Nuclear Data Measurements at the RPI LINAC

Y. Danon[1], G. Leinweber[2], R.C. Block[2], D.P. Barry[2], F.J. Saglime[1], M.J. Rapp[1],
M.J. Trbovich[2], C.E. Romano[1], R.M. Bahran[1], and J.G. Hoole[2]
[1] Rensselaer Polytechnic Institute, Troy, New York USA
[2] Bechtel Marine Propulsion Corp, Knolls Atomic Power Laboratory, Schenectady, New York USA

Email contact of main author: danony@rpi.edu

Abstract. The Rensselaer Polytechnic Institute (RPI) LINAC is a 60 MeV electron accelerator located in upstate New York, USA. A pulsed neutron source is used for a variety of experiments primarily related to nuclear data measurements. New capabilities at the facility include high energy (0.4-20 MeV) transmission and high energy scattering using proton recoil detectors. A mid-energy (1 eV-400 keV) Li-6 glass transmission detector is currently being constructed and tested. The laboratory also hosts a 66 metric-ton lead slowing down spectrometer (LSDS). New measurements at the laboratory include the total cross sections of elemental Be at 100 meters. These results have a significant impact on Be total cross sections, particularly below 1 MeV. Neutron scattering is measured using an array of detectors surrounding a scattering sample at a flight distance of 30 meters. Scattering data are digitized and processed using a pulse height discrimination and pulse shape analysis. The RPI-developed software distinguishes neutrons from gamma rays. Various libraries are compared to determine the closest match to the data. Scattering measurements on graphite, Mo, and Be have been recently completed. U-238 low energy resonance scattering was measured using a Li-6 detector, and a new scattering kernel for MCNP was verified. Filtered neutron beams enable high accuracy measurements of smooth cross sections in the energy range from 24 keV to 905 keV. Data from Be using this method was used to resolve discrepancies between evaluations of total cross section. Resonance parameters of Hf have been determined from data using the multilevel R-matrix Bayesian code SAMMY. The RPI LSDS was used for simultaneous measurements of the fission cross section and fission fragment mass and energy distributions as a function of the incident neutron energy. To qualify the system, data for U-235 and Pu-239 were collected and agree with previous data.

1. Introduction

Modern reactor computational methods have improved significantly over the past 20 years. Monte Carlo methods combine the capabilities to describe the geometry at a level of a CAD drawing, include different physics models in great detail, and solve time dependent problems. The accuracy of Monte Carlo analyses are now limited to the physics models and the nuclear data.

The Gaerttner Electron Linear Accelerator (LINAC) at Rensselaer Polytechnic Institute (RPI) was built as a pulsed neutron source designed for nuclear data measurements [1]. The facility started operation in 1961 and has since been used primarily for nuclear data research. The facility has undergone significant upgrades over the last decade. These improvements included replacement of major parts such as klystrons, thyratrons and pulse transformers, and a new injector system. This system allows operation with a 5 ns pulse width which is required for experimental systems operating in the energy range from 0.4 MeV to 20 MeV and will be described later. At maximum power the LINAC is capable of delivering about 12 kW of average electron power; typically experiments are done using several kW of average beam power. Neutrons are produced by the interaction of electrons with tantalum plates producing bremsstrahlung that interacts with the same plates to produce photo-neutrons with an evaporation spectrum [2].

2. Experiments

The activity at the RPI LINAC includes neutron transmission, capture, scattering, and fission measurements. The facility is equipped with various neutron-producing targets, flight paths, and detectors. Each experimental setup is designed to extract the highest quality nuclear data by exploiting the unique properties of the equipment and the specific requirements for high accuracy nuclear data in the particular energy regime. The primary technique is that of time-of-flight.

The laboratory also hosts a 66 metric-ton lead slowing down spectrometer (LSDS). The RPI LSDS was used for simultaneous measurements of the fission cross section and fission fragment mass and energy distributions as a function of the incident neutron energy.

2.1. Measurements in the Thermal Region

In the thermal energy region from a few milli-electron volts to 20 eV an enhanced thermal target is used to generate neutrons.[2] This water-cooled target contains an additional graphite moderator/reflector for maximum thermalization of the neutron source. A wide electron burst, 0.5-1.0 μs, is used to maximize neutron production in a region where energy resolution can be sacrificed for enhanced statistical accuracy. A long period between pulses allows data acquisition down to a few meV and identifies the time-independent background. For transmission, the detector is located at a flight path length of 15 m and consists of a 3-mm-thick Li-6 glass scintillator, phototube, and associated electronics. For capture the detector is a 4π annular 16-segment NaI multiplicity detector [3] located at a flight path length of ~25 m.

