Neutron Scattering Differential Cross Sections for ^{23}Na from 1.5 to 4.5 MeV

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Abstract

Measurements of neutron elastic and inelastic scattering cross sections from ^{23}Na have been performed for sixteen incident neutron energies between 1.5 and 4.5 MeV. These measurements were complemented by γ -ray excitation functions using the $(n,n'\gamma)$ reaction to include excited levels not resolved in the neutron detection measurements. The time-of-flight (TOF) technique was employed for background reduction in both neutron and γ -ray measurements and for energy determination in neutron detection measurements. Previous reaction model evaluations relied primarily on neutron total cross sections and four (n,n_0) and (n,n_1) angular distributions in the 5 to 9 MeV range. The inclusion of more inelastic channels and measurements at lower incident neutron energies provide additional information on direct couplings between elastic and inelastic scattering as a function of angular momentum transfer. Reaction model calculations examining collective direct-coupling and compound absorption components were performed.

Keywords: Elastic and inelastic neutron scattering, $^{23}\text{Na}(n,n)$, $^{23}\text{Na}(n,n')$ and $(n,n'\gamma)$ cross sections, ECIS06 calculations

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1. Introduction

The International Atomic Energy Agency (IAEA), the Japanese Atomic Energy Agency (JAEA), the French Alternative Energies and Atomic Energy Commission (CEA), and U.S. Department of Energy (DOE) have development
5 projects for advanced fast reactors based upon use of sodium as a liquid metal or molten salt coolant. Test facilities already exist and there are plans to build several fast reactors over the next 10 years, such as ASTRID by the CEA [1] or MYRRHA by the Belgian Nuclear Research Center [2]. There are many facets to designing a sodium-cooled fast reactor, and the nuclear physics com-
10 munity's contribution to these projects is to supply reliable values for neutron scattering cross sections. Elastic scattering differential cross sections impact the neutron density in the reactor and both the elastic and inelastic scattering impact energy absorption in the coolant and surrounding structural materials, particularly through γ -ray heating.

15 Recent evaluations [3, 4] of the ^{23}Na neutron scattering data revealed significant discrepancies in cross sections between the evaluated nuclear libraries, especially above 1 MeV where there is also a critical lack of measured data for inelastic and elastic differential cross sections.

A selected region of the ^{23}Na total cross sections is shown in Fig. 1. At en-
20 ergies less than 1 MeV, the cross sections can be predicted within an R-matrix treatment. At energies above 6 MeV, an energy-averaged optical model that is relatively insensitive to the number of excited levels [8] or their structure provides an adequate description. In the intermediate fast neutron energy range, 1 to 5 MeV, scattering is quite sensitive to structure. Neither of the two mod-
25 els cited is appropriate in this region, i.e., scattering cross sections must be measured. These measured scattering cross sections, including their angular dependencies, provide the critical information that guides the choice of scattering potential parameters for direct-coupling collective models. These parameters, once fixed, enable characterization of energy transfer to the reactor coolant and

Figure 1: ENDF/B-VII.1 database total cross sections [5] for neutron scattering on ^{23}Na shown with spherical optical model calculations using EMPIRE-3.1 [6] and global Koning and Delaroche parameters [7]. Shown are the various reaction components which contribute to the total cross section. Optical models only describe the average behavior. Our data provide information on the deviations that can be anticipated from implementable reaction models, particularly with respect to angular distributions and the compound nuclear absorption.

30 surrounding materials through coupled-channels potential representations.

Inelastic scattering cross sections to the first excited level can be extracted through direct neutron detection whereas for closely spaced levels the angle-integrated (n,n') cross sections are best determined through γ -ray detection measurements. Angular distributions of the (n,n') reaction provide the best
 35 information on the reaction mechanism, while γ -ray measurements provide the best information on the partition of reaction strength.

2. Methods

The accelerator at the University of Kentucky is a 7-MV single-ended model CN Van de Graaff with a pulsing/bunching system located inside the high-
 40 voltage terminal. Proton or deuteron beams emerging from the radio-frequency ion source are pulsed by sweeping the beam across a chopping aperture at

1.875 MHz. This ~ 10 -ns chopped pulse immediately passes through a klystron buncher that reduces the pulse width to ~ 1 ns. These ions are accelerated, bent by a 90° analyzing magnet, and impinged on a gas cell at the end of the
45 beamline. The primary neutron production reaction is ${}^3\text{H}(\text{p},\text{n}){}^3\text{He}$ in a gas cell constructed of stainless steel and lined with a tantalum foil and beam stopper. The entrance foil is $3.3\text{-}\mu\text{m}$ molybdenum. The inner gas cell length is 3 cm and operates at a pressure of nearly one atmosphere of tritium. Although the neutrons produced in this fashion are considered mono-energetic, there is some
50 total effective spread in energy due to straggling in the cell entrance foil, energy loss throughout the tritium gas, and a kinematic neutron spread across the scattering samples. A typical value for the total effective neutron energy spread is approximately 120 keV full-width at $E_n = 3.60$ MeV.

