Neutrons produced by 75 MeV/u ^{12}C-ion on thick targets*

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Abstract Fluence rates and angular distributions of the neutron emitted by 75 MeV/u ^{12}C-ion bombardment on thick Be and Au targets have been measured by means of the threshold detector activation method. Based on that, the neutron yields, emission rates in the forward direction and neutron dose equivalent rate distributions were deduced.
Keywords Intermediate energy heavy ion reaction, Neutron, Fluence rate, Yield, Dose equivalent rate

1 Introduction

The neutron angular distributions, yields and dose equivalent rate distributions for lower energy (E_p <20 MeV/u) heavy ion reactions have been investigated.[1~4] Some useful experimental data and some practical empirical formulas of neutron yield, angular distribution and neutron dose equivalent rate have been obtained in this energy region.[1,2] The Refs.[5-9] reported some experimental results about intermediate energy heavy ions on thick targets. This paper will present some latest experimental results of the fluence rate, dose equivalent rate, angular distributions, yields and emission rates in the forward direction of neutrons produced by 75 MeV/u ^{12}C-ion bombardment on thick Be and Au targets.

2 Experimental arrangements

The experiment has been performed at the Heavy Ion Research Facility of Lanzhou (HIRFL) by using a 75 MeV/u $^{12}C^{6+}$-ion beam (~20 nA) bombardment on thick Be and Au targets. Six sets of ^{19}F and ^{12}C activation samples at 1 m distance from the target in 0°, 30°, 60°, 90°, 120°, and 150° directions as the threshold detectors were irradiated by the emitted neutron radiation on an experimental platform which was at a side of the beam tube, the height of which was equal to that of the beam tube.

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

3 Results and discussion

The fluence rate distributions of E_n >11 MeV and 20 MeV neutrons emitted from 75 MeV/u ^{12}C-ion on thick Be and Au targets were directly measured. In order to obtain the number of total neutron and the number of E_n <11 MeV neutron it was supposed that the neutron number of E_n >20 MeV and E_n <11 MeV are about 45% and 35% of the total neutron produced by 75 MeV/u ^{12}C-ion beam on thick Be or Au targets, respectively, based on the neutron spectra of 41.7 MeV/u ^{12}C + Fe[10] and 100 MeV/u ^{12}C + C[11] reactions. Table 1 and Fig.1 give the results of the neutron angular distributions.

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Table 1 Neutron fluence rate and angular distribution data at 1 m distance from the target

Reaction	Neutron energy/MeV	Average neutron fluence rate/10^2n·(cm^2.s.nA)$^{-1}$						
		0°	30°	60°	90°	120°	150°	
75 MeV/u	>11	98.09	18.35	5.77	2.61	1.33	0.89	this work
^{12}C+Be	>20	56.19	14.89	3.18	1.39	0.58	0.35	
75 MeV/u	>11	59.29	13.81	5.19	2.32	1.25	0.75	this work
^{12}C+Au	>20	51.15	12.50	4.51	1.62	0.66	0.41	
50 MeV/u	>11	8.00	5.83	2.33	1.83	–	–	Ref.[6]
^{12}C+Cu	>20	4.33	2.83	1.16	0.67	–	–	
50 MeV/u	>11	188.38	56.56	9.45	2.72	1.01	0.76	Ref.[9]
^{18}O+Be	>20	121.50	21.60	3.42	0.87	0.37	0.19	
50 MeV/u	>11	64.07	20.69	5.60	1.79	0.67	0.51	Ref.[9]
^{18}O+Cu	>20	26.21	6.49	1.76	0.47	0.28	0.19	
50 MeV/u	>11	43.42	12.90	5.16	2.10	0.73	0.48	Ref.[9]
^{18}O+Au	>20	27.04	6.36	1.47	0.94	0.49	0.31	

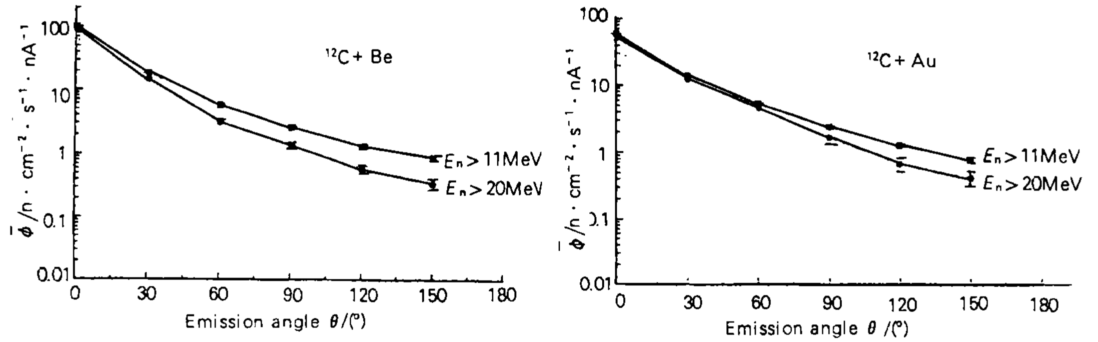

Fig.1 Neutron angular distribution curves at 1 m from the target for 75 MeV/u ^{12}C-ion on thick Be and Au targets

The neutron yield Y of ^{12}C-ion and the neutron emission rate in the forward direction can be obtained by integrating the angular distribution curve from 0° to 180° and from 0° to 90°, respectively. The results are listed in Table 2.

