Study of neutron activation yields in spallation reaction of 400 MeV/u carbon on a thick lead target *

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Abstract: The spallation-neutron yield was studied experimentally by bombarding a thick lead target with 400 MeV/u carbon beam. The data were obtained with the activation analysis method using foils of Au, Mn, Al, Fe and In. The yields of produced isotopes were deduced by analyzing the measured γ spectra of the irradiated foils. According to the isotopes yields, the spatial and energy distributions of the neutron field were discussed. The experimental results were compared with Monte Carlo simulations performed by the GEANT4+FLUKA code.

Key words: spallation reaction, activation analysis method, neutron production

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1 Introduction

Spallation reactions can be used to produce intense neutron fluxes with a high energy beam on a thick target with a high atomic number. Recently, the possible applications are rapidly growing in many fields, such as spallation neutron source (SNS) and accelerator driven system (ADS) [1, 2]. To design the spallation target and shielding of accelerator facilities it is necessary to estimate the production and distribution of the spallation reaction products, especially for the neutrons. Although the related researches have been carried out in Europe, USA, Japan and China for many years [3], we still need to accumulate more experiment data to test the applicability of all kinds of model descriptions. As a part of a complex research of SNS and ADS in China, we have studied the spallation reaction by irradiating a lead target with a high energy carbon beam. In this work, the spallation-neutron field was measured based on the activation analysis method [4], and the experimental results were compared with GEANT4 plus FLUKA simulations [5, 6].

2 Experiment setup

The experiment was performed at the HIRFL-CSR in Lanzhou, China. A $^{12}C^{6+}$ beam with energy of 400 MeV/u was used to bombard a massive cylindrical lead target. The diameter and total length of the target were 10 cm and 25 cm, respectively. The average beam intensity was 1.72×10^7 pps, as monitored by the proportional chamber. The irradiation of the beam lasted about 24 h to get sufficient fluence, the course of the irradiation is shown in Fig. 1. The activation foils of Al, Au, Mn, Fe and In were placed on the surface of the target so as to measure the leakage neutrons. The foils of each group were located at three longitudinal distances of 1.0, 5.0 and 11.0 cm from upstream surface of the target, see Fig. 2. A detailed description for the foils is given in Table 1. Two groups of Au foils were arranged on two opposite sides of the target and used to determine the position deviation of the beam. Via reactions (n, γ), (n, xn) and (n, xn, yp), the stable isotopes composing of the detector foils were transmuted into radioactive ones, which were identified by observing the characteristic γ rays. In order to determine the isotopes with different half-lives, each irradiated foil was measured several times by one HPGe detector with a relative efficiency of 65% and energy resolution of 1.90 keV at 1.33 MeV. The distance between the detector endcap and the foils was 3.0 cm. The detector efficiency was calibrated

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Table 1. The size of activations foils and the observed reactions, their thresholds, and the half-lives of the products.

activation foil	abundance(%)	area/mm^2	thickness/mm	reaction	threshold energy/MeV	half-life
^{197}Au	99.99	20×20	0.1	^{197}Au(n, γ)^{198}Au	—	2.69517 d
				^{197}Au(n, 2n)^{196}Au	8.1	6.1669 d
				^{197}Au(n, 4n)^{194}Au	24	1.584 d
^{27}Al	99.99	20×20	2.0	^{27}Al(n, α)^{24}Na	4.6	14.959 h
^{55}Mn	99.99	20×20	3.0	^{55}Mn(n, γ)^{56}Mn	—	2.5785 h
				^{55}Mn(n, 2n)^{54}Mn	10.5	312.12 d
				^{55}Mn(n, 4n)^{52}Mn	31.4	5.591 d
^{56}Fe	91.71	20×20	2.0	^{56}Fe(n, p)^{56}Mn	3	2.5785 h
				^{56}Fe(n, t)^{54}Mn	12.2	312.12 d
^{115}In	95.69	20×20	2.0	^{115}In(n, γ)^{116m}In	—	54.29 min
				^{115}In(n, n')^{115m}In	0.35	4.486 h
				^{115}In(n, 2n)^{114m}In	9.1	49.51 d
				^{115}In(n, 5n)^{111}In	33.5	2.807 d

