Trapezoidal pulse shaping for pile-up pulse identification in X-ray spectrometry *

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Abstract: Energy resolution is affected by the intrinsic energy resolution of the detector, ballistic deficit, pile-up pulses and noise. Pile-up pulses become the dominant factor that degrades energy resolution after the system is established, so pile-up rejection is often applied to obtain good energy resolution by discarding pulses that are expected to be contaminated by pile-up. However, pile-up rejection can reduce count rates and thus lower the measurement precision. In order to improve count rates and maintain energy resolution, a new method of pile-up pulse identification based on trapezoidal pulse shaping is presented. Combined with pulse width discrimination, this method is implemented by recording pulses that are not seriously piled up. Some experimental tests with a Cu-Pb alloy sample are carried out to verify the performance of this method in X-ray spectrometry. The results show that the method can significantly improve count rates without degrading energy resolution.

Key words: pile-up pulse identification, energy resolution, count rates, trapezoidal pulse shaping

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1 Introduction

Digital nuclear instrument systems not only have better performance than analog systems, but are also simpler to construct. Such a digital system consists of detector, front-end circuitry, ADC unit, FPGA processing unit, micro control unit (MCU) and computer system, as shown in Fig. 1. The output of the detector is amplified and filtered in the front-end circuitry to match the ADC which follows. Pulse shaping, baseline drift removal, pile-up pulse identification and pulse amplitude extraction, which are realized by electronics in an analog system, are now implemented in the FPGA processing unit. The MCU is used as a communicator between the FPGA and the computer.

When two incident particles arrive at the detector within the minimum resolving time of the system, the pulses pile up to form an output pulse of corrupted amplitude known as a pile-up pulse. Pile-up pulses can result in reduced energy resolution and increased dead time. The energy resolution represents the performance of the system. It is affected by the intrinsic energy resolution of the detector, ballistic deficit, pile-up pulses and noise [1]. Pile-up pulses become the dominant factor that

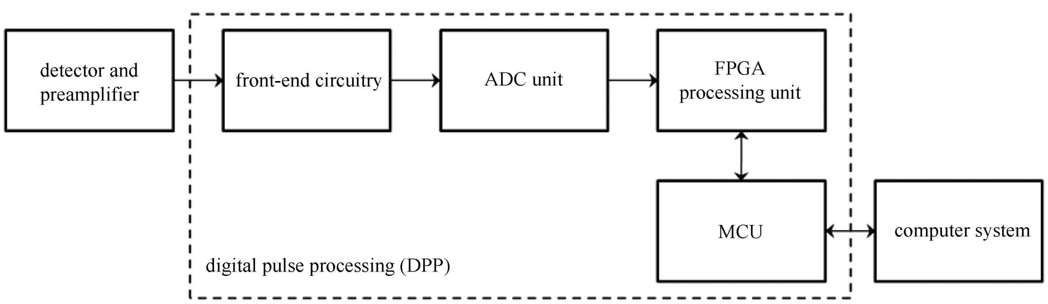

Fig. 1. Digital nuclear instrument system.

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degrades energy resolution after the system is established. In order to improve energy resolution, pile-up rejection is often applied to discard the pulses that are expected to be contaminated by pileup [2]. There are well-developed methods of dead time correction, including hardware methods and software methods, which correct counting losses due to pile-up pulses [3–5]. In addition, pile-up pulse identification and pile-up pulse separation are also described to reduce counting losses instead of correcting counting losses. A Gaussian curve fitting method has been proposed to identify pile-up pulses which have been digitized by the ADC [6]. M. Nakhostin demonstrated a method for the off-line digital processing of pile-up events from a germanium detector. The method is based on a digital pulse shaper [7]. Besides, Katsuyuki Taguchi incorporated a pile-up model, which was obtained by Monte Carlo simulations, to compensate for pulse pile-up effects in CdTe photon counting X-ray detectors [8]. Also, a model-based signal-processing algorithm for real time decoding of pulse pile-up events has been discussed by Paul A. B. Scoullar [9]. However, both the dead time correction and pile-up pulses identification require complex electronic circuits or algorithms that could have an effect on the reliability of the system. Furthermore, the separated pulse should have the true amplitude as it really is. In order to reduce pile-up pulses, a new method of pile-up pulses identification based on trapezoidal pulse shaping is presented in this paper. It is implemented by recording the pile-up pulses that can be distinguished in the FPGA processing unit.

