Mirror-symmetry structure of $A=27$, $T=1/2$ nuclei studied through strong, weak, and electromagnetic interactions

Y. Fujita,[1,*] H. Akimune,[2] I. Daito,[2] H. Fujimura,[2] M. Fujiwara,[2] M. N. Harakeh,[3] T. Inomata,[1] J. Jänecke,[4] K. Katori,[1] A. Tamii,[5] M. Tanaka,[6] H. Ueno,[1] and M. Yosoi[5]

[1]Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan

[2]Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan

[3]Kernfysisch Versneller Instituut, Zernikelaan 25, 9747 AA Groningen, The Netherlands

[4]Department of Physics, University of Michigan, Ann Arbor, Michigan 48109

[5]Department of Physics, Kyoto University, Sakyo, Kyoto 606-8224, Japan

[6]Kobe Tokiwa Jr. College, Nagata, Kobe 653-0824, Japan

(Received 1 September 1998)

Gamow-Teller (GT) transitions and $M1$ transitions from or to the ground states are analogous in the pair of $T=1/2$ mirror nuclei, if the excited states hold the mirror-symmetry properties. In order to study the mirror-symmetry structure of the $A=27$ mirror nuclei ^{27}Al and ^{27}Si, experimental data on GT transition strengths obtained from $^{27}\mathrm{Si}\rightarrow{}^{27}\mathrm{Al}$ β decay and from a good-resolution $^{27}\mathrm{Al}(^{3}\mathrm{He},t)^{27}\mathrm{Si}$ reaction at 150 MeV/nucleon and 0° have been compared with $M1$ transition strengths obtained from γ decay in ^{27}Al and $^{27}\mathrm{Al}(\gamma,\gamma')$ reaction. Good overall correspondence of transitions is observed for states up to nearly 9 MeV in excitation energy, where the particle-decay channel becomes important. The difference of excitation energies of analog states in the mirror nuclei are about 250 keV at this excitation energy. From a comparison of $B(M1)$ and $B(\mathrm{GT})$ strengths of the analogous transitions, the contribution of the isoscalar and the orbital terms in the $M1$ operator is found to become prominent in weak $M1$ transitions. [S0556-2813(99)03601-8]

PACS number(s): 21.10.Hw, 23.20.Lv, 25.55.Kr, 27.30.+t

I. INTRODUCTION

The $\Delta L=0$, $\Delta S=1$ spin-flip transitions observed in charge-exchange (CE) reactions are called Gamow-Teller (GT) transitions, while those studied by inelastic-scattering (IE) reactions are called $M1$ transitions [1,2]. Naturally the names of the transitions ''GT'' and ''$M1$'' come from the analogy with GT β decay and $M1\,\gamma$ decay which are caused by the weak and electromagnetic interactions, respectively.

The strengths of GT transitions, $B(\mathrm{GT})$, are important physical quantities in understanding nuclear structures. The most direct information on $B(\mathrm{GT})$ values is obtained from allowed GT β decays, but it is limited by the small accessible range in excitation energy. On the other hand, CE reactions, especially those performed at energies exceeding 100 MeV/nucleon, have been used as a means to map GT strengths over a wider range of excitation energies, relying upon a proportionality between the reaction cross sections at 0° and $B(\mathrm{GT})$ values [3].

The $M1$ transition strengths $B(M1)$ of γ decay are also fundamental quantities. From γ-decay measurements, $B(M1)$ values can be obtained up to the excitation energy where particle decay starts. Above the particle threshold, transition strengths can still be obtained through IE-type reactions. Backward-angle (e,e') experiments are favored. Hadron IE reactions, like the (p,p') reaction at very small scattering angles, can also be used.

If charge symmetry of the nuclear interaction is assumed, then for every state in one of the isospin $T=1/2$, odd-A mirror nuclei, an analog state with very similar structure should be found at a similar excitation energy in the other nucleus. Because of the analogous nature of states in the pair of nuclei, transitions from some state or its analog to another state or its analog are analogous. Therefore, the mirror-symmetry structure of a pair of mirror nuclei can be investigated by combining the information on the energies of analogous transitions and their strengths in hadron IE and CE reactions, β decays, and γ decays and (e,e'), which are caused by the strong, weak, and electromagnetic interactions, respectively.

In this paper, we report on the study of the mirror-symmetry structure of a pair of mirror nuclei, ^{27}Al and ^{27}Si, through the comparison of analogous transitions. As summarized in the compilation by Endt [4], the correspondence of states in this pair has been established in the low-excitation-energy region up to $E_x=5.5$ MeV by comparing spectroscopic information like excitation energies, spins, parities, and branching ratios obtained by γ-decay measurements [5]. A better and more sensitive test for the mirror-symmetry structure is to compare the strengths of the corresponding γ transitions in a pair of mirror nuclei, because it is known that the corresponding $\Delta T=0$ $M1$ transitions are expected to be of approximately equal strength, within a factor of 2, if transitions are of average strength or stronger [6]. The transition strengths $B(M1)$, however, have been compared only for several excited states up to $E_x=4.5$ MeV [7] due to the lack of reliable lifetime measurements for the higher excited states in ^{27}Si.

The excited states of ^{27}Si are reached through (p,n)-type CE reactions on the stable ^{27}Al target. The obtainable $B(\mathrm{GT})$ values are approximately proportional to $B(M1)$ values, as

*Electronic address: fujita@hep.sci.osaka-u.ac.jp

explained in detail in Sec. II. Then they can be compared with the $B(M1)$ values well studied from the γ-decay measurements in ^{27}Al. Early (p,n)-type CE reactions, on the other hand, were not so much suited to extract the spectroscopic information mainly due to the lack of energy resolution to resolve adjacent states of odd-A nuclei at intermediate energies exceeding 100 MeV/nucleon required to map B(GT) strengths. In order to achieve a good resolution for a (p,n)-type CE reaction at intermediate incident energies, it was found that the (^{3}He,t) reaction at an incident energy of 150 MeV/nucleon and at 0° was useful [8]. The good resolution allowed the study of the isospin structures of GT and $M1$ transitions for the $T_0=1$ nucleus ^{58}Ni and $T_0=0$ nucleus ^{28}Si [9,10]. The present study represents an extension of such good-resolution CE work to the $T_0=1/2$ nucleus ^{27}Al.

Assuming an analogous structure of the low-lying states of the pair of mirror nuclei, the B(GT) values known from measurements of β decay from the ^{27}Si ground state (g.s.) to a few low-lying states in ^{27}Al [4] are expected to be equal to the B(GT) values of the analogous transitions obtained in the ^{27}Al(^{3}He,t)^{27}Si reaction. Relying upon the proportionality between the B(GT) value and the cross section at 0°, the B(GT) values of the states at higher excitation energies could also be deduced. The B(GT) values are then compared to the $B(M1)$ values from measurements of γ rays [4] emitted in $M1$ transitions from the analog states in ^{27}Al to the g.s.

