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A multiple time-gated system for pulsed digital gamma-ray spectroscopy

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Neutron activation analysis (NAA) systems that use pulsed neutron generators (NGs) employ spectrum gating procedures to segregate nuclear processes by acquiring gamma-ray spectra separately when the generator is on (HIGH gate) and off (LOW gate). Often, the actual neutron burst lags the leading edge of the HIGH gate signal by a few µs. Thus, count rates vary not only between the on and off states of the NG, but within them as well. Recent advances in digital gamma-ray spectrometers that allowed the concurrent acquisition of data by sorting events into two separate spectra based on gate status suggested that a time-resolved analysis that further subdivided the neutron pulse cycle could obtain further information to separate gamma-rays produced by different nuclear reactions. In this paper we introduce a gating system for time-resolved NAA that is capable of concurrently acquiring as many as 16 spectra from up to 8 user-defined time intervals during each of the HIGH gate and LOW gate periods, each with all required timing and count rate information. We present the new gating system's implementation, operation and some first experimental test results.

Introduction

In neutron activation analysis (NAA) systems that use pulsed neutron generators (NGs), spectrum gating has been employed to segregate nuclear processes by separately acquiring gamma-ray spectra when the generator was on (HIGH gate) and off (LOW gate).[1,2] The gating signal from a 14 MeV d-T pulsed neutron generator, which is synchronous with the on and off states of the generator, can be used to direct a traditional gamma-ray spectrometer to measure either (1) the gamma-rays emitted from inelastic neutron scattering (INS) reactions when the generator is on (coincidence gating) or (2) the prompt gamma-rays from thermal neutron capture (TNC) when the generator is off (anti-coincidence gating), but not both concurrently within the same data collection run.

Advances in digital gamma-ray spectrometers have recently allowed the concurrent acquisition of both inelastic scattering and thermal capture data within a single run by sorting gamma-ray events into two separate spectra based on the instantaneous gate status.[3] In working with this system, we subsequently realized that, for accurate, quantitative data analysis, it would also be necessary to acquire accurate timing (real, live, and dead-time) and count rate information for the two gate states because counting rates varied not only between the on and off states, but within them as well, as the actual neutron burst often lags the leading edge of the HIGH gate signal by a few µs. This realization further suggested that a time-resolved analysis that further subdivided the neutron pulse cycle should produce additional information for separating the gamma-rays produced by different nuclear reactions (inelastic scattering, thermal neutron capture, etc.). A recent paper that implemented this approach manually showed encouraging results.[4]

We have previously outlined an approach to obtaining multiple time-resolved gamma-ray spectra using a digital spectrometer.[5] In this paper, we present the implementation, operation and first experimental results from this multiple time-resolved spectra (MTRS) system, which is capable of concurrently collecting data into as many as 16 spectra, each with all required timing and count rate information, from up to 8 user-defined time intervals within each of the HIGH gate and LOW gate periods.

Experimental

Implementation of the MTRS system

Our basic approach to obtaining real time multiple time-resolved spectra with a digital spectrometer was to tag each incoming pulse with its arrival time (relative to the neutron generator's gate signal) and subsequently sort its amplitude into the appropriate member of a set of on-board energy spectra, based on the value of the time tag. As many as 16 spectra are allowed, associated with up to 8 time intervals during the neutron generator gate's HIGH period and up to 8 more intervals during the gate's LOW period, as indicated schematically in Fig. 1.

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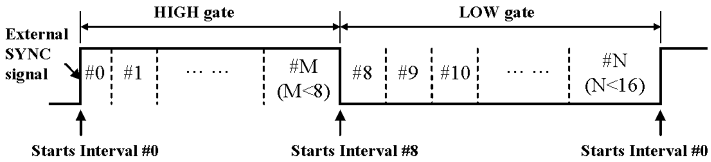

Fig. 1. Schematic showing the subdivision of external periodic SYNC signal into up to 8 intervals at HIGH gate and up to 8 intervals at LOW gate

