Nuclear Engineering and Technology 51 (2019) 263–268

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Study of n/γ discrimination using ^{3}He proportional chamber in high gamma-ray fields

Joonbum Choi, Junesic Park, Jaebum Son, Yong Kyun Kim*

Department of Nuclear Engineering, Hanyang University, Seoul, South Korea

A R T I C L E I N F O

Article history:
Received 9 February 2018
Received in revised form
5 July 2018
Accepted 20 August 2018
Available online 7 September 2018

Keywords:
^{3}He proportional chamber
Neutron detector
n/γ discrimination
Algorithm
High gamma-ray field

A B S T R A C T

The ^{3}He proportional chamber is widely used for neutron measurement owing to its high neutron detection efficiency and simplicity for gamma-ray rejection. In general, the neutron and gamma-ray signals obtained from the ^{3}He proportional chamber can be easily separated by the difference in the pulse heights. However, for a high gamma-ray field, the gamma-ray signal cannot be precisely eliminated by the pulse height due to gamma-ray pulse pileup which causes the pulse height of gamma-ray pulse to increase and making the pulses due to neutrons and gamma rays indistinguishable. In this study, an improved algorithm for n/γ discrimination using a parameter, which is the ratio of the rise time to the pulse height, is proposed. The n/γ discrimination performance of the algorithm is evaluated by applying it to ^{252}Cf neutron signal separation from various gamma-ray exposure rate levels ranging 0.1–5 R/h. The performance is compared to that of the conventional pulse-height analysis method in terms of the gamma elimination ratio. The suggested algorithm shows better performance than the conventional one by 1.7% (at 0.1 R/h) to 70% (at 5 R/h) for gamma elimination.

1. Introduction

There are many mixed neutron–gamma radiation fields such as those inside or outside nuclear power plants and accelerator facilities. For neutron measurements at these sites, it is important to separate the gamma-ray signals from the neutron signals to obtain only the neutron signal. The ^{3}He proportional chamber has been widely used for the neutron detectors in these fields owing to its high efficiency for neutrons and low sensitivity for gamma rays [1]. Even if the gamma-ray signals are mixed with the neutron signals, they can be easily eliminated by the pulse-height analysis method (PHA method) because the pulse heights of the gamma-ray signals are generally much lower than those of the neutrons in the ^{3}He detector [2]. However, at a high gamma-ray exposure rate, the gamma-ray signals cannot be easily rejected. As the gamma-ray exposure rate increases, the frequency of the gamma-ray signal increases, and signal pile-up occurs. The individual gamma-ray signals begin to overlap and grow. In a signal processing system, pulse height of such signals are enough to exceed the pulse height threshold for neutron events (cutoff energy) so that recognized as neutron signals. As a result, gamma-ray events can superimpose on the neutron spectra, and pulse height threshold for neutron events does not function [3]. In order to eliminate the gamma-ray signals precisely, even for high gamma-ray fields, an improved signal processing algorithm for n/γ discrimination is required. Until recently, research has been carried out for precise signal separation of ^{3}He detector [4,5].

In this study, an algorithm for distinguishing neutron and gamma-ray signals in high gamma-ray fields was developed. The algorithm was applied to data from ^{3}He proportional chamber for various neutron-gamma mixed fields. The high gamma-ray field was reproduced using a ^{252}Cf neutron source and intense ^{137}Cs gamma-ray sources at the gamma-ray irradiation facility at ORBITECH Co. Ltd. The detector signals were stored and analyzed using a flash analog-to-digital converter (FADC) to implement the algorithm considering both the pulse height and rise time.

2. Experimental setup

Neutron–gamma mixed spectra were obtained at the gamma-ray irradiation facility in ORBITECH Co. Ltd. In order to carry out tests in environments with various gamma exposure rates from 100 mR/h to 5 R/h, two different activity sources were used and the irradiation distance which is the distance between source and

* Corresponding author. Department of Nuclear Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul, 04763, South Korea.
E-mail address: ykkim4@hanyang.ac.kr (Y.K. Kim).

https://doi.org/10.1016/j.net.2018.08.013

Table 1
Information about the gamma-ray source and exposure rate corresponding to the irradiation distance.

