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THE DATA ACQUISITION SYSTEM FOR THE HHIRF SPIN SPECTROMETER

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I. The Spin Spectrometer

The Spin Spectrometer[1] at the Holifield Heavy Ion Research Facility (HHIRF) is a multidetector γ-ray spectrometer consisting of 72 separate NaI detector elements closely packed in a 4π geometry. The basic apparatus was constructed at Washington University and has been installed and implemented at the HHIRF at Oak Ridge National Laboratory. The spectrometer was designed especially for the investigation of the mechanisms of heavy-ion induced nuclear reactions and of the structure of nuclei with high angular momentum.

II. Electronics

The front-end electronics provide for each detector the γ-ray energy (E), the time (T) relative to the event strobe, a pile up (PU) indicator, and a gated latch (GL) bit. Support electronics provide the necessary strobes, gates, clear pulses, control, and real time multiplicity. All of this information is managed in CAMAC using the Event Handler[2] which performs a sparse data scan based on the pattern of the GL bits.

The signal from the photomultiplier (RCA 4522) tube base has a typical risetime of ~ 20 ns for the applied voltage of about -2000 V. The signal is amplified in a LRS 612A X10 amplifier and both outputs from the amplifier are used, one for the linear digitization, the other for the timing determination, as shown in Fig. 1.

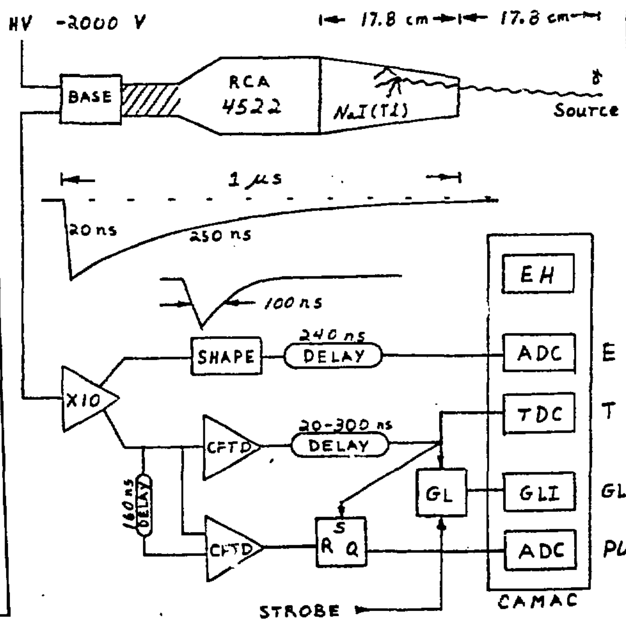

Fig. 1. Spin Spectrometer front end electronics.

The linear signal is first passively shaped to a roughly triangular shape with a base of about 250 ns. The purpose of this shaping is to reduce the effect of the long tail characteristic of pulses from NaI(Tl) detectors. Even though this shaped pulse is reasonably narrow, the charge integrating ADC needs to integrate over at least 600 ns of the pulse in order to achieve the full energy resolution of the detector. The portion of the baseline after the triangular pulse has an average value of zero but has instantaneous fluctuations which affect the resolution out to the 600 ns point. We consequently run the device with a gate of ~ 1000 ns so that the best energy resolution may be easily obtained. After having been shaped, the signal is attenuated and then run through 38.1 m (150 ft) of RG 174 coax cable to provide a delay of ~ 240 ns into an LRS 2249W integrating ADC. The ADC has an 11 bit capability (2048 channels), and the signal is attenuated so that the energy dispersion from the ADC is about 5 keV/channel, or 10 MeV full scale.

The timing signal is also passively shaped so as to reduce the long tail of the pulse somewhat and then is run into the constant-fraction timing discriminator (CFTD) which produces a prompt CFTD logic pulse and a CFTD logic pulse delayed by an adjustable one-shot, where the width of the prompt CFTD logic pulse is the chosen delay. Delays from 20 to 300 ns may be used but use of the PU circuitry requires that the delay be $\leq$ 80 ns. The average time resolution is 2.1 ns FWHM and 4.7 ns FWTM when measured using a ^{60}Co source with the threshold set at 80 keV.

