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

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SAGE (Russian-American Gallium Experiment)

Location: Nothern Caucasus, Baksan Valley, Russia (v. Neutrino)

Deep underground lab (under Mt. Andyrchi): 4700 m. w. e.

Global muon flux: $(3.03 \pm 0.19) \times 10^{-9}$ $(\mathrm{cm}^2\mathrm{s})^{-1}$

Fast neutron flux (>3 MeV): $(6.28 \pm 2.20) \times 10^{-8}$ $(\mathrm{cm}^2\mathrm{s})^{-1}$

Gamma-radiation suppression factor: $\times$(15–20)

Mass of gallium target: $\sim$50 tons

Uptime: 26 years (from 1990 up to now)

Exposition/Extraction: each month, 243 runs, 450 counting sets

Result (1990–2014): $64.4 \pm 2.4(\mathrm{stat.})^{+2.6}_{-2.8}(\mathrm{syst.})$ SNU[a]

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[a] 1 SNU is 10^{-36} interactions/target atom/s

What is the BEST

Gallium mass: $\simeq$50 (42.5 + 7.5) t.

Source: ^{51}Cr

Activity: $\simeq$3 MCi

$R1$**:** 680 mm

$R2$**:** 1260 mm

$\langle L \rangle$**:** 550 mm

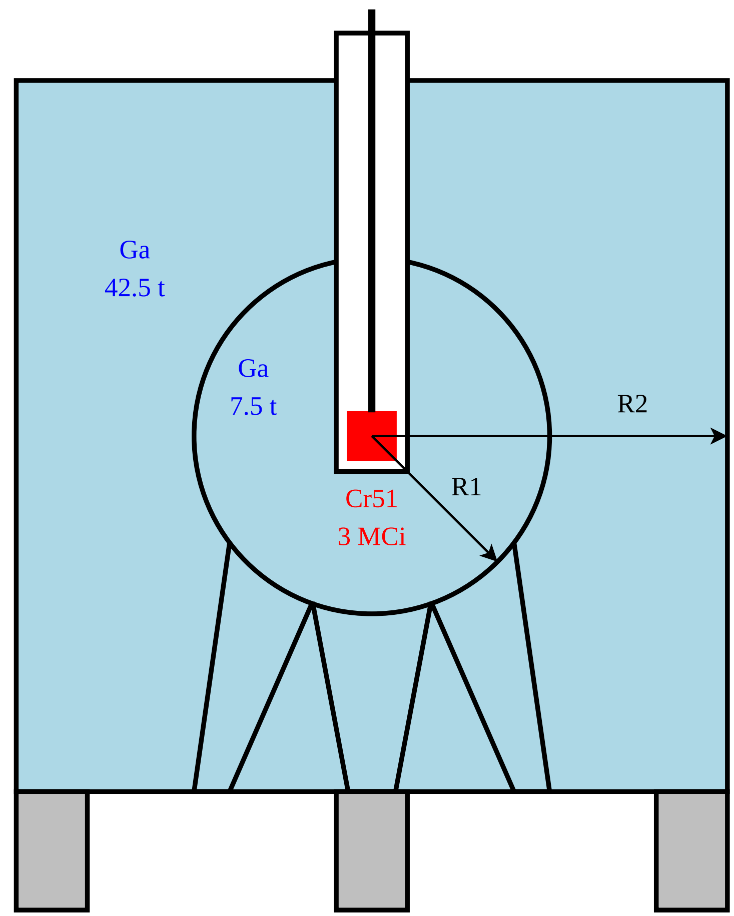
E_ν**:** 0.75 MeV (90%), 0.43 MeV (10%)

Sensitiv.: $\Delta m^2 > 0.5$ eV^2, $sin^2 2\theta > 0.1$

Errors: $\pm$3.7% (stat.), $\pm$2.6% (syst.)

Rate of captures: 64.5 at./d. (SOE)

Schedule: 10 irrad./9 days each



Ref.: V. N. Gavrin et al., arXiv:1006.2103 [nucl-ex], arXiv:1204.5379v1 [hep-ph]

^{71}Ge decay

$^{71}Ge(e^-, \nu_e)^{71}Ga$, $T_{1/2} = 11.43$ days.

^{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

SAGE counting system: YCT counters

Cathode length: $\simeq$50 mm

Wall thickness: 150–200 μm

Cathode diameter: 4 mm (int.)

Cathode: $\simeq$1 μm (pirographite)

Anode thickness: 11μm (tungsten)

