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# Spallation Yield of Neutrons Produced in Thick Lead Target by 400 MeV/u Carbon Ions *

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*Measurement of the neutron yield is performed at a primary energy of 400 MeV/u carbons for the Pb target. Water-bath activation-foil method is used in a moderation measurement with Au foils to detect the moderated neutrons. The neutron yield is determined to be* 18.4±2.1 *per carbon by integrating the neutron flux over the entire water volume. The corresponding simulation values are performed by Geant4 code with three models to compare with the experimental results. The comparison shows that the calculated result with the INCL model is in good agreement with the experimental data.*

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Recently, heavy-ion accelerators have been applied widely in many fields, such as nuclear physics, material physics and medical application, especially cancer therapy. In the Institute of Modern Physics (IMP), Chinese Academy of Sciences, the HIRFL-CSR (Cooling Storage Ring on the Heavy Ion Research Facility in Lanzhou, China) has been used for heavy-ion cancer therapy using the high-energy carbon ions. Several research facilities worldwide are operational to carry out similar research.[1] Unlike the traditional radiation therapies, heavy ion treatments could avoid damage to numerous healthy cells in the path to the tumor. However, when the high-energy heavy ions pass through the accelerator facility, many secondary particles such as electrons, gamma rays and neutrons are created via high-energy heavy-ion-induced reaction. The damage caused by the secondary particles is much more complex and cannot be easily ignored. For the safe design and shielding of the accelerator facility, it is necessary to estimate the production of the secondary particles. A common approach to predict the production by heavy ions is based on the simulation with Monte-Carlo radiation transport codes. The calculated results with Monte-Carlo codes on such reactions are not yet precise and mutually consistent enough for reliable and accurate predictions on neutron yields. The systematic studies on cross sections of residual nuclides by protons[2−7] and heavy ions[1,8−17] have being carried out. However, relatively few neutron-yield measurements have been performed on materials. It was thus decided to measure total neutron yields on thick, high-$Z$ targets using a water bath at a number of incident carbon energy in this work. The experimental results were compared with Geant4 simulations[18] to test the applicability of the code.

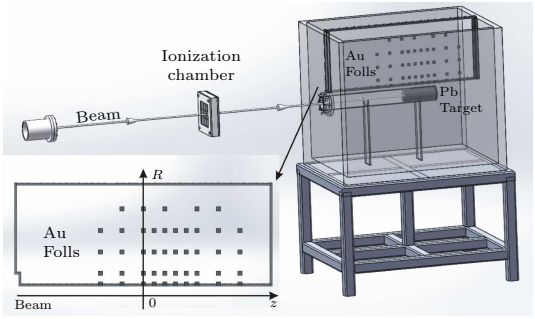


**Fig. 1.** Overview of the experimental arrangement.

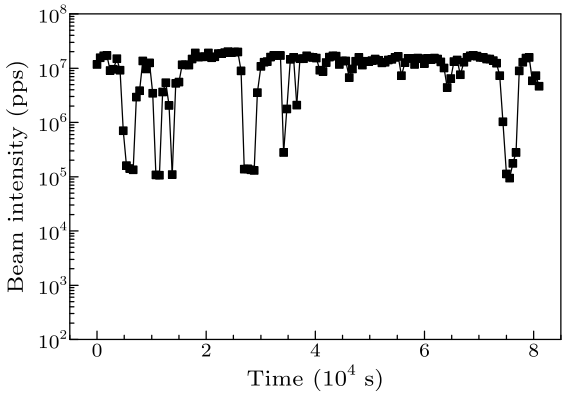


**Fig. 2.** Course of irradiation with 400 MeV/u carbons.

The experiment has been carried out on the HIRFL-CSR.[19] The measurement method is similar as in Ref. [7] by using the water-bath activation-foil method.[20] Figure 1 shows the schematic view of the overall experimental arrangement. A carbon beam

