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Basic Physics Data: Measurement of Neutron Multiplicity from Induced Fission

Fuel Cycle

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Basic Physics Data: Measurement of Neutron Multiplicity from Induced Fission

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1. RESEARCH ACTIVITIES

1.1 University of Michigan

1.1.1 Induced Fission of U-235 at LANSCE: 2012

From October 1 to October 17 a team of researchers from UM visited the LANSCE facility for an experiment during beam-time allotted from October 4 to October 17. Fig. 1 shows the measurement team and system at LANSCE. A total of 24 detectors were used at LANSCE including liquid organic scintillation detectors (EJ-309), NaI scintillation detectors, and Li-6 enriched glass detectors. Fig. 2 shows the schematic of the experiment. It is a double time-of-flight (TOF) measurement using spallation neutrons generated by a target bombarded with pulsed high-energy protons. The neutrons travel to an LLNL-manufactured parallel plate avalanche chamber (PPAC) loaded with thin U-235 foils in which fission events are induced. The generated fission neutrons and photons are then detected in a detector array designed and built at UM and shipped to LANSCE. Preparations were made at UM, where setup and proposed detectors were tested. The UM equipment was then shipped to LANSCE for use at the 15L beam of the weapons neutron research (WNR) facility.

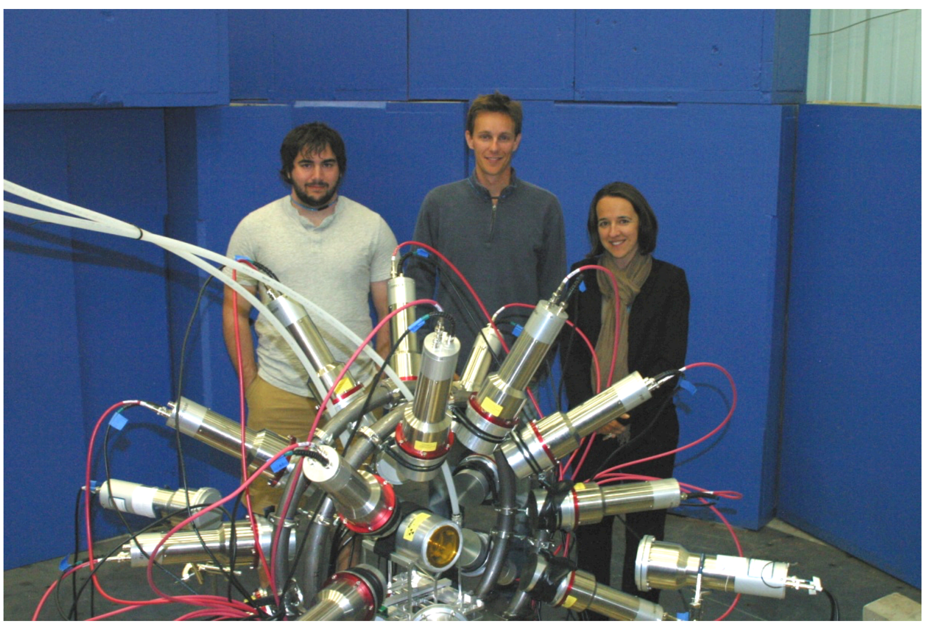

Fig. 1. Experimenters from the University of Michigan: from left, Brian Wieger (graduate student), Andreas Enqvist (postdoc) and Prof. Sara Pozzi (Principal Investigator). UM-measurement system surrounds the 235U PPAC, where neutron-induced fissions take place.

The double time-of-flight (TOF) setup used enables detection of both inducing fission neutron energy as well as energy and correlation of the emitted fission neutrons. The data was used for the investigation of energy and angle correlations. Additional parameters will be looked at both for validating our analysis with known data as well as for input to designing additional measurements.

We developed a variety of offline data analysis techniques that have been specifically tailored to this data acquisition system. The analysis consists of cleaning out unusable waveforms, finding and aligning the timing of the collected pulses, and determining the particle type (neutron or photon). The results focus on the neutron multiplicity distribution and the average neutron multiplicity.

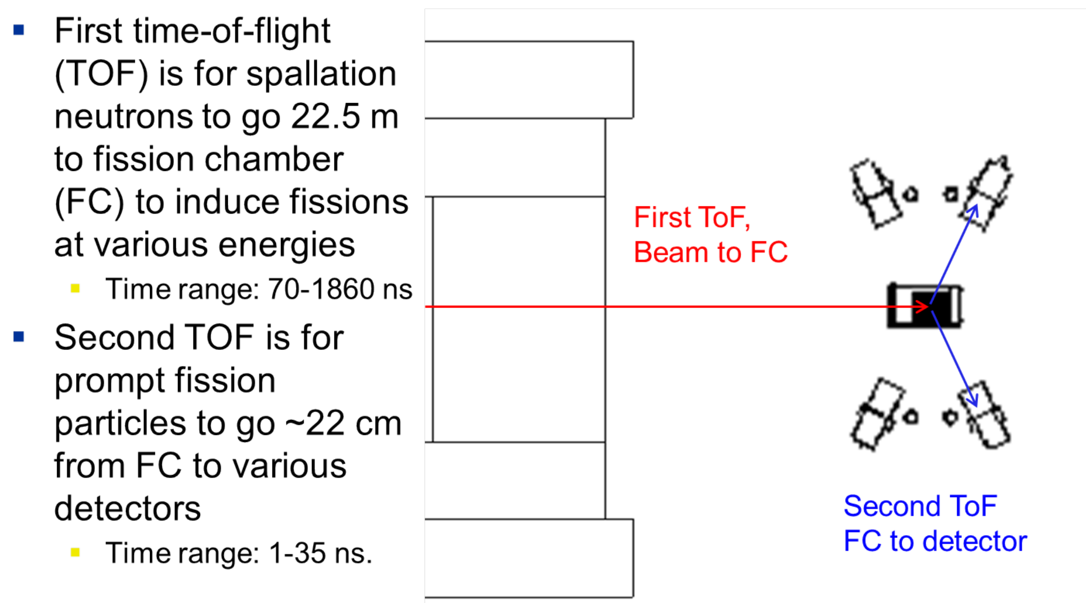

Fig. 2. Schematic of the double time-of-flight experiment.

A combination of pulse shape discrimination (PSD) algorithms was used for this measurement. Background subtraction is done per incident neutron energy-bin. A time-of-flight distribution is created for each energy bin and the mean of a time section is analyzed before and after the neutron region-of-interest. From this, the slope of a line that represents the time dependent background is calculated and then subtracted from the data.

A result from the experiment (TOF) is shown in Fig. 3. This data was obtained using the organic liquid scintillator detectors, which have good pulse shape discrimination capabilities. The timing accuracy of the measurement is vital and can be seen most prominently in the sharp gamma flash peak.

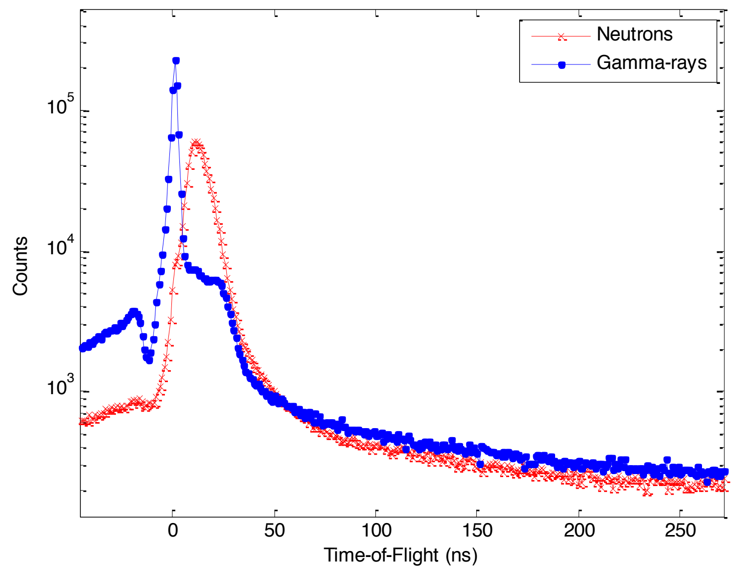

Fig. 3 Neutron and gamma-ray time-of-flight plot.

The energy-angle correlation is dependent on detecting multiple particles from the same fission. Fig. 4 details the amount of higher order neutron multiples that were seen in the data taken from LANSCE. As the energy of the fission, inducing neutron increases the number of neutrons emitted $\bar{\nu}$ increases. This enables high order neutron coincidences to be detected. At least two neutrons must be detected for the energy-angle correlation analysis. When four neutrons are detected, that event contributes with six unique data points, thus high order multiples are of high value.

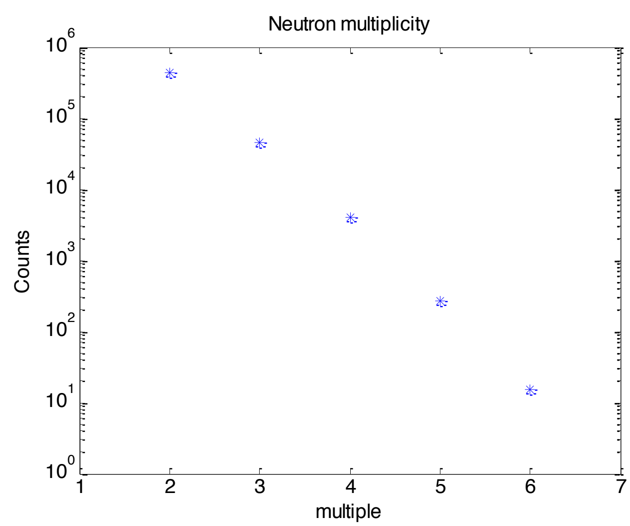

Fig. 4. Measured neutron multiples from U-235 induced fission.

