Registration of ^{71}Ge rare decays in radiochemical gallium experiments SAGE and BEST

A A Shikhin[1], V N Gavrin, V V Gorbachev, T V Ibragimova, A V Kalikhov and V E Yants

Institute for Nuclear Research, Russian Academy of Sciences, prospekt 60-letiya Oktyabrya 7a, Moscow, 117312, Russia

E-mail: gavrin@inr.ru, shikhin@inr.ru

Abstract. Registration systems of rare events from ^{71}Ge decay in radiochemical gallium experiments SAGE and BEST are presented, where miniature proportional counters are used as detectors. The registration of the events is provided by eight counting channels simultaneously in the energy range of 0.4–15 keV which includes the ^{71}Ge decays in the region of the L and K peaks with total efficiency up to 75%. Data analysis is based on full charge pulse shape recording using digital oscilloscope. Effective background discrimination is basically obtained due to low noise (<0.32 keV) and wide bandwidth (>100 MHz) of the system electronics. The design and main parameters of base components of the registration systems, description of electronics and comparison of their electrical and counting characteristics are given.

1. Introduction

Registration of ^{71}Ge rare decays is very specific task in radiochemical solar neutrino experiments such as SAGE [1, 2, 3] and calibration experiments with artificial neutrino sources [4, 5] based on SAGE also. These events are registered in very low-background environment during long time. Only few events of ^{71}Ge decay is registered inside counting run and each event is unique. Loss or over-count of one lets an error in data analysis up to ten percent. So, the requirements for counting system by reliability and stability of main parameters are very high.

SAGE continues to run nowadays. New Baksan Experiment on Sterile Transitions (BEST) [6] is proposed for detail investigation of so called "gallium anomaly" [7]. An active stage of preparation to BEST is ongoing in present time based on SAGE. The scheme of BEST assume doubling of sample numbers with ^{71}Ge content compare to SAGE. Half of them will be measured by the SAGE counting system [1]. New counting system for BEST will provide a counting of second half of ^{71}Ge samples.

2. Description of ^{71}Ge decay

Isotope of ^{71}Ge decays over e-capture ($^{71}\text{Ge}(e^-, \nu_e)^{71}\text{Ga}$, $T_{1/2} = 11.43$ days) [1]. There are few modes of the decay (see table 1), but the counting systems using small proportional counters (PC) [1, 3] registers K and L modes only.

[1] To whom any correspondence should be addressed.

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Table 1. ^{71}Ge decay modes and their correlations

EC	[%]	Radiation	[%]	Energy, keV
K	88.0	Auger e^-	41.5	10.37
		X rays + Auger e^-	41.2	9.2 + 1.2
		X rays + Auger e^-	5.3	10.26 + 0.12
L	10.3	Auger e^-	10.3	1.2
M	1.7	Auger e^-	1.7	0.12

PC registers electrons with high enough efficiency and X-rays with low one. As a result, it forms energy spectrum of ^{71}Ge that consists of two peaks: L (1.2 keV) and K (10.4 keV), each of which contains same number of events, as it is shown on figure 1 (solid line). Also, the spectrum from calibration ^{55}Fe X-rays source (5.9 keV) is shown here (points line).

An event from ^{71}Ge decay gives very small local volume of ionization inside PC, so called "point-like" ionization, which is characterized by very fast rising of charge pulse. Opposite, background β-particle gives a track in a counter volume. It leads to more or less slow rising of pulse ("extended ionization"), as it is shown on figure 2. Here 1, 2 — the charge pulses corresponding to events in K, L peaks of ^{71}Ge decay and 3 — the pulse from background event of small energy; X axis — time, ns; Y axis — voltage, arb. units.

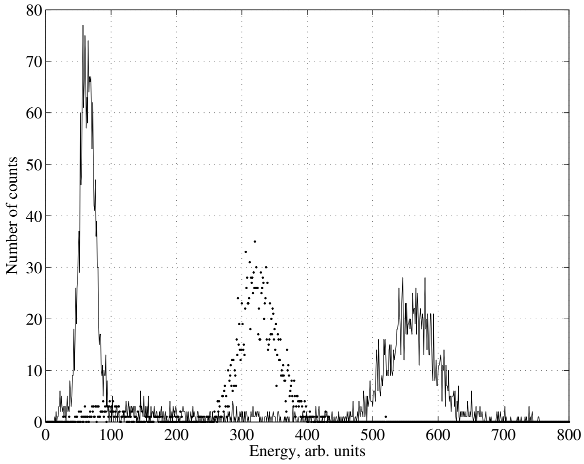

Figure 1. Spectra from ^{71}Ge decay and ^{55}Fe X-rays source in PC.

