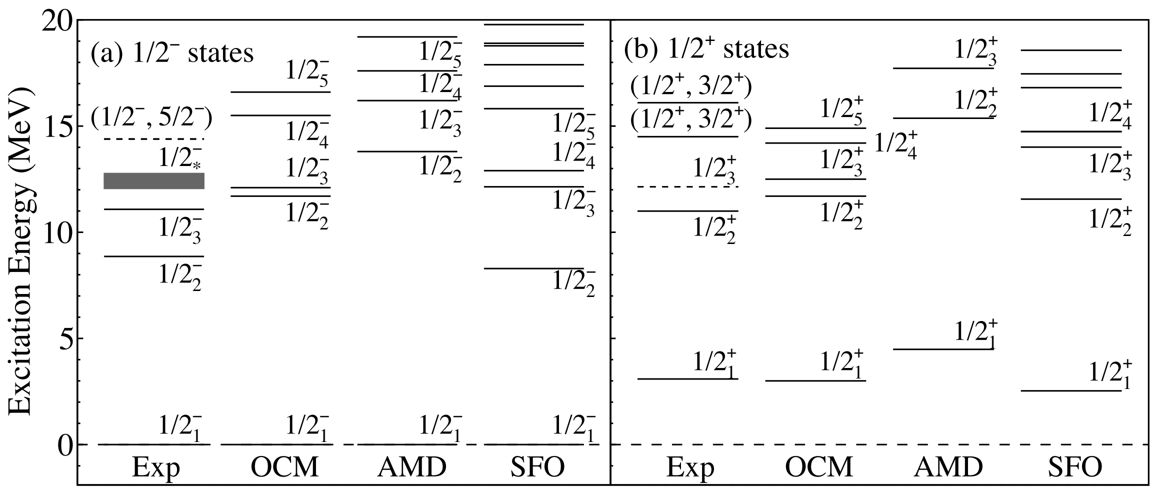

Fig. 9 Energy spectra for the (a) $1/2^-$ states and (b) $1/2^+$ states of ^{13}C obtained in this experiment, compared with the theoretical ones by the OCM, AMD, and shell model with the SFO interaction.

These states are not listed in Ref. [19], and these states are observed for the first time by the present MDA.

5. Discussion

5.1. $\Delta L = 0$ states

We compare the observed excitation-energy spectrum for the $1/2^-$ states with those obtained by the shell-model calculation using the SFO interaction [54] in Fig. 9(a). The shell-model calculation was carried out in the configuration space up to $2\hbar\omega$ using the code NuShellX [55]. Since we were not able to reliably separate and identify the multiple $1/2^-$ states near $E_x = 12.5$ MeV in this experiment, the five $1/2^-$ states around $E_x = 12.06$–12.78 MeV are presented together as the $1/2^-_*$ state in the gray box in Fig. 9(a). According to the experimental compilation [19], there exists a state at $E_x = 14.39$ MeV with the spin and parity of $1/2^-$ or $5/2^-$. This state is represented by dashed line although this state was not observed in this experiment. The observed excitation-energy spectra are reasonably reproduced by the shell-model calculation. The experimental EWSR fractions for the $IS0$ transitions are shown in Fig. 10(a). The sum of the experimental fractions for the five $1/2^-$ states at $E_x = 12.06$–12.78 MeV is shown as that for the $1/2^-_*$ state. Although each of the $1/2^-_2$, $1/2^-_3$, and $1/2^-_*$ states exhaust about 3% of the EWSR, the EWSR fractions calculated by the shell model are of the order of 10^{-4} and much smaller than the experimental values. It is considered that this is because the shell model cannot describe the cluster degrees of freedom at all. The excitation-energy spectrum and the $IS0$ strengths for the $1/2^-$ states by the $3\alpha + n$ OCM calculation [26] are shown in Fig. 9(a) and Fig. 10(b), respectively. The excitation-energy spectrum by the OCM calculation do not reproduce the observed spectrum very well, however, the observed sizable monopole strengths are much better reproduced by the OCM calculation than by the shell-model calculation. This fact suggests that the $1/2^-_2$, $1/2^-_3$, and several $1/2^-$ states around $E_x = 12.5$ MeV have a spatially developed cluster structure rather than a shell-model-like compact structure.

