Lawrence Berkeley National Laboratory
Recent Work

Title
A REMOTELY-OPERATED LOW BACKGROUND GERMANIUM MULTI-DETECTOR SPECTROMETER SYSTEM

Permalink
https://escholarship.org/uc/item/7783k54s

Author
Goulding, F.S.

Publication Date
1986-05-01

eScholarship.org Powered by the California Digital Library
University of California

LBL-21542
Preprint

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Engineering Division

RECEIVED
LAWRENCE
BERKELEY LABORATORY

APR 22 1987

LIBRARY AND
DOCUMENTS SECTION

Submitted to IEEE Transactions on Nuclear Science

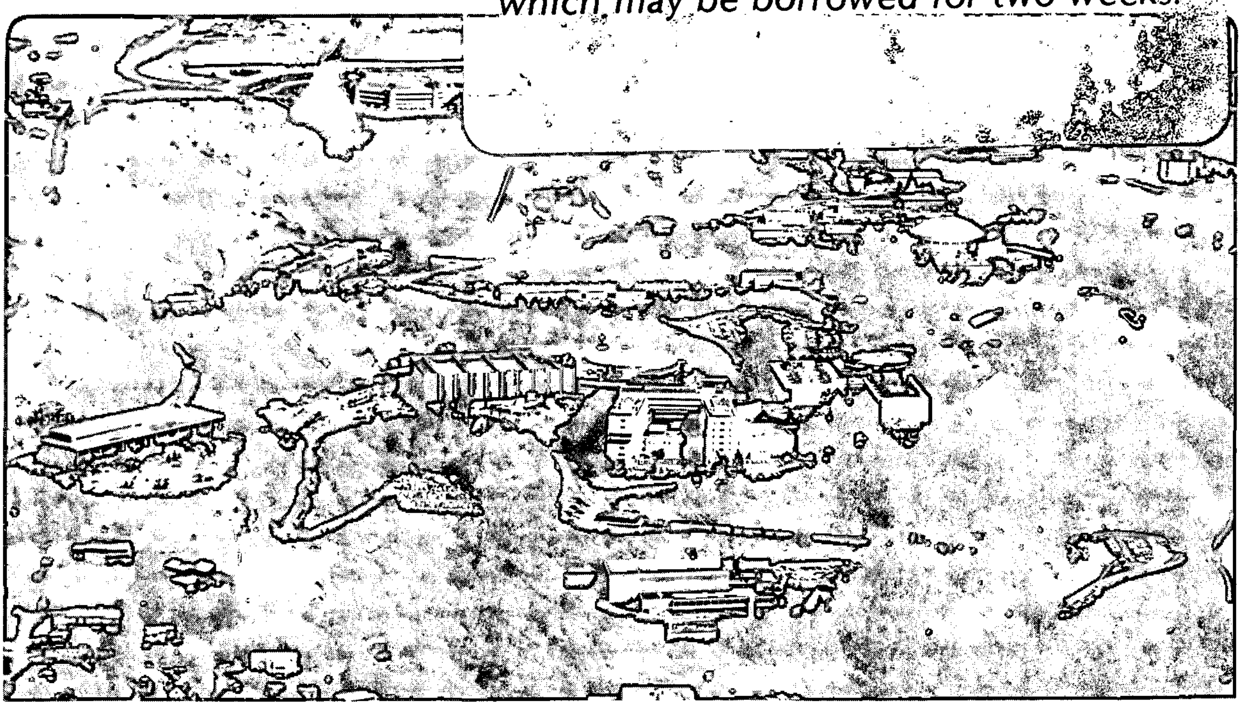
A REMOTELY-OPERATED LOW BACKGROUND GERMANIUM MULTI-DETECTOR SPECTROMETER SYSTEM

F.S. Goulding, C.A. Cork, D.A. Landis, P.N. Luke,
N.W. Madden, D.F. Malone, R.H. Pehl, A.R. Smith,
D.O. Caldwell, R.M. Eisberg, D.M. Grumm, D.L. Hale,
and M.S. Witherell

May 1986

TWO-WEEK LOAN COPY

This is a Library Circulating Copy which may be borrowed for two weeks.



LBL-21542 c.2

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

A REMOTELY-OPERATED LOW BACKGROUND GERMANIUM MULTI-DETECTOR SPECTROMETER SYSTEM LBL-21542

LOGISTICAL ASPECTS OF THE DESIGN

F.S. Goulding, C.A. Cork, D.A. Landis, P.N. Luke, N.W. Madden, D.F. Malone, R.H. Pehl, A.R. Smith
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720 U.S.A.
and
D.O. Caldwell, R.M. Eisberg, D.M. Grumm, D.L. Hale and M.S. Witherell
University of California, Santa Barbara, California 93106 U.S.A.

ABSTRACT

A system of data acquisition, data analysis, monitoring and gain stabilization used in a long-term, low background germanium double beta decay experiment is described. This system, which is essential to the remote underground operation of the spectrometer, may provide a model for similar experiments.

INTRODUCTION

In recent years there has been a substantial increase in interest in non-accelerator experiments designed to detect very rare processes. Usually these experiments consist of a complex detector array operated underground to reduce the effects of cosmic ray background. In addition, the design of the system, choice of materials, etc., are all aimed toward removing background due to natural uranium and thorium decay chains in the local environment.

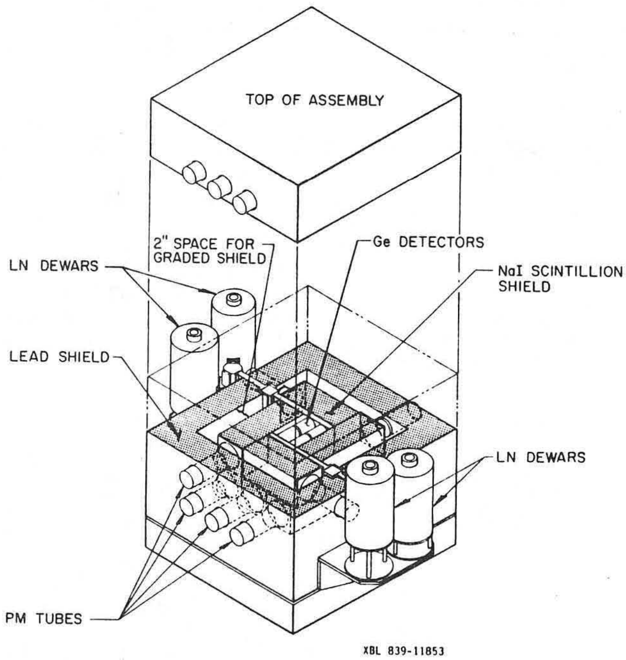
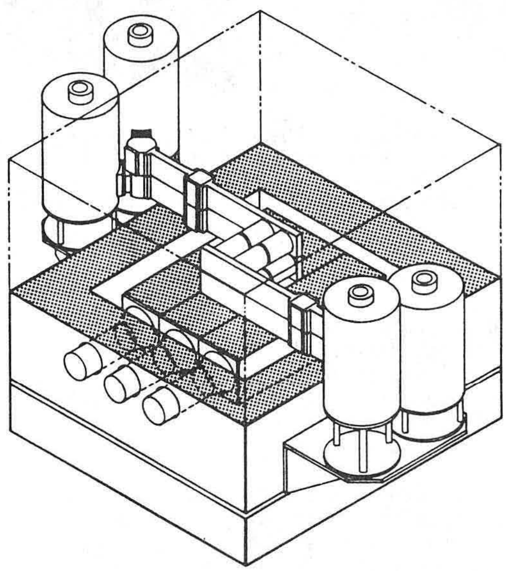


Fig. 1 Exploded view of the complete detector assembly with the upper layer raised.

We are conducting one of these experiments 700 ft under the Oroville Power Dam in Northern California. This experiment is designed to detect decays of ^{76}Ge atoms by simultaneous emission of two beta-particles (double beta decay mode) in Ge detectors; the half life limit we expect to be able to set in two years of operation approaches 10^{24} yrs which corresponds to ~0.5 disintegrations/year/kilogram of natural germanium. The detector system contains eight large volume (160 cm^3) coaxial Ge detectors (total mass 7.5 kg) surrounded by a Compton shield containing 10 very large (~6"x6"x12 to 20") NaI scintillation detectors. This detector array is enclosed in a low-activity lead shield weighing almost 15 tons. Figures 1 and 2, taken from previous papers[1,2], show the detector assembly and the photograph (Fig. 3) shows a top view of the partially assembled detector system. After 18 months of operation, no neutrinoless double beta decay events, (at a half life limit of $4x10^{23}$ yrs) have been observed. While continuing the double beta decay experiment we intend to use the same system, suitably augmented, to look for events caused by collisions in the detectors of WIMPS (weakly interacting massive particles) postulated to be contained in the universe's dark matter through which we travel at high velocity.