II. GT AND $M1$ TRANSITIONS IN MIRROR NUCLEI

In this section, we summarize the analogous nature of states in the pair of mirror nuclei and characteristics of transitions between them.

A. Analog states and analogous transitions

A pair of isospin $T=1/2$ mirror nuclei is characterized by $T_z=\pm 1/2$, where T_z is defined using the proton number Z and neutron number N as $T_z=(1/2)(N-Z)$. All other quantum numbers of corresponding states are the same. Thus, with the assumption that isospin is a good quantum number, for every state in one of the mirror nuclei, an analog state should be found in the other nucleus (see Fig. 1). The energy spectra should be almost identical in the pair of nuclei, although small differences are expected from the state-dependent differences in the Coulomb displacement energies. In addition, the Coulomb displacement energy itself allows the g.s. of the $T_z=-1/2$ nucleus to undergo β decay to the g.s. as well as to several low-lying states of the $T_z=+1/2$ nucleus.

As a result of the analogous nature of corresponding states in the mirror nuclei, four kinds of analogous transitions are expected. These are transitions from an initial to a final state in the same nucleus and all other transitions where the initial and/or the final state is replaced by the respective analog state. Transitions reversing the initial and final states are also possible. Some of the analogous $M1$ and GT transitions from or to the g.s. with spin value $J_{\text{g.s.}}\neq 0$ and with isospin $T=1/2$ are schematically shown in Fig. 1. To which extent mirror nuclei keep the symmetry structure can be investigated by studying the closeness of the energies and the

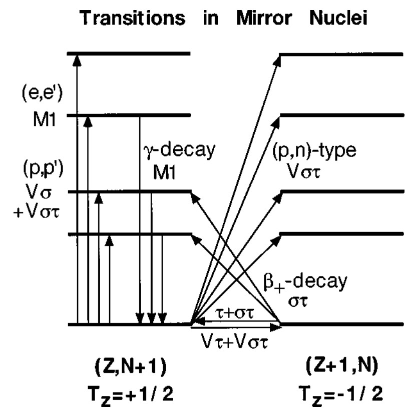

FIG. 1. Schematic level schemes are shown for $T=1/2$, odd-A mirror nuclei. Analogous transitions connecting the ground states in the mirror nuclei with excited states in the same nucleus and the conjugate nucleus are indicated. The type of reaction or decay and the relevant interactions causing each transition are shown along the arrows indicating the transitions.

strengths of the analogous transitions in γ decay, β decay, and CE reactions.

B. GT and $M1$ transition strengths in mirror nuclei

In $L=0$ β decays from the g.s. of the $T_z=-1/2$ nucleus to states in the $T_z=+1/2$ nucleus, GT-type transitions caused by the $\sigma\tau$-type operator are allowed for all decays. In addition, a Fermi-type transition caused by the τ-type operator makes a contribution only to the transition to the g.s., because the ground states are isobaric analog states of each other (see Fig. 1). Since the Fermi strength concentrates in the transition to the isobaric analog state, the full Fermi transition strength $B(\text{F})=1$ is expected for this transition.

In a mirror-nuclei pair, very similar B(GT) values are expected for the corresponding GT transitions studied in a (p,n)-type CE reaction on the g.s. of the $T_z=+1/2$ nucleus and the β_+ decay from the g.s. of the $T_z=-1/2$ nucleus. It is known that the 0° cross sections of hadron CE reactions, like (p,n), (n,p), or (^{3}He,t), performed at intermediate energies exceeding 100 MeV/nucleon are essentially proportional to the B(GT) values observed in β decays [3,8,11,12]. This is because of the simplicity of the reaction mechanism and the dominance of the interaction $V_{\sigma\tau}$ with the $\sigma\tau$-type operator at small momentum transfer [1,13]. We should be careful, however, in using the relationship, because the proportionality is assured only for the allowed GT transitions. It is suggested that the isovector tensor interaction $V_{T\tau}$ enhances the 0° cross sections of ''l-forbidden'' transitions with small B(GT) values [14].

Let us consider the GT and $M1$ transitions where either (1) the initial states with spin $J=J_i$ are analogous and the final state with spin $J=J_f$ is the same or (2) the initial state is the same and the final states are analogous. In the mirror nuclei shown in Fig. 1, we think of the GT transitions in the β_+ decay and the $M1$ transitions studied in the (e,e') reaction in case (1), while in case (2), we think of the (p,n)-type reaction and the (e,e') reaction.

Let us start from the reduced matrix elements in spin but not in isospin and follow the convention of Edmonds [44]. The B(GT) value for the transition from the initial state with spin J_i, isospin T_i, and z component of isospin T_{zi} to the final state with J_f, T_f, and T_{zf} is expressed [15] as

$$B(\mathrm{GT})=\frac{1}{2J_i+1}\left|\langle J_f T_f T_{zf}\| \frac{1}{\sqrt{2}}\sum_{j=1}^{A}(\boldsymbol{\sigma}_j\tau_j^{\pm 1})\|J_i T_i T_{zi}\rangle\right|^2 \tag{2.1}$$

$$=\frac{1}{2J_i+1}\frac{1}{2}C_{\mathrm{GT}}^2\left|\langle J_f T_f\|\sum_{j=1}^{A}(\boldsymbol{\sigma}_j\boldsymbol{\tau}_j)\|J_i T_i\rangle\right|^2, \tag{2.2}$$

where the Wigner-Eckart theorem is applied in the isospin space to obtain the second expression, and C_{GT} is the isospin Clebsch-Gordan (CG) coefficient $(T_i T_{zi} 1 \pm 1 | T_f T_{zf})$. For GT transitions in mirror nuclei, the + and − signs correspond to the β_+ decay and the (p,n)-type reaction, respectively. Since squared values of CG coefficients are the same for the β_+ decay and the analogous (p,n)-type reaction, the same $B(\mathrm{GT})$ values are expected for both of them.

