

U.S. Nuclear Data Measurement Activities

Argonne Nuclear Data Activities

Donald L. Smith
Technology Development Division
Argonne National Laboratory
Argonne, Illinois 60439
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Abstract

A compilation of information from the literature on the $^{33}\text{P}(p,\epsilon)^{32}\text{S}$ reaction was completed and presented in an ANL report. An investigation was conducted concerning an appropriate method for representing large errors in astrophysical reaction rates. It was concluded that the proper statistics was the log-normal distribution. Data acquired at JAERI on ^{238}U photo-fission by 6 MeV gamma rays from ^{16}N were analyzed and a journal paper was prepared and accepted for publication. A paper reporting on the examination of hydrogen-producing reaction cross sections for vanadium was published. Work on the production of radioactive ^7Be from neutron-induced sequential charged-particle reactions on lithium was reported at a conference on materials for nuclear fusion. An experimental investigation of 6 MeV g-ray production via the $^{19}\text{F}(p,\alpha)^{16}\text{O}$ reaction from thick CaF_2 and MgF_2 targets was completed and a paper reporting on the yield and angular distribution results has been accepted for publication. Use of these gamma rays for the detection of sensitive nuclear weapons materials has been investigated. Preliminary results from this work are promising. Measurements of neutron activation cross sections from 16–20 MeV for several new materials were completed at IRMM. A journal article that reports on earlier measurements in this project was published. Finally, a nuclear model parameter sensitivity study has been initiated. Results have been obtained for Cr and V and a paper reporting on this work is in preparation.

Neutron Activation Cross Sections

A journal paper reporting the results of neutron activation cross section measurements during 1996–1998 over the range 16–20 MeV for a variety of materials has been published. A new set of measurements was performed in September/October 1999 at IRMM, Geel, Belgium. This work is part of an on-going collaboration. Data analysis will commence later during FY2000.

Astrophysical Studies

Information on the $^{31}\text{P}(p,\epsilon)^{32}\text{S}$ reaction has been compiled from the literature in preparation for a comprehensive evaluation of this process. The results of this work are collected in Argonne National Laboratory Report ANL/NDM-140. It is available in

printed form and from the Internet at <http://www.td.ornl.gov/reports/ANLNDMReports.html>. An investigation was conducted in collaboration with ORNL to determine the proper statistical representation for large errors in astrophysical nuclear reaction rates. It was concluded that the log-normal probability distribution was appropriate for this purpose.

Gamma Rays from $^{19}\text{F}(p,\alpha)^{16}\text{O}$

This reaction is a prolific source of 6 MeV γ -rays when fluorine compound targets are bombarded with protons. Thick-target γ -ray yields and angular distributions resulting from 1.5–4.0 MeV proton bombardment of MgF_2 and CaF_2 were measured in collaboration with Ohio University. A journal paper on the results from this investigation has been accepted for publication. The possibility of employing this radiation source as a means to detect significant quantities of hidden nuclear weapons materials such as deuterium, beryllium, uranium, etc., has been investigated. Preliminary results from this work are encouraging. Significant neutron yields above background, due to $((n,n)$ and $((n,f)$ reactions, were observed while tested benign materials gave no significant signal.

Vanadium Hydrogen Production

The production of hydrogen in vanadium by fusion neutrons was investigated and reported in an earlier progress report. A journal paper on this work has been published.

Production of Radioactive ^7Be by Sequential Nuclear Reactions on Lithium

Measurements were performed at JAERI, Tokai, Japan, on the generation of radioactive ^7Be in bulk lithium exposed to 14-MeV neutrons from nuclear fusion. The production of ^7Be involves sequential nuclear reactions. Neutrons initiate the procedure while the second stage involves charged particles generated by primary neutron reactions. Good agreement between experiment and calculations was observed. Results from this work were reported at a conference on fusion nuclear materials in October 1999.

Parameter Sensitivity Studies for the Development of Nuclear Models

Working with an experimental database acquired from the ANL/IRMM collaboration —augmented with results from the literature —nuclear model calculations are being performed using the statistical/pre-compound reaction code STAPRE. The objective is to identify those sets of parameters that yield good fits to the data. Then, sensitivity parameters are calculated to examine how the results of nuclear model calculations, e.g., the selection of parameters, can be influenced by experimental data. This —in turn —provides useful guidance on the need for new measurements to better determine cross-section excitation functions. Results have been obtained to date on neutron reactions for chromium and vanadium from threshold to 20 MeV.

