Spectroscopic tool for proton-rich nuclei: The (^{3}He,^{6}He) reaction

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The angular distributions have been measured for the three-neutron pickup reaction (^{3}He, ^{6}He) at 74 MeV. The angular distributions measured show a clear dependence on the transferred angular momentum. This feature allows spin-parity assignments, suggesting this reaction to be a useful tool for studying proton-rich nuclei.

Nuclear physics has been expanding toward the proton and neutron drip lines in the *N*-*Z* plane. This has been opened up by intermediate- and high-energy heavy-ion works by using fragmentation products. However, the nuclei near the proton drip line could also be reached by multinucleon transfer reactions[1–3] in light-mass region. A few-neutron deficient nuclei can be reached by two-body reactions, and the nuclear level properties can be studied. These experiments also give high-precision determination of the masses. If the reactions are direct-like reaction processes, the angular distributions at forward angles often have a characteristic feature of transferred angular momentum (l) dependence, or even transferred total angular momentum (j) dependence. This feature is very useful in determining the spin parities of the residual states. However, there is an experimental difficulty that the cross sections generally decrease as one increases the number of nucleons transferred, something like 2 orders of magnitude for one additional nucleon. Two-neutron pickup reactions have often been used, but there are not so many experiments reported which used three-neutron pickup reactions. The (^{3}He, ^{6}He) reactions[1,2] have been used for determining the masses and locating the nuclear levels in some light nuclei. The four-neutron transfer reactions (^{4}He, ^{8}He) were used mostly for determining the masses of the residual nuclei.[3] For the three-neutron transfer reactions there was no angular distribution measurement reported before, to our knowledge, except for the work of Ref. 2, where a limited angular range was measured only for two states in the ^{13}C(^{3}He, ^{6}He) reaction, which were insufficient to discuss a general trend of the three-neutron transfer reaction. We have studied the (^{3}He, ^{6}He) reaction for many states with better statistics if it is useful for spectroscopy to derive the spin-parity informations for the residual states. This experiment, as was demonstrated by charge-exchange reactions,[4,5] will lead to the study of proton-rich nuclei of a relatively wide region, and also provide important information for nuclear astrophysical problems, e.g., stellar reaction rates in explosive hydrogen burning processes since they often involve unknown proton-rich nuclei.[4–6]

We report here the angular distribution measurement of the ^{24}Mg(^{3}He, ^{6}He)^{21}Mg reaction and an observation of a clear l dependence, which are very useful for assigning the spin parity of the residual states. A part of this experiment is published elsewhere.[6]

A 73.71-MeV ^{3}He beam of 0.5–1.0 μA was obtained from the sector-focusing cyclotron of the Institute for Nuclear Study, University of Tokyo. The reaction products ^{6}He were momentum analyzed by a QDD-type high-resolution magnetic spectrograph[7] and detected by a position-sensitive gas proportional counter[8] on the focal plane, which is backed up by a thin plastic scintillator for energy and time-of-flight measurement. The solid angle was set to 5.0 msr. The vertical position was also measured on the focal plane to reduce the background. The particle identification was made by using the energy signal, two energy loss signals, and the time of flight. Pileup rejection was also applied to reduce the background due to high-counting α particles. Since the cross sections are very small, it is crucial to get a high signal-to-noise ratio. The background level was reduced to about 1–2 nb/sr channel by setting carefully the gates for all these signals. The details of the experimental setup will be found elsewhere.[6]

The angular distributions of the (^{3}He, ^{6}He) reaction on ^{24}Mg have been measured for 13 levels in ^{21}Mg. Figures 1 and 2 show the angular distributions obtained for relatively strong transitions. The former shows angular distributions of different shapes, and the latter of the same shapes. The differential cross sections observed are generally small. For instance, the cross sections for the 0.208- and 3.347-MeV states are in the range of a few tens nb/sr. Nevertheless, the relatively strong transitions among them show characteristic features at forward angles as can be seen in the figures. The angular distribution measured for the 1.089-MeV state has a dip around 16°. This feature is also seen in all transitions in Fig. 2. The angular distribution for the 0.208-MeV state oscillates fast and has increasing cross sections at very forward angles, whereas the transition to the 3.347-MeV state shows a very dull peak at around 14°, and slightly decreasing cross sections as one goes to forward angles. However, the ground-state transition, which should have $l=2$ because of the known spin parity of the ground state ($J^{\pi}=5/2^{+}$) in ^{21}Mg, is much less oscillatory, and the cross sections are gradually increasing at forward angles. The important fact of the experimental result is that all these angular distributions in the figures show distinct behaviors at forward angles, which are similar to the general feature of the transferred angular momentum (l) dependence in direct multinucleon transfer reactions.[9]