The neutron dose equivalent rate distributions (Table 3 and Fig.2) were obtained by using both the neutron distributions of E_n <11 MeV, 11 MeV< E_n <20 MeV, and E_n >20 MeV, respectively, and the conversion factors for neutron fluence rate to neutron dose equivalent rate.[12]

It may be seen from Table 1 and 3 that the neutron fluence rate and the neutron dose equivalent rate decrease with increase of the emission angle and the neutron yield

Table 2 Neutron yield Y and emission rate S_n in the forward direction

Reaction	$Y/10^2$n·(^{12}C-ion)$^{-1}$			$S_n/10^8$n·(s.nA)$^{-1}$		
	>11 MeV	>20 MeV	Total	>11 MeV	>20 MeV	
75 MeV/u^{12}C+Be	5.9	4.7	10.5	0.61	0.45	this work
75 MeV/u^{12}C+Au	5.3	4.4	9.8	0.47	0.41	this work
50 MeV/u^{12}C+Cu	–	–	5.5	0.24	0.14	Ref.[6]
50 MeV/u^{18}O+Be	26.0	8.2	54.8	2.00	0.61	Ref.[5]
50 MeV/u^{18}O+Cu	9.1	3.0	20.7	1.60	0.50	Ref.[5]
50 MeV/u^{18}O+Au	6.9	3.1	14.9	0.49	0.21	Ref.[5]

of ^{12}C-ion increases with increasing the projectile energy per nucleon while the projectile variety and energy are unchanged. The neutron angular distributions are peaked obviously in the forward direction; the neutron fluence rate emitted at 0° direction is greater about two orders than that at 150°; the anisotropy is greater for projectile bombardment on lighter target. The distribution of E_n >20 MeV neutrons is more peaked in the direction than that of E_n >11 MeV neutrons. This conclusion is coincident with the tendency obtained in low energy heavy ion reaction studies.

Table 3 Neutron dose equivalent rate distributions at 1 m distance from the target

Reaction	Neutron dose equivalent rate/mSv·(h.nA)$^{-1}$						
	0°	30°	60°	90°	120°	150°	
75 MeV/u^{12}C+Be	25.51	4.62	1.27	0.57	0.26	0.20	this work
75 MeV/u^{12}C+Au	15.31	3.63	1.15	0.45	0.23	0.16	this work
50 MeV/u^{18}O+Be	42.66	16.45	4.61	1.27	0.67	0.48	Ref.[8]
50 MeV/u^{18}O+Au	10.05	4.26	2.45	1.36	0.56	0.37	Ref.[8]

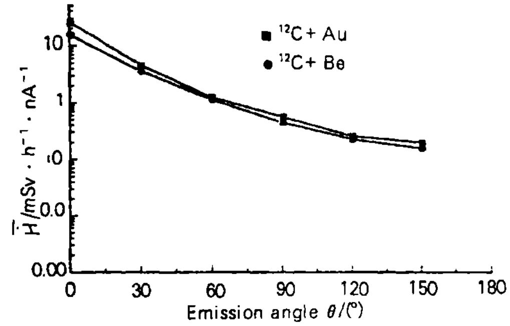

Fig.2 Neutron dose equivalent rate distributions

The neutron yield of 50 MeV/u ^{18}O-ion is greater than that of 75 MeV/u ^{12}C-ion while the target is same. This is because the ^{18}O-ion is a relative neutron rich nucleus and the resultant nucleus produced by the reactions of ^{18}O-ion on Be or Au targets have higher excitation energies than that by the reactions of ^{12}C-ion on same targets although the former have lower incident energy per nucleon.

The total neutron yield depends on the incident ion energy per nucleon while the ion variety and the target are identical. The experimental results listed in Table 2 verify this fact. In the study of low energy heavy ion, Clapier *et al* indicated that the production of neutrons is insensitive to the target material.[1] However, this work and Ref.[5] show that the total neutron yield depends obviously upon the targets while projectile and energy per nucleon are identical and the neutron yield of lighter target greater than that of heavier target.

The neutron dose equivalent rates in experimental target area produced by intermediate energy heavy ion reaction decrease with increase of the emission angle. Relevant to the total neutron yield, the neutron dose equivalent rate of lighter target is greater than that of heavier target at the same direction while the used projectile and energy are same. This conclusion is identical with that obtained in Ref.[9].

The energy range of emitted neutrons would be quite wide and the high energy neutron of E_n >20 MeV possesses main part of the total emitted neutrons in intermediate energy heavy ion reaction. Because of the energy response of a rem-meter, the great deviation would be produced to measure the dose equivalent of neutrons with it in intermediate energy heavy ion reactions. However, the trouble caused by rem-meter could be avoided by using the threshold detector method to measure neutron dose equivalent.

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