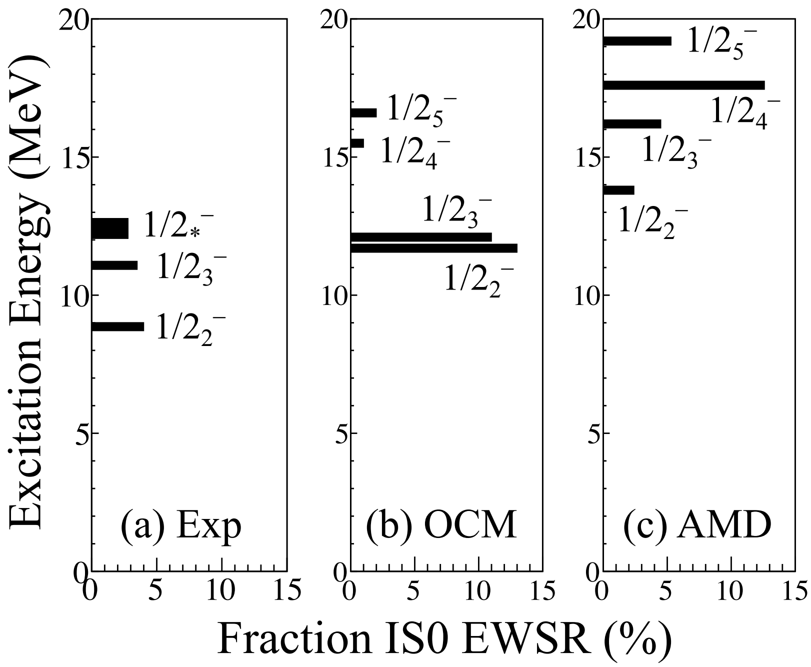

Fig. 10 The EWSR fractions obtained in this experiment compared with those theoretically calculated.

It is worthy to mention that a good mirror symmetry is preserved between ^{13}C and ^{13}N. The two $1/2^-$ states as the isobaric mirror states for the $1/2^-_2$ and $1/2^-_3$ states in ^{13}C were clearly observed in the excitation-energy spectrum for the ^{13}C(^{3}He, t)^{13}N reaction at $\theta_{\rm lab} = 0^\circ$ [56]. In addition to these $1/2^-$ states, a small bump at $E_x = 13.5$ MeV was observed at forward angles. Since this state is considered to be excited by the Gamow-Teller transition, its spin and parity are $1/2^-$ or $3/2^-$. It is expected that the mirror state for the 13.5-MeV state was observed in the present experiment. In Fig. 7, the $1/2^-$ states exist around $E_x = 12.5$ MeV in the $\Delta L = 0$ strength distribution and the $3/2^-_3$ and $3/2^-_7$ states exist in the $\Delta L = 2$ strength distribution. These $1/2^-$ and $3/2^-$ states are candidates for the mirror state for the 13.5-MeV state in ^{13}N. Since the mirror states for the $3/2^-_3$ and $3/2^-_7$ states were clearly obtained in the ^{13}C(^{3}He, t)^{13}N reaction, the $3/2^-_3$ and $3/2^-_7$ states are cannot be considered as the mirror state for the 13.5-MeV state. Therefore, the 13.5-MeV state might be the mirror state for the $1/2^-$ states around $E_x = 12.5$ MeV in ^{13}C.

The proton decay from the excited states in ^{13}N to the low-lying $T = 0$ states in ^{12}C were also measured in Ref. [56]. The measured branching ratios for the proton decay are compared with the theoretical ones calculated with the spectroscopic factor (S-factor) and penetrability in Table 3. It is noted that S-factor of the ^{12}C + n channels by the $3\alpha + n$ OCM calculation are used to obtain the theoretical branching ratios. The overall trend of measured branching ratio of each $1/2^-_2$ and $1/2^-_3$ state in ^{13}N is qualitatively explained by the OCM calculation. This result supports the good mirror symmetry between ^{13}C and ^{13}N, and indicates that the observed $1/2^-_2$ and $1/2^-_3$ states both in ^{13}N and ^{13}C correspond well to those predicted by the OCM calculation. The branching ratio from the $1/2^-_3$ state in ^{13}N to the 0^+_1 state in ^{12}C is as small as 0.05 ± 0.01, however, that to the 0^+_2 state in ^{12}C is as large

Table 3 Branching ratios for proton decay measured in the ^{13}C(^{3}He, t)^{13}N reaction [56] compared with those theoretically calculated. Noted that the S-factor for the $^{12}\mathrm{C}+n$ channels obtained by the $3\alpha+n$ OCM calculation is used for the theoretical branching ratios. For 13.5-MeV state, the theoretical values correspond to the $1/2^-_4$ state, whereas those in parentheses correspond to the $1/2^-_5$ state.