To find the neutron multiplicity distributions, the detected neutron multiples must be related to the actual number of neutrons emitted by the source. The scintillation detectors used in this measurement have a Watt spectrum averaged efficiency of 27.9% for the threshold used. Combined with the solid angle subtended by all detectors of 1.24 sr; we have a 2.76% chance of detecting an emitted neutron. Background-induced correlations were removed from the detected counts.

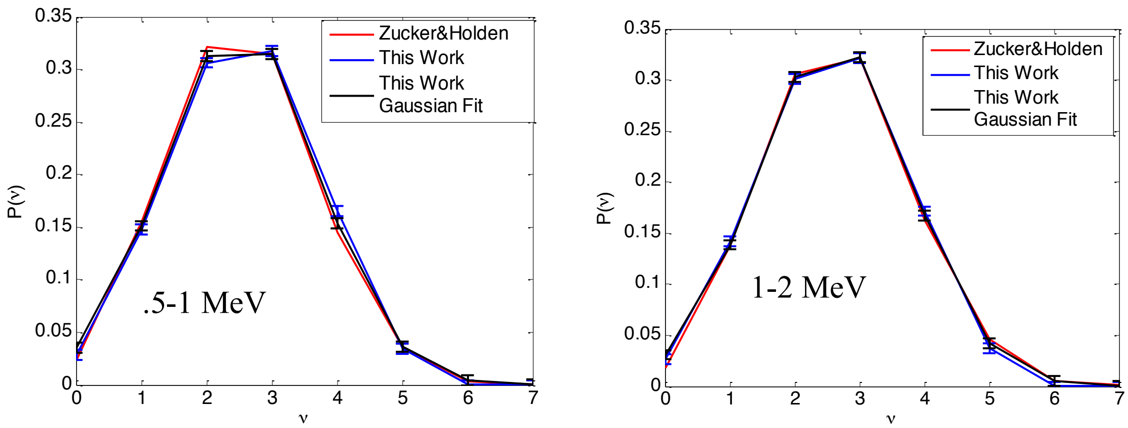

Fig. 5. Unfolded probability distribution of the number of neutrons emitted in induced fission in U-235. The results shown are for fissions induced by 0.5-1 MeV and 1-2 MeV beam neutrons, respectively.

The higher beam-energy fissions cannot be fully unfolded with the same methodology as used for Fig. 5. Instead, the flux is fitted to an appropriate Watt spectrum, and from that a good estimate of the proper average number of neutrons emitted in fission, $\bar{\nu}$, for each beam-energy can be obtained. This methodology can be extended almost up to 800-MeV neutron beam energy. Fig. 6 shows this methodology and the fitted spectra for a number of beam energies.

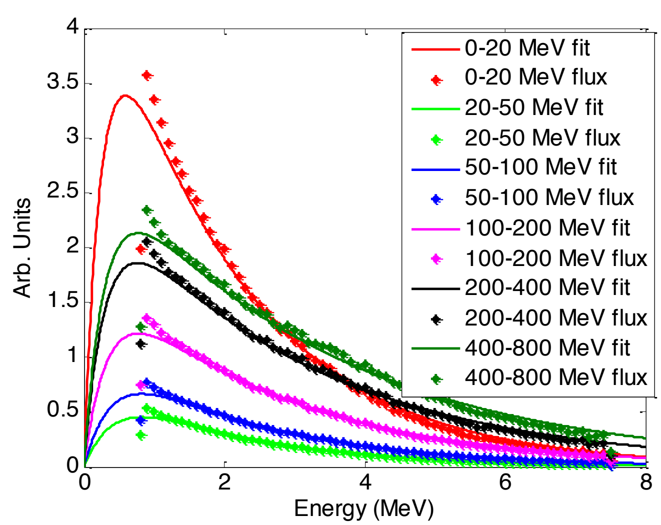

Fig. 6. Various fission spectra measured at LANSCE for different neutron-beam energies. The fission spectra have been fitted to Watt-spectra and from that full range fitted spectra quantities such as the number of prompt neutrons (integral of the curve) are obtained.

The average number of prompt neutrons emitted in each fission event, $\bar{\nu}$, is shown in Fig. 7. The data now extends further than previous measurements. Furthermore, we found that the previously used functional form is unable to predict the evolution of $\bar{\nu}$ at higher energies, therefore a modified trend function was used, which better captures the trend and behavior with the increasing beam-energy.

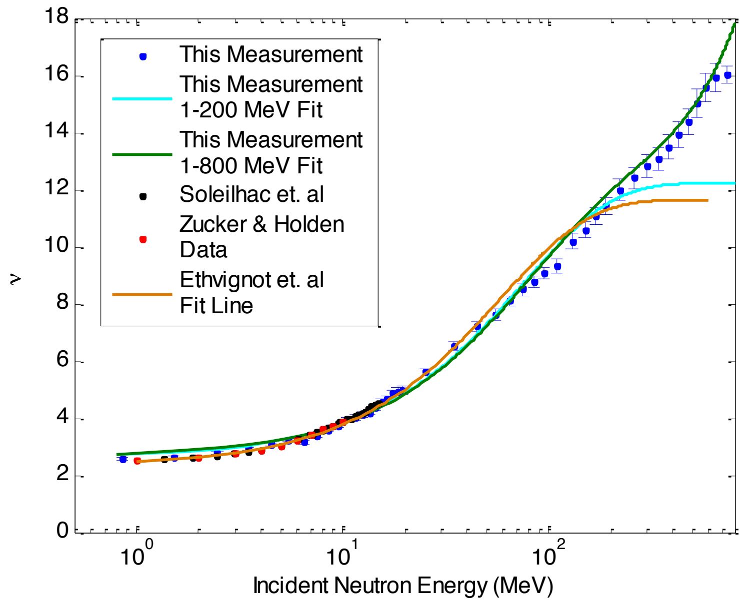

Fig. 7. $\bar{\nu}$ data obtained at LANSCE shown together with other data sets, as well as with a previously used trend line and a new modified parametric fit that correctly extends to higher energies.

1.1.2 Induced Fission of U-235 at LANSCE: 2013

A second measurement campaign at LANSCE took place near the end of the 2013 fiscal year to investigate the background and fission neutrons as a function of angle with respect to the incident neutron beam.

This campaign, which used the WNR 15 left neutron beam, was conducted between August 21 and September 3, 2013. Fig. 8 shows a purpose-built holder was designed and constructed at UM. This setup allowed for a large number of detectors being positioned at fixed angular intervals with respect to the incoming neutron beam. The aim is to characterize and understand the difference in emission spectrum and angular distribution as a function of the incoming neutron. The angular effect plays a larger role as the energy of the neutron is increased. Secondly, the effect of neutron background induced by the beam has a large angular dependence, which we hope to correctly characterize to improve on the corrections applied to the previous measurements campaign. Fig. 9 shows the setup and experimenters at LANSCE.

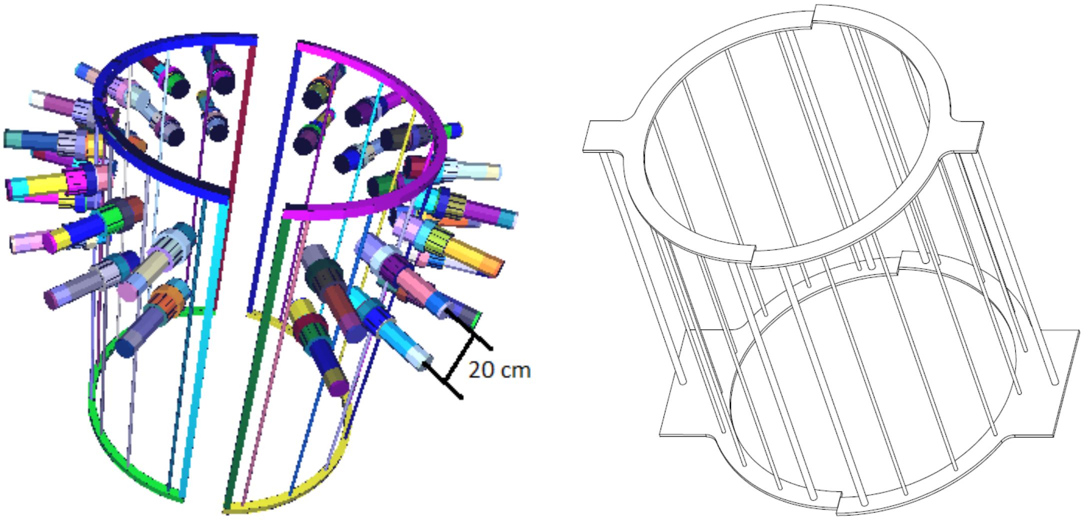

Fig. 8. New holder setup at LANSCE as conceptually visualized in MCNP models (left), and as detailed SolidWorks drawings used for the manufacturing (right).