The MTRS system reported here was implemented in a Field Programmable Gate Array (FPGA) and Digital Signal Processor (DSP) of a digital gamma-ray spectrometer (Polaris from XIA LLC). General gamma-ray spectroscopy functionalities such as fast filter triggering, pileup inspection and slow filter pulse-height measurement were already implemented in the FPGA (Xilinx Spartan XCS40XL).[5] For the MTRS application, new circuits were programmed into the FPGA to: (1) detect the rising or falling edge of the neutron gate signal, which is connected to the SYNC input of the spectrometer; (2) store user-defined time intervals in the on-chip RAM; (3) tag each detected gamma-ray event with its correct interval ID; and (4) track counting statistics data for each interval. The DSP (Analog Devices ADSP 2185) runs in interrupt mode: reading a raw pulse-height value and its interval ID from the FPGA each time it is notified by the FPGA that a valid event was detected. It then computes the pulse's energy and places it to the onboard spectrum associated with its interval ID. The DSP also periodically reads the counting statistics information from the FPGA and accumulates them by interval ID in real time as well.

Operating the MTRS system

The histograming of gamma-ray event energies into separate spectra and the accumulation of timing and count rate data for each time interval are determined by interval settings within the external SYNC signal, which serves as the gate signal to the spectrometer. The SYNC signal could be simply the ion source pulse from a pulsed neutron generator or come from an external delay and gate generator that adjusts the timing and width of the neutron pulse. Figure 1 shows the subdivision of the SYNC signal into up to 8 intervals in the HIGH state and up to 8 intervals in the LOW state. The first interval numbers in the HIGH and LOW gates are always #0 and #8, respectively, even if the total number of intervals is less than 8 in either gate state. The allocation of interval lengths in each gate state is user-defined; however, their sum must equal the state length. Thus at each rising edge of the SYNC signal, event and time counting always starts in interval #0, while at each falling edge of the SYNC signal, they always start at interval #8. This ensures the correct interval switching even if the neutron pulse frequency or gate state width drifts slightly with time.

There are two sets of timing and count rate data in the MTRS system. The first set, accumulated regardless of the gate status, includes real, live and dead time and input and output count rate (ICR and OCR). It is this overall real or live time that is used to stop the data acquisition by running to preset real or live time. The second set includes the same timing and count rate data that is accumulated independently for each interval within the same data acquisition period as the first set (Table 1). Real time (RT) is an interval's actual counting time. FTDT (fast trigger dead time) is the time when the fast trigger filter is above the trigger threshold and, therefore, cannot register any further triggers. It is used to make a small adjustment to the ICR. Live time (LT) is derived using formula:

$$LT = OCR/ICR \cdot RT.$$

Experimental measurements

A compact sealed-tube NG producing 14 MeV neutrons was set to operate in pulsed mode at 10 kHz repetition rate and 25% duty cycle. The neutrons were made to impinge on a 150 cm by 120 cm by 45 cm deep sand-pit filled with clean construction sand. Gamma-rays generated as a result of inelastic scattering (INS) or thermal neutron capture (TNC) reactions in the sand were detected using a $12.7 \times 12.7 \times 15.2\ cm^3$ NaI(Tl) detector whose output was connected to a current-to-voltage converter interfaced directly to the MTRS system. To supply an external gate signal to the MTRS system, the synchronization signal (SOURCE) that also pulses the ion source voltage of the NG, was connected to a Tennelec TC410 Delay and Gate Generator whose 1 μs delay TTL output was input to the SYNC input of the spectrometer, as seen in Fig. 2. The 1 μs delay was chosen for convenience since the TC410 does not allow a zero delay setting (minimum is 0.1 μs). The HIGH state of the SYNC pulse was extended to 27 μs, i.e., 3 μs more from the falling edge of the ion source pulse, based on our prior experience that the neutron generator still produces neutrons for about 2 μs after the high-to-low transition of the ion source pulse.[4]

The 27 μs HIGH gate of the SYNC pulse was divided into 7 intervals with interval #0 being 3 μs in length and intervals #1 to 6 all being 4 μs. The 73 μs LOW gate was allocated to 8 intervals with interval #8 of 3 μs and intervals #9 to 15 of 10 μs each.

Results and discussion

Individual interval spectra and sum spectra

Spectra acquired for each of the 7 HIGH gate intervals and each of the 8 LOW gate intervals after an 1800 s data acquisition run are shown in Figs 3a and 3b, respectively. The acquisition was stopped after the overall live time reached the preset 1800 s. The sum spectra shown in Figs 3a and 3b were calculated offline by summing all individual interval spectra in (a) and (b), respectively. The HIGH gate spectra, essentially inelastic scattering spectra, were labeled with major gamma-ray energies associated with common elements existing in the sand. Most noticeable is the Si (1.78 MeV) peak, while Al (2.21), O (3.68) and O (6.13) can also be observed. The Na (0.44) peak is probably due to the interactions of neutrons with the NaI(Tl) detector itself. The LOW gate spectra, mainly consisting of gamma-ray events from thermal neutron capture, showed energy peaks from elements such as Na (0.47), Si (1.78) and H (2.22), while peaks from Si (3.53), Si (4.93) and O (6.13) were much weaker. H was present in the detector shielding material, mainly in water.

