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Simulation of Pb(p,xn) and Bi(p,xn) Production Cross Sections in the Incident Proton Energy Range up to 3 GeV

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Abstract: A detailed design of the liquid Pb-Bi spallation target of the Accelerator Driven Systems (ADS) requires powerful and reliable computational tools that can accurately predict particles and nuclides production by the proton induced spallation reactions in the energy range of a few GeV. In this paper, the neutron production double-differential cross sections for Pb and Bi target materials at incident proton kinetic energies between 800 MeV and 3 GeV are studied by calculations with Monte Carlo simulation package Geant4. The simulated results of Geant4 with several physics models are compared with available experimental data. The simulated results generated by QGSP_BERT and QGSP_INCL_ABLA physics models of Geant4 well reproduce the available experimental data. The present results validated that Geant4 Monte Carlo simulation package is suitable for simulations of neutron production double-differential cross sections of proton induced reaction on Pb and Bi targets in the incident energy range up to 3 GeV.

Key words: Monte Carlo simulation; Accelerator Driven System; liquid Pb-Bi spallation target; neutron production cross section

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1 Introduction

In recent years, the wide range applications of Accelerator Driven Systems (ADS)[1−2] in many fields, such as transmutation of nuclear waste[3], nuclear energy generation[4], condensed matter physics, neutron sources for material irradiation and neutron scattering science, arouse a worldwide range of interest. USA, Japan, Korea, Russia, Europe *etc.* have developed ADS projects[5] for their needs and are underway vigorously. China has started to design ADS project[2] along the sustainable development of nuclear energy in China from the end of last century. This project mainly aims to high radioactive nuclear waste transmutation, nuclear fuel generation and clean energy production, *etc.*

Prophase researches of ADS show that there are many significant advantages to use Pb-Bi as liquid spallation target[2,6]. For the design of the liquid Pb-Bi target of the ADS, nuclear data in

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the energy region up to a few GeV are required. These nuclear data were usually obtained from experimental measurements and theoretical calculations. However, theoretical calculations play important roles where experimental data are sparse or difficult to measure. There are many nuclear models and transportation codes which can be often used to calculate in the energy region above a few hundred MeV, such as Intranuclear Cascade-Evaporation (INC/E)[7] model, Quantum Molecular Dynamics (QMD) model[8] and nucleon meson transport code (NMTC)[9], MCNP[10], Geant4[11−12] and FLUKA[13−14], *etc.*

In the present work, Geant4 with several physics models are used to simulate neutron production double-differential cross sections for the Lead target at incident proton kinetic energies between 800 MeV and 3 GeV. The accuracy of Geant4 simulation codes are examined by comparisons between the simulated results and experimental data. The neutron production double-differential cross sections for Bi target are predicted by using these validated Geant4 simulation codes.

2 Experimental data

The specific experimental setups are needed to measure the spatial and energy distribution of the neutrons produced in spallation reactions. Several groups[15−24] have measured the (p,xn) production double-differential cross sections for various target materials and at incident proton kinetic energies around 1 GeV. These experimental measurements are motivated by improving different simulation codes and validating spallation reaction models.

In the experiments, organic liquid scintillator (or plastic scintillator) detector are used for the neutron detection, and Time-of-Flight technique is employed to measure the neutron kinetic energy, where the start signal is provided by a (set of) beam counter(s) which mostly consists of a thin plastic detector, and the stop signal is generated by the arrival of the neutron at the neutron detector. Charged particles are swept out of the flight paths by magnets, and the remaining charged particles are distinguished from non-charged particles by using the veto scintillator detector which is placed in front of neutron detector. For the elimination of the gamma events from neutron ones, pulse shape discrimination (PSD) properties of neutron detector are used.

As an example, in Fig. 1 the experimentally measured Pb(p,xn) production double-differential cross section at detection angles from 30° to 150° for 800 MeV incident protons is shown. The spectra multiply by a factor of 10^{-n}(n=0, 1, 2, 3) from the top. The good agreements are achieved among these independent measurements. The experimental cross sections which are used in this paper are obtained from EXFOR database[25].

