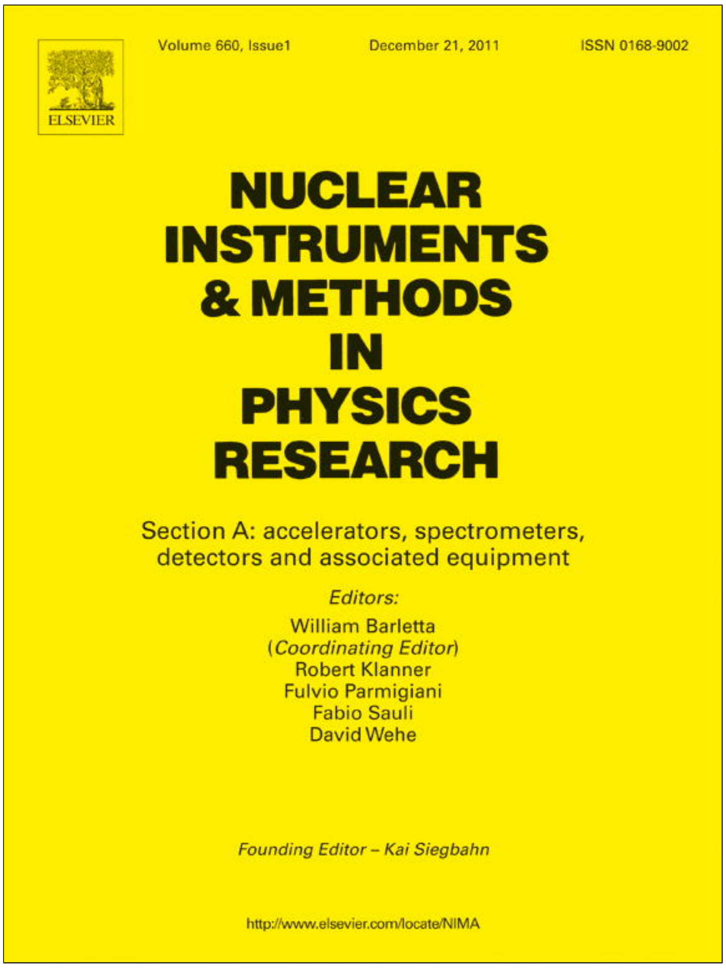

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Monte Carlo simulation of pulse pile-up effect in gamma spectrum of a PGNAA system

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ABSTRACT

We have applied a pile-up Monte Carlo simulation code on gamma spectrum of a prompt gamma neutron activation analysis (PGNAA) system. The code has been run in nonparalyzable mode for a specific geometry of a PGNAA system with ^{241}Am–^{9}Be source and NaI(Tl) detector to obtain the distortion due to "pile-up" in the pulse height of gamma spectrum. The results show that the main background in the nitrogen region of interest (ROI) is due to two pile-ups. We have also evaluated the variation of count rate and total photon sampling over the Monte Carlo spectra. At high count rates, not only the nitrogen ROI but also carbon ROI, and hydrogen peak are disturbed strongly. Comparison between the results of simulations and the experimental spectra has shown a good agreement. The code could be used for other source setups and different gamma detection systems.

1. Introduction

Prompt gamma neutron activation analysis (PGNAA) is a powerful technique for elemental analysis [1–4] and an alternative method for detecting hidden or buried explosives based on the detection of the 10.83 MeV γ-ray emerging from ^{14}N(n,γ)^{15}N reaction [5–7].

Pulse pile-up distortion is a common problem in radiation spectroscopy measurements with high count rates, and it can cause distortions in gamma spectra, and image destructions in digital imaging systems. Therefore, many experimental and computational efforts have been developed to reduce this effect on the output spectra [8–12]. Recently, Bolic et al. have presented two algorithms for pile-up correction in high count rate gamma ray spectrometry by NaI(Tl) detectors [8]. Rajput has presented a random coincidence summing of gamma rays and dead time count loss corrections in HPGe detector [9]. Moreover, Guo et al. have developed a Monte Carlo pile-up method to remedy pile-up distortion effects in pulse height spectra [12].

The MCNP code [13] has been employed in many optimization studies in PGNAA [10–12], but due to the distortion caused by pile-up effects in the experimental spectra at high flux fields, ideal theoretical optimization conditions are not the same as, or even close to, the experimental optimum conditions. We have used the pile-up code that we introduced in our previous paper; a Monte Carlo algorithm has been presented and applied for pile-up simulation in gamma camera count rate performance [10]. In the present work, we applied the pile-up simulation code to gamma spectroscopy system in PGNAA.

