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Antineutrino spectra and their applications

Summary of the Technical Meeting

IAEA Headquarters, Vienna, Austria
23-26 April 2019

Prepared by

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July 2019

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ABSTRACT

A summary is given of a Technical Meeting assembled to review the status-of-affairs in experiments, models and nuclear data associated with the determination of the anti-neutrino flux and spectrum as produced by reactor neutrinos. Participants discussed the latest experimental results in measurements and models and recommended future improvements in the data analysis, nuclear model corrections and nuclear decay data. There was overall consensus that the field of reactor neutrinos would benefit from international coordination in the form of an international working group. Details of the discussions and the proposed actions are presented in this summary report.

July 2019

Contents

1. Introduction 7
2. Motivation – short introduction to physics and measurements 8
3. Discussions and Recommendations..9
   3.1. Reactor neutrino experiments 9
   3.2. Antineutrino calculations 12
4. Conclusions 14

Summaries
1. Last Double Chooz results and observations with null nuclear power, Cécile Jollet 19
2. Reactor Antineutrino Flux Measurements at Daya Bay, Bryce Littlejohn 20
3. Summary of Antineutrino Spectrum Measurement at Daya Bay, Liang Zhan 20
4. Precise Measurement of Reactor Antineutrino Yield and Spectrum at RENO, Soo-Bong Kim 21
5. Measuring High Resolution Reactor Neutrino Spectrum with JUNO-TAO, Jun Cao........22
6. Global fits of reactor antineutrino flux measurements, Yu-Feng Li 23
7. CHANDLER: A New Technology for Surface-level Reactor Neutrino Detection, Jonathan Link 24
8. NEOS Phase-I and II, Seon-Hee Seo 24
9. Measurement of Antineutrinos from ^{235}U with PROSPECT at the High Flux Isotope Reactor, Karsten M. Heeger...25
10. The SoLid experiment, Antonin Vacheret...26
11. Using DANSS Antineutrino Detector for Industrial Reactor Power Monitoring, Dmitry Svirida...27
12. Implications of the PROSPECT Aboveground Reactor Antineutrino Detection Demonstration for Monitoring and Safeguards Applications, Nathaniel S. Bowden......28
13. Coherent elastic neutrino-nucleus scattering, Yuri Efremenkov....................................29
14. Antineutrino spectrum prediction and nuclear data, Patrick Huber..............................30
15. Current Status of Reactor Neutrino Spectra, Anna Hayes...31
16. First-forbidden transition in reactor antineutrino spectra, Leendert Hayen 31
17. Reactor Antineutrino as a New Frontier of FP Summation Calculations, Tadashi Yoshida 32
18. Updated Summation Method Model and New Prediction for the Reactor Antineutrino Detected Flux and Energy Spectrum, Muriel Fallot...32
19. Uncertainty Quantification in the Summation Method for Nuclear Reactor Antineutrinos, Alejandro A. Sonzogni...33
20. Pandemonium free beta decay data for antineutrino summation calculations, Alejandro Algora 34
21. Modular Total Absorption Spectrometer: the efficient array to study the beta-decay and anti-neutrino properties in fission products, Marzena Wolińska-Cichocka 34
22. Determination of anti-neutrino energy spectra in fission products, Krzysztof P. Rykaczewski...35

23. The impact of beta-delayed neutron emission on the determination of anti-neutrino energy spectra in fission products, Bertis C. Rasco 36
24. Extensive study of the quality of fission yields from experiment, evaluation and GEF for anti-neutrino studies and applications, Karl-Heinz. Schmidt 37
25. Calculation of Independent and Cumulative Fission Product Yields and Fission Spectrum with the Statistical Decay Theory, Toshihiko Kawano 38
26. Improving Nuclear Data for Neutron-rich Fission Products, Filip G. Kondev 38
27. Prospects for Spent Nuclear Fuel Safeguarding with Antineutrinos, Mădălina Wittel ...39

Annexes

1 – Agenda 41
2 – List of Participants...45
3 – Links to Presentations..53

1. Introduction

A Technical Meeting on “Nuclear Data for Antineutrino spectra and their applications” was held on 23-26 April 2019 at the IAEA Headquarters, Vienna, Austria. The purpose of this meeting was to review the current status of reactor neutrino measurements, with particular focus on the latest results on the anti-neutrino flux and spectrum and how they compare with the results of the two calculation methods, namely the conversion method and the summation method. Such a review is timely given the effort that has been expended over the past 10 years to improve the nuclear decay data of fission products that are relevant to the calculation of the anti-neutrino flux and spectra produced by a nuclear reactor. Following the recommendations for measurements for decay heat calculations as proposed by contributors to Subgroup 25 of the OECD-NEA Working Party on International Evaluation Cooperation of the Nuclear Science Committee in 2005/6 [1], a series of Total Absorption Gamma-ray Spectroscopy (TAGS) measurements were carried out by the Valencia-Nantes and Oak Ridge National Laboratory collaborations. A re-assessment of the original TAGS request list at an IAEA Consultants’ Meeting in 2009 led to an agreement to extend the requirements to the determination of antineutrino spectra [2]. Therefore, relevant specialists were invited to the IAEA at two Consultant’s Meetings, in 2014 and 2018, to discuss the recently performed and planned TAGS studies for the above-mentioned applications, and to produce a definitive re-defined list of priority radionuclides requiring TAGS measurements not only for decay heat but also for anti-neutrino spectra calculations in the 4-6 MeV energy range where the anti-neutrino ‘bump’ has been observed [3]. Over 70 nuclides have been studied intermittently between the IAEA meetings and several of the new data have been published and are available for use in summation calculations. The impact of these new data on the size of the anti-neutrino anomaly or bump remains to be assessed.

In light of the above developments and progress, the Technical Meeting organised by the IAEA, aim at assessing both the reactor neutrino experiments and new data produced by the various measurement collaborations, as well as the improvements in the conversion method and summation method predictions, after consideration of new nuclear theory developments and the latest TAGS decay data.

Arjan Koning, Head of the Nuclear Data Section, opened the meeting and Paraskevi Dimitriou, Scientific Secretary of the meeting, gave a brief introduction to the IAEA, the Nuclear Data Section and the purpose of the meeting. Alejandro Sonzogni (BNL) was elected Chair of the meeting and Muriel Fallot (Subatech-Nantes Univ.) and Bryce Littlejohn (Illinois Inst. Of Technology) were recommended to be the rapporteurs.

The meeting comprised of presentations by representatives of most of the long-baseline and short-baseline measurement campaigns, as well as by experts in the conversion and summation methods and decay data measurements. A few presentations on the progress in and potentials of the applications of anti-neutrino spectra measurements in remote monitoring of the operation of nuclear reactors were also given. The ensuing discussions were led by the convenors Patrick Huber (VTU) and Karsten Heeger (Yale Univ.) who gave an outline of the progress made and remaining outstanding issues. The discussions concluded with two sets of recommendations for reactor neutrino measurements and calculation methods, respectively.

A short introduction to the motivation for reactor neutrino physics is given in Section 2, while a summary of the technical discussions and the recommendations is provided in Section 3. Summaries of the presentations are given in Appendix 1. The adopted meeting agenda, list of participants and links to the presentations are available in Annexes 1, 2, and 3, respectively.

2. Motivation – short introduction to physics and measurements

Nuclear reactors are the brightest terrestrial source of antineutrinos, which are produced in the beta decays of neutron-rich fission fragments and span nearly all possible beta decay energies. Reactor antineutrinos have primarily been observed via inverse beta decay (IBD) interactions with protons in an experiment's detector target. Experimental studies at reactor-detector baselines ranging from hundreds of meters to hundreds of kilometres have resulted in landmark measurements of neutrino flavour oscillation, a fundamental property of the three Standard Model neutrinos related to the relative scales of their masses. Many studies at shorter (~10-100m) baselines have also probed the existence of flavour oscillation enabled by new sterile neutrinos not predicted by the Standard Model. *While most of these measurements were motivated by the promise of improved understanding of neutrino properties, the past decade has seen their parallel emergence as a valuable new nuclear physics benchmark.* By comparing measured reactor antineutrino fluxes and energy spectra to models generated using standard nuclear databases and theoretical approximations, these model inputs can be tested in a unique way complementary to more conventional means, such as fission product decay heat measurements [3].

Recently, the precision and diversity of available reactor antineutrino flux and energy spectrum datasets have been substantially advanced. Recent neutrino oscillation experiments, like Daya Bay, RENO, and Double Chooz have detected millions of antineutrinos from low-enriched (LEU) pressurized water reactors and produced precision measurements of their average energy spectrum and flux. The same high-statistics datasets have also been used to observe variations in antineutrino production at different points in these reactors' fuel cycles. A new generation of compact, on-surface detectors have begun providing first glimpses of antineutrino production at highly U-235-enriched (HEU) research reactors. The precision of these direct measurements now rivals or in some cases exceeds that of state-of-the-art reactor antineutrino models based on historical fission beta spectrum data or standard nuclear databases.

These recently obtained antineutrino datasets provide unique independent constraints on the production and properties of rare neutron-rich isotopes in nuclear reactors. The comparison of antineutrino models with the measured data can guide the identification of incorrect/incomplete nuclear datasets and modelling inputs for dominant or high-Q fission products, or impose new constraints on the properties of these isotopes. The availability of antineutrino datasets from different reactor fuel compositions allows the antineutrino-based investigation of many of these properties separately for the primary fission isotopes ^{235}U, ^{239}Pu and ^{238}U. Antineutrino datasets capable of providing such tests of nuclear data can also lead to improved source term uncertainties for antineutrino-based non-proliferation and verification applications.

In parallel with the experimental advances, the modelling of reactor antineutrino spectra has been the object of numerous studies. The systematic uncertainties associated with the antineutrino spectra deduced from the conversion of the integral beta spectra measured at the high flux reactor ILL have been thoroughly investigated as these spectra triggered the search of sterile neutrinos at nuclear reactors. At the same time, a large effort has been invested on the measurement of beta decay properties of fission products with the Total Absorption Gamma-ray Spectroscopy (TAGS) technique, improving significantly the quality of the antineutrino predictions based on the summation method and nuclear data. The advances made in the antineutrino models in conjunction with the recent results of reactor neutrino experiments shed new light on the reactor neutrino anomalies and provide new directions for future investigations.

3. Discussions and Recommendations

3.1. Reactor neutrino experiments

Goals and Objectives

A large number of reactor antineutrino experiments have been carried out in the past decade. Long baseline experiments include Daya Bay, Double Chooz, RENO, and KamLAND, while short baseline experiments include CHANDLER, DANSS, NEOS, Neutrino-4, Nucifer, PROSPECT, SoLid and STEREO. In addition, the neutrino scattering experiment COHERENT has also started to produce data. All these experiments aim at allowing us to achieve the following goals:

1. Understand reactor antineutrino flux and spectrum for fundamental physics.

2. Understand reactor antineutrino flux and spectrum for safeguards and monitoring applications.

3. Enrich the nuclear data and improve reactor models that enable predictions.

Accomplishments and Progress

Significant technological advances and development efforts carried out world-wide have allowed the scientific community to make remarkable progress. A review of the existing experimental reactor antineutrino detector facilities and a survey of the published data reveal several achievements listed below:

1. Made precision measurements of reactor antineutrino spectra at low enriched uranium (LEU) reactors. Current experiments are systematics limited. [4, 5, 6]

2. Observed the change in the reactor antineutrino spectrum and flux as a function of fuel evolution over several fuel cycles. [7, 8]

3. Performed modern measurements of the 235U spectrum at high enriched uranium (HEU) reactors. Current experiments are statistics limited. [9, 10]

4. Demonstrated technology and capability of performing precision IBD-based antineutrino measurements with surface-based detectors. [11]

5. Recent experimental discovery of coherent neutrino scattering opens access to detection of reactor antineutrinos with much larger cross sections than are available via IBD or scattering on electrons. [12]

6. Continued R&D efforts towards surface based, field-deployable, mobile high signal-to-background IBD-based detectors. [11, 13, 14]

Outstanding Issues

In spite of the progress and above-listed achievements, there still remain open questions about the antineutrino flux and spectrum distortion (bump) that need to be answered:

1. Modern LEU experiments see a 'bump' in the comparison of measured antineutrino spectra and model predictions. The origin of this discrepancy remains unknown.