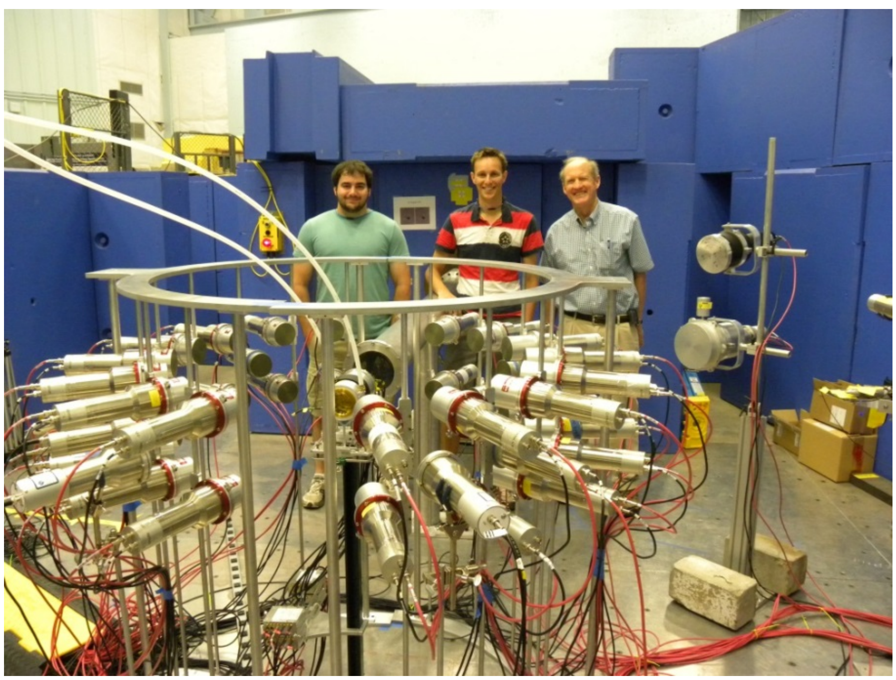

Fig. 9. Experimental setup used at LANSCE in Aug. - Sept 2013. Personnel from left: Brian Wieger (UM researcher), Andreas Enqvist (UM ass. research scientist) and Robert Haight (LANSCE Co-Principal Investigator).

The measurement system assigns a time-stamp to pulses as they arrive. The time-stamp corresponds to the trigger time in the digitizer, which opens the acquisition window; time-stamps from one or more channels can be compared to identify pulses that are likely from the same fission event. The time-stamp increments every 8 ns, and after several minutes, rolls over to zero to begin again. A global time stamp is used for timing purposes between detectors and the fission chamber. In order to correct for this, a script has been written that looks for channels that show poor agreement with the fission chamber and then applies a correction to that data to account for the lost period. This can be challenging because that channel may miss several time periods at once, or miss several time periods over the course of the measurement.

Fig. 10 shows the neutron and gamma-ray time-of-flight between the fission chamber and the detectors and a comparison between the 2012 and 2013 measurement campaigns. The flight path was doubled in the 2013 measurement and the extra distance yields improved separation between gamma-rays and high energy neutrons.

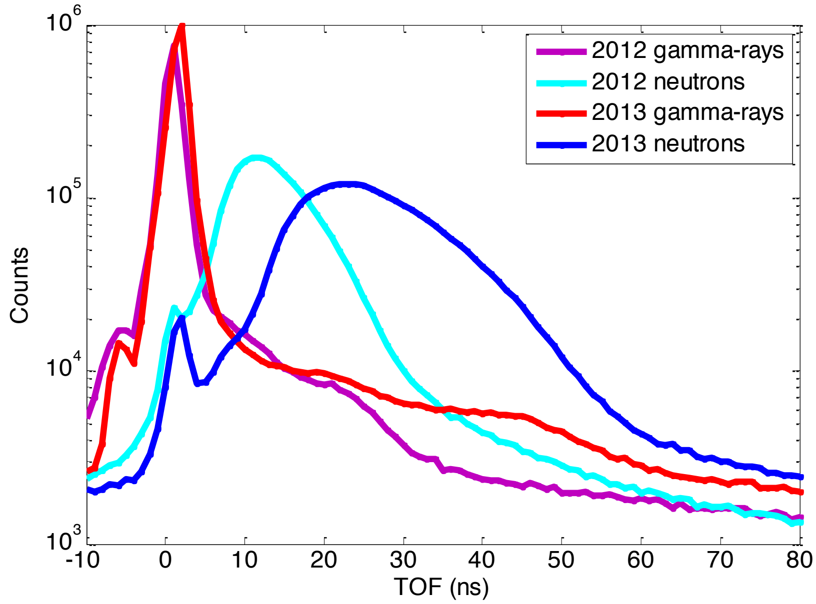

Fig. 10. This time-of-flight data shows a comparison between the measurement campaigns of 2012 and 2013. The longer flight path in 2013 gives better time separation between neutrons and gamma-rays, as can be seen around 5 ns.

The neutron flux incident on the detectors was used to find several fission parameters; including $\bar{\nu}$ and average neutron energy. Fig. 11 shows the neutron flux and a fitted Watt spectrum for several different inducing neutron energies.

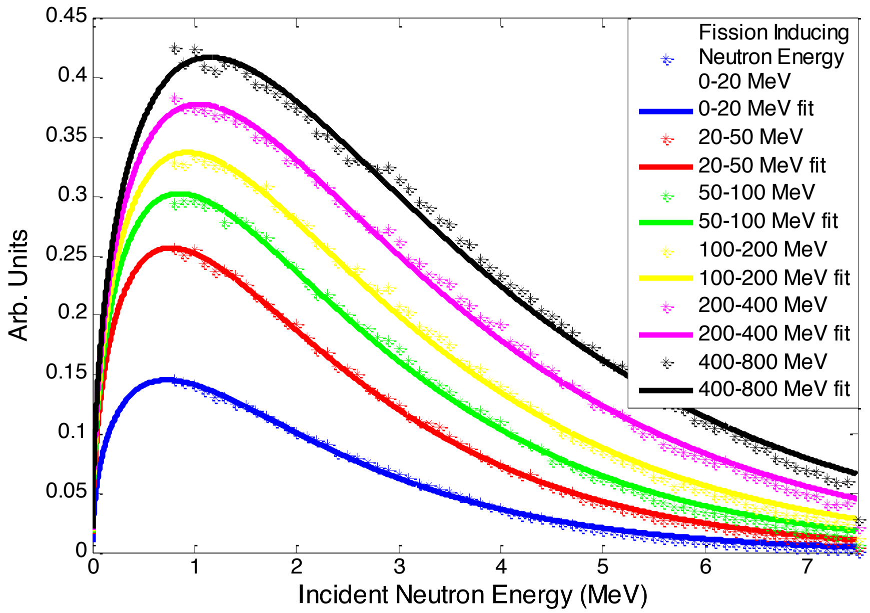

Fig. 11. Various fission spectra measured at LANSCE for different neutron-beam energies. The fission spectra have been fitted to Watt-spectra and from that full range fitted spectra quantities such as the number of prompt neutrons (integral of the curve) are obtained.

The average number of prompt neutrons emitted from fission is shown in Fig. 12. The figure shows a comparison of our two measurement campaigns as well as a reference. We see good agreement with the 2012 measurement campaign and good agreement with reference data sets at lower energies. Some discrepancies arise at higher energies and these are being investigated.

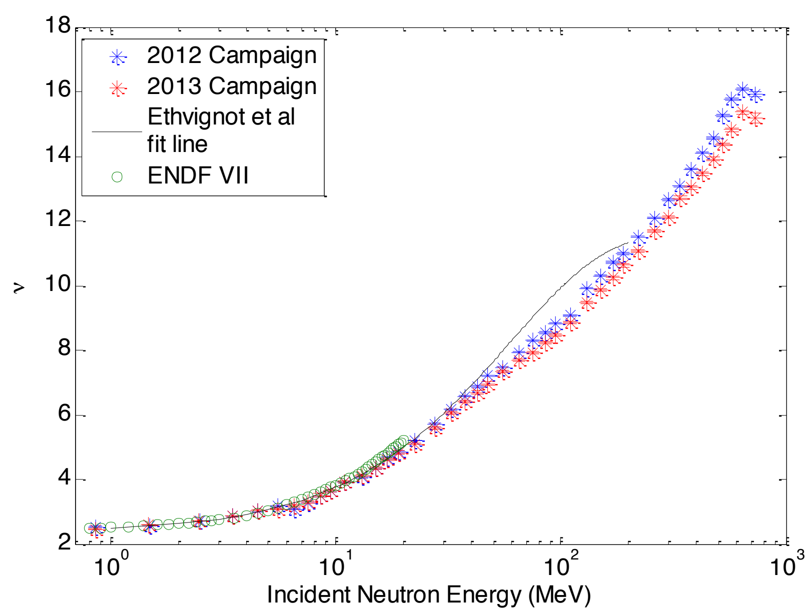

Fig. 12. $\bar{\nu}$ data obtained at LANSCE shown together with some other data sets, as well as with a previously used trend line. The agreement with previous data-sets is good, but some work is still needed.

Previous measurements at UM have used a Cf-252 spontaneous fission source to measure the neutron-neutron correlations versus the angle of separation between detectors. This correlation has been used to validate the MCNPX-PoliMi code. Using this same correlation from an induced fission source, we can extend the code to improve on the induced fission models. Fig. 13 shows data from the 2012 and 2013 measurement campaign. Comparison to the Cf-252 measurement, we expect to see a steeper distribution for U-235. The Cf-252 was more prone to cross-talk between the detectors than U-235 measurement campaigns at LANSCE and thus seems to agree with the U-235 data.

