Reactor antineutrino fluxes – status and challenges

Patrick Huber

Center for Neutrino Physics, Virginia Tech, Blacksburg, VA
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In this contribution we describe the current understanding of reactor antineutrino fluxes and point out some recent developments. This is not intended to be a complete review of this vast topic but merely a selection of observations and remarks, which despite their incompleteness, will highlight the status and the challenges of this field.

I. INTRODUCTION

The antineutrino flux from a nuclear reactor has become a matter of considerable interest over the past few years. The antineutrinos are created in the beta decay of the neutron rich isotopes produced as fragments in the fission of the reactor fuel. The interest in the resulting electron antineutrino flux originates from two communities. Basic research employs measurement of the flux to investigate neutrino oscillations including the possible existence of sterile neutrinos while the safeguards and threat reduction community would use the neutrino spectrum and its composition over time as indicator of the makeup of the fissile material in the reactor. The basic research focus is on the absolute neutrino flux while safeguards has greater interest in the spectrum shape which may have markers for particular species of the fuel. Significant uncertainty remains regarding both issues. Reactor neutrino experiments rely on inverse beta decay (IBD)

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

(1)
to detect the neutrino. This reaction has a neutrino energy threshold of $E_{\text{th}} \approx 1.8 \text{ MeV}$. Any uncertainty in the cross section directly relates to an uncertainty in the detected event rate or measured flux. The existing world average of the absolute value of the measured flux is 6% below the best prediction of that flux $\bar{F}_\nu$, which was recently confirmed by Daya Bay $[2]$, which known as the Reactor Antineutrino Anomaly (RAA).

Three recent very successful experiments (Daya Bay $[3]$, Reno $[4]$, Double Chooz $[5]$) focused on measuring the neutrino mixing angle $\theta_{13}$ and as a by-product provided the most precise and detailed measurements of the neutrino spectrum produced by pressurized water power reactors (PWR). All three measurements used well-calibrated detectors at three different reactor sites and observed an unexpected excess of neutrinos with energies between 4.8 and 7.3 MeV $[2]$. This result has forcefully brought home the notion that the neutrino fluxes are not as well understood as had been thought. At present, it is not clear what physics gives rise to the bump. It clearly must be attributed to the excess production of some isotope or isotopes with a beta decay end point energy in the interval of the observed bump. There was a belief that the reactor neutrino fluxes could be predicted to within 2%. This belief was founded on employing integral beta spectra measured in the 1980s at the Institute Laue-Langevin (ILL) by K. Schreckenbach and collaborators. They inserted foils of $^{235}\text{U}$, $^{239}\text{Pu}$ and $^{241}\text{Pu}$ into the ILL reactor to expose them to a thermal neutron flux and directly measured an integral beta spectrum created by the beta decaying isotopes produced by the neutron induced fission of each fissile isotope $[6-8]$. The beta electron spectroscopy was performed with a magnetic spectrometer which also provide the necessary electron/gamma separation. It is of note

$pahuber@vt.edu$

1 For the sake of brevity we will refer to electron antineutrinos as neutrinos throughout this paper.
that this type of measurement has been pioneered by Reines in 1958 [9] using an anti-coincidence
counter based on plastic scintillator; the same technique was employed in a recent measurement
of the integral beta spectrum of $^{238}\text{U}$ [10]. Those measurements and the inferred neutrino yield
for each fissile isotopes can be combined with the evolution of the fissile fuel composition over the
run time to make a prediction of the neutrino spectrum. Of course, there are some assumptions
and physics required in going from the beta spectrum to the neutrino spectrum but these were
presumed to be tractable. Thus, the bump observed in the neutrino flux came as a surprise as no
such bump could be generated using the ILL beta spectrum measurements. In principle one could
take a different tack from using the ILL measurements and employ information contained in the
very large data bases ENDF/B-VII.1 and JEFF-3.1.1 associated with the fission of $^{235}\text{U}$, $^{239}\text{Pu}$ and
$^{241}\text{Pu}$. These databases pull together a large body of experimental results to establish the fraction
of each isotope produced in the fission of a specific fuel element as well as the subsequent beta
decay branching ratios for each isotope. Naturally the use of such a procedure produces a large
uncertainty in the predicted neutrino spectrum, on the order of 15%, see for instance Ref. [11].
However using ENDF/ B-VII.1 one predicts a bump similar to that observed in the neutrino
measurements. As reported in [12] using the JEFF-3.1.1 no such bump is predicted. Reference [12]
discusses possible origins for the bump but provides no definite conclusions. Thus the bump in
the neutrino energy spectrum that at present cannot be traced to a particular fissile isotope and
an apparent 6% deficit in the total measured rate present serious obstacles to the use of neutrino
detection for either basic research or threat reduction.

