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ABSTRACT

Recent experience in instrumentation of several nuclear-physics experiments has demonstrated the feasibility of automating the data-acquisition phases of the experiment. Electronic circuits are employed wherever the rate of data flow would be slowed by the use of human operations. Information is selected, temporarily stored, and then recorded in a form suitable for immediate entry into a computer. Experimenters thus freed from the tedious aspects of data collection can devote their time to studying the results of the experiment.

Potentially useful nuclear events are first selected by the fast-logic (10^{-8} -sec) part of the instrumentation. Circuits performing simple logical functions are packaged in modular form for easy grouping into particular coincidence, gating, and mixing configurations. Circuits with slower response time ( > 10^{-6} sec) are used for temporary storage and recording operations. Automatic test routines are used to initially align the equipment as well as provide continuous calibration during the experiments.

Some of the high-speed circuits are described as well as the methods used to incorporate them into a large counting system.
INSTRUMENTATION OF MULTI-CHANNEL COUNTER EXPERIMENTS

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1. INTRODUCTION

The application of modern electronic data-handling techniques to nuclear physics has made it possible to perform complex counter experiments that were impractical with former methods. This report will discuss some of the work of the Counting Instrumentation Groups of the Lawrence Radiation Laboratory at Berkeley in this direction. As the number of counters per experiment increases, new ways are devised to portray and record the greater volume of information. One popular method has been to display the output of a number of counters--with appropriate time delays between them--on the traces of a multibeam oscilloscope and to photograph the display. The information thus recorded photographically is later read visually a trace at a time, and the necessary calculations are made manually or with the aid of an electronic computer.

During the past four years, several systems using electronic data handling have been developed for use wherever the rate of information flow would be slowed by human operations. Some of these operations are recording, selecting, and storing data. Table I indicates the advance in the number of information channels that have been handled as well as the increase in the information handling rate. Aside from supervising the operation of his electronic "slave", the experimenter thus freed of many tedious tasks can devote his time more valuably toward interpretation of the experimental results.
II. DESCRIPTION OF THE LATEST EXPERIMENT

The latest experiment performed by the Segre Group at Berkeley on pion-pion scattering illustrates the type of problem that can be accommodated by automated data-acquisition equipment. A beam of 1- to 2-Bev/c pions from the Bevatron was focused upon a liquid-hydrogen target. About one in $10^6$ of the pions in the beam collided with a proton in such a way as to produce a second pion and a low-energy neutron. These three particles emerged from the target and were detected by a large array of scintillators. The array was composed of 84 separate elements fitted together to form a $\pi$ steradian section of a sphere 5 ft in radius centered upon the target. A rear view of these counters is shown in Fig. 1. The array intercepted all particles emitted in the angular interval from 4 to 60 deg with respect to the beam. Twelve additional counters were arranged to extend the intercepted solid angle seen by the beam, and seven other counters provided additional means of identification. There were 103 counters in all. Since some counters were used to detect both pions and neutrons, a total of 187 information channels were employed. The maximum number that could have been handled was 210, a limit imposed only by the size of the present core planes. One 6810A or 7046 multiplier phototube was coupled to each scintillator element. Thus the coordinates of the three particles were measured by noting which of the counters generated an output. The energy of the neutrons was found by measuring the time between the occurrence of the prompt-pion phototube signals and the later neutron signal. With this information, a computer calculated from the kinematics of the event the physically possible events and separated them from the "false" events composed of background signals.
Table I. Annual progress in information-storage facilities by Counting Instrumentation Groups at Lawrence Radiation Laboratory.

