Evaluating deuterated-xylene for use as a fusion neutron spectrometer

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The spectrum of neutrons emitted by thermonuclear plasmas encodes information about the fuel ion distribution function. Measuring these fast neutron spectra with sufficient resolution allows for measurement of plasma properties like the ion temperature and strength and energy of fast ion populations. Liquid organic scintillators are a commonly used fast neutron detection technology because of their high detection efficiency and ability to discriminate between neutrons and gammas. However, performing detailed spectroscopy with these detectors is difficult because of the isotropic nature of neutron scattering on protons, the dominant mechanism of interaction. Deuterium-based scintillators have shown promise as a superior spectrometer technology because of the anisotropic nature of neutron scattering on deuterium, which significantly improves the condition number of the detector response matrix [C. C. Lawrence *et al*, NIM A, 729, 924 (2013)]. Deuterated-xylene, now available commercially, has advantages in light output and safety over benzene-based deuterated scintillators [F. D. Becchetti *et al*, NIM A, 820, 112 (2016)]. We present experimental spectrum unfoldings made by 2 inch right cylindrical protiated-xylene and deuterated-xylene detectors with response matrices generated with Geant4 and additional data from the literature. We compare their performance measuring the neutron spectrum produced by an AmBe source and deuterium-tritium (DT) neutron generators. We find that the deuterated scintillator outperforms the protiated one for AmBe and DT spectra, suggesting deuterated-xylene should be considered for future fusion neutron spectrometry applications.

I. INTRODUCTION

A. Applications of neutron spectrometry in fusion

Neutrons are one of the primary byproducts of both deuterium-deuterium (DD) and deuterium-tritium (DT) fusion reactions. Since they have no net charge, neutrons stream out of the strong magnetic field present in magnetic confinement fusion devices, making them straightforward to detect with instruments well outside of the machine itself. Thus, neutrons provide one of the few direct measures of fusion reactions occurring in a plasma. However, neutrons carry more information than just news of a fusion reaction. A portion of the initial fuel ion kinetic energy is coupled into the emitted neutron, resulting in a broadening of the 2.45 or 14.1 MeV neutron line emission from thermonuclear deuterium and deuterium-tritium reactions respectively. Thus, by measuring the magnitude and shape of this broadening, information about the fuel ion distribution function can be extracted. However, it is worth noting that while extracting the thermal component of the distribution function can be achieved from simply measuring the line broadening, extracting detailed nonmaxwellian features generally involves conducting simulations of an assumed distribution function whose parameters are modified until the simulation output matches measurement.

SPARC, a compact, high-field tokamak being built in Devens, MA by Commonwealth Fusion Systems[1] will be equipped with a spectrometric neutron camera capable of resolving the plasma neutron emission in time, space, and energy.[2] This system will require many (~ 10) compact neutron spectrometers capable of covering approximately four orders of magnitude in flux, and measurement of both DD and DT neutrons. Hence, deuterated-xylene is of interest as a detector technology for low power DT and DD operation.

B. Neutron spectrometry with liquid organic scintillators

Liquid organic scintillators are a popular choice for fast neutron detection because of their high efficiency and gamma/neutron discrimination capability. Neutrons interact with these detectors primarily via elastic scattering on hydrogen nuclei. These recoil nuclei then deposit their energy in the detector volume, a fraction of which is converted to photons that are measured with a photosensor like a photomultiplier tube (PMT). Detailed spectroscopy with liquid organics is significantly complicated as a result of scattering being the dominant interaction mechanism. Since scattering is isotropic in the center of mass frame for hydrogen nuclei and the energy transferred to a recoil nucleus is a strong function of scattering angle, even monoenergetic neutrons deposit a range of energies from zero to the entire energy of the incident neutron. This poor coupling between incident neutron energy and resulting pulse height (a measure of energy deposition) makes interpreting a measured pulse height spectrum (PHS) all but impossible by eye.

