MEASUREMENT OF TOTAL CROSS SECTION OF WATER AND O-16 IN THE MEV ENERGY RANGE

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ABSTRACT

The normalization of previous measurements of the total cross section of O-16 has been the subject of recent discussions within the Collaborative International Evaluated Library Organization (CIELO) project. In order to contribute to the resolution of this issue a new experiment was performed to measure the transmission of H_2O and then subtract the cross section of H to obtain the cross section of O-16. This method has several advantages: samples of low-impurity water are available, optical cells with low uncertainty path lengths are easy to obtain, the density of water is well known, and the total cross section of H is well known. In addition, a transmission measurement near 2.35 MeV where the cross section of O-16 has a minimum is mostly sensitive to the H cross section. This minimum helps to validate the normalization of the transmission measurement to the total cross section of H with uncertainty better than 1%. The measurement was done at the Gaerttner LINAC Center at Rensselaer Polytechnic Institute using transmission geometry with a flight path distance of 250 m and two H_2O samples. The total cross section of O-16 was obtained in the energy range of 0.5 MeV to 20 MeV, Between 3.2 MeV to 6 MeV the ENDF/B-VII.1 evaluation is 1.2±0.7% lower than new measurement, and the Cierjacks 1980 measurement is lower by lower by 3.2±0.7%

KEYWORDS
Oxygen, Water, Cross Section,

1. INTRODUCTION

Oxygen is an important material in many nuclear applications as it serves as a moderator and coolant in many systems. For that reason both oxygen and hydrogen are part of the CIELO (Collaborative International Evaluated Library Organization) project [1]. In the fast energy region above 0.5 MeV several total cross section measurements were used for evaluation of O-16; they are listed by Sayer in reference [2]. The highest energy resolution experiment is the one by Cierjacks et al. 1980 [3], which indicates that the reported measured cross section should be normalized to their previous 1968 experiment [4]. During the CIELO evaluation process there was some confusion over whether this normalization was applied to the EXFOR [6] data. Some indication that the EXFOR data were not normalized can be found in reference [3] where a normalization of 0.9663 was found for the Cierjacks 1980 total cross section between 3.45-3.72 MeV and was compared to the data of Johnson [6], which had a normalization of 1.

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In order to resolve these differences we designed a transmission experiment of water and used the ENDF/B-VII.1 [7] hydrogen total cross section to obtain the oxygen cross section. In addition, we used the minimum in the O-16 cross section near 2.35 MeV to assess the accuracy of the normalization of our experiment relative to the H cross section.

2. EXPERIMENTAL SETUP

The experiment was done at the Gaerttner LINAC Center at the Rensselaer Polytechnic Institute using the 250 m flight station and two liquid scintillator detectors. The experimental setup and the analysis method used are very similar to that described in reference [8]. The electron LINAC operated with a pulse width of about 7 ns, repetition frequency of 400 Hz, average current of about 10 μA, and electron energy of 52 MeV. For this experiment the bare bounce target and collimation system described in reference [8] was used. The detector configuration was similar to reference [8] with two detector modules used. To reduce the effect of the gamma flash a 5.08 cm filter of depleted U was placed in the beam. And to reduce the neutron overlap between LINAC pulses a B_4C filter with 0.05 atom/barn of B-10 was also place in the beam. Fission detectors were used as neutron beam intensity monitors and were located in the far-east beamline at a distance of about 8 m from the neutron production target. The monitors tracked the intensity fluctuation in the neutron beam and were used in the data analysis to normalize the open and sample data.

2.1. Samples

Samples of research grade water were used in quartz optical cells [9]. The cells were selected to have inner (liquid) thickness of 2.00±0.01 cm and 5.00±0.01 cm and had a quartz wall thickness of 1.25 mm. The diameter of the quartz cells was 5.0 cm (2.0”) and the beam collimation at the sample position was 3.5 cm (1.375”). An identical empty cell was also measured and was used in the water transmission calculation. Throughout the measurement a 13 cm thick graphite cylinder and an open position (no cell) were also measured. The transmission of this graphite sample was measured during several other measurements (see for example [8]) and agrees well with the ENDF/B-VII.1 evaluation. The graphite was used to validate the quality of the measurement and data analysis. The sample cell design was such that an air bubble could not form in the measured active area. Also, it was monitored by a camera to ensure that a bubble was not visible. The air temperature near the samples was monitored and was found to be 21±1°C during the whole experiment. Research grade pure water was used, and dissolved gasses were removed from the water by drawing a vacuum on each sample cell until boiling was observed.