XBL 839-11852

Fig. 2 Exploded view of the lower layers of detectors.

In common with all similar experiments, we must face the problem of background removal and of very careful labeling of individual events to permit detailed and critical study of candidate events by the scientific community if such events are observed. Furthermore, the experiment is operated remotely from our laboratory and unattended operation for prolonged periods is essential. These factors have resulted in the approach to the experiment and equipment design discussed in this paper.

One special feature of experiments using Ge detectors is the need to provide liquid nitrogen to cool the detectors. The procedure used in our case is to use four cryostats (3 liters) - one for each dual-detector system. Associated with each system is a backup 50 liter supply dewar and an automatic monitoring and transfer system that replenishes each local 3 liter cryostat about every 20 hrs (under command of a computer that monitors liquid nitrogen levels as well as many other parameters on an hourly basis). Visits are made to the Oroville site every 10 days or so to collect the latest data tapes and to refill the 50 liter supply dewars. The liquid nitrogen monitoring and transfer system was described in an earlier paper[3].

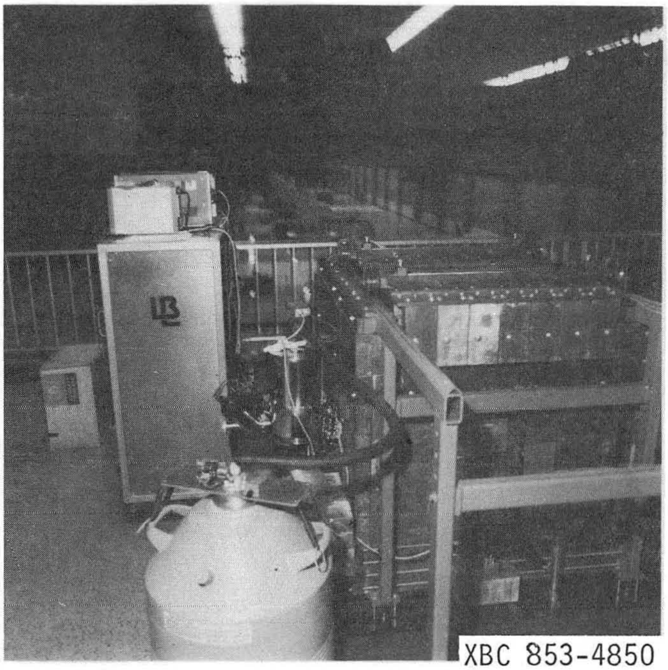


Fig. 3 Photograph of the detector assembly in its shield with the associated electronics in the power room of the Oroville Power Dam. The exciters for the turbine generators are in the background.

Another important feature of the system is the provision of non-interruptable power. In initial tests we were surprised to find that power is interrupted often for short periods of time in this location despite (or because of) its proximity to the hydro-electric source. A battery-operated 1800 watt non-interruptable power supply capable of handling 30 min of full system operation is used to overcome this problem.

The detector system itself was also fully described earlier[1,2] and the interested reader is referred to these papers. Results have been presented in other papers[4,5]. The focus here will be on the data acquisition and system monitoring equipment and on the remote processing of the data.

THE DATA ACQUISITION SYSTEM

Figure 4 is a diagram of the data acquisition and monitoring system employed in the experiment. Also shown in this figure is the non-interruptable power supply, the liquid nitrogen supply system and the redundant system of ion pump power supplies with battery backup.

The data acquisition system performs the following functions:

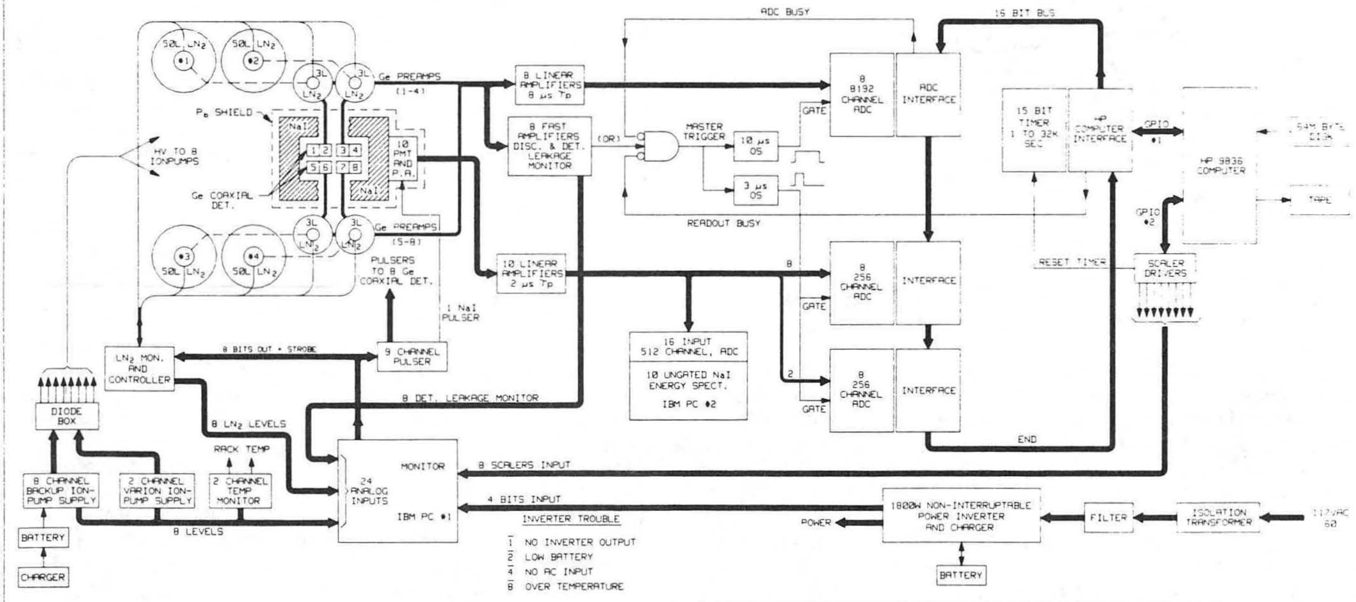
a) Eight preamplifiers and linear amplifiers are used to process the Ge detector signals. Because good resolution at high energies (where the ballistic deficit is an important contributor) is required, and the low counting rates permit long shaping times, a Gaussian pulse shape peaking in 8 µs is employed.

b) Signals from the preamplifier outputs also feed fast amplifiers (0.5 µs integration and differentiation) and discriminators to develop a master trigger for the data acquisition system when any Ge detector finds an event above a threshold of ~40 keV. No data is recorded by the main data acquisition system unless this condition is met. An auxiliary monitoring system containing IBM PC #2 is used to check the operation of the NaI detectors without requiring signals from Ge detectors.

c) The germanium signals feed 13-bit (8192 channels) ADC's that are gated on by a 10 µs waveform generated from the master trigger.

d) The 10 NaI detector photomultiplier output signals are amplified and shaped (2 µs peaking Gaussian) by linear amplifiers and the outputs from these amplifiers feed 8-bit ADC's operating on the large scale digitizer principle (i.e., a common-ramp multiple-channel Wilkinson-type ADC). Each ADC contains 8 channels and the units can be cascaded.

e) Interface units associated with the Ge 13-bit ADC block and the NaI ADC's provide for sequential scanning of the data and feeding a stream of 16-bit words characterizing each event into a GPIO interface on an HP9836 computer.

