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Intermediate structures in $^{12}C + ^{16}O$ system through alpha-induced reactions on ^{24}Mg

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Intermediate resonance have been studied in the $^{24}Mg(\alpha, {}^{12}C)\,{}^{16}O$ and $^{24}Mg(\alpha,\alpha')^{24}Mg$ reactions. The excitation functions were measured in the energy range between 22 and 26 MeV. Significant anomalies have been found at $E_{c.m.}$ (in $^{12}C + ^{16}O$ system) = 12.73, 13.7, 14.0, 14.35, and 14.76 MeV. Angular distributions of ^{12}C nuceli have been measured at these energies. The spins and parities of these intermediate resonance states are assigned as 7^-, 8^+, $9^-(8^+)$, 9^-, and 9^-, respectively. Angular distributions of the elastic and inelastic scattering have been measured at these energies.

[NUCLEAR REACTIONS $^{24}Mg(\alpha, {}^{12}C)$, $^{24}Mg(\alpha,\alpha')$, $22 \leq E_\alpha \leq 26$ MeV; measured $\sigma(E_\alpha)\theta_{lab} = 7°, 16°$, $E_\alpha = 22.77, 24.25, 24.65, 24.86, 25.13, 25.38$ MeV; measured $\sigma(\theta)$ deduced J^π, enriched target.]

I. INTRODUCTION

The intermediate structure in the $^{12}C + ^{16}O$ system has been extensively studied in recent years.[1,2] Significant anomalies have been found in the excitation functions for elastic and inelastic scattering and for various reaction channels.[3-9] The appearance of these structures is interpreted as coming from a nonstatistical origin.

There are several approaches to explain these anomalies. The existence of a broad rotational band has been predicted by Arima, Scharff-Goldhaber, and McVoy[10] from the analysis of the optical potential. The narrow widths of the excitation function anomalies, however, cannot be reproduced by the shape resonance theory alone. A double resonance mechanism has been postulated, wherein one of the nuclei in the entrance channel becomes excited and quasibound states occur in the optical potential corresponding to the interaction between the excited nucleus and the ground state nucleus.[11-13] Alternatively, an α-particle model is proposed by other authors.[14,15] The common feature in these theoretical descriptions is that broad entrance channel resonances couple to other intermediate degrees of freedom and cause the correlated structures.[16] Recently Baye and Heenen proposed a description of these structures based on a microscopic calculation.[17]

Based on the experimental data available, band structures have been proposed.[6,18,19] In many cases, however, the spins of the anomalies have not been firmly established. The investigation of these structures has been performed, so far, mostly by means of heavy ion induced reactions.

To understand these resonances, in particular to determine their J^π values, we have performed an experiment using the $^{24}Mg(\alpha, {}^{12}C)^{16}O$ reaction which produces the intermediate states of the same excitation energies as those reached by the heavy ion induced reaction. Angular distributions of the ^{12}C nuclei emitted from these states were measured. This method has the advantages that the contribution from the direct reaction is almost negligible compared with the case of the elastic scattering in the $^{12}C + ^{16}O$ system and that it is more reliable to determine the spin of the resonance states from the angular distributions.[20]

On the other hand, there are also theoretical models in which the low-lying states of ^{24}Mg nucleus are explained by a $^{16}O + 2\,\alpha$ cluster[21] and the low-lying states of ^{12}C nucleus are described by the 3 α cluster.[22] In order to study the correlation between heavy ions and α particles, the outgoing inelastic α channels were simultaneously measured. In this way the possibility arises of seeing to what extent the α particles couple to the quasimolecular states.

II. EXPERIMENTAL PROCEDURE

Excitation functions for the reactions of ^{24}Mg(α, ^{12}C)^{16}O and ^{24}Mg(α, α')^{24}Mg have been measured in the energy range of $E_\alpha = 22-26$ MeV using the analyzed beams from the Institute for Nuclear Study (INS) sector-focusing (SF) cyclotron and the Institute of Physical and Chemical Research (IPCR) cyclotron. Above 24 MeV incident energy the former accelerator was used. The data were generally taken in incident energy steps of 100 keV and sometimes in finer steps. The uncertainty of the incident energies of the α beam was approximately 20 kev.[23] At several energies angular distributions of ^{12}C and α particles were measured.