2.2. Measurements in the Resolved Resonance Region

In the epithermal energy region, from a few electron volts to ~2 keV, a tantalum target with a polyethylene moderator, the ‘bare bounce’ target [4], is used to generate neutrons. The target is located off of the flight path axis to reduce the effect of the ‘gamma flash’ of bremsstralung X-rays from each accelerator burst. The moderator is placed on-axis to the neutron flight path. An electron burst of width of 20-50 ns is used to balance adequate energy resolution and sufficient counting statistics. A filter of boron or cadmium is placed in the beam to prevent the overlap of neutrons below a few eV for boron or below 0.5 eV for Cd from being detected during the subsequent pulse. Neutron transmission measurements are done at the 25 m flight path with a 12.7-cm diameter, 1.27-cm-thick Li-6 glass scintillator housed in a light-tight aluminum box and coupled to two photomultiplier tubes.[5] The tubes are situated outside of the neutron beam to reduce resolution broadening of the data.

The same capture detector is used for epithermal measurements as is used for thermal measurements. The capture detector can also be used for capture-to-fission ratio measurements.[6] Resonance parameters are extracted from processed data using the Bayesian code SAMMY [7].

An example of resonance region results is shown in *FIG. 1.* Data from transmission and capture measurements of Hf are shown along with the SAMMY fits. The ‘Fit’ curves in the figure represent a single set of Hf resonance parameters [8].

Uranium-238 low energy resonance scattering was measured using a Li-6 detector to provide benchmarks for Monte Carlo models. Scattered neutron energy and angular distributions calculated with the free gas model as implemented in MCNP [9] and GEANT4 [10] were not sufficient to describe the experimental data. A new scattering kernel was developed and verified.[11]

2.3. Mid Energy (1 eV-400 keV) Measurements

In the keV energy region two techniques are used to measure total cross sections, traditional transmission and iron-filtered transmission. The tantalum target is placed off of the axis of the neutron flight path. The moderator is placed on-axis to the neutron flight path. The minimum electron burst width of 5-8 ns is used to maximize energy resolution.

A new modular transmission detector has been constructed and is currently undergoing testing at the 100 m flight path. The longer flight path enhances the energy resolution of the measurement. The detector consists of four independent modules. Each is based on the design of the transmission detector in the resolved resonance region, consisting of a Li-6 glass scintillator, light-tight aluminium box and two phototubes outside of the neutron beam. Each module is equipped with fast electronics needed to measure incident neutron energies in the hundreds of keV. This detector is capable of measuring transmission from 1 eV to 400 keV.

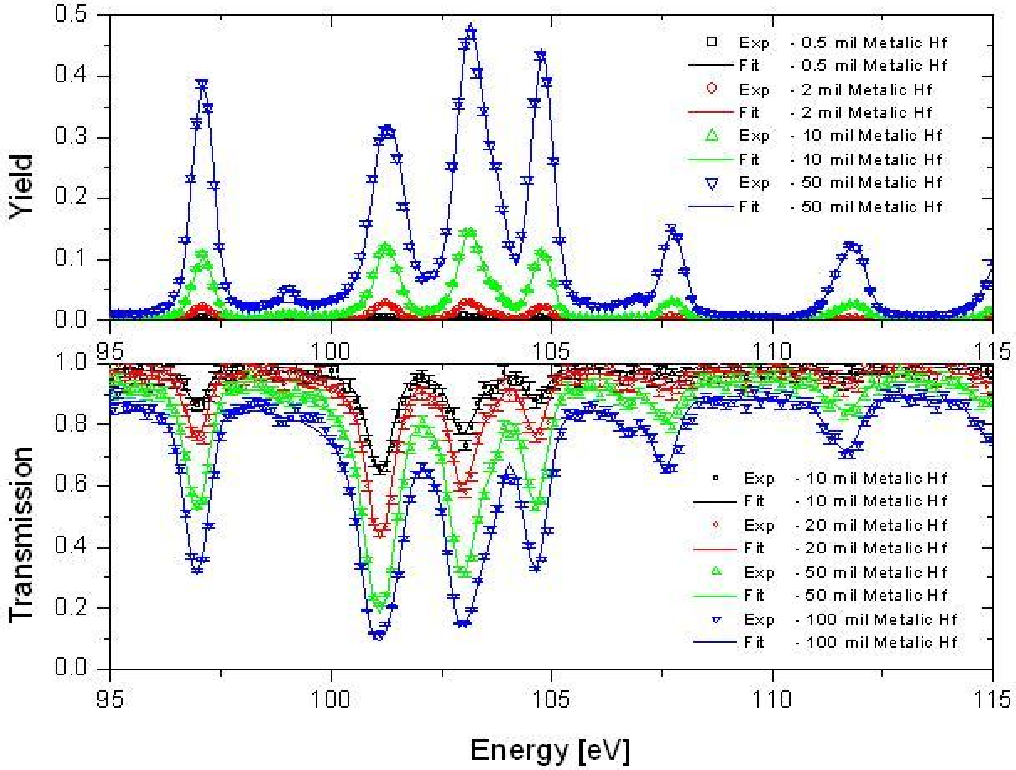


FIG. 1. Hf Transmission and Capture Yield 95-115 eV, experimental data (Exp) and SAMMY fit

