Thermal Cross Section Measurements At The RPI LINAC

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Abstract. Recently, a cold moderator was designed and developed for use at the Rensselaer Polytechnic Institute Linear Accelerator (RPI LINAC). This cold moderator proved to easily and safely couple to an existing neutron producing target, while enhancing neutron flux below 0.02 eV by up to a factor of 8 by cooling polyethylene down to 29 K. This cold moderator capability allowed for significantly improved counting statistics below 0.02 eV not previously possible due to a poor signal to background ratio. Additionally, testing was performed to characterize the energy resolution of the new cold moderator system and found the system easily capable of resolving resonances in Ta-181 at 4 and 10 eV, while also clearly resolving the Bragg edges found in Be metal below 0.01 eV. Following the design and development of a cold polyethylene moderator, a series of thermal total cross section measurements were performed for polyethylene, polystyrene, Plexiglas and yttrium hydride in the thermal region. These measurements serve to help validate thermal scattering law (TSL) evaluations in the 0.0005 – 1 eV energy range. For polyethylene and polystyrene, two sets of experiments were performed – one with the Enhanced Thermal Target (ETT) and another with the ETT plus the new cold moderator capability (ETTC). The yttrium hydride and Plexiglas measurements were only performed with the ETTC. The measurements for polyethylene help to validate the data processing methodology when using the ETTC, while extending the measured range of polyethylene down to 0.0005 eV. Two different Plexiglas, Plexiglas G and Plexiglas G-UVT, and two different concentrations of yttrium hydride, H/Y = 1.85 and 1.68, were measured. Overall, all materials had generally good agreement with their ENDF/B-VIII.0 TSL evaluations, though some discrepancies were noticed. In the case of the yttrium hydride, the high energy oscillations in the hydrogen cross section and the low energy Bragg edges in the yttrium cross section were clearly seen. These measurements represent the first total cross section measurements that encompass the entire thermal region from 0.0005 – 1 eV for polystyrene and yttrium hydride.

1 Introduction

Hydrogen dense materials are frequently used as neutron moderators and reflectors due to the high scattering cross section of hydrogen and its ability to down-scatter neutrons from fast to thermal energies in a few collisions. For this reason, hydrogen dense hydrocarbons such as polyethylene, polystyrene and Plexiglas (also referred to as plexiglass and Lucite) have been utilized as a moderator and/or reflector material in hundreds of critical benchmark configurations [1]. In addition, due to its high hydrogen concentration and excellent performance at high temperature, the U.S. Department of Energy (DOE) has begun investigating yttrium hydride as a neutron moderator for use in compact, high temperature reactor systems [2].

However, in order to accurately model and simulate hydrogen dense neutron moderators, the scattering interactions between neutrons and the molecules of the hydrogen dense moderator materials must be well understood. The impact of molecular bonds on the neutron scattering in a system is typically referred to as the 'molecular bond effect' and must be accounted for below a neutron energy of 1 eV. Typically, transport codes such as MCNP [3] account for the molecular bond effect of materials through the use of thermal scattering law (TSL) evaluations.

The molecular motions of a material are typically represented by a measured or calculated phonon spectrum, which serves as the basis of a TSL evaluation. The thermal scattering law $S(\alpha,\beta)$ is applied to these phonon spectra in codes such as NJOY [4] in order to calculate double-differential scattering cross section for use in transport codes. As with any calculated value, the double-differential scattering cross section generated from these TSL evaluations requires extensive experimental validation, especially due to the significant impact thermal scattering can have on system criticality. Total cross section measurements that span the entire thermal energy region

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serve as the most essential validation of TSL evaluations. This paper details the high accuracy total cross section measurements performed for polyethylene, polystyrene, Plexiglas and yttrium hydride from 0.0005 - 1 eV. Comparisons are made to various TSL evaluations and existing experimental data for each material, as applicable.

2 Neutron Production Targets

In order to produce the neutron flux required for the total cross section measurements in the thermal energy region, two different targets were utilized: the Enhanced Thermal Target (ETT) [5] and the Enhanced Thermal Target with a cold moderator coupled to it (ETTC) [6]. In order to produce neutrons, an approximately 55 MeV electron beam is directed towards a water-cooled Ta target inside of the ETT. As the electrons interact with the Ta they undergo bremsstrahlung radiation, producing high energy photons in the process. These high energy photons proceed to interact with the Ta further, producing neutrons through (γ,n) reactions.

