Reaction mechanism of the $^{12}C(^3He,\alpha)^{11}C$ reaction

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The mechanism of the reactions $^{12}C(^3He,\alpha)^{11}C$ leading to the $\frac{3}{2}^-$ ground state and $\frac{5}{2}^-$ second excited state of ^{11}C is studied using finite-range distorted-wave Born approximation with all one-step direct and exchange processes. By taking into account in detail the cluster structure of ^{11}C and ^{12}C, the transition to the $\frac{5}{2}^-$ state which is a j forbidden direct process can be explained well by the exchange process.

[NUCLEAR REACTIONS $^{12}C(^3He,\alpha)^{11}C$, finite-range distorted-wave Born approximation analysis, direct and exchange processes, cluster structure.]

Investigations of one-nucleon and few-nucleon transfer processes in the nuclear direct reaction yields highly useful information on the mechanism of these reactions, on the structure of the nucleus, and on the spectroscopic characteristics of the nuclear levels.[1] Recently, the experimental studies of the $^{12}C(^3He,\alpha)^{11}C$ reactions have been performed widely at various incident energies.[2–6] The observed transition to the $\frac{3}{2}^-$ ground state and the $\frac{1}{2}^-$ first excited state of ^{11}C have been analyzed by the direct pickup process of the 1-p orbit neutron. The transition to the $\frac{5}{2}^-$ second excited state is a j forbidden pickup process if the filling order of the simple shell model is followed. Therefore, the two-step mechanism, the pickup of an 1-$f_{5/2}$ orbit neutron and the knock-on mechanism have been proposed to explain such a shell model forbidden transition. Until now, the zero-range distorted-wave Born approximation (zero-range DWBA) has been employed[2–6] in analyzing data of angular distributions. As is well known, the zero-range DWBA can only predict shapes of angular distributions with an arbitrary normalization constant introduced to fit absolute magnitudes of the experimental data. Then, it is necessary for us to perform finite-range DWBA calculations. Also, it has been pointed out that the exchange process is important for the transfer reactions in the light nuclei.[7,8] Therefore, it is a very interesting problem whether we can explain the transition to the $\frac{5}{2}^-$ state of ^{11}C by the effect of the exchange process without the two-step mechanism.

In the present paper, we show exact finite-range DWBA calculations of the $^{12}C(^3He,\alpha)^{11}C$ reactions at the incident energy of $E(^3He)=34.7$ MeV[3] leading to the ground $\frac{3}{2}^-$ and second excited $\frac{5}{2}^-$ states of ^{11}C, including all one-step direct and exchange processes and taking into account in detail the cluster structure of ^{12}C and ^{11}C.

The total transition amplitude M for the reaction $T(a,b)R$ can be expressed by the sum of the direct transition amplitude M^D and the exchange one M^E.[7] The transition amplitude M^D in the prior form for

$$a(^3He)+T(^{12}C)[=C(n)+R(^{11}C)] \rightarrow R(^{11}C)+b(^4He)[=a(^3He)+C(n)]$$

is

$$M^D=\langle f^D|\, V^D_{aC}+V^D_{aR}-U_{aT}|\, i^D\rangle \ , \tag{1}$$

where V^D_{xy} is the transition interaction between x and y in the direct process. The U_{aT} is the optical model potential in the entrance channel. The wave functions[7] of the target nucleus T and the emitted particle b are represented as bound states of C and R, and a and C, respectively. Similarly, the exchange transition amplitude M^E in the prior form for

$$a(^3He)+T(^{12}C)[=b(^4He)+C(^8Be)] \rightarrow R(^{11}C)[=a(^3He)+C(^8Be)]+b(^4He)$$

is

$$M^E=\langle f^E|\, V^E_{ab}+V^E_{aC}-U_{aT}|\, i^E\rangle \ . \tag{2}$$

We assume the ground states of ^{12}C and ^{11}C and the second excited state of ^{11}C to be from Ref. 9,

$$^{12}C(\text{ground};0^+)=p^8[44]^1S_0 \ ,$$

$$^{11}C(\text{ground};\tfrac{3}{2}^-)=0.636p^7[43]^2P_{3/2}+0.569p^7[43]^2D_{3/2} \ ,$$

$$^{11}C(\text{second};\tfrac{5}{2}^-)=0.856p^7[43]^2D_{5/2}-0.185p^7[43]^2F_{5/2} \ .$$

TABLE I. Optical potential parameters.