2 Pile-up pulse recovery and identification

2.1 Trapezoidal pulse shaping

The detector output signal is usually processed to a Gaussian shape [10]. Pile-up pulse identification is executed after Gaussian pulse shaping in digital nuclear instruments. However, Gaussian pulse shaping cannot acquire the true amplitude of a pile-up pulse. As shown in Fig. 2, a pile-up pulse is obtained by adding another nuclear signal on top of the previous one. The amplitude of the nuclear signals is 1000 mV and the time constant is 5 μs. Gaussian pulse shaping is realized by a digital S-K filter [11]. It can be seen that Gaussian pulse shaping cannot separate the pile-up pulse, and the shaped pulse has a distorted amplitude. It should be discarded.

A trapezoidal pulse, whose rise time is equal to its fall time, provides a near optimum signal-to-noise ratio (SNR). The flat top of a trapezoidal pulse can also be flexibly set to adapt to different measurement conditions. It has the properties of noise suppression, pile-up pulse separation and ballistic deficit correction. The algorithm for trapezoidal pulse shaping proposed by Valtentin T. Jordanov is implemented in the FPGA processing unit to obtain the true amplitude of the pile-up pulses. The algorithm convolutes an exponential input signal with rectangular and truncated ramp functions [12, 13]. Fig. 3 illustrates the shaping process. There are three shaping parameters in the algorithm k, l and m. k represents the rise time of the trapezoidal pulse and l is the sum of the rise time and flat top. The trapezoidal pulse width is

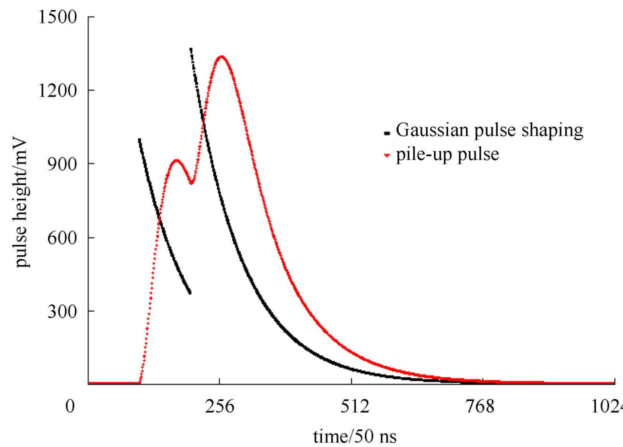

Fig. 2. (color online) Gaussian pulse shaping for a pile-up pulse.

