Neutron production at the heavy ion research facility in Lanzhou

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Abstract In this work, the neutron radiation field at Heavy Ion Research Facility in Lanzhou (HIRFL) was investigated. Total neutron yields, spectra and angular distributions in the bombardment of various thick targets by ^{12}C and ^{18}O ions with energies up to 75 MeV/u were obtained using the activation method. The neutron dose equivalent rates of 60 MeV/u ^{18}O on various thick targets at different angles were measured with a modified A-B remmeter. Our results are compared with those of other reports.

Key words HIRFL, heavy ion reactions, neutron radiation field

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1 Introduction

The neutron yields and spectra are very important parameters in radiation protection of heavy ion accelerators. The health physicists are interested in the neutrons from thick targets, which are close to the real neutron field at accelerator hall. Since the 1960s, the studies of heavy ion reactions have been developed from low energy region (E <50 MeV/u) to intermediate energy region (50 MeV/u< E <200 MeV/u) and high energy region (E >200 MeV/u). Hubbard et al.[1] measured the neutron yields of some heavy ions with energy about 10 MeV/u in 1960. Guo et al.[2] completed an experimental measurement of thick target neutron yields (TTNY) for low energy (0.9—6 MeV/u) heavy ion reactions, in their experiment, 14 different beams were accelerated and 12 different thick targets were bombarded at a 10 MeV tandem accelerator in 1987. T. Nkamura et al.[3] performed a series of experiments in 1998, in their experiments, neutrons of different incident ions with energy up to 800 MeV/u on different thick targets had been measured with TOF methods. Those are the most important experiments on TTNY and neutron spectra measurement.

For radiation protection purpose, the neutron field at Heavy Ion Research Facility in Lanzhou (HIRFL) was investigated. Neutron yields, spectra and angular distributions from various thick targets with incident ^{12}C and ^{18}O ions with energies up to 100 MeV/u were obtained respectively, by calculation and experimental measurement. In our experiment, the results also include contribution of the scattered neutrons, so the results are the real neutron field at the target area and practically useful.

2 Theoretical estimation

The neutron product cross sections from ^{56}Fe target bombarded by 192 MeV, 500 MeV, 700 MeV, 900 MeV and 1.2 GeV ^{12}C ion have been calculated using the Monte-Carlo method and HIC-1 code from H. W. Bertini et al[4]. The data used in present work are taken from this report.

According to these neutron emission differential cross sections, the neutron yield on thin targets can be expressed by:

$$\Delta y = \iint_{4\pi} \frac{N_{\rm a}}{A} \cdot \left(\frac{{\rm d}^2\sigma}{{\rm d}E_{\rm n}\cdot {\rm d}\Omega}\right) {\rm d}E_{\rm n}{\rm d}\Omega\ , \qquad (1)$$

where, $N_{\rm a}$ is Avogadro constant; A is the target atomic mass; $E_{\rm n}$ is neutron energy, ${\rm d}^2\sigma/{\rm d}E{\rm d}\Omega$ is double differential cross section. Then, integrate Δy in the range of incident ion (R), the yield on thick target Y was obtained.

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$$Y=\int_0^R \Delta y\cdot \mathrm{d}r\ . \qquad (2)$$

Using this method, the neutron yields and energy spectra of 58.3 and 100 MeV/u ^{12}C on thick Fe target were calculated. The neutron yields with the results from other reports[5—7] are shown in Fig. 1, the neutron spectra and dose equivalent rates are shown in Fig. 2 and Fig. 3 respectively.

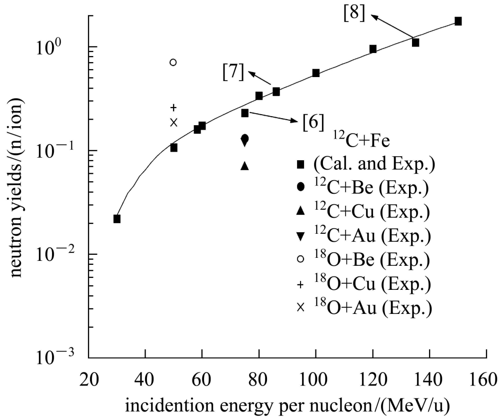

Fig. 1. Neutron yields varies with incident ion energy (Exp. for measured value and Cal. for calculated value).

