https://doi.org/10.61092/iaea.xgkd-frt1

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Nuclear Data Needs for Antineutrino Spectra and their Applications

Summary Report of the Technical Meeting

IAEA Headquarters, Vienna, Austria
16 – 20 January 2023

Prepared by

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April 2025

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1. INTRODUCTION

The second IAEA Technical Meeting on Nuclear Data Needs for Antineutrino Spectra and their Applications was held from 16 to 20 January 2023, at the IAEA Headquarters. The purpose of the meeting was to review the current state of reactor antineutrino measurements, focusing on their relevance to basic science, reactor antineutrino applications, and associated modelling and data, considering the publication of two key documents— the Snowmass 2021 White Paper [1] and the NNSA-funded Nu TOOLS Report [2].

Fifty participants from ten countries including IAEA staff participated in person and virtually to discuss and re-evaluate the following several key aspects:

- Scientific goals of reactor neutrino research and applications:
    - In basic science (Standard Model (SM), beyond the Standard Model (BSM), nuclear physics)
    - Applications (Reactor operation remote monitoring, spent fuel monitoring)
    - Nuclear data
    - Reactor physics
- Priorities for:
    - Experiments and theoretical developments
- Technology challenges and pathways to achieve the scientific goals:
    - Field and goal dependent
- Nuclear data requirements
- Other data aspects: databases, dissemination, open data, computational tools

This report summarizes the status, challenges, and future goals in reactor antineutrino research and applications, highlighting the need for improved measurements, coordination, and collaboration among different experimental efforts, enhanced models and nuclear data.

Summaries of participants' presentations are available in the Appendix. The agenda and participants' list are provided in Annexes I and II, respectively. All presentations are accessible on the meeting website: https://conferences.iaea.org/event/337/.

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[2] Nu Tools, Exploring Practical Roles for Neutrinos in Nuclear Energy and Security, prepared by the Nu Tools Executive Group, 2021, https://nutools.ornl.gov.

2. GENERAL RECOMMENDATIONS

The roundtable discussions led to the formulation of a set of general recommendations listed below:

1. **Advance our understanding of the isotopic composition and evolution of antineutrino data:**
    - We recommend continuing the analysis and critical evaluation of existing data, including conducting joint analyses to ensure comprehensive review.
    - We recommend establishing a coordinated international effort to conduct new measurements using multiple detectors across various reactor types. This approach will enable correlated measurements, improving the accuracy and reliability of the data.

2. **End-User engagement:**
    - We recommend maintaining active engagement with end users, support research and development for technology demonstrations, and explore the synergistic use of multiple signatures. Other isotopes may also become relevant for future advanced reactor systems.
3. **Error Quantification in Summation Models:**
    - We recommend continuing to quantify and reduce the errors and uncertainties in summation models to improve their predictive capabilities.
4. **Validation of models:**
    - We recommend new integral neutrino and beta measurements with similar levels of precision to validate our understanding of the models. These measurements should be prioritized.
5. **Improving microscopic nuclear data:**
    - We recommend continued efforts to improve microscopic nuclear data, such as fission yields and TAGS data, as well as high-resolution spectroscopy data, as they are crucial inputs to model development.
6. **Providing open and easy access to data:**
    - We recommend disseminating data in a standardized, unified format to facilitate comparison and usage across the field. Additionally, the community should explore the creation of a central repository for archival storage of this data.
7. **Enhancing collaboration and coordination:**
    - We recommend strengthening communication and information exchange between the various scientific communities, stakeholders, and end users to ensure alignment and collaboration.
    - We recommend establishing a working group under the auspices of the IAEA Nuclear Data Section. This group would support international coordination, advise on organizing meetings, and provide guidance on future activities related to antineutrino data and its applications.

3. EXECUTIVE SUMMARY

The technical discussions are summarized in the following subsections.

3.1. Reactor antineutrino experiments for basic science (SM, BSM)

- Reactor Antineutrino Anomaly (RAA): Significant progress has been made since the publication of the first IAEA meeting report in 2019, in ruling out portions of the sterile neutrino phase space, although some open regions (high Δm^2) remain to be investigated. It seems plausible that the ILL measurement is the root cause of the RAA, with ^{235}U levels being low. The Daya Bay fuel evolution measurement supports this hypothesis.

  There are missing pieces of information, however, such as the single core LEU measurement, combined LEU and HEU analysis, and improved fission beta spectra. In addition, there are no flux measurements below the 1.8 MeV IBD threshold.

  Priorities in the next 5-10 years:

    - improving uncertainties on SBL experiments,
    - understanding the ^{239}Pu flux,
    - reconciling DANSS measurements with other experiments, and
    - performing further joint analyses.

- Spectrum Anomaly: The understanding of the isotopic origins of the spectral distortion has improved, but the underlying cause is still unknown. Several experiments are conducting final analyses on their data sets, and new efforts are being proposed. Further joint analyses are in progress and planned.

  Pandemonium-affected data are still incorporated in the nuclear databases and the question of a potential bias in the ^{235}U ILL beta spectrum remains open. High-resolution IBD measurements are needed.

- Coordination: coordination and collaboration between different experimental efforts are crucial. Correlated HEU/LEU measurements and consistent reactor data are needed. Guidance on different reactor types from working groups would be helpful.

- Nuclear and reactor data needs:
  - ^{9}Li/^{8}He information for JUNO-TAO background
  - beta delayed neutron data for JUNO
  - Energy release (in form of heat) / fission
    - New calculation with conservative uncertainties
    - Energy in structural materials (Al for research reactor, steel for power reactors)

- Technology Pathway (Detectors, etc.): detectors expected to achieve high precision spectral measurements in future experiments (TAO and JUNO) are being developed.

  Conclusion: Progress is resource-limited, and coordination is needed across agencies and countries, potentially in the form of a Working Group.

3.2. Antineutrino applications: reactors, spent fuel

- Experiments, Demonstrator, Monitoring Capabilities: Significant advancements have been made in antineutrino applications for reactors and spent fuel. The publication of Nu Tools report and other reports, such as those by WoNDRAM (Workshop on Nuclear Data for Reactor Antineutrino Measurements), have discussed various use cases. Detector technology and prototypes are being developed to meet specific requirements and boundary conditions. New use cases are also being explored. Other highlights include the first observation of spent fuel (Double Chooz) and modern measurements of HEU spectra. A "multi-messenger" approach to reactor observations is being utilized, with antineutrino detectors serving as on/off monitors. Finally, new detector materials are being developed, potentially at an industrial level.

- Looking to the future: The primary goals for the next 5-10 years include:
  - Continuing to develop use cases for antineutrino applications,
  - Advancing R&D to demonstrate the technology,
  - Utilizing synergistic use of multiple signatures, as highlighted in Anna Hayes' presentation on “Combining reactor fission gas data with antineutrino data” (https://conferences.iaea.org/event/337/timetable/)
  - Developing the first integrated system for reactor observations,
  - Conducting measurements in different reactors for basic science, nuclear data, and operational purposes,
  - Deploying different detectors at the same reactor to understand systematics,
  - Increasing the involvement of reactor physicists and nuclear engineers.

- Cross-Cutting Needs and Synergies with SM+BSM: There is a need for coordinated efforts to leverage synergies between Standard Model (SM) and Beyond Standard Model (BSM) goals. Combining reactor fission gas data with antineutrino data, for example can enhance non-proliferation efforts and help determine the grade of plutonium in reactor spent fuel.

- Technology Pathways: The development of on surface and mobile detectors is crucial. New detector materials are being explored, potentially at an industrial level. The "multi-messenger" approach to reactor observations, combining various data sources, is being implemented. Benchmarks with Monteburns MCNP to Origen or Cinder90 are being used for comparison to central rods, with major discrepancies being less than 2% and minor actinides around 6%.
- Challenges: Several challenges need to be addressed
    - Background interference in measurements,
    - Lack of clear use cases and ideas for new applications,
    - The US-centric nature of Nu Tools and the need to understand the international environment,
    - Socialization and acceptance of Nu Tools,
    - Resource limitations.

3.3. Modelling flux and spectrum

- Status and Achievements: The summation model has shown agreement with flux evolution from Daya Bay, indicating significant improvement. Multiple summation models are currently in use. Steps have been taken towards quantifying errors in these models. A new measurement by Kurchatov Institute has been conducted to confirm the conversion method results and used shape factors.
- Looking to the future: The primary goals are to
    - Conduct inter-comparisons of different summation models,
    - Acquire new and improved input data, particularly fission yields for high energy,
    - Perform new conversion calculations using new integral data,
    - Generate theoretical predictions for spectra of new or other reactor types.
- Challenges: main open issues to be addressed are
    - Long-range correlations in the data,
    - Assessing and determining realistic uncertainties,
    - Obtaining better input data to improve model predictions.

3.4. Nuclear data

- Experiments: TAGS and High-Resolution Gamma-ray Spectroscopy measurements have been conducted and improved summation calculations have been achieved. New efforts are underway to refine beta shape calculations. Recommended isomeric fission yield ratios and beta delayed neutron data have been updated. New masses and Q values have been measured. There are ongoing attempts to improve beta shape calculations and the treatment of non-unique forbidden transitions.
- Evaluated Data: Evaluated libraries for fission yields and decay data have been updated. Efforts are being made to include covariance matrices with these evaluations to better quantify uncertainties.
- Reactor Data: Direct antineutrino spectral measurements and their evaluations are being used to extract isotope-specific spectra. These measurements are crucial for improving the accuracy of reactor data.
- Challenges: Main open issues include
    - Measuring TAGS data and high-resolution spectroscopy data related to the high-energy part of the spectrum,
    - Measuring beta-delayed neutron spectra,
    - Disentangling isomers and ground states,
    - Developing covariance matrices associated with the decay data measurements,

    - Measuring accurate fission yields and isomeric ratios,
    - Developing and validating new evaluated fission yield libraries with covariance matrices.
- Coordination, Communication, and Synergies: Coordination and communication among different research groups are essential for progress. Synergies between various experimental and theoretical efforts are being explored.
- Next Steps:
    - Continue efforts to refine beta shapes,
    - Maintain and expand TAGS measurement efforts,
    - Revise the TAGS priority list to improve the situation for the high-energy part of the spectrum,
    - Complete TAGS measurements for both electrons and gamma-rays,
    - Incorporate microscopic theory into beta shape calculations,
    - Perform intercomparisons of measured TAGS data to validate results,
    - Improve and validate theoretical models used for short-lived isotopes in the absence of experimental data,
    - Conduct high-resolution spectroscopy measurements,
    - Continue mass measurements and Q value determinations, including the identification of isomers,
    - Address the need for integral beta measurements to enhance data accuracy.