Neutron production rates are recorded with a long counter [9, 10] and a
55 time-of-flight (TOF) forward monitor (FM) NE-213 scintillator with pulse-shape discrimination (PSD). The long counter is positioned at 85° -left with respect to the beam direction. At 85° , the source-neutron energy is in a relatively smoothly varying region of the long counter efficiency curve [11], avoiding resonances. The FM is placed at 45° and above the scattering plane to provide a direct,
60 collimated view of the gas cell. Source neutrons are identified in the FM by TOF and PSD, the combination of which provides a very clean monitor of on-pulse neutron production.

Scattering samples were right circular cylinders hung 7.0 cm from the center of the gas cell. The sodium sample was 13.65 g of high-purity metal cast into a
65 20-mil walled polypropylene container with inner dimensions 3.02 cm in diameter and 2.27 cm in height. Similar empty polypropylene containers were used for background subtraction measurements. Two polyethylene solid cylinders of sizes $1.94\text{ cm} \times 2.41\text{ cm}$ and $0.96\text{ cm} \times 1.49\text{ cm}$ (diameter $\times$ height) were used as hydrogen cross section reference standards. In addition, similarly sized samples
70 of natural carbon and iron were employed for consistency checks.

The experimental hall was specially constructed for neutron TOF measurements. It has a high ceiling and a false floor which covers a 2.5-m deep pit.

Figure 2: TOF spectrum of 4.0-MeV neutrons scattered at 100° from ^{23}Na . Contributions from the container have been subtracted. Peaks corresponding to scattering to the various final states in ^{23}Na are labeled.

Neutron or γ -ray detectors are mounted on a carriage which can be rotated to cover scattering angles up to $\approx 155^\circ$ with respect to the incident beam direction. The carriage supports a full-length collimation system with flight paths up to 4 m.

During the neutron detection measurements, the neutron detector was mounted at distances of 2.2 to 3.8 m from the scattering samples. Neutrons were detected in an 11.5-cm diameter $\times$ 2.5-cm thick C_6D_6 liquid scintillator, which permitted PSD rejection of γ -ray events. The C_6D_6 detector provides better definition in the pulse-amplitude spectrum than non-deuterated scintillators, which was a benefit to the PSD methods of rejecting all but the desired neutron events. Restricting the detector thickness to 2.5 cm is important to preserve good timing resolution. Measurements were made at 10° intervals from 30° to 150° . Scattering yields were corrected for neutron attenuation and multiple scattering in the sample using forced-collision Monte Carlo methods. Absolute normalization of the cross sections was determined by measuring n-p scattering cross sections and comparing them to normalization standards [12, 13]. An example TOF spectrum is shown in Fig. 2.

90 During the $(n,n'\gamma)$ measurements, γ rays were detected using a Compton-suppressed n-type HPGe detector with 51% relative efficiency and an energy resolution of 2.1 keV FWHM at 1.33 MeV. To decrease the recorded neutron-induced events in the detector, the ADC was gated by setting a timing window on the prompt γ rays. These γ -ray events occur well in advance of the neutron-
 95 induced events in the TOF range. The detector efficiency was measured using γ -ray sources such as ^{56}Co , ^{152}Eu , and ^{226}Ra . The neutron scattering facilities, TOF neutron background suppression, neutron monitoring and data reduction techniques have been described elsewhere [14]. Gamma-ray excitation functions were measured for incident neutron energies between 1.5 and 4.0 MeV. Yields
 100 from the measurements were corrected for γ -ray detection efficiency and attenuation in the sample and were normalized to yields from a long counter which were corrected for energy-dependent efficiency and for the angular distribution of the $^3\text{H}(p,n)^3\text{He}$ source reaction in order to obtain relative γ -ray production cross sections. The absolute cross section normalization was obtained by comparison to ^{56}Fe cross sections, also measured during the same experiment and
 105 referred to the appropriately energy-averaged results [15]. The (n,n') cross section for a given level can be derived from the γ -ray production cross sections by considering the difference between the feeding and depopulating γ rays and is discussed in more detail below.

110 **3. (n,n') Measurements, Techniques, and Concerns**

Peaks in the TOF spectra were fitted with SAN12, a program written in-house that fits each neutron peak with two Gaussians plus an exponential tail. A specialized fitting code is required because neutron TOF peaks are relatively broad, have tails, and can overlap. SAN12 incorporates kinematic constraints
 115 on peak positions, widths, and tails. The uncertainty in the peak yield was determined by counting statistics and the ability to reliably extract the net peak yield from the TOF spectrum. The contribution from counting statistics can be made negligible by taking data for a sufficient time. The yields of dominant

peaks in the spectrum were determined to accuracies of 1-2 % at worst. For
120 spectra in which an inelastic scattering peak resides on the tail of an elastic
scattering peak, e.g., the 440-keV level in ^{23}Na , special care must be taken so
that peak-shape parameters vary smoothly. In difficult cases, peaks were fit
with a variety of techniques to determine an average yield and uncertainty.