<table>
<thead>
<tr>
<th>Year</th>
<th>No. data channels available</th>
<th>Maximum No. events stored in 0.1 sec.</th>
<th>Method of information storage</th>
<th>Method of data transmission to computer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1958</td>
<td>35</td>
<td>1</td>
<td>flip-flop</td>
<td>punched cards</td>
</tr>
<tr>
<td>1959</td>
<td>40</td>
<td>10</td>
<td>core storage</td>
<td>paper tape</td>
</tr>
<tr>
<td>1960</td>
<td>180</td>
<td>10</td>
<td>core storage</td>
<td>paper tape</td>
</tr>
<tr>
<td>1961</td>
<td>210</td>
<td>50</td>
<td>core storage</td>
<td>magnetic tape</td>
</tr>
</tbody>
</table>

III. ELECTRONIC CIRCUITS

The instrumentation for a previous experiment has already been reported.\(^2\)-\(^7\) The counting equipment for the recent experiment may be divided into five sections:

1. The nanosecond circuits that perform the system logic by separating the desired events from the background.
2. The coordinate detectors that measure the spatial positions of the three particles in each event.
3. Chronotron circuits to detect the velocity of the neutron from its time of flight.
4. A buffer core storage unit to temporarily remember the selected events and then record them on magnetic tape.
5. Test and monitoring circuits that allow the experimenter to examine and test the operation of the system.

An over-all block diagram is shown in Fig. 2.

IV. TUNNEL-DIODE DISCRIMINATOR

Extensive use has been made of a tunnel-diode discriminator described by KERN\(^8\). It provides an output pulse of uniform delay after the scintillation pulse and nearly uniform height for wide ranges of input amplitude and counting rate. It is much easier to perform subsequent operations when these "standardized" discriminator pulses are used. Between the phototube and discriminator, a clipping stub differentiates
the signal to produce first a negative—and then a positive-going waveform. The tunnel diode is biased to trigger near the zero crossing on the backswing of the signal. In time, this point is quite independent of amplitude. By proper selection of clipping-stub impedance and length, the variation in discriminator delay has been reduced to less than 0.5 nsec over a fifty-to-one range of input amplitude. The tunnel-diode is placed in one branch of a balanced bridge as shown in Fig. 3. Resistors R1 and R2 of the bridge are made to differ by a value that approximates the tunnel-diode positive resistance characteristic. No output signal is produced at transistor Q2 until the circulating current in the bridge is sufficient to overcome the bias and regenerate the tunnel diode. Thus feed-through from small pulses is minimized.

V. NANOSECOND LOGIC CIRCUITS

Selection of true events from the great background of unwanted interactions is accomplished in two steps. Part of the selection is done by the "fast-logic" circuits which respond to pulses in the few-nanosecond range. The final selection, however, is done by the computer. The fast-logic circuits perform functions such as gating, inhibiting, signal mixing, and splitting. Typical of these circuits are the signal splitter shown in Fig. 4 and the signal mixer of Fig. 5. The signal splitter can be made to have any reasonable number of outputs without interaction between them; the two-channel splitter is shown for illustration. The output rise time is 5 nsec for a step-function input. The gain is 0.8, and the maximum output amplitude is +1v or -2v.

In the same manner, the signal mixer is flexible with regard to the number of channels that can be used. The two-channel mixer produces an output pulse having a 4-nsec rise time for a step signal applied to either input. The unit illustrated is suitable for negative pulses; by substituting PNP transistors and reversing the supply potentials, it is suitable for positive signals.

The monitor output in each case is isolated by an emitter follower; this isolation makes the normal output almost independent of the monitor loading.
To preserve signal rise times between units, special care was given to the circuit packaging. A modular unit was desired that was inexpensive, used printed-circuit techniques, allowed interconnection of nanosecond pulses with coaxial cables, and provided connections for power and slow pulses through printed-circuit connectors. The resulting unit is shown in Fig. 6. It is available in a number of different widths and panel sizes.

