Isospin and spin-orbital structures of $J^{\pi}=1^{+}$ states excited in ^{28}Si

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Gamow-Teller (GT) states with $J^{\pi}=1^{+}$ excited by a (p,n)-type charge-exchange reaction on $N=Z$ nuclei with ground-state isospin $T=0$ have isospin $T=1$, while $M1$ states excited by inelastic scattering of electrons or protons can have either $T=0$ or $T=1$. The latter are the isobaric analog states of the GT states. By comparing the GT states observed in the good-resolution (^{3}He,t) reaction at 150 MeV/nucleon with the $M1$ states observed in inelastic electron and proton reactions, the isospin structure of the 1^{+} states in ^{28}Si has been determined. From an analysis of the strengths of corresponding 1^{+} states observed in the (^{3}He,t) and (e,e') reactions, the spin and orbital contributions to the $M1$ excitations have been deduced. [S0556-2813(97)05103-0]

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I. INTRODUCTION

The $L=0$ spin-flip mode excited by charge-exchange reactions is called the Gamow-Teller (GT) mode, while that excited by inelastic scattering is called the $M1$ mode [1]. All states populated by these modes on an even-even target nucleus have $J^{\pi}=1^{+}$. In light nuclei, the GT and $M1$ excitations can usually be observed as a distribution of well-separated discrete states. For an $N=Z$ self-conjugate target nucleus with $T_z=0$, the GT states have the isospin value $T=1$, while the $M1$ states can have the isospin values $T=1$ or $T=0$. As will be discussed in detail in Sec. II, the $T=1$ $M1$ states are the isobaric analog states of GT states.

Moreover, in hadron charge-exchange and inelastic scattering reactions the GT and $T=1$ $M1$ states are excited mainly by the $L=0$ spin- and isospin-flip part of the effective nuclear interaction. It is therefore expected that not only the Coulomb energy-corrected excitation energies are similar, but also that the excitation cross sections observed in both reactions are closely related to each other. Using these expectations, it should be possible to identify the isospin of a $M1$ state by studying the existence or the non-existence of the corresponding analogous GT state.

In inelastic electron scattering, $J^{\pi}=1^{+}$ states are excited by the $M1$ operator which consists of an orbital part $g_{l}\boldsymbol{l}$ and a spin part $g_s\boldsymbol{s}$. Thus the $M1$ strength obtained from the (e,e') reaction contains not only the spin, but also an orbital contribution. The latter can be studied by comparing (e,e') results with hadron results in which the contribution from the spin part is dominant.

The aim of present paper is to disentangle the isospin structure and the orbital and spin nature of 1^{+} states in the $N=Z$ target nucleus ^{28}Si by comparing level-by-level the results from three characteristic reactions, i.e., hadron charge-exchange, hadron inelastic scattering, and electron inelastic scattering reactions. The subject has already been discussed in several pioneering works on ^{28}Si [2–7]. In order to make a fruitful comparison, hadron results performed at intermediate energies should be used, for which the transition strengths for spin excitations are believed to be reliably obtained because of the simplicity of the reaction mechanism and the dominance of the spin- and isospin-flip interaction $V_{\sigma\tau}$ at small momentum transfer [1,8]. In the past, such a comparison, however, was limited by the relatively poor energy resolution obtainable in a charge-exchange reaction at intermediate energies. Recently it has become possible to measure the (^{3}He,t) reaction with a 150 MeV/nucleon ^{3}He beam [9]. This allowed, e.g., a good resolution (^{3}He,t) experiment for a ground-state isospin $T_0=1$ nucleus, ^{58}Ni, and enabled the identification of the isospin structure of GT states in ^{58}Cu by comparison with (e,e') data and also with (t,^{3}He) data [10]. The present study represents an extension of this sort of work to the $T_0=0$ target nucleus ^{28}Si. The results from the (^{3}He,t) reaction are compared with new results for the $M1$ strength from a recent ^{28}Si(e,e') measurement under 180° [11], and with data from the (p,p') reaction at $E_p=200$ MeV [5].

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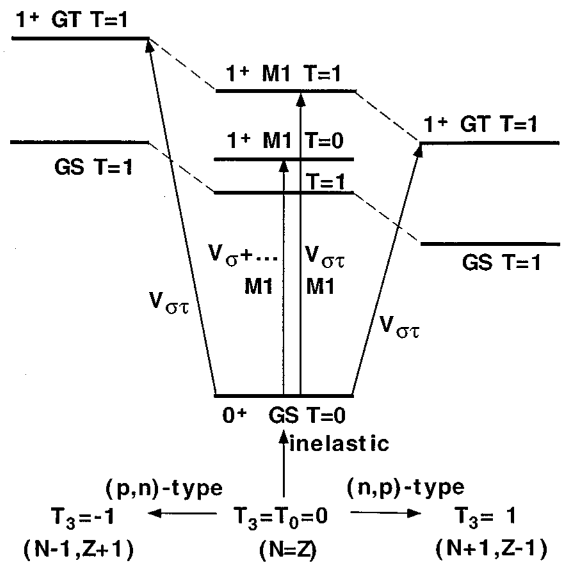

FIG. 1. Isospin of $J^{\pi}=1^{+}$ states excited on the ground state of an even-even nucleus with $T_0=0$ $(N=Z)$. The interactions mainly responsible for each excitation are shown along the arrows indicating the transitions. Isobaric-analog relationships among states are shown by broken lines. No quantitative significance is to be attached to the relative position of the levels.

II. CHARACTERISTICS AND EXCITATION OF $J^{\pi}=1^{+}$ STATES ON AN $N=Z$ EVEN-EVEN TARGET NUCLEUS

In this section we discuss the excitation features of $J^{\pi}=1^{+}$ states in hadron and (e,e') reactions for $N=Z$ even-even target nuclei with ground-state isospin $T_0=T_3=0$. With the usual assumption that isospin is a good quantum number, the excitation modes of the 1^{+} states with isospin $T=0$ and $T=1$ are summarized in Fig. 1 [12].

