Nuclear Instruments and Methods in Physics Research A 776 (2015) 75–82

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Method of fission product beta spectra measurements for predicting reactor anti-neutrino emission

D.M. Asner, K. Burns, L.W. Campbell, B. Greenfield, M.S. Kos *, J.L. Orrell, M. Schram, B. VanDevender, L.S. Wood, D.W. Wootan

Pacific Northwest Laboratory, Richland, WA 99352, USA

ARTICLE INFO

Article history:
Received 2 July 2014
Received in revised form
27 September 2014
Accepted 29 September 2014
Available online 18 December 2014

Keywords:
Proton beam
Beta decay
Anti-neutrinos
Reactor anomaly

ABSTRACT

The nuclear fission process that occurs in the core of nuclear reactors results in unstable, neutron-rich fission products that subsequently beta decay and emit electron antineutrinos. These reactor neutrinos have served neutrino physics research from the initial discovery of the neutrino to today's precision measurements of neutrino mixing angles. The prediction of the absolute flux and energy spectrum of the emitted reactor neutrinos hinges upon a series of seminal papers based on measurements performed in the 1970s and 1980s. The steadily improving reactor neutrino measurement techniques and recent reconsiderations of the agreement between the predicted and observed reactor neutrino flux motivates revisiting the underlying beta spectra measurements. A method is proposed to use an accelerator proton beam delivered to an engineered target to yield a neutron field tailored to reproduce the neutron energy spectrum present in the core of an operating nuclear reactor. Foils of the primary reactor fissionable isotopes placed in this tailored neutron flux will ultimately emit beta particles from the resultant fission products. Measurement of these beta particles in a time projection chamber with a perpendicular magnetic field provides a distinctive set of systematic considerations for comparison to the original seminal beta spectra measurements. Ancillary measurements such as gamma-ray emission and post-irradiation radiochemical analysis will further constrain the absolute normalization of beta emissions per fission. The requirements for unfolding the beta spectra measured with this method into a predicted reactor neutrino spectrum are explored.

1. Introduction

Neutrino experiments at nuclear reactors have played a vital role in the study of neutrino properties and flavor oscillation phenomenon. The observed antineutrino rates at reactors are typically lower than model expectations [1,2]. This observed deficit is called the reactor neutrino anomaly. Proposals exist for explaining this anomaly via non-standard neutrino physics models (sterile neutrinos, for example), and a new understanding of neutrino physics may again be required to account for this deficit. However, model estimation uncertainties may also play a role in the apparent discrepancy. An experimental technique is proposed to make precision measurements of the beta energy spectrum from neutron induced fission using a 30 MeV proton linear accelerator[1] as a neutron generator [3]. Each fission event produces fission products that decay and emit electrons (beta particles) and anti-neutrinos, and precise measurement of the beta energy spectrum is used to infer an associated anti-neutrino spectrum. The proposed new approach utilizes the flexibility of an accelerator-based neutron source with neutron spectral tailoring coupled with a careful design of an isotopic fission target and beta spectrometer. The use of a moderated accelerator-based neutron source has several advantages. First, by choosing an appropriate moderator and precisely controlling its temperature the neutron energy spectrum can be chosen to the required uncertainty. This is not necessarily true for a commercial power reactor where there are significant differences in moderator temperature between different parts of the reactor. Second, the proposed method allows for adjusting the neutron energy spectrum to reproduce various reactor types. The inversion of the beta spectrum to the neutrino spectrum is intended to allow further reduction in the uncertainties associated with prediction of the reactor neutrino spectrum.

Through the fission process, four isotopes, ^{235}U, ^{239}Pu, ^{241}Pu, and ^{238}U contribute more than 99% of all reactor neutrinos with energies above the inverse beta decay threshold (neutrino energy

* Corresponding author.
E-mail address: markskos@gmail.com (M.S. Kos).

[1] For example the Project X Injector Experiment at Fermilab -see http://www-bdnew.fnal.gov/pxie/.

http://dx.doi.org/10.1016/j.nima.2014.09.076
0168-9002/

≥ 1.8 MeV). The resulting predicted reactor neutrino flux is an accumulation of thousands of beta decay branches of the fission fragments. Reactor neutrino fluxes from the thermal fission of ^{235}U, ^{239}Pu, and ^{241}Pu are currently obtained by inverting measured total beta spectra obtained in the 1980s at a beam port at the High Flux Reactor of the Institut Laue-Langevin (ILL) [1]. Recent reevaluations of the 1980s data with a careful investigation and treatment of the various sources of correlated and uncorrelated uncertainties indicated an upward shift of about 3%, with uncertainties ranging from 2% to 29% across the neutrino spectrum [1]. Clearly any limitations of the original ILL beta spectrum measurements in terms of energy resolution, absolute normalization, and statistical counting uncertainties will propagate into the predicted reactor antineutrino spectra. For a single beta decay branch, the neutrino energy spectrum is directly related to the beta energy spectrum by conservation of energy. However, there are hundreds of fission products and thousands of beta decay branches making measuring each branch individually practically impossible (especially for ultra-short half-life isotopes). Thus measuring the cumulative beta spectrum remains the most viable technique for producing a representative spectrum used as a basis for inversion. The beta spectrum from the fission target can be deconstructed into a set of individual beta decays modeled either as 'virtual branches' [1] or matched to expectations based on the information in nuclear decay databases. Likewise a parallel measurement of the gamma-ray emission from the irradiated fission foil (in situ and post-irradiation), provides a means to check the normalization of the beta emission per fission. These aspects of the proposed measurement seek to improve the confidence of the underlying reactor neutrino spectrum predictions.

