Nuanced Beta Spectral Shapes and Their Role in Exploring Physics Beyond the Standard Model

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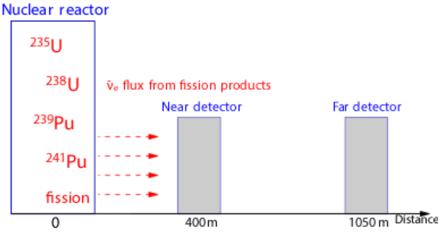
and

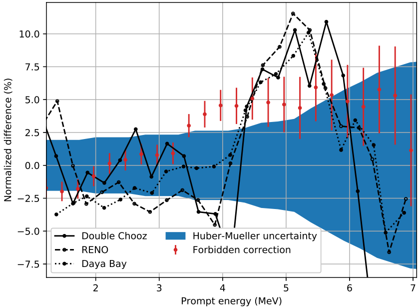
the spectral bump

Looking through the beta spectra: Reactor flux anomaly

The $\bar{\nu}_e$ flux from reactors has been measured in short-baseline neutrino-oscillation experiments[1]: Daya Bay (in Daya Bay, China; 6 reactors, 8 detectors), RENO (South Korea; 2 detectors 294m and 1383 m from 6 reactors) and Double Chooz (Chooz, France, 2 detectors 400m and 1050 m from 2 reactors, schematic figure below).

Spectral shoulder image: [2]





[1] RENO: Phys. Rev. Lett. 108 (2012) 191802; Double Chooz: J. High Energy Phys. 2014 (2014) 86; Daya Bay: Phys. Rev. Lett. 116 (2016) 061801.

[2] Phys. Rev. C 99 (2019) 031301(R) Phys. Rev. C 100 (2019) 054323

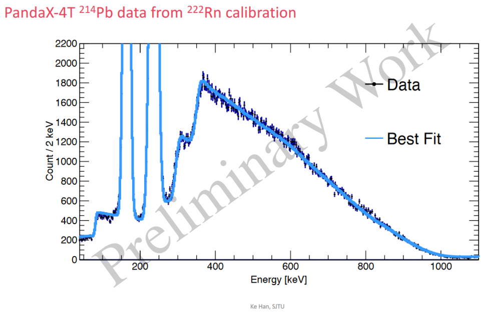
Investigating

^{214}Pb Beta Background Radiation Effects in the Rare Events Experiment: PandaX

Looking through the beta spectra: Background Beta Spectra

PandaX is an underground Dark matter and neutrino experiment in China, and often, one of the big issues detectors of this kind encounter is the background radiations from the many sources.

Our collaboration with PandaX analysis to further purify by calibration the detection involves the isotope ^{214}Pb's decays to ^{214}Bi. For the latest ^{222}Rn calibration:



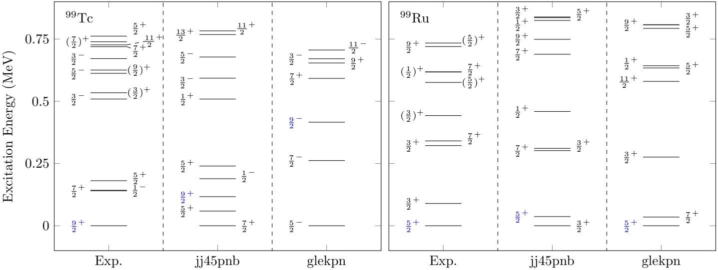
This curve consists of the contamination of ^{214}Pb, ^{212}Pb and ^{133}Xe and others.

- *NuShellX* is a Nuclear Shell Model (NSM) software[3] applicable for both Linux and Windows that calculates nuclear properties using proton-proton, proton-neutron, and neutron-neutron interactions. It can use OpenMP (Multiple cores) and has a vast amount of interactions already added to the program.
- *KSHELL* (NSM) is a software[4] usable in Linux. It has advantages over NuShellX as it can use most of NuShellX's interactions, while also being able to use OpenMP + MPI (Multiple Cores and Computer Nodes)
- The effective interactions have single-particle energies and nucleon spaces according to their area of fitting (That is, where they have been fit from.), also their TBME (Two-body matrix elements) and is limited, but an effective tool.

