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*Design and Development of the
Associated-Particle Three-Dimensional
Imaging Technique*

*L. E. Ussery
C. L. Hollas*

Los Alamos
NATIONAL LABORATORY

Los Alamos, New Mexico 87545

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DESIGN AND DEVELOPMENT OF THE ASSOCIATED-PARTICLE THREE-DIMENSIONAL IMAGING TECHNIQUE

by
L. E. Ussery and C. L. Hollas

ABSTRACT

We describe the development of the "associated-particle" imaging technique for producing low-resolution three-dimensional images of objects. Based on the $t(d,n)^4\text{He}$ reaction, the method requires access to only one side of the object being imaged and allows for the imaging of individual chemical elements in the material under observation. Studies were performed to 1) select the appropriate components of the system, including detectors, data-acquisition electronics, and neutron source, and 2) optimize experimental methods for collection and presentation of data. This report describes some of the development steps involved and provides a description of the complete final system that was developed.

I. INTRODUCTION

The associated-particle technique is a three-dimensional, low-resolution imaging technique for determining the location and chemical composition of hidden materials such as drugs or explosives. The technique is based on the use of fast neutrons produced by accelerating deuterium ions into a tritium target. This reaction produces neutrons and alpha particles of 14.7 and 3.5 MeV energies, respectively. The two particles are correlated in space and time relative to the production site in the tritium target and this correlation is used to tag a specific fraction of the neutrons that are used for imaging. The neutrons within this "beam" defined by the detection of correlated alpha particles, interact with the nuclei of the object under interrogation and can produce gamma radiation. The measurement of the time difference between the detection of the alpha particle and the detection of the gamma radiation provides a measurement of the distance traveled by the neutron before it scattered from a nucleus in the interrogated object. The energy spectrum of the gamma rays provides a method of identifying the nuclear species that the neutron scattered from, hence the type of material within the object. A

schematic representation of the technique is shown in Fig. 1.

The associated particle imaging technique consists of several subsystems that are combined to produce the complete system. The subsystems include

1. a portable neutron generator with an internal alpha particle detector,
2. some type of gamma-ray detector or array of gamma-ray detectors,
3. data acquisition system, and
4. a computer for interfacing to the data acquisition system and for data display.

Each of these systems is discussed individually as a separate section of this report.

II. NEUTRON GENERATOR

In designing a neutron generator to be used for this technique, we considered the following requirements. First, the generator must be rugged and portable. This requirement stems from the desire to be able to take the technique to the problem. Another requirement is that the generator

Fig. 1. Schematic diagram of the associated particle assay technique.

produce sufficient flux such that it is not the limiting factor in determining data acquisition times. Lastly, we decided that the generator must be of the sealed-tube configuration in order to reduce environment, health, and safety concerns. Based on these requirements, we produced the specifications listed in Table 1 for the neutron generator.

We investigated all known domestic sources of neutron generators and chose to work with MF Physics of Colorado Springs, CO, to produce the neutron generator. This choice was made based on the experience of the engineers at MF Physics in the production of neutron generators in many configurations for a wide range of applications.

As a result of our requirements for small size and ruggedness, there was a significant effort devoted to the design and fabrication of the 160-kV high-voltage supply for the neutron generator. This work was contracted out to Bertan Associates, Inc. This company has manufactured accelerator high-voltage power supplies for many years and had adequate resources to undertake the difficult task of shrinking the standard high-voltage supply design into something that would satisfy our requirements. The result of their efforts was a gas-filled high-voltage supply that was only approximately 25% as large as the standard supply for research-grade neutron generators.

III. ALPHA PARTICLE DETECTOR

There are a variety of detector types available for the detection of alpha particles. The detectors range from simple counters to complete spectroscopic quality detectors capable of measuring a detailed pulse-height spectrum for an alpha particle source. The measurement capabilities that are most important for the associated-particle application are speed, the ability to spatially segregate the alpha particles striking the detector, and the ability to survive the manufacturing process for the production of the neutron generator.

The best candidates that satisfy all measurement requirements include scintillators (both organic and inorganic) and silicon pin diodes. In the early stages of development of the associated-particle technique, we used a detector constructed of a very thin plastic scintillator film. This type of detector is ideal in several ways. First, the material is inexpensive and can be deposited in almost any thickness. The scintillation process in the material is very fast and produces a relatively large light output for signal detection. The biggest problem with this material is that it will not survive the manufacturing process for the sealed-tube neutron generator. Plastic scintillators were useful for overall development of the technique but were dropped from consideration when the decision was made to use a sealed-tube neutron generator configuration. Two types of inorganic scintillators were evaluated. These were gallium-activated zinc oxide and silver-activated zinc sulfide.

