SRAM single event upset calculation and test using protons in the secondary beam in the BEPC

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Abstract: The protons in the secondary beam in the Beijing Electron Positron Collider (BEPC) are first analyzed and a large proportion at the energy of 50–100 MeV supply a source gap of high energy protons. In this study, the proton energy spectrum of the secondary beam was obtained and a model for calculating the proton single event upset (SEU) cross section of a static random access memory (SRAM) cell has been presented in the BEPC secondary beam proton radiation environment. The proton SEU cross section for different characteristic dimensions has been calculated. The test of SRAM SEU cross sections has been designed, and a good linear relation between SEUs in SRAM and the fluence was found, which is evidence that an SEU has taken place in the SRAM. The SEU cross sections were measured in SRAM with different dimensions. The test result shows that the SEU cross section per bit will decrease with the decrease of the characteristic dimensions of the device, while the total SEU cross section still increases upon the increase of device capacity. The test data accords with the calculation results, so the high-energy proton SEU test on the proton beam in the BEPC secondary beam could be conducted.

Key words: BEPC; proton; SRAM; single event upset; SEU cross section

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1. Introduction

The spectrum of protons in space is widely distributed[1], and these protons can induce the proton single event upset (SEU) of an SRAM[2–6]. An SEU test can be conducted on the ground. Presently, 5 GeV proton accelerators have already been produced, however, in China the proton accelerator with the highest energy is the 35 MeV proton linear accelerator at the Institute of High Energy Physics, CAS used in the SEU experiment. It is therefore urgent for China to develop a proton source with a higher energy. The secondary beam of the test beam at the Beijing Electron Positron Collider[7, 8] (BEPC) contains a large proportion of protons with an energy level of 50–100 MeV. Thus, this study first calculated the proton irradiation environment, which is the first time that SEU calculation and test have been conducted on SRAM of CMOS technology with different characteristic dimensions under that type of radiation environment. This test has worked out the tendency of the SEU section of high-energy protons with characteristic dimensions of SRAM. The above is the first report on SEU test of intermediate energy protons in recent years.

2. Proton radiation environment

The electron energy that the linear accelerator sent onto the target is 1.89 GeV, and the electron quantity is $N_e = 12.5 \times 10^{10}$ s^{-1}. As shown in Fig. 1, the target is a Beryllium cylinder with a diameter of 2.5 cm and a length of 10.8 cm. When the electron is injected into the Be-target, the photonuclear reaction occurs with the generated secondary protons being scattered around. The distance between the geometrical target center and the devices is 16 cm, with a polar angle of 45° .

As shown in Fig. 2, the proton yield and fluence rate when the electrons hit the target was calculated. This was done by choosing 0–10° and six segments of the outgoing polar angle, and dividing per segment of polar angle into 0–20, 20–40, 40–60 MeV and 13 energy segments, conducting the analog computation of the double differential fluence rate when the electrons hit the target using Geant4[9−11] software. In the six segments of outgoing polar angle, the proton fluence rate is the uppermost at the segments of 40–50°. Under the current conditions, the energy of proton generated by BEPC ranges from about 50–100 MeV, and the proton fluence rate $U_p \approx 1.09 \times 10^4$ s^{-1}·cm^{-2}.

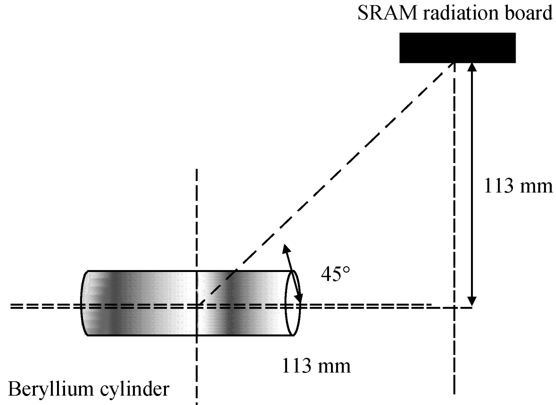

Fig. 1. SRAM radiation board in proton radiation environment.