2. Some parameter space of eV-scale sterile neutrinos suggested by global fits to existing neutrino data remains to be tested.

3. Directly measured isotopic antineutrino yields and spectrum uncertainties are unknown at the level of several percent.

4. Possible indications for fine structure have been suggested in the literature [15]. Further experimental investigation of these features should be performed.

5. We have no measurements of the spectrum of reactor antineutrinos with energies below the 1.8 MeV IBD threshold.

6. We have not completed measurements of secondary contributions to the antineutrino flux (spent fuel, samarium poisoning, non-equilibrium and non-linear isotopes, other non-fission contributions).

7. A coherent picture of isotopic fluxes and spectra has not yet emerged from modern antineutrino measurements.

8. We have not yet measured antineutrino spectra from reactor types other than HEU and light water LEU.

9. Not all published antineutrino data and necessary supplementary materials are available in tabulated electronic form.

10. Up-to-date summation antineutrino models are not easily accessible for use by neutrino experimentalists.

Methods for Addressing These Issues - Recommendations

Participants discussed possible ways of addressing the outstanding issues and made the following proposals/recommendations:

A. Continued Measurements and Analysis from Existing Detector and R&D Facilities

1. Improve on HEU antineutrino spectrum measurements with existing experiments. More than 10^5 IBDs are necessary to be systematics limited.

2. Provide absolute flux measurements at HEU reactors with existing experiments.

3. Improve precision flux and spectrum evolution measurements at LEU reactors.

4. Continue to explore coherent nuclear and electron elastic antineutrino scattering as a tool to probe low-energy reactor antineutrinos.

5. Make self-consistent comparisons of results from existing experiments.

B. Future Measurements and Investigations with New Detector Facilities

1. Perform a high-resolution (percent-level) and high-precision measurement of an LEU spectrum, preferably a single reactor over several fuel cycles.
    - i. *Provides a reference spectrum for future experiments, like JUNO.*
    - ii. *Provides a benchmark measurement to test nuclear databases.*
    - iii. *Provides increased reliability in measured isotopic IBD yields due to a larger sampled range of fission fractions.*
    - iv. *Provides an opportunity to improve nuclear physics knowledge of neutron-rich isotopes.*

2. Deploy mobile detector system(s) based on the same design/technology at multiple reactor types capable of making precision antineutrino flux and spectrum calibrations with common detector response systematics.
    - i. *Provides a library of templates for different reactor types useful for safeguards and reactor monitoring.*
    - ii. *Provides validated technologies for safeguards and reactor monitoring.*
    - iii. *Enables coincident measurements at a reactor facility to directly compare performance of differing technologies.*
    - iv. *Provides an opportunity to validate model predictions for different reactor types and fissile vectors.*

3. Perform measurement of the neutrino spectrum below the IBD threshold using coherent nuclear or electron scattering.
    - i. *Provides new information for antineutrino, reactor and nuclear models.*

C. Data Standardization and Dissemination

1. Establish standard plots and formats for flux/spectrum data and inputs to allow comparison of existing data. Further discussions will be pursued to define these criteria, but examples may include detector response matrices, records of experimental and analysis procedures, uncertainty accounting, and reactor parameters.

2. Encourage community use of only peer-reviewed, published data and results that provide the tabulated data and supplementary materials references above. Caution against use of historical data that does not provide a similar level of experimental detail as that described above.

3. Establish standards, processes, and locations for permanent public storage and access. Require peer reviewed publication for inclusion. The neutrino community would welcome the experience of the nuclear data community in dissemination and long-term storage.

3.2. Antineutrino calculations

Antineutrino flux models

In addition to the progress made in reactor neutrino experiments, there have also been significant developments in antineutrino calculations since the publication of the conversion models and the first « modern » summation model in 2011 by Huber and Mueller et al. [16, 17].

Conversion method
The conversion method (CM), which relies on the only available single measurement of the integral beta spectrum of ^{238}U by Schreckenbach et al. at ILL [[18], has been studied carefully with emphasis on evaluating the robustness of the uncertainties associated with the conversion models that led to the reactor anomaly.

Several publications since 2011 have pointed out that the total uncertainties were significantly underestimated [19, 20, 21, 22] (cf. the summaries of the presentations of A. Hayes, P. Huber and L. Hayen for more details).

The conversion procedure itself has been investigated [19,21] and has led to the realization that it suffers from larger uncertainties than expected due to the distribution of the average effective Z of the beta branches used in the fit of the ILL beta spectra.

There are also large uncertainties in the treatment of high Q-value forbidden non-unique transitions. Different treatments of these transitions may lead to different aggregate antineutrino spectral shapes while leaving the aggregate beta spectral shape unaffected [19, 20, 22]. The effect of these uncertainties is still not well understood.

Summation method
Meanwhile there has been significant improvement in the Summation Method (SM) calculations which rely heavily on nuclear data for fission yields and fission product decay data.

A large concerted experimental effort driven by several nuclear physics groups has resulted in a series of targeted Total Absorption Gamma-ray Spectroscopy measurements of a large number of isotopes relevant to anti-neutrino spectra [23-32]. The new TAGS decay data have led to significant improvement in the quality of the summation calculations (cf. the summary of Fallot for more details) [33].

Progress and Achievements

1. A good agreement has now been reached among the two models (CM and SM) for the shape of the antineutrino energy spectra of ^{235}U, ^{239}Pu and ^{241}Pu in the 2 to 5 MeV energy range. The spectral deviation in the 5 to 7 MeV antineutrino energy range observed between measurements and model predictions still cannot be explained.

2. The IBD flux predicted by the updated SM calculations is closer to the measured one compared to the SM predictions performed in 2011. The disagreement between SM flux and that measured by the global flux experiments has dropped from 7% to between 2 and 3% [33, 34].

3. With regards to the rate, the ^{235}U IBD yield measured by LEU reactor neutrino experiments is found to be lower than the CM prediction, in contrast to what is found for ^{239}Pu. This trend is also reflected in the summation calculations. The slope of the IBD yield as a function of burnup obtained with the SM is also in good agreement with the measured one [33, 34].

Outstanding issues and recommendations

A. Nuclear data

Both the CM and the SM depend strongly on the quality of the nuclear data inputs. A large effort has been devoted to improving both the nuclear models describing beta decay, and the nuclear decay data using experimental techniques such as TAGS and/or complementary high-resolution Gamma-ray spectroscopy. There have also been efforts to improve the fission yield data with the works performed by Sonzogni et al. [35] and Schmidt et al. [36]. However, some issues remain outstanding such as

1. Obtaining realistic estimates of the uncertainties in the SM. The propagation of uncertainties associated with the decay data and the fission yields on the summation method spectra is being investigated for the effect of uncertainty correlations. Some promising preliminary work in this direction has already been presented at this meeting (see Sonzogni's presentation and summary 17).

2. Improving fission yields on the basis of new measurements of fission fragments and the energy dependence of fission product yields [35-38]. Better knowledge of the fission yield isomeric ratios is also required.
   - The nuclear physics community is encouraged to perform measurements that would improve the relevant fission yield data. In this respect, the fission yields of the important contributors to anti-neutrino spectra (see table 3 of [3] and [39]) need to be re-visited to assess whether they need to be re-measured..

   With respect to the currently available evaluated fission yield libraries, the JEFF-3.3 [40] fission yield library is fairly compatible with current decay data libraries and should be used in summation calculations which are based on nuclear data. An international effort to improve the fission yield data libraries is planned by the IAEA.

3. Improving the treatment of forbidden non-unique shape factors of the beta decay spectra. Several models have been developed to compute these shape factors [19, 20, 22].
   - It is recommended that the calculations of the shape factors are validated with known data before they are used whenever it is possible.
   - New measurements of beta shapes of individual isotopes to constrain the theoretical predictions are also recommended.

   Targeted lists of forbidden non-unique transitions that contribute significantly to the antineutrino energy spectra based on the theoretical calculations of A. Sonzogni, A. Hayes and L. Hayen have been published [19, 22] and could serve as a guidance for measurements.
   - We recommend estimating the impact of the largest shape factors predicted by theory by including these shape factors computed by Hayen et al. (see presentation in this report) in the summation calculations and in conversion calculations.

4. Providing an assessment of the published values of the different sub-contributions to the total uncertainties of the conversion models.

5. Improving the predictive power of nuclear models for the beta decay or the fission process. Progress has been made in developing more reliable theoretical models for beta decay such as the gross theory [40], shell model and QRPA [42-44], and for fission including the semi-empirical GEF code [37] as well as stochastic and microscopic, self-consistent models [45].

   These models are expected to have an impact on summation antineutrino spectra. The model calculations provide a database that is complementary to the available evaluated libraries and additionally, an alternative way of calculating antineutrino spectra (see Yoshida's and Schmidt's presentations, summaries 15 and 22). They could also provide the required covariance matrices to propagate the uncertainties in summation calculations.

B. Reactor and integral data

In spite of the great amount of activity both in theory and experiment in the past two decades, the basis of the flux models remains still the integrated beta spectrum measurements by Schreckenbach et al. at ILL [18] in the late 1980s.

- It would be desirable to have a new measurement of the aggregate beta energy spectra for the main actinides to compare with the ILL measurements which constitute nowadays a unique reference. We recommend exploring the possibility of redoing such a measurement.

Details of the reactor matter and reactor specifics and the possible effect they may have on the measured spectra should be understood well. Possible items to look into are:

- Non-equilibrium, structural aluminium, Sm poisoning of the reactor core (see presentation of D. Svirida and summary 10)
- The neutrino flux and spectral shape from reactors are influenced by the calculated energy release per fission that is converted into heat. There are differences between the evaluated and the literature values and it is recommended that these differences be understood.
- The impact of different fuel (MOX, VTR).

4. Conclusions

Participants from reactor neutrino experiments, theory groups applying the conversion and summation methods, as well as developers of nuclear beta decay models, and nuclear experimentalists and data experts met to discuss the current state-of-affairs regarding the reactor antineutrino flux and spectrum measurements and their comparison with model calculations. A consensus was reached on the achievements and remaining outstanding issues.

In conclusion, participants agreed that

- an absolute calibration of the reactor antineutrino flux across the entire spectrum, in terms of modelling and measurements, would bring additional value for basic science (Weinberg angle, etc.) and for applications (reactor monitoring);

- the conversion method and summation methods are complementary and their strengths could be combined for the optimum results;

- with the current knowledge, the conversion and summation method error bars are larger than 3% and further work to properly quantify these uncertainties is encouraged;

- The nuclear physics community should make an effort to provide more relevant data (TAGS, beta shapes and other complementary data) for the dominant beta transitions based on the available priority lists.

- Stronger channels of communication with the reactor physicists/engineers would be helpful.

Participants also acknowledged that the discussions have benefitted from and will continue to benefit from international coordination.

They therefore recommend the creation of a working group (Antineutrino Flux Working Group) that maintains updated, fully documented antineutrino flux predictions and measurements for isotopes and reactors.

The scope of the working group will cover three specializations:

- standardized antineutrino data,
- standardized models,
- Antineutrino model input nuclear data and experiment.

The IAEA Technical Meeting proved to be useful for having productive discussions among the experts from different fields, such as reactor neutrino experiments, calculation methods and theory, as well as nuclear data. Future meetings may also benefit from the participation of reactor physicists or engineers.

Participants expressed their interest in having another similar meeting in 2 years to review the status and assess the progress in the field.

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Summaries of presentations

1. Last Double Chooz results and observations with null nuclear power, Cécile Jollet, CENBG (on behalf of the Double Chooz collaboration)

Reactor antineutrino oscillation experiments aim at the measurement of θ_{13} mixing angle through the observation of anti-ν_e→anti-ν_e transition. The discovery of a non-zero value of the θ_{13} mixing angle is an important breakthrough in neutrino oscillation physics, which opened the way for the CP violation search in the leptonic sector.