Nuclear Data Activities at LANSCE

Robert C. Haight and Ronald O. Nelson
Group LANSCE-3
Los Alamos National Laboratory
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ABSTRACT

Neutron total cross sections have been measured from 5 to 560 MeV on 31 elements and isotopes. For nearly all of the target materials, the data are accurate to better than 1% (both statistical and systematic) in 1% neutron energy bins. Neutron-induced photon production cross section measurements for oxygen have been completed from 4 to 200 MeV. Gamma-ray production cross sections on ^{235}U , ^{238}U and ^{239}Pu are in progress to with the goal of deducing (n,xn) ($x=1,2,3$) reaction cross sections. Fission-fragment yields are also being determined from these data. A new array, FIGARO, of high resolution gamma-ray detectors has been commissioned to study angular-momentum effects in nuclear reactions; data for discrete transitions following (n,xn) , (n,xp) and $(n,x\alpha)$ reactions on ^{59}Co are being analyzed. Neutron reactions that yield light charged particles have been completed for silicon and the results analyzed in terms of nuclear level densities and the effect of isospin conservation. Similar studies are in progress for $^{92,94,96}\text{Mo}$ over the neutron energy range from threshold to 60 MeV. A program of measurements of neutron capture on radioactive targets is in progress and a large $4-\pi$ detector of the capture gamma rays has been designed.

Neutron Total Cross Sections up to 560 MeV

We have completed a new set of total cross section measurements of 31 elements and isotopes spanning the periodic table. These measurements were supported by the Accelerator Production of Tritium (APT) project as part of a program to improve the physics in the modeling codes for neutron transport up to several hundred MeV. We employed the same techniques as used by Finlay et al. [Phys. Rev. C47, 237 (1993)] with refinements intended to allow measurements on separated isotopes and improved systematic error control. The goal of the new measurement was 1% statistical accuracy in 1% energy bins with systematic errors less than 1%. This was achieved for all but the smallest samples, for

which the statistical accuracy was as large as 3% in 1% bins, and for two isotopic samples where the systematic uncertainties measured up to 3.7%. Stringent checks of systematic errors in this measurement resulted in a reassignment of systematic uncertainties in the previous measurements by Finlay et al. The new data, along with those of Finlay et al., are being used in the development of a global optical potential from 20 to 2000 MeV, and the development of a simple parameterization of the total cross section based on a Ramsauer model. The total neutron cross sections for few nucleon systems ($n+d$ and $n+p$) are also used to test Faddeev calculations.

Neutron-Induced Photon Production Cross Sections for Oxygen

Photon-production cross sections for neutron-induced reactions on oxygen have been measured over the incident neutron-energy range from 4 to 200 MeV using a BeO sample. The data were taken using the WNR spallation neutron source. Two HPGe detectors were used to measure gamma rays in the range from 150 keV to 8.9 MeV at seven angles. Excitation functions and angular-distribution data have been extracted for 23 γ rays produced in neutron-induced reactions on oxygen and one γ ray from the ${}^9\text{Be}(n,t){}^7\text{Li}$ reaction. Good agreement is observed with some of the previous gamma-ray measurements, although there is a wide spread in the cross section values. A reevaluation of the oxygen cross sections based on the new data has been completed. As part of the evaluation of the data, neutron scattering cross sections were inferred. Good agreement with neutron scattering measurements is obtained. At neutron energies higher than 20 MeV comparison with GNASH model calculations have been performed. A paper is in preparation for submission to Nuclear Science and Engineering.

Measurement of partial gamma ray cross sections on U and Pu

Neutron-induced gamma-ray production cross section data have been obtained at the WNR spallation neutron source for samples of ${}^{235}\text{U}$, ${}^{238}\text{U}$, and ${}^{239}\text{Pu}$ with the GEANIE spectrometer as a joint LLNL and LANL endeavor. GEANIE consists of 26 HPGe detectors, 20 of which are escape suppressed with BGO shields. Data have been obtained for both (n,xn) and (n,f) reactions. Analysis of the data to determine cross sections for (n,xn) ($x=1,2,3..$) reactions is nearing completion.

