Bull. Inst. Chem. Res., Kyoto Univ., Vol. 59, No. 1, 1981

Excited States of ^{4}He Investigated via the ^{4}He(α, αp)^{3}H Reaction at 119 MeV

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Received December 4, 1980

Kinematically complete experiments were made for the ^{4}He(α, αp)^{3}H reaction at 119 MeV. Angular correlations were fitted with the Legendre polynomials and the cross sections integrated over the dacay angle were obtained as a function of the excitation energy. Peaks were observed at the excitation energies of 25.5, 27.5, 28.6, 29.5, 31.3 and 34.2 MeV. The results for the first five peaks seem to confirm the previous results for the ^{4}He(α, αd)^{2}H reaction.

KEY WORDS: ^{4}He(α, αp)/ ^{4}He excited states/ Angular correlations/

1. INTRODUCTION

Excited states of ^{4}He have been observed in the ^{4}He(α, α')^{4}He* and ^{4}He(α, αd)^{2}H reactions at 119 MeV.[1] In single energy spectra of α-particles are observed broad bumps extending from 25 MeV to 40 MeV of excitation energy and in α-d coincidence spectra are observed peaks at the excitation energies as E_{ex}=25.5, 27.8, 29.7, 31.7 and 35.3 MeV. For the last three states, the spins and parities are assigned as $J=2^+, 2^+(1^-)$ and 2^+, respectively. The results previously reported for the $T=0$ states above the d+d threshold are as follows; the 25.5–MeV (0^+, 1^-), 28.5–MeV 1^- and 31.7–MeV states by Haase *et al.*[2] and the 25.5–MeV 0^+ and 27.5–MeV 1^- states by Fukunaga *et al.*[3] The 31–MeV 1^- and 33–MeV 2^+ states also have been reported.[4] There are some discrepancies in the excitation energy and the spin and parity of these results. Then it is worthwhile to further investigate the $T=0$ states of ^{4}He through the p+t decay channel in addition to the d+d decay channel.

In the present experiment, $T=0$ states were selectively excited in the ^{4}He(α, α') ^{4}He* inelastic sacttering at 119 MeV and the scattered α-particles were measured in coincidence with the protons decaying from the excited states.

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2. EXPERIMENTAL PROCEDURE

By a 119 MeV α-particle beam of the AVF cyclotron at the Research Center for Nuclear Physics (RCNP) of Osaka University was bombarded a target of ^{4}He gas at pressure of 2 atm filled in a gas cell with windows of 10 μm Havar foil.

Alpha-particles and protons from the reactions were detected in coincidence by two ΔE-E telescopes. For each coincidence event, parameters ΔE_α, E_α, ΔE_p, E_p and $T_{\alpha p}$ (TAC) were obtained through an ordinary electronic system and were stored on a magnetic tape through the RCNP RAWDATA PROCESSOR-PDP 11 system. The arrangement of detectors and the block diagram of the electronic system are described in Ref. 1. Off-line analyses of the parameters were performed with the FACOM M-160AD system at the institute for Chemical Research of Kyoto University. The analyses comprised random coincidence subtraction, particle identification and reduction of two-dimentional E_α-E_p spectra.

3. RESULTS AND DISCUSSIONS

In the E_α-E_p spectra, yields were localized along the kinematical locus of three-body process. The yields were projected onto the E_α-axis. Figure 1 shows the energy spectra for the ^{4}He(α, αp)^{3}H reaction measured at four angle pairs of (θ_α, θ_p)=(25°, 35°), (25°, 45°), (25°, 55°) and (25°, 65°) in the laboratory system. Each point was obtained by smoothing counts over adjacent channels considering the energy resolution of about 1.4 MeV corresponded to about two channels. Error bars represent statistical uncertainty. The edges appearing at the highest energies

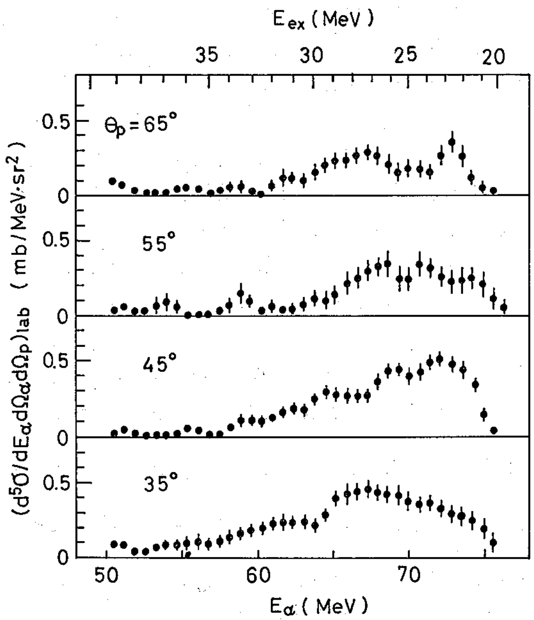

Fig. 1. Coincidence energy spectra for the ^{4}He(α, αp)^{3}H reaction. The α-particle angle was fixed at θ_α=25° and the proton angle was varied as θ_p=35°, 45°, 55° and 65° in the laboratory system.

