Experimental test of a new neutron threshold detector and its application

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Abstract The possibility of using ^{209}Bi as a new threshold detector to measure high-energy neutrons was investigated for the first time. At the same time the experiment measured successfully the emitted neutron fluence rate, energy spectrum and dose equivalent rate distributions in the heavy ion target area using a detector complex including ^{209}Bi, ^{115}In, ^{27}Al, ^{19}F and ^{12}C samples.

Keywords ^{209}Bi threshold detector, Experimental test, Neutron spectrum, Fluence rate, Dose equivalent rate

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1 INTRODUCTION

The neutron spectrum is very important for the nuclear structure study, nuclear reactor design and nuclear weapon development etc. In the health physics field, neutron spectrum data are applied extensively to the neutron shielding calculation, shielding design and the exact calculation of dose equivalent of high-energy neutron emitted in heavy ion reactions.

The nuclear recoil, the nuclear reaction (nuclear emulsion) and the TOF methods are usually used to measure the neutron spectrum. In general, nuclear recoil and reaction methods are only applicable to measure the neutrons of energy lower than 1 MeV. Before the 70's last century, the highest energy of measurable neutron was only about 30 MeV using the TOF method, moreover that needed many complicated experimental instruments and equipment with high performance and sufficient experimental space to ensure the flying distance of high energy neutron.[1] In addition, the energy of neutron emitted in the intermediate-energy heavy ion reaction induced by 78 MeV/u ^{12}C-ion is about 150 MeV which is much higher than 30 MeV. However, this kind of experiment is very difficult in practice because of higher cost, complicated technique and larger experimental field.

Recently, TOF technique has made considerable progress with the rapid development of the detector and electronics techniques. Some new reports of measuring high-energy neutron spectrum using the TOF method have been published.[2] It is sure that a great of cost would be necessary for this particular experiment.

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Although the accuracy is not so good, the threshold detector method is a simple and practical technique for measuring neutron spectrum in comparison with TOF, since, it is used usually in radiation studies and spectrum measurement of neutron emitted in low energy heavy ion reactions. However the highest neutron energy measured directly is only about 20 MeV, the neutrons with energy over 20 MeV couldn't be obtained. Recently, some experiments using about 4–5 lower energy threshold detectors and a special spectrum handle technique based on the Monte Carlo calculation have been reported[3,4] for obtaining a complete neutron spectrum.

In order to measure directly the neutrons emitted in the intermediate-energy heavy ion reaction with threshold detector the ^{27}Al(n, α)^{24}Na, ^{19}F(n, 2n)^{18}F, ^{12}C(n, 2n)^{11}C and ^{27}Al(n, 4p6n)^{18}F reactions were used to measure the neutrons with energy over 7, 11, 20 and 50 MeV respectively.[5,6] Understandably, the neutron energy was divided only into 5 intervals due to the number of threshold detectors used was only 4, in addition, the result of neutrons with energy great than 50 MeV measured using ^{27}Al(n, 4p6n) reaction was not so exact owing to lack of sufficient cross section data.[7]

In this experiment, the possibility of a new material used as a multifunction threshold detector was investigated to measure the neutron distributions in the intermediate energy heavy ion experimental target area.

2 THRESHOLD DETECTOR COMPLEX

2.1 A new threshold detector

Fig.1 shows the neutron excitation function curves of ^{209}Bi.[8] It could be seen from Fig.1 that the ^{209}Bi has very typical threshold detector characteristics, the threshold energy are about 7, 14, 23, 32, 40, 50, 60, 70 and 82 MeV for the reaction channels of (n, 2n)–(n, 10n) respectively. Obviously, it is the outstanding advantage that the neutron energy could be divided into 10 intervals using only a ^{209}Bi sample in an experiment. However, the ^{209}Bi had not been used as threshold detector up to now.

2.2 Threshold detector compose

Although the energy of neutrons emitted in the intermediate energy heavy ion reaction, theoretically, could be divided into 10 intervals using a ^{209}Bi sample in an experiment, unfortunately, its application is limited by the half-life of the product nucleus. In general, the frontal four product nuclei couldn't be measured due to the half-lives of product nuclei of ^{209}Bi (n, 2n), ^{209}Bi (n, 3n), ^{209}Bi (n, 4n) and ^{209}Bi (n, 5n) reactions are 3.8×10^5 a, 38 a, 6.24 d and 15.31 d respectively.

In our experiment, the ^{27}Al (n, α), ^{19}F (n, 2n) and ^{12}C (n, 2n) reactions were utilized to instead of the reactions of ^{209}Bi (n, 2n), ^{209}Bi (n, 3n) and ^{209}Bi (n, 4n) besides ^{115}In (n, γ) ^{115m}In reaction was used to measure neutrons over about 1.5 MeV. Unfortunately, there was no one suitable detector to instead of the ^{209}Bi (n, 5n) ^{205}Bi channel for measuring $E_n > 32$ MeV neutrons (see Table 1).