Neutron-Induced Photon Production Cross Sections for Cobalt

The new FIGARO (Fast neutron-Induced Gamma-Ray Observer) array of high resolution gamma-ray detectors has made its first measurements of gamma rays emitted from cobalt bombarded with neutrons from 1 to 200 MeV. Data for discrete transitions following (n,xn) , (n,xp) and $(n,x\alpha)$ reactions on ${}^{59}\text{Co}$ are being analyzed and will be compared with nuclear reaction model calculations previously used to interpret ${}^{59}\text{Co}(n,x\alpha)$ data taken previously here [S. M. Grimes, C. E. Brient, F. C. Goeckner, F. B. Boteman, M. B. Chadwick, R. C. Haight, T.

M. Lee, S. M. Sterbenz, P. G. Young, O. A. Wasson, and H. Vonach, Nucl. Sci. Eng. 124, 271 (1996)]. Angular moment effects as indicated by the gamma-ray data are being investigated. For the next running period, FIGARO will be upgraded with the addition of neutron detectors for $(n,xn+y\gamma)$ studies and conversion electron spectrometers, the latter on loan from the University of Pittsburgh.

Si(n,xp), (n,xd) and (n,xalpha) Reactions

Inclusive light charged-particle emission spectra and cross sections from neutron bombardment of silicon were measured at 30, 60, 90 and 135 degrees over the neutron energy range from threshold to approximately 60 MeV. Comparisons of our alpha-particle data with Hauser-Feshbach calculations, which include multi-stage emission processes and pre-equilibrium particle emission, indicate that the majority of alpha particles result from compound nuclear reactions. For proton and deuteron emission, direct and pre-equilibrium processes contribute significantly to the emission cross section. These data provide rigorous tests for the calculations while helping to guide the selection of input parameters such as nuclear level densities. The effects of assuming partial or complete isospin conservation are shown to be important for these reactions.

^{92,94,96}Mo(n,xp), (n,xd) and (n,xalpha) Reactions

Previous measurements of charged-particle emission in 15-MeV-neutron-induced reactions on molybdenum isotopes yielded data that were difficult to explain by conventional statistical and pre-equilibrium reaction models. [R. C. Haight, S. M. Grimes, R. G. Johnson, and H. H. Barschall, Phys. Rev. C23, 700 (1981).] With the goal of a better understanding of these reactions, measurements have been made at WNR from threshold to 60 MeV incident neutron energy. The wide range of neutron energies should permit a much better separation of contributions from the different reaction mechanisms. The data are presently being analyzed.

Neutron capture on radioactive targets: probing the s-process

Abstract presented at the Second International Conference on Fission and Neutron-rich Nuclei, University of St. Andrews, Scotland, June 28 to July 2, 1999, by J.B. Wilhelmy, M. M. Fowler, R. C. Haight, G. G. Miller, R. S. Rundberg, E. H. Seabury, J. L. Ullmann, (LANL) and M. Heil, F. Kaeppler, R. Reifarth, F. Voss, and K. Wisshak (Karlsruhe):

The pioneering work of Burbidge, Burbidge, Fowler and Hoyle (BBFH) in 1957 outlined the basic mechanism for heavy element nucleosynthesis in the stellar environment. However, some specifics of the s-process remain poorly determined. Central to these is an understanding of the ..branching point.. nuclei. These are isotopes that have half-lives such that there is a competition between beta decay and neutron capture. Such isotopes have a critical role in understanding the stellar temperature and neutron density and

thus the dynamics of nucleosynthesis. At Los Alamos we have begun a program to irradiate radioactive targets and measure the differential capture reactions that are required to unfold the details of stellar evolution. This program utilizes the high fluence available at the LANSCE neutron spallation source to investigate targets having mass on the order of 1 mg. The radioactive target material is obtained via spallation reactions at high intensity accelerators or from irradiations at nuclear reactors. For purification and preparation of the target material, we have dedicated chemical and isotope separator capabilities housed in hot cell environments. A 162-element 4π BaF₂ detector array that will permit highly segmented, calorimetric measurements on capture gamma rays is being procured for this program.

Nuclear Data Activities at UML

G. Kegel
University of Massachusetts, Lowell

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The $(n,n'\gamma)$ -technique has been used to measure gamma production cross sections and to obtain inferred level cross sections for thulium-169. The experimental results are in good agreement with theoretical calculations by P. Young. A joint UML–Los Alamos paper has been accepted for publication in Nuclear Physics A. (Y. J. Ko et al.)