A. $M1$ and GT $J^{\pi}=1^{+}$ states

In a simple shell-model (SM) picture, $M1$ states consist of both proton and neutron one-particle–one-hole (1p1h) configurations within a major shell. The GT states excited by (p,n)-type [or (n,p)-type] charge-exchange reactions consist of proton-particle–neutron-hole [or neutron-particle–proton-hole] with the same shell configurations as those of the $M1$ states.

The $M1$ states are further categorized into $T=0$ and $T=1$. Since the ground-state isospin is $T_0=0$, the $M1$ states with $T=0$ and $T=1$ are excited by the isoscalar (IS) and the isovector (IV) interactions, respectively, and thus they can be called ''IS states'' and ''IV states'' (see Fig. 1). On the other hand, charge-exchange reactions are caused solely by IV interactions leading to final nuclei with ground states of isospin $T_f=1$. Therefore only $T=1$ states are allowed for the $J^{\pi}=1^{+}$ states of the GT modes. It should be noted that the GT states excited by (p,n)-type reactions, the $T=1$ $M1$ states, and the GT states excited by (n,p)-type reactions have identical SM configurations. They belong to an isobaric triplet [12], which is indicated by dashed lines in Fig. 1.

B. Hadron reactions

In intermediate-energy (100 MeV/nucleon or more) charge-exchange reactions, such as (p,n) or $(^3\mathrm{He},t)$, the GT states become prominent at forward angles including 0° because of their $L=0$ nature and the dominance of the central part of the effective nuclear interaction $V_{\sigma\tau}$ at small momentum transfer [1,8,13]. For the projectile proton or ^{3}He with isospin 1/2, the 0° charge-exchange cross section for GT transitions with quantum numbers $(\Delta L=0,\Delta S=1,$ and $\Delta T=1)$ from a $J^{\pi}=0^{+}$, $T_0=0$ ground state to a $J^{\pi}=1^{+}$, $T=1$ GT state is approximately given by [14,15]

$$\frac{d\sigma^{\mathrm{CE}}}{d\Omega}(0°)\simeq K^{\mathrm{CE}}N_{\sigma\tau}^{\mathrm{CE}}|J_{\sigma\tau}(0)|^2B(\mathrm{GT}). \tag{2.1}$$

Here, $J_{\sigma\tau}(0)$ is the volume integral of the effective interaction $V_{\sigma\tau}$ at momentum transfer $q=0$, K^{CE} is the kinematic factor for the charge-exchange reaction, $N_{\sigma\tau}^{\mathrm{CE}}$ is a distortion factor which may change about 10% as a function of excitation energy, and $B(\mathrm{GT})$ is the squared GT matrix element

$$B(\mathrm{GT})=[M(\sigma)+M_{\Delta}]^2. \tag{2.2}$$

Here, $M(\sigma\ )$ is the nucleonic spin matrix element and M_{Δ} is the isobar contribution. Meson exchange contributions due to axial vector coupling are neglected here since they should be strongly suppressed by G parity conservation [16]. The $B(\mathrm{GT})$ value is given in units where $B(\mathrm{GT})=3$ for the beta decay of the free neutron.

In intermediate-energy hadron inelastic scattering experiments such as (p,p'), the $T=1$ $M1$ states become prominent at forward angles including 0°. They are also excited mainly through $V_{\sigma\tau}$ part of the effective nuclear interaction [1,13]. Neglecting noncentral components of the interaction and contributions from the nucleon exchange process, the 0° (p,p') cross section for transitions with the same quantum numbers as the GT transitions are approximately given by again using $J_{\sigma\tau}(0)$ and $B(\mathrm{GT})$ [15,17] as

$$\frac{d\sigma^{\mathrm{IE}}}{d\Omega}(0°)\simeq \frac{1}{2}K^{\mathrm{IE}}N_{\sigma\tau}^{\mathrm{IE}}|J_{\sigma\tau}(0)|^2B(\mathrm{GT}). \tag{2.3}$$

Here, K^{IE} is the kinematic factor for the inelastic scattering reaction and $N_{\sigma\tau}^{\mathrm{IE}}$ is a distortion factor. The same $B(\mathrm{GT})$ as for the GT transition is used because of the analog relationship of the $T=1$ $M1$ state. The factor (1/2) comes from the isospin Clebsch-Gordan coefficients of the projectile-ejectile combination. Therefore, we expect that for each pair of analog states the charge-exchange cross section at 0° and the (p,p') cross section at 0° are proportional to the $B(\mathrm{GT})$ value. In other words, they all show similar strength distributions as a function of excitation energy aside from a slight variation due to the different distortion factors.

In the excitation of the $T=0$ $M1$ states of the $N=Z$ nucleus, on the other hand, the interaction $V_{\sigma\tau}$ cannot contribute due to isospin selection rules. These states are excited by the spin interaction (V_{σ}) and the exchange term of the tensor interaction [18]. The main interactions causing the excitation of 1^{+} states are shown in Fig. 1 along the arrows indicating the transitions.