Source	Activity	Irradiation distance	Exposure rate
^{137}Cs	4.90 Ci	4062 mm	100 mR/h
	19.59 Ci	4941 mm	250 mR/h
		3506 mm	500 mR/h
		2488 mm	1 R/h
		1765 mm	2 R/h
		1122 mm	5 R/h

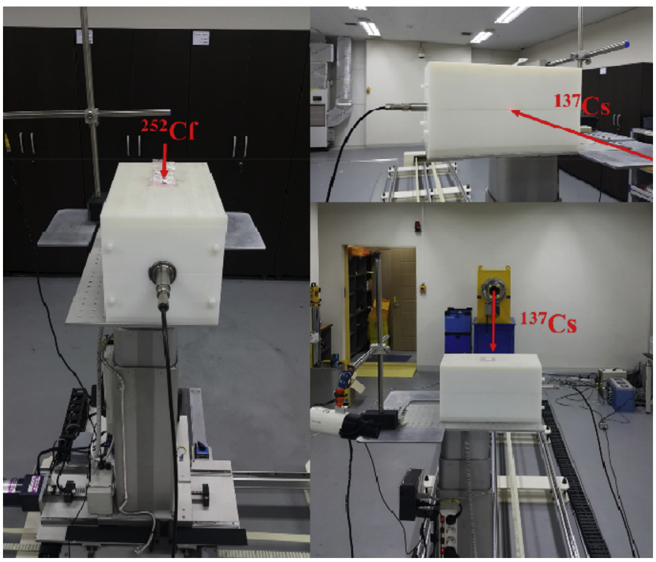

Fig. 1. Setup of the ^{3}He detector, PE shield, and sources.

detector was changed, as summarized in Table 1. The activity of the source and the irradiation distance were controlled by a system controller in the operating room located outside the facility. A 6.5-μCi ^{252}Cf source was used as a neutron source. The neutrons emitted from ^{252}Cf were moderated to thermal neutrons by a polyethylene (PE) shield. The PE shield has dimensions of 22 × 22 × 40 cm^3 with a 2-in. Hole at the center and was designed to place the ^{3}He detector in the hole. The ^{252}Cf source was attached to the outside surface of the shield. The side of PE shield containing the ^{3}He detector was positioned facing the gamma-ray source. Fig. 1 shows the setup of the ^{3}He detector, PE shield, and sources.

The CANBERRA 133NH30/5 5-bar ^{3}He proportional chamber was used as the detector in the measurement systems. An operating voltage of 1400 V was applied using Ortec 556 high-voltage power supply. The CANBERRA Model 2006 preamplifier was used to convert the radiation-induced charges into a voltage pulse whose height is proportional to the total charge collected for each event. The Ortec 572A amplifier was used for pulse shaping. The shaping time was set to 2 μs? The amplifier gain was set to 150 for the spectrum measurements (Exp. 1), whereas a gain of 50 was used for the storage of each pulse (Exp. 2), taking into account the storable range of the FADC. In Exp. 1, the Ortec 919E multichannel analyzer and Maestro software were used to record spectra. The time for each measurement was 300 s. In Exp. 2, each pulse was stored using the FADC (NOTICE FADC500) with 500-MHz sampling rate for the algorithm configuration. For the measurement of only gamma rays, 20,000 pulses were recorded, and 50,000 pulses were recorded for the both neutrons and gamma rays. Fig. 2 shows the experimental setup for Exp. 1 and Exp. 2.

