Simulation of background reduction and Compton suppression in a low-background HPGe spectrometer at a surface laboratory

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Abstract: High-purity germanium (HPGe) detectors are well suited to analyse the radioactivity of samples. In order to reduce the environmental background for an ultra-low background HPGe spectrometer, low-activity lead and oxygen free copper are installed outside the probe to shield from gamma radiation, with an outer plastic scintillator to veto cosmic rays, and an anti-Compton detector to improve the peak-to-Compton ratio. Using Geant4 tools and taking into account a detailed description of the detector, we optimize the sizes of these detectors to reach the design requirements. A set of experimental data from an existing HPGe spectrometer was used to compare with the simulation. For the future low-background HPGe detector simulation, considering different thicknesses of BGO crystals and anti-coincidence efficiency, the simulation results show that the optimal BGO thickness is 5.5 cm, and the peak-to-Compton ratio of ^{40}K is raised to 1000 when the anti-coincidence efficiency is 0.85. In the background simulation, 15 cm oxygen-free copper plus 10 cm lead can reduce the environmental gamma rays to 0.0024 cps/100 cm^3 Ge (50 keV–2.8 MeV), which is about 10^{-5} of the environmental background.

Key words: HPGe, Geant4 simulation, gamma background, anti-compton ratio

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1 Introduction

High-purity germanium (HPGe) detectors are widely used in different fields of experimental research, such as neutrino experiments and dark matter experiments. Due to their high energy resolution and efficiency, HPGe detectors are also used to analyze the radioactivity of materials. The Institute of High Energy Physics, Beijing (IHEP) built a HPGe detector three years ago, used for the low-radioactivity materials selected for the Daya Bay experiment. The future Jiangmen Underground Neutrino Observatory (JUNO) experiment, however, has a much stricter requirement for low background, beyond the reach of the current HPGe detector, so an ultra low-background HPGe spectrometer is required. This plays a very important role in minimizing the background, i.e. the natural radioactivity from the lab materials and cosmic rays. To reduce the adverse effects of cosmic rays [1, 2], and improve the ability to detect uranium and thorium, there are some general techniques which can be used, such as moving underground or into a cave, or using high purity and high density materials such as low-background lead and oxygen-free copper to shield the detector from gamma rays. These methods, however, are costly and inconvenient. Most surface labs add cosmic veto detectors and shielding materials to reduce the integral background count-rate of the HPGe spectrometer. The Compton plateau can be removed, further reducing the background, by placing an anti-Compton detector around the HPGe probe. It is impossible to completely remove the background, especially cosmic ray muons, at a surface lab. The environmental gamma background, with energy below 3 MeV, can be mostly suppressed by proper shielding materials, so it is crucial to accurately estimate the dimensions. Based on Geant4 Monte-Carlo simulation, relatively accurate geometry parameters can

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be obtained. In this article, we simulate the environmental gamma background and cosmic ray background and use a set of experimental data to check this simulation. Furthermore, suitable dimensions of components for a new HPGe detector, such as shielding lead and BGO crystal, are optimized.

2 Simulation and experiment

The environmental background can be roughly divided into two parts:

1) Cosmic rays, consisting of muons, neutrons and other nucleonic components;

2) α, β and γ rays, some of which come from the decay of radioactive elements (^{232}Th, ^{238}U, ^{60}Co, ^{40}K and so on) in the room materials, and others of which are secondary particles from the interaction between background radiation and materials. As the α and β rays have short radiation lengths, γ rays become the main background.

In this simulation, the minority components of cosmic rays, such as the nucleonic components, were ignored, as well as the material radioactivity from the spectrometry. We just consider the environmental gamma background and the muons and neutrons from cosmic rays.

A well-type HPGe detector from Canberra was used to check the simulation results. Its relative efficiency is 40% and crystal volume is 170 cm^3. The probe is shielded with 15 cm thickness of oxygen-free copper, which is divided into six layers with each layer being 2.5 cm thick; the inner volume of the copper shield is 35 cm×35 cm×55 cm. Fig. 1 shows the spectrometer setup. By adjusting the copper plate shielding layers, the shielding effect can be tested and the simulation results compared with these data for verification.