The ETT is used to produce a thermal neutron flux, and is suitable for total cross section measurements from 0.002 - 20 eV. The ETTC is used to measure total cross section at energies from 0.0005 - 3 eV. Figure 1 shows the net signal (background subtraction applied) for the ETT and ETTC after a LINAC power normalization was applied. Below 0.02 eV, the ETTC produces a net neutron gain up to a factor of 8 over the ETT. Additionally, the ETTC produces a higher signal-to-background ratio than the ETT below 0.02 eV. Both of these targets were used to perform total cross section measurements for moderator materials in the thermal energy region.

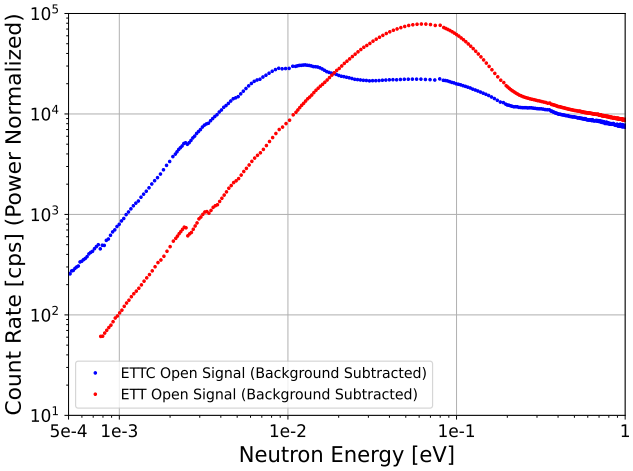

Figure 1: Net count rate for the ETT and ETTC after background subtraction. Bragg edges from in-beam Pb produce the structure at low energies.

3 Total Cross Section Measurements

Four neutron transmission measurements were performed for polyethylene and polystyrene each: two with the ETT and two with the ETTC. Additional measurements with the ETTC were performed for Plexiglas G and Plexiglas G-UVT - trademarked forms of poly(methyl methacrylate) or PMMA. Lastly, the ETTC was used to conduct four measurements of yttrium hydride: two for $YH_{1.85}$ and two for $YH_{1.68}$. The total cross section was then calculated using the measured transmission and the number density of the sample material. Covariance matrices were created for all measurements in order to accurately account for all quantifiable sources of experimental uncertainty. All RPI experimental data points shown for all measurements have a typical uncertainty between 1 - 2% and a maximum uncertainty of 5%. All samples were at 293 K and had an elemental impurity analysis performed, where no thermal neutron absorbers were present in significant quantities.

3.1 Polymers

The results of the four RPI polyethylene (PE) measurements are compared against experimental data from Granada [7] and Lee [8], as well as to the ENDF/B-VIII.0 [9] and ORNL/ESS/RPI [10] TSL evaluations for polyethylene in figure 2. Generally good agreement is observed at all energies for all experimental data and with the ENDF/B-VIII.0 and ORNL/ESS/RPI TSL evaluation. The measurements with the ETT for polyethylene served to validate the ETTC system for use in measuring total cross section at thermal energies. In addition, the measured cross section for polyethylene was extended down to 0.0005 eV. Some minor disagreements between the Lee and Granada experiments were present between 0.05 - 0.15 eV, with the RPI measurements falling between the two. In addition, the ENDF/B-VIII.0 evaluation is higher than the RPI experimental data by a few percent from 0.002 - 0.1 eV. The ORNL/ESS/RPI is higher than the RPI experimental data by a few percent from 0.002 - 0.02 eV.

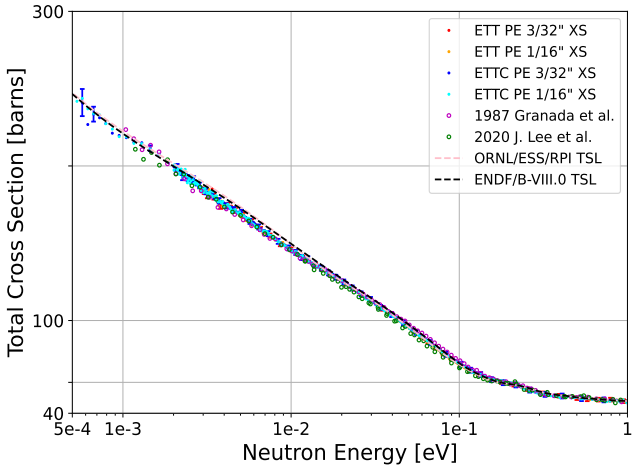

Figure 2: Total cross section for polyethylene from 0.0005 - 1 eV. Generally good agreement is seen for all energies between experimental data and evaluations.

