Snowmass2021 - Letter of Interest: Neutrino Detection and Ranging

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The oscillation of neutrinos means that the spectral shape is distorted (compared to the no-oscillation case) by a function proportional to a term $\sin(a \cdot \frac{L}{E})$. For reactor antineutrinos, L is the distance from the reactor core to the detector, E is the antineutrino energy, and a is a constant. When an MeV-scale reactor neutrino oscillates away from being an electron antineutrino (into a muon or tau particle) it is undetectable via the commonly used inverse beta decay interaction, being below the energy threshold for muon and tau production. Consequently, the electron antineutrino appears and disappears with distance, modulated by the $\sin(a \cdot \frac{L}{E})$ function. This basic phenomenon is the focus of a major global effort to precisely measure and understand the parameters governing oscillations. However, since the observed spectrum depends uniquely on the distance to the source, and we can also choose to 'run things backwards' making use of the increasingly well-known oscillation parameters to extract an estimate of the reactor standoff. Such estimates may be useful in a variety of nonproliferation applications related to reactor discovery and 'ranging'. Unlike radar, which requires a signal to be sent out and reflected back (with the famous $1/L^4$ attenuation), the antineutrino spectrum itself already encodes the distance from the source (independent of the reactor power, apart from statistics), and attenuates only as $1/L^2$. It is like radar with no power cost to the observer. (Except of course needing a huge neutrino detector!)

An opportunity will arise to demonstrate this unique property of antineutrinos at the Advanced Instrumentation Testbed (AIT) at the Boulby Underground Mine in Northern England. As described in a companion LOI, AIT will house (in succession) one or more kiloton-scale water-based detectors which will demonstrate technologies and methods relevant for remote antineutrino-based monitoring, discovery and exclusion of nuclear reactors. We anticipate the ability to extract a range estimate from the oscillated spectrum from the nearest reactor complex to AIT, the two Advanced Gas Reactors in Hartlepool, at $\sim 26km$ standoff. In this LOI, we consider the opportunity to make this measurement for the first time at the AIT site with a kiloton-scale detector, and describe an elegant Fourier-transform-based method for extracting the reactor standoff distance from the spectral shape.

NF Topical Groups: (check all that apply □/■)

■ (NF1) Neutrino oscillations
□ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
□ (NF4) Neutrinos from natural sources
■ (NF5) Neutrino properties
□ (NF6) Neutrino cross sections
■ (NF7) Applications
■ (NF8) Theory of neutrino physics
■ (NF9) Artificial neutrino sources
■ (NF10) Neutrino detectors
□ (IF2) Instrumentation Frontier/Photon Elements
□ (IF9) Cross Cutting and Systems Integration

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I. THE REACTOR STANDOFF DISTANCE IS ENCODED IN THE ANTINEUTRINO ENERGY SPECTRUM

Neutrino oscillations evolve over long distances from one type to another, cyclically. This is not the very short deBroglie wavelength of individual particles. Instead, at each distance, the oscillated spectrum is unique. In particular measuring the number of reactor electron antineutrinos versus energy encodes precisely the distance to the original unoscillated source of pure electron antineutrinos - in this case the reactor. The ranging capability implied by this relation has potential utility for nonproliferation. A goal for our collaboration is to demonstrate the potential of oscillation-based ranging in a direct experiment at AIT. In this LOI we describe the method for extracting the range using a Fourier transform of the neutrino spectrum.

Neutrino oscillations have 3 different wavelengths (parameterized as mass squared differences, of which two are close together), and amplitudes (paramterized as mixing angles. The faster oscillations, $\sim 4km$ at the $\sim 4MeV$ peak of the undistorted reactor spectrum, are good for resolving short ranges, while the longer $\sim 110km$ wavelength is useful for more distant reactors. The range of the source reactor, if measured by this method cannot be faked or distorted, and absolutely unique property of neutrinos. With adequate statistics, even the locations of multiple reactors can be sorted out [1].

While calculations have been published, [1], experimental focus has naturally been on physics, measuring the oscillation parameters, not nonproliferation. One detector gives a ring of possible locations, two give 2 possible solutions for location. With several large detectors one can sort out a small reactor from a number of operating power reactors. For nonproliferation applications at extended ranges, larger detectors than the kiloton-scale experiments at AIT will be required. However a kiloton-scale demonstration will serve as an important empirical demonstration of the method in a real-world environment, and has yet to be performed.

Sufficient energy resolution and sufficient counts are both required in order to specify a band on the Earth in which the reactor lies. Roughly, we expect that a few hundred events may suffice in terms of statistics. Energy resolution must be sufficient to discern the modulation peaks, the amplitude and frequency of which, when imprinted on the spectrum, imply a different value for resolution at each standoff distance. Figure 1 shows the distorted spectrum at the nominal 26 km Boulby distance, and at 20 and 30 km for comparison. As shown, even with the r^2 overall flux dependence on the standoff distance removed, the spectral patterns clearly differ due to oscillations.

