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Simulation of $^{12}C+^{12}C$ elastic scattering at high energy by using the Monte Carlo method*

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Abstract: The Monte Carlo method is used to simulate the $^{12}C+^{12}C$ reaction process. Taking into account the size of the incident ^{12}C beam spot and the thickness of the ^{12}C target, the distributions of scattered ^{12}C on the MWPC and the CsI detectors at a detective distance have been simulated. In order to separate elastic scattering from the inelastic scattering with 4.4 MeV excited energy, we set several variables: the kinetic energy of incident ^{12}C, the thickness of the ^{12}C target, the ratio of the excited state, the wire spacing of the MWPC, the energy resolution of the CsI detector and the time resolution of the plastic scintillator. From the simulation results, the preliminary establishment of the experiment system can be determined to be that the beam size of the incident ^{12}C is ϕ5 mm, the incident kinetic energy is 200–400 A MeV, the target thickness is 2 mm, the ratio of the excited state is 20%, the flight distance of scattered ^{12}C is 3 m, the energy resolution of the CsI detectors is 1%, the time resolution of the plastic scintillator is 0.5%, and the size of the CsI detectors is 7 cm×7 cm, and we need at least 16 CsI detectors to cover a 0° to 5° angular distribution.

Key words: simulation, kinetic energy, scattering angle, elastic scattering

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1 Introduction

From the recent theoretical results [1], we know that the tensor force plays an important role in nuclei-nuclei interaction when the double-folding potentials are decomposed of the spin-isospin components. When the elastic-scattering cross sections are divided into nearside and farside parts, the close relation can be clarified between the attractive-to-repulsive transition of the double-folding potentials and the characteristic evolution of the elastic-scattering angular distributions with increase of the incident energy in the range of E/A=100–400 MeV. However, so far no experimental evidence exists for the repulsive nature of heavy-ion optical potentials. Meanwhile, one can see that the transition energy strongly depends on the theoretical models used, namely, CEG07b with the three-body force (TBF) effect and the CEG07a without the TBF effect [1]. Therefore, the experimental determination of the transition energy through the precise measurement of elastic scattering provides quite important information about the TBF effect (particularly its repulsive component), which is one of the most important medium effects in high-density nuclear matter, and its energy dependence, in addition to the role of the tensor force that is one of the main origins of the energy dependence of the heavy-ion optical potentials in the present energy region. Therefore, on the basis of the theoretical analysis, we plan to perform experimental measurements of the elastic scattering angular distributions for the ^{12}C + ^{12}C system, particularly to carefully measure the characteristic evolution of the diffraction pattern with increase of the incident energy in the range of E/A=200–400 MeV.

In order to achieve the physical object, the para-

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meters, for example the detector size, the distance, the covering angles, etc, need to be determined. So the simulation must be done according to the actual experimental condition. In this paper we will discuss the simulation of the ^{12}C+^{12}C elastic scattering experiment at high energy. The Monte Carlo procedure is used to simulate the behaviors of incident ^{12}C particles, and figures about the relation between scattering angle and scattering kinetic energy are obtained. We also simulate the distribution of the scattered ^{12}C in the detectors, through obtaining the information, the detector size and position resolution can be assured.

2 Calculation and simulation

The simulation process of the incident ^{12}C particles interacting with target ^{12}C is divided into two steps. The first step is that when the incident ^{12}C particles with kinetic energy ($E_{\rm p}$) hit the ^{12}C target, they go forward a distance to lose kinetic energy, so the incident kinetic energy $E_{\rm p}$ is changed to $E'_{\rm p}$. The second step is on the basis of the first step, the incident ^{12}C particles with kinetic energy ($E'_{\rm p}$) are scattered along with a scattering angle θ, the kinetic energy of scattered ^{12}C particles is changed to $E''_{\rm p}$.

For the first step, random numbers can be generated in the software to simulate the incident ^{12}C beam produced by the accelerator beam line at the Institute of Modern Physics (IMP). The size of the beam is ϕ5 mm and the distributions of the particles in the x and y axes are normal.

Then the thickness of the ^{12}C target is assumed to be from 1 to 5 mm according to previous experience. One of the most useful functions in the software is that the thickness can be generated as a variable parameter and when the thickness is changed, the difference of the result on the diagram can be observed. In this way the best thickness of ^{12}C target can be found for the experiment.

