Measurement of the Elastic and Inelastic Differential Neutron Cross Sections for ^{23}Na between 1 and 4 MeV

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Elastic and inelastic neutron scattering angular distributions have been measured from ^{23}Na for incident neutron energies between 2 and 4 MeV at the University of Kentucky using neutron time-of-flight techniques. The cross sections obtained are important for applications in nuclear reactor development and other areas, and they are an energy region in which existing data are very sparse. Absolute cross sections were obtained by normalizing Na angular distributions to the well-known *np* cross sections.

1. Introduction

High precision neutron scattering data have become increasingly important in such diverse areas as the development of nuclear reactors and accelerator systems, astrophysics and space system design, radiation therapy and isotope production, and for shielding considerations.

For nuclear reactors alone, well-determined cross sections are needed for computer modeling calculations for reactor design and safety, for heat transfer properties and shielding, and Na cross sections in particular are needed for proliferation resistant thorium fast reactors. Elastic and inelastic neutron cross sections are especially important for use in transport codes and energy loss calculations, and for the inelastic neutron channel, the resulting γ rays can lead to heating of reactor materials. Knowledge of the (n,n) and (n,n') channels are often important for deducing the (n,p) and (n,α) cross sections which are also important for reactor design. For ^{23}Na, the existing inelastic neutron scattering cross sections are known to approximately 30% in the 2-6 MeV region and the desired uncertainties are on the order of 12-13% [1].

The focus of the research presented here is elastic and inelastic neutron differential scattering cross sections measured between 2 and 4 MeV on ^{23}Na. Existing ^{23}Na neutron measurements are particularly sparse in this energy region as shown in Fig. 1.

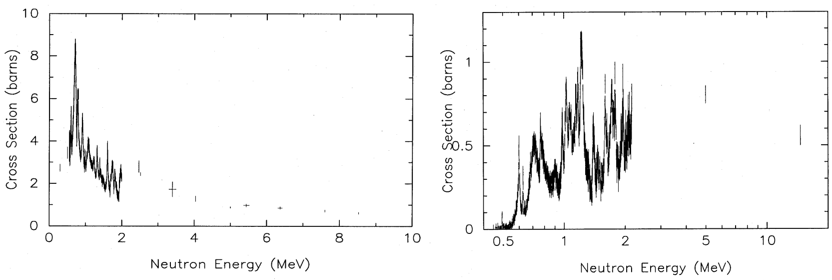

Fig. 1. Existing total Na elastic neutron cross sections are shown in the left figure and existing Na inelastic neutron cross sections are shown in the right figure [2].

2. Experimental Methods and Analysis

2.1. *Neutron TOF techniques*

Measurements were performed using the 7 MV CN Van de Graaff located at the University of Kentucky Nuclear Structure Laboratory. The rf discharge ion source is coupled to a 1.875 MHz pulsing and ~1 ns bunching system to produce a pulsed proton beam necessary for neutron time-of-flight (TOF) measurements. The ^{3}H(p,n) reaction was used to produce a nearly monoenergetic neutron beam in the forward direction emerging from the gas cell whose center was 7 cm from the scattering sample. Neutron production from the gas cell was monitored with a small NE213 scintillator; yields from this detector were used to normalize all angular distributions.

Cylindrical sodium samples with a diameter of 2.60 cm, a height of 2.67 cm and a mass of 16.26 g were used for the neutron scattering measurements. The metallic sodium sample was heat sealed inside a thin polypropylene container to reduce oxidation and for safety considerations. Neutron scattering from accessory samples of a blank polypropylene container, carbon, and polyethylene were measured to assist with background subtractions, cross section normalization, and physical data corrections. A 1″ thick × 5.5″ diameter C_6D_6 scintillator was used as the main detector for detecting scattered neutrons using neutron TOF techniques. This detector was well-collimated and shielded and located on a detector carriage that can be rotated though angles 0 to 150°. Pulse shape discrimination was used for both the monitor and main scintillators to eliminate γ-ray induced events. Example TOF spectra from the main detector for the Na sample plus container, the polypropylene container, and resulting container subtracted Na spectrum are shown in Fig. 2. Peak yields were extracted from the TOF spectra using a program that positions peaks to maintain energy separations fixed by kinematics, and then fits them with an asymmetric form that accounts for the time and energy spreads in the experiments.

