Applications of the Cyciae-100 cyclotron in neutron-induced single event effect

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Abstract

Neutron-induced single event effect is one of the significant factors affecting the reliability of semiconductor devices in avionics and ground facilities. The 100 MeV proton cyclotron in China Institute of Atomic Energy (Cyciae-100) provides white neutron and quasi-monoenergetic neutron induced by proton and W/Li bombardment. Based on the white neutron beam line of Cyciae-100, the white neutron energy spectrum is measured by neutron time-of-flight method with double scintillator spectrometer, as well as the theoretical energy spectrum calculated by the Monte Carlo method. The neutron irradiation test of two SRAMs with different technology nodes were carried out, and the neutron single event upset sections are obtained simultaneously. In addition, based on the quasi-monoenergetic neutron beam line, the simulation of neutron energy spectrum were carried out. As a conclusion, the white neutron and quasi-monoenergetic neutron provided by Cyciae-100 are well suitable applied to the study of neutron single event effects.

1. Introduction

Galactic cosmic rays and solar rays interact with nitrogen and oxygen in the earth's atmosphere to produce a large number of neutrons. Neutron incident semiconductor devices cause single event effects, leading to logic inversion and functional failure, which seriously threaten the safety and reliability of aircraft electronic systems. In addition, in the nuclear power stations and spent fuel reprocessing plants, neutron radiation also makes the visual surveillance system and electronic control systems in unreliable situation.

To measure the neutron-induced single event effect and evaluate radiation risks, accelerated testing can be conveniently performed using the ground-based neutron sources. In 2016, the first physical experiment Energy was carried out on the 100 MeV proton cyclotron (Cyciae-100, 100 MeV/200 μA) in China Institute of Atomic energy (CIAE). Through the design and construction of neutron target, both of W and Li targets, white neutron and quasi-monoenergetic neutron induced by proton and W/Li bombardment, which provides a good condition for experimental research of neutron radiation effects.

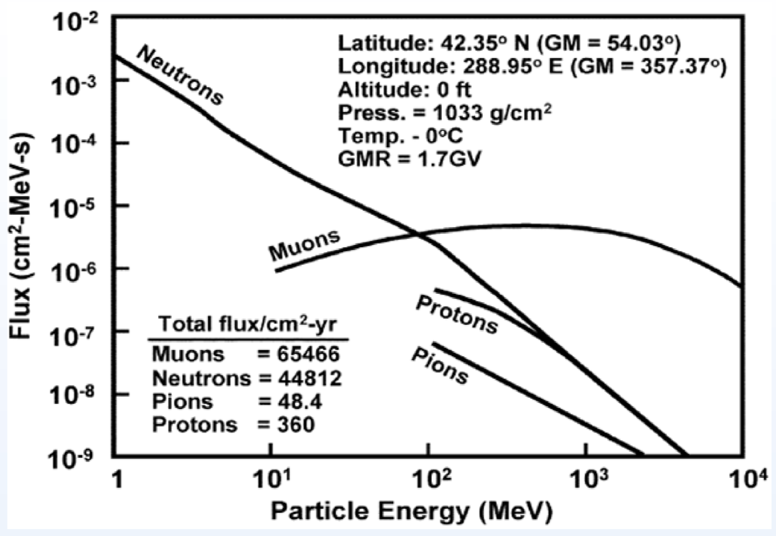

Fig.1 The atmosphere radiation environment
Ref: Zieger, IBM J. Res. Develop. 42(1998)125

Fig.2 The Cyciae-100 cyclotron

2. Model and Methods

In order to obtained the neutron spectrum, the neutron time-of-flight (TOF) experiment with two scintillator detector were performed. One liquid scintillator detector (scattering detector) is placed on the neutron beam behind the target, which is detect the start signal of flight neutron, and the other (main detector with high efficiency) is placed at a distance L and 45° direction of the proton beam, which is detected the stop signal of flight neutron. The gamma signal were removed by pulse shape discrimination (PSD), and the time spectrum of flight neutron were acquired by a DT5730 digitizer in the coincidence mode. Then, the detection efficiency of two liquid scintillators were simulated by Monte Carlo method, the neutron energy spectrum can be obtained by converting the time spectrum with formula (*). Base on the white neutron spectrum , The SEU Monitor (Europe space agency single event upset monitor) was applied to measure the cross section of neutron SEU.