Then the incident ^{12}C particles enter the ^{12}C target. Assuming one projectile ^{12}C is scattered by a target nucleus in the depth d of the target, and from the theory of range for particles interacting with the mediums, the kinetic energy of the projectile ^{12}C can be calculated at the reaction point, that is

$$R(E_{\rm p}) = \alpha\times E_{\rm p}^{\gamma}\times\left(\frac{m}{z^2}\right)+c\times m \Longrightarrow E'_{\rm p} = \left[\frac{R(E_{\rm p})-d-c\times m}{\alpha}-\frac{z^2}{m}\right]^{\frac{1}{\gamma}}, \quad (1)$$

where α, γ and c are the parameters which depend on target [2]. For ^{12}C they are constant and equal to 0.0024, 1.78 and 0, respectively. R is the range of the projectile in the medium, $E_{\rm p}$ is the incident kinetic energy of the projectile and $E'_{\rm p}$ is the kinetic energy of ^{12}C at the reaction point, d is the distance from the surface to the reaction point in the target, m and z correspond to the mass and charge numbers of projectile, respectively.

When the kinetic energy of incident ^{12}C particles is changed to $E'_{\rm p}$ through energy loss, the process enters the second step. At the reaction point the incident ^{12}C particles with kinetic energy ($E'_{\rm p}$) interact with the ^{12}C target, the incident ^{12}C particles are scattered along a scattering angle with a new kinetic energy ($E''_{\rm p}$). The kinetic energy ($E''_{\rm p}$) of scattered ^{12}C is calculated by using a relativistic method. For relativity we know that

$$E=\gamma m=E_{\rm k}+m \Longrightarrow E^2=p^2+m^2=\gamma^2m^2. \quad (2)$$

$$p=\gamma\beta m=(\gamma^2-1)^{1/2}m. \quad (3)$$

β=v/c, c is light velocity, $\gamma=\sqrt{1-\beta^2}$, $E_{\rm k}$ is the kinetic energy. Here we define the light velocity c=1. According to the conservation principle of momentum and energy,

$$\begin{aligned} E'_{\rm p}+E'_{\rm t} &= E''_{\rm p}+E''_{\rm t}, \\ p'_{\rm p} &= p''_{\rm p}\cos\theta+p''_{\rm t}\cos\varphi, \\ p''_{\rm p}\sin\theta &= p''_{\rm t}\sin\theta, \end{aligned} \quad (4)$$

$E'_{\rm p}$ and $p'_{\rm p}$ are the total energy and momentum of incident ^{12}C particles at the reaction point, respectively. $E'_{\rm t}$ is the total energy of ^{12}C target. $E''_{\rm p}$, $p''_{\rm p}$ and θ are the total energy, momentum and scattering angle of the scattered incident ^{12}C at the reaction point, respectively. $E''_{\rm t}$, $p''_{\rm t}$ and φ are the total energy, momentum and scattering angle of the scattered ^{12}C target, respectively. p and t denote the incident and target particles, respectively. We suppose that the ^{12}C target is static, so we know that $E'_{\rm t}=m$, $p'_{\rm t}$=0, $\gamma_{\rm t}$=1. By using Eqs. (2), (3) and (4) we can obtain the relation between the kinetic energy of scattered ^{12}C ($E''_{\rm p}$) and the scattering angle (θ),

$$E''_{\rm p}=\frac{2\cos^2\theta}{A-\cos^2\theta}m. \quad (5)$$

A=$\dfrac{\gamma_1+1}{\gamma_1-1}$. We can know A from the kinetic energy $E'_{\rm p}$ of incident ^{12}C.

If the multiple scattering effect is considered, the width of the projected angular distribution is given by [3–5]

$$\begin{aligned} \theta_0 &= \frac{13.6}{p\beta c}z\sqrt{x/X_0}\left(1+0.038\lg\frac{x}{X_0}\right), \\ \theta' &= \theta+\theta_0. \end{aligned} \quad (6)$$

Here p, (βc), and z are the momentum, velocity, and charge number of the incident particle, respectively, and x/X_0 is the thickness of the scattering medium in radiation lengths. So the slight difference of the scattering angle can be obtained outside the ^{12}C target. In fact, it is very small, about 0.001 rad difference, smaller than the resolution of the detector. As a result, we can just ignore it.