The GL bit is set if the internal delayed CFTD logic signal has any overlap with an externally generated strobe signal. The GL bit is interfaced into one of five 16-bit buffers interfaced to CAMAC.

The pile-up (PU) indicator is obtained from a constant fraction discriminator sensitive to the rear edge of the pulse (~ 160 ns delay). The discriminator is sensitive to pulse pile up when the pulses are $\geq$ 5 ns apart. The sensitivity is a complicated function of the relative sizes of the pulses but should be greatest for the more important kinds of pulse pile up. The PU indicator is a constant amplitude rectangular pulse whose width is a measure of the pulse width; an LRS 2249W integrating ADC converts this into a time-like parameter.

The intimate support electronics consist of the following modules: STROBE, CLEAR, GATED LATCH INTERFACE, USER'S GATED LATCH, and SELECT.

The STROBE module accepts an event trigger and then provides strobes for all the GL bits, gates for the energy ADC's, gates for the PU ADC's, start signals for the TDC's, various fanned-out strobes for user electronics, and a delayed strobe for the real time multiplicity summing circuit. The STROBE module goes busy at the beginning of the event trigger and stays busy until it receives a clear strobe from the CLEAR module. The STROBE busy logic condition is available to the user for determining system dead time.

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The CLEAR module can be triggered by a front panel pulse, or it can be triggered by the coincidence of the delayed strobe and a front panel clear request. In either case it simultaneously clears all GL bits, the STROBE busy, all ADC's and TDC's, and any user modules requiring a clear pulse.

The GATED LATCH INTERFACE module interfaces to CAMAC the 72 GL bits from the spectrometer plus 16 user GL bits. The bits are available in blocks of 16. The module also generates a 7 bit multiplicity parameter from the 72 GL bits, and these 7 bits are available as part of one of the 16-bit blocks. The module compares the multiplicity to front panel dials and outputs logic levels corresponding to <, =, or > the dial setting. These levels can be used with the delayed strobe in the CLEAR module to generate a fast (~ 200 ns after the strobe) clear signal.

The USER'S GL is a 16 bit gated latch buffer with 16 separate delays for the NIM fast logic inputs. The 16 bits are interfaced through the GL INTERFACE to CAMAC. The delayed signals are available for digitizing in a TDC.

The SELECT module can disable any, all, or none of the 72 GL bits or 16 user GL bits. The purpose of this module is to allow the computer to select a single detector or a particular group of detectors of interest. All GL signals are fast ORed together and this OR signal has the time characteristic of whichever detectors have been selected. Consequently, only one output needs to be checked in order to determine if all of the detectors have equivalent delays; the SELECT module specifies which detector is being monitored.

III. CAMAC Event Management

The parameters associated with the 72 NaI detectors and any user devices are interfaced into modules in two CAMAC crates. The basic electronics for just the spectrometer include 6 ADC modules for the energies, 9 TDC modules for the times, 6 ADC modules for the pile up indicators, and one gated latch interface.

All of this is managed by the Event Handler (EH), a fast, programmable, data-acquisition interface with a pair of CAMAC auxiliary controllers as CAMAC I/O devices. The EH has front panel inputs which can be used to inform it when an event has been triggered. For example, it can poll the busy signal from the STROBE module or can itself be triggered by one of the strobe signals. When it recognizes the beginning of an event it can read the NaI-detector multiplicity register to see whether sufficient detectors have fired, or it can examine the GL register for the user electronics and check the number and/or pattern of detectors which have fired. If the event does not meet the criteria specified in the EH program, the EH can then "crash" the event by a pulse to the CLEAR module. (It may also find that the CLEAR module has performed a hardware generated crash.) It would then go back to waiting for the next event.