Our results show that the pulse pile-up from the gamma rays of ^{241}Am–^{9}Be neutron source, and those coming form neutron interactions with sample and surrounding moderator has two distortion effects over the spectrum:

- an increase in the continuous background in the nitrogen ROI due to low energy pulses;
- escape of the pulses from the ROI to the higher energy region when the energy of pile-up pulse is more than the upper level of the ROI.

2. Monte Carlo simulation of pile-up effect in gamma spectroscopy

We have used the MCNP Monte Carlo code [13] to calculate the pulse height spectrum and detector efficiency for the geometry configuration of a PGNAA system. The simulated setup has been shown in Fig. 1. The moderator with 30 cm of paraffin thickness has a $28 \times 20 \times 34$ cm^3 cavity at the center, which

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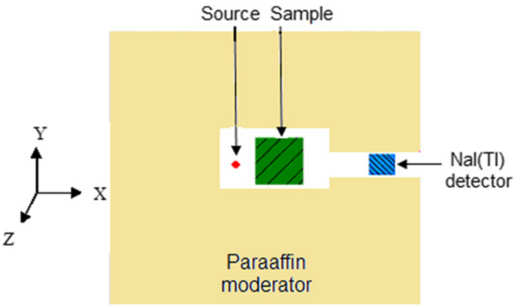

Fig. 1. Geometry setup of the PGNAA system. (sample is urea, N_2H_4CO). Sample dimensions are $15 \times 15 \times 10$ cm^3; distance between the source and the center of the sample, 11.5 cm; cavity dimensions are $28 \times 20 \times 34$ cm^3; paraffin thickness is 30 cm.

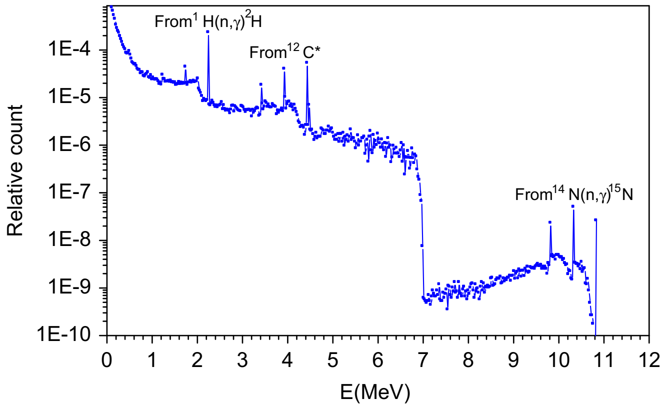

Fig. 2. Monte Carlo pulse height spectrum—output of MCNP code.

houses the urea (N_2H_4CO) sample of $15 \times 15 \times 10$ cm^3 dimensions at the middle. The distance between the source and the center of the sample is 11.5 cm.

The MCNP output pulse height spectrum (F8:p tally) of a 3×3 in^2. NaI(Tl) detector is presented in Fig. 2 with the main peaks at 2.23 MeV from ^{1}H(n,γ)^{2}H; 3.41 MeV double escape, 3.92 MeV single escape, and 4.43 MeV full energy from ^{12}C*; and 9.81 MeV double escape, 10.32 MeV single escape, and 10.83 MeV full energy from ^{14}N(n,γ)^{15}N. We have considered gamma rays from the neutron interactions with the surrounding materials, and also the 4.43 MeV gamma rays that are emitted from ^{241}Am–^{9}Be source [14]. Also, Fig. 2 shows the combination of the spectra of two groups of gammas: one, the 0–7 MeV gammas coming from thermal neutron capture in ^{12}C, ^{16}O, ^{14}N, ^{23}Na and ^{127}I; and the other, 10.83 MeV rays of ^{14}N(n,γ)^{15}N. We separated them to have a good MC error in the high energy range. A close review of the prompt gamma rays of ^{12}C, ^{14}N, ^{16}O, ^{23}Na, and ^{127}I suggests that the spectrum in the 4.43–7 MeV region has its origin mainly in the prompt gamma rays of ^{23}Na, ^{127}I, and ^{14}N.

It is clear that the simulated output spectrum by MCNP code does not take into account the actual energy resolution of the system, or the role of the pile-up distortion.