The idea of the experiment is to measure the large flux of neutrinos coming from the two reactor cores with two identical detectors. The first detector is located at about 400 meters from the reactor cores (where the oscillation probability is very small) whereas the second one is hosted in the former CHOOZ experiment laboratory at about 1 km from the reactors, at about the first maximum of oscillation. The ratio of the spectra measured at the far and near site gives a direct measurement of the mixing angle θ_{13}. This evaluation using two identical detectors allows for a cancellation of many systematic errors related mostly to the flux normalization and detector efficiency evaluation. Since the survival probability depends on the neutrino energy, the measurement of θ_{13} uses total rate information and spectral deformation.

The signal signature is given by a two-fold coincidence (space and time correlation) between the prompt signal given by the positron ionization and annihilation, and the delayed signal given by the γ's emitted in the neutron capture on Gd (~8MeV with a mean delayed Δt of ~30 µs with respect to the prompt signal) or H (2.2MeV with a mean delayed Δt of ~200 µs with respect to the prompt signal).

The Double Chooz experiment, which started data taking in 2011 with the far detector (FD) only, had a major role in the θ_{13} search giving for the first time indication of a non-zero value of the θ_{13} mixing angle, using for the first time the neutron capture on Hydrogen for an independent measurement, performing a reactor rate modulation analysis which allows to cross check our knowledge on the background, and observing spectral distortion dominated by the 5 MeV excess. The near detector (ND) started data taking in 2015 allowing to cancel out the largest systematic error due to the neutrino flux uncertainty.

The collaboration has analyzed a statistics corresponding to 481 days with the FD only and 384 days with both detectors. To exploit the FD single phase, the single detectors have been fitted simultaneously constrained by the inter-detector correlations (background shape, detection rate and rate+shape of flux). Compared to the model, a spectral distortion is clearly observable leading to a high χ^2/DoF of 182/112. However, doing the FD to ND ratio, all the traces of any remaining spectral distortion vanish, indeed once they are corrected for θ_{13} the spectra match within ~1 σ(stat). In addition, the distortion scales with reactor power ruling out the hypothesis of an additional background. An empirical model extension has also been introduced with increased uncertainties for the reactor systematics to demonstrate the accuracy of the θ_{13} measurement. Double Chooz has also measured the most precise mean cross-section per fission $\langle\sigma_f\rangle = (5.71\pm0.06) \times 10^{-43}\text{cm}^2$ to date, in good agreement with Bugey4 and the others experiments.

Several set of data with both reactors-off have been taken with FD and ND in 2017. These data allowed us to do a direct measurement of the backgrounds indeed a good agreement has been found with the model measurements (determined by the different vetoes). They have also permitted to observe the cooling down of the reactor core observing the remaining neutrinos. The evolution on short time windows (few first hours) and between the first and second days show how the rate and the spectrum change in time. A preliminary simulation shows a good agreement for the residual neutrino spectrum measured during the 21 days of reactor-off. A more precise simulation taking into account the real situation is under development. Moreover, profiting from several periods of reactor-off data permits us to use one period for calibration and then apply this calibration on another period to estimate the power using the number of neutrino interactions. We looked at the achievable resolution and at the sensitivity on reactor power variation as a function of the observation time window.

2. Reactor Antineutrino Flux Measurements at Daya Bay, Bryce Littlejohn, Illinois Inst. Of Technology (on behalf of Daya Bay collaboration)

The Daya Bay Reactor Antineutrino Experiment continues to produce world-leading precision in its measurements of reactor antineutrinos and neutrino oscillations. Daya Bay accomplishes these measurements by observing inverse beta decay (IBD) interaction rates and energy spectra with multiple detectors situated at different baselines from six low-enriched (LEU) pressurized water reactor (PWR) cores in a nuclear power generating station in Southeastern China [1]. The prolific antineutrino production rate at the 17.4 GW_{th} generating station, combined with the surrounding mountainous terrain and corresponding overburden provide ideal experimental conditions for high signal and low background detection rates. Following its first unambiguous measurement of the neutrino mixing parameter θ_{13} in 2012 [2], Daya Bay has continued to expand the precision and scope of its oscillation measurements.

Since 2014, Daya Bay has also produced an array of high-precision measurements of the reactor antineutrino flux produced by its LEU PWR cores. These measurements have confirmed the existence of a deficit in detected IBD yield per fission with respect to state-of-the-art reactor predictions, demonstrating a 1.5% precision superior to the quoted uncertainties of these predictions [3]. This discrepancy can be explained via short-baseline antineutrino disappearance enabled by the existence of eV-scale sterile neutrinos, or by inaccuracies in the aforementioned predictions. This measurement's precision is currently limited by uncertainty in the concentration of protons in the Daya Bay detectors' liquid scintillator antineutrino targets.

Daya Bay's measurements have also defined the variation in detected IBD yield with change in average reactor fuel content [4], providing a direct new window into the dynamics of antineutrino production in LEU PWR cores. Some reactor antineutrino models incorrectly predict this IBD yield evolution, a likely sign of inaccurate IBD yield predictions for specific fission isotopes, particularly the most-dominant U-235 isotope. Uncertainties on these measurements can be reduced through increased experimental statistics and new experimental constraints on antineutrino production by the sub-dominant LEU fission isotopes U-238 and Pu-241. Robustness of this result could also be further demonstrated through external validation of key reactor-based inputs, such as improved measurements of the burn-up dependence of reactor fission fractions, and detailed theoretical investigation of energy release per fission and sub-dominant dynamic reactor effects.

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3. Summary of Antineutrino Spectrum Measurement at Daya Bay, Liang Zhan, Inst. of High Energy Physics (On behalf of the Daya Bay Collaboration)

This talk reports a new measurement of the prompt energy spectrum of reactor $\overline{\nu_e}$ at Daya Bay with three times more $\overline{\nu_e}$ events and reduced systematic uncertainties compared with previous results [1]. Furthermore, the individual prompt energy spectra of two dominant isotopes (235U and 239Pu) are obtained for the first time by fitting the evolution of the prompt energy spectrum as a function of fission fractions from commercial reactors. The results in this talk is mainly taken from Ref. [2].

Left panel of Fig. 1 shows the spectrum comparison of the measurement with the normalized Huber-Mueller model prediction.

With a sliding 2-MeV window scanning, the largest local discrepancy is found in 4—6 MeV, with a significance of 6.3σ.

The global discrepancy of the entire spectrum in 0.7—8 MeV has a significance of 5.3σ. The contributions of the four isotopes (235U, 239Pu, 238U and 241Pu) to the total observed antineutrino spectrum are determined by their fission fractions which evolves during the reactor operation. The individual spectra of the 235U and 239Pu isotopes are extracted using a χ^2 fit to the evolution of the IBD prompt energy spectrum

Right panel of Fig. 1 shows the extracted 235U and 239Pu spectra together with their Huber-Mueller predictions normalized to the best-fit numbers of events for 235U (0.920) and 239Pu (0.990), respectively. In the energy window of 4—6 MeV, a 7% (9%) excess of events is observed for 235U (239Pu) spectrum compared with the normalized Huber-Mueller model prediction. The maximum local discrepancy is 4.0σ for the 235U spectrum, and only 1.2σ for the 239Pu spectrum because of larger uncertainties. The Daya Bay data indicates an incorrect prediction of the 235U spectrum, but such a conclusion cannot be drawn for the 239Pu spectrum.

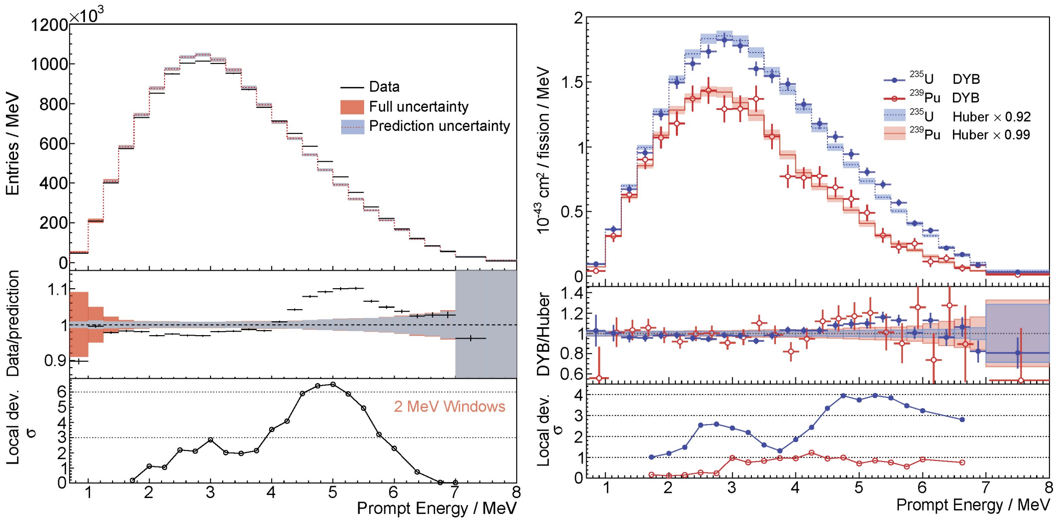

Fig.1 Left: Comparison of the predicted and measured prompt energy spectra. Right: Comparison of the extracted 235U and 239Pu spectra and the corresponding Huber-Mueller model predictions with the normalization.

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4. Precise Measurement of Reactor Antineutrino Yield and Spectrum at RENO, Soo-Bong Kim, Seoul National University (on behalf of the RENO collaboration)

The Reactor Experiment for Neutrino Oscillation (RENO) started data-taking from August, 2011 and has observed the disappearance of reactor electron antineutrinos to measure the smallest neutrino mixing angle theta13. The experiment has analyzed roughly 2200 days of data to make an accurate measurement of the oscillation amplitude and frequency based on energy and baseline dependent disappearance of reactor antineutrinos. The measured values are $\sin^2 2\theta_{13}$ = 0.0896±0.0068 (±7.6%) and $|\Delta m_{ee}^2|$ = (2.68±0.14)×10^{-3} eV^2 (±5.2%). The results are reported in Phys. Rev. Lett. 121, 201801 in November 2018.

RENO's precisely measured flux and spectral shape of reactor antineutrinos have shown a deficit in the flux and an excess in the region of 5 MeV relative to the most commonly used model. The observed inverse-beta-decay (IBD) yield using both near and far detectors is (93.7±2.0)% of the Huber and Mueller (HM) prediction where the error is largely attributed to the detection efficiency. We obtain a reactor antineutrino spectrum by unfolding its energy resolution and detector response from an observed prompt energy spectrum of the near detector.

We obtain measured daily IBD rates in a linear correlation with expected ones from the reactor thermal outputs and fuel isotope fission fractions. This exhibits 4-6% accurate monitoring of daily reactor antineutrino yield with a near detector and demonstrates a capability of remotely monitoring reactor thermal power. The 5 MeV excess is also strongly correlated with the reactor thermal power indicating that the excess indeed comes from the reactor.

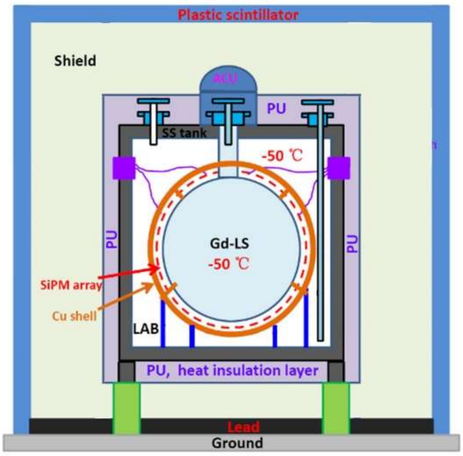
Furthermore, we observe fuel-composition dependent variation of reactor antineutrino yield at confidence of 6.6σ using the near detector. The total observed IBD yield per fission is $(5.84\pm0.13)\times10^{-43}$ cm^2/fission and 0.940±0.020 of the HM prediction. The best fit to the fuel-composition dependent variation finds the IBD yield of 235U per fission to have a 2.8σ deficit with respect to the HM prediction. We find that reevaluation of 235U's antineutrino yield per fission may solve the reactor antineutrino anomaly. We also report a hint of correlation between the 5-MeV excess and the 235U fuel isotope fraction in 2.9σ confidence level. The results are submitted to PRL under review and expected to be published soon. A manuscript is uploaded as arXiv:1896.00574.