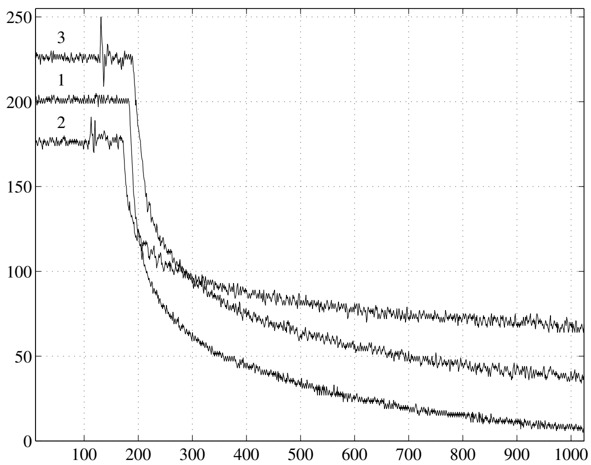

Figure 2. Charge pulse shapes of events in PC.

3. SAGE counting system

The counting system for SAGE uses small PCs as detectors for ^{71}Ge decay because they has extremely low background and high enough registration efficiency for electrons. Each solar run gives only few atoms of ^{71}Ge. They are enclosed inside volume of the PC and their decays must to be counted by the piece. Up to eight PCs can be installed simultaneously to the system. The PCs model YCT [3] have cathode length of $\simeq$50 mm, wall thickness of 150–200 μm, cathode diameter of 4 mm, cathode thickness $\simeq$1 μm (graphite) and anode thickness of 11μm (tungsten). Standard gas mixture consists of (10–20)% GeH_4+Xe under pressure 620–640 mm. The gain is 10^3–10^4 at high voltage of $-$(1100–1300) V. Energy resolution is equal to 19–22% (5.9 keV). Registration efficiencies are 0.372 ± 0.011 (for L peak) and 0.382 ± 0.011 (for K peak), volume efficiency is 0.967 ± 0.010. Background of the PCs is 20.2 ± 1.4 (for L peak) and 13.0 ± 1.1 (for K peak) per year.

The shield for PCs consists of two parts: an internal active (anti-coincidence system) and outer passive shields. Main part of the active shield is large scintillation detector based on NaI(Tl) crystal with $\varnothing 230 \times 230$ mm sizes and $\varnothing 90 \times 150$ mm well. The energy resolution of the detector is 10% ($E_\gamma = 1173$ keV), efficiency is 81% ($E_\gamma = 511$ keV) and total background rate is 1.85 ± 0.06 s^{-1} ($E_\gamma =$ 60–3000 keV). The detector volume is viewed by four photo-multipliers (PMTs) with $\varnothing$3 inches each. External passive shield consists of few layers of low-background metals (inner to outer): 24 mm of copper, 210 mm of lead and 55 mm of steel. Upper cover of the shield consists of 32 mm of copper and 250 mm of steel. All internal volumes of the shield are ventilated by evaporated liquid nitrogen for ousting of atmospheric radon.

The detail description of the SAGE counting system electronics is given in [1, 8, 9].

4. Description of counting system for BEST

The system development is based on the SAGE counting system structure and includes all experience obtained during its long time operation. But the system for BEST is not a “clone” of the SAGE system. Its all main parts: the passive and active shields for PCs, the counters themselves, small signal electronics for counters, functional structure of the system and on-line software were developed anew. Of course, new system has the same (or better) performance data, the same set of systematic uncertainties associated with counting, same background and complete compatibility with the SAGE standard data analysis.

Passive shield for counters consists of 130 mm internal layer of copper, 20 mm intermediate layer of steel and 300 mm outer layer of led. The upper cover of the shield consists of 200 mm of steel, which is the base for hydraulic system, intended for moving the internal (active) part of the shield. Active shield operates in anti-coincidence mode with the signals from PCs. It consists of low background NaI(Tl) detector $\varnothing 200\times200$ mm, which has a well $\varnothing 100\times150$ mm that holds inside up to 8 PCs. Volume of the detector is viewed by 4 PMT’s model ET 9757QL ($\varnothing$3 inches). The NaI(Tl) crystal has a stainless steel body, Teflon reflector and quartz windows. Energy resolution of the detector is 7.6% ($E_\gamma = 1460$ keV) and background rate in the shield is 3.24 ± 0.03 s^{-1} ($E_\gamma =$ 40–3500 keV).