2. Neutron production and spectra

The neutron spectrum in a nuclear reactor core is composed of three different energy ranges. Neutrons from fission are emitted with an average energy of about 2 MeV and a most probable neutron energy of 0.73 MeV. Fig. 1 shows a representative neutron spectrum for a fuel pin in a pressurized water reactor (PWR). In such a reactor, the fast portion of the neutron spectrum, with energies greater than 0.1 MeV, has a shape similar to the primary fission neutrons. In an operating reactor, fine structures in the neutron spectrum are introduced by absorption resonances on the fuel, moderator, and structural materials. In the intermediate epi-thermal neutron energy range, from 0.1 MeV down to about 1 eV, the neutrons are slowing down with a characteristic 1/E dependence. This is due to elastic scatters in the moderator removing a constant fraction of the neutron energy per collision (on average). The thermal portion of the spectrum, below $\sim$1 eV, is characterized by a thermal Maxwellian flux shape, where the neutrons are in thermal equilibrium with the moderator. The peak energy of the thermal flux depends upon the temperature of the moderator material. Higher temperatures will shift the peak to higher energies. At room temperature, the peak thermal flux is at 0.0265 eV, while for the PWR conditions in Fig. 1 the coolant is around 320 °C. The magnitude and shape of the thermal spectrum depends on the relative volume fractions of moderator and fuel, and on the presence of burnable poisons or neutron absorbers inside the fuel or mixed in the moderator. The relative magnitudes of these three regions of the neutron spectrum depend a great deal on specific reactor conditions. Neutron spectra at the beginning and end of an operating cycle will differ because of changing fuel isotopics from burnup, buildup of fission products, burnout of burnable poison in the fuel, and (in the case of PWRs) deliberate changes in the boron concentration in the coolant through the cycle. The neutron spectra in various parts of the reactor core will vary because of increased leakage and/or reflection near the upper and lower surfaces and outer edges of the core compared to the interior of the core. For boiling water reactors (BWRs), the coolant/moderator water density varies axially from full density water near the bottom of the core to full steam at the top of the core.

The primary fissioning isotopes in a typical commercial power reactor are ^{235}U, ^{239}Pu, ^{241}Pu, and ^{238}U. Fig. 2 shows the fission cross-sections for these four isotopes. The cross-sections for ^{235}U, ^{239}Pu, and ^{241}Pu are fairly flat at high energies, have a series of sharp resonances in the intermediate energy range, and a 1/v shape at thermal energies. Both ^{239}Pu and ^{241}Pu have broad low energy resonances that reside at the transition between the thermal neutrons and the epi-thermal neutrons. Uranium-238 has a threshold for fission at approximately 1 MeV, and therefore does not fission at lower energies. Where the spectral variability impacts the neutrino anomaly is through the fission product yields. There is a known dependence in fission product yields with the energy of the neutron causing fission. This is illustrated in Fig. 3, which compares the fission product mass yields for thermal (0.025 eV) and 0.5 MeV neutrons for ^{235}U fission. Large differences can be seen for fission product masses in the central valley and for the lower and upper mass ranges.

A major advantage of an accelerator neutron source over a neutron beam from a thermal reactor is that the fast neutrons can be slowed down or tailored to approximate various power reactor spectra. This provides an advantage for control in studying how changes in the neutron spectra (i.e. in the reactor core) affects the resulting fission product beta spectrum. Furthermore, the ^{238}U

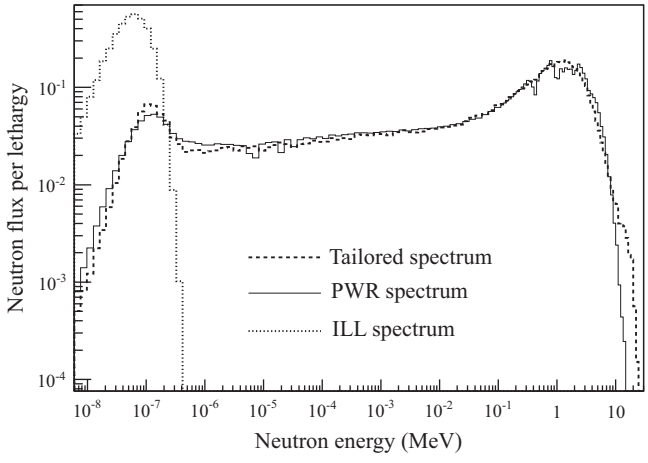

Fig. 1. The neutron energy spectra from a PWR reactor, D_2O thermalized neutrons (as at ILL), and the tailored spectrum from the 30 MeV proton source.

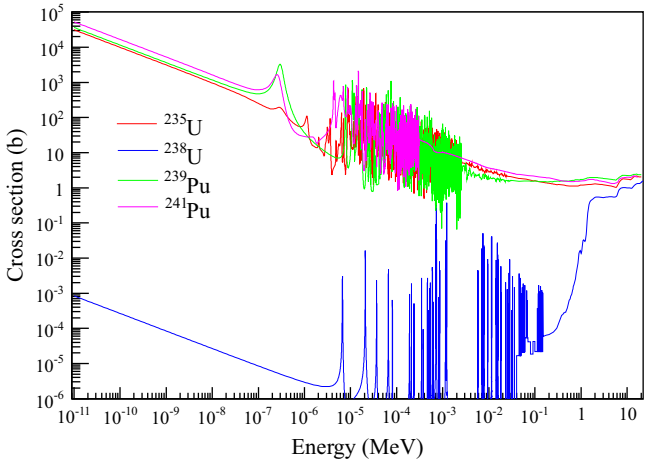

Fig. 2. The fission cross-sections of key fuel isotopes.