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MONTE CARLO SIMULATION OF THE FULL MULTIPLICITY DISTRIBUTIONS MEASURED WITH A PASSIVE COUNTER

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ABSTRACT

The objective of the work here is to validate the Monte Carlo code MCNP-PoliMi using comparisons with experimental data for the specific problem of neutron multiplicity counting with He-3 detectors. Measurements of various fissionable samples have been made with an active well coincidence counter (AWCC) operating in passive mode at the PERLA laboratory at Joint Research Center site in Ispra, Italy. The MCNP-PoliMi postprocessor was upgraded to explicitly simulate the deadtime in the PERLA measurement electronics. The results from MCNP-PoliMi have been compared to the measured data from ^{252}Cf sources and several plutonium and plutonium oxide samples. Very good agreement between the simulated and measured multiplicity distributions has been observed for multiplet orders as high as 25.

Key Words: Multiplicity, MCNP, MCNP-PoliMi

1. INTRODUCTION

The distinction of fissile material from benign material is of great concern to the United States and the world. The principal difference between fissile and benign materials is neutron multiplication. Consider the decay of a material in the presence of a detection system capable of accurately recording the emissions: for a benign material, such as lead, the reaction emissions would largely be single-particle in nature whereas a fissile material would undergo multi-particle chain reactions. The result would be many particles (neutrons and photons) arriving at the detectors within a given time window. Such a grouping of particles is referred to as a “multiplet.” The distribution of these multiplets holds important information regarding the nature of the interrogated sample.

Multiplicity counting has been well established as an assay method for plutonium samples in the area of nuclear materials control and accountability [1-3]. The multiplicity distributions are acquired by specialized electronics packages that separately record the number of times specific numbers of neutrons are detected during a fixed time window. These passive counting systems rely on neutrons emitted by spontaneous fission; these neutrons are typically counted using polyethylene-moderated ^{3}He proportional counters [4].

Previous work has been done validating Monte Carlo codes with experimental multiplicity data [5, 6]. The objective of the work here is to use this experimental data to validate the Monte Carlo code MCNP-PoliMi for the specific problem of neutron multiplicity counting. Passive measurements of various fissionable samples have been made with an active well coincidence counter (AWCC) operating in passive mode at the PERLA laboratory at Joint Research Center site in Ispra, Italy. These results will be compared to Monte Carlo simulations and the system performance will be assessed.

2. MONTE CARLO MODELING

Monte Carlo codes have been widely used to design and analyze measurement systems of many types and configurations. However, when modeling the time-correlated events resulting from fission reactions and chains, the widely-used Monte Carlo code MCNPX has some limitations. Therefore, the MCNP-PoliMi code was chosen for the simulations here.

2.1. Description of the MCNP-PoliMi Code

In standard MCNPX it is only possible to simulate a single source neutron per history making accurate simulation of neutron multiplicity distributions extremely difficult. [7]. An enhanced version of MCNP4c, MCNP-PoliMi, preserves standard MCNP code structure while correcting this deficiency, although it introduces some assumptions [8]. MCNP-PoliMi is capable of simulating multiple correlated source neutrons from a single history (e.g. a spontaneous fission event). These source neutrons are sampled from a multiplicity distribution to ensure that the correct numbers of particles with appropriate energies are created.. MCNP-PoliMi version 1.2.4 is capable of running with all standard MCNP source types and includes several specific spontaneous-fission-source definitions (i.e., ^{252}Cf, ^{240}Pu, ^{242}Pu, ^{242}Cm, ^{244}Cm), as well as (α, n) sources from plutonium isotopes as well as ^{241}Am. These distributions contain accurate representations of the energy and multiplicity distributions of both neutrons and gamma rays.

MCNP-PoliMi produces a specialized output file that includes a detailed account of all interactions occurring within certain geometric cells specified by the user; these cells typically correspond to the radiation detectors in the system. A specialized post-processing code is then used to process this output to generate the response from a given radiation detector. This code has been recently extended to model detection in a ^{3}He multiplicity counter [9]. An extended deadtime module has been developed to apply this model to an active well coincidence counter.