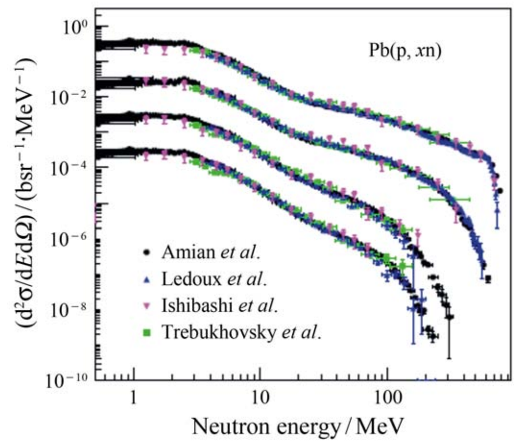

Fig. 1 (color online) Comparison of experimental neutron production double-differential cross section with measurement of different groups at detection angles from 30° to 150° for 800 MeV incident protons is shown. The spectra multiply by a factor of 10^{-n}(n =0, 1, 2, 3) from the top.

3 Simulation

Geant4 is a toolkit for simulating the passage of particles through matter. It is widely used in particle and nuclear physics, accelerator physics, medical science, astrophysics, aerospace studies. User can choose an abundant set of physics models to handle the interactions of particles with matter over an extended energy range. For the convenience, Geant4 provides a lot of physics lists which are created by specific physics model or combination of several physics models.

In the simulation presented in this paper, Geant4 with LHEP, QGSP_BERT, QGSP_BIC, QGSP_INCL_ABLA physics models are used to simulate neutron production double-differential cross sections for Pb and Bi targets at incident proton kinetic energies between 800 MeV and 3 GeV. A simple model of the targets is used and the target thickness is 0.078 cm. The detection angles of neutron production are 30°, 60°, 120° and 150°. In the following, LHEP, QGSP_BERT, QGSP_BIC, QGSP_INCL_ABLA physics lists will be discussed.

LHEP uses low energy and high energy parametrized models. And it's one of the fastest models of hadronic interactions. QGSP_BERT uses theory driven modeling for the reactions of energetic pions, kaons, and nucleons. It includes the Bertini intra-nuclear cascade model with excitons, a pre-equilibrium model, a nucleus explosion model, a fission model, and an evaporation model. Intermediate energy nuclear reactions from 100 MeV to 5 GeV are treated for protons, neutrons, pions, photons and nuclear isotopes. QGSP_BIC is similar to the QGSP_BERT physics list, except that below a kinetic energy 3 GeV a Binary Cascade model, which is a hybrid between a generalized classical cascade and a quantum molecular dynamics model, is used instead of the Bertini Cascade. QGSP_INCL_ABLA physics list is provided by INCL4 model coupled to ABLA evaporation model as implemented in Geant4. It provides an up to date modeling tool particularly for spallation studies for hadron projectile energy range 200 MeV∼3 GeV and a detailed description of double differential energy spectrum of cascading particles and remnants. Further information on the Geant4 physics lists can be found in Ref. [11] and [26].

4 Results and Discussion

Spallation reactions[1,7] are defined as interactions between a light projectile (proton, neutron, or light nucleus) with the high energy from several hundreds of MeV to several GeV and heavy target nuclei (*e.g.*, lead) which is split to a large number of hadrons (mostly neutrons) or fragments. Spallation has two stages: intra-nuclear cascade and de-excitation. There are many nuclear models and transportation codes used for spallation reactions. Most of them are based on the intranuclear cascade (INC) model for the first stage of the reaction and evaporation model for the second steps. Geant4 provides a lot of physics lists which are created by specific physics model or combination of several physics models. In this section, the results obtained from the simulation of (p,xn) production cross sections using GENAT4 with several physics models will be discussed.

4.1 Pb(p,xn) production double-differential cross sections

As examples of the level of agreement between simulations and experiments, neutron production double-differential cross sections are shown in Fig. 2 for 800 MeV protons on Lead target at the detection angles of 30°, 60°, 120°, 150° and in Fig. 3 for 1.2 GeV, 1.6 GeV, 2 GeV, 3 GeV protons on Lead at 30°.

