Experimental spectra analysis in THM with the help of simulation based on the Geant4 framework *

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Abstract: The Coulomb barrier and electron screening cause difficulties in directly measuring nuclear reaction cross sections of charged particles at astrophysical energies. The Trojan-horse method (THM) has been introduced to solve the difficulties as a powerful indirect tool. In order to understand experimental spectra better, Geant4 is employed to simulate the method. Validity and reliability of simulation data are examined by comparing the experimental data with simulated results. The Geant4 simulation of THM improves data analysis and is beneficial to the design for future related experiments.

Key words: Geant4 simulation, Trojan-horse method, astrophysical-energy, charged particle reaction, quasi-free reaction

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1 Introduction

Understanding energy production and nucleosynthesis in stars requires increasingly precise knowledge of the nuclear reaction rates at the energies of interest [1]. However, at astrophysical temperatures, nuclei react at very low energies, much lower than the Coulomb barrier for charged particles. The reaction cross sections are very small due to the Coulomb barrier, so that direct measurement is almost impossible. To overcome the experimental difficulties arising from the small cross sections and the electron screening, the Trojan-horse method (THM) [2–10] has been introduced.

THM provides a valid alternative approach to measure unscreened low-energy cross sections of reactions between charged particles. In the method, suitable three body reactions are measured under quasi-free kinematic conditions with beam energies above their Coulomb barrier. The method can also be used to retrieve information on the electron screening potential when ultra-low energy direct measurements are available.

Geant4 [11, 12], developed by CERN, is a well established Monte Carlo framework for simulation of particle passage through matter. Its application areas include high energy, nuclear and accelerator physics, as well as studies in medical and space science.

In this paper, we develop a simulation program based on the Geant4 framework for THM research in order to understand the experimental spectra better.

2 Trojan-horse method

THM belongs to an indirect measurement method in experimental nuclear astrophysics. The basic assumptions of the THM have been discussed extensively elsewhere [1–4, 6] and detailed theoretical derivation of the formalism employed can be found in [3].

The diagram of THM is shown in Fig. 1. The method is based on the quasi-free reaction mechanism, which allows us to derive indirectly the cross section of a two-body reaction

$$\mathrm{A+x \to C+c}, \tag{1}$$

from measurement of a suitable three-body process

$$\mathrm{A+a \to C+c+b}. \tag{2}$$

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The nucleus a is considered to be dominantly composed of clusters x and b (a=x⊕b).

After the breakup of nucleus a due to the interaction with nucleus A, a two-body reaction occurs between the transferred particle x and nucleus A, whereas nucleus b does not participate and acts as a spectator. The energy in the entrance channel E_{Aa} is chosen above the height of the Coulomb barrier, so as to avoid a reduction in cross section.

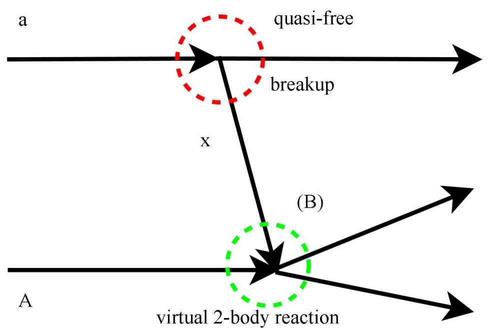

Fig. 1. Diagram of the Trojan-horse method.

At the same time, the effective energy of the reaction between A and x can be relatively small, mainly because the energy E_{Aa} is partially used to overcome the binding energy ε_{a} of x inside a (Eq. (3)), and the Fermi motion of x inside a compensates at least partially for the A+a relative motion (Eq. (4)).

$$E_{\mathrm{Ax}}^{\mathrm{qf}}=E_{\mathrm{Aa}}\left(1-\frac{\mu_{\mathrm{Aa}}}{\mu_{\mathrm{Bb}}}\frac{\mu_{\mathrm{bx}}^2}{m_{\mathrm{x}}^2}\right)-\varepsilon_{\mathrm{a}}, \quad (3)$$

$$E_{\mathrm{Ax}}=E_{\mathrm{Ax}}^{\mathrm{qf}}\pm E_{\mathrm{xb}}. \quad (4)$$

Since the transferred particle x is hidden inside nucleus a (so called Trojan-horse nucleus) and the collision of A with x takes place in the nuclear interaction region, the two-body reaction is free of Coulomb suppression and, at the same time, not affected by electron screening effects.