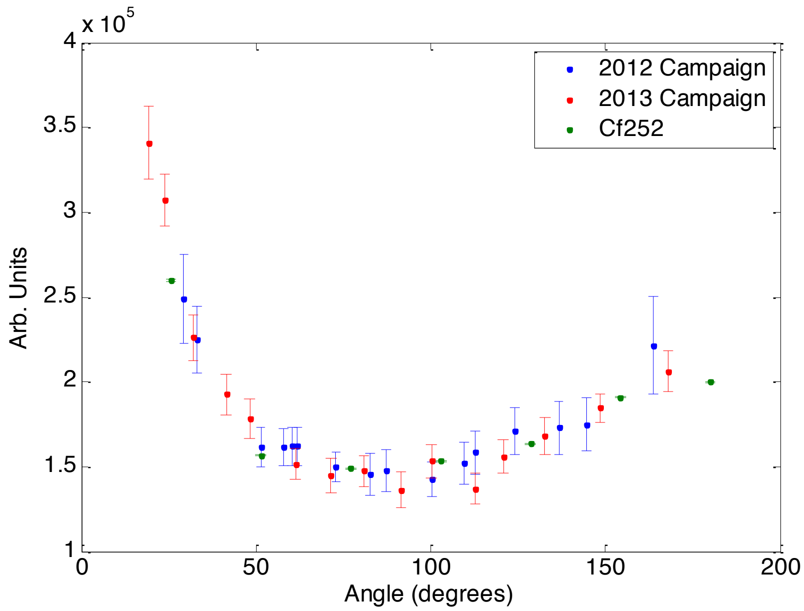

Fig. 13. Number-angle correlations, showing neutron doubles for detectors at specific angles of separation. Comparison to a Cf-252 measurement performed at UM. U-235 data shown is with fission inducing neutron energy below 10 MeV.

To find the neutron-neutron coincidence angle, a number of factors must be considered: there are 10 fission plates, each of which is subjected to a flux profile. The distance to the two detectors depend both on the position of the fission as well as the interaction position in the detector; the incoming neutrons are more likely to interact in the first part of the detector. The 3-dimensional positions of fission and the two-detector interaction positions are then used to calculate the neutron-neutron correlation angle, as shown in Fig. 13. The experimental data will only detail which detectors triggered and what plate in the fission chamber. This information is used with the distributions in this program to enable us to correctly use counting statistics to divide data into arbitrary angular binning. Fig. 14 illustrates the process involved in this correction for a pair of detectors.

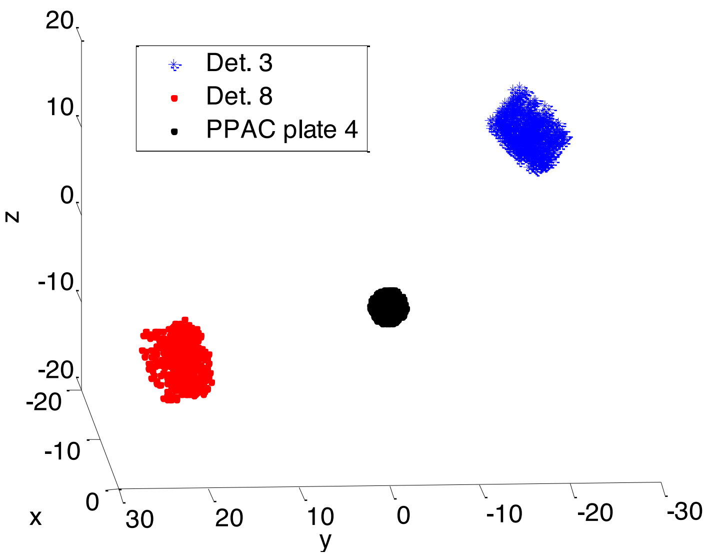

Fig. 14. Interaction position sampling in 2 detectors and a single PPAC plate. The first interaction position is sampled as a decaying exponential based on the cross section of the detector material.

1.1.3 Correlated neutron emissions from Cf-252

Correlated-neutron emission probabilities and average energies for two detected neutrons as a function of the angle between the two neutrons were measured for Cf-252. Experimental results were compared to several Monte Carlo models that include the number, energy, and angular distributions of prompt neutrons from fission. The measurement system consists of an array of 14 EJ-309 liquid scintillation detectors, arranged in a ring around a Cf-252 source directly on a thin metal table at distance of 20 cm. The setup allowed the measurement of coincident neutrons for angles between detectors of 26, 51, 77, 103, 128, 153, and 180 degrees.

Fig. 15 shows the measured neutron-neutron, cross-correlation functions as a function of time delay for all detector pairs. The result shows that correlated neutron detections are more prevalent at small and large angles, and less prevalent at approximately 90 degree angles. This result is in agreement with the fact that, in binary fission, neutrons are emitted from fission fragments that are accelerating (or are fully accelerated) in opposite directions. Two neutrons could be emitted from opposite fragments (favoring correlations at 180 degrees) or from the same fragment (favoring correlations at 26 degrees, in our setup); emission at correlation angles of 90 degrees is less probable. The number of correlated neutrons measured at angles of 103, 129, and 154 degrees increases gradually, leading up the 180 degree maximum. Likewise, the number of correlated neutrons measured at angles of 77, 56, and 26 degrees increases gradually.

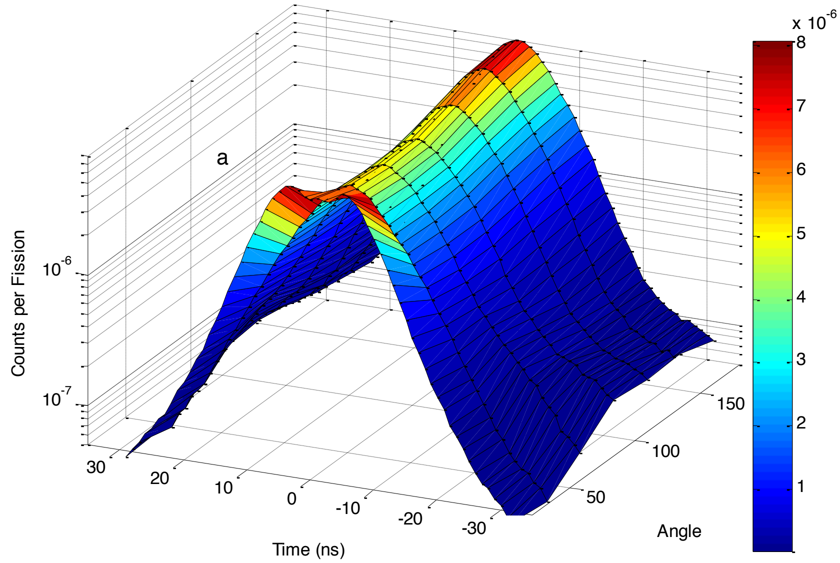

Fig. 15. Measured neutron-neutron cross-correlation functions for the detector pairs as a function of angle between detectors for spontaneous fission of Cf-252.

We simulated the experiment using MCNPX [18] and MCNPX-PoliMi v. 2.0.5. These codes offer several models of neutron emission from spontaneous fission events. In the MCNPX code, the neutrons are emitted isotropically, and their energy distribution is not dependent on the number of neutrons emitted in a given fission event. In MCNPX-PoliMi, there are several fission models available for the emission of fission neutrons from spontaneous fission. For all of the models tested in this work, the angular distribution of neutron emission in the laboratory frame of reference depends on the direction of the light fission fragment (which is selected isotropically).

Fig. 16 shows the measured and simulated time distribution of neutron-neutron correlations for detector angles of 77 degrees (a) and 180 degrees (b). A difference in the shape and magnitude is observed: the wider cross-correlation in the case of neutrons emitted at 77 degrees compared to the 180 degrees indicates a larger distribution of neutron energies. The magnitude of the cross-correlation for 180 compared to 77 degrees indicates the greater probability of neutron emission in the direction of the fission fragments. Fig. 16(c) shows the relative difference of the time of flight distributions of Fig. 16 (a) and Fig. 16(b), showing a close to 50% increase of correlated pairs of neutrons at approximately 0 ns time delay for the 180 degree angle compared to the 77 degree angle.

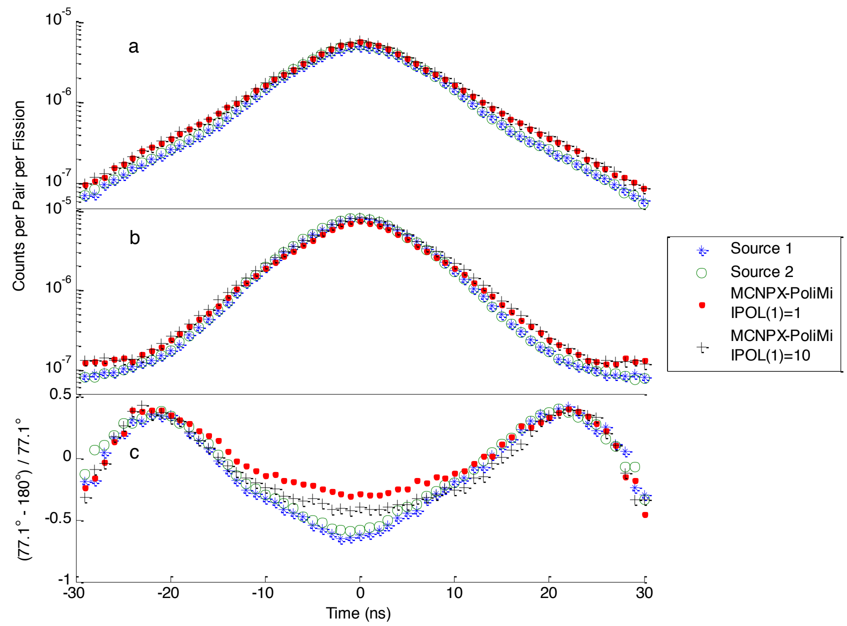

Fig. 16 Time distribution of neutron-neutron correlations for the angles of 77 degrees (a) and 180 degrees (b) and the relative difference between them (c). Detection threshold is 40 keVee.

1.1.4 Pu-240 Spontaneous Fission Neutron Correlations

A measurement of a plutonium metal sample was performed at the Joint Research Centre in Ispra, Italy to characterize neutron angular distribution anisotropy from Pu-240 spontaneous fissions. The 0.84 g Pu_{eff} sample emits 99.5% of neutrons from Pu-240. A majority of the prompt neutrons are emitted from the fully accelerated fission fragments; these neutrons carry momentum from the fission fragments, resulting in an anisotropic neutron angular distribution in the laboratory reference frame.