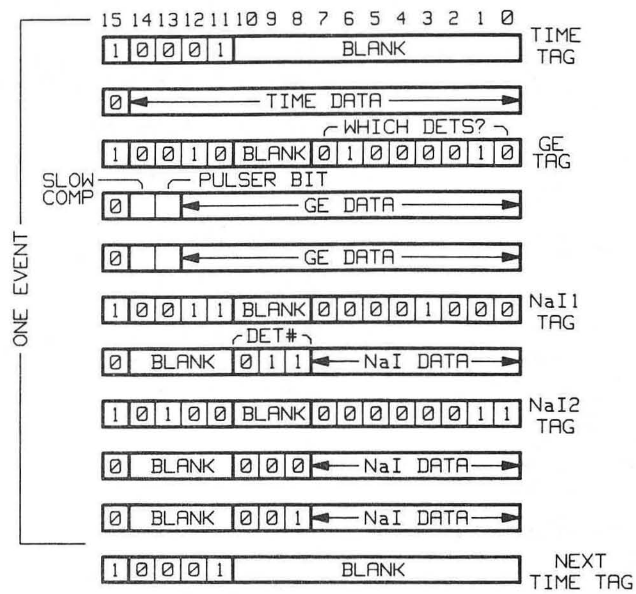


XBL 8612-3897

Fig. 4 Block diagram of the detector assembly, processing electronics, monitoring and data acquisition systems.

f) The main purpose of the HP9836 computer is to buffer event by event data in a 20,000 byte memory buffer, then to transfer the data to a 64 Mbyte hard disk associated with the computer. These transfers occur about every 2 hrs. Certain histograms are also generated by the computer to permit an immediate check on the validity of data as needed. A streamer tape unit associated with the HP9836 computer is used to record the data from the disk. This tape is taken to the laboratory at the end of each 10-day run.

g) A timer with 1 second resolution is provided and the time since 00.00 hrs, 1/1/85, is recorded as part of the data stream with each event.



XBL 8610-3896

Fig. 5 Showing the recorded data format for events. A condition on recording an event is that at least one Ge detector must register a signal.

Event data is recorded in the format shown in Fig. 5. Each event consists of a set of 16-bit words with the most significant bit (#15) indicating whether the word is an identifying tag word or real data. In tag words, the value of bits #11-14 indicate the type of tag (#1 = time data, #2 = Ge detector data, #3 = first group of eight NaI detectors, #4 = second group of NaI detector data). In each case, the tag word is followed by a series of data words presenting the data associated with the tag. For example,

a) The time tag word is followed by a 15-bit number containing the time data for the event.
b) Each of the last 8 bits of the NaI and Ge tag words indicate which detectors contain data.
c) Ge detector data words contain the ADC data (last 13 bits), an indicator bit #13 showing whether the data refers to a reference pulser pulse (see next section) and another indicater bit #14 showing whether the signal has a slow component. The slow component indicator is not used at the present time, but is available for use in the future.
d) NaI detector data is structured similarly to the Ge detector data but only bits #0-7 are employed to represent ADC data. Bits #8-10 provide a (redundant) indication of the NaI detector ID#.

THE MONITORING SYSTEM

The traditional method of carrying out a remote long-term experiment involves the use of graduate students located at the experiment site. The ready availability of personal computers and modems makes it possible to monitor an experiment remotely with less frustration for all concerned. Therefore, the decision was made to provide a complete remote monitoring system for this experiment.

Elements of the monitoring system are shown in Fig. 4. An IBM PC located at the experiment reads monitoring information from these elements hourly and automatically transmits twice daily, sending the monitoring data to another IBM PC at LBL. If the telephone transmission fails (a rare occurence), the computer at the experiment automatically dials again each hour until a successful transmission is made. Validity of the received data is checked and if errors are detected, the data is retransmitted. The system is also protected from interference by casual telephone callers - a problem that has proved important in our experience.

Printout of the monitoring data can be initiated at any time at LBL. A typical output is shown in Fig. 6; this will be used in the following discussion of the monitoring system. The following analog parameters are monitored directly:

a) Liquid nitrogen levels in the four 50 liter supply dewars.
b) Liquid nitrogen levels in the four (~3 liter) cryostats associated with each dual-detector system.
c) The ion pump power supply currents. Each of the four detector systems is equipped with a pair of ion pumps (A & B) to provide redundancy; while one power supply is used to power the "A" pumps, a separate one is used to supply the "B" pumps. Failure of a power supply or single ion pump will cause no damage to a system, but measuring the supply currents ensures that we receive immediate notice of the problem. Incidentally, a deviation of any monitored parameter outside preset limits initiates hourly transmission of data to LBL instead of the normal twice daily transmission.
d) Failure of power would result in both ion pump power supplies being shut down. Consequently, eight back-up battery power supplies are provided. The output voltages of these supplies are monitored hourly to ensure their availability at all times.
e) The DC level at the output of all preamplifiers is monitored to provide an indication of any changes in detector leakage currents.
f) Temperatures in the two equipment racks are monitored to check the operation of ventilation fans.

All of the forementioned parameters are fed to a 24-channel 8-bit ADC board in IBM PC #1 used for monitoring. Digital inputs and outputs (under program control) are also used as follows:

a) One set of outputs triggers the liquid nitrogen filling system when the level in any cryostat falls below a preset level defined in the program.
b) A standard amplitude pulser (nine channels) is triggered by another set of outputs from monitoring PC #1. One channel (#9) feeds all the NaI detectors (at the same time as Ge detector #4) while the remaining channels feed the eight Ge detectors.

