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APPLICATION PROGRESS OF CYCIAE-100 HIGH CURRENT PROTON CYCLOTRON*

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Abstract

A new RIB facility, Beijing radioactive ion-beam facility (BRIF) had been constructed at CIAE. A 100 MeV H$^-$ cyclotron (CYCIAE-100) is selected as the driving accelerator which can provide a 70–100 MeV, 10 pA–520 µA proton beam for basic and applied research in the field of nuclear science and technology. The application of this facility has promoted the development of frontier scientific research in China, such as radioactive nuclear beam physics, nuclear data, neutron physics and space radiation effects. Recently, quasi-monoenergetic neutron source above 20 MeV and the white light neutron source with the best time resolution were completed, which had filled the gap in the measurement of neutron data in the range of energy of 100 MeV in China. In this paper, the main milestones in the use and development of CYCIAE-100 high current proton cyclotron are reviewed, the scientific applications based on platform are described, and the important topics in proton applications based on intermediate energy are discussed, including space radiation hardening, neutron standard radiation field and biological radiation damage mechanism.

INTRODUCTION

BRIF was started at CIAE in 2004. The project outline is shown in Fig. 1. It consists of a 100 MeV cyclotron, an isotope separator online system (ISOL), modification of the existing tandem, a superconducting Linac booster (SCL), various experimental terminals, and an isotope production station [1].

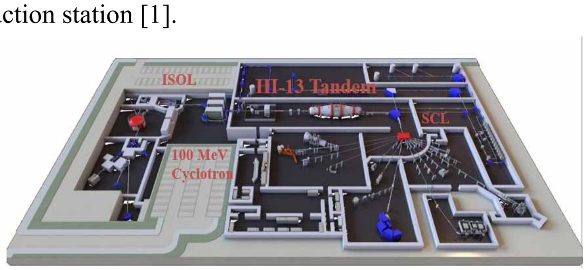

Figure 1: Layout of BRIF.

On July 4th 2014, first 100 MeV/20 µA proton beam shot on the target from CYCIAE-100, and the achievement was awarded as Top10 scientific achievements of 2014 in China. Figure 2 illustrates the main parts of the cyclotron. It is connected with five beamlines as follows:

- Northward can supply beam to ISOL beamline and isotope target terminal.
- Southward can supply beams to three beam lines that are White light neutron target line (15 m neutron tube and 30 m neutron tube), single event effect test bench and quasi-monoenergetic neutron source terminal.

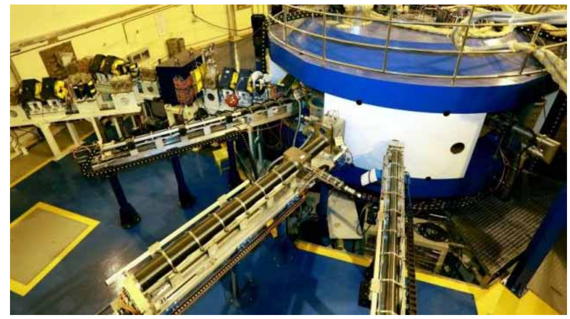

Figure 2: The CYCIAE-100 cyclotron.

APPLICATION ON CYCIAE-100

Up to Dec 2022, CYCIAE-100 has produced over 5000 hours beam time for users. Users are from different area institutes for nuclear physics, medical schools and institutes for electronic and space technology universities. The Usage of Cyclotron in our lab mainly focused on nuclear physics research, nuclear reaction, nuclear data, radiation effect Research proton-neutron SEE, radiation hardness, medical and other applications including medical isotope production and proton therapy.

Nuclear Reaction

Innovative achievements in radioactive nuclear beam physics had been carried out. The highest quality Na-20 radioactive beam is produced by using high resolution ISOL device in 2015, and the strange decay mode of β-γ-α of ^{20}Na is discovered for the first time in the world which brought China's nuclear astrophysics, radioactive nuclear beam physics and other scientific research into the international forefront. The ^{20}Na energy spectrum diagram is shown in Fig. 3.

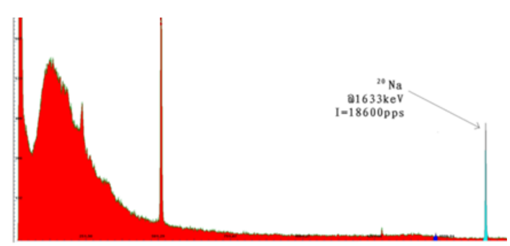

Figure 3: ^{20}Na energy spectrum diagram.

