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Response function simulation of the anti-coincidence detector based on NaI crystal with a complex shape in registration systems for the experiments SAGE and BEST

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Abstract. Response function simulation using Geant 4 for the detector based on NaI crystal of complex shape in registration systems for the SAGE and BEST experiments is presented. Cylindric NaI crystal has a large well for placing up to eight proportional counters. The detector is using as anti-coincidence shield for counters and an instrument for analysis of different γ-rays sources. The result of detector response function simulation for different background sources and their registration efficiency are given.

1. Introduction

Scintillation detectors based on NaI(Tl) crystals are used as anti-coincidence shield in low-background counting systems for radiochemical solar neutrino experiments, such as SAGE [1, 2, 3] and calibration experiments with artificial neutrino sources [4, 5] based on SAGE also. In these experiments rare events of ^{71}Ge decays are registered inside small proportional counters in low-background environment during very long time. Scintillation detector has a well of cylindrical shape, where up to eight proportional counters can be placed simultaneously. ^{71}Ge itself does not produces any γ-rays at its decay. So, any event with arbitrary energy, which is registered by scintillation detector in coincidence with event in proportional counter is a background. From this point of view the role of anti-coincidence system is trivial. Nevertheless, there are few e-capture isotopes, which produces γ-rays at their decay and which has an interest either as background with cosmogenics nature (^{69}Ge and ^{68}Ga (daughter of ^{68}Ge decay)) or decay itself (^{127}Xe as a product of solar neutrinos interaction with nuclei of iodine target). In all pointed above cases it's necessary to know the response function of the scintillation detector on γ-lines and efficiencies of full and partial absorptions for energies of all these sources.

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

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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. It is completely compatible with SAGE counting system in all main parts, but its shield for proportional counters and scintillation detector for anti-coincidence system are developed anew. Therefore, knowledge of the response function and registration efficiencies of new scintillation detector are very important for further combine using of both systems in BEST.

2. Main objects of the job

Main objects of the job consists in following.

1. Build the model of real NaI(Tl)-based detector using Geant 4 simulation software and determine influence of its different components to the response function.
2. Find the model response on γ-sources (^{60}Co, ^{137}Cs and ^{22}Na) placed in calibration position and associate them with real calibration spectra.
3. Find the model response on γ-sources (^{40}K, ^{208}Tl and ^{214}Bi) uniformly distributed in the detector volume and associate them with real background spectra.
4. Find the model response on gamma-sources (^{68}Ga, ^{69}Ge and ^{127}Xe) placed in the position of proportional counter inside the detector well.
5. Calculate efficiencies of full and partial absorptions for energies of all these sources in the detector.
6. Determine possible sources of increased background of the detector.
7. Explain some peculiarities of measured spectra.

3. The detector description

The detector is based on NaI(Tl) scintillation assembly, developed and produced by "Amkris" (Kharkov, Ukraine) according to technical task from INR RAS. It has cylindrical shape ⌀200×200 mm with large well ⌀100×150 mm. The detector is developed as low background device. So, the envelope and all main parts of the detector made of stainless steel. Teflon is used as light reflector. The detector volume is viewed through four quartz windows by 3-inch photomultipliers (PMTs) model ET9757QL. Volume of the detector is 5105.1 cm^3, mass is 18.74 kg. Due to complex shape and complicated conditions of light collection the measured value of energy resolution depends on different conditions of the detector irradiation by external calibration γ-source. Therefore, the value of energy resolution $R = 7.6\%$ was obtained from the ^{40}K peak (1460 keV) of the detector background spectrum (see section 5, figure 3). Measured rate of background inside passive shield is $V_{bg} = 3.24 \pm 0.03$ s^{-1} (E_γ = 40–3500 keV).

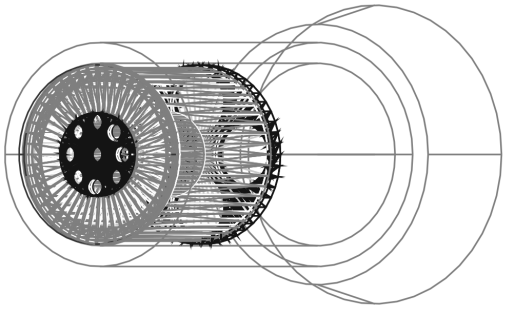

Figure 1. Graphical presentation of the detector model.

NaI(Tl) scintillation assembly is enclosed inside "intermediate" copper shield. It consists of cylindrical layer with length of 495 mm and wall thickness of 25 mm surrounded the assembly, 22 mm bottom cover of complex shape and 130 mm upper conical cover with near diameter of 314 mm and distant diameter of 360 mm. Graphical presentation of the detector model based on real design scheme is shown on figure 1.

