Neutron Elastic Scattering Differential Cross Sections on ^{13}C

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Abstract. Neutron elastic scattering cross sections on natural carbon serve as a reference standard in the incident energy range 10 eV to 1.8 MeV. The 2017 standards evaluation [1, 2] is 0.5 to 2.0% higher in that energy range than the 2006 standards evaluation [3]. In addition the ENDF/B-VIII.0 release split the natural carbon cross sections into the isotopes ^{12}C, ^{13}C, and ^{14}C for the first time. These details call for the re-measurement of the ^{13}C cross sections in sensitive regions. Ten elastic scattering angular distributions were recently measured for incident neutron energies between 0.5 and 3.25 MeV at the University of Kentucky Accelerator Laboratory (www.pa.uky.edu/accelerator/) using nanosecond pulsed beams and time-of-flight techniques. An overview of neutron production and detection, the new digital data acquisition system, and data analysis will be presented. Results are compared with data from previous measurements and database evaluations.

1 Introduction

The elastic scattering, angle-integrated neutron cross sections on natural carbon are considered a reference *standard* in the energy rage of 10 eV to 1.8 MeV with uncertainties in the range of 0.68% to 0.71%. The ENDF/B-VII.1 library [4] contains only cross sections for natural carbon, while in the ENDF/B-VIII.0 library [5], the carbon cross sections are provided as isotopic cross sections for the individual isotopes, ^{12}C and ^{13}C. This change resulted in the 2009 ^{nat}C reference standard differing from the 2017 reference standard by an amount greater than the uncertainties of the cross sections. (See Ref [1], Fig. 56.) This deviation occurred because of changes in the ^{13}C evaluated cross sections. Neutron elastic scattering angular distribution measurements in the region $E_n > 1$ MeV only exist from the 1970 - 1980s Ohio University work of Lane [6] *et al.* (1.25 to 6.5 MeV) and Resler [7] *et al.* (4.5 to 11 MeV) and the 1960s Los Alamos total cross-section work of Auchampaugh *et al.* [8]. To provide additional information, we performed measurements in the $E_n = 0.50$ to 3.25 MeV region.

Although the natural abundance of ^{13}C is only 1.06%, variations in the ^{13}C cross sections can have significant impact on the ^{nat}C standard at a level that exceeds the quoted uncertainties, as illustrated in Fig. 1, which shows that variations in the ^{13}C cross sections are greater than the uncertainties in the ^{12}C values.

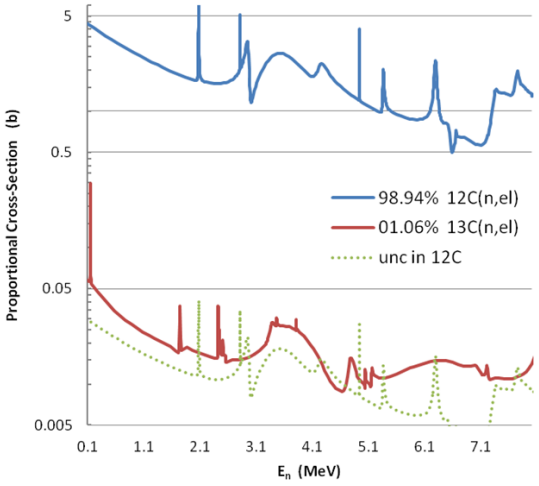

Figure 1. ENDF/B-VIII.0 angle-integrated neutron scattering elastic cross sections [5] for ^{12}C (blue, upper) and ^{13}C (red, lower). Cross sections are shown scaled by each isotope's natural abundance. A third dotted line indicates the uncertainty in the ^{nat}C cross sections. Variations in the ^{13}C cross sections are greater than these uncertainties, which implies better knowledge or confirmation of the ^{13}C cross sections is desirable.

2 Measurement Techniques

Neutron scattering differential cross-section measurements have been performed at the University of Kentucky

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Table 1. Measurement Information

^{13}C Enrichment	98(1)%
Mass	40.75(2) g
Sample Dimensions	3.60(5) cm dia
	3.20(5) cm ht
Polyethylene Mass	6.4417(2) g
Sample Dimensions	1.940(5) cm dia
	2.410(5) cm ht
^{nat}C Mass	10.9852(2) g
Sample Dimensions	2.010(5) cm dia
	2.010(5) cm ht
Source Center-Sample Center	10.6(1) cm
Sample Center-Detector Face	298.0(5) cm

Accelerator Laboratory (UKAL) for 60 years. During the last fifteen years, these measurements have focused on satisfying nuclear data needs for improved descriptions of the neutron reaction mechanism in the E_n = 1 - 8 MeV region desired for nuclear database applications.

