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M-C simulation of shielding effects of PE, LiH and graphite fibers under 1 MeV electrons and 20 MeV protons

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Abstract Shielding effects of different materials under 1 MeV electron and 20 MeV proton beams were simulated with Geant4 code. It was found that shielding effects of polyethylene and graphite fibers are much better than aluminum. Energy depositions in the phantom shielded by the materials are calculated, with the least energy deposition by graphite fiber shielding. The results show that graphite fibers are good radiation shielding material in space programs.

Key words Monte Carlo method, Radiation shield, Shielding materials

CLC numbers TL71, V520.6

1 Introduction

In manned aircraft space programs, radiation dose delivered to the astronauts should be estimated, so as to evaluate radiation hazards to them and take suitable protection measures[1]. Because of limitations in experiment conditions (such as time, space and detector), however, it is not practical and convenient to make the dosimetry measurement, and computer simulation is an effective choice.

The energetic particles in the space radiation environment are mainly electrons of probably 0.11~3.5 MeV and protons from the sun [2]. In this paper, shielding effects of different materials under 1 MeV electron and 20 MeV proton beams were simulated with Monte Carlo method.

Monte Carlo codes in common use include MCNP[3], EGS4 [4], Geant4 [5], etc. In this work, we used Geant4, which was developed by European Organization for Nuclear Research to treat various kinds of particles in a wide range of energy. With abundant physical models, it has been used extensively in high-energy physics, nuclear physics, accelerator engineering, medical science, bioscience, radiation protection, etc [6].

2 The shielding materials

Space radiation protection has a number of limitations in terms of the load and cost. It is impossible to shield the space craft completely. Therefore, compromise shall be made for reducing the dose as much as possible with attainable shielding materials[7].

An ideal shield material shall have maximum number of electrons per unit mass, maximum nuclear reaction cross section per unit mass and minimum production of secondary particles. This means the materials having high hydrogen content[8].

There are two criterions to evaluate shielding effect of materials: 1) small numbers of the transmitted electrons and bremsstrahlung photons (for electron shielding), or small numbers of the transmitted protons and neutrons (for proton shielding), and 2) less energy deposition in the air or the phantom [9-12].

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Polyethylene (PE), a hydrocarbon of the highest hydrogen content, is widely used as shielding materials [13]. Hydrogen lithium is widely used as shielding material in nuclear reactors. Graphite fibers, as a material of very high hydrogen content (Table 1), can be used in spacecrafts. In the simulations, shielding materials of 2.9 mm PE, 3.3 mm LiH and 1.6 mm graphite fibers were used. They have the same equivalent thickness of 0.27 g/cm^2. Aluminum (1 mm thick), as a traditional shielding material, was also simulated for comparison.

Table 1 Elemental contents of the shielding materials

Materials	Weight fraction / %		Density / g·cm^{-3}
PE	C, 85.7	H, 14.3	0.92
LiH	Li, 87.5	H, 12.5	0.82
Graphite fibers	C, 32.4	H, 67.6	2.25

An ICRU (International Commission on Radiation Units and Measurements) phantom of 15 cm thickness and 1 g/cm^3 density was chosen as the model of body tissue. Its H, C, N and O contents are 10.1%, 11.1%, 2.6% and 76.2wt%, respectively.

3 Results and discussion

3.1 The 20 MeV proton simulation

The results are shown in Table 2, Fig.1 and Fig.2. The protons transmitted from the aluminum distribute mainly at about 14 MeV. From PE and LiH, the transmitted protons are mainly about 11 MeV. The numbers of protons transmitted from the three kinds of materials are pretty much the same. From PE, the number of neutrons, as secondary particles from (p, n) reactions, is about one tenth of that from aluminum. From the LiH, however, the neutron numbers is larger than that from aluminum. The shielding effect of the graphite fiber material is the best of all. Virtually no protons come out of it, and the neutron number is only about one fiftieth of that from aluminum.

