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Study on the Correction Method for the Dead-time Effects of Neutron Detectors Due to Pulsed Radiation

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Gas detectors based on a ^{3}He proportional counter play an important role in monitoring the ambient dose equivalent in nuclear reactors and particle accelerators, and the time resolution of such gas detectors is directly related to the accuracy of dose equivalent values when gas detectors are used in pulsed neutron fields. In this article, the dead-time of a proportional ^{3}He counter is measured experimentally, and two methods to correct for the omitted counts resulting from the dead-time effect are adopted. The moderation time of neutrons passing through the moderator of a neutron detector is calculated by means of Monte Carlo simulation software; thus, the equation between the neutron counting rate and the correction coefficient in accelerator radiation fields is deduced. In the other method, the parameters of the correction equation are derived experimentally in the pulsed radiation fields around accelerators, and the correction equation is determined. The dead-time effects of neutron detectors due to pulsed radiation can be corrected effectively by using the two methods introduced in this paper.

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I. INTRODUCTION

Studies on particle detection in pulsed radiation fields began in the 1940s [1]. The dead-time effect of proportional counters can lead to an inaccuracy in dose equivalent measurements; thus, dose monitoring in pulsed radiation fields has its own particularity. With the development of accelerator technology and particle physics, accelerators with high energy or high current are being developed. Meanwhile, radiation protection for personnel near accelerators is becoming increasingly important. The beam time character determines the particularity of neutron radiation fields around accelerators. The duty cycle is defined as the percentage of the beam time compared to the total time. High-energy accelerators always have a very low duty cycle. For example, the beam pulse width of the 22 GeV electron linear accelerator in the Stanford Linear Acceleration Center is 1 ∼ 2 μs, and the beam frequency is nearly 360 Hz, so the duty cycle could be less than 0.1% [2]. The beam pulse width of the 2.5 GeV electron linear accelerator in BEPCII (Beijing Electron Positron Collider II) is 1 ns or 2.5 ns, and the beam frequency is 50 Hz, so its duty cycle is about 10^{-7} [3]. When the accelerator works with an extremely low duty cycle, pulsed radiation fields will be generated around the accelerator because of the beam loss. Ultimately, the radiation field will also be associated closely with the primary beam even if the pulsed radiation fields are outside the shield.

II. EARLIER APPROACHES

Three ways to solve the previous problem can be used by researchers in various research institutions. One method is correcting the omitted counts caused by the dead time by using the equation of accelerator beam parameters [4,5]. Second, measuring the accumulated dose passively by activation is also an effective solution [6,7], or the number of neutrons taking part in the reaction can be calculated on the basis of amplitude of the output signal pulse, and the effect of the omitted counts can be corrected [8,9].

Wang *et al.* [8] proposed a method of correcting the omitted counts of a neutron detector in pulsed neutron fields. They propose the omitted-counts correction