Gas mixture: (10–20)% GeH_4+Xe

Gas pressure: 620–640 mm

High Voltage: $-$(1100–1300) V

Gain: 10^3–10^4

Energy resolution (5.9 keV): 19–22%

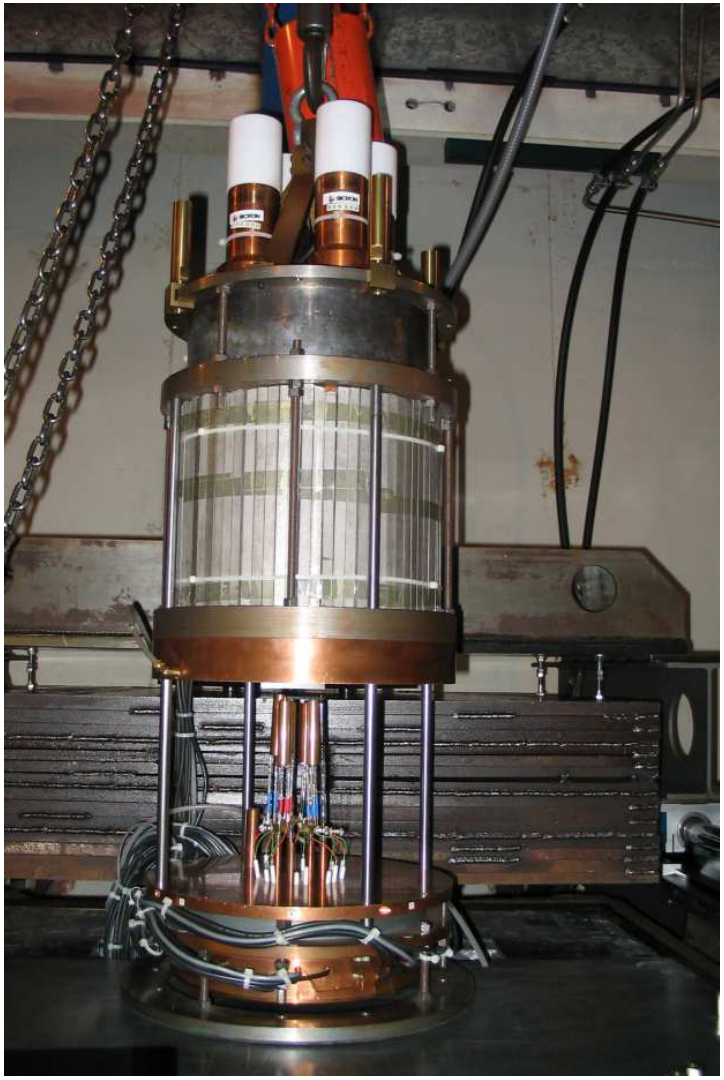
Eff.: 0.372 ± 0.011 (L), 0.382 ± 0.011 (K)

Vol. Eff. 0.967 ± 0.010

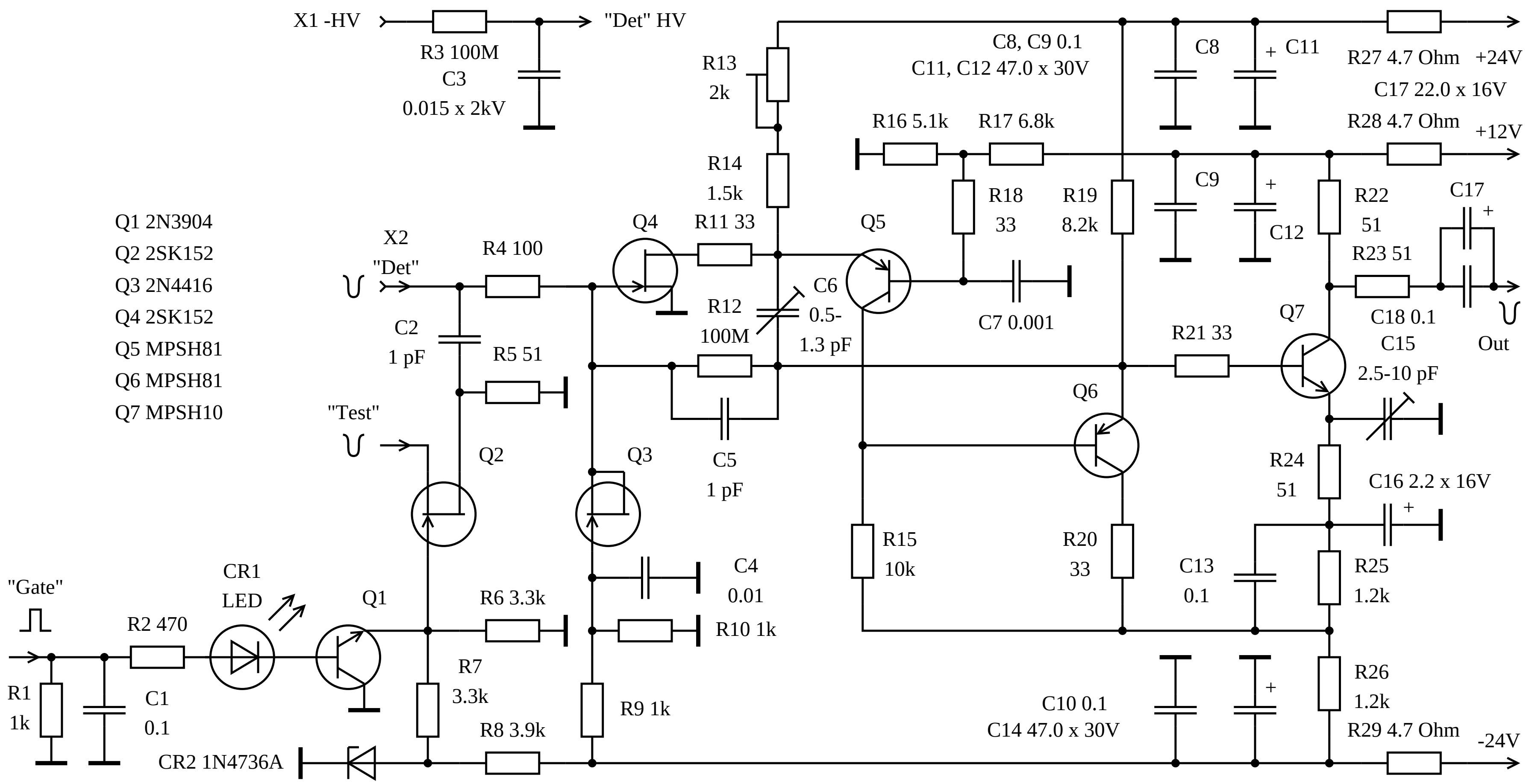
Bkg: 20.2 ± 1.4 (L), 13.0 ± 1.1 (K) y.$^{-1}$