The experimental setup schematic is shown in Fig. 1. After the target, the scattered ^{12}C particles will fly over a distance L to arrive at the detector along with the scattering angle. Then L can be considered as a variable parameter, when the flight distance L is different, the changes of the final results can be observed. According to IMP's facility, we need 3 to 5 meters distance at most. So we must adapt our detector and choose the best resolution to clearly distinguish the ^{12}C particles with other nuclei. Meanwhile, ^{12}C has an excited state with 4.4 MeV, which corresponds to inelastic scattering. In the experiment we hope that the inelastic scattering can be distinguished from the elastic scattering.

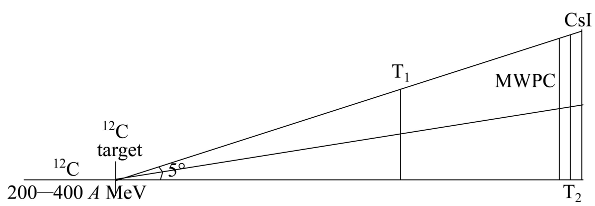

Fig. 1. The schematic of the experimental setup for 200–400 A MeV $^{12}C+^{12}C$ system.

Along the flight of the scattered ^{12}C, the scattered ^{12}C particles are move through the detector system, which is composed of one multi-wire proportional chamber (MWPC), two plastic scintillators (T_1 and T_2) and a CsI(Tl) detector. An MWPC and two plastic scintillators are used to obtain the particle position and the time of flight (TOF) information of scattered ^{12}C, respectively. At the end, a CsI(Tl) detector is used to stop the ^{12}C particles and to provide the kinetic energy signal. So the energy resolution η_E of the CsI detectors and the time resolution η_t of the plastic scintillators can be set as variable parameters, so

$$E_{obs}=E_1''+\eta_E\times E_1'',\quad t_{obs}=t+\eta_t\times t, \qquad (7)$$

E_{obs} and t_{obs} are the region of the actual detected kinetic energy and time by using detectors. By adopting η_E and η_t, the simulation results of the relation between scattering angle (from 0° to 5°) and scattering kinetic energy can be acquired, which are shown in Fig. 2. The two curves correspond to the elastic and inelastic scattering when ^{12}C nuclei lie in the ground state and the excited state with energy 4.4 MeV, respectively. When the beam size, incident kinetic energy, thickness of target, ratio of excited state, flight distance, wire spacing of the MWPC, the resolution of energy and time, etc. are changed, we hope that the two curves can be distinguished between each other, then the optimized parameters can be found.

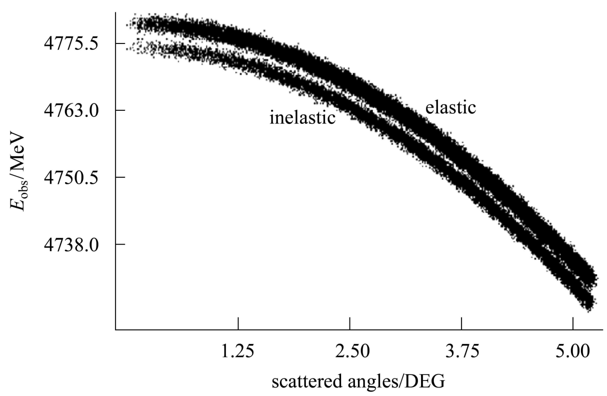

Fig. 2. Relation between the scattering angles θ and the actual detected kinetic energy E_{obs}.

3 Results and discussion

According to the above method, there are eight parameters to be designed as variables in the software. They are the beam radius (R_X and R_Y), incident kinetic energy (E_{inc}), target thickness (tThick), ratio of excited state $^{12}C^*$ (Rexcite), flight distance of scattered ^{12}C (Lflight), the wire spacing of the MWPC (spacing), energy resolution of the CsI detector (η_E) and the time resolution of the plastic scintillator (η_t). The best simulated results for the experiment can be acquired, as shown in Fig. 3 for the relations between scattering angles (from 0° to 5°) and scattering kinetic energy, which correspond to (a), (b), (c), (d), (e), (f) and (g), besides (h) for the relation between scattering angles and TOF with time resolution of plastic scintillators. In Fig. 3 the two curves are similar to those in Fig. 2, which represent the ground state ^{12}C and the excited state $^{12}C^*$.

