Neutron yields and emission rates in the forward direction for 50 MeV/u ^{18}O-ion on thick Be, Cu, Au targets*

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Abstract Total neutron yields and neutron emission rates in the forward direction for 50 MeV/u ^{18}O-ion on thick Be, Cu, Au targets have been measured using an activation technique. The results indicate that neutron yields and emission rates in the forward direction depend on the atomic number of target nuclei, i.e. the lighter target the greater neutron yield and neutron emission rate. Meanwhile, the neutron yield of ^{18}O-ion is greater than that of ^{12}C-ion when target nucleus and incident energy per nucleon are identical.
Keywords Threshold detector, Neutron activation, Heavy-ion reactions, Neutron yield, Neutron emission rate

1 Introduction

In the studies of health physics, neutron dosimetry and neutron shielding, neutron yield and neutron emission rate are very important data, which are relevant directly to the neutron fluence rate emitted, the neutron dose equivalent rate in the experimental hall and the shielding thickness around the experimental target chamber.

Since the 60′s, the studies of heavy ion reactions have been developed from low energy region ($E_{\mathrm{p}} < 50$ MeV/u) to intermediate energy region (50 MeV/u< E_{p} <200 MeV/u) and high energy region ($E_{\mathrm{p}} > 200$ MeV/u). However, it might be seen from the references that the investigation and study of the neutron yield and neutron emission rate were mainly concentrated on lower energy region in which the incident energy per nucleon is below 20 MeV/u.

Hubbard *et al.*[1] measured the neutron yields of some heavy ions with about 10MeV/u in the 60′s, their results indicated that neutron yield increases with incident ion energy per nucleon and target nucleus mass, however, the variation of neutron yield is not marked in the range from Cu to Pb targets.

In 1983, Clapier *et al.*[2] reported some experimental results based on the studies of heavy ion reactions with about 15 MeV/u and gave a following empirical formula estimating total neutron yield

$$Y(w, Z) = c(Z) \cdot w^{\beta(Z)} \tag{1}$$

where w is the incident ion energy per nucleon, in MeV; Z is the atomic number of incident ion; $c(Z)$ and $\beta(Z)$ are fitting parameters. Clapier's results indicate that the total neutron yields of low energy heavy ion reactions are in the range of $2\times10^{-5} \sim 10^{-3}$ n/ion, which is lower 2~3 orders than that of light ion with the same energy; the variation of neutron yields is not marked when the ion energy per nucleon is the same and the neutron yields depend on the range of ions in target and on the Coulomb barriers of the projectile-target system.

In 1987, Guo Zhi-Yu *et al.*[3] completed the experimental measurement of neutron yields for low energy (0.9~6 MeV/u) heavy ion reactions, in which 14 different beams were accelerated and 12 different thick targets were bombarded on a 10 MeV tandem accelerator. The experiment measured systematically total neutron yields for each projectile-target combination and obtained several tens neutron yield data. The results indicated that neutron yields for each projectile-target depends strongly upon the energy per nucleon and the mass of projectile, and upon the atomic number of target nucleus for given energy and variety of projectile. Based on the data an empirical formula of neutron yield as a function of neutron dose equivalent rate was given

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$$Y = 8.8 \times 10^4 \overline{D} \quad (2)$$

where $\overline{D}$ is the average neutron dose equivalent rate at 1 m from the target.

As mentioned above, some experimental results and regularities about neutron yields for low energy heavy ion reactions have been obtained. However, the present report is concerned to intermediate energy heavy ion reactions.

2 Method and detectors

Previous experimental results indicated that the energy spectra of neutrons emitted in heavy ion reactions are rather complicated, the maximal energy of neutrons and the proportion of neutrons with energy over 20 MeV keep going up with increasing incident ion energy per nucleon, the former can reach twice the projectile energy per nucleon and the later can be about 60% of total neutron number for the reaction of 100 MeV/u $^{12}C+C$.[4~6]

Neutrons with 1~100 MeV have threshold reaction features.[7] Therefore the neutrons energy composition can be measured by choosing some suitable threshold reactions. In this work, ^{27}Al, ^{19}F, ^{12}C and ^{27}Al were used to measure the neutrons of energy over 7 MeV, 11 MeV, 20 MeV and about 50 MeV with $^{27}Al(n,\alpha)\,^{24}Na$, $^{19}F(n, 2n)^{18}F$, $^{12}C(n, 2n)^{11}C$, $^{27}Al(n, 4p6n)^{18}F$ reactions, respectively. The cross sections of the reactions and the relevant parameters chosen for threshold detectors can be found from Fig.1 and Table 1.