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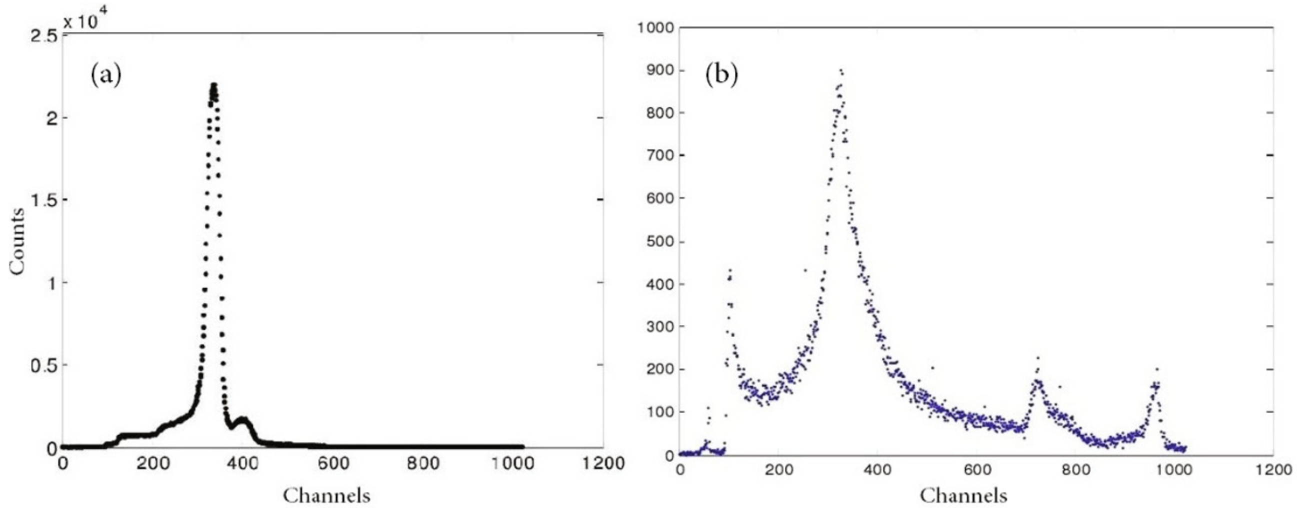

Fig. 1. (Color online) Pulse amplitude spectrum of the BF_3 detector with (a) uniform radiation fields and (b) pulsed radiation fields.

method by corrected the output pulse amplitude of the detector. In the article, the output signal and the pulse amplitude spectrum of the neutron detector in electron accelerator radiation fields are given. The detector consists of BF_3 proportional counter tubes and moderated polyethylene. Superposition of signals emerges because of uneven signals. Two or three or more neutron signals are recorded as one neutron pulse. An obvious difference existed between the two kinds of pulse amplitude spectra in different radiation fields. There is a peak caused by the superposition of two or three neutron signals of the pulse amplitude spectrum in pulsed neutron fields. Fig. 1 shows the pulse amplitude spectra. The pulse amplitude spectrum from the multi-channel pulse amplitude analyzer and the output signals of the digital oscilloscope demonstrate that in radiation field neutron detectors based on proportional counters, counts will be omitted.

The method to correct the omitted counts of neutron detectors by using pulse amplitude spectrum is based on the pulse amplitude spectrum shown in Fig. 1(b). The region of interest of the superposition of 2 and 3 neutrons equally divide the abscissa axis in Fig. 1(a), which shows a single neutron pulse amplitude spectrum; then, the probability of each signal about two or three neutrons of different energies is determined, the different regions of interest are integrated, and then the number of counts is obtained. According to the different superposition of neutrons, the counts multiplied by the appropriate coefficient is the total neutron counts. Finally we get the corrected equation

$$N = N_1 + 7.12N_2 + 8.13N_3 + 9N_4, \tag{1}$$

Where N_1, N_2, N_3, and N_4, represent the number of one-neutron pulses, the number of two superimposed pulses of neutrons, the number of three superimposed pulses of neutrons, and the number of four superimposed pulses of neutrons, respectively. In addition, the dead time effect of multi-channel pulse amplitude analyzer is analyzed. The dead time of the multi-channel analyzer t_d is 6 μs, the rise time of input pulse t_r is 1.2 μs, and the busy time of the system t_b is 7.2 μs. A superimposed pulse of 2 neutrons represents $2 + t_d/t_r$ counts, a superimposed signal of 3 neutrons represents $3 + t_d/t_r$ counts, and a superimposed signal of 4 neutrons represents $4 + t_d/t_r$ counts. The corrected equations can be derived by considering only the dead time of the multi-channel analyzer:

$$N = N_1 + 7N_2 + 8N_3 + 9N_4. \tag{2}$$

By comparing Eqs. (1) and (2), we see that correction factors result from the dead time of the multi-channel