The $M1$ transitions are caused by the magnetic dipole ($M1$) interaction whose operator consists of an orbital part $g_l\boldsymbol{l}$ and a spin part $g_s\boldsymbol{s}$ $[=(1/2)g_s\boldsymbol{\sigma}]$. The $M1$ operator is further rewritten as the sum of isoscalar (IS) and isovector (IV) components (for example, see Refs. [10,15]). Again starting from the reduced matrix elements in spin but not in isospin, the $B(M1)$ value can be written [15]

$$B(M1)=\frac{1}{2J_i+1}\frac{3}{4\pi}\left|\langle J_f T_f T_{zf}\|\{IS\}-\sum_{j=1}^{A}\left(\frac{1}{2}(g_l^{\pi}-g_l^{\nu})\boldsymbol{l}_j+\frac{1}{2}(g_s^{\pi}-g_s^{\nu})\;\frac{1}{2}\boldsymbol{\sigma}_j\right)\tau_j^0\;\;\mu_N\|J_i T_i T_{zi}\rangle\right|^2 \tag{2.3}$$

$$=\frac{1}{2J_i+1}\frac{3}{4\pi}\left|\langle J_f T_f\|\{IS\}-C_{M1}\sum_{j=1}^{A}\left(\frac{1}{2}(g_l^{\pi}-g_l^{\nu})\boldsymbol{l}_j+\frac{1}{2}(g_s^{\pi}-g_s^{\nu})\;\frac{1}{2}\boldsymbol{\sigma}_j\right)\boldsymbol{\tau}_j\;\;\mu_N\|J_i T_i\rangle\right|^2 \tag{2.4}$$

$$=\frac{1}{2J_i+1}\frac{3}{4\pi}\frac{1}{4}(\mu_p-\mu_n)^2\;C_{M1}^2\left|M'(IS)+M'(l)-\langle J_f T_f\|\sum_{j=1}^{A}(\boldsymbol{\sigma}_j\boldsymbol{\tau}_j)\;\|J_i T_i\rangle\right|^2, \tag{2.5}$$

where the Wigner-Eckart theorem is applied in the isospin space to obtain the second expression. The quantity μ_N is the nuclear magneton, and C_{M1} is the isospin CG coefficient $(T_i T_{zi} 10 | T_f T_{zf})$, where $T_{zf}=T_{zi}$ holds for an $M1$ transition. For bare protons and neutrons, the orbital and spin gyromagnetic factors are $g_l^{\pi}=1$, $g_l^{\nu}=0$ and $g_s^{\pi}=5.586$, $g_s^{\nu}=-3.826$, respectively. The coefficient for the $\sigma\tau$ term, and therefore the transition matrix element of this term, is the largest in a usual case. The coefficient is taken out in the third expression. The $M'(\mathrm{IS})$ and $M'(l)$ are the transition matrix elements proportional to the IS term and the IV orbital term, respectively. The relationships $\mu_p=(1/2)g_s^{\pi}\mu_N$ and $\mu_n=(1/2)g_s^{\nu}\mu_N$ are also used.

The ''quasi''proportionality between $B(\mathrm{GT})$ and $B(M1)$, therefore, is expressed as

$$B(M1)\approx\frac{3}{8\pi}(\mu_p-\mu_n)^2\frac{C_{M1}^2}{C_{\mathrm{GT}}^2}B(\mathrm{GT}). \tag{2.6}$$

Here, the numerical factor is $2.643\mu_N^2$ if the magnetic moments of the free nucleons are used. For the transitions between $T=1/2$ states in mirror nuclei, the factor 1/2 is obtained as the ratio of squared CG coefficients.

Discussions on the similarity of analogous γ and β transitions from $T_i=T_>$ members of isospin multiplet states with $T_>=T_f+1$ to the same final state with $T=T_f$ is found, for example, in Refs. [6,16–18]. The formalism presented here also includes the case of analogous $M1$ and GT transitions with $T_i=T_f$.

The ''quasi''proportionality of Eq. (2.6) is disturbed by the constructive or destructive interference of the IS terms with the IV terms in the $M1$ transition. In addition, the orbital term may interfere constructively or destructively with the spin term. These interference effects are strongly dependent on the configuration of the state. In ^{28}Si, for example, even a complete cancellation is observed between the orbital and spin terms [10]. Moreover, as discussed in detail in Refs. [19,20], contributions from meson-exchange currents (MECs) are expected to enhance the IV spin term in the $B(M1)$ strength relative to $B(\mathrm{GT})$ by about 20%–85%.

III. EXPERIMENT AND DATA EVALUATION

A. β-decay data and (^{3}He,t) experiment

From the study for the β decay of the ^{27}Si g.s., log ft values are known for decays to several excited states of ^{27}Al up to $E_x=2.866$ MeV [4,21,22]. $B(\mathrm{GT})$ values are calculated using the relationship [23]

$$B(\mathrm{F})+\left|\frac{g_A}{g_V}\right|^2 B(\mathrm{GT})=\frac{6145\pm 4}{ft(1+\delta_R)(1-\delta_C)}. \tag{3.1}$$

Here, the radiative correction term $(1+\delta_R)=1.014$, the Coulomb correction term $(1-\delta_C)=0.997$, and the ratio $(g_A/g_V)=1.266\pm0.004$ were used [23,24]. The $B(\mathrm{GT})$ values are listed in column 3 of Table I. For the g.s. transition, both GT and Fermi transitions contribute. The $B(\mathrm{GT})$ value for this transition was calculated assuming $B(\mathrm{F})=1$.

In order to map $B(\mathrm{GT})$ to higher excitation energies, a ^{27}Al(^{3}He,t) experiment was performed. A 150 MeV/nucleon ^{3}He beam from the $K=400$ separated-sector cyclotron at RCNP, Osaka University, was used to bombard a 4

TABLE I. The GT transition strengths $B(\mathrm{GT})$ from ^{27}Si $\rightarrow ^{27}$Al β decay and those obtained in the ^{27}Al(^{3}He,t)^{27}Si reaction. Mirror symmetry is assumed for the strengths of these GT transitions in deriving the latter from the former. For details of the derivation, see text. The excitation energies are given in units of MeV.

States in ^{27}Al			States in ^{27}Si		
		β decay		(^{3}He,t) [a]	
E_x [b]	$2J^{\pi}$ [b]	$B(\mathrm{GT})$ [b]	E_x [b]	E_x	$B(\mathrm{GT})$
0.0	5^+	0.307 ± 0.044	0.0	0.0	(0.416 ± 0.035) [c]
1.014	3^+	$2.0\times10^{-4}\pm3\times10^{-5}$	0.957	0.98	(0.005 ± 0.001) [d]
2.211	7^+	0.079 ± 0.006 [e]	2.164	2.17	0.081 ± 0.007
2.735	5^+	0.039 ± 0.004 [e]	2.648	2.65	0.046 ± 0.005
2.982	3^+	0.173 ± 0.012 [e]	2.866	2.88	0.171 ± 0.015
			3.804	3.81	0.079 ± 0.007
			4.289	4.30	0.097 ± 0.009
			4.475	4.49	0.019 ± 0.003 [f]
				5.30	0.024 ± 0.003 [f]
				5.51	(0.007 ± 0.001) [d]
				5.84	(0.008 ± 0.002) [d]
				6.06	0.022 ± 0.003 [f]
				6.35	0.060 ± 0.006
				6.64	0.109 ± 0.010
				7.22	0.086 ± 0.010
				7.45	0.145 ± 0.015
				7.81	0.159 ± 0.016
			8.226 [g]	8.21	0.067 ± 0.008
				8.53	0.075 ± 0.009
				9.00	0.036 ± 0.006
				9.25	0.055 ± 0.009
				9.42	0.023 ± 0.007 [f]
				9.67	0.037 ± 0.007
				9.95	0.063 ± 0.009