3.1. C_6D_6 Detector Efficiency

125 The general energy dependence of the C_6D_6 detector efficiency is describable
analytically [16, 17]; however, details of this dependence involve taking into ac-
count complications such as sub-threshold pulse pileup and light absorption in
the scintillator fluid. Rather than attempting to model the detector efficiency
with Monte Carlo or closed-form expressions, it was measured at each E_n for
130 best accuracy. We make use of the $^3\text{H}(\text{p},\text{n})^3\text{He}$ angular distribution and kine-
matics. The detector carriage was repositioned to pivot about the center of the
gas cell and TOF spectra were taken at angles from 0° to 140° . The known
 $^3\text{H}(\text{p},\text{n})^3\text{He}$ angular distribution specifies how many neutrons are emitted to-
ward the C_6D_6 detector at angle θ_{lab} , and the (p,n) reaction kinematics provide
135 a range of neutron energies as the angular distribution is measured. We define
the efficiency as the scattered neutron yield per $d\sigma/d\Omega_{Tpn}$ cross section for each
measured laboratory detector angle, as given by:

$$eff(E_n) = \frac{Yield_{Tpn}(\theta_{lab})}{FM \cdot \frac{d\sigma}{d\Omega_{Tpn}}(\theta_{lab})} \quad (1)$$

where $Yield_{Tpn}$ is the C_6D_6 detector yield of source neutrons at lab angle θ_{lab} ,
FM is the forward monitor yield for the measurement, and $d\sigma/d\Omega_{Tpn}$ is the
140 $^3\text{H}(\text{p},\text{n})^3\text{He}$ cross section at angle θ_{lab} . The best yield extraction methods pro-
duce uncertainties of 1 to 2%. Uncertainties in the $^3\text{H}(\text{p},\text{n})^3\text{He}$ cross sections are
the largest contributing factors to the detector efficiency $eff(E_n)$ uncertainty,
and one of the largest contributors to the overall uncertainty in the neutron
scattering cross sections.

145 The $d\sigma/d\Omega_{Tpn}$ cross sections can be taken from one of two references: the
DROSG-2000 program series [18, 19], or the evaluated ENDF database [13]. The

Figure 3: Efficiency curve for the C₆D₆ detector at $E_n = 4.00$ MeV. The figure is illustrated with regions important for the various reaction channels.

DROSG values are based on $^3\text{H}(\text{p},\text{n})^3\text{He}$ experimental measurements performed at Los Alamos and at the Institute for Reference Materials and Measurement (IRMM) [18]. Absolute uncertainties in those cross sections are given as $\sim 7\%$ and uncertainties in the angular dependence as 3% . The ENDF values are produced through the nuclear data evaluation process on the ^4He compound nucleus system, the description of which is constrained by many types of experimental measurements [20, 21, 22, 23]. Absolute uncertainties in the ENDF values appear to be $\sim 5\%$. Our absolute ^{23}Na cross sections are not impacted by the overall scale of the detector efficiency, but they are sensitive to the energy dependence, because the scattered neutron energies change considerably as a function of scattering sample and detection angle. Discrepancies between the two references [13, 18] of $\pm 10\%$ have been reported [24], with the largest differences observed at forward and backward angles. Below $E_p = 4.0$ MeV, there is no basis to choose one set of cross sections over the other. Above $E_p = 4.0$ MeV the descriptions of Ref. [18] provide an energy dependence which more closely matches the anticipated shape of the C₆D₆ detector efficiency. An example efficiency curve is shown in Fig. 3. Fortunately, this effect primarily impacts the absolute scale of $eff(E_n)$ in the neutron energy regions of interest

165 to the $^1\text{H}(\text{n},\text{n})$, $^{23}\text{Na}(\text{n},\text{n}_0)$, and $^{23}\text{Na}(\text{n},\text{n}_1)$ reactions and not the shape of the efficiency curve. The uncertainty in the detector efficiency is related to the slope uncertainty in the regions of interest, and we adopt a value of $\pm 3\%$.

3.2. Container Subtraction

The sodium sample is enclosed in a thin-walled polypropylene container. An
 170 empty-container TOF spectrum was subtracted from the whole-sample TOF spectrum to provide a Na-only spectrum for analysis. MCNP [25] simulations were performed and indicate any container self-shielding/multiple scattering corrections are negligible, or at least very small on average over the whole TOF spectrum. To test the validity of the container subtraction, the normaliza-
 175 tion factor was varied slightly for TOF spectra at different incident energies and scattering angles, and a search was performed for residual background or oversubtraction effects on the Na-only spectrum. Any undetected issues in the container subtraction primarily impact the $^{23}\text{Na}(\text{n},\text{n}_1)$ TOF peak due to its size and relationship to the carbon and hydrogen TOF peaks from the polypropy-
 180 lene container. In cases where there was obviously a problem, the data were eliminated from further analysis.