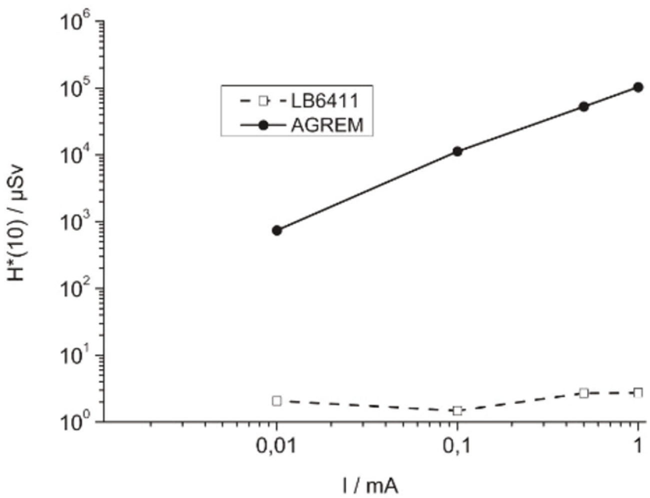

Fig. 2. Neutron dose equivalent $H^*(10)$ as measured as a function of the proton current for the AGREM and the LB6411 neutron monitors.

pulse amplitude analyzer. Therefore, this correction method has little effect.

Luszik-Bhadra *et al.* [6] measured the ambient dose equivalent in pulsed neutron fields by using silver detectors and gas detectors synchronously. Figure 2 shows the neutron ambient dose equivalent measured by using two detectors under different beam currents: AgRem is the activation detector based on silver and LB6411 is one kind of gas detector based on a ^{3}He proportional counter encased by a polyethylene moderator and cadmium absorption layer. As the figure shows, when the beam current is 1 mA, the ambient dose equivalent ratio of the 2 kinds of detectors is $10^5/10^1$. Gas detectors visibly have serious omitted counting when the beam current is large.

Li and Tang [7] did a similar study. The detector was a GM counter encased by 6.5 cm-thick moderated paraffin wax and a layer of 0.25 mm-thick silver foil. The experiment was conducted at the 500 MeV Proton Synchrotron at KEK (High Energy Accelerator Research Organization). The result was compared with that obtained using a rem counter and a gas detector based on a BF_3 counter tube encased by a polyethylene moderator. The omitted counting of gas detectors even can reach even 75% at the highest radiation field, yet the omitted counting with a silver detector does not exceed 2.5%.

Dinter *et al.* [10] determined the moderated time of neutrons in four kinds of common moderators, calculated the missing data derived from the time, and then obtained the correction factors when neutron detectors were used in pulsed neutron field around accelerators. Ruby and Rechen presented activation detectors respectively applicable to 14 MeV [11] and 2.5 MeV [12] pulsed neutron fields. The ^{207}Pb detector has a higher sensitivity than the standard silver detector, and the ^{90}Zr detector has a slightly higher detection efficiency. Slaughter and Pickles [13] used a 2.5 mm-thick silver activation detector, which can measure the neutron count rate of radiation fields up to $10^7 s^{-1}$, to measure the pulsed neutron field. Caresana *et al.* [9, 14] designed a neutron detector named LUPIN, which was comprised of a ^{3}He tube, logarithmic amplifier, and LabVIEW program. The amplifier was changed from a general linear amplifier to a logarithmic amplifier. As a result, the output signals were changed from voltage signals to current signals. The total charge in the gas tube due to the nuclear reaction was calculated. The real number of neutrons that participated in nuclear reaction was finally derived.

The introduction above mentions the research situation about this subject in each research institution. Research on the dead time of neutron detectors often uses activation detectors. This kind of detector is a passive detector. Due to the half-life of the radionuclide, the measurement cannot be conducted in real-time. For example, ^{110}Ag needs about 2 minutes to reach equilibrium, and ^{108}Ag needs 12 minutes. Thus, this kind of detector cannot be used continuously. The cooling-down time must be long enough to obtain accurate measurement results, so it cannot solve the problem of real-time measurement. A method to correct the omitted counting of neutron detectors by using the pulse amplitude spectrum cannot prove its accuracy. The correction formula can be deduced based on the accelerator's beam parameters, and the method is more scientific and effective in correcting the instrument readings on the basis of the correction equation. Different accelerator radiation fields contain their particularities, so obtaining a specific correction factor for a given radiation field is reasonable.

