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INELASTIC SCATTERING CROSS SECTIONS OF VIBRATIONAL STATES IN ^{232}Th FOR NEUTRONS FROM 2.3 TO 3.0 MeV

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Abstract: Neutron inelastic scattering measurements on ^{232}Th have been carried out in the incident neutron energy range 2.3 to 3.0 MeV. Cross sections have been obtained for the following vibrational levels or level groups: (714.2 + 730.3) keV; (774.1 + 774.4 + 785.2 + 829.5) keV; (872.7 + 883.3 + 889.6) keV; and 960.2 keV. In addition we have obtained cross sections for the 6^+ ground state rotational band level at 333.2 keV. Excitation functions have been measured at 125° in 100 keV steps, and angular distributions have been measured at 2.4 MeV over the angular range 25° to 135° in 10° steps. The data are compared to ENDF/B-V.

Introduction

In previous work[1, 2] the Lowell group has performed neutron inelastic scattering cross section measurements on the two even-A actinides ^{232}Th and ^{238}U for states above 600 keV in excitation at incident energies up to 2.1 MeV. These measurements on vibrational levels complement our work[3, 4] on the 0^+, 2^+ and 4^+ members of the ground state rotational bands in these nuclei. Theoretical analyses[3, 5] have shown the importance of the direct interaction contribution to the reaction mechanism for inelastic scattering from the ground state rotational band levels above 1.5 MeV incident energy. In our earlier work[1, 2] in which we measured angular distributions at 2.0 MeV on vibrational levels in the 600-1100 keV excitation energy range there is some evidence of a direct interaction contribution but the compound nucleus process still appears to predominate. However data at even higher excitation energies are needed in order to determine whether the direct interaction becomes the dominant reaction mechanism for these vibrational levels as it does for the ground state rotational band.

Two significant experimental difficulties must be addressed in order to make these measurements: (1) the levels are closely spaced and (2) the cross sections are small. These factors of course lead to inevitable trade-offs between resolution and neutron yield. In this experiment we have optimized various experimental parameters which enabled us to obtain cross sections for groups of levels as well as a few individual levels.

Figure 1 shows the level scheme of ^{232}Th up to 1 MeV. In the results which follow we show cross sections for three level groups: (714.2 + 730.3) keV; (774.1 + 774.4 + 785.2 + 829.5) keV; and (872.7, 883.3, and 889.6) keV. In addition we have measured cross sections for the gamma vibrational level at 960.2 and for the 333.2-keV state, the 6^+ member of the ground state rotational band. We have measured excitation functions at 125° for these states from 2.3 to 3.0 MeV in 100 keV steps and angular distributions at 2.4 MeV from 25° to 135° in 10° steps.

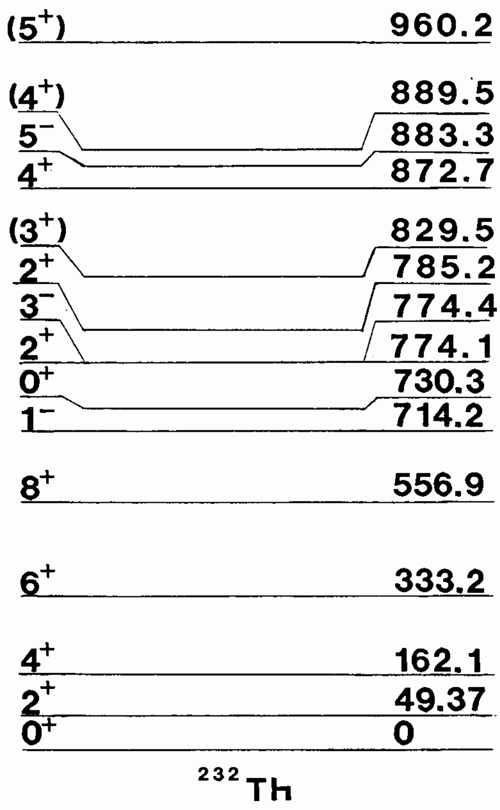

Fig. 1. Level scheme of ^{232}Th

Experiment

The data were taken using the neutron time-of-flight spectrometer at the University of Lowell 5.5 MV Van de Graaff Accelerator Laboratory. Neutrons were produced via the ^{7}Li(p,n)^{7}Be reaction in thin metallic lithium targets which were prepared in situ using a resistive heating evaporator incorporated into the target assembly of the accelerator beam pipe vacuum system. The proton beam was pulsed at a 5 MHz repetition rate and compressed via a Mobley bunching system to pulses of less than 0.5 ns duration. The thorium scattering sample was a circular disk of 3.67-cm diameter and 1.02-cm thickness with a mass of 124.7 g. A 5.5 percent by atom oxygen contamination was found to be present and care had to be exercised in order to account for elastic scattering peaks due to oxygen in the time of flight spectra.