2.1 Gamma background simulation

For the surface HPGe detector background simulation, traditional γ background simulation methods in Geant4 [3] usually have three steps. The first step is to construct the physics list file, and add the appropriate physical processes in accordance with the purpose of the simulation.

The second is to build the geometry, not only of the spectrometer but also of the room layout; the more detailed the geometry, the more accurate the simulation results. The last step is the particle generator, which is the most important; usually just natural radiation from the radon, ^{40}K, uranium and thorium series are considered. For these simulations, the first two steps are relatively simple, no matter how complex the room is. The third step is the most difficult, in two aspects: the initial position of the radioactive decays and the radioactivity levels of various objects in the room - these data are difficult

Fig. 1. (color online) HPGe spectrometer with 15 cm copper shielding.

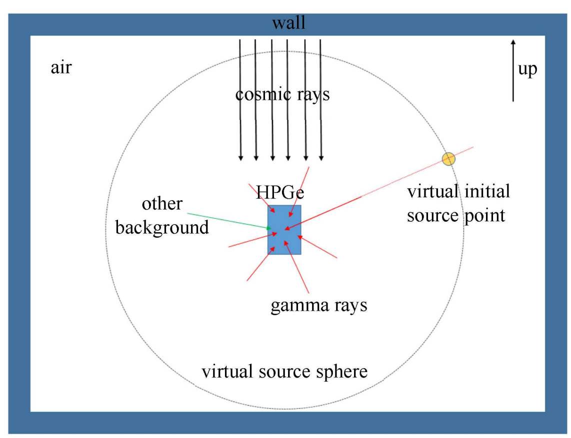

Fig. 2. (color online) Virtual source sphere surrounding HPGe.

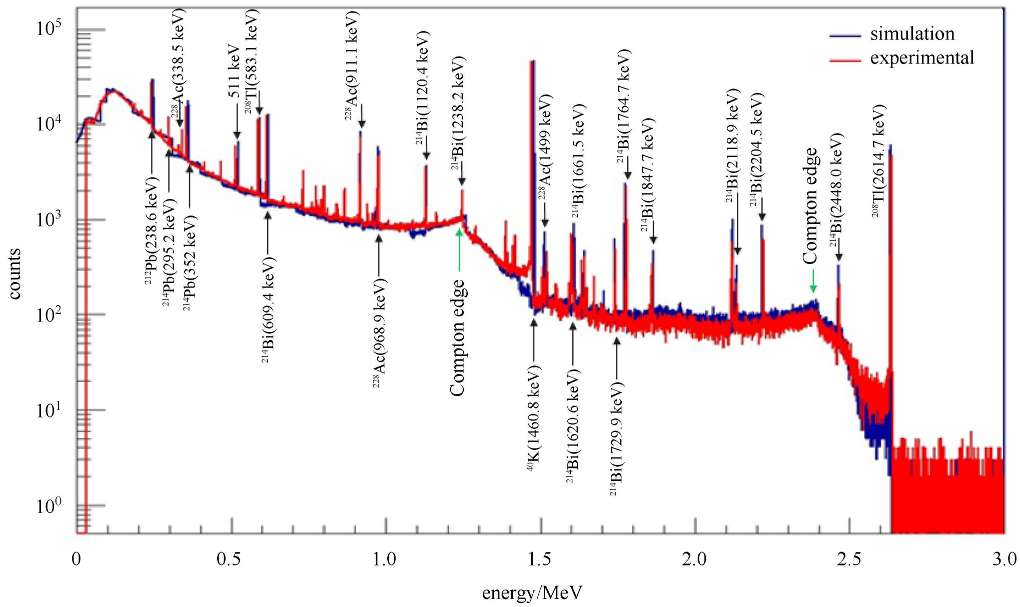

Fig. 3. (color online) Experimental and simulated γ ray spectrum of detected background from unshielded HPGe detector.

to obtain.