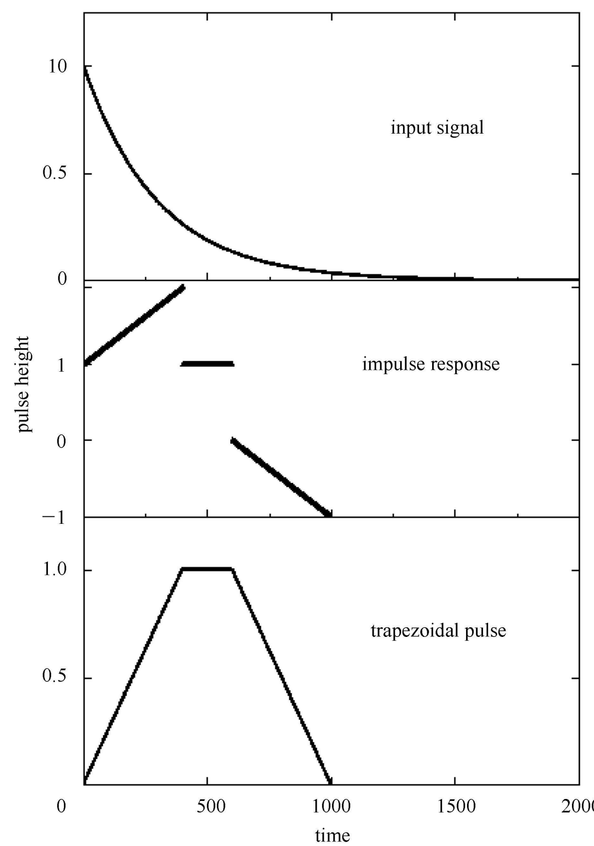

Fig. 3. Trapezoidal pulse shaping algorithm.

given by $k+l$. m is the time constant of the input signal and is relative to the trapezoidal pulse shape. When m is equal to the time constant of the input signal, a symmetrical trapezoidal pulse can be obtained [14]. Fig. 4 shows the results of trapezoidal pulse shaping for the pile-up pulse in Fig. 2. It indicates that trapezoidal pulse shaping can recover the true amplitude of the pile-up pulse and the pile-up pulse can also be separated by setting k and l properly.

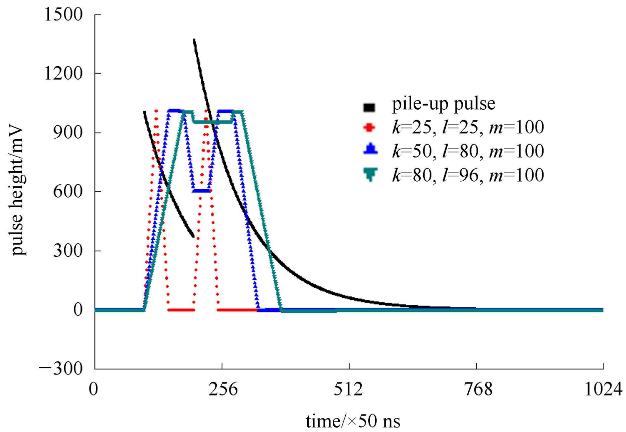

Fig. 4. (color online) Trapezoidal pulse shaping for a pile-up pulse.

Practically, the trapezoidal pulse width is limited to the detector's intrinsic energy resolution. Therefore, the pile-up pulses still occur. Fig. 5 shows the measured pulses after real time trapezoidal pulse shaping. The pulses are digitized by the ADC, then they are processed by trapezoidal pulse shaping with k=120, l=136, m=64. It can be seen that both pulse 1 and pulse 2 are pile-up pulses. Conventional pile-up rejection techniques will discard these events. However, with the new method of pile-up pulse identification, pile-up pulses like pulse 1 can also be recorded, thus increasing count rates. Under the condition of high count rates, the new method can improve count rates significantly.

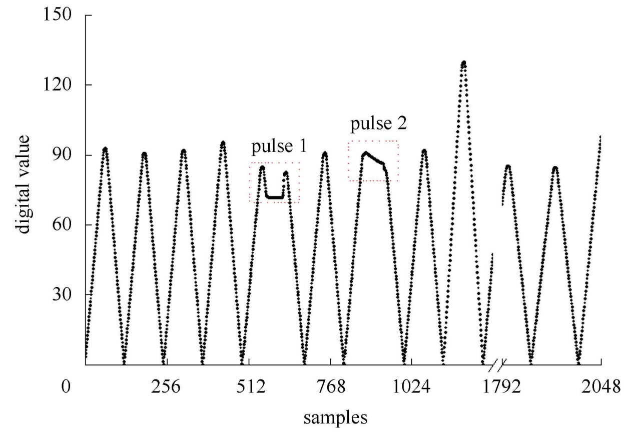

Fig. 5. Measured pulses after real time trapezoidal pulse shaping.