Gallium-activated zinc oxide ($\text{ZnO}(\text{Ga})$) is ideal for high-counting-rate applications with a subnanosecond rise time and a decay constant of ~ 1.5 ns. Its light output is approximately equivalent to plastic scintillators. It also has a high melting point of 1975°C , making it ideal for including in a sealed-tube neutron generator configuration. We were able to obtain ~ 50 g of powder that was used to fabricate some thin scintillators for evaluation. In order to obtain the thin detectors that we required, we worked with the Polymers & Coatings Group (MST-7) in the Materials Science and Technology Division of LANL to develop a method of spraying the material onto a quartz glass window. As the coating process was being developed it was noted

that the particle size of the scintillator material varied over a very wide range and most of the material was sufficiently large to prohibit it from being used in the spraying process to apply thin layers. The MST-7 personnel made the decision to grind the material to produce a more uniform particle size and in the process destroyed the scintillator properties of the material. We did not know until after this process that we had the only commercially available material to be found anywhere. As a result of the destruction of the scintillator material we were forced to pursue silver-activated zinc sulfide as our scintillator of choice for the alpha particle detector.

Table 1. Specifications for portable neutron generator for the associated-particle imaging technique.

1. The (d,t) neutron generator shall be capable of producing a total neutron flux of 10^9 14-MeV neutrons per second during routine operation.
2. The generator shall be of a sealed-tube configuration.
3. The generator shall be capable of a total output in excess of 10^8 14-MeV neutrons per second after operating for 800 hours at a total production rate of 10^8 neutrons per second.
4. The accelerator shall be capable of producing an accelerating voltage of 160 kV.
5. The generator shall produce a beam spot at the tritium target not to exceed 3 mm in diameter.
6. The generator shall consist of a continuous duty cycle unit (100% dc).
7. The tritium target shall be mounted at 45 degrees relative to the incoming beam direction.
8. The sealed tube shall accommodate an alpha particle detector as specified by and provided by the group NIS-6 at Los Alamos National Laboratory (LANL).
9. The generator shall operate with the axis between the beam spot and the center of the alpha particle detector in a horizontal plane.
10. The generator assembly shall incorporate the necessary cooling capability to allow for continuous operation of periods up to 0.5 hour at full output.
11. The cooling system shall incorporate a "system shutdown" interlock that halts operation in the event of a cooling failure.
12. The entire generator assembly shall be sufficiently rugged to allow for the deployment of the unit for field measurements.
13. NIS-6 personnel shall be allowed to monitor milestone completion and performance test results, on site, at regular intervals, during the entire design and fabrication process.
14. Vendor shall provide complete documentation of operating parameters, procedures, and drawings.

Silver-activated zinc sulfide ($\text{ZnS}(\text{Ag})$) is not as good for very high-counting-rate applications as $\text{ZnO}(\text{Ga})$ because of its relative long decay constant of ~ 70 ns. However, for our use this would still be fast enough for the expected counting rates. This scintillator also produces ~ 3.3 times as much light as the $\text{ZnO}(\text{Ga})$. One must exercise caution when depositing a layer of the material, however, in order to avoid self-attenuation losses in the detector itself. We were able to obtain enough of this material to have Rexon Components, Inc., fabricate several detectors of varying thicknesses in order to evaluate the response of the material to alpha particles and optimize the light output and detection efficiency. As a result of our evaluation we chose to use a thickness of approximately 5 mg/cm^2 and had three windows plus a test window fabricated by Rexon Components.

We knew from previous experience that a large number of deuterons scatter from the tritiated target into the alpha particle detector, limiting its counting rate capabilities. In order to eliminate this problem, we found that we could cover the scintillator window with a thin layer of some metal, such as aluminum or nickel, to filter out the deuterons while allowing the alpha particles to pass through and be detected. After applying the scintillator to the glass windows, we arranged for MST-7 to apply a layer of aluminum to the scintillator window to provide this filter. These scintillator windows were tested for alpha particle response with a check source and shipped to MF Physics for incorporation into the sealed-tube neutron generator. Time constraints for the completion of the project did not permit a complete analysis of the aluminum coating on the windows and this led to a problem that severely limits the counting-rate capability of the alpha particle detector. We determined at a later time that the aluminum deposit was not as thick as requested. This discrepancy resulted in a large fraction of the scattered deuterons reaching the scintillator and producing very high rates at low neutron production rates.