3.3. Angular Variation of Reaction Yields and Differential Cross Section

We define the scattered neutron angular distribution W_X for a reaction channel X as

$$W_{X,cm}(\theta_{cm}) \stackrel{cm}{\leftarrow} W_{X,lab}(\theta_{lab}) = \frac{Yield_X(\theta_{lab})}{FM \cdot eff(E_n) \cdot N} \quad (2)$$

185 where $Yield_X$ is the area of the TOF peak for X , and N is the number of atoms of the nucleus of interest in the sample. During analysis, the angular distributions are required in both the center-of-mass (cm) and laboratory reference frames and the symbol $\stackrel{cm}{\leftarrow}$ is a reminder that the solid-angle transformation equations are used.

190 Conversion to absolute cross sections is performed with reference to a hydrogen cross section standard, so that

$$\frac{d\sigma}{d\Omega_{cm}} = f W_{X,cm}(\theta_{cm}) \quad (3)$$

where f is the conversion factor determined by

$$f = \left\langle \frac{\frac{d\sigma}{d\Omega}_{H,cm}(\theta_{cm})}{W_{H,cm}(\theta_{cm})} \right\rangle \quad (4)$$

and the $\langle \dots \rangle$ denotes an average over several measured angles between $\theta_{lab} = 30 - 50^\circ$. The factor f must also include corrections for neutron attenuation and multiple scattering in the polyethylene (CH_2) sample, which are discussed
195 in the following section.

Recommended values for the $\text{H}(\text{n},\text{n})$ total cross sections are taken from Tables XVIII and XIX of Ref. [12] and Ref. [13], respectively. Both references provide the same absolute angle-integrated $\text{H}(\text{n},\text{n})$ values which are known to
200 $\pm 0.30\%$ or better in our energy range. The differential cross sections vary by $\pm 0.5\%$ from the isotropic estimate, which is much smaller than the uncertainties incurred in $eff(E_n)$. Because of the small discrepancy, we consider $d\sigma/d\Omega$ to be isotropic in the cm frame.

3.4. Attenuation and Multiple Scattering Corrections

The neutron flux entering the sample and the neutrons scattered toward
205 the detector both undergo attenuation. Incoming and outgoing attenuation reduces counts in the TOF spectrum. The attenuation effect in our samples reduces the yields between 5 to 13% depending on the sample and detection angle. Multiple scattering in the sample redirects additional neutrons toward
210 the detector and increases counts in the TOF spectrum. The multiple scattering effect is only a few percent since the solid angle subtended by the collimated detector is quite small compared to 4π . Measured differential cross sections are corrected for attenuation and multiple scattering effects with the code MULCAT [26]. The code performs an iterative Monte Carlo calculation, taking as input
215 the uncorrected experimental differential cross sections and using them with known total cross sections and information on the $^3\text{H}(\text{p},\text{n})^3\text{He}$ source reaction to estimate the corrected differential cross sections. MULCAT then repeats this process, using now the estimated cross sections as input; the whole process is iterated until the differential cross sections converge. The Kentucky group

220 has much experience with the code on medium-to-heavy mass, single-element samples [27, 28, 29, 30, 31, 32, 33]

To evaluate the accuracy of the MULCAT corrections, a consistency-check technique was adopted. A simulation was designed using MCNPX to describe the experimental setup and simulate expected yields in an array of detectors. 225 Starting with $^{12}\text{C}(\text{n},\text{n})$ neutron scattering cross sections from the ENDF evaluated database, an MCNPX simulated angular distribution for neutrons scattering from a cylindrical carbon sample was generated. These simulated differential scattering cross sections were then used as input to MULCAT to produce simulated corrected cross sections to compare with the original ENDF values. This 230 modeling revealed that MULCAT performs much better than its own Monte Carlo-predicted calculational uncertainties (10 to 13%); differences at angles greater than 70° are 2 to 5%. The consistency check technique at the most forward angles is difficult to evaluate as these angles are sensitive to approximations made in converting the output of MCNP to the input for MULCAT 235 relating to the beam uniformity, divergence and finite size of the gas cell, and mass distribution in the sample. These are particularly sensitive at forward angles where cross sections change rapidly with angle.

The multiple scattering and attenuation corrections are also tied directly to the conversion of measured yields into cross sections. Our measurements 240 are made with polyethylene, a two-element sample, but MULCAT treats only one element at a time. Thus we begin with a sample yield, $W_{H,cm}(\theta_{cm})$, and normalize to the known value of $d\sigma/d\Omega_{H,cm}$ to produce f . This starting value of f taken directly from the measurements provides only an estimate. The proper value of f must be found through an additional MULCAT manually iterative 245 process. The neutron flux incident on the polyethylene sample is attenuated by both C and H, as are the scattered neutrons. In addition, these elements are very light and one must be aware of the scattered neutron energies and the detector energy response. MCNP simulations indicate the proper way to handle the situation is to first run MULCAT on the hydrogen content in the polyethylene 250 and then divide by the attenuation factor for the C content. The actual manner

of handling the issue of two elements provides an uncertainty of at most 1%. The standardization procedure was performed on two sizes of polyethylene samples to judge the quality of our technique. The total uncertainty in the value of f ranges from 1 to 6%.

