BSM Explanation of the 5 MeV Bump in the Reactor $\bar{\nu}_e$ Spectrum

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Motivation:

Currently, there are two anomalous findings associated to reactor neutrinos. The first is the $\sim 6\%$ mismatch between the predicted and observed rates in short-baseline reactor experiments. The other, more recent one, is the excess of neutrino events around 5 MeV, the so-called reactor bump. We demonstrate for the first time that the bump can be explained in a beyond the Standard model framework by introducing eV-scale sterile neutrino and its hidden interactions with nucleons. Fascinatingly, such sterile neutrino can also explain the discrepancy between the measured and predicted antineutrino fluxes, yielding a simultaneous solution to both aforementioned anomalies.

What we do:

- We introduce *eV-scale sterile neutrino* (ν_s) to which active neutrinos produced in nuclear reactors can partially oscillate. Such neutrinos with $E_{\bar{\nu}_s} > 9.38$ MeV can induce ${}^{13}\text{C}(\bar{\nu}_s, \bar{\nu}_s' n)^{12}\text{C}^*$ in the presence of non-standard interactions. To this end, we consider spontaneously broken $U(1)_X$, under which only quarks (nucleons) and sterile neutrino are charged.
- The de-excitation of ${}^{12}\text{C}^*$ yields a prompt 4.4 MeV photon, while the thermalization of the product neutron causes proton recoils, which in turn yield an additional prompt energy contribution with finite width. In combination, this mimics neutrinos with the energy around 5 MeV.

Methods

- Instead of computing the cross section for ${}^{13}\text{C}(\bar{\nu}_s, \bar{\nu}_s' n)^{12}\text{C}^*$, we obtain it from the measured QED Mott cross section for the process ${}^{13}\text{C}(e, e'n)^{12}\text{C}^*$

$$\frac{d\sigma'}{dE_n}(E_{\bar{\nu}}, E_n) = \zeta^2 \times \frac{d\sigma}{dE_n}(E_i = E_{\bar{\nu}}, E_n),$$

  where the rescaling factor is the effective coupling ζ^2.
- We convolve the obtained neutron spectrum with the neutrino flux

$$\frac{d\widetilde{\phi}_n}{dE_n}(E_n) = 0.006 \times \int dE_{\bar{\nu}} \underbrace{\frac{d\sigma'}{dE_n}(E_{\bar{\nu}}, E_n)}_{\text{neutron spectrum}} \cdot \underbrace{\frac{d\phi_{\bar{\nu}}}{dE_{\bar{\nu}}}(E_{\bar{\nu}})}_{\text{flux}}$$

- Due to required $E_{\bar{\nu}} \gtrsim 9.4$ MeV we augment the HM fluxes by including an additional power-law component beyond 8 MeV. This is in accord with both ab initio calculations and upper bounds from Daya Bay at such energies.
- To determine the amount of prompt energy resulting from the proton recoils we use Birks' law

$$E = \int \frac{\left(\frac{dE}{dx}\right) dx}{1 + k_B \left(\frac{dE}{dx}\right)}$$

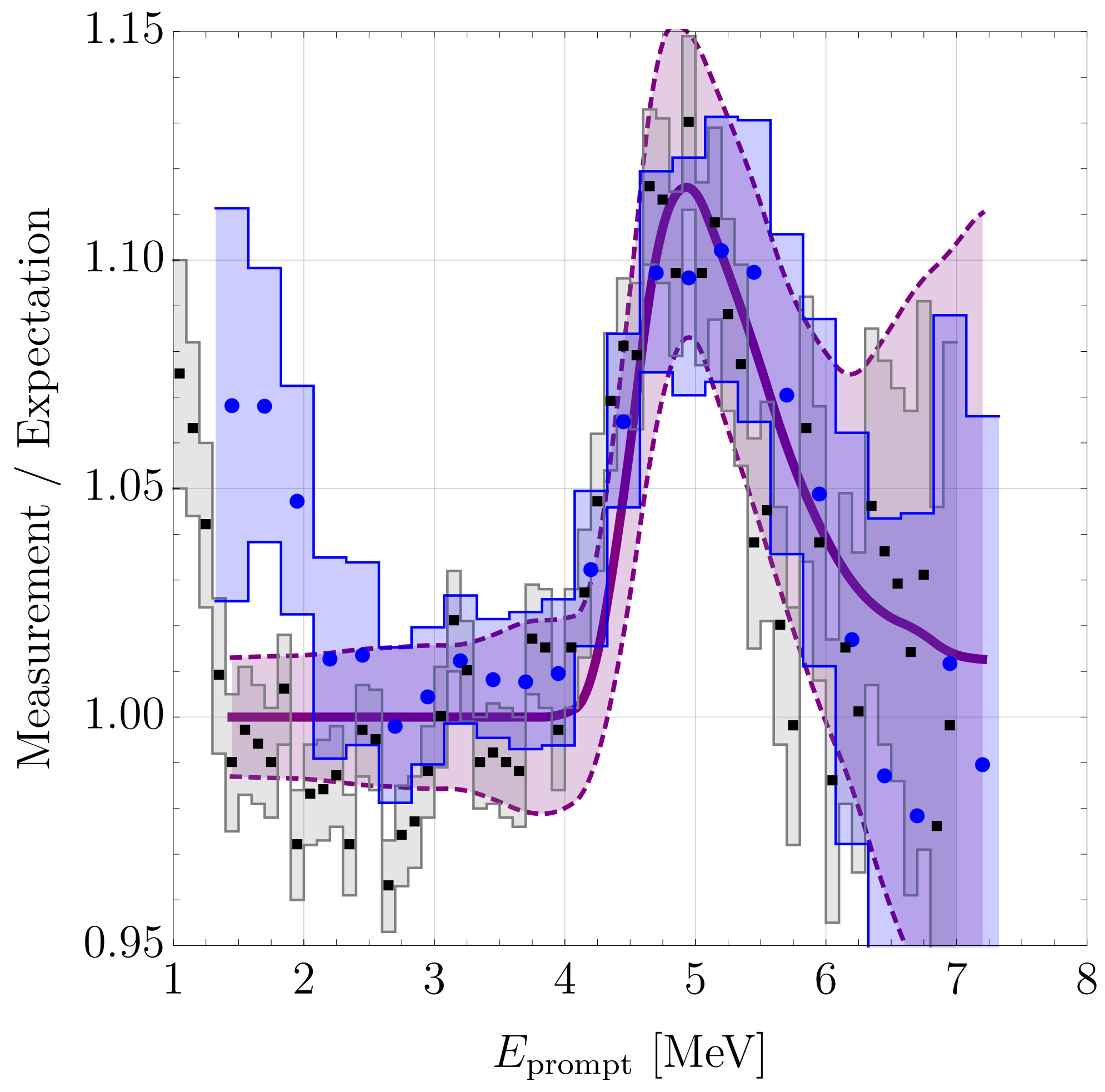
- we do not allow transitions to the ground state of ${}^{12}\text{C}$. Otherwise, the result would be a steep upturn of the prompt energy spectrum at low energies that is excluded by the data
- for vector interaction, forbidding ground state transitions is an *ad hoc* assumption
- in contrast, in the presence of axial interactions it is possible to eliminate such transitions
- we simulate ${}^{13}\text{C}$–$\bar{\nu}$ events using Monte Carlo methods for a range of mediator masses, power law indices (I) of the flux component at $E_{\bar{\nu}} \gtrsim 8$ MeV and the couplings ζ
- we compare the smeared spectrum against the ratio of measurement-to-expectation of the prompt energy spectrum via χ^2-test
- the following uncertainties are taken into account :
  - uncertainties and correlations of Daya Bay data
  - theoretical neutrino flux uncertainties
  - Mott cross section uncertainties for ${}^{13}\text{C}(\bar{\nu}_s, \bar{\nu}_s' n)^{12}\text{C}^*$

