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Angular Distribution of the $^{12}C(^6He, ^7Li)^{11}B$ Reaction *

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Angular distribution of the $^{12}C(^6He, ^7Li)^{11}B$ transfer reaction is measured with a secondary ^6He beam of 36.4 MeV for the first time. The experimental angular distribution is well reproduced by the distorted-wave Born approximation (DWBA) calculation. The success of the present experiment shows that it is feasible to measure one-nucleon transfer reaction on a light nucleus target with the secondary beam facility of the HI-13 tandem accelerator at China Institute of Atomic Energy (CIAE), Beijing.

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In recent years, there has been great interest in studying the nuclear reactions induced by radioactive ion beams, especially by short-lived exotic nuclei. Those nuclei are important in nuclear astrophysics and provide a new opportunity to study nuclear structure and reactions in a wider freedom of isospin.[1]

As is well known, ^6He is considered to be a two-neutron-halo nucleus, its two loosely bound valence neutrons ($S_{2n} = 927.4 \pm 0.8$ keV) may have an important influence on elastic scattering, fusion, charge-exchange, break up, pick-up and two-neutron transfer reactions etc.; the reactions induced by it have been studied extensively.[2−9] A major part of the research is directly dedicated to the investigation of the ^6He exotic structure. The neutron-proton halo structure for the 3.56 MeV 0^+ state of ^6Li is observed by the measurement of the $^1H(^6He,^6Li)n$ reaction.[10] There are some studies about ^6He on ^{12}C target reactions to extract information about the reaction mechanism,[11,12] nuclear forward glory effect,[13] and interaction potential[14] etc. As far as we know, no angular distribution of the $^{12}C(^6He,^7Li)^{11}B$ reaction has been reported.

In this Letter, the angular distribution of the $^{12}C(^6He,^7Li)^{11}B$ reaction is measured with a 36.4 MeV ^6He secondary beam, and analyzed with the distorted-wave Born approximation (DWBA) calculation.

The experiment is carried out at the secondary beam facility[15,16] of the HI-13 tandem accelerator, Beijing. The experimental setup is similar to previous $^{11}C(d,n)^{12}N$,[17] $^8Li(d,n)^9Be$,[18] $^8Li(d,p)^9Li$[19] and $^{13}N(d,n)^{14}O$[20] experiments, as shown in Fig. 1. A 46 MeV ^7Li primary beam from the tandem accelerator impinges on a 4.8-cm-long deuterium gas cell at the pressure of 1.5 atm. The front and rear windows of the gas cell are Havar foils with a thickness of 1.9 mg/cm^2. The ^6He ions are produced via $^2H(^7Li,^6He)^3He$ reaction. After the magnetic separation with a dipole and the focalization with a quadruple doublet, a 37.7 MeV ^6He secondary beam is delivered and then collimated by two apertures in diameter of $\phi 7$ mm–$\phi 5$ mm. The main contaminants of the secondary beam are ^7Li ions from Rutherford scattering of the primary beam in the gas cell windows and beam tube. In order to eliminate its interference to the ^7Li products from the $^{12}C(^6He,^7Li)^{11}B$ reaction, a 23 μm-thick silicon ΔE detector is placed at 20 mm upstream of the secondary target, which serves as both particle identification and beam normalization. The energy loss spectrum of the ΔE detector is shown in Fig. 2. One can see that the ^7Li contaminants in the secondary beam can be absolutely discriminated by the one dimension gate of the ^6He peak. The typical beam intensity of the secondary beam is approximately 3000 pps, the purity is 99% with an energy resolution of 0.64 MeV for a long-term measurement.

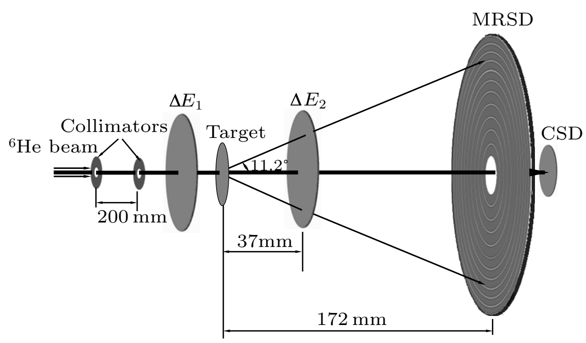

Fig. 1. Schematic layout of the experiment.