[3] B.A. Brown, W.D.M. Rae, Nuclear Data Sheets, Volume 12, 115-118 (2014)

[4] N. Shimizu, T. Mizusaki, Y. Utsuno, and Y. Tsunoda, Computer Physics Communications 244, 372 (2019).

Overview of Nuclear Shell Models: *NuShellX and KSHELL*



Level schemes for ^{99}Tc and ^{99}Ru with their corresponding NSM-computed values using the interactions *jj45pnb* and *glekpn*. For more info see: ArXiV 2312.07448

- These software programs can compute level schemes of isotopes given an assumed closed core and the valence space of the interaction. Truncations can be made to reduce the huge dimensionality of the matrices and thus calculation time.
- One can then use these software programs to calculate the one-body densities (OBDs), which can be used in turn to calculate the Nuclear Matrix Elements (NMEs). These are then used to compute the β decay's half-lives and spectra.
- Factors such as g_A^{eff}, ε_{MEC} and sNMEs play a major role in determining the shape and half-life of decays.

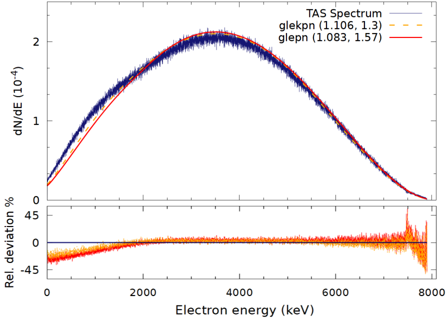
^{92}Rb β-spectrum for Reactor Flux Anomaly

The β^- decay of ^{92}Rb with a Q value of 8.095 MeV:

- The allowed simulation of TAS data show a surplus in low-energy electrons.
- Slight surplus around 4-6 MeV. $\rightarrow$ Could be the reason for the reactor spectral shoulder.
- Deficit in low-energy electrons implies smaller cross section for IBD detection*
  $\rightarrow$ TAS vs NSMs have a drop in the total flux by 2.6%-4.6%.

*: A. C. Hayes and P. Vogel, Annual Review of Nuclear and Particle Science 2016 66:1, 219-244 (2016).

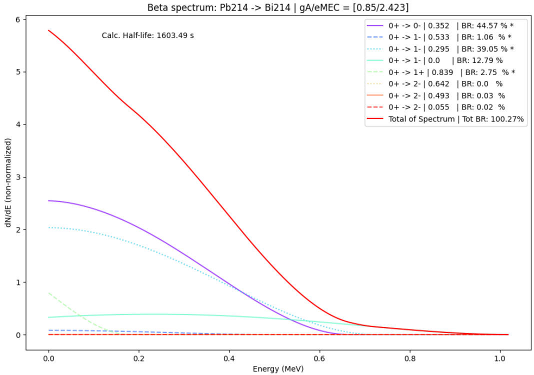
Comparison of the computed total spectrum with the TAS spectrum. Computations done by using two available shell-model interactions.



TAS spectrum obtained from the TAS-measured (A. Algora *et co.*) branchings assuming all transitions to be allowed.

^{214}Pb Background decays in Rare Event detectors

- The level schemes and β-decays of ^{214}Pb were calculated using the *khpe* interaction. The selection of the g_A^{eff} was based on a previous study of the same interaction and isotope. ([a])
- The ε_{MEC} analysis was done studying the effects on both ^{214}Pb and ^{212}Pb 0^+ to 0^- decays that agreed with the experimental half-life.
- The study involved fitting the small relativistic nuclear matrix elements (sNMEs) to the experimental half-life and comparing them to the CVC-expected value for each individual decay.