Table 2 Number of neutrons and transmitted protons by a 20 MeV proton in unit area (1cm^2)

Particles	Materials			
	Al	PE	LiH	Graphite fibers
Transmitted protons	2.49×10^{-2}	2.49×10^{-2}	2.47×10^{-2}	0
Neutrons	1.32×10^{-4}	1.088×10^{-5}	7.12×10^{-4}	2.521×10^{-6}

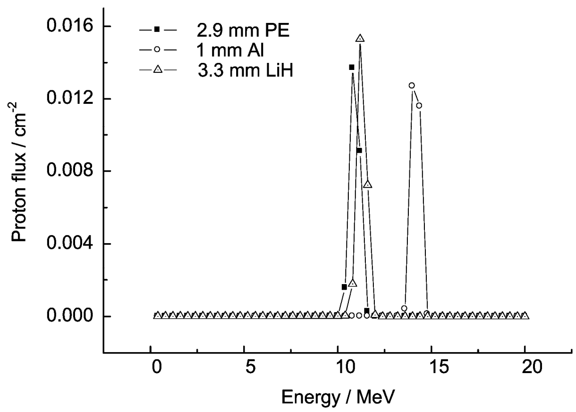

Fig.1 Transmitted proton spectra from shielding materials of the same equivalent thickness.

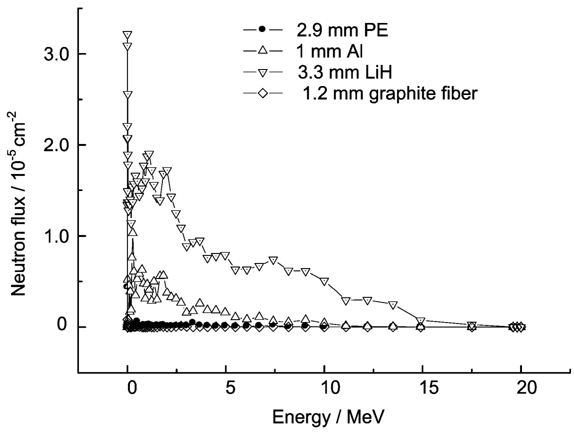

Fig.2 Neutron spectra by a 20 MeV proton in shield materials of the same equivalent thickness.

Therefore, a 1.6 mm layer of graphite fibers was chosen in the following simulations. As shown in Fig.3, a 20 MeV proton deposits 9.76×10^2 eV on the surface of the phantom shielded by graphite fibers and 4.42×10^3 eV in the bulk, while it deposits 7.36×10^4 eV on the surface and 7.74×10^4 eV in the bulk when it is shielded by 1 mm Al, a further indication of better shielding effect of graphite fibers than aluminum.

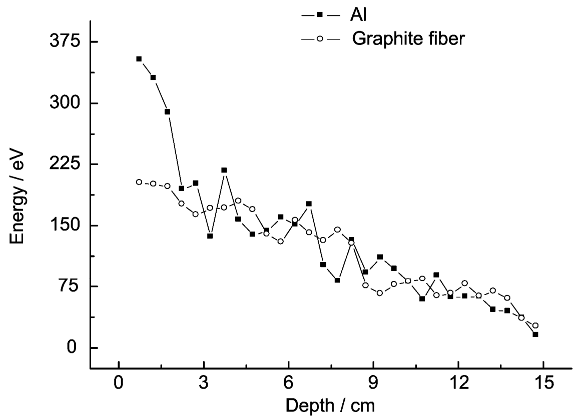

Fig.3 Energy deposition of a 20 MeV proton in the phantom shielded by Al or graphite fibers.

In comparison with normal graphite, graphite fiber material has higher hydrogen content, more compact molecular structure and higher electron density. That is why a 20 MeV proton deposits almost all its energy in it, and the neutron number is reduced effectively.

3.2 The 1 MeV electron simulation

The results of transmitted electrons and photons are given in Table 3, Fig.4, and Fig.5. The energy of transmitted electrons transmitted from aluminum distribute mainly at about 0.6 MeV. From PE and LiH, the transmitted electrons are about 0.4 MeV and 0.5 MeV, respectively. The number of transmitted electrons from PE and Al are almost the same, but the number of transmitted electrons from LiH is larger. From graphite fibers, the transmitted electrons, only about 0.1 MeV, are just one tenth as much as the number of transmitted electrons from aluminum.

The bremsstrahlung photons produced in PE is about two thirds as much as that of aluminum. In LiH and graphite fibers, the photon number is about half of PE.