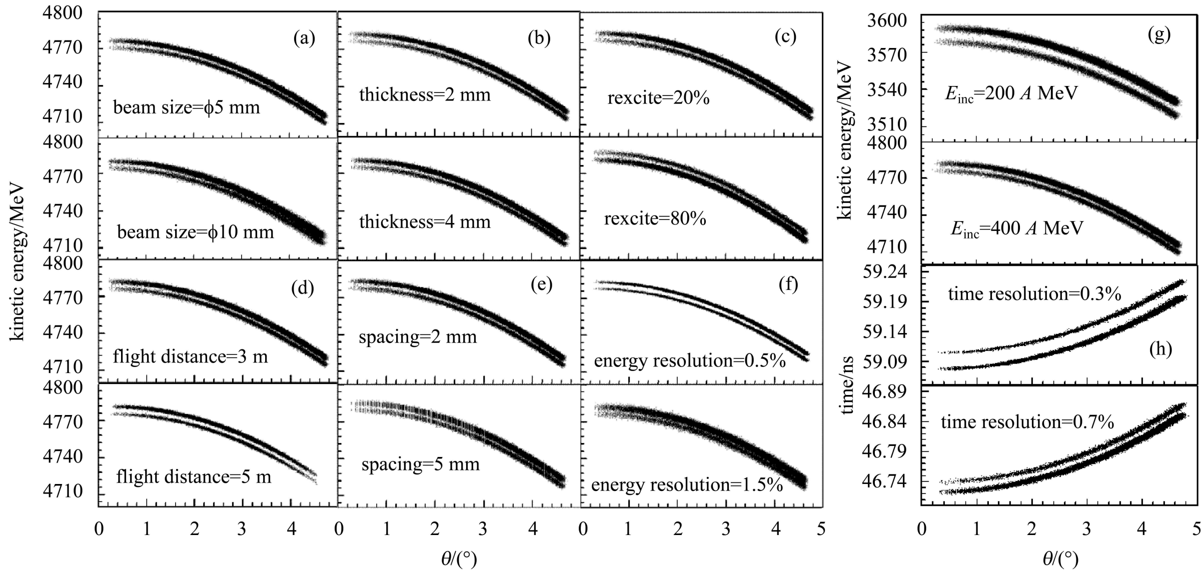

Fig. 3. The relation between scattering angles (from 0° to 5°) and scattering kinetic energy with different variable parameters which correspond to (a) beam size, (b) target thickness, (c) excited ratio of the excited state with 4.4 MeV, (d) flight distance, (e) wire spacing of the MWPC, (f) energy resolution of the CsI detectors, (g) incident kinetic energy, besides (h) for the relation between scattering angles and TOF with time resolution of the plastic scintillators.