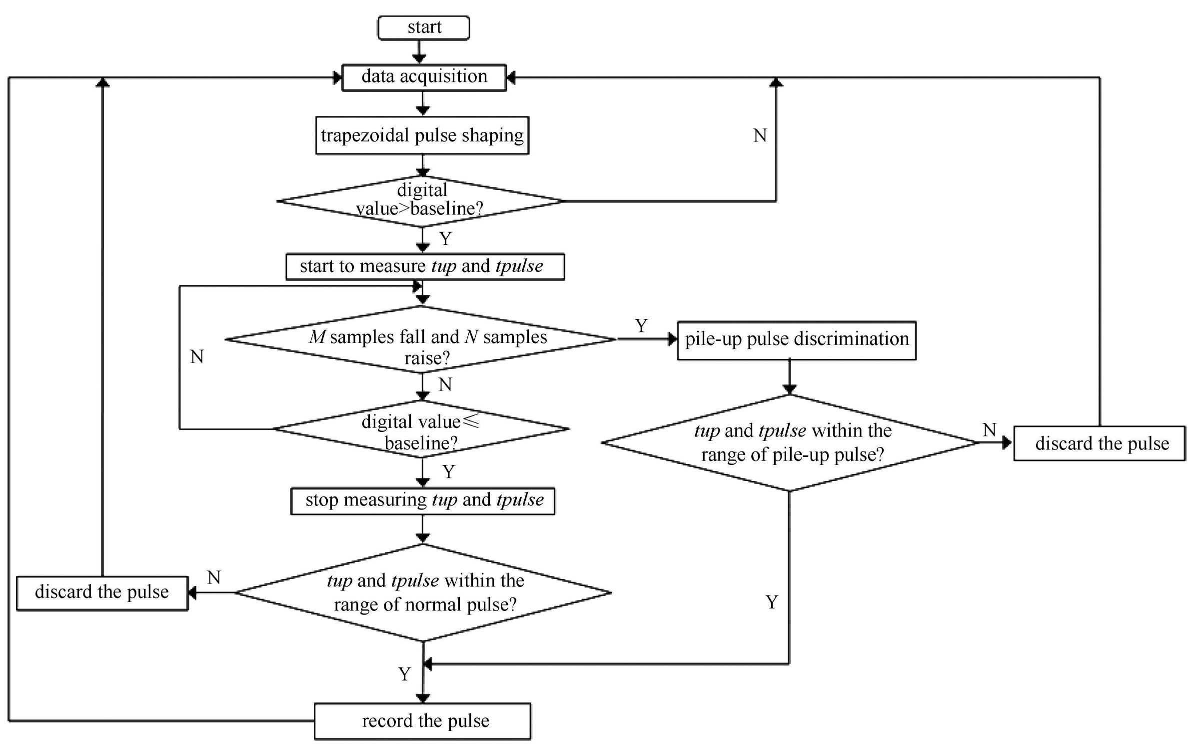

Fig. 6. Program flowchart of pile-up pulse identification algorithm.

2.2 Pile-up pulse identification algorithm

Pile-up pulses are identified by whether there is rising data during the falling edge of the shaped pulse (trapezoidal pulse). If there is, the pulse is recognized as a pile-up pulse. In order to discriminate flat-topped pulses, singular pulses and pile-up pulses like pulse 2, pulse width discrimination is applied. Pulse width discrimination includes two parameters, *tpulse* and *tup*. *tpulse* is defined as the shaped pulse width, which is decided by $k+l$. *tup* is half of *tpulse* and is applied to discard shaped pulses that are not symmetrical. The range of *tpulse* and *tup* are determined by the characteristics of the detector output signal. Only when *tpulse* and *tup* for a pulse are within a set range can the pulse be recorded. The pile-up pulses identification algorithm follows the steps below.