255 3.5. Example Results for ^{23}Na

Numerical values for the differential cross sections measured during this investigation may be retrieved from the EXFOR database (entry 14403). The $E_n = 4.0$ MeV measured differential cross sections are shown in comparison to previously existing data and evaluated databases in Fig. 4. Angle-integrated
260 elastic $^{23}\text{Na}(n,n_0)$ cross sections agree with the ENDF/B-VII.1 [34] and JENDL-4.0 [35] evaluations rather well, while the JEFF-3.1.2 [36] evaluated data are significantly higher.

4. $(n,n'\gamma)$ Measurements, Techniques, and Concerns

Information on γ -ray measurements at the laboratory, analysis techniques,
265 and numerous examples for nuclear structure investigations are described in detail in Ref. [14]. We only briefly mention the techniques employed.

4.1. γ -ray Excitation Functions

For γ -ray excitation functions, the detector carriage was positioned at 125° and spectra (Fig. 5) were taken as the incident neutron energy was increased.
270 Because the γ rays are emitted from residual nuclear states of definite parity, the angular variation is expressed as $W(\theta_\gamma) = A_0 [1 + a_2 P_2(\theta_\gamma) + a_4 P_4(\theta_\gamma)]$, where P_L are the Legendre polynomials. Higher-order terms do not occur for dipole and quadrupole transitions. The coefficient A_0 is the intensity of the γ ray and is used to determine the branching ratios of transitions from a level.
275 The quantity $4\pi A_0$ is the angle-integrated γ -ray production cross section when properly normalized. The coefficients a_2 and a_4 reflect the spins of the levels and the multipolarities of the transitions [37]. By choosing a detection angle of 125° , the $a_2 P_2$ term in the angular distribution is identically zero. The $a_4 P_4$

Figure 4: Comparison of measured 4.00-MeV elastic scattering cross sections (solid points with uncertainties) to previous data (left) and the evaluated nuclear libraries (right). The shape of $d\sigma/d\Omega$ changes quickly at angles $>80^\circ$ with energy. Rapid changes at large angles are consistent with the compound nuclear resonance structure observable in $(n,n'\gamma)$ measurements.

Figure 5: $^{23}\text{Na}(n,n'\gamma)$ spectrum at $E_n = 4.0$ MeV incident energy. Transitions important for extracting cross sections are indicated.

term is typically small if the bombarding energy is significantly above the level
 280 energy. Because ^{23}Na is a half-integer spin nucleus, transitions tend to be of
 mixed E2/M1 multipolarity. Donati *et al.* [38] measured $(n,n'\gamma)$ γ -ray angular
 distributions for the first six excited states from $E_n = 0.52$ to 4.23 MeV. The
 largest a_4 observed would produce a discrepancy of $<7\%$.

Another important matter to consider is the role of sample size on the
 285 measured intensities. Sample-related neutron multiple scattering and incident
 neutron and outgoing γ -ray attenuation corrections were performed with an
 in-house code, GAMBIT, which is based upon the Engelbrecht treatment for
 $(n,n'\gamma)$ scattering on cylindrical samples [39, 40, 41]. The Engelbrecht correc-
 tions have an estimated uncertainty of $\sim 4\%$. Branching ratios calculated for the
 290 2076, 2391, and 2983-keV levels differ by $<2\%$ of accepted values, indicating the

assumptions made above are quite good for ^{23}Na .

To convert A_0 coefficients to γ -ray production cross sections, we compare properly corrected yields to a γ -ray cross section standard. Unfortunately, high-quality γ -ray standards do not exist for few-MeV $(n,n'\gamma)$ scattering, although
 295 several are under development. We make a comparison to the $^{56}\text{Fe}(n,n')$ inelastic cross sections from the ENDF evaluation [42]. The production cross section for γ_i in ^{23}Na is then

$$\sigma_{Na,\gamma_i} = \left(\frac{Yield_{Na,\gamma_i}}{N_{Na}} \right) \left\langle \frac{br_{j,trans-k} \bar{\sigma}_{Fe,levelj}}{(Yield_{Fe,\gamma_k}/N_{Fe})} \right\rangle \quad (5)$$

where the quantity in $\langle \dots \rangle$ is the conversion factor between normalized yield and cross section averaged over a collection of γ rays in ^{56}Fe . The symbol
 300 $\bar{\sigma}_{Fe,levelj}$ denotes the cross section for $^{56}\text{Fe}(n,n_j)$, for the j^{th} level, averaged over the incident neutron energy spread. The ^{56}Fe cross sections undergo rapid fluctuations and we take the uncertainty in $\bar{\sigma}_{Fe,levelj}$ to be the the root-mean-square deviation in the averaging interval. The symbol $br_{j,trans-k}$ denotes the branching ratio for transition k from level j . Thus, $br_{j,trans-k} \bar{\sigma}_{Fe,levelj}$ is
 305 the production cross section for the ^{56}Fe γ ray k . To determine the conversion factor, we considered 13 measurements derived from four levels at eight incident neutron energies. The best selections are well above threshold for the level but before significant feeding occurs. The resulting quantity $\langle \dots \rangle$ has a statistical uncertainty of $\sim 6\%$.