4. The model description

The detector model is developed using Geant 4 simulation software (patch 10.2.0)[2].

The model includes next objects (or "volumes"): NaI(Tl) crystal, reflector (Teflon), damper (Teflon), stainless steel case, quartz windows, copper elements of passive shield described above.

Software description of mentioned "volumes" is maintained in `DetectorConstruction` file. Sensitive volume of the detector is defined by `SensitiveDetector` function which is created by subroutine of the same name. `SensitiveDetector` function accepts a parameter in the form of defined "volume" and creates sensitive region for calculation of energy loss produced by ionization particle. Calculation of energy loss and type of secondary particles is provided by `DetHit` and `DetEventAction` subroutines. Registered portion of energy is stored in corresponding bin of histogram, which is recorded to ASCII data file at the end of simulation for further analysis.

The physics of processes and interactions is provided by `DetPhysicsList` subroutine, which includes the library `G4EMLOW6.48` with data files of low energy electromagnetic processes. The "Livermore physics" is used as a model of interactions in our case. Based on [8] the library `G4RadioactiveDecay4.3.2` with data files of radioactive decay and hadronic processes is included also for modeling radioactive decay of different nuclei.

Radioactive source in any form is created by subroutine `DetPrimaryGeneratorAction`. This subroutine was modified for using together with `The General Particle Source` (GPS) system. This system of commands allows to generate a source of different shape, size and activity. For applying of these commands enough to create a special macros and changes in this macros does not requires recompiling the whole project. Using GPS, the ions of all mentioned in section 2 isotopes were generated.

For graphical presentation of the detector model `OpenGL` libraries are used. At the same time the files of special format `.heprep` are created. These files contains information about coordinates of "volumes" used in the model, coordinates of particle tracks and information about their nature. This type of files is intended for visualization system `HepRep` (Generic Interface Definition for HEP Event Display Representables). `HepRep` system allows to work with the graphical model of the detector and tracks of particles off-line.

5. Result

Calibration spectra of the detector are shown on figure 2. Efficiencies of registration for calibration sources are given in table 1. Calibration procedure carried out using sources without collimation at 1 m distance from the bottom along the detector axis. The detector was located inside "intermediate" copper shield (see section 3) in position above opened passive shield of the counting system (massive construction of lead and steel). The detector model does not includes many of these instants. Also, the model does not maintains now the processes of light collection and absorption inside the detector volume with simplification purpose. So, there is some difference between real and model spectra outside the peaks of full absorption. But inside the peaks conformity is sufficient and information about energy scale and resolution was taken from here. The values of efficiencies in this case are small because of long distance to the sources. The last column in table 1 represents the efficiencies of partial absorption with any energy release in the detector volume.

The background spectrum, basic model background components and their superposition are shown on figure 3. The detector was enclosed inside passive shield. All model components are uniformly distributed over the detector volume except ^{40}K. It has two sources. First one is located on the surface of quartz windows (imitation of the PMTs background). Second one is distributed over NaI(Tl) volume. The aim is investigation of reasons of increased

[2] https://geant4.web.cern.ch/geant4/

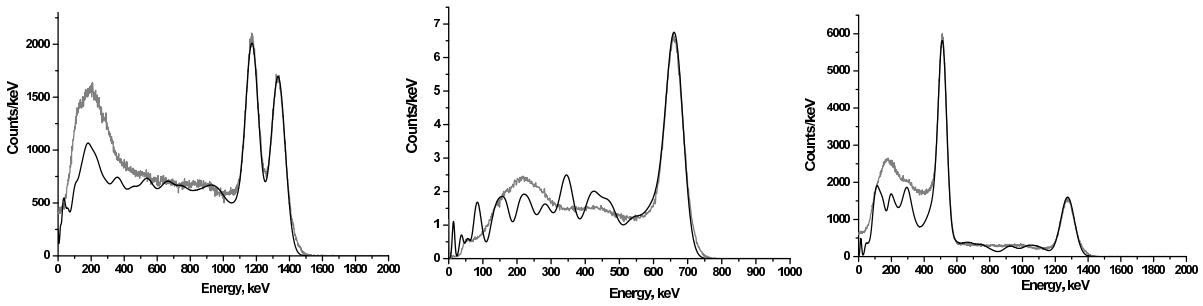

Figure 2. Calibration spectra from different γ-sources, from left to right: ^{60}Co, ^{137}Cs and ^{22}Na. Grey lines — real spectra, black lines — model spectra.

Table 1. Efficiencies of registration for calibration sources (%).