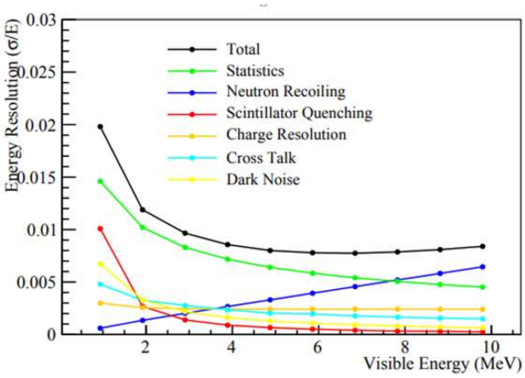
5. Measuring High Resolution Reactor Neutrino Spectrum with JUNO-TAO, Jun Cao, Institute of High Energy Physics (on behalf of the JUNO Collaboration)

Taishan Antineutrino Observatory (TAO) is a ton-level liquid scintillator (LS) detector at 30-35 meters from a core of the Taishan power plant in Guangdong, China. It is proposed as a satellite experiment of Jiangmen Underground Neutrino Observatory (JUNO), to precisely measure the reactor neutrino spectrum with as high as possible energy resolution. The main purposes are 1) to provide a reference spectrum for JUNO to eliminate the possible model dependence in determining the neutrino mass hierarchy due to fine structures in reactor neutrino spectrum; 2) to provide a benchmark for the inspection of nuclear data by comparing with the *ab initio* reactor neutrino spectrum.

The detector uses 2.6 ton gadolinium-doped LS (1 ton fiducial volume) contained in a spherical acrylic vessel and viewed by 10 m^2 SiPM of photon detection efficiency higher than 50%. Neutrino inverse beta decays in LS will be 2000 (4000) events per day with (without) detection efficiency considered, providing enough statistics. The LS detector has to operate at -50 degrees Celsius or lower to reduce the dark noise of SiPM. 4500 photoelectrons per MeV (1.5%/sqrt(E) photon statistical resolution) are expected. Taking into account the LS quenching, neutron recoil, dark noise, cross talk, and charge resolution, the energy resolution is expected to be sub-percent in most energy region of interest.

The detector R&D has been started for more than one year. A LS recipe has been developed and showed good transparency and light yield at -50 degrees. SiPM has also been tested at the same temperature. Simulation shows that cosmogenic fast neutron backgrounds can be well controlled with proper shielding, muon veto, and pulse shape discrimination. The laboratory in a basement at 10 m underground has been surveyed. The JUNO-TAO experiment is expected to be online in 2021.





JUNO-TAO detector scheme

Expected Energy Resolution

6. Global fits of reactor antineutrino flux measurements, Yu-Feng Li, Institute of High Energy Physics

Reactor antineutrino anomaly (RAA) is the rate deficit of the reactor antineutrino flux measurements compared to the predictions of the new flux model (Huber+ Muller model). We have investigated the possible solution to RAA [1] by considering all the previous reactor rates measurements and new fuel evolution measurements from Day Bay and RENO.

The global fits of the reactor rates measurements turn out to favor the equal suppression for different fission isotopes at the level of 1.7σ [2]. The fuel evolution data of Daya Bay and RENO disfavor the equal suppression at the level of 2.9σ, and favor a suppression of the U-235 flux while keeping the flux of Pu-239 consistent with the model prediction [1]. Combining both the reactor rates and fuel evolution data, we have investigated all the possible solutions to RAA and obtained the following useful conclusions [1]:

a) A common inaccuracy of all beta conversion predictions is disfavored at 3.0σ;

b) A deficit for the U235 rate is always obtained for both oscillation-including and -excluding hypotheses;

c) The contribution from oscillation is not conclusive, in which oscillation-including hypothesis is moderately favored over the oscillation-excluding one at the level of 1-2σ;

d) If oscillation is not considered, the global fits favor a second deficit contribution from U-238 at the level of 2.4σ.

Finally we want to stress that a spectral ratio measurement at different baselines in the short baseline reactor antineutrino experiments will give a direct test of the oscillation hypothesis [3] and quantify their size of the contributions in RAA. The preliminary results from DANSS and NEOS are interesting indications [4] and future test is required to resolve this anomaly.

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7. CHANDLER: A New Technology for Surface-level Reactor Neutrino Detection, Jonathan Link, Virginia Tech

The CHANDLER technology is bases on cubes of wavelength-shifting plastic scintillator, arraigned in a rectangular array, and thin sheets of lithium-6 (^{6}Li) loaded zinc sulfide (ZnS) scintillator. Light from a cube is directed, by total internal reflection, along the rows and columns of cubes where it is readout by photomultiplier tubes (PMTs). The position of an event is determined to be in the cube that lies at the intersection of the row and column of the hit PMTs. This highly segmented readout method, known as a Raghavan optical lattice (ROL), gives the event position to the precision of a single cube. The sheets are for detecting neutrons, which capture on the ^{6}Li, fissioning it into alpha and triton particles, which deposit their energy in the ZnS. Light from the ZnS is absorbed by the wavelength-shifter in the plastic cubes and retransmitted such that it too can be captured by total internal reflection.

This configuration is ideal for detecting electron antineutrino ($\bar{\nu}_e$) interactions through the inverse beta decay process, where the $\bar{\nu}_e$ exchanges charge with a proton in the plastic cubes, producing a positron and a neutron. The positron is detected as a prompt narrow pulse of light, while the neutron produces a delayed signal in the ZnS. Due to the nature of the ZnS scintillator, this delayed signal is 20 times longer then the prompt.

In 2017, the 80-kg MiniCHANDLER prototype was installed in a 4.5-meter trailer and deployed for four and a half months to the North Anna Nuclear Generating Station. There it was parked outside the containment building of Reactor 2, about 25 meters from the core center. The data taken during this deployment was used to make an observation of reactor neutrinos (Alireza Haghighat, 2018). This observation makes MiniCHANDLER the first mobile neutrino detector, the first unshielded reactor neutrino detectors and one of the world's smallest neutrino detectors.

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8. NEOS Phase-I and II, Seon-Hee Seo, Center for Underground Physics, Institute for Basic Science (on behalf of the NEOS collaboration)

The observation of a 6% deficit of electron anti-neutrinos from very short baseline (VSBL) reactor neutrino experiments is a strong motivation to search for eV scale sterile neutrinos. The uncertainties of the past VSBL neutrino measurements are still not so significant (3 sigma level), so that to confirm or refute the hypothesis of active to sterile neutrino oscillation to explain the deficit, improvements in the measurements in the total flux, spectral shape as well as the L/E dependence of the observed neutrinos are required. This would be also a very important input to improve the models on reactor neutrino fluxes/spectra based on improved nuclear data base.

The main goal of NEOS (NEutrino Oscillation at Short baseline) is to search for eV scale sterile neutrinos and it is located in the tendon gallery of the 5th reactor core at Hanbit Nuclear Power Plant in Younggwang, Korea. The baseline distance is about 24 m with about 20 m.w.e. overburden. Thermal power of the 5th reactor is about 2.8 GWth.

NEOS target consists of a homogeneous liquid scintillator (1,000 liters) detector with about 0.5% Gd

loading. To enhance pulse shape discrimination (PSD) power, Ultima-Gold F was added to 10%. Total 38 PMTs (8 inches) are attached at the two side walls of buffer region in the lay-down cylindrical shape detector. For energy calibration in NEOS phase-I (NEOS-I), radioactive source (137Cs, 60Co, PoBe, and 252Cf) data were taken every week, and 40K from the installed PMTs and 208Tl from borated PE passive shielding were also included for the calibration. To validate the energy conversion in NEOS-I, 214Bi and 12B events from 222Rn decay chain and cosmic muon spallation, respectively, were sampled, and very good agreements between data and MC were obtained. Energy resolution was measured as about 5% at 1 MeV. During NEOS-I, data was taken from August 2015 to May 2016 resulting in 180 (46) days of reactor-ON (OFF) data. About 2,000 IBDs/day with a signal to background ratio of 22 was observed with the phase-I data set but no strong evidence of sterile neutrino was observed when comparing spectral shapes of the prompt energy spectra between NEOS and Daya Bay. Note that NEOS has also observed the 5 MeV excess and it is the only VSBL experiment observed it so far.

The first observation of the 5 MeV excess is from using power reactors where four main isotopes (235U, 239Pu, 238U, and 241Pu) contribute to the most (> 99.9%) of the electron anti-neutrino flux via nuclear fission processes. It is natural to ask which isotope contributes to the 5 MeV excess. It could be solely from 235U since it is the one produces most neutrinos but it could be also from other isotopes. To answer this question, VSBL reactor neutrino community became very active by using research reactors which use highly enriched 235U fuel. Unlike most other VSBL reactor neutrino experiments NEOS uses a power reactor. The main purpose of NEOS phase-II (NEOS-II) is to take data for one complete fuel cycle (~500 days) to observe time evolution of reactor neutrino spectrum and to measure individual spectra from 235U and 239Pu.

NEOS-II detector is a refurbished NEOS-I detector using new GdLS and it was installed in 2018 at the same location. Data taking goes smoothly since its operation in September 2018 and calibration data is taken every other week. We plan to have a new result in 2019 with the first 6 months of reactor-ON data before obtaining our final results with ~500 days data.

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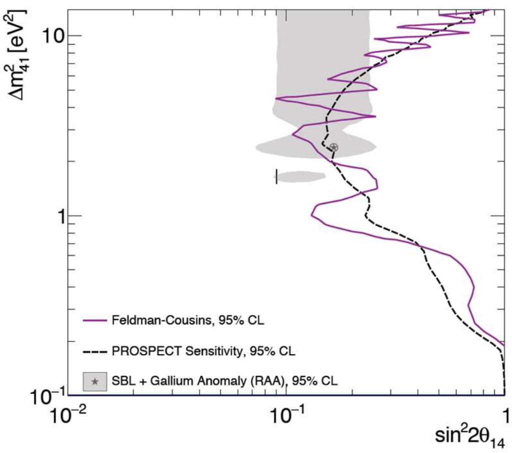
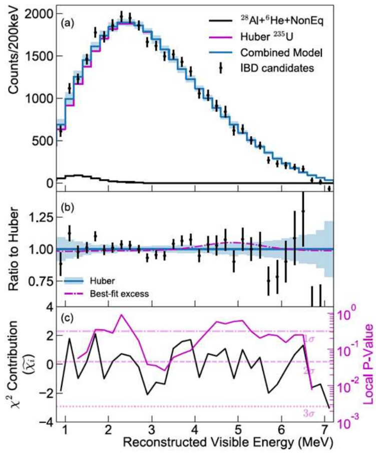
9. Measurement of Antineutrinos from ^{235}U with PROSPECT at the High Flux Isotope Reactor, Karsten M. Heeger, Yale University (for the PROSPECT Collaboration)

PROSPECT, the Precision Reactor Oscillation and Spectrum Experiment, is a reactor neutrino experiment designed to search for short-baseline, sterile neutrino oscillations and to make a precision measurement of the ^{235}U reactor antineutrino spectrum [1]. It uses a 4-ton, segmented ^{6}Li-doped liquid scintillation detector under minimal overburden located at 7.9m from the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL) to measure the prompt energy spectrum from inverse beta-decay on protons. During its first year of operation the detector exhibited excellent pulse shape discrimination and world-leading energy resolution demonstrating the potential of a surface-based, segmented detector for basic and applied neutrino science. PROSPECT has published initial results on both the search for short-baseline neutrino oscillation as a signature of eV-scale sterile neutrinos and the first modern measurement of the ^{235}U reactor antineutrino spectrum from HFIR. Initial operations of PROSPECT showed that the observation of reactor antineutrinos can be achieved at 5σ statistical significance within two hours of on-surface reactor-on data taking. Based on data collected during 33 live days of reactor operation at a nominal power of 85MW PROSPECT detected some 25461±283 candidate reactor neutrino events through the inverse beta decay event reaction. A reactor-model independent analysis of the inverse beta decay prompt energy spectrum as a function of baseline showed no signs of sterile neutrinos. It constrains significant portions of the previously allowed sterile neutrino oscillation parameter space at 95% confidence level (CL) and disfavors the best fit of the Reactor Antineutrino Anomaly (RAA) at 2.2σ CL [2]. Subsequent data taking yielded an enlarged data set of 31678±304 inverse beta decays (IBD). This represents the largest sample from HEU fission to date, 99% of which are attributed to ^{235}U. A comparison of the Huber ^{235}U model to the measured spectrum shows broad agreement but reveals deviations in two localized energy regions. The measured ^{235}U spectrum shape is found to be consistent with a deviation relative to prediction equal in size to that observed at low-enriched uranium power reactors in the antineutrino energy region of 5-7 MeV. PROSPECT is currently statistics limited.



