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Simulation of the response functions of an extended range neutron multisphere spectrometer using FLUKA

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Abstract: In this paper, the distribution of radiation field in the CSNS spectrometer hall at Dongguan, China, was simulated by the FLUKA program. The results show that the radiation field of the high energy proton accelerator is dominated by neutron radiation, with a broad range of neutron energies, spanning about eleven orders of magnitude. Simulation and calculation of the response functions of four Bonner spheres with a simplified model is done with FLUKA and MCNPX codes respectively, proving the feasibility of the FLUKA program for this application and the correctness of the calculation method. Using the actual model, we simulate and calculate the energy response functions of Bonner sphere detectors with polyethylene layers of different diameters, including detectors with lead layers, using the FLUKA code. Based on the simulation results, we select eleven detectors as the basic structure for an Extended Range Neutron Multisphere Spectrometer (ERNMS).

Key words: neutron multisphere spectrometer, neutron spectrum, energy response, FLUKA, ^{3}He-filled spherical proportional counter

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1 Introduction

At present three large accelerators are in operation or under construction at the Institute of High Energy Physics (IHEP), China. These are the Beijing Electron-Positron Collider, the CSNS (China Spallation Neutron Source) high energy proton accelerator and the ADS high current proton linac. The radiation field produced by high energy accelerators is complicated, as it is composed of several components such as neutrons, photons, neutrinos and so on. The field is dominated by neutron radiation, and the neutron energy varies from thermal neutrons to high energy neutrons of GeV magnitude. Measurement of neutron spectra plays an important reference and guidance role in the work of physical experiments and radiation protection. They can provide personal dose data for staff working in the radiation field, a basis for the calibration of radiation protection instruments, and reference data for the design of radiation devices.

The neutron multisphere spectrometer, which is also called a Bonner sphere spectrometer, was first introduced in 1960 by Bramblett et al [1]. A typical system consists of a series of polyethylene moderating spheres ranging from 2 inches to 12 inches in diameter, with a thermal neutron-sensitive detector placed at the center.

In order to improve the accelerator protection level, and protect the health of accelerator workers and surrounding residents, the Radiation Protection Department of the IHEP Accelerator Center is working on establishing an Extended Range Neutron Multisphere Spectrometer (ERNMS). The primary work of establishing the system is determining the structure, which can be done by reliable and accurate simulation and calculation.

In this paper, analysis of the accelerator radiation field and simulation of the response functions of the ERNMS is done using the FLUKA program [2]. FLUKA is a Monte Carlo code that covers almost all particles at nearly all energies. FLUKA covers a broad range of applications, spanning from detector design to accelerator shielding, target design, activation, dosimetry and so on.

2 Analysis of the CSNS spectrometer hall radiation field

Taking the main shielding tunnel in the CSNS spectrometer [3] hall as an example, simulation and calculation of the radiation field around the shielding wall was done with the FLUKA program.

There is a long beam tunnel of about 15 meters in the CSNS spectrometer hall. The shielding structure of the tunnel consists of a 1.5 meter thickness of stainless steel inside and 1 meter of ordinary concrete outside. The concrete and stainless steel are all underground in order to

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reduce the radiation dose from ground scattering of the workers working in the hall. A stereogram of the tunnel was created with the FLUKA program and exported by SimpleGeo [4], as shown in Fig. 1.

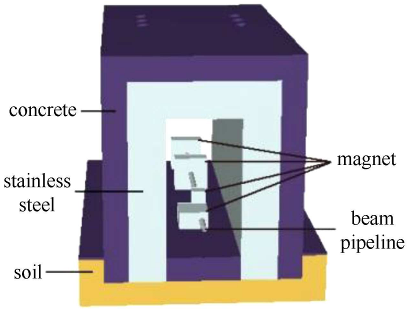

Fig. 1. (color online) Stereogram of the tunnel.

The energy of the proton beam is 1.6 GeV, and the beam loss rate is 1 W/m. In FLUKA, the type, energy, divergence, cross section and direction of incident particles are defined by the 'BEAM' card and 'BEAMPOS' card. The 1 W/m line-loss model cannot be implemented using the above-mentioned two cards, we need to write the line-loss code in FORTRAN in order to ensure homogeneous beam loss along the Z axis.

The curves of neutron and gamma dose rate along the Y axis, where the Y axis is defined as perpendicular to the wall and the beam line is at 0, are shown in Fig. 2. As we can see from the figure, the gamma dose rate is about a hundredth of the neutron dose rate in the tunnel, and after passing through the stainless steel and concrete layer, the gamma dose rate is less than a tenth of the neutron dose rate at a distance of 4 meters from the beam line. It is therefore necessary to pay more attention to neutron dose for proton accelerators.