To study these characteristic behaviors at forward angles, exact finite-range distorted-wave Born approximation (DWBA) calculations have been performed using the code TWOFNR.[10] The selection rule of the (^{3}He, ^{6}He) reaction is simple if a target of 0^+ is used. Because of the spin parities of the target and ejectile (both have 0^+), the transitions have a single value for the transferred angular momentum (l) and two possible values for the transferred total angular momentum $j=l\pm\frac{1}{2}$. The transitions should satisfy the energy conservation law, $\sum(2n_i+l_i)=2N+L+2\nu+\lambda$, where n_i, l_i are the node and the angular momentum of each constituent nucleon in the shell model, N, L are those of the $3n$ cluster relative to the core, and ν, λ are those of the internal motion in the $3n$ cluster. The $3n$ cluster transferred in ^{6}He should have $\lambda=1$ ($\nu=0$) as an internal motion (not relative to ^{3}He). Thus, for example, in the ^{24}Mg(^{3}He,^{6}He) reaction to the low-lying states $N=2$ and $L=1$ should be used for the target system in the $l=0$ transition of the cluster, and $N=1$ ($L=3$) and $N=2$ ($L=1$) in $l=2$, etc. The calculations with these different spin couplings for the bound states of the $3n$ cluster do not change the basic oscillation phases in the angular distribution shapes, which are predominantly determined by the l value. The optical potential parameters were obtained from Ref. 11 for ^{3}He and from those of ^{6}Li in Ref. 12 for ^{6}He, which are summarized in Table I. The calculated trend including the oscillation

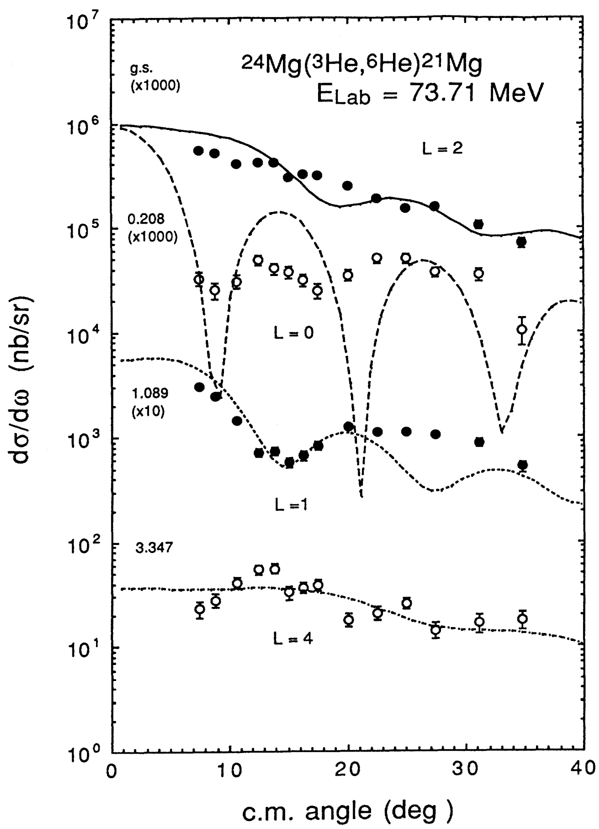

FIG. 1. Typical angular distributions of the ^{24}Mg(^{3}He, ^{6}He)^{21}Mg reactions for the states denoted. The lines are the result of the exact finite-range DWBA calculations for the transferred angular momenta indicated, where the relative motions of the $3n$ cluster in ^{24}Mg were taken as $(N,L)=(1,3)$, (2,1), (1,2), and (0,5) for $L=2$, 0, 1, and 4 transitions, respectively.