3.5. Data preservation and dissemination

- Status: Significant progress has been made in making data available to the community through publications in scientific journals. The Daya Bay (DYB) experiment has set a standard in sharing data, demonstrating the importance of having supplementary data available to ensure impactful results. There is an ongoing discussion about the need for a central tool or repository to manage and share data effectively. The US needs to provide a comprehensive data management plan, as it is becoming a standard practice to make data available satisfying FAIR principles. Steps are being taken to establish central repositories, and understanding community needs is crucial. A working group can help summarize, define, and advise on these needs.
- Challenges: Several challenges need to be addressed such as
    - Standardizing information to ensure consistency and usability.
    - Deciding what data to keep and archive, and what can be analysed in the future.
    - Investments are needed to enable central storage and management of data.
- Communication: Effective communication is essential for the success of data management and sharing initiatives. This includes:
    - Promoting the importance and benefits of data sharing within the community.
    - Effectively communicating the status and progress of data management efforts.
    - Ensuring that reports go through a vetting process to maintain accuracy and reliability.
- Next steps: To move forward, the following actions are recommended
    - Provide both antineutrino spectra and information preferred by collaborations, including unfolded spectra and covariance matrices.
    - Unify the format (e.g., binning) for shared use to ensure consistency.
    - Archive reactor information along with neutrino data to provide comprehensive datasets.
    - Establish a standard repository for reactor antineutrino data to facilitate access and analysis.

3.6. Coordination in reactor antineutrino research

- Status: Joint work has been published in the field, indicating collaborative efforts. Adding another dataset to precision data may not be entirely useful without a clear plan for joint analysis. There is a need for a structured plan for joint analysis, including data from different types of reactors and input data for calculations. Coordinated work on fission yields should continue following the IAEA CRP, and decay data also requires inspection and coordination at international level, particularly regarding beta shapes.

  Conclusion: Different levels of coordination and cooperation are necessary to advance the field.

- Challenges: Standardizing information and deciding what data to keep and archive for future analysis. The proposed working group can help advise on what data to store and archive. Investments are needed to enable central storage and management of data. Coordination and cooperation need to be more frequent and technical, with meetings every two years to share details cooperatively. Experimental efforts require ongoing communication during the R&D phase.

  Conclusion: Establishing a high-profile working group or advisory group, such as the IAEA Working Group, can provide regular meetings and international advisory committee attention.

- Communication: promote the importance and benefits of coordination within the community. Effectively communicate the status and progress of coordination efforts. Ensure reports go through a vetting process to maintain accuracy and reliability. Invite the safeguards community as observers to working group meetings, potentially leading to future collaboration.

- Next Steps: Coordinate and understand the opportunities with realistic assumptions about real-world applications. Work together to improve nuclear and reactor antineutrino data. Explore and learn about the multi-faceted basic science problem, which may ultimately lead to practical applications. Ensure existing neutrino collaboration is consistent and speaking the same language with the aim to go further in coordination.

4. CONCLUSIONS

Our understanding of the Reactor Antineutrino Anomaly (RAA) and spectral distortions has improved significantly since the last meeting in 2019. Experiments have improved our knowledge of isotopic origins, though the underlying causes remain unknown. Major advancements have also been made in developing antineutrino applications for reactors and spent fuel. New tools and detector technologies are being explored, while future goals include conducting measurements in different reactors to enhance our understanding.

The summation model has shown better agreement with flux evolution, and steps have been taken to quantify errors. Improvements in TAGS measurements and beta shape calculations have been achieved. Evaluated libraries for fission yields and decay data are being updated, with efforts to include covariance matrices.

An important aspect in this effort, especially considering the international involvement, is the need for effective coordination and data management.

Communication and collaboration are also essential for progress in the field. Regular technical meetings and the establishment of a high-profile working group can enhance coordination.

Participants concluded that the regular IAEA Technical Meetings offer a unique platform for achieving the above goals.

APPENDIX – Presentation Summaries

1. Residual reactor antineutrino measurement with the Double Chooz experiment, A. Onillon (TU Munich)

On behalf of the Double Chooz collaboration

Double Chooz [1] is a reactor antineutrino experiment designed to measure the θ13 mixing angle. The experiment is located at the Chooz-B nuclear power plant in the French Ardennes. It consists in two liquid scintillator detectors respectively located at an average baseline of ~400 m and ~1050 m of the two 4.25 GW pressurized water reactors of the plant. Antineutrinos are detected via the inverse beta decay (IBD) process. The θ13 mixing angle is inferred by comparing the IBD spectrum measured in the near and the far detectors with their respective prediction. In 2017, the experiment benefited of four periods with both reactors simultaneously turned off for a combined total time of ~24.5 days. These periods enabled a measurement of the residual antineutrinos flux and spectra using both detectors.

A reactor off period at the Chooz-B plant typically happens when one reactor is stopped for refuelling while the other one undergoes a planned shutdown for maintenance operation or an unplanned shutdown resulting from unexpected technical or environmental issue. During such period, a residual antineutrino flux originating from the beta decay of isotope with long lifetime accumulated in the burnt nuclear fuel is expected. This flux is produced by the burnt fuel assemblies still contained in the reactors but also from the spent fuel assemblies stored in the storage pools located few tens of meters away from each reactor.

A prediction of the residual antineutrino flux and spectra expected in both detectors was calculated by coupling activities of fission product contained in the fuel assemblies located in the cores and the pools with their respective antineutrino spectra. Fission product activities were simulated with the APOLLO-2.8 and DARWIN-3 codes [2, 3] while antineutrino spectra were generated with the BESTIOLE [4] code. The number of expected IBD events is found to be dominated by the beta decay of the two isotopes of 144Pr (~53%) and 106Rh (~37%). Considering its dominant contribution to the total expected flux, a particular attention was given to the modelling of the dominant 1st non-unique forbidden transition of the 144Pr. Advanced nuclear structure calculations of its shape factor were performed using the NushellX code [5]. A preliminary comparison between the prediction and the data with background subtracted obtained in both detectors was achieved. This data set was obtained by using the so called "total neutron capture" technique first reported in [6]. This method relies on an increased detection volume for the selection of IBD neutrino candidates that leads to a significant boost in statistic (~2.5x) when compared to standard selection technique. A good agreement between the data and the predictions is obtained for both detectors. In the near detector, the preliminary numbers of residual IBD antineutrinos measured and predicted are respectively of 106 ± 18 and 88 ± 6. The measurement is dominated by statistical uncertainty while the prediction is dominated by the uncertainty associated to the modelling of the transition shape factor.

Residual antineutrinos measurement by short baseline experiments installed at commercial power plant is very challenging due to the very low number periods, if any, where all reactors are turned off and because of the very low fluxes involved. This unique measurement demonstrates for the first time the ability of IBD experiment to measure reactor antineutrino from spent fuel and emphasize the potential of very short baseline experiments for future more precise measurement.

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2. Status update on the RENO experiment, J. Yoo (Seoul National Univ.)

On behalf of the RENO Collaboration

We present a status update on the RENO experiment. The RENO experiment consists of near and far detectors located at 294 and 1 383 m, respectively, from the center of the six reactor cores of the Hanbit Nuclear Power Plant, Yonggwang, Korea. Six pressurized water reactors, each with a maximum thermal output of 2.8GW$_{th}$, is situated in a linear array spanning 1.3 km with equal spacing. In the prompt event of inverse beta decay (IBD) energy region of 1.2-8.5 MeV, a total of 120,383 (989,736) candidates were observed in the far (near) detector in 2908 (2509) days of detector operation (Aug. 2011 - Feb. 2020). The left panel of Fig. 1 shows the measured prompt energy spectrum compared with the Huber-Mueller (HM) model predictions. The measured absolute reactor antineutrino flux is R = 0.941 ± 0.019 compared to the HM prediction. The correlation between 5 MeV excess, and ^{235}U fission is about 2.9σ [1]. The measured reactor antineutrino spectrum and flux is reported in Ref. [2]. The right panel of Fig. 1 shows the best fit together with the allowed region of neutrino mixing parameters of $\sin^2 2\theta_{13}$=0.0892±0.0044(stat.)±0.0045(sys.), and $|\Delta m^2_{ee}|$=2.74±0.10(stat.) ±0.06(sys.)(x10^{-3}) eV^2. The first sterile neutrino search using RENO data only is reported in Ref. [3]. The combined search with NEOS collaboration for high mass (eV) sterile neutrinos is reported in Ref. [4].

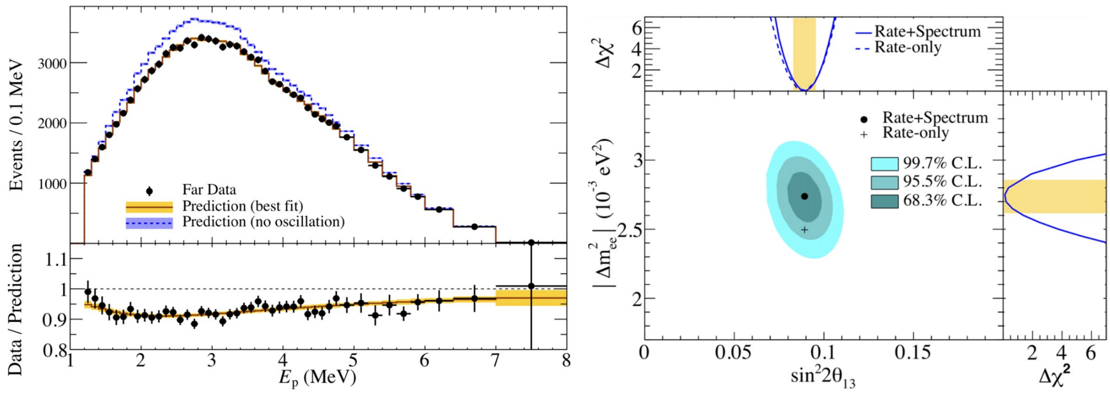

Figure 1: Left: Measured prompt spectrum of inverse beta decay events of 2900 days of RENO antineutrino data. Right: Corresponding constraint of neutrino oscillation parameters of Δm^2_{ee} — $\sin^2 2\theta_{13}$.

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3. Summary of latest results at Daya Bay, L. Zhan (IHEP, CAS)

On behalf of the Daya Bay Collaboration

This talk reports the latest results from Daya Bay experiment, including the first measurement of high-energy reactor antineutrinos at Daya Bay [1], the measurement of θ_{13} and Δm^2_{32} [2] and sterile neutrino search [3].