Measurements of angle-integrated cross sections at the UKAL with uncertainties less than the 7% achieved previously is unlikely. We do, however, have the unique ability to make differential cross-section measurements. The angular dependence of the scattering cross sections is used to set model parameters for potential scattering (Optical Model + corrections) and resonance scattering (CN state properties, channel mixing, resonance interference, and subthreshold tailing) amplitudes that determine model integrated cross sections.

The UKAL standard measurement techniques and procedures are well described in Refs. [9–11], and [12] concerning ^{23}Na, ^{54}Fe, ^{56}Fe, and ^{nat}Si. Recently, a digital data acquisition system based upon CAEN VT1782 and VT1730SD modules was implemented that provides new opportunities for experimental investigations [13]. The CAEN system allows us to record neutron events at lower energies than could be done previously with analog electronics (See Fig. 2), thus expanding the dynamic range for accepted neutron events from the EJ301 scintillation detector. This saves valuable experimental beamtime.

The ^{13}C scattering sample and matching empty aluminum container are the same ones used in the Edwards Laboratory, Ohio University measurements [6, 7]. Neutron scattering from hydrogen in a polyethylene sample was compared to the H(n,n)H standard cross sections [5] for absolute normalization. Below $E_n \sim 0.6$ MeV, neutrons scattered from hydrogen are too low in energy to properly register in the EJ301 neutron detector and cross sections were normalized to ^{nat}C. Sample masses and geometries are provided in Table 1.

3 Results

Rather than displaying the differential cross sections as a function of angle, more insight is obtained by viewing the results in terms of the Legendre polynomial coefficients, a_L^{ENDF}, as defined in Eqn. (1) below.

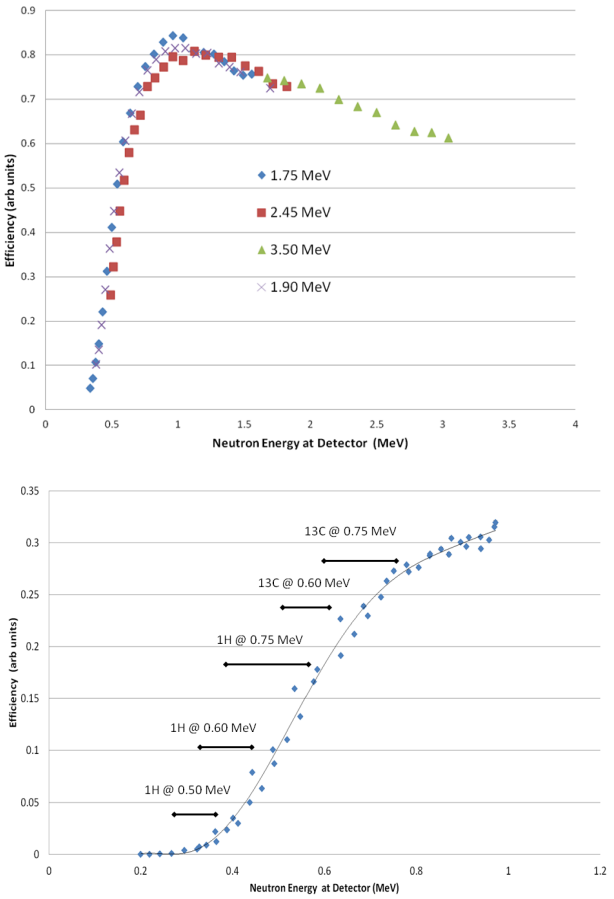

Figure 2. Neutron detector efficiency. (top) Detector efficiency determination from ^{3}H(p,n) measurements at four proton energies. (bottom) Detector efficiency measurements emphasizing the <1 MeV region. The kinetic ranges of several measurements spanning 30^o to 150^o are indicated with bars. In the case of 0.5 MeV neutrons, the energy range is too low to trust the results from a H(n,n) cross-section normalization, hence the need to use a natural carbon sample.

The differential cross section

$$\frac{d\sigma}{d\Omega} = \frac{\sigma_s}{2\pi} \sum_L \frac{2L+1}{2} a_L^{ENDF} P_L(cos\theta) \qquad (1)$$

defines the expansion coefficients of order L in the ENDF convention [14], $P_L(cos\theta)$ is the Legendre polynomial of order L, θ is the scattering angle, and σ_s is the scattering cross section. This approach greatly magnifies variations in the angular distributions. Legendre coefficients as a function of energy for $^{13}C(n, n_0)$ are shown in Fig. 3. These coefficients are very sensitive to the theoretical R-matrix model description. A similar analysis was performed previously by Lane *et al.* [6] and Resler *et al.*[7].