^{13}N state	^{12}C state		$3\alpha+n$ OCM	
E_x (MeV)	E_x (MeV)	exp. [56]	S-factor	branching ratio
$8.92(1/2^-_2)$	$0.00(0^+_1)$	0.60 ± 0.09	0.02	0.54
	$4.44(2^+_1)$	0.30 ± 0.05	0.07	0.46
$10.83(1/2^-_3)$	$0.00(0^+_1)$	0.05 ± 0.01	0.01	0.08
	$4.44(2^+_1)$	0.54 ± 0.09	0.20	0.73
	$7.65(0^+_2)$	0.43 ± 0.16	0.22	0.19
13.5	$0.00(0^+_1)$		0.00(0.01)	0.00(0.05)
	$4.44(2^+_1)$		0.00(0.08)	0.00(0.25)
	$7.65(0^+_2)$		0.05(0.23)	1.00(0.71)

as 0.43 ± 0.16 despite the smaller Q-value in the 0^+_2 channel. The measured branching ratio to the 0^+_2 state is larger than that by the OCM calculation, indicating that the $1/2^-_3$ state is more strongly coupled to the 0^+_2 state than predicted by the OCM calculation. On the other hand, the measured branching ratio to the 2^+_1 state is as large as that to the 0^+_2 state, and the 2^+_1 state is considered to be coupled to the $1/2^-_3$ state as strong as the 0^+_2 state. This large coupling to the 2^+_1 state is also predicted in the OCM calculation. Therefore, the α condensed nature of 0^+_2 state is not considered to be dominant in the $1/2^-_3$ state.

The small bump at $E_x=13.5$ MeV in ^{13}N has a much larger decay width to the 0^+_2 state than that to the 0^+_1 and 2^+_1 state (see Fig. 8 in Ref. [56]). This is consistent with the OCM calculation if this bump corresponds to the $1/2^-_4$ or $1/2^-_5$ state, both of which have much larger decay width in the 0^+_2 channel than those in the 0^+_1 and 2^+_1 channels. Therefore, it is expected that the $1/2^-$ states around $E_x=12.5$ MeV in ^{13}C are the candidate for the $3\alpha+n$ condensed state which are strongly coupled to the 0^+_2 states in ^{12}C. The fact that these $1/2^-$ states locate slightly above the $3\alpha+n$ decay threshold also supports this expectation. However, it is claimed that the $1/2_{2,3,4,5}$ states have the dominant configuration of $^{9}\mathrm{Be}+\alpha$, not the $^{12}\mathrm{C}(0^+_2)+n$ in the OCM calculation. An extra neutron should be in p-wave when it is added in the 0^+_2 state in ^{12}C to form the $1/2^-$ states in ^{13}C. The effective α–n force used in the OCM calculation [57] has the strong parity dependence. Since the odd-parity α–n force is significantly attractive, it reduces the size of the 0^+_2 state to make the $^{8}\mathrm{Be}+\alpha$ correlation in the $3\alpha+n$ system. The extra neutron is bound with the ^{8}Be and thus the $^{9}\mathrm{Be}+\alpha$ cluster structures are formed in the $1/2^-$ states. Therefore, the $3\alpha+n$ condensed state does not exist in the negative parity states, and the observed $1/2^-_2$, $1/2^-_3$ and several $1/2^-$ states around $E_x=12.5$ MeV are considered to have the $^{9}\mathrm{Be}+\alpha$ cluster structures.