(1) Baseline threshold. Shape the ADC output signal and estimate the value of the digitized pulse. If the value is above the threshold, it starts to measure *tup* and *tpulse*.

(2) Peak detection. If the shaped pulse falls for M samples consequently, the pulse enters the falling edge and the peak value is detected.

(3) Pile-up pulse identification. If the shaped pulse rises for N samples during the falling edge, the pulse is treated as a pile-up pulse.

(4) Pulse width discrimination. The pulse can be recorded only if *tpulse* and *tup* for a pulse (a normal pulse or a pile-up pulse) are within the set range. Otherwise, it is discarded.

M is the factor of falling edge judgment and N represents the factor of pile-up pulses identification. The pile-up pulse identification algorithm is implemented in the FPGA processing unit and a program flowchart of the algorithm is shown in Fig. 6.

3 Experimental tests

Figure 7 shows a Digital Pulse Processing (DPP) board for X-ray spectrometry. A silicon drift diode (SDD) detector made by Amptek is used as a sensor. An amplifier associated with a C-R high pass filter is applied in the front-end circuitry to amplify and shape the detector output to optimize digitalization. Different shaping times for the ADC input signal can be obtained by adjusting the high pass filter. The ADC which follows digitizes the output of the front-end circuitry at 20 MSPS, and the digitized values are sent to a FPGA (XC3S500E) for further processing directly. The output of the FPGA is transmitted to a MCU (C8051F500) by a serial peripheral interface (SPI) at 5 Mbps. The communication between the MCU and the PC is through a CAN interface which is provided by the MCU. In the experimental tests, the values of the resistor and capacitor in the high pass filter were 680 Ω, 4700 pF respectively. This means that the shaping time for the ADC input signal was 3196 ns.

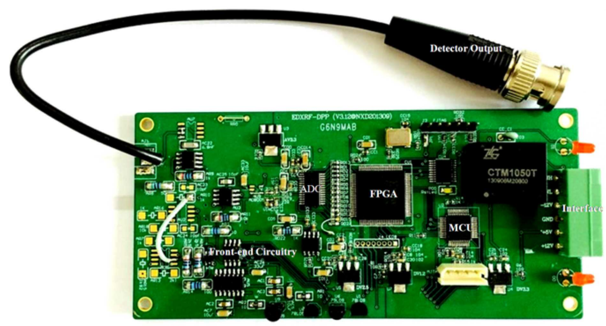

Fig. 7. DPP board for X-ray spectrometry.

Table 1. Test results from experiment A.

number	Mn/CPS	Fe/CPS	Ni/CPS	Cu/CPS	Zn/CPS	Pb/CPS	Sn/CPS
1	44.164	64.844	80.824	6020.379	4524.505	17.743	33.670
2	43.955	65.026	79.065	6034.316	4520.345	17.726	32.823
3	45.745	64.485	78.891	6043.182	4504.113	17.572	34.627
4	45.116	65.540	79.123	6030.118	4510.239	17.436	33.277
5	44.733	66.230	80.097	6034.191	4522.826	19.100	33.224
6	44.759	65.677	79.041	6047.780	4501.198	17.318	34.217
7	44.909	66.833	78.515	6048.016	4514.740	17.117	33.313
8	45.204	65.476	80.979	6027.782	4497.612	17.836	34.090
9	45.249	66.865	79.577	6025.295	4487.936	17.740	33.637
10	46.083	65.437	79.015	6027.138	4503.958	17.119	31.720
average	44.992	65.641	79.513	6033.820	4508.747	17.671	33.460
max	46.083	66.865	80.979	6048.016	4524.505	19.100	34.627
min	43.955	64.485	78.515	6020.379	4487.936	17.117	31.720
range	2.128	2.380	2.464	27.637	36.569	1.983	2.907
relative range	0.047	0.036	0.031	0.005	0.008	0.112	0.087

Table 2. Test results from experiment B.