Sixteen organic liquid scintillators, stacked in two concentric 8-detector rings, were used to measure neutron-neutron correlations from the plutonium metal. Pulse shape discrimination was used to discern neutron detections from gamma ray detections. The simulation model of the measurement is shown in Fig. 17. There are 120 detector pairs with 13 unique angles.

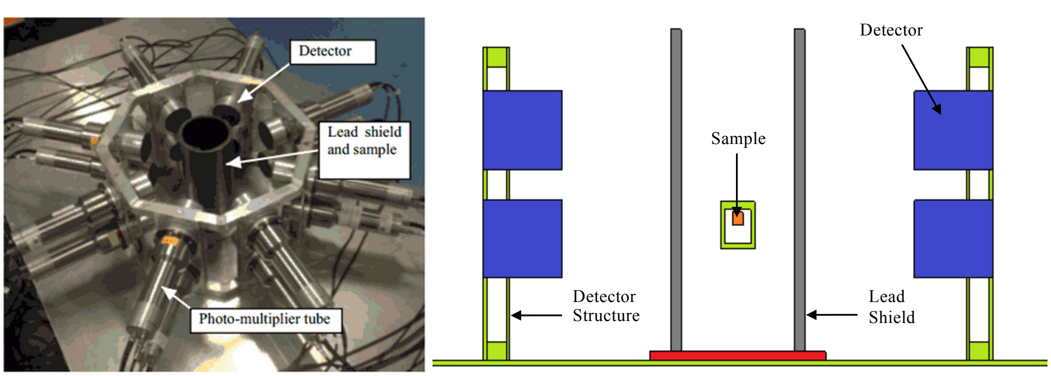

Fig. 17. Measurement setup in Ispra, Italy.

The experimental geometry was completely modeled in MCNPX-PoliMi. The source term was defined as a volumetric ^{240}Pu spontaneous fission source with a small amount of ^{242}Pu (approximately 1%). All of the features described in the previous section were applied in the plutonium source definition. The MPPost code was used to calculate cross-correlation distributions for neutron-neutron, neutron-photon, photon-neutron, and photon-photon events.

Fig. 18 shows an absolute comparison of the simulated and measured neutron-neutron cross-correlation for detectors separated by 82-degree pairs (eight total detector pairs); excellent agreement is observed.

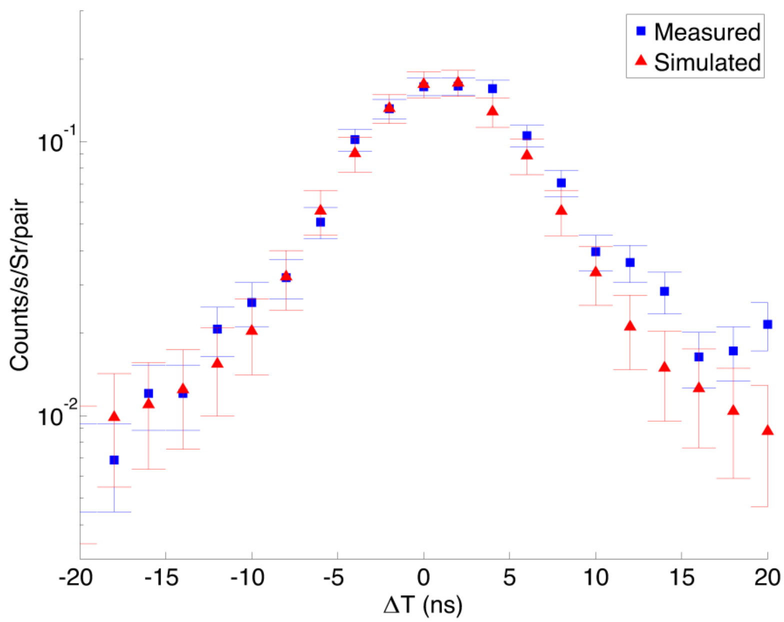

Fig. 18. Neutron-neutron cross-correlation distribution for detector pairs separated by 82 degrees for a plutonium metal measurement.

For each unique angle, the neutron-neutron cross-correlation time distributions were integrated to give the total count rate at a particular angle, shown in Fig. 19. The detector angles were determined by a –PoliMi estimate of the average detection position in the top and bottom row of detectors using a mesh tally of neutron flux. The measurement results indicate neutron angular anisotropy: a neutron is more likely to be emitted at small angles or very large angles relative to another neutron than to be emitted at angles around 90 degrees. MCNPX-PoliMi spontaneous fission sampling routines model this neutron anisotropy. PoliMi version 2.0.0 and version 2.0.8 use different angular distribution models: a purely energy-dependent model and an energy dependent-model that also samples the number of neutrons emitted from each fission fragment. Fig. 19 shows that both of these PoliMi spontaneous fission neutron sampling routines agree better than the isotropic model in MCNPX v2.7.0.

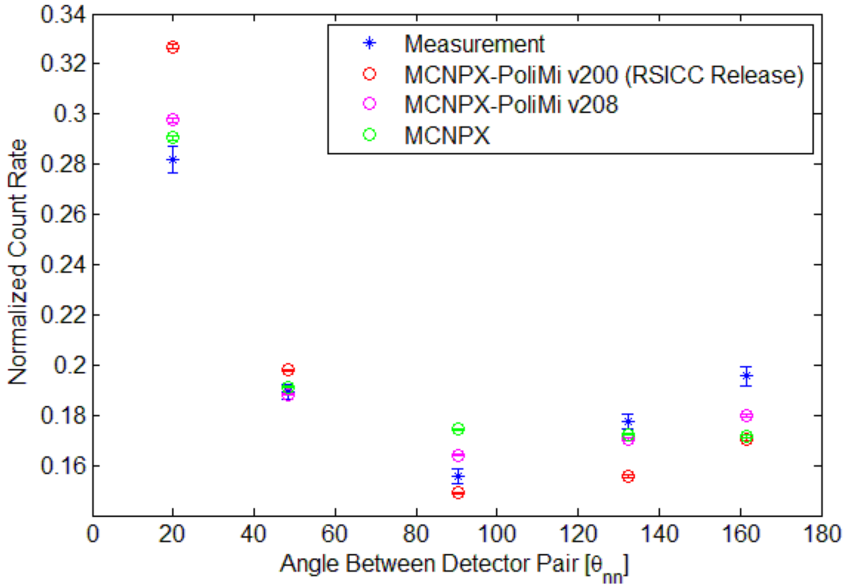

Fig. 19. Normalized count rate distribution of neutron-neutron correlations as a function of detector pair angle for a plutonium metal measurement, -PoliMi v2.0.0 (RSICC relsease), -PoliMi v2.0.8, and MCNPX fission source with –PoliMi detector cell collision recording.

1.1.5 Photofission

Figure 20 shows the unfolded neutron multiplicity distribution from photofission normalized to the $\bar{\nu}$ calculated by using the neutron flux. The $\bar{\nu}$ is found by calculating the neutron flux incident on the detectors and dividing that by the number of fissions that occurred. This was calculated over a wide range of energies (1 – 800 MeV neutrons and photofission) and was normalized to the ENDF/B-VII data. To find the neutron multiplicity distributions, the detected neutron multiples must be related to the actual number of neutrons emitted by the source.

The number of neutrons emitted from photofission as a function of photon energy has been previously determined. An average value of 3.8 corresponds to an average energy of 16 MeV for photons that induce photofission. While the actual photons created from the spallation reaction will have energies much greater than this, the photonuclear cross section for ^{235}U is a giant dipole resonance between 5 and 20 MeV. Consequently, the energy of photons inducing photofissions is confined to this energy range.

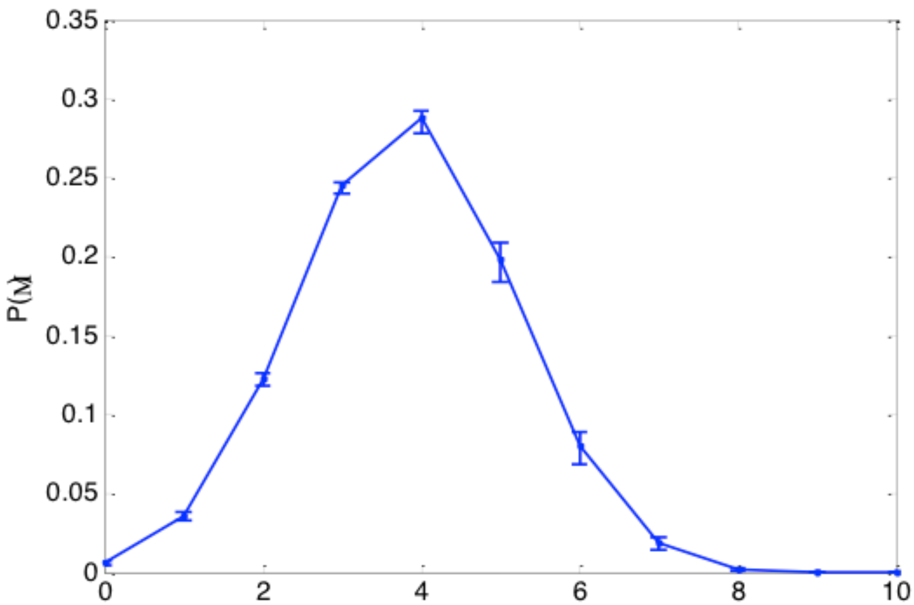

Fig. 20. The measured neutron multiplicity distribution from photofission normalized to the $\bar{\nu}$ calculated from the neutron flux, $\bar{\nu}$ =3.8

1.1.6 Variance Reduction: Implicit Correlation Method

MCNPX-PoliMi and MPPost can reliably model cross-correlation measurements of spontaneous fission sources, but computation time can be improved with implicit correlation nonanalog methods. Analog simulations of cross-correlation measurements with these codes are extremely time-consuming because the probability of correlated detection is extremely small, approximately equal to the product of the probabilities of a single detection in each detector. The cost of the implicit correlation method is comparable to the cost of simulating single event detection in the lowest efficiency detector. This method is especially useful in the nuclear nonproliferation and safeguards fields for simulating correlation measurements of shielded special nuclear material.