For forward angle detection of the ^{12}C nuclei, the energies of which ranged from 18 to 7 MeV in the laboratory system, a counter telescope composed of 6.8 and 30 μm silicon detectors backed by a rejection counter for light particles was used. A serious experimental problem is the distinction of the true events from the C recoil which is induced by the scattering from the small amount of built-up carbon contaminant on the target. A recoil counter with large solid angle was placed to catch elastically and inelastically backed-scattered α particles so that the associated C recoil could be dropped off with a fast-slow anticoincidence system. Mixing of the contaminant into the true events arising from the broadening of the emitting cone of recoil carbon by multiple scattering was checked by an independent measurement using a carbon target. By taking a large solid angle ratio (about 1500 : 1) for the recoil counter to the forward counter, where the solid angle of the latter is about 0.05 msr, the mixing of the above events was suppressed to a negligible level.

The second counter, 15 or 20 μm thick, backed by a veto counter, was placed 30° in back of the forward counter. Due to the kinematics, with this counter, there was no need for particle identification.

Targets were self-supporting enriched ^{24}Mg foil and had a thickness of 100–300 μg/cm^2 which was determined by the Coulomb scattering of 2.5 MeV protons from the tandem accelerator in the Research Centre for Nuclear Science and Technology at the University of Tokyo. In the measurement of the angular distribution, a monitor counter at fixed angle was used for normalization.

In the measurements at INS, several counters were used for simultaneous measurements of the excitation functions for elastic and inelastic α-particle scattering from ^{24}Mg at the backward anles. The scattering chamber had a rotatable upper lid[24] to which these counters were attached, and angular distributions for ^{24}Mg(α, α)^{24}Mg were measured simultaneously with those of ^{24}Mg(α, ^{12}C)^{16}O reaction. When taking this data, the total width of the beam spread was about 40 keV at the maximum.

III. RESULTS

A. Excitation functions for ^{24}Mg(α, ^{12}C)^{16}O and ^{24}Mg(α, α')^{24}Mg reactions

In Fig. 1 the excitation functions for the ^{24}Mg(α, ^{12}C)^{16}O reaction at the laboratory angle of 7° and partly at 16° are shown. The angle of 7° corresponds to the backward angle ($\theta_{c.m.} = 170°$) in the inverse reaction ^{12}C(^{16}O, α)^{24}Mg and was chosen for the large cross section coming from the resonance contribution.

Several structures can be seen in this figure. At $E_\alpha = 22.77$ MeV, corresponding to $E_{c.m.} = 12.73$ MeV (hereafter, $E_{c.m.}$ means the center-of-mass energy in the ^{12}C + ^{16}O system), a large enhancement appears. There are prominent peaks at the $E_\alpha = 22.77$ MeV. 23.90, 24.25, and 25.13 MeV at the $\theta_L = 7°$ and their cross sections seem to be gradually decreasing with E_α. Though at $\theta_L = 7°$ a relatively small structure can be seen, at $\theta_L = 16°$ a prominent peak appears at $E_\alpha = 24.65$ MeV. In general, at a certain angle, it cannot be decided by the excitation function only whether the structures arise from the resonances or fluctuations. However, the results of the Hauser-Feshbach calculations, the details of which will be described in the next section, are shown in the figure, and a comparison of the experimental data with this calculation suggests that the above structures are candidates of the resonances.

Alternatively, one can adopt the correlations in different channels. The excitation functions for ^{24}Mg(α, α')^{24}Mg reactions together with the ^{24}Mg(α, ^{12}C) reaction are shown in Fig. 2. The

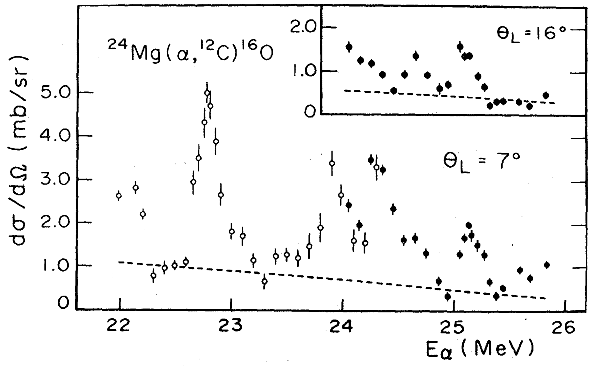

FIG. 1. Experimental excitation function for the reaction ^{24}Mg(α, ^{12}C)^{16}O. Open circles are data obtained at IPCR and solid dots are those obtained at INS. Dotted curve is Hauser-Feshbach calculation using the parameters of Table II.