Thus the interesting two-body reaction cross section can be extracted from the measured three-body reaction using the relation formulation Eq. (5) after selecting the quasi-free events:

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}E_{\mathrm{Cc}}\mathrm{d}\Omega_{\mathrm{Bb}}\mathrm{d}\Omega_{\mathrm{Cc}}}=KF|W|^2P_l\frac{\mathrm{d}\sigma_l}{\mathrm{d}\Omega}(\mathrm{Ax}\rightarrow\mathrm{Cc}), \quad (5)$$

where KF is the kinematical factor, W is the momentum distribution of the spectator b inside the Trojan-horse nuclei a, and P_l is the penetration function.

In our work, the THM has been used to study two important astrophysical nuclear reactions related to ^{9}Be abundance:

$$^2\mathrm{H}(^9\mathrm{Be},\alpha^6\mathrm{Li})\mathrm{n}\Longrightarrow{}^9\mathrm{Be}(\mathrm{p},\alpha)^6\mathrm{Li}, \quad (6)$$

and

$$^2\mathrm{H}(^9\mathrm{Be},\mathrm{d}^8\mathrm{Be})\mathrm{n}\Longrightarrow{}^9\mathrm{Be}(\mathrm{p},\mathrm{d})^8\mathrm{Be}, \quad (7)$$

where the deuteron is used as the Trojan horse nucleus, due to its d = p⊕n structure [5], and the proton acts as a participant while the neutron is a spectator to the virtual two-body reaction.

3 Experimental setup

The measurements of the reactions Eq. (6) and Eq. (7) were both performed at the Beijing National Tandem Accelerator Laboratory at the China Institute of Atomic Energy. The experimental setup for the reaction Eq. (7) was installed in the nuclear reaction chamber at the R60 beam line terminal as shown in Fig. 2. A $^9\mathrm{Be}^{2+}$ beam at 22.44 MeV provided by the HI-13 tandem accelerator was used to bombard a deuterated polyethylene target $\mathrm{CD_2}$ placed vertically to the beam axis. The thickness of the target was about 160 μg/cm^2. In order to reduce the anglular uncertainty coming from the large beam spot, a linear target with width 1 mm was used.

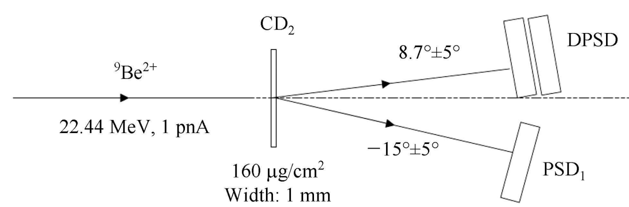

Fig. 2. Experimental setup of Trojan-horse method for the reaction Eq. (7).

A position sensitive detector ($\mathrm{PSD_1}$) was placed at $15^\circ\pm5^\circ$ to the beam line direction and about 240 mm from the target to detect outgoing deuterons, and a DPSD (Dual Position Sensitive Detector, consisting of $\mathrm{PSD_u}$ in the upside and $\mathrm{PSD_d}$ downside) was used at $8.7^\circ\pm5^\circ$ in the other side of the beam line and 250 mm distance from the target to detect the two alpha particles decayed from the unstable outgoing particle ^{8}Be. The arrangement of the experimental setup was modelled in the Monte Carlo simulation in order to cover a region of quasi-free angle pairs. The trigger for the event acquisition was given by coincidence of signals from the PSD and DPSD.

The reactions Eq. (6) can also be measured with $\mathrm{PSD_1}$ detecting alpha and $\mathrm{PSD_u}$ detecting ^{6}Li particles in coincidence.