[a] Present work.
[b] From Ref. [4].
[c] Including Fermi-transition strength.
[d] $B(\mathrm{GT})$ value seems to be not reliable; see text.
[e] Standard $B(\mathrm{GT})$ value used for calibration.
[f] $B(\mathrm{GT})$ value seems to be less reliable; see text.
[g] From Ref. [28].

mg/cm^{2}Al foil. The beam current of ^{3}He^{2+} particles was $\sim$ 5 nA. The ejectile tritons were analyzed by the QQDD-type spectrometer Grand Raiden [25]. In order to realize good energy resolution, the dispersion-matching technique [26] was used for 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. The ray-trace 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 $\pm$ 10 mr in the x direction (no cut is made in the y direction). With an energy resolution of 160 keV [full width at half maximum (FWHM)], fine structure was observed up to $E_x>10$ MeV. The proton separation energy (S_p) of ^{27}Si is at $E_x=7.46$ MeV. Above this energy, a gradual increase of the underlying continuum was observed.

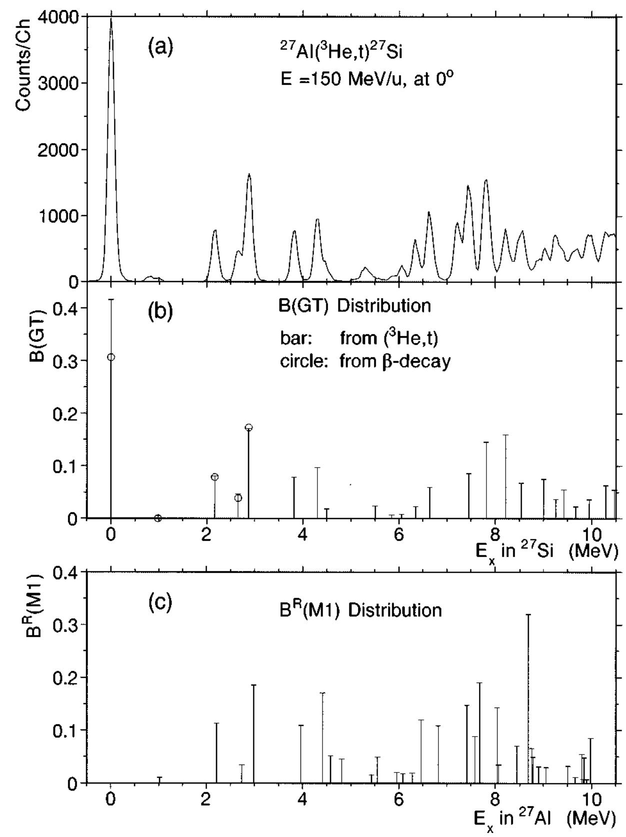

FIG. 2. The ^{27}Al(^{3}He,t) spectrum at 0°, and comparison of the $B(\mathrm{GT})$ strength distribution derived from the ^{27}Al(^{3}He,t) reaction and the $B^R(M1)$ distribution deduced from the measurements of γ transitions in ^{27}Al. (a) The 0° ^{27}Al(^{3}He,t) spectrum. (b) $B(\mathrm{GT})$ strength distribution determined from the present ^{27}Al(^{3}He,t) reaction; see text for details. The $B(\mathrm{GT})$ values from β decay are also shown as circles. The large difference of the $B(\mathrm{GT})$ values to the g.s. is due to the additional contribution from the Fermi transition in the (^{3}He,t) reaction (see text for more details). (c) $B^R(M1)$ strength distribution deduced from the γ-transition data. For the definition of $B^R(M1)$, see text.

The gross features of the ^{27}Al(^{3}He,t) spectrum near 0° are quite similar to those of the 0° ^{27}Al(p,n) spectrum obtained at $E_p=120$ MeV and shown in Ref. [3] for the energy range up to $E_x=5.5$ MeV. This confirms that the (^{3}He,t) reaction at a bombarding energy of 150 MeV/nucleon is a single-step direct reaction. It also suggests that the relevant effective interaction $V_{\sigma\tau}$ is similar for the (p,n) and (^{3}He,t) reactions at a comparable incident energy per nucleon [8,12,27].

The excitation energies were calibrated using well-known low-lying discrete states observed in the ^{12,13}C(^{3}He,t) spectra as reference. Owing to the large negative Q value of the ^{12}C(^{3}He,t) reaction, the excitation energies of ^{27}Si could be determined by interpolation up to 17 MeV. These excitation energies are given in column 5 of Table I. By comparing with literature values compiled by Endt [4] and given in column 4 of Table I, the differences in excitation energies are observed to be less than 20 keV. In addition, in the (p,γ) reaction on an unstable ^{26}Al target [28], a state at 8.226 MeV, which is about 800 keV above the S_p, was identified to have $J^{\pi}=7/2^+$ and was found to decay partly to the g.s. We believe that this state corresponds to the 8.21 MeV state observed in the present (^{3}He,t) reaction, because no other prominent state connected with the $J^\pi=5/2^+$ g.s. by a GT-type transition is observed within 300 keV. Therefore, in the region up to $E_x=10$ MeV, we estimate the uncertainties in the excitation energies to be about 30 keV, and for all cases less than 50 keV.

Cross sections for $L=0$ transitions decrease with increasing scattering angle beyond 0°, whereas those for $L=1$ and higher multipoles increase. The 0° spectrum shown in Fig. 2(a) was compared with a spectrum centered at 1° (not shown). All prominent peaks showed a similar relative decrease in strength, suggesting that they are GT states with $L=0$ characteristics.

Experimental evidence suggests that there exists proportionality between B(GT) values and 0° cross sections of (^{3}He,t) reaction performed at 150 MeV/nucleon [8,10]. Assuming this proportionality, the conversion factor was determined from the 0° cross sections of the strongly excited states at $E_x=2.17$ and 2.88 MeV and the B(GT) values of the corresponding β transitions. As seen from Table I and also from Fig. 2(b), very good proportionality is observed for these two states within the experimental uncertainties. The apparently larger B(GT) value of the g.s. transition in the (^{3}He,t) reaction is due to the additional contribution from the Fermi component corresponding to the transition strength B(F)=1, whereas in deriving the B(GT) value from the β-decay data, the contribution from the Fermi transition has been subtracted.