If the event is acceptable, the EH performs any setup necessary for the data stream and then waits for the various modules to finish digitizing. At the end of the digitizing-busy time, it examines each bit of the 72-bit gated latch and reads and transmits the relevant parameters for each bit that is set. In this way, it performs a sparse data scan. In the current EH there is a 1-μs penalty for each zero channel; in the next version of the EH, the penalty should be essentially zero. When all parameters for the spectrometer and for the user electronics have been transmitted, an end-of-event word is transmitted and the final clean up of the electronics is performed. The CAMAC modules are cleared and the front-end electronics are cleared. The EH then waits for the next trigger.

The sole logic link with the downstream data acquisition computer is performed through a First-In-First-Out (FIFO) buffer. The computer can set two bits in the FIFO: PAUSE and HALT. The EH is linked to the FIFO and can sense these bits and implements them in software. HALT implies that all activity should cease and BUSY should be asserted. The removal of HALT is generally implemented as being a time to clear LAM enables, reset all modules, and remove any crate inhibit, before going into a wait-for-event loop.

PAUSE as asserted by the computer implies that a HALT is imminent, so finish whatever is in progress, but hold BUSY asserted so as to allow no more events. In fact PAUSE as sensed by the EH is the logical OR of three conditions; a computer PAUSE, a user on/off switch, or a 3/4-full condition in the FIFO. In any case, the typical PAUSE implementation is to finish the event and leave BUSY asserted.

The present EH controlled front-end system has a typical time requirement for sending all of the information to the computer: 100 μs for ADC digitizing, 70 μs for the sparse data scan, N*6 μs for N "relevant" detectors, and 30 μs to clear. Thus for a N = 20 (a typical average number for many experiments), the front-end deadtime is 320 μs and the maximum average rate is 3000 events/s.

IV. Data Organization

The data organization is made to match that expected by the L002 format of the HHIRF data acquisition system. In this format the most significant bit is reserved for control words of which there are two (in hexadecimal):

1) "FFFF is an end-of-event word, and
2) "8000 + N, where N is an index.

The index indicates where in an array the succeeding data words are to be placed. Since the Spin Spectrometer can generate three words per detector, this index is incremented by 3 for each detector. The following is a possible event stream:

"8000 + 217	1 more than 3*72
E-Ge(Li)	+217 User device
T-Ge(Li)	+218
"8000 + 1	Begin the NaI's
E_1	+1
T_1	+2
PU_1	+3
"8000 + 19	Skip 2 through 6
E_7	+19
T_7	+20
PU_7	+21
"8000 + 181	Skip 8-60
E_{61}	+181
T_{61}	+182
PU_{61}	+183
"FFFF	End-of-event

The user parameters are put to the front to make data processing more convenient and possibly faster. But note that these data are indexed beyond the spectrometer data block. For general programming convenience, the spectrometer block always has the same form. Then, whatever transformations are required, the transforming routines can always use the same indices for the spectrometer.

V. Transformations

The raw data from the data acquisition system require a number of transformations, most of them very simple. It has become a reasonable observation that software fixes to hardware problems are quicker, cheaper, and possibly better than detailed hardware improvements. One group of these corrections arises largely from known and accepted deficiencies in the electronics hardware or in the patience of the researchers using the equipment.

The ADC's and TDC's generally have a pedestal; that is, zero energy does not appear in the first channel ("zeroth" channel). In addition, the electronics may not be linear so that higher order correction terms are required.

$$\text{Energy Pulse Height} = E_0 + E'*I + E''*I^2$$

where I is the channel number. E_0 = -Pedestal. We find that it is difficult to reduce the 2nd order term E" to zero for all 72 detectors, though it is generally fairly small. For energies greater than 5 MeV, this correction could be important.

