第 36 卷 第 4 期 原 子 核 物 理 评 论 Vol. 36, No. 4
2019 年 12 月 Nuclear Physics Review Dec., 2019

Article ID: 1007-4627(2019) 04-0471-06

Comparison Between Experiment and Simulation for the Fission Chamber Used in Fast Neutron Detection

GUAN Yuanfan[1,2], YANG Herun[1,2], DUAN Limin[1,2,†], ZHANG Junwei[3], YUAN Xiaohua[1,2], HE Zhiyong[1,2], ZHANG Xueying[1,2], HU Rongjiang[1,2], LU Chengui[1], MA Peng[1,2], WEI Xianglun[1,2], LI Meng[1,2], GAN Zaiguo[1,2], YANG Chunli[1], ZHANG Hongbin[1], CHEN Liang[1]

(*1. Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*;
2. University of Chinese Academy of Sciences, Beijing 100049, China;
3. North China University of Water Resources and Electric Power, Zhengzhou 450000, China)

Abstract: A fission chamber coated with two layers of ^{238}U fissile materials has been developed for the measurements of fast neutrons. The developed fission chamber can operate in the pulse mode, the mean square voltage mode, and the current mode to perform the flux measurement over a large dynamic range. The pulse mode of the fission chamber has been tested with a ^{252}Cf neutron source by measuring the detection efficiency. To evaluate both the mean square voltage mode and the current mode, the pulse amplitudes from the fission chamber in different gas pressures have been measured with the ^{252}Cf source. Then, the pulse amplitudes from the fission chamber have also simulated with the Geant4 Monte Carlo software tool. The simulation can explain measured results, detection efficiency is highest [$(4.30\pm0.7)\times10^{-7}$] when gas pressure is 2.64×10^{5} Pa and energy spectrum of fission fragments is clearly, so the fission chamber can work in different modes.

Key words: fission chamber; fast neutron measurement; detection efficiency; pulse amplitude; Monte Carlo simulation

CLC number: O532.33 **Document code:** A **DOI:** 10.11804/NuclPhysRev.36.04.471

1 Introduction

Neutron measurements are very useful in many fields, in particular, in the advanced nuclear energy system. Because neutrons are not charged particles, neutrons can only be detected with the methods of the secondary charged particles produced by some reactions, such as nuclear recoils, nuclear fissions, and so on. Fission chamber is a type of neutron detectors which are based on nuclear fissions. In the 1950s, Westinghouse Electric Corporation built a fission chamber that was capable of enduring severe operational conditions[1−2]. In France, a miniature fission chamber was developed at the French Atomic Energy Commission (CEA) to be dedicated to an experimental nuclear reactor in the 1960s[3−4]. Today, there is still a need for fission chambers which are capable of withstanding intense radiation fields, capable of performing in-core reactor measurements, capable of discriminating neutron signals from background gamma ray signals[5−11].

In this paper, we report the fission chamber for fast neutron measurements. Fast neutron measurements are very useful in the neutron monitoring of advanced nuclear reactors. Recently, several reactor systems with fast neutron spectrum, cooled with gas, sodium, or a heavy liquid metal (*e.g.* lead or lead - bismuth eutectic, LBE)[5], have been selected for the advanced nuclear energy. Another example for fast neutron measurement is China initiative Accelerator Driven System (CiADS)[12], which consists of an accelerator, a LBE-cooled subcritical reactor, and a spallation target located at the center of the reactor core. To measure neutrons with a fission chamber, a fissionable material (*e.g.*, ^{235}U) is usually deposited on the cathode or the anode of the fission chamber. In our fission chamber, a ^{238}U coating has been used,

Received date: 19 Apr. 2019; **Revised date:** 18 Jun. 2019
Foundation item: National Natural Science Foundation of China (U1432123, 11575268, 11875301, 11675238)
Biography: GUAN Yuanfan(1984–), female, Lanzhou, Ph.D student, working on detection technology
† **Corresponding author:** DUAN Limin, E-mail: lmduan@impcas.ac.cn.

because it is easy to obtain the ^{238}U isotope in comparison with the ^{235}U isotope. In addition, with a higher neutron energy threshold, a ^{238}U-coated fission chamber is suitable for the fast neutron measurements. In this paper we discuss mainly the application of the ^{238}U-coated fission chamber in three modes. The experimental measurement and the theoretical simulation will be compared for the fission chamber in pulse mode.