In the inverse beta-decay (IBD) prompt energy region of 8-12 MeV, nearly 9000 IBD candidates are observed with a 1958 days of data collection. A multivariate analysis is developed to separate 2500 IBD signal events from backgrounds. The left panel of Fig. 1 shows the measured prompt energy spectrum compared with the model predictions. The hypothesis of no reactor antineutrinos with energy above 10 MeV is rejected with a significance of 6.2 standard deviations. The unfolded antineutrino spectrum above 7 MeV is provided as a data-based reference for other experiments.

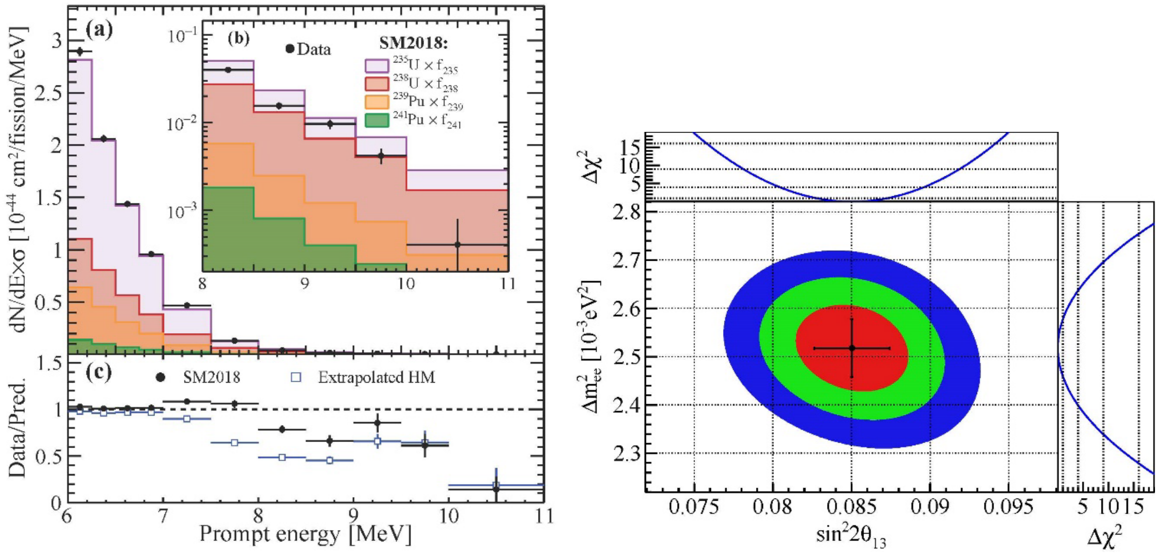

Figure 1: Left: Measured prompt energy spectrum compared with the predictions from the SM2018 model and the extrapolated Huber-Mueller model. Right: The Δm^2_{ee}— $\sin^2 2\theta_{13}$ contours and the best fit points.

The θ_{13} and Δm^2_{32} is measured using the final sample of 5.55 x 10^6 IBD candidates with neutron captured on gadolinium. The right panel of Fig. 1 shows the Δm^2_{ee}— $\sin^2 2\theta_{13}$ contours and the best fit points. The results of the oscillation parameters are $\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$, $\Delta m^2_{32} = (2.466 \pm 0.060)$ x 10^{-3} eV for the normal mass ordering or Δm^2_{32} = -(2:.571±0.060) x 10^{-3} eV for the inverted mass ordering.

A combined analysis of sterile neutrino search is performed with accelerator and reactor neutrino data from MINOS, MINOS+, Daya Bay and Bugey-3 [3]. A stringent limit of rejecting the sterile neutrino is provided.

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4. Reactor antineutrino flux and spectrum measurement at Daya Bay, F. An (Sun Yat-sen University)

- The Daya Bay Experiment finished data taking and acquired the largest sample of reactor antineutrino data to date: 5.5 million events with neutron captured on Gd.
- The updated fuel evolution study shows:
  - The measured average flux, as well as its evolution, are inconsistent with the predictions of the Huber-Mueller model.
  - The SM2018 model agrees with the average flux and its evolution but fails to describe the energy spectrum.
- First extraction of the ^{235}U spectrum from commercial reactors and first measurement of ^{239}Pu spectrum.
  - ^{235}U and ^{239}Pu might have similar excess in 4~6 MeV range, with 4σ and 1.2σ deviations, respectively.
  - ^{235}U is more likely to be responsible for "reactor antineutrino anomaly".
- First combination between Daya Bay (LEU) and PROSPECT (HEU) to reduce the ^{235}U spectrum uncertainty.
- The unfolded isotope antineutrino spectra provide a data-based prediction for reactor antineutrino experiments.

5. Status of the SoLid experiment and analysis developments, A. Vacheret (LPC Caen)

The SoLid neutrino experiment is located at the SCK-CEN in Mol, Belgium. It is installed in the Hall of the BR2 reactor in direct line of sight with the reactor core at minimum distance of approach of 6.3 m. The experiment comprises a detector system made of 12 800 5 cm x 5 cm x 5 cm scintillating cubes (PVT + LiF:ZnS) and read out by 3 200 SiPMs. The system is made of 5 detector modules comprising 10 detector planes containing each, 256 cubes. The system has a dimension of 80 cm (W) x 80 cm (H) x 260 cm (L) and is installed inside an ISO-container, itself surrounded by a 50 cm thick water enclosure and under a similar thickness of polyethylene slabs to shield the experiment against external background.

The experiment has been running from spring 2018 to summer 2020 for the first phase of the experiment (Phase-I) [1]. The second phase (Phase II) ran from December 2021 to July 2022 after a successful upgrade of the model of SiPMs to improve the light yield (+40%). The detector system has operated smoothly for the duration of the data taking with limited intervention and maintenance.

The Oscillation analysis of Phase-I is underway after a series of developments of the calibration and neutrino selection that has significantly improved the overall analysis resulting in a competitive S:B, efficiency of detection and energy resolution needed to perform a competitive oscillation analysis and antineutrino spectrum measurement.

- The first improvements were obtained on the reconstruction of the prompt signal, the calibration method using horizontal muons to encode local variation of the detector response and fibre attenuation effects. Those effects can be described in a system matrix and applied directly to the reconstruction taking care of all the effects at once.
- Another notable development has been on the energy estimator that is leveraging the detector cube granularity to collect 97% of the deposited positron energy.
- We revisited the energy scale measurements using a combination of samples made of electron-positron pairs data from AmBe source data, B-12 and cosmic muons data demonstrating a very good linearity of the response over a large range of energy and confirming the excellent linearity provided by the choice of the PVT scintillator.
- The segmentation and the imaging capability of the system has also been used to developed a BDT selection in 2022, based on various high level quantities to provide a S:B ~ 1:3 and at least 80 events per day whilst keeping a flat efficiency as a function of energy (within 5%).

Finally, a simple demonstration of the new bayesian fit method using the B-12 energy spectrum as a proxy of the IBD energy spectrum was presented showing very stable results.

The SoLid experiment aim is to release a competitive result on the Phase-I dataset later in 2023 that will include all the developments presented and now several important aspects of the analysis are understood and controlled to the percent level.

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6. Toward the coherent neutrino scattering detection at nuclear reactors with the NUCLEUS experiment, T. Lasserre (IRFU, CEA, Univ. Paris-Saclay)

On behalf the Nucleus collaboration

Coherent elastic neutrino scattering on nuclei (CEvNS) is a Standard Model process predicted in 1973 but first observed only in 2017 for accelerator neutrinos. The CEvNS cross section is quadratic with the number of neutrons in the nucleus and, in medium-sized nuclei, it can be up to two orders of magnitude larger than in other neutrino interactions. Therefore, once the technology will be mature, its study would allow to measure reactor neutrinos with miniaturized neutrino detector. This may happen within the next ten years in fundamental research institutions.

NUCLEUS [1] is an experiment designed to observe the coherent elastic scattering of neutrinos on nuclei. The experiment will be performed at the Chooz-B nuclear power plant in France which provides an intense flux of anti-neutrinos. The objective of NUCLEUS is to realize a very precise measurement of the coherent elastic scattering below 100 eV using cryogenic ultra-sensitive detectors. Currently, the NUCLEUS facility is being commissioned at the shallow underground laboratory of the Technical University of Munich, where the experiment will be fully validated before being transferred to the Chooz reactor site.

CEvNS detection is, in any case, a challenge because of the very low recoil energy of the nucleus, which is on the order of tens or hundreds of eV for MeV reactor neutrinos. The CEvNS study thus requires a very intense neutrino or anti-neutrino source in the MeV range, a very low threshold detector of the order of 10 eV, and effective control of the background level in the sub-keV range. The detector characteristics can be satisfied by cryogenic bolometers developed over the last decades for the direct study of dark matter. The NUCLEUS experiment is developing a precision measurement of CEvNS using cryogenic bolometers made of gram-scale modules of CaWO4 and Al2O3 crystals as targets which operate at 15 mK.

The NUCLEUS experiment is now in its blank assembly phase. The design of the experiment was finalized in 2022. Assembly is expected to be completed in 2023, when the commissioning phase will begin. The deployment of the NUCLEUS detector at the Chooz nuclear power plant is planned for the years 2024 and the beginning of the physics phase for the beginning of 2025. This first phase of NUCLEUS with 10 g target crystals aims at demonstrating the presence of the CEvNS signal. A second phase with a 1 kg scale detector is planned in the future to measure the CEvNS cross-section with an uncertainty of a few % and to demonstrate nuclear reactor monitoring capabilities.

References

[1] The NUCLEUS Collaboration, Eur. Phys. J. C **77** (2017) 506.

7. NEOS-II status report, Sunny Seo (Inst. for Basic Science)

NEOS-II using a homogeneous Gd-LS detector (~1 ton), has collected 388 (112) reactor-on (-off) data covering a full fuel cycle from Sept. 2018 to Oct. 2020 at the 5th reactor site (~24m baseline) of the Hanbit Nuclear Power Plant in Yonggwang, Korea. This led to 1784.8+/- 2.1 (61.3+/- 0.4) IBD signal (background) events/day with an excellent signal-to-background ratio of 29.

A continuous decrease in light yield challenged NEOS-II, and about a 46% decrease was observed at the end of the data-taking. However, the light-yield decrease was successfully handled by correcting the charge to 208Tl peak (2.61 MeV), adjusting the energy resolution of all data sets to 7.3%, which is obtained from the final data set, and adjusting IBD selection criteria values slightly to keep the same detection efficiency. The cause of the light-yield decrease is still not fully understood, but we suspect a possible cause would be an inflow of moisture/oxygen to GdLS and/or a high concentration (~0.5%) of Gd.

