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"Fast Neutron Capture with a White Neutron Source"

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Abstract

A system has been developed at the Los Alamos National Laboratory to measure gamma-rays following fast neutron reactions. The neutron beam is produced by bombarding a thick tantalum target with the 800 MeV proton beam from the LAMPF accelerator. Incident neutron energies, from 1 to over 200 MeV, are determined by their times of flight over a 7.6-m flight path. The gamma-rays are detected in five 7.6 x 7.6-cm cylindrical bismuth germanate (BGO) detectors which span an angular range from 45° to 145° in the reaction plane. With this system it is possible to simultaneously measure the cross section and angular distribution of gamma-rays as a function of neutron energy. The results for the cross section of the $^{12}\text{C}(n,n'\gamma=4.44 \text{ MeV})$ reaction at 90° and 125° show good agreement with previous measurements, while the complete angular distributions show the need for a large a_4 coefficient which was not previously observed. Preliminary results for the $^{12}\text{C}(n,n'\gamma=15.1 \text{ MeV})$ reaction have also been obtained. The data obtained for the $^{40}\text{Ca}(n,\gamma_0)$ reaction in the region of the giant dipole resonance demonstrate the unique capabilities of this system. Future developments to the neutron source which will enhance the capabilities of the system will be presented.

1. Introduction

In this paper we will describe a system recently constructed at the Los Alamos National Laboratory to study γ -rays following fast neutron induced reactions. The system consists of a pulsed spallation neutron source and an array of five bismuth germanate (BGO) scintillators. The basic system has been described previously¹ so we will concentrate mainly on the modifications implemented during the past year. We will present some preliminary results on the $^{12}\text{C}(n,n'\gamma=4.44 \text{ MeV})$, $^{12}\text{C}(n,n'\gamma=15.1 \text{ MeV})$ and the $^{40}\text{Ca}(n,\gamma_0)$ reactions that show the capabilities of this system. We will conclude the paper with a description of a proposed upgrade to the neutron production source that will significantly enhance the performance of the system.

2. Neutron Source

The neutron beam is produced by a spallation reaction of the 800 MeV proton beam from the Los Alamos Meson Physics Facility (LAMPF) on a thick tantalum cylinder. The time structure of the beam consists of macro-pulses with a repetition rate of 12 Hz and micro-pulses within each macro-pulse. Each macro-pulse is approximately 700 μsec wide and is made up of sharp (less than 300

psec wide) micro-pulses whose separation can be varied from 1 μ sec to over 500 μ sec. This produces a maximum pulse rate of approximately 8,400 proton pulses/second. The number of neutrons/sr/sec for one μ amp of proton beam is plotted as a function of neutron energy in Fig. 1. Typical proton beam currents are 70 namps.

The collimation of the neutron beam from the tantalum production target to the sample is shown in Fig. 2. The major changes to the system have been: 1. the removal of the concrete shielding wall behind the detector stand, 2. the removal of a significant amount of lead shielding from around the magnet trough and, 3. the installation of a fission chamber in the neutron beam. The first two improvements have reduced the backgrounds in the detectors. The fission chamber monitors the neutron flux by measuring the fission yield from a thin ^{235}U foil. The fission chamber, located at 5.9 m from the neutron production target, is shielded from the detectors so that it does not significantly contribute to the background. The sample is located 7.6 m from the neutron production target. With this flight path the neutron energy resolution, which is dominated by the time resolution of the detector system, is approximately 200 keV at 10 MeV. There are no filters or absorbers in the neutron beam, and the beam is stopped 80 m downstream from the sample.

Figure 1. The neutron flux (neutrons/sr/MeV/ μ amp) as a function of neutron energy. Typical proton beam currents are 70 namps.

3. Detector System

The detector system consists of five 7.6 x 7.6-cm cylindrical BGO scintillators. A more complete description of the characteristics of BGO detectors is given in ref. 1. The detectors were placed 35.5 cm from the center of the sample at angles of 145, 125, 90, 55, and 45 degrees. Approximately 12 cm of ^6LiD was placed in front of each detector to scatter neutrons away from the BGO crystal, and each detector was surrounded by approximately 1 cm of lead. The time resolution of the system was measured to be 1.6 nsec for gamma-ray energies greater than 2.0 MeV.