2 Fission chamber development

The fission chamber is a cylindrical detector which contains one inner cylinder and one outer one. As shown in Fig. 1, the outer cylinder with a diameter of 27 mm is used as both the cathode and the sensor body, while the inner cylinder with a diameter of 21 mm is used as the anode. The two electrodes which have fissile material deposits emit fission fragments when exposed to a neutron field. These fission fragments produce an instantaneous current pulse between the electrodes.

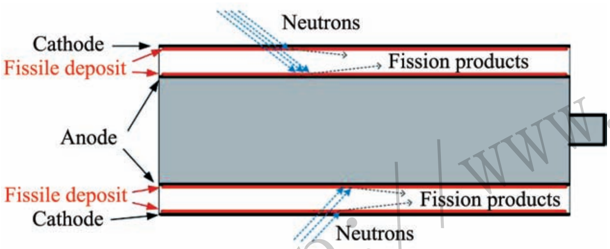

Fig. 1 (color online) The schematic drawing of the fission chamber with two layers of fissile deposits.

Two layers of fissile deposits are put in the fission chamber, one in the cathode and another one in the anode, in order to improve the detection efficiency. The fissile material deposit can be chosen such that the detector is sensitive to either thermal neutrons or fast neutrons. In our fission chamber, the ^{238}U deposits have been used, because it is easy to obtain ^{238}U isotope in comparison with the ^{235}U isotope. In addition, with a higher neutron energy threshold, a ^{238}U-coated fission chamber is suitable for the fast neutron measurements. The thickness of ^{238}U-coating, the length of the coating, and other technical data for the fission chamber can be found in Ref. [13].

The space between the electrodes has to be filled with gas to aid in detector operation. Either argon (Ar) or air can be used as filling gas for the developed fission chamber. The filling gas can be operated in both gas-flow and gas-closed condition. In the following text we will discuss the experimental measurement of neutrons when using Ar with different pressures as the working gas.

3 Measurement of detection efficiency

Fission chambers can be used in three operation modes, pulse mode, Campbelling mode, and current mode (*e.g.* Refs. [11–12, 14]). Campbelling mode is also known as "fluctuation mode" or "mean square voltage mode", because the neutron flux is obtained by calculating the mean square value of the voltage value of detector signal. At low neutron fluxes, the fission rate in the fissile deposit is low enough. The average delay between two pulses produced by fission is much larger than the pulse duration. These pulses can be counted so as to obtain an event rate closely related to the detector fission rate. Thus, this mode is known as "pulse mode". With the increasing of the neutron flux, pulses inside the chamber overlap and pulses can no longer be individually processed anymore. The neutron flux has to be extracted with the methods of Campbelling mode, and current mode.

In this section, we discuss the experimental measurement of the fast neutrons with the developed fission chamber. The measurement was performed with a ^{252}Cf source on August, 2018. As shown in Fig. 2, the source was put on the surface of the fission chamber. The minimal distance between the source and the coating inside the outer cylinder is 2 mm, because the thickness of the outer cylinder is 1 mm and the thickness of the source container is 1 mm. The sensitive length of the detector is 100 mm. The activity of the ^{252}Cf source was measured to be 3.7 MBq on March 1, 2014. With a half-life of 2.645 years, the activity of the ^{252}Cf source was 1.14 MBq on August, 2018. The total number of the neutrons emitted from the source is 1.26×10^5/s in August, 2018.

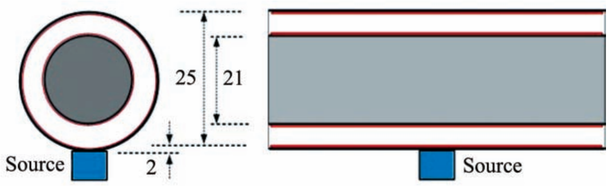

Fig. 2 (color online) A cutaway view of the fission chamber and the ^{252}Cf source.