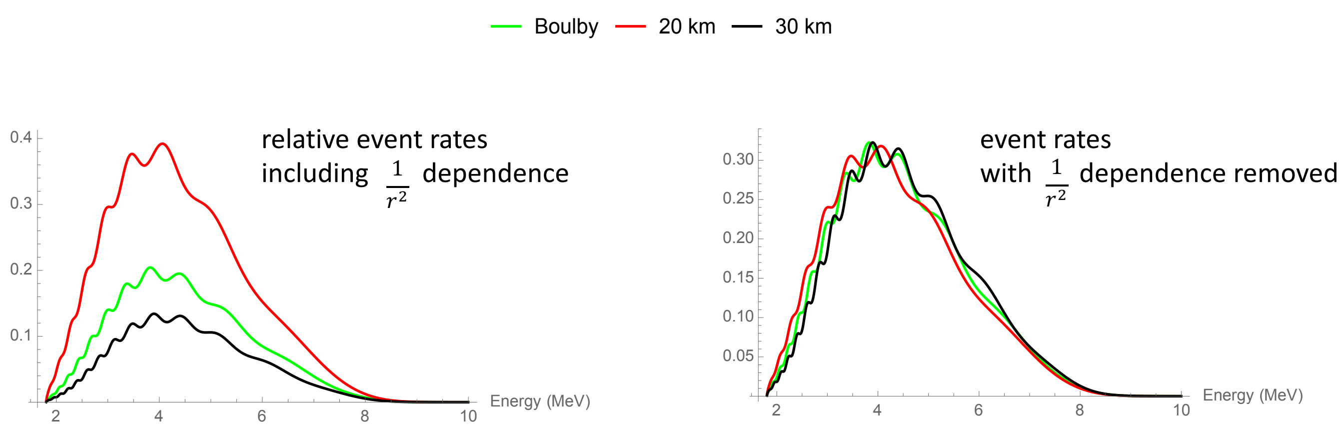

FIG. 1. oscillated spectra at Boulby, at 26 km 20 km and 30 km.

II. FOURIER TRANSFORM METHODOLOGY

Given the involvement of periodic functions, Fourier analysis comes naturally to mind as a tool to extract a range estimate. The oscillating terms depend upon mass difference squared δm^2 times distance (L) / neutrino energy (E). We know the oscillation parameters rather well, and we will observe the energy of the IBD events. If we do a Fourier transform on $1/E$ we should find a peak at the distance to the source $\delta m^2 L$. If there were only one oscillating term there would be one peak. One can think of the neutrino spectrum as a Fourier transform 'window function', tapering off high and low, and thus most conveniently suppressing sidelobes in the FT. Actually there are three oscillation lengths, two close together and one further out. For experiments at a distance such as Hartlepool to Boulby only the shorter periods will have a few cycles (around 7 at $4MeV$ while the longer cycle $\sim 110km$ will have no peak due to our only seeing a fraction of a single cycle at $4MeV$, and only ~ 1 cycle at $1MeV$. (For long range monitoring in the hundreds of km the long wavelength will have made many cycles at the lowest observed energies, while the short period will likely be washed out due to many cycles per unit of energy resolution). This provides a nice visualization of the oscillations. The multiple peaks in fact prove to be useful as being pursued in the Juno Project to discern the mass ordering. We will know this hierarchy by the time NE operates and will be able to use the full prior knowledge of the six mixing parameters in the electron antineutrino survival probability to recover the range L. In practice one may use a convolution with a correlation function including the oscillations to squeeze out maximal range resolution. IN this context, low energies are important (since lower energies contain more oscillation cycles) as is neutrino energy resolution (to resolve the peaks).

III. SUMMARY

Neutrinos are unique carriers of information about their flight distance, unlike any other fundamental particle (namely, unlike photons). Photon pulses do evolve due the effects of the medium, such as dispersion and Faraday rotation. Neutrinos however carry an observable 'yardstick', built into their oscillatory behavior. This is a property of the particle not the medium, and cannot be altered or suppressed. With a sufficient number of events (likely a few hundred) from a given source, one can uniquely determine the range over which the neutrinos have flown. (Distortions through the earth are negligible in this regard as long as the index of refraction of the neutrinos is small, as indeed it is. There is a more complicated story when one should consider MSW effects, but those are not important for any NP application).

Just as neutrinos from a source cannot be faked or hidden, neither can one obscure the source distance information carried by the neutrino spectrum. No other particle in Nature has this property. Moreover, having extracted the range by a spectral method that does not depend on the total flux, one can fix the distance and independently resolve the reactor source thermal power. While the statistical constraints are serious, the method may be applicable in sufficiently large detectors and dwell times. Experiments at AIT will give us an opportuntity to demonstrate and explore the utility of this novel method for reactor range-finding.

[1] Glenn R. Jocher, Daniel A. Bondy, Brian M. Dobbs, Stephen T. Dye, James A. Georges, John G. Learned, Christopher L. Mulliss, and Shawn Usman. Theoretical antineutrino detection, direction and ranging at long distances. *Phys. Rept.*, 527:131–204, 2013.