However it is possible to extract detailed spectroscopic information from liquid scintillators if information about how incident neutron energy couples to a resulting pulse height distribution is well known. The details of this mapping from neutron energy space to pulse height space can be captured by a simple matrix equation: $\mathbf{R}\phi = \mathbf{h}$ where ϕ is a vector of length n which specifies the neutron flux in n discrete energy bins, $\mathbf{h}$ is a vector of length m which specifies the number of counts in m discrete pulse height bins, and $\mathbf{R}$ is an $n \times m$ matrix which maps from neutron energy space to pulse height space which we call the response matrix. The pulse height vector $\mathbf{h}$ is our measured quantity, but the neutron flux spectrum ϕ is our desired quantity.

Unfortunately for most liquid scintillators, $\mathbf{R}$ is a poorly

conditioned matrix as a result of the isotropic nature of neutron scattering on protons. This means that the inverse problem we seek to solve is ill-posed, and simple inversion does not result in a robust solution. The process of solving this ill-posed inverse matrix equation is known as spectrum unfolding, and is one of the ways by which ion temperature can be measured with a liquid scintillator. Many codes have been developed to solve such ill-posed problems, including GRAVEL[3] and MAXED[4]. This technique has been used to measure the ion temperature of deuterium plasmas on the JET tokamak.[5]

However, deuterium-based liquid scintillators can provide superior unfolding performance as a result of the anisotropic nature of neutron scattering on deuterium, which results in a strong peak on the backscatter edge of the pulse height spectrum. This ridge greatly improves the condition of the response matrix, which reduces the ill-posed nature of the spectrum unfolding problem.

The spectrum unfolding performance of deuterated and protiated scintillators has been compared for the deuterated benzene based scintillator EJ315 and EJ309 by Lawrence *et al*.[6] This work indicated that deuterated scintillators did improve unfolding performance versus protiated scintillators. However benzene scintillators have drawbacks, as they are lower in light output and benzene poses a substantial chemical hazard. Deutereated-xylene, whose trade name is EJ301D, offers light output comparable to modern protiated liquid scintillators like EJ309 and is substantially less hazardous than benzene based scintillators, motivating its selection for evaluation as a fusion neutron spectrometer.

II. MEASURED PULSE HEIGHT SPECTRA

To evaluate the unfolding performance of deuterated-xylene relative to its protiated counterparts, a pair of identical right cylindrical detector units were acquired containing EJ301D and EJ301 from Eljen Technology, Inc. Each detector consists of a 2 inch diameter 2 inch tall cylindrical scintillator volume coupled to a Hamamatsu R7724 2 inch photomultiplier tube. For all measurements presented, a voltage of -1000 Volts was used for the deuterated-xylene detector and -900 Volts used for the protiated detector. The anodes of the tubes were connected directly to the digitizer input. Both units were energy calibrated using a Na-22 gamma source before each measurement using the technique described by Safari *et al.*[7] A series of measurements were made of two neutron sources: an Americium-Beryllium (AmBe) source and a DT neutron generator.

A CAEN DT5730 500 Ms/s 14-bit digitizer equipped with CAEN's Digital Pulse Processing for Charge Integration and Pulse Shape Discrimination (DPP-PSD) firmware was used to acquire data using the CoMPASS software. Pulse shape discrimination (PSD) was used to separate neutron and gamma counts for both detectors. Identical settings were used for both detectors, with the long gate set to 300 ns, the short gate to 50 ns, and the pre-gate to 24 ns. Pulse magnitude was evaluated as the integral over the long gate interval. Figs. 3 and 4 plot

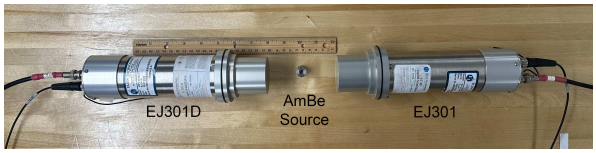

FIG. 1. Photo of EJ301 and EJ301D liquid scintillators simultaneously measuring neutron emission from a 10 mCi Americium-Beryllium neutron source.