After obtaining the pulse height spectrum from MCNP, we broadened it with a Gaussian function corresponding to the measured 7.2% energy resolution of the NaI(Tl) detector for 0.662 MeV gammas from ^{137}Cs as a spread-function, although we know that energy resolution improves as photon energy increases. The pile-up simulation has been done according to the pile-up algorithm described in Ref. [10]. In the analysis of the pile-up, the time resolution τ of the pulse-processing system is defined as the minimum time required for separating two events and avoiding pile-up. Thus, the events that arrive at the amplifier with Poisson distribution are assumed to pile-up only if they occur within a time interval less than τ. True events are assumed to occur at a rate n, but, due to the pile-up, the recording system will perceive counts at a lower rate m. For a nonparalyzable detection system, the following relation holds among these three parameters:

$$m = \frac{n}{1+n\tau} \tag{1}$$

In general, the probability for a given count to be formed from the pile-up of $(x+1)$ true events in nonparalyzable detection system is [10,15]

$$P(x) = \frac{(n\tau)^x e^{-n\tau}}{x!} \tag{2}$$

The following analytical function has been used for the pulse shape with t_0 as starting time, and a_0 as amplitude:

$$F(t) = \begin{cases} 4a_0(1-e^{-((t-t_0)/\tau_p)})e^{-((t-t_0)/\tau_p)}, & t \geq t_0 \\ 0, & t \leq t_0 \end{cases} \tag{3}$$

in which $\tau_p = 0.230\,\mu s$ is the time constant of the NaI(Tl) crystal. The first component of the pulse function, $(1-e^{-((t-t_0)/\tau_p)})$, corresponds to the activation of the NaI(Tl) crystal when gamma radiation interacts with the crystal, and the second component, $e^{-((t-t_0)/\tau_p)}$, shows its deactivation according to the exponential decay law. The summation of three pulses with different amplitudes (a_0=5, 4, 3) and random starting times (t_0=0.0945, 0.2854, 0.4507) is shown in Fig. 3. It can be easily seen that the pile-up pulse has the maximum amplitude of 8.658. We have then run the Monte Carlo code in nonparalyzable mode [15] with $\tau = 1\,\mu s$ as the time resolution of the detection system.

As described in Ref. [10], for any true count rate the degree of pile-up, n_p, is determined by Eq. (2) and a random number (r) with uniform distribution in [0,1] interval. If $r < P(0)$, one pulse has been sampled from the Gaussian-spread Monte Carlo pulse height spectrum and the event is considered free of pile-up. If $\sum_{i=0}^{k-2} P(i) < r \leq \sum_{i=0}^{k-1} P(i)$, n_p pulses (n_p=k) are sampled from the Gaussian-spread Monte Carlo pulse height spectrum. With the number of pulses determined, the starting time of each pulse is set by a new random number with uniform distribution in [0,τ] interval. Finally, the resulting pile-up pulse is obtained by linear superposition of the n_p pulses [10]. The absolute maximum of the resulting pulse is set as its amplitude and then recorded in the corresponding energy channel.

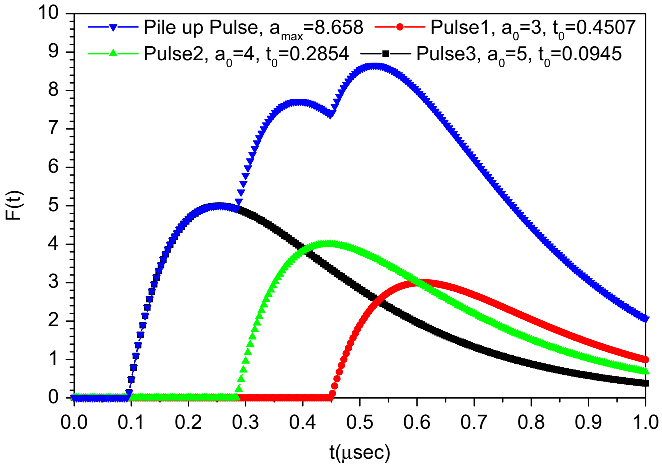

Fig. 3. Summation of the three pulses with different amplitudes and random starting times.

3. Results and discussion

The pile-up code has been run for two situations: one with nitrogen present and one without. Results are shown in Fig. 4. The nitrogen ROI- from 9.5 to 11.5 MeV- is clearly visible in our MC spectrum. Comparison of the experimental and computational spectra is presented in Fig. 5. It can be seen that except the 4.5–6 MeV and 7.2–9 MeV intervals, where the MC result is less than the experimental, two spectra are well matched. In order to find a good value for time resolution, τ, we have done the simulation with different values and have found that $\tau = 1\ \mu s$ is in good agreement with the experimental results.