of α-particles are due to the kinematical limit. Near the edges, part of yields were lost because, there, the energy of protons coincident with α-particles became lower than the minimum value for the detected proton energy. Accordingly angular correlations were measured for the excitation energies above 23 MeV.

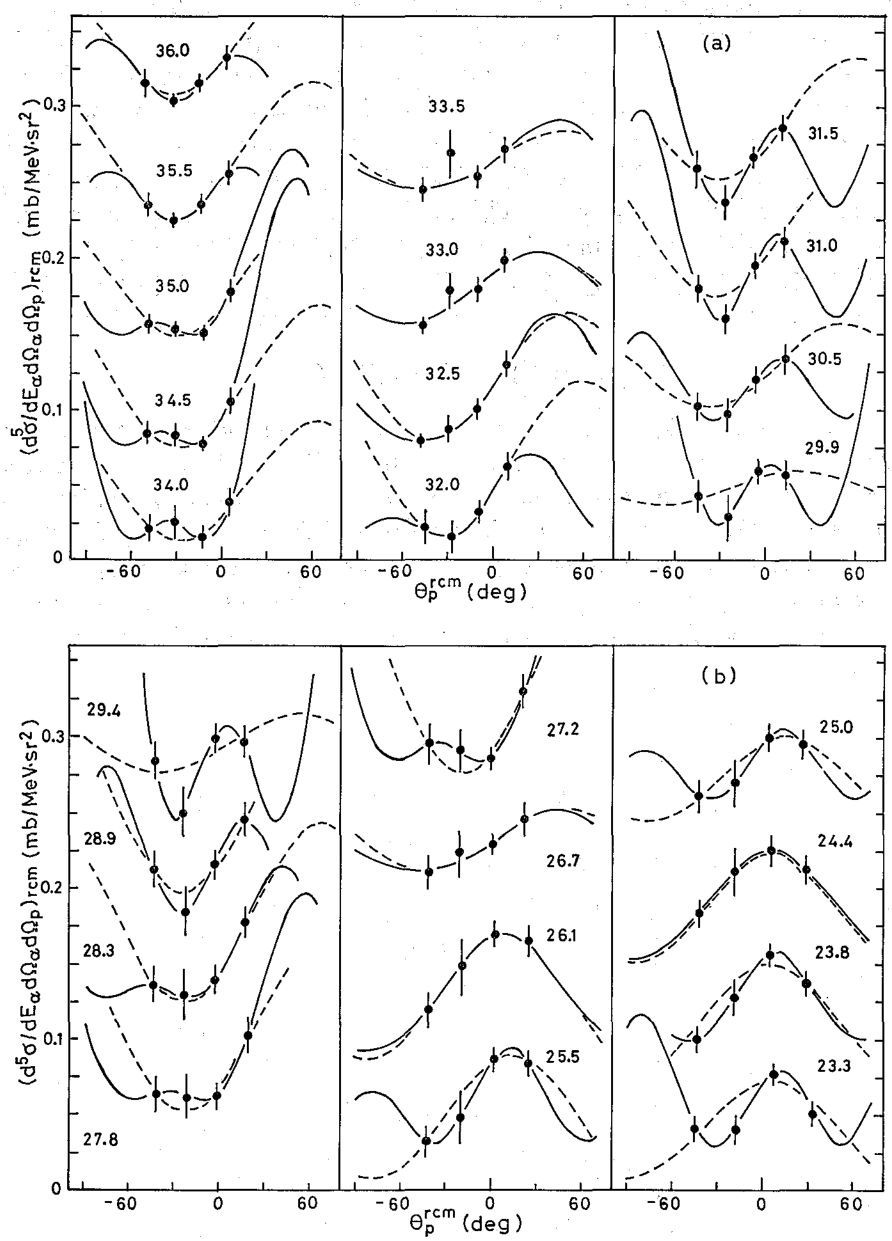

Fig. 2. Angular correlations for the ^{4}He(α, α')^{4}He*(p)^{3}H reaction at $\theta_\alpha=25°$. Full circles represent experimental points and full lines the Legendre polynomials fit with $k_{max}=4$ and dashed lines the one with $k_{max}=2$. The angular correlations are designated with the corresponding excitation energies for ^{4}He* and are shown by shifted upward successively by a factor 0.075.