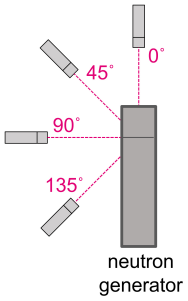

FIG. 2. Schematic diagram of the four angular positions at which measurements of the DT neutron generator were made with each detector.

the measured neutron pulse height spectra for the DT neutron generator and AmBe source respectively. Especially in fig. 3, the peaked nature of the deuterated-xylene response can be clearly seen. However, in both plots the lower light output of the deuterated scintillator is also apparent.

As a first test of unfolding performance, an AmBe source was measured because of its complex, fast neutron spectrum. Both detectors were placed equidistant and opposite each other around the source, and data was acquired simultaneously from both. Fig. 1 shows the experimental setup. Fig. 5 plots PSD histograms for the two detectors when irradiated by the AmBe source. We see that excellent separation of neutron and gamma counts is possible for both detectors, but deuterated-xylene achieves greater separation than the protiated scintillator. This superior pulse shape discrimination capability is another advantage of deuterated scintillators which results from the greater stopping power of recoil deuterons as compared to recoil protons of the same energy.

Four measurements were made of an MF Physics A325 DT neutron generator with the accelerating potential set at 90 kV, which has been previously characterized with a single-crystal diamond detector.[8] The detectors were placed at four different angles with respect to the target plane, with 0 degrees corresponding to the detector being aligned with the axis of the generator, and 90 degrees being in the target plane. Fig. 2 shows a diagram of the experimental setup.

III. SIMULATING RESPONSE MATRICES FOR SPECTRUM UNFOLDING

As discussed above, extracting neutron spectrum information from a measured liquid scintillator pulse height spec-

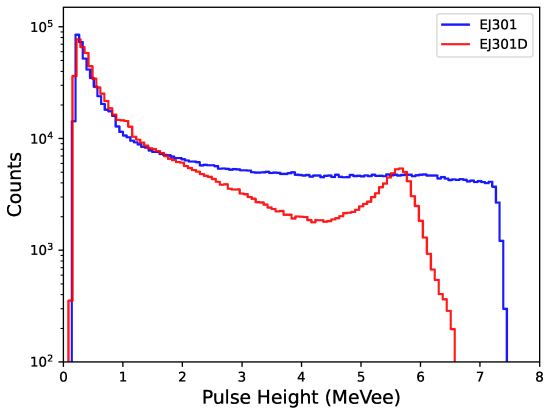

FIG. 3. Plot of pulse height spectra measured with identical 2 inch cylindrical liquid scintillator detectors irradiated by a DT neutron generator, one filled with standard protiated EJ301 and the other deuterated EJ301D. The anisotropy of neutron scattering on deuterons results in a strong peak at the backscatter edge of of the pulse height spectrum in the EJ301D detector, which can be advantageous for making spectral measurements.

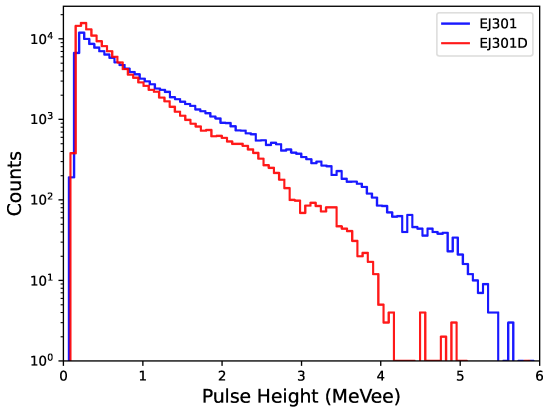

FIG. 4. Plot of pulse height spectra with identical 2 inch cylindrical liquid scintillator detectors irradiated by an Americium-Beryllium neutron source, one filled with standard protiated EJ301 and the other deuterated EJ301D. While it is clear that the EJ301D detector produces less total light than EJ301, the EJ301D pulse height spectrum is also more featured, suggesting extracting spectral information may be easier.

trum requires accurate knowledge of the response matrix. The most accurate way to acquire such a matrix is experimentally through the use of monoenergetic neutron beams, but this requires specialized, large accelerator facilities. In this study we choose to simulate the response matrix computationally.