SAGE counting system: counters shield

- NaI(Tl) detector:
  - $\varnothing 230 \times 230$ mm size
  - $\varnothing 90 \times 150$ mm well
  - $R = 10\%$ ($E_\gamma = 1173$ keV)
  - $\varepsilon = 81\%$ ($E_\gamma = 511$ keV)
  - $\upsilon_{\mathrm{bg}} = 1.85 \pm 0.06$ s^{-1} ($E_\gamma = 60$–3000 keV)
  - $4 \times 3''$ PMT's
- External shield:
  - 24 mm Cu
  - 210 mm Pb
  - 55 mm Fe
  - 32 mm Cu+250 mm Fe upper cover
- N_2 venting from Rn

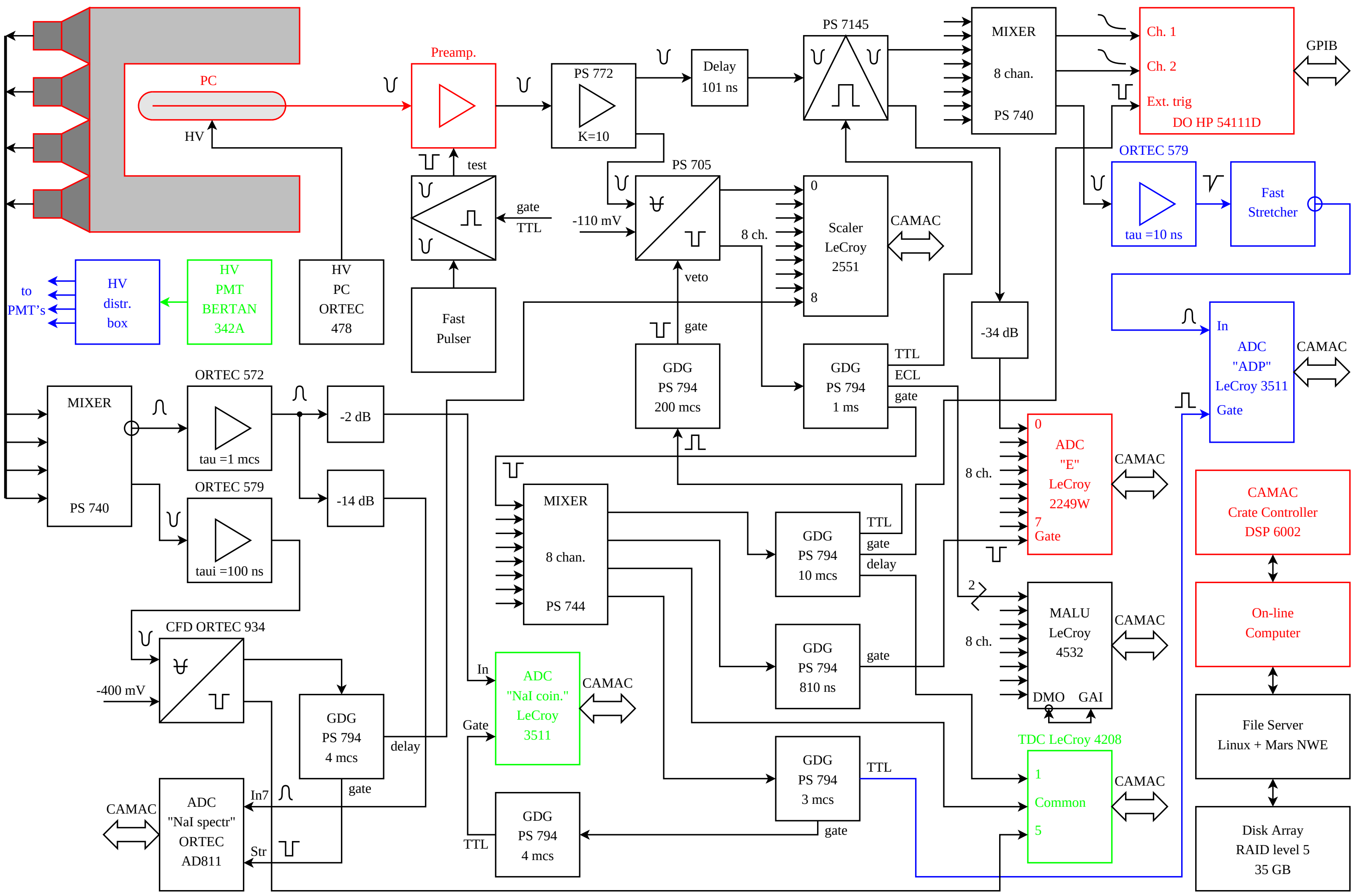


SAGE counting system: charge-sensitive preamplifier



Ref.: A. A. Shikhin, Preprint INR RAS 1230/2009

SAGE counting system: the Functional diagram



Ref.: A. A. Shikhin, Preprint INR RAS 1285/2011

Voltage pulse shape from counter anode

for point-like ionization[a]:

$$u(t) = U_0 \ln(1 + \frac{t}{t_0}) \;, U_0 = \frac{N_0 M e_0}{2C \ln \frac{b}{a}} \;, t_0 = \frac{a^2 \ln \frac{b}{a}}{2U_{HV} \mathrm{K}_+ \frac{p}{p_0}} \;;$$

for extended ionization[b]:

$$u(t) = \frac{U_0}{T_N} \left[(t + t_0) \ln(1 + \frac{t}{t_0}) - t \right] \quad 0 \leqslant t \leqslant T_N \,,$$