Because the flux of the neutrons from the ^{252}Cf source is low, the fission chamber can work in pulse mode. During the measurement, the pulses from the fission chamber were amplified by a preamplifier and sent to a CF8000 octal constant fraction discriminator to cut off the background noises with low pulse amplitudes. Then, the pulse counts were recorded by the data acquisition system. Fig. 3 shows the measured pulse counts as a function of the voltage values in the anode. In order to observe the detection efficiency in the different gas pressure, the Ar gas pressures of 8.8×10^4, 1.76×10^5, 2.64×10^5, and 3.217×10^5 Pa have been used, respectively. In order to better cut off the noise background and the gamma rays, the thresholds in the discriminator CF8000 are adjusted, when either the voltage or the gas pressure are changed. As shown in Fig. 3, the measured pulse counts decrease slightly when applying a high voltage of more than 400 V. This is because the noises or background increase slightly when the high voltage increases. During the measurement, the threshold in the discriminator has been increased slightly, in order to exactly cut off the noises or background. Thus, several neutron-induced pulses with low amplitudes may be cut.

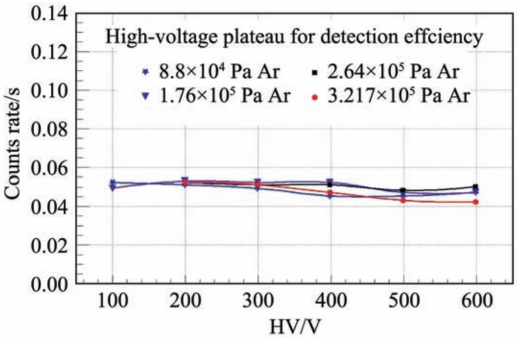

Fig. 3 (color online) The measured count rates of the fission chamber as a function of the voltage values.

Table 1 The pulse counts and the detection efficiency of the fission chamber

Gas pressure/Pa	Counting rate/s	E_{Exp}
8.8×10^4	0.0497 ± 0.008	$(3.94\pm0.6)\times10^{-7}$
1.76×10^5	0.0505 ± 0.008	$(4.01\pm0.6)\times10^{-7}$
2.64×10^5	0.0542 ± 0.009	$(4.30\pm0.7)\times10^{-7}$
3.217×10^5	0.0472 ± 0.008	$(3.75\pm0.6)\times10^{-7}$
Mean results	0.0502 ± 0.008	$(3.98\pm0.6)\times10^{-7}$

Table 1 lists the measured pulse counts and the detection efficiencies of the fission chamber with the gas pressures of 8.8×10^4, 1.76×10^5, 2.64×10^5, and 3.217×10^5 Pa, respectively. The pulse count for a given pressure is the averaged value of the pulse counts with 6 voltages from 100 to 600 V(8.8×10^4, 1.76×10^5 Pa) or 5 voltages from 200 to 600 V(2.64×10^5, and 3.217×10^5 Pa). The detection efficiency in Table 1 has been calculated as follows.

$$E_{\mathrm{Exp}}=\frac{F}{N}, \tag{1}$$

where N is the number of the neutrons which are emitted from the source. F is the measured pulse number which is also the number of the detected neutrons. The incoming neutron number, N is obtained from the neutron flux of the source.

4 Pulse amplitude and energy deposition

With the increasing of the neutron flux, the fission rate in the fissile deposit is high enough. The pulses induced by fission products are so much that the average delay between two pulses is much smaller than the pulse duration, *i.e.* the two pulses inside the chamber overlap. Then, the neutron flux has to be extracted with the methods of Campbelling mode, and current mode. In Campbelling mode, the neutron flux is obtained by calculating the mean square value of detector signal, while the output current of detector signal is measured in current mode. Thus, both Campbelling mode and current mode depend on the signal amplitude from the fission chamber.

In order to investigate whether our fission chamber works well in Campbelling mode and current mode, we have observed the signal amplitude from the chamber with ^{252}Cf source. During the measurement, the signals from the fission chamber were amplified by a preamplifier and an amplifier. The signals from the amplifier were then converted into digitals by an Analog-to-Digital Converter (ADC) and recorded in the data acquisition system.

The pulse amplitudes from the fission chamber have also simulated with the Geant4 Monte Carlo software tool. The Geant4 toolkit has been employed widely in basic physics research to simulate the propagation of particles and nuclei in extended media (*e.g.* Refs. [15–17]). The Geant4 toolkit provides several sets of physics models which simulate interactions of protons and neutrons with atomic nuclei. In the simulation, the neutron energy spectra of ^{252}Cf have been used to simulate the fission of ^{238}U. In the neutron-induced fission, the masses, the charges, the velocities, and the moving directions of two fission fragments are obtained. Since the two fission fragments move in the opposite directions, only one fragment can move out from the ^{238}U coating and come into the filling gas between two electrodes. Based on the Ramo-Shockley theorem, the charge q collected by the anode can be calculated as follows[18].

$$q=\sum_{i=1}^{N}\frac{x_i}{D}e=Q\times\frac{\overline{x}}{D}, \tag{2}$$

where D is the distance between the anode and the cathode. Q is total charges produced by the fission fragment. $\overline{x}=\sum_{i}^{N}\frac{x_i}{N}$ is the averaged distance from the electrons to the anode.