Because of the lack of data for the third step, a measured gamma background spectrum from another HPGe detector was used to obtain the original gamma spectrum. To anti-solve the HPGe tested gamma spectrum, we need two parameters: one is the gamma ray count rate, the other is the corresponding detection efficiency. Because the second parameter is related to the initial position of the gamma photons, which could come from the room walls, tables, equipment and so on, it is hard to get an accurate position and in fact it is not necessary to know it; a virtual initial point around the HPGe probe is enough. Imagine a closed surface surrounding the HPGe detector, which can be any shape such as a sphere, cube or some other more complex surface; different surfaces will bring out a different original virtual gamma spectrum. We chose a spherical surface, as shown in Fig. 2. Every gamma photon entering into the probe will have a crossing point on the sphere, which is assumed to be the gamma ray initial position. Using the General Particle Source (GPS) tool from Geant4, combining the detection efficiency and energy resolution of the probe, we simulate the full energy peak efficiency and Compton plateau efficiency of specific gamma rays, then anti-solve the tested gamma spectrum and get the virtual gamma background spectrum.

First, we measured the background spectrum in the laboratory without any shielding, analyzed it and then calculated the original spectrum of the virtual source sphere. The calculated spectrum varies with the shape of the probe and the radii of the virtual source sphere. Fig. 3 shows the experimental spectrum compared with the simulation spectrum. There are many peaks, most of which are radiation from ^{214}Bi, ^{208}Tl and ^{228}Ac, the daughters of ^{238}U and ^{232}Th. It is easy to find two main peaks, ^{40}K at 1460.8 keV and ^{208}Tl at 2614.7 keV. The Compton edges and Compton plateaus of these two peaks are obvious, while the escape peaks are small. Ignoring some small peaks, the simulated and experimental data are consistent with each other. Some simulated peaks, however, are offset a little compared to the experiment, due to the non-linearity of the ADC conversion. In the unshielded HPGe simulation, the direct impact of cosmic rays on the HPGe probe is ignored, because the count rate of the integral background below 3 MeV induced by cosmic rays is only one five-hundredth of the γ ray background.

Secondly, we changed the thickness of the copper shielding and simulated the shielding effect. Limited by

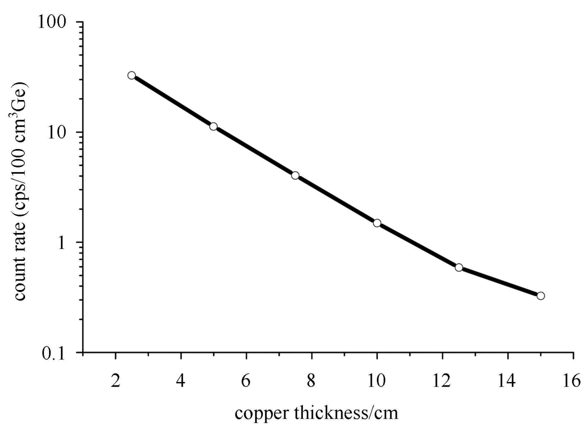

Fig. 4. Simulation of room environment γ rays integral background shield with different thickness copper.

the experimental conditions, the bottom side as the support device was set as 15 cm, and only the other five sides were tuned. Fig. 4 presents the count rate of the integral background from 50 keV to 2.8 MeV. The simulation results show that the background is obviously suppressed when the thickness of copper shielding increases, and the logarithm of the count rate has a linear relationship with the copper thickness. When the copper shielding is 15 cm thick, the integral background of room gamma rays is reduced to about 0.3 cps/100 cm^3 Ge, which is about one-thousandth of the level without any shield.

2.2 Cosmic ray simulation

Cosmic rays induce background arising from the interactions of nucleons and muons with materials surrounding the germanium detector. Particles penetrating the lead and copper shielding produce a background in the detector. The muon spectrum at sea level has been measured in many experiments, but the results are not the same in different regions due to the different geographical environments. Cosmic data measured at Beijing [4, 5] have been used to generate the direction and energy distribution of cosmic ray particles. Fig. 5 is the simulated muon particle spectrum.

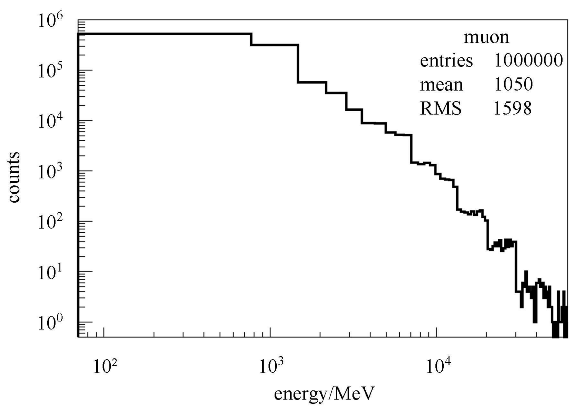

Fig. 5. Simulated cosmic muon spectrum (1 million particles).