The B(GT) values of the other GT states observed in the (^{3}He,t) reaction were deduced from the yields for the relevant peaks and the same conversion factor. The yields were obtained accurately by exerting a peak-decomposition program using the peak shape of a well-separated peak as reference. These B(GT) strengths are included in column 6 of Table I and plotted in Fig. 2(b). The errors are mostly due to the uncertainty of the conversion factor as the result of uncertainties in the β-decay B(GT) values used for the calibration. Errors from the peak deconvolution process are also added. A correction for the conversion factor due to a possible dependence on excitation energy is not included. Consulting the systematic study performed for the (p,n) reaction [3], an additional several percent error may have to be considered for the B(GT) values of the states near $E_x=10$ MeV.

The good proportionality observed for transitions with large B(GT) does not appear to be valid for the weakly excited state at 0.98 MeV. Here, the value relying upon the proportionality is more than one order of magnitude larger than the B(GT) value from the β-decay measurement. As mentioned, this enhancement is probably due to the contribution from the $V_{T\tau}$ interaction. Based on this observation, we judge that the small B(GT) values less than 0.01 obtained for the 5.51 and 5.84 states are also not reliable. Since reasonable agreement is observed for the 2.65 MeV state with a B(GT) value of 0.046, it is believed that B(GT) values similar to or larger than this value are reliable. The values $0.01<B(\mathrm{GT})<0.03$ obtained for the states at 4.49, 5.30, 6.06, and 9.42 MeV are, therefore, considered less reliable.

In the ^{27}Al(d,^{2}He) reaction exciting analog states of $T=3/2$ states, the GT transition strength was observed only above $E_x=4.78$ MeV in ^{27}Mg [29], which corresponds to $E_x=11.4$ MeV in ^{27}Si. Therefore, all states below this energy have isospin $T=1/2$.

B. $M1\,\gamma$-transition strength in ^{27}Al

For the study of $\Delta L=0$ and $\Delta S=1$ transition strengths in ^{27}Al, detailed data on $M1\,\gamma$ transitions to the g.s. are available from the compilation by Endt [4]. For each excited state in ^{27}Al, the $M1\,\gamma$-transition strength $B(M1)$ (in units of μ_N^2) to the g.s. is calculated (see, e.g., Ref. [30]) using the known lifetime (mean life) τ_m (in units of sec), gamma-ray branching ratio B (in %) to the g.s., $M1$ and $E2$ mixing ratio δ, and γ-ray energy E_γ (in MeV) as

$$B(M1)=\frac{1}{\tau_m}\frac{1}{E_\gamma^3}\frac{\mathrm{B}}{100}\frac{1}{1+\delta^2}\frac{1}{1.76\times10^{13}}. \tag{3.2}$$

Data on mixing ratios δ are taken from Refs. [4,31]. They are, however, not available for the $E_x=5.433$ and 5.551 MeV states. For these states $\delta=0$ is assumed. It is suggested that this is a good approximation [32], but the $B(M1)$ values for these transitions assuming $\delta=0$ should be considered upper bounds. In order to determine the $B(M1)\uparrow$ values which would be obtained in an (e,e')-type transition from the g.s. with the spin value $J_{\mathrm{g.s.}}$ to the jth excited state with the spin value J_j, the $B(M1)$ values obtained in the γ decay are modified by the $2J+1$ factors of the jth state and the g.s. as

$$B(M1)\uparrow=\frac{2J_j+1}{2J_{\mathrm{g.s.}}+1}B(M1). \tag{3.3}$$

The $B(M1)\uparrow$ values are given in column 3 of Table II.

In addition to the γ-decay data in ^{27}Al, detailed (γ,γ') [nuclear resonance fluorescence (NRF)] data are available for the ^{27}Al target for states above $E_x=2.98$ MeV [32]. Since NRF tends to select levels which can be reached from the g.s. with a dipole operator, the information on $M1$ transitions becomes richer up to a higher excitation region. The $B(M1)\uparrow$ values are calculated from the values of the g.s. radiative width $g\Gamma_0$ (in units of eV):

$$B(M1)\uparrow=86\frac{g\Gamma_0}{E_\gamma^3}\frac{1}{1+\delta^2}, \tag{3.4}$$

where $g=(2J_j+1)/(2J_{\mathrm{g.s.}}+1)$. The $g\Gamma_0$ values used in the calculation (column 4 of Table II) are mostly taken from Ref. [32], but for the states up to $E_x=8.676$ MeV they are recalculated using the branching ratios compiled later in Ref. [4]. Data on mixing ratios δ are not available for the states at 5.433, 5.551, 6.081, 6.821, and 7.677 MeV and for the states with $E_x\geqslant 8.675$ MeV. For these states $\delta=0$ is assumed. The NRF $B(M1)\uparrow$ values are given in column 5 of Table II.

In addition, (e,e') data measuring $B(M1)\uparrow$ values directly are available for five states in the region between $E_x=6.84$ and 8.06 MeV [33]. They can be used to check the validity of the $B(M1)\uparrow$ values calculated from the measurements of γ transitions.

Table II shows rather good agreement within the errors between the γ-decay and NRF $B(M1)\uparrow$ values. The γ-decay

TABLE II. States in ^{27}Al and the deduced $M1$ transition strengths from the g.s. to them. Results of measurement of γ transitions in ^{27}Al and ^{27}Al(γ,γ') are compiled. For details of the derivation of $B(M1)\uparrow$, see text.

