Atomic electron influence on the beta particle emission
- Fermi function shift by screening potential V_0
- Different models for atomic electron distribution (Thomas-Fermi statistical model, Hartree-Fock method, etc): $V_0 = 20.7 \pm 1.4\,\mathrm{eV}$
- Error propagated by Taylor expansion of the correction term.
- Second biggest error source with conservative hypothesis.



Accuracy killer: weak magnetism

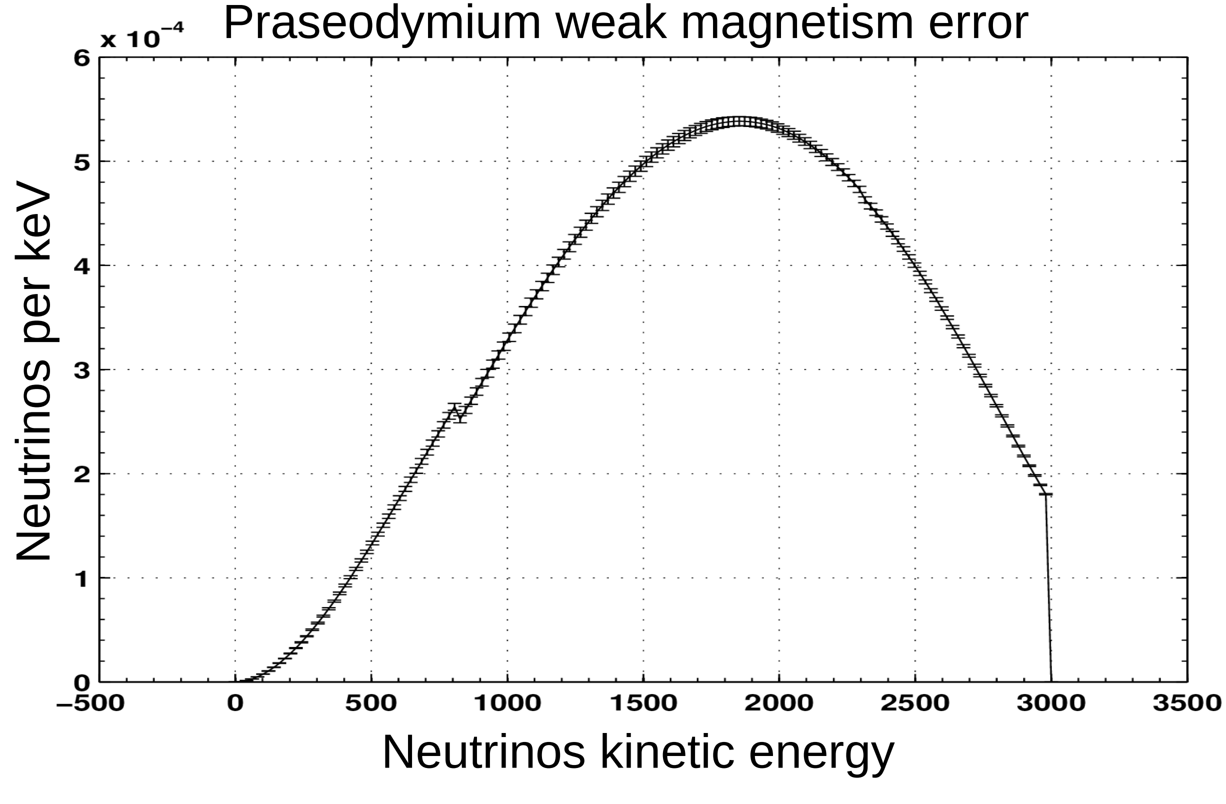
- Analogous of the electromagnetic induced currents for a moving Coulomb field, for the weak interaction
- Modeled as a linear correction $1+\delta_{WM} W$

Usual evaluation of δ_{WM}: consider nucleus as a system of free nucleons: no interaction between them

→ Neutron decay case $\delta_{WM} = 0.5\% \pm 0.5\,\%\,\mathrm{MeV}^{-1}$

- Weakest corrective term
- But largest uncertainty (arbitrary fixed)