Data from each detector were stored in a 512-by 512-channel two dimensional array of neutron time-of-flight versus gamma-ray pulse height. The 1.25 megawords of data were recorded on magnetic tape at four hour intervals during each run to monitor the progress and stability of the run.

Figure 2. Experimental setup showing collimation of neutron beam and location of detector system.

4. Data analysis

The processing of the data is performed in several stages. The time independent background (i.e., thermal neutron capture in the detector, gamma-rays following thermal capture, or cosmic rays) was removed by subtracting out the pulse height spectrum associated with neutron flight times preceeding the gamma flash. The data were corrected for time correlated backgrounds (i.e., neutrons scattered from the sample directly into the detector) by measuring the pulse height spectrum of a Be sample and subtracting it from the data. Be was chosen because of its small gamma-ray production

cross section. The data were corrected for the energy dependence of the incident neutron flux and the variable neutron energy bin widths. The data were binned into appropriate neutron and gamma-ray bins. Monte-Carlo techniques were used to determine the effective sample thickness including neutron absorption. No corrections were made for gamma-ray attenuation in the sample.

The detector response was removed from the pulse height spectrum using the unfolding code "FERD" ². The response matrix required by the unfolding code for each detector was calculated using the Monte-Carlo radiation transport code "CYLTRAN" ³ and was measured using the mono-energetic tagged photon facility at the University of Illinois. The measured line shape for a 10 MeV gamma-ray in our detector is shown in Fig. 3. The solid line represents the calculated response function ⁴. The full width at half maximum is approximately 10%. The response matrix also contains the efficiency and solid angle for each detector. The unfolded spectrum was fit to a sum of gaussian functions. The area under each gaussian is the differential cross section at that gamma-ray and neutron energy.

To calibrate the absolute efficiency of the fission chamber neutron monitor, we normalized our $^{12}\text{C}(n,n'\gamma=4.44\text{ MeV})$ at 90° and 125° to data taken at the Oak Ridge Electron Linear Accelerator (ORELA) by Dickens et. al. ⁵. The relative flux is based on the $^{235}\text{U}(n,f)$ cross section given in the ENDF/B-IV data set.

Figure 3. Response function for a 10 MeV gamma-ray in our 125° 7.6 x 7.6-cm BGO detector. The squares are the measured data, the line represents the calculated line shape.

Figure 4. a. Cross section, b. a_2 coefficient, and c. a_4 coefficient for the $^{12}\text{C}(n,n'\gamma=4.44\text{ MeV})$ reaction as a function of incident neutron energy.

Figure 5. a. Cross section (ref 7), b. a_2 coefficient, and c. a_4 coefficient for the $^{12}\text{C}(p,p'\gamma=4.44\text{ MeV})$ reaction as a function of incident proton energy. The connected points are from ref. 8, and the circles are from ref. 9.

5. Results and Discussion

Data were obtained over a 12 hour period for the $^{12}\text{C}(n,n'\gamma)$ reaction. The sample consisted of a 2.54-cm-diam, 5.08-cm-long cylinder of natural carbon weighing 48 grams. Fig. 4a shows the integrated cross section for the 4.44 MeV gamma-ray for neutron energies from threshold up to 25 MeV. The shapes of the 90° and 125° cross sections agree very well with the ORELA results. The data were fit to an expansion in Legendre polynomials including terms to a_4 . The a_2 coefficients are shown in Fig. 4b and the a_4 coefficients are shown in Fig 4c.

Our results for the a_2 coefficients are different from the evaluated 6 ORELA results because we measured enough angles to fit the angular distributions to terms including a_4 . The previous data on this reaction were obtained at only two angles so the determination of a_4 was not possible. The present results do not give the unphysically large values for the a_2 coefficients that were present in the ORELA data. As seen from Fig 4c the values of the a_4 coefficients are large, ranging from -1.0 to +0.5, confirming the problem with the ORELA results.

Figure 6. The cross section for the $^{12}\text{C}(n, n' \gamma = 4.44 \text{ MeV})$ reaction for incident neutron energies from threshold to 200 MeV.

Figure 7. a. Cross section, b. a_2 coefficient for the $^{12}\text{C}(n,n'\gamma=15.1\text{ MeV})$ reaction plotted as a function of neutron energy.