3. Results and discussion

3.1. ^{3}He neutron spectrum at a high gamma field

The gamma ray exposure rate was varied from 100 mR/h to 5 R/h. The spectrum of the gamma ray fields is shown in Fig. 3. As the gamma-ray exposure rate increases, gamma ray signals increase and are overlapped on the wall effect region of neutron spectrum. In this case, n/γ discrimination using the difference in the pulse heights is no longer acceptable. At more than 100 mR/h, a large number of gamma-ray signals are not rejected by the general ^{3}He detector's cutoff energy (150 keV) because most piled-up gamma-ray signals exceed the cutoff energy. Additionally, it was observed that the Q-value peak broadened slightly to a high-energy channel in the neutron spectrum. This is because the pulse height of neutron–gamma pileup events increased. However, it does not have a significant influence in terms of signal separation.

The energy spectrum obtained by the Exp. 1 setup without a ^{252}Cf neutron source at identical gamma-ray exposure rates to those of Fig. 3 was shown in Fig. 4. From the results, the energy (End energy) where the gamma-ray spectra end was found at each gamma-ray exposure rate in order to evaluate the effect of the piled-up gamma rays quantitatively and is listed in Table 2. If the neutron and gamma-ray signals were discriminated by the End energy as the cutoff energy, it caused a considerable loss of the neutron signal because the End energy was close to 191 keV or exceeded 191 keV, which is the minimum energy of the wall effect

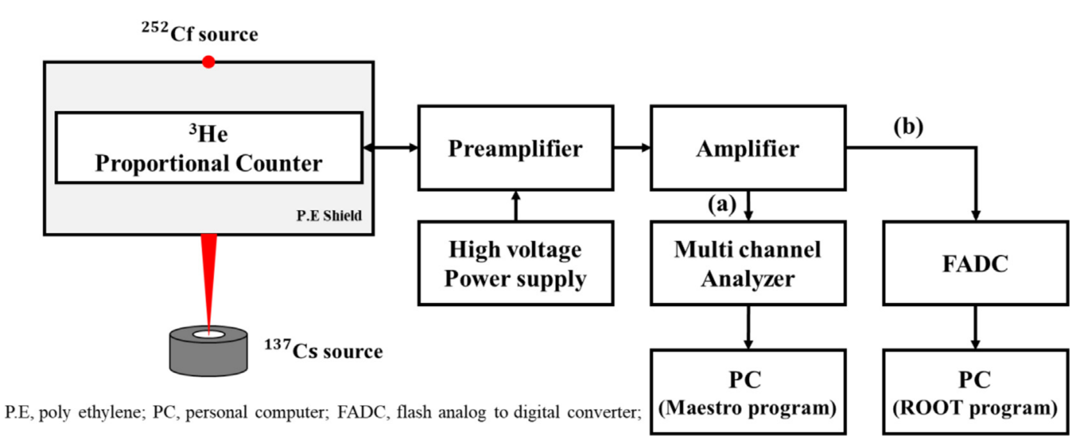

Fig. 2. Schematic of the experimental setup for (a) Exp. 1 and (b) Exp. 2.

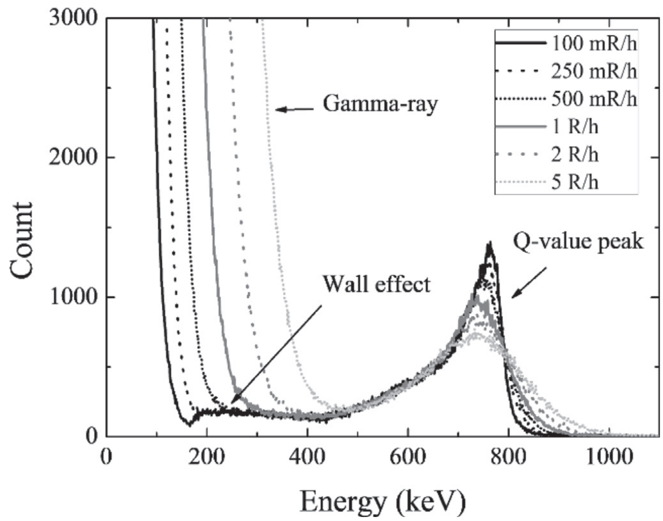

Fig. 3. ^{252}Cf energy spectrum using the ^{3}He detector for various gamma-ray exposure rates of 0.1–5 R/h.