$$mc^2 = \frac{m_0c^2}{\sqrt{1-(\frac{\upsilon}{c})^2}} = E + m_0c^2 \qquad t = \frac{L}{\upsilon} = \frac{m_0c^2+E}{\sqrt{E(2m_0c^2+E)}}\cdot\frac{L}{c}$$

$$c = 2.9979\times10^8\,\mathrm{m/s} \qquad m_0c^2 = 939.552\cdot c^2\,\mathrm{MeV}$$

$$t = 3.3356\frac{(E+939.552)L}{\sqrt{E(E+1879.1462)}}[\mathrm{ns}]$$

$$E = m_0c^2\left(\frac{1}{\sqrt{1-(\frac{L}{tc})^2}}-1\right) \qquad (*)$$

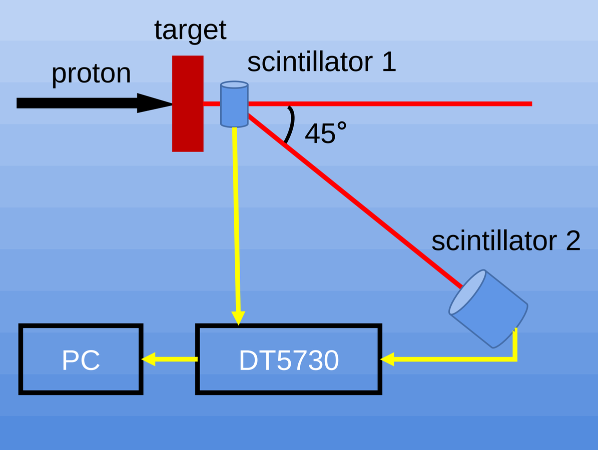

Fig.3 The measurement of white neutron spectrum

3. Results and Discuss

The white neutron target is tungsten copper alloy WCu7, 93% of which is tungsten, 12 mm thickness and 75 mm diameter. After passing through 2 mm copper and 5 mm water, 100 MeV protons bombard the 12 mm thick neutron target. Figure 5 (d) shows the measured energy spectrum, and compare to the theoretical spectrum by Monte Carlo simulation. With 100 MeV / 1 μA proton, 3.28×10^4 n/(cm²·s) neutron from 3 MeV to 100 MeV were produced at the position 15 m away from the target in 0 degree direction, and neutrons above 10 MeV account for 12.4%. In addition, the neutron SEU cross section of the SEU Monitor (250 nm, 16 Mbit, 3.3 V) is 31.0 upsets/h with 3 μA proton, that is 5.47×10^{-15} upsets/(cm²·bit) .

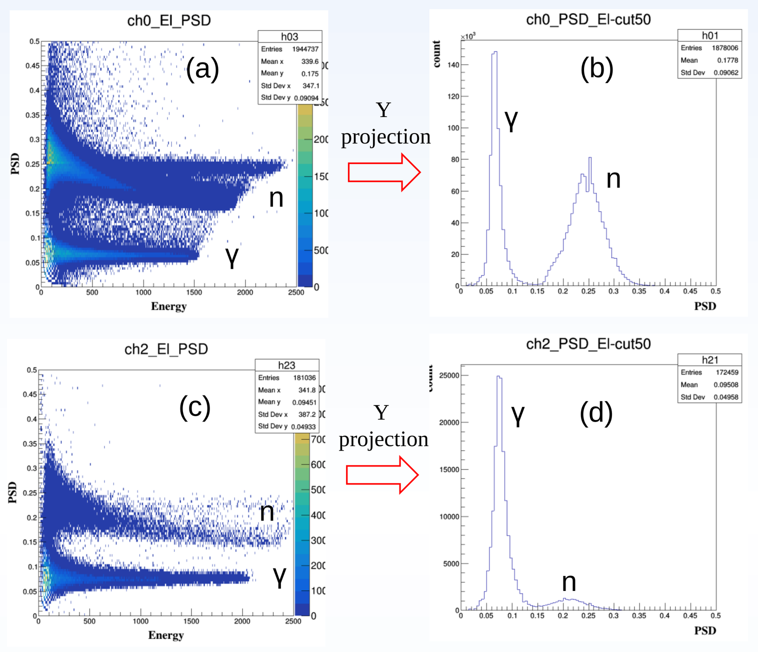

Fig.4 Scintillator counts(a and b for the scattering detector, c and d for the main detector)