Future experimental tests

The specific explanation for the 5 MeV bump, put forward here, results in nontrivial expectations at several experimental facilities :

- Daya Bay should observe antineutrino flux above 8 MeV
- PROSPECT relies on pulse shape discrimination so the proton recoil contribution to our signal (which is at the level of 20%) is likely to cause these events to be rejected as background
- due to the relatively long distance over which the 4.4 MeV photon deposits its energy, these events would be rejected in the finely segmented detectors like STEREO, SOLID or DANSS
- experiments dedicated to neutrino-nucleus coherent scattering, such as COHERENT and CONUS will be able to disfavor or confirm our model
- the region of the parameter space preferred by the Daya Bay data is within the reach of the next-generation direct detection dark matter experiments
- the reaction ${}^{17}\text{O}(\bar{\nu}, \bar{\nu}'n)^{16}\text{O}^*$ is unlikely to be observed at water Cerenkov detectors primarily because the abundance of ${}^{17}\text{O}$ (0.03%) is significantly lower than that of ${}^{13}\text{C}$ (1.07%). Furthermore, the energy levels of the excited states and the neutron separation energy for ${}^{17}\text{O}$ are different in comparison to ${}^{13}\text{C}$. Therefore, we predict that neither Gd-doped Super-Kamiokande nor WATCHMAN will see a bump.
- eV-sterile neutrino will be confirmed of disfavored at short baseline neutrino oscillation experiments (see new results from STEREO)
- the constraints on dark photons will improve with more data from LHCb and beam dump experiments

Reactor neutrino data fit



- $\chi^2/\text{dof} = 10.3/21$
- best-fit curve (solid purple) shown for $\{M_X, \log_{10}\zeta, I\} = \{100\ \text{keV}, -5.25, 12\}$
- for sterile neutrino mass and the mixing angle with $\bar{\nu}_e$ we take $\Delta m_{41}^2 = 0.4$ eV^2 and $\sin^2 2\theta_{ee} = 0.04$, respectively, in agreement with the results from global fits

The Model

We introduce a fourth species of neutrino (ν_s) with nonzero charge under $U(1)_X$, and allow for nucleons to also be charged. The relevant kinetic part of the interacting Lagrangian is

$$\mathcal{L} = g_X X_\mu (Y_\nu \overline{\nu}_s \gamma^\mu \nu_s + \overline{p}\gamma^\mu p + Y_n \overline{n}\gamma^\mu n),$$

where g_X is the $U(1)_X$ coupling constant, and Y_ν (Y_n) is the sterile neutrino (neutron) charge in units of g_X.
For this model the effective coupling yields

$$\zeta^2 = \frac{1}{2}\sin^2 2\theta_{ee} \left(\frac{6 + 7Y_n}{6}\right)^2 Y_\nu^2 \left(\frac{g_X}{e}\right)^4 .$$

- we employ $Y_n = -0.65$ for which the limit from COHERENT experiment is maximally relaxed
- we find a viable parameter region for $Y_\nu \sim 10$
- the preferred parameter space where all the present bounds are avoided is at $M_X \sim 1$ MeV and $g_X \sim 10^{-3}$