2.2. MCNP-PoliMi Model Description

The Canberra JCC-51 active well coincidence counter (AWCC), shown in Figure 1, consists of 42 ^{3}He neutron detectors imbedded in polyethylene in a cylindrical arrangement around a central sample cavity with AmLi neutron sources above and below. The AWCC was modeled completely in MCNP-PoliMi with the exception of the AmLi sources because the experiments were performed in passive mode. A total of six different samples were measured at PERLA: low-intensity ^{252}Cf, high-intensity ^{252}Cf, Pu metal, small-volume PuO_2 powder, large-volume PuO_2 powder and mixed-oxide (MOX) powder. The various fissionable sample sources were modeled with as much detail as possible including all appropriate spontaneous fissions and (α, n) contributions. Any casings or containers were also modeled in order to reflect as much of the PERLA experiment as possible. Source emissions were evenly distributed in time over approximately 100 s (the data collection time in the measurements). The total number of Monte Carlo source histories for each simulation was calculated using the exact experimental data collection times and the activity of each sample. The sample activity was calculated using the sample mass and the spontaneous fission and (α, n) specific activities. Source contributions that were less than 1% of the total were neglected; the total source activities were re-normalized to account for these small approximations.

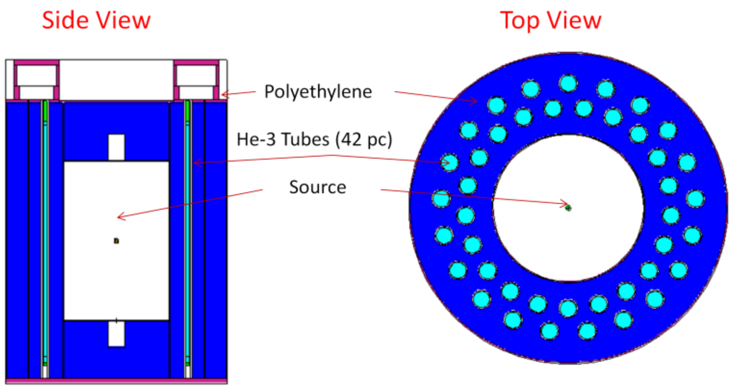

Figure 1. MCNP-PoliMi model of a Canberra JCC-51 active well coincidence counter.

3. Description of the Post Processor

The MCNP-PoliMi postprocessor was upgraded to explicitly simulate the deadtime in the PERLA measurement electronics. The enhanced post processing code operated in three distinct stages. The first stage removed all events from the PoliMi output file that were not neutron captures on helium occurring inside of the ^{3}He tubes. The remaining events are then sorted according to their time of interaction.

Next, the event times are processed through the measurement circuit electronics of the detector system (see Figure 2). The measurement electronics system divides the 42 ^{3}He tubes into six groups of seven detectors each. The signal from each detector group is sent to a separate amplifier. Then, the signal from each amplifier is collected in a single OR gate. The deadtime of each ^{3}He tube was modeled individually. Once an event occurred in a live tube, the amplifier associated with that tube is checked (the dead times of the six amplifiers were also modeled individually). If the amplifier is dead, the pulse was rejected and if the amplifier is live, the status of the OR gate was checked. If the OR gate is dead then the pulse was rejected otherwise it is accepted. The output of this post-processing step is a list of acceptable pulses (those which occur in a live tube, amplifier and OR gate).

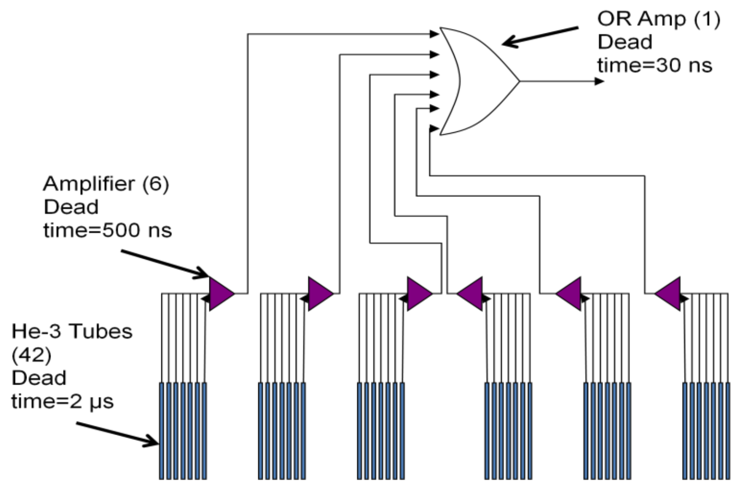

Figure 2, Circuitry of the detector system.