C. $M1$ excitation in (e,e')

In the (e,e') reaction, the $M1$ states are excited by the magnetic dipole ($M1$) interaction whose operator consists of an orbital part $g_l \boldsymbol{l}$ and a spin part $g_s \boldsymbol{s}$. The $M1$ operator can also be written as the sum of IS and IV terms [1,19]

$$\boldsymbol{\mu}=\left\{\sum_{j=1}^{Z}(g_l^{\pi}\boldsymbol{l}_j+g_s^{\pi}\boldsymbol{s}_j)+\sum_{j=1}^{N}(g_l^{\nu}\boldsymbol{l}_j+g_s^{\nu}\boldsymbol{s}_j)\right\}\mu_N \quad (2.4)$$

$$=\left\{\sum_{j=1}^{A}\left(\frac{1}{2}(g_l^{\pi}+g_l^{\nu})\boldsymbol{l}_j+\frac{1}{2}(g_s^{\pi}+g_s^{\nu})\boldsymbol{s}_j\right)-\sum_{j=1}^{A}\left(\frac{1}{2}(g_l^{\pi}-g_l^{\nu})\boldsymbol{l}_j+\frac{1}{2}(g_s^{\pi}-g_s^{\nu})\boldsymbol{s}_j\right)\tau_z(j)\right\}\mu_N, \quad (2.5)$$

where μ_N is the nuclear magneton. For bare protons and neutrons, the orbital and spin gyromagnetic factors are $g_l^{\pi}=1$ and $g_l^{\nu}=0$, and $g_s^{\pi}=5.586$ and $g_s^{\nu}=-3.826$, respectively. The z component of the isospin operator $\tau_z(j)=1$ for neutrons and -1 for protons. Through the IS and the IV parts of the spin operator $\boldsymbol{s}_j$ [the first and the second terms in Eq. (2.5)], the (e,e') reaction can excite $T=0$ and $T=1$ $M1$ states in the $N=Z$ nucleus, respectively. The $T=1$ states, however, are much more strongly excited due to the fact that the coefficient of the IV spin part is larger by a factor of about 5 than that of the IS spin part.

Adding the contributions from isobar and meson exchange currents (MEC's), the squared $M1$ matrix element $B(M1)$ for $T=1$ states can be written approximately [11,20]

$$B(M1)=\frac{3(\mu_p-\mu_n)^2}{8\pi}[M(\sigma)+M(l)+M_{\Delta}+M_{\rm MEC}]^2. \quad (2.6)$$

Here, $M(l)$ represents the nucleonic orbital contribution and the numerical factor is $2.643\mu_N{}^2$ if the bare gyromagnetic factors are used. The orbital part may interfere destructively or constructively with the spin part. This could lead to suppression or enhancement of excitation strength, which is strongly dependent on the configuration of a state. Moreover, as discussed in detail in Refs. [11,20], contributions from non-nucleonic degree of freedom $M_{\rm MEC}$ play a larger role in the $M1$ transitions than in GT transitions. The ratio of cumulative sums for $B(M1)$ and $B({\rm GT})$

$$R(M1/{\rm GT})=\frac{\Sigma B(M1)/2.643\mu_N{}^2}{\Sigma B({\rm GT})} \quad (2.7)$$

was defined as a measure to estimate the combined effects of orbital and MEC. In the absence of these contributions, the ratio R should be unity. In SM calculations, it is predicted that the orbital contributions almost cancel when the $M1$ strengths are summed over a large region of excitation [11,21]. Thus, the ratio defined by Eq. (2.7) should show the effect of MEC, i.e., $R(M1/{\rm GT})\approx R_{\rm MEC}$ should hold. It is known that $R_{\rm MEC}$ has a value about 1.3 in ^{28}Si [11,22]. Since the effect of the MEC should be independent of the wave function of the individual state, the above ratio of $B(M1)$ and $B({\rm GT})$ for the jth pair of isobaric analog states divided by $R_{\rm MEC}$

$$R_{\rm OC}^{j}(M1/{\rm GT})=\frac{B^j(M1)/2.643\mu_N{}^2}{B^j({\rm GT})}\frac{1}{R_{\rm MEC}}, \quad (2.8)$$

should show the orbital contribution. The $R_{\rm OC}^{j}$ should be greater than unity in the case of constructive orbital contribution and less for destructive case.

In order to directly compare the transition probabilities for $M1$ states obtained from (p,p') and (e,e') scattering, the squared matrix element for the spin transition, defined similarly to $B(M1)$, is often used [17]

$$B(\sigma)=\frac{3(\mu_p-\mu_n)^2}{8\pi}[M(\sigma)+M_{\Delta}]^2. \quad (2.9)$$

This value differs from $B({\rm GT})$ defined by Eq. (2.2) by the factor of $2.643\mu_N{}^2$.

III. THE EXPERIMENT

The ^{28}Si(^{3}He,t) experiment was performed at RCNP, Osaka. A 150 MeV/nucleon ^{3}He beam from the $K=400$ RCNP ring cyclotron was used to bombard a 9 mg/cm^2 natural Si foil. A beam current of $\sim$ 5 nA ^{3}He^{2+} beam was used. The ejectile tritons were detected with the QQDD-type spectrometer Grand Raiden [23]. In order to realize good energy resolution, the dispersion-matching technique was used for the beam transport. The spectrometer was set at 0° and scattered particles were accepted within $\pm$ 20 mr in both horizontal (x) and vertical (y) directions. After momentum analysis by the spectrometer, tritons were detected with a multiwire drift-chamber system allowing for track reconstruction. More details of the experiment are given in Ref. [24].

The raytrace information made it possible to subdivide the acceptance angle of the spectrometer by a software cut. Figure 2(a) shows the 0° spectrum for the angular range $\pm$ 1.7 mr in the x direction (no cut is made in the y direction). With the achieved energy resolution of 130 keV (FWHM), fine structure was observed up to $E_x\approx 8$ MeV. The gross features of the spectrum are quite similar to those observed in the ^{28}Si(p,n) reaction at $E_p=136$ MeV [7]. This confirms that the (^{3}He,t) reaction at a bombarding energy exceeding 100 MeV/nucleon is a single-step direct reaction, and that the relevant effective interaction $V_{\sigma\tau}$ is similar for the (p,n) and (^{3}He,t) reactions at a comparable incident energies per nucleon [9,25,26].