At each energy and angle, spectra were taken on three scattering samples, ^{232}Th, ^{238}U and natural iron, all of which were disk-shaped and oriented with respect to the beam direction in such a way as to minimize the time spread due to neutrons scattered from different parts of the sample. The results of the ^{238}U measurements will be reported later. The iron measurements provided a standard against which to check our results in addition to providing standard spectral line shapes for neutrons and gamma rays.

Three time-of-flight systems were employed as in previous Lowell work.[1, 2, 3] The main detector consisted of a 1.27-cm thick NE213 liquid scintillator mounted on an RCA8854 photomultiplier tube. The other two detectors, employing plastic scintillators which have been described elsewhere,[1, 2] served as normalization monitor and target monitor.

The NE213 scintillator for the main detector was chosen, as opposed to the faster plastic scintillator used in our earlier work,[1,2] in order to take advantage of its n-γ discrimination capability in reducing gamma-ray background which becomes significant above 2 MeV. The n-γ discrimination circuit was a commercial version of the circuit of Sperr et al.[6], produced by Canberra Industries (Model Number 2160A). Time-of-flight spectra for neutrons and for gamma rays were accumulated simultaneously for each data run in order to ensure that the n-γ discrimination circuit was performing properly throughout the measurements. Figure 2 shows a typical ^{232}Th background subtracted time-of-flight spectrum taken at 2.4 MeV . The n-γ discriminator accounted for a five-fold reduction in the random background.

The scatterer to main detector flight path was 286 cm. The relative efficiency of the main detector was determined by comparison with a calibrated ^{235}U fission chamber. The main detector was moved to 0° in order to measure the incident fluence for each set of scattering runs.

Data Analysis

As can be seen in Figure 2 the neutron time-of-flight spectrum at these high incident energies is extremely complex. In order to obtain peak areas and thus cross sections careful unfolding techniques must be used. The details of these peak extraction techniques are the subject of another paper at this conference by the Lowell group (see Kegel, Aliyar, Chang, Egan, Horton and Mittler). The unfolding code we used was developed specifically for these studies. The technique relies on the fact that we were able to determine the location of a peak in our time-of-flight spectrum to within half of a channel or about 50 ps.

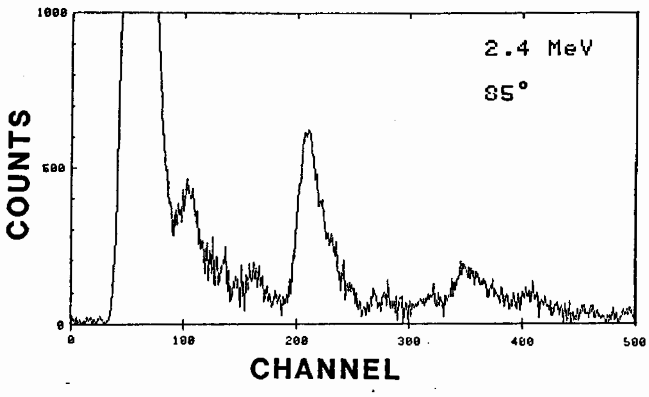

Fig. 2. Background subtracted neutron time-of-flight spectrum for ^{232}Th at 2.4 MeV and $\Theta = 85^{\circ}$.

The isolated peak shapes from the iron scattering measurements provided typical peak shapes for three neutron energies (elastic scattering of the first and second neutron groups from Li(p,n), inelastic scattering of the first group of neutrons from the 847 keV state in ^{56}Fe) and the prompt gamma peak. The neutron peaks all showed a tail on the late or low energy side while no tail was evident on the gamma-ray peak. This enabled us to generate a time-of-flight spectrum for scattering from ^{232}Th from which the tails of the neutron peaks have been removed. Such a spectrum is shown in Fig. 3 which was obtained from the spectrum of Fig. 2.