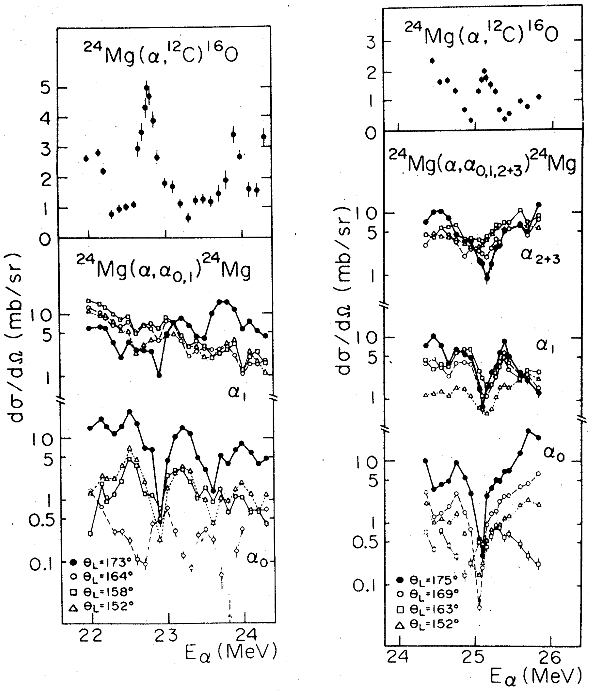

FIG. 2. Experimental excitation functions for elastic and inelastic scattering of α particles from ^{24}Mg at several backward angles. Lines are drawn only to guide the eye.

measurements at the backward angles in these scatterings are expected to reflect the compound nucleus formation process or resonance contribution. Strong correlations appear between the excitation functions of $^{24}Mg(\alpha, ^{12}C)^{16}O$ and $^{24}Mg(\alpha, \alpha')^{24}Mg$ reactions. In particular, around $E_\alpha = 25.1$ MeV yields of the elastic and inelastic scatterings show sharp dips. Around $E_\alpha = 22.9$ MeV also, the elastic scatterings reduce large magnitude though the inelastic scattering has a smaller structure. These dips appear to occur at nearly the same energies as the enhancements of the outgoing heavy ion channel.

B. Angular distributions

Considering the above results, angular distributions were measured in the $^{24}Mg(\alpha, ^{12}C)^{16}O$ channel at the following energies at the anomalous peaks: at $E_\alpha = 22.77$, 24.25, 24.65, and 25.13 MeV.

Around the $E_\alpha = 25.13$ MeV, we measured in addition, the angular distributions at the neighboring off-resonance energies, both in $^{24}Mg(\alpha, ^{12}C)^{16}O$ and $^{24}Mg(\alpha, \alpha_0)^{24}Mg$ reactions. Concerning the peak at $E_\alpha = 23.90$ MeV which corresponds to the $E_{c.m.} = 13.7$ MeV, the anomaly was already investigated by the members of our group in the $^{12}C + ^{16}O$ incident reactions and the results are published else-

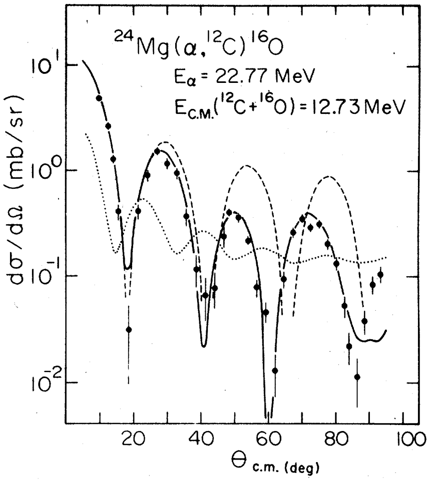

FIG. 3. Angular distribution for $^{24}Mg(\alpha, ^{12}C)^{16}O$ at $E_\alpha = 22.77$ MeV. Solid curve is Legendre polynomial expansion fit (obtained coefficients are given in Table I), dashed curve is square of the Legendre polynomial of order 7 and dotted curve is Hauser-Feshbach calculation.

where.[25] Obtained angular distributions are shown in Figs. 3–7.

IV. SPIN ASSIGNMENTS AND DISCUSSIONS

A. Method of analysis

In case there exists a single resonance with a definite spin, the reaction cross sections in the angular distribution should exhibit the pattern of the squares of a single Legendre polynomial. In general, background nonresonant amplitude makes the appearance of the structure more complicated.