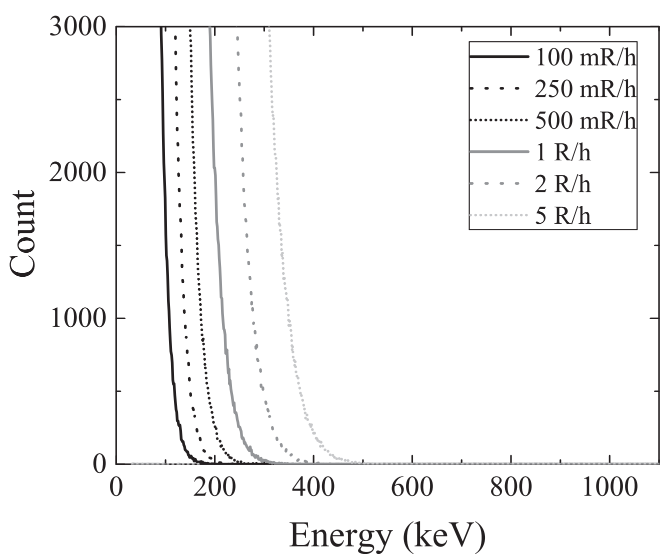

Fig. 4. Gamma-ray energy spectrum from the ^{3}He detector for various gamma-ray exposure rates of 0.1–5 R/h.

continuum in the neutron energy spectrum [2].

3.2. Improved n/γdiscrimination algorithm

The typical neutron and gamma-ray signals from the experiment are shown in Fig. 5. Most of the neutron signals showed a higher height and shorter rise time than those of the gamma rays because the energy deposited by a gamma ray is much lower than that of a neutron, which originated from a reaction with a high Q value. In terms of the rise time, neutron pulses generally have a shorter rise time than that of the gamma-ray signals and have a specific distribution determined by the reaction positions in the detector geometry [2]. These characteristics of neutron and gamma-ray signals were also reported in Ref. [6].

Owing to the wide distribution of the neutron rise time, there were many overlapping regions with the gamma rays; therefore, it was difficult to clearly separate the neutron and gamma-ray signals by the rise time only for thermal neutron measurement. On the other hand, separation method using the rise time has been applied to neutron spectroscopy since the signals from the ^{3}He (n,p)T reaction always have greater rise time than the signals from the ^{3}He recoils [7]. It was also used for n/γ discrimination from fast neutron measurement using hydrogen proportional chamber [8]. However, it is expected that there is a greater difference between the neutron and gamma-ray signals if both characteristics (the pulse height and rise time) are taken into account with the rise-time-to-pulse-height ratio (R/H) even in thermal neutron measurement. One study confirmed that separation performance at low gamma-ray background using this method in practice [4]. Further, at a high gamma-ray exposure rate, it is expected that the R/H still forms a similar distribution at a low gamma-ray fields and n/γ discrimination can be performed on the same basis. It is because the rise time and pulse height of neutron–gamma pile-up events remain nearly unchanged compared to those of the original neutron signal, and those of the gamma–gamma pile-up events increase by a similar rate. Therefore, the deterioration in the separation performance due to gamma-ray pile-up can be compensated.

On the basis of the characteristics of the two types of pulses mentioned above, a signal processing algorithm was developed using the data analysis framework ROOT [9]. The flow diagram of the algorithm is presented in Fig. 6. The procedure is as follows:

1. Signal identification using a noise threshold. In this step, the noise and true pulse signal are distinguished.
2. Finding the baseline and pulse height. In this step, the baseline is defined as the average signal height before and after a pulse is generated. The point at which the highest height occurs is determined as the peak point. Then, the height of the baseline to the peak point is defined as the pulse height.
3. Finding the starting point of a pulse. The point where the signal height from the baseline meets 10% of the pulse height is considered as the starting point of a pulse. Then, the rise time is calculated, yielding the time interval from the starting point to the peak point. Finally, the pulse height and rise time of each pulse are stored, and the neutron and gamma-ray signals are distinguished by their R/H.

