Improved modeling of reactor antineutrino spectra

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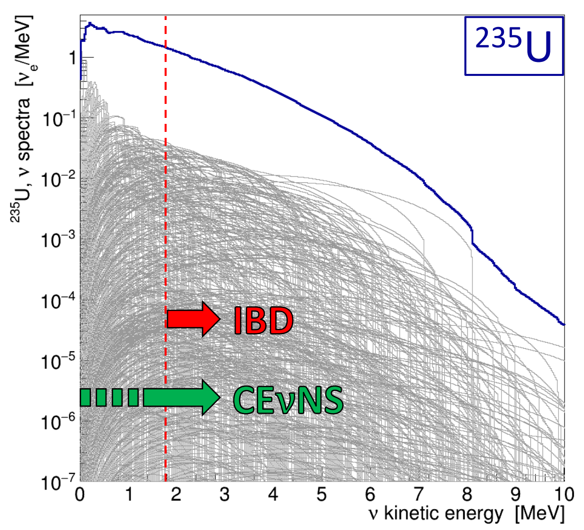
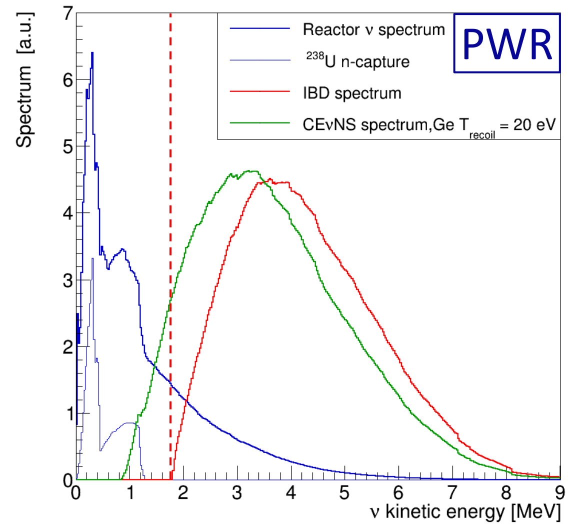
1. REACTOR ANTINEUTRINOS

- Reactor $\bar{\nu}_e$ flux origin:
  - Commercial reactor (PWR): ^{235}U > ^{239}Pu > ^{238}U > ^{241}Pu fission (~80%) and n-capture on ^{238}U (~20%)
  - Research reactor: ^{235}U fission and n-capture on structural material
- ~800 β⁻ emitters among fission products
  - Successive β-decays of unstable fission products
  - ~6 $\bar{\nu}_e$ emitted for one fission
  - Fission spectrum is a superposition of thousands of β-branches
- Reactor flux $\sim 2 \times 10^{20}\ \bar{\nu}_e.s^{-1}.GW_{th}$
- Detection: IBD, 1.8 MeV threshold
  CEνNS in near future, thresholdless
- Reactor $\bar{\nu}_e$ spectrum prediction:
  - Conversion method, used in current predictions but limited to 2-8 MeV
  - Summation method, only possibility below 1.8 MeV, but based on uncomplete nuclear databases, model approximations and large uncertainties

⇒ **Need to improve and extend predictions**





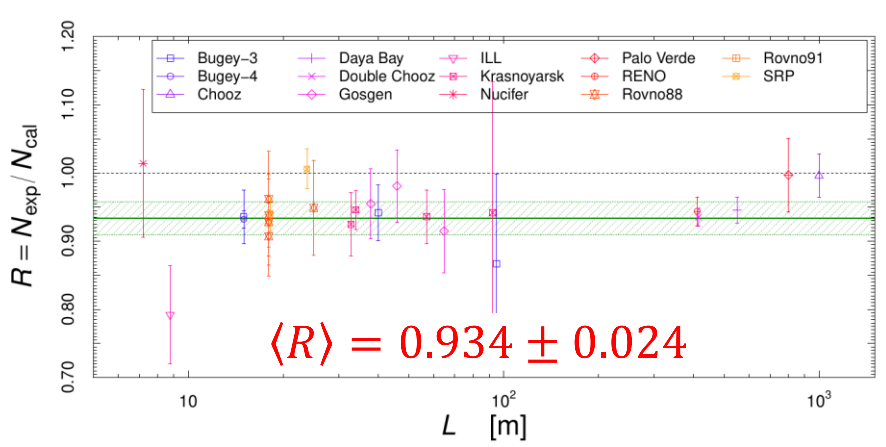
2. TENSIONS BETWEEN IBD EXPERIMENTS & PREDICTIONS