Total neutron cross sections have been measured for Al-27, Tb-159, Tm-169, and U-235 in the 200-to-400-keV range. Most results are in good agreement with ENDF evaluations, where available. Data for U-235 are lower than the evaluation; this discrepancy is under investigation. (P.-N. Seo et al.)

Both, the $(n,n'\gamma)$ and the (n,n') techniques have been used to measure gamma excitation functions and neutron angular distributions in Tb-159. Data acquisition and reduction are in progress at this time. (P.-N. Seo et al.)

The distribution function governing the number of prompt fission gamma rays is studied by measuring double, triple, and quadruple coincidences of prompt gamma rays emitted by a fissioning nucleus. The theoretical study has been completed and the experimental part has been initiated. (C. Ji et al.)

NIST Nuclear Data Activities

Allan D. Carlson
Ionizing Radiation Division
National Institute of Standards & Technology

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Measurements have been completed of the hydrogen scattering cross section in a Ohio University–NIST–LANL collaborative experiment. These measurements were made at 10 MeV neutron energy at the Ohio University Accelerator Laboratory. The $D(d,n)$ neutron source reaction with a gas target cell was used as the neutron source. The differential cross section was measured at 11 angles simultaneously with ${}^3\text{He}$ –E detector telescopes at each angle. This removes problems associated with the very accurate monitoring of the neutron beam intensity which was required with a number of previous experiments for which data were taken one angle at a time. Measurements were made at laboratory angles of 0° , and at equivalent angles on both sides of the neutron beam axis of $\pm 12^\circ$, $\pm 24^\circ$, $\pm 36^\circ$, $\pm 48^\circ$ and $\pm 60^\circ$ in order to provide consistency checks on the results. These angles correspond to the range from 180° to 60° in the center of mass system. The data have been analyzed. The results, which have uncertainties of about 1%, are in best agreement with an evaluation by Arndt. Plans are being made for an extension of this experiment to 14 MeV neutron energy to allow direct comparisons with the data sets which caused the large cross sections at back angles in the CMS for the ENDF/B–VI evaluation.

The most accurate measurements of coherent scattering lengths have been made using a special neutron interferometer at the NIST Neutron Interferometry and Optics Facility. Measurements have been made for silicon and ${}^{208}\text{Pb}$. For silicon, the coherent scattering length was determined to an accuracy of 0.005% which is an improvement of a factor of 5 in accuracy compared with the best previous measurement. The coherent scattering length is related to the phase shift and can be used directly in certain analysis codes, such as R-matrix analyses, for evaluation of nuclear cross sections. They were used in the $\text{H}(n,n)$ evaluation by Hale and in the ${}^{235}\text{U}(n,f)$ evaluation work by Moxon.

A cryogenic calorimeter has been built so that more accurate determinations of the neutron fluence can be obtained. With the calorimeter the neutron fluence is determined from the heat produced from the ${}^6\text{Li}(n,t){}^4\text{He}$ reaction by monoenergetic neutrons (~ 4 meV) absorbed in a ${}^6\text{Li}$ target which is black to neutrons. The goal is to measure the neutron fluence to an accuracy of 0.1%. The artifact standard neutron source NBS–1 will then be compared with the total emission rate from this calibrated monoenergetic beam by using a manganese bath. It is expected that an improvement in accuracy of the NBS–1 standard source to a total uncertainty of 0.2% to 0.3% will be realized. The neutron beam can also be used for very

accurate cross section measurements. Also the improvement in the accuracy in NBS-1 will have an immediate effect on a large number of cross section measurements which were made using sources calibrated in baths which have been calibrated with NBS-1, such as those of Knoll at the University of Michigan.

Measurements have been made at the NIST ^{252}Cf neutron source facility of a number of cross sections and cross section ratios, integrated over the ^{252}Cf fission neutron spectrum, to check the quality of evaluations. Recent work was done relating to the iron nonelastic cross section. This work has led to concerns about this cross section. Experiments are being designed to measure the transmission of neutrons through spherical shells of iron. Comparison of these data with results obtained with evaluated cross sections will indicate energy regions where additional work should be done on these cross sections. Nonelastic cross section measurements will be made in those regions. This work is being done in a collaboration with Ohio University and the Pennsylvania State University.