As seen in Fig. 1, in the energy spectra are observed no sharp peaks but broad bumps extending up to about 35 MeV of the excitation energy and at higher excitations the cross sections decrease to nearly zero. Then angular correlations are analysed for each excitation energy. The differential cross sections in the laboratory system $(d^5\sigma/dE_\alpha d\Omega_\alpha d\Omega_p)_{lab}$ are transformed to the ones in the $^4He^*$ recoil center-of-mass system $(d^5\sigma/dE_\alpha d\Omega_\alpha d\Omega_p)_{rcm}$. In Fig. 2 they are plotted with full circles as a function of the proton decay angle θ_p^{rcm}, where the direction $\theta_p^{rcm}=0°$ is defined as the direction of the recoil momentum of $^4He^*$ in the laboratory system.

The scattering angle of α-particles in the center-of-mass system varies from $\theta_\alpha^*=58.1°$ for $E_{ex}=23.3$ MeV to $\theta_\alpha^*=67.7°$ for $E_{ex}=36.0$ MeV corresponding to the angle in the laboratory system $\theta_\alpha^{lab}=25°$. The angular range for protons in the recoil center-of-mass system varies from $-43.7°<\theta_p^{rcm}<32.7°$ for $E_{ex}=23.3$ MeV to $-49.5°<\theta_p^{rcm}<3.0°$ for $E_{ex}=36.0$ MeV corresponding to $25°<\theta_p^{lab}<65°$.

The angular correlations are fitted with the Legendre polynomials as

$$(d^5\sigma)_{rcm} = \sum_k A_k P_k(\cos(\theta_p^{rcm}-\theta_0^{rcm})) ,$$

where the summation is taken over even values of k and the symmetry angle θ_0^{rcm} is searched for as well. The purposes of the fit are (1) to obtain the cross section integrated over the decay angle, which is equal to the coefficient A_0 multiplied by a factor 4π and (2) to obtain the maximum value of k characterizing the shape of angular correlation. The fits were performed for only two cases $k_{max}=2$ and 4. This seems to be reasonable because the excitation energies are not far from the p+t threshold and then the lowest two or three values of the decay angular mo-

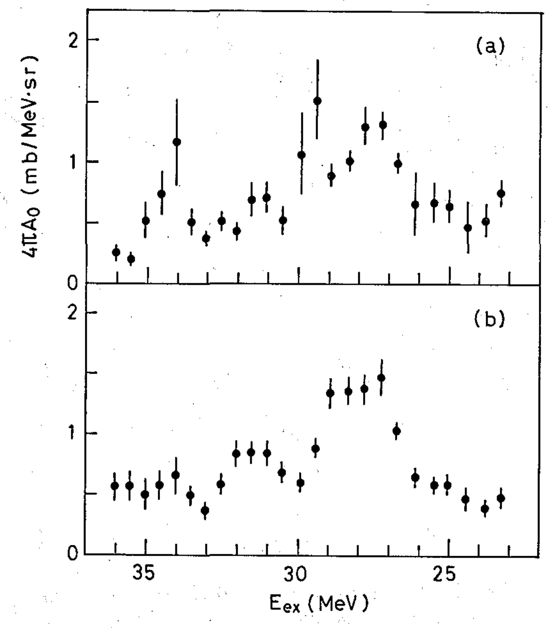

Fig. 3. Coefficients A_0 of the Legendre polynomials, multiplied by a factor 4π. The upper part (a) corresponds to the fit with $k_{max}=4$ and lower part (b) to the fit with $k_{max}=2$.

Table I. Excitation energies of ^{4}He*, values of k_{max} obtained in the Legendre polynomials fit for the angular correlations and spins and parities assigned previously.

Present Result ^{4}He(α, αp)^{3}H		Previous Result[1)] ^{4}He(α, αd)^{2}H	
E_{ex}(MeV)	k_{max}	E_{ex}(MeV)	J^{π}
25.5		25.5	
27.5	4 or 2	27.8	
28.6	2		
29.5	4	29.7	2^+
31.3	4 or 2	31.7	2^+ or 1^-
34.2	4		
		35.3	2^+

mentum l can contribute to the reaction.