As the scattering angle increases, the cross sections of $L=0$ states decrease, whereas those of $L=1$ and higher multipoles increase. The GT states with $L=0$ were distinguished from $L\neq 0$ states by comparing the 0° spectrum shown in Fig. 2(a) with a spectrum centered at 1.1° by looking for the states showing the similar relative decrease in strength. The GT states are indicated by their excitation energies. The excitation energies were calibrated using well-known low-lying discrete states observed in the ^{12,13}C(^{3}He,t) spectra as references. Owing to the large negative Q value of the ^{12}C(^{3}He,t) reaction, the excitation energies of ^{28}P were de-

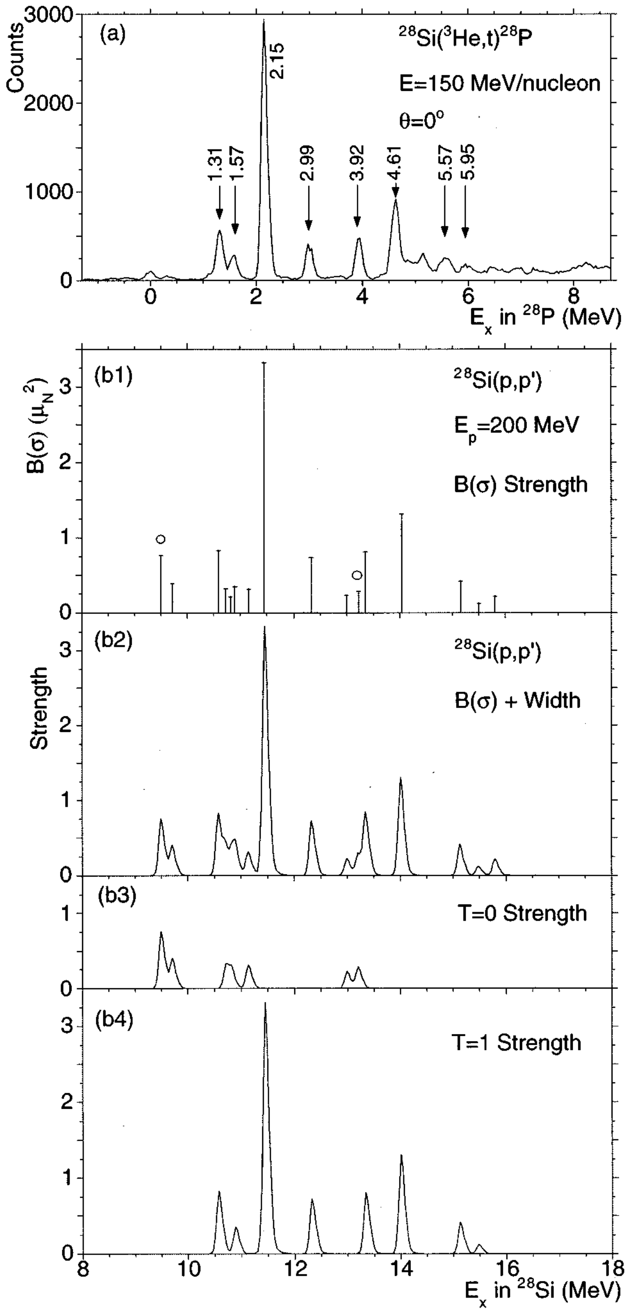

FIG. 2. Comparison between the 0° ^{28}Si(^{3}He,t) spectrum and the strength distribution $B(\sigma)$ obtained in the ^{28}Si(p,p') experiment [5]. (a) The 0° ^{28}Si(^{3}He,t) spectrum. (b1) $B(\sigma)$ distribution observed in the ^{28}Si(p,p') experiment; see text for details. (b2) Reconstructed (p,p') spectrum after convoluting with the experimental energy resolution of the (^{3}He,t) experiment. (b3) Reconstructed (p,p') spectrum for the $T=0$ states after the isospin assignment by making a comparison between the spectra shown in (a) and (b2). (b4) Same as (b3), but for the $T=1$ states. (b) is shifted relative to (a) with an excitation energy of 9.3 MeV, the amount of Coulomb displacement energy.

termined up to 8 MeV by interpolation. In this region, we estimate the uncertainties to be less than 50 keV. The determined excitation energies are in good agreement with those from (^{3}He,t) reaction at a ^{3}He beam energy of 200 MeV [27] and also with those from the (p,n) measurement performed at $E_p=136$ MeV [7] given in Table I .

For (p,n) reactions at bombarding energies exceeding 100 MeV, it has been established that the relationship of Eq. (2.1) holds for the 0° cross section and the B(GT) value [14,28], and the same is suggested for the (^{3}He,t) reaction at 150 MeV/nucleon [9,26]. The B(GT) values were normalized to $B(\mathrm{GT})=0.96$ for the 2.15 MeV state, the strongest peak in the observed spectrum. This value was determined in the ^{28}Si (p,n) reaction based on the ''universal'' conversion factor between the B(GT) value and the observed cross section [7,22]. The B(GT) values of the other GT states can then simply be obtained from the yields for the relevant peaks. The extracted B(GT) strengths are given in Table I. It is estimated that they contain $\sim\pm10\%$ error inherited from the ambiguity of B(GT) determination in the (p,n) reaction and the error of at most 5% in determining the ratio of yields for the states other than 2.15 MeV state.

The results from the high-resolution ^{28}Si(p,p') reaction at $E_p=200$ MeV by Crawley *et al.* [5] are given in Table I. The excitation energies and the cross sections of $M1$ states were determined from the analysis of the (p,p') spectrum measured with a resolution of 60 keV (FWHM) in the range $\theta_{\mathrm{lab}}=2°$ to 12°. The cross sections were converted to $B(\sigma)$ with the help of distorted-wave Born-approximation (DWBA) calculations using the effective nucleon-nucleon interaction of Franey and Love [29].