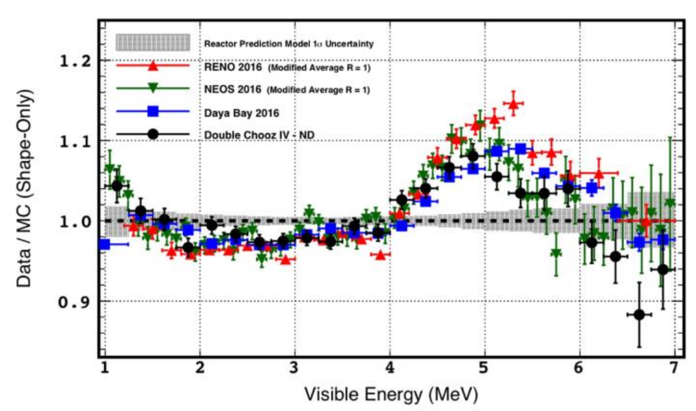
- Tensions wrt to Huber-Mueller (HM) model: ^{235}U and ^{239,241}Pu conversion [1] + ^{238}U summation [2]
- Rate anomalies:
  - Reactor $\bar{\nu}_e$ anomaly (RAA): ~6% deficit at 2.8σ statistical significance [3,4]
  - Change in the measured IBD rate wrt to fuel composition incompatible with HM predictions [5]
- Shape anomaly: shape of measured IBD spectra incompatible with HM predictions

Possible interpretations:

- New physics (*e.g.* sterile neutrinos)
- Detection effect (*e.g.* residual bias in the energy scale)
- **Bias in the predictions**
- **Underestimated prediction uncertainties**

⇒ **New evaluation of summation prediction & uncertainties**





3. REVISED SUMMATION MODELING AND UNCERTAINTY BUDGET

SPECTRUM MODELING

β-branch spectrum : $S_\beta(E) = K \times F(Z,A,E) \times pE(E-E_0)^2 \times C(E) \times \delta(Z,A,E)$

(Fermi function; Phase space; Shape factor; Corrections: radiative cor. (RC) + weak magnetism (WM))

Fission spectrum: $S_f(E) = \sum_i FY_f^i \sum_b BR_i^b S_\beta(E)$

(Fission yield; Branching ratio)

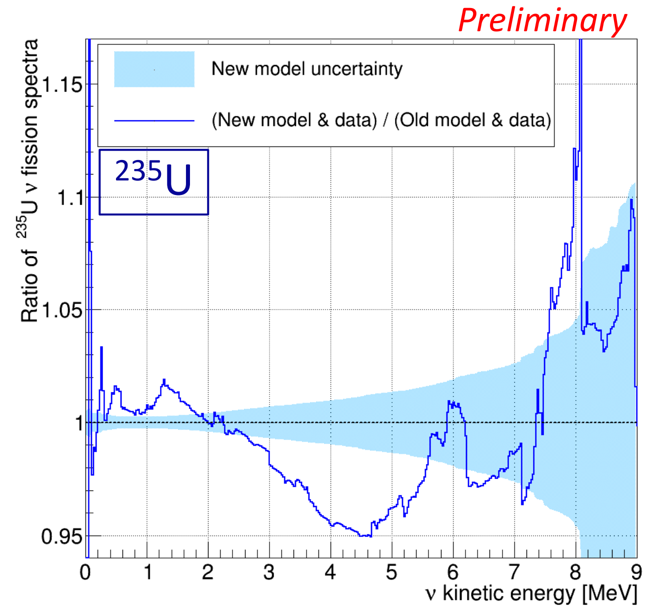
- f: fissionable isotope
- i: fission product
- b: isotope branch

- β-branch spectrum for a daughter nucleus (Z, A)
- Energy conservation at the branch level with available energy $E_0 = E_\nu + E_\beta$
- Summation prediction with the BESTIOLE code [4]: refined modeling + revised uncertainties

	Former	This work
Nucleus	Point-like	Spherical with a finite-size
Atomic screening	Null	Screened nuclear potential w/ Salvat params [6]
Fermi function	Analytical	Numerical (Behrens & Bhuring formalism [7])
Shape factor	Polynomial w/ const. coef.	Polynomial w/ coef. depending on nuclear potential
Correction	Simplified RC + WM	Simplified RC + refined WM