			(γ,γ')		
E_x [b] (MeV)	$2J^{\pi}$ [a]	γ decay $B(M1)\uparrow$ (μ_N^2)	$g\Gamma_0$ [b] (meV)	$B(M1)\uparrow$ (μ_N^2)	Adopted value $B(M1)\uparrow$ (μ_N^2)
0.0	5^+	–	–	–	–
1.014	3^+	0.015 ± 0.001			0.015 ± 0.001
2.211	7^+	0.150 ± 0.004			0.150 ± 0.004
2.735	5^+	0.046 ± 0.007			0.046 ± 0.007
2.982	3^+	0.245 ± 0.013	95 ± 26	0.308 ± 0.083	0.245 ± 0.013
3.957	3^+	0.145 ± 0.012	106 ± 12	0.147 ± 0.017	0.145 ± 0.012
4.410	5^+	0.226 ± 0.028	230 ± 31	0.231 ± 0.031	0.226 ± 0.028
4.580	7^+	0.069 ± 0.008	85 ± 9	0.077 ± 0.008	0.069 ± 0.008
4.812	5^+	0.061 ± 0.009	94 ± 13	0.059 ± 0.010	0.061 ± 0.009
5.433	7	0.021 ± 0.007[c]	63 ± 42	0.034 ± 0.023[c]	0.021 ± 0.007
5.551	5^+	0.066 ± 0.012[c]	130 ± 25	0.065 ± 0.013[c]	0.066 ± 0.012
5.960	7	0.028 ± 0.020	114 ± 82	0.045 ± 0.033	0.028 ± 0.020
6.081	3	0.025 ± 0.006[c]	64 ± 13	0.025 ± 0.006[c]	0.025 ± 0.006
6.285	7^+	0.026 ± 0.011	85 ± 36	0.030 ± 0.013	0.026 ± 0.011
6.463	5	0.158 ± 0.019	490 ± 55	0.156 ± 0.018	0.158 ± 0.019
6.533	7^+	$2\times10^{-4}\pm1\times10^{-4}$	222 ± 163	$7\times10^{-4}\pm5\times10^{-4}$	–
6.821	$(3,7)^+$		530 ± 40	0.144 ± 0.011[c]	0.144 ± 0.011
7.413	7^+	0.195 ± 0.018	906 ± 135	0.190 ± 0.028	0.195 ± 0.018
7.578	5^+	0.117 ± 0.026	587 ± 118	0.115 ± 0.023	0.117 ± 0.026
7.677	$(3,5)^+$		996 ± 274	0.189 ± 0.052[c]	0.250 ± 0.080[d]
8.037	7	0.189 ± 0.019	1126 ± 112	0.185 ± 0.019	0.189 ± 0.019
8.065	$(3,5)^+$		280 ± 86	0.046 ± 0.014	0.046 ± 0.014
8.442	7	0.093 ± 0.024	1208 ± 244	0.173 ± 0.035	0.093 ± 0.024
8.675	$(7,9^+)$		3207 ± 866	0.423 ± 0.114	0.423 ± 0.114
8.754	5		680 ± 80	0.087 ± 0.010[c]	0.087 ± 0.010
8.774	5^+		510 ± 120	0.065 ± 0.015[c]	0.065 ± 0.015
8.897	5^+		340 ± 80	0.042 ± 0.010[c]	0.042 ± 0.010
9.052	5^+		340 ± 100	0.039 ± 0.012[c]	0.039 ± 0.012
9.502			430 ± 110	0.043 ± 0.011[c]	0.043 ± 0.011
9.658			160 ± 40	0.015 ± 0.004[c]	0.015 ± 0.004
9.796	7^+		790 ± 430	0.072 ± 0.039[c]	0.072 ± 0.039
9.822	3^+		120 ± 70	0.011 ± 0.006[c]	0.011 ± 0.006
9.840	5		710 ± 160	0.064 ± 0.014[c]	0.064 ± 0.014
9.893			110 ± 60	0.010 ± 0.005[c]	0.010 ± 0.005
9.977	$(5,7)^+$		1300 ± 300	0.113 ± 0.026[c]	0.113 ± 0.026

[a]From Ref. [4].
[b]From Ref. [32] with corrections using branching ratios from Ref. [4].
[c]Mixing ratio $\delta=0$ is assumed.
[d](e,e') result from Ref. [33] is taken into account.

$B(M1)\uparrow$ values based on the compilation by Endt [4] are always adopted when available, because the calculated errors are usually smaller. Others are from NRF, while the value for the 7.677 MeV state is slightly modified to arrive at a consistency with the (e,e') value [33].

It is suggested that the 8.774 MeV state in ^{27}Al is a member of the $T=3/2$ isospin quartet states [4]. We suspect, however, that this state is a $T=1/2$ state, because of the reason given at the end of previous subsection.

IV. DISCUSSIONS

A. Correspondence of states

In earlier works, the symmetry structure in the mirror nuclei ^{27}Al and ^{27}Si was studied through the comparison of excitation energies, spins, parities, and branching ratios obtained in γ-decay measurements up to $E_x=5.5$ MeV [4]. Here the symmetry structure is studied not only from the correspondence of excitation energies, but also from the

TABLE III. Correspondence of states in ^{27}Al and ^{27}Si deduced from the similarity of $M1$ and GT transition strengths. Results of measurement on electromagnetic (EM) transitions [γ transition and (γ,γ')] in ^{27}Al and (^{3}He,t) reaction on ^{27}Al are compared. For details of the definition and derivation of $B^R(M1)$, see text. The excitation energies are given in units of MeV.

States in ^{27}Al			States in ^{27}Si	
E_x [a]	$2J^{\pi}$ [a]	$B^R(M1)$	E_x [b]	B(GT) [b]
0.0	5^+	–	0.0	(0.416 ± 0.035) [c]
1.014	3^+	$0.011\pm5\times10^{-4}$	0.98	(0.005 ± 0.001) [d]
2.211	7^+	0.114 ± 0.003	2.17	0.081 ± 0.007
2.735	5^+	0.035 ± 0.005	2.65	0.046 ± 0.005
2.982	3^+	0.185 ± 0.010	2.88	0.171 ± 0.015
3.957	3^+	0.109 ± 0.009	3.81	0.079 ± 0.007
4.410	5^+	0.171 ± 0.021	4.30	0.097 ± 0.009
4.580	7^+	0.052 ± 0.006	4.49	0.019 ± 0.003 [e]
4.812	5^+	0.046 ± 0.007		
5.433	7	0.016 ± 0.005	5.30	0.024 ± 0.003 [e]
5.551	5^+	0.050 ± 0.009		
			5.51	(0.007 ± 0.001) [d]
5.960	7	0.021 ± 0.015	5.84	(0.008 ± 0.002) [d]
6.081	3	0.019 ± 0.004		
			6.06	0.022 ± 0.003 [e]
6.285	7^+	0.019 ± 0.009		
6.463	5	0.120 ± 0.014	6.35	0.060 ± 0.006
6.821	$(3,7)^+$	0.109 ± 0.008	6.64	0.109 ± 0.010
7.413	7^+	0.148 ± 0.014	7.22	0.086 ± 0.010
7.578	5^+	0.088 ± 0.019	7.45	0.145 ± 0.015
7.677	$(3,5)^+$	0.190 ± 0.020		
8.037	7	0.143 ± 0.015	7.81	0.159 ± 0.016
8.065	$(3,5)^+$	0.035 ± 0.011		
8.442	7	0.070 ± 0.018	8.21	0.067 ± 0.008
8.675	$(7,9^+)$	0.320 ± 0.086		
8.754	5	0.066 ± 0.008 [f]	8.53	0.075 ± 0.009
8.774	5^+	0.049 ± 0.012		
8.897	5^+	0.031 ± 0.007		
9.052	5^+	0.030 ± 0.009		
			9.00	0.036 ± 0.006
9.502		0.033 ± 0.008 [f]	9.25	0.055 ± 0.009
9.658		0.012 ± 0.003 [f]	9.42	0.023 ± 0.007 [e]
9.796	7^+	0.055 ± 0.030		
9.822	3^+	0.008 ± 0.005		
9.840	5	0.049 ± 0.011		
9.893		0.007 ± 0.004		
			9.67	0.037 ± 0.007
9.977	$(5,7)^+$	0.085 ± 0.020		
			9.95	0.063 ± 0.009

[a]From Ref. [4].
[b]Present work.
[c]Including Fermi-transition strength.
[d]B(GT) value seems to be not reliable; see text.
[e]B(GT) value seems to be less reliable; see text.
[f]Correspondence is less certain.