From the comparison of the simulation results with experimental data which is obtained from EXFOR database, the following conclusions are obtained. LHEP physics list is not suitable for this kind of simulation for the whole energy range. QGSP_BIC physics lists can well reproduce experimental data below incident proton energy 800 MeV, while simulation results are smaller than experimental data above 800 MeV. The QGSP_BERT and QGSP_INCL_ABLA physics lists can well reproduce experimental data for incident proton energy range up to 3 GeV.

4.2 Bi(p,xn) production double-differential cross sections

On above, the accuracy of Geant4 simulation codes are demonstrated by comparing between the simulated results of Pb(p,xn) production double-differential cross sections and experimental ones. Here, the simulated results of neutron production double-differential cross sections for Bi target materials and at incident proton kinetic energies between 800 MeV and 3 GeV, using validated Geant4 simulation codes are shown in Fig. 4 and 5.

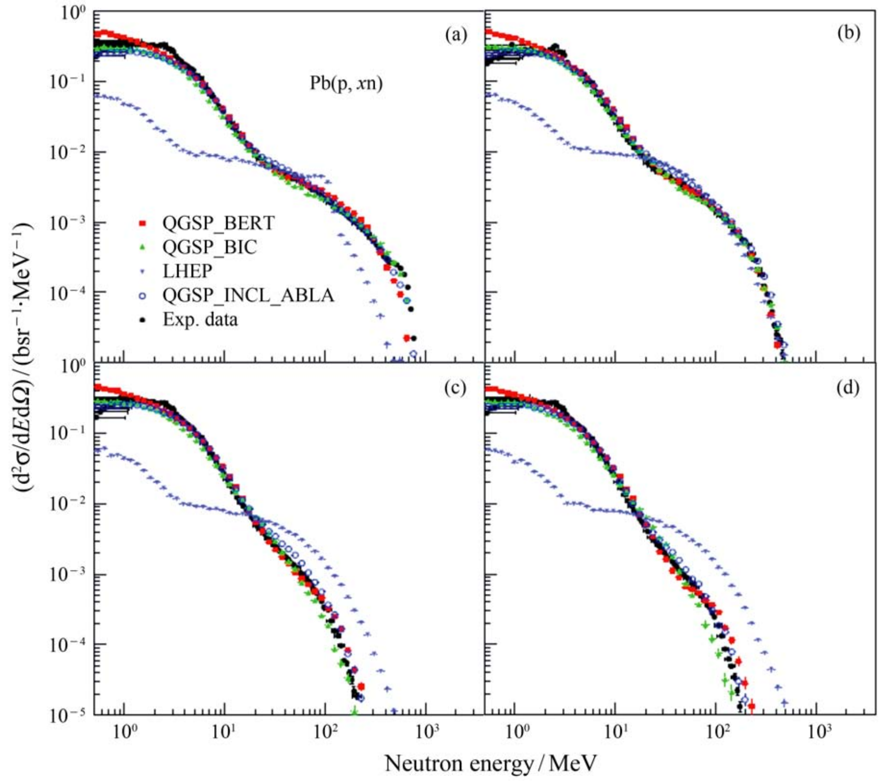

Fig. 2 (color online) Neutron production double-differential cross sections for 800 MeV proton on Pb target at the detection angles of 30^0(a), 60^0(b), 120^0(c), 150^0(d).