The sensitivity and 95% confidence level sterile neutrino oscillation exclusion contour from the 33 live-day PROSPECT reactor-on dataset [2].



Measured prompt energy spectrum of inverse beta decay events compared to prediction based on the Huber model [3].

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10. The SoLid experiment, Antonin Vacheret, Imperial College London (for the SoLid collaboration)

SoLid is a very short baseline reactor neutrino oscillation experiment located at the BR2 reactor in Mol, Belgium. The SoLid collaboration has 50 members from 11 institutes, representing 4 countries.

The goal of the experiment is to search for short distance oscillation of electron antineutrino to test the sterile neutrino hypothesis. SoLid will also measure with high statistics the pure Uranium-235 antineutrino spectrum from the BR2 core which could help understanding the origin of the shape distortion called the bump.

SoLid has a unique take on those measurements; it uses an innovative highly segmented solid scintillation technology [1, 2] that provides a linear response in energy with good resolution and unprecedented spatial and time reconstruction of antineutrino interactions [3].

The BR2 reactor is a tank-in-pool reactor dedicated to in-core irradiation with a unique bevelled design. It runs on average 6 cycles of around 22 days per year with thermal power varying between 40 and 80 MW depending on the needs. The BR2 reactor facility is under strict security access, which limits the level of maintenance and access to the detector during operation. The SoLid detector has therefore been designed for robustness and minimal maintenance over the 4-5 years duration of the experiment.

The detector is made of PVT scintillator cubes (5 cm x 5 cm x 5 cm) combined with LiF:ZnS(Ag) phosphor screens to detect the product of the inverse beta decay reaction. The scintillation cubes are assembled in mechanical frames containing each 256 cubes and read out by 64 SiPMs. The full detector is composed of five independent detector modules, each made of 10 detector planes, providing a total fiducial mass of 1.6 tonnes segmented in 12 500 cubes and 3 500 read out channels. The detector uses a low noise custom-made electronics providing individual SiPM voltage bias and signal amplification. The data from each 64 SiPMs of a plane is digitized at 40 MHz by a digital board.

The need for triggering at low threshold on neutron signals required an efficient trigger strategy to reduce to manageable rate the 3Tb/s of data generated by the detector. To that end, a new trigger based on pulse counting has been developed in the firmware to trigger only on neutron signals and buffering time windows before and after the trigger signals simultaneously across 6 planes around the trigger plane.

On site, the detector modules are placed inside a customised ISO-freight container that provides a first isolation from the outside, shielding the detector from temperature variations and electronic noise. Passive shielding is then added around the container in the form of Cadmium plates, 50 cm thick water bricks and PE plates to reduce the gamma-ray and fast neutron backgrounds. The detector has been taking stable data for almost a year in the BR2 restricted reactor area, showing few percent level stability in energy scale and efficiency. Automatic calibration of the detector with the CALIPSO[4] and in-situ CROSS robot shows excellent uniformity of the cube response both in neutron efficiency and light yield resulting in an energy resolution of around 12% at 1 MeV. The main challenge of the experiment is to match the S:B of other experiments but without the possibility of using neutron/gamma PSD. The analysis of the first large dataset is currently ongoing with unique techniques developed to address the external and internal backgrounds present in the experiment. In particular, a new pulse shape discrimination technique was developed to reduce the Bi-Po-214 background and topological categories have been developed to maximise discrimination of both type of backgrounds. A first result using the data accumulated over this first year of running is expected later this year.

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11. Using DANSS Antineutrino Detector for Industrial Reactor Power Monitoring, Dmitry Svirida, National Research Centre "Kurchatov Institute" (for the DANSS Collaboration)

DANSS is a highly segmented antineutrino detector with a sensitive volume of one cubic meter. 2500 strips of plastic scintillator with gadolinium loaded reflective coating are read out individually by SiPMs and in groups of 50 by conventional PMTs. The position of the detector directly below an industrial 3 GW reactor combines the advantage of the highest antineutrino flux with the overburden of 50 m.w.e., provided by the reactor elements and its biological shielding. The distance to the antineutrino source can be changed in the range 10.7 to 12.7 m by means of a lifting gear, thus allowing the studies of the spectrum variations for the sterile neutrino searches. The inverse beta decay (IBD) process is used for the antineutrino detection. After applying of a number of carefully optimized cuts, including those based on fine segmentation, DANSS counts up to 5000 IBD events per day with only about 3% of the background from cosmic muons, which gets carefully subtracted.

With its high stability and unprecedented IBD count rate DANSS proofs the applicability of the antineutrino detectors for the long term monitoring of the reactor power. The present analysis is based on about 1.6 million IBD events recorded in 17 months of detector operation. The statistical accuracy of each two-day measurement is about 1.5%, while the overall systematic uncertainty is estimated below 0.5%. Rates at different detector positions are equalized by factors from toy MC with reactor burning profiles and detector size. Common normalization to the reactor power is used for the whole analysis period. With the ^{239}Pu fission fraction in the range (0.25-0.39) the dependence of the antineutrino spectrum shape and of the total counting rate on the fuel burn up is clearly observed. A correction based on the actual fuel composition brings the measured IBD rates into the good agreement with the conventional thermal power measurements, except for the first month of the fuel campaign.

The excessive antineutrino yield during this period can be attributed to the effect of samarium poisoning. Accumulation of the ^{149}Sm arises from the β-decay of ^{149}Pm ($T_{1/2}$=53.3 hr), which, in turn, is a decay product of ^{149}Nd, the latter having a noticeable fission yield of about 1.1%. At full reactor power the equilibrium is maintained by the loss of ^{149}Sm in neutron capture, which happens with huge cross-section of 40800 barn and ends up in ^{150}Sm, equally stable and inert to neutrons. In several days after the reactor shutdown all the ^{149}Pm decays, resulting in the accumulation of significant amounts of ^{149}Sm. This is called 'poisoning' since the core reactivity noticeably drops. Typically for power reactors, only about one third of the fuel cartridges is replaced with the fresh ones during the reload. Right after the startup, only the old cartridges are poisoned and burning is emphasized in the fresh fuel. But only the old cartridges contain previously accumulated ^{239}Pu, and thus ^{235}U fission is accented in new fuel. The measured 2% excess in the IBD counting rate corresponds to about 20% of relative change in ^{235}U fission fraction. The effect of samarium poisoning remains noticeable for about one month, in agreement with the equilibrium setting time of 30 days for typical values of PWR core parameters.

12. Implications of the PROSPECT Aboveground Reactor Antineutrino Detection Demonstration for Monitoring and Safeguards Applications, Nathaniel S. Bowden, Lawrence Livermore National Laboratory (for the PROSPECT Collaboration)

PROSPECT is a reactor antineutrino experiment whose primary goals are to search for short-baseline neutrino oscillations and perform a precise measurement of the ^{235}U reactor antineutrino energy spectrum [1]. Since March 2018, PROSPECT has operated a 4 ton antineutrino detector less than 10m from the 85MW_{th} High Flux Isotope Reactor (HFIR) at the Oak Ridge National Laboratory. PROSPECT has demonstrated the ability to detect ~750 antineutrino events per day with a signal-to-background ratio greater than 1 in an aboveground location with almost no overburden [2]. Additionally, PROSPECT has performed a high resolution ^{235}U spectrum measurement in this same adverse background environment [3].

This first demonstration of a full-scale system operating without cosmic-ray attenuating overburden meets one of the goals set forth by the attendees of the "*Workshop on Antineutrino Detection for Safeguards Applications*" hosted by the IAEA Novel Technologies Group in 2008 [4]. An aboveground detection capability "*will enable a wider set of operational concepts for IAEA and reactor operators, and will likely expand the base of reactors to which this technology can be applied*," since deployments are no longer limited to locations with overburden.

Indeed, the performance of the PROSPECT detector meets or closely approaches the requirements for reactor monitoring capabilities examined by the Applied Antineutrino Physics (AAP) community. The simplest application is monitoring operational status – is a reactor on or off? PROSPECT can infer the operational status of HFIR to 5σ confidence after only two hours of data taking, assuming that the reactor off background rate has been previously measured [2]. Useful operational state sensitivity has been found for other research reactor types of nonproliferation interest [5]. While a dedicated sensitivity analysis has not yet been completed, it is also apparent from the collected event statistics, the excellent long-term stability of the detector, and the good signal-to-background ratio [2], that PROSPECT has the ability to infer reactor power. This is notable, since the detector operates at a high-power research reactor, the sole facility type at which IAEA makes direct power measurements for safeguards [4]. A system like PROSPECT would allow this measurement to be made in a non-intrusive manner with no connection to plant systems. The spectral measurement capability of PROSPECT is more than sufficient for use case studies that have examined the spectrum changes that result from changes to reactor core fuel isotopics [6]. With conceivable increases in background rejection and target mass, a PROSPECT-like detector could meet IAEA timeliness requirements for material diversion [5].

The next step in technology development for reactor monitoring applications is a high sensitivity, mobile aboveground antineutrino detection capability. This would enable the rapid and non-intrusive deployment of antineutrino systems to essentially any reactor facility. The PROSPECT aboveground demonstration has already motivated a use study based upon this deployment modality [7]. Such a system would also enable spectrum measurements at multiple reactors with different fissile vectors, providing the means to validate reactor spectrum predictions with common detector systematics and a set of benchmarks for reactor monitoring applications.

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13. Coherent elastic neutrino-nucleus scattering, Yuri Efremenkov, Univ. of Knoxville (for the COHERENT collaboration)

Coherent elastic neutrino-nucleus scattering (CEvNS) was predicted in 1974 as a consequence of the neutral weak current [1, 2]. Although the cross section is large compared to other neutrino interactions at neutrino energies below 100 MeV, first detection of this Standard Model (SM) process took 43 years due to the challenge of detecting tiny nuclear recoils. Recent developments in low radioactivity and low threshold detector techniques led, for the first time, to observation of this process by the COHERENT collaboration at the ORNL Spallation Neutron Source using a 14 kg CsI detector [3]. This is the first operational hand-held neutrino detector.

At low neutrino energies this process has 100 times larger cross section than Inverse Beta Decay (IBD) and 1000 times more than neutrino – electron scattering. In addition, the process does not have a fixed energy threshold e.g. 1.8 MeV for IBD. The lowest neutrino energies observable by CEvNS depends only on the detection threshold of the detector. At present about a half dozen collaborations around the world are working on detection of CEvNS from nuclear power plants using a variety of detection technologies. If successful, it will be possible to build reactor neutrino monitoring detectors with mass tens of kilograms rather than ton-scale detectors depending on conventional IBD technology.

The COHERENT collaboration will continue to study this process with high precision using multiple targets. Such studies will lead to development of a variety of detection technologies and will test SM predictions for CEvNS cross sections. Deviations from predicted cross sections will be indicative of physics beyond the SM. An initial goal of collaboration is to test the SM prediction of proportionality of the CEvNS cross section to neutron number squared, N^2 [4] with carefully measured CEvNS cross sections for various targets.