2.2. Data acquisition

The data acquisition system was described in reference [8]. Time of flight (TOF) spectra were recorded for 14.8 hours for each of the H_2O samples, 8 hours for the empty quartz cell, 7.1 hours for open and 7.7 hours for the graphite sample. The data were saved in multiple files each representing ~17 minutes of acquisition time. Having multiple files for each sample enabled a statistical analysis for the quality of the runs and monitor normalization.

3. DATA ANALYSIS

As a first step a code that performs multiple statistical tests was used to check the integrity of the data. This code computed the variation of the sample-to-monitor ratios to find anomalies in the data. The data were then dead time corrected and summed. The transmission, T_i, of each water sample, for each TOF channel i, was calculated from:

$$T_i = \frac{R_i^{Sample} - f_b^{Sample} B^{Sample}(t_i) - B_0^{Sample}}{R_i^{Open} - f_b^{Open} B^{Open}(t_i) - B_0^{Open}} \tag{1}$$

The time dependent background rates for the sample $B^{Sample}(t_i)$ and empty cell (and open) $B^{Open}(t_i)$ were determined by a MCNP simulation as described in reference [8]. This background was primarily from neutrons that slowed down and were captured in the H within the liquid scintillator resulting in 2.2 MeV gammas. R_i^{Sample} and R_i^{Open} are sample and open (or empty cell) monitor normalized counting rates at TOF channel i; f^{Sample} and f^{Open} are the sample and open time dependent background normalization factors. And B_0^{Sample} and B_0^{Open} are the sample and open time independent background rates (room background). The background rate was normalized to the sample and open rates at TOF greater than the TOF corresponding to 0.4 MeV neutrons. For these TOF channels the contribution from capture gammas is evident and the counting rates decrease with TOF as predicted from an MCNP simulation of the time dependent capture rate in the detector volume [8].

Once the transmission of the sample, T_i, was found it was converted to cross section of water, $\sigma_t^{H_2O}$ by:

$$\sigma_t^{H_2O}(E_i) = -\frac{1}{N}\ln(T_i), \tag{2}$$

where N is the number density of the sample. From equation (2) the O-16 cross section can be obtained by:

$$\sigma_t^{O}(E_i) = \sigma_t^{H_2O}(E_i) - 2\sigma_t^{H}(E_i), \tag{3}$$

where $\sigma_t^{H}(E)$; the total cross section of H was taken from the ENDF/B-VII.1 evaluation.

4. RESULTS

The transmission of the two water samples is shown in Figure 1 together with the ENDF/B-VII.1 calculated transmission and the transmission of H showing the agreement in the O-16 cross section minimum at 2.34 MeV. The overall agreement between the experiment and evaluation is good through entire energy range.

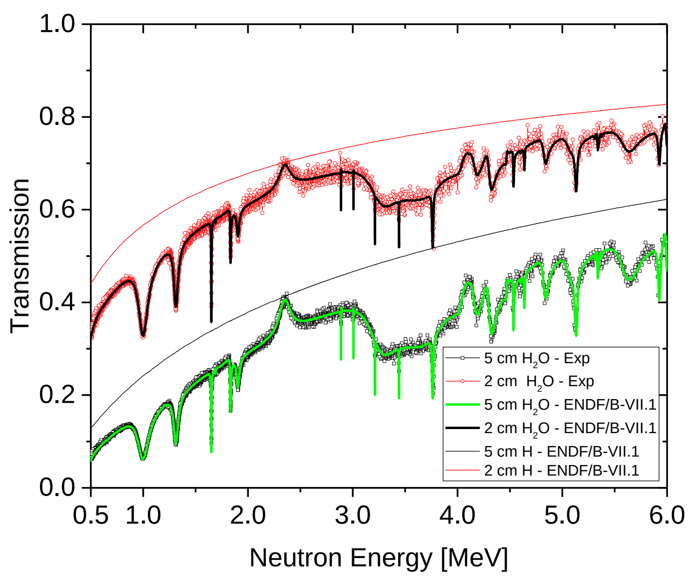

Figure 1 – Neutron transmission through 5 cm and 2 cm water samples

The measured data were converted to cross section and compared with other evaluations, ENDF/B-VII.1 and two other CIELO candidate evaluations by Leal [10] and Hale [11], as shown in figure 2. The '2' in the plot legend denotes the 2^{nd} iteration, which was the latest CIELO evaluation available at the time of this writing. Overall, the agreement between the experiment and evaluations is good, and it is hard to visibly resolve differences on the order of 3%, which was the goal of this measurement. Looking at small energy ranges around resonances some shifts in resonance energies were visible; however, it is not a systematic shift because only some resonances seem shifted.

