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Measurements of Thick Target Neutron Yields from 100 to 800 MeV/Nucleon Heavy Ions

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We have measured angular and energy distributions of neutrons produced by 100 and 180 MeV/u He, 100, 180, 400 MeV/u C, 100, 180, 400MeV/u Ne, 400MeV/u Ar, 400MeV/u Fe, 400MeV/u Xe and 800MeV/u Si ions stopping in thick carbon, aluminum, copper and lead targets using the HIMAC (Heavy-Ion Medical Accelerator in Chiba) of NIRS (National Institute of Radiological Sciences), Japan. The neutron spectra in the forward direction have broad peaks of about 60 to 70 % of the incident particle energy per nucleon due to the break-up process and spread up to almost the twice of the projectile energy per nucleon. The neutron spectra are similar for the same incident energy for different projectile particles. The experimental results are compared with the calculations using the HIC code, and the calculated results agree with the measured results within a factor of 2. This systematic study on neutron production from thick targets by high-energy heavy ions is the first experimental work performed by NIRS and will be useful for designing the shield of the high-energy heavy-ion accelerator facility.

KEYWORDS: Neutron spectra, heavy ion, high energy, HIC code, angular distribution, total neutron yields, stopping-length target

I. Introduction

Recently, high-energy heavy ions have been used in various fields of nuclear physics, material physics and medical application, especially cancer therapy. At the National Institute of Radiological Sciences (NIRS) in Chiba, Japan, the HIMAC (Heavy Ion Medical Accelerator in Chiba) has been used for the heavy ion cancer therapy for the last three years, and the GSI (Gesellschaft für Schwer Ionen) in Germany has just started heavy ion cancer therapy. Several institutes in the world have started or planned to build the radioactive beam facility where high-energy radioactive heavy ions are used for investigating exotic nuclei, nuclear synthesis and so on.

To design these facilities, the radiation shielding is essential to protect workers and nearby inhabitants from an amount of penetrating neutrons produced by high-energy heavy ions. The data on the energy - angle distribution of secondary neutrons from a thick target which fully stops heavy ions, so called thick target neutron yield (TTY), are indispensable to estimate radiation source terms for accelerator shielding design. For projectiles of energy higher than 100MeV/u, several experimental results on TTY have been published on neutron production from proton incidence, however for heavier ions, there is only one set of experimental data on TTY for 160 and 177.5MeV/u helium ions. Recently, Heilbronn et al. published two reports on TTY for 155MeV/u He, 155MeV/u C and 272, 435MeV/u Np ions. Our group also performed a systematic study on TTY using the HIMAC and published three papers on TTY for 100, 180MeV/u He, 100, 180, 400MeV/u C and 100, 180, 400MeV/u Ne ions. This work is a summary report of this systematic study on TTY including some newly obtained results for 400MeV/u Ar, 400MeV/u Fe, 400MeV/u Xe and 800MeV/u Si ions. The measured spectra are compared with those calculated with the HIC code based on an intranuclear - cascade and evaporation model.
Table 1 Projectile types with their incident energy per nucleon and target thickness that was estimated to stop the incident particles completely.

<table>
<thead>
<tr>
<th>Incident particle type and energy [MeV/u]</th>
<th>Target thickness [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>He [100]</td>
<td>C [5.0], Al [4.0], Cu [1.5], Pb [1.5]</td>
</tr>
<tr>
<td>He [180]</td>
<td>C [16.0], Al [12.0], Cu [4.5], Pb [5.0]</td>
</tr>
<tr>
<td>C [100]</td>
<td>C [2.0], Al [2.0], Cu [0.5], Pb [0.5]</td>
</tr>
<tr>
<td>C [180]</td>
<td>C [6.0], Al [4.0], Cu [1.5], Pb [1.5]</td>
</tr>
<tr>
<td>C [400]</td>
<td>C [20.0], Al [15.0], Cu [5.0], Pb [5.0]</td>
</tr>
<tr>
<td>Ne [100]</td>
<td>C [1.0], Al [1.0], Cu [0.5], Pb [0.5]</td>
</tr>
<tr>
<td>Ne [180]</td>
<td>C [4.0], Al [3.0], Cu [1.0], Pb [1.0]</td>
</tr>
<tr>
<td>Ne [400]</td>
<td>C [11.0], Al [9.0], Cu [3.0], Pb [3.0]</td>
</tr>
<tr>
<td>Ar [400]</td>
<td>C [7.0], Al [5.5], Cu [2.0], Pb [2.0]</td>
</tr>
<tr>
<td>Fe [400]</td>
<td>C [4.0], Al [3.0], Cu [1.5], Pb [1.5]</td>
</tr>
<tr>
<td>Xe [400]</td>
<td>C [3.0], Al [2.0], Cu [1.0], Pb [1.0]</td>
</tr>
<tr>
<td>Si [800]</td>
<td>C [23.0], Al [17.0], Cu [6.5], Pb [6.5]</td>
</tr>
</tbody>
</table>