number	Mn/CPS	Fe/CPS	Ni/CPS	Cu/CPS	Zn/CPS	Pb/CPS	Sn/CPS
1	61.322	87.06	99.004	6712.496	4994.14	28.289	37.579
2	59.876	87.265	100.638	6696.166	5013.396	28.733	37.088
3	60.655	88.077	98.626	6716.884	5002.969	29.653	37.999
4	58.812	87.448	100.404	6705.32	5013.603	28.999	37.773
5	61.052	88.091	101.474	6692.941	5000.353	29.315	36.952
6	60.52	87.91	100.859	6710.728	5030.911	28.309	36.04
7	59.06	88.059	99.987	6712.438	5017.65	28.231	38.117
8	58.724	85.834	99.682	6721.132	5013.053	28.537	37.047
9	60.226	87.057	101.582	6700.012	5026.432	28.953	37.036
10	59.454	88.257	100.827	6705.978	5030.873	28.803	36.211
average	59.970	87.506	100.308	6707.410	5014.338	28.782	37.184
max	61.322	88.257	101.582	6721.132	5030.911	29.653	38.117
min	58.724	85.834	98.626	6692.941	4994.140	28.231	36.040
range	2.598	2.423	2.956	28.191	36.771	1.422	2.077
relative range	0.043	0.028	0.029	0.004	0.007	0.049	0.056

The values of M, N and the range of tup, $tpulse$ are related to the characteristics of the detector output signal. In the tests, the rise time of the detector output signal was about 400 ns and the pulse width was approximately 6 μs. The trapezoidal pulse shaping algorithm was implemented in the FPGA with k=120, l=136, m=64 (based on the sampling rate of the ADC and the time constant). Therefore, the shaped pulse width was 12.8 μs ((120+136)×50 ns). Both M and N are set to 5. The ranges of tup and $tpulse$ were set as follows. The parameters mentioned above were decided by experimental results.

Normal Pulses: 90×50 ns$<tup<$140×50 ns, 180×50 ns$<tpulse<$280×50 ns.

Pile-up Pulses: 4×50 ns$<tup<$140×50 ns, 16×50 ns $<tpulse<$280×50 ns.

3.1 Count rates improvement

Two experiments were carried out to verify the performance of the proposed method. Each one was tested 10 times under the same measurement conditions. A Cu-Pb alloy sample was used as the experimental sample. Experiment A does not integrate the method of pile-up pulses identification, while Experiment B does. The count rates of different elements are shown in Table 1 and Table 2. It can be seen that the count rates of Cu increases 11.2% in Table 2. The results show that the proposed method can improve count rates.

3.2 Energy resolution for the 8.05 keV peak of Cu

The performance of the pile-up pulse identification method in terms of energy resolution has also been evaluated by increasing X-ray tube current. Spectra measured with different currents are illustrated in Fig. 8. As depicted in Fig. 9, the output count rates (OCR) could vary across a range of 14–40 KCPS with this method. With a 3-fold increase in OCR, the energy resolution degraded by 6.4%. The energy resolution for the 5.89 keV peak is

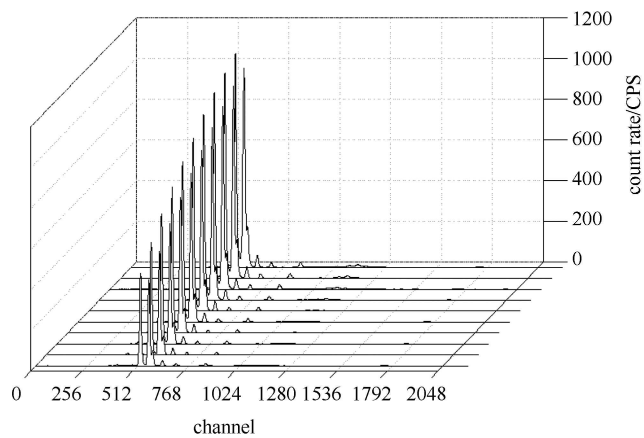

Fig. 8. Spectra with different X-ray tube currents.