NSM Calculation of β-shape using the interaction 'khpe'. (*) denote where the excitation energies have been modified by their experimental values. Branching ratio percentages are related to the total experimental half-life

[a] DOI: 10.1103/PhysRevC.102.065501

^{214}Pb Background decays in Rare Event detectors

- One of the main contributions of the Radon calibration stems from ^{214}Pb, as can be seen. The added ^{214}Bi curves are NSM-computed.
- The PandaX LXe TPC detector shows the beta curves starting from a dislocation from the axis equal to the gamma energy emitted. As this is a '5D' detector calorimeter, it precisely measures 3D position, energy, and timing information on the event. Ranging from < 1 keV to 10 MeV.
- Note: There are a few other contributions in this calibration, such as ^{212}Pb, ^{133}Xe, and others.

PandaX-4T ^{214}Pb data from ^{222}Rn calibration

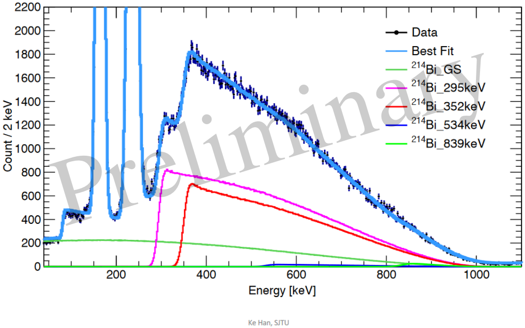
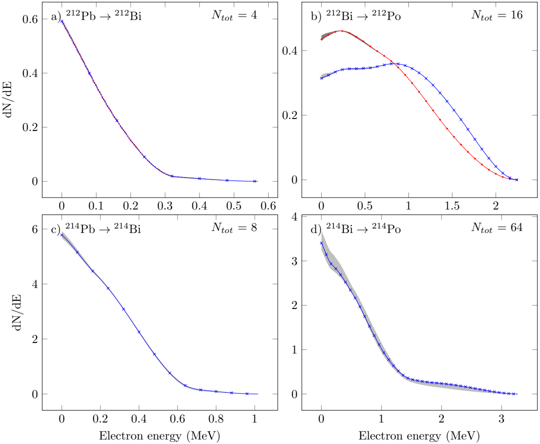


Image provided by Ke Han on behalf of the PandaX collaboration

$^{212-214}$Pb Decay Chains for Rare Event detectors

- The $^{212-214}$Pb-Bi-Po decay chains' spectral shapes display the small relativistic Nuclear Elements (sNMEs) dependency [a] in with the shaded regions. Two fitting values for the sNMEs that reproduce the half-life can be found for each individual transition.
- Panel b) demonstrates a strong dependency in the sNME choice between the two; Other examples of curves with strong sNME dependency can be found at ([b])
- Due to the high N_{tot} and the quadratic nature of the sNMEs, the total spectra of ^{214}Bi-Po has a large shaded area.

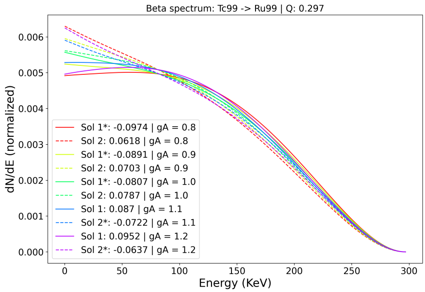


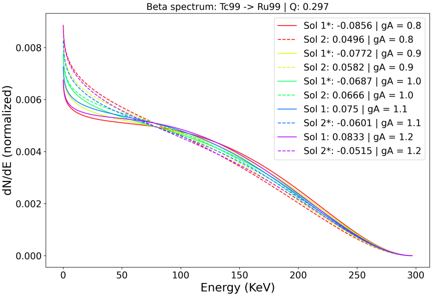
The beta spectral shapes of $^{212-214}$Pb-Bi-Po chain with the interaction 'khpe' are displayed with the N_{tot} of curves used to produce the shaded regions. Figure reproduced from ([b])