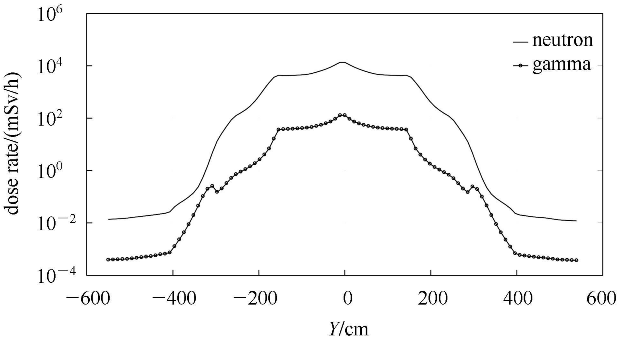

Fig. 2. Neutron and gamma dose rate along the Y axis.

Figure 3 shows the neutron lethargy spectrum for the left side of the shielding tunnel. As can be seen from the figure, not only is there a thermal peak in the neutron radiation field, but there are also two obvious peaks: the evaporation peak and cascade peak in the high energy range.

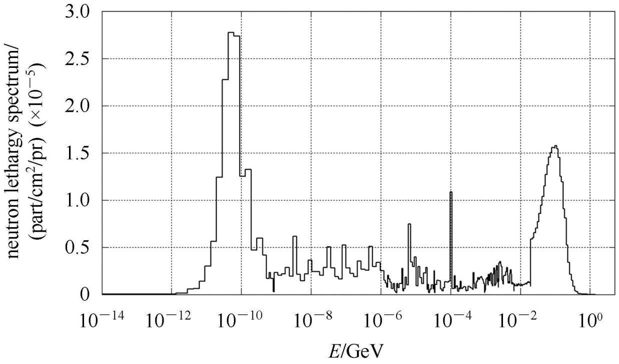

Fig. 3. Neutron lethargy spectrum for the left side of the shielding tunnel.

In order to obtain a better understanding of how neutron flux varies with energy, we divide the neutron energy range from thermal neutrons to GeV magnitude into five groups of equal logarithmic interval, and compute the integrated neutron flux for each group. The result shows that the neutron flux for energy greater than 20 MeV accounts for about 35% of the whole neutron flux.

Changing the flux integral groups to dose integral groups according to the neutron flux to dose conversion factors given by ICRP [5], we find that the dose from neutrons of energy greater than 20 MeV accounts for 50% of the total neutron dose. This requires that we not only focus on lower and middle energy neutrons, but also pay attention to high energy neutrons when measuring the neutron radiation field.

3 Simulation method and model

3.1 Operating principle

Each traditional Bonner sphere detector consists of a ^{3}He-filled spherical proportional counter which is used as the central thermal-neutron-sensitive detector or bare detector, and a polyethylene sphere used as the moderating layer. The spherical geometry can ensure the response isotropically, which is good for measurements. In order to increase the response to high energy neutrons, high Z element layers such as lead were added because of their large (n, xn) cross section for high energy neutrons.

Intermediate and low energy neutrons are slowed down mainly through elastic scattering with hydrogen and carbon in the polyethylene layer. Apart from the above moderating method, high energy neutrons are also slowed down by inelastic scattering with high Z elements. As the moderating procedure goes on, neutrons lose their energy and thermalize. Some of these moderated neutrons interact in the central detector via the ^{3}He(n, P)T reaction.

$$^3\text{He}+\text{n}\rightarrow\text{T}+P+0.765\ \text{MeV}. \qquad (1)$$

The cross section of thermal neutron with ^{3}He is approximately 5400 barns, which is quite large. Protons and tritium produced by the nuclear reaction ionize in the ^{3}He gas. After proportional amplification, the ionizing particles cause a pulse charge output in the electrodes, which is then recorded by a nuclear electronics circuit to get counts.

The response of a Bonner sphere detector to a given neutron spectrum is given by the following equation [6]:

$$N=\int_{E_{\min}}^{E_{\max}} R(E)\varPhi(E)\mathrm{d}E, \tag{2}$$

where N is the number of detector counts, $R(E)$ is the response function for the detector at energy E (counts per unit neutron fluence), and $\varPhi(E)$ is the energy-dependent neutron spectrum (n/cm^2).

The response functions can be obtained by MC simulation, while the counts can be obtained by measurement, so we can get the neutron spectrum through appropriate deconvolution methods.

