Monte Carlo simulation of neutron shielding performance of iron spherical shell

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Abstract. Neutron Shielding with different energy is one of the important issues in radiation safety. To investigate the neutron shielding performance of iron spherical shell, this paper built a simple physical model of iron spherical shell; the neutron transport processes in iron spherical shell with different thicknesses were numerically simulated by using Monte Carlo method. For isotropic neutron source with energy ranging from 0.1 keV to 14 MeV, the numbers of leakage neutrons and gamma rays from iron spherical shell with different thicknesses has been obtained. The simulation results show that both the energy of neutron source and the thickness of iron spherical shell shield have a significant influence on number of leakage neutrons and gamma rays. For iron spherical shell shield, the number of leakage neutrons decreases with the increase of thickness of iron spherical shell when the normalized number of leakage neutrons is less than 1 (i.e. when the number of neutrons absorbed by iron is few), but increases with the increase of thickness of iron spherical shell when the normalized number of leakage neutrons is greater than 1 (i.e. when the reaction of (n, 2n) occurs in neutron transportation process). For neutron source with energy of 2 MeV, the normalized number of leakage neutrons decreases with the increase of thickness of iron spherical shell shield; the ratio of number of leakage neutrons to leakage gamma rays increases with the increase of thickness of iron spherical shell shield for a certain range of thickness.

1. Introduction
With the rapid development of nuclear technology and its application, the problem of radiation safety is becoming more and more important. How to evaluate the neutron shielding ability of typical materials has become one of the focus issues of concern [1-3]. Iron is a typical metal material used in the research of radiation protection physics. Li Wenqian[4]calculated the neutron shielding performance of spent fuel tanks. It is shown that for iron with thickness of 45 cm and boron containing polyethylene with thickness of 15 cm composite shield, the dose rate outside the storage tank can meet the safety requirements, and the released gamma rays can be attenuated by iron. He Tie[5] used the alpha particle method combined with the time of flight technology to measure neutron induced prompt gamma spectra of metals such as iron and lead. The neutron source energy used in experiments is 14 MeV. Tang Shibiao[6] simulated out the energy spectrum of the characteristic gamma rays induced by the neutron excitation of iron. For spherical shell shielding problems [7-8], Yang Huazhong calculated the neutron shielding process of natural iron by using Monte Carlo method, and the energy spectrum distribution of transmission neutron was compared under different shield thickness [9]. Zhao Xinhui [10] used Monte Carlo method to simulate the 14MeV neutron shielding performance of the iron collimator, and compared it with the metals such as lead, tungsten and bismuth. The results reported in
literature [10] show that the number of gamma rays produced by iron is the largest in the four metals which are iron, lead, tungsten and bismuth with the same thickness.

In the research works, most are on iron materials for neutron shielding, but few is on neutron shielding by spherical shell structure, and less attention has been paid to the number ratio of the leakage neutrons ($n$) to the leakage gamma rays ($\gamma$) after neutron shielding by iron material. This article will focus on the shielding performance of iron spherical shell structure to neutrons with different energies by using Monte Carlo method, and the influence of the thickness of the spherical shell on the number of the leakage neutrons $N_n$ and the number of the leakage gamma rays $N_\gamma$, and the $N_n/N_\gamma$ value is studied, which will provide a reference for the design and theoretical analysis of neutron shielding by iron in practice.

2. Physical model and method

We establish a physical model which is shown in figure 1 to simulate the neutron shielding process in iron spherical shell. The isotropic mono-energetic neutron source locates at the center of the iron spherical shell. The energy of the neutron source is 0.1 keV, 1 keV, 10 keV, 100 keV, 1 MeV, 2 MeV, and 14.1 MeV, respectively. The interior of the spherical shell is a vacuum, and the radius of the vacuum ball is 10 cm, the thickness of the spherical shell is $d_r$.

The neutrons with different energies have different forms of interaction with the iron nucleus. The thermal neutron with energy of 0.0253 eV and the thermal motion of the iron atoms will reach a state of equilibrium; the neutron with energy of 1 eV~1 keV will be absorbed due to resonance interaction with the iron; the reaction of neutron with energy of 1 keV~0.5 MeV to iron nuclei is mainly elastic scattering; when the energy of neutron is above 0.5 MeV, the reaction of neutron to iron nuclei is mainly elastic scattering and inelastic scattering.

![Figure 1. The physical model of neutron shielding by iron spherical shell.](image)

In the model, the thickness of the shielding layer of the spherical shell is 0.1 cm~20 cm. The number of leakage neutrons and leakage gamma rays that cross the outer surface of the shielding material is recorded. If the number of neutron source is $N_0$, the number of neutrons and the gamma rays which can penetrate the iron spherical shell is $N_{in}$ and $N_\gamma$, then the normalized number of leakage neutrons $N_n$ and the normalized number of leakage gamma rays $N_\gamma$ is defined as $N_n = N_{in} / N_0$ and $N_\gamma = N_\gamma / N_0$, respectively.