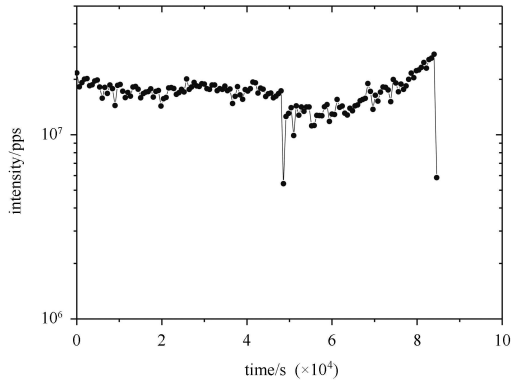

Fig. 1. Course of irradiation with 400 MeV/u carbons.

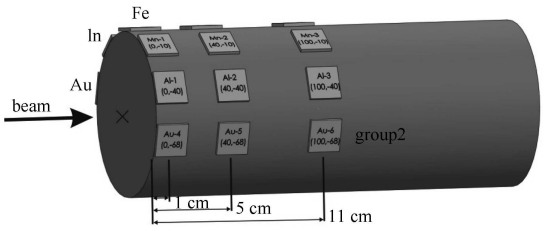

Fig. 2. Scheme of placement of the activation foils.

with the standard point-like sources ^{60}Co, ^{133}Ba, ^{137}Cs and ^{152}Eu.

3 Results and discussion

The measured γ spectra were processed by the GAMMA-W code, which was applied to calculate the net γ-peak areas via an unfolding algorithm using a least-squares fit [7]. Considering the decay during irradiation, cooling, and measurement, the activation yields R (i.e., number of activated nuclei per nucleus of the activated foil and per one incident carbon) of the corresponding radioactive nuclei could be determined according to the relation

$$R=\frac{c\lambda \mathrm{e}^{\lambda t_\mathrm{d}}}{\epsilon_\gamma I_\gamma N_\mathrm{t} f_\mathrm{s} I_\mathrm{c}(1-\mathrm{e}^{-\lambda t_\mathrm{c}})(1-\mathrm{e}^{-\lambda t_\mathrm{irr}})}, \quad (1)$$

where C is fitted area of the γ-peak; I_γ is intensity of this γ transition per decay; f_s is self-absorption correction factor of γ transition; I_c is average beam intensity; ϵ_γ is detector efficiency; N_t is the nuclear number of the foil; λ=ln2/$T_{1/2}$ is disintegration constant; t_d is time from the end of irradiation to the beginning of the measurement; t_irr is time of irradiation; and, t_c is time of measurement. The relationship between experimental yields R and neutron flux can be derived with the following equation:

$$R=\int_0^\infty \Phi(E_\mathrm{n})\sigma(E_\mathrm{n})\mathrm{d}E_\mathrm{n}, \quad (2)$$

where the integration of product of neutron flux $\Phi(E_\mathrm{n})$ (neutron/MeV/carbon/cm^2) and cross section $\sigma(E_\mathrm{n})$ of corresponding reaction is made over neutron energy E_n. As a function of the position along the target, the activation yields produced in Al, Au, Mn, Fe and In foils are shown in Fig. 3. Errors in the figure concern the statistical error, the coincidence summing effect of γ transition, inaccuracy of the I_γ, and ϵ_γ. Systematic errors, such as the inaccuracy of the beam intensity and direction, contribute about 10%.

Because of the large size of the target (Φ100×250), as well as the small beam section ($FWHM$=2.5 cm), it can be believed that most of the radioactive nuclei in the foils are not induced by the emitted neutrons but by the beam or other spallation products. As shown in Fig. 3, it is found that the productions of ^{198}Au, ^{116}In and ^{56}Mn (in Mn foils), which are produced in (n, γ) reactions, have no major difference along the longitudinal direction. The reason for this could be the quite homogeneous field of thermal neutrons on the surface of the target that give constant contribution to the productions in different positions. The homogeneous field is mainly produced in two processes. One is the evaporation phase in the spallation reaction, where the produced thermal neutrons have nearly isotopes angular distributions [3]. On the other hand, the leakage neutrons are multi-scatted by the lab equipments surrounding the spallation target,