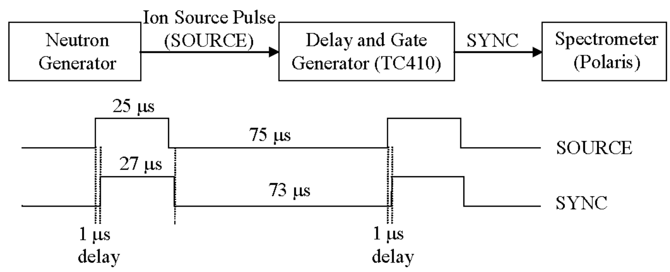

Fig. 2. Schematic showing the timing relationship between the ion source pulse from the neutron generator and the SYNC pulse input into the spectrometer after a delay and gate generator

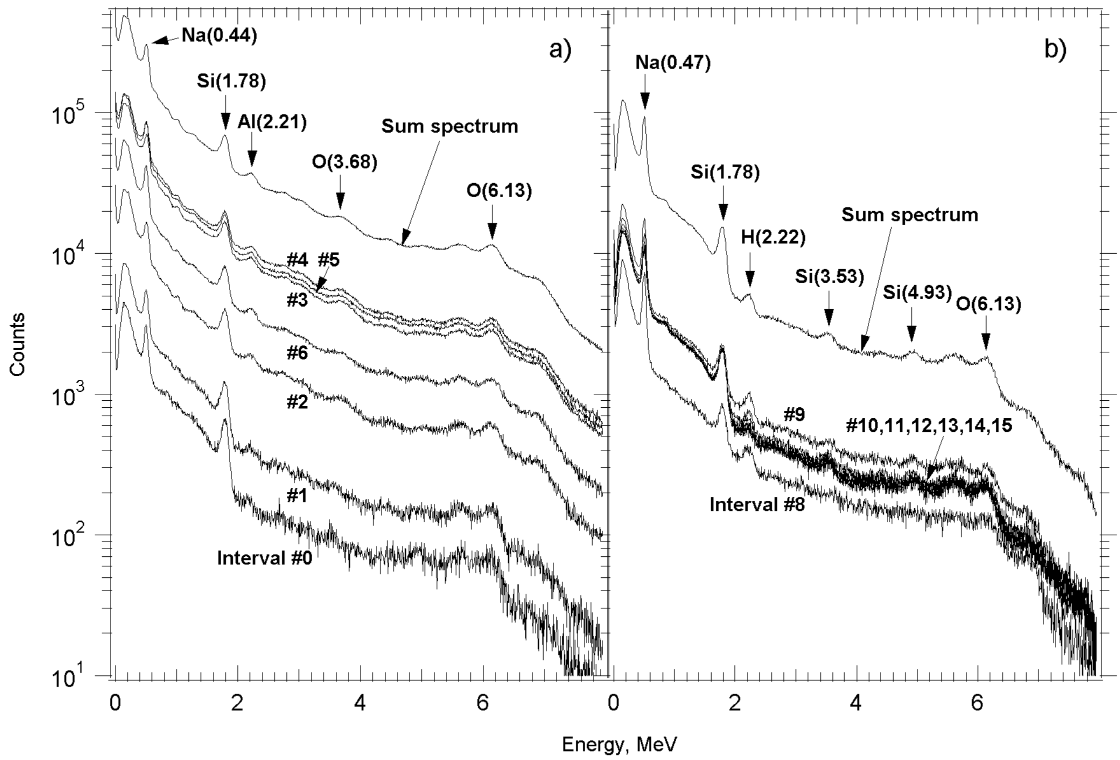

Fig. 3. The 7 individual spectra and their sum acquired during the HIGH gate (a); and the 8 individual spectra and their sum acquired during the LOW gate (b)

