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NEUTRON ENERGY RANGES IN THE CORE OF DIFFERENT REACTORS

Annotation. *Continued efforts in experimental measurements and theoretical modeling of fission yields for different neutron energies are crucial to resolving these discrepancies and enhancing the accuracy of reactor antineutrino models. In simulations of different reactor core designs, we find that a significant portion of fissions—ranging from 5% to over 40%—are caused by non-thermal neutrons. Our findings also indicate that comparisons of antineutrino measurements between reactors with low-enriched and highly-enriched fuels can overlook the differences in their fission neutron energy distributions.*

Keywords. *Antineutrino, beta spectra, isotope, thermal fission, low-enriched uranium, resonant neutrons.*

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ДИАПАЗОНЫ ЭНЕРГИЙ НЕЙТРОНОВ В АКТИВНОЙ ЗОНЕ РАЗЛИЧНЫХ РЕАКТОРОВ

Аннотация. *Постоянные усилия в экспериментальных измерениях и теоретическом моделировании выходов деления для различных энергий нейтронов имеют решающее значение для разрешения этих несоответствий и повышения точности моделей антинейтрино реакторов. При моделировании различных конструкций активной зоны реактора мы* *обнаружили, что значительная часть делений — от 5% до более 40% — вызвана нетепловыми нейтронами. Наши результаты также указывают на то, что сравнение измерений антинейтрино между реакторами с низкообогащенным и высокообогащенным топливом может упустить из виду различия в их распределениях энергии нейтронов деления.*

Ключевые слова. *Антинейтрино, бета-спектры, изотоп, тепловое деление, низкообогащенный уран, резонансные нейтроны.*

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TURLI REAKTORLARNING YADROSIDAGI NEYTRON ENERGIYASI DIAPAZONLARI

Annotatsiya. *Eksperimental o’lchovlar va turli neytron energiyalari uchun bo’linish samaradorligini nazariy modellashtirish bo’yicha doimiy harakatlar mavjud tafovutlarni hal qilish va reaktor antineytrino modellarining aniqligini oshirish uchun juda muhimdir. Turli xil reaktor yadro konstruktsiyalarini simulyatsiya qilishda biz bo’linishlarning muhim qismi - 5% dan 40% gacha - termal bo'lmagan neytronlar tufayli yuzaga kelishini aniqlaymiz. Bizning natijalarimiz shuni ko’rsatadiki, reaktorlar o’rtasidagi antineytrino o’lchovlarini past boyitilgan va yuqori boyitilgan yoqilg’i bilan taqqoslash ularning bo’linish neytron energiyasini taqsimlashdagi farqlarni e’tiborsiz qoldirishi mumkin.*

Kalit so’zlar. *Antineytrino, beta-spektrlar, izotop, termal bo‘linish, kam boyitilgan uran, rezonansli neytronlar.*

Introduction

The primary method to predict reactor electron antineutrino ($\bar{\nu}_e$) production involves converting observed electron spectra to the connected antineutrino spectra released during fission daughters of beta decay. Cumulative spectroscopic findings of beta particles produced by the decay of daughters, resulting from the thermal fission of relevant actinides in nuclear reactors, namely uranium-235 (^{235}U), plutonium-239 (^{239}Pu), and plutonium-241 (^{241}Pu)are essential inputs for this methodology. These measured beta spectra are analyzed by fitting them as a combination of several representative nuclear charges in "virtual" beta branches. These branches are then kinematically transformed into corresponding $\bar{\nu}_e$ spectra, accounting for various second-order corrections. These converted and corrected spectra for all virtual beta branches cconstitute the predicted $\bar{\nu}_e$ spectrum for each fissioning isotope. However, it's worth noting that the beta spectrum following the fission of uranium-238 (^{238}U) was not measured at the thermal neutron beam line of the ILL, as fast neutrons cause the great large quantities of ^{238}U fissions. Given that this isotope makes up less than 10% of those fissions in reactors that are important to research on antineutrinos,, it is considered less critical for these predictions. For uranium-238 (^{238}U), flux predictions have been generated through (*ab initio)* calculations, also known as 'summation' calculations, which utilize standard databases for fission yields and beta decay measurements. It is worth noting that recently, beta-conversion electron antineutrino ($\bar{\nu}_e$) spectra for ^{238}U over 2.9 MeV have been computed using new measurements of beta spectra from fast-neutron-induced fission [1-2].

In contrast, the beta-conversion $\bar{\nu}_e$ spectra for uranium-235 (^{235}U), plutonium-239 (^{239}Pu), and plutonium-241 (^{241}Pu) by Huber are currently the most commonly utilized in the field. This is mostly because to their excellent precision and specified methods of transformation limitations.

However, summation predictions, while valuable for analyzing reactor systemic instabilities $\bar{\nu}_e$ predictions are inherently less precise. They typically carry around 10 % of problems in the spectrum structure that are somewhat less clarified and problems in their numerical normalizations. Despite these limitations, they serve as an important tool in understanding systematic uncertainties in reactor $\bar{\nu}_e$ predictions.

