CIELO-related nuclear data measurements at the Gaerttner LINAC Center at RPI

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Abstract

The Gaerttner LINAC Center at Rensselaer Polytechnic Institute (RPI) has been conducting neutron-induced transmission, scattering, capture and fission measurements on materials that are relevant to the Collaborative International Evaluated Library Organization (CIELO). Fission and capture measurements of ^{235}U in the resonance region were performed with the RPI multiplicity detector. Grouping the data in the energy range of 1 000 eV to 1 500 eV supports a capture cross-section that is lower than ENDF/B-VII.1 and closer to JENDL-4.0. Neutron scattering measurements have been made with incident energy range from 0.5 MeV to 20 MeV for ^{56}Fe and ^{238}U. For back-angle scattering the new data for ^{238}U show discrepancies from ENDF/B-VII.1 and are in better agreement with the JENDL-4.0 evaluation. High-energy resolution transmission of ^{56}Fe was measured in the energy range from 0.5 to 20 MeV and shows good agreement with the evaluations and previous measurements with a lower uncertainty above 4 MeV. Methods and results from these experiments will be discussed.

Introduction

The Gaerttner LINAC Center at Rensselaer Polytechnic Institute (RPI) has been conducting nuclear data research since its inception in 1961 (Gaerttner, Yeater and Fullwood, 1961). The centre houses a 60 MeV pulsed electron accelerator that can deliver a maximum beam power of about 10 KW. The centre includes several neutron production targets and detection systems that are located in different flight paths at 15 m, 25 m, 30 m, 45 m, 100 m and 250 m. Recent measurements include neutron transmission, capture, scattering and prompt fission neutron spectrum. The facility also houses a lead slowing-down spectrometer that is used for fission, (n,α) cross-section measurements for samples with small cross-sections or small mass (Thompson, *et al.*, 2012) and for measurements of fission fragment mass and energy distributions (Romano, *et al.*, 2010).

Some of the measurements that were recently completed or are still in progress include materials that are of interest to the Collaborative International Evaluated Library Organization (CIELO) and can thus contribute new data to the evaluation process. Recent relevant activity includes neutron scattering from ^{56}Fe and ^{238}U, neutron capture measurements of ^{235}U, neutron transmission measurements of ^{56}Fe and fission neutron distributions for ^{238}U.

Neutron scattering measurements for ^{238}U and ^{56}Fe

A neutron scattering system based on an array of eight EJ-301 liquid scintillators was used to measure neutron scattering in the energy range from 0.5 MeV to 20 MeV (Saglime, *et al.*, 2010; Barry, *et al.*, 2013). The sample is located at a distance of 30.07±0.02 m from the pulsed neutron source and the detectors are located at a distance of 0.50±0.01 m. Two detectors were kept at each scattering angle and the measured angles were 27, 45, 60, 77, 112, 130, 153 and 156 degrees relative to the neutron beam direction. The detector data is collected by digitisers and processed into a time-of-flight (TOF) spectrum. The neutron flux shape incident on the sample was measured using a ^{235}U fission chamber and was corrected for transmission through all the materials in the beam path. The EJ-301 detection efficiency as a function of energy was measured by placing the detectors in the neutron beam (at the sample position) and using a low intensity beam. Using this measurement and the known flux shape, the energy dependence of the neutron detection efficiency was obtained for each of the eight detectors.

Data analysis includes pulse shape discrimination (PSD) to reduce contributions from gammas. Because PSD can result in 1-2% false neutron detection (gammas that were mistakenly detected as neutrons), and the gamma emission from inelastic scattering and fission in the ^{238}U sample was relatively high, an additional gamma rejection method was developed. In this method the fraction of false neutrons resulting from the PSD classification method was measured as a function of the gamma pulse area using several gamma sources. For the scattering measured data, the product of this fraction with the number of PSD classified gammas provides an estimate of the false neutrons. This method reduces the contribution to the neutron count from false neutrons to less than 0.005%.