The implicit correlation method uses single detection histories to produce correlation tally information; consequently the number of correlation scores produced per source event is greater than a corresponding analog simulation. To do this, subsets of uncorrelated neutron histories are formed. If any set of simulated fission neutrons has both the same multiplicity and the same LFF direction in a particular MCNPX-PoliMi problem, those neutrons are uncorrelated within that set. Within an uncorrelated set of neutron histories, each neutron's initial direction and energy are sampled from the same distributions. As a result, it is possible to produce uncorrelated neutron detection sets by discretizing light fission fragment direction and sorting neutron histories by the source neutron multiplicity.

The new method was implemented in MCNPX-PoliMi in the measurement geometry shown in Fig. 21. The results of the implicit-correlation calculation, as well as the analog calculation and measured data are plotted in Fig. 22. The method demonstrated good agreement with analog simulation and measurement results and a speed-up of a factor of 500 over analog calculations. The improvement in computation time is on the order of the quotient of the probability of a single detection and the probability of a correlated detection, which is large in most practical applications.

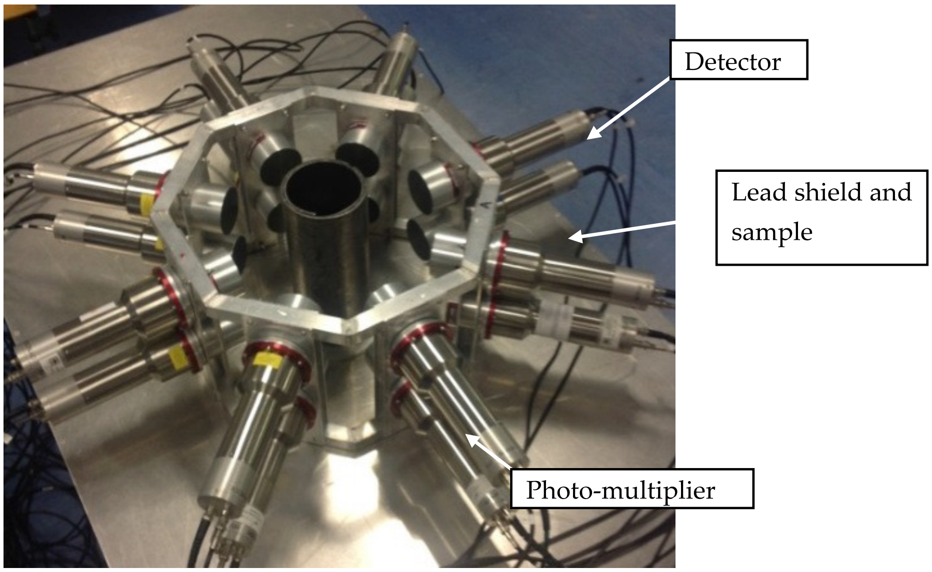

Fig. 21. The FNMC measurement setup with a plutonium metal sample centered inside a lead shield.

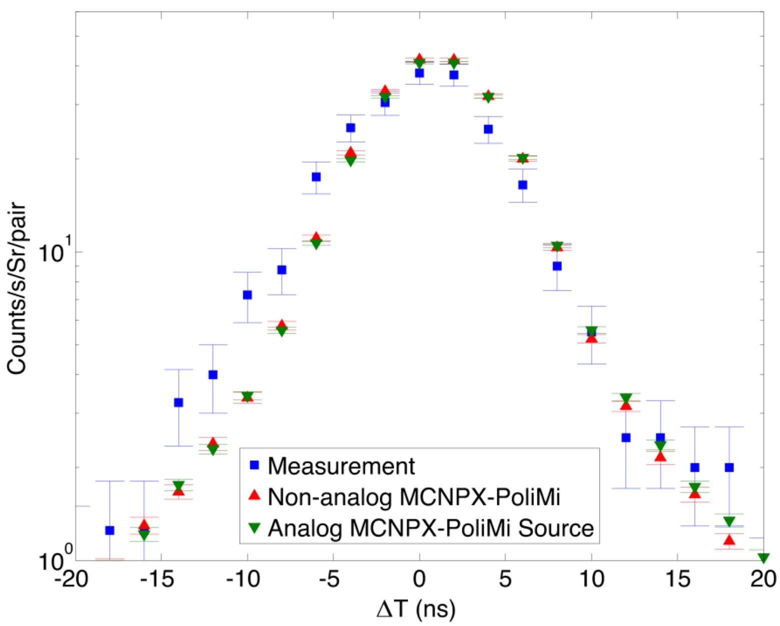

Fig. 22. Neutron-neutron cross-correlation distribution results for: a non-analog calculation of 10^8 fission histories with MCNPX-PoliMi and MPPost; an analog calculation of 10^9 fission histories with MCNPX-PoliMi and MPPost; an analog calculation of $9{\times}10^7$ fission histories with an MCNPX defined spontaneous fission source in –PoliMi and with MPPost; and a 135 minute measurement.

In Figure 23, discretization errors of a few percent were observed in the peak of the cross-correlation distribution and those errors would be lesser in practical problems, i.e. a shielded source. Finer discretization and more fission histories in the calculation could improve the agreement between implicit correlation and analog simulations. Further studies to analyze the implicit correlation method's performance in shielded problems would be useful. Additionally, further research will seek to expand this method to spatially distributed spontaneous fission sources and induced fission problems.

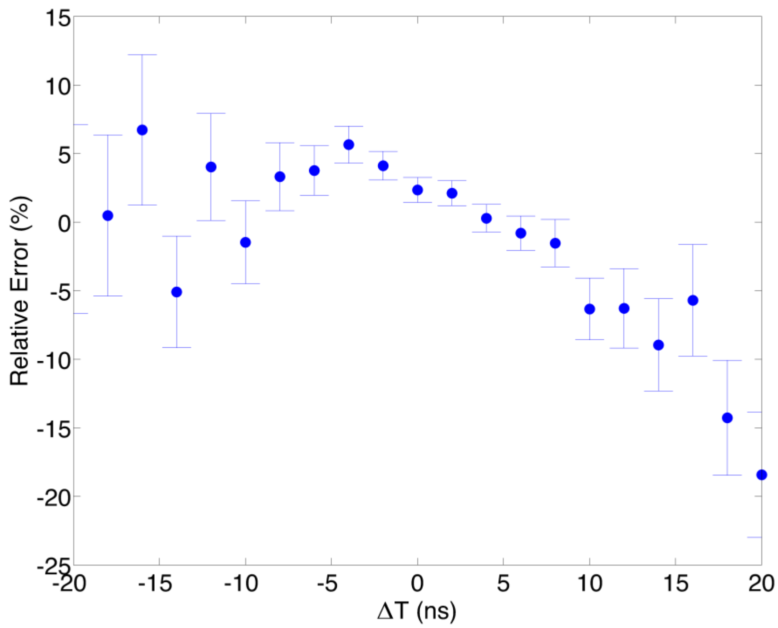

Fig. 23. The non-analog cross-correlation distribution relative error using the MCNPX-PoliMi analog calculation as a reference.

1.2 LANSCE

The fission chamber was installed in the experimental area after beam characteristics had been taken, shown in Fig. 24. The characterization of the beam involved measuring the beam profile, general neutron flux and background. Beam filters have been installed in the form of lead and polyethylene to reduce the pulsing overlap as well as to reduce some of the photon flux.

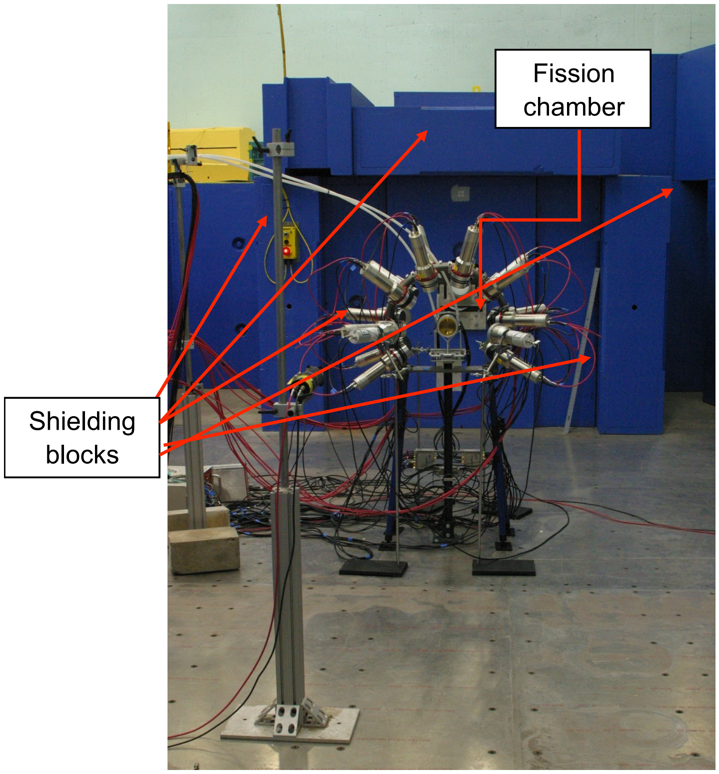

Fig. 24. The new flight path and experimental area where neutron multiplicity measurements are made. The view is looking toward the neutron source, somewhat obscured by the newly installed parallel plate avalanche chamber, as well as the University of Michigan detector setup surrounding it. The aluminum floor covers a pit 18 x 18 x 7 $feet^3$, which serves as a "get lost" area for scattered neutrons.