Table 1 Threshold detectors compose and replacing detectors

Threshold energy E_n(MeV)	Reaction	Product nucleus life $T_{1/2}$	Replacing detector		
			Threshold energy E_n(MeV)	Reaction	Product nucleus life $T_{1/2}$
1.5	$^{115}In(n, n')^{115m}In$	4.49 h			
7	$^{209}Bi(n, 2n)^{208}Bi$	$3.68 \cdot 10^5$a	7	$^{27}Al(n, \alpha)^{24}Na$	15.02 h
14	$^{209}Bi(n, 3n)^{207}Bi$	38a	11	$^{19}F(n, 2n)^{18}F$	109.7 min
23	$^{209}Bi(n, 4n)^{206}Bi$	6.24 d	20	$^{12}C(n, 2n)^{11}C$	20.38 min
32	$^{209}Bi(n, 5n)^{205}Bi$	15.31 d			
40	$^{209}Bi(n, 6n)^{204}Bi$	11.22 h			
50	$^{209}Bi(n, 7n)^{203}Bi$	11.76 h			
60	$^{209}Bi(n, 8n)^{202}Bi$	1.72 h			
70	$^{209}Bi(n, 9n)^{201}Bi$	108 min			
80	$^{209}Bi(n, 10n)^{200}Bi$	36.4 min			

2.3 Manufacture of threshold detectors

^{27}Al, ^{209}Bi and ^{115}In detectors were made of high purity metal materials of 99.99%. Based on their special physical properties the vacuum melting method was utilized to manufacture the ^{209}Bi detector that avoided the oxidation of ^{209}Bi materials in the manufacture process and the ^{115}In detector was made with a roller. Table 2 shown the parameters of threshold detectors.

Table 2 Parameters of the threshold detectors

Threshold detector	Reaction	Threshold energy(MeV)	Average σ ($10^{-31}m^2$)	$T_{1/2}$ of product nucleus	Material of detector	Dimension of detector(mm)
^{115}In	$^{115}In(n, n')^{115m}In$	~1.5	~171	4.49 h	High purity In	$\phi 40 \times 1.0$
^{27}Al	$^{27}Al(n, \alpha)^{24}Na$	~7	~45	15.02 h	High purity Al	$\phi 40 \times 2.0$
^{19}F	$^{19}F(n, 2n)^{18}F$	~11	~40	109.7 min	Teflon	$\phi 40 \times 5.0$
^{12}C	$^{12}C(n, 2n)^{11}C$	~20	~22	20.38 min	Polyethylene	$\phi 40 \times 5.0$
^{209}Bi	$^{209}Bi(n, 5n)^{205}Bi$	~32	~528	15.31 d	High purity Bi	$\Phi 40 \times 4.0$
^{209}Bi	$^{209}Bi(n, 6n)^{204}Bi$	~40	~104	11.22 h	High purity Bi	$\phi 40 \times 4.0$
^{209}Bi	$^{209}Bi(n, 7n)^{203}Bi$	~50	~151	11.76 h	High putiy Bi	$\phi 40 \times 4.0$
^{209}Bi	$^{209}Bi(n, 8n)^{202}Bi$	~60	~20	1.72 h	High putiy Bi	$\phi 40 \times 4.0$
^{209}Bi	$^{209}Bi(n, 9n)^{201}Bi$	~70	~8	108 min	High putiy Bi	$\phi 40 \times 4.0$
^{209}Bi	$^{209}Bi(n, 10n)^{200}Bi$	~80	~3	36.4 min	High putiy Bi	$\phi 40 \times 4.0$

3 EXPERIMENTAL

The experiment was carried out in the rapid chemistry terminal area at HIRFL, the Heavy Ion Research Facility of Lanzhou, in January 2001. A ^{12}C-ion beam from the ECR ion-source, projector and main accelerator passed through a hole in a concrete shielding wall, then through a pair of quadrupole lenses and a collimating slit to a thick Au target.

The thickness of which was slightly greater than the range of heavy ions in the target. The 78 MeV/u ^{12}C beam of about 19 nA was completely stopped in the target and a copper beam stopper and the change was collected and recorded by a beam integrator.

All threshold detectors were disc shaped as listed in Table 2. The sample cells were located on a horizontal platform, which was at the side of the beam tube and the height of which was equal to that of the beam tube and located at a distance of 1 m from the target to be irradiated in the radiation field of neutrons emitted in the reaction of 78 MeV/u ^{12}C-ion on thick Au target. Fig.1 in Ref.[5] gave the layout of the detectors around the target.