II. Experimental Procedure

1. Experimental Arrangement

The energy of neutrons produced in the target was measured by the time-of-flight (TOF) method. Fig. 1 shows the experimental geometry of a typical arrangement of 3 neutron counters. A thin NE102A plastic scintillator (30mm diam. by 0.5mm thick) was placed just behind the end window of the beam line as a beam pick-up scintillator. The output pulses from this scintillator were used as the start signal of the TOF measurement. These output pulses were also used to count the absolute number of projectiles incident on the target. A target was set on the beam line 10 cm behind the beam pick-up scintillator. The beam spot size incident on the target was about 1.5 cm diameter and the beam height was 1.25m above the concrete floor of the experimental area. The NE213 liquid scintillator (12.7cm diam. by 12.7cm thick), which is designed to expand the dynamic range of output pulses for high energy neutron measurements \((14)\), was used for neutron detector (E counter), and the NE102A plastic scintillator (15 cm by 15cm square and 0.5cm thick) for \(\Delta E\) counter was placed in front of the E counter to discriminate charged particles from noncharged particles, neutrons and photons. Three sets of E and \(\Delta E\) counters were used for simultaneous angular distribution measurements at three different angles. The detectors were located 2 m at large angles to 5 m at small angles away from the target to provide better energy resolutions in the forward directions where there are larger yields of high energy neutrons. In order to minimize neutrons in-scattering, no local shielding was used near the detectors. By interposing an iron shadow bar 15cm by 15cm square and 60cm thick between the target and detector, the background neutron components from room scattering were measured.

2. Target dimensions

The incident energies of heavy ions and the target materials with their thicknesses are given in Table 1. Target materials are C \((1.77g/cm^3)\), Al \((2.7g/cm^3)\), Cu \((8.93g/cm^3)\) and Pb \((11.34g/cm^3)\) and each target has a shape of 10cm by 10cm square and its thickness was determined to stop the incident particles completely. When the measurements were carried out at large angles, the target was set at 45 degree to the beam line to minimize the attenuation effect of neutrons through the target.

3. Data acquisition electronics

A simplified schematic diagram of the detecting circuits is shown in Fig. 2. The timing signal from the beam pick-up scintillator was divided into two pulses, and one pulse was fed to a constant fraction discriminator (CFD) to start a 2048 channel CAMAC time-to-digital converter (TDC) and to count the number of incident beam particles. The other pulse was fed to a charge-integrated type 2249A analog to digital converter (ADC) to produce the stop signal of TDC and the gate of ADC. Two signals of E counter were sent through different delay cables to two channels of ADC to measure the total and slow light components. The anode signal from each E counter was split into three pulses. One signal was fed to a CFD to produce the stop signal of TDC and the gate of ADC. Two signals of E counter were sent through different delay cables to two channels of ADC to measure the total and slow light components. The anode signal from each E counter was also fed to ADC to get pulse height data. These digital data from the CAMAC system were recorded event by event on a 3.5 inch Magneto-Optical disk with the personal computer using the KODAQ (Kakuken On-line Data Acquisition System) data taking system \((15)\).

III. Data Analysis

As neutrons and gamma rays do not scintillate the \(\Delta E\) counter, the neutron and gamma ray events could be selected from the charged particle events, by using two-dimensional \(\Delta E\)-E graphical plots. After this discrimination, the neutron and the gamma ray events were clearly separated by using two-dimensional graphical plots of total-slow pulse height components of the E counter. After each experimental run, each E counter was calibrated with a \(^{60}\)Co gamma-ray source, and the

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Compton edge in the gamma-ray spectrum was used as the energy calibration point. After obtaining the TOF spectrum of neutrons, it was converted into the energy spectrum of neutrons. For this conversion, the detection efficiency is essential. The experimental data of the detection efficiency for this scintillator has been published by Nakao et al.\textsuperscript{(14)}, but there is no data for neutrons of energy higher than 135 MeV. Therefore, the neutron detection efficiency was calculated with the Monte Carlo code by Cecil et al. \textsuperscript{(16)}.