Table 3 Transmitted electrons and bremsstrahlung photons by a 1 MeV electron in unit area ($1cm^2$)

Paticles	Materials			
	Al	PE	LiH	Graphite fibers
Transmitted electrons	3.77×10^{-1}	3.85×10^{-1}	5.31×10^{-1}	2.82×10^{-2}
Bremsstrahlung photons	5.45×10^{-2}	3.62×10^{-2}	1.76×10^{-2}	1.83×10^{-2}

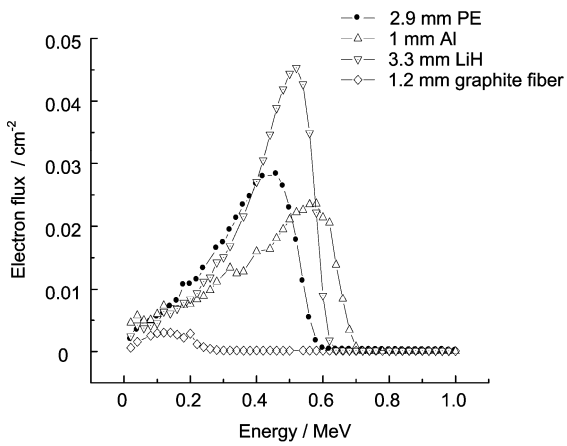

Fig.4 Transmitted electron spectra from shielding materials of the same equivalent thickness.

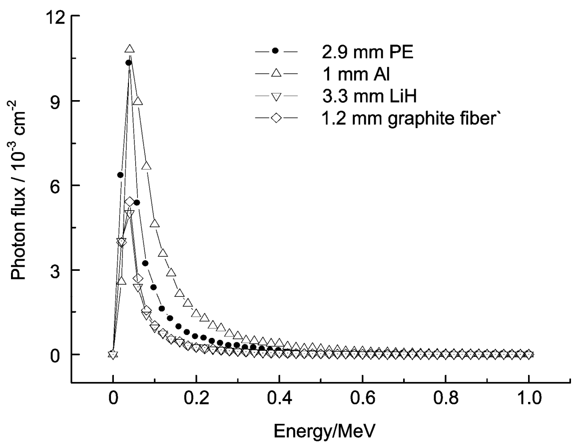

Fig.5 Bremsstrahlung spectra in shielding materials of the same equivalent thickness.

As shown in Fig.6, a 1 MeV electron deposits 2.09×10^3 eV on the surface of the phantom shielded by the graphite fibers and 2.40×10^3 eV in the bulk, while it deposits 3.88×10^3 eV on the surface and 4.72×10^3 eV in the bulk, both doubling the energy deposition in the former case.

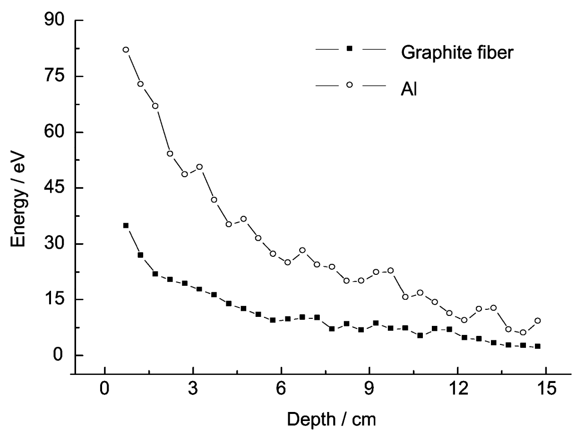

Fig.6 Energy deposition of a 1 MeV electron in the phantom shielded by Al or graphite fibers.

For different materials under electron beams, the probability of bremsstrahlung photon is proportional to the square of generating atomic number and energy of incident electrons[14]. Graphite fibers with carbon and abundant hydrogen can reduce bremsstrahlung. For primary electrons, the shielding capability of graphite fibers is also superior because of its compact structure. Therefore, graphite fiber is an efficient material for electron shielding.

4 Conclusion

In this paper, shielding effects of different materials under 1 MeV electron and 20 MeV proton beams have been simulated with MC method, and the energy deposited in the phantom offers a further validation about the shielding capability of the materials. The shielding capability of these materials can be summarized by comparing the data simulated with Geant4. Numbers of neutron and photon from PE are both smaller than that from aluminum, but other parameters are nearly the same as aluminum. For the shielding by hydrogen lithium, most parameters are dissatisfactory. Especially numbers of transmitted electrons and neutrons are both larger than that of aluminum. The shielding effect of graphite fiber is the best for shielding either electrons or protons. The superior shielding capability of graphite fiber is also validated by the simulation of energy deposited in a phantom. Graphite fiber, as a material of very high hydrogen content, can be regarded as a kind of new materials applied to radioprotection in theory.

The simulation is carried out only upon a simplified phantom in this paper. If the energies deposited in some critical organs are needed to be precisely simulated, a more complicated geometry model of human body should be adopted. The results could be helpful to the radioprotection of astronauts.

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