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New approach to spin assignments of intermediate structures in ^{12}C(^{16}O,^{12}C[2_1^+])^{16}O

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Magnetic substate populations for the 2^+ state at 4.44 MeV in ^{12}C were measured in resonant ^{12}C+^{16}O inelastic scattering by the γ-ray recoil method. The m-substate population has been determined in the coordinate frame where a quantization axis is taken along the center of mass scattering angle of a reaction product. This coordinate frame gives an advantage that a resonance spin J can be obtained directly from m-substate angular distributions compared with the beam-axis frame. In addition a decay L value is sensitive to the relative intensity between each m-substate cross section. Our data suggest a spin assignment of $J^\pi = 16^+$ or 17^- for the structures at $E_{\rm c.m.} = 29.8$ MeV and 31.8 MeV. Both structures are determined to decay dominantly through the aligned configuration of $L = J - 2$.

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Recent measurements of the magnetic substate populations in resonant inelastic scattering have provided us with important information for clarifying the reaction mechanism on the observed resonance behavior [1–7]. The m-substate population has been determined so far in some different coordinate frames each of which gives information about different aspects of the reaction mechanism. For instance, quantization along the normal to the scattering plane allows the determination of the spin alignment and the magnitude of the polarization, while quantization along the beam axis can serve as a sensitive probe of the dominant angular momenta [1–6]. Wuosmaa *et al.* obtained the single and correlated m-substate population parameters for 2^+ (1.37 MeV) and 2^+-2^+ excitations in ^{24}Mg+^{24}Mg in the regions of two strong resonances seen in inelastic scattering through the γ-ray angular correlation measurement [4,5]. The angular distribution for the $m = 0$ substate cross section measured in the beam-axis frame showed prominent oscillations in phase with $P_{34}^2(\cos\theta_{\rm c.m.})$ at $E_{\rm c.m.} = 45.7$ MeV, where P_{34} is the Legendre polynomial of order 34. To interpret the oscillations they considered a decay of a single isolated resonance with a spin J. Then the angular distribution for a single magnetic substate in the beam-axis frame is written as

$$\sigma_m(\theta_{\rm c.m.}) = \left|\sum_L a_L(L2-mm|J0)Y_L^m(\theta_{\rm c.m.},0)\right|^2, \qquad (1)$$

where Y_L^m is a spherical harmonics and a_L is the amplitude for the decay through L. The angular distribution is shown to be quite sensitive to the decay L value. The angular distribution for the $m = 0$ substate can be well approximated by $\sigma_{m=0}(\theta_{\rm c.m.}) \propto P_L^2(\cos\theta_{\rm c.m.})$ if one decay L value dominates. They concluded from the oscillation in the $m = 0$ angular distribution that the 45.70-MeV resonance decayed through one preferred L value of $L = 34$.

The m-substate population has been extracted properly from a line shape of excited reaction products which are broaden by γ decay in flight, when a quantization axis is taken along the center of mass scattering angle of the products [7,8]. The line shape reflects the γ-ray angular distribution which has a characteristic pattern for a different magnetic substate. In this coordinate frame, the line shape is described only by the diagonal elements of the density matrix for a finite kinematic momentum shift k of $dp/p/d\theta_{\rm lab}$, so that the m-substate population is extracted properly from the line shape. On the other hand, when a quantization axis is taken along the laboratory scattering angle of the products, not only diagonal elements but also off-diagonal elements should be taken into account in the line shape analysis [9]. The m-substate angular distribution of Eq. (1) described in the beam axis frame is transformed into the center of mass ejectile-axis frame by rotating the beam axis frame by $\theta_{\rm c.m.}$ around the y axis and is written as

$$\sigma_m(\theta_{\rm c.m.}) = \left|\sum_{L\mu} a_L(L2-\mu\mu|J0)Y_L^\mu(\theta_{\rm c.m.},0) \times d_{\mu m}^2(\theta_{\rm c.m.})\right|^2, \qquad (2)$$

where $d_{\mu m}^2(\theta_{\rm c.m.})$ is the d function which describes a rotation around the y axis. From the coupling rule for the d function [10], Eq. (2) reduces to

$$\sigma_m(\theta_{\rm c.m.}) = \left|\sum_L a_L(J2-mm|L0)Y_J^m(\theta_{\rm c.m.},0)\right|^2 = |A_J^m Y_J^m(\theta_{\rm c.m.},0)|^2, \qquad (3)$$