The fabrication of the neutron generator tube required processing of the tube/alpha-detector

assembly at elevated temperatures under high vacuum in order to remove all impurities from the inner surfaces of the unit. The test window of scintillator and aluminum coating was used to determine the maximum safe processing temperature for this step of fabrication.

IV. GAMMA-RAY DETECTORS

A. Selection Criteria

Two principal requirements must be met by any gamma-ray detector considered for use with the associated-particle technique. First, the detector must be capable of good time resolution: not more than 2 ns and preferably 1 ns or better. The time resolution directly affects the spatial resolution that can be obtained by the technique. Second, the detector must exhibit moderately good energy resolution. The energy resolution is important for interpretation of complicated spectra and for improving signal-to-noise for weak gamma-ray peaks on a significant continuum background.

B. Time Resolution Measurements

We performed a carefully controlled series of measurements using a ^{60}Co gamma-ray source to measure the time resolution for a series of gamma-ray detector candidates that included three scintillators—sodium iodide ($\text{NaI}(\text{TI})$), bismuth germanate (BGO), and barium fluoride (BaF_2)—as well as one high-purity germanium (HPGe) semiconductor-type detector. The detectors were evaluated in a coincidence experiment where a fast plastic scintillator, BC-418, was used as the second detector of the coincidence pair. The time resolution results from these measurements are shown in Table 2. The time resolution performance result is indicated by the measured full-width-at-half-maximum (FWHM) of the recorded time peak for each coincidence measurement. The contribution of the plastic scintillator and the counting electronics was removed, leaving only the contribution from each individual gamma-ray detector candidate.

Table 2. Results of Time Resolution Measurements for Gamma-Ray Detector Candidates.

Detector Type	Detector Size (cm)	FWHM (ns)
NaI(Tl)	7.6 x 7.6	1.5
BGO	7.6 x 7.6	3.1
BaF ₂	7.6 x 7.6	0.4
HPGe	30% ^a	2.6

^a Efficiency relative to 7.6 x 7.6 cm NaI(Tl) detector at 1332.5 keV energy.

Based on these measurements and our time resolution performance requirement, we chose to evaluate only BaF₂ and NaI(Tl) scintillators. Our discussion will be focused on the evaluation and use of BaF₂ as the gamma-ray detector of choice. This material was chosen as the primary detector candidate because of its superior timing properties. When this project was begun, BaF₂ had not been in use as a gamma-ray detector material for very long and there were many unanswered questions regarding its use and its limitations. The properties and performance of NaI(Tl) are well known and will not be discussed at great length here. This material was our secondary gamma-ray detector candidate. There are situations when one will need to use a high-purity germanium detector in order to sort out the details of a very complicated energy spectrum.

C. BaF₂ Detector Characterization

Barium fluoride has been of interest as a gamma-ray detector, primarily in high-energy physics, for about 10 years. The primary interest in this scintillator stems from the fact that its light emission consists of two components. One of these components is extremely fast with a decay constant of less than 1 ns and is responsible for the excellent timing properties of the scintillator. The other component of the light emitted by the scintillator is considerably slower with a decay constant of approximately 600 ns. However, the total light output is about 16% (13% in slow component and 3% in the fast component) of that

available from NaI(Tl), which is why the achievable energy resolution is not as good as that available with NaI(Tl). One difficulty that arises when working with BaF₂ is that the light emitted by the scintillator is in the blue/ultraviolet region of the spectrum. The peak emission wavelength for the fast component of the scintillation light occurs at ~220 nm and the peak emission wavelength for the slow component occurs at ~310 nm. This means that one must use a photomultiplier tube (PMT) with a quartz window in order to collect any of the emitted light from the fast component of the scintillator.

Initially we chose to evaluate 3-in.-diam by 3-in.-long cylindrical crystals of BaF₂ scintillator and were using an EMI 9821QKB PMT (manufactured by Thorn EMI Electron Tubes, Inc.). In addition to the quartz window, this photomultiplier has the required properties of a fast rise time, short signal transit times, and significant gain. These properties are important in order to optimize both the energy and time resolution of the gamma-ray scintillator. This was the only photomultiplier in 3-in. diameter that met our performance criteria. With this configuration we were able to measure a time resolution of approximately 0.65 ns and an energy resolution of approximately 9.5% using detector assemblies fabricated for us by Rexon Components. After adding a transistor-stabilized voltage divider to the photomultiplier we were able to maintain ~2% gain stability over a very broad range of counting rates.