Iron-filtered transmission is a technique that produces discrete bands of neutrons with extremely low background. The bare (no additional moderator), on-axis target is used to generate neutrons. The minimum electron burst width of 5-8 ns is used to maximize energy resolution. The single-module Li-6 glass transmission detector used in the resolved resonance region is employed for this measurement. The flight path length is 25 m. This method uses a thick filter in which the resonance potential interference minima reduce the total cross section to nearly zero. The filter creates a neutron beam with sharp peaks at discrete energies. Transmission measurements using a 30 cm iron filter can provide 19 discrete data points in the energy range from 24 keV to 960 keV. The advantage of this method is that the filter removes all the neutrons except those that can go through the cross section minima, and results in a very low background measurement. Such a low background measurement enables high accuracy total cross section measurements. Measurements were done on graphite (carbon) and Be. The results for Be above 500 keV are shown on *FIG. 2*. The data lie above the ENDF/B-VII.0 cross section curve and actually agree better with the ENDF/B-VI.8 evaluation (not shown) in this energy region.[12]

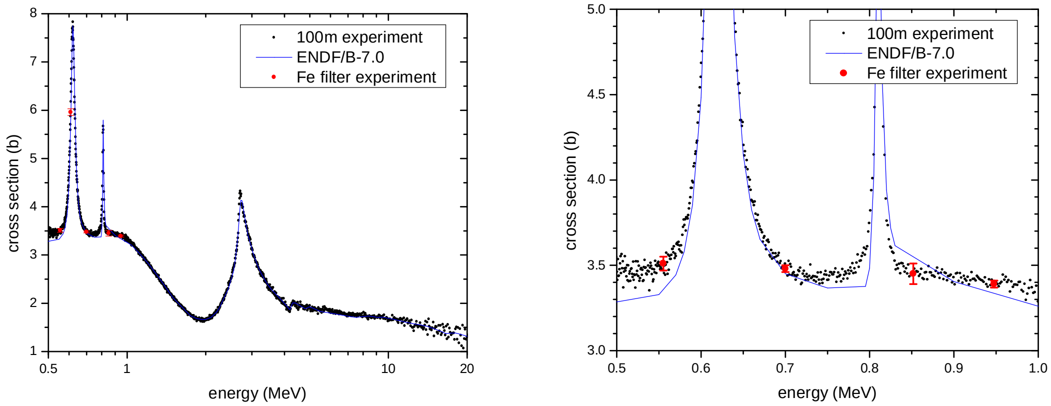
2.4. High Energy (0.4-20 MeV) Measurements

The high-energy capabilities at the RPI LINAC consist of transmission total cross section measurements and quasi-differential scattering measurements. The bare, on-axis target and minimum pulse width are used to maximize high energy neutron flux and energy resolution.

The transmission detector consists of modular EJ-301 liquid scintillator proton recoil detectors each coupled to two photomultiplier tubes. Each module is 12.7 cm thick, 18.3 cm wide, and 35.6 cm long. Either two or four modules are used for data acquisition at 100 m.

The detector system was designed with fast electronics to take advantage of the five-nanosecond wide neutron pulse being generated by the linear accelerator. The system is located at the 100 m flight path length to collect the high resolution time of flight data necessary for measurements in this energy range.

Extensive modeling with the MCNP5 code[9] was used in the design optimization of the detector. These Monte Carlo calculations were also used to characterize the background function, facilitating the processing of the data into cross section. Methods were validated using graphite as a standard. Carbon contains sharp resonance structure and there is abundant data and agreement among major cross section evaluated libraries. Once graphite data were acquired, processed, and successfully compared to published cross section libraries, the system was employed to measure Be.[13] A graphite standard was cycled throughout the series of Be sample thicknesses to ensure proper operation of the system. Results of the Be measurement are shown in *FIG. 2 (a)*. The Be measurement shows agreement above 1 MeV but as shown in *FIG. 2 (b)* displays some difference with ENDF/B-VII.0 in the range of 0.5 to 1 MeV. This difference of about 8% below ~0.6 MeV is in agreement with the results of the iron-filtered Be measurement also shown on the figure.