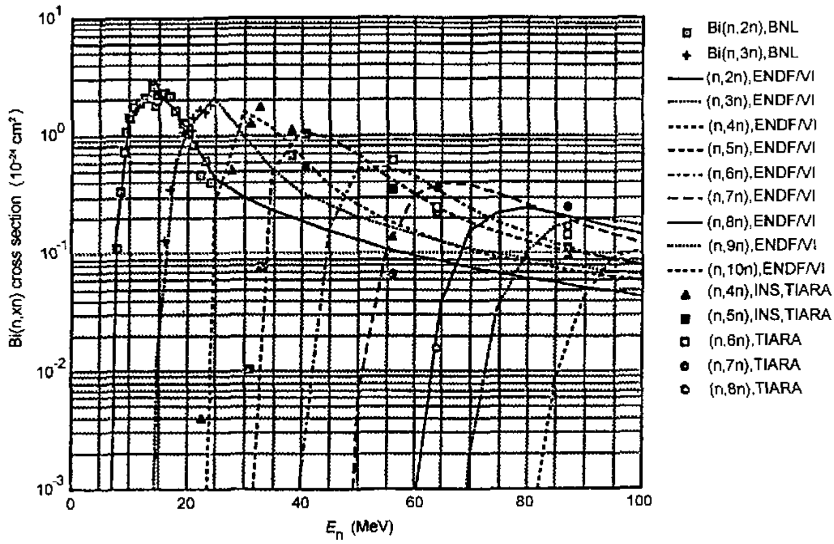

Fig.1 Cross section curves of ^{209}Bi bombarded by neutrons

The γ-activities of the detectors irradiated was measured by an analysis system composed of a PC-multichannel analyser and HPGe detectors. The efficiency of the system was calibrated using a standard ^{152}Eu γ-source.

4 RESULTS AND DISCUSSION

The neutron fluence rate, spectrum and dose equivalent rate measured in the experiment were practical distribution of neutrons in the experimental terminal area. Because the focus function of the accelerator was not so good, a part of the beam had strayed and bombarded on the beam tube and the collimating slit.

4.1 Neutron fluence rate and angular distributions

Table 3 and Fig.2 gave the neutron fluence rate and angular distributions measured in the rapid chemistry experimental terminal area. Following results could be seen:

Table 3 Neutron fluence rates at 1 m distance from the target

E_n (MeV)	Φ(cm^{-2}·s^{-1}·nA^{-1})					
	0°	30°	60°	90°	120°	150°
>1.5	7.57×10^3	4.11×10^3	4.16×10^3	4.01×10^3	3.72×10^3	5.85×10^3
>7	6.99×10^3	8.76×10^2	5.05×10^2	4.15×10^2	3.85×10^2	1.67×10^3
>11	6.06×10^3	5.83×10^2	2.52×10^2	2.02×10^2	2.29×10^2	1.33×10^3
>20	5.52×10^3	4.14×10^2	1.49×10^2	1.58×10^2	1.18×10^2	9.89×10^2
>40	3.95×10^3	2.47×10^2	6.82×10^1	2.93×10^1	2.44×10^1	4.12×10^2
>50	2.42×10^3	2.07×10^2	2.52×10^1	1.57×10^1	2.12×10^1	3.53×10^2
>60	1.82×10^3	1.23×10^2	1.46×10^1	1.12×10^1	1.06×10^1	1.04×10^2

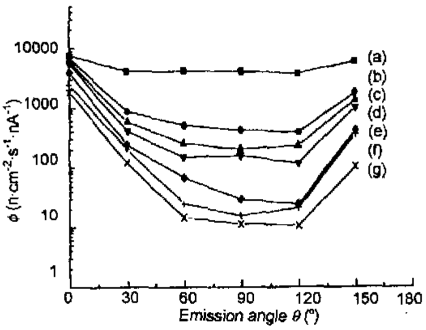

Fig.2 Neutron fluence rate distribution At 1 m from the target
(a) E_n >1.5 MeV, (b) E_n >7 MeV,
(c) E_n >11 MeV, (d) E_n >20 MeV,
(e) E_n >40 MeV, (f) E_n >50 MeV,
(g) E_n >60 MeV

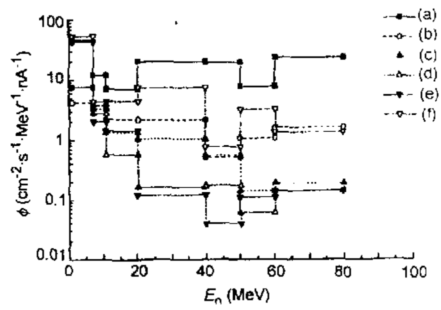

Fig.3 Neutron spectrum distributions at 1 m from the target
(a) 0°, (b) 30°, (c) 60°, (d) 90°, (e) 120°, (f) 150°

(1) The distribution of neutrons with energy greater than 1.5 MeV tends to be isotropic distribution in the whole range from 0° to 150°.