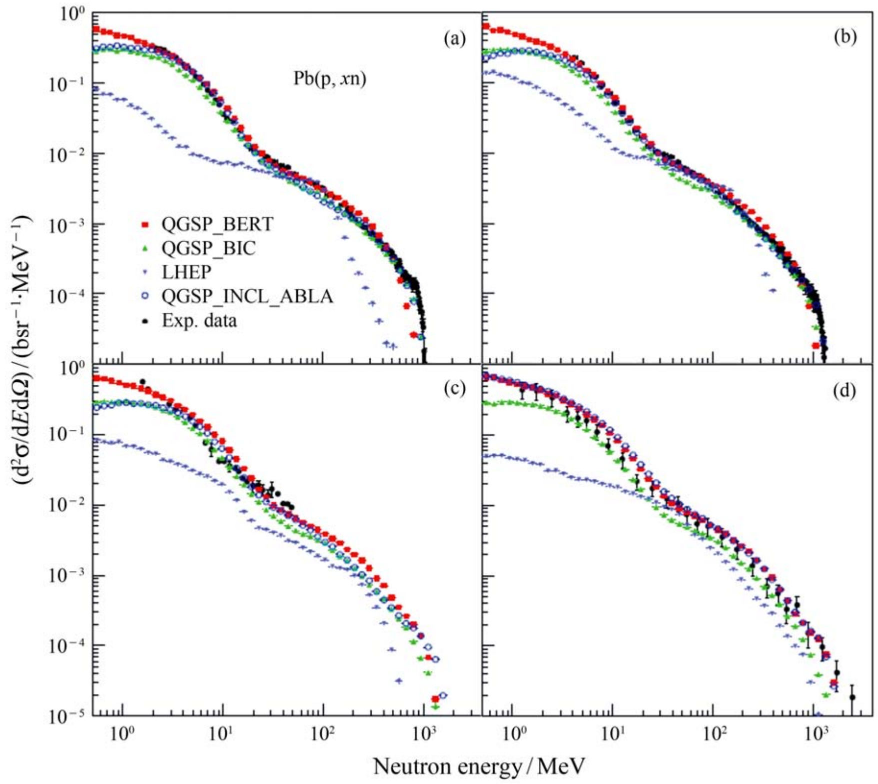

Fig. 3 (color online) Neutron production double-differential cross sections for 1.2 GeV (a), 1.6 GeV (b), 2 GeV (c), 3 GeV (d) proton on Pb target at the detection angle of 30°.

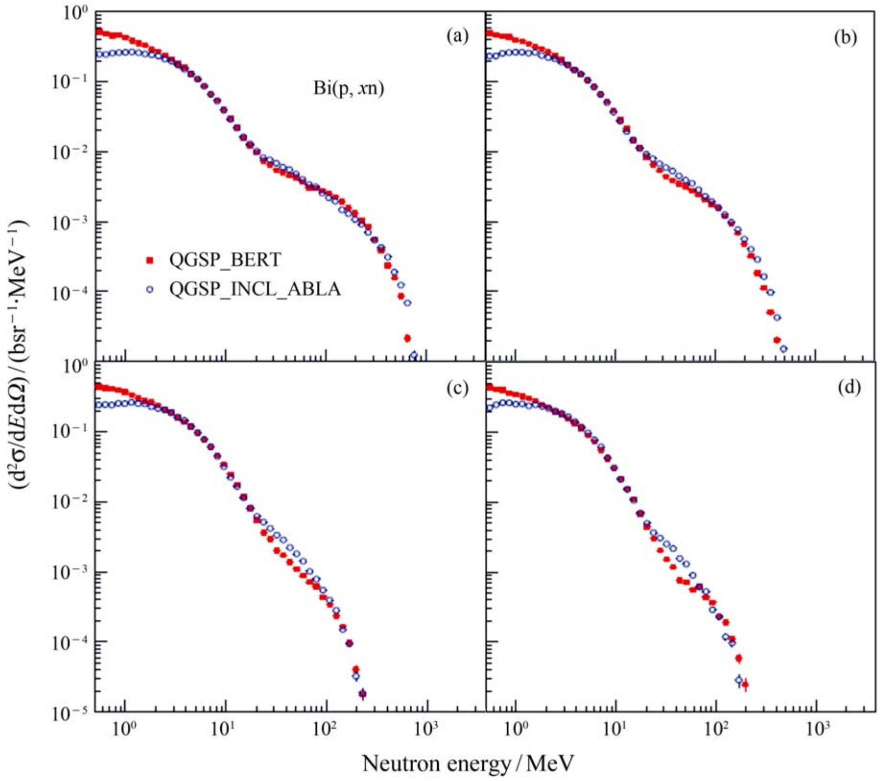

Fig. 4　(color online) Neutron production double-differential cross sections for 800 MeV proton on Bi target at the detection angles of 30°(a), 60°(b), 120°(c), 150°(d).