For basic neutrino research, the question is whether the 6% deficit is due to nuclear physics
or due neutrino oscillation involving one or several eV-scale sterile neutrinos. The eV-scale sterile
neutrino interpretation is also supported by a range of anomalies, where none taken individually is
statistically very significant, but which in combination point towards an eV-scale sterile neutrino,
for a review see Ref. [13].

The basic application for threat reduction and nuclear non-proliferation safeguards relies on the
predicted spectral difference in neutrino emission between uranium and plutonium isotopes, which
allows to infer the plutonium content of a reactor without reference to its past operating history
and without the need to modify reactor operations [14]. The basic concept has been proposed
by Borovoi and Mikaelyan in 1978 [15] and in many past reactor experiments a clear correlation
between the neutrino signal and the state of the reactor was found (for early results see [16–
18]). For an actual real-word application a much better quantitative understanding of the spectral
differences in neutrino yields between different fissile isotopes is required.

The field of geoneutrino research as an experimental science is quite young [19] and has made
significant progress in the past few years [20, 21]. The sources and distribution of heat in the
Earth interior is an important question in geophysics as it closely relates to the composition of
the Earth and it is this heat which drives plate tectonics and the geodynamo. There are basically
three potential sources for heat inside the Earth: contraction or gravitational binding energy,
chemical energy and radioactivity. The overwhelming majority of radiogenic heat stems from the
decay chains of potassium-40, uranium-238 and thorium-232. For a review of the relation between
radiogenic heat and Earth composition models see for instance Ref. [22]. The latter two decay
chains in uranium-238 and thorium-232 produce neutrinos above the inverse beta decay threshold
and thus are solely responsible for the observed signals mentioned above. The next crucial data set
will come from JUNO, however a large background of reactor neutrinos will have to be accurately
subtracted [23]. This subtraction requires a very good understanding of in particular the low-energy
part of the reactor neutrino spectrum between IBD threshold and about 3.5 MeV.
II. NEUTRINO YIELDS

More than 99% of the power in reactors, in a uranium fuel cycle, is produced in the fission of four isotopes: $^{235}\text{U}$, $^{239}\text{Pu}$, $^{238}\text{U}$, and $^{241}\text{Pu}$. A reactor with fresh fuel starts with only fissions in the uranium isotopes and plutonium is produced via neutron capture on $^{238}\text{U}$ as the burn-up increases. The total neutrino flux from a reactor $\phi$ can be written as

$$\phi(E) = \sum_I f_I S_I(E),$$

where $f_I$ is the fission rate in isotope $I$ and $S_I(E)$ is the neutrino yield for the isotope $I$. The thermal power of the reactor is also given in terms of the fission rates

$$P_{\text{th}} = \sum_I f_I p_I,$$

where $p_I$ is the thermal energy release in one fission of the isotope $I$; we use the values for $p_I$ given in Ref. [24]. In order to be able to disentangle the contributions of the four isotopes, we need to know the neutrino yields $S_I$. These neutrino yields, in principle, are given by the neutrino spectra $\nu_k(E)$ of each fission fragment $k$ and the cumulative fission yield for each fragment, $Y^I_k$,