In normal operation, the pulser sequence is triggered once per minute with 1 second delay between the germanium detectors (i.e., Ge #1 → 1 s → Ge #2 → 1 s → Ge #3 → etc.). Each pulser output drives through its germanium detector capacitance into the preamplifier, then through the whole pulse processing system being treated in exactly the same way as real detector signals.

```
First record#:  108
---------------------------------------------------------------------------------------------------------------------------------------
Hr|    Dewars   | Cryostats  | I/P PS| I/P PS Backup |              Preamp Offset Volts                  |   |   |   |      Scaler             |Pls|Power
  |    Liters   |  %Full     | MicAmp|      KV       |     (Divide by 10^10 for Current)                 |   |   |   |      Counts             |Cts|Status
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

   Date: 09-13-1986
00 47 42 41 42 91 87 88 87 369 310 2.5 2.6 2.6 2.5 1.78 1.78 1.65 1.78 1.12 1.47 1.33 2.29  64  77  0  0  0  0  0  0  0  0 60 15
01 47 42 41 42 87 84 85 84 369 306 2.5 2.6 2.6 2.5 1.78 1.76 1.63 1.78 1.12 1.47 1.33 2.29  64  76120117117118  0  1117117 60 15
02 47 42 41 42 84 80 81 81 369 302 2.5 2.6 2.6 2.5 1.78 1.76 1.63 1.78 1.12 1.47 1.33 2.29  64  76  0  0  0  0  0  0  0  0 60 15
03 47 42 41 42 80 77 78 77 365 298 2.5 2.6 2.6 2.5 1.78 1.78 1.65 1.78 1.12 1.45 1.33 2.31  64  76116114114114  0  1115115 60 15
04 47 42 41 42 76 73 74 74 369 302 2.5 2.6 2.6 2.5 1.76 1.76 1.63 1.78 1.12 1.47 1.31 2.29  64  75  0  0  0  0  0  0  0  0 60 15
05 47 42 41 42 73 70 71 71 369 310 2.5 2.6 2.6 2.5 1.76 1.76 1.63 1.78 1.10 1.47 1.31 2.29  63  75118115115116  0  1115115 59 15
06 47 42 41 42 69 66 67 67 369 306 2.5 2.6 2.6 2.5 1.76 1.76 1.63 1.78 1.10 1.45 1.31 2.29  63  75  0  0  0  0  0  0  0  0 60 15
07 47 42 41 42 65 62 64 64 369 310 2.5 2.6 2.6 2.5 1.76 1.76 1.63 1.76 1.10 1.47 1.29 2.29  64  74118115115116  0  1115115 60 15
08 47 42 41 42 62 59 60 61 369 302 2.5 2.6 2.6 2.5 1.75 1.75 1.61 1.76 1.10 1.47 1.27 2.31  65  75  0  0  0  0  0  0  0  0 60 15
09 47 42 41 42 58 56 57 57 369 310 2.5 2.6 2.6 2.5 1.75 1.75 1.63 1.76 1.10 1.47 1.25 2.31  65  75121117117117  0  1117118 60 15
10 47 42 41 42 55 52 54 54 369 298 2.5 2.6 2.6 2.5 1.73 1.73 1.61 1.75 1.10 1.47 1.25 2.29  66  74  0  0  0  0  0  0  0  0 60 15
11 47 42 41 42 51 49 51 51 369 310 2.5 2.6 2.6 2.5 1.73 1.73 1.63 1.73 1.10 1.47 1.24 2.29  66  75121118119119  0  1118118 60 15
12 47 42 41 42 48 45 47 47 369 306 2.5 2.6 2.6 2.5 1.73 1.73 1.61 1.73 1.10 1.47 1.24 2.29  66  75  0  0  0  0  0  0  0  0 60 15
13 47 42 41 42 44 42 44 44 369 294 2.5 2.6 2.6 2.5 1.71 1.71 1.63 1.73 1.10 1.47 1.22 2.27  66  75120117117117  0  1117117 60 15
14 47 42 41 42 41 38 40 41 373 302 2.5 2.6 2.6 2.5 1.71 1.71 1.59 1.71 1.10 1.47 1.22 2.29  66  76  0  0  0  0  0  0  0  0 60 15
   ***** LN FILL NOW *****
15 44 40 38 39 95 91 92 91 369 294 2.5 2.6 2.6 2.5 1.71 1.71 1.61 1.71 1.10 1.47 1.20 2.29  66  76118119119119  0  1119119 60 15
16 44 40 38 39 91 88 89 88 369 294 2.5 2.6 2.6 2.5 1.69 1.71 1.61 1.71 1.10 1.45 1.18 2.29  66  76  0  0  0  0  0  0  0  0 60 15
17 44 40 38 39 88 84 85 84 369 294 2.5 2.6 2.6 2.5 1.69 1.67 1.59 1.69 1.10 1.47 1.18 2.29  66  75115113113113  0  1113113 59 15
18 43 40 38 39 84 81 82 81 369 310 2.5 2.6 2.6 2.5 1.69 1.67 1.57 1.69 1.08 1.47 1.16 2.31  66  76  0  0  0  0  0  0  0  0 60 15
19 44 40 38 39 81 77 78 78 369 290 2.5 2.6 2.6 2.5 1.67 1.67 1.59 1.69 1.10 1.47 1.16 2.31  64  76118115114114  0  1115115 60 15
20 44 40 38 39 77 73 75 74 369 306 2.5 2.6 2.6 2.5 1.67 1.67 1.59 1.67 1.08 1.47 1.16 2.29  64  75115112113113  0  1112112 60 15
21 43 40 38 39 73 70 71 71 369 294 2.5 2.6 2.6 2.5 1.67 1.67 1.59 1.67 1.10 1.47 1.14 2.29  65  75  0  0  0  0  0  0  0  0 60 15
22 43 40 38 39 70 67 67 67 369 306 2.5 2.6 2.6 2.5 1.67 1.65 1.57 1.67 1.08 1.47 1.14 2.29  66  74119118118118  0  1118118 60 15
23 44 40 38 39 66 63 64 64 369 298 2.5 2.6 2.6 2.5 1.65 1.65 1.57 1.65 1.08 1.47 1.12 2.29  63  75  0  0  0  0  0  0  0  0 60 15

---------------------------------------------------------------------------------------------------------------------------------------
Hr:    Dewars   | Cryostats  | I/P PS: I/P PS Backup :              Preamp Offset Volts                  :   :   :      Scaler             :Pls:Power
  :    Liters   :  %Full     | MicAmp:      KV       :     (Divide by 10^10 for Current)                 !   :   !      Counts             !Cts:Status
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

   Date: 09-14-1986
00 43 40 38 39 62 59 61 61 369 298 2.5 2.6 2.6 2.5 1.65 1.65 1.57 1.65 1.08 1.47 1.12 2.29  63  74118117117117  0  1117117 60 15
01 43 40 38 39 59 56 57 58 369 306 2.6 2.6 2.6 2.5 1.65 1.65 1.57 1.65 1.08 1.45 1.10 2.29  63  74  0  0  0  0  0  0  0  0 60 15
02 43 40 38 39 55 52 54 55 369 306 2.6 2.6 2.6 2.5 1.65 1.65 1.57 1.65 1.08 1.47 1.10 2.29  62  74118117117117  0  1117117 60 15
03 43 40 38 38 52 49 51 51 369 298 2.5 2.6 2.6 2.5 1.63 1.65 1.57 1.63 1.08 1.47 1.08 2.31  62  74  0  0  0  0  0  0  0  0 60 15
04 43 40 38 38 48 45 47 48 369 294 2.5 2.6 2.6 2.5 1.63 1.63 1.55 1.63 1.08 1.47 1.06 2.27  62  73120117117117  0  1117117 60 15
05 43 40 38 38 45 42 44 44 369 294 2.5 2.6 2.6 2.5 1.63 1.63 1.55 1.63 1.08 1.47 1.06 2.29  62  73  0  0  0  0  0  0  0  0 59 15
06 43 40 38 38 41 38 41 41 369 298 2.5 2.6 2.6 2.5 1.61 1.61 1.55 1.61 1.08 1.47 1.04 2.29  62  73113112112112  0  1112112 60 15
   ***** LN FILL NOW *****
07 40 37 35 35 95 92 92 91 369 298 2.6 2.6 2.6 2.5 1.61 1.61 1.55 1.61 1.08 1.47 1.04 2.29  62  73  0  0  0  0  0  0  0  0 60 15
08 40 37 35 35 92 88 89 88 365 286 2.5 2.6 2.6 2.5 1.59 1.61 1.53 1.59 1.08 1.47 1.02 2.29  62  73118115115115  0  1115115 60 15
09 40 37 35 35 88 85 85 85 369 302 2.6 2.6 2.6 2.5 1.59 1.59 1.53 1.59 1.08 1.45 1.00 2.29  62  73  0  0  0  0  0  0  0  0 60 15
---------------------------------------------------------------------------------------------------------------------------------------
 |<- BACK-UP -->|<-CRYOSTATS->|<-- ION ->|<--- CHECK ON --->|<------------ PREAMP DC OUTPUT ------------>| RACK |<---- CHECK OF PULSER ---->|  |
 |   SUPPLY     |   % FULL    |  PUMP    |   ION PUMP       |      (DET LEAKAGE INDICATOR)              | TEMP |     COUNTS THROUGH         |  |
 |   DEWARS     |             | CURRENT  |   BACK-UP        |                                           |      |        SYSTEM              |^ |^
   (liters)                                  SUPPLY                                                                  PULSER INPUTS/HR---'  |
                                                                                                          NON-INTERRUPTABLE PS STATUS-------'
```

Fig. 6 An example of the monitoring data received twice daily by automatic transmission to LBL (Berkeley).

The resulting stored pulser events are used for gain stabilization purposes as described in the following section. In addition, the pulser counts are used as part of the monitoring system to check that the full counting chain (including the data acquisition computer) is working correctly. To accomplish this result, each time a memory buffer is dumped onto the disk, the pulser events are read back from the disk and are sent as a train of pulses to eight scalers (one for each detector) included in the monitoring PC #1. The PC monitoring program reads these scalers each hour and resets the scaler. The numbers in columns 25-32 are used to check this operation. Figure 16, to be discussed in the next section shows the pulser sequence interleaved with normal gamma-ray counts.

c) The 4-bit input in the interface board in PC #1 is used to check the status of the non-interruptable power supply. Not shown in Fig. 4 is a separate non-interruptable supply used to power the monitoring PC #1. This is provided so that monitoring and transmission of data to LBL continues even in a total power failure condition.

OFF-LINE DATA REDUCTION

Data tapes from the experiment are dispatched about every 10 days to LBL (Berkeley) and UCSB (Santa Barbara). Data is reduced and analyzed in parallel at both sites using two different computers to make sure that any results are independently checked at two places. Only the data reduction system at LBL will be described here because the functions performed at the two places are essentially the same.

The data is initially transferred from the HP9836 data tapes into an IBM PC equipped with two 10 Mbyte Bernoulli disks, one of which is used to store programs and final histogram data while the other stores event by event data transcribed directly from the original HP9836 data tapes. A single 10 Mbyte disk can hold about 30 days of the original eight-detector data. This illustrates the value of high-capacity removable disks in experiments where data volumes can become very large. At the moment, 18 months of data (initially four detectors, most recently eight detectors) are contained on 12 10 Mbyte disks.

The data analysis and reduction programs perform a number of functions:

a) Calibration of the data and attaching the calibration information to the data records. Programs used in this operation include:
   1) SORT: This is the initial sorting program. It simultaneously sorts all the data for Ge detectors in a 600 keV range generating raw histograms of the data. Sorts are performed for the ranges 40-640 keV and 1400-2000 keV, chosen to contain the 352 keV peak of ^{214}Pb, the 1461 keV peak of ^{40}K and the pulser peak located approx at channel 1910. (Note that the energy scale used is ~1 keV/channel.) These two sorts are performed in ~45 min on a typical 10-day run.
   2) CENTROID: Determines the centroid of the 3 peaks mentioned in the previous paragraph (for each detector).
   3) CALC: Using the information from CENTROID, this fits a linear energy scale to the ^{214}Pb and ^{40}K lines, thus deriving the zero and energy scale and also the equivalent pulser energy for each detector averaged for the whole 10-day run.
   4) CAL: This processes the data records and calculates the energy scale specific to each record

using the pulser peak position measured for this record and the previously derived equivalent pulser energy. This procedure is used because gamma-ray peaks in a single record contain very few counts and only the pulser peak has enough counts to provide adequate statistics to be used for gain stabilization. CAL attaches calibration data to each record. This data is used by later programs to correct the spectral data precisely to a 1 keV/channel scale with zero energy offset.