The Michigan-Los Alamos collaboration used the beam during the period October 22 – September 2, Fig. 25. Although this period was near the beginning of the run cycle, the beam was reasonably good and extensive data were obtained.

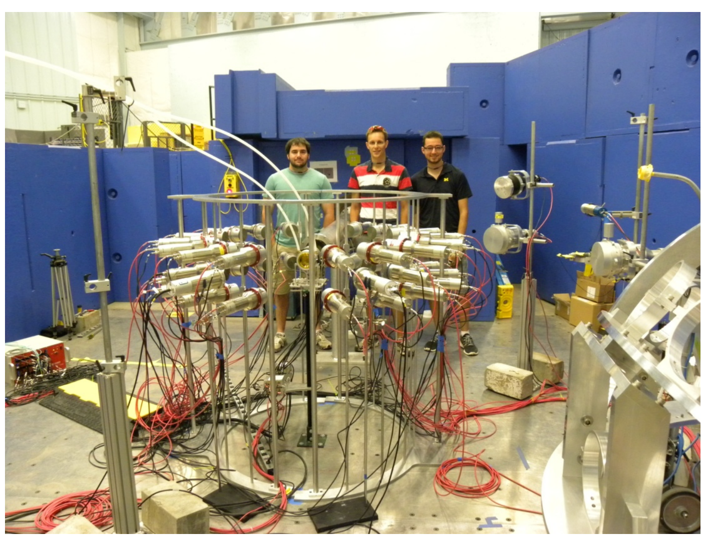

Fig. 25. Array of neutron and gamma-ray detectors from the University of Michigan together with experimenters. The ^{235}U PPAC is installed in the center of the array.

Prior to the beam period, an effort was undertaken to reduce the background. The beamline was realigned to look at the neutron production target, which had been moved about 1 cm.

Following calculations on the effects of air scattering, an evacuated beam tube was installed to reduce scattering (visible in Figs. 1 and 2). By expelling air from the last ~ 6 meters of flight path, the background of scattered neutrons was significantly reduced.

A ten-foil ^{239}Pu parallel-plate avalanche counter (PPAC) was completed by the Lawrence Livermore National Laboratory (LLNL) and installed. This PPAC was not used in the Michigan runs in 2012 because of the complication of the high rate of alpha particles. Instead, the LLNL PPAC containing ^{235}U was used. We are using the ^{239}Pu PPAC for LANL experiments and learning how to handle the high alpha rate. Plans for future Michigan experiments will include the ^{239}Pu PPAC.

Improvements in the fission chamber design. One of the major challenges to this measurement is the separation of fission events from the naturally occurring alpha-particle decay of Pu-239, where the rate is approximately 23 million alphas per second. Although the energy loss in the gas in the fission chamber is much greater for fission fragments than for alpha particles, the tail of the pulse height distribution for alpha particles overlaps with the fission events. We have improved the situation by reversing the polarity of the electrodes in the fission chamber, which is a parallel-plate avalanche detector provided by Lawrence Livermore National Laboratory (see Figure 26). Although alpha particles and fission events are still not cleanly separated, there is a significant reduction in the alpha-particle tail. This develop will aid future Michigan experiments that include Pu-239.

A large array of ^{6}Li-glass neutron detectors has been established. We completed the installation of an array of 22 detectors using ^{6}Li-glass scintillators (see Figure 27). We digitize each one of these detectors separately along with the 10 sections of the fission detector. The array now includes metal foils around each of the photomultiplier tube bases to reduce electrical pickup from the neutron detectors by the high-gain electronics of the fission chamber modules

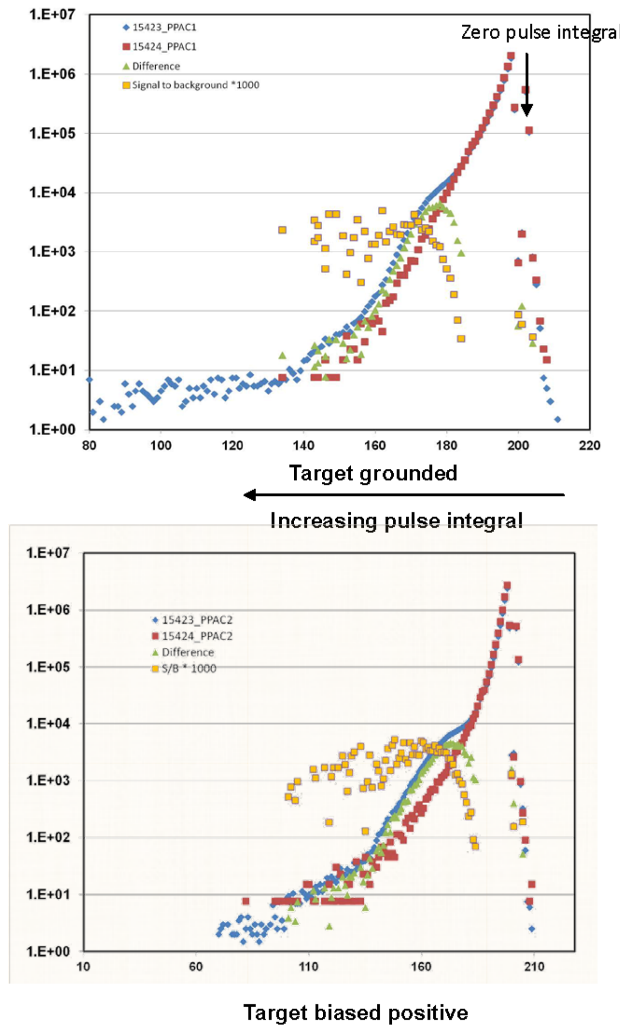

Fig. 26 Pulse-integral spectra from the fission chamber with two different polarities of the electric field within the chamber. The symbols are for (blue diamonds) shutter open (that is fissions plus alphas), (red squares) shutter closed (alphas only), (green triangles) difference of the first two (fissions only) and (yellow squares) ratio of fissions to alphas (that is, signal-to-background ratio) times 1000 for presentation clarity. The top figure is with the electric field in the normal direction; the lower figure is with the field direction reversed. Although neither field direction cleanly separates fissions from alphas, the latter increases the signal-to-background ratio by 50%.

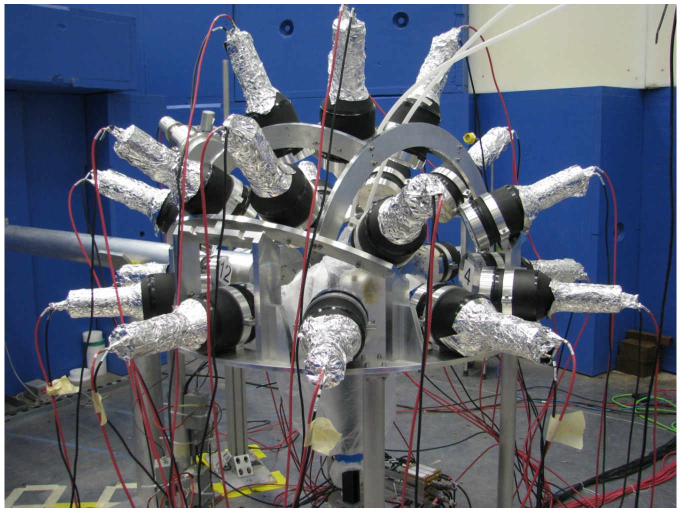

Fig. 27. Array of 22 Li-6-glass neutron detectors all looking at a Pu-239 fission chamber, which is inside a plastic bag for safety considerations. The neutron beam is inside the evacuated aluminum pile to the left of the figure until exiting the vacuum and then going into the fission chamber.

The LANSCE accelerator schedule was extended for operation January 7 – February 3, 2014, to compensate for downtime earlier in the cycle. Unfortunately for Target-4 experiments, including Chi-Nu, cooling of the neutron production target failed, with the result that there was only intermittent beam for the early part of this period and no beam after January 14. The silver lining was that the failure occurred near the end of the run cycle rather than at the beginning of the next cycle, planned for October, when the beam is planned to be at 100 Hz for WNR. Repairs of the neutron production target are in progress.

The 10-channel ^{239}Pu PPAC was used in all the beam-on experiments in January. The bias was negative so that the direction of the electric field in the PPAC was opposite to the usual. From previous measurements, this "opposite" direction gives reduced alpha-particle interference in the fission fragment pulse-height spectra. This PPAC has recently been sent back to its source at Lawrence Livermore National Laboratory for rewiring so that the same "opposite-direction field" can be achieved with positive bias, which is what the electronics were intended to use.

The ^{6}Li-glass scintillator array of 22 neutron detectors was used for all the LANL runs with neutron beam. Each detector was carefully calibrated to give the same pulse height spectrum for calibration gamma-ray sources and for thermal neutrons.

Neutron spectra from ^{252}Cf (spontaneous fission) were acquired to calibrate the efficiency of the ^{6}Li-glass detectors and, more generally, to understand the detector response, which includes scattering from the support stand, the other detectors, and components of the PPAC itself. Monte Carlo calculations including detector response using MCNP-PoliMi reproduce the measured data very well.

Most of the background with the beam on is now understood as a product of alpha background in the PPAC and low-energy neutron background in the 6Li-glass detectors. Thus the background has both time-dependent and time-independent components. Results of the analysis of data taken by LANSCE-NS are consistent with those of the Michigan group. In fact, their analysis pointed the way to our understanding of "faster-than-light" events, which are caused by accidental coincidences.