3.2 Simulation methods

The energy response function of the neutron multisphere spectrometer is defined as the number of reaction counts caused by the incident neutrons of a unit flux from a parallel source; namely, as the following equation:

$$R(E)=N/\varPhi(E), \tag{3}$$

where N is the number of detector counts, and $\varPhi(E)$ is the neutron flux at energy E(n/cm^2).

For a Bonner sphere with diameter d, the response function is calculated by the following equation:

$$R_{\mathrm{d}}=a_5 n_{\mathrm{He}}\Sigma_j\phi_j\sigma_{\mathrm{n,p}}(\bar{E}_j), \tag{4}$$

where a_{s} is the cross sectional area of the incident neutron (cm^2), n_{He} is the atomic density of ^{3}He in the detector (n/cm^3), ϕ_j is the neutron flux which is recorded in the ^{3}He tube (n/cm^2), and $\sigma_{\mathrm{n,p}}(\bar{E}_j)$ is the cross section of reaction ^{3}He(n,p)T at energy $\bar{E}_j\in(E_j,E_{j+1})$ (cm^2).

The neutron flux in the ^{3}He tube was recorded by the USRTRACK card of the FLUKA code, while the nuclear cross section data came from international neutron libraries [7]. The response functions for each detector were calculated using 39 energy points (3 points per decade, 1.0×10^n, 2.0×10^n, 5.0×10^n) from 0.001 eV to 5 GeV.

3.3 Method validation

By adopting a simplified model and choosing four detectors with diameters of 0 (i.e. the bare detector), 6.5, 17 and 34 centimeters respectively, FLUKA and MCNPX [8] programs were used to simulate the response functions of neutron energy from 0.001 eV to 20 MeV. Fig. 4 shows the simulation results. As we can see from the figure, the two curves are largely consistent. Considering the difference in how events are simulated between the two programs, this tiny error is acceptable. It proves that it is feasible to use the FLUKA code to simulate the response functions of neutron detectors and that the corresponding calculation method is correct.

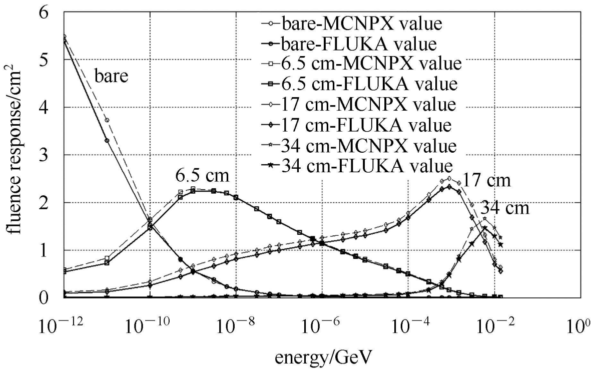

Fig. 4. The differences between FLUKA and MCNPX simulation results. The dotted curve represents MCNPX results, while the solid curve represents FLUKA results.

3.4 Simulation model and related parameters

Figure 5 shows the actual model of the Bonner sphere used for simulation and calculation. A ^{3}He-filled spherical proportional counter (type 27036, LND Ltd, USA) is used as the central thermal neutron-sensitive detector. The shell is stainless steel and the inside and outside diameters are 1.96 and 2 inches. There is a lead layer and related brace (called a stem) at the top and bottom. The pressure of the ^{3}He gas is five atmospheres and the ^{3}He atomic density is 12.525×10^{19} atoms/cm^3. The densities of the moderating material, polyethylene (PE), and the compensating material, lead, are 0.92 g/cm^3 and 11.35 g/cm^3 respectively. Outside the PE is air. The outermost layer of the simulation is a blackhole region, which is not shown in the figure. The cross section of the

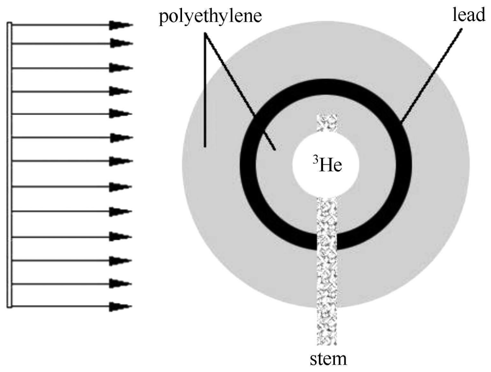

Fig. 5. Actual model of the Bonner sphere used in simulation of the neutron multisphere spectrometer.

incident neutron beam is circular, with the radius equal to the maximum radius of the detector. The neutrons are not tracked once they go into the blackhole region. In order to improve accuracy, the number of incident neutrons is set to 10 million. An improper variance reduction technique will reduce the precision of the calculated results, so we do not use a variance reduction technique.

