AN IMPROVED MEDICAL SPECTROMETER

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An improved solid-state version of the medical spectrometer (1) has been designed to meet the need for a simple and reliable instrument to be used for assay of radionuclides in the field of nuclear medicine. In conjunction with a suitable detector, the spectrometer provides a complete counting instrument with low long-term drift and excellent protection against line-voltage fluctuations. It is constructed in modular sections (Fig. 1): a preamplifier, linear amplifier, pulse-height analyzer, scaler-timer, high-voltage supply and "howler" (2). The modules can either be used separately or as one integral unit. A model of the spectrometer is shown in Fig. 2.

The spectrometer is designed for use with a sodium iodide detector, and it successfully tolerates the large pulses and high counting rates that accompany the use of large detecting crystals, which are common in the nuclear medical field. Coarse and fine gain controls on the front panel of the amplifier permit gain adjustment without involving the high-voltage supply. The built-in howler, together with the up and down offset buttons for the window position, make gain adjustment quick and easy. The instrument is currently performing effectively under hospital conditions, and it may well prove equally useful in non-medical fields.

PREAMPLIFIER

The preamplifier module is composed of the charge-sensitive amplifier, the first differentiator and a line-driver output group. It is located in the detector assembly for two reasons: (1) to eliminate the noise at the input of the charge-sensitive amplifier due to the capacitance of the connecting cable, and (2) to permit driving of the cable, at low impedance, after the first differentiation, and thus with a narrower pulse.

The operation of the preamplifier may be determined by referring to Fig. 3. A scintillation in the crystal liberates a small burst of electrons from the photocathode of the photomultiplier tube (V1), and the burst arrives at the tube’s output amplified a hundred-thousand-fold or more. The output is fed to the FET input (Q1) of the charge-sensitive amplifier. This amplifier (Q1, Q2, Q3, Q4) is a standard circuit that provides a charge of the 3.9 pF capacitor (C6), which has a discharge time constant of approximately 400 µsec. The output of this group is...
an emitter-follower (Q4) which serves as a low-impedance driver for the first RC differentiator (R24, C9). This differentiator provides the first pulse shaping of the detected signal, reducing the pulse duration. Resistor R22 provides pole-zero compensation to eliminate the undesired undershoot of the differentiated signal (3). Stages Q5 and Q6 serve as a low-impedance driver for the 100-ohm cable that connects the detector with the linear amplifier.

Two limiting circuits are included in the preamplifier in order to protect the system from the very large overloads that would otherwise result when cosmic rays hit the large scintillating crystals currently in use. Such signals are clipped at the base of the photomultiplier tube by diodes D1 and D2. The input signal to the line-driver group is prevented from exceeding 1.2 volts by diodes D4 and D5.

**LINEAR AMPLIFIER**

The linear-amplifier module consists of a shaping amplifier, an inverting amplifier, the main amplifier and the output amplifier. It is linear up to an output voltage of 10 volts with a maximum output of 20 volts. The amplifier is dc-coupled throughout except for the differentiating stage; this helps to prevent base-line shifts with changes in counting rate and with overloads. Each stage of the linear amplifier has a bandpass of 10 MHz.

The input to the linear amplifier is a positive-going signal applied at the base of Q1 (Fig. 4). Stages Q1 through Q4 provide additional signal shaping by shortening the decay time of the pulse. Signal shaping is accomplished by the addition of a resistor and two capacitors to the normal feedback circuit.

Diodes D1 and D2 limit the pulse to 3.0 volts before it enters the main amplifier. The CA3030 IC operational amplifier is used in the main amplifier group. This amplifier provides a maximum gain of 50. Since the CA3030 has limited positive signal capability, the signal is first inverted by the inverting amplifier (Q5 through Q9). Coarse gain selection is made by switch SW1, located on the amplifier.
panel. This control provides gain in steps between 1.5% and 100% of full gain. To maintain a balanced input to the CA3030, the coarse gain control steps along two balanced resistor strings. The fine gain control varies R28 in the feedback loop of the inverting amplifier. Its range is from around 0.45 to 1, which bridges the 1:2 steps in the coarse gain control.

Stages Q10 and Q11 provide a low-impedance output for the main amplifier. Switch SW2 provides a selection of operation in either the single- or double-differentiated mode. Under double differentiation, the dc feedback to the base of Q2 is taken from the output of Q11. Should a second differentiation not be desired, the dc feedback is taken from the output of the linear amplifier. The output group (Q12-Q16) provides a gain of 10 and a low-impedance drive for the 100-ohm cable connecting the linear amplifier with the single-channel analyzer.

**SINGLE-CHANNEL PULSE-HEIGHT ANALYZER**

Figure 5 shows the schematic of the pulse-height analyzer, which is composed of the upper and lower discriminators, an anticoincidence circuit, a one-shot multivibrator and the output driver stage. The upper and lower discriminators (Q3-Q12 and Q14-Q23, respectively) are identical. Their reference voltages are taken from a 2-mA current string at the bases of Q2 and Q13. The input to the analyzer is applied at the bases of stages Q3 and Q14.