Set		r_C (fm)	Real V (MeV)	Real r_R (fm)	Real a_R (fm)	Imaginary W (MeV)	Imaginary r_W (fm)	Imaginary a_W (fm)	Type	Ref.
1	^{3}He	1.4	123.3	1.10	0.751	14.72	1.205	0.834	Surface	3
	α	1.3	202.6	1.30	0.700	12.00	1.300	0.700	Surface	3
2	^{3}He	1.4	165.0	1.26	0.800	9.96	2.160	0.800	Volume	11
	α	1.3	194.0	1.38	0.800	8.50	1.600	0.800	Volume	11

In the present study, we need the spectroscopic amplitudes for the following cases.

(i) $^{12}C(^3He,\alpha)^{11}C(ground)$. For the direct process, ^{12}C(ground) $\rightarrow n+{}^{11}$C(ground) and $\alpha\rightarrow{}^3\text{He}+n$. For the exchange process,

$$^{12}\text{C(ground)}\rightarrow\alpha+{}^8\text{Be}(p^4[4]^{11}L_J)$$

and

$$^{11}\text{C(ground)}\rightarrow{}^3\text{He}+{}^8\text{Be}(p^4[4]^{11}L_J)\ .$$

(ii) $^{12}C(^3He,\alpha)^{11}C(second)$. For the exchange process,

$$^{12}\text{C(ground)}\rightarrow\alpha+{}^8\text{Be}(p^4[4]^{11}L_J)$$

and

$$^{11}\text{C(second)}\rightarrow{}^3\text{He}+{}^8\text{Be}(p^4[4]^{11}L_J)\ .$$

The core states of $^8\text{Be}(p^4[4]^{11}L_J)$ that are taken into account are the ground state ($^{11}S_0$), the first excited state ($^{11}D_2$) and the second excited state ($^{11}G_4$). The theoretical spectroscopic amplitudes[7] of $S(^{12}\text{C}\rightarrow n+{}^{11}\text{C})$ and $S(\alpha\rightarrow{}^3\text{He}+n)$ are 1.706 and -1.414, respectively. The spectroscopic amplitudes for ^{12}C(ground) $\rightarrow\alpha+{}^8$Be, ^{11}C(ground) $\rightarrow{}^3$He $+{}^8$Be, and ^{11}C(second) $\rightarrow{}^3$He $+{}^8$Be are taken from Ref. 10.

The radial wave functions of the bound states are solved by making use of a real Woods-Saxon potential (strength V, nuclear radius r_R, and diffuseness a_R) with the Coulomb potential of a uniformly charged sphere of radius r_C. The parameters (r_R and a_R) for $^{12}\text{C}\rightarrow n+{}^{11}\text{C}$, $\alpha\rightarrow{}^3\text{He}+n$, $^{12}\text{C}\rightarrow\alpha+{}^8\text{Be}$, and $^{11}\text{C}\rightarrow{}^3\text{He}+{}^8\text{Be}$ are taken from the real part of the appropriate optical potentials.[11] The strength V of the potential is determined so as to reproduce the experimental nucleon (or nucleon cluster) separation energy. The transition potentials $V^D_{aC}=V(^3\text{He}+n)$ and $V^D_{aR}=V(^3\text{He}+{}^{11}\text{C})$ for the direct process and $V^E_{ab}=V(^3\text{He}+\alpha)$ and $V^E_{aC}=V(^3\text{He}+{}^8\text{Be})$ for the exchange process are taken from the real part of the corresponding optical potentials.[11] In Table I, we show the parameters of the optical potentials of Woods-Saxon form with the Coulomb potential of the uniformly charged sphere of radius r_C. In Fig. 1, we compare the calculated finite-range DWBA cross sections with the experimental data.[3] In the reaction $^{12}\text{C}(^3\text{He},\alpha)^{11}\text{C}(\text{ground};\frac{3}{2}^-)$, the cross sections for the total transition amplitude M are calculated with the optical potential parameter set 1 and with a normalization constant 0.8. The main contribution to the cross section was found to be from the pickup process of $\langle f^D|V^D_{aC}|i^D\rangle$ in (1). In the reaction