In Fig. 6, we have presented the total MC spectra with no pile-up (true), and with double, triple, and quadruple piled-up pulse sub-spectra. These sub-spectra can be obtained just by Monte Carlo simulation. As can be seen, the main background is due to double piled-up pulses, especially in the nitrogen ROI. About 30% of the counts in the ROI are due to free pile-up, 56% belongs to double piled-up pulses, 13% are from triple, and only around 1% from quadruple piled-up events. It can be seen that the pile-up removes pulses from the proper position in the pulse height spectrum, and the area under the nitrogen ROI in the spectrum will no longer be a true measure of the total events of the ROI.

The effect of total photon sampling with the same count rate over the MC spectra is shown in Fig. 7. The nitrogen ROI shows up better by increasing the total counts.

As we know, the disturbance of spectrum is directly related to the count rate of events in the detection system. The MC spectra for 10^4, 10^5, 2×10^5, 5×10^5, and 10^6 count rate values are shown in Fig. 8, where the total photon sampling was equal to 10^8. We see that at high count rates, not only the nitrogen ROI is affected strongly, but also the carbon ROI (3.2–4.5 MeV) and hydrogen peaks at 2.23 MeV are distorted effectively. In Table 1, we have recorded the effects of different degrees of pile-up in the count rates related to the spectra in Fig. 8. These results have been presented in Fig. 9 as well.

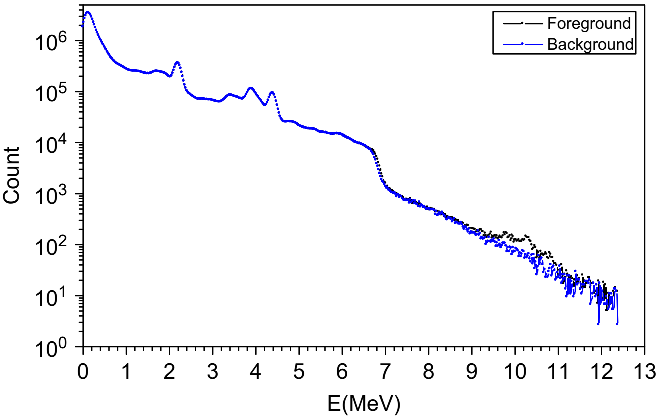

Fig. 4. MC pulse height spectra with, and without, nitrogen in the sample.

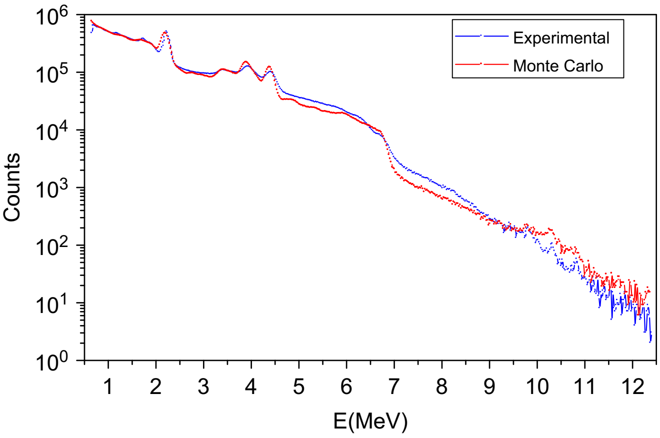

Fig. 5. Comparison of experimental pulse height spectrum with MC result.

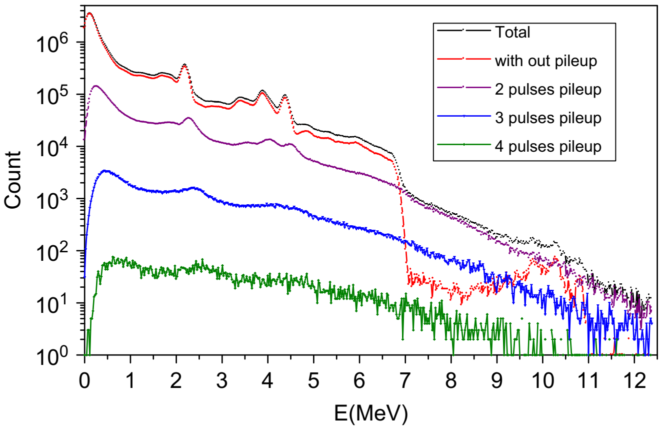

Fig. 6. Total MC spectra with no. 2, 3, and 4 pulse- pile-ups sub-spectra.