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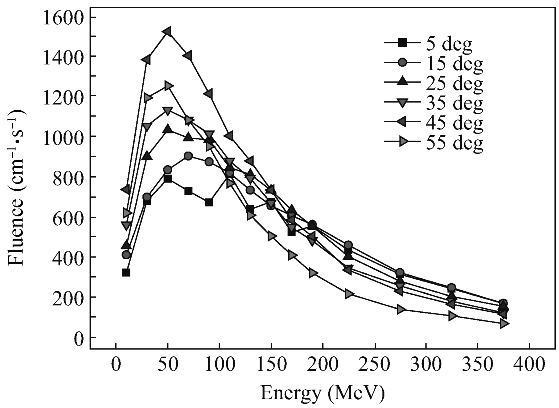

Fig. 2. Double differential fluence of proton in second beam on BEPC.

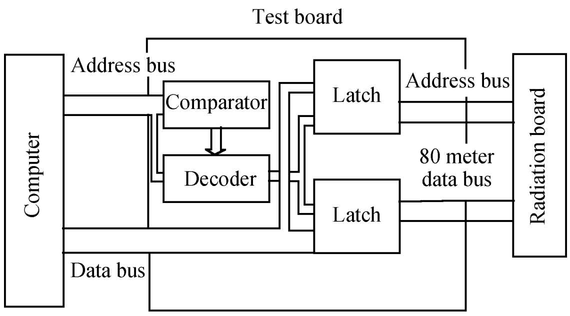

Fig. 3. Test system for SEU of SRAM devices in second proton beam on BEPC.

3. Single event effect test on BEPC

We adopted the SRAM SEU test system developed by our institute (see Fig. 3); an SEU test system of SRAMs on the BEPC platform has been established. Problems, such as anti-jamming of a weak signal during remote transmission and system stability, have been resolved under the mixed radiation field. Software design has reduced the switching number of each logic device as far as possible, so as to reduce possibility of interface introduction, as well as to reduce the electrical level variation of the long transmission line. Electrical level variation of each time can be limited within one cable, so as to avoid interfacing with each other during signal transmission.

The test procedure is: to write specific initial values in all SRAM logic addresses, such as 55H; save the initial values in the buffering zone, and then conduct proton irradiation. When the definitive period of irradiation is completed, read the data from the SRAM memory and compare it with the value stored in the buffering zone, counting the total SEU bits and recording the SEU addresses. The proton fluence rate and irradiation time is recorded, so as to work out total fluences of incidence proton. Finally the proton SEU section in SRAM device could be obtained (see Fig. 4).

The proton SEU tests have been conducted on four types of capacity of SRAM device (see Table 1) with different CMOS technology characteristic dimensions made by RENESAS; and the statistics have been conducted on the proton SEU sections with different characteristic dimensions of SRAM devices.

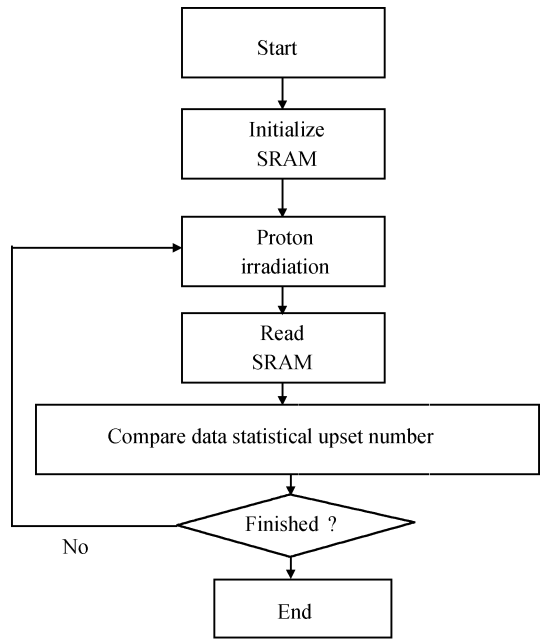

Fig. 4. Test flow for single event upsets (SEUs) of SRAM devices in the second proton beam at the BEPC.

4. Results and discussion between experiment and theory

4.1. Test data

As shown in Fig. 5, in the test, the upset bits increase linearly with the increase of proton fluence, and this is evidence that an SEU has taken place in the SRAM. When the SEU test is completed, its reading/writing function is normal. The SEU section could be obtained through the statistics of test data.