As the detectors aged, however, we discovered that the energy resolution became progressively worse, eventually reaching ~11.5%. After considerable study we determined that the problem was the result of instabilities in the PMTs. We were able to observe random instantaneous gain shifts of up to 30% from the PMT. We returned the detector assemblies to the manufacturer, Rexon Components, for disassembly and replacement of the PMTs. It was decided, after almost one year of effort, that the photomultipliers we had chosen could not be manufactured in a manner that would result in a stable, usable detector assembly, and we were forced to search again for a PMT that could meet our performance requirements. We found that Hamamatsu Corporation had just introduced a

new PMT, R4143, with essentially identical performance specifications, and we were able to obtain one for evaluation. At about the same time, REXON Components informed us that it had developed a method to shift the emitted light to higher wavelengths, thus possibly eliminating the need for a PMT with a quartz entry window.

As a result of our struggle with the EMI photomultiplier we decided to investigate the wavelength shifter as a potential solution to the need for a PMT with a quartz entrance window. Initially, we evaluated a 2-in.-long by 2-in.-diam BaF_2 scintillator assembly provided on loan by REXON Components. The scintillator was mounted on a Hamamatsu R1306 PMT, which was not only significantly slower but also provided much less amplification of the collected signal. With this assembly we were able to measure a time resolution of ~ 1.5 ns for the wavelength-shifted BaF_2 . Before reaching a final conclusion, we returned the assembly to REXON Components along with a fast 2-in. 9813B, EMI PMT. It is significant to note that this PMT uses a standard borosilicate entrance window instead of quartz. With the reconfigured detector assembly we were able to measure a time resolution for the wavelength-shifted BaF_2 of ~ 0.63 ns. This is somewhat worse than our earlier value of 0.4 ns but well within our requirement and did not necessitate the use of a quartz PMT. As a result of this measurement, we made a trip to the REXON Components factory in Beachwood, Ohio, and performed a detailed study of BaF_2 scintillators treated with the new wavelength shifter to determine the optimum wavelength-shifted configuration for our 3-in. detectors.

The measurements performed at the REXON factory were conducted using numerous combinations of BaF_2 crystals, with and without wavelength shifter, and using both quartz and borosilicate versions of the Hamamatsu R4143 PMT. The conclusions that we reached as a result of these measurements were

1. the best possible energy resolution degraded from our original 9.5-10% at 662 keV to ~ 10 -11% when the wavelength shifter was used and
2. the best time resolution that we could obtain for one of the 3-in. BaF_2 detectors was ~ 0.66 ns using the wavelength shifter.

Figure 2 shows the time spectrum for the best measurement using a wavelength-shifted BaF_2 crystal on a borosilicate PMT. The total time resolution is approximately 0.83 ns. When the contribution from the plastic scintillator, used as the second branch of the timing circuit, and the contribution from the timing electronics were removed, the estimated time resolution for the BaF_2 was 0.66 ns.

D. Detector Cooling Experiments

In an effort to improve the performance of our wavelength-shifted detector assemblies, we performed a series of measurements to evaluate the effect of cooling the detectors on the energy resolution. We first became aware of cooling studies with BaF_2 through a paper by Wisshak, Guber, and Käppeler¹ that reported significant improvement in the energy resolution of BaF_2 crystals with decreasing temperature. However, the measurements reported in this work were not performed on crystals that included a wavelength shifter, and it was not clear that our results would be consistent with the earlier work.

Figure 2. Time spectrum for wavelength-shifted BaF_2 scintillator mounted on a borosilicate photomultiplier tube.

The cooling experiments were performed using a model EC1x environmental chamber manufactured by Sun Electronic Systems, Inc. A BaF_2 detector assembly was placed inside a radiation shield made of lead and lithium-loaded polyethylene, and this entire configuration was placed inside the environmental chamber. A cross-section view of the radiation shield is shown in Fig. 3 to illustrate the lead and polyethylene configurations. The shield served two purposes. First, it reduced room background contribution to the energy spectrum that we measured during the cooling studies. Second, the added mass in contact with the BaF_2 crystal allowed us to control the rate of cooling in order to avoid physical damage to the crystal. The measurements were performed over a temperature range from 5 to 25°C using ^{137}Cs and ^{60}Co radiation sources. The temperature uncertainty at each measured temperature was $\pm 0.2^\circ\text{C}$. Two significant results were observed from these studies. First, the energy resolution (at 662 keV) improved from 11.2% at 25°C to 9.6% at 5°C. Second, the signal gain increased by approximately 40% as the temperature dropped from 25°C to 5°C, indicating a similar increase in light output of the crystal. These two observations are documented in Figs. 4 and 5. Figure 4 shows the improvement in energy resolution as a function of temperature, and Fig. 5 shows the change in signal gain as a function of temperature.