As for the cosmic neutron or cosmic induced neutron background, data measured at Yorktown [6] were used, because Yorktown has a similar latitude and altitude to Beijing, so the ground cosmic ray neutron intensity should be similar. Fig. 6 is the neutron spectrum simulated according to the data. The spectrum has three broad peaks: a high-energy peak centered at about 100 MeV and extending up to about 10 GeV, a nuclear evaporation peak centered around 1 or 2 MeV, and a thermal peak about 10^{-8}–10^{-7} MeV.

The background caused by cosmic rays includes direct and secondary particle influences, with the secondary particles giving the largest contribution to the background spectrum. A plastic scintillator is usually placed around the HPGe detector as a cosmic veto detector to shield against this background. By adjusting the appropriate gate width and gate length, the best anti-coincidence effect can be tested. Fig. 7 shows the distribution of cosmic generated gamma particle lifetimes at the probe surface; it is clear that most are less than 10 μs, while for a traditional HPGe spectrometer, the molding time of the preamplifier is about 6–8 microseconds.

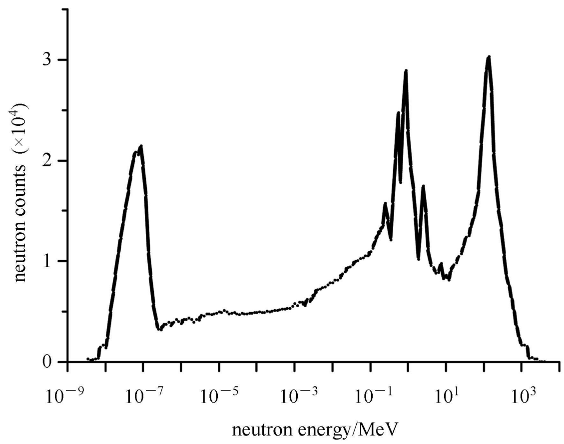

Fig. 6. Simulated cosmic neutron spectrum (1 million particles).

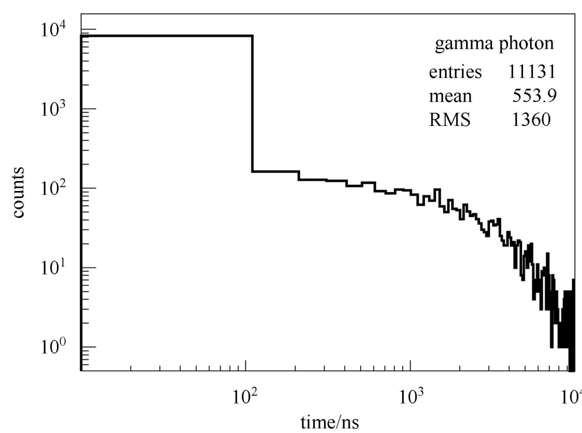

Fig. 7. (color online) Simulated cosmic generated gamma particle lifetimes.

Figure 8 shows the simulation results. The background induced by cosmic muons reaches a maximum at 5 cm thickness of copper, then decreases slowly with increasing the copper thickness. The dash lines show the proportion of particles in the range 50 keV–2.8 MeV compared to the total background count rate (30 keV–∞); the percentage is about 40% at 2.5 cm copper and increases to 50% when the copper is thicker. This means there is about 50% background outside our energy range of interest. These background particles will bring a little system dead time but do not influence the sample analysis. For the neutron induced background, the simulation results show that the count rate decreases with the increase in copper thickness, and the dash line shows that there are only 20% outside our energy range of interest. In addition, the neutron induced background is about one-tenth of the muon background.