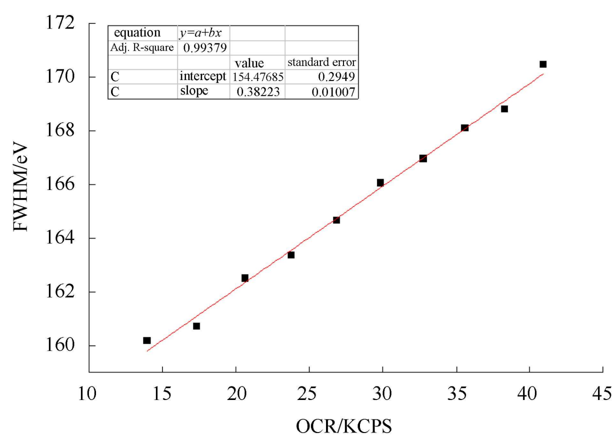

Fig. 9. Energy resolution and OCR.

136 eV when the OCR is 13.95 KCPS. This value degrades to 142 eV when the OCR increases to 40.93 KCPS.

4 Conclusions

Energy resolution and count rate represent the performance of a detector system. In conventional measurement, count rate is compromised for the sake of energy resolution. A new method of pile-up pulse identification, based on trapezoidal pulse shaping, is presented in this paper and can improve count rates. The method improves count rate by recording those pile-up pulses that are not badly piled up. A pulse width discrimination method is applied to discard the pulses that are distorted. Four parameters including M, N, *tup*, *tpusle* are applied to identify pile-up pulses; these are determined by the characteristics of the detector output signal. The parameters can be adjusted for use with different detectors.

References

1 ZHANG Ruan-Yu. On the Study of Digital Nuclear Spectrum System (Ph. D. Thesis). Sichuan: Sichuan University, 2006 (in Chinese)

2 WANG Jing-Jin. Nuclear Electronics. Beijing: Atomic Energy Press, 1983. 242 (in Chinese)

3 Bradley A Roscoe, A Keith Furr. Nucl. Instrum. Methods, 1977, **140**: 401

4 Richard M Lindstrom, Ronald F Fleming. Radioact Radiochem, 1995, **6**(2): 20

5 Danon Y, Sones B, Block R. Nucl. Instrum. Methods Phys. Res., Sect. A, 2004, **524**: 287

6 DI Yu-Ming, FANG Guo-Ming, QIU Xiao-Lin et al. Atomic Energy Science and Technology, 2008, **42**(4): 370 (in Chinese)

7 Nakhostin M, Podolyak Z, Regan P H et al. Rev. Sci. Instrum., 2010, **81**(10): 103507

8 Taguchi K, Frey E C, WANG Xiao-Lan. Med. Phys., 2010, **37**(8): 3957

9 Scoullar P A B, Mclean C C, Evans R J. Real Time Pulse Pile-up Recovery in A High Throughput Digital Pulse Processor. Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC). Valencia: World Scientific, 2011

10 CHEN Shi-Guo. Design and Realization of The Gaussian Shaping Filtering in Digital Nuclear Instrument System (Ph. D. Thesis). Sichuan: Sichuan University, 2005 (in Chinese)

11 ZHOU Jian-Bin, ZHOU Wei, HONG Xu. Nucl. Sci. Tech., 2013, **24**(6): 060401

12 Valentin T. Jordanov, Glenn F. Nucl. Instrum. Methods Phys. Res., Sect. A, 1994, **345**: 337

13 Valentin T. Jordanov, Glenn F. Knoll, Alan C. Huber et al. Nucl. Instrum. Methods Phys. Res., Sect. A, 1994, **353**: 261

14 ZHOU Jian-Bin, WANG Min, ZHOU Wei et al. Atomic Energy Science and Technology, 2014, **48**(2): 352 (in Chinese)