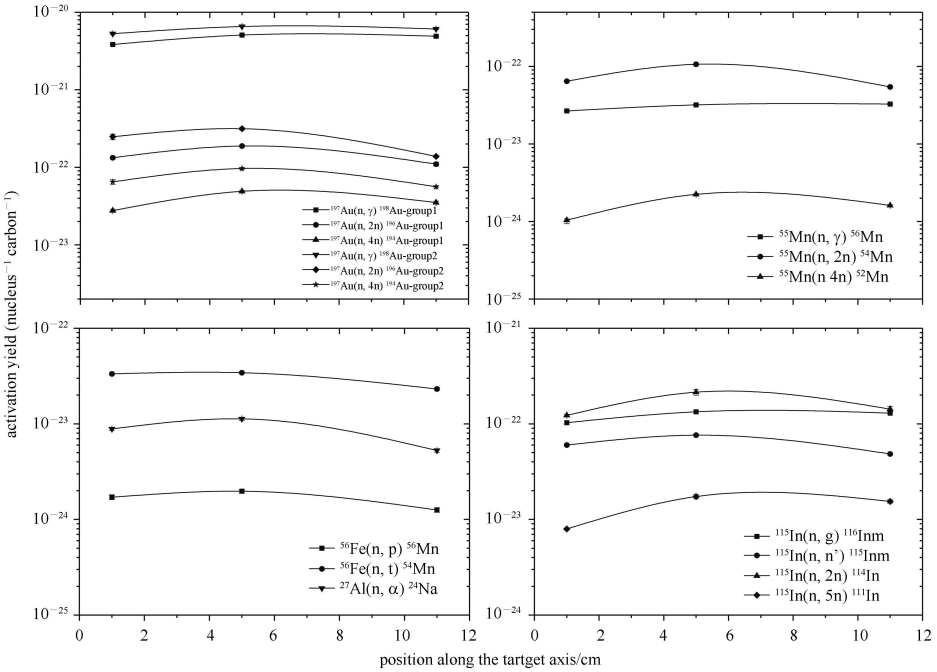

Fig. 3. (color online) Longitudinal distributions of activation yields of the foils.

which also leads to the homogeneous field of thermal neutrons as a background. For the isotopes produced in threshold reactions, the activation yields at the 1 cm and 11 cm are more or less the same and both are lower than the yields at 5 cm. Therefore, we can conclude that the intensity of the fast neutron field at the position of 5 cm is higher than that at the other two positions.

4 Comparison between simulation and experiment

The processing of the experimental data was accompanied by simulations of the neutron production and activation yields. The simulation of the spallation reaction was performed by GEANT4. The intranuclear cascade stage and the equilibrium stage were included in the simulation of the course. The simulated energy spectra for the surface of the naked target are shown in Fig. 4. As seen in the figure, the maximum intensity of the neutron field emitted from target is located at 5 cm. The energetic spectrum at the end of the target is similar to the simulation at the beginning. Qualitatively, we drew the same conclusions from the experimental results, see Fig. 3. Combining the simulated neutron spectra, the activation yields of the foils were calculated by FLUKA. The default FLUKA neutron cross sections for energies below 20 MeV were generally taken from ENDF/B-VIIRO library [8], while for higher energies they were mostly calculated by FLUKA itself. The activation yields of In foils were not calculated because the FLUKA could not give the proportion of the isomer in the isotope production. A comparison of activation yields between experimental data with the calculated value is shown in Fig. 5. For the neutron capture reactions, the large ratios indicate that the experimental values are much greater than the simulated results. In contrast, the ratios for threshold reactions are in the region of 0.3 to 1.0. In other words, the local discrepancies are as small as a factor of 3 in extreme cases.

We also simulated the energy spectra over the surface for the naked target and the target with a support frame, see Fig. 6. The support frame consisted of a block of medium-density fiberboard (30 cm×30 cm×16 cm) and a table filled with aluminum alloy (60 cm×120 cm×5 cm).

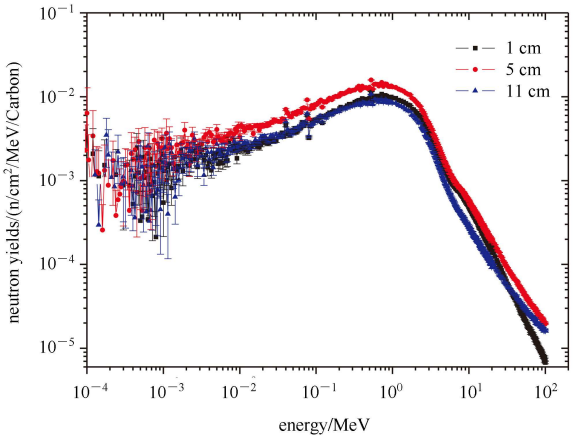

Fig. 4. (color online) GEANT4 simulations of neutron spectra at different longitudinal positions.