Nuclear Data

Quasi-monoenergetic neutron source above 20 MeV and the white light neutron source with the best time resolution were completed. In order to take the calibration of high energy neutron that is a bottleneck restricting space neutron

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detection, the quasi-monoenergetic neutron reference radiation field in the energy region above 20 MeV is established that is shown in Fig. 4. The quasi-monoenergetic neutron target consists of three beryllium targets with thickness of 0.4 mm, 0.5 mm and 0.6 mm and one fluorescent target. China is the second country in the world with neutron reference radiation field and calibration ability in the energy region above 20 MeV.

Figure 4: Quasi-monoenergetic neutron source.

Also, white light spectrum neutron nuclear data Measurement platform is constructed by proton bombardment of tungsten target to produce neutrons. The collimator is set in the neutron pipe. The co-axiality error between neutron collimation hole and neutron beam pipe is less than 0.10 mm. The collimator is composed of 35 cm copper at the front end and 65 cm iron at the rear segment. Four kinds of collimating aperture choices of 30 mm, 60 mm, 100 mm and complete shielding are selected. Measurement of spectrum are done by double liquid scintillation neutron time-of-flight method. The results show neutron energy range is 3-100 MeV. When the proton current is 1 μA, the measured neutron Fluence in the energy region of 3-100 MeV is about 3.28×10^4 $cm^{-2}s^{-1}$.

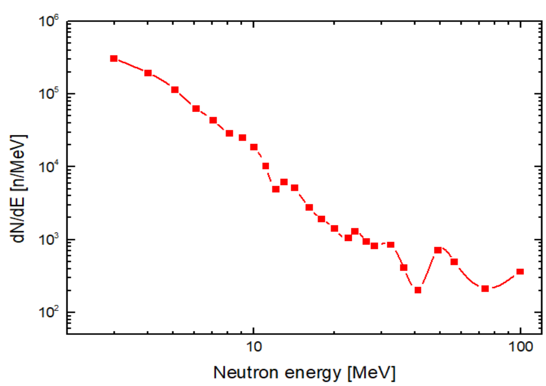

Figure 5: 3-100 MeV neutron energy spectrum diagram.

The first neutron single event effect (SEE) experiment was carried out using neutron beam line. Three kinds of SRAM devices with different characteristic sizes were tested by single event reversal (SEU). The chip shows malfunction to some extent Respectively.

Radiation Effect

Nowadays, cell density of devices in the circuit continues to increase, the range of radiation of a single particle can cover multiple devices. Furthermore, the charge collection effect is caused by multiple nodes in the circuit, and the displacement effect is produced in the circuit. A new proton single event effect line is reconstrued. Figure 6 illustrates the components of this line. The proton single event effect irradiation device is mainly composed of five systems: beam lowering system, beam scattering system, energy degrader system, beam diagnosis system and sample platform.

The cyclotron is a strong current accelerator, which generally provides an initial current of the order of μA, while the single particle effect experiment generally requires a weak beam of nano-Ampere level, so it is necessary to reduce the proton beam intensity. Therefore, the effect of beam reduction can be achieved by using a quadrupole lens to disperse the beam in the X and Y directions, and then intercept a small part of the beam in the centre through the slit.

The original beam spot provided by the accelerator is generally small, while the single particle effect experiment generally needs a uniform large beam spot to cover the whole electronic chip, so it is necessary to enlarge the beam spot size.

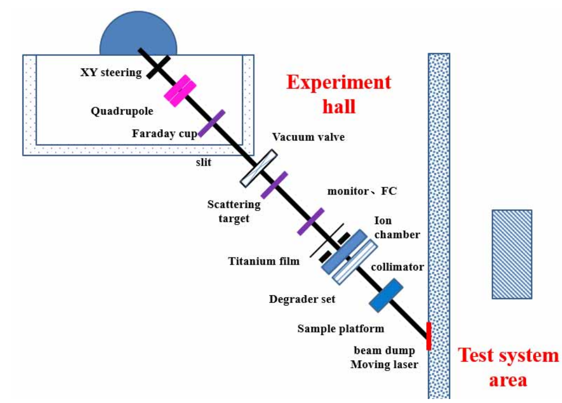

Figure 6: Proton single event effect line diagram.

Therefore, by using the method of beam expansion by double scattering targets, the proton beam forms a Gaussian distribution after passing through the first scattering target, and then passes through the second scattering target, because the heavy nuclear material in the center has stronger scattering ability and has a stronger weakening effect on the beam current. after a certain flight distance, a large area uniform beam spot can be obtained in the sample plane.

Accelerators can only provide proton beams with initial energy of 75-100 MeV, while single-particle effect experiments generally need proton beams with a wide energy range to measure a more complete cross-section curve, so it is necessary to reduce proton energy. Therefore, by placing a group of energy-reducing sheets with accurately calculated thickness on the beam line, the fast switching of proton beams in a certain energy range can be realized by the combination of multiple energy-reducing sheets.