$\gtrapprox 1\,\%$ of neutrino spectrum

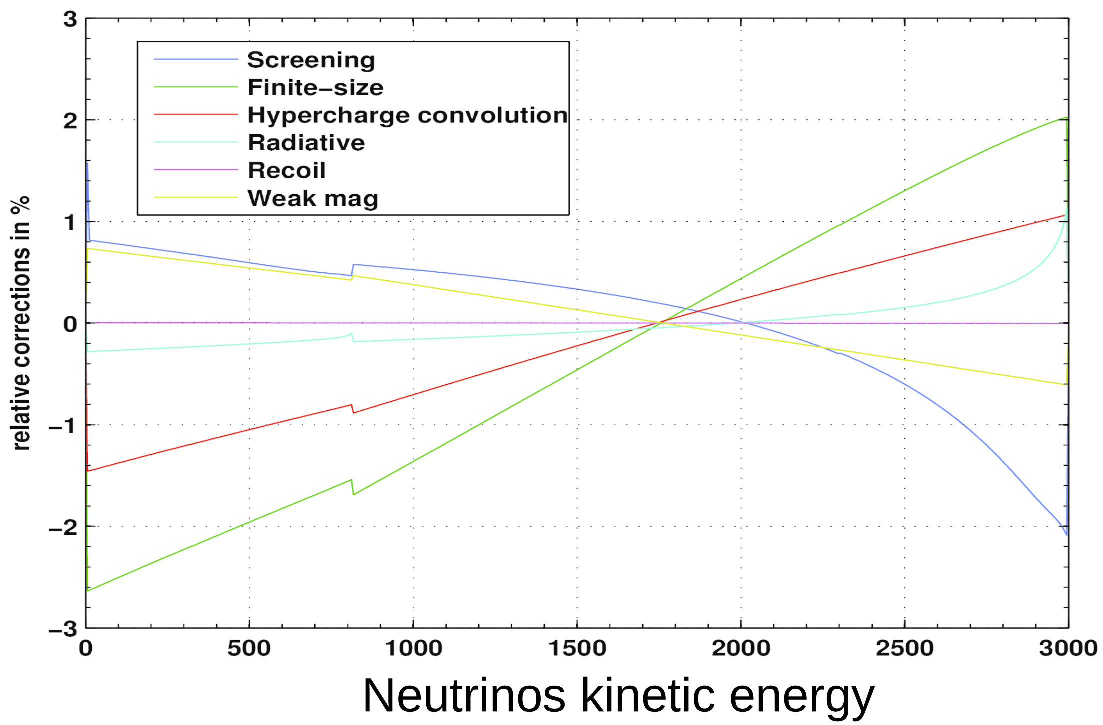


Corrections evaluation for 144Pr

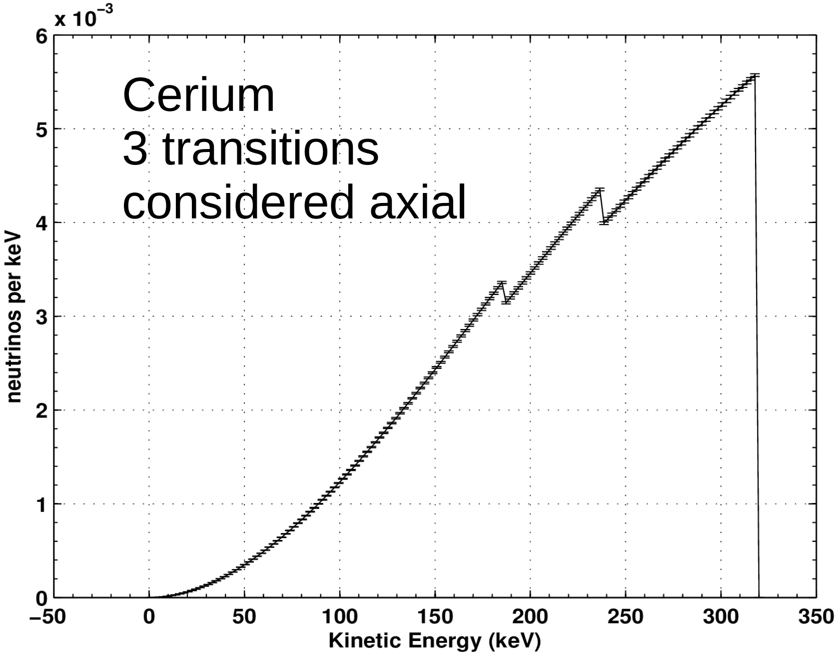
Correction	Amplitude in neutrino spectrum %	Error in %
Recoils and neutrino mass	0.013	-
Finite-size for electromagnetism	4.68	< 0.00005
Finite-size for weak interaction	2.53	< 0.1
Radiative QED correction	1.56	≈ 0.07
Screening term	2.94	0.25
Weak magnetism	1.34	1.34