Table 1 Parameters of the threshold detectors

Threshold detectors	^{27}Al	^{19}F	^{12}C	^{27}Al
Activation reactions	$^{27}Al(n,\alpha)^{24}Na$	$^{19}F(n,2n)^{18}F$	$^{12}C(n,2n)^{11}C$	$^{27}Al(n,4p6n)^{18}F$
Threshold energy/MeV	7	11	20	50
Average cross-section[7~9]/$10^{-31}m^2$	~45	~40	~22	~7
$T_{1/2}$ of the produced nuclei	15.02 h	109.7 min	20.38 min	109.7 min
Material of threshold detector	HP ^{27}Al	teflon	polythene	HP ^{27}Al
Dimension of activation sample/mm	$\phi40\times2$	$\phi40\times5$	$\phi40\times5$	$\phi40 \times 2$

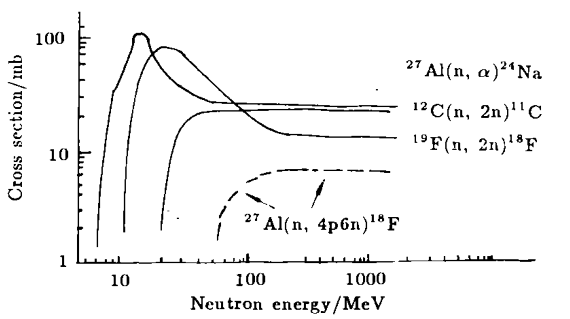

Fig.1 Cross section curves of several neutron reactions

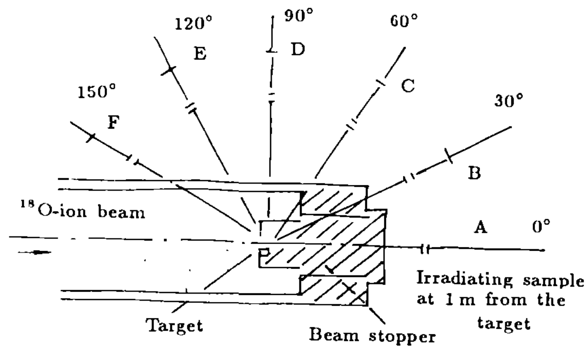

Fig.2 Geometrical arrangement of samples irradiated around the target

3 Experimental

The experiment was carried out on HIRFL. A 50 MeV/u ^{18}O-ion beam passes through a hole in concrete shielding wall and a deflecting magnet, then through a pair of quadrupole lenses and a collimating slit into a small experimental chamber in the rapid chemical terminal area and bombards thick targets. ^{18}O-ion beam was completely stopped in a copper beam stopper and was collected and recorded by a beam integrator. The thicknesses of Be, Cu, Au targets are greater than the ranges of ^{18}O-ion in them.

Threshold detectors were placed on an experimental platform along a side of beam tube at the height as the same as the beam tube (see Fig.2). The ^{27}Al, ^{19}F and ^{12}C detectors were put at the positions A-F and irradiated in the field of neutrons emitted in the reactions of 50 MeV/u ^{18}O-ion on thick Be, Cu, Au targets, respectively. The activities of samples irradiated were measured by a pc-multichannel analyser and a HPGe detector. The efficiency of the system was calibrated using a standard ^{152}Eu γ source.

4 Results and discussion

The angular distributions of emitted neutrons measured in the reactions of ^{18}O-ion on the thick Be, Cu and Au targets are shown in Fig.3. In order to obtain total neutron yield we suppose that the distribution of neutrons emitted from 50 MeV/u ^{18}O-ion on thick Be, Cu, Au targets is similar to that from 41.7 MeV/u ^{12}C-ion on a thick Fe target,[4,6] in which E_n >11 MeV neutrons possess 47.5% of total neutron number, and then the neutron yields and neutron emission rates in the forward direction for 50 MeV/u ^{18}O-ion on Be, Cu, Au targets are determined from angular distribution curves measured in this work (see Fig.3), the results are listed in Table 2.