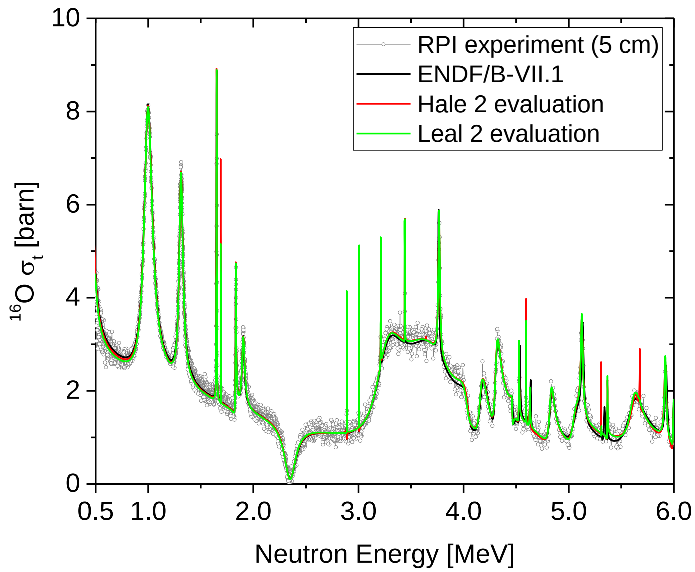

Figure 2 – Measured O-16 cross section with the ENDF/B-VII.1 evaluation and two CIELO candidate evaluations by Leal and Hale.

In order to quantify the differences between the RPI experiment and other data sets and evaluations the experimental data and evaluations were first grouped and then the ratio of other sets to RPI experiment (C/E_{RPI}) were calculated for each energy group. Grouping was done by integrating the cross section data with respect to energy. It might be argued that due to resolution effects it is better to integrate the transmission and compare it to transmission calculated from the evaluations; grouping was also computed in this way and was found to have negligible difference in the calculated C/E_{RPI}. Figure 3 shows the grouped cross section and figure 4 is the C/E_{RPI} ratios calculated for the ENDF/B-VII.1 evaluation and two CIELO candidate evaluations by Leal and Hale.

The C/E_{RPI} ratios illustrate that it is possible to determine deviations between the evaluations and RPI experimental data larger than the uncertainties in the current experiment. Larger deviations are shown near strong resonances due to energy shifts. Below 0.7 MeV the evaluations are higher than the RPI experiment. The measurement of the carbon sample was in good agreement with the evaluation between 0.5 to 0.7 MeV, which suggests that additional experimental data below 0.7 MeV is needed to verify this observation.

Finally, the cross section was integrated between 3.2 – 6 MeV, and C/E_{RPI} was calculated for different evaluations and experimental data sets, as shown in Table I. The C/E_{RPI} found for the H normalization using ENDF/B-VII.1 was 1.003±0.007, which provides an estimate of the normalization uncertainty in addition to the statistical uncertainty (±0.002). This value was calculated by integration of the measured total cross section of water and ENDF/B-VII.1 cross section of H in an interval of 1.5 keV around the resonance-potential interference minimum at 2.351 MeV. The measurement was corrected for the small

O-16 cross section at the minimum (0.11 b) using its ENDF/B-VII.1 value, which resulted in a correction of 2% to the measured H_2O cross section integral at the minimum.

This comparison indicated that the EXFOR data for the Cierjacks 1980 experiment was not normalized to his 1968 experiment and that the 1968 experiment agrees with the normalization found in the current measurements.