Figure 3. BaF_2 gamma detector radiation shield.

Figure 4. Plot of energy resolution as a function of temperature for a cooled barium fluoride detector.

Figure 5. Plot of gain change as a function of temperature for a cooled barium fluoride detector.

E. Final Detector Configuration

The final array of gamma-ray detectors consisted of nine shielded and cooled BaF_2 detector assemblies in a 3x3-in. square configuration. Each detector was housed inside a radiation shield as shown in Fig. 3. In order to cool the detectors, cooling plates were constructed by sandwiching copper tubing between aluminum cooling plates that were placed in contact with the detector shields. A NESLAB Coolflow CFT-75 refrigerated recirculator was used to circulate a mixture of ethylene glycol and distilled water through the copper tubing and cool the detectors to 6°C. (If necessary, the entire array can be reconfigured for a particular application by restacking.)

V. DATA ACQUISITION HARDWARE

A. System Requirements

The data acquisition and analysis system developed for the associated-particle imaging project is able to acquire multiple parameter data consisting of

1. a time difference,
2. a gamma-ray energy,
3. a gamma-ray detector identification, and
4. an alpha particle pixel identification.

These four parameters are stored in computer memory and then processed in near real-time to provide three-dimensional density distributions of the major elemental constituents of the object under interrogation.

When designing the data acquisition system we determined that there were two possible architectures that we might be able to use: CAMAC (Computer Automated Measurement and Control) and VMEbus (Versa Module Eurocard). Our primary requirements were

1. a high data throughput capability,
2. an ability to process many event combinations quickly for near real-time analysis and display of results,

3. the availability of commercial components, and
4. ease of system reconfiguration, if necessary.

We chose the VMEbus architecture because of its 32-bit address capability and its ability to provide parallel processing with multiple central processing units (CPUs) residing on the bus. The ease of expanding the memory and adding additional CPUs was also a consideration. It is possible to combine VMEbus with CAMAC to produce a data acquisition system similar to that developed by CERN, but we chose to keep the system simple and use only VMEbus. The front-end electronics required to process input signals for the VMEbus consist primarily of commercially available Nuclear Instrumentation Methods (NIM) electronics. Two special modules, one NIM and one VME, were designed and fabricated by NIS-6 personnel. These modules are described below.

B. Front-End Hardware

The front-end electronic hardware used in the data acquisition system is shown schematically in Fig. 6. The system primarily comprises NIM electronic modules. There are two custom electronic modules designed and fabricated by NIS-6 personnel that reduced the complexity, space, and cost requirements for the system. The electronic module type, manufacturer, model number, and number of units used in the system are tabulated in Table 3.

A limited description of an alpha pixel/gamma-ray detector data channel follows. The discussion is relevant to any combination of alpha-pixel and gamma-ray detector. A brief discussion of signal consolidation used for multiple alpha detector pixels and a full array of gamma-ray detectors is presented when necessary to clarify the data processing operation.

The fast anode signal from one pixel of the alpha-particle detector is processed by the constant-fraction discriminator (CFD) to derive a fast-logic signal. The output from the CFD is first delayed by the delay module (DM), then input to the ID and timing (IDTIM) module. The delay

Figure 6. Block diagram of signal processing electronics for a single alpha detector/gamma detector combination.

Table 3. The Front-End Electronic Modules.

ID	MFR	Model	Ch./Unit	No. of Units
LFOM	LeCroy	429A	4	1
FOM	Phillips Scientific	748	8	2
CFDM	Phillips Scientific	715	5	3
DM	EG&G- ESN	DV-8000	8	3
TAC	Tennelec	TC862	1	5
LGSM	Tennelec	TC310	2	1
SUMA	Tennelec	TC253	2	1
IDTIDM	Custom	128Y-270645	NA	1

assures that for "true" alpha-particle and gamma-ray coincidence events, the signal from the alpha-particle detector arrives at the IDTIM module later than the signal from the gamma-ray detector, thus providing the correct timing reference.