$$u(t) = \frac{U_0}{T_N} \left\{ T_N \left[\ln \left(\frac{t + t_0 - T_N}{t_0} \right) - 1 \right] - (t + t_0) \left[\ln \left(1 - \frac{T_N}{t + t_0} \right) \right] \right\}$$

$$T_N \leqslant t \leqslant \infty \,.$$

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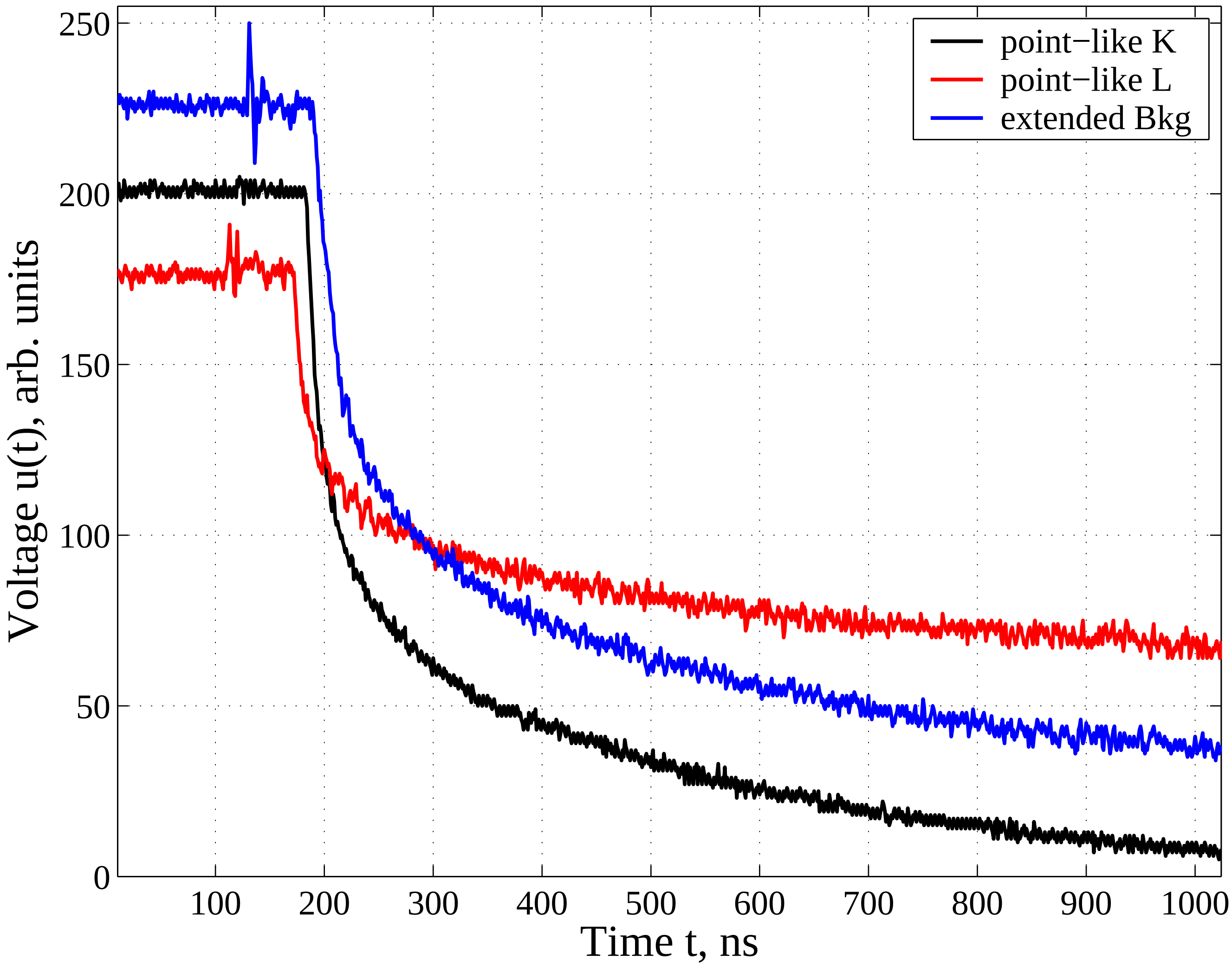
[a] D. H. Wilkinson Ionization Chambers and Counters (Cambridge University Press), Cambridge, England, 1950