The PCs for the BEST counting system has the same design, counting characteristics and background as counters for the SAGE system [3]. Transversal cross section of new counters is slightly less compare to counters for SAGE, that let possibility to set them inside special module. These modules were designed to provide mechanical shielding of the counters, their stable gain, background, shield from external soft X-rays and radon.

The charge-sensitive preamplifier (CSPA) for the BEST counting system is based now on integrated high-speed operational amplifiers (OA) (figure 3) which has reached nowadays good enough set of technical characteristics by noises and bandwidth[2]. The first inverting stage of CSPA is based on JFET Input Voltage Feedback OA ADA4817, which has voltage noise density of 4 nV/$\sqrt{\text{Hz}}$ (at 100 kHz). The second inverting stage of CSPA is based on ultra-fast Current Feedback OA AD8000 with high output current (up to 100 mA). Common gain of CSPA is 0.3 V/pF, rise time is $\leqslant$3.5 ns and bandwidth is $>$100 MHz.

The functional diagram of the BEST counting system electronics is shown on figure 4. Abbreviations here are: HV — High Voltage; PMT — Photomultiplier Tube; PS — Phillips Scientific modules; DPO — Digital Phosphor Oscilloscope; GDG — Gate and Delay Generator; MALU — Majority Logic Unit. The system based mainly on commercial NIM and CAMAC equipment. It consists of two main branches. First one is “Counter channel” for registration information from PC’s and their pulse shape recording (the chains from PC to DPO Tektronix TSD3052C, Scaler, QDC and MALU). Second one is “NaI channel” for registration information from NaI(Tl) detector (the chains from NaI(Tl) to two ADC’s — one for background spectra

[2] http://www.analog.com

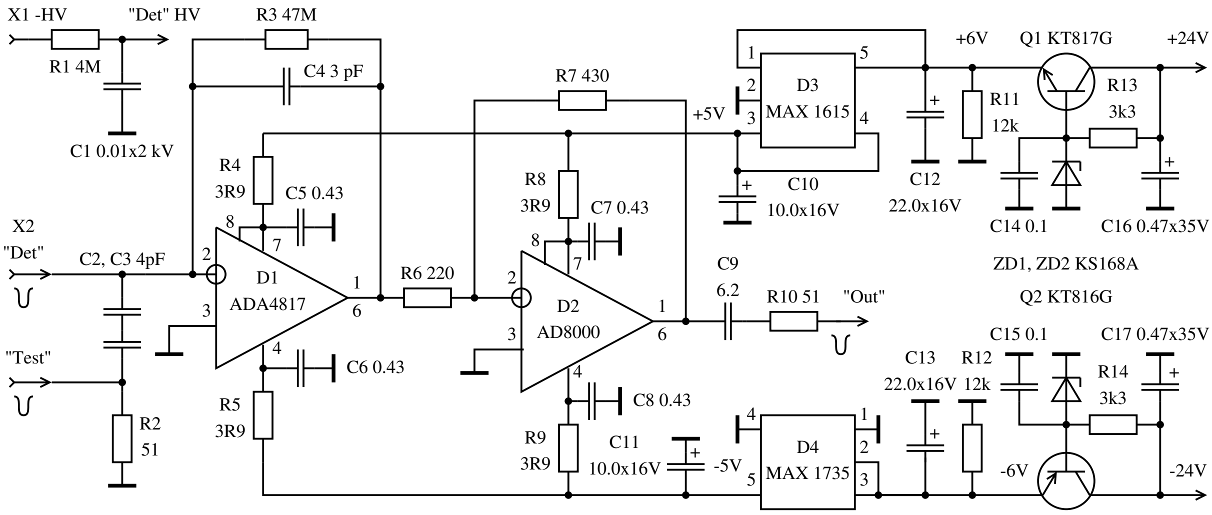

Figure 3. Integrated OA charge-sensitive preamplifier.

recording, another one for NaI events recording in coincidence mode with events in "Counter channel"). Structure and operation logic of the system are mainly similar to the SAGE system with a few differences in coincidence channel. New important future of the system is hardware synchronization between DPO and CAMAC subsystems.

5. Main performance data for the SAGE and BEST systems

Main performance data for the SAGE and BEST systems are presented in table 2. Maximal values of the parameters are shown in brackets. It's seen that the BEST system has double reserve of data precision.

Table 2. Main performance data for the SAGE and BEST systems.