The goals of NEOS-II are to extract IBD yields, separate 235U and 239Pu spectra, and search for sterile neutrinos. A preliminary result on 235U (239Pu) IBD yields is obtained as y235 = (6.32 +/- 0.18)x10-43 cm2/fission (y239 = (4.66 +/- 0.26)x10-43 cm2/fission) as shown in Fig. 1, assuming 45% detection efficiency that has to be finalized. The 235U to 239Pu ratio is obtained as 1.36 +/- 0.06, which agrees with the KI model [V. Kopeiken et al., PRD 104, L071301(2021)] but shows a tension with the Huber model at 2σ level.

Figure 2 shows a preliminary result on the spectral separation of 235U (blue points) and 239Pu (magenta points) for NEOS-II. The 5 MeV bump is observed in the 235U spectrum, but it's inconclusive for 239Pu due to the low statistics. Note that once the detection efficiency of NEOS-II is finalized, these preliminary results could be changed. Independently, an analysis of the search for sterile neutrinos is still ongoing, but very close to obtaining a preliminary result soon.

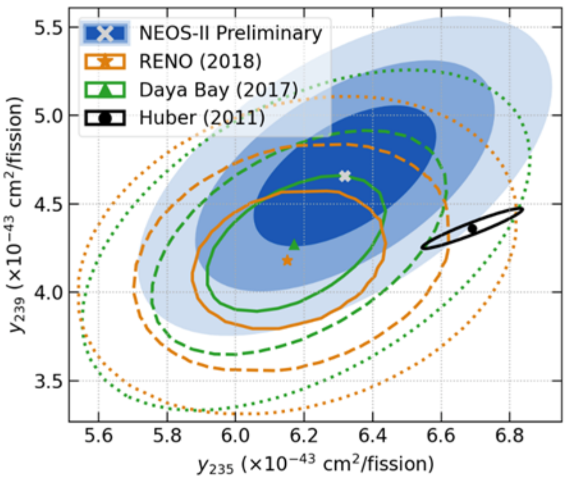


Fig.1 Comparison of IBD yields for NEOS-II (blue), RENO (orange), Daya Bay (green), and HM model (black).

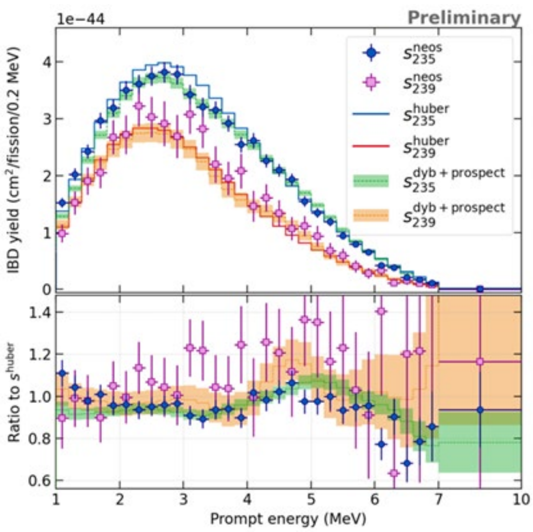


Fig. 2 ^{235}U and ^{239}Pu spectra for NEOS-II, a joint analysis of Daya Bay and Prospect, and Huber model.

8. Reactor antineutrino with the DANSS detector, D. Svirida (KCTEP)

For the DANSS collaboration

The DANSS detector at the Kaliniskaya NPP is located right below the 3 GWth PWR of its 4th unit. A lifting platform allows the change in the distance between the detector and the reactor in the range 10.9 to 12.9 m, center to center. The reactor body and its biological shielding provides an overburden of 50 m.w.e., attenuating the cosmic ray flux in the detector hall by a factor of 6. The detector is composed of 2500 plastic scintillator strips, organized in 100 layers with alternating direction, and resulting in 1 m3 sensitive volume with fine segmentation. Each strip has 3 WLS fibers for the light collection. The central fiber is read out individually by a SiPM, while the side fibers from 50 strips of the same direction are bundled at a cathode of a regular PMT. Gadolinium loaded strip coating provides the neutron capture from the IBD reaction, used for antineutrino detection.

DANSS sets world records in antineutrino detection. Counting rates of up to 5000 events per day made it possible to collect more than 6.5 million antineutrino events in 6 years of very stable operation. The data sample is extremely clean and features the signal to background ratio in excess of 50. Possibility to measure spectra at different distances from the antineutrino source with the same detector makes it almost an ideal tool for the sterile neutrino searches. In spite of only moderate energy resolution of 34% at 1 MeV which limits the sensitivity of the experiment, the most stringent exclusion reaches $\sin^2 2\theta_{ee}=4\cdot 10^{-3}$, while the best RAA and GA point is reliably excluded even by partial statistics. Yet two Feldman-Cousins allowed regions with similar confidence level of more than 2σ are not significant enough to claim existence of the sterile neutrino.

With the statistical accuracy of about 1.5% in every two days DANSS can be used for independent reactor power monitoring. Raw detector counts show clear dependence on the fuel composition variations with the campaign time. A correction based on the H-M model brings the antineutrino counts into perfect agreement with the thermal power measurements. Extremely stable detector operation allows to use single normalization for the whole 6-year observation period.

To study the fuel composition dependencies fractional slopes and relative IBD yield were calculated following the Daya Bay approach to allow the direct comparison. The DANSS results are slightly more sensitive for the fuel evolution, than those from Daya Bay, and slightly closer to H-M predictions, yet almost agree with both. Yet the range of the ^{239}Pu fraction variation is notably larger at DANSS due to the single core environment.

A simple expression was proposed to derive the ratio σ_5/σ_9 of IBD yields of ^{235}U to ^{239}Pu from the measured slope of the total relative IBD yield. Because of the direct ratio calculation, its error is smaller than that presented by Daya Bay, while the value is on the opposite side of the H-M prediction and is much closer to it.

The well-known discrepancy between the experimentally observed spectra and model predictions, the so called '5 MeV bump', is seen by DANSS with very good statistical significance, but its shape is very labile. Only small shift by 50 keV of the measured energy value changes the shape dramatically. With the current energy resolution of the detector, the direct comparison to other experiments is impossible, but RENO data smeared to the DANSS energy resolution still shows about twice larger discrepancy. I.e., DANSS result is again closer to the H-M model predictions.

DANSS is a small and very heterogeneous detector, and it's only the latest improvements in Monte-Carlo simulations together with the new approach to the calibration procedure showed truly reliable results. This allowed making first steps in the direction towards absolute IBD yields. The preliminary estimate is below the H-M model, but within the experimental uncertainties. Also, it is closer to the model than the world average.

DANSS is a beautiful detector, but its moderate energy resolution limits the experiment sensitivity. While continuing data taking, the upgrade of the DANSS detector is being prepared. New strip design will include 8 WLS fibers read out from both ends. The preliminary tests show very promising results in the homogeneity of the light collection and in the total number of photoelectrons, both concepts playing a critical role in the achievement of 12% at 1 MeV energy resolution. The increase of the sensitive volume will provide twice larger event rate. With these parameters DANSS will be able to probe Neutrino-4 and BEST results already after 1.5 years of running.

The data analyzed so far indicate better agreement with H-M model than those from other experiments:

- reactor power monitoring is purely statistical after H-M correction;
- fractional slopes and relative IBD yield are slightly more sensitive for the fuel evolution than DB, and closer to H-M predictions;
- ratio of IBD yields σ_5/σ_9 coincide with H-M prediction, unlike DB;
- the 'bump', if any, is twice less pronounced than should be even with DANSS energy resolution;

- Absolute counts agree with H-M: average 0.98 ± 0.04 (very preliminary).

DANSS continues data taking and its analysis and a challenging detector upgrade is under preparation.

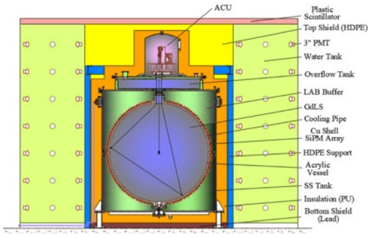
9. JUNO-TAO status and prospect, R. Li (IHEP, CAS)

JUNO-TAO (Taishan Antineutrino Observatory) is a satellite experiment of JUNO. It will be placed in a basement of the experimental hall, 30 m away from the Nuclear Power Plant core. TAO will start commissioning in Dec. 2023.

Motivation:

1) To measure the precise reactor antineutrino spectrum with high energy resolution (<2% at 1 MeV). The spectrum shape precision is better than 1% in 2-5 MeV. 2)To provide a benchmark measurement for nuclear database. 3) To measure isotopic neutrino spectrum. 4)To provide increased reliability and verification of the technology for reactor monitoring and safeguard. 5)To search for sterile neutrino around 1MeV

Detector:



The TAO detector consists of a Central Detector (CD) and an outer shielding and veto system. The CD consists of 2.8-ton Gadolinium-doped liquid scintillator (GdLS) filled in a spherical acrylic vessel and viewed by 10 m2 SiPM, a spherical Copper Shell that supports the SiPMs, 3.45-ton buffer liquid, and a cylindrical stainless-steel tank insulated with 15-cm thick melamine foam. The outer shielding includes 1.2 m water in the surrounding tanks, 1 m High Density Polyethylene (HDPE) on the top, and 10 cm lead at the bottom. The water tanks, instrumented with Photomultipliers, and the Plastic Scintillator on the top comprise the active muon veto system.

Background:

IBD	1838/day
Singles from radioactivity	100 Hz
Muon rate	67 Hz/m^2
IBD-like before veto	3682/day
IBD-like after veto	44/day
Accidental background	129/day
^{8}He & ^{9}Li	<20/day

Because of the shallow overburden, the cosmogenic background is a crucial issue for TAO. Correlation background is the most important part, since the accidental background can be measured precisely. Neutrons generated more on the high-Z material, such as copper shell and lead. Double neutron background (most generated on copper shell) dominates because of the spill-in and spill-out between the GdLS and LAB buffer. So we plan to dope 0.1% Gd in LAB buffer and it can suppress ~1/2 background. Because of this, the PTFE coating for stainless steel inside face and copper shell is necessary, including all the screws and flanges. The compatibility of electronics and SiPMs with GdLAB is good. And we add 10-cm HDPE above lead to shield neutrons generated on the lead. After the optimization of veto strategy and applying PSD (Reject ~83% fast neutron with 100% signal kept), the B/S is 1.8%.

Status of every part:


Copper Shell


Stainless steel tank


Acrylic vessel

GdLS: Production finished, store in IHEP.

SiPM: Efforts of QA/QC is ongoing.

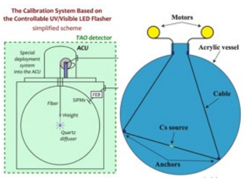
Central detector:

Copper shell: Up semi-sphere almost finished, down semi-sphere will be finished in a mouth.