$$S_I(E) = \sum_k Y^I_k \nu_k(E),$$

where $k$ typically runs over about 800 isotopes. In practice, we do not know the neutrino spectrum of a given fission fragment, but have only information regarding the beta spectrum and in many cases this knowledge is inaccurate, incomplete, or entirely missing. Even for a well known beta spectrum, significant complications arise from the conversion of a beta spectrum into a neutrino spectrum since each individual beta decay branch has to be treated separately. As a result, a direct computation of the neutrino yields $S_I$ via the summation of all individual neutrino spectra will be of limited accuracy [11, 25], but in many cases is the only available method.

A more accurate method is based on the measurement of the integral beta spectrum of all fission fragments [6–8, 26] and subsequently the neutrino spectrum can be reconstructed from those measurements [27]. This method is less dependent on nuclear data about individual fission fragments but is not entirely free from uncertainties related to effects of nuclear structure [27, 28]. In particular Hayes et al. [28] pointed out that forbidden decays which can make up as much as 40% of all neutrinos in certain energy ranges can have a significant impact on the predictions. The reason is, that in forbidden decays the spectrum of emitted neutrinos depends on details of the underlying nuclear structure, and generally no information at this level of detail is available.

Until the 2011 work by a group from Saclay [25], the results from Refs. [6–8] obtained in the 1980s at the Institut Laue-Langevin in Grenoble were considered the gold standard. The Saclay group, in preparation of the Double Chooz neutrino experiment [5], revisited the previous results in an attempt to reduce the uncertainties. Instead, they found a upward shift of the central value of the average yield by about 3% while the error budget remained largely unchanged. This result, in turn, requires a reinterpretation of a large number of previous reactor neutrino experiments, since this changes the expected number of events. Together with the changes of the value of the neutron lifetime [29] and corrections from so-called non-equilibrium effects, the previous experiments appear to observe a deficit in neutrino count rate of about 6%; this is called the reactor antineutrino anomaly and was first discussed in Ref. [1]. The initial result on the flux evaluation and the 3% upward shift has been independently confirmed [27]. A plausible explanation could come in the form of a new particle, a sterile neutrino, which is not predicted by the Standard Model of particle
TABLE I. Rates and mean energies \langle E \rangle for a 1 MW$_{th}$ reactor in a 1 t detector at a standoff of 10 m measuring for 1 year for each individual isotope, assuming that only this isotope is fissioning. The three different flux models are explained in the text. Ratios are given relative to $^{235}$U. From Ref. [30].

|        | ENSDF | Fallot | Huber |
|--------|-------|--------|-------|
|        | events ratio | $\langle E \rangle$ [MeV] ratio | events ratio | $\langle E \rangle$ [MeV] ratio | events ratio | $\langle E \rangle$ [MeV] ratio |
| $^{235}$U | 3826 | 1 | 4.48 | 1 | 3905 | 1 | 4.28 | 1 | 4252 | 1 | 4.25 | 1 |
| $^{238}$U | 5836 | 1.53 | 4.59 | 1.024 | 6076 | 1.56 | 4.45 | 1.040 |
| $^{239}$Pu | 2442 | 0.64 | 4.26 | 0.950 | 2536 | 0.65 | 4.13 | 0.965 | 2796 | 0.66 | 4.04 | 0.951 |
| $^{241}$Pu | 3551 | 0.93 | 4.47 | 0.998 | 3515 | 0.90 | 4.23 | 0.988 | 3872 | 0.91 | 4.13 | 0.971 |

physics. Given the far-flung consequences of the existence of this sterile neutrino a considerable level of research activity ensued.