4 Experimental spectrum analysis with the help of Geant4 simulation

The first step of the data analysis work is the energy and angle calibration of PSD and DPSD. After the calibration of the detectors, we have the energy and momentum of the particles detected by PSD_1, PSD_u and PSD_d. Then we reconstruct ^{8}Be from (E_u, E_d, θ_u, θ_d) on the assumption that the particles detected by DPSD are two α. The energy and momentum of the third particle n of the exit channel ^{9}Be+d→^{8}Be+d+n are calculated from (E_1, E_2, θ_1, θ_2), where particle1 is d and particle2 is ^{8}Be.

The most important thing to do before using THM to extract information of the 2-body reaction ^{9}Be+p→^{8}Be+d from the 3-body reaction ^{9}Be+d→^{8}Be+d+n is to select the right events which satisfy the three body reaction of the quasi-free reaction mechanism apart from all the other outgoing channels. There are many exit channels from the same entrance channel of ^{9}Be+d, for example, the ^{9}Be+d→α+^{6}Li+n channel can be detected as well. Other than the exit channels from ^{9}Be+d, there are more outgoing channels from the reaction of the beam bombarding other elements in the target, such as ^{12}C and ^{1}H.

Therefore, it is particularly important to understand the experimental spectrum in the events selections. In order to understand the experimental spectrum better, Geant4 simulation is applied to the THM study in our work.

The simulation program consists of two parts: the event generator and the detector response to the outgoing particles. A new simple event generator code was written in C^{++} instead of PYTHIA, the normal FORTRAN code in high energy physics, to create momentum information for outgoing particles from different nuclear reactions. The event generator mainly creates kinematical output for two-body and three-body nuclear reactions with resonance at some excited energy levels; the quasi-free process and sequential decay processes are considered in the three-body reaction generator code.

The detector response part is built on the Geant4 simulation framework, the detector and target construction parameters are defined according to the experiment setup. The deuterated polyethylene target CD_2 (with its thickness=160 μg/cm^2, width=1 mm, height=1 cm) is placed at the center of the reaction chamber vertically to the beam axis. The detector PSD_1 is placed at 15° to the beam line direction and about 240 mm from the target, and the DPSD (consisting of PSD_u in the upside and PSD_d downside) is placed at 8.7° in the other side of the beam line and 250 mm distance from the target. Each PSD consists of 500 μm thickness silicon sensitive area with 320 nm silicon entrance window, length 47 mm, width 8 mm. The physics processes of particle passage through matter are set in the default FTFP_BERT physics list of Geant4. This physics list requires data files for electromagnetic and hadronic processes.

A G4NNEvtInterface class according to the G4HEPEvtInterface is built to link the new event generator output to the Geant4 simulation framework.

Some of the Geant4 simulation results will be shown below and compared with the experimental data.

4.1 *E*-*θ* spectrum of 2-body reactions

Figure 3 (left) shows the experimental spectrum of E_u-θ_u detected by PSD_u. The points in Fig. 3 (right) show Geant4 simulation of the reaction ^{9}Be+d→d+^{9}Be. The $E_{^9\mathrm{Be}}$-$\theta_{^9\mathrm{Be}}$, whose curve looks like a parabola, is easy to find in the experiment spectrum.

There is also a small arc between E_u (16 MeV–20 MeV) in Fig. 3 (left). The simulation result shows that it comes from the ^{9}Be+p→p+^{9}Be elastic scattering process (the blue points in Fig. 3 (right)). This means that there are also some ^{1}H in the CD_2 target.

The simulation result of the ^{9}Be+^{12}C→^{9}Be+^{12}C elastic scattering process is also shown in Fig. 3 (right, the green points), which meets the curve of E_u∼22 MeV in the experimental spectrum.