Stainless steel tank: Finished, store in IHEP.

Acrylic sphere: Finished, delivered to IHEP.

Calibration: Simulation study finished. Production finished; test is going on.

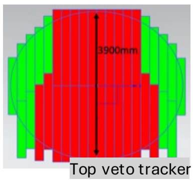

Calibration system

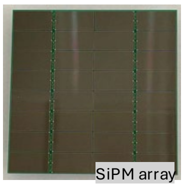
Muon veto: Design finished, top veto tracker production ongoing.

Electronics: Front-end production ongoing, back-end production almost finished.

TDAQ: Test almost finished, stability test ongoing.

1:1 prototype in IHEP: Assembly in March, 2023.





10. Status of the JUNO experiment, Z. Yu (IHEP, CAS)

On behalf of the JUNO collaboration,

The Jiangmen Underground Neutrino Observatory, JUNO, is a multipurpose neutrino experiment located at 700-m underground at Southern China. It features a 20 kton ultrapure liquid scintillator detector with unprecedent energy resolution to address many topics in neutrino and astro-particle physics.

By measuring reactor neutrinos from eight reactor cores of Yangjiang and Taishan nuclear power plant, with six years of data, the neutrino mass ordering can be determined at a 3σ significance, and three neutrino oscillation parameters can be measured to a precision of 0.5% or better. These sensitivities are estimated based on the simulated signals and backgrounds with the up-to-date properties of detector components. The prediction of neutrino signals, in particularly the spectral shape, relies on the JUNO-TAO experiment. A fitter level joint analysis framework has been developed for a proper treatment on correlation of systematics.

The construction of JUNO detector is going smoothly. There are five plants to purify the liquid scintillator, and the plant commissioning is starting. Scintillation lights are detected by 17,612 20-inch photomultiplier tubes (PMTs) and 25,600 3-inch PMTs. All PMTs have been tested and water-proofed, and more than 200 have been installed on the detector. The output signals of PMTs are digitalized in underwater electronics boxes and sent to the electronics room via ethernet cables. A joint test of PMTs, electronics, the data acquisition and detector control system was performed in the end of 2022. It was found that all installed components were working well, and the electronics noises were a half of the designed value. The detector assembly is expected to finish by end of 2023.

11. Nu Tools study, M. Foxe (Pacific Northwest National Lab.)

A summary of the Nu Tools study that was performed in recent years was presented. The study was commissioned by NNSA DNN R&D. The executive group consisted of individuals from U.S.A. laboratories and universities. The executive group then interviewed national and international end-users to evaluate the role of Antineutrinos in Nuclear Energy and Security. The report can be found at nutools.ornl.gov and was summarized in the presentation.

The following findings were a result of the study, divided into two categories: one that applies to all the use-cases (cross-cutting findings) and one that dealt with use-case specific findings.

Cross Cutting Findings

- End-User Engagement: The neutrino technology R&D community is only beginning to engage attentively with end-users, and further coordinated exchange is necessary to explore and develop potential use cases.
- Technical Readiness: The incorporation of new technologies into the nuclear energy or security toolbox is a methodical process, requiring a novel system such as a neutrino detector to demonstrate sufficient technical readiness.

- Neutrino System Siting: Siting of a neutrino-based system requires a balance between intrusiveness concerns and technical considerations, where the latter favor a siting as close as possible.

Evaluation of the use-case findings was performed with the following developed criteria:

1. Need for a new or improved capability → Determined by end-user communities.
2. Existence of a neutrino signal → Determined by technology development community.
3. Availability of a neutrino detection technology → Determined by technology development community.
4. Compatibility with implementation constraints → Determined by end-user communities

Use Case Findings

- Current International Atomic Energy Agency (IAEA) Safeguards: For the vast majority of reactors under current IAEA safeguards, the safeguards community is satisfied with the existing toolset and does not see a specific role for neutrinos.
- Advanced Reactors: Advanced reactors present novel safeguards challenges which represent possible use cases for neutrino monitoring.
- Future Nuclear Deals: There is interest in the policy community in neutrino detection as a possible element of future nuclear deals involving cooperative reactor monitoring or verifying the absence of reactor operations.
- Reactor Operations: Utility of neutrino detectors as a component of instrumentation and control systems at existing reactors would be limited.
- Non-Cooperative Reactor Monitoring or Discovery: Implementation constraints related to required detector size, dwell time, distance, and backgrounds preclude consideration of neutrino detectors for non-cooperative reactor monitoring or discovery.
- Spent Nuclear Fuel: Non-destructive assay of dry casks is a capability need which could potentially be met by neutrino technology, whereas long-term geological repositories are unlikely to present a use case.
- Post-Accident Response: Determining the status of core assemblies and spent fuel is a capability need for post-accident response, but the applicability of neutrino detectors to these applications requires further study.

12. Status of CHANDLER, J. Link (Virginia Tech)

CHANDLER is a reactor antineutrino detector technology being developed at Virginia Tech. It consists of alternating layers of wavelength-shifting plastic-scintillating cubes and thin sheets of lithium-6 loaded zinc sulfide (ZnS) scintillator. The plastic cubes serve as the primary source of hydrogen for the inverse beta decay target, and to detect the positron, while the 6Li-loaded ZnS is there to tag the neutrons through thermal capture on 6Li. Light is transported along the rows and columns of cubes by total-internal-reflection and detected in photomultiplier tubes (PMTs) at the ends of each row and column. Light from the ZnS sheets is absorbed by the wavelength shifter in the cubes and re-transmitted so that it too can be transported through the cube rows and columns. In this way, the location of an interaction or neutron capture can be determined to within the precision of a single cube. This method of reading out a large scintillating volume using optically connected cubes is known as a Raghavan optical lattice, named after our late colleague, Raju Raghavan, who developed this idea for his proposed solar neutrino detector, known as LENS [1]. In 2017, we deployed out 80 channel, 80 kg MiniCHANDLER prototype at the North Anna Nuclear Generating Station in Mineral, Virginia for four and a half months, including one month of shutdown. With this data we were able to demonstrate an observation of reactor antineutrinos at 5.5 σ [2]. We are currently upgrading MiniCHANDLER with new optics, including high quantum efficiency PMTs, optical light guides and new electronics. We will redeploy the detector to North Anna in the spring of 2023. CHANDLER is one of two technologies under consideration in the NNSA's Mobile Antineutrino Demonstrator (MAD) project.

Measuring Isotope-Specific Antineutrino Reference Spectra

As Daya Bay has shown, the different fissile and fissionable isotopes have different antineutrino spectra, and I believe this is the key to most neutrino applications, including tracking burn-up, by measuring the evolution of the fissile isotopes through spectral changes; measuring power, but first you have to know where you are in the burn-up; and identifying material diversions, by looking at the neutrino spectra, before and after shutdowns or other fuelling activities, and comparing to expectations from the declared activities. Fitting the observed spectrum with the isotope-specific reference spectra would give the most complete picture of what's going on in the core. But how do we get these reference spectra? The 235U spectrum can be directly measured in HEU reactors, but the other isotopes require a fit-based extraction. To do this requires data from different types of reactors, and different periods in the fuel cycle, chosen to maximize the spread of the isotopic fission rates. As an example, we (A. Erickson, P. Huber and J. Link) looked at a "virgin" reactor core, using all-new LEU fuel. A virgin core starts with no plutonium, and from simulation we found that it takes about 30 days for the fission rate of 239Pu to match that of 238U. Similarly, 200 days pass before the 241Pu fission rate reaches 10% of all plutonium fissions. We found that combining virgin core data with data from a steady-state LEU core significantly reduces the flux uncertainty on all four isotopes. Compared to adding HEU data, the addition of virgin core data has its greatest impact on the uncertainty of the two plutonium isotopes. Combining all three types of data further lowers the flux uncertainties.

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13. Update on antineutrino-based safeguard approaches for spent nuclear fuel, Y. Schnellbach (RWTH Aachen)

Spent nuclear fuel (SNF) is produced during reactor operations, with the total amount of estimated to be c. 300,000 t [1]. The stored amount of SNF material, excluding anything being reprocessed, increases by c. 7,000 t per year. SNF chiefly consists of natural 238U, fission products and minor actinides. However, there is a small amount of 235U (<0.8%) and 239/241Pu (c. 1%), which are both of interest to safeguards. While the proportion is small, given the total amount of SNF, this qualifies as "significant material" overall (8 kg of 239Pu).

Current safeguards for SNF strongly rely on access control, inventories, seals, and surveillance, with improved surveillance tools under R&D. Direct interrogation of the contents is challenging due to the heavy requisite shielding of storage casks. A novel approach is to extend the current R&D for antineutrino reactor safeguards to SNF [2]: while the antineutrino emission from SNF is several orders of magnitude lower, key fission fragments continue to beta-decay for decades to centuries, producing a detectable antineutrino signature. The key beta decay chain is 90Sr with a half-life of 28.8 y decaying into 90Y, which has a half-life of 2.7 d and emits antineutrinos of up to 2.2 MeV. Similar beta decay chains are 144Ce/144Pr, 106Ru/106Rh and 88Kr/88Rb.

Several types of technology potentially suitable for SNF monitoring were considered: Previous efforts of the group investigated the use of Liquid ARgon Time Projection Chambers (LAr-TPC). The read-out via anode wire plane allows for scalability as the detector volume can be read out by instrumenting a single face of the volume. Measurement of the drift time and segmentation of the read-out plane make a high-resolution reconstruction of the event possible, including detection of all final state particles. The main downsides are the need for a cryostat and the high energy threshold for antineutrino interactions. This is especially challenging as the 90SR/90Y neutrino spectrum only extends to 2.2 MeV.

Alternative drift media are now under investigation to replace LAr, including liquid organic (LOr) dielectrics. LOr has two key advantages: operation at non-cryogenic temperatures and abundant constituent hydrogen as target for inverse beta decays (IBD) providing an antineutrino detection threshold of 1.8 MeV. IBDs are a well-understood detection channel with a double coincidence signal providing strong background rejection. One of the most promising LOr media is currently tetramethylsilane (TMS) (Si(CH3)4), where basic feasibility as drift medium has been established in the past years [3].

Simulations of an 80 m3 detector volume of TMS using GEANT4 have shown that a single IBD interaction will deposit energy across the medium in several locations that can be associated with the positron track, annihilation photons, neutron-induced proton recoils, and the neutron capture. The separation of these energy depositions can be resolved with a TPCs and provides extra information to reject background and may provide limited directionality on an event-by-event basis [4].