There are several factors which impact the shape of the detector response matrix which must be accounted for in any computational model. This includes neutron scattering physics, non-linearity in scintillator light output, the intrinsic resolution of the coupled scintillator-PMT system, and the ability to separate gamma and neutron PHS. For the purposes of this calculation we assume that neutrons and gammas can be perfectly separated, and seek to model the other three effects.

To model the neutron scattering physics, a simple Geant4 model of the detector was made using grasshopper,[9] a Geant4 front end. The detector was modeled as a 2 inch right cylindrical volume of either standard protiated-xylene or deuterated-xylene. Neutrons were launched towards the circular face of the detector in a 5mm diameter beam, with a uniform energy distribution between 1 and 20 MeV. Energy deposition from recoil hydrogen nuclei was then tallied as a function of incident neutron energy.

In order to account for the nonlinearity in light output for recoil ions in liquid scintillators, we make use of known light output functions published previously in the literature. For the protium-based EJ301, we make use of the data published by Verbinski et al.[10], and for deuterium-based EJ301D, we make use of the function published by Becchetti et al.[11] When binning the response matrix in pulse height space, we make use of a light-output conformal binning structure as described by Lawrence.[12] This procedure involves generating bins in neutron energy space, and then using the light output function to transform them into a nonuniform bin structure in light-output space, which has been shown to improve the condition of the matrix.

Liquid scintillator systems possess a finite light output resolution as a result of the statistical nature of photon detection with PMTs and imperfections in the electronics processing chain. This finite resolution is normally modeled as a gaussian broadening, where the amount of broadening $\Delta L/L$ is a function of the light output L:

$$\frac{\Delta L}{L} = \sqrt{\alpha^2 + \beta^2/L + \gamma^2/L^2} \tag{1}$$

where α, β, and γ are fit from experiment, and $\Delta L/L$ is the normalized FWHM. For the purposes of this study, we adopt the values measured by Lawrence for a 3 in diameter 2 in tall cylindrical EJ309 detector. These values are 0.065 , 0.061, and 0.033 for α, β, and γ respectively and light output in units of MeVee.[12]

Fig. 6 plots the simulated response matrices for deuterated-xylene and protiated-xylene respectively. The backscatter ridge resulting from the anisotropy of neutron scattering on deuterium can clearly be seen in the EJ301D response matrix. We also note that the maximum pulse height observed for a given incident neutron energy is lower in the EJ301D matrix versus the EJ301 matrix. This is a result of the mass difference between neutrons and deuterons, which results in the neutron only being able to impart at most 8/9ths of its original energy to the recoil deuteron.

IV. EXPERIMENTAL RESULTS

All spectrum unfoldings presented below were performed with the TREVISO[13] code using the Maximum-Likelyhood Expectation Minimization (MLEM) algorithm.