The simulation was performed to obtain $N_n$ and $N_\gamma$, and it was carried out through Monte Carlo N-Particle Transport Code version 4B (MCNP4B)[11], which is a general particle transport program for simulating the interaction of radiations with matter. In the simulation experiment, the neutron and gamma rays transmission geometry was set up as shown in figure 1. Tally F1 was used to obtain simulation results. This tally card provides neutron and gamma ray currents over the outer surface of the iron spherical shell. The total number of histories which have been transported is $2 \times 10^7$ in every simulation-run. All the simulation results obtained by MCNP4B program were reported with less than 3% error.
3. Results and discussions

3.1. The case of incident neutron energy above 1 MeV

The simulation results for the case of incident neutron with energy of 1 MeV are shown in figure 2. It is the relationship between the number of leakage neutrons and gamma rays from outer surface of the spherical shell with the thickness of the iron spherical shell. From figure 2 (a), it can be seen that in the case of incident neutron with energy of 1 MeV, the number of leakage neutrons decreases with the increase of thickness of the iron spherical shell, and the normalized number is less than 1; while the number of leakage gamma rays firstly increases with the increase of the thickness, and then reaches the maximum value 0.0952 when the thickness reaches to about 3 cm, after that, the number of leakage gamma rays decreases with the increase of thickness. The results show that with the increase of the iron spherical shell thickness, more and more gamma rays are produced by interactions of neutron with iron shell; when the thickness is thin, the number of leakage gamma rays increases with the increase of the shell thickness due to less absorbed by thin iron shell; when the thickness is thick, although the number of produced gamma rays is large, but the iron shell absorption effect is also increased, so that the number of leakage gamma rays decreases with the increase of iron spherical shell thickness.

Figure 2 (b) is the relationship between the ratios of the number of leakage neutrons to the number of leakage gamma rays \(N_n/N_\gamma\) with the thickness of the iron spherical shell. The simulation results show that the normalized number of leakage neutrons is above 0.995 and the normalized number of leakage gamma rays is below 0.09, so the \(N_n/N_\gamma\) value is lower than 10. The minimum value of \(N_n/N_\gamma\) appears when the iron spherical shell thickness is 3 cm, \(N_n/N_\gamma =10.5\). When thickness of iron spherical shell is less than 3 cm, the \(N_n/N_\gamma\) value decreases rapidly with the increase of thickness, while the \(N_n/N_\gamma\) value increases with the increase of thickness when thickness of the iron spherical shell is greater than 3 cm. Therefore, when the thickness of iron spherical shell is increased to about 3 cm, the lowest value of \(N_n/N_\gamma\) has been reached; the \(N_n/N_\gamma\) value can’t continue to decrease when the thickness of the iron shielding layer is enhanced.

![Figure 2](image-url)  
**Figure 2.** Simulation results for the case of neutron source with energy of 1 MeV. (a)The number of leakage neutron, gamma; (b) The ratio of number of leakage neutrons to leakage gamma rays.

Figure 3 is the simulation results of the number of leakage neutrons and leakage gamma rays and its ratio versus thickness of iron spherical shell at different neutron energy. From figure 3(a), it is shown that when \(E_n=14.1\) MeV, the normalized number of leakage neutrons is greater than 1, indicating that (n, 2n) reaction occurs between neutron and Fe, and the normalized number of leakage neutrons increases with the increase of the thickness of the iron spherical shell in the range of 0–20 cm considered in this paper.

In the earlier works reported in literature [9], a fast-neutron transport code has been made up to simulate neutrons which were yielded by T(d,n)^4He reaction shielded by a spherical shell of natural
iron. When the thickness of spherical shell of natural iron is 4 cm and 9 cm, the transmission coefficients of neutron are 1.087 and 1.132, respectively. The results of the number of leakage neutrons in figure 3(a) are 1.067 and 1.110 for iron spherical shell with thickness of 4 cm and 9 cm. Our simulation results show reasonably good agreement with the results in literature [9]. There is a slight difference of 2.5% between ours with the earlier results reported in the literature, this is because the calculation conditions are not exactly the same.

![Figure 3](image_url)

**Figure 3.** Simulation results of the number of leakage neutrons and leakage gamma rays and its ratio versus thickness of iron spherical shell. (a) Neutrons; (b) Gamma rays; (c) Ratio of the number of leakage neutron to leakage gamma rays.

Figure 3(b) is the variation of the number of leakage gamma rays with the thickness of the iron spherical shell. It can be seen that when the incident neutron energy is 14.1 MeV, the number of leakage gamma rays is significantly higher than that of the incident neutron with energy of 1 MeV or 2 MeV, and the number of leakage gamma rays reaches the maximum when the iron spherical shell thickness is 5 cm. As shown in figure 3(c), under a certain thickness, the higher the energy of the incident neutron is, the lower the $N_n/N_\gamma$ value is.