[b] S. R. Elliott NIM A **290** (1990) 158–166

Pulse shapes of events in proportional counter

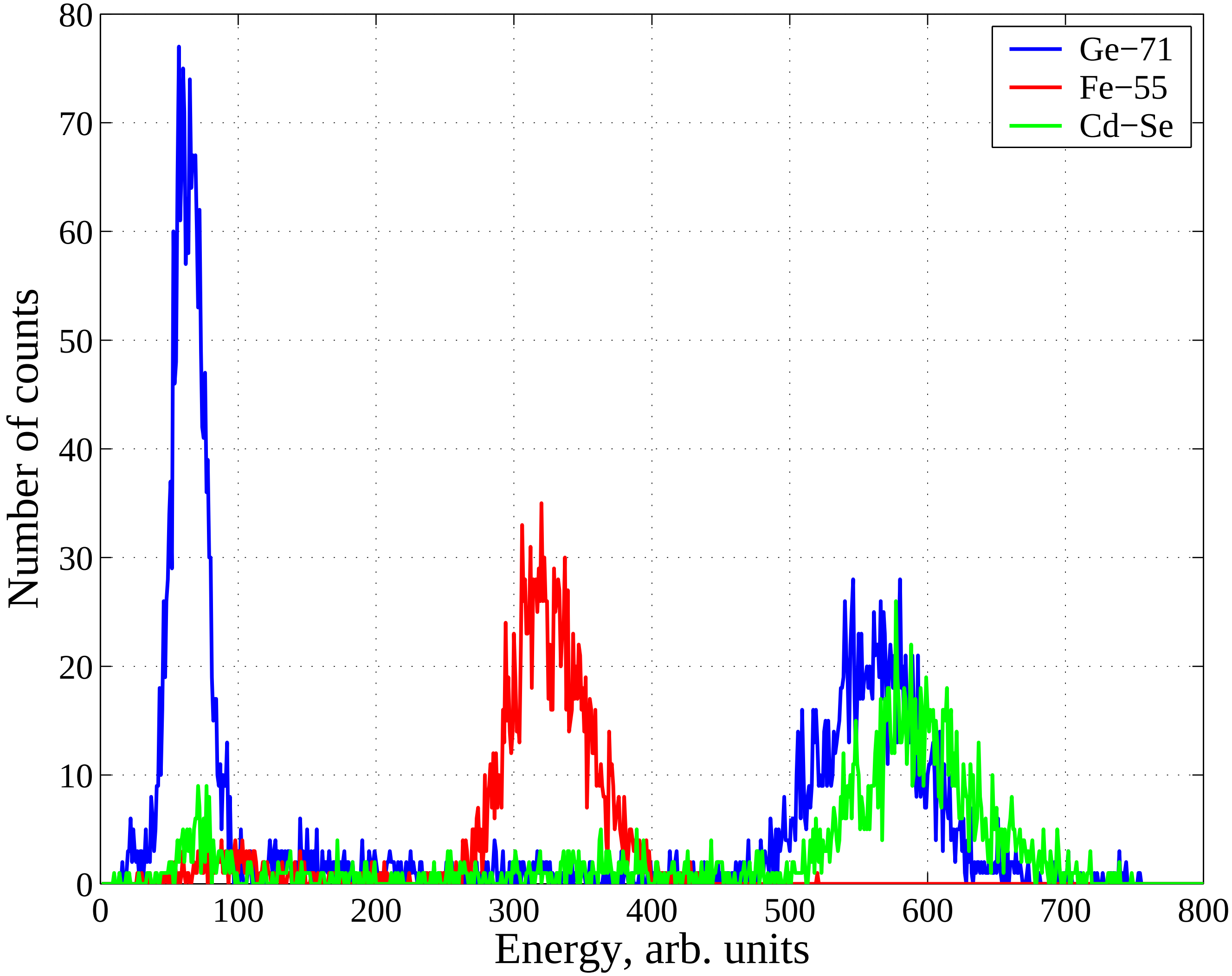


Current and voltage amplitudes at counter output

($M = 10^4$, $t_0 = 0.36$ ns, $W_i = 22$ eV, $a = 5.5$ μm, $b = 2$ mm, $C = 1$ pF)

E_0, keV	0.3	1.2	5.9	10.4	16.0
N_0	14	55	268	473	727
$i(0)$, μA	5.28	20.73	101.0	178.3	274.0
U_0, mV	1.90	7.46	36.36	64.18	98.64

Spectrum of ^{71}Ge decays in proportional counter



The systematic uncertainties related to counting (SAGE solar runs)

Origin	uncertainty, %
Volume efficiency	± 1.0
End losses	± 0.5
Monte Carlo interpolation	± 0.3
Shifts of gain	-1.1
Resolution	$-0.7/+0.5$
Rise time limits	± 1.0
Lead and exposure times	± 0.8
Total	$-2.1/+1.8$

Ref.: J. N. Abdurashitov *et al.* Phys. Rev. C **80**, 015807 (2009)

Main requirements for BEST counting system

1. 8 additional counting channels besides existing system.
2. Main performance characteristics same as for existing system.
3. Data format compatible with the existing standard data analysis.
4. Same systematic uncertainties related to counting.
5. Same (or better) background.
6. Possibility for further development and improvement.

Stages of development the counting system for BEST

1. Preparing the room for the counting system.
2. The basis for new passive shield.
3. Construction of new passive shield.
4. New NaI(Tl) detector for anticoincidence system.
5. Hydraulic mechanism for detector movement in the shield.
6. New low-background proportional counters.
7. The modules for proportional counters and calibration method.
8. The charge-sensitive preamplifiers.
9. Functional structure of the acquisition electronics.
10. The acquisition software.
11. Performance and long-time background measurements.

The passive shield

- Quartz sand pad.
- Basis on low-background concrete cubes of 200^3 mm^3.
- Internal layer of copper: 107.5 mm around, 130 mm down and up.
- Intermediate layer of steel: 20 mm down and around.
- External layer of lead: 300 mm down and around($\simeq$1000 bricks).
- Upper cover: 100+100 mm of steel.
- Total mass of materials — about 20 t.

Main performance data of NaI(Tl) detector

Made: "Amkris", Kharkov, Ukraine

Size: $\varnothing 200\times 200$ mm

Well: $\varnothing 100\times 150$ mm

PMTs model: $3''$ ET9757QL (4 pieces.)