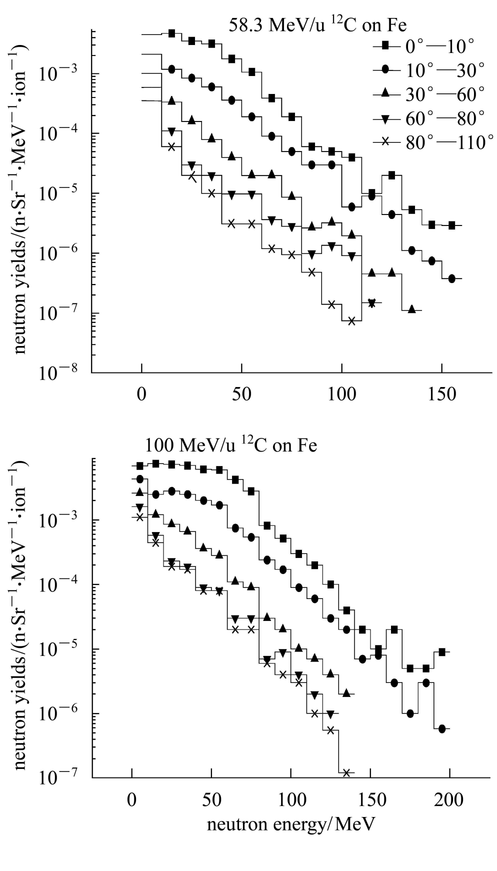

Fig. 2. Calculated neutron spectra from 58.3 and 100 MeV/u ^{12}C on thick Fe.

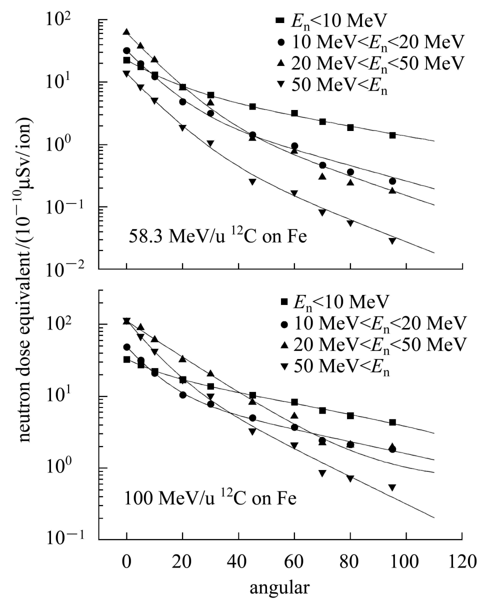

Fig. 3. Calculated neutron dose equivalent caused by 58.3 and 100 MeV/u ^{12}C ion at 1 m from thick Fe target.

3 Experiment

Two experiments were carried out at HIRFL. One is to measure the neutron flux rates and yields of 50 MeV/u ^{18}O ion and 75 MeV/u ^{12}C ion on thick Be, Cu and Au targets with a thickness greater than the ranges of the heavy ions by using activation method at the rapid chemical terminal of HIRFL. The heavy ion beams were delivered by SSC.

^{19}F, ^{12}C and ^{27}Al are chosen to measure neutrons of energy over 7, 11, 20 and above 50 MeV in ^{19}F (n, 2n) ^{18}F, ^{12}C (n, 2n) ^{11}C, ^{27}Al (n, α) ^{24}Na, ^{27}Al (n, 4p6n) ^{18}F reactions respectively. Relevant parameters of threshold detectors are listed in Table 1. The geometrical arrangement of the samples around the target were the same as that given in Ref. [8].

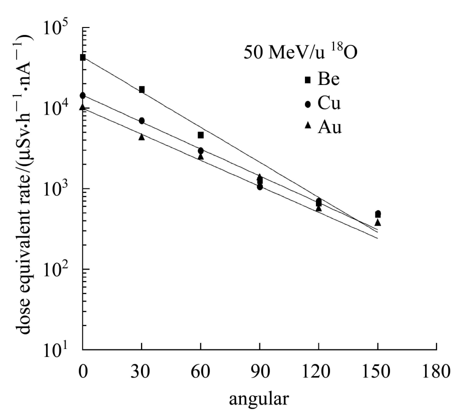

Fig. 4. Neutron dose equivalent rate at 1 m from thick targets.

After irradiation, the activities of the residual nuclei of the samples were measured with an analysis

Table 1. Parameters of the thresholds detectors.

thresholds detectors	activation reaction	product nucleus	threshold energy/MeV	average cross section/($10^{-31}m^2$)	$T_{1/2}$ of product nucleus	detector material	sample dimension/mm
^{27}Al	(n,α)	^{24}Na	7	~45	15.02 h	HP^{27}Al	Φ40×2
^{19}F	(n,2n)	^{18}F	11	~40	109.7 min	teflon	Φ40×5
^{12}C	(n,2n)	^{11}C	20	~22	20.38 min	Polythene	Φ40×5
^{27}Al	(n,4p6n)	^{18}F	50	~7	109.7 min	HP^{27}Al	Φ40×2

Table 2. Measured and calculated neutron yields Y.