In the simulation, when changing any one of the eight variables, the others have to be fixed. So their original values are set as: R_X=R_Y=2.5 mm, $E_{\rm inc}$=400 A MeV, tThick=2 mm, Rexcite=20%, Lflight=4 m, spacing=2 mm, $\eta_{\rm E}$=1%, $\eta_{\rm t}$=0.5%。 R_X and R_Y are designed on the basis of the condition of the ^{12}C beam at the IMP. From the theory analysis and simulation result, a large beam size will affect the identification of the two curves. Especially in large angles, there is a serious overlap, as shown in Fig. 3(a). Finally, under the experimental conditions, the beam size is set as ϕ5 mm. With the increase of target thickness, the energy loss of incident ^{12}C increases, as well as the effect of multiple scattering which will cause a large difference in scattering angle. From Fig. 3(b), in order to obtain better identification of the two curves, which means less overlap in large angles, the target thickness chosen should be 2 mm. During the interaction for ^{12}C+^{12}C at 200–400 A MeV, there will be elastic scattering, inelastic scattering and other breakup reactions. Among all the coupled reaction channels for elastic scattering, inelastic scattering, which produces the 4.4 MeV excited state ^{12}C*, gives the biggest contribution and causes a great effect on the elastic scattering angular distributions. In the simulation result, it is easy to observe that with the increase of the ratio from 0–50%, the identification between two curves becomes worse. But it is still feasible to separate them, as shown in Fig. 3(c). To make the smallest angle resolution 0.1°–0.2° for the angular distribution of elastic scattering, according to the standard wire spacing of the MWPC, which is 2–5 mm, the flight distance of scattered ^{12}C should be at least 3 m because of Lflight ×tan (0.1°) ⩾5 mm. If experimental conditions permit, the flight distance should be as long as possible, as shown in Fig. 3(d). But after considering the vacuum chamber, scattered ^{12}C reacts with air, and causes lots of energy loss and a scattering angle difference. Also, because of space limitations, the size of the MWPC and the CsI detectors, the final choice of flight distance should be 3 m. The wire spacing of the MWPC will greatly affect the angle distribution of scattered ^{12}C. From Fig. 3(e) it is observed that the smaller the wire spacing is, the better the identification of the two curves is. As a result, 2 mm is best for the experiment. From Formula (7), the energy resolution will greatly affect the identification between ground state ^{12}C and excited state ^{12}C*. When the resolution is larger than the energy gap 4.4 MeV of two curves, the overlap will be very serious, especially in large angles. So under the permitted CsI scintillator conditions, we choose the energy resolution around 1%, as shown in Fig. 3(f). As discussed in the introduction, the ^{12}C+^{12}C experiment has to carefully measure the characteristic evolution of the diffraction pattern with the increase of the incident energy in the range of E/A=200–400 MeV. As seen in Fig. 3(g), with the increase of the incident energy, overlap begins to appear in large angles. However, it still can be clearly identified between the two curves. That is to say, our experimental requirement is feasible for 200–400 A MeV. A plastic scintillator is used to detect the time signal, which has a decay time of about several nanoseconds. From the simulation result, shown in Fig. 3(h), we know that in order to clearly separate the two curves, a time resolution 0.5% for the TOF is needed.

The distribution of scattered ^{12}C particles on the MWPC is shown in Fig. 4 (circle). The ranges of both of the X and Y directions are almost from −300 mm to 300 mm. In order to take sufficient data of scattered ^{12}C particles, we need to cover at least half of the distribution we get. For CsI scintillators, every size is 7 cm×7 cm, That is to say, we need at least 16 CsI scintillators to be composed of detector arrays, which are shown in Fig. 4 (square).

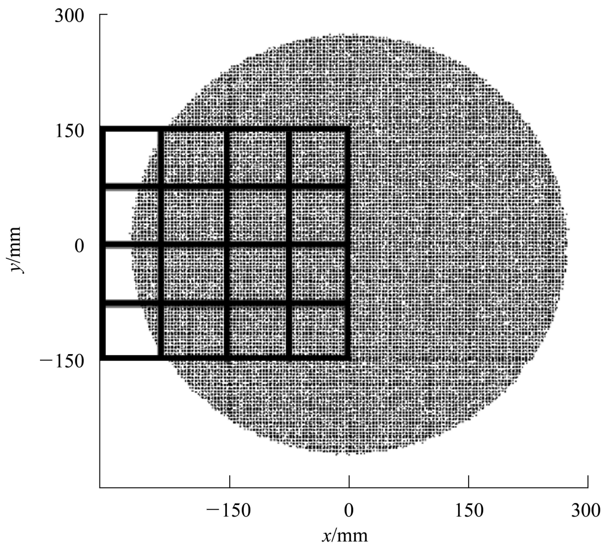

Fig. 4. The position distribution of scattered ^{12}C on the MWPC and the CsI detectors. The circle and the square correspond to the distribution on the MWPC and the CsI detectors, respectively.

4 Conclusion

From the simulation results of the relation between scattering angle (from 0° to 5°) and scattering kinetic energy, and the distribution of scattered ^{12}C particles on the MWPC, according to the facilities' surroundings of the IMP in Lanzhou, in order to reach the accuracy of 200–400 A MeV $^{12}C+^{12}C$ elastic scattering experiment, the beam size is less than ϕ5 mm, and the distance between the target center and the MWPC detector center should be at least 3 m. The other experimental parameters are also determined. The thickness of the ^{12}C target is 2 mm. The wire spacing of the MWPC is 2 mm, the energy resolution of the CsI detectors and the time resolution of the plastic scintillators are 1% and 0.5%, respectively.

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