The final stage of the postprocessor applies the shift register analysis (see Figure 3) to the list of acceptable pulses to determine the multiplicity distribution. The shift register activates on a trigger pulses then looks back in time and counts the previously received pulses. This is done by applying a short predelay, -4.5 μs, then opening a -64-μs window relative to the initial trigger pulse. Events recorded in this time window contribute to the total multiplicity distribution (reals plus accidentals (R+A)). The shift register also opens a second -64 μs window at -1024 μs relative to the trigger pulse. Counts recorded in this second window contribute the background accidental distribution (A). This intent for opening this second window after a long delay is that the initial spontaneous fission neutrons will no longer be present in the system. Therefore, the background rate of neutrons can be measured. The postprocessor cycles through all of the acceptable pulses and treating each pulse as a trigger pulse, building the complete R+A and A distributions.

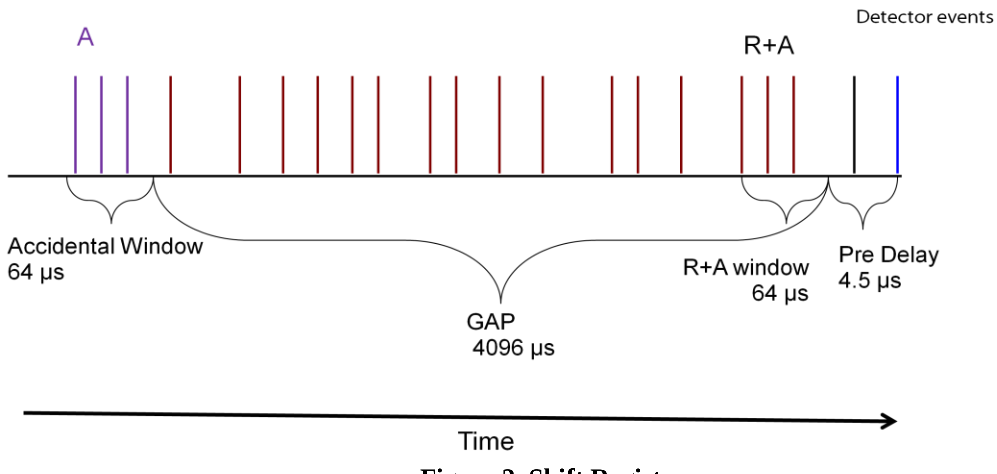

Figure 3, Shift Register

The PERLA measurement data contained only the times of events recorded. Consequently, the effects of the electronics were not needed. Therefore, the PERLA data were read directly into the final portion of the post processing to apply the shift register calculation.

4. RESULTS

The experimental data were collected at the PERLA laboratory at the Joint Research Centre site in Ispra, Italy for six different sources measured in ten 100-s measurements. The R+A and A distributions from the MCNP-PoliMi simulated data and PERLA measured data were generated using the enhanced postprocessor and then compared for each of the six measurement sources.

4.1 Low-intensity ^{252}Cf source

The first of the six samples measured was a weak source of ^{252}Cf with an activity of 3781 n/s. This source was modeled as an isotropic point source at the center of the AWCC cavity. The casing around the source was neglected.

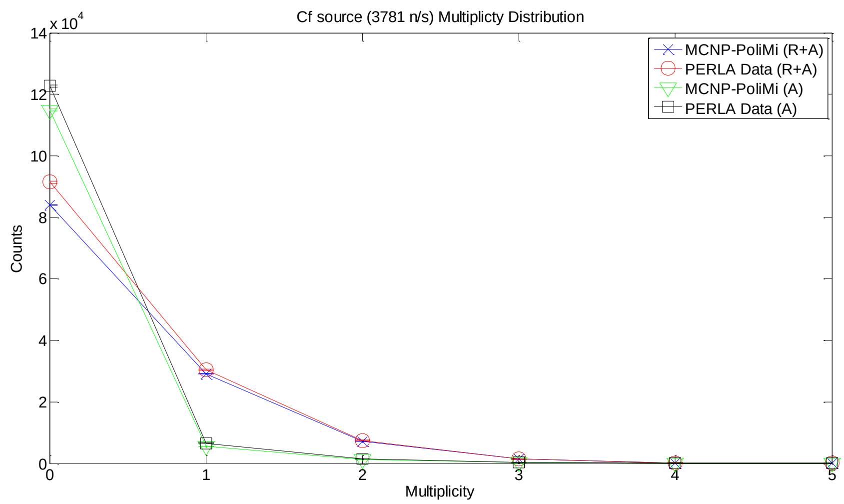

Figure 4, Multiplicity distribution comparison for weak ^{252}Cf source (3781 n/s)

Figure 4 shows that the simulated distributions for the weak ^{252}Cf source are very close to the distributions from the measured PERLA data. This shape of the R+A distribution is as expected for a weak source of spontaneous fission neutrons. Most of the trigger events are uncorrelated neutrons; this is shown by the zero-order multiplet being the most probable. The accidentals distribution shows that after an extended time after the trigger pulse the most probable number of counts in the 64 μs window is also zero, which is also expected for a low activity source.