Current work is focussing on building a small-scale prototype with several centimetres drift length to test purification systems and drift properties using radioactive sources. A GEANT4 and electron drift simulation will be tuned with the findings of the small-scale prototype to enable accurate predictions of the TMS behaviour in a larger scale system with sufficient target volume for antineutrino observations.

Finally, ongoing reaction simulation work has been continued using the ONIX simulation package [5] to determine isotope vectors for fuel assemblies at reactor discharge. This isotope composition is then used in conjunction with the NDS ENSDF database to determine antineutrino spectra emitted. This approach will allow the modelling of SNF spectra for different reactor types.

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14. Coherent elastic neutrino-nucleus scattering, Y. Efremenko (Univ. of Tennessee)

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] and later with 22.4kg liquid argon detector [4].

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 like 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.

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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15. Some of the work performed at BNL in the last 3.75 years, A. Sonzogni (BNL)

We started our presentation with a short description of the ENDF/B-VIII.1b decay data sub-library contents that are relevant for the calculation of nuclear reactors antineutrino spectra, in particular, the nuclides with beta intensities from TAGS experiments as well as those derived from Tengblad et al. total beta spectra measurements. We also indicated the issues when incorporating these types of data as well as a comparison with a library that doesn't include them.

We then presented an analysis of the electron spectra data measured by Dickens and collaborators following the thermal neutron induced fission of ^{235}U and ^{239,241}Pu, which have been used to derived decay heat data. Using summation model corrections, these data can be converted to ratio of electron spectra under equilibrium conditions, and thus compared with the ILL results, as well as with those from the Kurchatov Institute data for 235U and 239Pu. Our results agree better with the KI values. However, the ratio of 235U to 239Pu and 239Pu to 241Pu point out to a possible 241Pu contamination in the 239Pu target at both the ILL and KI experiments.

We also presented our study on the electron antineutrino spectrum in the 7 to 11 MeV energy spectrum. Our summation calculations underestimate the Daya Bay's results, and since many of the nuclides contributing to that area lack experimental data, we perform a sensitivity study to identify the main contributors by using a simple model to obtain the largest possible IBD antineutrino spectrum. Several nuclides were identified this way, such as for instance ^{102}Y.

Finally, we performed an analysis of the Daya Bay's high statistics data, obtaining that the optimal binning to reveal fine structure is 250 keV since at higher or lower binning the effect of individual fission fragments gets less distinctive, resulting in a higher chi-square value in the ratio of adjacent spectrum points plot.

16. Summation Method Model – Nantes, M. Fallot (SUBATECH-Univ. Nantes)

Prepared by Magali Estienne & Muriel Fallot and presented by M. Fallot (Nantes, France), in the name of Subatech (Nantes, France) and IFIC, CSIC-Univ (Valencia, Spain) collaborators and Karl-Heinz Schmidt.

In this talk a historical summary of the Summation Method Model developed by the group of Nantes has first been introduced. The evolution of the ingredients of the model over the years have been presented and the role of uncertainties present in nuclear databases in the calculations has been stressed; emphasizing the, now well known, Pandemonium effect that was shown to be of particular importance in antineutrino summation calculations in the seminal paper [1] in which the ingredients of the model were detailed.

The need for total absorption gamma spectroscopy (TAGS) measurements in antineutrino summation calculations in order to overcome this bias was introduced. The results of our calculations including a decade of decay data measurements obtained by the Nantes-Valencia collaboration [2] were presented and their impact discussed. These summation predictions were the state of the art of our model in 2019 [3] period of the previous IAEA Technical Meeting [4] in which several points of improvements were discussed and summarized. They were reminded in the present contribution.

The last part of the presentation was dedicated to the presently on-going activities and developments of our team to improve its summation calculations. 1) Some ingredients of the model itself have been updated (in collaboration with L. Hayen) leading to a small change in the global flux of ~0.25%. 2) The impact of new TAGS decay data of ^{95}Rb and ^{137}I [5], ^{96gs}Y and ^{96m}Y [6] and ^{99}Y, ^{142}Cs and ^{138}I [7] of the Nantes-Valencia collaboration have been shown. A 1.8% deviation in antineutrino IBD yield w.r.t. Daya Bay is obtained. 3) Some dedicated efforts were devoted to fission yield study in the framework of the GEF code in collaboration with K.-H. Schmidt [8]. Among other things, GEF was tuned for antineutrinos thanks to a detailed study of experimental measurements of fission yields available worldwide. 4) Concerning the shape anomaly, some concentrated efforts are employed to study the impact of first forbidden decays in the summation calculations. Here two activities are currently on-going. From the theoretical point of view, the inclusion of the first-forbidden operators [9] has been performed in the pnQRPA approach of [10]. This work in on-going within a collaboration between Subatech and S. Péru (CEA-DAM) and M. Martini (IPSA, Paris). From the experimental point of view, a new detector system to study beta spectrum shapes from fission products was designed and built in the framework of Nantes-Surrey-Valencia collaboration. The first experiment with this setup has been performed in 2022 at IGISOL IV. The analysis is on-going [11].

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17. Revisiting the summation calculation of reactor antineutrino spectra, L. Périssé (ILANCE, CNRS / Univ. of Tokyo)

Over the last decades, Inverse Beta Decay (IBD) antineutrino ($\bar{\nu}_e$) experiments at short and very short baselines from nuclear reactors have revealed significant discrepancies on the rate and shape of measured spectra compared to state-of-the-art predictions. Experimental biases and the existence of a sterile neutrino have been mostly ruled out as the origin of these discrepancies, and the validity of the predictions is thus questioned. In this context, a revised prediction of reactor $\bar{\nu}_e$spectra using the summation method (SM) has been done. The estimation of SM spectrum uncertainties is a difficult task that needs to address the limitations of nuclear databases (completeness and accuracy) as well as the approximations associated to the modeling of the β-decay theory. This prediction includes for the first time an attempt at providing a comprehensive uncertainty budget for both the modeling and nuclear data. The robustness and limitations associated to this uncertainty budget have been investigated.

In the SM, $\bar{\nu}_e$ fission spectra of uranium and plutonium isotopes are calculated as the sum of $\bar{\nu}_e$ spectra of every fission product (FP) β-transitions weighted by their branching ratio and by the activity of the parent nucleus. A branch spectrum is expressed as a product of a phase space, a Fermi function, a shape factor and other corrections. One of the main improvements of this revision is about the modeling of the shape factor, a term that depends on the spin and parity changes between the parent and daughter nuclei. β-transitions are classified based on these changes and are labeled as allowed, unique forbidden and non-unique forbidden transitions, respectively making ∼47%, ∼9% and ∼39% of a reactor IBD flux. All relevant non-unique transitions were previously modeled as allowed ones under the so-called ξ-approximation. However, this approximation is expected to be incorrect for all transitions having endpoint energy larger than the IBD threshold, with an unknown impact. In this work, the shape factors of 23 important non-unique transitions, making 27% of a reactor IBD flux, have been modeled with nuclear structure calculations using the NuShellX code. A typical reactor IBD flux is decreased by about 1.3±0.2% with this new modeling. In this work, fission yields from JEFF3.3 and nuclear data from ENSDF [1] are used. Since FP with high Q_β energy can be subject to the Pandemonium effect, which induces an overestimation of a reactor IBD flux, ENSDF data of important FP are replaced by up-to-date Pandemonium-free data. This includes 84 total absorption γ-spectroscopy (TAGS) measurements and βγ data from Rudtsam et al. for 44 isotopes [2], totaling ∼55% of a reactor IBD flux. Since a residual Pandemonium effect could still be present in 29 isotopes [3], a correction is derived by comparing isotope spectra modeled using TAGS data or with ENSDF data. A typical reactor IBD flux is decreased by 2.2±2.4% with this correction.

With this new modeling, the total uncertainty of a reactor IBD yield is estimated to be in the order of 3%. This uncertainty is dominated by the uncertainty associated to the residual Pandemonium correction (2.5%), followed by the uncertainty derived from the modeling of isotopes using Tengblad's data (1.5%) and the modeling of nuclides with no data (0.8%). This prediction exhibits good agreement with experimental IBD yields of ^{235}U and ^{239}Pu. No significant spectral difference is observed in the 5-7 MeV range mainly due to large experimental and prediction uncertainties, with a ≲2.3σ significance over 2-8MeV.

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18. CONFLUX – A flexible, modular reactor neutrino flux calculation framework, X. Zhang (LLNL)

An accurate knowledge of individual β spectral shapes is of paramount importance for the flux predictions emerging from a nuclear reactor. While the significance of β spectral shape corrections was recognized early on in the interpretation of the reactor flux and spectral anomaly ('the bump') [1], the complexity of the calculation of so-called forbidden transitions inhibits precise predictions. A subset of these forbidden transitions with large relative yields

were calculated within the nuclear shell model, showing larger than anticipated changes in the shape factors [2]. The resultant changes to the predicted antineutrino flux make it a good candidate to partially resolve the spectral distortion in the antineutrino flux. This prompted several on-going experimental campaigns aimed at precisely measuring the shape of individual transitions, with close collaboration from theorists.

One of the difficulties identified at the 2019 Technical Meeting was the large barrier to entry for external contributions due to the complicated infrastructure of coupling several nuclear databases. The CONFLUX program was created to partially alleviate this difficulty, providing robust flux predictions including the most state-of-the-art theoretical descriptions of β decay spectra [3]. Once completed, this will provide a possibility for standardized flux predictions with an interface for directed contributions from external users.

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19. Improving nuclear data for neutron-rich fission products, F.G. Kondev (ANL)

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 & Gammasphere in order to address a number of opportunities for nuclear data research.

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. Specifically, in the case of ^{104}Nb, 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.

20. Nuclear data measurements at ORNL, B. Rasco (ORNL)

Oak Ridge National Laboratory's (ORNL) Modular Total Absorption Spectrometer (MTAS) was delivered to ORNL in 2011 and performed experiments there until 2018. Most of these experiments were focused on measuring complete beta-decay feeding patterns of dominant fission products. Previously reported results included measurements of dominant reactor antineutrino fission products such as ^{86}Br, ^{89}Kr, ^{89}Rb, ^{90}Rb, ^{90}Kr, ^{92}Rb, ^{96}Y, ^{137}Xe, ^{137}I, ^{139}Xe, and ^{142}Cs.