Reduced spectra such as that depicted in Fig. 3 were then unfolded using a sequence of programs: POSTH which generates the peak positions of all expected peaks in the thorium spectrum including those due to the second neutron group from Li(p,n) as well as "wrap-around" peaks; MAGE which generates a pseudo-Gaussian fit to the peaks in the iron spectrum (see Kegel et al., this conference); and BANGU which unfolds the spectrum giving peak areas and uncertainties. In BANGU the peak heights are allowed to vary in the fitting procedure but not the peak positions.

The solid line in Fig. 3 represents the fit to the spectrum obtained from BANGU. The locations of the levels contributing to the spectrum are shown with the excitation energies given in keV. Energies marked with an asterisk indicate peaks due to the second neutron group from the Li(p,n) reaction.

The data were corrected for finite sample size effects using the code IMBUI[7] and multiple scattering corrections were carried out using an order-of-scattering approach via the code GAVEA[4]. Both of these codes were written specifically for disk scatterer geometry.

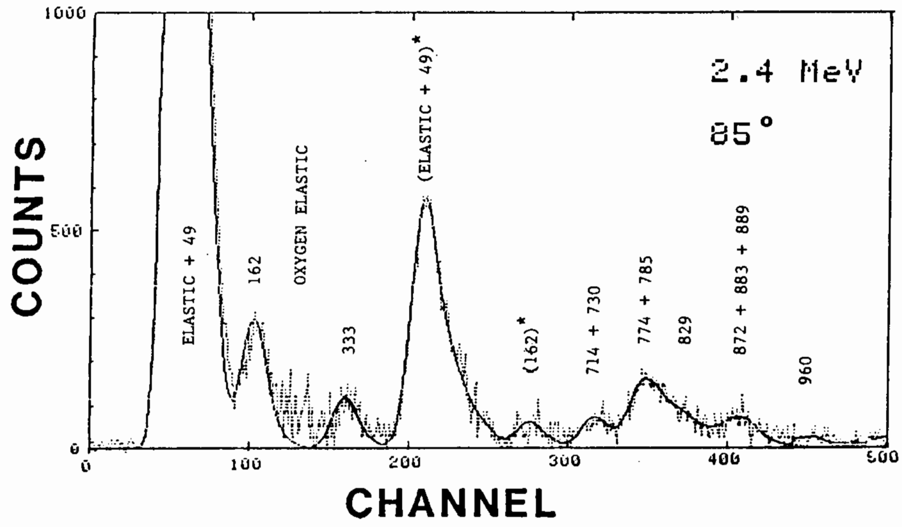

Fig. 3. Reduced neutron time-of-flight spectrum for ^{232}Th at 2.4 MeV, Θ = 85°. The line is the fitted spectrum from BANGU. Peaks labeled with asterisks are due to the second neutron group from Li(p,n).