(a) *(b)*

FIG. 2. Be total cross section measured with the high energy transmission detector using combined samples with time of flight data grouped into 6.4 ns channels (a) full range, (b) zoomed view

The quasi-differential scattering detector system consists of 8 liquid EJ-301 scintillator proton recoil detectors surrounding a scattering sample. The scattering sample is placed 30 m from the neutron source to balance neutron flux intensity with energy resolution. The detectors are placed 50 cm from the scattering center. The data acquisition system consists of 8 Acquiris digitizing multichannel analyzers (MCAs). The advantage of digitizing over real-time electronic discrimination is profound. Data may be reprocessed after the fact, methods refined, and discrimination criteria varied. The processed data are compared with the expected detector response based on Monte Carlo simulation of the scattering experiment using existing nuclear data evaluations. In this way, high accuracy neutron scattering experimental benchmarks, combined with high accuracy Monte Carlo simulations, can be used to assess differences among nuclear data evaluations. Experiments were done with C, Be, and Mo samples.[14]

The resulting time-of-flight spectra for Be, data and simulation, for a single forward angle at 26 deg. are shown in *FIG. 3*. The ENDF/B-VI.8, ENDF/B-VII.0, and JEFF 3.1 libraries are all in very close agreement (only ENDF/B-VII.0 is shown). The thin sample scattering results agree with the Monte Carlo calculation more closely than the thick sample scattering results. In the thick sample case, there is almost twice as much multiple scattering taking place as in the thin sample. This suggests that small errors in the scattering cross section evaluation used in the simulation are accumulating resulting in a noticeable error for the thick sample.

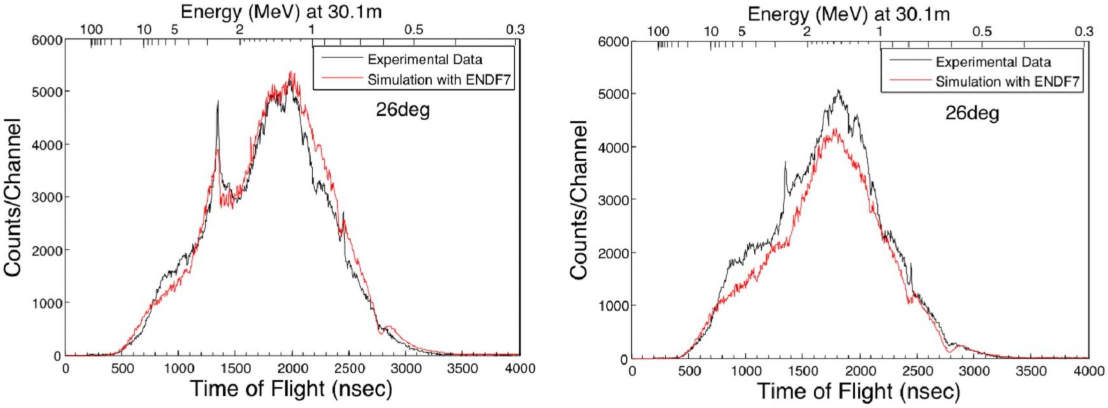


FIG. 3. Be Scattering Results: 4 cm thick sample (left) and 8 cm thick sample (right)

2.5. Measurements with the Lead Slowing Down Spectrometer (LSDS)

The RPI lead slowing down spectrometer (LSDS) is a 1.8 m-on-a-side cube of high purity lead with a pulsed neutron source in its center. The LSDS is driven by the RPI LINAC generating a pulsed electron beam that hits an air-cooled tantalum target in the center of the lead pile. The fast neutrons slow down by successive scattering interactions with the lead. The resulting slowing down energy spectrum at a given slowing down time is approximately a Gaussian with a full width at half maximum (FWHM) of about 30%, and the average neutron energy corresponds to the slowing down time at the peak of the distribution. This enables measurements in a method similar to time-of-flight (TOF) experiments. As a result of the neutron scattering, the flux in the LSDS is very high, about 3-4 orders of magnitude higher than an equivalent distance (5.6 m TOF experiment). This high neutron flux allows measurements of very small samples (sub micrograms) or very small cross section. The LSDS is currently used for simultaneous measurements of fission cross sections and fission fragment mass and energy distributions of small samples. This is very useful for the study of actinides for which this information does not exist and large samples are unavailable. A double gridded fission chamber is placed inside the LSDS and is used for measurements of energy and relative angle of the fission fragments from which the mass can be deduced.[15]

3. Conclusions

The RPI LINAC is a 60 MeV electron accelerator used for a variety of experiments primarily related to nuclear data measurements. New capabilities at the facility include high energy (0.4-20 MeV) transmission and high energy scattering using proton recoil detectors. A mid-energy (1 eV-400 keV) Li-6 glass transmission detector is currently being tested. The laboratory also hosts a 66 metric-ton lead slowing down spectrometer (LSDS). These tools have been employed in multiple configurations to measure nuclear data over a wide energy range of a few meV to 20 MeV. Experiments at the RPI LINAC optimize neutron-producing targets, burst widths, flight path lengths, detector types, computational modeling, data reduction and analysis methods to provide high accuracy nuclear data.

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