TREATMENT OF THE TRANSITION TYPES

Type	$\bar{\nu}_e$ [%]	IBD [%]	Modeling
Allowed	60	45	Robust and accurate
Unique forb.	10	10	Robust and accurate
Non-unique forb.	30	45	
• Main: ^{92}Rb + ^{96}Y + ^{144}Pr	2	12	Advanced: nuclear shell model [8]
• Others	28	33	Simplified: ξ-approximation



UPDATE OF NUCLEAR DATABASE

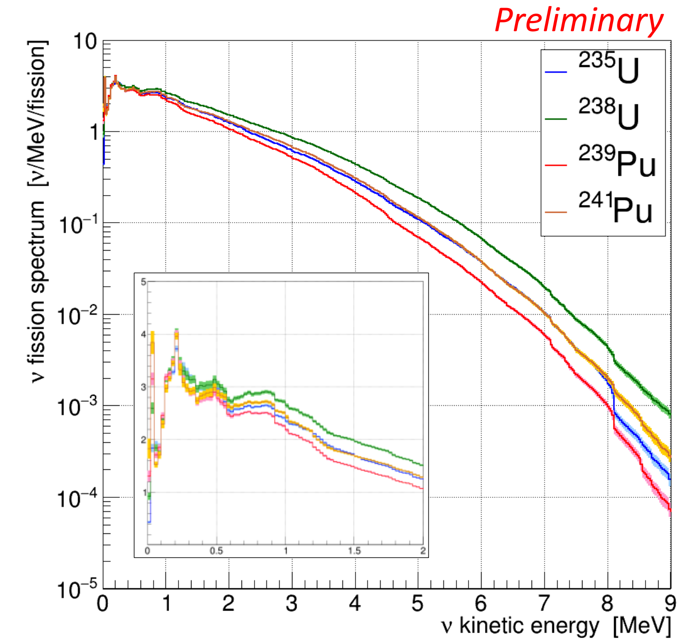
- β⁻ emitter list from NUBASE-2020
- TAGS > direct β spectrum measurement [9] > ENSDF-2020
- Effective modeling for fission products with no data [10]
  - 3 equiprobable branches with $E_0 = \left\{ {}^{Q_\beta}/_3, {}^{2Q_\beta}/_3, Q_\beta \right\}$

⇒ **Negligible impact of improved modeling (<0.1% on IBD yield), important impact of nuclear database update (-2.7% on IBD yield)**

MODELING OF UNCERTAINTIES

	Source	Uncertainty type	Branch correlation	Propagation method
Nuclear data	Endpoint energy (E_0)	Shape only	Fully correlated	MC simultaneously over E_0 and the different $J\pi$ couples
Nuclear data	Spin-parity ($J\pi$)	Shape only	Uncorrelated	
Nuclear data	β⁻ intensity (I_β) Branching ratio (BR)	Normalization: $\sum BR = I_\beta$ • $\sigma(I_\beta) = 0 \rightarrow$ Shape only • $\sigma(I_\beta) > 0 \rightarrow$ Shape + Norm.	Before MC: unknwon After MC: maximize IBD yield uncertainty	Mixed: MC + Analytical
Nuclear data	Fission yield (FY)	Normalization		Analytical
Modeling	Weak magnetism (WM)	Shape only	Uncorrelated	Uncertainty obtained by comparing 2 β-branch modelings w/ and w/o the correction
Modeling	Radiative correction (RC)	Shape only	Uncorrelated	
Modeling	Non-unique forb. branch (NU)	Shape only	Uncorrelated	

4. NEW PREDICTION WITH SUMMATION METHOD



Preliminary

		^{235}U		
		$\bar{\nu}_e$	$\langle\sigma_{IBD}\rangle$	$\langle\sigma_{CE\nu NS}\rangle$
		6.08 [$\bar{\nu}_e$/fis]	6.50 [10^{-43} cm²/fis]	11.50 [10^{-41} cm²/fis]
Normalization uncertainty [%]	FY	0.30	1.07	0.87
	BR + I_β	0.03	0.63	0.47
	E_0 + Jπ	-	0.19	0.14
	σ	-	0.10	-
	NU	-	0.49	0.34
	WM	-	0.04	0.02
	RC	-	0.01	0.01
	Pande	-	-	-
	Total	0.31	1.35	1.06

NU, WM, RC: Preliminary model, work in progress. Pande: Work in progress.