Since the last meeting ORNL evaluated and published several additional isotopes. These include ^{88}Kr and ^{88}Rb, ^{98}Nb, and have submitted the full A=142 decay chain, which includes ^{142}La - an important antineutrino contributor within hours of after reactor shutdown. The ^{88}Kr and ^{88}Rb publication [Shuai, et al. PRC 105, 054312 (2022)] discusses in detail the evaluation of uncertainties for MTAS extracted beta-feeding intensities. In addition, it demonstrates some evidence for identifying beta-energy shapes, showing the difference in MTAS between an allowed shape and a first-forbidden unique shape of the ^{88}Rb ground-state feeding. The ^{98}Nb focused paper [Rasco, et al., PRC 105, 064301 (2022)] focuses on improving the gamma-less component of the ^{98}Nb beta decay and thereby improving the precision by a factor of 2 for the antineutrino generating components of this decay. This is done by extracting the ground shape feeding directly and using the segmented beta trigger to identify the decay to the first excited 0+ level which decays via conversion electrons without any gamma rays. This improved precision increases the number of IBD detectable antineutrinos per ^{98}Nb decay. Lastly the A=142 paper [Wolińska-Cichocka, et al.] validates the beta-feeding intensities for ^{142}La and ^{142}Ba and further demonstrating reliability of MTAS extractions of complex decay-feeding intensities and improving ENSDF antineutrino predictions for ^{142}La.

In 2018 MTAS began operating on-line at the CARIBU facility at Argonne National Laboratory and performed experiments there until 2021. The MTAS move from ORNL to CARIBU required an extension of the lead shielding structure to 8 foot height. The beam diagnostic cross with the channeltron counters and position sensitive plastic beta counter (UTK) was added in front of MTAS. A position sensitive plastic beta detector was placed behind the activity collection spot at the Moving Tape Collector. Two HPGe gamma counters monitored the collected activity in coincidence with the beta plastic counter.

The total absorption gamma measurements were performed for several isobaric chains of refractory elements at mass numbers A=107, 106, 105, 104, 102, 101 and 99 following the ANL proposal by Rykaczewski et al, while the decay chains of A=136 and A=132 (including 132Sn) were investigated following Rasco et al project. Additionally, within later experiment, MTAS data were obtained for A=144 isobaric chain and 128Sb. All these radioactive nuclei were produced by 252Cf fission and were extracted from the gas cell, and separated using CARIBU high-resolution mass separator, often enhanced by the Multi Reflection Time of Flight Separator (MRTOF). MRTOF isolates a single radioactive isotope.

Results from these runs include a 72% reduction of the number of interacting anti-neutrinos emitted in the decay of long-lived activity of ^{104}Nb and an increased measured average gamma energy per ^{104}Nb decay of 4550(60) keV. The preliminary decay heat value for ^{105}Mo decay is 2.78(39) MeV, with the error bar to be reduced in the final analysis (T. Ruland, PhD thesis, LSU). Earlier TAS measurement (Algora et al., PRL 105, 2010, 202501) listed 2409(93) keV. For the decay of ^{106}Tc, we observed 77% increase of the decay heat [M. Cooper, PhD thesis, UTK). For ^{107}Tc activity, the decay heat was measured to 2.21(10) MeV (P. Shuai et al.,2023, to be published), while earlier TAS result by Algora 2010 was 1.822(450) keV.

In general, but not always as seen in ^{98}Nb, MTAS results shift the reference reactor anti-neutrino energy spectrum towards lower energies reducing the reactor antineutrino anomaly (RAA). The shoulder (aka bump) of higher energy antineutrino is increasing, since we point out to the smaller number of interacting high energy anti-neutrinos at the reference flux.

21. Decay experiments by the Nantes-Valencia Collaboration, A. Algora (IFIC, CSIC-Univ. of Valencia)

On behalf of the Subatech (Nantes, France) and IFIC (Valencia, Spain) collaboration.

In this talk first the need for total absorption gamma spectroscopy (TAGS) measurements in relation to summation calculations of the antineutrino spectrum and decay heat was introduced. Then new results obtained by the Nantes-Valencia collaboration were presented and their impact discussed. These results cover cases recently analyzed and published by the collaboration. Highlights include examples produced in fission as isomers like ^{96m,96}Y (Guadilla et al, PRC 106, 014306 (2022)). In this case the challenge of the E0 transitions and how to properly handle that in the TAGS analysis was presented.

The study of the beta decay of ^{99}Y was also shown. This case was analyzed by the Nantes collaboration. The cumulative impact in summation calculations of ^{99}Y, ^{138}I, and ^{142}Cs in summation calculations was discussed.

A new way of extracting ground state feedings using the counts detected in the beta detector and beta-TAS coincidences was also presented (Guadilla et al. PRC 102, 064304 (2020)) and their impact in the analysis of ^{103}Tc decay was discussed. This method is an extension of a procedure introduced earlier by Greenwood et al. (Greenwood et al. NIM A317 (1992) 175). Using the new method ground state to ground state transitions of important decays for the antineutrino spectrum were determined and the new values were compared with earlier results.

Finally, on-going activities were presented. A new TAGS measurement performed at IGISOL IV in September 2022 was shown and the new detector system to study beta spectrum shapes was presented. This setup was constructed in the framework of Nantes-Surrey-Valencia collaboration and commissioned in 2022. Preliminary Monte Carlo simulations of beta shapes and comparisons with the measured beta decay spectrum shape of the ^{114}Pd-^{114}Ag decay were presented.

22. Fission yields modelling and evaluation, A.E. Lovell (LANL)

Talk LA-UR-23-20398

Los Alamos is leading a multi-institutional effort to re-evaluate independent and cumulative fission product yields (FPYs) in the ENDF library. The FPYs in the current library, ENDF/B-VIII.0, have been largely unchanged since the original evaluation of England and Rider in the 90s, with the except of an additional data point at 2 MeV incident neutron energy for ^{239}Pu(n,f). Additionally, there are no correlations included in the current evaluation, only uncertainties. Recently, there has been a significant experimental effort to measure short-lived FPYs as well as energy-dependent values, beyond first-chance fission (e.g. at incident energies above 5 MeV). Additionally, there have been significant modeling improvements in calculating the independent and cumulative FPYs consistently with other prompt and delayed fission observables.

One such model that uses the Hauser-Feshbach statistical decay has been integrated into the BeoH code, e.g. PRC 103, 014615 (2021). BeoH needs information about the compound nucleus before fission as well as information about the initial conditions of the excited fission fragments. The pre-scission quantities, such as multi-chance fission probabilities, the average excitation energy causing fission, and the probability of pre-fission neutron emission, are calculated with the CoH_3 code. Fission fragment initial conditions in mass, charge, total kinetic energy, spin, and parity are phenomenologically parametrized and constrained by experimental data, where available. The mass distribution is described as a combination of three Gaussians, the charge distribution is taken to be the Wahl systematics, and the total kinetic energy is parametrized as linear as a function of incident neutron energy, with a Gaussian distribution for each mass. Once the initial conditions for each possible mass-charge combination are determined, the Hauser-Feshbach statistical decay is used to de-excite each fragment through the emission of prompt neutrons and gamma rays. Isomeric states are tracked. Afterwards, a time-independent calculation is performed to determine the cumulative FPYs from the independent FPYs, using the decay data library of ENDF/B-VIII.0. (Of course, other decay libraries can be included to test the dependence of the cumulative FPYs but using ENDF/B-VIII.0 – and future decay library releases – ensures consistency between the independent and cumulative FPY ENDF libraries.) Through this procedure, we can consistently calculate prompt neutron and gamma-ray multiplicities, energy spectra, delayed neutron multiplicities, as well as independent and cumulative fission product yields.

To perform the evaluation, we combine our model and experimental data through a Kalman filter, where updated parameter values and covariances are produced simultaneously. The updated model parameters are run back through BeoH to calculate new mean observable values. Cumulative FPYs and prompt and delayed neutron multiplicities are included in the optimization. We have preliminary optimizations for ^{252}Cf(sf), ^{235}U(n,f), ^{238}U(n,f), and ^{239}Pu(n,f). For the neutron-induced fission reactions, we have produced calculations from thermal to 20 MeV incident neutron energies in 1 MeV steps. Through the model correlations, uncertainties are overall reduced compared to the ENDF/B-VIII.0 evaluation, even though individual FPY uncertainties have increased. The correlations between the FPYs at each calculated incident energy have been computed as well, and the mean values for the cumulative FPYs show reasonable agreement with the ENDF/B-VIII.0 values.

Moving forward, we are incorporating into the fitting procedure updated decay data evaluated by Brookhaven National Laboratory as well as FPY values that they have corrected to take into account more recent structure data. We are additionally tweaking the fission fragment initial conditions to better reproduce FPYs of interest and account for model stiffness. Validation efforts are underway.

23. Implementation of a Monte-Carlo type fit procedure in GEF, K.-H. Schmidt

The application of the summing method for the calculation of anti-neutrino production in fission requires total independent fission yields and isomeric ratios as input data. Experimental and evaluated data are available for a limited number of systems; they cover the four strongest contributors in nuclear reactors, ^{235}U(n_{th},f), ^{238}U(n_{fast},f), ^{239,241}Pu(n_{th},f). The semi-empirical GEF model [1] can provide these data also for other systems, which may become important for new types of nuclear reactors or other applications. In addition, it may help to improve the quality of evaluations in case of poor or contradictory experimental information [2].

The adjustable parameters of the GEF model ensure that the model agrees to a high degree with available experimental data, and its theoretical basis of general theorems, rules and ideas provides a considerable predictive power. This is demonstrated by a recent comparison of mass yields over a large range of fissioning systems [3].

The GEF model describes practically the whole fission process, in particular the division of the flux between the different fission channels and the corresponding fluctuations, the charge polarization, the division of excitation energy between the nascent fragments and their deformation at scission, the emission of prompt neutrons and gammas, the radioactive decay, including the beta decay, the production of antineutrinos and delayed neutrons, and the cumulative yields. Therefore, the parameters must be fitted to a diversity of data like post-neutron fission yields (masses and isotopes), isomeric ratios, total kinetic energies, fragment-mass-dependent prompt-neutron multiplicities, delayed-neutron yields, decay heat, as well as anti-neutrino multiplicities and spectra.

In spite of the technical difficulties connected with weighting the data of different nature, considering correlations in the data and applying analytical fitting algorithms to the GEF results with their statistical fluctuations, a Monte-Carlo fit procedure has been implemented recently in GEF-Y2023/V1.1 [4]. By adjusting 39 parameters with the new fit procedure, a reduction of the Chi-square (deviations between calculated and empirical values) by almost 50% was achieved with respect to the previously applied eye fit. The predictive power of the GEF model for systems with no or poor empirical data is expected to be appreciably enhanced.