To follow the operation of the discriminators, let us consider the lower one. The main functional group is the Darlington-type differential pair, Q14-Q17. The reference voltage is adjustable from —10 to 0 volts by the E dial, R12, located on the front panel; this establishes the minimum voltage to be detected. For example, assume this reference level to be set at —5 volts. Q14 and Q15 of the differential pair are normally cut off and will remain in this state until the signal level at the base of Q14 reaches 0 volts, the bias held on the base of Q17. Since the input signal is ac-coupled, it must have a magnitude of 5 volts before detection occurs. Any signal of 5 volts or greater will cause Q14 and Q15 to conduct, cutting off Q16 and Q17. C7 serves as a speed-up capacitor for the transition. The resulting positive-going signal on the collector of Q16 excites the Schmitt trigger (Q20, Q21), the output of which is shifted in level and inverted for feedback to turn on Q19 causing the reference point of Q17 to change from 0 to —5 volts. The differential pair will then return to its original state when the input signal returns to 0 volts. This causes the Schmitt trigger to return to its stable state, completing the formation of the output pulse.

The reference voltage for the upper discriminator is selected by the ΔE dial (R5) on the front panel. This potentiometer can vary the reference voltage from 0 to +3 volts. Should the input signal level reach or surpass this reference level, the same action occurs as for the lower discriminator, resulting in a negative-going output pulse at the collector of Q12.

In the **differential** mode of operation, the anticoincidence stage (Q24) prevents the passage of pulses from the lower discriminator to the one-shot multivibrator should the input pulse be of sufficient amplitude to fire both discriminators. In this case, the output signal of the upper discriminator (collector of Q12) saturates Q24, shorting the output of the lower discriminator. This circuit ensures that,
in the differential mode, only those input voltages whose amplitudes fall between the lower and upper reference levels will be counted. The range of voltages accepted in the differential mode is sometimes referred to as the window. In the integral mode of operation, Q24 is disabled and all pulses generated by the lower discriminator are passed to the one-shot (Q26, Q27). The output of the one-shot is a 1-μsec, negative 12-volt pulse which is passed to the scaler-timer module through a 100-ohm cable driven by the low-output-impedance driver stage (Q28-Q31).

Switches SW1 (E-shift down) and SW2 (E-shift up) facilitate the positioning of the photopeak in the center of the window. The photopeak as seen by the sodium iodide detector is not sharp, and its center may be difficult to locate. The E-shift switches allow a narrow window to be offset by an equal amount toward each of the steeply sloping sides of the peak where small changes in window position cause large changes in counting rate. When the offset counting rates are equal, the photopeak is centered in the pulse-height-analyzer window.

**SCALER-TIMER**

The logic and signal flow used in the scaling and timing circuits are shown in Fig. 6. This module uses integrated circuits extensively. A panel switch (SW5) permits the selection of either the preset time mode, in which the detector's pulses are counted during a known time, or the preset count mode, in which the number of counts is preselected and the time needed to accumulate them is measured in hundredths of a minute.

The main functional units in this module are two scalers: (1) a blind scaler (S1-S8), which determines the turn-off point of the counting operation, and (2) a readout scaler (S9-S14), which displays the measured count or time. The inputs to these scalers are interchanged by the MODE switch, SW5. The timing function is provided by counting the 60-Hz power line with an appropriate scale-down factor. In the preset time mode the readout scaler counts the detector's pulses while the blind scaler counts the 60-Hz power line, delivering a turn-off pulse at the end of a preselected interval ranging from 0.1 to 200 min (SW6). An "∞" position provides for very long counts with manual shut-off. In the preset count mode the readout scaler counts the 60-Hz power line, dividing by 36 for hundredths of a minute, while the blind scaler, counting the detector's pulses, provides a turn-off pulse at the

**FIG. 6.** Logic and signal-flow diagram of scaler-timer.
end of a preselected count ranging from 500 to 40,000 (SW7). In either mode the turn-off pulse is fed to FF3. This applies a ground signal to the start-stop flip-flop (FF1), which shuts off the count by closing gate G7. Should the operator prematurely terminate a count by pushing the STOP button, counting can be resumed by pushing the START button. If the count runs to termination by the blind scaler, however, the RESET button must be pressed before a new count can be started.