The measured data was compared to detailed MCNP simulations that included the pulsed neutron source energy spectrum, the neutron pulse width and the energy dependent neutron detection efficiency. All the materials in the neutron beam path including 1.9 cm natural U filter, aluminium and water in the target structure, and Mylar vacuum windows were also included in the simulation. The simulations were done using several evaluated cross-section libraries to determine which evaluation fits the data best. To verify the experimental procedures and the quality of the simulations a 7-cm thick graphite sample was always measured in the same experiment by cycling between the sample, the graphite sample and no sample (a background component).

Neutron scattering from ^{238}U

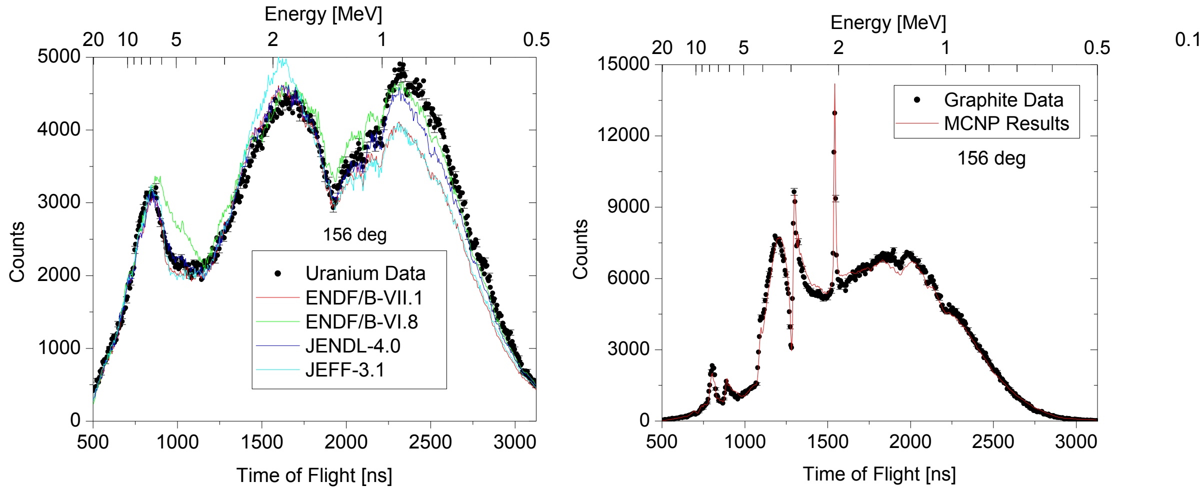
A cylindrical sample containing depleted uranium (0.2% ^{235}U) with thickness of 0.979±0.002 cm, diameter of 7.618±0.002 cm, and mass 841.08±0.02 g was used in this experiment. Preliminary results were given in Daskalakis, *et al.* (2012); however, they did not include the newly developed pulse rejection method which resulted in reduction of the experimental data near time-of-flight of 1 000 ns.

Examples of the experimental data and the MCNP simulations for backscattering to an angle of 156° are shown in Figure 1 for both ^{238}U and graphite. The graphite data is used to quantify the systematics of uncertainties under the assumption that the ENDF/B-VII.1 evaluation of graphite is perfect. For ^{238}U the evaluation which fits the experimental data best when using a χ^2 measure is JENDL-4.0.