In Tab. I (taken from Ref. [30]) the event rate predictions for various flux models are compared for the four fissile isotopes. The ENSDF flux model represents a crude summation calculation and is based on thermal neutron fission yields of $^{235}$U, $^{239}$Pu, and $^{241}$Pu from the JEFF database, version 3.1.1 [31]; the fast neutron fission yield of $^{238}$U from the ENDF-349 compilation [32]; and on the beta-decay information contained in the Evaluated Nuclear Structure Data File (ENSDF) database, version VI [33]. The neutrino spectrum is derived following the prescription in Ref. [27]. This calculation reproduces the measured total beta spectra [6–8, 26] to within about 25%. A detailed summation result has been derived by Fallot et al. [11], where the ENSDF entries are replace with high quality experimental data (where available) and a a selected mix of databases is used. Fallot’s calculations reproduces the measured total beta spectra [6–8, 26] to within 10%. A direct inversion of the neutrino spectra from the total beta data was performed in Ref. [27] for the isotopes $^{235}$U, $^{239}$Pu, and $^{241}$Pu. To date this represents the most accurate neutrino yields for those isotopes. The absolute values are significantly different between models, but once normalized to the predictions for total rate and mean energy of $^{235}$U, these results become very similar. Therefore, we conclude that the difference in neutrino yield and mean energy between the fissile isotopes is consistently predicted by the various flux models – which should come as no surprise since these differences have their origin in the fission yields.

These results indicate a certain level of robustness in predictions, but this impression needs to be tempered by the recent observation of a bump-like feature. The shoulder recently observed in the neutrino flux from PWRs as measured by Reno [11], Daya Bay [3] and Double Chooz [5] was unexpected and its origin still uncertain. This shoulder cannot be reproduced if one uses as input the Schreckenbach measurements [6–8] of the integral beta spectra of the daughters produced by thermal neutron fission of reactor fuel. A subsequent publication by Dwyer and Langford [34] indicated that a shoulder similar to the one observed could be produced using for input the beta decays in a subset of ENDF/B-VII.1 [35] fission database. If one uses the fission database JEFF-3.1.1 [31] as input no shoulder is produced. This is not surprising as the uncertainties in the databases are large relative to the size of the shoulder.

It would be useful if the observed shoulder could be uniquely assigned to the decay of the daughters of a specific fuel type. If the shoulder is due to the thermal neutron fission of $^{235}$U, $^{239}$Pu or $^{241}$Pu then Schreckenbach’s measurements would be called into serious question. The recent measurement of the beta spectrum of the decay of the daughters of the fast fission of $^{238}$U [26] is not sufficiently precise to show the presence of a shoulder. Hayes and collaborators [12] investigate the possible origins of the observed shoulder and propose the following list

1. Beta decay of non-fissionable material in the reactor
2. Shape of the beta and neutrino spectrum for $\Delta J^{\Delta \pi} = 0^-$ first forbidden decays

3. Beta decay of the daughters of the fast fission of $^{238}\text{U}$

4. Beta decay of daughters of the epithermal fission of $^{235}\text{U}$, $^{239}\text{Pu}$ and/or $^{241}\text{Pu}$

5. Errors in Schreckenbach’s ILL beta spectra

Taking at face value RENO’s claim that the shoulder they observe makes up 2% of the total yield of events, allows the first of the proposed causes to be readily dismissed. One shortcoming is, that the modelers [25, 27] created the neutrino spectrum from Schreckenbachs beta spectrum assuming that all the beta decays were allowed rather than taking account of the fact that some of the most important decays are $\Delta J^{\Delta \pi} = 0^-$, so-called non-unique first forbidden decays. These decays have no weak magnetism correction which increase their contribution relative to what the modelers provided. This is because weak magnetism typically decreases the antineutrino component of an allowed axial transition above half of the end point energy. Treating these decays more correctly increases their yield in the region of the bump [12] by somewhat less than 1% of the total yield so it cannot account for all of the shoulder. Not enough is known of the decay of the daughters produced by the fast fission of $^{238}\text{U}$ so it certainly could contribute to the shoulder. RENO observes the largest shoulder in the neutrino flux and cites the largest contribution from the fission of $^{238}\text{U}$. To account for the entire shoulder the isotopes dominating the shoulder region would have to be 4 times larger in JEFF-3.1.1 and 2 times larger in ENDF/B-VII.1 [12]. Thus it appears that 3) likely makes some contribution to the shoulder.