Reactor Simulations

№	Thermal			Resonance			Fast		
	BOC (%)	MOC (%)	EOC (%)	BOC (%)	MOC (%)	EOC (%)	BOC (%)	MOC (%)	EOC (%)
^{235}U	80.86	82.43	83.12	16.68	15.34	14.76	2.46	2.23	2.13
^{238}U	0.00	0.00	0.00	0.06	0.05	0.06	99.94	99.94	99.94
^{239}Pu	91.92	92.20	92.44	6.93	6.68	6.46	1.15	1.12	1.09
^{241}Pu	84.57	85.60	86.17	14.21	13.26	12.73	1.22	1.14	1.10

Table 1: The breakdown of fission contributions from different neutron energy intervals for the four main fissioning isotopes in a PWR reactor is provided for three distinct periods: the start, middle, and end of the reactor cycle(BOC,MOC,EOC). Each isotope's contribution is expressed as a percentage of the total fissions and adds up to 100% for each period.

Reactor simulations are essential tools in nuclear engineering. They are used to modelling and analyze the behavior, performance, and safety of nuclear reactors. These simulations incorporate various physical and mathematical models to replicate the complex interactions within a reactor. A Pressurized Water Reactor (PWR) is one of the most common nuclear reactors used for electricity generation. It uses ordinary (light) water as both the coolant and the moderator, and it operates at high pressure to prevent the water from boiling within the reactor core. The comparatively big core, measuring about 3–4 meters in diameter and active length, produces around 3500 MWt of electricity. UO_2 cylindrical fuel pellets arranged into fuel rods comprise the fuel. Fuel assemblies are located in the core and consist of a 17-by-17 square lattice of fuel rods. The enrichment of new gasoline is around 4.2%. Commercial reactors typically run for 18 to 24 months before switching out fuel and refueling. Eight cores in the PWR MCNP model represent a typical Westinghouse four-loop core. Burnable absorbers as neutron poisons and an exact batch representation of fuel (fresh, once-burned, and twice-burned) are included in the model. The High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory is a high-performance research reactor known for its intense neutron flux, with a thermal power output of 85 MW. Its compact cylindrical core, which uses highly enriched uranium fuel and is surrounded by a beryllium reflector, supports many scientific and practical applications. These include the production of medical and industrial isotopes, neutron scattering experiments, materials testing, and various primary and applied research projects. HFIR's design includes robust safety features, such as multiple control rods and emergency cooling systems, ensuring safe and reliable operation [3-4].

The High Flux Isotope Reactor (HFIR) is a prominent research reactor known for its high neutron flux and diverse applications. The reactor has undergone numerous upgrades to enhance its performance, safety, and capabilities. These upgrades ensure that it remains a state-of-the-art facility for scientific research and isotope production. It provides one of the highest steady-state neutron fluxes of any research reactor worldwide. It is highly valuable for neutron scattering experiments and other scientific applications requiring high neutron intensity.HFIR produces a variety of isotopes, including californium-252, plutonium-238, and others used in medicine, industry, and research. It plays a crucial role in the supply chain for these critical materials. HFIR is a pressurized, light-water-cooled moderated, flux-trap type reactor. It operates at a thermal power of up to 85 megawatts (MW).

The National Bureau of Standards Reactor (NBSR) is a key facility for neutron-based research. It has several neutron beam lines for a variety of scientific experiments, facilities for sample irradiation and materials testing, and an operating capacity of a maximum of 20 megawatts (MW). The Core Dimensions are cylindrical, about 66 cm in diameter and 48 cm in height.

	Thermal				*Resonance*				*Fast*			
	Beam (%)	PWR (%)	HFIR (%)	NBSR (%)	Beam (%)	PWR (%)	HFIR (%)	NBSR (%)	Beam (%)	PWR (%)	HFIR (%)	NBSR (%)
^{235}U	100.00	82.43	85.88	94.38	0.00	15.34	12.36	4.93	0.00	2.23	1.76	0.69
^{238}U	NA	0.00	NA	NA	NA	0.05	NA	NA	NA	99.94	NA	NA
^{239}Pu	100.00	29.66	NA	NA	0.00	69.44	NA	NA	0.00	0.90	NA	NA
^{241}Pu	100.00	37.79	NA	NA	0.00	61.42	NA	NA	0.00	0.80	NA	NA

Energy Range	Fraction of Total Fissions (%)				
	ILL Beam	PWR	HFIR	BR3	AFR
Thermal	100 (NA)	83.8 (77.1)	83.8 (85.2)	83.8 (80.3)	83.8 (0.0)
Epithermal	0 (NA)	16.2 (14.9)	(13.5)	(13.9)	(35.7)
Fast	0 (NA)	0 (8.1)	(1.3)	(5.8)	(64.4)

Table 2: Percent of total fissions from each of the three primary fission neutron ranges for the ILL beamline, for a LEU pressurized water reactor (PWR), for the HEU HFIR and LEU BR3 reactors, and for an advanced fast reactor, averaged over a single fuel cycle.