VI. CHRONOTRON

The determination of the neutron energy by finding its time of flight is typical of measurements that lend themselves to automated readout. The interval of interest is from 11 to 43 nsec. A nine-channel, parallel-access chronotron compares the flight time of prompt pions with the slower neutrons. The 32-nsec interval is divided into seven periods, with two additional channels. One of the latter channels indicates neutron pulses arriving too early, and another, those arriving too late. A block diagram of the chronotron is shown in Fig. 7. The splitting transformer divides the reference signal into nine similar pulses. Each of these is delayed by a different amount and compared to the neutron signal in a diode sampling circuit. The appropriate output among the nine is indicated by the sampling circuit having the greatest output voltage. A diode matrix converts the signals to a binary-coded output for storage purposes. A test routine is fed through the chronotron circuits whenever they are not used for actual time measurement. Figure 8 shows the test routine simultaneously presented for four chronotrons. Each of the available time intervals is displayed in sequence as a binary number from top to bottom on the cathode-ray tube screen. During the experiment the chronotrons have maintained their timing to within 0.5 nsec over a period of 24 hr.
VII. MEMORY AND READOUT

The buffer store provides a temporary memory for random events until they can be transferred in an orderly fashion to a permanent memory. In this experiment, a 2100-bit buffer store transfers the coordinate and timing data from each event onto magnetic tape for permanent record. For coordinate information, one ferrite core is associated with each information channel for each event recorded. The timing information uses a binary-coded octal system. After ten events are stored, the buffer store is read out onto magnetic tape, and the store is again ready to accept events. Since the total starting and stopping of the tape transport requires only 10 msec, several groups of ten events each can be recorded during a 0.1-sec Bevatron beam burst. The magnetic tape is recorded in a manner that allows immediate entry to an IBM 704 or 709 computer for analysis. The logic circuits for the core store are designed for microsecond response times. For these rise times, circuits can be constructed on printed-circuit boards and housed in plug-in frames. A typical unit is the 1-Mc scaler flip-flop; a schematic circuit diagram is shown in Fig. 9. A printed-circuit board containing two flip-flops is shown in Fig. 10. This unit can be used either as a binary scaler or a flip-flop by simply inserting or removing one link connection (shown near Q-1 in Fig. 9). As a scaler, the unit circuit operates at rates up to $10^6$ counts per second for input signals greater than 6 v and a rise time less than 0.75 μsec. The saturated output stages will drive a load shunted by a 250-pf capacitor and give a 0.1-μsec rise time and a 0.4-μsec fall time.

VIII. TEST ROUTINES AND MONITORING

With the automation of the data-acquisition phases of an experiment, it is imperative that error-detection methods be speeded up. Otherwise, an excessive amount of time is consumed repairing even a minor system malfunction. In two recent experiments, test routines were evolved to initially align the system, calibrate it while it runs, and rapidly localize threshold drift or catastrophic failures. The monitoring program feeds light or electrical test pulses into several points of the system. This allows one to compare actual operation with the
desired response.

The most comprehensive test very nearly simulates the response of the entire system to nuclear events without the Bevatron even operating. Light pulses injected with appropriate timing into the scintillation counters check the operation of all the succeeding instrumentation including the calculations made by the computer. Field-emission light pulsers developed by KERNS et al. are mounted on the front surface of the scintillation detectors. They emit 1-to 2-nsec pulses with less than 0.2-nsec jitter. Up to 64 light pulsers can be operated at one time.

Operation of the equipment following the phototubes can be checked by injecting electrical test signals at the inputs of the tunnel-diode discriminators. A test pulser has been constructed that generates signals at two levels: 80% and 110% of the normalized pulse amplitude for each channel. At the 80% level none of the counter channels should indicate an output, but at the 110% level all of the channels should have triggered. An alarm indicates the failure of any channel to trigger properly. The test-pulser signal is split into a number of channels by a passive distributor shown in Fig. 11. To keep the 10-nsec pulses from being shorted out by the series-parallel connections shown, ferrite cores are used for isolation. The rapid recognition of a large mass of information is always difficult. A display panel has been used here to observe data during the actual running of the experiment as well as test patterns during error checking. The panel consists of an array of incandescent lights arranged in the same spatial pattern as the scintillation counters in the experiment. One set of lights is for the pion signals, the other for the neutron signals. While the whole data-acquisition system can store many events per Bevatron beam burst, an observer has difficulty in remembering more than one event at a time. Thus it was decided to display only every tenth event in any burst. The last event is displayed continuously until the next Bevatron pulse.