3.3. n/γ discrimination using the improved algorithm

Fig. 7 shows the signal processing results for the measured data of neutrons with various gamma-ray exposure rates. Fig. 7 (a) to (d) correspond to the 2D plots of the pulse height versus rise time, and (e) to (h) spectra of rise time to pulse height ratio (R/H). In Fig. 7 (a) to (d), both pulse height and rise time of the gamma-ray signal increased sharply as the exposure rate increased. The maximum pulse height and rise time of the gamma-ray were changed from about 500 to 1000 and from 10,000 to 30,000 ns, respectively. The pulse height of neutron appeared from 400. Thus, several gamma-ray signals could be classified as neutron signals with the existing

Table 2
End energy (keV) at the various gamma-ray exposure rate ranging 100 mR/h to 5 R/h.

Exposure rate	100 mR/h	250 mR/h	500 mR/h	1 R/h	2 R/h	5 R/h
End energy (keV)	185.38	234.98	278.06	336.81	417.75	514.35

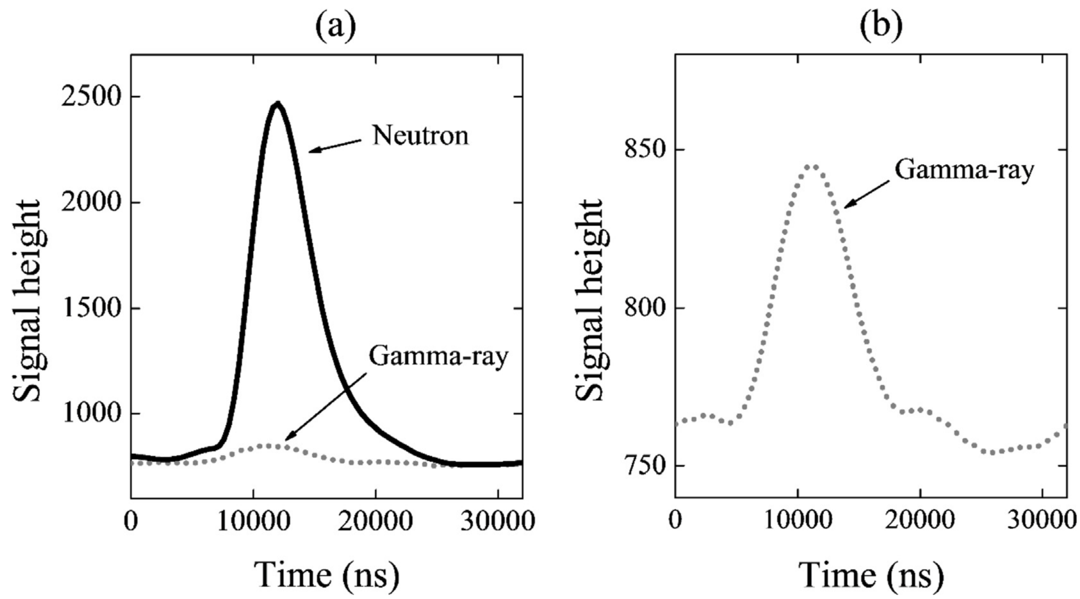

Fig. 5. Pulse shapes of (a) neutrons and (b) gamma rays.

PHA method. In Fig. 7 (e) to (h), on the other hand, it is shown that neutron and gamma-ray signals can be separated by R/H value 10, when the improved algorithm was applied.

For a quantitative comparison with the existing method, the measured data for only the gamma rays with various exposure rates were analyzed with the improved algorithm and PHA method.