310 The neutron inelastic cross section to a particular final level in ^{23}Na can be calculated from the γ -ray production cross sections by summing the production cross sections of its de-exciting γ rays and subtracting the production cross sections of the transitions feeding the level (see Fig. 6). Angle-integrated neutron inelastic cross sections obtained in this manner do not suffer from the
 315 overlapping peaks of (n,n') measurements.

Figure 6: Gamma-ray decay scheme for levels studied during these measurements. All energies are in keV. The corresponding (n, n') reaction channels are indicated on the left. Gamma-ray energies are provided for transitions with branching ratios $>10\%$.

4.2. Example Results for ^{23}Na

Four example γ -ray excitation functions are shown in Fig. 7 and are compared with recent results from GELINA/IRMM [43]. The GELINA/IRMM measurements exhibit higher resolution and more detail than ours, but they
320 require several months of beamtime, while our measurements have lower resolution, but are measured in shorter time periods. Our results are in excellent agreement with the GELINA data averaged over the energy spread of our measurements. Numerical values for the cross sections measured during this investigation may be retrieved from the EXFOR database (entry 14403).

325 The neutron inelastic scattering cross sections from the ENDF library [34] are larger than our values by $\sim 15\%$, while cross sections from the JEFF library [36, 44] are smaller than our results by $\sim 15\%$. Our measurements are in agreement with the values in the JENDL-4.0 library [35]. These comparisons are illustrated in Fig. 8.

Figure 7: Comparison of measured γ -ray excitation functions with those of the GELINA/IRMM group [43]. Data from the present measurements are shown with uncertainties. The agreement is excellent considering the experiments use different normalization techniques and the neutron energy resolutions are significantly different. Our results support the normalizations used in the GELINA data [43].

Table 1. Angle-integrated cross sections from the present measurement. For each energy, the first row contains values determined from (n,n') measurements and the second row, values from (n,n'γ) measurements.

E_n (MeV)	n_0 (b)	n_1 (mb)	n_2 (mb)	n_3 (mb)	n_4 (mb)	n_5 (mb)	n_6 (mb)	n_7 (mb)
1.48	2.27(16)	470(38) 268(21)						
1.75		544(38)						
2.05	2.54(17)	640(45) 566(45)						
2.25		671(54)	50(4)					
2.44	1.24(11)	310(25)						
2.50		534(43)	69(6)	8(1)				
2.80	1.73(12)	550(39) 561(45)	120(10)	33(3)	2.4(5)			
2.89	1.53(11)	420(29)						
3.06		366(29)	100(8)	78(6)	76(6)	83(7)	0.7(4)	
3.07	1.15(09)	410(29) 358(29)	100(8)	71(6)	74(6)	10(1)	1.0(4)	
3.19	1.34(09)	450(36) 448(36)	103(8)	61(5)	45(4)	7.3(7)	20(2)	
3.20	1.48(10)	480(38)						
3.40	1.61(11)	410(29)	160(22)					
3.50	1.43(10)	310(25) 377(30)	110(13) 153(12)	68(5)	48(4)	59(5)	61(5)	
3.57	1.54(11)	395(32)	180(16)					
3.60	0.98(07)	280(28) 312(25)	130(14) 175(14)	41(3)	51(4)	29(3)	70(6)	
3.80	1.40(10)	328(26)	215(17)					
4.00	1.13(08)	310(25) 239(19)	177(14) 172(14)	72(6)	63(5)	36(3)	72(6)	19(2)
4.50	1.15(10)	3248(22)	79(7)					

5. Interpretation

Nuclear structure interpretations of ^{23}Na are rather limited. The most recent discussion is that of Durell [45] which indicates that significant deformation is present in this mass region, particularly for the Na and Mg isotopes. The ^{23}Na level scheme is generally discussed as a collective-rotational system built on a strongly bound core structure. The neutron scattering cross sections would also reflect the collective rotational structure.

Although the 1 - 4 MeV range is dominated by overlapping resonances, an energy-averaged reaction model treatment at the highest energies can be considered. The cross sections of the total, (n,n_0) , and (n,n_1) channels have become smooth above 3 MeV (see Figures 1, 5, and 6). Resonance behavior is still apparent in the other inelastic channels.