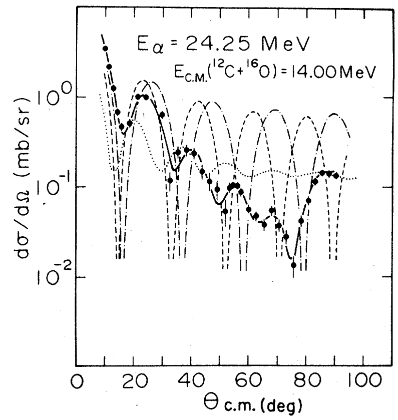

FIG. 4. Angular distribution for $^{24}Mg(\alpha, ^{12}C)^{16}O$ at $E_\alpha = 24.25$ MeV. Solid curve is Legendre polynomial expansion fit, dashed curve is square of the Legendre polynomial of order 9, dot-dashed curve is square of the Legendre polynomial of order 8, and dotted curve is Hauser-Feshbach calculation.

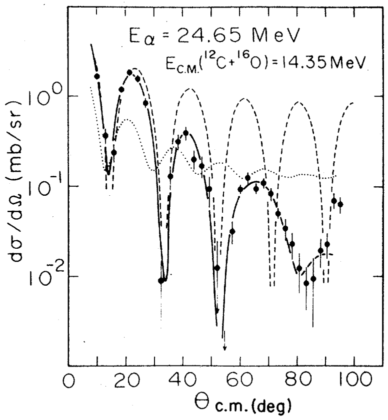

FIG. 5. Angular distribution for ^{24}Mg(α, ^{12}C)^{16}O at E_α = 24.65 MeV. Solid curve is Legendre polynomial expansion fit, dashed curve is square of the Legendre polynomial of order 9, and dotted curve is Hauser-Feshbach calculation.

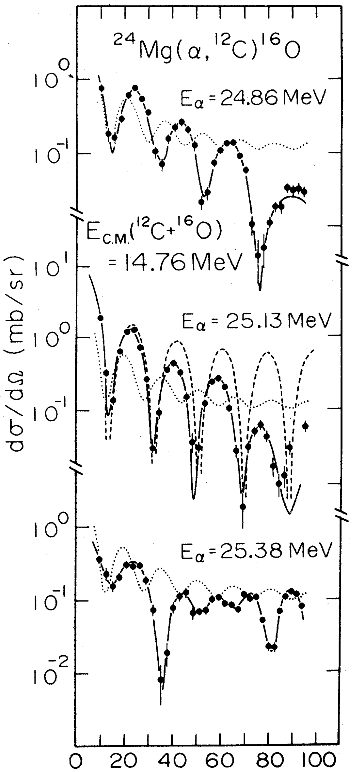

FIG. 6. Angular distributions for ^{24}Mg(α, ^{12}C)^{16}O at E_α = 24.86, 25.13, and 25.38 MeV. Solid curve is Legendre polynomial fits, dashed curve is the square of the Legendre polynomial of order 9, and the dotted curves are Hauser-Feshbach calculations.

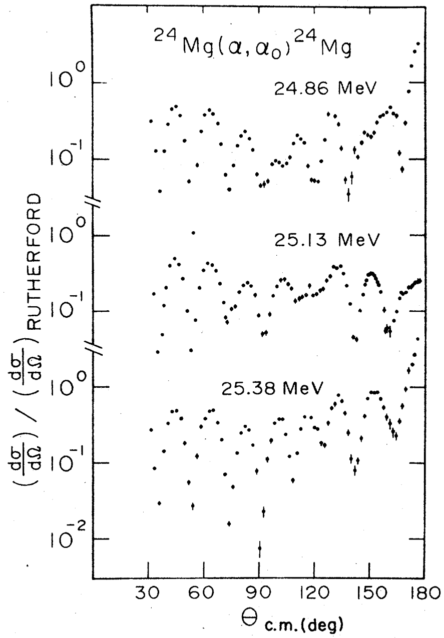

FIG. 7. Experimental angular distributions (ratio to σ_R) for elastic scattering of α particles from ^{24}Mg at E_α = 24.86, 25.13, and 25.38 MeV.

