Neutron Scattering Cross Section Measurements for ^{169}Tm via the (n,n') Technique

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Abstract. The neutron physics group at the University of Massachusetts Lowell (UML) has been involved in a program of scattering cross-section measurements for highly deformed nuclei such as ^{159}Tb, ^{169}Tm, ^{232}Th, ^{235}U, ^{238}U, and ^{239}Pu. Ko *et al.* have reported neutron inelastic scattering data from ^{169}Tm for states above 100 keV via the (n,n'γ) reaction at incident energies in the 0.2 MeV to 1.0 MeV range. In the present research, in which the time-of-flight method was employed, direct (n,n') measurements of neutrons scattered from ^{169}Tm in the 0.2 to 1.0 MeV range were taken. It requires that our 5.5-MeV Van de Graaff accelerator be operated in the pulsed and bunched beam mode producing subnanosecond pulses at a 5-MHz repetition frequency. Neutrons are produced by the $^7Li(p,n)^7Be$ reaction using a thin metallic elemental lithium target.

INTRODUCTION

It is well known that the nuclei near the A-160 region are highly deformed; their excited states configure themselves in a series of rotational and vibrational bands, which are coupled to single-particle levels in the case of odd-A nuclei. Neutron cross-section measurements for these nuclei provide data for developing a consistent theory covering the excitation of these levels, and for better understanding of nuclear properties, structures, and reaction mechanisms. Even though nuclei near the A-160 region are usually not used in nuclear reactors, they have similar level structures to actinides that are used in reactors. Therefore, the data obtained from these nuclei are also useful for testing reaction models for actinides.

(n,n'γ) And (n,n') Techniques

Direct measurements (n,n'), observing the scattered neutrons, and indirect measurements (n,n'γ), observing de-excitation gamma rays, are two common experimental techniques for measuring neutron scattering cross sections. The (n,n'γ) procedure involves two steps: 1) measuring each gamma-ray production cross section, and 2) from the known level scheme and branching ratios deducing the inelastic level cross sections. In the (n,n') approach cross sections are obtained from direct measurements of scattered neutrons by means of the time-of-flight method. The (n,n') measurements are complementary to the (n,n'γ) measurements and are especially useful in obtaining cross sections for the lower-lying levels.

For cross-section determination, the (n,n') method is considered more reliable since the scattered neutrons are directly measured. However in cases where the level density of the nuclei is high, the accurate determination of the inelastic cross section of each level by (n,n') becomes very difficult due to the conflict between neutron energy resolution and neutron yield. One of the advantages of the (n,n'γ) technique is that it is sensitive enough to measure cross sections near level thresholds. Near threshold measurements of de-excitation gamma rays are, in general, more sensitive than those of inelastic neutrons. The (n,n'γ) technique, however, is fraught with difficulties because the multipole character of the radiation must be known in order to determine internal conversion coefficients. For transitions between closely spaced levels internal conversion competes

CP769, *International Conference on Nuclear Data for Science and Technology,*
edited by R. C. Haight, M. B. Chadwick, T. Kawano, and P. Talou

strongly with γ-ray emission, so that their gamma-decay rates are often too small to measure. Therefore the measurements obtained via the (n,n') and (n,n'γ) techniques often complement each other .

Previous Neutron Scattering Measurements Of ^{169}Tm

In 1969, the gamma-ray spectrum from the ^{169}Tm(n,n'γ) reaction was measured by V. M. Romanenko *et al.* [1]. The γ-ray spectra were obtained and the de-excitation gamma rays were identified, but no inelastic or gamma production cross sections were reported. Measurements of neutron inelastic scattering cross sections for ^{169}Tm were made by Y. J. Ko [2] via the (n,n'γ) technique in 2000. The present research provides neutron scattering cross section measurements for ^{169}Tm via the (n,n') technique. Measurements such as these are particularly difficult because odd-A deformed nuclei like ^{169}Tm have many closely spaced excited nuclear states requiring premium resolution in the time-of-flight spectrometer.