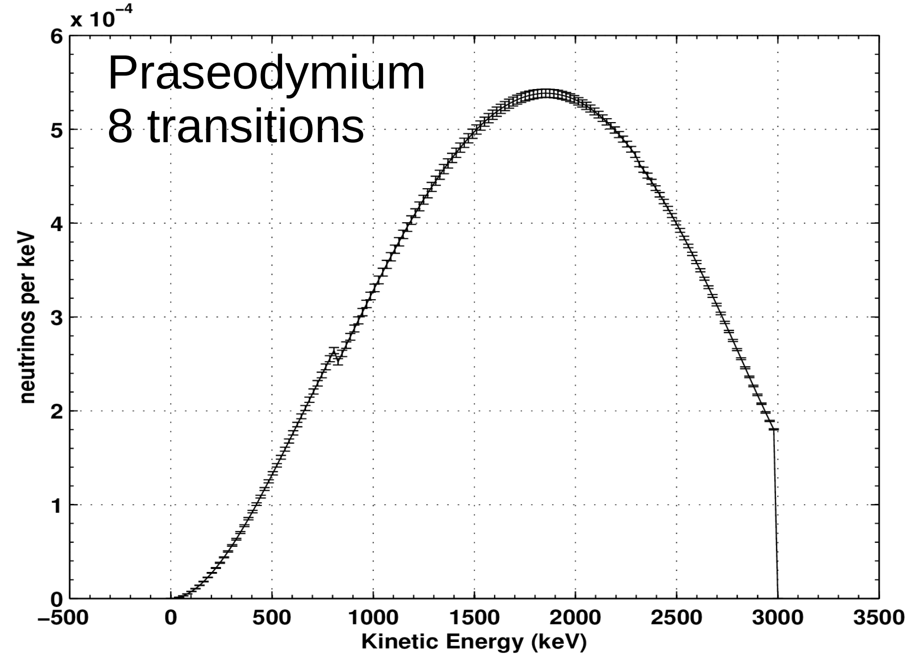
- Dismiss recoil right now
- Obvious domination from **weak magnetism**