The fast anode signal from a gamma-ray detector PMT is split into two separate signals by a linear fan-out module (FOM). One branch of this signal is used to derive a fast logic signal from the constant fraction discriminator (CFD). Two outputs from the CFD are used. The first output signal is input to the IDTIM module. When the signals from both the alpha-particle and gamma-ray detectors arrive at the IDTIM module within a specified time period, typically 20 to 50 ns, the IDTIM module will provide four output signals. One of these is a logic pulse that is routed into a logic fan-out module (LFOM), which splits the signal and provides two output signals. One of the outputs is used to provide the START signal to a time-to-amplitude converter (TAC). The other output signal is used to provide a gate input to a linear gate-and-stretcher module (LGSM), which is described below. The second and third pulses from the IDTIM module, designated the ID pulses, are analog pulses with amplitudes that are unique to the particular combination of alpha-particle detector input and gamma-ray detector input that were present within the specified time window. A fourth output, a train of four pulses, is also a logic pulse that is used to trigger the VMEbus analog-to-digital converter (ADC). The second output from the gamma-ray detector CFD is delayed by a delay module (DM), and then input as the STOP signal to the TAC. The TAC output is discussed later.

The second branch of the gamma-ray detector signal from the FOM is input to one channel of the custom charge-integrating amplifier (CHGA). This module produces an amplified output that is the input to a linear gate-and-stretcher module (LGSM). A gate signal to the LGSM is used to ensure that only those gamma-ray signals associated with coincident events are allowed to pass through.

The output from the single TAC channel is summed with other TAC outputs associated with

any gamma-ray detector in the detector array through a linear sum amplifier (SUMA). This output is presented to Channel 0 of the ADC. A trigger from the IDTIM module, consisting of four signals that are separated by 5- μ s intervals, is used to initiate the digitization and storage of the TAC signal by the ADC. The conversion process requires approximately 5 μ s to complete.

The output from the LGSM is delayed to arrive at Channel 1 of the ADC 5 μ s after the TAC signal. The LGSM outputs for all gamma-ray detector channels are summed using a linear sum amplifier, as with the TAC signals. The second signal from the trigger then initiates the digitization and storage of the LGSM signal by the ADC. The result of the conversion is stored in the next buffer memory location of the ADC after the result of the TAC conversion.

The two ID pulses from the IDTIM module are input into Channels 2 and 3 of the ADC. The third and fourth in the series of trigger pulses from the IDTIM module then initiate the digitization and storage of the ID signals by the ADC. The results of these conversions are stored in the next buffer memory locations of the ADC after the result of the LGSM conversion.

The description of the event contained in the four analog signals from the TAC, the LGSM, and the two ID pulses from IDTIM module is at this stage present as four data words that are sequentially located within the buffer memory of the ADC.

C. The VMEbus Hardware

The VMEbus hardware used in the data acquisition and analysis system is comprised of commercially available VMEbus modules, except for the custom charge-integrating amplifier mentioned above in the front-end electronics hardware section. The module type, manufacturer, model number, and number of units used in the system are tabulated in Table 4.

Two central processing units (CPUs) are resident on the VMEbus. One CPU, designated VME1, is a Motorola MVME 147 CPU module,

Table 4. The VMEbus Modules.

ID	MFR	Model	No. of Units
CPU	Motorola	MVME 147	1
CP	Force	CPU-33XB	1
MEM	Micro Memory	MM-6326	1
MEM	Clearpoint	VMERAM/4M	1
ADC	Acromag	AVME9325-5	2
SCALER	LeCroy	1151N	2
CHGA	Custom	128Y-270808	1

which has a Motorola 68030 central processor running at 33 MHz. This CPU has 4 Mbytes of memory on board. VME1 also has an Ethernet port, and four RS232 ports for communication with external devices. The other CPU module, designated VME2, is a FORCE 33XB CPU module, which also has a Motorola 68030 central processor running at 33 MHz. The FORCE CPU has one megabyte of on-board memory. Two RS232 ports are available on this module. A Micro Memory 16-Mbyte memory module and a Clearpoint 4-Mbyte memory module provide additional data storage capabilities. Two Acromag AVME9325 ADC modules provide the interface between the front-end electronics and the VMEbus hardware. A LeCroy 1151N 16-channel scaler module provides counting capabilities for external signals used to monitor experimental parameters.