Body: Stainless steel

Reflector: Teflon

Windows: Quartz

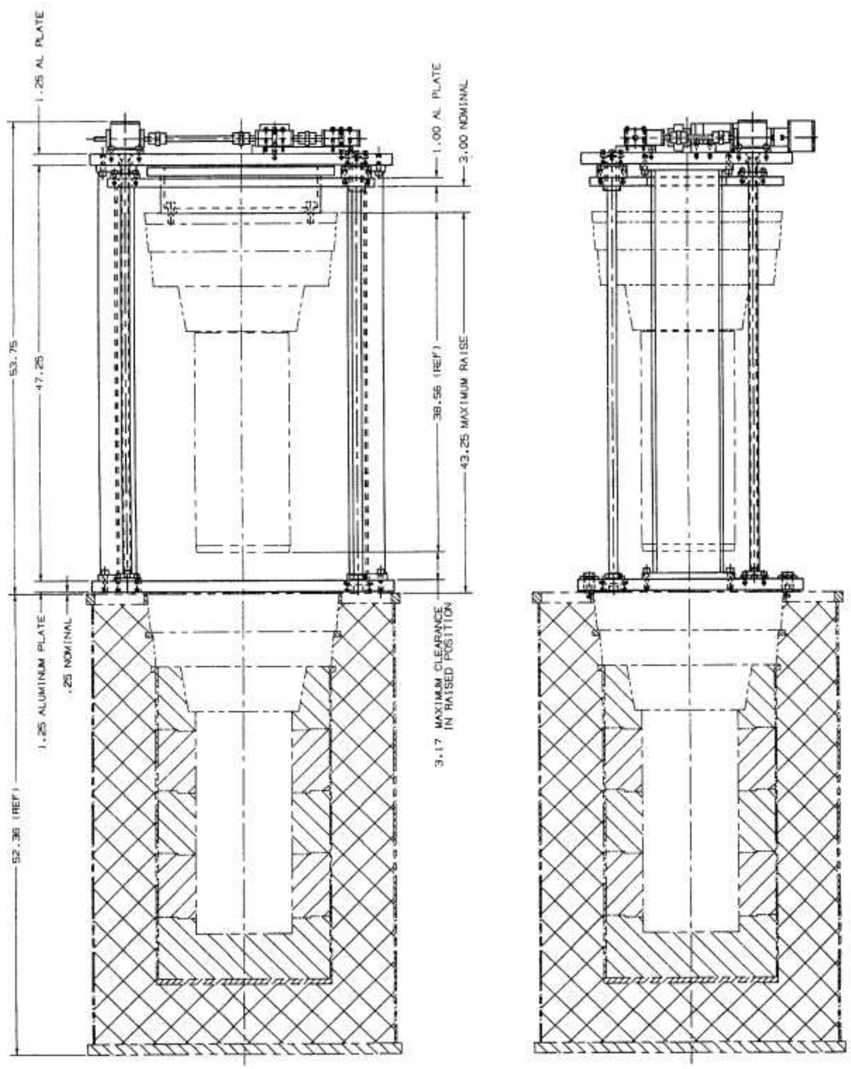
Volume: 5105.1 cm^3

Mass: 18.74 kg

Resolution: $R \simeq 7.6\%$
($E_\gamma = 1460$ keV)

Bkg: $v_{\text{bg}} = 3.24 \pm 0.03\ \text{s}^{-1}$
($E_\gamma = 40$–3500 keV)