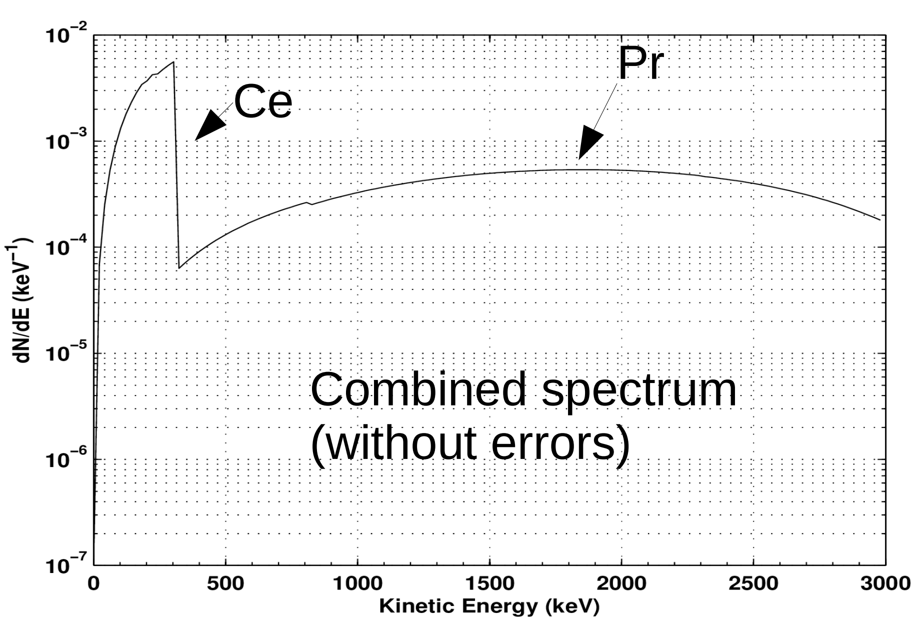
- Summary →

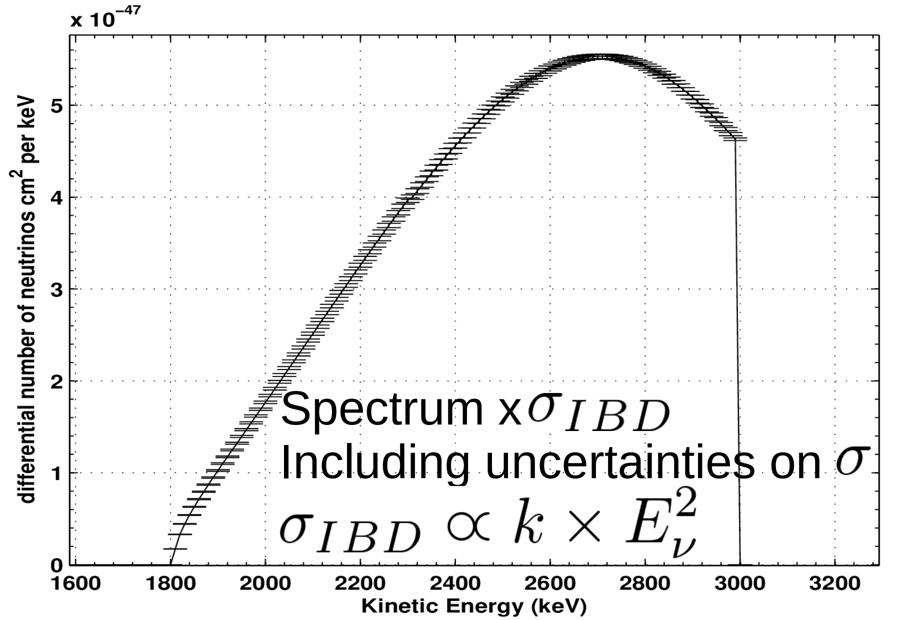


Cerium source spectra

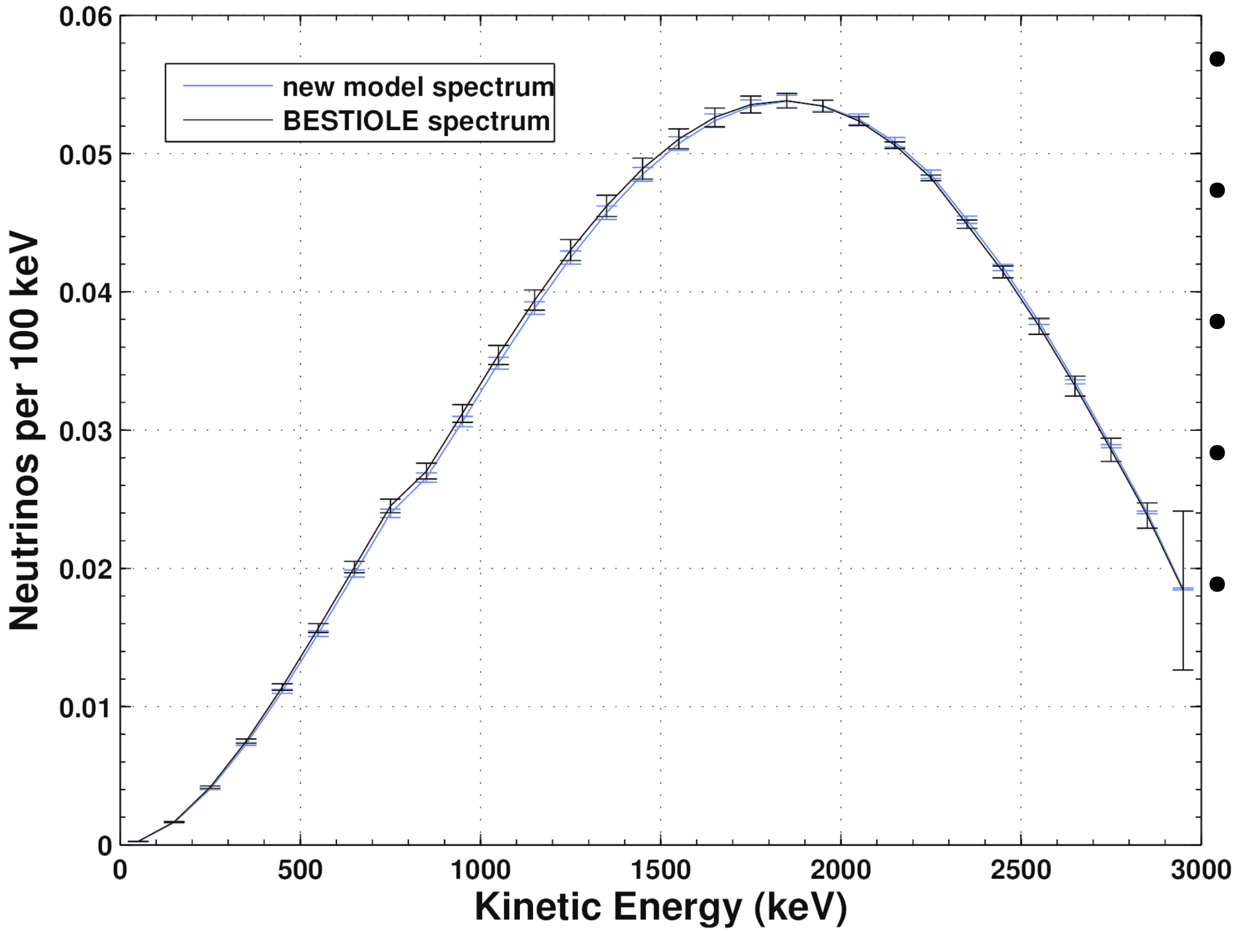








Comparison with BESTIOLE



- Good agreement with BESTIOLE prediction
- An older implementation of corrected Fermi Theory