Schreckenbach’s measurements were carried out using the thermal flux of the ILL reactor while the 3 measurements observing the shoulder were carried out at PWRs. Is it possible that the harder neutron flux spectrum in a PWR relative to the one at ILL could produce more fission products that create the shoulder? While there appear to be large fluctuations [36–39] in the ratio of symmetric to asymmetric fission the average over the epithermal resonances is quite compatible with what is measured with a thermal flux. The lone exception might be $^{239}\text{Pu}$ that has an isolated and prominent fission resonance at 0.3 eV. Fission of this resonance must play a larger role in the neutron spectrum of a power reactor than is the case for fission at thermal energies. Thus 4) could make a contribution to the bump. The possibility of an error in the ILL beta spectrum measurements must also be entertained. In the discussion of possibility 2) it was pointed out that using the ILL beta spectrum measurements and properly accounting for $\Delta J^{\Delta \pi} = 0^-$ transitions can only account for half of the shoulder. This raises the possibility that these measured beta spectra are not correct. Certainly the measurements were not easy and the spectrometer employed [40] was complex. Further the signal to background in bump region was 2.5/1 and it is not clear how the background subtraction was carried out. One should not dismiss the possibility of error in the ILL beta spectra. A high statistics measurement of the neutrino flux at a research reactor fueled with highly-enriched uranium (HEU) will produce neutrinos only via the fission of $^{235}\text{U}$ and should settle some of the issues raised above.

Assuming that the Daya Bay result on the bump holds, we can ask the question, which fissile isotope does it come from? To demonstrate how a multi-reactor deployment of a 5 ton detector can elucidate this question, we compare the following four types of reactors: a Daya Bay like pressurized water reactor (DYB), a pressurized water reactor with 1/3 of reactor-grade MOX fuel (MOX3), a research reactor like the BR2 in Belgium running on highly enriched uranium (BR2) and a fast breeder reactor like the Fast Breeder Test Reactor (FBTR) in India. For DYB the fission fraction of reactor characteristics correspond to values of the actual data taking period at Daya Bay [41], while for the others, we used semi-realistic models in terms of reactor power, reactor up-time and detector distance. Specifically, the fission fractions in the four fissile isotopes for the 1/3 MOX are
FIG. 1. Shown is the result for the ratio of data to prediction of a simulated experiment at MOX3 with the true bump in $^{238}$U. This is based on a one year run of a 40% efficient, 5 ton detector. The scatter in the simulated data (blue points) arises from a combination of statistical fluctuations and the systematic uncertainty of the underlying reference spectra. The shaded region indicates the 1 $\sigma$ range from the fit and for comparison we show the expectation for MOX3 if the bump were in $^{239}$Pu.

based on a 3D, pin-level 1/8-core simulation [42]. For BR2 we make the simplifying assumption that all fissions take place in $^{235}$U and we have tested that a few percent of fission in other isotopes does not change the results. For the FBTR we take the core simulation performed for a full size Indian Fast Breeder from Ref. [13] as proxy. We assume that there is no breeding blanket and we neglect fission in the even plutonium isotopes which overall contribute about 5% of fissions. The reactor parameters and fission rates are summarized in Tab. II.