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A pure carbon foil with a thickness of 1.7 mg/cm^2 serves as the secondary target to measure the ^{12}C(^{6}He,^{7}Li)^{11}B reaction. The energy of ^{6}He ions at the middle of the carbon foil is 36.4 MeV. A 300-μm-thick multi-ring semiconductor detector (MRSD) with a center hole is used as a residue energy (E_r) detector which composes a $\Delta E - E_r$ counter telescope together with a 23-μm-thick silicon ΔE detector and an independent 300-μm-thick center silicon detector (CSD). Such a detector configuration covers the laboratory angular range from 0° to 11.2°, and the corresponding angular range in the center-of-mass frame is from 0° to 18.4°.

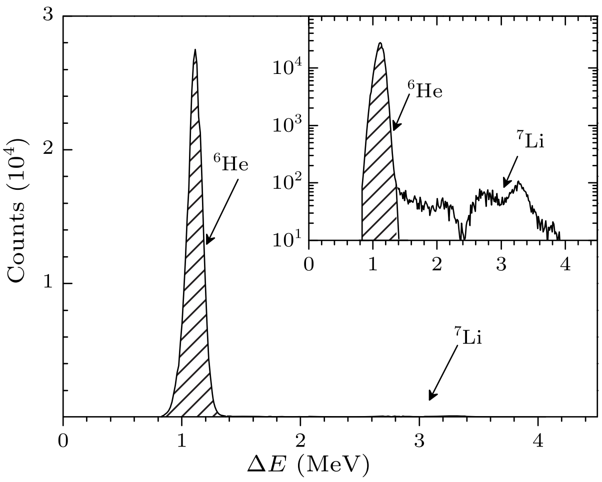

Fig. 2. Linear and logarithmic energy loss spectrum of the upstream ΔE detector. The hatched area denotes the ^{6}He ions which are used to measure the ^{12}C(^{6}He,^{7}Li)^{11}B reaction.

The total number of incident ^{6}He ions is approximately 0.84×10^8. About 76 ^{7}Li events are found for all the runs and all the rings. As an example, Fig. 3 shows the $\Delta E - E_r$ scatter plot of the second ring of MRSD. The black dots denote the events caused by pure ^{6}He ions and the gray dots denote the events caused by all ions in the secondary beam. One can see that the interference of ^{7}Li contaminants can be absolutely eliminated by using the upstream ΔE. For the sake of saving CPU time in dealing with the experimental data, we set a cut at $\Delta E = 2.0$ MeV. All the events below the cut are scaled down by a factor of 100, most of the events below the cut are ^{6}He ions, while the ^{7}Li events are above the cut and remain unchanged. The two-dimensional gate is the ^{7}Li kinematics region from the ^{12}C(^{6}He,^{7}Li)^{11}B reaction based on the Monte Carlo simulation, corresponding to the second ring. The simulation takes into account the beam spot size, geometrical factor, resolution of the detectors, angular and energy straggling effects in target and detectors.

The differential cross section of ^{12}C(^{6}He,^{7}Li)^{11}B can be expressed as

$$\frac{d\sigma}{d\Omega} = \frac{\Delta N}{I N_s \Delta\Omega}, \tag{1}$$

where ΔN and $\Delta\Omega$ are the number of ^{7}Li events in the two-dimensional gate and the solid angle of the corresponding ring, respectively, N_s is the number of ^{12}C atoms per unit area for the carbon target and I is the total number of incident ^{6}He ions. A test experiment is performed to verify the calculated solid angles using a ^{239}Pu source. The differential cross sections in the center-of-mass system for the ^{12}C(^{6}He,^{7}Li)^{11}B reaction is then obtained, as shown in Fig. 4 with filled circles. The uncertainties of differential cross sections mainly result from the statistics and the assignment of ^{7}Li gates in the $\Delta E - E_r$ scatter plots through the Monte Carlo simulation. The angular uncertainties are about 0.7° in the laboratory frame considering the following points: the beam spot size, the angular divergence of the secondary beam, the angular straggling in two ΔE detectors and target. The data of two neighbor rings are merged due to the fact that the angular errors are larger than the angular width of the rings.