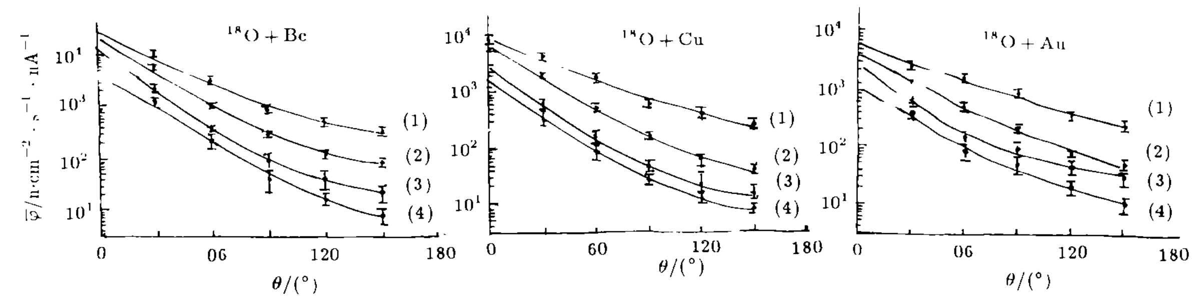

Fig.3 Emitted neutron angular distribution curves
(1)E_n >7 MeV, (2) E_n >11 MeV, (3) E_n >20 MeV, (4) E_n >50 MeV

Table 2 Total neutron yield of ^{18}O-ion Y and neutron emission rates in the forward direction 2π solid-angle S_n for the reactions produced by 50 MeV/u ^{18}O-ion and ^{12}C-ion

Reactions	$Y/10^{-2}$ n·(^{18}O-ion)$^{-1}$					$S_n/10^8$n·s^{-1}·nA^{-1}	
	E_n >7 MeV	E_n >11 MeV	E_n >20 MeV	E_n >50 MeV	Total	E_n >11 MeV	E_n >20 MeV
^{18}O + Be	42.6	26.0	8.2	3.6	54.8	2.00	0.61
^{18}O + Cu	19.2	9.1	3.0	1.7	20.7	1.60	0.50
^{18}O + Au	14.5	6.9	3.1	1.6	14.9	0.49	0.21
^{12}C + Cu[10]	–	–	–	–	5.5	0.24	0.14

Reported results of low energy heavy ion reaction studies indicate that neutron yield depends mainly on the incident ion energy per nucleon and on the target nucleus.[1~3] The following conclusions could be obtained from this work:

4.1 Total neutron yield and neutron emission rate depend upon the atomic number of target nucleus, and those of lighter targets are greater than those of heavier targets when incident ion energies per nucleon are identical.

4.2 By using two different incident ions with identical energy per nucleon, for example 50 MeV/u ^{12}C and ^{18}O, to bombard the same target, the total neutron yield of ^{18}O-ion is greater than that of ^{12}C.[10] The reason is that ^{18}O is neutron -rich nucleus compared with ^{12}C nucleus. It illustrates that the neutron yield depends on the variety of projectile nucleus too.

4.3 In the three reactions studied, ^{18}O and ^{9}Be are both neutron-rich nuclei and the excitation energy of resultant nucleus produced by $^{18}O+Be$ is greater markedly than those produced by $^{18}O+Cu$ and $^{18}O+Au$, therefore, the neutron yield of $^{18}O+Be$ reaction is greater than those of others.

4.4 The variation regulation of neutron emission rates in the forward direction 2π solid-angle is similar to that of neutron yields. If the beam current could reach the values listed in Tables 3 then E_n >11 MeV and E_n >20 MeV neutron emission rates of 10^9n/s in the forward direction could be reached. It may be seen from Table 3 that E_n >20 MeV neutron emission rates in the forward direction would reach 10^9 n/s for the three reactions if the beam currents are greater than 16, 20 and 50 nA, respectively, for E_n >14 MeV neutron, estimating approximately, that would be greater than 10, 15, and 35 nA, respectively.

Table 3 Beam current I needed if neutron emission rate in forward direction 2π solid-angle reaches 10^9 n/s

Reactions	E_n >11 MeV		E_n >20 MeV	
	$S_n/10^8 n \cdot s^{-1} \cdot nA^{-1}$	I/nA	$S_n/10^8 n \cdot s^{-1} \cdot nA^{-1}$	I/nA
50 MeV/u $^{18}O+Be$	2.00	>5	0.61	>16
50 MeV/u $^{18}O+Cu$	1.60	>7	0.50	>20
50 MeV/u $^{18}O+Au$	0.49	>20.5	0.21	>50

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