Neutron scattering for ^{56}Fe

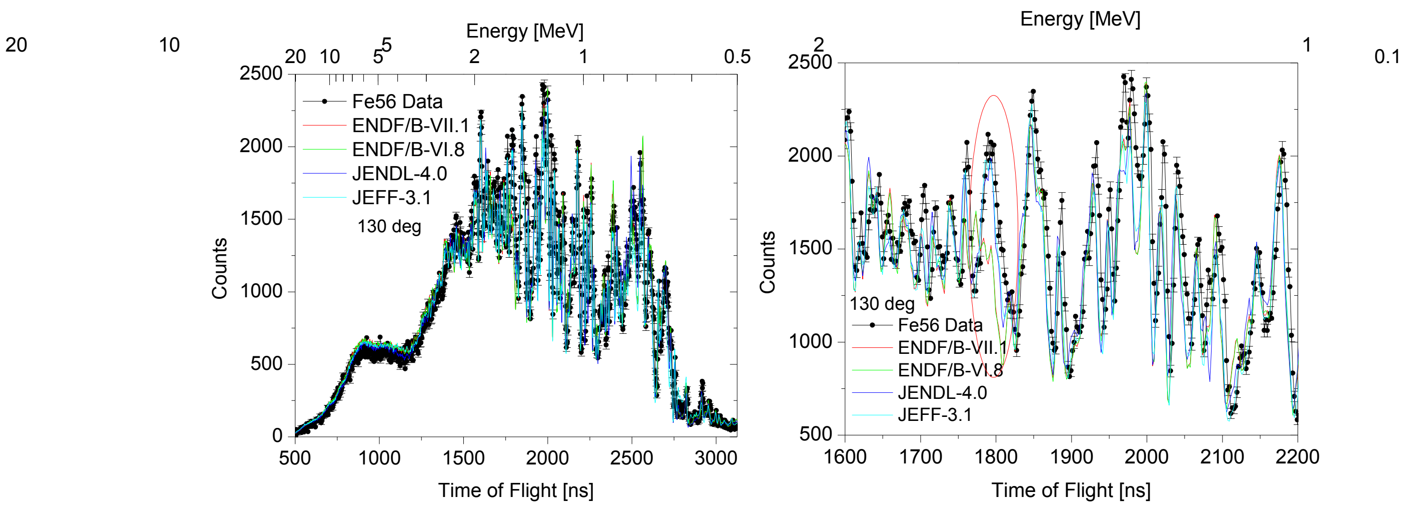
Similar measurements were completed with an ^{56}Fe sample (99.87% ^{56}Fe). The sample was square with approximate dimension of 7.70 cm × 15.25 cm × 3.23 cm thick and mass of 2951.0±0.5 g.

Figure 1: Measured ^{238}U scattering compared with several MCNP simulations of the experimental system (right); measured graphite scattering compared with simulation using the ENDF/B-VII.1 evaluation (left)



The data analysis and simulation methodology were identical to the ^{238}U analysis. The experimental data and simulations with several evaluations are shown in Figure 2 for a scattering angle of 130°. Figure 2 serves as an example of the available measured data and how it can be used to benchmark different cross-section evaluations. The energy resolution is sufficient to resolve ^{56}Fe resonance structure up to 2 MeV. The right plot in Figure 2 shows a zoomed window which highlights a region where ENDF evaluations do not match the data as well as the JENDL-4.0 and JEFF-3.1 evaluations. This type of comparison provides an indication of energy regions where improvements in elastic or inelastic scattering are needed. The data analysis discriminates neutrons with energy below 0.5 MeV, for ^{56}Fe, where the first inelastic state is at 847 keV; this implies that below incident energy of about 1.35 MeV the system records only elastic scattering. Increasing the threshold during the data analysis allows measuring elastic scattering to higher energy and to enable separation of elastic from inelastic scattering. Overall the evaluation which fits the experimental data best when using a χ^2 measure is JEFF-3.1.

Figure 2: Measured ^{56}Fe scattering compared with several MCNP simulations of the experimental system (left); zoom in the region between 1-2 MeV (right)