Energy, keV	511	662	1173	1274	1332	Abs. Eff.
^{60}Co	—	—	0.029	—	0.028	0.183
^{137}Cs	—	0.043	—	—	—	0.150
^{22}Na	0.115	—	—	0.054	—	0.440

detector background compare to the same in the counting system for SAGE. In a case of ^{214}Bi isotope only γ-lines with the probability of occurrence more than 1% were generated[3]. This was done to reduce total computing time. Again, there is some difference between real and model spectra outside the peaks, in primary at low energies. Comparison of the shapes of ^{40}K background components shows that its origin is disposed mainly in the PMTs, not in the the detector volume itself. Otherwise the peak for energy 609 keV from ^{214}Bi would be invisible. It is one of the reasons to replace the PMTs in near future. Modeling is shown that ^{208}Tl background γ-source (^{232}Th origin) have not peak of full absorption it the detector of such geometry, therefore its peak is invisible on real background spectrum.

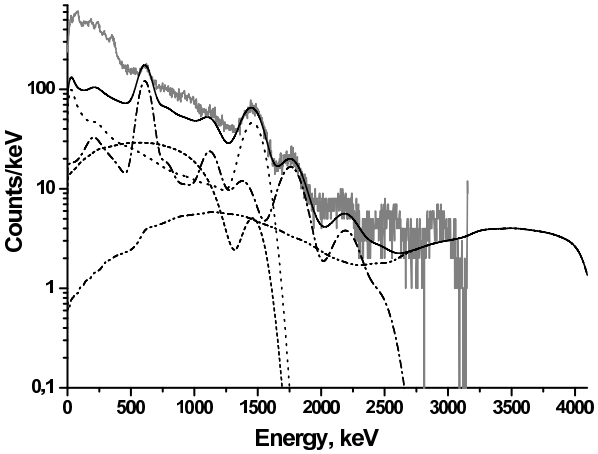

Figure 3. Background spectra. Grey line — real spectrum, black lines: (——) — sum of the model components, (· · · · · ·) — ^{40}K from PMTs, (— · —) — ^{214}Bi, (— · · —) — ^{208}Tl, (– – –) — ^{40}K from the detector volume.

The model response on different γ-sources in a place of proportional counter is shown on figure 4. Geometry and positioning of the sources inside the detector well corresponds to the same for proportional counter. Calculated efficiencies of registration for these sources are given in table 2. Data in the last column has the same sense as in table 1. Modeling is shown that complex geometry of the detector does not prevents one to count these sources with high enough efficiency. Given result should be compared with real data from the counter filled with ^{69}Ge and ^{127}Xe contamination in the future.

[3] http://www.nndc.bnl.gov/chart/

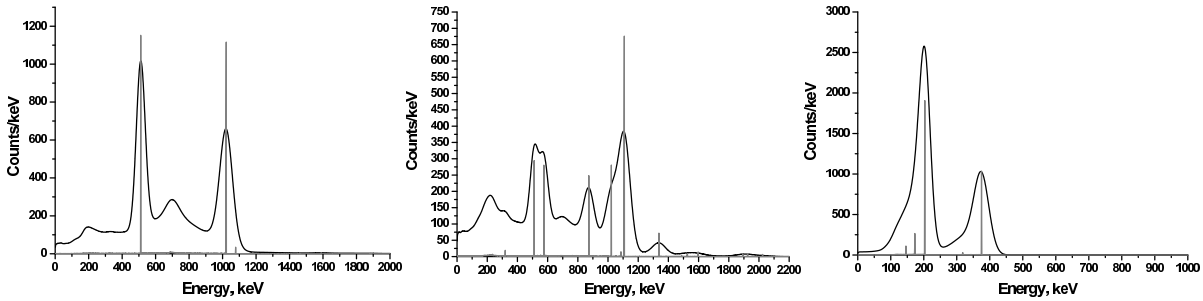

Figure 4. Model response on different γ-sources in the place of proportional counter, from left to right: ^{68}Ga, ^{69}Ge and ^{127}Xe. Grey lines — model response, black lines — model response with consideration of energy resolution of real detector.

Table 2. Efficiencies of γ-lines registration for sources in the place of proportional counter (%).

Energy, keV	145	172	203	375	511	574	872	1107	1336	1460	Abs. Eff.
^{127}Xe	43.0	17.2	46.2	99.5	—	—	—	—	—	—	78.7
^{69}Ge	—	—	—	—	10.5	35.0	34.5	31.0	27.0	—	69.5
^{68}Ga	—	—	—	—	10.5	—	—	—	—	—	87.5
^{40}K	—	—	—	—	—	—	—	—	—	28.0	77.0

6. Conclusion

The job is mainly done with the detector of the registration system for BEST, but model can be easy applied to the detector of the SAGE registration system with corresponding adjustment. This is only the beginning of a large job. It will be continue for the detector of the SAGE registration system, which has another geometry, shield and environment. These results are important for further using of both systems in BEST.

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