Hydraulic mechanism and moving part of the shield



Proportional counter model YCN

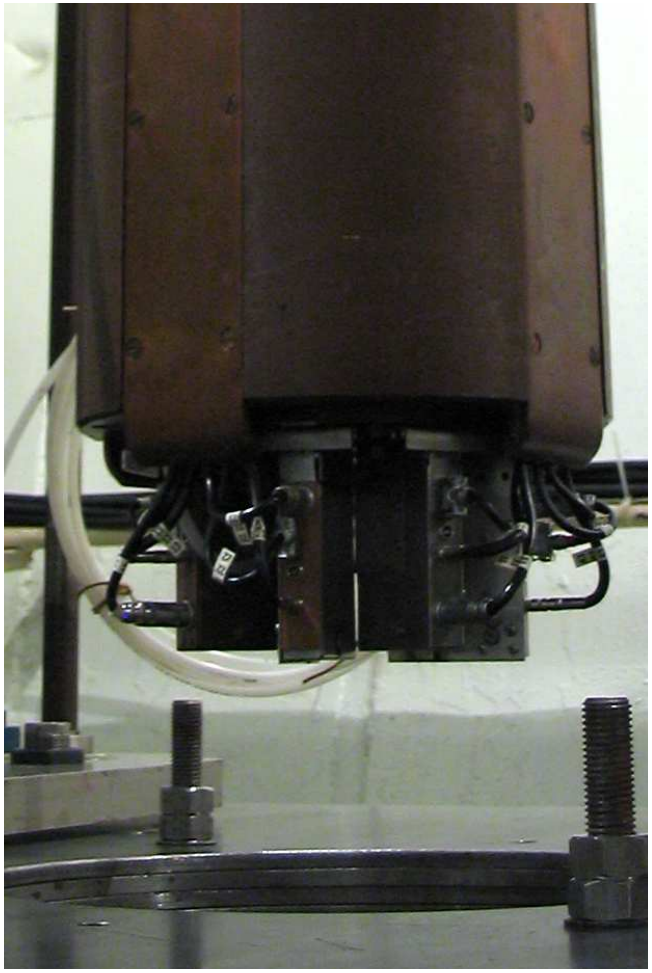
The counter and acryl pen case

Assembled case with the counter

The module for proportional counter

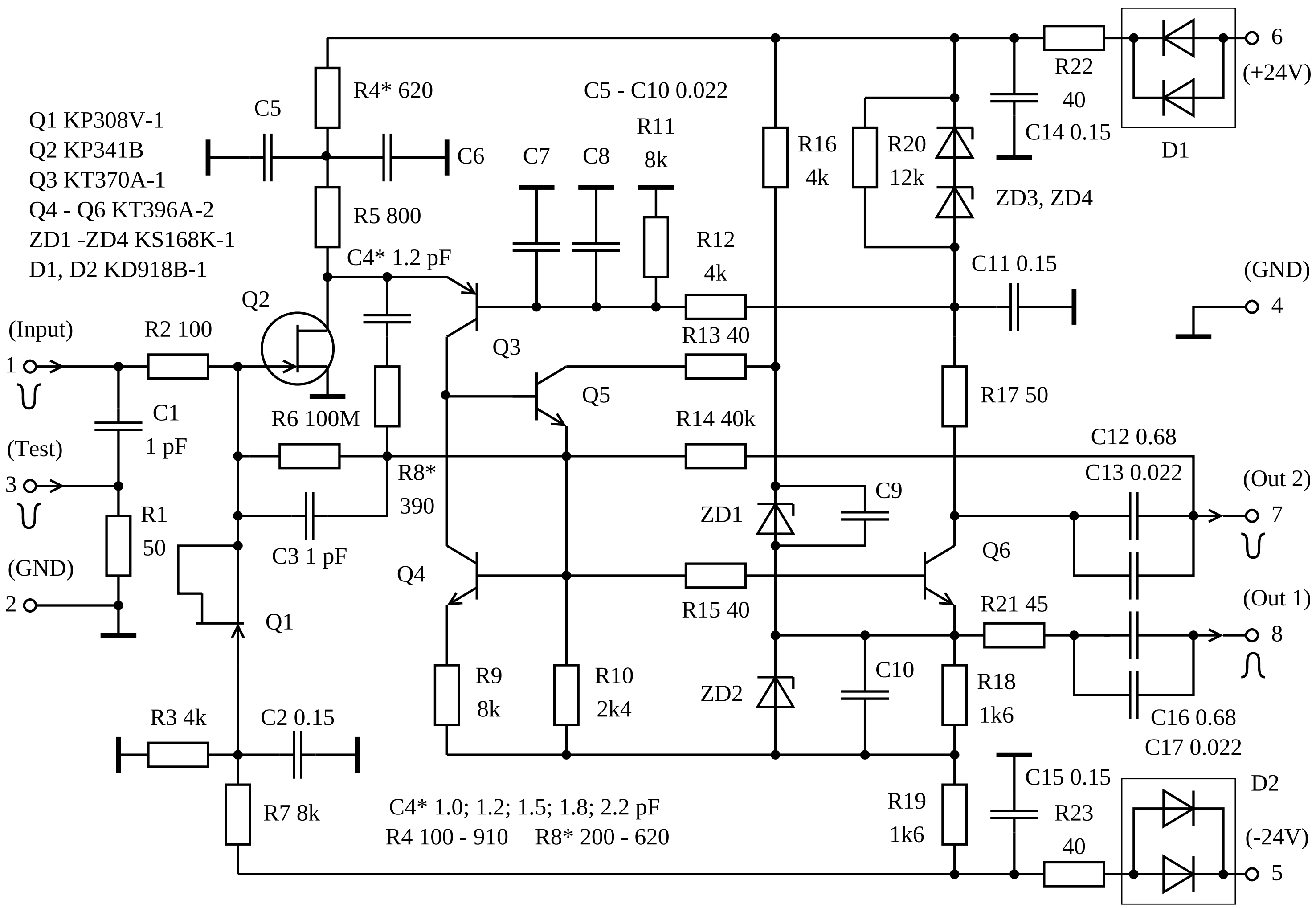
Counter positioning in the module

Modules set in NaI(Tl) detector



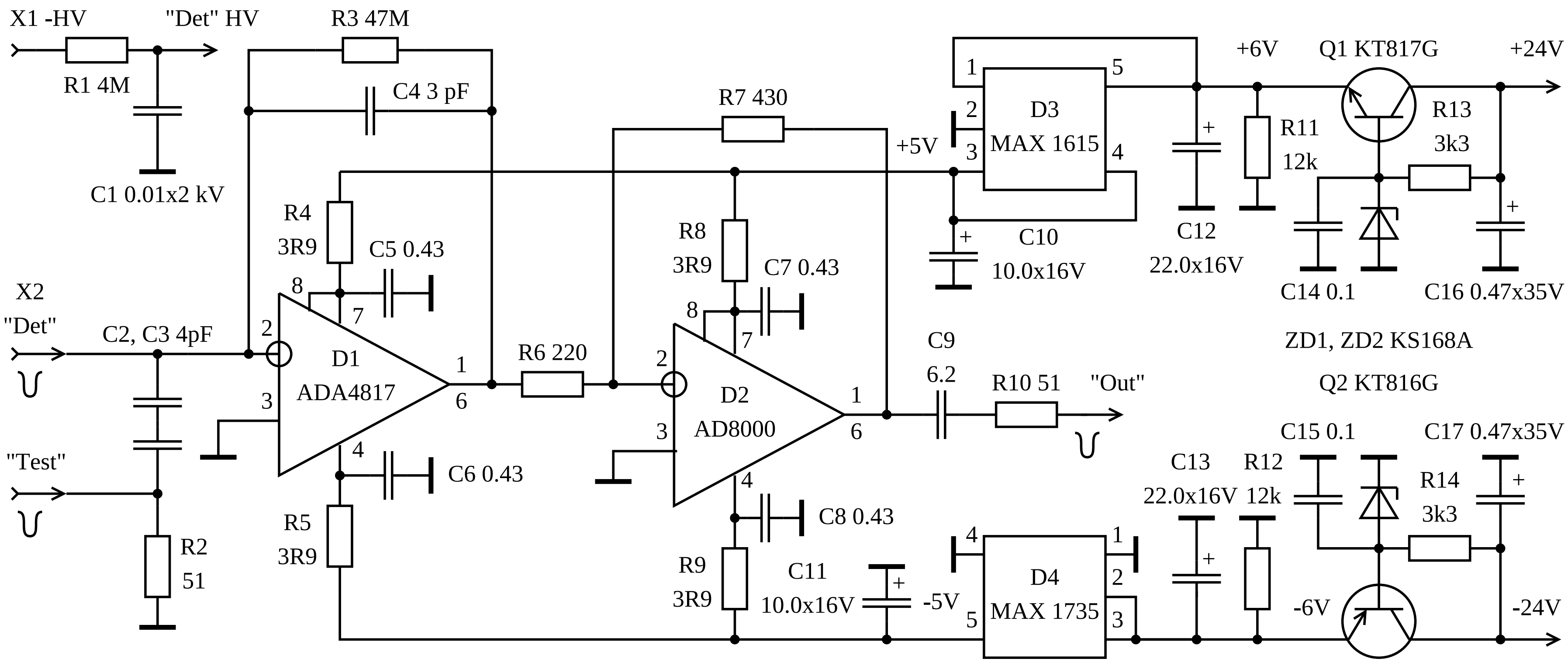
Hybrid charge-sensitive preamplifier "The Charge":