TIME-OF-FLIGHT METHOD

The time-of-flight (TOF) method is employed in this research to obtain neutron scattering data directly in the form of time spectra. The flight time of the scattered neutrons for different energy levels could be calculated knowing the energy, mass and flight length of the neutron; therefore, neutron peaks in the TOF spectrum corresponding to different energy levels could be identified. The neutron TOF method at the University of Massachusetts Lowell requires that the Van de Graaff accelerator be operated in the pulsed and compressed beam mode. The proton beam generated by the ion source in the accelerator terminal is chopped into bursts of about 10 ns duration separated by 200 ns. The time duration of these bursts is reduced to less than 1 ns by a post-acceleration Mobley bunching system. Neutrons are produced by the ^{7}Li(p,n)^{7}Be reaction during the proton bombardment of a thin lithium target. It must be noted that since the proton beam pulses have a period of 200 ns, events separated in time by multiples of 200 ns are superimposed on one another in the time spectrum. Therefore gamma rays in the TOF spectrum can appear later than the elastic neutron peak, even though their flight time is much shorter. Figure 1 depicts the flight time of the elastically scattered neutrons and that of the first three exited states (8-keV, 118-keV, and 139-keV energy levels in which the flight distance from the thulium scatterer to the detector is chosen to be 130 cm so that the scattered neutrons are detected without interference from the prompt gamma rays. The incident neutron energy in this case is 600 keV.

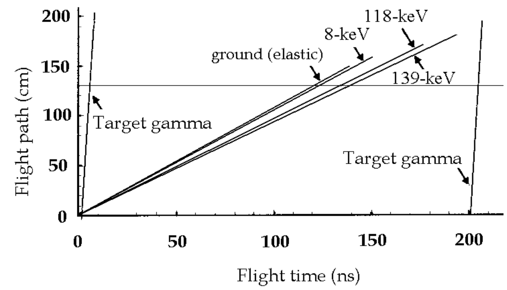

FIGURE 1. Neutron and γ-ray flight schedule. The horizontal line represents the flight path (130 cm) used in this experiment.

EXPERIMENTAL ARRANGEMENT

The experimental arrangement for the (n,n') measurements is shown in Figure 2.

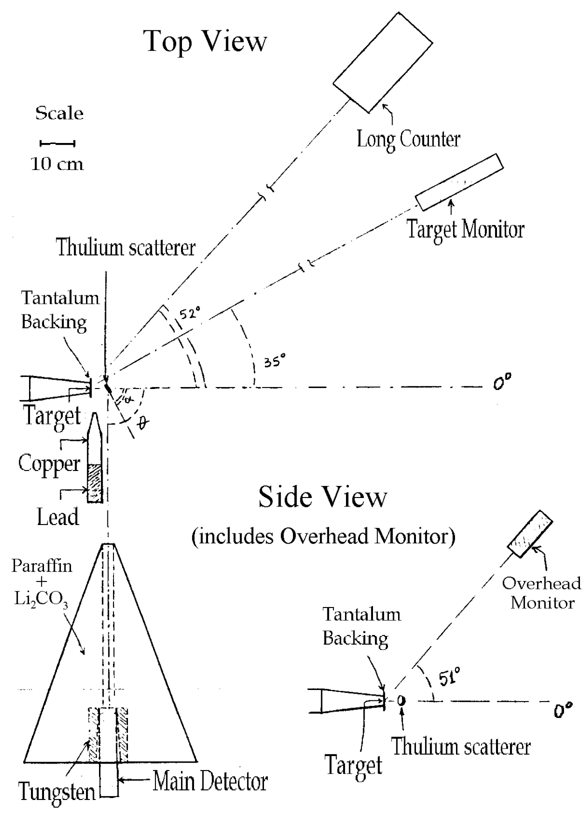

FIGURE 2. Schematic diagram of the experiment.

Four detectors were used in this experiment: the main detector, the overhead monitor, the target monitor, and the long counter. The main detector is used for detecting the scattered neutrons. It is also used to measure the incident neutron fluence. The overhead monitor is used for normalizing the scattering runs and incident fluence runs. The target monitor is used for monitoring the target thickness during the target making. The long counter is used for counting neutrons and serves as a back up counter for the overhead monitor.