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with energy 400 MeV/u hits a cylindrical lead target to generate the spallation neutrons. The Pb target with 10 cm diameter and 25 cm length was located in the center of a water container. The container full of water approaching 1.2 $m^3$ made the primary neutrons from the radiation source moderated and contained within the water volume. The moderated neutrons were detected by the activity induced in an array of Au activation foils which had 2×2 $cm^2$ in size and 50 μm in thickness. The center of the upstream surface of target was regarded as the origin of coordinates ($Z = 0$, $R = 0$). Thus the axial coordinates of the foils were $Z = -20$, $-10$, 0, 5, 10, 15, 20, 25, 35 and 45 cm along the target axis. The radial coordinates of the foils were $R = 7.5$, 13.5, 23.5, 33.5 and 43.5 cm above the target axis, respectively. The average beam intensity was $1.15 \times 10^7$ pps as determined by an air ionization chamber which was placed in front of the target and was calculated by the plastic scintillator. The irradiation continued for 22 h to obtain sufficient beam fluence, and the course of irradiation is shown in Fig. 2.

The activity of the irradiated Au foils were measured by a high-purity germanium (HPGe) detector. The relative efficiency and energy resolution of the detector were 65% and 1.90 keV at 1.33 MeV, respectively. The absolute efficiency was calibrated with the standard sources $^{60}$Co, $^{133}$Ba, $^{137}$Cs, and $^{152}$Eu.

The activity for each foil was determined by measuring the peak intensities of the characteristic $\gamma$ ray with energy of 412 keV from $^{198}$Au. The measured activities have also been corrected for $\gamma$ self-absorption and for neutron self-shielding effects. Typical counting statistics errors are 1–1.5%. The activity at the end of irradiation according to the relationship

$$A_0 = \frac{C\lambda e^{\lambda t_d}}{m f_s I_\gamma \varepsilon_\gamma (1 - e^{-\lambda t_c})}, \tag{1}$$

where $C$ is the counts in a net full-energy peak at $\gamma$-ray of 412 keV with an abundance $I_\gamma$, which is detected with efficiency $\varepsilon_\gamma$, $m$ is the mass ($g$) of the Au foil, $f_s$ is the correction factor for $\gamma$ self-absorption, $t_c$ is the counting time, $t_d$ is the decay time between end of irradiation and beginning of counting, and $\lambda = \ln 2/T_{1/2}$ is the decay constant of the $^{198}$Au. Figure 3 presents the Au-foil activity data for irradiation. The total number $N_0$ of produced $^{198}$Au at the end of irradiation has the relation of $N_0 = A_0/\lambda$ with $A_0$. The production rate $A_{cd}$ per carbon of $^{198}$Au can be given by

$$N_0 = A_{cd} \sum_{i=1}^{n} I_{beam}(i) e^{-\lambda(n-i)\Delta t}, \tag{2}$$

where $I_{beam}(i)$ is the beam current for irradiation time interval $\Delta t$, and $n\Delta t$ is the irradiation time.

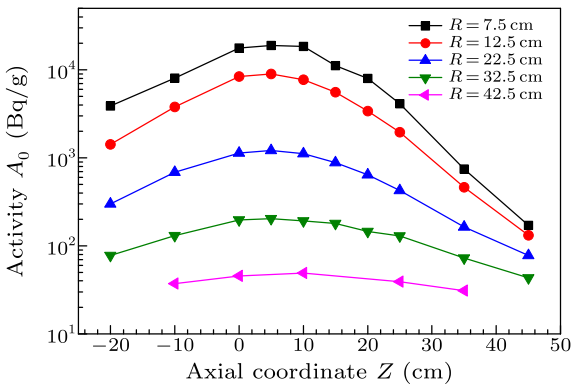


**Fig. 3.** Activity distributions of $^{198}$Au in the water bath.

The produced neutrons were slowed in the bath volume, and the neutron field should be averaged over the Maxwell distribution of neutron energies. For the thin foils, we simply have

$$A_{cd} = N\sigma_{th}\phi_{th} = N\Big(\frac{\sqrt{\pi}}{2}\sqrt{\frac{T_0}{T_n}}\sigma_0\Big)\phi_{th}, \tag{3}$$

where $N$ is the nucleus number of Au foil, $\sigma_{th}$ is the cross section $(n,\gamma)$ reaction for thermal neutrons at the temperature of $T_n$ ($T_0 = 293.6$ K), $\sigma_{th}$ equals $\sigma_0 = 98.708$ barn at the temperature of $T_0$, and $\phi_{th}$ is the thermal neutron flux ($n/cm^2$) as functions of $R$ and $Z$.