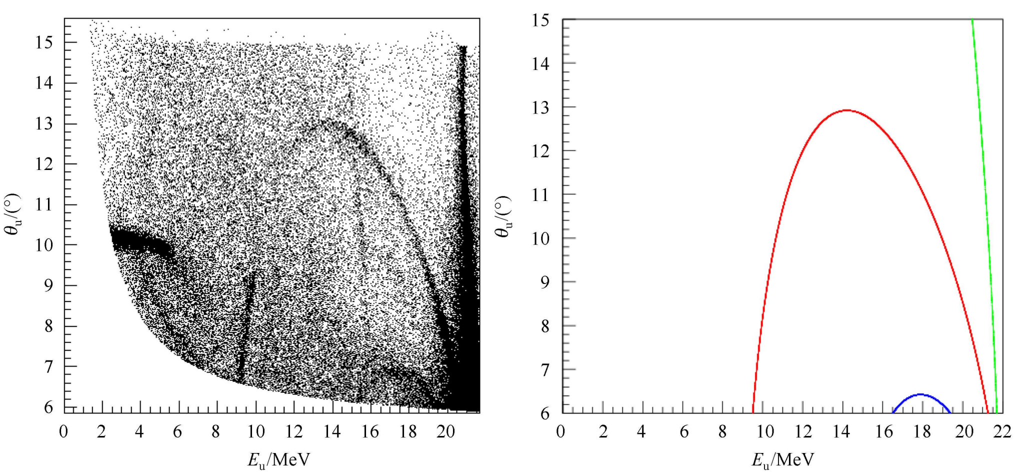

Fig. 3. Comparison of experimental spectrum E_u-θ_u (left) with simulated one (right).

The E-θ curve of outgoing particles from two body reactions can give a validity test to the detector calibration. It can also give information of elements in target.

4.2 E_1-E_u spectrum: kinematic focus

Figure 4(left) is the two-dimensional energy spectrum E_1-E_u of the experimental data. Simulation results of different reaction channels are shown in Fig. 4(right).

The red points are the simulation of ^{9}Be+d$\rightarrow\alpha+^6$Li+n reaction from the quasi free process, which are interesting for the THM reaction Eq. (6).

The blue points are the simulation of ^{9}Be+p$\rightarrow\alpha+^6$Li reaction caused by the beam bombarding ^{1}H in the target.

The green points are the simulation of ^{9}Be+d$\rightarrow$t+α+α reaction channel, which are not easy to find.

All these points can be found in the experiment spectrum.

The black points, which puzzled us for a long time, are the simulation result of ^{9}Be+d$\rightarrow$d+^{9}Be elastic scattering results. Normally, the spots of the elastic scattering in the two-dimensional energy spectrum should be in the line of E_1+E_u=22.4 MeV. We finally found out the reason using the simulation program. It is because the detector cannot deplete all the energy of the emitted high energy deuteron particles due to the limitation of the detector thickness (500 μm).

It can be seen that the simulation program can give us great help to get a better understanding of the experiment spectra.

4.3 E_u-E_d spectrum: reconstruction of ^{8}Be

The important step in data analysis is the reconstruction of the ^{8}Be particle from two α particles detected by DPSD. Fig. 5(left) is the experimental spectrum of E_u-E_d.

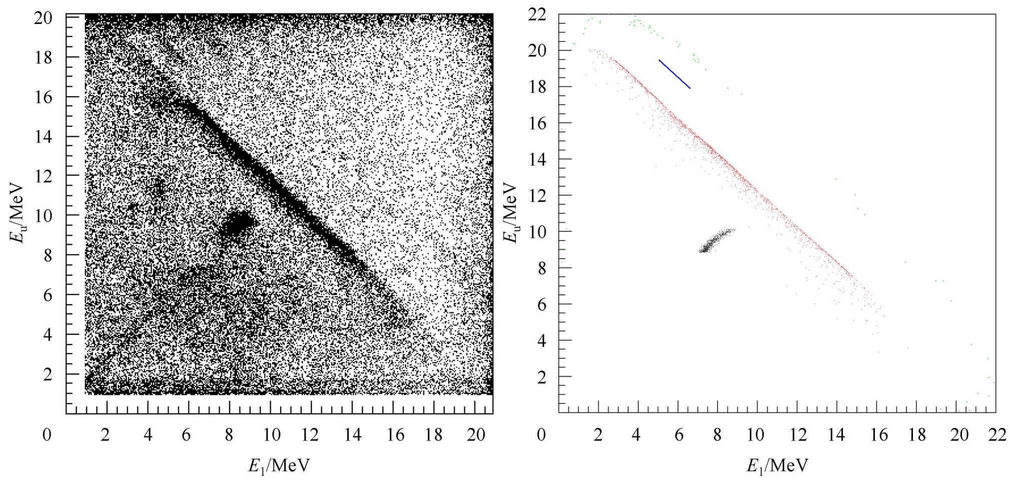

Fig. 4. (color online) Comparison of experimental spectrum E_1-E_u (left) with simulated one (right).