4.2. Model of proton SEU section calculation

Assuming the fluence rate of the incident proton is Φ with the unit as cm^{-2}, if the status of the N bit of the memory cell is upset in a certain device, the proton SEE cross-section of this device will be:

$$\sigma = \frac{N}{\Phi K}. \quad (1)$$

Its unit is cm^2. If it is divided by the total amount "K" of the memory cell of the device, each unit cross-section can be worked out[12].

According to nuclear reaction theory, the possibility of a proton taking part in a nuclear reaction on silicon wafer with thickness of d is as follows:

$$P = 1 - e^{-n\sigma_T d}, \quad (2)$$

where n means silicon atomicity within the unit volume; σ_T means the total cross section within which the proton takes part in a nuclear reaction (elastic scattering, non-elastic scattering and nuclear transformation) with silicon. Assuming that the effective area of device is A, then the proton number of incidence of the device is $A\Phi$, among them, the $A\Phi P$ proton will take part in a nuclear reaction with silicon. If among the above reacted protons, ε percentage of protons has deposited energy in the sensitive volume through reaction, which is larger than

Table 1. Parameters of SRAM devices for experiment.

Type	Manufacturer	Capacity (mode)	Feature size (μm)	Operating voltage (V)
M5M5V108DFP	RENESAS	1 M (128 k × 8 bit)	0.25	3.3
R1LP0408CSP	RENESAS	4 M (512 k × 8 bit)	0.25	5
HM62V8100	RENESAS	8 M (1 M × 8 bit)	0.18	3.3
HM62V16100	RENESAS	16 M (2 M × 8 bit)	0.13	3.3