Figure 8. a. Cross section, b. a_2 coefficient for the $^{12}\text{C}(p,p'\gamma=15.1\text{ MeV})$ reaction. the connected point are from ref. 11, the triangles are from ref. 12 and the circles are from are the 90° differential cross section from ref. 13.

It is interesting to compare our results with those for inelastic proton excitation of the 4.44 MeV level. The $^{12}\text{C}(p,p'\gamma=4.44 \text{ MeV})$ results are shown in Fig. 5 for: a. the cross section, b. the a_2 ,^{8,9} and c. the a_4 ,^{8,9} coefficients. If we shift the proton energy scale up 3 MeV to account for the difference in binding energies between ^{13}C and ^{13}N , we see good agreement for the compound resonances in these nuclei. In particular, the cross sections are remarkably similar and much of the structure observed in the cross section and angular distribution coefficients is present in both reactions.

The excitation function for the $^{12}\text{C}(n,n'\gamma=4.44 \text{ MeV})$ reaction from threshold up to 200 MeV is plotted in Fig. 6. Suggestions of broad structures are evident around 20 MeV. Similar structure has been observed in proton inelastic scattering to this level.¹⁰

The $^{12}\text{C}(n,n'\gamma=15.1 \text{ MeV})$ results are shown in Fig. 7, and the $^{12}\text{C}(p,p'\gamma=15.1 \text{ MeV})$ ^{11,12,13} results are shown in Fig 8. In contrast to the 4.44 MeV data, where the cross section over the low energy resonances has similar magnitudes, the 15 MeV cross section is approximately a factor of four less in the neutron reaction than in the proton reaction. Only above 25 MeV are the cross sections similar. Also shown in Fig. 7b are the a_2 coefficients obtained from fitting our data. The a_2 coefficients for the proton reaction are shown in Fig. 8b. In this case, as in the case of the 4.44 MeV transition, the angular distribution coefficients are in good agreement when the proton energy scale is shifted by approximately 1.5 MeV.

Figure 9. The 90° differential cross section for the $^{40}\text{Ca}(n, \gamma_0)$ reaction.

The $^{40}\text{Ca}(n,\gamma_0)$ reaction was chosen for study because it has been previously investigated¹⁴ and would allow us to evaluate our system for fast neutron capture. Because the cross section for this reaction at the peak of the giant dipole resonance is approximately four orders of magnitude smaller than the cross section for the inelastic excitation of the 4.44 MeV state in ^{12}C , a larger (159 gram) sample was used and the opening of the neutron beam collimator was increased to raise the neutron flux at the sample. The 90° differential cross section is plotted in Fig. 9 where we have normalized our data to previous measurements.¹⁴ The data shown were acquired in approximately 48 hours. The shape agrees very well with previous measurements.

6. Future plans

At present the major limitation of this system is the low pulse rate. To acquire data in a reasonable amount of time, a large instantaneous count rate is required which results in pulse pile-up problems. A new beam transport system and a new neutron production target are being planned that will allow a factor of five increase in the number of macro-pulses/sec and raise the maximum micro-pulse rate to approximately 42,000 proton pulses/sec. This will increase our data rate a factor of five without increasing pulse-pile up. In addition, this new target position will allow viewing the production target at angles more forward to the incident proton beam. This will result in a greater flux (approximately a factor of two at 50 MeV) of high energy neutrons with a correspondingly smaller increase in low energy neutrons. The intensity in each micro-pulse will be increased by a factor of five which will allow us to increase our flight path with a corresponding improvement in neutron energy resolution. At present the beam time at the facility is shared with condensed matter experiments, with nuclear physics experiments receiving somewhat less than 20% of the available time. In the new configuration it should be possible to multiplex the proton beam and run simultaneously with the condensed matter experiments. This will increase the available running time for fast neutron physics by a factor of five. Therefore, the overall improvement in the system including pulse rate, beam intensity, and available running time should be at least a factor of 50.

7. Conclusions

The use of a white neutron source in conjunction with an array of detectors has shown itself to be a powerful tool for studying neutron induced gamma-ray reactions. We have shown that high quality data can be obtained in a short time over a wide energy range on inelastic gamma-ray cross sections and angular distributions. We are presently able to perform fast neutron capture measurements but, with the planned upgrade to the neutron source, the ability of doing these types of measurements will be greatly enhanced.

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