III. DEAD TIME OF THE ^{3}HE PROPORTIONAL COUNTER

The time resolution is an intrinsic property of the particle detectors. Detectors can distinguish the minimum time interval between two successive incident particles. τ is defined as the resolution time. Detectors cannot accurately record other incident particles after one incident particle gets into the detectors within τ time, so τ is also known as the dead time.

Even neutron fields where the flux is not large, each signal derived by a proportional counter is reputed to be independent; thus, a time interval τ exists in which no other new pulse can be recorded. In this case, if other any of the two signal pulse interval is less than τ, the second pulse will not be recorded. If the average number of incident particles per unit time is assumed to be m, the number of pulses recorded in unit time is n; then, the busy time of the counter is represented as $n\tau$, and the total number of pulses that get into the counter but cannot be recorded within this time is $mn\tau$, which is the omitted counting $m - n$. Thus,

$$m - n = mn\tau. \tag{3}$$

The relationship between m and n is

$$m = \frac{n}{1 - n\tau}. \tag{4}$$

The "double source method" and the "decay of radioactive source method" are commonly used methods for determining a proportional counter's dead time [15]. Other methods, such as "changing the reactor power method" [16], the "variance expectation ratio method" [17], *etc.*, can also be used.

The dead time of the spherical ^{3}He proportional counter tube used in the subject is determined by using the "double source method". Under the same experimental conditions, the separate counts of the two radioactive sources n_1 and n_2, the coinstantaneous counting of the two sources n_{12} and the background count n_b are measured. Thus, the true counts of source 1 and source 2 and the coinstantaneous true count of two sources are

$$m_1 = \frac{n_1}{1-n_1\tau} - \frac{n_b}{1-n_b\tau}, \quad (5)$$

$$m_2 = \frac{n_2}{1-n_2\tau} - \frac{n_b}{1-n_b\tau}, \quad (6)$$

$$m_{12} = \frac{n_{12}}{1-n_{12}\tau} - \frac{n_b}{1-n_b\tau}. \quad (7)$$

The number of particles getting into the counter per unit time from the two sources equals the total number of particles getting into the counter from source 1 and source 2 separately per unit time, which is given by

$$m_{12} = m_1 + m_2, \quad (8)$$

$$\Rightarrow \frac{n_{12}}{1-n_{12}\tau} + \frac{n_b}{1-n_b\tau} = \frac{n_1}{1-n_1\tau} + \frac{n_2}{1-n_2\tau}. \quad (9)$$

The solution is

$$\tau = \tau' \left[1 + \frac{\tau'}{2}(n_{12} - n_b)\right], \quad (10)$$

in which τ' is

$$\tau' = \frac{n_1 + n_2 - n_{12} - n_b}{2(n_1 - n_b)(n_2 - n_b)}. \quad (11)$$

Owing to τ and τ' being on the order of magnitude of µs, $\tau = \tau'$ can be taken in the experiment.

The instruments used in this experiment are an ORTEC NIM chassis, a preamplifier, the main amplifier, a high-voltage power supply, a scaler, a ^{3}He proportional counter, and two neutron sources. Source 1 is a 20 MBq ^{252}Cf spontaneous fission neutron source. Its neutron emission rate is 2.87×10^6 n/s. Source 2 is an Am-Be neutron source. Its neutron emission rate is 5.18×10^5 n/s. The dead time of the ^{3}He proportional counter is 39.22 µs, are measured in the experiment.