In order to determine the spin of the resonance, the angular distribution is fitted with a Legendre polynomial expansion following the method of analysis in Ref. 26,

$$\frac{d\sigma}{d\Omega}=\sum_{k=0}^{k_{\max}} a_k P_R(\cos\theta)\,, \qquad (1)$$

where the P_k's are Legendre polynomials and the a_k's are all real. The highest order $k_{\max}$ necessary to fit the data corresponds to the smaller of the double of the maximal contributing angular momenta in the entrance and outgoing channels

$$k_{\max} \leq \text{smaller of } (2l_{\text{in, max}}),\,(2l_{\text{out, max}})\,. \qquad (2)$$

The calculated results are listed in Table I and the χ^2 fit curves obtained by Eq. (1) are shown in Figs. 3–7 together with the measured angular distributions.

We made a calculation in terms of Hauser-Feshbach formula,[27] which reflects the energy averaged compound-nucleus cross sections. The cross section for a reaction with spin-zero particles is expressed as follows[28]:

$$\frac{d\sigma}{d\Omega}=\frac{1}{4k^2}\sum_{Jll'cc'} A_{cc'}^{Jll'}\frac{T_c^J \times T_{c'}^J}{\sum_{c''} T_{c''}^J}\,P_L(\cos\theta)\,,$$

where the $A_{cc'}^{Jll'}$ is a geometrical factor of angular momentum coupling, and the T_C^J is the transmission coefficient of channel C for the formation of

TABLE I. A part of coefficients in Legendre polynomial expansion for ^{24}Mg(α, ^{12}C)^{16}O angular distributions.

E_α (MeV)	22.77	24.25	24.65	24.86	25.13	25.38
b_2[a]	2.70	3.34	3.30	2.34	2.93	0.92
b_4	3.14	4.45	3.47	1.40	2.82	0.84
b_6	3.23	4.36	3.08	1.36	3.20	0.43
b_8	2.96	4.83	2.42	0.76	2.91	−0.66
b_{10}	4.43	4.69	2.83	1.08	2.96	−0.81
b_{12}	4.35	5.47	3.17	1.82	3.90	−0.14
b_{14}	5.10	5.47	4.23	2.14	4.19	0.28
b_{16}	3.15	5.39	6.47	4.14	5.05	1.44
b_{18}	···	4.22	6.16	2.82	5.97	−0.33
b_{20}	···	2.62	3.47	···	2.85	−0.60
b_{22}	···	0.92	0.95	···	···	−2.24
χ^2/N	3.7	3.7	1.7	2.3	2.0	2.5

[a] $b_k = a_k/a_0$. a_k is from Eq. (1) in text.

compound nucleus with spin J. The optical potential parameters for each open channel used were from Ref. 29 and the level density parameters were deduced from Ref. 30. Calculated results of the transmission coefficients and the partial wave cross sections in the two representative examples are shown in Table II. (There, only incident and outgoing channels are listed for transmission coefficients. We adopt the following open channels for the calculations, ^{27}Al + p, ^{27}Si + n, ^{26}Al + d, ^{25}Mg + ^{3}He, ^{24}Mg + α, ^{20}Ne + ^{8}Be, ^{12}C + ^{16}O.)

B. Spin assignments

1. $E_\alpha = 22.77$ MeV ($E_{c.m.} = 12.73$ MeV)

The angular distributions are shown in Fig. 3. The χ^2 fit curve including up to order 16 well reproduces the experimental data, and the coefficient of order 14 is the largest among the others. The spin-parity of this resonance is determined to be 7^-. The experimental angular distribution shows the dominance of $l = 7$ at the forward angles and differs from the curve $|P_7(\cos\theta)|^2$ at large angles.

From the Hauser-Feshbach calculations, it can be understood that higher partial waves than $l = 7$ have the possibility of some contributions. The calculated cross section is about 1 mb/sr at $\theta_{c.m.} = 10°$ which is one-fifth of the anomalous peak. This background may be the reason why the experimental angular distribution deviates from $|P_7(\cos\theta)|^2$ at large angles.

Concerning this anomaly, Viggars *et al.*[8] found a deep minimum at $E_{c.m.} = 12.9$ MeV in the excitation function for the ^{12}C(^{16}O, ^{20}Ne)^{8}Be reaction. Taras *et al.*[19] observed an intermediate resonance

TABLE II. Optical model transmission coefficients and the partial wave cross sections in ^{24}Mg(α, ^{12}C)^{16}O reaction by the Hauser-Feshbach calculations.