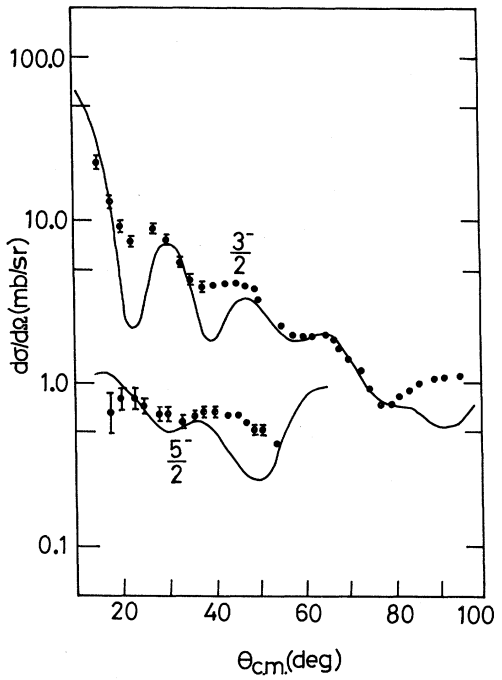

FIG. 1. Angular distributions for the reactions $^{12}\text{C}(^3\text{He},\alpha)^{11}\text{C}$ (ground state; $\frac{3}{2}^-$) and $^{12}\text{C}(^3\text{He},\alpha)^{11}\text{C}$ (second excited state; $\frac{5}{2}^-$) at $E(^3\text{He})=34.7$ MeV (Ref. 3). The curves for the $\frac{3}{2}^-$ and $\frac{5}{2}^-$ states of ^{11}C are results of the calculated cross sections for M^D+M^E and M^E, respectively.

$^{12}C(^3He, \alpha)^{11}C(second; \frac{5}{2}^-)$, the cross sections for (2) are calculated with the optical potential parameter set 2 and with a normalization factor 3.3. The heavy-particle stripping process of $\langle f^E | V^E_{\alpha C} | i^E \rangle$ in (2) is the dominant term in M^E.

In conclusion, both of the differential cross sections are in good agreement with the experimental data without any two-step process, if the cluster structure of ^{11}C and ^{12}C is correctly taken into account. The recently reported results of two-step zero-range DWBA analyses without exchange process for reactions leading to the forbidden transitions at the incident energies of 100–140 MeV (Ref. 6) and 11 MeV (Ref. 5) suggest that another reaction model is further required in understanding the reaction mechanism. This gives support to our present model. A one-step finite-range DWBA analysis, making use of our nucleon-cluster spectroscopic amplitudes, seems to be a useful tool to investigate many-nucleon cluster transfer reactions. It would be very interesting to make further studies of such j forbidden reaction as $^{12}C(p,d)^{11}C(\frac{5}{2}^-, 4.31$ MeV) and $^{12}C(t, \alpha)^{11}B(\frac{5}{2}^-, 4.46$ MeV) by our method. Experimental data at backward angles and intermediate incident energies are desirable, because the theoretical cross sections for the exchange process are predicted to have backward peaks.

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