It is notable to compare the present experimental results with the predictions of the recent AMD calculation [27]. The excitation-energy spectrum by the AMD calculation is presented

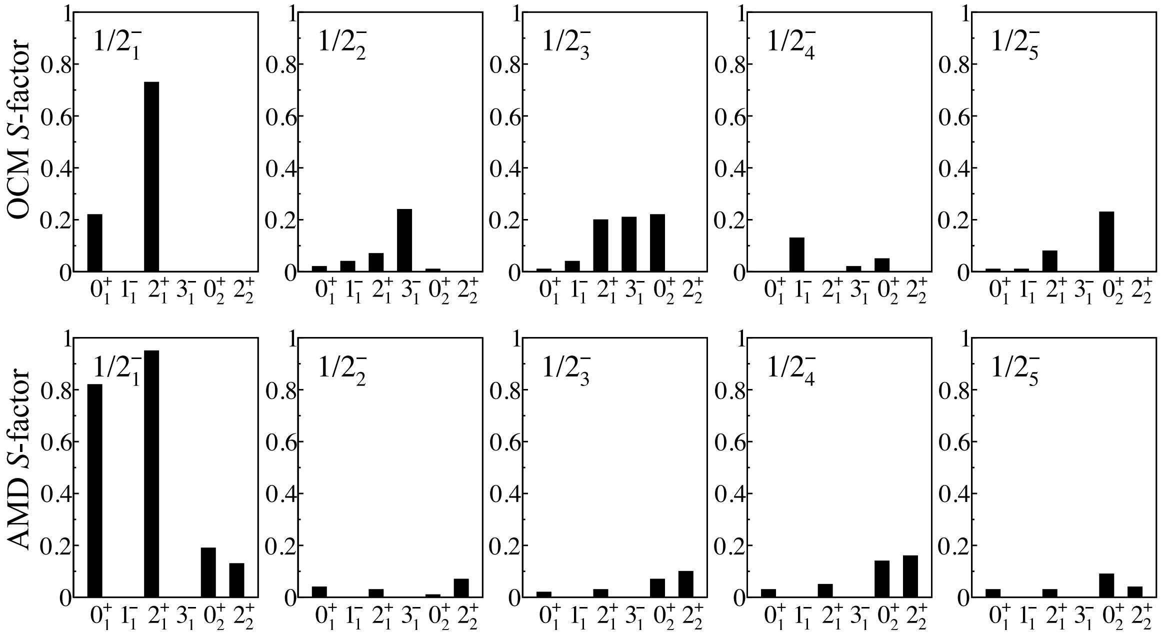

Fig. 11 The S-factor for the $1/2^-$ states calculated by the OCM and AMD calculations in the $^{12}\mathrm{C}+n$ channels.

in Fig. 9(a). The calculated spectrum does not reproduce the observed spectrum, and the excitation-energies of the excited $1/2^-$ states are overestimated in the AMD calculation. The S-factor calculated by the AMD are compared with those by the OCM in Fig. 11. Except for the ground state, the $1/2^-$ states predicted in the OCM and AMD calculations do not correspond to each other. It was mentioned in Ref. [27] that the model space of the AMD calculation might not be large enough to describe the cluster states in ^{13}C.

5.2. $\Delta L = 1$ *states*

The experimental excitation-energy spectra for the $\Delta L = 1$ states are compared with theoretical ones in Fig. 9(b). The $1/2^+_3$ state at $E_x = 12.14$ MeV is shown by the dashed line because this state was not observed in this experiment. The spin and parity of the 14.5-MeV and 16.1-MeV states observed in the $\Delta L = 1$ spectra in Fig. 7 are either $1/2^+$ or $3/2^+$. Assuming that the spin and parity of both the 14.5-MeV and 16.1-MeV states are $1/2^+$, the observed excitation-energy spectra are reasonably reproduced by the OCM and shell-model calculations.

The excitation energy of the $1/2^+_1$ state is well reproduced by all the theoretical calculations. According to the AMD and OCM calculations, this state is indicated to have a compact shell structure. The experimental value of the EWSR fraction for the $IS1$ transition for the $1/2^+_1$ state was $0.63 \pm 0.03\%$, which is in agreement with the calculated results by the AMD (???) and the shell model (0.31%). Therefore, the $1/2^+_1$ state is considered to have a shell-model like structure. On the other hand, the observed spectra of the excited states higher than 10 MeV are overestimated by the AMD calculation, whereas those are reasonably reproduced by the OCM and the shell-model calculations. These states are indicated to have developed-cluster structures by the OCM and AMD calculations. It was mentioned