Table I also shows the $M1$ strengths extracted from the (e,e') experiment performed with the 180° scattering facility [30,31] at the superconducting Darmstadt electron linear accelerator (S-DALINAC) [11]. The 180° spectrum was measured with a resolution of about 80 keV (FWHM). The derived data are in good agreement with previous electron scattering work [32], but considerably extend the investigated energy range.

IV. DATA ANALYSIS AND DISCUSSIONS

A. Isospin decomposition

In the comparison of $M1$ states with GT states observed respectively in (p,p') and (^{3}He,t) reactions, only the $T=1$ $M1$ states should be seen in correspondence with the GT states, and the ratios of cross sections should be about the same for all pairs of correspondingly observed states. The comparison was made between our ^{28}Si(^{3}He,t)^{28}P results and those from the ^{28}Si(p,p') reaction at $E_p=200$ MeV [5]. As a result of the analysis of the (p,p') reaction, it was reported that two $M1$ states at $E_x=9.50$ and 13.22 MeV have $T=0$, while the others have $T=1$ judging from the flatter shape of the angular distributions of $T=0$ states compared to those of $T=1$ states. To those two $T=0$ states much smaller $B(\sigma)$ values were assigned for a given value of experimental differential cross section than to the other states assigned to $T=1$. In order to compare the (p,p') results with the (^{3}He,t) spectrum in the form of cross-section ratio, we recalculated the $B(\sigma)$ values of those $T=0$ states assuming the same conversion factor between cross section and $B(\sigma)$ as was used for $T=1$ transitions by using the values given in Table III of Ref. [5]. Then all $M1$ states should show the $B(\sigma)$ values nearly proportional to the observed cross sections. The strength distribution for such modified

TABLE I. Strength distribution of 1^+ states in reactions on ^{28}Si target. For the details of B(GT) values of present (^{3}He,t) reaction, see text. In the (p,p') part, the column "E_x in ^{28}P" is added to show the correspondence of E_x's with those of charge exchange reactions. The isospin T's are the values assigned in the present work.

(^{3}He,t) [a]		(p,n) [b]		(p,p') [c]			Isospin	(e,e') [d]	
E_x	B(GT)	E_x	B(GT)	E_x	E_x in ^{28}P [e]	$B(\sigma)$	T	E_x	$B(M1)$
				9.50	0.22	0.09	0		
				9.72	0.44	0.39	0		
1.31	0.21	1.25	0.20	10.59	1.31	0.83	1	10.594	0.19
				10.73	1.45	0.32	(0)	10.725	0.11
				10.82	1.54	0.21	0		
1.57	0.10	1.59	0.11	10.90	1.62	0.35	1	10.901	0.90
				11.16	1.88	0.31	0		
2.15	0.96 [f]	2.10	0.96	11.45	2.17	3.32	1	11.445	4.42
2.99	0.15	2.94	0.15	12.33	3.05	0.73	1	12.331	0.87
				12.99	3.71	0.23	0		
				13.22	3.94	0.03	0		
3.92	0.17	3.87	0.16	13.35	4.07	0.81	1		
4.61	0.35	4.59	0.41	14.03	4.75	1.31	1	14.030	0.37
		5.02m	0.14						
5.57	(0.08)	5.55	0.09	15.15	5.87	0.42	1	15.147	0.23
5.95		5.91	0.09	15.50	6.22	0.12	(1)	15.50	0.26
				15.80	6.52	0.22	(0)		
		6.50m	0.02						
								17.56	0.18
		8.27m	0.05						
		9.17m	0.07						

[a]Present work.
[b]B. D. Anderson *et al.* ([7]); states indicated with m is of mixed L nature.
[c]G. M. Crawley *et al.* ([5]).
[d]C. Lüttge *et al.* ([11]).
[e]Expected E_x of analog state in ^{28}P assuming the Coulomb displacement energy of 9.28 MeV.
[f]Normalized to the (p,n) value.

$B(\sigma)$ values is shown in Fig. 2(b1), where the two states with rescaled $B(\sigma)$ values are marked with small circles. Figure 2(b) is shifted with an excitation energy of 9.28 MeV relative to Fig. 2(a), since the isobaric analog state of a well-established 1^+ state at 10.59 MeV state in ^{28}Si is observed at 1.31 MeV in ^{28}P [33].

In order to make the (p,p') results directly comparable with the (^{3}He,t) spectrum, the $B(\sigma)$ distribution shown in Fig. 2(b1) was convoluted with the peak shape of the well-separated $E_x=2.15$ MeV level in the (^{3}He,t) spectrum. From the argument given in Sec. II, the difference between the reconstructed (p,p') spectrum shown in Fig. 2(b2) and the (^{3}He,t) spectrum shown in Fig. 2(a) should be attributed to the $T=0$ states excited in the (p,p') reaction. In the excitation of a 1^+ state, $L=2$ amplitude, in addition to that of $L=0$, is expected. A 1^+ state with large $L=2$ contribution was studied, for example, in ^{38}Ar(p,n) reaction [34]. Such a state with large $L=2$ contribution had minimum cross section at 0°. We select states with decreasing angular distribution, indicating a small contribution of $L=2$ amplitude, if any. Additionally, the $L=0$ and $L=2$ amplitudes of the isobaric analog states observed in the (p,p') and (^{3}He,t) reactions should have the same phase. Therefore, we believe that the $L=2$ contribution will not lead to an incorrect identification of corresponding states, and thus to an incorrect isospin assignment.