The operations performed by these four programs are normally carried out for an entire 10-day run and the assumption is made that the pulser itself is stable during a run (a run might contain 100-300 records) so the pulser peak position reflects gain charges in the system. We have observed only minute zero changes, so no correction is needed for zero drift. The pulser stability appears to be ~.01% during a 10-day run.

b) A single program AUTO automatically sequentially sorts 600 keV intervals (from 40-4240 keV) and generates histograms with gain corrections made for each record using the gain data provided by CAL. If the run number is nn, this generates a file, PHAnn.dta, containing energy corrected histograms for all Ge detectors. AUTO requires about 3 hrs to generate fully gain-stabilized histograms on an 8-detector 10-day run. A program OUTPUT combines histograms from any selected number of runs and allows plotting or printing of the resulting spectra for any detector or all detectors summed. This process is completed in a minute or two.

c) In view of the importance that may be placed on a single event it is essential for us to be able to select and study single events in detail. Two programs quickly accomplish this:
   1) EVENTS: Allows scanning of selected records and listing of all events where an energy within a selected range is deposited in a Ge detector. The signals in any or all detectors and their time of occurrence are listed.
   2) HISTORY: Allows printout of a selected number of events and their time of occurrence preceeding a single event that the experimenter selects in the output of EVENTS.

A common use of these programs is to use EVENTS to print out all events where a Ge detector has a 2000-2099 keV signal (range of interest near the 2.041 MeV energy of double beta decay), then to select certain events, using HISTORY to look for any correlation with events immediately preceeding the ones of interest. In this way, suspicious "burst" events could be eliminated. In fact, no such cases have been detected in our work. The ability to rapidly access and study single events and their environment in a data set accumulated over 18 months is a unique aspect of this experiment.

d) A program CAT allows the display of the complete catalog of data on all runs. This data is generated and updated when AUTO runs.

Typical results from these data analysis programs are shown in Figs. 7-16. Figure 7 shows the complete catalog of runs carried out from February 1985 to June 1986. For the remaining figures we have selected Runs #1-44. Figure 8 shows a printout of the summed histogram for all detectors over this 15 month period for the energy range 40-640 keV. Actually, the counts given in each bin are 10 times the actual count accumulated; this is an artifact of the gain compensation which interpolates between channels with an accuracy of 0.1 channel. Figure 9 shows a plot, for detector #4 alone, of the spectrum (40-640 keV), while Figs. 10-14 show the summed spectra for all detectors from 40-3040 keV. The success of the gain stabilization program is illustrated by the observation that the energy resolution at 2.6 MeV is ~3.2 keV; note - this is for all detectors added together for 15 months of operation. This result is as good as we normally obtain in our laboratory for an overnight run with a single detector.

Run#	Data Disk#	--------Data Disk-------- 1st Rec#	Last Rec#	No of Dets	Hours
4	1	343	428	4	144
3	1	259	342	4	138
2	1	175	258	4	128
1	1	1	174	4	244
5	1	429	520	4	144
7	1	529	624	4	142
8	1	625	742	4	166
9	1	745	830	4	120
10	2	1	102	4	140
11	2	103	172	4	99
12	2	173	292	4	169
13	2	295	400	4	144
14	2	401	502	4	140
17	3	1	153	4	213
18	3	154	312	4	220
16	2	603	720	4	160
15	2	503	602	4	134
19	3	313	473	4	220
20	3	474	614	4	194
21	3	615	769	4	215
24	4	264	332	4	91
22	4	1	139	4	190
23	4	139	263	4	172
26	4	333	456	6	141
28	4	457	591	6	163
29	5	1	141	6	162
30	5	142	342	6	231
31	5	343	507	6	190
32	5	508	646	6	159
33	5	647	827	6	209
34	6	1	222	6	257
35	6	223	448	6	259
36	6	449	673	6	259
37	7	1	203	6	234
38	7	204	409	6	239
39	7	410	608	6	232
40	7	609	829	6	250
41	8	1	321	6	376
42	8	322	486	6	192
43	8	487	685	6	232
44	8	686	830	6	170
27	9	1	139	6	157
45	9	140	299	8	149
46	9	300	546	8	232
47	9	547	740	8	185
49	10	183	351	8	162
52	11	1	215	8	208
53	11	216	427	8	205
51	10	465	688	8	216
50	10	352	457	8	102
54	11	428	600	8	167
55	11	601	765	8	161
56	12	1	195	8	188
57	12	196	366	8	163

Fig. 7 A table of information on all runs since the experiment started in February, 1985. This is the output of the program CAT.

Figure 15 shows a partial list of events from data disk #8, records #1-34, where a Ge detector absorbs between 2000-2099 keV. Candidate events for double beta decay of ^{76}Ge must occur in a single detector and produce a 2.041 MeV signal (±2 keV). No event in this figure satisfies these criteria. The event in detector #4 at Record #16, position 5047 was selected for examination of the 25 events preceeding it (using HISTORY). Figure 16 shows the result. We see that the event prior to the selected one occurred 4 seconds before it and resulted in a 1.131 MeV deposit in Ge detector #1 and a small energy deposit in NaI detector #7. Note that HISTORY operates on the raw original data (not energy corrected) whereas EVENT corrects the energy scale. This accounts for the apparent slight energy difference in the selected event in detector #4.

CONCLUSION

As shown by the results given in the previous section, we have demonstrated that high-resolution multi-detector spectroscopy can be carried out reliably for very long periods of time. The remote monitoring system has given us confidence in the operation of the experiment at all times and, on occasion, has indicated the need to travel to the remote site to correct potential problems. In 18 months of operation of 6 detectors, only 16 hrs of data was lost and that was in a single incident following the installation of new (faulty) equipment. This is testimony to the reliability of the system and to the value of redundancy in certain parts of the design.

Runs: 1-44 Det# All (Counts x 10)