4 Simulation results and analysis

The fluence response functions of a number of traditional Bonner detectors with different diameters are shown in Fig. 6. We can get the following conclusions from the figure: the naked detector, which has no moderating and compensating materials, has a significantly large response for the thermal neutrons, whose peak value is about twice that of other detectors' peak values; with the increase of diameter of the polyethylene layer, the peak of the curve moves from low energy to high energy, with the peaks gathered around two areas, which are around 10^{-8} GeV and 10^{-3} GeV respectively; for the larger detectors, such as detectors of 15 or 18 inches, their overall response is relatively low; for all the detectors, the response at high energy is very low.

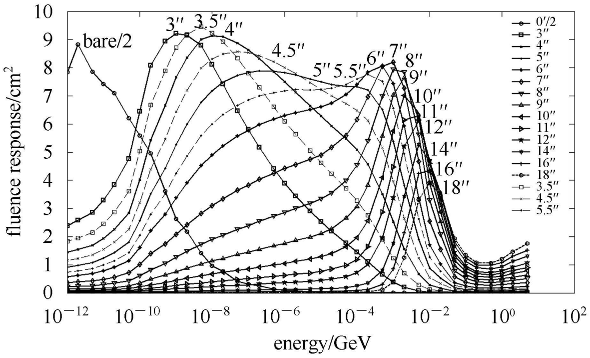

Fig. 6. Calculated fluence response, as a function of neutron energy, for a number of traditional Bonner detectors with different diameters.

Figure 7 shows the fluence response functions of several detectors with lead layers. As a comparison, the figure also includes the curves of the response functions of several traditional Bonner detectors. For neutron energies below 10 MeV, they behave like several intermediate sized Bonner detectors (5–8 inch), but above 20 MeV the responses increase significantly. This provides additional information for the deconvolution procedure in high energy fields.

A larger response means higher sensitivity for neutron detectors. The ideal composition of a neutron multi-sphere spectrometer is an unlimited number of detectors with different diameters. However, in view of the cost and practical application, only several spheres should be selected as the fundamental structure for the ERNMS. There are several selection principles to refer to: firstly, the detectors should have a large energy response, so we should focus on the peak value of each curve and the corresponding energy; secondly, the corresponding energies of the peaks of the selected curves cover as wide an energy range as possible; thirdly, the curves should be high resolution; lastly, but not least, we should grasp the balance between accuracy and usability.

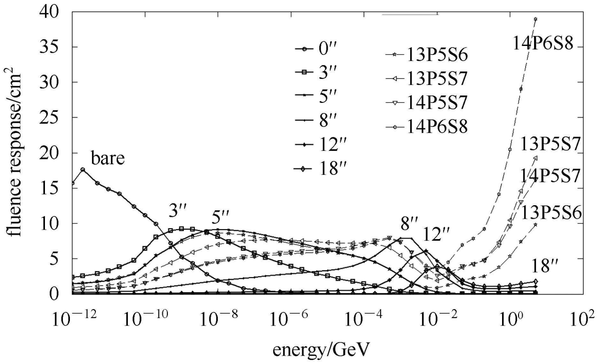

Fig. 7. Calculated fluence response, as a function of neutron energy, for several Bonner spheres and for four detectors with lead layer, e.g. the configuration “I3P5S6” consists of a ^{3}He tube placed inside a 3-inch PE sphere which is covered by a Pb shell with a 5-inch diameter, all of which are embedded in a 6-inch PE sphere.

Considering the above principles and analyzing the simulation results carefully, we select nine traditional Bonner spheres with diameters of 0, 3, 4, 5, 6, 7, 8, 10 and 12 inches respectively, and two detectors with lead layers of type I3P5S6 and I4P5S7, as the basic structure of the ERNMS system.

5 Conclusions

Measurements of neutron spectra are of important guiding significance for radiation protection workers. Through simulating the CSNS spectrometer hall, we know that neutrons are the most important radiation source in the radiation field of high energy accelerators and the neutron energies cover a wide range. The main work of this paper is to simulate the response functions of various Bonner spheres and detectors with lead layers, and through analysis of the simulation results, selecting 11 different detectors as the basic structure of the ERNMS.

Calculation of the response functions is the basis of developing an ERNMS system. It not only provides a theoretical basis for determining the structure of the ERNMS, but also yields the corresponding matrix for the later deconvolution procedure. Simulation results always need to be verified by actual experiments. The next step is to process, assemble and debug the spectrometer, and then perform related calibration and experimental work in several standard neutron source fields and accelerator fields.

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