The four polystyrene (PS) measurements are compared against a preliminary ORNL/RPI TSL evaluation for

polystyrene in figure 3 where generally good agreement is seen over all energies. The preliminary ORNL/RPI TSL evaluation is within 2% of the experimental data at the vast majority of energy points. These four measurements represent the first total cross section measurements that encompass the entire thermal energy region for polystyrene.

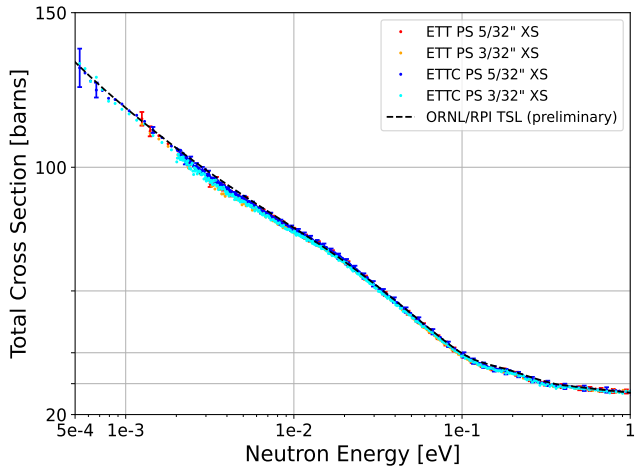

Figure 3: Total cross section for polystyrene from 0.0005 - 1 eV. Generally good agreement is seen for all energies between experimental data and evaluation.

Two different forms of Plexiglas were measured: Plexiglas G and Plexiglas G-UVT. Plexiglas G represents a common, general use form of Plexiglas, while Plexiglas G-UVT represents a more pure form of Plexiglas. Both of these materials were measured over the entire thermal energy region and compared with experimental data from Sibona [11] and Drozdowicz [12], as well as the ENDF/B-VIII.0 and ORNL/RPI [13] TSL evaluations for PMMA, shown in figure 4.

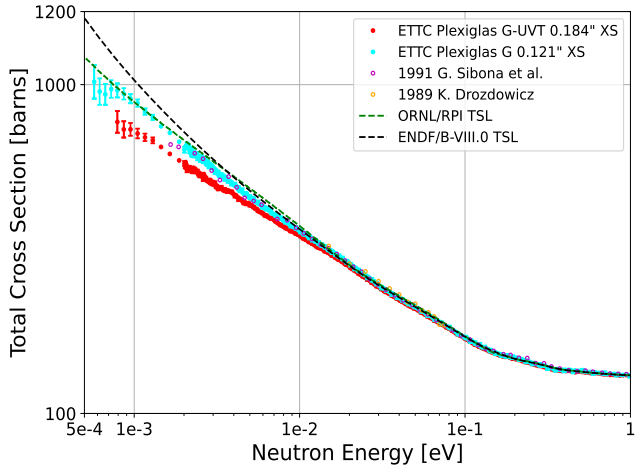

Figure 4: Total cross section for Plexiglas G and Plexiglas G-UVT from 0.0005 - 1 eV. Generally good agreement is seen for energies above 0.02 eV between experimental data and evaluation.

Above 0.02 eV, good agreement is seen between the RPI measurements, the existing experimental data and both of the TSL evaluations. However, below 0.02 eV a divergence in cross section occurs between the Plexiglas G and Plexiglas G-UVT samples. This divergence is likely due to the presence of octadeconoic acid additive in the Plexiglas G sample that is not present in Plexiglas G-UVT. The experimental data from Sibona and Drozdowicz agrees with the Plexiglas G sample. In addition, a divergence is also seen between the ENDF/B-VIII.0 TSL evaluation for Plexiglas and the RPI experimental data below 0.02 eV. The ORNL/RPI TSL evaluation for Plexiglas agrees with the Plexiglas G measurement within a few percent over all energies.