The AVME9325 module is a 12-bit ADC with the ability to digitize a voltage level that is present for 5 μ s and is captured in one of two sample-and-hold units. There is a memory buffer in the module that is large enough to store 64,000 two-byte data words. The capture and conversion is initiated by the arrival of a trigger signal. Sixteen analog inputs to the ADC can be scanned sequentially. Four inputs are used for this application. The 12-bit conversion of the voltage level and the storage of the result in the memory buffer are accomplished in approximately 5 μ s. The AVME9325 is operated in a buffer mode in which a flag is set to halt data acquisition after a preselected number of conversions is accomplished. VME2 is programmed such that it polls the AVME9325 each second and checks for the

condition of the "data acquisition finished" flag. When a poll finds the flag set, the events in the AVME9325 buffer memory are read by VME2 and stored in both a multidimensional data array, for on-line data analysis and presentation, and also in a list mode in the Clearpoint 4-Mbyte memory module. The list-mode data can be used for any off-line data analysis that may be required after the measurement has been completed.

D. The Charge-Integrating Amplifier

The charge-integrating amplifier that is used for this project is a modification of a unit developed, initially, for another program.² The module, designated VMEMCA, consists of three major components: the VMEMCA motherboard, 12 plug-in MCA boards, and a Mizar MZ8135 CPU board. The VMEMCA motherboard has the circuitry for interfacing the 12 plug-in MCA cards with the MZ8135 CPU board. The motherboard also contains control digital-to-analog converters (DACs) that set the gain, offset, and lower-level discriminator on each of the MCA boards, the circuitry for generating over-threshold digital outputs, and the circuitry for driving activity-indicator light-emitting diodes. Each of the 12 MCA boards is a stand-alone, self-gated, pulse-height analysis circuit that consists of a programmable gain amplifier, a lower-level discriminator, and a charge integrator. The linear output signal from each charge integrator channel is used as input into the LGSM module that was described above.

E. The Computer Workstation

The computer workstation, a Sun Microsystems IPX, is connected to the VMEbus hardware through the Ethernet port on the MVME147 CPU, VME1. The workstation provides overall control of the VMEbus hardware and provides graphical display of the data in near real-time. The workstation is also connected to a Tektronix Phaser 200i color printer that can be used to generate color-coded data output from an image.

F. Data Acquisition Software

The computer programs used by both the VMEbus CPUs and the workstation CPU are all written in the C programming language. The UNIX operating system underlies SunOS windows running on the workstation. The UNIX operating system is used for software development and for executing non-real-time applications. The VxWorks operating system from Wind River Systems Inc., is running on the two VMEbus CPUs and is used to execute real-time tasks associated with data acquisition. VxWorks provides methods to use the UNIX remote login procedure that allows for interaction between real-time and non-real-time environments. Thus, each CPU residing on the VMEbus can be logged onto and controlled directly from a window on the workstation. Alternately, each CPU on the VMEbus can be accessed directly via a terminal through one of the RS232 ports on the VME CPU. VxWorks is also a development system for the VMEbus CPUs. Within VxWorks, all of the C language programming code is developed on the workstation using the workstation's file and text editing resources. A specific programming module is tested as far as possible until specific resources residing only on the VMEbus are required. The GNU C cross compiler resident on the workstation is then used to generate an object module suitable for execution by the Motorola 68030 CPUs residing on the VMEbus. This object module is then downloaded into the target VMEbus CPUs over Ethernet. Execution of the module can then be initiated through a window on the SUN workstation that is connected to the remote CPU.

VI. DATA ANALYSIS SOFTWARE

A suite of C program modules was written to run on the two VME CPU modules to control data acquisition and to perform subsequent analysis of the data. An interactive graphics program, which was written using the SUN XGITM graphics interface package with SUN OpenWindowsTM, provided a convenient method of controlling data acquisition, analysis and display.

A. VMEbus Programs

The Force CPU-33XB CPU module, VME2, is used exclusively to control data acquisition by the AVME9325-5 ADC modules, and subsequent storage of the data in the two VMEbus memory modules, as described above. Table 5 lists the executable program codes used by VME2. Briefly, globals_xyte.o reserves global shared memory locations of variables that are accessed by the other codes. The three codes cnfg9325.o, slostpl9325.o, and init9325.o configure, control and initialize the Acromag AVME9325-5 ADC modules. The four megabyte memory module is zeroed by clrhisto4meg.o. The data residing in the two AVME9325-5 buffer memories are read and stored in multi-parameter data arrays and as a data list in the two VME memory modules by the two codes hist_xyte.o and histo_real_time.o. The lrsrwscale.o code controls, reads, and stores in

Table 5. The executable program modules loaded on the two VMEbus CPU modules.