Nuclear Data Activities at Ohio University

S. M. Grimes and T.N. Massey
Ohio University, Athens, Ohio

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Measurements have been made of the n, p and α particles produced from ${}^6\text{Li}$ and ${}^{10}\text{B}$ ions incident on ${}^{27}\text{Al}$ and ${}^{28}\text{Si}$ targets. These data are being analyzed to obtain level density and spin cutoff information

Level density predictions for $20 \leq A \leq 41$ from a number of compilations have been compared with values deduced from level counting. A new relation for the behavior of the level density parameter (a) and the energy shift (Δ) as functions of N and Z is developed. It is concluded that the new parameterization agrees reasonably well with data over the range $0 \leq U \leq 20$ MeV. This new compilation is compared with the results of microscopic Fermi gas calculations and moment method calculations.

Determinations of stopping-target spectrum of neutrons from the ${}^{27}\text{Al}(d,n)$ reaction have been published. The measurements were made at a deuteron energy of 7.44 MeV and at angles of 90° , 110° , and 120° using NE-213 detectors. Further measurements were made at 120° with a fission chamber. The absolute neutron fluence was determined at each energy bin to better than 5%. The resulting data provide a means of calibrating a neutron detector over the range $0.2 \leq E_n \leq 15$ MeV.

Measurements have been made of the spectra of neutrons produced from the ${}^9\text{Be}(p,n)$ reaction using stopping targets, which is being considered for neutron cancer therapy. Data have been obtained for proton energies of 3., 3.4, 3.7, 4., and 4.5 MeV. Angular distributions have been made over the range from 0 to 148° for the measurements at 3., 3.7, and 4. MeV. Somewhat smaller ranges have been measured for the additional proton energies. The detector used for these measurements was indirectly calibrated using the ${}^{27}\text{Al}(d,n)$ source reaction. This work is a collaboration with MIT which is ready for publication.

Work has been done on the $\text{B}(d,n)$, $\text{Be}(d,n)$ and boron nitride(d,n) spectra for detector calibration studies, for cancer therapy use, and interrogating luggage for contraband at airports. There is more structure in the spectra for the lighter targets. This work was done in collaboration with ANL.

Neutron total cross sections from 6 to 120 MeV corresponding to a large body of data obtained at LANSCE have been analyzed with the nucleon Rasmussen model. Nuclei with A

values from 9 to 238 were included in the fit. Good representation of the data as functions of A and E was found, with fits generally matching data to about 2%. Above 120 MeV, the Ramsauer model begins to deviate from the data. This work was done in collaboration with LLNL and Oregon State University.

Measurements of the elastic scattering angular distribution for the n - p system at 10 MeV neutron energy have been completed. This is a collaboration with NIST and LANL. Data were obtained at 0E, 12E, 24E, 36E, 48E and 60E in the laboratory system. The measurements are accurate determinations of the shape of the angular distribution which will be important data for the upcoming evaluation of the hydrogen scattering standard.

Preliminary measurements have been made of the $^{10}\text{Be}(p,n)$ reaction. The data are excitation functions at 0E in the laboratory system for proton energies from 1.5 to 4.0 MeV. Further work is planned with angular distribution measurements at 10 to 14 angles. This work will provide data on the ^{11}B compound nucleus which through an R -matrix analysis can improve the $^{10}\text{B}(n,\nu)$ standard cross section.

Nuclear Data Activities at ORNL

K. Guber and L. Leal
Oak Ridge National Laboratory
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²³³U cross sections: Two sets of fission cross-section measurements have been completed on the 80-meter flight path. Transmission measurements have been performed after a sample target was successfully retrieved from the Building 3019 storage wells and was brought to the ORELA experimental area in Building 6010. A cryogenic device has been purchased for use in low temperature measurements for better Doppler broadening resolution. Using this device, measurements can be performed at temperatures of about 10E K. This allows measurements to be extended up to about 1 keV and a level spacing of 0.4 eV. The samples are used on the 80-meter flight path. Measurements were made for two sample thicknesses. The analysis in the resonance region (up to 600 eV) is now completed. Analysis is now underway in the unresolved energy region.