Results

Due to the low fission cross-sections at low neutron energies, nearly all uranium-238 (^{238}U) fissions are prompted by fast neutrons. Conversely, fast fissions constitute only 1-2% or less of the total for the other isotopes.Throughout the reactor cycle, each energy range's fractional contributions exhibit minimal variation, remaining constant within a few percentage points. However, most of the variation occurs during the initial days of the cycle.

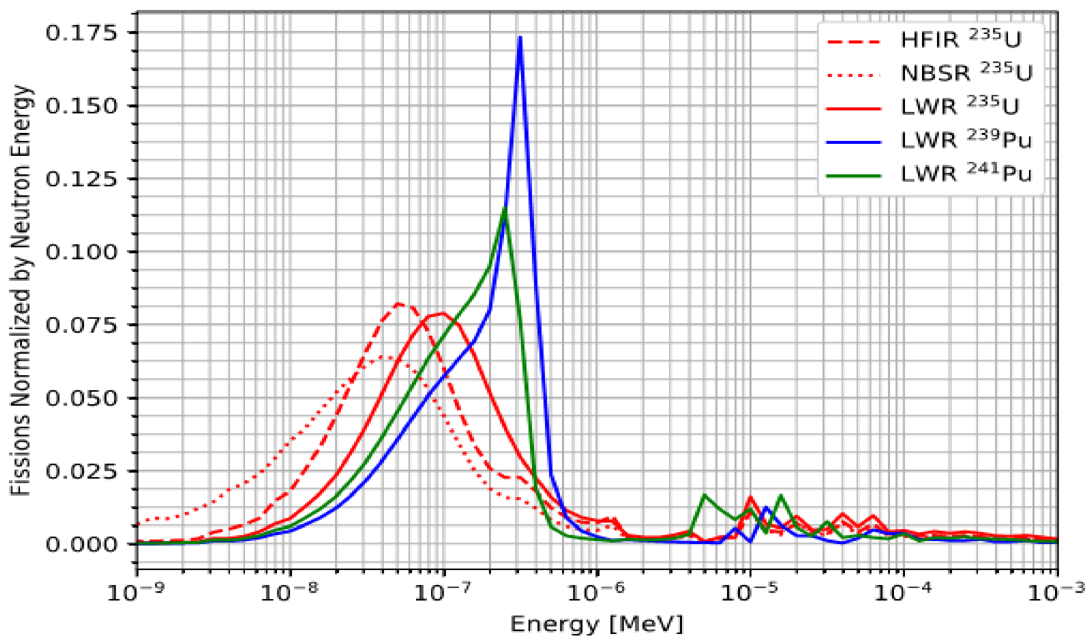

Figure 1: Fission contributions normalized (top) and cumulative (bottom) for ^{235}U, ^{239}Pu, or ^{241}Pu in PWR/LWR, HFIR, and NBSR reactors

against incident neutron energy. Since HFIR and NBSR nuclear power plants are HEU, only ^{235}U curves are given.

The significant rates of non-thermal fission are elaborated further in Figure 1, which depicts the relative contributions of fission plotted against the energy of incident neutrons, alongside the cumulative contribution as neutron energy increases. Distinct peaks and changes are discernible for the three isotopes within the resonant range, reflecting the resonances in fission cross-sections within this energy range.Particularly striking peaks are observed at 0.3 eV and 0.2 eV for plutonium-239 (^{239}Pu) and plutonium-241 (^{241}Pu). These peaks correspond to broad resonances in each isotope's fission cross-section.

Summary

We produced summation $\bar{\nu}_e$ estimates for fissions resulting from neutrons that fit the previously stated considerably non-thermal energy profile and from neutrons that are completely thermal using the Oklo nuclear modeling techniques. We next examined antineutrino spectra and fluxes between these two cases.

We found that the differences in the $\bar{\nu}_e$ spectrum and the inverse beta decay (IBD) yields between these instances for ^{235}U, ^{239}Pu, and ^{241}Pu are less than the corresponding uncertainty boundary of beta-conversion for each isotope. Nevertheless, because of their significant contributions from non-thermal fission, ^{239}Pu and ^{241}Pu show the most significant spectrum deviations. In the 5-7 MeV area and below, the difference in the $\bar{\nu}_e$. The spectrum between these two situations is less than 3.5% in circumstances similar to a reactor with pressurized water reactor (PWR)-like fission fractions. Moreover, the variation in IBD yield is significantly smaller than 1%. This result implies that variations in flux evolution between data and beta-conversion predictions, as well as anomalies in reactor antineutrino flux and spectrum, are unlikely to be caused by the handling of fission neutron energy. These results appear consistent with any fission yield database and approach to partial nuclear structure data handling.

We have observed that ^{235}U spectra of HEU and LEU reactor cores are comparable, while there are differences in non-thermal fission contributions.

Therefore, fission neutron energy discrepancies may be ignored when comparing IBD yield and energy spectra over most HEU and LEU reactor trials, even if our analysis did not include all sorts of "thermal" core configurations. This result is relevant to joint analysis of sterile fluctuations in reactor experiments, cooperative HEU-LEU programs to identify the isotopic origin of reactor flux and spectrum abnormalities, and worldwide evaluations of reactor and spectrum observations.

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