Parameter	SAGE	BEST
Number of counting channels	8	8
Energy range (counter channel), keV	0.37–15	0.3–16
Bandwidth (pulse shape channel), MHz	100	$>$ 100
Rise time (pulse shape channel), ns	3.5	$\leqslant$ 3.5
Digitizing frequency (pulse shape channel), GHz	1	1 (5)
Frame volume (pulse shape channel), points	10^3 (8kB)	10^3 (10^4)
Digital resolution of DPO (pulse shape channel), bit	8	8 (9)
Digital resolution in the "Energy" channel, bit	11	11 (12)
Gate width in the "Energy" channel, ns	800	1100–1200
Dead time, ms	340	270
Digital resolution in NaI channel, bit	10 (13)	10 (11)
Shaping time constant in NaI channel, μs	1	1.1
Anti-coincidence gate width, μs	4	5
Energy range (NaI channel), keV	60–3000	60–3000

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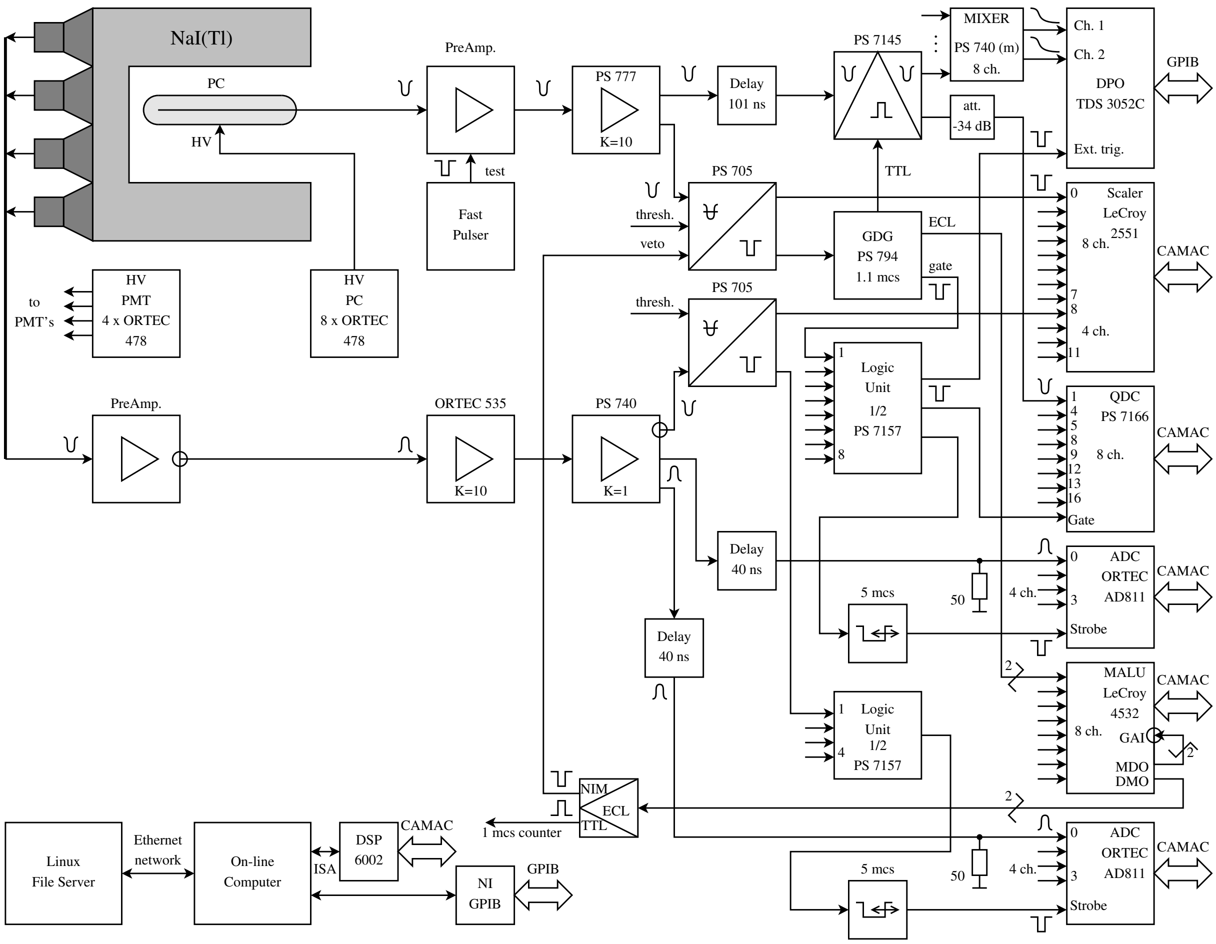

Figure 4. The functional diagram of the counting system for BEST.

Conclusion

Both counting systems are completely ready to operation in BEST. Now they counts the samples from two-zone gallium target of BEST which is irradiated by solar neutrinos. Extractions from one are performs according to the standard SAGE technology. It's seems to be as calibration of the target by the Sun.

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