In order to carry out the single particle effect experiment, it is necessary to measure the beam parameters such as proton irradiation Fluence and uniformity. The proton beam flux is measured by on-line monitoring of transmission ionization chamber, plastic scintillator detector or Faraday cup. The plastic scintillator detector is used at low injection rate and the Faraday cup is used at high injection rate.

With the SEE platform, CIAE jointly carried out the first experiment on the proton single event effect. Fill the gap in the anti-radiation experiment of intermediate energy protons in China. Then, experimental verification of key technologies of LHC/ATLAS single crystal diamond detector was done. In order to verify resistance to proton irradiation, test comparation of protons and heavy ions radiation damage mechanism of 0.18 µm CMOS devices were carried out. Results show no obvious SEL and SEFL occurred when the total dose of $5E^{10}$ in turn reached.

Medical and other Applications

In the face of complex space radiation environment, Proton radiation has an important effect on the life and health of astronauts of space mission. The batch of important data of intestinal microflora of mice irradiated by intermediate energy proton were successfully obtained and confirmed for the first time that proton irradiation had an effect on intestinal microflora in mice. The findings enhance the health protection ability of astronauts, which will provide a solid scientific and theoretical support for the smooth promotion of China's deep space exploration.

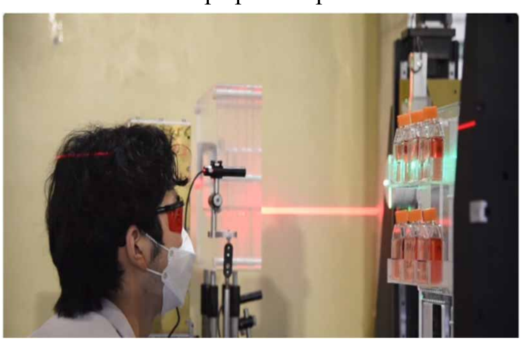

Figure 7: Experiment samples.

Additional, sensitivity of nasopharyngeal carcinoma and glioma to proton irradiation is determined. A375 cancer cells were irradiated by proton to study the changes of cell survival rate, cell cycle change, apoptosis and DNA damage with dose.

Radiotherapy, a common method for the treatment of cancer. FLASH imaging is delivered at an ultra-high dose rate (> 40 Gy/s), meanwhile reducing the normal tissue toxicity. On the N3 line of CYCIAE-100, three-dimensional water phantom PTW, Bragg peak ionization chamber, reference ionization chamber and finger ionization chamber were used for dose measurement [2, 3]. The ultra-high dose rate of 40.76 Gy/s (204.9 for 5 second) is obtained in this test, which can be used in the study of proton FLASH as shown in Fig. 8.

Figure 8: Proton FLASH set.

In radioactive isotope development study, medium energy proton can be used to radiated kinds of target materials for rare isotope. Through the design and research of isotope solid target system, a high-power solid target radionuclide experimental device has been successfully developed, and core technologies have been mastered. The first-time test of Ac-225 with 100 MeV cyclotron has been completed. ^{221}Fr characteristic ray proved the existence of mother nuclide of ^{225}Ac shown in Fig. 9. It has laid a solid foundation for the research of other nuclides related to the production of accelerators.

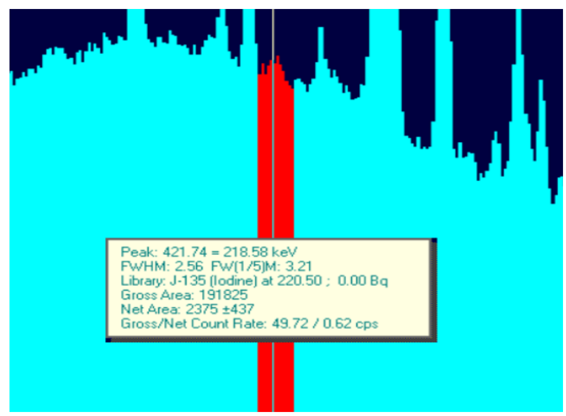

Figure 9: ^{225}Ac-^{221}Fr: characteristic ray.

CONCLUSION

CYCIAE-100 facility as the core of BRIF, is playing more and more important role in the nuclear data, radiation effect, agriculture, medical and isotope production area. We will continue to improve the performance and efficiency of the accelerator, complete the upgrading of aging devices, and maintain the stability of the beam.

In the future, it is planned to continue to expand the facility capacity, and give full play to the potential of large scientific devices in the application of accelerator neutron sources and nuclear waste transmutation (ADS), and make vital contributions to the promotion of the country's nuclear scientific and technological strength.

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