The ^{252}Cf PPAC was used for two weeks by a group from the University of Kentucky, Prof. Michael Kovash, PI, to test the response of their new detector system to neutrons and gamma rays. The two large detectors are constructed of multiple, alternating thin sheets of plastic scintillator. The idea is that neutrons produce proton recoils that have a short range in scintillator material, whereas gamma rays produce Compton electrons that have a much larger range. By separating events that trigger more than one layer from those that trigger only one layer, a separation between gamma rays and neutrons can be achieved. The detectors also yield position information along their 2-meter lengths. This project is part of the Stewardship Science Academic Alliance, a program funded by NNSA.

The ^{252}Cf parallel plate avalanche counter (PPAC) was used to develop data acquisition software. It was also provided data so that Monte Carlo models of neutron scattering could be tested with a detailed description of the physical setup including details of the PPAC and the structure supporting the neutron detectors (see Figure 25).

Modeling results showed that replacing some components of the PPAC with hydrogen-free materials can reduce significantly the neutron scattering. Consequently, we have returned the PPACs to their source at Lawrence Livermore National Laboratory to replace the G-10 supporting rings with aluminum rings and replacing the CH_2 insulators with those made of glass.

Most of the background with the beam on is now understood as a product of alpha background in the PPAC and low-energy neutron background in the ^{6}Li-glass detectors. Results from the University of Michigan were confirmed by LANL measurements. Thus the background has both time-dependent and time-independent components.

The LANL data acquisition system (DAQ) has been significantly upgraded so that we now do not lose data when the neutron source is operated at 40 macropulses per second.

We organized and hosted the Fission School & Workshop (FIESTA), Sep. 8-12, 2014. There were 34 participants in the Workshop and 29 students for the school, many of whom also stayed for the workshop. Most of the Workshop presentations are available at the website: http://t2.lanl.gov/fiesta2014/workshop.shtml

2. PATENTS/PUBLICATIONS/PRESENTATIONS

2.1 Journal papers

1. A. Enqvist, B. M. Wieger, L. Huang, M. Flaska, S.A. Pozzi, R. C. Haight, H. Young Lee and C. Yen Wu, "Neutron-Induced 235U Fission Spectrum Measurements Using Liquid Organic Scintillation Detectors" PHYSICAL REVIEW C 86, 064605 (2012). http://link.aps.org/doi/10.1103/PhysRevC.86.064605
2. A. Enqvist, C. C. Lawrence, B. M. Wieger, S. A. Pozzi, T. N. Massey, "Neutron Light Output Response and Resolution Functions in EJ-309 Liquid Scintillation Detectors", Nucl. Instr. Meth. A 715 (July 2013) p. 79. http://dx.doi.org/10.1016/j.nima.2013.03.032
3. S. A. Pozzi, B. Wieger, A. Enqvist, S. D. Clarke, M. Flaska, M. Marcath, E. Larsen, R. C. Haight, and E. Padovani, "Correlated Neutron Emissions from Cf-252," Nuclear Science and Engineering, vol. 178(2), pp. 250-260, 2014.
4. M. J. Marcath, S.D. Clarke, B.M. Wieger, E. Padovani, E.W. Larsen, S.A. Pozzi, "An Implicit Correlation Method for Cross-Correlation Sampling, with MCNPX-PoliMi Validation." Accepted for publication in Nucl. Sci. Eng., December 2014.
5. S. D. Clarke, B. M. Wieger, A. Enqvist, S. A. Pozzi, R. C. Haight, H. Y. Lee, B. A. Perdue, E. Kwan, C.-Y. Wu, and R. A. Henderson. "Measurement and Simulation of Correlated Neutrons from Photofission of ^{235}U.", In progress.
6. B. M.Wieger A. Enqvist, S.D. Clarke, S.A. Pozzi, R.C. Haight, H.Y. Lee, B.A. Perdue, E. Kwan, C-Y. Wu and R.A. Henderson, "U-235 Induced Fission Measurements with a White Neutron Source", In Progress.
7. A. Enqvist, B. M. Wieger, S. D. Clarke, S. A. Pozzi, R. C. Haight, H. Y. Lee, B. A. Perdue, E. Kwan, C-Y. Wu and R.A. Henderson, "Energy-angle Correlation of Neutron Emission from ^{235}U induced fission", In Progress.

2.2 Conference proceedings and presentations

1. M. J. Marcath, T. Shin, S. D. Clarke, J. L. Dolan, M. Flaska, E. Larsen, S. A. Pozzi, and P. Peerani, "Plutonium Metal Spontaneous Fission Neutron Cross-Correlation Measurements," *Accepted to the 2014 IEEE Nuclear Science Symposium*, Seattle, WA USA, Nov. 8 – 15, 2014.
2. S. D. Clarke, M. J. Marcath, M. L. Ruch, J. L. Dolan, M. Flaska, E. W. Larsen, E. Padovani, P. Peerani, and S. A. Pozzi, "Advances in the MCNPX-PoliMi Code for Nuclear Safeguards Applications," *Proceedings of the Institute of Nuclear Materials Management 55th Annual Meeting*, Atlanta, GA, USA. July 20 – 24, 2014, available online.

3. S. A. Pozzi, B. Wieger, S. Ward, S. D. Clarke, M. Flaska, M. J. Marcath, E. W. Larsen, A. Enqvist, R. Vogt, P. Talou, and E. Padovani, "Experiments and Simulations of Correlated, Prompt Emissions in Cf-252," *Proceedings of the Institute of Nuclear Materials Management 55th Annual Meeting*, Atlanta, GA, USA. July 20 – 24, 2014, available online.
4. A. Enqvist, B. M. Wieger, S. D. Clarke, S. A. Pozzi, R. C. Haight, H. Y. Lee, B. A. Perdue, E. Kwan and C.-Y. Wu, "Energy-Angle Correlation of Neutron Emission from 235U Induced Fission," *Proceedings of the Institute of Nuclear Materials Management 54th Annual Meeting*, Palm Desert, CA, USA, July 14 – 18, 2013, available online.
5. B. M. Wieger, A. Enqvist, S. D. Clarke, S. A. Pozzi, R. C. Haight, H. Young Lee, Brent Perdue, E. Kwan and C. Yen Wu, "Neutron multiplicity distribution measurements of ^{235}U induced fission," *Proceedings of the Institute of Nuclear Materials Management 54th Annual Meeting*, Palm Desert, CA, USA, July 14 – 18, 2013, available online.
6. S. A. Pozzi, A. Enqvist, B. Wieger, S. D. Clarke, M. Flaska, M. Marcath, E. Larsen, R. Haight, N. Puppato, E. Padovani, "New Models for Prompt Neutron Emissions from Nuclear Fission," *Proceedings of the Institute of Nuclear Materials Management 54th Annual Meeting*, Palm Desert, CA, USA, July 14 – 18, 2013, available online.
7. J. L. Dolan, E. C. Miller, A. C. Kaplan, L. Huang*, A. Enqvist, M. Flaska, S. D. Clarke, A. Tomanin, P. Peerani, D. L. Chichester, and S. A. Pozzi, "Passive Measurement of Organic-Scintillator Neutron Signatures for Nuclear Safeguards Applications," *2012 IEEE Nuclear Science Symposium Conference Record*, Anaheim, CA USA, Oct. 27 – Nov. 3, 2012, on CD-ROM.
8. S. A. Pozzi, S. D. Clarke, W. Walsh*, E. C. Miller, J. Dolan, M. Flaska, B. M. Wieger, A. Enqvist, E. Padovani, J. K. Mattingly, D. Chichester, and P. Peerani, "Validation of MCNPX-PoliMi Fission Models," *2012 IEEE Nuclear Science Symposium Conference Record*, Anaheim, CA USA, Oct. 27 – Nov. 3, 2012, on CD-ROM.

3. PROJECT PARTICIPANTS

Details an all project participants are given below in the following format:

1. Name
   a. Project role
   b. Nearest person-month worked
   c. Contribution to the project
   d. Funding support
   e. Collaborated with individuals in a foreign country
   f. Travelled to a foreign country

1.1. Principle Investigators

1. Sara Pozzi
    a. PI
    b. 1.0
    c. Project leadership
    d. This grant
    a. JRC staff in Ispra, Italy
    b. Travel to the JRC, Ispra, Italy in May 2014 for Pu measurements
2. Robert Haight
    a. PI
    b. 1.0
    c. Contact person at the LANSCE facility
    d. This grant
    e. None
    f. None

1.2. Research Faculty and Staff

1. Andreas Enqvist
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    b. Eight
    c. Data analysis, measurement planning and execution
    d. NEUP grant
    e. None
    f. None
2. Brian Wieger
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    c. Monte Carlo simulations and error analysis
    d. This grant
    e. None
    f. None
3. Shaun Clarke
    a. Assistant Research Scientist in Nuclear Engineering and Radiological Sciences, University of Michigan
    b. 1.0

c. Supervises students, performs and guides Monte Carlo simulations and laboratory measurements
d. Other research grants
e. None
f. None

1.3. Students

1. Matthew Marcath
    a. Ph.D. student in Engineering, University of Michigan
    b. 1/2011 – present
    c. MCNP-PoliMi simulations EJ-309-based detector systems; Monte Carlo variance reduction techniques
    d. Nuclear Nonproliferation and International Safeguards Fellowship
    e. JRC staff in Ispra, Italy
    f. Travel to the JRC, Ispra, Italy in May 2014 for Pu measurements
2. Charles Sosa
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    f. None
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    c. Monte Carlo simulations and analysis
    d. Supported by this grant
    e. None
    f. None
4. Steve Ward
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    c. Data analysis
    d. Supported by this grant
    e. None

f. None