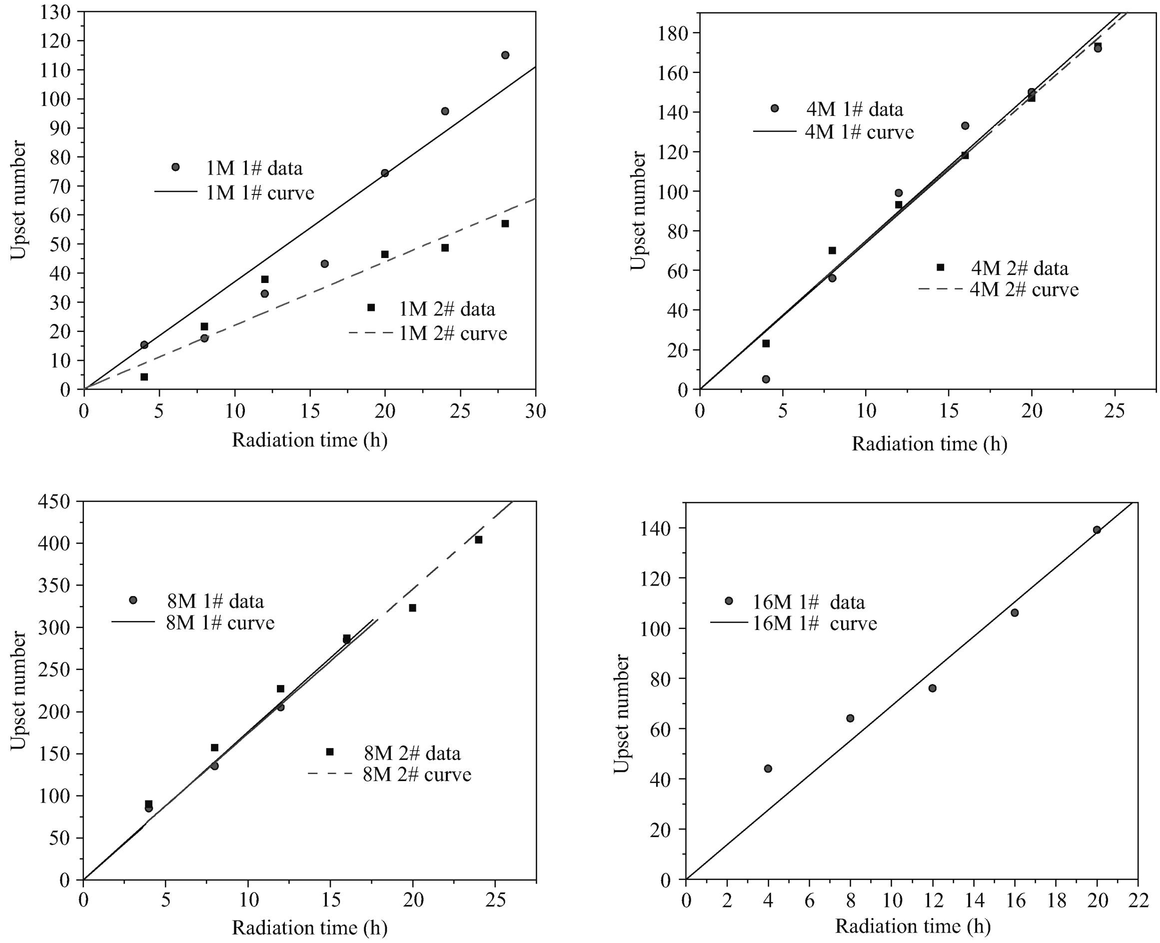

Fig. 5. Upset number of SRAM devices in second proton beam on BEPC.

SEU energy threshold value E_{thr}, then SEU will occur. Accordingly, SEU number can be expressed as

$$N = A\Phi P\varepsilon = A\Phi\varepsilon(1 - \mathrm{e}^{-n\sigma_{\mathrm{T}}d}). \tag{3}$$

Then the proton SEU section:

$$\sigma = A\varepsilon(1 - \mathrm{e}^{-n\sigma_{\mathrm{T}}d}). \tag{4}$$

When $n\sigma_{\mathrm{T}}d \ll 1$,

$$\sigma = n\sigma_{\mathrm{T}}V\varepsilon, \tag{5}$$

where $V = Ad$ is the effective volume of the device. Generally, $n\sigma_{\mathrm{T}}d \ll 1$, Equation (5) could be used to calculate the proton SEU section. The sections of protons reacting with silicon will be different due to their energy; σ_{T} is a function of proton energy. The reaction scale factor of a proton with energy exceeding the energy threshold value E_{thr} in sensitive volume is ε, which depends on SEU energy threshold value E_{thr} and sensitive volume of memory unit V_{s}, and also relates to the energy of incidence proton E. Therefore, Equation (5) can be accurately expressed as

$$\sigma = nV\sigma_{\mathrm{T}}(E)\varepsilon(E, E_{\text{thr}}, V_{\mathrm{s}}). \tag{6}$$

Provided that the SEU energy threshold value E_{thr} and the sensitive volume of memory unit V_{s} are known, ε can be worked out via an MC simulation calculation and then the SEU section can be worked out by Eq. (6).

A back biased PN junction exists among the SRAM, the drain region of the P2 pipe and the N^- substrate (① in Fig. 6), similarly, a back biased PN junction also exists among the drain region of the N2 pipe and the P^- well (② in Fig. 6), both of

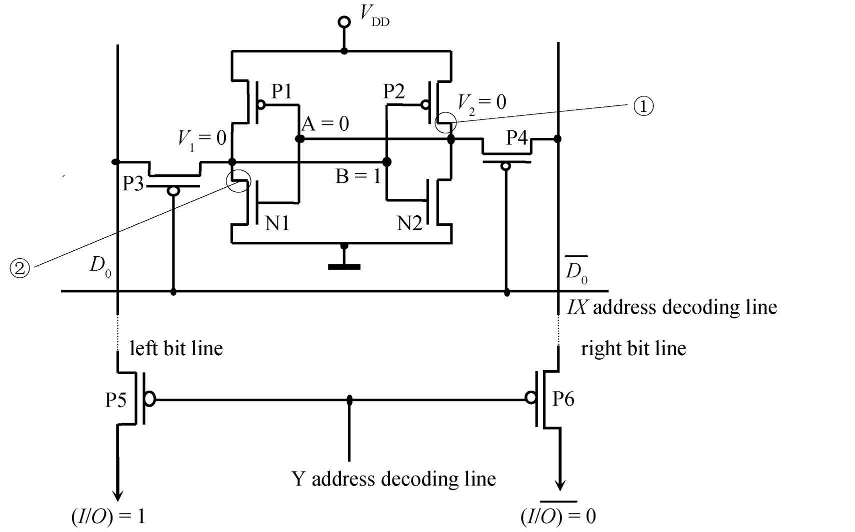

Fig. 6. SEU schematic of a CMOS static storage cell[14].