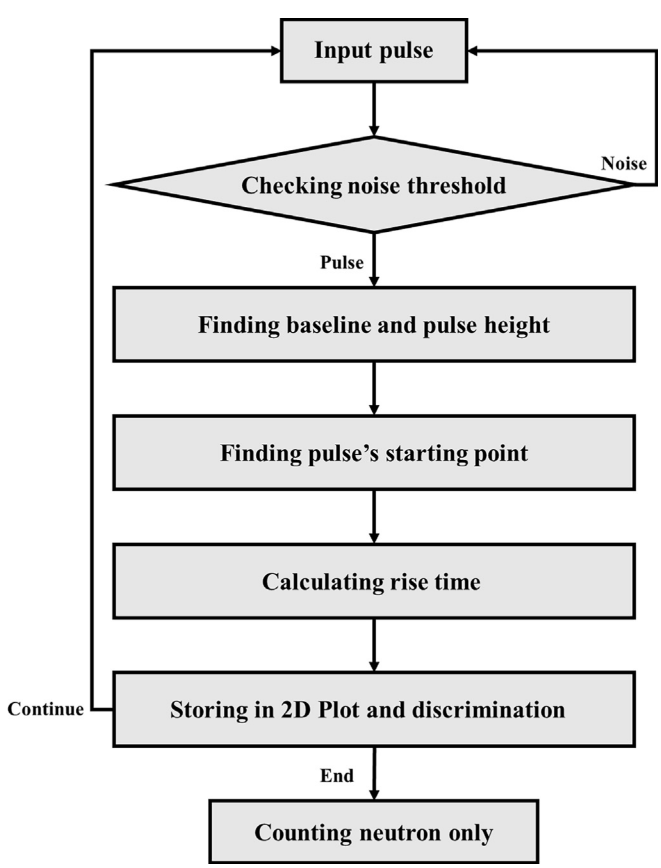

Fig. 6. Flow diagram of the improved signal processing algorithm.

After eliminating the gamma-ray signal using each method, the performance was compared using the gamma elimination ratio (R_r) [10], defined as follows:

$$R_r = \frac{G_r}{G_t} \times 100(\%) \quad (1)$$

where G_t is the total number of gamma-ray events before elimination, and G_r is the number of eliminated gamma-ray events. The signals below a pulse height of 337 (150 keV) were removed as gamma rays in the PHA method, and the signals above an R/H of 10 were eliminated as gamma rays. The R/H of 10 was set as the discrimination criterion of the improved algorithm to minimize the loss of neutron signals and the overestimation by gamma-ray signals. The true pulse, excluding the noise among the 20,000 pulses, was G_t. Table 3 summarizes the results of the comparison, and Fig. 8 shows R_r for each exposure rate. It was confirmed that there was little difference in the performance at 100 mR/h, but the difference continuously increased with the gamma-ray exposure rate.

4. Conclusion

Experiments using the ^{3}He proportional chamber were carried out at high gamma-ray exposure rates from 100 mR/h to 5 R/h. From the analysis of energy spectra, it was confirmed that it was difficult to precisely discriminate the neutron and gamma-ray signals using the existing PHA method in high gamma-ray fields. In order to overcome this disadvantage, an improved algorithm for n/γ discrimination using the ratio of the rise time to the pulse height was proposed and applied. The separation performance was evaluated by the gamma elimination ratio. As a result, the performance of the improved algorithm was enhanced compared to that of the existing PHA method by 1.7% at 100 mR/h, 4.3% at 250 mR/h, 9.4% at 500 mR/h, 21.1% at 1 R/h, 60.8% at 2 R/h, and 70% at 5 R/h. In the future, we have a plan to fabricate the system which the algorithm is applied, and confirm the possibility of real-time signal separation without loss of signals like the existing PHA method. It is expected to be applied in a neutron dosimeter in nuclear power plants where various gamma ray backgrounds exist, or a neutron detector for spent-fuel analysis.