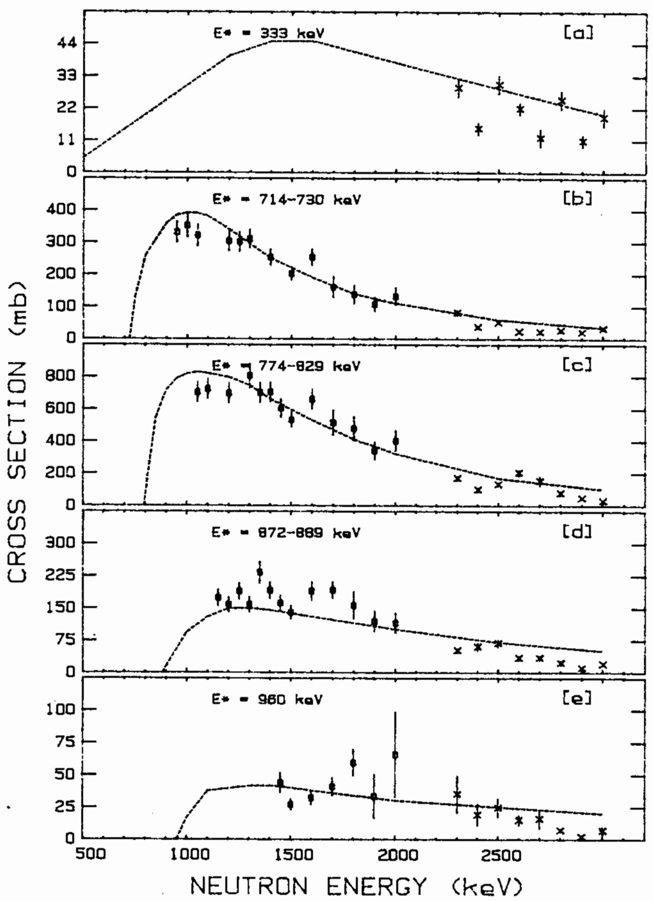

Fig. 4. Excitation functions for ^{232}Th inelastic scattering: (a) 333.2-keV level (b) 714.2 + 730.3 keV group (c) 774.1 + 774.4 + 785.2 + 829.5 keV group (d) 872.7 + 883.3 + 889.6 keV group (e) 960.2 keV level. The x's represent the present work. The o's represent the data of Ref. 1. The line is the ENDF/B-V evaluation.

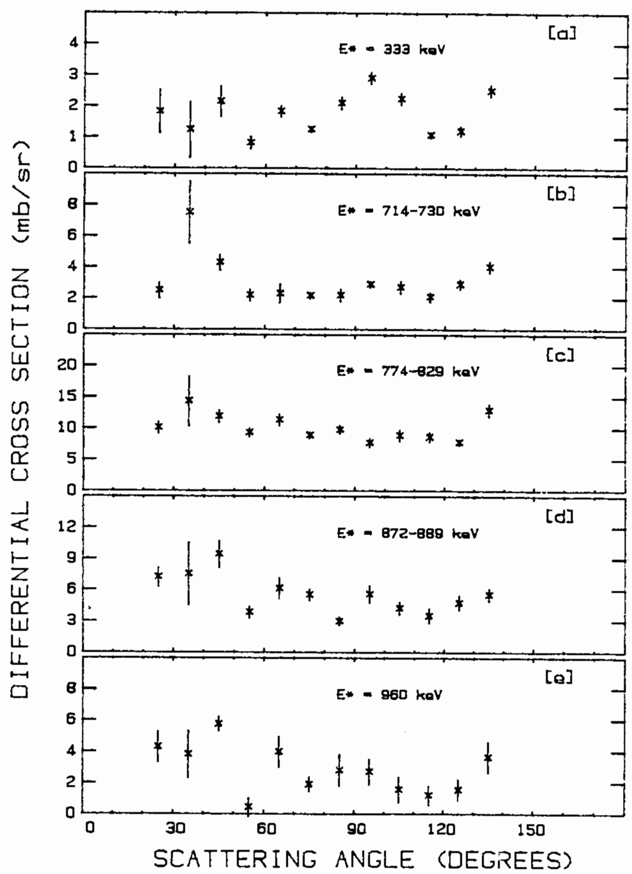

Fig. 5. Angular distributions at 2.4 MeV for the same levels and level groups as Fig. 4.

Results

Figure 4 shows our excitation function data for the 6^+, 333-keV level of the ground state rotational band; the 714 + 730-keV group, the 774 + 785 + 829-keV group, the 873 + 883 + 889-keV group; and the 960-keV level. The data up to 2.0 MeV are those of Ref. 1 while those above 2.0 MeV are from the present work. Integrated cross sections have been obtained from the 125^{o} differential cross sections by multiplying by 4π. This procedure appears to be justified based on the lack of asymmetry of the angular distributions shown in Fig. 5. The solid line is the ENDF/B-V evaluation.

Figure 5 shows the angular distributions obtained for these same levels or level groups at 2.4 MeV. Although the cross sections are small with considerable uncertainties the angular distributions do not exhibit substantial asymmetry. This result is consistent with our 2.0-MeV angular distribution data.

Conclusion

It must be emphasized that we regard the data reported here in as preliminary. Further analysis is in progress. We have measured a second set of angular distribution data at 2.8 MeV as well as a complete companion set of data on ^{238}U. These results will be reported in the near future.

Acknowledgements

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