Fig. 4(a), Fig. 5(a), Fig. 6(a), and Fig. 7(a) show the simulated pulse amplitudes of fast neutrons with

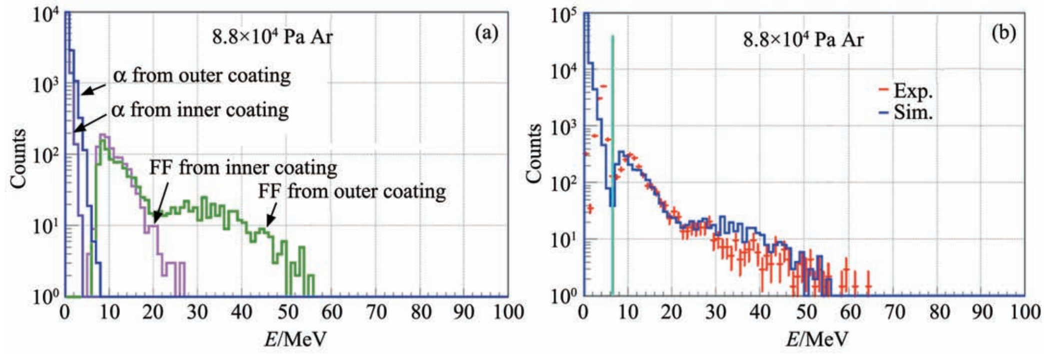

Fig. 4 (color online) The pulse amplitudes of fast neutrons from ^{252}Cf source with fission chamber in the argon gas pressure of 8.8×10^4 Pa. (a) Simulation results. FF and α denote the fission fragments and the α particles generated by neutron-induced fissions. (b) Comparison between the experimental and simulated results.

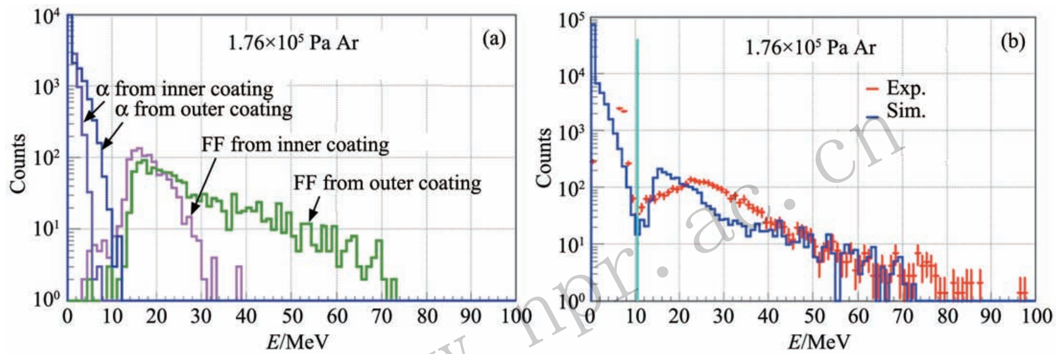

Fig. 5 (color online) Same as Fig. 4 but in the argon gas pressure of 1.76×10^5 Pa.