The first pass correction to the time difference is

$$\text{Time Difference} = T_0 + T'*I.$$

In general the time response is linear to the degree required by most experiments, but T_0 is a function of the amplitude, T_0 = function (amplitude). This dependence on amplitude is very difficult to correct in hardware but can be done easily in software.

Problems with the pile up indicator are very similar to those with the time response.

$$\text{Pile Up Indicator} = PU_0(\text{Amplitude}) + PU'*I$$

where PU_0 contains the ADC pedestal, any basic offset, and the dynamic slewing of the signal with pulse amplitude.

The next set of corrections arises from problems associated with the dynamics of the device as an instrument used in nuclear physics at this particular institution. Our main interest is in the study of systems in which there is always a mixture of γ rays and neutrons associated with events of interest -- but we wish to study the two types of radiation separately. How well we can separate the effects of one from the other is crucial to many of our experiments. The method we use to distinguish γ rays from neutrons is the time-of-flight method. The inner radius of the spectrometer is 17.8 cm, and the detectors are 17.8 cm deep. It takes a typical neutron (E_n < 5 MeV) more than 5 ns to reach the front face of any crystal, and with a time resolution of ~ 2 ns, separating neutrons from γ-rays is straightforward. See Fig. 2.

The timing resolution of an individual detector can be no better than is available from the trigger source. If the spectrometer is triggered by a Ge(Li) detector with an intrinsic timing resolution of 5 ns, then each NaI detector in coincidence with the Ge(Li) will exhibit a timing resolution dominated by this poor timing resolution, and neutron discrimination

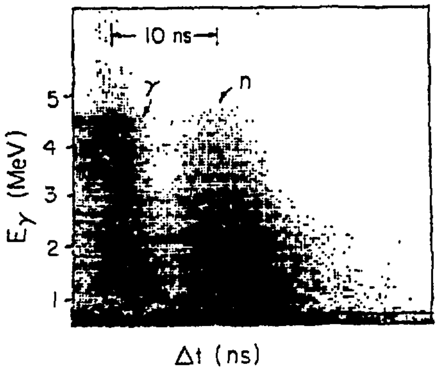

Fig. 2. Neutron and γ-ray time-of-flight spectrum.

will be much poorer than is required. Fortunately, a software fix is available.

It is possible to average over all of the NaI detectors involved in a many γ-ray event and establish a trigger time independent of the actual trigger source and with a timing resolution far better than that for an individual NaI, which is ~ 2 ns. For a single detector:

$$TDC = T_{NaI} - T_{trigger}$$

where TDC is the time difference measured in a TDC, T_{NaI} is the absolute NaI triggering time, and $T_{trigger}$ is the triggering time of the trigger source.

$$\Delta^2 TDC = \Delta^2 T_{NaI} + \Delta^2 T_{trigger}$$

gives the mean square deviation (timing resolution) of the TDC time difference and shows that the resolution is limited by the timing resolution of the trigger source. But consider a single event involving K γ rays. If we define T_t as the average of the K measurements of the time then

$$T_t = \frac{\sum^{k} T_{NaI}}{K} - T_{trigger}$$

since $T_{trigger}$ is the same for all detectors. But since the K values of T_{NaI} represent K independent measurements of T_t, the uncertainty in T_t is the average uncertainty in T_{NaI} divided by the square root of K.

$$\sigma(T_t - T_{trigger}) \cong \bar{\sigma}_{T_{NaI}} / \sqrt{K}$$

If 25 γ rays are measured, and the average uncertainty in T_{NaI} is about 2 ns, then the uncertainty in T_t is < 0.5 ns. This now represents a "trigger" timing resolution so good that the individual measurements for the various detectors can be fully exploited.

In an actual event, the K γ rays would have been mixed with N neutrons, and one has to iterate to obtain the answer. A value of T_t is first determined from all of the data, and a 10 ns window around this value is used to exclude some of the neutrons. A better T_t is now calculated and a 5 ns window around it will exclude most or all of the neutrons. The third pass generally determines T_t with essentially no neutron contamination. This method has been successful even with K as low as 5.