IV. METHOD OF THE CORRECT EQUATIONS IN WHICH PARAMETERS ARE CALCULATED

If τ is the dead time of one neutron dosimeter, the relationship between the actual count m and the observed count n in the pulsed neutron field around an accelerator is [4]

$$\frac{m}{n} = \frac{f\Delta t}{f\Delta t - n\tau}, \quad (12)$$

where Δt is the beam's pulse width, and f is the beam's frequency. Thus, the relationship between n and the correction coefficient m/n can be deduced to be

$$n = \frac{f\Delta t}{\tau}\left(1 - \frac{1}{m/n}\right). \quad (13)$$

Proportional counter tubes that are commonly used in neutron monitoring are thermal neutron counters. Usually, a certain thickness of a moderator encases the count

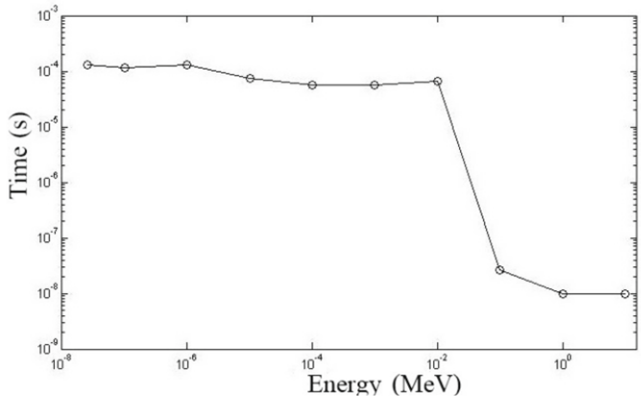

Fig. 3. Moderation time of neutrons passing through the moderator.

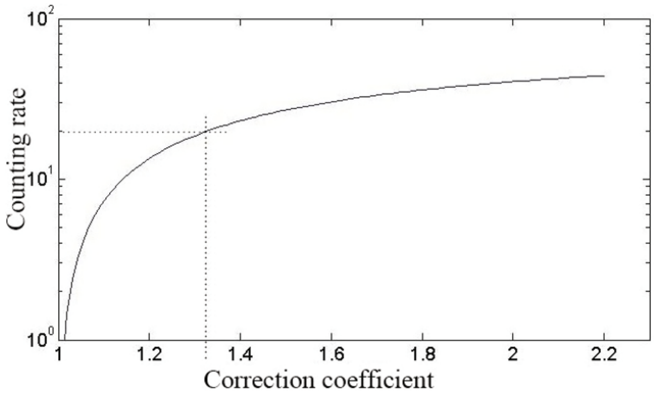

Fig. 4. Relationship between the counting rate and the correction coefficient of the neutron detector used in BEPCII.

tube, so the neutron detection efficiency can be improved by moderating neutrons at several MeV to thermal neutrons. The time is considerable, generally from dozens to hundreds of µs. If the beam's pulse width is replaced with the moderation time in the Eq. (13),

$$n = \frac{ft_m}{\tau}\left(1 - \frac{1}{m/n}\right). \quad (14)$$

The dead time of the tube is known. If the moderation time is determined, then the true count rate can be calculated by using the observed count rate. A Monte Carlo simulation program can simulate neutrons passing through the moderator, and the moderation time can be recorded. The simulation model is set as the moderator of the detector: the inner polyethylene layer is 1.9 cm thick; boron polyethylene is 0.6 cm thick; the lead is 0.6 cm thick, and the outer polyethylene is 6.5 cm thick. Ten energy points from thermal neutrons to 10 MeV are simulated. Fig. 3 shows the moderation time of neutrons passing through the moderator. The average moderation time is 63 µs.

When this kind of neutron detector is used in the radiation field of the BEPCII linear accelerator, the moderator time of neutrons arriving at the tube is extended to 63 μs, the beam frequency of BEPCII is 50 Hz, and the dead time of the neutron detector is 39.22 μs. The relationship between the counting rate and the correction coefficient is shown in Fig. 4. For instance, when the observed counting rate of the neutron detector is 20 cps, the real counting rate which is about 26.6 cps, can be determined by multiplying a correction coefficient of approximately 1.33. This method can be used for the known radiation fields and known detectors. If the moderation time or the beam's pulse parameters of accelerators are not certain, the method is not suitable.