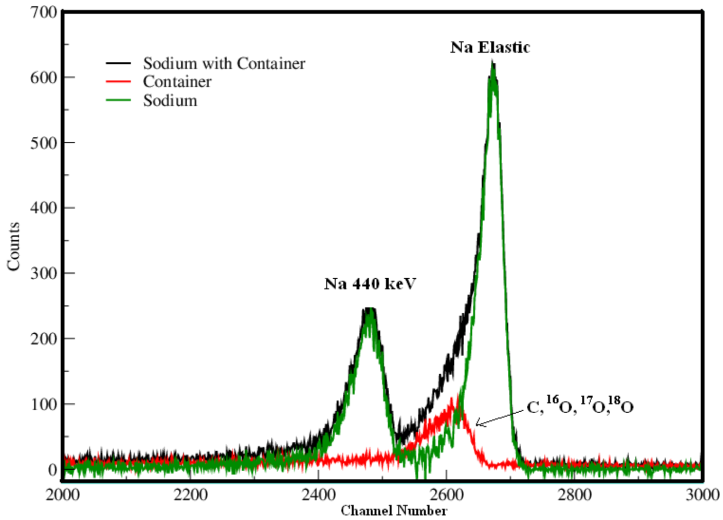

Fig. 2. Neutron TOF spectrum showing the resulting Na spectrum once the container spectrum is subtracted from the Na with container spectrum.

2.2. *Main C_6D_6 Detector Efficiency*

The neutron detection efficiency of the C_6D_6 detector is energy dependent, and this relative energy dependence must be determined before the angular distributions of the scattered neutrons can be deduced. The ^{3}H(*p*,*n*) neutron production reaction was used to obtain the efficiency under the same experimental conditions as used for the neutron scattering experiment for the measurements reported here. To determine the relative efficiency, the C_6D_6 detector was positioned to look directly at the gas cell and the neutron yield was measured as a function of angle. The efficiency was deduced using the evaluated ^{3}H(*p*,*n*) angular distribution [3] along with the kinematically determined neutron energy at each angle and is given by

$$eff(E_n) = \frac{Y_{^3H(p,n)}(\theta)}{Y_{FM}\,\frac{d\sigma}{d\Omega}_{^3H(p,n)}(\theta)}, \qquad (1)$$

where $eff(E_n)$ is the relative detector efficiency at neutron energy E_n at angle θ, $Y_{3H(p,n)}$ is the main detector yield, Y_{FM} is the monitor yield, and $d\sigma/d\Omega$ is the source reaction cross section at angle θ. The relative deviation $d\sigma/d\Omega_{3H}$ (θ) is important for Na cross sections determination and is estimated to be 3% [3].

2.3. *Cross Sections*

The uncorrected and un-normalized relative angular distribution of the scattered neutrons *W(θ)* is then determined by the following expression:

$$W_{Na,lab}(\theta) = \frac{Y_{Na}(\theta)}{Y_{FM}(\theta)\, eff(E_{n\,for\,Na})\, N_{Na}} \tag{2}$$

where Y_{Na} is the yield of the peak of interest, Y_{FM} is the forward monitor yield, $eff(E_{n\ for\ Na})$ is the efficiency of the main C_6D_6 detector at the energy of the scattered neutron, and N_{Na} is the number of Na nuclei in the scattering sample. Similarly, $W_{H,lab}$, is deduced for *np* scattering from the polyethylene sample, which is used as the neutron cross section standard since the *np* total cross sections are known to about 0.3% in the 2-4 MeV region. The neutron scattering differential cross sections for Na are then determined by forming the ratio of $W_{Na,lab}$ and $W_{H,lab}$ and scaling to the evaluated *np* cross sections [4],

$$\frac{d\sigma}{d\Omega}_{Na}(\theta) = \left(\frac{W_{Na,lab}(\theta)}{W_{H,lab}(\theta)}\right)\left(\frac{\sigma_{Tot}^{n-H}}{4\pi}\quad 4\cos(\theta_L)\right) \tag{3}$$

The last factors in Eq. (3) are the angle-integrated elastic cross section for ^{1}H(*n*,*n*), which is isotropic in the center-of-mass frame, and transformed to the laboratory frame.