	$E_\alpha = 22.77$ MeV			$E_\alpha = 25.13$ MeV		
	T_l			T_l		
l	^{24}Mg + α	^{12}C + ^{16}O	σ_l (mb)	^{24}Mg + α	^{12}C + ^{16}O	σ_l (mb)
0	1.000	0.958	0.0199	1.000	0.991	0.0077
1	1.000	0.997	0.0231	1.000	0.988	0.0085
2	1.000	0.958	0.0270	1.000	0.987	0.0101
3	1.000	0.975	0.0368	1.000	0.989	0.0132
4	1.000	0.976	0.0542	1.000	0.972	0.0186
5	0.999	0.904	0.0813	1.000	0.997	0.0298
6	0.999	0.980	0.156	0.999	0.946	0.0478
7	0.997	0.902	0.280	0.997	0.956	0.0897
8	0.987	0.651	0.427	0.995	0.986	0.186
9	0.916	0.602	0.873	0.978	0.796	0.329
10	0.618	0.249	0.647	0.847	0.718	0.635
11	0.212	0.041	0.114	0.444	0.646	0.839
12	0.042	0.011	0.0217	0.109	0.142	0.154

in exit channels of neutron, proton, deuteron, and α particles from the ^{12}C + ^{16}O reaction at $E_{\mathrm{c.m.}} = 12.77$ MeV, and they speculate the spin of the resonance to be 8 from the consideration of semiclassical grazing orbit.

2. $E_\alpha = 23.9$ MeV ($E_{c.m.} = 13.7$ MeV)

The peak at $E_\alpha = 23.9$ MeV corresponds to the $E_{\mathrm{c.m.}} = 13.7$ MeV anomaly which Halbert *et al* attribute to a nonstatistical enhancement in the ^{12}C(^{10}O, α)^{24}Mg reaction.[5] A spin assignment of 9^- was reported with the ^{12}C - ^{16}O elastic scattering.[31] From the ^{12}C(^{16}O, ^{20}Ne)^{8}Be reaction, Brady *et al.*[32] indicate the existence of a broad resonance (centered at $E_{\mathrm{c.m.}} = 13.15$ MeV) and a narrow resonance (at $E_{\mathrm{c.m.}} = 13.75$ MeV), the spins of which are both $l = 8$.

This anomaly was also investigated by the members of our group and they concluded[25] from the simultaneous fits of angular distribution and excitation functions for elastic scattering and from the angular distribution of ^{12}C(^{16}O, α)^{24}Mg that the resonance state must have the spin of 8^+.

3. $E_\alpha = 24.25$ MeV ($E_{c.m.} = 14.00$ MeV)

In Fig. 4, comparison with the Legendre polynomial suggests the feature of order 8 or 9 or the mixing of these two kinds of orders. The coefficients of the χ^2 curve also reflects this description. Because there is a strong resonance of spin 8^+ neighboring this anomaly ($E_{\mathrm{c.m.}} = 13.7$ MeV), it is probable that it has the intrinsic spin of 9^- affected by the tail of the neighboring resonance.

4. $E_\alpha = 24.65$ MeV ($E_{c.m.} = 14.35$ MeV)

In Fig. 5 the peaks and valleys of the forward diffraction coincide very well with the 9th order of Legendre polynomial, but they deviate much at large angles. Considering that the J^π characteristic of the angular distribution is most clearly demonstrated in the first few maxima and that interference effects with nonresonant and overlapping resonant terms confuse the characteristic pattern at the intermediate and back angles, this structure must be evidence of 9^- resonance. Lumpkin *et al.*[33] reported that the excitation function for $J = \frac{11}{2}^+$ state of ^{27}Al at $E_x = 4.51$ MeV in the ^{12}C(^{16}O, p)^{27}Al reaction exhibits resonancelike behavior at $E_{\mathrm{c.m.}} = 14.36$ MeV. They suggest the spin of this resonance to be 8 ± 2.