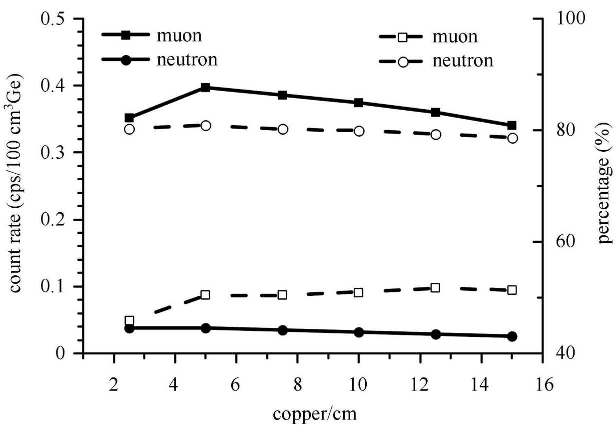

Fig. 8. (color online) Simulated cosmic induced background. Solid lines are cosmic (muon and neutron) generated background count rate (50 keV– 2.8 MeV, left y axis), dash lines are the percentage compared to all background count rates (30 keV– ∞ right y axis).

2.3 Comparison between simulation and experimental data

By changing the copper thickness from 2.5 cm to 15 cm in 2.5 cm intervals, the test data of integral background count rate was acquired. There the radon radioactivity should be considered.

Radon is a naturally occurring gas with a half-life of 3.8 days, produced continuously from the natural decay of ^{238}U, which is distributed all over the earth. As a consequence, ^{222}Rn and ^{220}Rn are the main sources of internal radiation exposure to human life, and their decay daughters also generate background radiation. Measurements of radon concentration have been performed in many parts of the world [7–9], with the results strongly affected by geological and geophysical conditions. The indoor radon level in Beijing is about 20–60 Bq/m^3, with the average about 35 Bq/m^3 [10]. Because the radon inside the detector was not taken into account in the virtual spectrum, its radiation should be simulated separately. Taking into account the radon and its daughter particles, considering the internal space of the detector, the simulation results show that the background caused by radon is about 0.27 cps/100 cm^{3}Ge; this simulation result is based on the data provided by the literature. Because the radon level of our laboratory is not available, the simulation result of radon radioactivity is untrusted. One way to remove the radon is to replace the air with pure nitrogen; then, by testing the background radiation in the two situations, the radioactivity due to radon can be determined. For our laboratory, the integral background without nitrogen injection is about 1.112 cps/100 cm^{3}Ge, and after 5 hours' nitrogen injection, the number is down to 0.866 cps/100 cm^{3}Ge, so the radon radioactivity is 0.246 cps/100 cm^{3}Ge.

Table 1 presents the count rate of integral background from 50 keV to 2.8 MeV. The gamma background is obviously suppressed when the thickness of copper shielding increases, while the cosmic induced background changes little, so the influence of cosmic rays dominates when the copper is thicker.

Table 1. Integral background count rate (50 keV–2.8 MeV) comparison between data and simulation.

copper	simulation (cps/100 cm^{3}Ge)				experiment data	Sim./Exp.
thickness/cm	gamma	muon	neutron	sum	(cps/100 cm^{3}Ge)	(%)
2.5	32.87	0.351	0.045	33.27	37.14	89.6
5.0	11.23	0.398	0.045	11.67	13.70	85.2
7.5	4.049	0.386	0.041	4.48	4.88	91.8
10	1.494	0.374	0.037	1.91	2.14	89.3
12.5	0.590	0.360	0.035	0.99	1.13	87.6
15	0.326	0.340	0.031	0.70	0.79	88.6

The simulation results are lower than the data, the difference being about 15% for a 5.0 cm thick layer and 12% for other layers. The inconsistency comes from the following aspects: the virtual source spectrum is not entirely accurate; the unconsidered cosmic ray components could make the simulation results lower than the test data; the simulation program codes could have some slight error when simulation conditions such as simulation times and initial particles are changed. Even though there is a slight difference, the simulation can be used to estimate the thickness of the outer shield materials and find the optimal dimensions of the HPGe spectrometer.