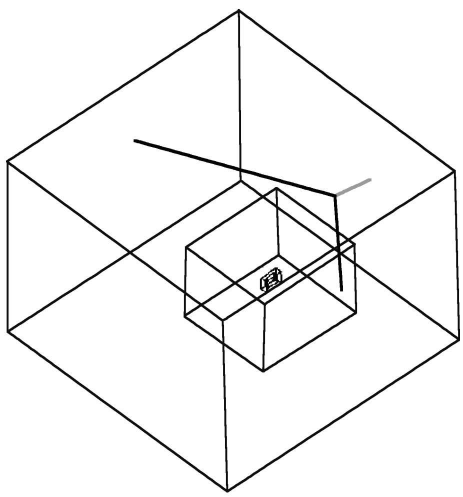

Fig. 7. Geant4 for volumes of three parts considered in M–C method and a forced collision occur.

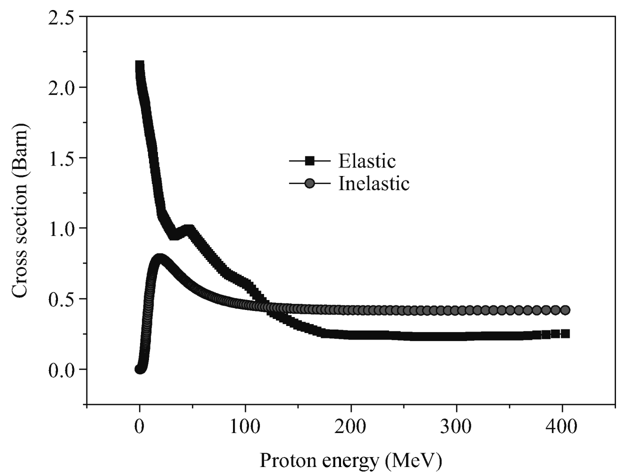

Fig. 8. Nuclear reaction cross section of proton in Si.

which are SEE sensitive volumes[13]. A semiconductor physics simulation can be applied to calculate the thickness and critical charge of the back biased PN junction.

Figure 7 shows the volumes of the three parts considered in the Monte Carlo method, of which the external is a vacuum box, containing an active volume of silicon, the back biased PN junction and the drain region inside.

In addition, due to lower possibility for nuclear reaction between protons and silicon, the calculation method of forced collision is therefore selected. The formulas below demonstrate a sample of source particle position. The active volumes are respectively located at the region of $[-a, a]$, $[-b, b]$ and $[0, c]$ at three coordinate axis. Σ_t is a macroscopic total cross-section of a proton with certain energy. ξ_1, ξ_2 and ξ are random numbers equally distributed within [0, 1]. Inelastic scattering between proton and silicon is forced (see Fig. 4). The three trajectories represent the proton, the silicon atom and the gamma ray.

$$\begin{cases} x_0 = (2\xi_1 - 1)a, \\ y_0 = (2\xi_2 - 1)b, \\ z_0 = -\frac{1}{\Sigma_t} \ln\left[1 + \xi\left(e^{-\Sigma_t c} - 1\right)\right]. \end{cases} \tag{7}$$

The particle shall be multiplied by a weight factor $W(z_0)$ after each flight.

$$W(z_0) = 1 - e^{-\Sigma_t c}. \tag{8}$$

4.3. Comparison between test data and calculation data

The nuclear reaction cross section of a 50–100 MeV proton in Si is about 1 Barn (see Fig. 8). The dimensions are 9.4 × 9.4 × 8.5 μm^3[12], when the number of incident proton is 2.358 × 10^4, an nuclear reaction event will happen, at this time, the

Table 2. Result of SEU test of SRAM devices in proton environment.

Model		Feature size (μm)	SEU cross section (cm^2/bit)		
Type	Number		Experiment	Exp average	Calculation
M5M5V108DFP	1#	0.25	9.00×10^{-14}	7.15×10^{-14}	6.58×10^{-14}
	2#	0.25	5.30×10^{-14}		
R1LP0408CSP	1#	0.25	4.55×10^{-14}	4.52×10^{-14}	2.53×10^{-14}
	2#	0.25	4.49×10^{-14}		
HM62V8100	1#	0.18	5.35×10^{-14}	5.30×10^{-14}	3.08×10^{-14}
	2#	0.18	5.24×10^{-14}		
HM62V16100	1#	0.13	1.02×10^{-14}	1.02×10^{-14}	1.05×10^{-14}

fluence of the incident proton is 2.67×10^{10} cm^{-2}, ε can be worked out via an MC simulation calculation and the result is about 0.001. The proton SEE cross-section of this device will be 3.75×10^{-14} cm^2.