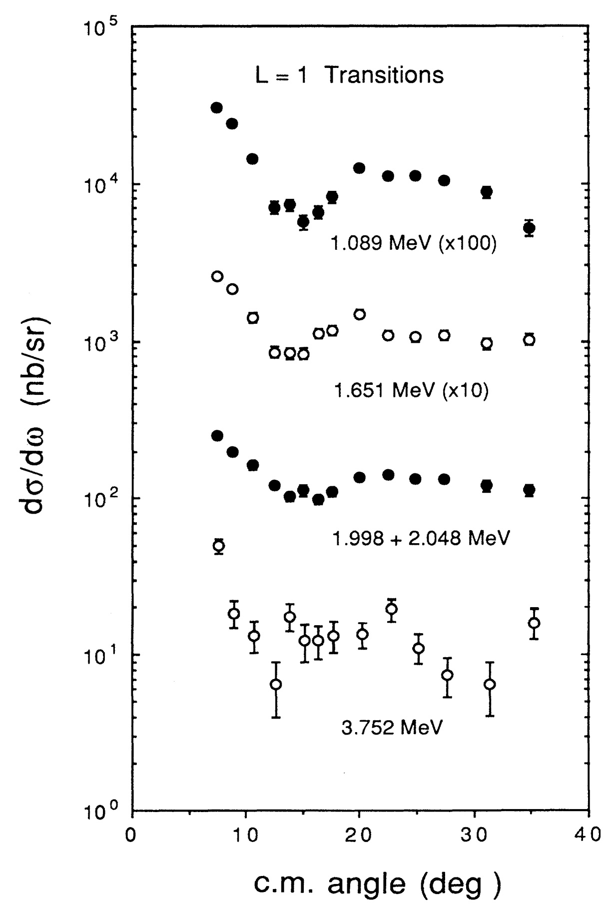

FIG. 2. Angular distributions of $l=1$ transitions.

TABLE I. Optical potential parameters.

Set	V	r_r	a_r	W	r_i	a_i	r_c
$^3He+^{24}Mg$	160	1.633	0.375	35	1.015	1.767	1.3
$^6He+^{21}Mg$	64.7	1.25	0.717	13	1.25	0.80	1.3
Bound state	a	1.25	0.65				1.25

[a]The depth was adjusted to reproduce the binding energy.

phases are rather insensitive to the choice of these parameters.

The calculated angular distributions are also shown in Fig. 1. The calculations show little change for different total angular momentum transfers $j=l\pm\frac{1}{2}$ with the same l, indicating a characteristic feature of l, where the parity is given by $(-1)^l$. The general shapes of the angular distributions at forward angles are reasonably well reproduced by the calculations with the l values indicated in Fig. 1 except for the $l=2$ transition, where the oscillation amplitudes are much smaller in the data. In the present calculations, the best fit was not searched for by modifying the optical potential parameters nor binding potential parameters, but simply the general features such as the peak and valley angles should be compared in the angular distributions.

Although the general features are explained by direct DWBA calculations, the reaction mechanism cannot be concluded yet. There should be a complication due to multistep processes, since the cross sections are small. The present success of the DWBA calculations to reproduce the overall experimental trend could be similar to the (^{3}He,t) reaction at 55 MeV,[4,5] where the angular distribution shapes are well characterized by the transferred angular momentum associated in direct DWBA calculations, although considerable two-step process contributions are expected. A similar feature is also known in the two-nucleon transfer reactions like (p,t) and (^{18}O, ^{16}O) reactions. This should be studied carefully with using coupled-channel analysis.

Here, we avoided to discuss the absolute cross sections, to which we need microscopic form factors together with coupled-channel calculations. Such analysis needs elaborate works, but will be fruitful in obtaining further spectroscopic information for the residual states. It should also be noted that for assigning the spins ($j=l+\frac{1}{2}$ or $j=l-\frac{1}{2}$), one needs of course to consult with the known levels of the mirror nucleus, i.e., ^{21}F for ^{21}Mg, or one has to reserve the ambiguity for $j=l\pm\frac{1}{2}$. However, in practice, the present l assignment by comparing the shapes with experimental angular distributions of strong transitions as well as the direct DWBA calculations is very useful for studying the nuclear property of unknown states. Of course, spin-parity assignment becomes difficult for weak transitions, because the shapes of the angular distributions are not defined well by the statistics of the measurement as well as the complication of the reaction mechanism.

In summary, the (^{3}He, ^{6}He) reaction has been investigated at 74 MeV. This reaction has been shown to have a clear l dependence, indicating this reaction to be a useful tool for the nuclear spectroscopy of the proton-rich nuclei. Detailed analysis of the reaction will be useful to deduce further spectroscopic information.

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