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where A_J^m is an amplitude given by $A_J^m = \sum_L a_L(J2-mm|L0)$. Equation (3) shows that a resonance spin J can be determined directly from the m-substate angular distribution in the ejectile-axis frame, while the m-substate angular distribution depends on the decay L value in the beam-axis frame. In addition the decay L value can be determined from the relative intensity between each m-substate cross section. The strength of the cross section for each m-substate is described by $|A_J^m|^2$ and is sensitive to the configuration between L and J. For large J values, the ratio of $|A_J^m|^2$ for $|m|=0$, $|m|=1$, and $|m|=2$ is approximately 3, 4, and 1 for the aligned configuration of $L=J-2$ and for the antialigned configuration of $L=J+2$, respectively, while the ratio is approximated to be 1, 0, and 3 for the nonaligned configuration of $L=J$.

In the present work we measured the m-substate population by the γ-ray recoil method [7,8] in order to assign spin values of resonances observed at $E_{\mathrm{c.m.}} \approx 30$ MeV in $^{12}\mathrm{C}+^{16}\mathrm{O}$ inelastic scattering. The γ-ray recoil method is available when a high-energy resolution is achieved for the particle spectrum. We obtained the m-substate population for the 2^+ state at 4.44 MeV in $^{12}\mathrm{C}$ in the single excitation. Momentum spectra of $^{12}\mathrm{C}$ from $^{12}\mathrm{C}+^{16}\mathrm{O}$ inelastic scattering were measured with a high resolution at JAERI tandem accelerator by using the heavy-ion magnetic spectrograph "ENMA" [11]. The spectrograph has a characteristic feature that the kinematic momentum shift k is well compensated, so that a high-energy resolution is achieved over a wide range of k. We used the advantages of the reversed knematics for the backward-angle measurement by bombarding a $^{12}\mathrm{C}$ target (50 μg/cm^2 in thickness) with an $^{16}\mathrm{O}$ beam. The entrance slit of the spectrograph was opened 1.1° horizontally and 2.2° vertically which corresponded to a solid angle of 0.8 msr. A typical $^{12}\mathrm{C}$ spectrum is shown in Fig. 1. A line shape broadened by the γ decay in flight is clearly seen for the momenta of $^{12}\mathrm{C}(2^+)$ due to a high-energy resolution of $\sim$ 120 keV. The m-substate population is obtained by unfolding the broadened line shape.

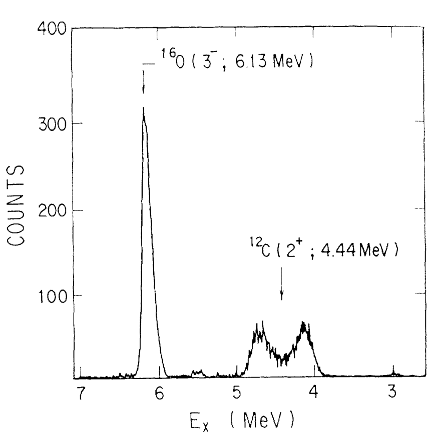

FIG. 1. Typical spectrum of $^{12}\mathrm{C}$ from $^{12}\mathrm{C}(^{16}\mathrm{O},^{12}\mathrm{C})^{16}\mathrm{O}$ inelastic scattering. The line shape of $^{12}\mathrm{C}(2^+)$ is broadened by the γ decay in flight.

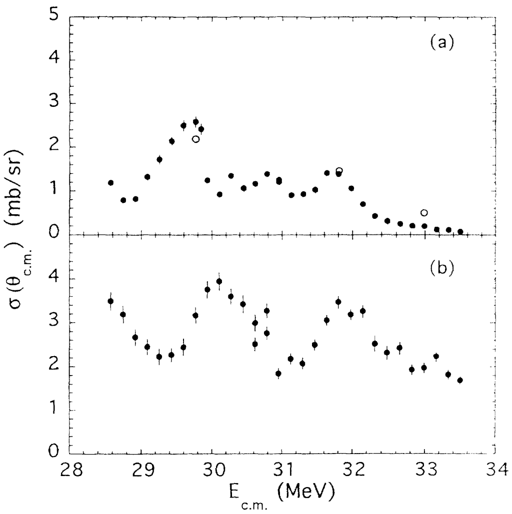

FIG. 2. Excitation functions measured in $^{12}\mathrm{C}+^{16}\mathrm{O}$ inelastic scattering at $\theta_{\mathrm{lab}} = 7.1°$ (filled circles) (a) for the single $^{12}\mathrm{C}(2^+)$ channel and (b) for the mutual $^{12}\mathrm{C}(2^+)$-$^{16}\mathrm{O}(3^-,0_2^+)$ channel. Open circles show data averaged over $148.6° \leq \theta_{\mathrm{c.m.}} \leq 171.4°$.