''quasi''proportionality of $B(M1)$ and B(GT) values for the analogous transitions from the ground state of ^{27}Al. In order to compare the strengths directly, it is convenient to modify the $B(M1)\uparrow$ values obtained from the study of electromagnetic transitions into values directly comparable with the B(GT) values from the CE reactions and β decay. Based on Eq. (2.6), the following modifications are performed: (1) the $B(M1)\uparrow$ values are divided by the numerical factor $2.643\mu_N^2$

for the conversion of different coupling constants in $M1$ and GT transitions, and (2) these values are multiplied by a factor of 2 compensating for the different isospin CG coefficients. We call the modified $B(M1)$ values to be compared to the B(GT) values renormalized $B(M1)$ values and use the notation $B^R(M1)$. The evaluated $B^R(M1)$ values are listed in column 3 of Table III and shown in Fig. 2(c).

From the comparison of Fig. 2(b) showing the B(GT) distribution and Fig. 2(c) showing the $B^R(M1)$ values, it is clear that the overall correspondence of the two strength distributions is good up to around $E_x=8.5$ MeV in ^{27}Al. Our further aim is to establish a level-by-level correspondence from the similarity of the transition strengths and the excitation energies of states in the pair of nuclei. The advantage of the present comparison is that the level spacing of states is reasonable, since correspondence should be found only for these states selectively connected by the $M1$ and GT transitions from the g.s. of ^{27}Al. In establishing the correspondence, it is important to think of the fact that the Coulomb displacement energies can depend on the excitation energy. There is a tendency that a state in ^{27}Si is found at a lower excitation energy than the corresponding state in ^{27}Al, and the difference in the excitation energies gradually increases as a function of excitation energy. For example, the analog to the 8.44 MeV state in ^{27}Al seems to shift to lower energy of 8.21 MeV in ^{27}Si. In addition to the ''shift,'' it is known that the Coulomb displacement energies depend on the configurations of the respective states [34,35], and an energy ''fluctuation'' of about 50 keV can be expected. A consistent correspondence in transition strengths and in excitation energies is seen only if ''shifts'' and ''fluctuations'' in excitation energy are taken into account.

It is observed that the best overall agreement is attained for the two strength distributions if the correspondence of states shown in Table III is considered. Some of the peaks observed in the (^{3}He,t) reaction as single peaks are resolved into doublet states owing to much better resolution of the γ-decay measurements. In such a case, the probable correspondence is indicated in Table III by the } sign. Above $E_x=8.5$ MeV, however, the level-by-level correspondence becomes less clear. At higher energies, the J^π assignment from the measurement of γ transitions becomes less reliable, and no data on the mixing ratio are available. This suggests that some of the transitions can be dominantly $E2$ transitions. In addition, above the S_p of 8.27 MeV in ^{27}Al, the proton decay starts to compete with the γ decay, which makes the γ measurements less reliable. For example, for the state at 8.675 MeV carrying a large $B^R(M1)$ value, it appears that no corresponding state with comparable B(GT) strength is observed in the (^{3}He,t) reaction.

B. Excitation energies

Based on the correspondence of states listed in Table III, systematics of the differences of excitation energies $\Delta E_x(^{27}\text{Al-}^{27}\text{Si})$ has been investigated. For doublets, a centroid energy is used. The result is plotted (open circles) in Fig. 3 as a function of E_x in ^{27}Si and compared with the compilation of Ref. [4] (solid squares). It is clear that the ΔE_x values generally increase as E_x increases; a relationship $\Delta E_x=0.028E_x$ is found. The increased differences at higher excitation energies seem to be ascribed to Thomas-Ehrman (TE) shift [36,37]. Since the S_p in ^{27}Si (7.46 MeV) is much lower than the neutron separation energy (S_n) in ^{27}Al (13.06 MeV), it is expected that the proton wave function in ^{27}Si extends farther outside the nucleus. The modification in the wave function due to the Coulomb force, therefore, is expected to be larger and will cause a larger TE shift [34,35].

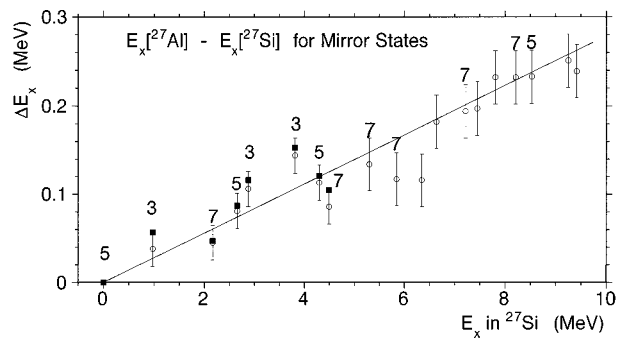

FIG. 3. The difference of excitation energies $\Delta E_x(^{27}\text{Al-}^{27}\text{Si})$ as a function of E_x in ^{27}Si. The ΔE_x values derived from the E_x values in the (^{3}He,t) reaction (open circles) and those from compilation [4] (solid squares) are plotted. The increase of the ΔE_x values as a function of E_x is roughly given by the relationship $\Delta E_x=0.028E_x$ as indicated by the solid line. The $2J$ values are shown for the states for which definite J values are known from Ref. [4].

A wavy pattern is clearly seen for the ΔE_x values in the region below $E_x=7$ MeV. It is found that this wavy structure below 5 MeV is attributed to the dependence of the ΔE_x values on the J values of states. This can be seen from the $2J$ values given in Fig. 3. Typically $J=3/2$ states have about 30 keV larger ΔE_x than $J=5/2$ states, while $J=7/2$ states have 20 keV smaller values.

C. Strengths

Although we have seen a good overall correspondence for the states in ^{27}Al and in ^{27}Si through the comparison of the $B^R(M1)$ and the B(GT) distributions, there are noticeable differences in the excitation strengths of the corresponding states in a level-by-level comparison. Since all transitions are among $T=1/2$ states, the differences can be attributed to the different nature of the operators involved in the γ decay and the (^{3}He,t) reaction. The CE reaction is of pure IV nature, and it is known that at 0° and at intermediate incident energies the effective operator is to a very good approximation of the $\sigma\tau$ type [1,13] except for very weak transitions. On the other hand, the $M1$ operator includes the IS and the IV components, and each of these contains an orbital term in addition to the spin term, as shown in Eq. (2.4). Thus, in an $M1$ transition between states with $T=1/2$, not only the dominant IV spin term but also the minor IS term can make some contributions. Furthermore, the orbital contribution, although usually believed to be small, can sometimes be significant [10]. Since the contributions of IS term and IV orbital term to the IV spin term are either constructive or destructive depending on the structure of the state, it is stated that differences in strengths by up to $\sim$50% might be expected compared to a pure GT transition [6,38].