²⁷Al cross sections: Neutron capture cross sections have been measured on the 40-meter flight path. Resonance analysis of previously measured transmission data on the 80-meter flight path has been completed. Also, analysis of neutron inelastic scattering data measured at the GELINA facility and provided by that laboratory, have been analyzed to assign spins to the observed resonances. The resonance analysis extends to 850 keV.

Natural Chlorine: Transmission measurements have been completed on the 80-meter flight path. Capture measurements are underway.

Silicon: The capture measurements are finished. Resonance parameters have been obtained.

These measurements are made in support of the Nuclear Criticality Safety Program of the DoE.

Nuclear Data Activities at RPI

R. C. Block
Rensselaer Polytechnic

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Summary

The Gaertner LINAC Laboratory has made neutron transmission and capture measurements up to several hundred eV on samples of Zr, Nb, Mo, Sm, Nd, Ho, Er, Tm, Hf, and W. A new neutron time-of-flight target has been built and installed and a new ${}^6\text{Li}$ glass transmission detector was made. The electron linear accelerator is being refurbished with new klystrons, a new RF transport system and the reinstallation of the ninth accelerating section. These improvements are intended to provide a more powerful and monoenergetic electron beam. Details of this experimental work are given below:

Cross Section Measurements

Zr Measurements – Neutron capture and transmission measurements were performed up to several keV with metallic Zr samples. The capture measurement was made at the 25m flight path station with the 16 section multiplicity capture detector, and the transmission measurements were performed at the 25m flight path station with a ${}^6\text{Li}$ glass scintillation detector. Resonance Parameters were determined by a combined analysis of all 11 data sets (4 capture and 7 transmission) using the least squares multi-level R-matrix code REFIT. The present measurements were undertaken to resolve discrepancies between common usage evaluated data, ENDF/B-VI, and the measurements of Salah et al. (M. Salah, et al., "Accurate Determination of the Parameters of the 292.4-eV Resonance of ${}^{91}\text{Zr}$ and the 301.1-eV Resonance of ${}^{96}\text{Zr}$," Proc. Int. Conf. on Nuclear Data for Basic and Applied Science, Santa Fe, NM (1985). The Present measurements Support the Salah et al. conclusions. Specifically, the present results confirm the assignment of $J=3$ for the ${}^{91}\text{Zr}$ 292.5 eV resonance, and include all significant resonances up to 2.5 keV. The Zr resonance parameters determined in the present measurement are compared with the ENDF/B-VI parameters. This work has been published in Nuclear Science and Engineering.

Ho, Er and Tm Measurements – Transmission and capture measurements from thermal up to 20 eV have been performed as part of the doctoral thesis of Y. Danon and a paper based on this work has been published in Nuclear Science and Engineering. Transmission and capture measurements to about 100 eV also have been made.

W Measurements – Transmission, capture and self-indication measurements have been carried out up to 200 eV as part of the doctoral thesis of C. Werner.

Nb, Mo, Sm, Nd, and Hf Measurements – Capture and transmission measurements have been carried out from thermal to several hundred eV neutron energy.

Facility Developments

Accelerator Refurbishment – The linear electron accelerator is being refurbished with new and rebuilt klystrons to bring the RF power source to its original level. A new RF power distribution system is also being explored to improve the quality of the R.F. such that a more stable and monoenergetic beam can be obtained. The ninth accelerator section, removed several years ago to develop a low-energy beam port, will be reinstalled at the end of the accelerator to provide a 9-section linac optimized for neutron production. Seven (out of 10) new or rebuilt klystrons have been received. This refurbishment is expected to be completed this fall. Cross section measurements have continued during the upgrade.

Neutron Targets– A new neutron target has been constructed and tested for time-of-flight measurements in the epithermal energy range. This is an unshielded target which has a polyethylene moderator placed at back angles relative to the Ta photoneutron source. It has superior time-of-flight resolution, as compared to the older shielded bounce target design in use for over 30 years. This new target has been installed for future epithermal time-of-flight measurements. This work was developed as part of the M.S. thesis of Mark Overberg.

Transmission Detector – A new ${}^6\text{Li}$ glass neutron transmission detector has been built. This detector has only the ${}^6\text{Li}$ glass in the neutron beam line, with two photomultipliers placed outside of the beam line. This geometry reduces the effects of neutron resolution broadening that occur when the photomultiplier, housing, reflector and light diffuser scatter neutrons into the ${}^6\text{Li}$ glass.