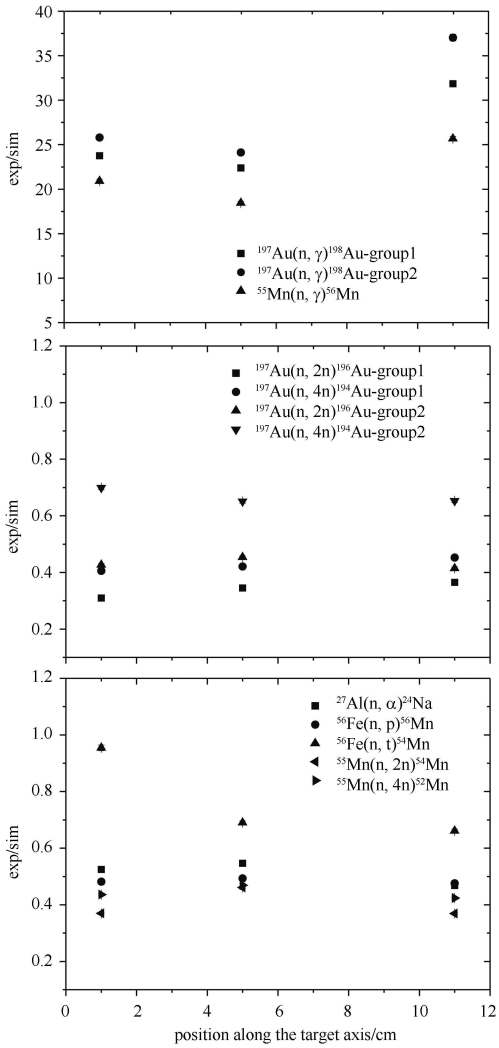

Fig. 5. (color online) Comparison of the experimental yields of activated isotopes versus the yields from the GEANT4 plus FLUCA simulation.

As shown in Fig. 6, the calculation that consisted of a support frame obviously gave more flux for the thermal neutron. In the region with an energy less than 1 keV, the total neutron flux is about 40 times of the target with support frame to that without. Compared with the difference of the former, there are no big changes between the two spectra for the fast neutron. This indicates that the simulations in Fig. 5 substantially underestimate the contribution of the background to the thermal neutron field. As the same time, we can conclude that even if the experiment environment is very complex, we could still reach a general qualitative agreement between the experimental data and the simulations for high-energy neutron production.

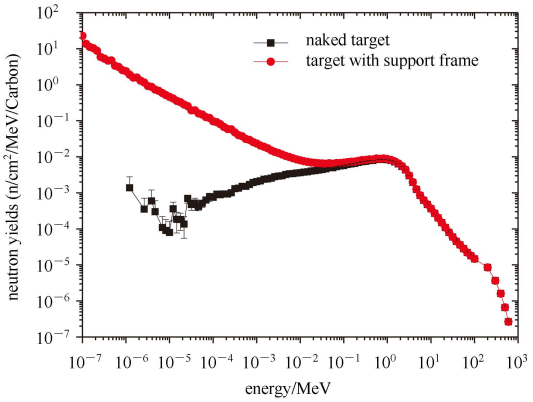

Fig. 6. (color online) Simulations of neutron spectra for the target with support frame and without.

5 Summary

In summary, we have studied neutron production in the reaction of high energy carbons by bombarding a thick lead target. The intensity and distribution of the neutron fields were measured by the neutron activation analysis method. By analyzing the activation yields in different positions, it is found that the maximum intensity of the fast neutron field produced in the spallation target was located at a position of 5 cm from the target forehead. In contrast with the former, the homogeneous field of thermal neutron was measured on the surface of the target. We also compared the experiment data with the simulations. It was shown that the calculations were in agreement with the experimental data in magnitudes for fast neutron production, and it should be emphasized that the simulations for neutron capture reactions must value the contribution of the lab setup.

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