2.4. *Attenuation and Multiple Scattering Corrections*

Cross sections determined via Eq. (3) must be corrected for neutron attenuation and neutron multiple scattering in the sample. The code MULCAT [5] uses an iterative forced-collision Monte Carlo approach. Starting from experimental data (values from Eq. (3)), the perturbed angular distribution is calculated and the resulting change in the estimated angular yield used to back-calculate the unperturbed cross section. The procedure is iterated until the process stabilizes. An example ^{23}Na(*n*,*n*) angular distribution at E_n =3.2 MeV, before and after corrections, is shown in Fig 2. Corrections range from 10-16% of the cross section.

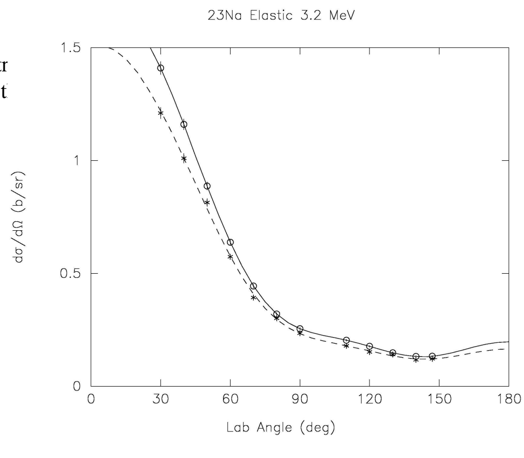

Fig. 2. Elastic neutr 3.2 MeV. The dotted line represents t ents unperturbed

3. Results and Conclusions

Angular distributions of elastically and inelastically scattered neutrons have been measured at 12 incident neutron energies between 1.48 and 4.0 MeV; results from three of those measurements are shown in Fig. 3. These data along with angular distributions at nine other incident neutron energies will provide information important for nuclear reactor design and safety considerations.

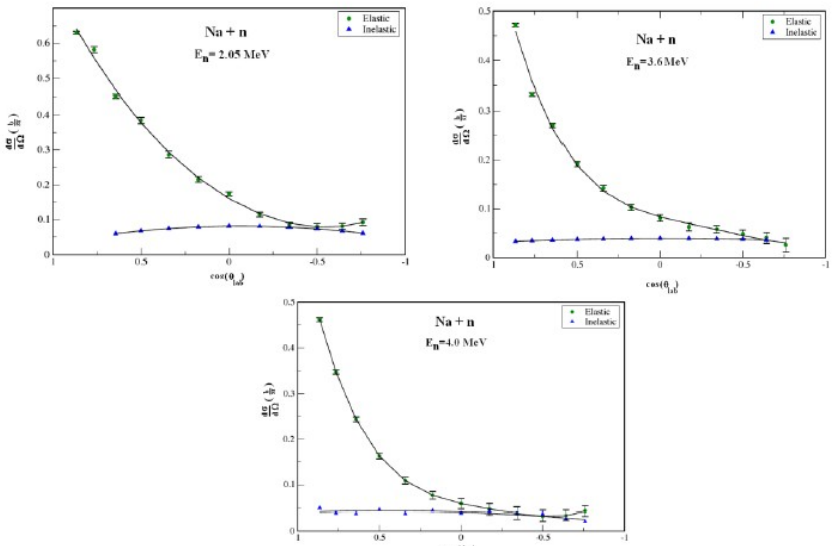

Fig. 3. Elastic and inelastic neutron scattering differential cross sections for Na at E_n=2.05, 3.60, and 4.00 MeV.

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6

References

1. G. Aliberti, G. Palmiotti, M. Salvatores, T. K. Kim, T. A. Taiwo, M. Anitescu, I. Kodeli, E. Sartori, JC Bosq, and J. Tommasi, Ann. Nucl. Energy **33,** 700 (2006).

2. Experimental Nucl. Reaction Data EXFOR/CSISRS www.nndc.bnl.gov.

3. Horst Liskien and Arno Paulsen, Nuclear Data Tables 11, 569 (1973).

4. NNDC, ENDF/B-VII, H(*n*,*n*), A.D. Carlson, NIST, (2006); EVAL-OCT05, DIST-DEC06, G. M. Hale, LANL.

5. John R. Lilley, "MULCAT-BRC, A Monte Carlo Neutron and Gamma-Ray Multiple Scattering Correction Program," Internal Service de Physique et Techniques Nucléaire, Centre d'Etudes de Bruyères-le-Châtel, Report P2N/934/80, (1980).