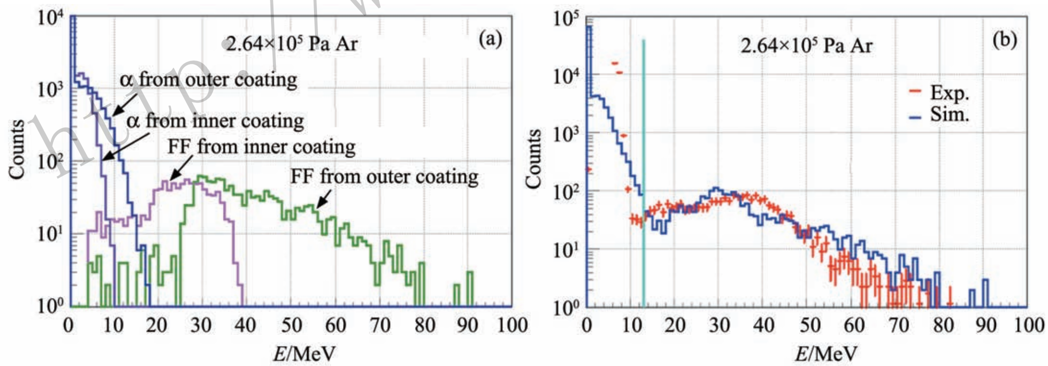

Fig. 6 (color online) Same as Fig. 4 but in the argon gas pressure of 2.64×10^5 Pa.

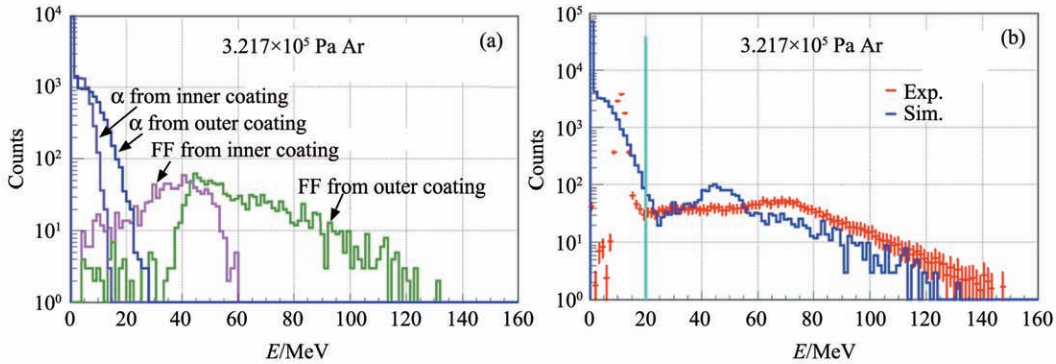

Fig. 7 (color online) Same as Fig. 4 but in the argon gas pressure of 3.217×10^5 Pa.

the fission chamber in the argon gas pressure of 8.8×10^4, 1.76×10^5, 2.64×10^5, and 3.217×10^5 Pa, respectively. It is shown clearly that the pulse amplitudes for the fission fragments from the outer coating are higher than that from the inner coating. This is because the electrons generated by the fragments from the outer coating have longer drift distance. From Eq. (2), we know that the charge q collected by the anode increases with the increasing drift distance. Thus, the pulse amplitudes for the fragments from the outer coating are higher. In Ref. [18], it was also observed that the pulse amplitudes for the fragments from the outer cathode are higher than that from the inner anode.

Fig. 4(b), Fig. 5(b), Fig. 6(b), and Fig. 7(b) show the measured pulse amplitudes of fast neutrons with the fission chamber in the argon gas pressure of 8.8×10^4, 1.76×10^5, 2.64×10^5, and 3.217×10^5 Pa, respectively. The pulse amplitudes increase with the increasing gas pressure. In the gas pressure of 3.217×10^5 Pa, the measured pulse amplitudes attain 100 MeV. On the other hand, the pulse amplitudes for the gamma ray from ^{60}Co are about 0.2 MeV[13]. The pulse amplitude generated by neutron-induced fission is several hundred folds higher than that for the gamma ray. The results mean that the effect of gamma rays can be eliminated easily when fission chamber works in Campbelling mode and current mode. Both the measured results and simulation results indicate that the developed fission chamber works well.

5 Conclusion

A fission chamber coated with two layers of ^{238}U fissile materials has been developed for the measurements of fast neutrons. The pulse mode of the fission chamber has been tested with a ^{252}Cf neutron source by measuring the detection efficiency with different high voltages in the several gas pressures. The measured results indicate that the developed fission chamber work well in pulse mode. To evaluate both the mean square voltage mode and the current mode, the pulse amplitudes from the fission chamber have been measured with the ^{252}Cf source. The pulse amplitude generated by neutron-induced fission is several hundred folds higher than that from gamma ray. The effect of gamma rays can be eliminated easily when fission chamber works in Campbelling mode and current mode. The pulse amplitudes from the fission chamber have also simulated with the Geant4 Monte Carlo software tool. The simulation results explain well the measured results. Both the measured results and simulation results indicate that the developed fission chamber works well.