V. METHOD OF THE CORRECT EQUATIONS IN WHICH PARAMETERS ARE DERIVED EXPERIMENTALLY

In the pulsed neutron fields around accelerators, the effect of the duty factor of the beam pulse on the counting rate of the tube is [5]

$$m = \frac{n}{1 - \frac{n\tau}{f\Delta t}\left(1 - \frac{\tau}{2\Delta t}\right)}. \quad (15)$$

The moderation time is usually between dozens to hundreds of microseconds, and the beam's pulse width is typically less than a microsecond. If the beam's pulse width in Eq. (15) is replaced with t_m and $\frac{\tau}{2t_m}$ in Eq. (15) is negligible, the result is

$$m = \frac{n}{1 - \frac{n\tau}{ft_m}}. \quad (16)$$

If the dead time and the moderation time of the detector are known, the true counting rate can be calculated from Eq. (16) and the observed counting rate. This is the method of correction equations using derived parameters. Generally, the beam's pulse parameters for accelerators are known, but the moderation time of the detector is not. The omitted counting correction can be achieved on the basis of the relationship between the beam current and the real counting rate. In the neutron pulsed field around an accelerator, the dose rate is proportional to the observed counting rate, and the true counting rate is proportional to the beam current of the accelerator [18]:

$$\begin{cases} R = a \cdot n \\ m = b \cdot I \end{cases}, \quad (17)$$

where R is the actual measured dose rate, I is the beam current of the accelerator, and a, b are constants. The relationship between the dose rate and the beam current can be deduced from Eqs. (16) and (17) and is given by

$$R = \frac{abI}{1 + \frac{b\tau}{ft_m}I}. \quad (18)$$

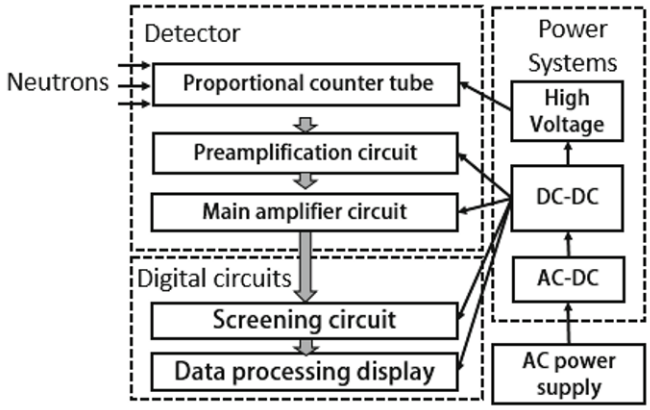

Fig. 5. Block diagram of the detection system.

Equation (18) shows that in a high-intensity accelerator radiation field, $R = ab/\frac{b\tau}{ft_m} = \frac{aft_m}{\tau}$ is the upper limit on the measurement of the dose rate. When the beam current is low, R is a straight line with a slope of approximately ab. If the data for different dose rates and beam currents can be measured in a certain accelerator radiation field, a nonlinear fitting can be made to get the constants according to Eq. (18). Thus, moderation time can be calculated, and the correction coefficient of the detector can be derived.

VI. DETERMINATIONS OF THE CORRECTION COEFFICIENT WHEN THE DETECTOR IS APPLIED IN

The detector discussed in this article is based on a ^{3}He proportional counter, and the detection system's block diagram is shown in Fig. 5. The BEPCII is a high-energy electron accelerator. High-energy photons are produced by an electromagnetic cascade shower of high-energy electrons hitting a target, and neutrons are produced by the (γ, n) reaction. During at the machine research time of BEPCII, the beam is driven into the beam dump. The detector is placed near the beam dump, the beam current is changed, the dose rate is measured, and the relationship between the dose rate and the beam current can be derived. A nonlinear fitting of the experiment data gives the constants in Eq. (18). Finally, the relationship between the true counting rate and the observed counting rate can be derived. The experiment is carried out in the linear accelerator tunnel using an easily adjustable and stable 2.09 GeV positron beams. The beam's pulse width is 20 ps, and the beam's frequency is 50 Hz. The flux of the electron gun can be controlled by adjusting the bias voltage, so as to control the export positron beam current. The beam's current is calculated by using the readings of the beam current transformer multiplied by the coefficient 0.23. Table 1 shows the experimental results.