Input and output count rate

Figure 4 shows the input count rate (ICR) and output count rate (OCR) recorded for each of the 15 intervals during the 1800-second data acquisition run. During the initial 3 μs (interval #0) which is ~4 μs after the pulsed neutron generator was turned on, very few neutrons were generated. The count rates gradually rose thereafter. At interval #3 (11–15 μs), a sharp increase of ICR was observed, putting the ICR well above 150 kcps. The ICR continued to climb in intervals #4 and 5, reaching a maximum of about 260 kcps in interval #5. It started to fall in interval #6 (23–27 μs) indicating that the neutron generator was turned off at about 25 μs. The thermalization of fast neutrons during the LOW gate was reflected in the gradual decrease of ICR in intervals #8 to 15, reaching about 6.7 kcps in interval #15. By noticing that the ICR reached a near equilibrium level at about 7 kcps after interval #12 (60–70 μs) as also of interval #0 within the HIGH gate where there is no neutron production, we can conclude that the thermal capture prompt gamma-ray count rates will be almost constant within the LOW and HIGH gates. We estimated the "thermal" component of the HIGH gate ICR to be about 4% of the average ICR of intervals #2 to 6. The OCR closely followed the ICR except in intervals #3 to 6 where the pileup and dead time losses were significant.

The ICR vs. neutron pulse timing curve in Fig. 4 can also be used to determine the optimal setting of the HIGH and LOW gates so that the "inelastic" and thermal prompt gamma-spectra would be relatively free from each other's interference.

Counting times

One way to verify the accuracy of the MTRS system's operation is to compare each interval i's actual counting time (RT_i) to its "theoretical" counting time, i.e., interval length, because over the periodic neutron pulse, each interval was allocated a fixed percentage of the total real counting time. This "measured" interval width can be found from:

$$\text{Measure interval length}_i\ (\mu\text{s}) = \frac{RT_i}{\sum_{j=0}^{15} RT_j} \times 100\ \mu\text{s} \quad (1)$$

The measured interval lengths in Table 1 are seen to be very close to their defined lengths. The slight deviations shown in intervals #6, 8 and 15 were comparable to the resolution of neutron pulse width, which was about 0.5 μs at neutron generator frequency range of 8 to 16 kHz.

Table 1 also shows that the sum of RT_i of all intervals was about 0.65% lower than the overall real time, and that led to the slightly larger sum of LT_i compared to the overall live time. This small real time loss was caused by the method used in the FPGA to accumulate the real time which in turn was caused by the resource limits of the FPGA. Implementing the MTRS circuits in a more advanced FPGA can solve this problem.

Major net peak area rates

Figure 5 shows the net peak area rate of major energy peaks as a function of time interval within the neutron pulse. The net peak area for each interval was first derived by calculating the net counts in each peak by subtracting a background obtained through linear interpolation of the continuum underneath a peak. The net peak area rates were then determined by dividing the net counts by the live time of each interval. All the "inelastic" peak area rates showed a very similar pattern to the curve of ICR vs. neutron pulse timing within the HIGH gate shown in Fig. 4. Most of the thermal prompt gamma net peak area rates (except for Na and H) remained at near equilibrium level in the LOW gate. This is consistent with the findings in Reference 4. Since the thermal prompt gamma net peak area rates reach an equilibrium value, it would be possible to subtract the "thermal contamination" from the "inelastic" peaks that have the same energy value. The elements Na (0.47 MeV) and H (2.22 MeV) showed decreasing intensity with respect to the time intervals within the LOW gate. Further studies are needed to understand the mechanism behind this phenomenon.