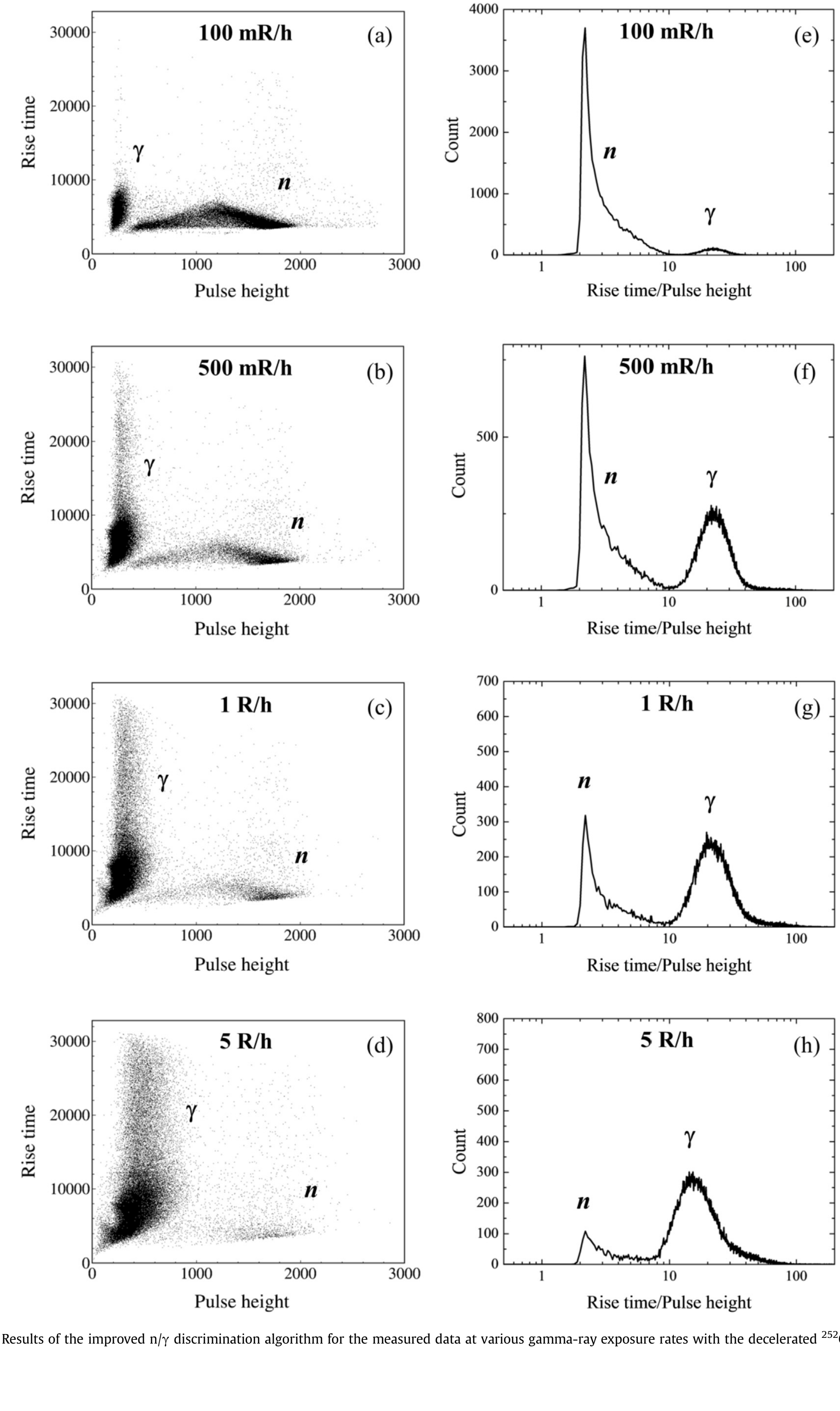

Fig. 7. Results of the improved n/γ discrimination algorithm for the measured data at various gamma-ray exposure rates with the decelerated ^{252}Cf source.

Table 3
Results of a comparison between the PHA method and the improved n/γ discrimination algorithm.