4.2 High-intensity ^{252}Cf source

The second source that was measured in this measurement campaign was ^{252}Cf with an activity of 497200 n/s. This source was also small enough that is was modeled as an isotropic point source located in the center of the AWCC cavity. The casing of the source was again neglected.

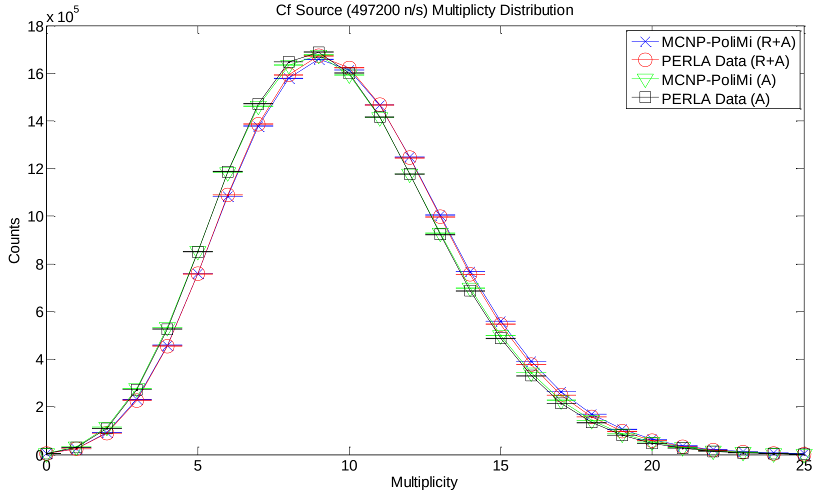

Figure 5. Comparison of PERLA experimental results to MCNP-PoliMi simulation for a 497200 n/s ^{252}Cf source in an passive well coincidence counter.

Figure 5 shows excellent agreement observed between the MCNP-PoliMi results and the PERLA experiment, up to multiplet-orders as high as 25 for both the R+A and A distributions. The shape of the distribution is expected for sources with such a high activity: for every trigger event, some additional neutrons will be recorded in the counting window. For this case, nine neutrons inside of the 64-μs window was most probable number in the R+A distribution. The accidentals distribution is very similar to the R+A distribution but shifted slightly towards lower multiplet-orders. This is expected because of the long delay between the trigger pulse and the opening of the accidental window, this decreases the chance of detecting events correlated with the initial trigger.

4.3 Plutonium metal disk

The third source was a plutonium metal disk at the center of the AWCC cavity. This metal disk was a PuGa alloy (1.5% Ga), 0.6-cm thick and 3.3 cm in diameter. The plutonium certified mass was 9.455 g. The isotopic composition was 0.13% ^{238}Pu, 75.66% ^{239}Pu, 21.49% ^{240}Pu, 1.95% ^{241}Pu and 0.77% ^{242}Pu with an Am/Pu ratio of 0.0186. These isotopics were measured in July, 1996 [10].

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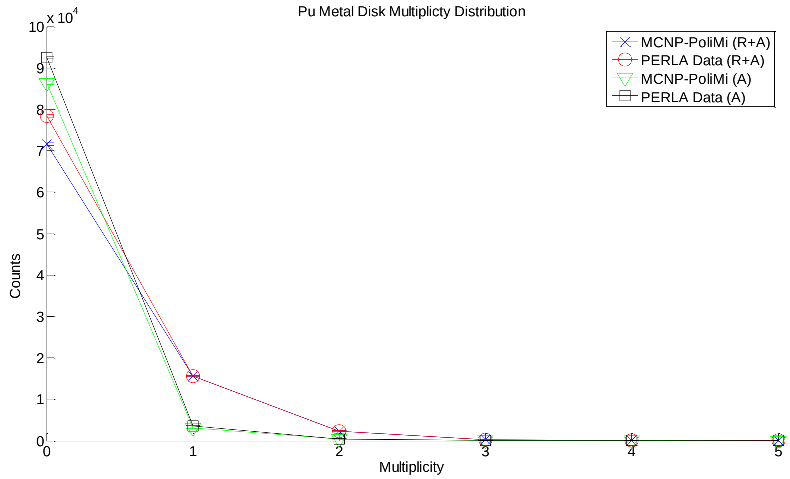