(Vydolob, Kuptsov: VT-E5883 TU, 1990)

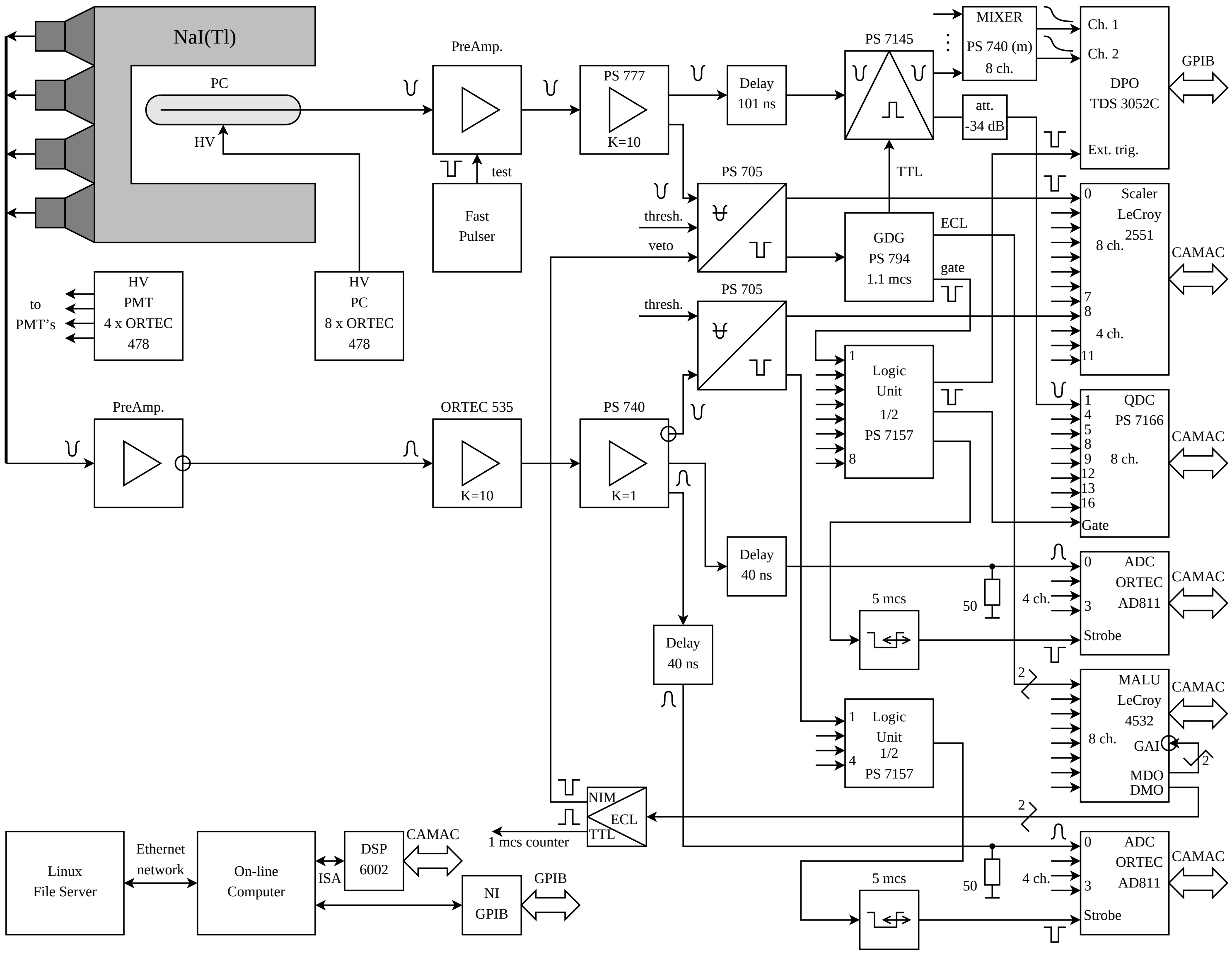


Integrated OA charge-sensitive preamplifier:

(D. V. Serebryakov, A. A. Shikhin, INR RAS, 2015)



BEST: the functional diagram of counting system



"BEST System at work" — GGNT underground lab

Main performance data for SAGE and BEST systems

(max. values of the parameters are shown in brackets)

Parameter	SAGE	BEST
Number of counting channels	8	8
Energy range (counter channel), keV	0.37–15	0.3–16
Risetime (pulse shape channel), ns	3.5	< 3
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)
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
Anticoincidence gate width, μs	4	5
Energy range (NaI channel), keV	60–3000	60–3000