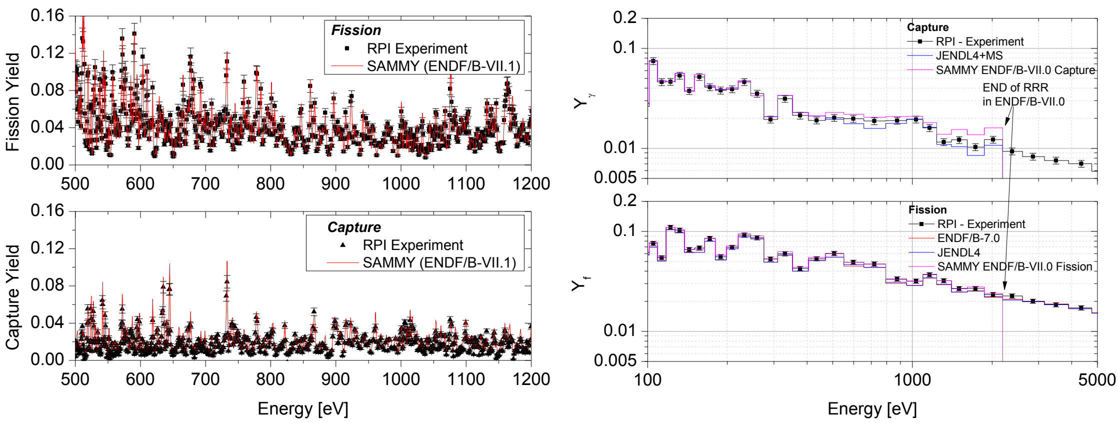


Simultaneous fission and capture measurements of ^{235}U

A method for simultaneous measurement of fission and capture was developed at RPI by utilising the RPI multiplicity detector (Williams, *et al.*, 2013) located on a 25.5 m flight path. The method uses the gammas emitted from capture and fission to measure both interactions without the need for a fission chamber. This enables the use of a larger sample (20 g, 93.33% ^{235}U). The high gamma detection efficiency of the multiplicity detector and its segmentation enable the use of the total energy deposition and multiplicity to separate fission from capture. The basic principle is that an event with total gamma energy deposition above the neutron binding energy of ^{235}U can only come from fission (or background) and below this energy it is a mix of fission and capture. Once the fission yield of the sample was measured, a normalisation procedure with two known resonances at low energy was used to find the fraction of fission that should be subtracted from the spectrum with total energy below the binding energy. For measurements in the energy range of 0.01-20 eV the thermal point and the 11.7 eV resonance were used for normalisation and for higher energy measurements the resonances at 11.7 eV and 19.0 eV were used, more details are given in Williams, *et al.* (2013). Additional correction was applied to the data to reduce contributions from scattered neutrons that were captured in the detector. Because of their high energy, the contribution from fission neutron was negligible. The outcome of this process was fission and capture yields with uncertainties in the range 5-8%.

The results are shown in Figure 3 with SAMMY calculations of the capture and fission yields. The left plot shows high resolution data in the energy range where differences between ENDF and JENDL exist. The right plot is the grouped yield which provides a better indication of the lower capture cross-section that was found compared to the ENDF/B-VII.0 evaluation. The resolved resonance region (RRR) for the JENDL-4 evaluations ends at 500 eV, which does not allow inclusion of SAMMY multiple scattering calculations above this energy. Instead the plotted curve was generated by a simple single collision yield calculation. The multiple scattering contributions were estimated based on the difference between a SAMMY calculation using ENDF/B-VII.0 and a simple first collision calculation of the capture yield using the ENDF/B-VII.0 cross-section. As expected the fission yields calculated from both evaluations are in very good agreement with the RPI experimental data. There is also good agreement between the evaluations and the experiment for capture yield below 500 eV. Above 500 eV the experimental capture yield is lower than ENDF/B-VII.0 and closer to JENDL-4.0.

Figure 3: Measured fission and capture yields of ^{235}U shown with SAMMY calculations using ENDF/B-VII.0 parameters (left); the grouped yields together with the ENDF/B-VII.0 and JENDL 4.0 evaluations (right)