3 Simulation result of new detector

For a surface HPGe detector, the background is only suppressed to about 1 cps/100 cm^{3}Ge (50 keV–2.8 MeV) by 15 cm thick copper. Such a background level is suitable for testing ordinary objects, but not for many low background samples. Therefore, a new ultra low-background HPGe spectrometer, as shown in Fig. 9, is under construction. Compared with the old spectrometer, the new one has three advantages: the active cosmic ray shielding detectors made of plastic scintillator; the lead layers around the copper; and the anti-Compton detector made of BGO crystal. With the Geant4 simulation code, the dimensions of the BGO crystal and the lead layers have been optimized.

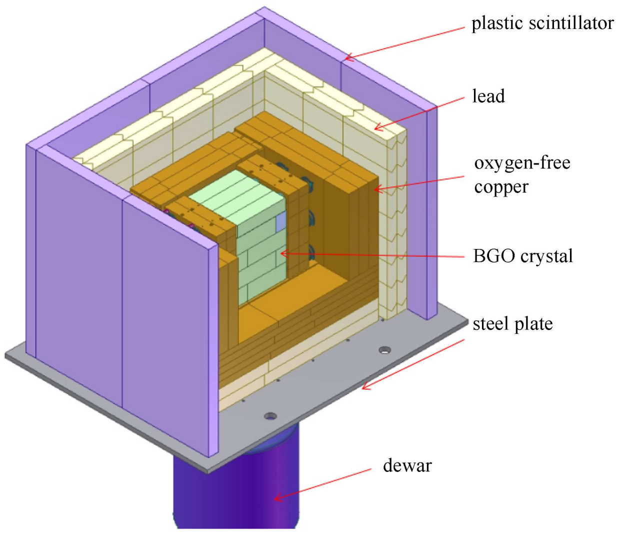

Fig. 9. (color online) Sketch of low background anti-Compton γ spectrometer.

In the middle of the spectrometer is a four-inch well-type HPGe detector from Canberra with a relative efficiency of 120%. The resolution is 2.1 keV at 1.33 MeV. The nominal size of the Ge crystal is 86.3 mm diameter and 85.8 mm height with a 4.89 mm front gap, and the aluminum shell is 1.5 mm thick. Outside the probe is an anti-Compton detector made from 22 BGO crystals. Each BGO crystal couples with a 2 inch low-background PMT for a single readout, and the inner volume of the BGO crystals is 14 cm×14 cm×30 cm. Surrounding the BGO crystals are sheets of oxygen-free copper and lead to shield the γ background. The cosmic veto detector is made of a plastic scintillator, which is installed as the outermost layer and covers all sides except the bottom.

3.1 Anti-Compton detector simulation

Usually, the sample will be placed on the top surface of the probe for measurement. The gamma rays from the sample come into the probe, and lose energy by the Compton effect. If the γ particle is completely captured by the probe, a full energy peak will be obtained. In most cases, because of Compton scattering, the γ particles penetrate through the probe depositing only a part of their energy - these are Compton plateau events, which are useless for the radioactivity analysis, and sometimes even increase the errors. An anti-Compton detector surrounding the HPGe probe helps to veto those events and improve the detecting ability of the spectrometer.

Early Compton suppressors were usually based on the NaI scintillator for its high light output and large size, but NaI crystal is a little deliquescent and its radiation length is relatively short. For a low-background HPGe spectrometer, a bigger inner detector will increase the dimensions of the shielding materials, and result in more weight and background for the spectrometer. We chose the $Bi_4Ge_3O_{12}$ (BGO) scintillator as the anti-Compton detector, for its high density (7.13 g/cm^3). It offers an γ-ray absorption coefficient which is about 2.5 times greater than that of NaI. Although the resolution of BGO is poorer, as a veto detector, the detection efficiency is more important, and on this point BGO is better than NaI and CsI crystals [11].

The anti-Compton detector was designed like a cubic shell by using 22 BGO crystals. The precise dimensions and relative position of the BGO crystals to the HPGe probe were described in simulation. A point ^{40}K source was placed 2.5 cm above the top surface of the HPGe, and the energy resolution was set at about 2.1 keV at 1460.8 keV. One way to improve the peak-to-Compton ratio is to increase the detecting efficiency of BGO by using thicker and brighter crystals; another is to increase the anti-coincidence efficiency. Fig. 10 shows the simulation results considering the two factors. It is obvious that the peak-to-Compton ratio increases with the increase of BGO thickness, and 5.5 cm is a key point, after which the Compton suppression improves a little. For the ideal anti-coincidence efficiency 1.0 (100%), the upward