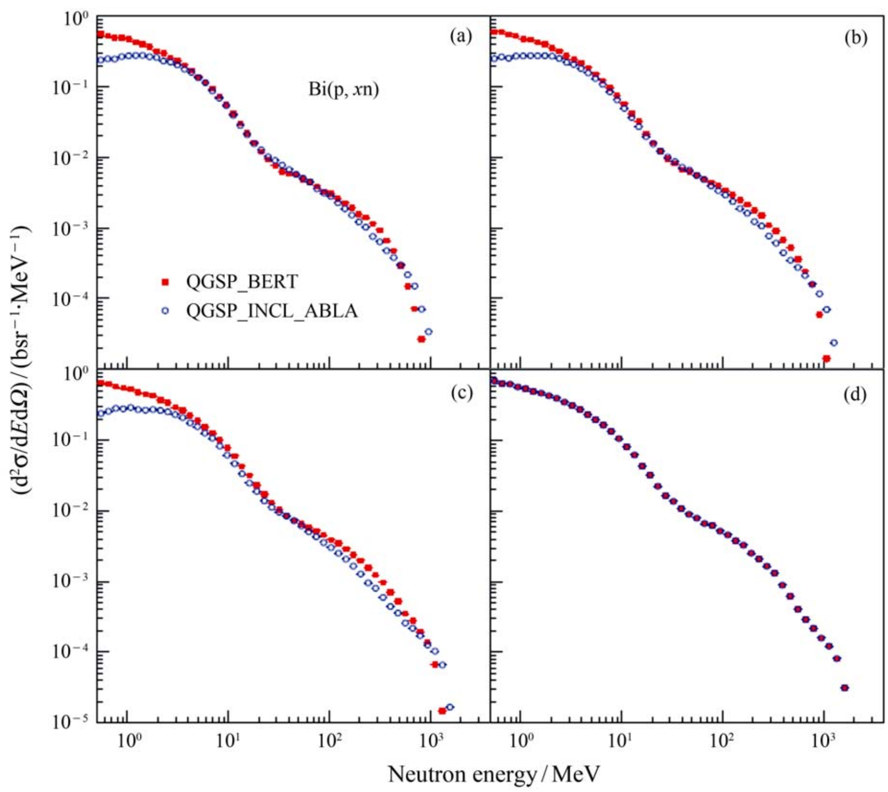

Fig. 5　(color online) Neutron production double-differential cross sections for 1.2 GeV (a), 1.6 GeV (b), 2 GeV (c), 3 GeV (d) proton on Bi target at the detection angle of 30°.

5 Summary

The neutron production double-differential cross sections for Pb target materials at incident proton kinetic energies between 800 MeV and 3 GeV are demonstrated by calculations with Monte Carlo simulation package Geant4. The accuracy of Geant4 simulation codes are obtained by comparing between the simulated results and experimental data. At the same time, the neutron production double-differential cross sections for Bi target materials and at incident proton kinetic energies between 800 MeV and 3 GeV, using validated Geant4 simulation code, are predicted. The present results validated that Geant4 Monte Carlo simulation package can be used to simulate neutron production double-differential cross sections of proton induced reaction on Pb and Bi targets in the incident energy range up to 3 GeV.

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$E_p \leqslant 3$ GeV 质子入射铅、铋引起的中子产生双微分截面的模拟

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摘要： 加速器驱动次临界系统(ADS)液态Pb-Bi散裂靶的设计中，需要可靠的理论计算工具精确地预言几个GeV能量范围的质子引起的散裂反应产生的各种粒子和核素。利用蒙特卡罗模拟软件包Geant4计算研究了800 MeV至3 GeV质子入射铅、铋材料引起的中子产生双微分截面。比较了Geant4不同物理模型得到的模拟结果与现有的实验数据。其中，Geant4的QGSP_BERT和QGSP_INCL_ABLA物理模型模拟结果很好地再现了实验数据。本工作证实了Geant4蒙特卡罗模拟软件包适合用于能量高达3 GeV的质子入射铅、铋引起的中子产生双微分截面的模拟计算。

关键词： 蒙特卡罗模拟；加速器驱动次临界系统；液态Pb-Bi散裂靶；中子产生截面

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