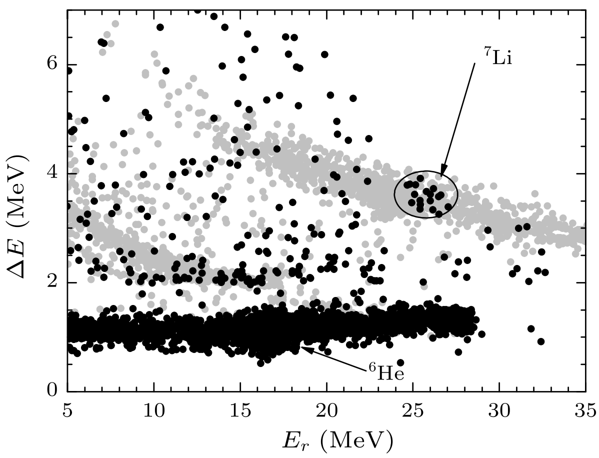

Fig. 3. Scatter plot of ΔE vs E_r for the second ring of the detector. The black dots denote the events caused by pure ^{6}He ions and the gray dots denote the events caused by all ions in the secondary beam.

A DWBA code FRESCO[21] is utilized to analyze the angular distribution of the ^{12}C(^{6}He,^{7}Li)^{11}B reaction. The single-particle wave function is obtained by solving the Schrödinger equation using a Woods-Saxon potential with standard geometrical parameters ($r_0 = 1.25$ fm and $a = 0.65$ fm), the depth is adjusted to reproduce the observed binding energy of the valence proton. The optical potentials for entrance and exit channels expressed as

$$\begin{aligned} U(r) =& -\frac{U_V}{1+\exp\left(\frac{r-R_R}{a_R}\right)} - i\frac{W_V}{1+\exp\left(\frac{r-R_I}{a_I}\right)} \\ & - 4i\frac{W_S}{a_I}\frac{d}{dr}\Big[1+\exp\Big(\frac{r-R_I}{a_I}\Big)\Big]^{-1} + U_C, \end{aligned} \tag{2}$$

are used in the calculation, where

$$U_C = \begin{cases} \frac{Z_P Z_T e^2}{2R_C}\left(3 - \frac{r^2}{R_C^2}\right), & r \le R_C, \\ \frac{Z_P Z_T e^2}{r}, & r > R_C \end{cases} \quad (3)$$

$$R_k = r_k\left(A_P^{1/3} + A_T^{1/3}\right), \quad k = R, I, C, \quad (4)$$

Z_P, Z_T and A_P, A_T are the numbers of charges and masses of the projectile and target, respectively.

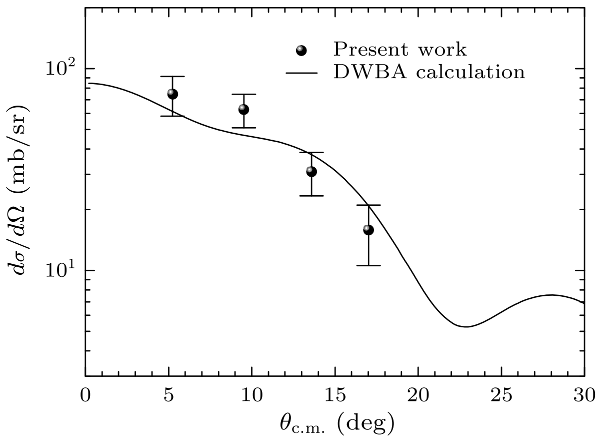

Fig. 4. Angular distribution of the $^{12}C(^6He,^7Li)^{11}B$ reaction at $E_{\rm c.m.} = 24.2$ MeV.

Table 1. Optical potential parameters used in the DWBA calculation. The potentials have a standard Wood–Saxon form, where U_V, r_R and a_R are the depth, radius and diffuseness of the real potentials, W_V, W_S, r_I and a_I are those for the imaginary potentials. U and W are in MeV, r and a are in fm.

Channels	Entrance	Exit
U_V	141.7	188.4
r_R	0.76	0.79
a_R	0.67	0.69
W_V	8.04	
W_S		7.74
r_I	1.25	1.25
a_I	0.99	0.64
r_C	1.30	1.25

The optical potential parameters for the entrance channel used in the DWBA calculation are deduced from ^{6}Li+^{12}C elastic scattering.[22] Those for the exit channel are deduced by fitting the elastic data of ^{7}Li on the ^{11}B target.[23] All the parameters are listed in Table 1. The experimental differential cross sections can be well reproduced by the DWBA calculation as shown in Fig. 4.

In summary, the angular distribution of the $^{12}C(^6He,^7Li)^{11}B$ reaction is measured at $E_{\rm c.m.} = 24.2$ MeV for the first time. The angular distribution is well reproduced by the DWBA calculation. The success of the present experiment shows that it is feasible to measure a one-nucleon transfer reaction on a light nucleus target (such as a carbon target) with the secondary beam facility of the HI-13 tandem accelerator at the China Institute of Atomic Energy (CIAE), Beijing.

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