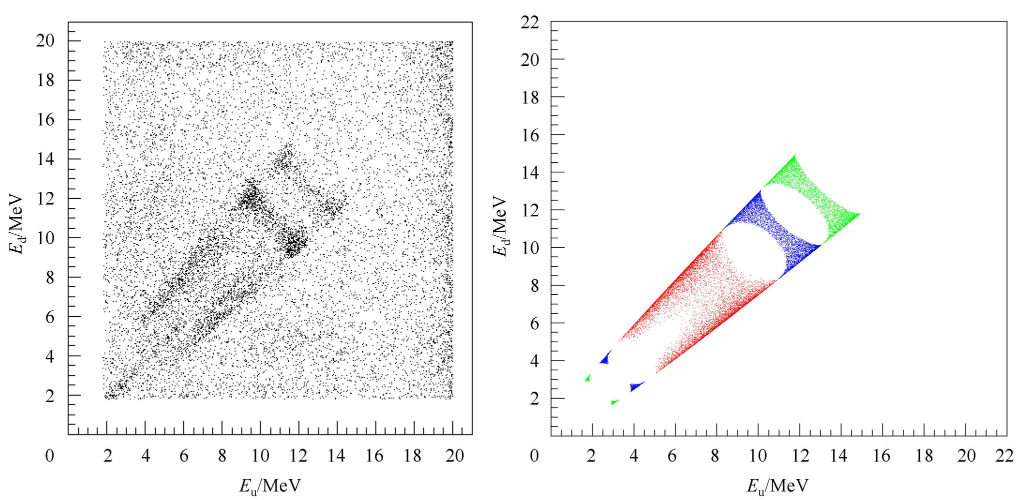

Fig. 5. (color online) Comparison of experimental spectrum of reconstruction for ^{8}Be (left) with simulated one (right).

The simulation result of α particles decayed from ^{8}Be of ^{9}Be+d→^{8}Be+d+n reaction is shown in Fig. 5 (right, the red points). You can see the agreement between the simulated data and the low energy range of the experimental data ($E_u \in$(5–10 MeV)). We find from the simulation that the high energy parts are not from the ^{9}Be+d→^{8}Be+d+n reaction channel which is interesting for us.

A simulation of α particles decayed from ^{8}Be in the ^{9}Be+d→^{8}Be+t reaction channel is given in Fig. 5 (right, the green points). It is in good agreement with the experimental data points located in the high energy area ($E_u \in$(12–14 MeV)).

Another simulation of α particles decayed from ^{8}Be ground state of $^9\mathrm{Be}+\mathrm{d} \rightarrow {}^8\mathrm{Be}^*+\mathrm{t} \rightarrow {}^8\mathrm{Be}+\mathrm{t}+\gamma$ reaction channel after the ^{8}Be* transfered from the first excited state to the ground state by emitting a gamma ray is shown in Fig. 5 (right, the blue points), which can show good agreement with the middle energy range ($E_u \in$(10–12 MeV)) in the experimental data.

In summary, with the help of the simulation, we can find out the origin of different parts of the experiment data, thus we can choose the right events by a graphical cut, only including the interesting reaction channels in the experimental spectrum to avoid the interference of other channels.

At present, the simulation program cannot deal with many-body (larger than 4) reactions and the occasional coincidence which is not a real nuclear reaction event in the experimental spectrum background.

4.4 Future applications

The simulation code is also very useful in research work such as the energy loss and angular dispersion of particles passing through a ΔE detector or the dead layer of detectors. The simulation results can help us in the design of the THM experiment, as well as in particle identification and error analysis in data analysis.

5 Summary

A simulation system based on the Geant4 framework was established and applied to the THM experimental study. The validity and reliability of the simulation system are examined by comparing the experimental data with the simulated results in our work. The simulation system can provide useful information to understand the experimental spectra better in data analysis, and it is beneficial to the design of future related experiments.

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