[a] DOI: 10.1103/PhysRevC.109.014326

[b] DOI: 10.1103/PhysRevC.109.034321

^{99}Tc Sensitivity and Atomic Exchange Corrections





NSM Calculation of the β-shapes using the interaction 'jj45pnb'. (*) denotes the sNMEs closest to the CVC-value. All curves presented reproduce experimental half-life.

- The Atomic exchange correction has been developed for allowed-beta decays ([a]) but was applied for this 2nd forbidden non-unique decay.
- This isotope is of importance for the ^{100}Mo double beta decay studies and for the effective weak-axial coupling determination.

[a] DOI: 10.1103/PhysRevC.107.025501

Conclusions and Outlook

- It is clear that further research into the effective value of g_A, sNME and forbidden non-unique nuclear structured computations are essential and have direct impacts in studies of rare β decays, β shapes and neutrino physics with impacts in the searches for ***Beyond the Standard Model Physics.***

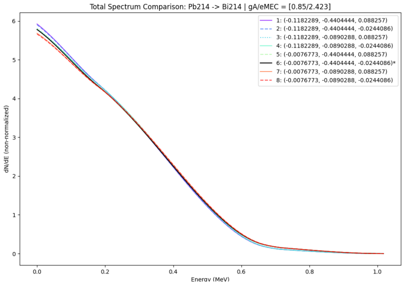
- More experimental work is needed to further pinpoint g_A, sNMEs, and ε_{MEC} especially with β-shape analysis !

- Applying the combined mechanisms here mentioned altogether might already improve both the anti-neutrino anomaly and the background issues.

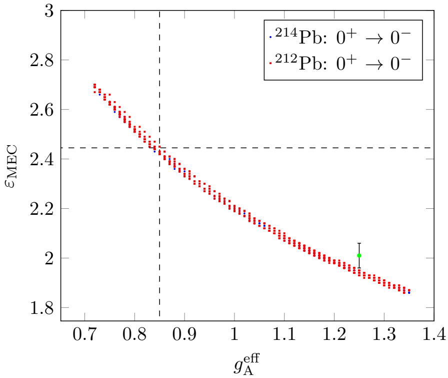
And...

Thank you for your attention!

Beta shapes: More infos



sNME Analysis: All combinations of sNMEs used in the study. (*) denotes the closest to CVC-predicted values.

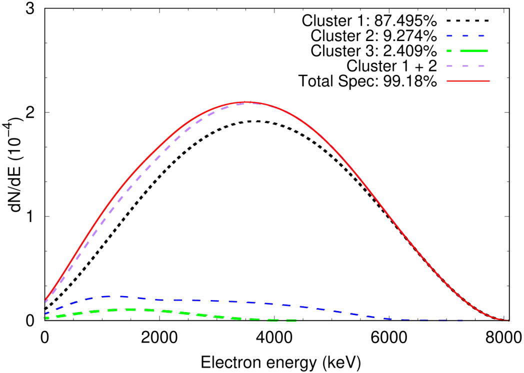


Enhancement Current: The possible combinations that fit the experimental half-life within 0.1% relative error. Green dot is a previous study on the same region A=214 for the range of the mesonic enhancement current.

^{92}Rb β-spectrum for Reactor Flux Anomaly

- One of the major contributors to reactors' beta decays after fission is ^{92}Rb. Using TAGS experimental branchings, and clustering the states calculated in NuShellX, one can plot the beta shape.

- The clustering of states was done to select the pairs of [g_A^{eff}, ε_{MEC}] which would fit the experimental data. Further information can be found at PhysRevC.106.024315



Spectral decomposition of *glekpn*-interaction's clusters. Cluster 1 being only the ground-state to ground-state decay. Percentages in comparison to the experimental full half-life.