For the following analysis we extract the shape, position and amplitude of the bump from the Daya Bay data [41]. We use as reference spectrum for $^{235}$U, $^{239}$Pu and $^{241}$Pu the ones from Ref. [27] and for $^{238}$U the spectrum from Ref. [25]. The bump appears relative to these reference spectra and therefore any uncertainties in the reference spectra itself will make it harder to detect the bump. We will use the uncertainties as quoted in Ref. [27] for $^{235}$U, $^{239}$Pu and $^{241}$Pu and assume a flat 10% error for $^{238}$U. Note, that the reference spectra provide, except for the bump, an excellent description of the Daya Bay data. We now can artificially choose to put the bump into one isotope while ensuring to reproduce the right amplitude in Daya Bay. We simulate data for a 5 ton detector with a 40% detection efficiency and 1 year data taking. We impose random fluctuations for counting statistics and separately for the underlying systematic uncertainty of the reference spectra. In Fig. 1 we show the result of one of these simulated experiments at MOX3 with the true bump in $^{238}$U. The shaded region indicates the 1 $\sigma$ range from the fit and for comparison we show the expectation for MOX3 if the bump were in $^{239}$Pu.

We then in turn fit this data with the bump being in $^{235}$U and then in $^{238}$U etc. and compute a $\chi^2$ difference, where we leave the total event rate as a free parameter. This exercise is repeated 16,000 times, and we thus obtain a distributions for the $\chi^2$ and their differences $\Delta \chi^2$. For instance in Fig. 2 we show the $\Delta \chi^2$ distribution for the true bump in $^{238}$U and the blue histogram is the result if we fit the data with the correct bump. The reason for the non-zero $\Delta \chi^2$ in this case is the systematic uncertainty of the reference spectra. The orange histogram is obtained by fitting this data with the bump being in $^{239}$Pu. $\chi_c$ is defined by requiring that 95% of all cases in the

| Reactor | power stand-off duty factor | $^{235}$U | $^{238}$U | $^{239}$Pu | $^{241}$Pu | Events |
|---------|-----------------------------|----------|----------|-----------|-----------|--------|
| DYB     | 2 800 25                    | 1.0586   | 0.076    | 0.288     | 0.05      | 2,188,000 |
| MOX3    | 3 200 25                    | 1.051    | 0.066    | 0.39      | 0.031     | 2,402,000 |
| BR2     | 60 5.5                       | 0.41     | 0       | 0       | 0       | 297,000  |
| FBTR    | 60 10                        | 0.40     | 0.0093   | 0.10     | 0.71      | 95,000   |

TABLE II. Properties and fission fractions for a set of representative reactors. Event numbers given are based on a one year exposure of a 40% efficient, 5 ton detector.
FIG. 2. Shown is the $\Delta \chi^2$ distribution for the true bump in $^{238}$U. The blue histogram shows the result if we fit the data assuming that the bump is in $^{238}$U. The orange histogram is obtained by fitting this data with the bump being in $^{239}$Pu. $\chi_c$ is defined by requiring that 95% of all cases in the blue histogram are below this value. These results are based on a one year exposure of a 40% efficient, 5 ton detector.

blue histogram are below this value\textsuperscript{2} in this example $\chi_c = 191.8$. Next, we look how many cases in the orange histogram also fall below $\chi_c$, which in this example are 4 out of 16,000 or 0.025%. That is in only 0.025% cases we would conclude (wrongly) that $^{239}$Pu contains the bump, whereas in 95% of the cases we would conclude (correctly) that the bump is in $^{238}$U. In other words with an efficiency of 95% we can reject the bump being in $^{239}$Pu at 3.67 standard deviations.

We repeat this exercise for each type of reactor and all 16 combinations of true and fitted bump being in a given isotope. Clearly, DYB will see the same signal no matter which isotope contains the bump as per definition of this analysis, it serves to set the size and position of the bump. The BR2 will see a very strong signal for a bump ($>4\sigma$) if the bump is in $^{235}$U and see no bump if it is in any of the other isotopes. To diagnose the case where the bump is in $^{238}$U or either in $^{239}$Pu or in $^{241}$Pu requires reactors with increased plutonium and/or $^{238}$U fission fractions like MOX3 and FBTR. The resulting rejection power is shown in Tab. III.