In addition to the peaks of 9.50 and 13.22 MeV states identified as $T=0$ in the (p,p') reaction [5], we notice additional peaks in Fig. 2(b2) which are not observed in the spectrum of (^{3}He,t), suggesting that they are also $T=0$ candidates. As the result of a careful comparison, the best agreement with the (^{3}He,t) spectrum was achieved by assuming the $T=0$ and $T=1$ strength distributions shown in Fig. 2(b3) and in Fig. 2(b4), respectively. The $T=0$ nature of the 9.50 and 13.22 MeV states was confirmed. In addition the states at 9.72, 11.16, and 12.99 MeV are suggested as $T=0$ states. We also give a tentative $T=0$ assignment to the 10.73 MeV state, but the simultaneous observation of the state in the (e,e') reaction (see Table I) casts some doubt on this because of the usual suppression of IS $M1$ states in (e,e') scatterings. All of these states are excited in the (p,p') reaction with less intensity than the main $T=0$ state at 9.50 MeV. It is not clear if a peak corresponding to the 10.82 MeV state exists in the (^{3}He,t) spectrum due to limited resolution. It is believed, however, that the state has $T=0$ because no corresponding peak is observed in the (e,e') reaction. As a counterpart to the 15.50 MeV state, there exists a level in the (^{3}He,t) spectrum at $E_x=5.95$ MeV, but a defi-

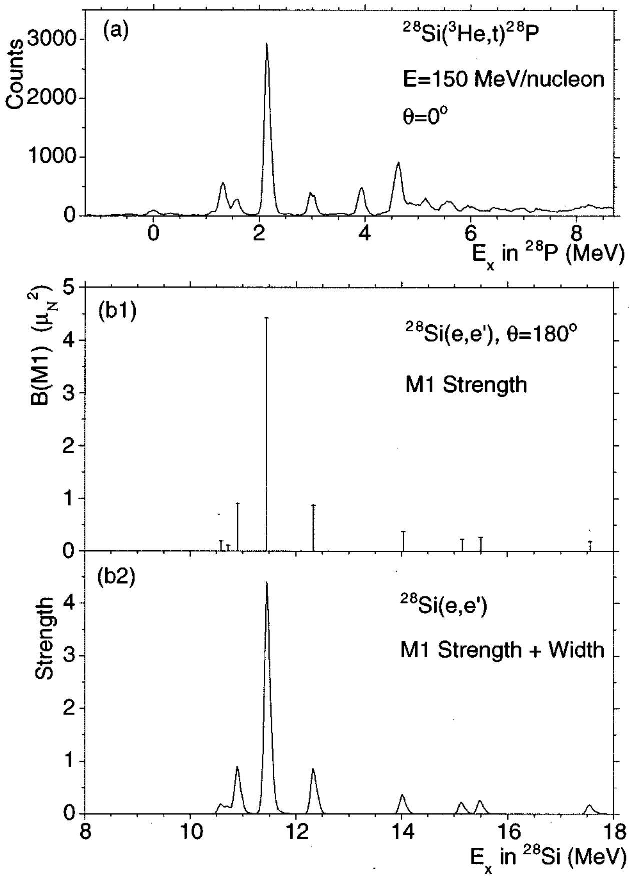

FIG. 3. Comparison between the 0° ^{28}Si(^{3}He,t) spectrum and the strength distribution $B(M1)$ obtained in the ^{28}Si(e,e') experiment [11]. (a) The 0° ^{28}Si(^{3}He,t) spectrum. (b1) $B(M1)$ distribution obtained in the ^{28}Si(e,e') experiment; see text for details. (b2) Reconstructed (e,e') spectrum after convoluting with the experimental energy resolution of the (^{3}He,t) experiment. (b) is shifted relative to (a) with an excitation energy of 9.3 MeV, the amount of Coulomb displacement energy. The ordinates of (a) and (b) are roughly adjusted to reflect the orbital contribution; see text for details.

nite $L=0$ assignment was not possible. No peak corresponding to the 15.80 MeV state is found in the (^{3}He,t) spectrum which would indicate $T=0$ for this state. The isospin values assigned in the present study are summarized in Table I.

Due to the new identification of $T=0$ states, the total IS $B(\sigma)$ value for the (p,p') reaction more than doubles, and seems to fulfill approximately the SM predictions given in Ref. [5]. On the other hand, the $T=1$ strength should decrease accordingly, and we can calculate a quenching factor of $N=0.65$ for the $T=1$ strength by using the $B(\sigma)$ values given in Ref. [5]. The larger quenching for the $T=1$ strength than for the $T=0$ strength suggests that the Δ-h excitation, which causes the quenching only for the IV strength, cannot be excluded as a mechanism for the quenching contrary to the conclusion given in Ref. [5].

B. Decomposition of spin and orbital parts

The $B(M1)$ strength distribution is shown in Fig. 3(b1). By comparing with the ^{28}Si(^{3}He,t) spectrum shown in Fig. 3(a), it is noted that the correspondence of peaks is quite good, much better than for the comparison between (p,p') and (^{3}He,t) [see Fig. 2(b2) and Fig. 2(a)]. This can be understood from the fact that in the (e,e') reaction $T=1$ states are strongly excited, while the $T=0$ states are hindered. The identification of $T=1$ and $T=0$ states made by the comparison between (p,p') and (^{3}He,t) spectra is supported except for the doubtful case of the weak 10.73 MeV level.

TABLE II. The ratio R_{OC} showing the orbital contribution for $T=1$ $M1$ states in ^{28}Si. The experimentally obtained R_{OC}'s are compared with those from shell-model calculations using the USD interaction [35]. Values of $R_{OC}>1$ (<1) suggest constructive (destructive) interference. For the definition of R_{OC}, see text.