The pulsed SNS neutrino beam and dedicated well-shielded location in the SNS target-building basement (called Neutrino Alley) offers great opportunities to study various CEvNS detection technologies and test SM predictions.

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14. Antineutrino spectrum prediction and nuclear data, Patrick Huber, Virginia Tech

The currently most widely used reactor neutrino flux model, the so-called Huber-Mueller (HM) model, is based on the conversion of integral beta spectrum measurements performed in the late 1980s at the ILL [1-3]. These measurements were performed with good precision for thermal neutron fission of 235U, 239Pu and 241Pu and more recently with significantly less precision for fast neutron fission of 238U [4]. For 235U, 239Pu and 241Pu the HM model is based on the ILL data and the details of the conversion procedure can be found in [5]. The spectrum for 238U stems from a summation calculation [6] and there is reasonable agreement between this summation result and a conversion of the integrated beta spectrum for 238U within the considerable experimental error bars.

Without going into the technical details of the conversion method, it is important to understand that this method, as currently all other methods, are based on the assumption of allowed (or unique forbidden) beta decays. Within the allowed approximation nuclear data enters in two ways into the conversion method: for the estimation of the weak magnetism contribution, which is believed to be under control [7]; and in the so-called effective nuclear charge parameter $\bar{Z}$. $\bar{Z}$ is needed to compute the effect of the Fermi-function and other electromagnetic effects on the outgoing electron. The approach taken in [5] is to fit a second order polynomial in the endpoint energy to the actual atomic number distribution of fission fragment beta decay branches. In the same reference a closure test is performed, i.e. a summation calculation is performed and the resulting integral beta spectrum is computed. This beta spectrum is then converted to a neutrino spectrum using above description. The resulting converted neutrino spectrum can be directly compared to the neutrino spectrum from the summation calculation. The difference between the two neutrino spectra is founds to be consistently less than 0.1%. This demonstrates that above simple parameterization of $\bar{Z}$ does not introduce a bias in the converted neutrino spectrum. Overall, the combined uncertainty on inverse beta decay interaction rates from weak magnetism and the $\bar{Z}$ parameterization amount to 1.5% compared to an overall 2-3% uncertainty, with error budget being dominated by the normalization of the ILL data. A more detailed discussion of associated issues can be found in the contribution by A. Hayes-Sterbenz.

Summarizing, the original error estimates presented in the HM model within the allowed approximation are reasonable. However, the lack of agreement between the HM model prediction and measured neutrino spectra in both the absolute rate and spectral shape in the 5MeV region indicates a breakdown of the allowed approximation. As a result the HM error bars at best present a lower limit to the actual uncertainties. While many criticisms of the HM model have been published and also been discussed at this workshop, no quantitative models which simultaneously can describe the measured precision reactor neutrino spectra and the integral beta decay data exists to date. Furthermore, many avenues for improving our overall understanding of this problem have been presented, but no specific proposal how to arrive at a better, i.e. more reliable and/or more precise, general reactor flux model was put forward. It is worthwhile to note, that summation and conversion calculations seem to agree to a significant degree on the shape of the spectrum; the disagreement in total rate between the HM predictions and the latest summation calculations, as presented by M. Fallot at this meeting, is well within the quoted HM uncertainties. This fact seems to point to a common failure in those otherwise highly complementary approaches. From the theoretical side a main suspect are forbidden beta decays and the possible existence of sizable spectrum shape distortions in those decays [8, 9], which would affect both conversion and summation calculations in a similar manner.

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15. Current Status of Reactor Neutrino Spectra, Anna Hayes, Los Alamos National Laboratory

Knowledge antineutrino spectra emitted from reactors and their associated uncertainties are crucial for neutrino oscillation studies. The spectra used to-date have been determined by either conversion of measured electron spectra to antineutrino spectra or by summing over all of the thousands of transitions that makeup the spectra using modern databases as input. The method used to choose an effective charge for the fission fragments introduces the larges uncertainty in the conversion method. The uncertainties in the subdominant corrections to beta-decay plague both methods, and estimates of these uncertainties are available in the literature. Improving on current knowledge of the antineutrino spectra from reactors will require new experiments. Such experiments would also address the so-called reactor neutrino anomaly and the possible origin of the shoulder observed in the antineutrino spectra measured in recent high-statistics reactor neutrino experiments.

16. First-forbidden transition in reactor antineutrino spectra, Leendert Hayen, KU Leuven

An accurate theoretical calculation of the antineutrino spectrum shape is the central element in the traditional reactor anomaly analysis. Despite its importance, large uncertainties remain in its determination, ranging from fission yields, database uncertainties and theoretical spectrum shapes. We report on the role of forbidden, (non-)unique transitions in the so-called summation approach. Using the available nuclear database information, we show that (non-unique) forbidden transitions are dominant in the experimentally feasible region between 2 and 8 MeV, contrary to what is usually found in the literature.

Using large-scale shell model calculations, we have - for the first time - explicitly determined the shape factor in the nuclear shell model for a large sample of dominant forbidden transitions. Through inclusion of these transitions, more than 50% of the ILL electron ux in the 4-7 MeV window is accounted for. Many of the calculated shape factors show behaviour significantly different from the usual allowed transition. In particular, first-forbidden non-unique transitions with $\Delta J = 1$ are found to show differences on the order of 30-60% over the spectral range. Due to the contribution of higher-order operators, also in $\Delta J = 0$ significant changes on the order of 20% are found for transitions between higher-spin states.

Through a combination of the flux coverage of forbidden transitions and the calculated shape factors, minimal changes are found for the electron spectrum while significant deviations occur in the antineutrino spectrum. This has a significant impact on the analysis of the spectral shoulder, the statistical significance of which is shown to be reduced. Increased uncertainties throughout the calculated spectra inevitably lead to increased uncertainties in the theoretically predicted antineutrino flux. Through a proposed parametrisation of our calculated shape factors, these results can be extended to allow for a better treatment of non-unique forbidden transitions both within the summation and conversion models.

17. Reactor Antineutrino as a New Frontier of FP Summation Calculations, Tadashi Yoshida, Tokyo Institute of Technology

In fission-reactor technology, the summation method of fission products (FP) has extensively been used as a basic and practical tool to calculate the reactor characteristics of crucial importance such as the reactor decay heat (DH) and the delayed neutron emission. We applied this method to calculate the energy spectra of antineutrinos ($\bar{\nu}_e$) from fissile samples under neutron irradiation and from reactor cores. In order to obtain the $\bar{\nu}_e$-spectrum from each FP nuclide which is necessitated therein, we fully utilized the gross theory of beta-decay which has successfully been applied to the DH evaluation. By comparing the two kinds of the FP summation calculations, the well-experienced DH and the challenging $\bar{\nu}_e$-spectra, we shed light on the special feature of the reactor ν_e-spectrum evaluation of fission reactors. Anyway, our calculation is independent of the so-called pandemonium problem and is complementary to the summation calculations based on the experimental decay data of each FP nuclide. Our result supports the recent direct $\bar{\nu}_e$-spectrum measurements carried out at power reactors. On the basis of our calculation we investigated the role of the isomeric states in formation of reactor-antineutrino spectra. The difference in their spin-parity J^π from their own ground states gives rise to remarkable differences in their $\bar{\nu}_e$-spectra associated with their beta-decay. We have to use reliable $\bar{\nu}_e$-spectra and fission yields both of the isomeric and the ground states for the summation calculations where the gross theory helps us much. The impact of the pandemonium problem was also investigated in depth on the basis of our theoretical method.

18. Updated Summation Method Model and New Prediction for the Reactor Antineutrino Detected Flux and Energy Spectrum, Muriel Fallot, Subatech-Nantes University

The accurate determination of reactor antineutrino spectra is still a challenge. In 2017 the Daya Bay collaboration has released a measurement of the evolution of the antineutrino flux with the fuel content of the reactor core [1]. These results have been confirmed by the RENO experiment in 2018 [2] and the Daya Bay collaboration in 2019 with enhanced statistics [3]. The observed deficit of the detected flux compared with the predictions of the conversion model [4, 5] could be quasi-totally explained by the data arising from the fissions of ^{235}U while the part dominated by the fissions of ^{239}Pu would be in good agreement with the conversion model. The summation method (SM), based on the fission product beta decay data and the nuclear data of fission yields was re-developed in 2011 [4] in order to predict reactor antineutrino spectra from any fuel under any irradiation condition without restriction of the antineutrino energy range. It was shown that the Pandemonium effect [6] affects the evaluated nuclear databases containing the required beta decay data. The level of uncertainties on these SM spectra was then estimated to be of the order of 10 to 20% depending on the considered energy range. In [7] new TAGS results revealed to have a major impact on the antineutrino spectral shape. Since then the Nantes-Valencia collaboration has carried out two experimental campaigns during the last decade at the University of Jyväskylä, Finland, measuring a large set of data in order to improve the quality of the predictions of the summation method (SM) [8]. The details on the experimental TAGS technique, the spectrometers used and the careful analysis of these data were presented by A. Algora at this meeting. Recently, the SM model of [7] has been updated using the most recent evaluated beta decay databases and the TAGS results from the two experimental campaigns mentioned above [8] have been included in a new summation calculation [9]. The impact of the TAGS results for fifteen nuclei on the detected antineutrino flux and on the energy spectrum have been studied. The predicted antineutrino spectrum and flux have been compared without any renormalization with that obtained by the Daya Bay experiment and presented at this meeting. The new SM reactor spectrum exhibits a better agreement with the measured Daya Bay spectrum than that obtained with the converted spectra of [4, 8] in the 2 to 6 MeV energy range. The TAGS data of [8] improve the agreement also in the region of the shape anomaly, but still the bump is there meaning that for the moment, it cannot be explained by ingredients of the nuclear databases. Overall the SM model shows a fairly good shape agreement with converted spectra up to 6 MeV. The normalization of the SM ^{235}U spectrum in is better agreement with the Daya Bay results than the conversion prediction. The Inverse Beta Decay (IBD) yields dependency with the fission fraction of ^{239}Pu including the TAGS data published in 2012, 2015, 2017 and 2019 has been calculated using our summation calculation. The impact of their inclusion is a systematic reduction of the predicted IBD yields, leading to a reduction of the discrepancy with the Daya Bay results down to a 1.9% only. This result implies an increasingly smaller discrepancy with the inclusion of future TAGS data, leaving less room for the reactor anomaly. The SM predictions remain robust in the 2 to 5 MeV range at the 2% level, i.e. a better situation than the "10%" of missing information published in 2011. These results reflect the improvement of the quality of the summation model during this decade thanks to the TAGS experimental effort and the direct impact of the TAGS results on the predictions of the IBD yield.

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19. Uncertainty Quantification in the Summation Method for Nuclear Reactor Antineutrinos, Alejandro A. Sonzogni, Brookhaven National Laboratory

Our presentation covered three different aspects of our nuclear reactor antineutrino research. First, we quickly presented the method developed to reveal the signature of individual fission products from an antineutrino spectrum, which was published in PRC in 2018. Then we presented a comparative study of the Bugey-3 and NEOS data, observing that the fine structure observed on top of the spectra aligns well and actually corresponds to the ripples generated by ^{92}Y, ^{99}Zr, ^{99}Nb and ^{143}La. Finally, we showed the fine structure pattern agrees well with the prediction from the nuclear databases and is not compatible with some parameters from the 3+1 model.

The 2nd project we presented dealt with the development of cumulative fission yield correlation matrices to obtain realistic estimate of IBD antineutrino spectra and yields. The starting point is to use independent correlation matrices from the GEF code by K.-H. Schmidt et al, in conjunction with the JEFF-3.3 independent fission yields and the ENDF/B-VIII.0 decay data sub-library. Our preliminary results indicate that off-diagonal terms account for about 40%-50% of the total uncertainty balance and should be included in all summation calculations.