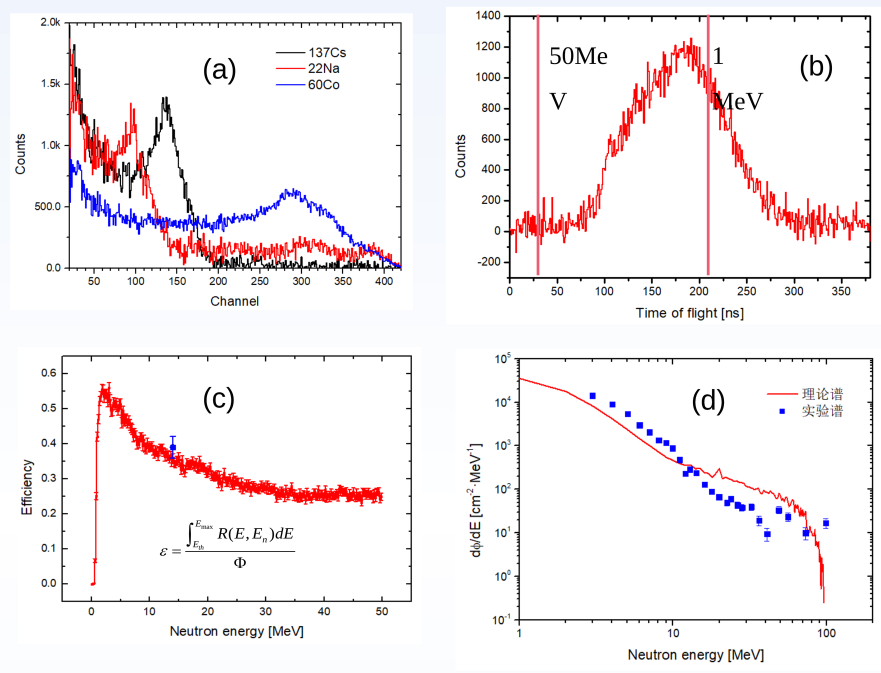

Fig.5 Data processing of neutron spectrum(a for scintillator energy calibration, b is the time spectrum of ToF, c for scintillator efficiency calibration, d is the neutron energy spectrum)

Tab.1 Neutron distributions in different sources

Neutron source	Ratio of neutron		
	1-10 MeV	10- 100 MeV	> 100 MeV
IEC @12 km	36.5%	37.2%	26.3%
JEDEC @0 km	35%	35%	30%
Yangbajing @4300km	35.6%	32.1%	32.3%
CYCIAE-100 15 m @ 0°	83.4%	16.6%	0%
CSNS 76 m @180°	81.7%	16.8%	1.5%
CSNS 20m @ 41°	50%	28%	22%
LANSCE	52%	26%	22%
ISIS	92%	7%	1%
ANITA	65%	28%	7%
PNPI	57%	29%	14%
RCNP	57%	25%	18%

Fig.6 Measurement of neutron SEU

The quasi-monoenergetic neutron target is natural Li, 6 mm thickness and 52 mm diameter. Figure 9 shows the theoretical spectrum by Monte Carlo simulation, with 100 MeV / 1 μA proton, 2.92×10^4 n/(cm²·s) neutron from 0 MeV to 100 MeV were produced at the position 5 m away from the target in 0 degree direction, and monoenergetic peak neutrons account for 51.8%.

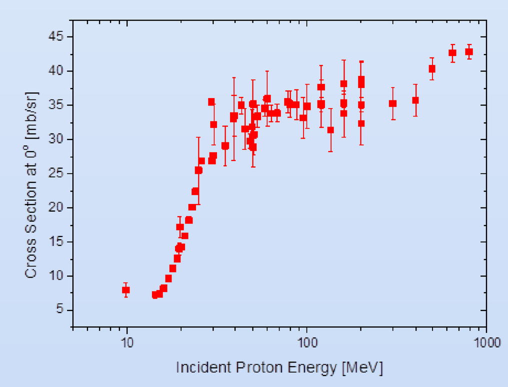

Fig.7 Nuclear reaction cross-section of $^7Li(p,n_{0,1})^7Be$

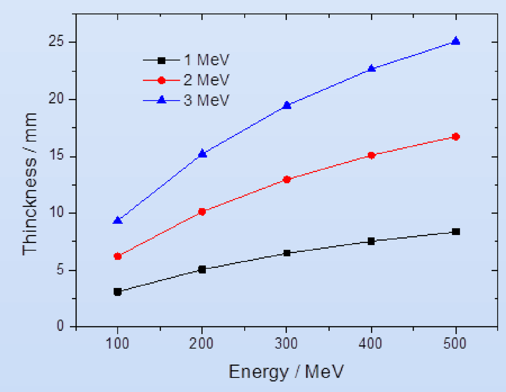

Fig.8 Proton energy deposition in Li by SRIM

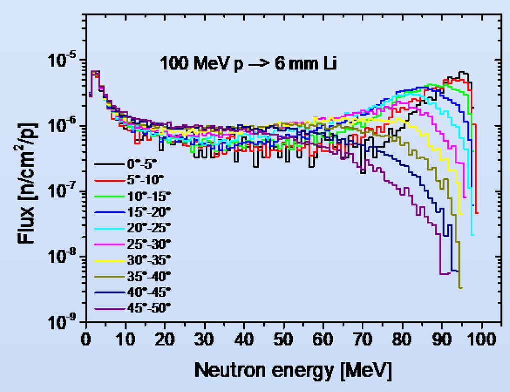

Fig.9 Neutron spectrum of 100 MeV p → 6 mm Li

4. Conclusions

The white neutron spectrum measurement and the first neutron single event effect test were performed based on the Cyciae-100 cyclotron in CIAE. With 100 MeV/1 μA proton, 3.28×10^4 n/(cm²·s) neutron provided to irradiate the electronics device. Considering the neutrons above 10 MeV account for 12.4%, the white neutron source is more suitable to test the neutron radiation effects for nuclear industry rather than for atmospheric environment.

The quasi-monoenergetic neutron spectrum simulated by Monte Carlo method, with 100 MeV/1 μA proton, 2.92×10^4 n/(cm²·s) neutron were provided to irradiate the electronics device. 70-100 MeV protons can derived from the Cyciae-100 directly, so four quasi-monoenergetic neutron spectrum are available for neutron radiation effects.