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24. Impact of isomeric yield ratios on antineutrino spectra, A. Mattera (BNL)

Background

Isomeric yield ratios (IYR) represent the fraction of the direct yield of a fission product that populates the isomer (Yisom) expressed as a fraction of the total independent yield (IY) of that nuclide. In the current ENDF/B fission yield evaluations, IYR values are provided for over 100 fission products with a long-lived isomer using a one-parameter theoretical model developed in the late 1970s by D.G. Madland and T.R. England [1]. The Madland-England phenomenological model splits the IY between the isomer and ground state based on the spin of these two levels, when these are known. While fit to the experimental data available at the time the model was developed, this parametrization provides IYRs with an accuracy of ≈ ±50% [2]. IYRs affect the total antineutrino spectra, as they weigh the contribution of β--decay branches coming from the decay of the isomer vs the ground state (Fig. 1).

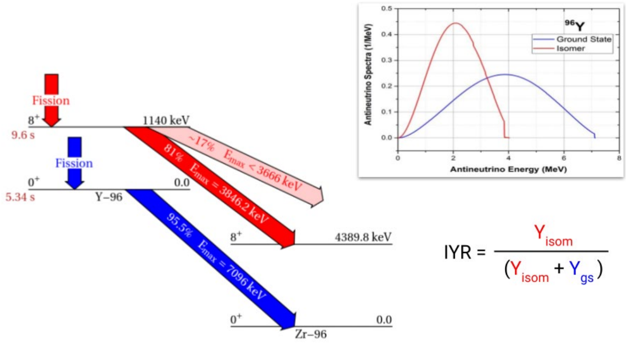

Figure 1: β⁻-decay of the isomer and the ground-state of a fission product can lead to dramatically different antineutrino spectra (top-right panel) and the IYR determines how each of these branch spectra contribute to the total antineutrino spectrum.

The effect of a new set of recommended experimental IYRs on antineutrino spectra

A compilation and evaluation of IYRs providing updated values for 42 fission products from low-energy neutron-induced fission was recently published [3] and showed the limitations of the Madland-England model. Using the newly published recommended IYRs, we studied their effect on antineutrino calculations with two different approaches: (A) estimating the total contribution of the updated IYRs on the antineutrino spectra of all major actinides of interest for reactor antineutrino spectra (^{235,238}U, ^{239,241}Pu). In addition to the 42 IYRs evaluated for low-energy neutron-induced fission, the IYR of ^{96}Y, a known contributor to the high-energy part of the antineutrino spectra, was fixed to 0.5, based on values from high-energy proton-induced fission reported in Ref. [3]. (B) performing a sensitivity study for all isotopes that have a long-lived isomer, that identified a number of isotopes whose IYR - not experimentally determined - could cause a dramatic shift in the total antineutrino spectrum at energies above 5 MeV (^{96}Y, ^{134}Sb, ^{100}Nb, ^{146} La, ^{90}Rb).

Conclusion and Recommendations

Models have proven unsatisfactory in the prediction of IYRs [3], and experimentally determined IYRs should be the foundation of values included in new FY evaluations. Only a small fraction of fission products has been measured and given the importance for antineutrino spectra, new experimental efforts are required.

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25. Gamma-ray analysis of the β-decay contributors to the antineutrino spectrum, S. Kim (BNL)

Motivation

Recent measurements of $\bar{\nu}_e$ show that there exists a spectral bump in the 5-7 MeV region with respect to the Huber-Muller prediction. One of the several proposed explanations is that the bump may be due to the excess strengths of β-decaying nuclides [1]. The follow up study reveals that using improved fission yield values can significantly alter the calculation, producing different results [2]. This demonstrates the need and usage of the accurate fission yield data.

Experiment

After ^{235}U and ^{239}Pu samples are irradiated with the thermal neutrons from High Flux Isotope Reactor, the gamma-ray spectra are measured (Fig. 1). We select the 8 fission products shown to be among the main contributors to the $\bar{\nu}_e$ spectrum in the 5-7 MeV region. Table 1 shows that the two main evaluated fission yield libraries, JEFF3.3 and ENDF/B-VIII.0, provide different independent fission yield values for the same nuclides. Expected number of the gamma-rays detected by the high purity Germanium detector is determined using JEFF3.3 fission yield library, gamma-ray intensity from ENDF/B VIII.0 decay data sublibrary, and detector efficiency.

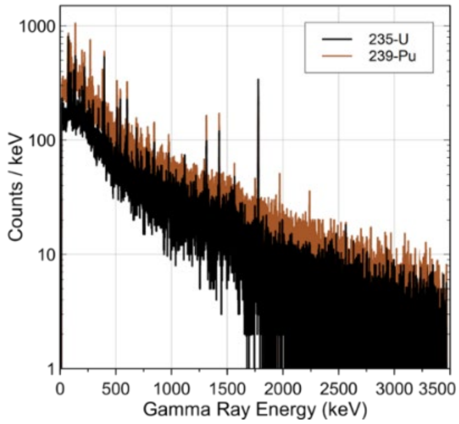

Figure 1: Measured gamma ray spectra from ^{235}U and ^{239}Pu samples are shown (left).

Y_{IF}	93-Se	93-Br	93-Kr	93-Rb
JEFF3.3 (2017)	No data	6.25E-05	6.14E-03	2.71E-02
ENDF/B-VIII.0 (2018)	2.46E-08	3.08E-05	4.86E-03	3.07E-02

Table 1: Jeff3.3 and ENDF/B-VIII.0 fission yield libraries contain different independent fission yield values for the same nuclides.

The measured gamma-ray counts are determined using a non-linear fitting method.

Results

Results for ^{95}Sr, ^{100}Nb and ^{140}Cs show that the expected and measured gamma-ray counts are consistent for both ^{235}U and ^{239}Pu. This indicates potentially reliable fission yield values in the JEFF3.3 library for these nuclides. Results for the remaining nuclides are unsatisfactory due to insufficient fission yields and low statistical significances. The analysis shows that the largest contribution to the uncertainty in the expected gamma-rays comes from the fission yield uncertainty.

Conclusion

Fission yield libraries contain different fission yield values for the same fission products, leading to very dissimilar results for the $\bar{\nu}_e$ spectrum analysis. This demonstrates that up-to-date and accurate fission yield data are necessary for reliable $\bar{\nu}_e$ spectrum evaluation and prediction. Additional experimental data are needed to check and confirm current values in the fission yield libraries.

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Technical Meeting on Nuclear Data Needs for Antineutrino Spectra Applications

16-20 January 2023
Meeting Room CR4, IAEA, Vienna

ADOPTED AGENDA

Monday, 16 January 2023

Opening Session (08:45-09:00)

Welcome – Introduction (KONING, Arjan; DIMITRIOU, Paraskevi (Vivian))

Reactor antineutrino measurements (09:00 - 12:45)

09:00	Measurement of residual reactor antineutrino by Double Chooz	ONILLON, Anthony
09:40	RENO Experiment	YOO, Jonghee
10:20	Coffee break	
10:50	SNOWMASS 2021 WHITE PAPER	LITTLEJOHN, Bryce
11:35	Daya Bay I-Isotope spectrum, flux evolution and joint analysis w PROSPECT	AN, Fengpeng
12:15	Daya Bay II-high-energy neutrinos, oscillations	ZHAN, Liang

Lunch break (12:45 - 14:15)

Reactor antineutrino measurements (14:15 - 17:05)

14:15	PROSPECT I	BOWDEN/HEEGER
14:55	SOLID Experiment	VACHERET, Antonin
15:35	Coffee break	
15:45	STEREO Experiment	LHUILLIER, David
16:25	NUCLEUS Experiment	LASSERRE, Thierry

Tuesday, 17 January 2023

Reactor antineutrino measurements (09:00 - 12:50)

09:00	NEOS Experiment	SEO, Seon-Hee
09:40	DANSS Experiment	SVIRIDA, Dmitry
10:20	Coffee break	
10:50	JUNO-TAO Experiment	LI, Ruhui
11:30	JUNO Experiment	YU, Zeyuan
12:10	PROSPECT II	BOWDEN/HEEGER

Lunch break (12:45 - 14:15)

Reactor antineutrino applications (14:15 - 17:50)

14:15	NU TOOLS	FOXE, Michael
14:55	Mobile Antineutrino Demonstrator	BOWDEN, Nathaniel
15:35	Coffee break	
15:50	CHANDLER Experiment	LINK, Jonathan
16:30	Update on Antineutrino-based Safeguard Approaches for Spent Nuclear Fuel	SCHNELLBACH, Yan
17:00	COHERENT Experiment	EFREMENKO, Yuri

Annex I

Wednesday, 18 January 2023

Reactor antineutrino modelling and nuclear data (09:00 - 12:40)

09:00	Antineutrino modelling overview	HUBER, Patrick
09:45	SUMMATION CALCULATIONS	SONZOGNI, Alejandro
10:20	Coffee break	
10:50	SUMMATION CALCULATIONS-NANTES	ESTIENNE/FALLOT
11:30	New Ab-initio reactor calculations	PERISSE, Lorenzo
12:10	CONFLUX - A Flexible, Modular Reactor Neutrino Flux Calculation Framework	ZHANG, Xianyi

Lunch break (12:40 - 14:10)

Reactor antineutrino modelling and nuclear data (14:10 - 17:40)

14:10	Nuclear data measurements at ANL	KONDEV, Filip
14:50	Nuclear data measurements at ORNL	RYKACZEWSKI, Krzysztof
15:30	Coffee break	
15:50	Nuclear data measurements-IFIC/Valencia-Nantes	ALGORA, Alejandro
16:30	Combining reactor fission gas data with antineutrino data	HAYES-STERBENZ, Anna Catherine
17:10	Fission Yields Modelling and Evaluation	LOVELL, Amy

Dinner, 19:00: Huth Gastwirtschaft

Thursday, 19 January 2023

Reactor antineutrino modelling and nuclear data (09:00 – 11:05)

09:00	Implementation of a comprehensive Monte-Carlo-type fit procedure in GEF	SCHMIDT, Karl-Heinz
09:30	Beta spectroscopy needs and impact on the global data set-Hayen	HAYEN, Leendert
10:00	BNL contribution II	MATTERA, Andrea
10:20	BNL contribution III	KIM, Sam
10:35	Coffee break	

Roundtable discussion (11:05 – 12:30)
Convenor: HEEGER, Karsten

Lunch break (12:30 - 14:00)

Roundtable discussion cont'd (14:00 – 17:30)

Coffee break (15:30)

Friday, 20 January 2023

Roundtable discussion cont'd (09:00 – 11:00)

Coffee break (10:30)

Drafting recommendations (11:00 – 12:20)

Closing (12:20-12:30)

Technical Meeting on Nuclear Data Needs for Antineutrino Spectra Applications

16 – 20 January 2023

IAEA, Meeting Room CR4

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