(2) The tendency of neutron distributions peaked in the forward direction is more and more evident with the increase of neutron energy.

(3) The neutrons are obviously increasing in 60°–150° backward direction, this is due to the fact that some strayed ^{12}C-ion beam bombards on the beam tube nearby, as mentioned above.

4.2 Neutron spectrum

Neutron spectrum distribution measured was shown in Table 4 and Fig.3, which divided the neutron energy into 7 intervals: 1.5–7 MeV, 7–11 MeV, 11–20 MeV, 20–40 MeV, 40–50 MeV, 50–60 MeV and >60 MeV. Here only neutron fluence rate data between 20–40 MeV were given due to lack a threshold detector for measuring 30MeV neutrons. In addition, E_n >70 and 80 MeV neutrons could not been identified, this is because that the cross sections of channels (n, 9n) and (n, 10n) are only 8 and 3 mb respectively and that the half-lives of the two product nuclei are too short.

Table 4 Experimental data of neutron energy distribution

E_n	Φ(cm^{-2}·s^{-1}·nA^{-1})					
(MeV)	0°	30°	60°	90°	120°	150°
1.5–7	0.58×10^3	3.23×10^3	3.66×10^3	3.59×10^3	3.34×10^3	4.18×10^3
7–11	0.93×10^3	2.87×10^2	2.53×10^2	2.13×10^2	1.56×10^2	0.34×10^3
11–20	0.54×10^3	1.69×10^2	1.03×10^2	0.44×10^2	1.11×10^2	0.34×10^3
20–40	1.57×10^3	1.67×10^2	8.08×10^1	1.29×10^1	0.94×10^1	5.77×10^2
40–50	1.53×10^3	0.40×10^2	4.30×10^1	1.36×10^1	0.32×10^1	0.59×10^2
50–60	0.60×10^3	0.84×10^2	1.06×10^1	0.45×10^1	0.86×10^1	2.49×10^2
>60	1.82×10^3	1.23×10^2	1.46×10^1	1.12×10^1	1.06×10^1	1.04×10^2

According to general law of neutron energy distribution for heavy ion reaction the peak of neutron spectrum would occur at the neutron energy slight lower than incoming ion energy per nucleon. In this experiment the peak of neutron spectrum would be about 70 MeV, therefore the fall-off part of spectrum could not be measured, the neutrons with energy greater than 60 MeV had a rather great portion, which include all neutrons with energy from 60 MeV to 150 MeV.

4.3 Neutron dose equivalent rate distribution

The neutron dose equivalent rate distribution in the rapid chemistry experimental terminal area of the HIRFL was shown in Fig. 4, which was obtained approximately using the conversion coefficients for neutron fluence to ambient dose equivalent.[9] It could be seen that the distribution tendency of neutron dose equivalent rate was similar to neutron fluence rate distributions due to same reason prior mentioned.

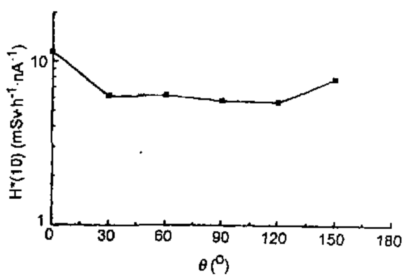

Fig.4 Ambient dose equivalent rate per nA beam current at 1 m from the target versus angle of neutron emission

5 CONCLUSION

Up to now the maximal neutron energy measurable using the threshold detector is about 20 MeV. Although the reaction of ^{27}Al (n, 4p6n) ^{18}F was reported as a threshold reaction to measure neutron with energy over 50 MeV, the result measured is not so accurate due to lack of sufficient cross section data. It could be seen from the cross sections of ^{209}Bi (n, xn) reactions that the cross section curves have evident characteristic of threshold detector, however, none report using ^{209}Bi as a threshold detector is published yet.

The fact, ^{209}Bi could be used as a valuable neutron threshold detector to measure neutrons with energy greater than 40, 50 and 60 MeV respectively, is tested preliminarily at list, *although the neutrons of* E_n >30, 70 *and* 80 MeV *could not be identified due* to various reason mentioned in the text. However, we are sure that the neutrons of E_n >30, 70 and 80 MeV respectively could also be measured using the same detector if the irradiated time is sufficient. We would go a step further for this purpose.

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