Table 1. Results of the experiment in BEPCII.

No.	BCT Voltage (mV)	Beam Current (mA)	Counts /300 s	Dose Rate (μSv/h)
1	85	19.55	29595	47.234
2	100	23	30876	49.277
3	115	26.45	32525	51.908
4	130	29.9	33696	53.779
5	145	33.35	35003	55.865
6	160	36.8	36438	58.155
7	175	40.25	37278	59.494
8	190	43.7	38608	61.618
9	205	47.15	39684	63.336
10	220	50.6	40397	64.472
11	235	54.05	41485	66.208
12	250	57.5	41502	66.237
13	265	60.95	42309	67.52
14	280	64.4	43212	68.966
15	295	67.85	43489	69.404
16	310	71.3	44334	70.757

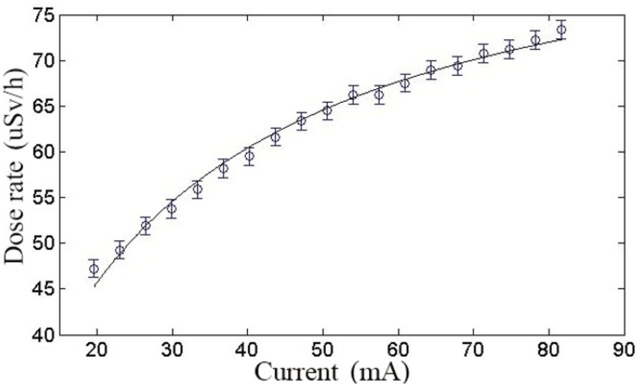

Fig. 6. Nonlinear fitting results and the experimental data.

A nonlinear fitting of the experimental data gives $a = 0.06$ μSv/h, $b = 80.77$ mA^{-1}, and $\frac{b\tau}{ft_m} = 0.05$. The result is shown in Fig. 6. In the figure, the horizontal axis is the beam current, and the vertical axis is the total neutron dose rate. The total dose rate and the beam current should have a linear relationship, but due to the omitted counting of the neutron detectors, that relationship becomes nonlinear.

When the beam current is low, the dose rate measured by the detectors is the true dose rate. When the beam current is high, omitted counting will occur on account of the dead time of the proportional counter. In Fig. 6, the relationship between the dose rate and the beam current is nonlinear, which once again proves that the omitted counting phenomenon does exist in accelerator pulsed radiation fields. According to the results,

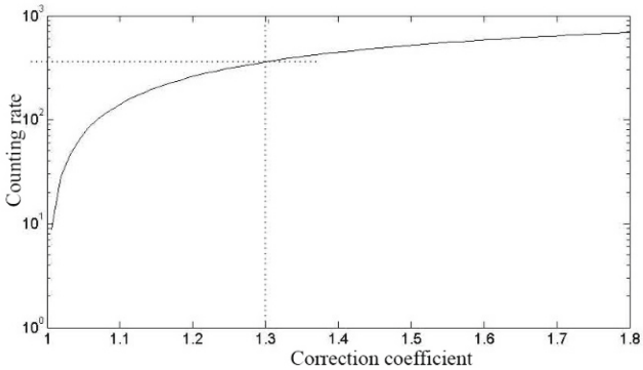

Fig. 7. Relationship derived from experiments to obtain the observed count rate and the correction coefficient.