- Used to predict reactor spectra
- Already compared to experimental data
- Finite-size, radiative and impulse approximation weak magnetism terms

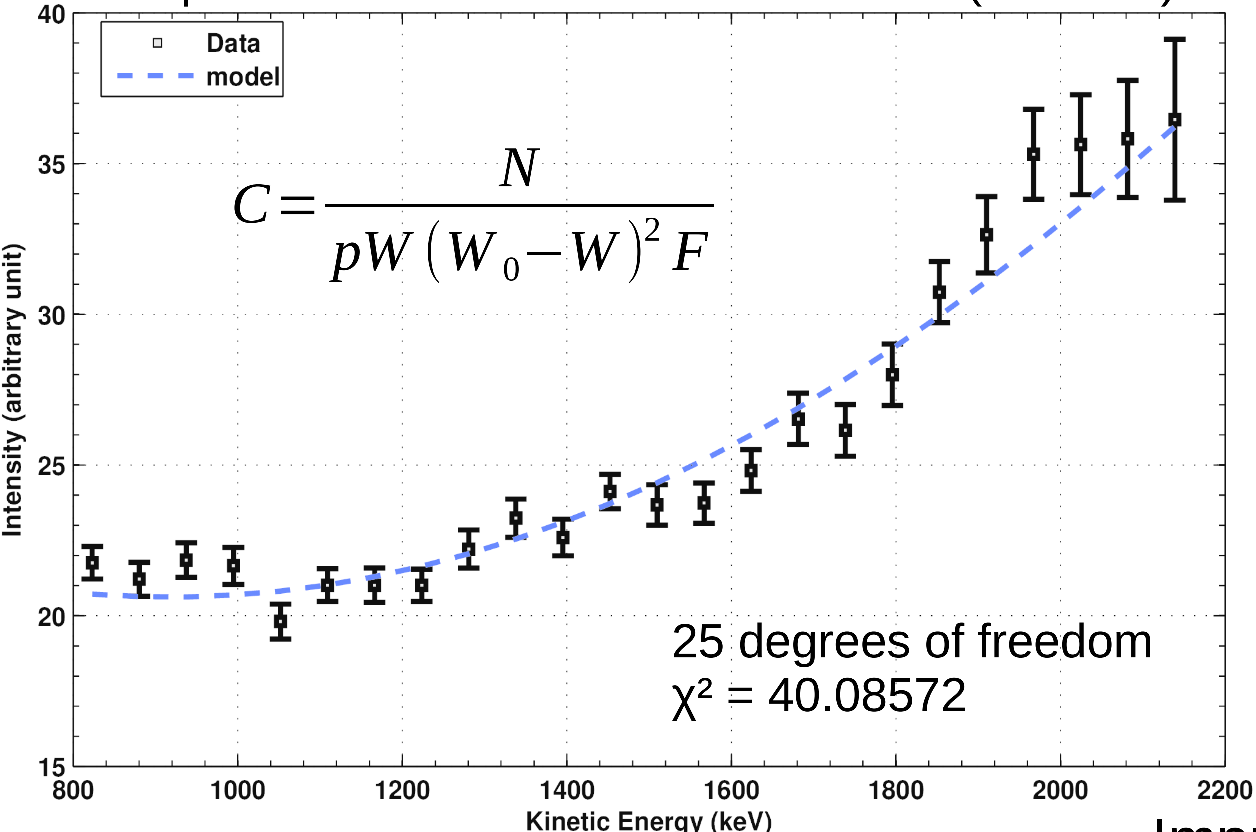
144Pr spectra from BESTIOLE in red and our model in blue