E = 40	15784	16860	18091	18180	18612	20045	24859	31396	32086	28101
E = 50	25718	24832	24537	25293	25910	25470	25806	25434	25859	25051
E = 60	25681	26459	25459	27365	27452	27996	27421	27898	27469	25800
E = 70	25454	24982	25386	26513	27533	29033	30349	31440	29442	26507
E = 80	24601	25027	24209	24972	27079	26566	25886	26022	26600	24859
E = 90	24760	26026	29068	33681	31561	25278	22195	21473	21464	21225
E = 100	20301	20308	19823	20166	20041	20097	19750	19757	20505	19887
E = 110	19756	19905	20005	20225	19886	19140	19134	19122	19652	18909
E = 120	19091	22739	28153	27237	20855	18824	18262	17906	17309	17495
E = 130	17469	17728	17782	17912	17200	17396	18590	19987	19098	17834
E = 140	17547	17513	19583	24771	29130	23784	17600	15893	16613	16186
E = 150	16493	16233	15651	15687	16185	16292	15681	15752	15733	15653
E = 160	15670	15004	15483	15485	15954	14800	14817	14390	14598	14321
E = 170	14111	13834	13662	14096	14765	14589	15013	14133	13918	13701
E = 180	13307	13395	13612	13456	15252	21874	30371	23354	15550	12340
E = 190	12258	12510	12195	11579	11956	11976	12127	11985	12303	12420
E = 200	11703	11742	11314	11511	11357	12369	12291	11292	10595	11171
E = 210	11510	11640	11122	10512	10592	10564	10458	10865	10688	10553
E = 220	10242	10595	10246	10341	10328	10263	10242	9852	9764	10099
E = 230	9672	10071	10158	9382	10510	10948	12157	13402	19253	23195
E = 240	16813	15685	19453	15261	10077	8376	8459	8559	8121	8329
E = 250	8445	7929	8486	7961	8238	8515	8750	9227	8258	7932
E = 260	7775	8031	7707	7661	7181	6936	7520	7695	7924	9236
E = 270	9928	9584	8532	7429	6960	7118	7129	7037	7186	7003
E = 280	6555	6771	6963	7300	7103	7417	6858	6676	6680	6637
E = 290	6240	6779	6583	7773	15173	29071	24119	10803	6596	7117
E = 300	8024	7281	7114	6820	5955	5744	5450	5499	5300	4856
E = 310	5200	5388	5452	5614	5323	4858	4924	5265	4800	4750
E = 320	4966	4641	5003	5060	5231	5038	4407	4752	4822	5211
E = 330	5810	5068	4490	4516	4216	4456	4159	4809	6371	6410
E = 340	5167	4198	4320	4142	3945	4247	4074	3940	3676	4192
E = 350	9395	28963	45328	26591	7470	3549	3184	3026	3338	3068
E = 360	3154	2881	2894	3046	3076	2779	2881	2661	2723	2826
E = 370	2739	2813	2757	2884	2978	2569	2428	2485	2523	2647
E = 380	2671	2990	2655	2364	2221	2505	2450	2291	2403	2244
E = 390	2310	2300	2405	2256	2142	2372	2126	2157	2309	2364
E = 400	2203	2505	2665	2491	2225	2099	1955	1858	1827	2041
E = 410	1934	1964	1821	1885	1889	1729	1783	1675	1643	1817
E = 420	1703	1598	1674	1745	1616	1522	1987	3707	4733	3491
E = 430	2093	1426	1356	1597	1604	1531	1484	1292	1491	1638
E = 440	1560	1602	1633	1448	1578	1729	1565	1471	1334	1454
E = 450	1306	1454	1399	1404	1436	1360	1310	1476	1400	1221
E = 460	1314	1437	1731	2447	2290	1679	1240	1436	1375	1295
E = 470	1131	1220	1384	1169	1125	1335	2234	3744	4209	2556
E = 480	1565	1488	1350	1119	1177	1031	1218	1334	1399	1368
E = 490	1169	944	1218	1286	1089	1285	1175	1088	1026	1096
E = 500	1168	1195	1108	1082	1179	1192	1115	1189	1420	1514
E = 510	1601	1878	1981	1665	1230	1210	1044	1091	1047	1137
E = 520	994	1105	1184	1136	1081	902	1057	1127	1054	1056
E = 530	1195	1139	985	1144	1115	1076	1115	1000	939	915
E = 540	894	931	997	1037	1015	1027	1106	1002	1063	1030
E = 550	1037	933	1034	977	726	934	981	935	1014	988
E = 560	1106	1085	1063	1144	882	847	749	840	977	1096
E = 570	1260	1236	1240	1577	1390	1188	971	827	1037	980
E = 580	1046	977	1338	1682	1497	921	854	825	896	939
E = 590	999	921	754	760	761	923	1061	853	973	1390
E = 600	2226	2251	1339	855	904	1137	1172	1790	3052	5009
E = 610	4385	2025	1034	905	856	883	794	833	821	899
E = 620	884	772	775	787	754	884	904	726	842	950
E = 630	736	789	989	882	851	1181	1320	1129	842	848

TOTAL ACTUAL COUNTS = 508898.8

Fig. 8 Digital output of a 600 keV interval histogram for the sum of all detectors. The numbers given are 10x actual counts; this is an artifact introduced by gain stabilization which corrects gain shifts to 0.1 channels.

ACKNOWLEDGMENTS

We thank the staff at the Oroville Power Dam Facility for their generous assistance in the initial setting up of the experiment and the California Department of Water Resources for giving permission for us to use their facilities for this experiment.

This work was supported by the Office of High Energy Physics of the U.S. Department of Energy and was carried out at LBL under Contract No. DE-AC03-76SF00098 and at UCSB under Contract No. DE-AT03-79ER70023.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

REFERENCES

1. F.S. Goulding et al, "Semiconductor Detectors and Double Beta Decay", IEEE Trans. Nucl. Sci., NS-31, No. 1, 285 (1984).
2. F.S. Goulding et al, "The LBL/UCSB ^{76}Ge Double Beta Decay Experiment: First Results", IEEE Trans. Nucl. Sci., NS-32, No. 1, 463 (1985).
3. D.A. Landis, N.W. Madden and F.S. Goulding, "A Reliable Automatic Liquid Nitrogen Filling System", IEEE Trans. Nucl. Sci., NS-33, No. 1, 399 (1986).
4. D.O. Caldwell et al, "Limit on Lepton Nonconservation and Neutrino Mass from Double Beta Decay", Phys. Rev. Lett., 54, No. 4, 281-284 (1985).
5. D.O. Caldwell et al, "Half-Life Limit on the Zero-Neutrino and Two-Neutrino Double Beta Decay of ^{76}Ge", Phys. Rev. D, 33, No. 9, 2737-2739 (1986).

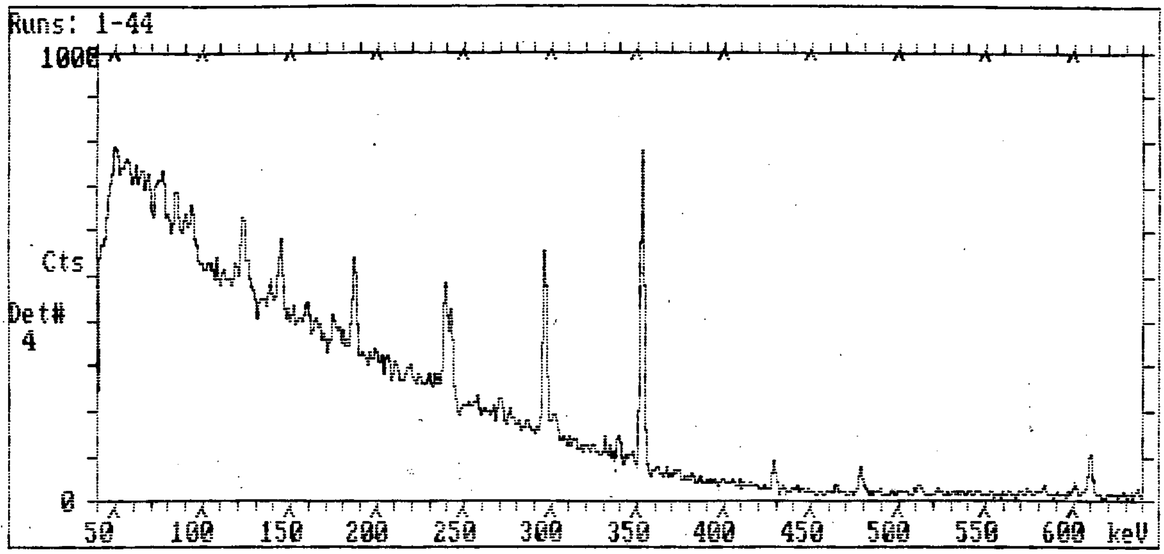


Fig. 9 15 month spectrum for detector #4 for the interval 40-640 keV.

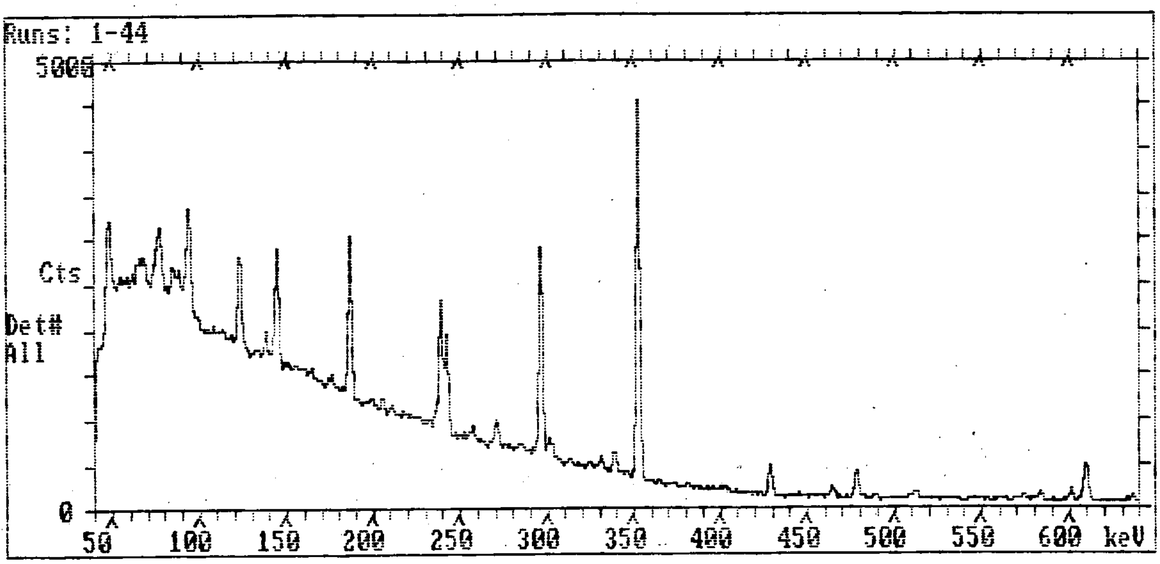


Fig. 10 15 month spectrum for the sum of 6 detectors (40-640 keV).