The goal of last project we presented was to quantify the level of disagreement between the Daya Bay spectrum, Daya Bay evolution data, and the ILL electron data. We found that, unlike the other 3 fuel nuclides, adjusting the ^{235}U Huber spectrum to match the Daya Bay spectrum can also account for the evolution data. We also found that by reducing the ^{235}U Huber spectrum by 8% and adjusting the ^{238}U Mueller and ^{239}Pu Huber spectra, the Daya Bay data can be reproduced. Finally, we implemented a reverse conversion method, that is, fitted a number of average beta branches to an IBD spectrum to obtain the corresponding electron spectrum. In this way we were able to obtain the level of disagreement with the ILL data for the different scenarios discussed above.

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20. Pandemonium free beta decay data for antineutrino summation calculations, Alejandro Algora, IFIC-Univ. Valencia (for the Jyväskylä TAS collaboration)

In this presentation the status of the total absorption measurements performed by the Valencia group in collaboration with the Subatech group (Nantes) was shown. The main motivation of the performed measurements has been to improve the quality of the antineutrino summation calculations and the predictions of the decay heat in reactors.

The measurements have been performed at the IGISOL IV facility of the Univ. of Jyväskylä using a combination of techniques: the ion guide technique that can provide beams of refractory elements, the JYLF penning trap that provided beams of high isotopic/isomeric purity and employing state of the art total absorption instrumentation and analysis techniques [1-3]. Considerable effort has been devoted to reduce the effect of known systematic errors (isobar contaminations, summing pile-up, etc.) and to the continuous improvement of the analysis techniques and the quality of the Monte Carlo simulations. This systematic study that was started around 2009 by our collaboration was preceded by a sensitivity study performed by the Nantes group that identified the top beta decay contributors per energy bin in the antineutrino spectrum. The result of that effort has been the measurement and analysis of more than 30 cases of large relevance for the topic of the workshop that provide beta decay data free from the Pandemonium effect. All measurements published until know and their impact in the antineutrino spectrum have been presented [4-5] as well as some recently analysed cases of particular relevance [6-9].

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21. Modular Total Absorption Spectrometer: the efficient array to study the beta-decay and anti-neutrino properties in fission products, Marzena Wolińska-Cichocka, Univ. of Warsaw and JINPA/ORNL Physics Division (for the MTAS collaboration)

The Modular Total Absorption Spectrometer (MTAS) [1-3] has been designed, constructed and commissioned at Oak Ridge National Laboratory. MTAS consists of 19 hexagonal modules of a total weight ~1000 kg of NaI(Tl) detector material and is surrounded by over 5000 kg of lead shielding and neutron capture foam. The MTAS γ-ray efficiency for full single γ energy absorption is about 82% at 500 keV and 72% at 5 MeV and its total efficiency (e.g. the probability of registering any portion of the incoming γ-ray energy) is ~98.9% at 500 keV [3]. The total gamma absorption spectroscopy is necessary to reduce or resolve the Pandemonium problem [4] and to obtain the true β-decay strength pattern and the following energy spectra β, γ and antineutrino emitted from fission products.

At ORNL, were have measured over 70 decays of ^{238}U proton-induced fission products. In particular, it includes 22 decays of high priority for anti-neutrino high-energy features [5, 6].

The ^{142}Cs → ^{142}Ba→ ^{142}La → ^{142}Ce was among the studied decay chains. These nuclides have very different Q_β value (from ~2.2 MeV to ~7.3 MeV) and the sum of their cumulative yield in the ^{238}U+n_{th} fission normalized to 841% is 14.2%. The ^{142}Cs activity is the third most important contributor to the high energy ῡ spectra in nuclear reactors [5, 6, 7]. The decays, of ^{142}Ba and ^{142}La are good test cases, since these decays were studied previously with total absorption spectrometer [8] and using high energy resolution techniques [9].

MTAS spectra for ^{142}Ba decay, with relatively low Q_β of 2.2 MeV, confirm the decay pattern listed at ENSDF/ENDF data bases. For the „mid" Q_β value like 4.5 MeV of ^{142}La, MTAS analysis allowed us to correct the β-feeding. For example, β-feeding to the 1st excited state and the ground state to ground state was modified, with respect to the results high-resolution spectroscopy [9] and earlier TAS measurement of Greenwood [8]. The significant changes at the decay scheme were obtained from MTAS results for ^{142}Cs, the nucleus which is farther from stability with higher Q_β=7.3 MeV, and has high importance for reactor anti-neutrinos [7].

The volume of MTAS active material, its efficiency and unprecedented modularity defines its high discovery potential.

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22. Determination of anti-neutrino energy spectra in fission products, Krzysztof P. Rykaczewski, ORNL Physics Division

The Modular Total Absorption Spectrometer (MTAS) has been constructed at ORNL to study β-decays of fission products in order to improve reactor decay heat and anti-neutrino spectra data. This 1-ton NaI(Tl) detector array [1-3] has been coupled to an isotope separator capable of selecting proton-induced ^{238}U fission products. After two years of commissioning and off-line calibrations, the experimental campaigns were performed in 2012, 2015 and 2016. These experiments yielded the decay data for nearly 80 fission products. Evaluated and interpreted data on about 15 activities has been published [4-7]. These activities represent about 6% of the cumulative yield in the $^{238}U+n_{th}$ fission normalized to 100%.

MTAS spectra deconvolution profits from its large efficiency reaching 98% for the absorption of full or partial energy of a single gamma ray, and its radial segmentation. Not only a total absorption gamma spectrum is fitted during the analysis, but the modified β-decay scheme is verified through the response of individual MTAS rings [1-3]. The MTAS-aided results for nuclei abundant in nuclear reactors and are well studied through high-energy resolution, but low efficiency detectors are dramatic. For example, the decay heat released through photon emission in ^{89}Kr and ^{139}Xe went up by 18% and 31%, and the number of interactions between emitted anti-neutrinos and matter went down by 34% and 18%, respectively.

The integral effect of three most important activities for the high energy anti-neutrinos [8, 9], the ^{92}Rb, ^{96}Y and ^{142}Cs [4], increased the reported "bump-like" structure at 5-7 MeV by additional 2% (from previous ~ 10% vs the flat low energy part). Accounting for several MTAS-studied activities [5], after folding with the fission yields, led to the increase of a decay heat up to 3% and to the reduction of the reference anti-neutrino flux by over 2%. This result influences respectively the analysis of the "reactor anti-neutrino anomaly", where the deficit of observed vs expected anti-neutrino events was reported at the 95% level. It is possible that the evaluation of MTAS aided data, together with the results from Valencia team measurements will reduce the discrepancy between the expected and measured antineutrino flux below the reported error bars. However, the presence of the "bump" in the reactor anti-neutrino is unlikely to be reduced by the total absorption gamma spectrometry [4, 5].

Further analysis and measurements of activities abundant during the nuclear fuel cycle will profit from a recent DOE funding of MTAS related activities (November 2018).

It is anticipated that in total MTAS results will cover about 30-35% out of 100% of the cumulative yields for all four major nuclear fuel components, ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu.

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23. The impact of beta-delayed neutron emission on the determination of anti-neutrino energy spectra in fission products, Bertis C. Rasco, JINPA/ORNL Physics Division

The precise prediction, to better than 1%, of the antineutrino flux from nuclear reactors is a challenging goal. Recent results from total absorption spectrometry and improvements in fission branching ratio knowledge have improved summation calculations of the antineutrino flux predictions. Recent measurements at Oak Ridge National Laboratory using the Modular Total Absorption Spectrometer (MTAS) have contributed new information about the beta decay of neutron rich nuclei that are produced by fission. The new information provided by MTAS includes direct measurements of ground-state to ground-state feeding [1-4], the observation of pandemonium effected nuclei [5] and the corrected beta-feeding pattern [1-3], and the use of a novel measurement technique to measure the neutron branching fraction, P_n, and the emitted neutron energy envelope [3].

In addition to measuring beta-decaying nuclei properties, it is important to consider the role that beta-delayed neutron emission plays in the leptonic energy available to the antineutrino and the beta in more neutron rich beta decays. The process of beta-delayed neutron emission inherently reduces the leptonic energy from the beta decay since it involves only beta decays to energies above the neutron separation energy. But the neutron branching fractions are only measured at the 10% level of precision [6]. Uncertainties in the P_n can either increase or decrease the leptonic energy available depending on whether the P_n value is overestimated or underestimated.

Most of beta-delayed neutron emitters do not have large direct fission yields, but for these the P_n have larger values and have also have larger uncertainties. In addition to impacting the available leptonic energy, beta-delayed neutron emission can influence the cumulative fission yields, shifting the yields to lower total nucleon number. For the more exotic neutron rich nuclei the P_n uncertainty is larger. And in addition to the possible accumulation of changes over many nuclei, nuclei in this region are where very high energy antineutrinos are dominantly generated. Hence any understanding of the antineutrino flux generated from these exotic nuclei depends on the beta-delayed neutron emission rates.

Looking to the future, in order to gain high precision knowledge of the antineutrino flux (~0.1% level) accurate knowledge of P_n values becomes important.

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24. Extensive study of the quality of fission yields from experiment, evaluation and GEF for anti-neutrino studies and applications, Karl-Heinz. Schmidt

The understanding of the anti-neutrino production in fission and the theoretical calculation of the anti-neutrino energy spectra in different, also future, types of fission reactors rely on the application of the summation method, where the individual contributions from the different radioactive nuclides that undergo a beta decay are estimated and summed up. The first step of this kind of calculation is the most accurate estimation of the independent fission-fragment yields. They depend on the fissioning nucleus and on the energy spectrum of the incident neutrons.

Evaluations from different nuclear-data centres (for example JEFF, ENDF, JENDL) aim to provide reliable fission yields on the basis of available experimental data. They are presently mostly based on radiochemical measurements and they are restricted to fission induced by thermal, fast and 14-MeV neutrons for a small number of fissioning systems. The accuracy suffers from uncertainties in the spectroscopic nuclear properties. Experiments with powerful spectrometers, for example at LOHENGRIN [1], provide much more accurate mass yields and a Z resolution for light fragments from thermal-neutron-induced fission of a few suitable target nuclei. The innovative inverse-kinematics approaches [2, 3] provide excellent resolution in A and Z of all fission fragments for a large variety of fissioning systems. Due to some problems, e.g. in the resolution of the induced energy, they have not yet been exploited for evaluations.

On the theoretical side, the general fission model GEF [4] has been developed. It combines a few general theorems, rules and ideas with empirical knowledge. GEF covers almost all fission observables and is able to reproduce measured data with high accuracy while having remarkable predictive power by establishing and exploiting unexpected systematics and hidden regularities in the fission observables.

In an extended study [5], the benefit from cross-checking the results of different experimental approaches and GEF for improving the quality of nuclear data is demonstrated in a systematic survey of 24 fissioning systems. In particular, the sources of uncertainties and erroneous results from different experimental approaches are analysed, the capacity of GEF for identifying erroneous data and predicting the fission yields in cases (in terms of fissioning systems and excitation energies), which are presently not accessible to experiment, is shown, and some dedicated calculations on the production of anti-neutrinos are presented. Severe shortcomings in the evaluated fission-yield data for 9 systems are revealed, and recommendations for an improved evaluation, which emphasizes the importance of accurate data and the inclusion of the GEF code.

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25. Calculation of Independent and Cumulative Fission Product Yields and Fission Spectrum with the Statistical Decay Theory, Toshihiko Kawano, Los Alamos National Laboratory

The deficiencies in the current ENDF FPY data library were summarized, and the status of FPY model development toward a new evaluated FPY data files was reported. The FPY data in the libraries are given at three neutron-incident energies, the thermal, fast, and 14-MeV, which is insufficient to apply to nuclear reactor applications when the fast neutrons are causing fission in a system. The new evaluation at LANL takes account of the energy dependence of FPY by applying the Hauser-Feshbach Fission Fragment decay model developed at LANL and Tokyo Institute of Technology. Some preliminary results were shown to demonstrate the predictive capability of the model, which includes the cumulative FPYs for selected isotopes, the energy dependencies of the average number of prompt and delayed neutrons. By combining the beta-decay model, which is also developed at LANL, the anti-neutrino and beta spectra as well as the delayed neutron emission can be calculated. LANL incorporates microscopic fission theories into the model to reduce phenomenological parameterization for the cases where experimental information is scarce. A recent development of the number projection method clearly demonstrates the even-odd staggering in the charge distribution, which cannot be obtained by the neutron and proton density distributions.