Comparison with old data

(*0- to 0+ Beta Transition 144Pr → 144Nd,* Fred T. Porter and Paul P. Day, Physical Review 114, 1959)

Promising preliminary test with Porter's data

Shape factor C for 144Pr second branch (2.3 MeV)



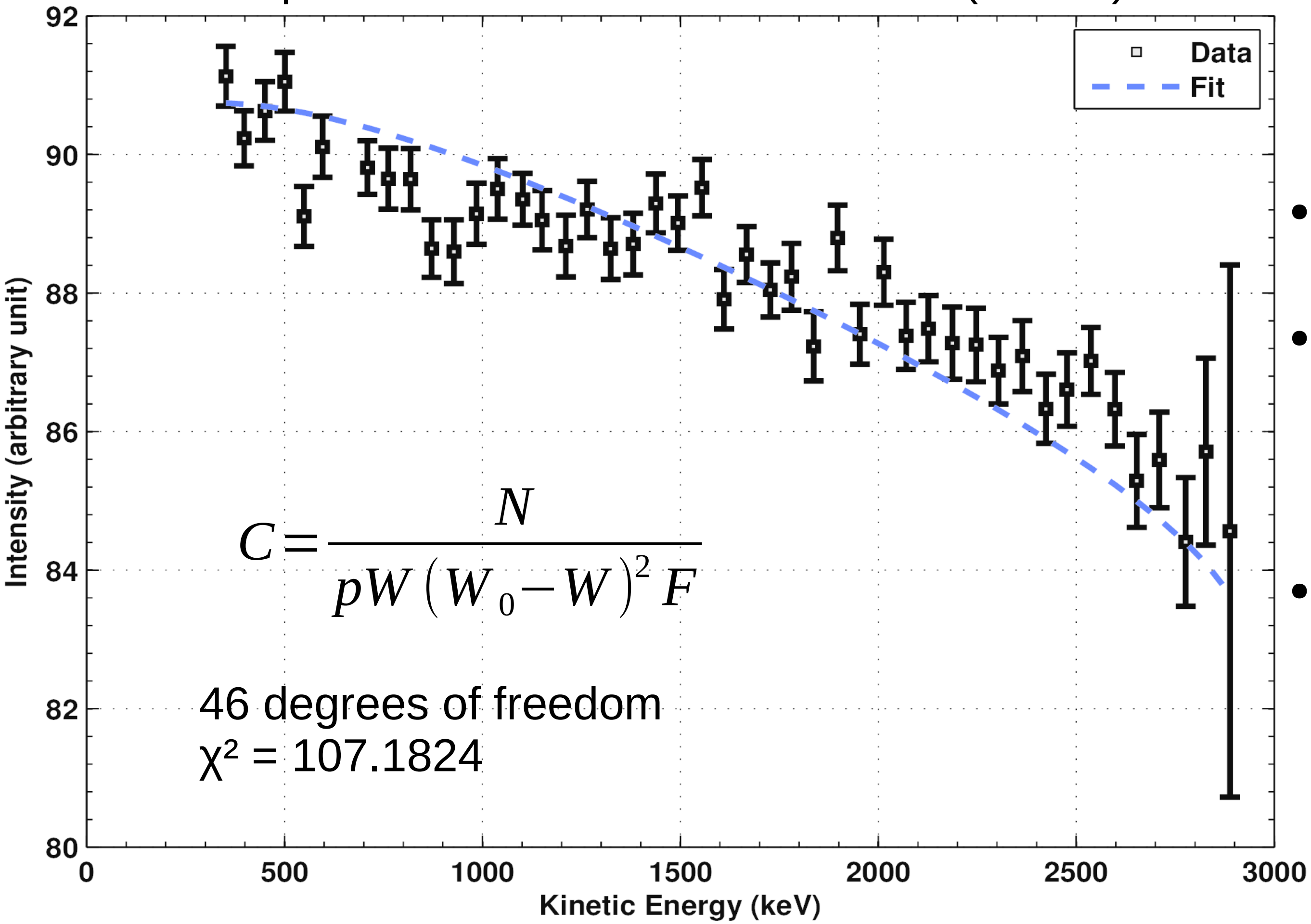
- 1st forbidden branch → phase space factor $p_e^2 + p_\nu^2$
- Tabulated data should allow to constrain corrections uncertainties.