The clear and strong deformation of ^{23}Na must be reflected in a direct-coupling scattering model, which also will include those compound absorption components which usually are treated as being structure-independent, except for the fluctuation effects on the compound absorption components of elastic scattering as studied by Moldauer [46]. The strong fluctuations in any model for ^{23}Na must consider relaxing Moldauer's conclusions about width-fluctuation effects.

Differential cross sections are composed of contributions from the compound nucleus and direct reaction mechanisms; however, the compound nuclear portion may be influenced by isolated resonance effects not addressable within the optical model treatment. This is certainly the case for inelastic scattering to the second and higher excited levels, where the resonances are clearly resolved.

We have investigated the applicability of the coupled-channel (CC) code ECIS06 [47] at incident energies above 3.6 MeV for the (n,n_0) and (n,n_1) differential cross section data sets. Initial optical model parameters are available from Strohmaier [48], who examined $E_n > 5$ MeV (n,x) data for the purpose of

Figure 8: Comparison of evaluated nuclear data library neutron inelastic cross sections to those determined from the current $(n,n'\gamma)$ measurements. For the (n,n_1) channel, agreement is best with the scaling of the JENDL-4.0 values. JENDL-4.0 lacks detail in the (n,n_2) and (n,n_3) channels but the scaling is adequate. ENDF/B-VII contains more detail in these channels and the agreement is adequate with the exception of the large resonance at $E_n \sim 3.7$ MeV in the (n,n_2) channel. The JEFF-3.1.2 evaluation underpredicts the cross sections above $E_n \sim 2.5$ MeV in all channels.

Figure 9: ^{23}Na rotational band structure as assigned by Ref. [45].

360 applying the results to radiation dosimetry. A list of appropriate optical model
parameters is provided in Table 2. Parameters are provided for the central po-
tential V , the volume absorption potential W_V , the surface absorption potential
 W_S , spin-orbit potential V_{so} , and the coupled-channels coupling strengths β_2
and β_4 . The depth of spin-orbit potential for all energies was set to 6.0 MeV.
365 Calculations were completely insensitive to that potential at all energies. The
main volume potential, V , shows a slight decrease with increasing energy consis-
tent with general expectations. It is interesting that the 3.57 and 4.50 MeV data
required volume absorption, W_V , while all other energies clearly favored surface
absorption, W_S . The 3.57 MeV data also preferred an anomalously higher β_2 .
370 We found no merit to including a β_4 coupling term in the potential for any
incident neutron energy.

The simplest comparison to offer is the angle-integrated elastic and inelastic
cross sections at a few energies, provided in Table 3. The variation of cross
sections for the presumed ground-state rotational band of the coupled-channels
model is reasonably consistent with the variation observed in the (n,n') and
375 $(n,n'\gamma)$ measurements.

Table 2. Optical Model Parameters.

Strohmaier Parameters Ref [48]									
E_n	V	r_V	a_V	W_V	r_{W_V}	a_{W_V}	W_S	r_{W_S}	a_{W_S}
<10	50.0	1.17	0.65	-	-	-	33.168+0.144E	1.28	0.58
$V_{so} = 6.0$ $r_{so} = 1.01$ $a_{so} = 0.58$ $\beta_2 = 0.36$ $\beta_4 = 0.20$ <i>Moldauer Elastic Enhancement Factor = unknown</i>									
Local Parameters									
E_n	V	r_V	a_V	W_V	r_{W_V}	a_{W_V}	W_S	r_{W_S}	a_{W_S}
3.20	50.0	1.17	0.65	-	-	-	3.8	1.28	0.58
3.57	53.5	1.12	0.65	3.0	1.20	0.55	-	-	-
3.60	53.0	1.17	0.56	-	-	-	0.4	1.32	0.54
3.80	53.5	1.16	0.65	-	-	-	1.2	1.20	0.58
4.00	51.5	1.18	0.70	-	-	-	0.7	1.20	0.58
4.50	52.5	1.20	0.65	3.0	1.16	0.60	-	-	-
$V_{so} = 6.0$ $r_{so} = 1.20$ $a_{so} = 0.58$ $\beta_2 = 0.35$ $\beta_4 = 0.0$ <i>Moldauer Elastic Enhancement Factor = 1.4</i> <i>Rotationally Coupled Levels 0, 440, 2076, 2704 – keV</i>									

380 Details of reaction models are revealed in angular distributions. We start by
 considering our highest measured energy, 4.5 MeV (see Fig. 10). We utilize a
 slight variation from the optical model parameter set of Strohmaier and allow
 coupling to the first four levels of the ground-state band. The angle-integrated
 elastic cross section obtained in the calculation, 1.173 b, is consistent with our
 385 measured value, 1.15(04) b, and that obtained with the Koning and Delaroche
 prediction from the code EMPIRE [6] (see Fig.1). The agreement in the (n,n₁)
 channel is also excellent. The measured (n,n₂) channel is drastically smaller
 than the model calculations. This discrepancy is not unexpected as the (n,n₂)
 channel still exhibits somewhat isolated resonance behavior, which is apparent
 390 in the γ -ray excitation functions (see Fig. 7). The elastic scattering angular
 distribution is well described at forward angles, but the rise predicted after the
 main diffraction minimum near 130° is not observed in the data. This rise in
 the ECIS06 calculation may be because the Strohmaier-determined potential is

too strong for this energy. Weakening the potential slightly could shift the minimum out $\sim 10^\circ$, and then the apparent backward-angle rise would not occur. The (n,n_1) channel calculations have an appropriate balance between the direct and compound processes to well describe the measurements. For the (n,n_2) channel, an energy-averaged compound treatment is clearly too strong.