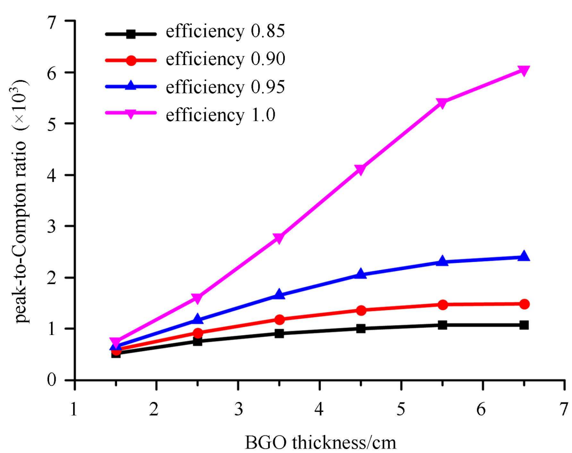

Fig. 10. Peak-to-Compton ratio of ^{40}K 1460.8 keV γ as a function of BGO thickness at different anti-coincidence efficiencies.

Table 2. Simulation count rate of integral background (50 keV–2.8 MeV) shielded by lead.

lead thickness/cm	simulation(cps/100 cm^3Ge)				
	gamma	muon	neutron	cosmic veto(97%)	sum
2	0.1139	0.3262	0.0291	0.01066	0.1246
4	0.0351	0.3129	0.0290	0.01026	0.0454
6	0.0119	0.3087	0.0286	0.01012	0.0220
8	0.0032	0.2970	0.0266	0.00971	0.0129
10	0.0024	0.2885	0.0270	0.00946	0.0118
12	0.0008	0.2757	0.0252	0.00903	0.0098

trend also slows down after 5.5 cm, and the peak-to-Compton ratio is almost the same at 5.5 and 6.5 cm thickness when the anti-coincidence efficiency is below 0.9 (90%). The electronics system affects the anti-coincidence efficiency a lot in the real measurement. By adjusting the gate width and relative time corresponding to the probe signals, the optimal working status can be obtained.

3.2 Lead shielding simulation

Because low-background lead is so rare, we chose ordinary lead plus oxygen-free copper to shield the γ rays. Oxygen-free copper has lower radioactivity than other materials, and when placed on the inner side of the lead can shield from the background due to the lead material. The most important performance index of the new low-background HPGe spectrometer is that the integral background count rate from 50 keV to 2 MeV is lower than 0.01 cps/100 cm^3Ge crystal, so environmental γ-rays, as one source of background, must be reduced to a tenth or a fifth of the orignal level. Table 2 shows the simulation results of environmental gamma and cosmic muon background after shielding with different thicknesses of lead; 10 cm of lead reduces the gamma background to 0.0024 cps. As for the cosmic background, the simulation results show that with 10 cm of lead, the muon background is 0.2885 cps/100 cm^3Ge and neutron background is 0.027 cps/100 cm^3Ge. According to our results above, five sides covered by the 5 cm thick plastic scintillator can reduce more than 97% of the cosmic ray induced background; Table 2 shows that 10 cm thick lead with the 5 cm cosmic ray veto detector is even better.

4 Summary

Low-background HPGe detectors usually use a lot of shielding materials, which leads to a heavy and difficult-to-disassemble device. Geant4 simulation is a good way to evaluate the design in advance, and optimize the dimensions of the detector. The background simulation method presented in this study is suitable for the shielding materials simulation, because the virtual source spectrum generated through the actual measurement background is fairly accurate. For our new HPGe spectrometer, the simulation results show that 5.5 cm thick BGO crystal is the optimal choice for the anti-Compton detector, and 15 cm oxygen-free copper plus 10 cm lead could suppress the gamma integral background to 0.0024 cps/100 cm^3Ge crystal, which is one fifth of the design requirement. In addition, for the real experiment, devices placed in the copper (such as cables and PMTs) are fatal background sources for the HPGe probe, so low-radioactivity types of these devices should be chosen for HPGe detectors. Furthermore, continuous pure nitrogen filling in the detector could suppress most of the radon radiation.

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