VME1	VME2
globals_xyte.o	globals_xyte.o
mv_2p512.o	cnfg9325.o
mv_2pxy.o	slostpl9325.o
soft_match_rt.o	init9325.o
clrhisto10g.o	clrhisto4meg.o
clrhistomem.o	hist_xyte.o
replay_rt.o	histo_real_time.o
dgSVME2pxy.o	lrsrwscale.o
proj512.o	main_xyte.o
ppp.o	wrt_xyte.o
zero_16meg.o	soft_match.o
wrt_xyte.o	rpl_hist_xyte.o
rpl_hist_xyte.o	go.o
list_data_io.o	cutz.o

memory the data from the LeCroy 1151N Scaler Module. The `main_xyte.o` code controls the execution of all of the above codes and initiates the data acquisition routine. The list mode data is written to a file on the workstation by the code `wrt_xyteolist_data.o`. The code `rpl_hist_xyte.o` provides a method of reanalyzing the data stored in the list and constructs one two-parameter data array dependent upon energy and time and another two-parameter data array dependent upon the x and y position of the detected alpha particle. The energy spectra obtained from each of several barium fluoride detectors is matched in energy dispersion and offset by the code `soft_match.o` and then combined into a single-energy variable in the energy-vs-time two-parameter data array. The `go.o` code simply provides a short command to execute the `main_xyte.o` code. The code `cutz.o` provides a method to change analysis parameters used by the code `rpl_hist_xyte.o`.

The Motorola MVME 147 CPU, VME1, is used to provide data analysis and communication to the workstation. Table 5 also gives the executable program codes used by VME1. Briefly, `globals_xyte.o` reserves global shared-memory locations of variables which are accessed by the other codes. The two codes `mv_2p512.o` and `mv_2pxy.o` move two-parameter data from the 4-Mbyte memory module into the onboard memory of VME1. The energy spectra obtained from each of several barium fluoride detectors is matched in energy dispersion and offset, and then combined into a single-energy variable in the energy-vs-time two-parameter data array by the code `soft_match.o`. The two codes `clrhisto10g.o` and `clrhistomem.o` zero out the multi-parameter data arrays and the list data array. The code `replay_rt.o` provides a method in real time of reanalyzing the data stored in the list and constructs one two-parameter data array dependent upon energy and time, and another two-parameter data array dependent upon the x and y position of the detected alpha particle. The code `dgSVME2pxy.o` provides the communication with the workstation over Ethernet using "datagram" packets. The code `proj512.o` controls the execution of all of the above codes. The `ppp.o` code simply provides a short command to execute the `proj512.o` code. The code `zero_16meg.o` writes a zero to each

memory location in the 16-Mbyte memory module. The code `rpl_hist_xyte.o` provides an off-line method of reanalyzing the data stored in the list and constructs one two-parameter data array dependent upon energy and time and another two-parameter data array dependent upon the x and y position of the detected alpha particle. The code `list_data_io.o` either writes the list data to a file on the workstation or reads the list data from a file on the workstation and stores it in the list data array for use by the `rpl_hist_xyte.o` code.

B. The Workstation Programs

The SUN XGL graphics interface is used to display the data, and the SUN OpenWindows toolkits are used to provide a convenient method of user interaction. The OpenWindows toolkits provide a panel containing several labeled "buttons." A particular button can be selected by means of the computer's mouse. The selected button then causes the initiation of an associated C program.

An example of the graphics display and user interface is shown in Fig. 7, which is a print of the workstation computer screen. The data presented as a histogram represents the gamma-ray energy spectrum obtained from a hollow sphere composed of a compound containing hydrogen, oxygen, nitrogen, and carbon. The panel at the top contains the buttons that, when activated, initiate selected programs.

The x -vs- y gamma-ray intensity distribution is shown in Fig. 8. The color of the pixel is representative of the number of gamma rays associated with the x - y position of the pixel. The intensity range from high to low is represented, in descending order, by orange, yellow, green, blue, pink, and purple. The x - y distribution is made for a particular time slice corresponding to a z position through the middle of the hollow sphere. The higher intensity found in the pixels toward the right of the circle results from the location of the gamma-ray detector array near the right side of the hollow sphere.

Figure 7. A sample screen of the program's graphical user interface.

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Figure 8. x-y gamma-ray intensity distribution for one time slice through the center of a hollow sphere.

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