All cases can be identified with better than 3 standard deviations except the distinction between the bump being in $^{238}$U versus $^{241}$Pu, where the combination MOX3 and FBTR can reach about $1.3\sigma$. Note that at this point this analysis is limited by the systematic uncertainty of the underlying reference spectra. However, the very same measurements will be able to deliver very precise new reference spectra and thus the ultimate sensitivity will be significantly higher. However, this analysis requires a very detailed reactor modeling to determine the uncertainties of the fission fractions. There are examples in the literature, e.g. Ref.\textsuperscript{44}, and a similar exercise needs to be repeated for the specific reactor in question. It also obvious that at least one reactor with a high plutonium content needs to be added.

| MOX3       | $^{235}$U | $^{238}$U | $^{239}$Pu | $^{241}$Pu |
|------------|-----------|-----------|-------------|-------------|
| Fit/True  | -         | $>4$      | $>4$        | $>4$        |
| $^{238}$U  | $>4$      | -         | 3.8         | 0.6         |
| $^{239}$Pu | $>4$      | 3.7       | -           | $>4$        |
| $^{241}$Pu | $>4$      | 0.7       | $>4$        | -           |

| FBTR       | $^{235}$U | $^{238}$U | $^{239}$Pu | $^{241}$Pu |
|------------|-----------|-----------|-------------|-------------|
| Fit/True  | -         | $>4$      | $>4$        | $>4$        |
| $^{238}$U  | $>4$      | -         | 3.8         | 1.1         |
| $^{239}$Pu | $>4$      | 3.6       | -           | $>4$        |
| $^{241}$Pu | $>4$      | 1.1       | $>4$        | -           |

TABLE III. Number of standard deviations at which for a given true bump a given fitted bump can be rejected while maintained a 95% acceptance. Note, the MOX3 and FBTR data is correlated due the underlying common reference fluxes and hence standard deviations can not be added in quadrature. These results are based on a one year exposure of a 40% efficient, 5 ton detector.

\textsuperscript{2} In other words, for this hypothesis test, we set the error of the 1st kind to 5%, that is we reject the true null hypothesis in 5% of all cases.

\textsuperscript{3} This corresponds to the error of the 2nd kind, that is we accept the null hypothesis although it is wrong. The complement of this number corresponds to the power of the test.
A similar analysis was presented recently in Ref. [45] where the focus was on a comparison of regular PWRs and research reactors running on HEU, providing a clean $^{235}\text{U}$ signal. The results presented here agree reasonably well with those of Ref. [45], but we also show that reactor with very different plutonium concentrations will be required to untangle the bump. A major technical difference between the two analyses is that here we fully account for the current uncertainties of the reference spectra, whereas in Ref. [45] a smooth interpolation through the bump region is used, which is equivalent to assuming that reference spectra will have very significantly improved by the time this measurement is perform. Thus, in reality the sensitivity will be in-between the results of those two analyses.