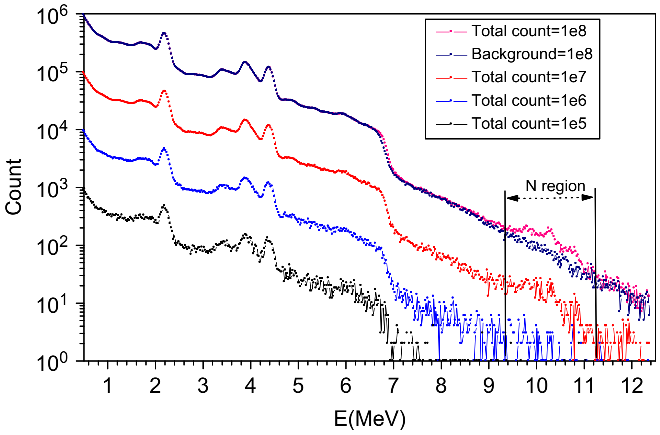

Fig. 7. MC spectra for diffrent number of photon samplings with the same count rate, and its effect over the nitrogen ROI.

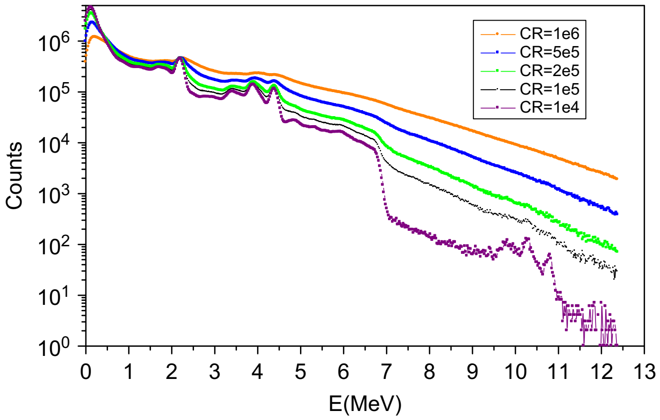

Fig. 8. MC spectra with different count rates in the detection system for a 100-million-photon sampling.

Table 1
Monte Carlo results of different events at various count rates.

Kind of recorded event	Count rate					
	1	10,000	100,000	200,000	500,000	1,000,000
Without pile-up count	1E8	9.803E7	8.187E7	6.703E7	3.680E7	1.354E7
Count from 2 pulses pile-up	0	1.952E6	1.638E7	2.683E7	3.676E7	2.706E7
Count from 3 pulses pile-up	0	1.966E4	1.637E6	5.360E6	1.840E7	2.706E7
Count from 4 pulses pile-up	0	1.28E2	1.089E5	7.140E5	6.136E6	1.805E7
Count from 5 pulses pile-up	0	0	5.373E3	7.159E4	1.534E6	9.022E6

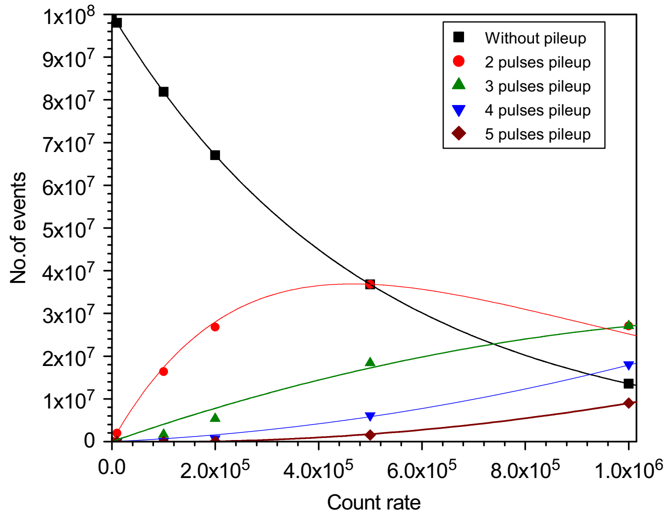

Fig. 9. Recorded events from free pile-up to 5 pulses pile-up as a function of count rate (total photon sampling was 1E8).

4. Conclusion

By applying the pile-up Monte Carlo simulation code in nonparalyzable mode for the PGNAA system, we have obtained the interesting MC spectra and sub-spectra. The results have shown that the main background in the nitrogen ROI is due to two pulses pile-up, about 56% of counts. Moerever, at high count rate the nitrogen and carbon ROIs are distorted effectively. The code can also be applied for other detection systems by substituting some input parameters like the values of τ and τ_p parameters, which are free to be changed by users.

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