References:

[1] BAER W, SWIFT F O. Review of Scientific Instruments, 1952, **23** (1): 55.
[2] BAER W, BAYARD R T. Review of Scientific Instruments, 1953, **24** (2): 138.
[3] GUERY M. PATENT GB, 1963, **938**: 594.
[4] JAMMES C, FILLIATRE P, LOISEAU P, *et al.* Nucl Instr and Meth A, 2012, **681**: 101.
[5] ALEMBERTI A, SMIRNOV V, SMITH C F, *et al.* Progress in Nuclear Energy, 2014, **77**: 300.
[6] JAMMES C, FILLIATRE P, GESLOT B, *et al.* IEEE Trans. on Nucl Sci, 2012, **59**: 1351.
[7] JAMMES C, CHAPOUTIER N, FILLIATRE P, *et al.* Nuclear Engineering and Design, 2014, **270**: 273.
[8] REICHENBERGER A M, UNRUH C T, UGOROWSKI B P, *et al.* Annals of Nuclear Energy, 2016, **87**: 318.
[9] VERMA V, FILLIATRE P, HELLESEN C, *et al.* Annals of Nuclear Energy, 2016, **94**: 487.
[10] BORELLA A, ROSSA R, VAN DER MEER K. Annals of Nuclear Energy, 2013, **62**: 224.
[11] ALFONSO A, DAVID R. Nucl Instr and Meth A, 2016, **825**: 6.
[12] HE Y C, QIAN W B, HE Z Y, *et al.* Nuclear Physics Review, 2017, **34**: 263.
[13] GUAN Y F, YANG H R, DUAN L M, *et al.* Radiation Detection Technology and Methods, 2019, **3**(3): 1.
[14] GESLOT B, UNRUH C T, FILLIATRE P, *et al.* IEEE Trans Nucl Sci, 2012, **59**: 1377.
[15] ALLISON J, AMAKO K, APOSTOLAKIS J, *et al.* IEEE Trans Nucl Sci, 2006, **53**: 270.
[16] AGOSTINELLI S, ALLISONAS J, AMAKO K, *et al.* Nucl Instr and Meth A, 2003, **506**(3): 250.
[17] ZHAO Q, HE ZH Y, YANG L, *et al.* Chinese Physics C, 2016, **40**: 076203.
[18] TAIEB J, LAURENT B, BELIER G, *et al.* Nucl Instr and Meth A, 2016, **833**: 1.

用于快中子探测的裂变电离室实验及模拟结果比较

关远帆[1,2]，杨贺润[1,2]，段利敏[1,2,†]，张俊伟[3]，袁小华[1,2]，贺智勇[1,2]，张雪荧[1,2]，胡荣江[1,2]，鲁辰桂[1]，马 朋[1,2]，魏向伦[1,2]，李 蒙[1,2]，甘再国[1,2]，杨春莉[1]，张宏斌[1]，陈 亮[1]

(1. 中国科学院近代物理研究所，兰州 730000;
2. 中国科学院大学，北京 100049;
3. 华北水利电力大学，郑州 450000)

摘要： 本文报道了一种用于快中子测量的裂变电离室的实验及模拟结果对比，该电离室的裂变材料为^{238}U，分别电镀在电离室的阳极和阴极。裂变电离室通常有三种工作模式：脉冲模式、均方电压模式和电流模式，从而在大动态范围内实现中子注量测量。我们利用^{252}Cf中子源对工作在脉冲模式的裂变电离室效率进行了测量，同时为了评估均方电压模式和电流模式，测量了裂变电离室在不同气压下的脉冲幅度，并通过Geant4蒙特卡罗软件对裂变电离室的脉冲幅度进行了模拟。模拟可以解释实验结果，当工作气压是2.64×10^5 Pa时探测效率最高[$(4.30\pm0.7)\times10^{-7}$]，且裂变碎片能谱清晰，表明裂变电离室可以工作在不同模式下。

关键词： 裂变电离室；快中子探测；探测效率；脉冲幅度；蒙特卡罗模拟

收稿日期： 2019-04-19 **修改日期：** 2019-06-18
基金项目： 国家自然科学基金资助项目(U1432123, 11575268, 11875301, 11675238)
† **通信作者：** 段利敏，E-mail: lmduan@impcas.ac.cn。