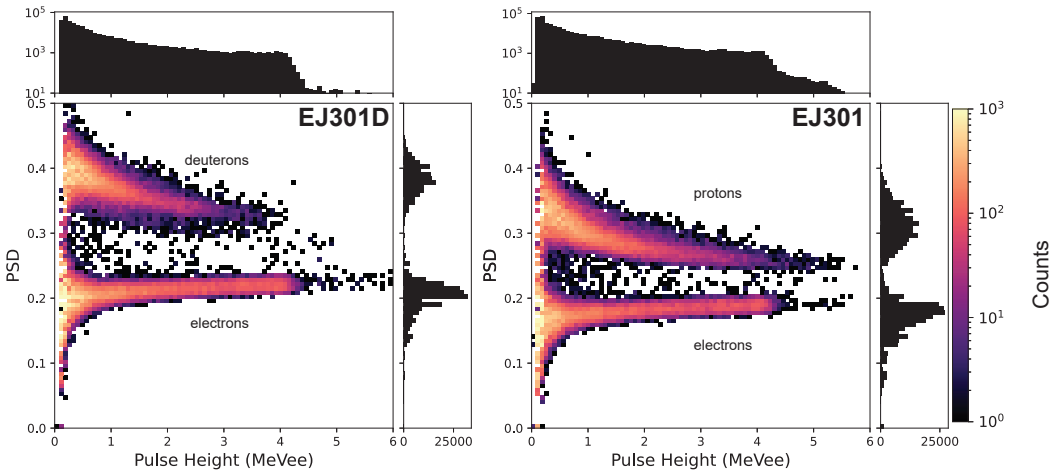

FIG. 5. Pulse shape discrimination histograms for deuterated-xylene (EJ301D) and protiated-xylene (EJ301) detectors irradiated by an AmBe source. Neutron counts are able to be well separated from gamma counts in both detectors, but the deuterated detector shows a greater separation thanks to the greater stopping power of deuterons as compared to protons. The histograms above and to the right of each 2D plot show the total, unseparated pulse height spectrum and 1D pulse shape discrimination plots respectively.

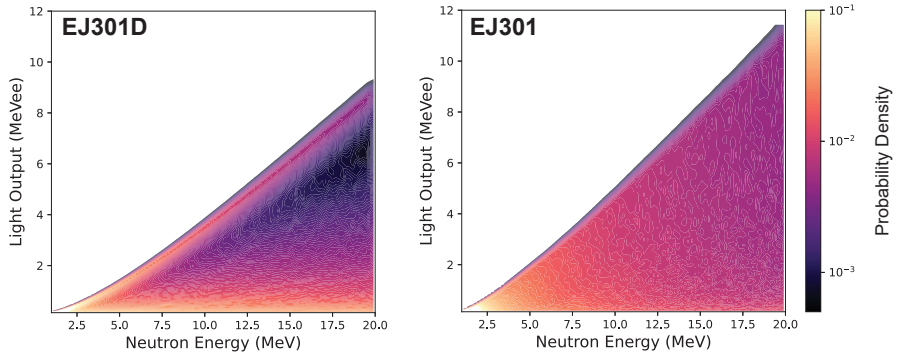

FIG. 6. Simulated response matrices for 2 inch right cylindircal deuterated-xylene (EJ301D) and protiated-xylene (EJ301) liquid scintillators. We clearly observe a ridge on the backscatter edge of the deuterated xylene response matrix, which is advantageous for spectrum unfolding.

A. AmBe Source

Fig. 7 plots unfolded spectra compared to the AmBe ISO reference spectrum for deuterated and protiated xylene, respectively. We observe that the deuterated detector is able to resolve finer features of the AmBe spectrum, including the small peak at 6.5 MeV and the dip between the 3 and 5 MeV peaks, which are not accurately reconstructed by the protiated scintillator. This is compelling evidence of the deuterated scintillator's superior unfolding performance. We also observe that the protiated detector overestimates the energy of certain peaks by 600 - 800 keV, specificall the 6.5 MeV peaks and above. We discuss this in greater detail in the following section.

B. DT neutron generator

Fig. 8 plots the unfolded spectra from the DT generator as a function of angle with respect to the generator axis for both deuterated-xylene and protiated-xylene. Results from a previous characterization with sCVD diamonds are plotted in gray. We find that both detectors are able to reconstruct the relative anisotropy of the generator emission, but the protiated detector misses the absolute peak by approximately 800 keV. This offset is similar to the one observed in the protiated-xylene measurements of the AmBe source, suggesting the offset is a result of the detector and analysis technique themselves and not the sources used.