Figure 2 shows excitation functions for the single $^{12}\mathrm{C}(2^+)$ and the mutual $^{12}\mathrm{C}(2^+)$-$^{16}\mathrm{O}(3^-,0_2^+)$ channels measured at $\theta_{\mathrm{lab}} = 7.1°$ in the energy range from $E_{\mathrm{c.m.}} = 28.5$ to 33.5 MeV in steps of $\delta E_{\mathrm{c.m.}} = 117$ keV. Single 2^+ excitation cross sections averaged over $148.6° \leq \theta_{\mathrm{c.m.}} \leq 171.4°$ are also superimposed at $E_{\mathrm{c.m.}} = 29.8$, 31.8, and 33.0 MeV by open circles which do not deviate much from the data at $\theta_{\mathrm{lab}} = 7.1°$. Intermediate structures are observed at $E_{\mathrm{c.m.}} \approx 30$ and 32 MeV in both channels. The intermediate structure at $E_{\mathrm{c.m.}} \approx 32$ MeV was observed in the $^{16}\mathrm{O}(0_2^+)$ inelastic scattering channel and assigned tentatively to have a spin value of 16^+ by Katori *et al.* [12].

The m-substate angular distributions for the single 2^+ excitation were measured in the scattering angle range from $\theta_{\mathrm{lab}} = 4°$ to 19° in steps of $\delta\theta_{\mathrm{lab}} = 1°$ at $E_{\mathrm{c.m.}} = 29.8$ and 31.8 MeV on-resonances and 33.0 MeV off-resonance. Figure 3 shows the m-substate angular distributions which are characterized by their prominent oscillations. The errors which come mainly from the unfolding procedure are smaller than the size of the data points. To extract spin values we subjected the angular distributions of all substates to a fitting procedure. We assumed that the structures in the cross section were dominated by a single value of J. The experimental angular distributions were then fitted by Eq. (3). Results of our calculations are shown in Fig. 3. For the structure at $E_{\mathrm{c.m.}} = 31.8$ MeV we obtain satisfactory fits of comparable quality for $J=16$ (dashed line) and 17 (solid line) and we suggest a spin assignment of $J=16$ or 17. For the structure at $E_{\mathrm{c.m.}} = 29.8$ MeV we have χ^2 minima for $J=16$ (dashed line) and 17 (solid line). However the $|m|=1$ and 2 cross sections are not reproduced well compared with the $m=0$ cross section. The $|m|=1$ cross section for $\theta_{\mathrm{c.m.}} < 160°$ is nearly flat while the fit oscillates. The $|m|=2$ angular distribution is out of phase with the calculation and are not fitted by another single