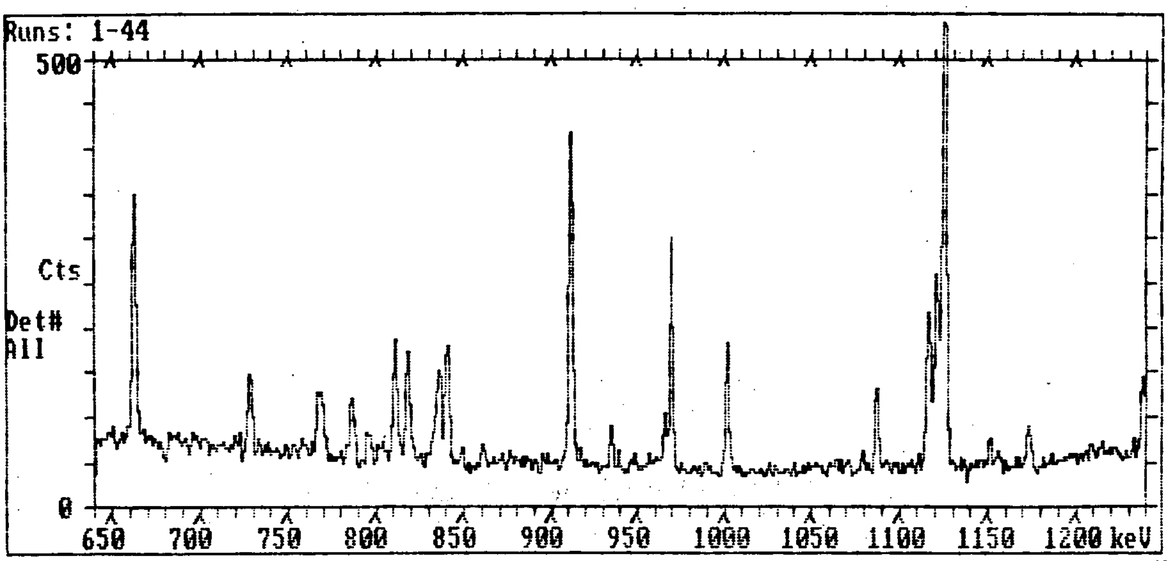


Fig. 11 15 month spectrum for the sum of 6 detectors (640-1240 keV).

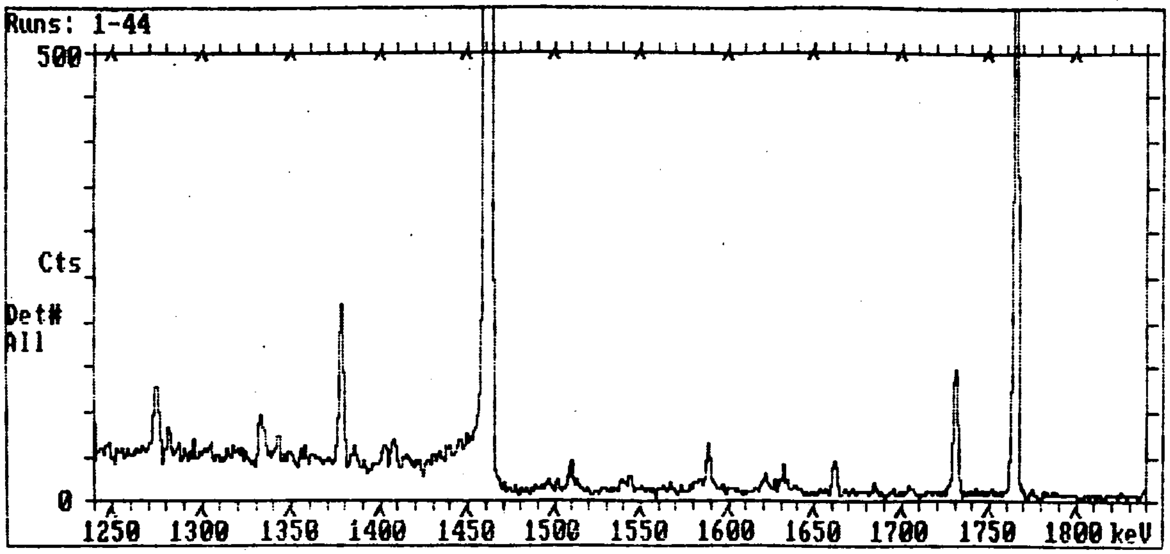


Fig. 12 15 month spectrum for the sum of 6 detectors (1240-1840 keV).

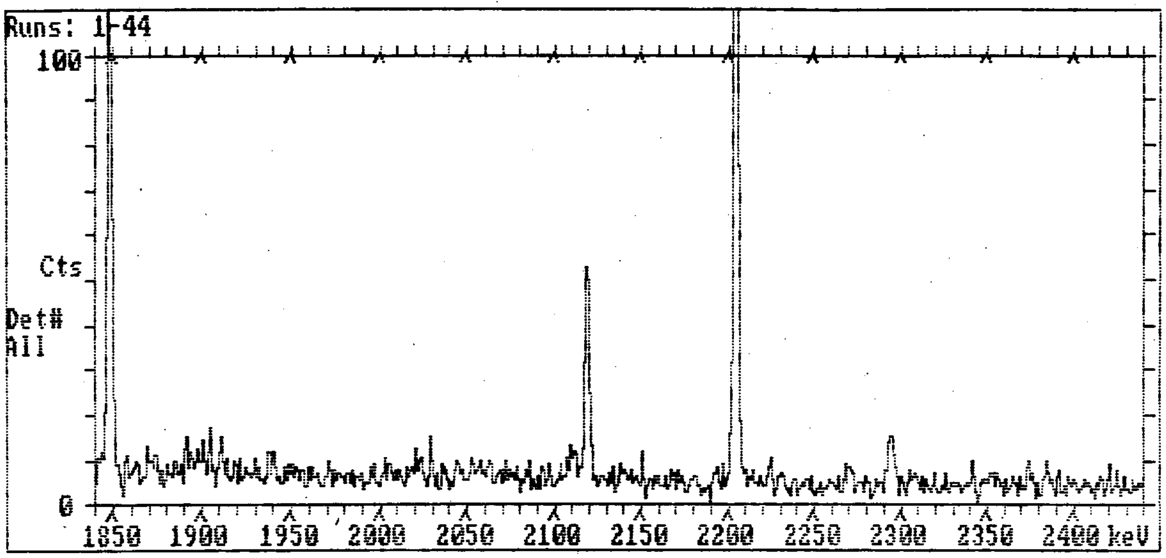


Fig. 13 15 month spectrum for the sum of 6 detectors (1840-2440 keV).

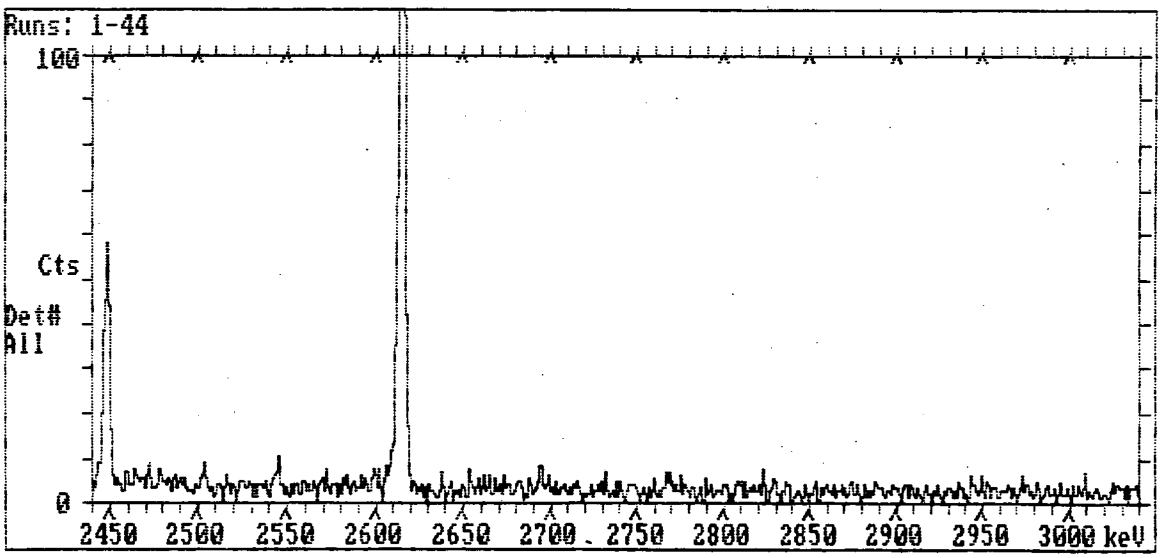


Fig. 14 15 month spectrum for the sum of 6 detectors (2440-3040 keV).