All the neutrons emitted from the source are slowed down and ultimately absorbed in the water. Thus we could obtain the total number of neutrons per carbon by carrying out the flux $\phi_{th}(r,z)$ integration over the water volume with the following relation

$$N_c^{tot} = \int_R \int_Z \Sigma_{th}\phi_{th}(r,z) 2\pi r dr dz. \tag{4}$$

The macroscopic absorption cross section $\Sigma_{th}$ ($cm^{-1}$) in the water for thermal neutron is determined by $\sigma_h$ for hydrogen and $\sigma_o$ for oxygen

$$\Sigma_{th} = \frac{\rho N_A}{A} \cdot (2\sigma_h + \sigma_o). \tag{5}$$

The cross sections of $\sigma_h$ and $\sigma_o$ are 332 mb and 2 mb, respectively. Here $\rho = 1$ g/$cm^3$ is the density of water, and $N_A$ is Avogadro's number, and $A$ is the mass number of $H_2O$. To integrate the flux over the measurement volume cubic splines were fitted to the logarithm of the measured flux distributions. Like Ref. [1] this was carried out first for the axial ($Z$) distributions at each radius ($R$) where measurements had been made, then radially. Following the procedure outlined above, the yields of the neutron emitted from the target were determined to be

$$N_c^{tot} = 18.4 \pm 2.1 n/\text{carbon}. \tag{6}$$

Errors in the result concern the statistical error, the coincidence summing effect of $\gamma$ transition, inac-

curacy of $\epsilon_\gamma$, and systematic errors, such as the inaccuracy of the beam intensity and direction. An exponential extrapolation was used and this contribution increased the flux volume integral by ≈5%.

The processing of the experimental data was accompanied by simulation with the Geant4 code. The simulation of spallation reaction consists of three stages: intra-nuclear cascade (INC) stage, pre-equilibrium stage, and de-excitation (evaporation or fission) stage. For the calculation of neutron yield, we chose three physics lists which included QGSP_BIC_HP, QGSP_BERT_HP and QGSP_INCLXX. The list of QGSP applies the quark gluon string model for high-energy interactions of protons, neutrons, pions, Kaons and nuclei. The HP means that the simulation uses the data-driven high-precision neutron package (NeutronHP) to transport neutrons from thermal energies to 20 MeV. The binary cascade (BIC) model could better describe production of secondary particles produced in reactions of protons and neutrons with nuclei. The Bertini model (BERT) produces more secondary neutrons and protons than other models in calculation. INCL (INCLXX) could be used for reactions induced by light nuclei (up to $A = 18$). All the models are described in details in Refs. [20–23], and references therein.

The calculated neutron yields with different models are listed in Table 1. We can find out that only the result by using INCL code is consistent with the experimental value within error. Other results are both larger than the experimental result, but the maximum difference is less than 15%. The reason could be that the Bertini model and the binary model are not suitable to perform the spallation reaction induced by light nuclei (carbon).

**Table 1.** Calculated neutron yields ($n$/carbon) with Geant4.

| INC model | Calculated yield |
|---|---|
| QGSP_BIC_HP | 20.01±0.01 |
| QGSP_BERT_HP | 21.59±0.01 |
| QGSP_INCLXX | 17.28±0.01 |

In summary, we have studied the neutron production from lead target irradiated with 400 MeV/u carbon beam. The data are measured with the classical water bath method. The neutron yield is deduced by the exponential integration method. The neutron yield in the reaction is calculated by the Geant4 code. It is found that the calculated result using the INCL is generally consistent with the experimental value. However, the measured results are less than the calculated values using the Bertini and the binary models. The comparison implies that the INCL model is more suitable than other models to perform the reaction induced by light nuclei (carbon).

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