26. Improving Nuclear Data for Neutron-rich Fission Products, Filip G. Kondev, Argonne National Laboratory

Details of the existing and future capabilities for decay data measurements on fission products (FP) at the Argonne National Laboratory were presented. One of the main goals is to take advantage of the unique capabilities available at the CARIBU facility at Argonne National Laboratory that provides high-purity and quality beams of almost all fission products and the availability of state-of-the-art detector equipment, such as the CPT and BPT, MR-TOF, X-array detector array of CLOVER Ge detectors and the SATURN tape station and Gammasphere in order to address a number of opportunities for nuclear data research.

To date, two different approaches are separately used to study FP properties. One is based on discrete γ-ray spectroscopy with a limited number of high-resolution Ge counters, the other is associated with a calorimetric technique utilizing low-resolution NaI detectors, known as Total Absorption Spectrometry (TAS). While the former approach was affected by the limited number of Ge detectors used in those measurements and, as a consequence, from the reduced efficiency for high-energy gamma rays and the absence of coincidence studies, the TAS technique suffers from the poor energy resolution and the lack of detailed knowledge of the FP decay schemes, which is imperative in order to obtain reliable results. In addition to early program at INEEL (presently INL), TAS measurements have been recently carried out by groups at Valencia (Spain) and ORNL. However, there seems to be notable differences between experimental results obtained by different groups which are not well understood at present. It is also worth noting, that significant theoretical modeling and unfolding procedures are needed in the analysis of the TAS data, which could result in large uncertainties in the deduced beta-decay feeding distributions. A new approach aimed at significantly improving the FP decay data was presented, which combines the discrete γ-ray spectroscopy and TAS using a single detector device, the world's most powerful γ-ray multi-detector array Gammasphere, in conjunction with the unique, high-purity FP beams provided by the CARIBU facility at Argonne National Laboratory. Gammasphere is a uniquely powerful tool for studying FP decays because of its large solid-angle coverage (~90% of 4π) that leads to excellent efficiency, both for discrete γ-ray spectroscopy with Ge counters (about 40% of the solid angle coverage) and for calorimetry via combination of data from Ge and BGO detectors.

The development of the new Gammasphere decay station, comprising of target chamber, tape-moving system and particle detector array (HEART - HExagonal ARray for Triggering), was presented. The commission experiment took place during the week of December 17-21, 2018. The experimental campaign was successful and a beta-gamma coincidence efficiency of 75(2)% was achieved. Data were collected for the ^{144}Ba, ^{144}La, ^{146}Ba, ^{146}La and ^{146}Ce isotopes and results from these measurements were presented. Specifically, in the case of ^{146}La, the decays of the ground state and the isomer were clearly isolated and resolved. Our analysis is continuing and the preliminary evaluation shows significant differences with the known evaluated ENDF/ENSDF data.

27. Prospects for Spent Nuclear Fuel Safeguarding with Antineutrinos, Mădălina Wittel, RWTH Aachen University

A large amount of spent nuclear fuel (SNF) has been produced both in civilian as well as in military applications of nuclear energy in the past decades. Moreover, due to the growing demand for (clean) energy, several countries like China, India, Russia and the United Arab Emirates are planning to increase their nuclear capacity which would in turn lead to a more rapid increase in the quantity of spent fuel. The presence of fissile material in the spent fuel constitutes an important verification challenge since it could be covertly diverted for weapons production. This underlies the necessity for safeguarding spent fuel repositories.

Several detection techniques can be employed for this purpose, e.g. seals, video monitoring remote radiation detection, etc. However, especially in view of identifying potentially hidden SNF repositories, an important source of information could come from the antineutrinos produced by isotopes still present in the nuclear waste. Isotopes such as strontium-90 undergo beta decay, thus emitting antineutrinos that would be capable of propagating through a significant amount of shielding material without being attenuated. At the same time, the small antineutrino reactions' cross-sections posit considerable challenges for the detector design and realisation. The typical neutrino detection technology usually involves measuring scintillation light or Cherenkov radiation in large detectors, several kiloton in size. For verification purposes, both the directionality capability of the detector as well as its dimensions are very important, specifically with regard to the deployment requirements.

In this talk, we discussed the prospect of utilising a new neutrino detection technique involving highly granular, imaging liquid argon detectors. This technology is presently developed and validated by the neutrino physics community, thus aligning the nuclear verification efforts with the forefront of fundamental science. Liquid argon detectors offer the advantage of unprecedented precision in measuring (anti)neutrino energies, incidence directions, and would have a remarkable spatial resolution which is needed to filter out background events.

We presented the outline of a feasibility study for employing this emergent type of (anti-)neutrino detectors in the context of nuclear waste verification efforts. We noted that it is crucial that our SNF antineutrino spectra calculations accurately follow the nuclear data community's prescriptions. Furthermore, we also addressed the fact that, due to the novelty of the liquid argon technology, a few antineutrino reactions like the antineutrino-nucleus coherent scattering are yet to be measured.

As the liquid argon technology matures in the context of (anti)neutrino detection, we propose that utilising it for spent fuel safeguarding is worth investigating.

APPENDIX 1

IAEA

Technical Meeting on

Nuclear Data for Antineutrino Spectra and their Applications

23 - 26 April 2019
IAEA, Vienna
Meeting Room M5, Bldg. M

ADOPTED AGENDA

Tuesday, 23 April

13:00 – 14:00	**Registration (IAEA Registration Desk, Gate 1)**
14:00 – 14:30	**Opening Session**
	Welcoming address Introduction (15´) Administrative matters Election of Chairman and Rapporteur Adoption of the Agenda
14:30 – 18:10	**Participants' Presentations**
14:30 – 15:10	C. Jollet, *CENBG / FR*
15:10 – 15:30	B. Littlejohn, *Ilinois Inst. of Technology / USA*
15:30 – 15:50	L. Zhan, *IHEP / CPR*
15:50 – 16:20	*Coffee break*
16:20 – 16:50	S.-B. Kim, *Seoul National Univ./ ROK*
16:50 -17:20	J. Cao, *IHEP / CPR*
17:20 – 17:40	Y. Li, *IHEP / CPR*
17:40 – 18:10	J. Link, *Virginia Tech. / USA*

Wednesday, 24 April

09:00 – 17:30	**Participants' Presentations** (cont'd)
09:00 – 09:30	S.-H. Seo, *IBS / ROK*
09:30 – 10:00	A. Vacheret, *Imperial College / UK*
10:00 – 10:30	D. Svirida, *ITEP / RU*
10:30 – 11:00	*Coffee break*
11:00 – 11:30	K. Heeger, *Yale Univ. / USA*
11:30 – 12:00	N. Bowden, *LLNL / USA*
12:00 – 12:30	Y. Efremenko, *Tennessee Univ. / USA*
12:30 – 14:00	*Lunch*

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14:00 – 14:30	P. Huber, *Virginia Tech. / USA*
14:30 – 15:00	A. Hayes-Sterbenz, *LANL / USA*
15:00 – 15:30	L. Hayen, *Leuven Univ. / BEL*
15:30 – 16:00	*Coffee break*
16:00 – 16:30	T. Yoshida, *Tokyo Inst. Technology / JP*
16:30 – 17:00	M. Fallot, *Subatech / FR*
17:00 – 17:30	A. Sonzogni, *BNL / USA*
19:00	***Dinner in a Restaurant (see separate information)***

Thursday, 25 April

09:00 – 12:45	**Participants' Presentations** (cont'd)
09:00 – 09:30	A. Algora, *IFIC Valencia Univ. / ES*
09:30 – 09:40	M. Wolinska, *Warsow Univ. / PL*
09:40 – 09:55	K. Rykaczewski, *ORNL / USA*
09:55 – 10:15	B. Rasco, *ORNL / USA*
10:15 – 10:45	*Coffee break*
10:45 – 11:15	F. Kondev, *ANL / USA*
11:15 – 11:45	K.-H. Schmidt, *DE*
11:45 – 12:15	T. Kawano, *LANL / USA*
12:15 – 12:45	M. Wittel, *RWTH Aachen / DE*
12:45 – 14:15	*Lunch*
14:15 – 16:00	**Round-table discussion**
16:00 – 16:30	*Coffee break*
16:30 – 18:30	**Round-table discussion** (cont'd)

Friday, 26 April

09:00 – 10:30	**Round-table discussion** (cont'd)
10:30 – 11:00	*Coffee break*
11:00 – 12:30	**Round-table discussion** (cont'd)
12:30 – 14:00	*Lunch*
14:00 – 16:00	**Round-table discussion / Drafting of recommendations**
16:00	**Closing of the meeting**

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Round-table Moderators: K. Heeger, P. Huber, A. Sonzogni

Topics:
Neutrino experiments: anomalies and sterile hypothesis; uncertainties-systematic-non-linearity; short vs long-baseline exps; agreement and discrepancies;
Conversion method: uncertainties of integral beta spectra; impact of forbidden transitions; impact of weak magnetism; recommendations for uncertainties; corrections; new measurements.
Summation method: impact of latest decay data measurements; uncertainties from experiment and theory; uncertainties in TAGS data; evaluated nuclear data libraries;
Reactor monitoring: data needs and perspectives.
Data curation and preservation.
Conclusions: long-baseline and short-baseline experiments; neutrino anomalies and sterile hypothesis; conversion vs summation method; new experimental data needs; nuclear data needs;
Recommendations: what needs to be done? Next meeting.

ANNEX 1

IAEA

TM on Nuclear Data for Antineutrino Spectra and their Applications

23 – 26 April 2019
IAEA, Vienna

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ANNEX 2

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ANNEX 3

Links to Presentations

#	Author	Title	Link
1	P. Dimitriou	Introduction	PDF
2	C. Jollet	Last Double Chooz results and observations with null nuclear power	PDF movie
3	B. Littlejohn	Daya Bay antineutrino flux measurements	PDF
4	L. Zhan	Daya Bay spectrum measurements	PDF
5	S.B. Kim	Precise Measurement of Reactor Antineutrino Yield and Spectrum at RENO	PDF
6	J. Cao	TAO-JUNOS experiment	PDF
7	Y. Li	Global reactor flux analysis	PDF
8	J. Link	CHANDLER: A New Technology for Surface-level Reactor Neutrino Detection	PDF
9	S.-H. Seo	NEOS I & II	PDF
10	A. Vacheret	SoLiD	PDF
11	D. Svirida	DANSS experiment	PDF
12	K. Heeger	PROSPECT	PDF
13	N. Bowden	PROSPECT Applications	PDF
14	Y. Efremenko	Coherent elastic neutrino-nucleus scattering	PDF
15	P. Huber	Antineutrino spectrum prediction and nuclear data	PDF
16	A. Hayes	Current status of the reactor neutrino spectrum	PDF
17	L. Hayen	First-forbidden transition in reactor antineutrino spectrum	PDF
18	T. Yoshida	Reactor antineutrino as a new frontier of FP summation calculations	PDF
19	M. Fallot	Updated Summation Method Model and New Prediction for Reactor Antineutrinos Detected Flux and Energy Spectrum	PDF
20	A. Sonzogni	Uncertainty quantification in the summation method for nuclear reactor antineutrinos	PDF
21	A. Algora	Pandemonium free beta decay for antineutrino summation calculations	PDF
22	M. Wolinska	Modular Total Absorption Spectrometer	PDF
23	K. Rykaczewski	Determination of anti-neutrino energy spectra in fission products	PDF
24	B.C. Rasco	Determination of anti-neutrino energy spectra in fission products	PDF
25	F. Kondev	Improving Nuclear Data for Neutron-rich Fission Products	PDF
26	K.-H. Schmidt	Extensive study of the quality of fission yields from experiment, evaluation and GEF for anti-neutrino studies and applications	PDF
27	T. Kawano	Calculation of Independent and Cumulative Fission Product Yields and Fission Spectrum with the Statistical Decay Theory	PDF
28	M. Wittel	Prospects for Spent Nuclear Fuel Safeguarding with Antineutrinos	PDF

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