reaction	Y(10^{-2}n/ion)				
	>7 MeV	>11 MeV	>20 MeV	>50 MeV	total
measured					
50 MeV/u ^{18}O+Be	42.6	26.0	8.2	3.6	54.8
50 MeV/u ^{18}O+Cu	19.2	9.1	3.0	1.7	20.7
50 MeV/u ^{18}O+Au	14.5	6.9	3.1	1.6	14.9
75 MeV/u ^{12}C+Be		5.9	4.7		10.5
75 MeV/u ^{12}C+Au		5.3	4.4		9.8
calculated		>10 MeV	>20 MeV	>50 MeV	total
58.3 MeV/u ^{12}C+Fe		6.09	3.66	0.69	12.52
100 MeV/u ^{12}C+Fe		26.34	19.25	5.95	40.66

system composed of multi-channel analyzer and an HPGe detector. The efficiency of the system was calibrated using a standard ^{152}Eu γ source. The measured results are given in Table 2 and Fig. 4, Fig. 5. The comparisons of measured and calculated results are also shown in Table 2 and Fig. 5.

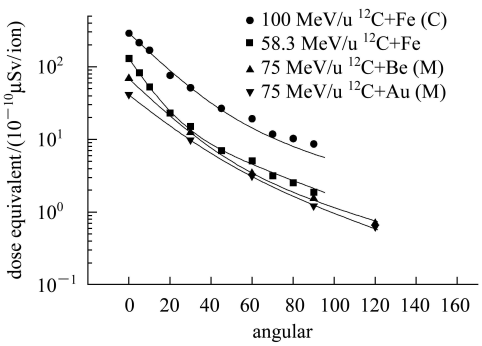

Fig. 5. Neutron dose equivalent at 1 m from thick targets (C for calculated and M for activation measured results).

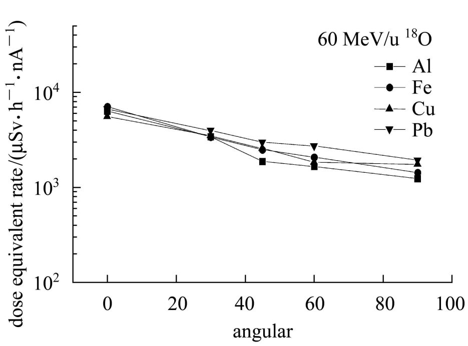

Fig. 6. Neutron dose equivalent rates at 1 m from thick targets (measured with remmeter).

Another experiment is to measure the neutron dose equivalent rate from 60 MeV/u ^{18}O+Cu reaction with a modified Anderson-Braun remmeter[9] which are widely used in neutron dose measurements. The remmeter was placed at the same positions as the samples were placed in previous experiment and was previously calibrated with a standard Am-Be neutron source at the Institute of Modern Physics (IMP). These results are shown in Fig. 6.

4 Discussion

Some conclusions can be drawn from the above results:

(1) Neutron yields of heavy ion reactions strongly dependant on the incident energy per nucleon, the TTNY increases with incident energy per nucleon almost exponentially at intermediate energy region. The TTNY also depends on the target materials. The TTNY on thick Be target is higher than others apparently, because ^{9}Be is a unique stable nuclide which has the lowest bounding energy.

(2) Neutron angular distributions from collisions of medium energy heavy ion on various targets are strongly peaked in the forward direction and high energy neutrons are more apparent.

(3) Significant numbers of neutrons are emitted with energy higher than the incident energy per nucleon and a few of them can even reach about twice of the energy. When incident particle energy is rising, the contribution of high energy neutron to dose equivalent is more important.

(4) It can be seen from Fig. 1, the neutron yields at 60 MeV/u are about 1.7 times that of 50 MeV/u in the ^{12}C+Fe. Fig. 7 shows comparison of the dose equivalent rate at 60 MeV/u measured with remmeter divided by a factor of 1.7 and the dose equivalent rate at 50 MeV/u measured with activation method

for ^{18}O+Cu reaction. The dose equivalent rate in the forward direction obtained with activation method is higher than that obtained by A-B remmeter, and the difference is reduced with increasing the angle. It seems that the modified A-B remmeter still underestimates the high energy neutron, since the high energy neutrons are strongly peaked in the forward direction.

Although the lack of systematic neutron data causes some difficulties in radiation protection, the close agreement of the calculated and measured values make it acceptable to estimate the neutron production for radiation protection purpose with the above theoretical method and the neutron cross sections. And the measured results give the real neutron field at the target area of HIRFL, which are practically useful for radiation protection.

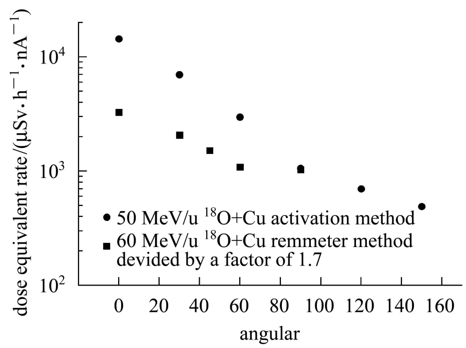

Fig. 7. Comparison of measured neutron dose equivalent rates at 1 m from thick target.

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