### IV. Calculation of the Neutron Spectra

These experimental results were compared with calculations. The neutron spectra were calculated by using the Heavy Ion Code, HIC\textsuperscript{(13)}. The HIC code is a Monte Carlo code that calculates continuum state transitions between projectile and target in heavy ion reactions at energies above 50 MeV/u. The assumption in the model is that the reaction can be represented by the interaction of two Fermi gases that pass through each other. In this code, an intranuclear-cascade and an evaporation model are used. As the HIC code only gives the double differential neutron production cross section, so called thin target yield, the calculations were performed for a series of thin target yield calculations, which were then summed to obtain the neutron yields from heavy ions stopping in a thick target, considering the projectile continuous energy loss and the projectile number attenuation in the target, as follows,

\[
\frac{d^2\phi}{dE d\Omega} = \sum_{i=1}^{k} \sigma_n N P_m \frac{\Delta E_s}{\Delta x_m} \left( \frac{\Delta E_s}{\Delta x_m} \right)
\]

\[
P_n = P_{n}^{\prime} \exp\left(-\sigma_n^{\prime\prime} N \Delta x_m \right)
\]

where \(s_n\) is the double differential neutron production cross section calculated by HIC, \(N\) is the atomic density of target, \(P_m\) is the number of beam particles in the target \((P_m = 1.0)\), \(\Delta E_s / \Delta x_m\) is the stopping power calculated by the SPAR code\textsuperscript{(17)}, \(\sigma_n^{\prime}\) is the total reaction cross section given as an experimental for-
V. Results and Discussions

1. Neutron spectra

Measured neutron spectra for C target bombarded by 100, 180 and 400 MeV/nucleon C projectile are shown in Fig 3 to 5, as examples. Neutron spectra measured in the forward direction have a broad peak at high-energy end, especially a large bump at 0 degree and this peak becomes more prominent for lighter target and for higher projectile energy. The peak energy of this bump is about 60 to 70% of the projectile energy per nucleon. This means that these high energy neutron components produced in the forward direction by a break-up process and the momentum transfer from projectile to target nuclei are both higher for lighter nucleus and higher projectile energy than for heavier nucleus and lower projectile energy. The energy of the neutrons in the forward direction extends to about twice that of the incident particle energy per nucleon. This can be explained in the following. When the Fermi energy is approximated to be 40 MeV, the relative velocity of a nucleon in a nucleus, becomes 0.28. The relative velocities of 100 MeV/u, 180 MeV/u and 400 MeV/u projectiles are 0.43, 0.54 and 0.71, respectively. Thus, the composite relative velocities of a nucleon in a projectile are 0.63, 0.71 and 0.83, and the resultant nucleon energies can be estimated as 270 MeV, 400 MeV and 730 MeV for 100 MeV/u, 180 MeV/u and 400 MeV/u projectiles, respectively.

2. Comparison with calculation

The calculated spectra are also shown in Fig 3 to 5 with the experimental results. These figures clarified that a broad high energy peak in the forward direction appears around the incident particle energy per nucleon, while on the other hand the measured peak appears about 60 to 70% of that as described before. This marked discrepancy may come from the fact that the HIC calculation which does not include the effects of neither the nuclear potential nor the viscosity of nuclear matter.

Fig. 4 Neutron spectra from the 180 MeV/nucleon C ion in the C target.
fails to express the break-up process. The superposition of thin target yields in the calculation pretty well gives the measured thick target yield at large neutron emission angle where the breakup process is negligibly small, although the extranuclear cascade reaction are neglected in this superposition.

3. Angular distribution

Fig. 6 shows the neutron yields integrated above 5MeV for each emission angle. All of the results suggest that the angular distribution become more forward peaked for higher energies of the incident projectiles. The neutron yield is larger for a lighter target nucleus in the forward direction, and at large angles the yields become larger for a heavier target nucleus. This reveals again that the neutron production at the forward angles mainly occurs by the direct reaction process that reduces in magnitude with increase of emission angle and at large angles the low energy neutrons via equilibrium process dominate the yields.

4. Total Yields

The total neutron yields above 5MeV were integrated over a hemisphere from 0° to 90°, and they are shown in Fig. 7. The total neutron yields become slightly larger with increase of the target mass, but their dependence on the target mass is very small compared with the difference of neutron numbers of the target. The difference in neutron yields between He, C and Ne ion projectiles is also very small, but the yields from Ar and Fe ion projectiles are larger than from the those lighter ions. These differences in neutron yields might be caused by the neutron production cross section, the thickness of the target and neutrons produced by secondary charged particles.

VI. Conclusion

We measured angular and energy distributions of neutrons produced by 100 and 180 MeV/u He, 100, 180, 400 MeV/u C, 100, 180, 400MeV/u Ne, 400MeV/u Ar, 400MeV/u Fe, 400MeV/u Xe and 800MeV/u Si ions stopping in carbon, aluminum, copper and lead targets. The neutron spectra in the
forward direction have a broad peak at about 60 to 70% of the incident particle energy per nucleon due to break-up process and extend up to almost twice the projectile energy per nucleon. The experimental results were also compared with the calculations using the HIC code, and the calculated results agree with the measured results within a factor of 2 margin of accuracy. This is the first systematic study on neutron production from thick targets by heavy ions and will be useful for shielding design of high-energy heavy ion accelerator facilities.

ACKNOWLEDGMENT

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—References—