Exposure rate	Total number of gamma rays (G_t)	Number of eliminated gamma rays (G_r)		Gamma elimination ratio (R_r)	
		PHA method	Improved algorithm	PHA method	Improved algorithm
100 mR/h	19999	19638	19994	98.2	99.9
250 mR/h	19986	19106	19985	95.6	99.9
500 mR/h	19946	18050	19945	90.5	99.9
1 R/h	19824	15620	19805	78.8	99.9
2 R/h	19745	7605	19606	38.5	99.3
5 R/h	19459	5469	19088	28.1	98.1

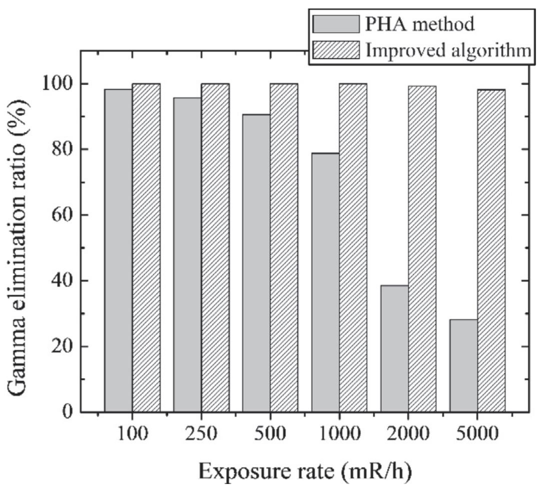

Fig. 8. Gamma elimination ratios of the PHA method and improved algorithm.

Conflicts of interest

All authors have no conflicts of interest to declare.

Acknowledgments

This work was supported by Korea Ministry of Trade, Industry and Energy (20161520101350).

References

[1] T.W. Crane, M.P. Baker, Neutron detectors, in: D. Reilly (Ed.), Passive Nondestructive Assay of Nuclear Materials, Nuclear Regulatory Commission, 1991, pp. 386–391. NUREG/CR-5550.
[2] G.F. Knoll, Radiation Detection and Measurement, John Wiley & Sons, New York, 2010, pp. 519–552.
[3] N.H. Johnson, D.H. Beddingfield, ^{3}He Neutron Detector Performance in Mixed Neutron Gamma Environments, Los Alamos National Laboratory, 2001 document LA-UR-02-0147.
[4] T.J. Langford, et al., Event identification in ^{3}He proportional counters using rise time discrimination, Nucl. Instrum. Meth. Phys. Res. Sect. A Accel. Spectrom. Detect. Assoc. Equip. 717 (2013) 51–57.
[5] C.L. Wang, et al., Improved neutron-gamma discrimination for a ^{3}He neutron detector using subspace learning methods, Nucl. Instrum. Meth. Phys. Res. Sect. A Accel. Spectrom. Detect. Assoc. Equip. 853 (2017) 27–35.
[6] D.H. Beddingfield, N.H. Johnson, H.O. Menlove, ^{3}He Neutron proportional counter performance in high gamma-ray dose environments, Nucl. Instrum. Meth. Phys. Res. A 455 (2000) 670–682.
[7] A. Sayres, M. Coppola, ^{3}He neutron spectrometer using pulse risetime discrimination, Rev. Sci. Instrum. 35 (4) (1964) 431–437.
[8] N.P. Hawkes, Pulse shape discrimination in hydrogen-filled proportional counters by digital methods, Nucl. Instrum. Meth. Phys. Res. Sect. A Accel. Spectrom. Detect. Assoc. Equip. 574 (1) (2007) 133–136.
[9] R. Brun, F. Rademakers, ROOT – an object oriented data analysis framework, Nucl. Instrum. Meth. Phys. Res. A 389 (1997) 81–86.
[10] M. Ōbu, T. Ichimori, K. Shirakata, Gamma-ray discrimination in a proton-recoil spectrometer for a fast reactor spectrum measurement, Nucl. Instrum. Meth. 89 (1970) 131–139.