3.2 Yttrium Hydride

Two different compositions of yttrium hydride were measured: $YH_{1.68}$ and $YH_{1.85}$. The RPI measurements were compared with existing experimental data from Brand [14] and Vorderwisch & Wasserroth [15], as well as against two sets of TSL evaluations, shown in figure 5. The first set represents H-in-YH_x and Y-in-YH_x TSL evaluations from ORNL [16] processed with NJOY. The second set represents ENDF/B-VIII.0 H-in-YH_x combined with the Y-in-YH_x TSL evaluation from Zerkle & Holmes (Z&H) [17] processed with the NDEX code suite [18]. In general, good agreement is seen over all energies between the RPI experimental data, existing experimental data and both sets of TSL evaluations.

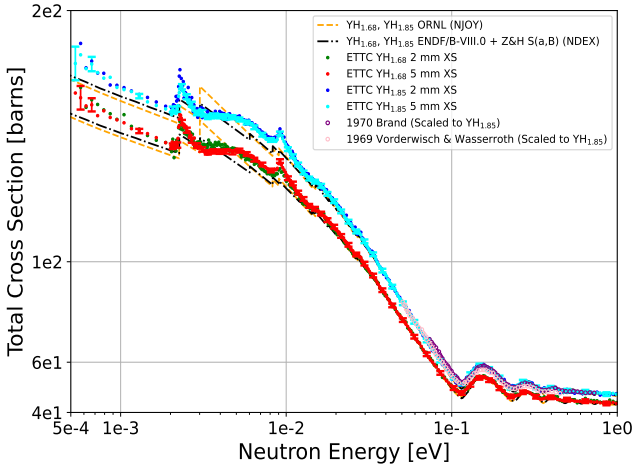

Figure 5: Total cross section for $YH_{1.68}$ and $YH_{1.85}$ from 0.0005 - 1 eV. Generally good agreement is seen for all energies between experimental data and evaluation.

However, below 0.01 eV some differences are seen between the RPI measurements and both sets of TSL evaluations in the Bragg edges that stem from Y-in-YH_x. There are discrepancies both in the energy location and cross section amplitude of the Bragg edges. In addition, some discrepancies are present in the cross section oscillations that stem from the H-in-YH_x scattering cross section, shown

in figure 6. Good agreement is seen between the RPI experimental data and both evaluations for the first oscillation around 0.15 eV, but both sets of evaluations become increasingly out of sync with the experimental data as the energy increases. While anharmonic behavior is present in yttrium hydride at room temperature, its impact on neutron scattering is not fully understood. In addition, impurities present in the yttrium hydride samples could be disrupting the phonon spectrum and producing the discrepancy seen here. It should be noted that the differences seen between the two evaluations themselves are partially due to the energy mesh grid inside of NJOY being too coarse.

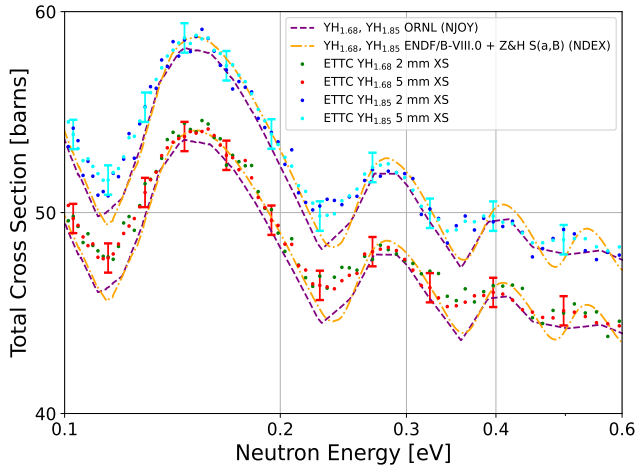

Figure 6: Total cross section for $YH_{1.68}$ and $YH_{1.85}$ from 0.1 - 0.6 eV. A coarse energy grid in NJOY is partially responsible for differences between TSL evaluations.

4 Conclusions

Using the ETT and ETTC targets, 14 separate neutron transmission measurements were conducted for polyethylene, polystyrene, Plexiglas and yttrium hydride over the entire thermal energy region. The ETT measurements served to validate the performance of the ETTC for cross section measurements in the thermal region. Generally good agreement was found between the RPI measurements and existing TSL evaluations over most energies. However, some discrepancies were present and discussed. It is recommended to perform additional measurements for yttrium hydride where the sample has a higher purity and is more thoroughly characterized.

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