HIGH-VOLTAGE SUPPLY

The schematic of the high-voltage supply is shown in Fig. 7. This supply uses a conventional series-regulated design but is completely solid-state in construction. A voltage doubler (C11-C14) supplies approximately 1,400 volts dc to the collector of a high-voltage transistor (Q20) used as the series-regulating element. This transistor, which was developed for use in the horizontal output stage of a television receiver, can withstand 1,500 volts from collector to emitter. Regulated voltage is taken from its emitter through a 270-ohm resistor (R48) and filtered by a 0.1 μF capacitor (C17). To achieve regulation, selector switches (SW1, SW2) pick off a fraction of the output voltage, and this is compared with the voltage of a temperature-compensated Zener diode (D14). Any voltage difference is amplified by a high-gain (∼ 50,000) error amplifier (Q10-Q15) and applied as a correction signal from base to emitter of the series-regulating transistor. Power for the error amplifier is supplied by a small power supply giving plus and minus 12 volts with reference to the high-voltage output terminal. Both this small supply and the differential amplifier “float” at the output potential, using the high terminal as their reference.

To protect the regulating circuit against extreme variations in line voltage, a “preregulator” acting on the ac supply voltage has been included in the circuit. The output of the voltage doubler (C11-C14) at 90 volts ac input is nominally 1,400 volts dc. Since output is proportional to input, at 140 volts ac input the voltage doubler would supply 2,180 volts dc to the series regulating element. This volt-
age would exceed the series transistor's rating and destroy the power supply.

To prevent this high-voltage condition, a full-wave bridge rectifier supplying a 2N3773 power transistor (Q1) is connected in series with the power-supply transformer primary. Q1 is driven by a small amplifier (Q17-Q19) which samples the output from a secondary winding of the power transformer. As long as this secondary winding supplies less than 10 volts ac, Q1 is kept saturated; any attempted increase in secondary voltage brings Q1 out of saturation, so that the difference between 90 volts ac and the line voltage is lost across the regulator circuit. Thus only 90 volts ac is allowed to appear across the power transformer primary. The signal supplied to the transformer has a truncated sine waveform which benefits the rectifier-filter circuits in the power supply, since its peak and rms values are more nearly equal than those of a sine waveform. Since the 2N3773 "preregulator" transistor can dissipate adequate power, all the power supplies of the spectrometer are supplied via the preregulator. In most cases, this should eliminate the need for a Sola or other constant-voltage transformer. The preregulator is surprisingly effective and accounts for a good part of the high-voltage supply's immunity to line-voltage changes.

Stability of the output voltage depends mainly on the stability of the reference Zener (D14). If a type 1N827A is used, the following results may be expected for an output voltage of 1,000 volts nominal:

- Maximum voltage drift from turn-on to warmup < 1 volt.
- Warmup time approximately 30 min.
- Drift after warmup < 50 mV for normal room temperature changes (most of the observable drift is due to temperature variations).
- Hum and noise < 5 mV rms.
- Stability re line voltage: less than 20 mV output change (at 1,000 volts) for a line-voltage change from 90 to 140 volts (= 0.000046% output change for 1% line change).

HOWLER

The howler circuit (Fig. 8) drives a small, 8-ohm speaker with a sinusoidal signal whose frequency depends on the pulse rate presented to the howler. Pulses from the discriminator drive a one-shot multivibrator (Q1-Q4), the output of which is a series of pulses of width selected by the range switch (SW1). Each output pulse is diode-coupled by D2 to an RC timing circuit (R19, C16). The average voltage on S16 is proportional to the pulse rate of the input signal. This voltage is used to frequency-
modulate an oscillator (Q6) whose nominal frequency is 200 kHz, with a maximum deviation of 10 kHz. Output of the modulated oscillator is mixed (Q7-Q10) with a fixed-frequency oscillator signal of 200 kHz from Q11 to produce an audio signal varying in frequency from 0 to 10 kHz. This signal is coupled via a volume control (R34) through a power amplifier (Q12-Q17) to a small loudspeaker, providing an auditory indication of the counting rate from the discriminator.

Since the loudspeaker demands a rather high current, a decoupled positive and negative 12-volt supply (Q18-Q25) is provided to isolate the howler circuit from the other spectrometer circuits. This also ensures that the 200-kHz signals will not interfere with circuits external to the howler module, which have their own positive and negative 12-volt supply.

SUMMARY

A flexible, modularly-designed pulse-height spectrometer has been developed and is now under field test. Although planned primarily for the field of nuclear medicine, this unit may be used in other scintillation spectrometry applications. Designed for use with a sodium iodide detector, the instrument covers an energy range from a few keV to several MeV. The linear amplifier, with continuously variable gain from 30 to above 3,000, is linear to an output voltage of 10 volts, and may be operated in either single- or double-differentiating modes. The base line is stable at high counting rates, and pole-zero compensation provides good overload performance. The pulse-height discriminator uses a zero-crossover design with a window opening of up to 30% of the base level. A scaler-timer section provides preset time intervals from 0.1 to 200 min in convenient steps; it also provides preset counts ranging from 500 to 40,000 with the elapsed time displayed in steps of 0.01 min. A solid-state, series-regulated supply provides high voltage for the photomultiplier tube, maintained to within 0.002% throughout a line-voltage range of 90 to 140 volts. The long-time drift is less than 0.025%/hr.

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REFERENCES