The display panel is arranged to show (a) events going into the buffer store, (b) events recorded on magnetic tape, or (c) the difference between conditions (a) and (b). The first condition checks the circuits.
ahead of the buffer store, the second condition checks the entire system, and the third allows one to check the performance of the store and tape transport.

The light bulbs (General Electric No. 344) glow brightly at 12v and draw about 20 ma; they glow very dimly at 5v and draw about 9 ma. Circuits are arranged so that binary 1 is the bright condition, binary 0 the dim condition. Both of these conditions can be distinguished easily from an open circuit or a defective bulb.

IX. CONCLUSIONS

The complexity of recent counter experiments has demanded new ways of gathering experimental data. We believe that the methods used here are a worthwhile approach to an automated data-acquisition system.

The use of modular circuit packages provides the needed flexibility for performing a wide variety of experiments with a limited number of components.

The general usefulness of semiconductor components for counting instrumentation has adequately been demonstrated. Except for the detectors and a few electron tubes in amplifiers and monitors, all of the active components are solid-state devices. Over 4000 transistors are used in the system described. In regard to reliability, the entire system has run for several days without requiring an unscheduled maintenance period. The savings in rack space, power dissipated as heat, and operating time due to high reliability have shown solid-state devices to be superior to their thermionic counterparts.

Success with our error-checking techniques shows that an adequate test routine makes a great saving in the accelerator time needed for any experiment. Further savings can be made in initially setting up an experiment by providing test routines to check individual circuits and subsystems as they are put into operation.

We believe that data-acquisition systems are in their infancy and that, even today, systems involving many more channels and larger storage capacity are entirely feasible.
ACKNOWLEDGMENTS

The encouragement by members of the Segrè experimental group is deeply appreciated, particularly the guidance of Dr. Clyde Wiegand. The electronic development described here is the work of a large number of persons, including Quentin A. Kerns, Thomas A. Nunamaker, Stanley C. Baker, Frank Evans, Arthur E. Bjerke, and Gerald C. Cox.
FOOTNOTES

*This work was done under the auspices of the U. S. Atomic Energy Commission.


FIGURE LEGENDS

Fig. 1. Rear view of counter array with signal shapers and test equipment in foreground.

Fig. 2. Block diagram of instrumentation for a multi-channel counter experiment.

Fig. 3. Schematic diagram of tunnel-diode discriminator.

Fig. 4. Schematic diagram of two-channel signal splitter.

Fig. 5. Schematic diagram of two-channel signal mixer.

Fig. 6. Shielded package for nanosecond circuits.

Fig. 7. Chronotron block diagram.

Fig. 8. Display of binary-coded test signals of four chronotron channels.

Fig. 9. Basic 1-Mc flip-flop schematic diagram. The link is removed for flip-flop operation and inserted for scaling and complementing.

Fig. 10. Printed-circuit board containing two 1-Mc flip-flop circuits.

Fig. 11. Schematic diagram of test-pulse distributor. Each group of four miniature 50-ohm cables makes four turns around a toroid.

Fig. 12. Light display panel.

Fig. 13. View of part of the fast-logic circuits with the coincidence-discriminator units, buffer store, test and control circuits, and magnetic-tape transport.
Beam-telescope counters

Test Liquid generator and signals

Four C.R.T. raster display

Test generator and C.R.T. raster display

N gate counters circuits

Chronotrons

Time information (12 bits)

Coordinate information (187 bits)

Light display of first event

Event has occurred

Simulated phototube pulses

Self-testing circuitry

Return signals from tape punch

Buffer store and control circuit

Magnetic-tape transport

MU-23124

Fig. 2
Fig. 3
Fig. 4
Fig. 5
Figure 6
Fig. 7
Fig. 9
To even channels

12.5 ohm Ferrite toroids

To similar circuit to feed odd channels

Fig. 11
Fig. 13
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