The results of the fits are shown in Figs. 2 and 3, and Table I. In Fig. 2 the curves fitted with $k_{max}=4$ are represented by the solid lines and the curves fitted with $k_{max}=2$ by the dashed lines. These two groups of the fitted curves give similar goodness of fit for most of the excitation energies, except that for $E_{ex}=23.3$, 29.4 and 29.9 MeV, the curves fitted with $k_{max}=4$ are favored compared with the ones fitted with $k_{max}=2$. In Fig. 3 are plotted the coefficient A_0 multiplied by a factor 4π against the excitation energy. The upper part (a) of the figure corresponds to the fit with $k_{max}=4$ and the lower part (b) to the one with $k_{max}=2$. It should be noted that there remains an ambiguity in the analysis of the angular correlations owing to the measured angular ranges smaller than 90°, as mentioned above. In fact, for each angular correlation are obtained two solutions which give the same distributions with the symmetry angles shifted by 90° from each other and also with the different coefficients A_0. The points in Fig. 3 are obtained by averaging these two values of the coefficient. In Fig. 3(a) are observed peaks at $E_{ex}=25.5$, 27.5, 29.5, 31.3 and 34.2 MeV and in Fig. 3(b) two bumps in the energy ranges from 27 MeV to 29 MeV and from 31 MeV to 32 MeV. The high energy part of the first bump in Fig. 3(b) corresponds to the peak at $E_{ex}=27.5$ MeV in Fig. 3(a) and the low energy part, its center being at $E_{ex}=28.6$ MeV, to a minimum in Fig. 3(a). The second bump in Fig. 3(b) corresponds to the peak at $E_{ex}=31.3$ MeV in Fig. 3(a). Uncertainty in the assignment of the peak position is of ± 0.3 MeV. The excitation energies corresponding to the observed peaks and bumps are listed in Table I together with the values of k_{max} obtained in the Legendre polynomials fit. Among the listed excitation energies, four values, that is, $E_{ex}=25.5$, 27.5, 29.5 and 31.3 MeV agree with the corresponding values previously reported within the uncertainty.

The peak at $E_{ex}=29.5$ MeV in Fig. 3(a) nearly corresponds to a minimum between two bumps in Fig. 3(b) and two angulr correlations near $E_{ex}=29.5$ MeV are fitted uniquely with $k_{max}=4$, the fit with $k_{max}=2$ giving a poor goodness of fit, as seen in Fig. 2. Therefore, the present experiment confirms the 29.7-MeV 2^+ state observed in the ^{4}He(α, αd)^{2}H reaction. For the peak at $E_{ex}=31.3$ MeV in Fig. 3(a), the corresponding bump is observed in Fig. 3(b) and the angular correlations near $E_{ex}=31.3$ MeV are well fitted with both $k_{max}=4$ and 2. Then for the 31.7–MeV 2^+ or 1^- state observed in the $^4He(\alpha, \alpha d)^2H$ reaction, the spin remains not decided between the two alternatives also in the present experiment. The peak at $E_{ex}=34.2$ MeV in Fig. 3(a) is thought not to correspond to the 35.3–MeV 2^+ state previously reported, because a difference in excitation energy of about 1 MeV is out of the uncertainty. Moreover, no peak is observed at the corresponding energy in Fig. 3(b), though the angular correlations near $E_{ex}=34.2$ MeV are fitted with both $k_{max}=4$ and 2. Then it seems improbable to conclude the peak at $E_{ex}=34.2$ MeV from the present data. On the other hand, there is no indication of the 35.3–MeV 2^+ state.

The peak at $E_{ex}=27.5$ MeV ($k_{max}=4$ or 2) can correspond to the 27.5–MeV 1^- state reported by Fukunaga *et al.*[3] if $k_{max}=2$ is taken. The bump at $E_{ex}=28.6$ MeV ($k_{max}=2$) observed in Fig. 3(b) seems to correspond to the 28.5–MeV 1^- state reported by Haase *et al.*[2] The 25.5–MeV state is weakly excited in the $^4He(\alpha, \alpha p)^3H$ reaction at 119 MeV.

ACKNOWLEDGMENTS

The authors would like to express their thanks to Professor H. Ogata for the valuable suggestions and discussions for the methods of data taking. The authors also thank the staff and the cyclotron crew of the Research Center for Nuclear Physics of Osaka University for their kind help during the experiments. Off-line data analyses were made with the FACOM M-160AD system at the Institute for Chemical Research of Kyoto University.

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