### 3.2. The case of incident neutrons with low energies

Figure 4 is the simulation results of $N_n$, $N_\gamma$ and $N_n/N_\gamma$ value versus thickness of iron spherical shell at the case of neutron with energy of 0.1 keV -100 keV. Figure 4 shows that for low energy neutron and the iron spherical shell thickness remained unchanged in 0–8 cm, $N_n/N_\gamma$ value increases firstly and then decreases with the incident neutron energy. So, when the iron spherical shell thickness is determined, there will be an incident neutron energy which can make $N_n/N_\gamma$ value get the maximum. At the case of incident neutron energy of 0.1 keV, 1 keV and 10 keV, the $N_n/N_\gamma$ value decreases with increase of iron spherical shell thickness, and when the thickness is less than 1 cm, the decline rate of $N_n/N_\gamma$ value is fast, while when the thickness is greater than 1 cm, the decline rate of $N_n/N_\gamma$ value is slow. For the case of incident neutron energy of 100 keV, $N_n/N_\gamma$ value decreases firstly and then increases with the increase of iron spherical shell thickness. For neutron energy of 100 keV, the number of leakage neutrons is 0.9998 when the thickness of iron spherical shell is 0.1 cm, and the number is 0.9719 when the thickness is 20 cm, that is to say, there is no significant change in the number of leakage neutrons with change in thickness of iron spherical shell. The main reason is that there is resonance absorption reaction in radiative capture cross section when the neutron energy is around 100 keV which is shown in figure 5(b). For neutron with energy of 0.1 keV, 1keV , 10keV and 100keV, the total cross section of the interaction between neutron with $^{56}$Fe is 11.73 barn, 9.3 barn, 4.2 barn and 3.59 barn, and the radiative capture cross section is $3.82 \times 10^{-2} \text{barn}$, $7.84 \times 10^{-3} \text{barn}$, $4.36 \times 10^{-4} \text{barn}$ and $8.61 \times 10^{-5} \text{barn}$, respectively. In the range of thickness is 0.1 cm to 16 cm, the higher the total cross section is or the lower the radiative capture cross section is, the smaller the number of leakage neutrons is and the larger the number of leakage gamma rays is. The neutron with energy of 100 keV is an exception, although the radiative capture cross section for neutron with energy of 100 keV is the lowest, there are
many resonance absorption reactions around energy of 100 keV, and this will lead to generate more gamma rays.

As shown in figure 4(c), it can be seen that the $N_n/N_\gamma$ value is greater than 50 even if the iron spherical shell thickness reaches 5 cm for neutron energy below 100 keV. For example, at the incident neutron energy of 10 keV, and iron spherical shell thickness 5 cm, the $N_n/N_\gamma$ value is 884. The main reason for that the $N_n/N_\gamma$ value is very high for low neutron energies is that the gamma rays generation cross-section (i.e. radiative capture cross section) corresponding to low neutron energies takes up a small proportion of the total reaction cross section [12], resulting in smaller numbers of leakage gamma rays. Different from the results of figure 2, the number of leakage gamma rays firstly increases rapidly and then decreases slowly with thickness of iron spherical shell, this is because the average energy of secondary gamma rays produced by interactions between low-energy neutrons and iron is relatively high, and it is not easy to be absorbed by iron. For high neutron energies of 1MeV, 2MeV and 14.1MeV, the number of leakage gamma rays begin to decrease rapidly with thickness of iron spherical shell when the thickness is higher than 2 to 4 cm, while the number of leakage gamma rays in figure 4(b) for low neutron energies will decrease with thickness of iron spherical shell when the thickness is greater than 20 cm which is not shown in figure 4(b). The main reason for this is that the radiative capture reaction of low energy neutron with iron which generates gamma rays is higher than the reaction of high energy neutron in addition to the resonance energy point.

**Figure 4.** Simulation results of the $N_n$, $N_\gamma$ and $N_n/N_\gamma$ value versus thickness of iron spherical shell for the case of low energy neutron. (a) Neutron; (b) Gamma rays; (c) The ratio of the number of leakage neutrons to leakage gamma rays.

**Figure 5.** The cross sections of the interaction between neutrons with $^{56}$Fe. (a) Total cross sections. (b) Radiative capture cross sections.

4. Conclusions
The physical model of neutron shielding by iron spherical shell was established in the paper, and the number of leakage neutrons, number of leakage gamma rays, and its ratio was obtained by using
Monte Carlo method. The results show that the iron spherical shell thickness and neutron energy will significantly affect the number of leakage neutrons. When the incident neutron energy is higher and the normalized number of leakage neutrons is less than 1, the number of leakage neutron decreases with the increase of iron spherical shell thickness; On the contrary, when the incident neutron energy is lower and the normalized number of leakage neutron is greater than 1, the thicker the iron spherical shell thickness is, the greater the number of leakage neutrons is. The number of leakage gamma rays which is generated by interactions of neutron with iron shell increases firstly and then decreases with the increase of the thickness of iron spherical shell. In a certain range of iron spherical shell thickness, the \( \frac{N_n}{N_\gamma} \) value decreases firstly and then decrease with the increase of the thickness. In neutron shielding by using iron spherical shell, it is necessary to consider the number of leakage neutrons and leakage gamma rays to select a reasonable thickness, the thickness of the iron spherical shell is not as thicker as better.

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