Table 3. Comparison of selected cross sections with ECIS06 calculations.

Neutron Energy (MeV)	Level Energy (MeV) J^π	ECIS06 $\sigma(n,n')$ (mb)	Measured $\sigma(n,n')$ (mb)	Measured $\sigma(n,n'\gamma)$ (mb)
~ 3.57	0.000, $3/2^+$	1333	1540(110)	
	0.440, $5/2^+$	393	395(32)	312(25)
	2.076, $7/2^+$	187	180(16)	175(14)
	2.703, $9/2^+$	52	-	41(3)
4.0	0.000, $3/2^+$	1465	1130(80)	
	0.440, $5/2^+$	335	310(25)	239(19)
	2.076, $7/2^+$	214	177(14)	172(14)
	2.703, $9/2^+$	97	-	72(6)
4.50	0.000, $3/2^+$	1172	1150(100)	
	0.440, $5/2^+$	253	248(22)	
	2.076, $7/2^+$	172	79(7)	
	2.703, $9/2^+$	87	-	

The agreements and discrepancies are similar at our next lowest energy, 4.00 MeV, as shown in Fig. 11. At this incident energy and below, the drop in the (n,n_1) cross section at $\theta > 120^\circ$ is apparent and is not an artifact of data analysis difficulties. This feature exists over a range of incident neutron energies and indicates direct coupling is important and not simply resonance interference effects. The strength of the (n,n_2) channel is well described, but this is likely fortuitous rather than a success of the reaction model.

Figure 12 displays ECIS06 calculations at 3.6 MeV along with measurements at two nearby energies. The data shown in this figure emphasize the residual effects of resonances. The magnitude of the elastic differential cross sections appear to be fluctuating about the optical model direct component, but the same angular decrease is observed experimentally. The rise after the diffrac-

Figure 10: Comparison of measured neutron scattering angular distributions and ECIS06 calculations at $E_n = 4.50$ MeV.

Figure 11: Comparison of measured angular distributions and ECIS06 calculations at $E_n = 4.00$ MeV.

Figure 12: Comparison of measured angular distributions at $E_n = 3.57$ and 3.60 MeV with ECIS06 calculations at $E_n \sim 3.60$ MeV. The (n,n_1) channel has two noticeably different angular distributions at neutron energies only 30 keV apart; the ECIS06 calculation reproduces the shape for $E_n = 3.57$ MeV.

tion minimum in the elastic angular distribution has disappeared. The strength
of the compound elastic process appears to be too large; however, this can be
modified in the calculations for ^{23}Na by altering the comprehensive Moldauer
elastic enhancement factor developed on a review of scattering over a large en-
ergy range. Thus a reduced enhancement factor is appropriate for this nucleus.
The strength of the (n,n_1) and (n,n_2) channels is reproduced adequately and
the impact of direct coupling in the (n,n_1) angular distribution is apparent.

In general, we find that the Strohmaier parameters [48] provide an ade-
quate description of the forward-angle elastic differential cross sections. The
compound elastic process, apparent at angles $> 90^\circ$, is too large in the default
calculation, indicating the imaginary potential should be substantially reduced.
Dispersive optical model calculations in this mass region also point to smaller

absorption at lower energies [49].

6. Summary

Elastic (n,n) and inelastic (n,n') differential cross sections and angle-integrated
430 $(n,n'\gamma)$ cross sections for scattering from ^{23}Na are reported. Angle-integrated
elastic $^{23}\text{Na}(n,n_0)$ cross sections agree with the ENDF/B-VII.1 [34] and JENDL-
4.0 [35] evaluations rather well, while the JEFF-3.1.2 [36] values are significantly
higher. Inelastic scattering cross sections from the ENDF library over-predict
435 the measured cross sections by $\sim 15\%$, while cross sections from the JEFF li-
brary under-predict the measured values by $\sim 15\%$. Our inelastic measurements
agree with the JENDL evaluations quite nicely. On the other hand, the angular
dependence of the (n,n_1) differential cross sections, particularly the suppression
or enhancement at forward versus backward angles, indicate the presence of
direct coupling. This is a result of the strong deformations known in the neigh-
440 boring nuclei in this mass region, which requires larger contributions of direct
processes to describe the inelastic channels at lower energies than is typical with
coupled-channel treatments.

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