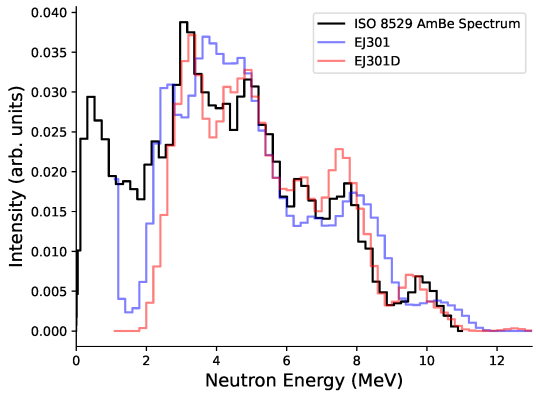

FIG. 7. Unfolded neutron spectra from deuterated-xylene (EJ301D) and protiated-xylene (EJ301) detectors irradiated by an AmBe source compared to the ISO reference spectrum. EJ301D is able to resolve all of the major features of the spectrum, unlike the protium-based EJ301.

V. CONCLUSION

Two liquid scintillators, identical except for the isotope of hydrogen used in the organic solvent, were used to measure a series of neutron spectra to determine if deuterium-based detectors provide superior spectroscopic performance for fusion neutron measurements. Geant4 was used in combination with existing information in the literature about light output functions and intrinsic resolution to build simple models of the detectors' response matrices. The MLEM algorithm was then used to unfold measured pulse height spectra. Measurements were made with an AmBe source and a DT generator at four different angles. We showed that deuterated-xylene has superior PSD performance as compared to protiated-xylene, but neutrons and gammas were well separated in both detectors for the measurements made here. We found that the deuterated scintillator outperformed the protiated one for both AmBe and DT spectra. This suggests that deuterated-xylene should be strongly considered for future fusion neutron spectroscopy applications.

ACKNOWLEDGMENTS

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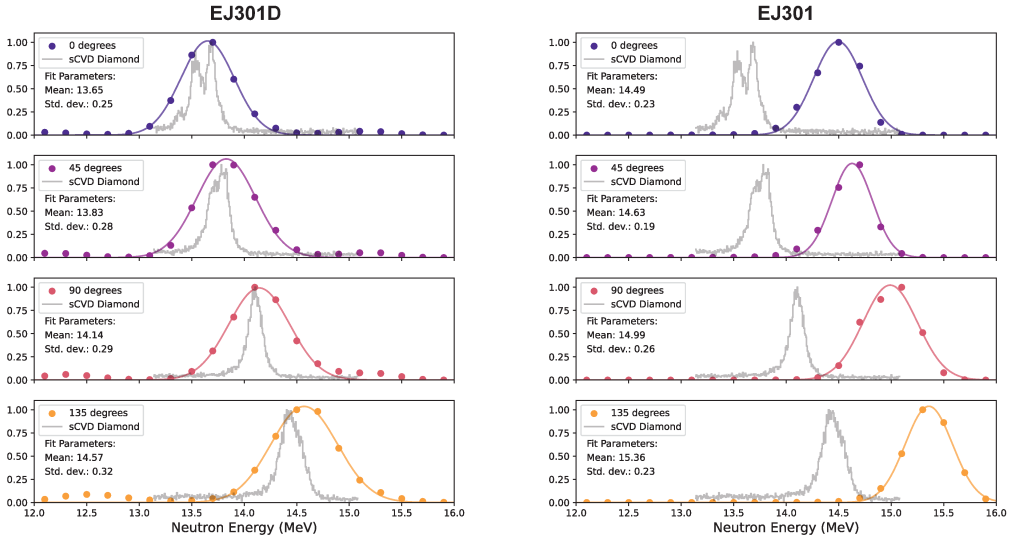

FIG. 8. Unfolded neutron energy spectra at four different angular positions with respect to the axis of a cylindrical DT neutron generator measured with deuterated-xylene and protiated-xylene detectors. We find that the deuterated detector is able to better reconstruct the variation in neutron energy with angle than the protiated one.