Experiment			Shell model	
E_x in ^{28}Si (e,e')	E_x in ^{28}P (^{3}He,t)	R_{OC}	E_x in ^{28}Si	R_{OC}
10.594	1.31	0.26	10.81	0.85
10.901	1.57	2.6	11.19	2.96
11.445	2.15	1.3	11.52	1.53
12.331	2.99	1.7	12.64	0.86
	3.92	0.0	13.37	0.02
14.030	4.61	0.31	14.37	0.54
15.147	5.57	0.84		

It should be noted that the ratio of excitation strengths observed in (^{3}He,t) and (e,e') is rather different for each pair of corresponding states. From the discussion of Sec. II, it is suggested that the difference in the ratio stems from the orbital contribution to the $M1$ operator given in Eq. (2.4) in addition to the spin contribution which is common to both reactions. The orbital part may play a destructive or a constructive role in the excitation of different 1^{+} states, strongly dependent on the wave function of the state [11]. The possibility of separating orbital and spin contributions to the IV $M1$ transitions was proposed by Petrovich *et al.* [2], and a comparison of the (p,n) reaction at 135 MeV with an (e,e') reaction was made by Anderson *et al.* [4] for three levels in ^{28}Si.

Using the B(GT) and $B(M1)$ values listed in Table I, the ratio R_{OC} showing the orbital contribution was calculated for each pair of isobaric analog states using Eq. (2.8) and the value $R_{MEC}=1.3$ [22]. The results are given in Table II. To facilitate comparison of the spectra, the $B(M1)$ strength distribution was convoluted with the peak shape of the ^{28}Si(^{3}He,t) reaction [Fig. 3(b2)]. The ordinates of Figs. 3(a) and (b) are roughly adjusted to reflect the orbital contribution; since the R_{OC} for the main peak at 11.45 MeV (2.15 MeV in ^{28}P) is 1.3, the height of the 11.45 MeV $M1$ peak in Fig. 3(b2) is adjusted to be 1.3 times larger than the corresponding GT peak at 2.15 MeV in ^{28}P. The most extreme case is noted for the 3.92 MeV state in ^{28}P where no noticeable strength is observed in the (e,e') reaction. Also, we see that the strength ratios for the 1.31 MeV and the 1.57 MeV states in ^{28}P are reversed in the (e,e') reaction. Furthermore, the 4.61 MeV state in the (e,e') reaction is reduced to only one third of its strength in the (^{3}He,t) reaction. From the values of R_{OC} given in Table II, destructive interference between spin and orbital contributions is seen for the excitation of the $M1$ states which are the analogs of the GT states at 1.31, 3.92, and 4.61 MeV, while constructive interference is suggested for the 1.57, 2.15, and 2.99 MeV states.

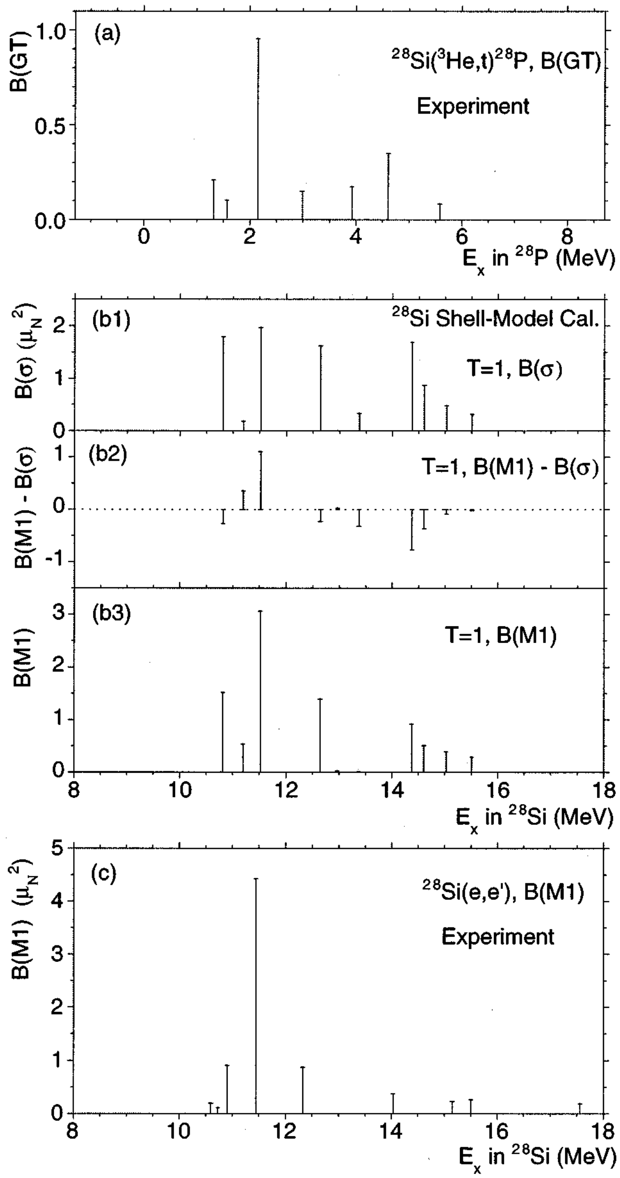

FIG. 4. Comparison between the experimentally obtained and SM calculated $B(\mathrm{GT})$ and $B(M1)$ distributions. (a) The experimental $B(\mathrm{GT})$ distribution from the $^{28}\mathrm{Si}(^3\mathrm{He},t)$ reaction. (b) Results of SM calculations; see text for details. (b1) The $B(\sigma)$ distribution. (b2) Difference between the $B(M1)$ and $B(\sigma)$ strengths, showing the ''effective'' orbital contribution for each state. (b3) The $B(M1)$ distribution. (c) Experimental $B(M1)$ distribution from the (e,e') reaction. (b) and (c) are shifted relative to (a) with an excitation energy of 9.3 MeV, the amount of Coulomb displacement energy. The ordinates of (a) and (c) are roughly adjusted to reflect the orbital contribution.