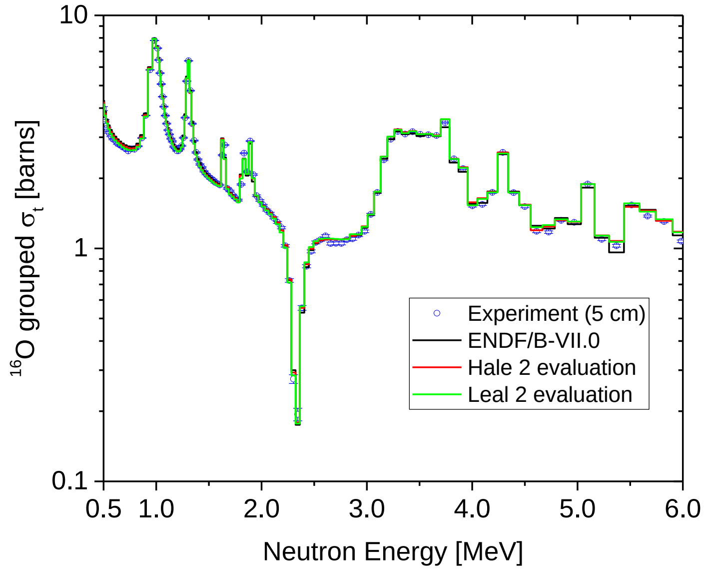

Figure 3 – Grouped measured total cross section of O-16 and ENDF/B-VII.1 evaluation and two CIELO candidate evaluations by Leal and Hale

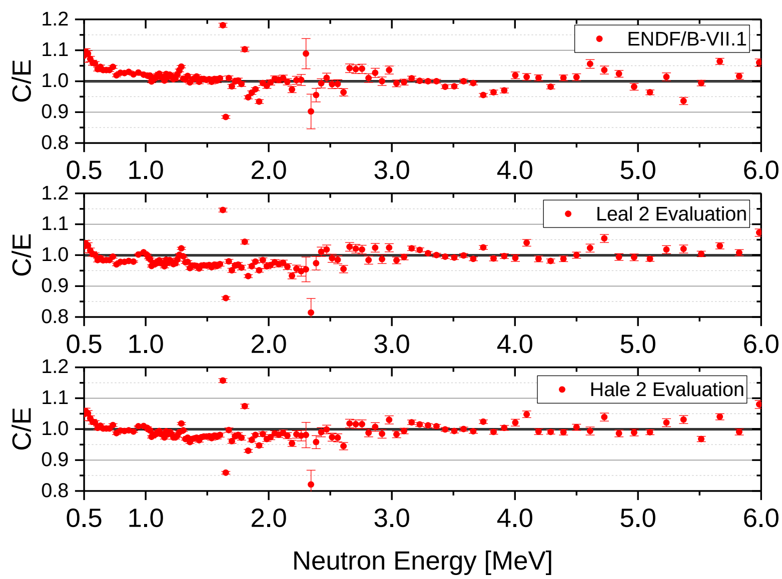

Figure 4 – C/E ratios between the experimental data and evaluation

Table I – C/E_{RPI} calculated between 2.3 – 6 MeV for several evaluations and experiments. The statistical uncertainty on the ratios is 0.002.

Data Set	C/E_{RPI}
ENDF/B-VII.1 [7]	0.988
Leal 2 [10]	1.004

Hale 2 [11]	1.005
Cierjacks 80 [3]	0.968
Cierjacks 68 [4]	1.009
Johnson [6]	0.996

5. CONCLUSIONS

The total cross section of O-16 between 0.5 – 20 MeV was calculated from the measured transmission though 2 cm and 5 cm thick samples of water. The normalization of the experiment was verified at 2.35 MeV where O-16 has a minimum in the cross section. In this minimum the ENDF/B-VII.1 total cross sections are 0.11 b, and 5.3 b for O-16 and two H atoms respectively. At the 2.35 MeV minimum the ratio of the ENDF/B-VII.1 H evaluation to the measured cross section was found to be 1.003±0.007. Grouping the data allowed comparison with evaluations and other data sets as a function of neutron energy and was used to indicate energy regions where the evaluations could be improved. Integration of the cross section in the energy range from 3.2 to 6 MeV was used to test the normalization of the evaluations and the total cross section of the Cierjacks 1980 experiment as found in EXFOR. It was determined that the Cierjacks 1980 data need to be normalized by dividing it by 0.968. It was also found that the ENDF/B-VII.1 evaluation is about 1.2±0.5% lower than the current data and that the candidate CIELO evaluations are in agreement with the new data.

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