Figure 6, Comparison of multiplicity distributions for the Pu metal disk

Figure 6 shows only a slight deviation between the PERLA measurements and the MCNP-PoliMi simulation multiplet-order zero, but the higher-order multiplets are all within statistical error. The plutonium metal disk has a calculated sample activity of 2230 n/s, a low activity, which is verified by the shape of the R+A distribution. The R+A distribution shows a rapid decrease, with almost no counts greater than multiplet-order four. The accidental distribution matches the behavior shown by the low-activity ^{252}Cf source.

4.4 Small sample of plutonium oxide powder

The fourth measured sample was a small sample of plutonium oxide powder with a total mass of 59.13 g and an estimated density of 2.6 g/cm^3. This source was placed on a 10-cm aluminum ring placed inside the AWCC cavity. This sample was inside of a model-200 container which consists of two AISI-304 stainless steel cylinders. These details were included in the MCNP-PoliMi simulation. The plutonium certified mass was 50.339 g, the isotopic composition was 0.17% ^{238}Pu, 72.53% ^{239}Pu, 25.07% ^{240}Pu, 1.23% ^{241}Pu and 1.00% ^{242}Pu, with an Am/Pu ratio of 0.0314. These isotopics were measured in August, 2008.

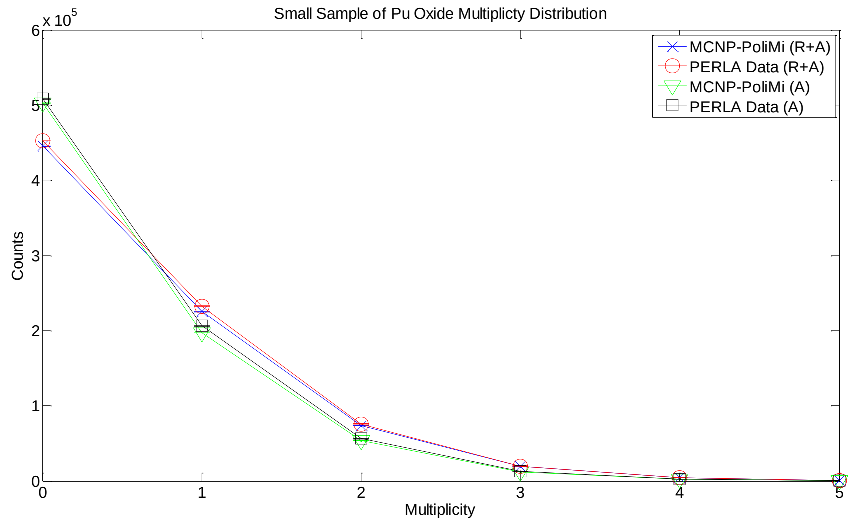

Figure 7, Comparison for the Small sample of Pu Oxide

Figure 7 shows excellent agreement between the PERLA measured data and the MCNP-Polimi simulated data for the R+A distribution and the A distribution up to a multiplet-order five. This sample had a calculated source activity of 22556 n/s. Therefore, most of the trigger events do not have any subsequent events and the distribution drops nearly to 0 by multiplet-order five. The trend in the accidental distribution is similar to the other low-activity sources.

4.5 Large sample of plutonium oxide powder

The fourth measured sample was a small sample of plutonium oxide powder with a total mass of 1148.96g and the same composition as the small plutonium oxide sample. This sample was inside of a model-1000 container (a larger version of the model-200) that was placed on the bottom of the AWCC cavity. This source has a calculated source activity of 438300 n/s, making this the second-strongest source measured in this measurement campaign.