### III. NON-LINEAR EFFECTS IN REACTOR FLUXES

In Ref. [46] the effect of neutron capture isotopes on the antineutrino spectrum is investigated and corrections of up to 1% for PWRs and several per cent for naval reactors are found in the low-energy neutrino flux. Candidate isotopes can be found by looking at isotopes which can undergo (two neutrino) double-beta decay: fission fragments are generally produced a few beta decays away from stability and they will decay in their mass chain down to the first stable isotope they encounter, e.g. for the $A = 100$ mass chain this will be $^{100}\text{Mo}$. The next isotope in this chain is $^{100}\text{Tc}$ which itself beta decays with an endpoint of 3.2 MeV, well above IBD threshold, however it can not be produced by beta decay of $^{100}\text{Mo}$ due to nucleon-pairing effects, that is why $^{100}\text{Mo}$ only double-beta decays. Thus production of $^{100}\text{Tc}$ via beta decay is impossible and its direct fission yield is negligible. However, $^{99}\text{Tc}$ is not blocked by a double-beta decay isotope and thus is produced as a result of beta decays along the $A = 99$ mass chain. Again thanks to pairing effects, $^{99}\text{Tc}$ has a sizable neutron capture cross section of about 17 b which yields $^{100}\text{Tc}$, which in turn contributes to the low-energy end of the neutrino spectrum. Under some simplifying assumption the rate of $^{99}\text{Tc}$ production is proportional to the neutron flux, $\Phi_n$, but the capture rate to $^{100}\text{Tc}$ is proportional to neutron flux and the rate of $^{99}\text{Tc}$ production and as a result the rate of $^{100}\text{Tc}$ production is proportional to $\Phi_n^2$, that is it has a non-linear dependence on the neutron flux in contrast to regular fission fragments which have a linear dependence. There is a simple analytic theory for the size of the resulting correction, however this is accurate only within 50%. For a more precise calculation a detailed reactor burn-up calculation is required and these detailed results are presented in Ref. [46].

### IV. SUMMARY

Nuclear reactors have been the workhorse of neutrino physics from it’s very beginning as an experimental science [47] and much has been learned about neutrino properties from a series of experiments spanning many decades. Recently, a very precise determination of $\theta_{13}$ has been achieved by using reactors as a neutrino source and employing the comparison of data obtained with near and far detectors, which essentially obviates the need to understand the reactor neutrino flux.

Till 2011 reactor antineutrino fluxes appeared to be well understood at the level of about 2% uncertainty, but as outlined here and elsewhere, this confidence was mistaken. As often with complex problems, the closer one looks the larger the uncertainty becomes. Predicting the inverse beta decay event rate with a reactor as neutrino source is extraordinarily complex as it requires a quantitative understanding of reactor physics to determine the neutron flux and fission rates. From this information together with the fission yields the isotopic composition of the reactor needs to be determined. For each isotope a detailed understanding of its various beta-decay branches is
required and since about 30–40% of all neutrinos in the relevant energy regime are from forbidden
decays, the details of nuclear structure can not be avoided. Also, there is a number of low-energy
effects related to isotopes which have comparatively long half-lives giving rise the non-equilibrium
correction. These same isotopes also contribute to neutrino emissions from spent nuclear fuel,
which, if spent fuel is present on site, have to be accounted for. More recently also non-linear
effects in form of neutron capture isotopes have been pointed out which will greatly complicate the
comparison of data from different reactors.

The precise measurements obtained at the near detectors of several experiments also clearly
highlight the limitations of our understanding of reactor neutrino fluxes: the 5 MeV bump remains
a conundrum. We explored certain experimental tests which could be performed as was done in
Ref. [15] and it is clear that even just assigning the responsible fissile isotope requires a continued
effort. The prediction of non-linear isotopes can be verified by measuring the abundance of the
stable end-point isotopes. A series of close-range reactor measurements is planned, which will add
further information about reactor antineutrino fluxes, but is worthwhile to point out that with the
Daya Bay data set a very precise measurement is available. The vicissitudes encountered close to
a reactor, that is a lack of overburden and reactor related backgrounds, will make it a challenge to
achieve comparable precision.

A central role in this tale is played by the beta spectrum measurements performed by Schreck-
enbach et al. in the 1980s. They constitute the single point of failure for many predictions and
thus the question is: Can these measurements be reproduced with similar precision? We did not
touch on efforts to improve the data on beta decays of the individual isotopes by using totally
active gamma spectroscopy, see for instance Ref. [18], or the uncertainties inherent in fission yields.
Efforts to improve nuclear data bases will be very beneficial to the issues outlined here. It will
require a broad and sustained effort by many communities to unravel the riddle of the reactor
antineutrino flux, with potentially large discoveries to be made.

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