Main final purpose:
Improving weak magnetism model

Comparison with old data

(*0- to 2+ Beta Transition 144Pr → 144Nd,* Fred T. Porter and Paul P. Day, Physical Review 114, 1959)

Shape factor C for 144Pr first branch (3 MeV)



1st forbidden branch

- Work needed on the main phase space term
- Possible instrumental effects (e.g. detector resolution) to be taken into account.
- Study of higher order effects (e.g. radiative)

Next steps

- Improving the model robustness and precision
- Beta spectroscopic measurements at LNHB (Saclay):
    - 100 kBq cerium nitrate solution samples on their way
    - Liquid chromatography separation
    - Spectroscopy with liquid scintillator for both nuclei
- Taking advantage of already available data.

Main references

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- National nuclear data center, http://www.nndc.bnl.gov
- K.S. Krane and D. Halliday, *Introductory nuclear physics.* Wiley, 1987
- H. Behrens and W. Bühring, *Electron Radial Wave Functions and Nuclear Beta-Decay,* Clarendon Press, 1982.
- Patrick Huber. *Determination of antineutrino spectra from nuclear reactors,* Phys. Rev. C, Aug 2011.
- Thomas Mueller, *Expérience Double Chooz : simulation des spectres antineutrinos issus de réacteurs* PhD thesis, IRFU/SPhN
- A. Sirlin. *Radiative correction to the electronic neutrino (antineutrino) spectrum in β decay*, Phys. Rev. D, Jul 2011
- D. H. Wilkinson, *Evaluation of beta-decay,* series of seven articles in Nuclear Instruments and Methods in Physics Research, 1989-1998

Backup slides

Cerium-Praseodymium Source

144 Pr
Z=59
N=85

Branching ratio	I^π	Q_β(keV)	type	V-A Ratio
97.9 %	0^+	2997.5	1st forbidden	A 100 %
1.04 %	2^+	2301.0	1st forbidden	A 100 %
1.05 %	1^-	811.8	Allowed	A 100 %
$6.70 \cdot 10^{-3}\%$	0^+	913	1st forbidden	A 100 %
$1.4 \cdot 10^{-3}\%$	2^+	1436.5	1st forbidden	A 100 %
$8.7 \cdot 10^{-4}\%$	0^+	322.2	1st forbidden	A 100 %
$6.2 \cdot 10^{-4}\%$	2^+	924.7	1st forbidden	A 100 %
$3.0 \cdot 10^{-4}\%$	0^+	254.6	1st forbidden	A 100 %
$1.5 \cdot 10^{-4}\%$	1^+	342.6	1st forbidden	unknown

Three more negligible transitions from excited states

144 Ce
Z=58
N=86

Branching ratio	I^π	Q_β(keV)	type	V-A ratio
76.5 %	0^-	318.7	1st forbidden	A 100 %
3.9 %	1^-	238.6	1st forbidden	unknown
19.6 %	1^-	185.2	1st forbidden	unknown

Two transitions from Praseodymium above IBD threshold

IBD Cross section

- Corrected cross section with radiative correction, recoil terms and weak magnetism, as described in *Radiative corrections and recoil effects in the reaction* $\bar{\nu}_e + p \rightarrow e^+ + n$ *at low energies,* Fayans, S. A., Sov. J. Nucl. Phys. 1985.

- Valid approximation in the 0-3 MeV range.

- Uncertainty dominated by the cross section prefactor, so depending on neutron lifetime.