Beta shapes: More infos

CVC-value formula

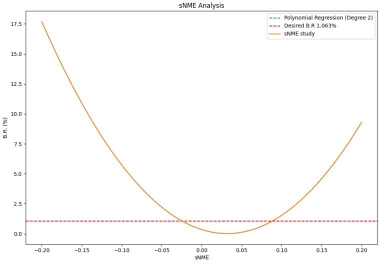
I. SMALL RELATIVISTIC VECTOR NME

Formulae from Behrens and Bühring (*Electron Radial Wave Functions and Nuclear Beta-decay*, Clarendon, Oxford, 1982), hereafter called B&B. For K:th-forbidden non-unique β^- decays we have

$$
\begin{aligned}
{}^{V}\mathcal{M}^{(0)}_{KK-11} &= \frac{1}{\sqrt{K(2K+1)}}\left[\frac{(W_0+M_pc^2-M_nc^2)R}{\hbar c}+\frac{6}{5}\alpha Z\right]{}^{V}\mathcal{M}^{(0)}_{KK0}/R \\
&= \frac{1}{\sqrt{K(2K+1)}}\left(\frac{\Delta_{T,T-1}R}{\hbar c}\right){}^{V}\mathcal{M}^{(0)}_{KK0}/R \qquad (1)
\end{aligned}
$$

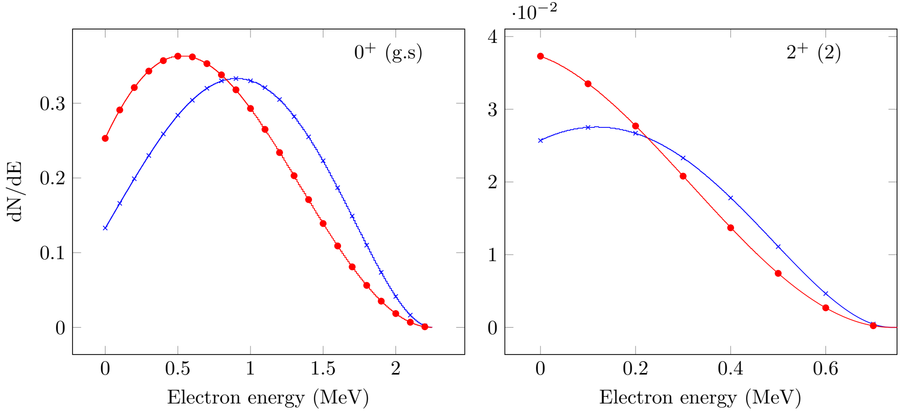
where W_0 is the end-point energy, M_pc^2 (M_nc^2) is the proton (neutron) rest-mass energy, $R = 1.2A^{1/3}$ fm is the nuclear radius, Z the proton number of the β^- daughter nucleus, $\alpha \approx 1/137$ the fine-structure constant and $\Delta_{T,T-1}$ the excitation energy of the isobaric analog state (IAS). Here $R\Delta E_c/\hbar c \approx 6\alpha Z/5$, where ΔE_c is the Coulomb-displacement energy.

Pattern usually found when seeking for sNMEs



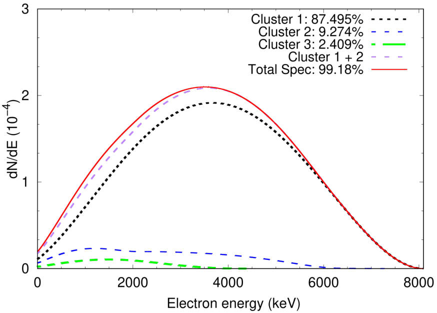
Beta shapes: More infos

^{212}Bi sNME-sensitive shapes



Beta shapes: More infos

Computed cumulative electron spectrum

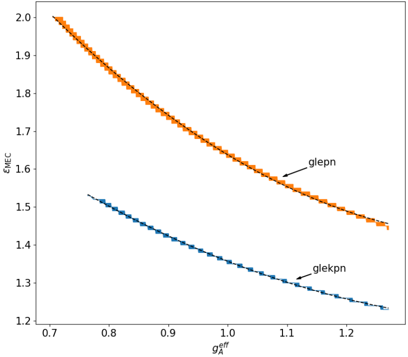


Cluster 1: gs-to-gs transition (based on TAS-measured branching)