5. $E_\alpha = 25.13$ MeV ($E_{c.m.} = 14.76$ MeV)

We can see a sharp structure at both angles in the excitation functions. Branford *et al.*[6] insisted on the possibility of the existence of intermediate structures at this energy together with other anomalies. Angular distributions were measured at the on- and off-resonance energies. These are displayed in Fig. 6. Compared with the data at the off-resonance energies of lower and upper sides, the angular distribution at $E_\alpha = 25.13$ MeV exhibits a strong diffraction pattern and clearly indicates that this intermediate resonance has the spin parity of 9^-. The χ^2 fit curve including up to order 20 well reproduces the experimental data and the coefficient of order 18 is much larger than that of the order 20. At the off-resonance energy of the $E_\alpha = 24.86$ MeV, some amounts of the effect of the resonance tail can be seen. At the higher side of the resonance, the angular distribution drastically changes. The Hauser-Feshbach calculations are performed and the order of magnitude in the cross sections at the off-resonance energies is reproduced very well. In this energy range, the grazing angular momentum is 11, that is, the partial wave of $l = 11$ has a transmission coefficient of 0.5 It is obvious that this resonance arises not from the kinematical matching of grazing angular momentum but from the intrinsic structure itself in the compound nucleus ^{28}Si.

C. Angular distributions of ^{24}Mg(α, α_0)^{24}Mg

The excitation functions for α scatterings from ^{24}Mg at the several backward angles show sharp dips around $E_\alpha = 25.1$ MeV. The similar phenomena also occur around $E_\alpha = 22.9$ MeV. These dips appear to occur nearly at the same energies as the existence of the resonance states.

In order to study these phenomena more carefully, angular distributions for elastic scattering have been measured at the same three energies as the outgoing ^{12}C + ^{16}O channel around the $E_{\mathrm{c.m.}} = 14.76$ MeV resonance. The results are shown in Fig. 7. The forward cross sections at three different energies are quite similar. At backward angles the cross sections rise steeply toward 180° at off-resonance energies which may be one of the examples in the so-called backward angle anomaly (BAA).[34] However, the cross sections are strongly damped at the energy corresponding to the resonance in the heavy ion channel.

This fact suggests that there can be a relation between the BAA phenomena in the α-^{24}Mg scattering and the molecular resonance in the ^{12}C + ^{16}O system. There are many theoretical pictures on the backward rising of the α-4N nucleus scattering.[35-37] Most of them indicate a broad resonancelike mechanism which is characterized by a single partial wave. If this picture is valid for α-^{24}Mg channel in the present reaction, a resonance of ^{12}C + ^{16}O system having the same angular momentum with the characteristic wave related to the BAA easily couples to $\alpha + {}^{24}$Mg channel. In a microscopic theory, it is probable that an incident α particle can couple with 2 α clusters in ^{24}Mg nucleus to form a ^{12}C nucleus in an excited state and induce a long lived resonance.[21] The sharp dips of the excitation function at very backward angles can be expressed by a formula including the Breit-Wigner resonance term.[20] In the present case, however, the excitation functions at larger angles than 150° have similar dips at the resonance energy and cannot be reproduced by a simple resonance formula.

V. CONCLUSION

A strong correlation was found between the excitation functions of the ^{24}Mg(α, ^{12}C)^{16}O reaction and those of the α-^{24}Mg elastic scattering, especially at $E_{\text{c.m.}} = 12.77$ and 14.36 MeV. This fact confirms the existence of the resonances at these energies in the $^{12}C + {}^{16}O$ system. The spin parities were determined for $E_{\text{c.m.}} = 12.77$ MeV 7^- and 14.76 MeV 9^- from the analysis of the angular distributions.

Angular distributions at the on-resonance energies in the ^{24}Mg(α, ^{12}C) reaction show the characteristic enhancement of the resonance at the forward angles. These are superposed on the nonresonant background for which the Hauser-Feshbach calculations give a reasonable explanation. These feature are also found at $E_{\text{c.m.}} = 14.00$ MeV and $E_{\text{c.m.}} = 14.35$ MeV and they can be also understood to be the resonances. The spin-parities were estimated to be 9^- (or 8^+) for $E_{\text{c.m.}} = 14.0$ MeV and 9^- for 14.35 MeV.

Recently, extensive experimental study has been performed on the $^{12}C + {}^{12}C$ system. In this system, resonances of the same spin are grouped in clusters and form a broad enhancement region.[38] In the $^{12}C + {}^{16}O$ system this pattern has not been confirmed experimentally, although in the sub-Coulomb energy region such structure has been reported[39] and in the higher energy region a possibility has been discussed.[40] In our result, the existence of at least two or three 9^- resonances were found in the vicinity of $E_{\text{c.m.}} = 14$ MeV in the $^{12}C + {}^{16}O$ system. This fact reveals that the similar structure as the $^{12}C + {}^{12}C$ system also exists in the $^{12}C + {}^{16}O$ system.

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