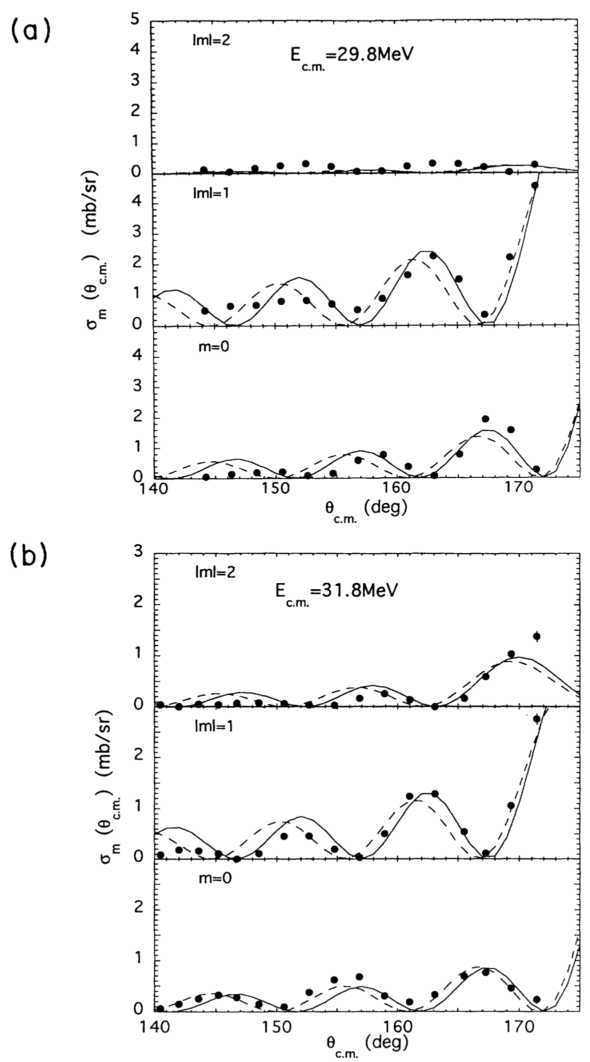

FIG. 3. Angular distributions for m-substate cross sections measured at (a) $E_{\mathrm{c.m.}} = 29.8$ MeV and (b) 31.8 MeV on-resonances. The fits to the data assume isolated resonances of $J^{\pi} = 17^{-}$ (solid line) and 16^{+} (dashed line).

TABLE I. Strength of the cross section $|A_J^m|^2$ for magnetic substates along with spin assignment. The ratio of the amplitude a_L of the nonaligned configuration to the aligned configuration has been estimated from the strength.

$E_{\mathrm{c.m.}}$ (MeV)	J^{π}	$\lvert A_J^m\rvert^2$ (mb) $m=0$	$\lvert m\rvert = 1$	$\lvert m\rvert = 2$	$\left\lvert \frac{a_{L=J}}{a_{L=J-2}} \right\rvert$
29.8	16^{+} or 17^{-}	3.5	7.2	0.4	0.12
31.8	16^{+} or 17^{-}	2.0	3.7	1.4	0.13
33.0		0.6	0.8	0.7	0.23

value of J. Presumably the $|m| = 1$ and 2 cross sections can be explained with contributions to the cross section from a direct reaction process as suggested by Wuosmaa *et al.* [5].

Table I shows the strength of the cross section $|A_J^m|^2$ for each m substate obtained through the fitting procedure. The $|m| = 2$ cross section has small strength compared with the other m-substate cross sections at two resonances. This implies that the decay of the resonances proceeds dominantly through either of $L = J \pm 2$. However, penetration effects make the contribution of $L = J + 2$ small compared with that of $L = J - 2$ [13]. The amplitude a_L for the decay through L can be estimated from the strength by requiring that the difference between Coulomb and hardsphere phase shifts varies little between any two of three L values [6]. The ratio of the a_L of the nonaligned configuration of $L = J$ to the aligned configuration of $L = J - 2$ is represented in Table I. The ratio is 12–13 % at two resonances. On the other hand, the strength for the $|m| = 2$ cross section becomes comparable to the one for the other m cross sections at 33.0 MeV off-resonance. The $|m| = 2$ angular distribution (not shown in Fig. 3) has an oscillatory pattern that suggests that $J = 19$ or 20 is the dominant J value. The ratio of the a_m of the nonaligned configuration to the aligned one is estimated to be about 23%.

In summary, we have measured the m-substate angular distributions in $^{12}\mathrm{C}+^{16}\mathrm{O}$ inelastic scattering to the 2^{+} (4.44 MeV) state in $^{12}\mathrm{C}$ at $E_{\mathrm{c.m.}} = 29.8$ and 31.8 MeV on-resonances and 33.0 MeV off-resonance. The quantization axis has been taken along the center of mass scattering angle of the reaction products. The resonance spin J has been determined directly from the m-substate angular distributions and the decay L value has been obtained from the relative intensity between each m-substate cross section. The spin value has been assigned to be $J^{\pi} = 16^{+}$ or 17^{-} for the structures at $E_{\mathrm{c.m.}} = 29.8$ and 31.8 MeV. Both structures have been determined to decay dominatly through the L value of the aligned configuration $L = J - 2$. The measurement for the m-substate populations in this coordinate frame therefore can be a very powerful tool in clarifying the nature of high spin structures in heavy-ion inelastic scattering.

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