Cluster 2: known 1*st*-forbidden transitions (based on TAS-measured branchings)

Cluster 3: unresolved higher-energy 1*st*-forbidden and allowed transitions

Pool of combinations by the clustering method for both interactions.



Relative cluster half-life error of 2.5% for the gs-to-gs decay and 25% for secondary cluster. Arrows point to selected combinations with less than 0.25% error in the main gs-to-gs half-life prediction

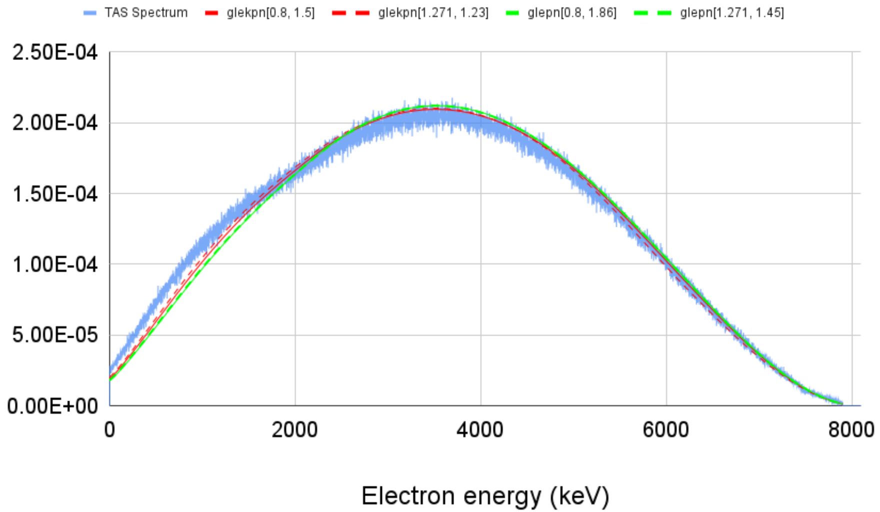
Nucleon spaces and interactions

GLEPN Model Space
P2P3/2,1F5/2,2p1/2,1g9/2,3s1/2,2d5/2,2D3/2
N2P3/2,1F5/2,2p1/2,1g9/2,3s1/2,2d5/2,2D3/2
GLEKPN Model Space
P1F7/2,1F5/2,2P3/2,2P1/2,1G9/2

N1G9/2,1G7/2,2D5/2,2D3/2,3S1/2

Energy (keV)	J^π	*glekpn*	*glepn*
0.0	0^+	0^1	0^1
814.98	2^+	1102^2	848^2
1384.79	2^+	1926^2	1793^2
1778.33	$2^{(+)}$	2341	2074^2
2053.9	(2^+)	-	2347
2088.39	$0^{(+)}$	-	-
2140.82	1^+	2405^2	2552^2
2765.7	0^+	2863^2	2924
2783.6	$[2^+]$	2974	3011
2820.89	$([2^+], 1)$	3513^2	3437^2

Limits on gA


TAS Spectrum
glekpn[0.8, 1.5]
glekpn[1.271, 1.23]
glepn[0.8, 1.86]
glepn[1.271, 1.45]
2.50E-04
2.00E-04
1.50E-04
1.00E-04
5.00E-05
0.00E+00
0
2000
4000
6000
8000
Electron energy (keV)