Below 3 MeV, the reaction is explained mainly by potential scattering with four narrow resonances. The features in the region 3 to 5 MeV are dominated by three overlapping broad resonances at E_n = 3.35 MeV, $J^\pi = 1^+$, (Γ_{tot} ~0.18 MeV); 3.51 MeV, 1^-, (~1 MeV); 3.71 MeV, 2^-, (~0.9 MeV); and 4.35 MeV, 1^-, (~0.5 MeV) [6]. Note that each resonance stands out in different Legendre coefficients. Between 3.5 and 5.0 MeV there is a significant

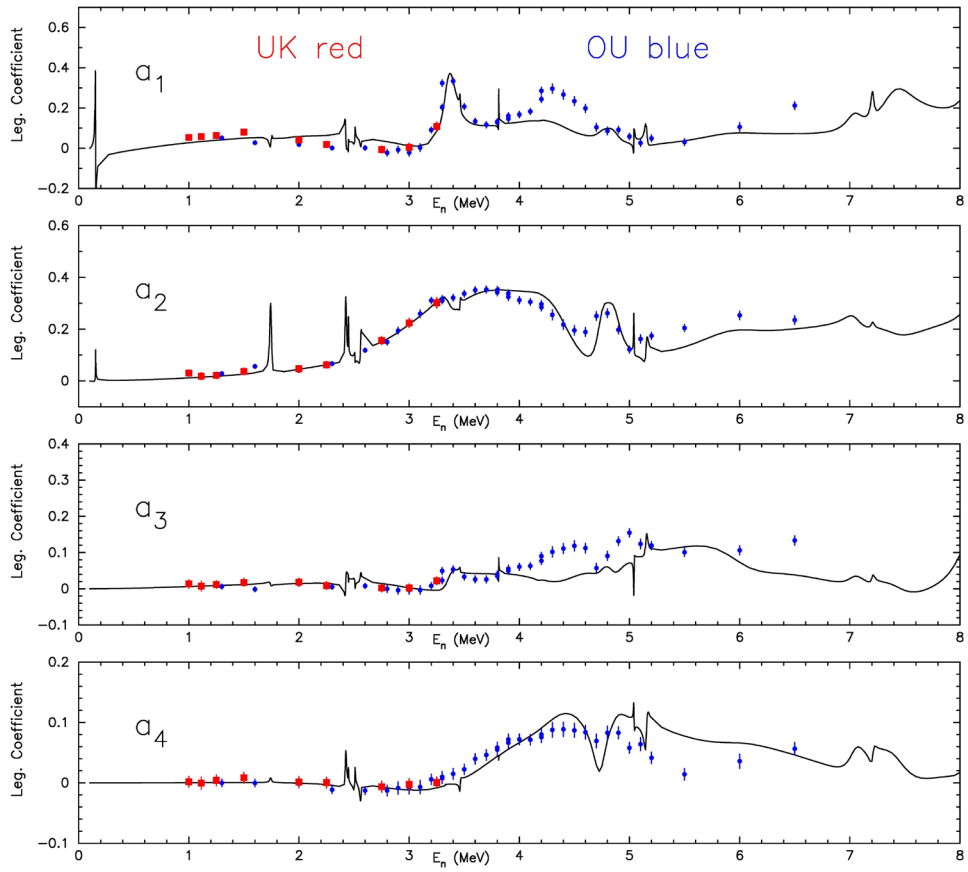

Figure 3. Legendre coefficients for neutron elastic scattering differential cross section. The UKAL newly measured values (red) follow those of the ENDF/B VIII.0 (black line) [5] and Ohio data (blue) [6] extremely well up to 3.5 MeV. The Ohio University R-matrix fits are not shown.

discrepancy between the measurements or Ref. [6] and the adopted ENDF/B VIII.0 [5] values. The UKAL collaboration plans to remeasure this region in future experiments.

4 Summary

Measurements of neutron elastic scattering differential cross sections for ^{13}C(n,n′) were made in the incident energy region of 0.50 to 3.25 MeV at the UKAL. The Legendre expansion coefficients were found consistent with the ENDF/B-VIII.0 [5] values below 3.25 MeV. Between 3.5 and 5.0 MeV, ENDF/B-VIII.0 values significantly disagree with the earlier results of Ref. [6]. We plan to perform more measurements in that region to help resolve the discrepancy.

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