C. Comparison with shell-model calculations

The experimentally extracted strengths are compared with SM predictions for $T=1$ strength in Fig. 4. The SM calculations were carried out in the full sd model space by using Wildenthal's USD interaction [35] and the computer code OXBASH [36]. The $B(\mathrm{GT})$, $B(\sigma)$, and $B(M1)$ strengths were obtained by applying GT, spin, and $M1$ operators, respectively, on the initial- and final-state wave functions predicted by the USD interaction. The results using free-nucleon operators are presented in Fig. 4(b). The use of effective operators reduces the strengths of all states, but it does not affect the shape of distribution as a function of excitation energy. Furthermore, the calculation shows almost the same shape for the $B(\mathrm{GT})$ and $B(\sigma)$ strength distributions, if the Coulomb displacement energy of 9.3 MeV is applied.

The most impressive feature in the calculation is that for most of the $T=1$ states identified in the present comparison of three reactions, a corresponding SM state is predicted. There is good overall correspondence of the experimentally observed states with those predicted in the SM calculations. In contrast to the good prediction of the excitation energies, the strengths were not so well reproduced. As shown in Fig. 4(b1), the predicted $B(\sigma)$ strengths [and also the corresponding $B(\mathrm{GT})$ strengths; not shown] are somewhat different from the experimental $B(\mathrm{GT})$ strengths shown in Fig. 4(a). The 2.15 MeV state in ^{28}P and the corresponding isobaric analog state at 11.45 MeV state in ^{28}Si dominate the experimental spectra, whereas the SM calculation predicts four strong states. The same was pointed out in the calculation of $B(\mathrm{GT})$ values [7] and in the calculation of $B(\sigma)$ values [5]. A similar tendency is observed in the comparison of (e,e') experimental result [Fig. 4(c)] and the SM calculation for $B(M1)$ [Fig. 4(b3)].

It is interesting to see how the orbital contribution in the $M1$ strengths, which is deduced from the comparison between the (e,e') and $(^3\mathrm{He},t)$ results, is reproduced in the calculation. The difference between the calculated $B(M1)$ values and the $B(\sigma)$ values is shown in Fig. 4(b2). The difference plotted in Fig. 4(b2), therefore, show the ''effective'' contribution of the orbital part of the $M1$ operator. It is interesting to note that the total ''effective'' contribution of the orbital part almost cancels out as mentioned in the earlier paper [11], but the contribution to each state is rather large. As an extreme example, we can point out the following. The 3.92 MeV state in ^{28}P is clearly observed in the $(^3\mathrm{He},t)$ reaction with a $B(\mathrm{GT})$ value of 0.17. Its analog state is expected at around $E_x \approx 13.2$ MeV in ^{28}Si, and was actually found at 13.35 MeV in the (p,p') reaction [5]. In the (e,e') reaction, however, the state is not observed. In the SM calculation a destructive interference of the orbital part is predicted for the 13.4 MeV state in Fig. 4(b2). The expected $B(M1)$ is very small, reproducing the almost total cancellation of the spin part and the orbital part for the state. Similarly the constructive contributions are reproduced for the analogs of the GT states at 1.57 and 2.15 MeV states, and the destructive contributions for the analogs of the GT states at 1.31 and 4.61 MeV. The R_{OC} values calculated from the SM results are given in Table II. It is found that the agreement with the experimental values are generally good.

V. SUMMARY

The $L=0$ spin-flip modes excited on the ground state of an even-even $N=Z$ nucleus with ground-state isospin $T=0$ have a unique isospin structure different from $N\neq Z$ nuclei, since the isospin character of the transition is uniquely defined by the isospin character of the mode being finally excited. Inelastic scattering of protons, e.g., excites both $T=0$

and $T=1$ modes, and they are excited by IS- and IV-type of interactions, respectively. In charge-exchange reactions, however, only the $T=1$ mode is excited by IV-type of interactions. This is the isobaric analog of the $T=1$ mode observed in inelastic scatterings. Using the isospin selectivity of these two types of reactions, i.e., the (p,p') reaction and the $(^3\mathrm{He},t)$ reaction, the isospin $T=0$ or 1 of each $J^\pi=1^+$ state in the $N=Z$ nucleus $^{28}\mathrm{Si}$ was identified. The comparison on a level-by-level basis became possible because of the improved energy resolution of charge-exchange data, i.e., the present $(^3\mathrm{He},t)$ reaction. Some of the states earlier given a $T=1$ assignment are now identified as $T=0$ states. Thus, larger integrated strength is attributed to the isoscalar and less to the isovector $M1$ transitions. The result of rearrangement suggests a non-negligible role of the Δ-h quenching mechanism, which couples to isovector $M1$ transitions only.

In order to study the response to different probes, excitation strengths of the $T=1$ 1^+ states were compared for the $(^3\mathrm{He},t)$ and the (e,e') reactions. In the $(^3\mathrm{He},t)$ reaction at $0°$, the $V_{\sigma\tau}$ part of the effective nuclear interaction is responsible for the excitation of the $T=1$, 1^+ states, while in the (e,e') reaction, the $M1$ operator causing both spin and orbital excitations is responsible. The constructive and destructive effects of the orbital contribution are quite different from state to state, but roughly cancel for the summed strength. The obtained ratios of the $M1$ to the GT matrix elements together with the strength distribution as a function of excitation energy provide a stringent test for the SM calculation. The SM results using the USD interaction could reproduce the excitation energies of the $T=1$, 1^+ states and the ratio of spin and orbital contributions for them, but rather strong concentration of strength to one state, which is observed at 1.31 MeV in the $(^3\mathrm{He},t)$ experiment, was not so well reproduced.

It was demonstrated that the intrinsic structure of $J^\pi=1^+$ states in a self-conjugate nucleus can be established in detail through the comparison of results from different reactions with different selectivity. We believe such an analysis is important for a deeper understanding of the characters of various modes in nuclei.

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