Data Disk# 8 Records 1 to 34 Det# 0 Energies 2000 to 2099

Time	Posn	Ge Detectors 1	2	3	4	5	6	7	8	NaI Group1 1	2	3	4	5	6	7	8	NaI Group2 1	2	3	4	5	6	7	8	TOTALS Ge	NaI	All
Rec# 6																												
35675093	3851	-	620	-	-	2081	-	-	-	1.62	-	0.29	3.48	-	-	-	-	3.52	-	4	133	194	-	-	-	2.709	8.91	11.62
35677875	8699	2088	-	-	-	-	-	-	-	0.54	-	-	0.24	-	-	-	-									2.088	0.78	2.87
Rec# 7																												
35681278	6919	-	-	2037	-	-	-	-	-	-	-	-	-	0.58	-	0.29	-									2.037	0.87	2.91
Rec# 8																												
35684272	4251	-	-	2040	-	-	-	-	-	0.44	-	-	-	-	-	-	-	-	0.22	-	-	-	-	-	-	2.040	0.66	2.71
35685387	7029	-	-	2011	-	-	-	-	-	....																2.011	0.00	2.01
Rec# 9																												
35688399	4025	-	-	-	-	2027	-	-	-	0.48	-	-	-	-	-	-	-									2.027	0.48	2.51
35688849	5157	-	-	-	-	-	2095	-	-	-	-	-	-	-	-	0.57	-									2.095	0.57	2.67
Rec# 13																												
35707584	9331	-	-	2082	-	-	-	-	-	0.52	-	-	-	-	-	-	-									2.082	0.52	2.61
Rec# 14																												
35708668	1759	-	28	109	-	2002	-	-	-	3.46	3.46	0.13	3.48	-	1.17	-	1.42	3.52	3.49	9	207	353	-	324	2	2.139	20.16	22.30
Rec# 16																												
35718796	5047	-	-	-	2099	-	-	-	-	....																2.099	0.00	2.10
Rec# 17																												
35723810	6635	-	-	-	2045	-	-	-	-	1.33	0.56	-	-	-	0.13	0.68	-	-	-	4	-	-	-	-	-	2.045	2.70	4.75
35723815	6657	-	2009	472	-	-	-	-	-	3.48	-	3.48	3.48	3.46	0.88	0.87	3.46	-	-	29	36	-	-	-	290	2.481	19.12	21.61
Rec# 18																												
35726175	2017	2006	1149	-	1621	-	-	-	-	3.48	3.43	3.48	3.46	3.46	3.51	3.45	3.46	3.52	0.58	272	9	121	-	27	104	4.776	31.86	36.64
35728182	7037	-	-	-	-	-	2083	-	-	3.48	1.05	-	3.48	0.60	3.51	3.45	0.10	-	3.52	205	162	-	40	40	-	2.083	19.20	21.28
35728746	8401	-	-	172	2073	-	-	-	-	-	3.46	3.48	3.48	-	1.42	-	3.36	-	-	-	185	-	-	277	7	2.245	15.21	17.45
35729270	9755	2028	-	-	-	-	-	-	-	-	3.46	0.45	1.78	-	3.51	-	-	-	-	-	4	-	-	346	-	2.028	9.21	11.24
Rec# 19																												
35731509	5053	-	2074	-	-	-	-	-	-	-	-	0.24	1.29	-	-	-	0.35									2.074	1.87	3.95
Rec# 22																												
35743150	1857	-	-	-	-	2057	-	-	-	-	1.45	2.29	3.48	-	0.96	-	-	-	-	-	100	-	-	-	-	2.057	8.19	10.25
35744524	5231	-	2056	-	8029	-	-	-	-	3.48	-	3.48	3.45	-	3.51	1.13	3.46	3.52	-	220	9	22	-	2	124	10.085	22.03	32.12
Rec# 23																												
35749953	7499	1207	2076	353	-	2577	-	-	-	3.48	3.44	1.96	3.48	-	3.51	-	3.45	3.52	-	23	41	99	-	360	9	6.213	22.87	29.09
Rec# 24																												
35752732	4295	-	-	2061	8079	-	-	-	-	0.15	2.98	3.48	3.48	-	3.51	-	1.42	-	0.64	-	135	-	-	107	2	10.140	15.67	25.81
Rec# 27																												
35765006	3963	-	2072	-	-	-	-	-	-	....																2.072	0.00	2.07
Rec# 28																												
35770805	7973	-	2040	-	-	-	-	-	-	-	-	-	0.48	-	-	-	-									2.040	0.48	2.52
Rec# 30																												
35778079	4923	-	-	2050	-	-	-	-	-	....																2.050	0.00	2.05
35779167	7399	8139	1950	1044	1949	2029	7542	-	-	3.48	3.46	3.48	3.48	3.46	3.51	-	3.46	3.52	3.52	260	238	387	-	360	112	22.653	31.39	54.05
Rec# 33																												
35791407	5839	-	-	-	2014	-	-	-	-	3.48	3.46	-	3.48	-	-	0.52	-	-	-	148	79	-	-	-	-	2.014	10.95	12.96
35792271	7933	-	-	-	96	-	2049	-	-	-	-	-	-	-	-	0.16	-	-	0.84	-	-	-	-	-	-	2.145	1.00	3.15
Rec# 34																												
35797044	9141	2058	-	-	-	-	-	-	-	3.48	2.04	-	3.48	-	-	-	-	-	-	144	131	-	-	-	-	2.058	9.00	11.06

Fig. 15 Output of the program EVENTS showing those events containing germanium detector signals in the energy range 2000-2099 keV on data disk #8 in records 1-34. Energy signals in all detectors are shown. The first column contains time information while the second one identifies the position of the event in the record.

Record# 16 Position# 5047

Delta t		Ge Detectors 1	2	3	4	5	6	7	8	NaI Group1 1	2	3	4	5	6	7	8	NaI Group2 1	2	3	4	5	6	7	8
95	Pulser	1916	-	-	-	-	-	-	-	....															
94	Pulser	-	1922	-	-	-	-	-	-	....															
93	Pulser	-	-	1907	-	-	-	-	-	....															
91	Pulser	-	-	-	1922	-	-	-	-	30	22	77	26	30	41	40	56	44	28	-	-	-	-	-	-
90	Pulser	-	-	-	-	1909	-	-	-	....															
89	Pulser	-	-	-	-	-	1914	-	-	....															
81		-	-	341	-	-	-	-	-	....															
67		-	-	-	-	-	248	-	-	-	-	-	-	-	-	-	15	-	41	-	-	-	-	-	-
66		-	-	112	-	-	-	-	-	....															
64		-	-	-	184	-	-	-	-	-	-	-	20	-	-	-	31								
62		293	-	-	-	-	-	-	-	....															
59		-	-	-	998	-	-	-	-	-	-	-	-	-	21	-	-	-	81	-	-	-	-	-	-
45		-	-	-	-	154	-	-	-	....															
35	Pulser	1915	-	-	-	-	-	-	-	....															
34	Pulser	-	1922	-	-	-	-	-	-	....															
32	Pulser	-	-	1907	-	-	-	-	-	....															
31	Pulser	-	-	-	1924	-	-	-	-	30	22	77	26	30	41	40	56	44	28	-	-	-	-	-	-
30	Pulser	-	-	-	-	1909	-	-	-	....															
29	Pulser	-	-	-	-	-	1914	-	-	....															
23		-	144	-	-	-	-	-	-	....								80	-	-	-	-	-	-	-
15		-	449	-	-	-	-	-	-	40	-	-	-	-	-	-	21								
13		-	-	331	-	-	-	-	-	....															
10		-	-	-	791	-	-	-	-	-	-	-	33	-	-	-	-								
6		274	-	-	-	-	-	-	-	-	71	-	-	-	-	-	-								
4		1131	-	-	-	-	-	-	-	-	-	-	-	-	-	22	-								
0		-	-	-	2112	-	-	-	-	....															

Fig. 16 Output of the program HISTORY. This shows the 25 counts preceeding that at position #5047, record #16 on data disk #8 (see Fig. 15). Pulser signals are included and the first column indicates the time in seconds prior to the selected event.

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720