Target Making

At the end of the beam line, a 0.04-cm-thick tantalum backing is placed. An electrically heated evaporator containing lithium metal, which is mounted inside the beam pipe, is used for making the lithium target. As lithium evaporates, and builds up on the tantalum, its film thickness is monitored by the target monitor by observing the TOF spectrum of the neutrons that are generated via the ^{7}Li(p,n)^{7}Be reaction when bombarded with a proton beam. The evaporation terminates when the desired thickness is obtained. Targets of 15-20 keV thickness are used for this experiment.

Neutron Scattering Measurements

Neutron scattering measurements were made for 600-keV incident neutron energy at angles 35°, 55°, 75°, 105°, 115°, and 125°. After each scattering run, a background run, in which the scatterer was taken out, was made. The duration of these scattering runs and background runs were about 6-8 hours each. Figure 3 shows the neutron TOF spectra at 600-keV incident neutron energy at angle 105° of a scattering and the corresponding background run along with the background subtracted TOF spectrum.

Before every scattering measurement the main detector was moved to zero degrees to measure the incident neutron fluence. Figure 4 shows the main detector TOF spectrum at zero degrees for 600-keV incident neutron energy with a flight path of 138 cm.

Since the same detector was used for measuring incident neutron fluence and scattered neutron fluence, only the relative efficiency of the detector is needed to determine the differential cross sections. The relative efficiency of the main detector is measured by comparison to that of a ^{235}U fission chamber.

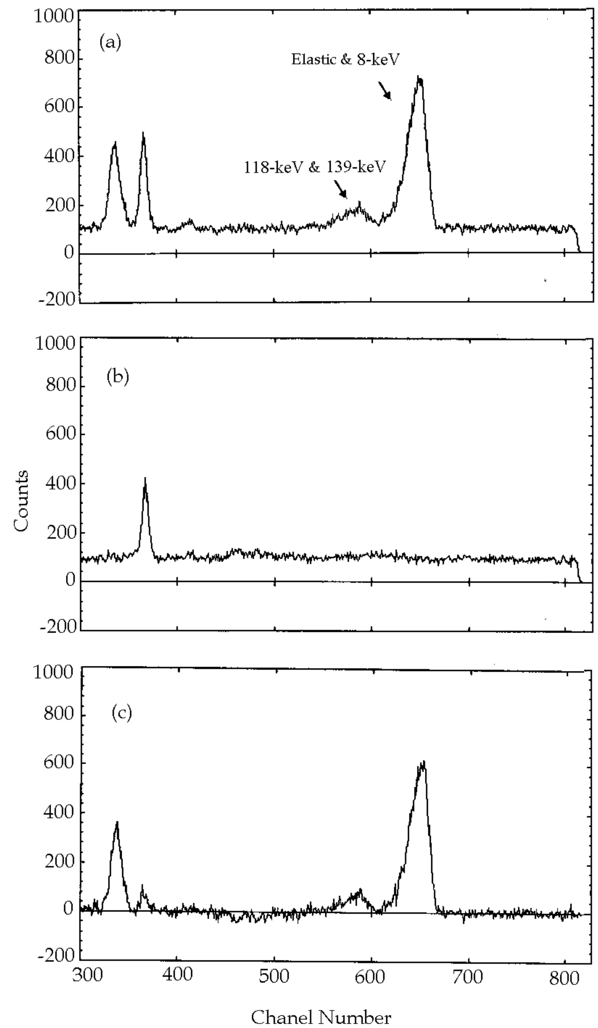

FIGURE 3. (a) Neutron TOF spectra for a 600-keV scattering run at angle 105°. (b) Corresponding background run. (c) Background subtracted neutron TOF spectrum. The flight path was 130 cm.