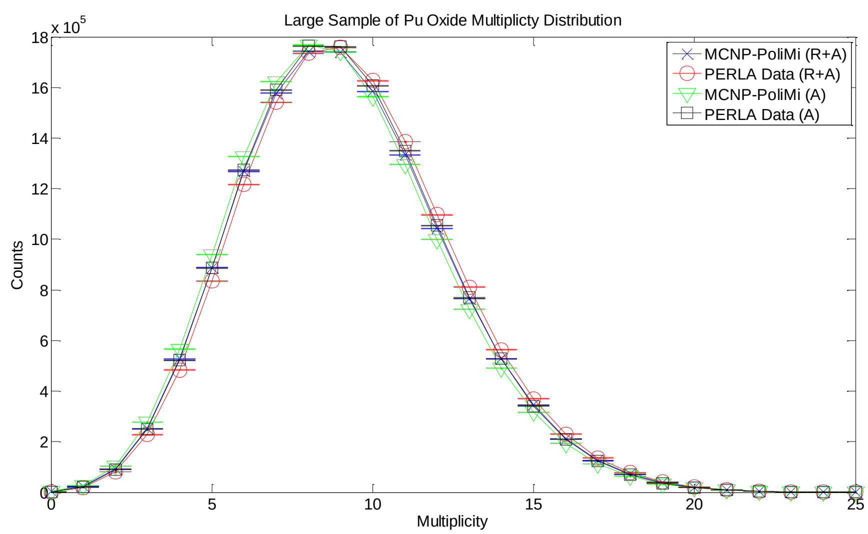

Figure 8, Comparison of multiplicity distributions for the large sample of Pu oxide

Excellent agreement is observed in Figure 8 for both the R+A and A distributions up to multiplet-orders of 20. The shape of these distributions is very similar to those shown for the strong ^{252}Cf source.

4.6 Mixed-oxide powder

The final sample was a mixed oxide (MOX) powder sample with a mass of 1011.13g. The uranium has a natural enrichment, modelled with a density of .9 g/cm^3. The plutonium isotopic composition was 0.17% ^{238}Pu, 66.54% ^{239}Pu, 28.02% ^{240}Pu, 3.26% ^{241}Pu and 2.01% ^{242}Pu with an Am/Pu ratio of 0.0081. These isotopics were measured in December, 1988 [10]. The composition was corrected for radioactive decay between the source characterization date and the date of the experiment. This sample was modelled inside of a model-2500 container placed at the bottom of the AWCC cavity. The model-2500 container is another double walled stainless steel containers but with different dimensional ratios than the model-200 and 1000. The MOX powder had a calculated activity of 73040 n/s.

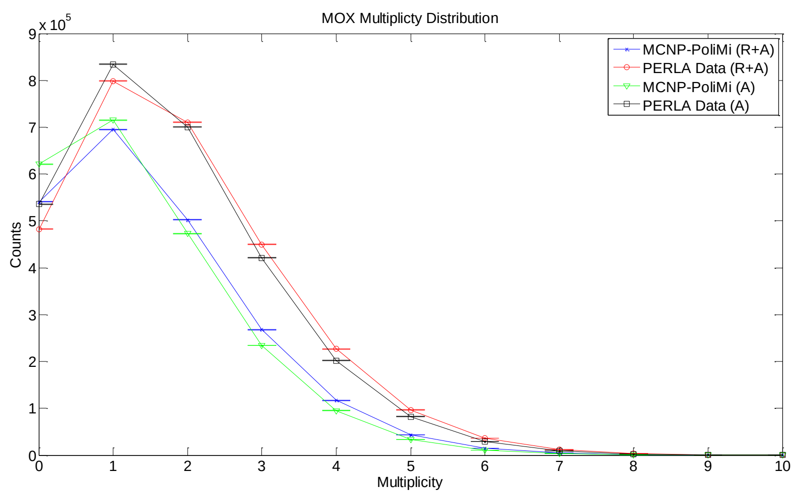

Figure 9, Comparison of the multiplicity distribution for the MOX sample

The comparison of the R+A and A distributions for the MOX sample in Figure 9 show that the trends of the PERLA data are accurately captured by the MCNP-PoliMi simulation. However, there is a noticeable difference in the number counts for each multiplet bin. For the MOX, with an intermediate activity, there is a shift in the shape of the distributions from the lower-activity cases towards the parabolic shape that is characteristic of the more active sources. This shows that counting zero events after the trigger pulse is no longer the most probable.

4. CONCLUSIONS

The post processor for the MCNP-PoliMi code has been enhanced to model multiplicity counting in a Canberra JCC-51 AWCC including the electronic deadtime and shift-register calculations. A total of six different samples were measured: low-intensity ^{252}Cf, high-intensity ^{252}Cf, Pu metal, small-volume PuO_2 powder, large-volume PuO_2 powder and mixed-oxide (MOX) powder. The results from MCNP-PoliMi have been compared to measured data for the passive multiplicity measurement of these samples. Very good agreement was observed for multiplets as high as order 25.

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