$\langle\sigma_{CE\nu NS}\rangle$: Ge, T_{recoil} = 20 eV

CAVEAT: UNCERTAINTY MODEL NOT YET FINALIZED

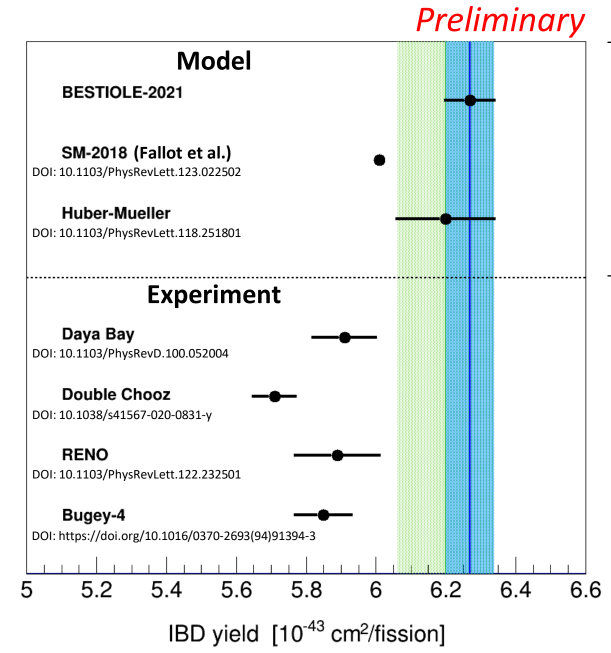
- NU, WM and RC modeling uncertainties to be revised (probably underestimated)
- Uncertainty of fission products with no data to be checked (probably underestimated)
- Remaining uncorrected Pandemonium effect in candidate isotopes
  - Candidate isotopes contribute up to 20% (resp. 17%) of ^{235}U $\bar{\nu}_e$ flux (resp. IBD yield)
  - Specific uncertainty to be added

PRELIMINARY COMPARISON WITH EXPERIMENTS AND OTHER PREDICTIONS

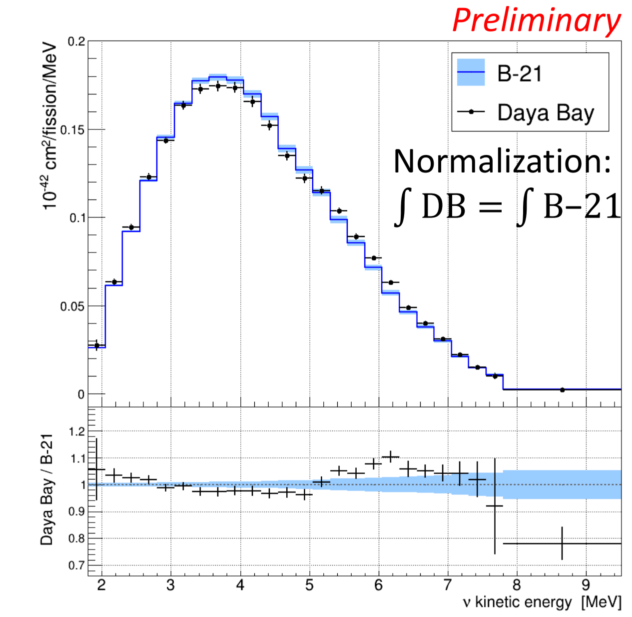
- Daya Bay fission fractions [11]:
  ^{235}U = 0.564
  ^{238}U = 0.076
  ^{239}Pu = 0.304
  ^{241}Pu = 0.056

Preliminary

	$\langle\sigma_{IBD}\rangle$ [10^{-43} cm²/fis] B-21 (this work)	HM	SM-2018	Daya Bay [11]	STEREO [12]
^{235}U	6.50 ± 0.09	6.69 ± 0.15	6.28	6.10 ± 0.15	6.34 ± 0.22
^{238}U	10.32 ± 0.15	10.10 ± 1.00	10.14	-	-
^{239}Pu	4.72 ± 0.07	4.36 ± 0.11	4.42	4.32 ± 0.25	-
^{241}Pu	6.93 ± 0.10	6.04 ± 0.60	6.23	-	-



The experiments exhibit different fuel compositions that can impact the IBD yields up to 0.5%.



Spectrum comparison of Daya Bay [13] and BESTIOLE (B-21)

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5. CONCLUSION & NEAR FUTURE

- ✓ Refined β-branch modeling
- ✓ Updated nuclear database
- ✓ New uncertainty model
- Update comparison and address anomaly origin
- Publication in preparation
- Provide prediction <1.8 MeV for CEνNS exp.