The 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 irradiated foils. According to the isotopes yields, the spatial and energy distribution 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 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. For designing 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, there are still needs 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 12C6+ beam with energy of 400 MeV/nucleon 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 1.72107 pps as monitored by the proportional chamber. The irradiation of the beam continued for 24 hours, and 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. 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 for several times by one HPGe detector with 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 with the standard point-like sources 60Co, 133Ba, 137Cs and 152Eu.

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

Fig. 2. Scheme of placement of activation foils.

3 Result and Discussions

The measured $\gamma$ spectra were processed by the GAMMA-W code which was applied to calculate the net $\gamma$-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

$$R = \frac{c \lambda e^{-\lambda t_d}}{\epsilon_s I_s N_t f_s I_c (1 - e^{-\lambda t_c})(1 - e^{-\lambda t_{ irr}})}$$

where $C$ is fitted area of the $\gamma$-peak; $I_s$ is intensity of this $\gamma$ transition per decay; $f_s$ is self-absorption correction factor of $\gamma$ transition; $I_c$ is average beam intensity; $\epsilon_s$ is detector efficiency; $N_t$ is nuclear numbers of the foil; $\lambda = \ln 2/T_{1/2}$ is disintegration constant; $t_d$ is time from the end of irradiation to the beginning of the measurement; $t_{ irr}$ is time of irradiation; $t_c$ is time of measurement. 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 $\gamma$ transition, inaccuracy of the $I_s$ and $\epsilon_s$. Systematic error, such as the inaccuracy of the beam intensity and direction, contributes 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 induced by the emitted neutrons but 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, $\gamma$) reactions, have no major difference along the longitudinal direction. The reason 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 spallation reaction where the produced thermal neutrons have nearly isotopes angular distributions [3]. On the other hand, the leakage neutrons are multi-scattered by the lab equipments surrounding the spallation target which also lead 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 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 other two positions.

Fig. 3. Longitudinal distributions of activation yields of the foils.

Fig. 4. GEANT4 simulations of neutron spectra at different longitudinal positions.
Fig. 5. Comparison of the experimental yields of activated isotopes versus the yields from the GEANT4 plus FLUKA simulation.

4 Comparison Between Simulation and Experiment

The processing of the experimental data was accompanied by simulations of the neutron production and the activation yields. The simulation of the spallation reaction was performed by GEANT4. The Intranuclear cascade stage and the Equilibrium stage were consisted in the simulation of the course. The simulated energy spectra are shown in Fig 4. As seen in the figure, the maximum intensity of the neutron field emitted from target is located at the 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. Those default FLUKA neutron cross sections for energy below 20 MeV were generally taken from ENDF/B-VIIRO library, for higher energy were mostly calculated by FLUKA itself. The activation yields of In foils were not calculated because of that FLUKA couldn't give the proportion of the isomer in the isotope production. The 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 simulated results. The reason should be attributed to that the simulations substantially underestimate the contribution of background to the thermal neutron field. In the contrary, 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. This indicates that GEANT4 plus FLUKA codes could produce overall yield magnitudes quite well for fast neutrons.

5 Conclusion

In summary, we have studied the neutron production in the reaction of high energy carbons bombarding a thick lead target. The intensity and distribution of neutron field 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 in the position of 5 cm from the target forehead. Different from 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 lab setup.

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