This arithmetic is very close to the experimental explanation, and the result is in the same order of magnitude as the result from Eq. (6).

The brief test result of the SEU cross section is shown in Table 2. The test result shows that the SEU section per bit will decrease with the decrease of the characteristic dimensions of device, while the total SEU section still increases upon the increase of device capacity. By comparing the test data of the secondary beam proton SEE in the SRAM device and Geant4 calculation result using Eq. (6), we can find both of them are in the same order of magnitude and very close.

5. Conclusion

The protons in the secondary beam at the BEPC are first analyzed. Under the current conditions, the energy of a proton generated by the BEPC is about 50–100 MeV, and the proton fluence rate is $U_p \approx 1.09 \times 10^4$ $s^{-1} \cdot cm^{-2}$. At the present time, the test platform of the SEU is good transitional instrument relative to the strong proton beam. In the BEPC secondary beam proton radiation environment, the proton SEU cross section for different characteristic dimensions have been calculated and the test of SRAM SEU cross section has been designed and a good linear relation between SEU in SRAM and fluence was found, which is evidence that SEU has taken place in the SRAM. The SEU cross sections were measured in SRAM with different characteristic dimensions. The test result shows that the SEU cross section per bit will decrease with the decrease of characteristics dimensions of device, while the total SEU cross section still increases upon the increase of device capacity. The test data accords with the calculation results, so the high-energy proton SEU test on the proton beam in the BEPC secondary beam could be conducted.

References

[1] Li Taosheng, Chen Jun, Wang Zhiqiang. Brief introduction to space radiation environment. Radiation Protection Bulletin, 2008, 28(2): 1

[2] Petersen E L. Nuclear reactions in semiconductors. IEEE Trans Nucl Sci, 1981, 33(6): 1571

[3] Hamm R N, Rustgi M L, Wright H A, et al. Energy spectra of heavy fragments from the interaction of proton with communications materials. IEEE Trans Nucl Sci, 1981, 28(6): 4004

[4] Doucin B, Patin Y, Lochard J P, et al. Characterization of proton interactions in electronics components. IEEE Trans Nucl Sci, 1994, 41(6): 592

[5] Miroshkin V V, Tverskoy M G. Two parameter model for predicting SEU rate. IEEE Trans Nucl Sci, 1994, 41(6): 2085

[6] He Chaohui, Yang Hailiang, Geng Bin, et al. Experiment study on proton single event effects in SRAM. Nucl Electron Detection Technol, 2000, 20(4): 253

[7] Chen Hesheng. Beijing electron positron collider. Bulletin of Chinese Academy of Sciences, 2008, 23(4): 364

[8] Wang Shuhong, Pei Guoxi, Sun Yaolin. BEPC II Linac upgrade and beam commissioning. High Energy Physics and Nuclear Physics, 2006, 30(S1): 150

[9] Agostinelli S, Allison J, Amako K, et al. Geant4—a simulation toolkit. Nuclear Instruments and Methods in Physics Research, 2003, A506: 250

[10] Allison J, Amako K, Apostolakis J, et al. Geant4 developments and applications. IEEE Trans Nucl Sci, 2006, 53(1): 270

[11] Wellisch J P, Kossov M, Degtyarenko P. Electro and gamma nuclear physics in Geant4. Computing in High Energy and Nuclear Physics, La Jolla, California, March 2003

[12] Wang Yuanming, Chen Wei, Guo Hongxia, et al. Single event upset cross section calculation for secondary particles induced by proton using Geant4. Atomic Energy Science and Technology, 2010, 44(12): 1505

[13] He Chaohui, Li Guozheng, Luo Jinsheng. Analysis of single event upset in CMOS SRAMs. Chinese Journal of Semiconductors, 2000, 21(2): 175

[14] Yang Hailiang, Li Guozheng, Jiang Jinghe. Experimental studies on equivalency of single event effect induced by protons and neutrons. Nuclear Electronic & Detection Technology, 2002, 22(2): 158