This solves a major problem in distinguishing neutrons by time of flight, and it provides a precise trigger time for user detectors, particularly for time-of-flight systems used to measure heavy ion masses or neutron energies.

Another troublesome problem is associated with neutrons. In an event in which 25 γ rays and 10 neutrons are emitted, there is a high probability that at least one of the NaI detectors has detected both a γ ray and a neutron. Since the γ ray arrived first, time of flight cannot be used to identify the presence of the neutron -- and the pulse amplitude measured is that of both the γ ray and the neutron. Because neutrons are capable of depositing relatively large amounts of energy in a detector, it is important that their contaminating presence be spotted. The pile up indicator circuit can in most cases detect a subsequent neutron pulse if it is at least 5 ns after the primary pulse. If a pile up neutron is detected, the energy can then be taken as:

1) $E - \bar{E}_n$ subtract an average neutron energy,
2) $\bar{E}_\gamma$ substitute an average γ-ray energy

When all corrections and calculations have been performed, one obtains:

1) K, the number of detected γ rays
2) E_γ, the γ-ray pulse height in each detector
3) T_t, a good trigger time base
4) T_γ, the individual γ-ray times in case a measurable lifetime is involved
5) N, the number of detected neutrons
6) θ and ϕ, the detection angles for each γ ray
7) ΣE_γ, the total γ-ray pulse height.

VI. Considerations and Limitations

Many of the most straightforward experiments put tremendous demands on the data acquisition and data processing computers. But, because of the potential richness of the information available from the Spin Spectrometer, it is difficult to decide what of it to throw away. A very simple experimental setup to study high angular momentum induced by heavy ion reactions uses a Ge(Li) detector measured in coincidence with the spectrometer. Typical reactions can produce more than 30 γ rays, produce an average number of γ rays near 20, and produce 6 to 10 neutrons. Consequently 30 or so detectors will on the average be triggered by a single event. Since four 16-bit words (or 8 bytes) are transmitted per detector, more than 240 bytes per event need to be transmitted. An event rate of 1 kHz implies a data rate of ~ 250 kbytes/s; an event rate of 4 kHz implies ~ 1 Mbyte/s.

At present we face the following approximate data rate limitations

1) 120 kbytes/s maximum into 1600 BPI, 75 IPS tape drives.
2) 600 kbytes/s maximum throughput on the CAMAC branch highway.
3) 750 kbytes/s at a maximum event rate of 3 kHz determined by the front-end data acquisition electronics.

In the near future, we plan to install 6250 BPI, 75 IPS tape drives which should move the maximum spooling rate close to the limit imposed by the branch highway. Changes to the front-end hardware will increase the event rate capability by at least a factor of 2.

One 3-day experiment easily managed to generate 300 tapes, and the advent of 6250 BPI drives will scarcely reduce that rate of generating tapes.

Real-time preprocessing at these data rates is presently out of the question. The basic processing described in the previous sections has been done on a fairly competent minicomputer, and the data rate achieved was of the order 10 kbytes/s or less. This is too great a price to pay currently, and piles of tapes loom in our immediate future.

One must not become too gloomy. Many, perhaps a majority, of the currently planned experiments will have quite manageable data rates and will generate a tape an hour rather than the 8 per hour of the "worst" experiments.

VII. Conclusions

The Spin Spectrometer is a device which is conceptually straightforward but in practice can be almost overwhelming. The load that this device places upon the support computers, both for data acquisition and for processing, is enormous. Part of this is due to the choice of correcting in software for deficiencies in the hardware. But most of the burden arises from the fact that this is a device designed from the beginning to measure in enough different dimensions that computers would be required for even the simplest of its operations. Our immediate challenge is not only to develop software sufficiently fast so as to analyze some of these data in one man's lifetime but to develop also the understanding of the characteristics of the device which will allow us to understand the physics we have set out to study.

References

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