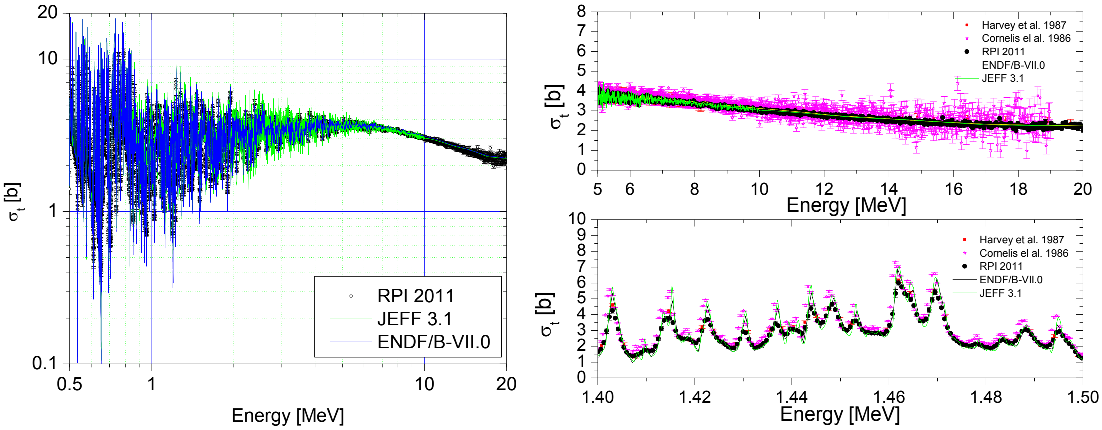


Transmission of ^{56}Fe

Transmission of metallic ^{56}Fe samples (99.87% ^{56}Fe) with thickness of about 3.22 cm and 7.69 cm were measured at a 250 m flight path using 12.7 cm thick large area modular liquid scintillator detector (EJ-301) [8]. This transmission set-up is useful for the energy range from 0.5-20 MeV and has a signal to background ratio of about 250 at 2 MeV. The transmission data for the two samples was converted into cross-section and the weighted average is show in Figure 4 together with other experimental data and the ENDF/B-VII.1 evaluations.

Overall the RPI experimental data and the ENDF evaluations are in very good agreement. Above 5 MeV the RPI data has low uncertainty compared to previous measurements. This data can be used for further improvement of the resonance evaluation of ^{56}Fe and to improve the cross-section at the higher energy region above 5 MeV. Since two sample thicknesses were measured, a correction of the average cross-section for resolution broadening (Fröhner, *et al.*, 1996) can be accurately done for energies above the resolved resonance region.

Figure 4: Measured ^{56}Fe cross-section and calculations using the ENDF/B-VII.0 and JENDL-4.0 evaluations (left); a zoomed plot showing the low (bottom right) and the high (top right) energy regions is shown in the right plot compared to several other data sets and evaluations



Prompt fission neutron measurement

A system for measurement of prompt fission neutron spectra was developed based on a double time-of-flight measurement (Blain, Daskalakis and Danon, 2013). The sample was located about 30 m from the pulsed neutron source, liquid (EJ-301) and plastic (EJ-204) scintillator detectors were used to measure the fission neutron and were placed about 0.5 m from the sample. A fission tag was generated using four BaF_2 detectors that were in close proximity to the sample. The gamma tag method allows fast timing and also enables the use of larger samples. The system was first tested using a ^{252}Cf fission chamber where the gamma tagging method was compared to the more commonly used fission tagging method. In order to calculate the fission spectrum from the measured spectra the neutron detection efficiency was determined with the SCINFUL code (ORNL, 1988). For the case of EJ-301 it was found the SCINFUL code results were in good agreement with measurement of the energy dependent efficiency described above.

Results from ^{252}Cf were given in Blain, Daskalakis and Danon (2013) and are in good agreement with the evaluations. The system is currently being used for measurements on a ^{238}U sample.

Conclusions

The experimental programme at the Gaerttner LINAC Center at Rensselaer Polytechnic Institute performed several measurements of $^{235,238}U$ and ^{56}Fe which are relevant to the CIELO project. The experiments include fast neutron scattering from ^{56}Fe and ^{238}U, fast neutron transmission through ^{56}Fe and capture and fission yields of ^{235}U. The scattering data provide a benchmark for new evaluations that will be performed during the CIELO project. The ^{56}Fe transmission data and ^{235}U capture yield data can be used to improve the evaluated cross-sections. A system for measurement of prompt fission neutron spectra using the gamma tagging method was developed and demonstrated for ^{252}Cf; measurements on ^{238}U are in progress.

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