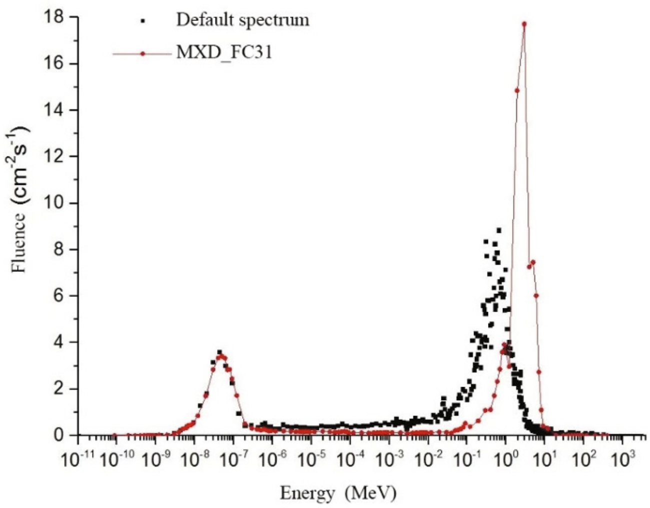

Fig. 8. (Color online) Energy spectrum of the BEPCII linear accelerator's neutron radiation field.

the calculated t_m is 1217 μs, so the relationship between the observed counting rate and the correction coefficient can be derived from Eq. (16), and the result is shown in Fig. 7. Comparing Fig. 4 and Fig. 7 shows that, when the correction coefficient is 1.3, the corresponding observed counting rate is about 350 cps from the experimental results, where is quite different from the simulation results. The reason is that the moderation time derived by the experiment is larger than that of the simulation.

In the experiment, the distance between the detector and the beam dump is about 5 m, so a certain amount of time is required for neutrons to reach the detector, and the needed time will be different for different energies. Thus, this time is broadened and should be included in the moderation time. The neutron spectrum of the linear accelerator's neutron radiation field was measured using an extended-range neutron multisphere spectrometer, and is shown in Fig. 8 [19]: 22% are thermal neutrons, and 72% are between 0.1 MeV and 10 MeV. Without the relativistic effects, thermal neutrons take about 2000 μs to travel a 5 m distance, but 2 MeV take about

361 μs. Thus, the total time is broadened to 1000 μs, which is consistent with the experimental results.

VII. CONCLUSION

Correction methods for the counts omitted due to the dead time in pulsed neutron fields have both advantages and disadvantages. Passive activation detectors have low sensitivities and are not convenient for measuring pulsed neutron fields. Moreover, they can usually be affected by γ-rays. The correction for the omitted counts based on the pulse amplitude is limited because the radiation fields of accelerators vary considerably. The main factors influencing the omitted counts for a neutron detector in the pulse radiation fields around accelerators include the beam's frequency, the dead time of the proportional counter and the moderation time. According to the revised equation, parameters can be calculated, and correction curves in a particular field can be derived. This is the method of correction equations obtained by deriving the parameters. When the moderation time cannot be determined, the relationship between the dose rate and the observed counting rates can be derived based on two equations: the relationship between the true dose rate and the beam current, and the relationship between the dose rate and the observed counting rates. Finally, the parameters in the equation can be derived experimentally. That is the method of correction equations in which parameters are derived experimentally.

The experiment is carried out in pulsed radiation fields with different intensities, and the relationship between the true counting rate and the correction coefficient is derived, based on the parameters, from a nonlinear fitting to the experimental results in BEPCII linear radiation fields. When the two methods are compared, the method of correction equations in which parameters are derived experimentally is found to be more accurate. This method can correct for omitted counts of neutron detectors when used in pulse radiation fields around accelerators. When neutron's time of flight in the experiment is taken into account, the difference between the two methods is tiny; at the same time, the experimental results verify the reliability of the Monte Carlo simulation results. Thus, the two methods can be used to correct effectively for the effect of the dead time in a neutron detector.

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