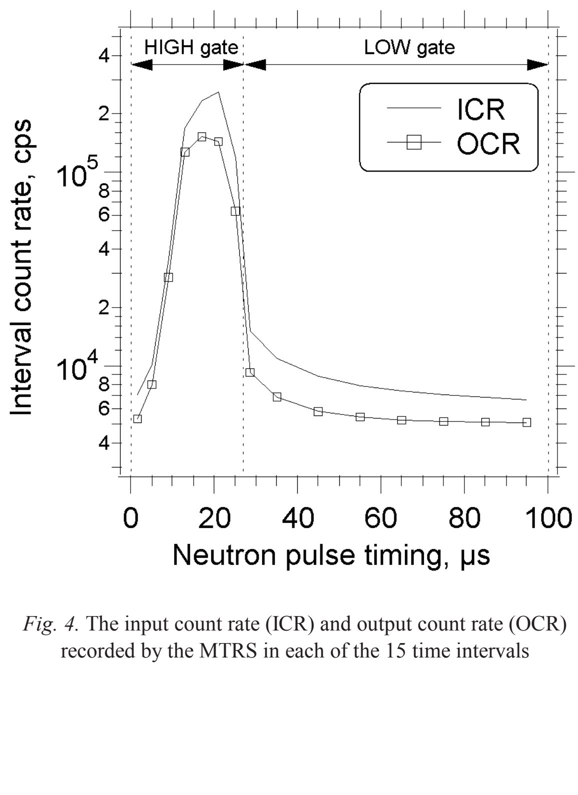

Fig. 4. The input count rate (ICR) and output count rate (OCR) recorded by the MTRS in each of the 15 time intervals

Table 1. Counting statistics recorded for each MTRS interval after an 1800-second data acquisition run

Interval #	Range, μs	Length, μs	RT, s	FTDT, s	LT, s	Measured length, μs
0	[0, 3]	3	78.96	0.338	58.94	3.00
1	[3, 7]	4	104.72	0.609	81.63	3.98
2	[7, 11]	4	104.72	1.887	83.99	3.98
3	[11, 15]	4	104.72	8.856	78.94	3.98
4	[15, 19]	4	104.55	12.313	68.50	3.98
5	[19, 23]	4	104.55	13.601	57.67	3.98
6	[23, 27]	4	103.94	7.520	55.07	3.95
7	Not used	0	0.00	0.000	0.00	0.00
Subtotal:	[0, 27]	27	706.16	45.123	484.74	26.86
8	[27, 30]	3	78.08	0.715	47.60	2.97
9	[30, 40]	10	263.53	1.708	166.38	10.02
10	[40, 50]	10	263.43	1.393	173.80	10.02
11	[50, 60]	10	263.36	1.254	181.39	10.02
12	[60, 70]	10	263.53	1.179	186.95	10.02
13	[70, 80]	10	263.70	1.134	191.56	10.03
14	[80, 90]	10	263.53	1.098	195.93	10.02
15	[90, 100]	10	264.18	1.075	200.55	10.05
Subtotal:	[27,100]	73	1923.34	9.557	1344.16	73.15
Total:	[0, 100]	100	2629.50	54.68	1828.90	100.00
Overall:			2646.61	57.52	1800.00	

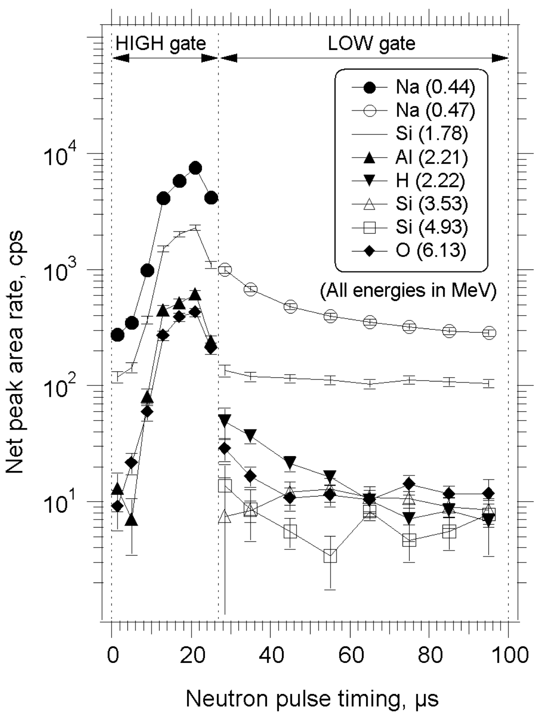

Fig. 5. The net peak area rate (net peak counts in each interval divided by its live time) of major elements as a function of time within the neutron pulse

Conclusions

A multiple time-gated system was developed for pulsed digital gamma-ray spectroscopy that is capable of concurrently acquiring up to 16 time-resolved spectra each with all required timing and count rate information. A maximum of 8 user-defined time intervals can be set for each of the HIGH and LOW gate periods. Experimental tests have shown the system produced correct timing and count rate information for each of the time intervals and that it can be used to improve the detection sensitivity of multiple elements in complex samples. The gating system can also be used to determine the optimal setting of the HIGH and LOW gates in order to improve the quality of the inelastic and thermal prompt gamma-spectra.

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