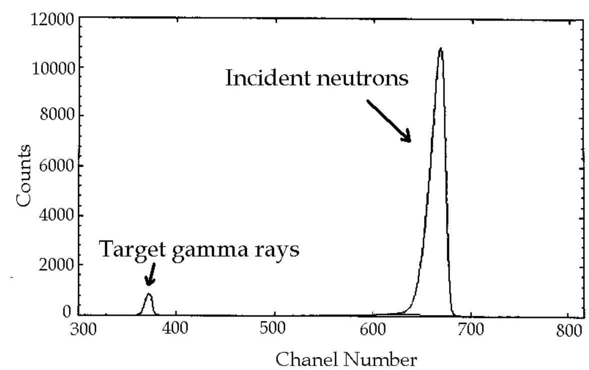

FIGURE 4. The main detector TOF spectrum at zero degrees for 600-keV incident neutron energy. The flight path was 138 cm.

DIFFERENTIAL CROSS-SECTION COMPUTATION

The differential cross section of the scattered neutrons at an arbitrary angle θ is

$$\frac{d\sigma(\theta)}{d\Omega} = \frac{y_s \eta_0}{y_0 \eta_1 C V}\left(\frac{R_s R_d}{R_s + R_d}\right)^2 \frac{\Psi}{\Phi} \quad , \qquad (1)$$

where y_s is the scattered neutron yield, y_0 is the incident neutron yield, η_0 is the main detector efficiency for incident neutrons, η_1 is the main detector efficiency of the scattered neutrons, C is the concentration of nuclei in the scatterer, V is the volume of the scatterer, R_s is the distance from scatterer to target, R_d is the distance from scatterer to main detector, Φ is the integral over the scatterer volume that takes into account neutron attenuation and the finite size of the scatterer [3], and Ψ is the multiple scattering correction factor [4].

PRELIMINARY RESULTS

The neutron scattering measurements on thulium are in progress. We show here preliminary results of cross-section measurements to date. The corrections for finite sample size, attenuation, and multiple scattering have yet to be applied. The detector efficiency for the inelastic neutrons is assumed to be the same as that for the elastic neutrons. Figure 5 shows the differential cross-section angular distribution for 600-keV incident neutrons for the combination of the $1/2^+$ ground state and the $3/2^+$ 8-keV first exited level.

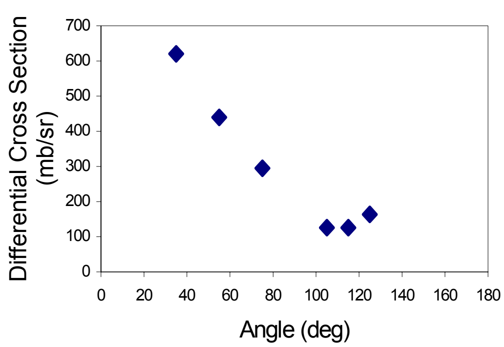

FIGURE 5. Differential cross section for elastically scattered neutrons (including the 8-keV level energy neutrons).

Figure 6 shows preliminary results for the combination of the $5/2^+$ 118-keV level and the $7/2^+$ 139-keV level.

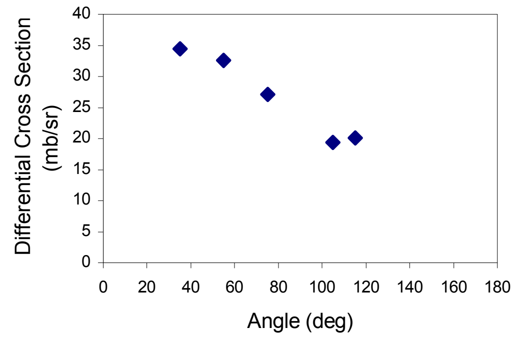

FIGURE 6. Differential cross section for 118-keV and 139-keV level energy neutrons.

The full scope of the project involves measurements at higher incident energies at 11 angles from 35º to 135º, concentrating on the low-lying levels in excitation. Comparison will be made with the (n,n'γ) result of Ko et al. [2]

ACKNOWLEDGMENTS

This work is supported in part by the United States Department of Energy.

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