The IS and orbital contributions, however, cannot explain the fact that the $B^R(M1)$ values are as a whole larger than the corresponding $B(\mathrm{GT})$ values as seen from the comparison of Figs. 2(b) and 2(c). Contributions from MECs are known to enhance $B(M1)$ strength over the corresponding $B(\mathrm{GT})$ strength [10,19,20,39,40]. The enhancement is traced back to larger and additive contributions of the vector MECs over the axial-vector MECs which are active in $M1$ and GT transitions, respectively [41]. In order to remove the constructive and destructive contributions of both IS and orbital terms, it was proposed to sum up the strengths over a wide range of excitation energy [19]. Such cancellation of orbital contributions is rather well seen in a shell-model calculation [42] and also observed in an experiment on a ^{28}Si target [10]. We assume the cancellation also for the IS contribution, which is expected to be small [6]. The cumulative sums of $B^R(M1)$ and $B(\mathrm{GT})$ values were calculated for the states with reliable $B(\mathrm{GT})$ values and good correspondence in the region up to $E_x=8.2$ MeV in ^{27}Si. Using the values given in Table III, the enhancement factor R_{MEC} defined by

$$R_{\mathrm{MEC}}=\frac{\sum B^R(M1)}{\sum B(\mathrm{GT})} \tag{4.1}$$

is found to be 1.4. Since the sum is for a limited region in excitation energy, it is not appropriate to extract any definite conclusion for the factor R_{MEC}. We should stress, however, that the value R_{MEC} obtained above is consistent with previous values of 1.20–1.85 [10,19,20,39,40], which were obtained for the pure IV ($\Delta T=1$) transitions starting from even-even self-conjugate nuclei ^{24}Mg and ^{28}Si.

By comparing the $B(M1)$ and the $B(\mathrm{GT})$ strengths of the analogous transitions starting from the $T=0$ target nucleus ^{28}Si, the orbital contribution in the $B(M1)$ strength was deduced for each $M1$ transition [10]. Similarly by comparing the analogous $B(M1)$ and $B(\mathrm{GT})$ strengths of the $\Delta T=0$ transitions in $T=1/2$ mirror nuclei, it is possible to extract the combined contribution of the IS term and the IV orbital term in the $B(M1)$ strength. Since the effect of MEC should be independent of the wave function of the individual state, the ratio of $B^R(M1)$ and $B(\mathrm{GT})$ for the jth pair of corresponding states divided by R_{MEC},

$$R^j_{\mathrm{ISO}}(M1/\mathrm{GT})=\frac{B^R_j(M1)}{B_j(\mathrm{GT})}\frac{1}{R_{\mathrm{MEC}}}, \tag{4.2}$$

should show the combined IS-orbital contribution to the jth $M1$ transition and indicate how the IV spin term is modified. The R_{ISO} should be greater than unity if the combined contributions are constructive and less for the destructive case. Using the $B^R(M1)$ and $B(\mathrm{GT})$ values listed in Table III and the value $R_{\mathrm{MEC}}=1.4$, the R_{ISO} ratios were calculated for those $M1$ transitions for which the corresponding GT transitions are observed as singlets with rather reliable $B(\mathrm{GT})$ values. The results are shown in Fig. 4 for the $M1$ transitions in ^{27}Al as a function of $B(M1)\uparrow$ value. It is interesting to note that the R_{ISO} value tends to deviate from unity by more than a factor of 2 when the $B(M1)\uparrow$ is less than approximately 0.1. This shows that the combined IS-orbital contribution is rather large in weaker transitions and the ''quasi''proportionality of the $B(M1)$ values for $\Delta T=0$ $M1$ transitions and the analogous $B(\mathrm{GT})$ values is lost. This finding is interpreted as follows; since the IS term and the IV orbital term are always small, the dominance of the IV spin term of the $M1$ operator is guaranteed if the transitions are at least of average strength. The IV spin term, however, can also be small. Then the relative contribution of the IS term and the IV orbital term becomes significant although the transition itself is weak. A similar discussion applies to the corresponding $\Delta T=0$ $M1$ transitions in mirror nuclei [6,43].

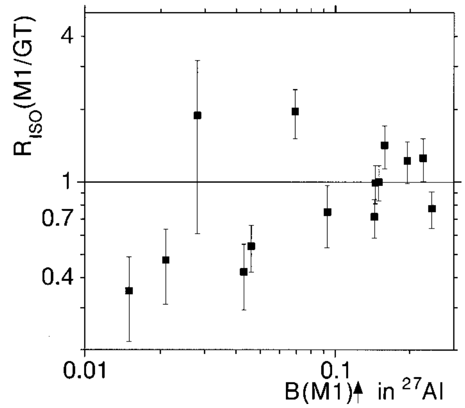

FIG. 4. The ratio R_{ISO} for the $M1$ transitions in ^{27}Al. The ratio is sensitive to the combined contribution of IS term and IV orbital term to each $M1$ transition. Values of $R_{\mathrm{ISO}}>1$ (<1) suggest constructive (destructive) interference of these terms with the IV spin term. For the definition of R_{ISO}, see text.

V. SUMMARY

The mirror-symmetry structure of the pair of $A=27$ mirror nuclei ^{27}Al and ^{27}Si was studied through comparison of $\Delta L=0$, $\Delta S=1$ transitions within and between these nuclei, which are respectively called $M1$ and GT transitions. The known $B(\mathrm{GT})$ distribution obtained from the β-decay measurements of ^{27}Si was extended by using data from the present ^{27}Al(^{3}He,t)^{27}Si experiment with good energy resolution measured at 0° and intermediate bombarding energy. The extended $B(\mathrm{GT})$ distribution was then compared with the $B(M1)$ distribution obtained from $M1\gamma$ transitions in ^{27}Al and the ^{27}Al(γ,γ') reaction.

From the similarity of the strength distributions of the transitions, a good correspondence of the structure in the ^{27}Al-^{27}Si mirror pair was established up to excitation energies of $E_x\approx 9$ MeV where the proton-decay channel becomes important in ^{27}Al. The difference in excitation energies of corresponding states is about 250 keV at this excitation energy. The difference is approximately proportional to the excitation energy, but it also depends on J values.

From a comparison of $B(M1)$ and $B(\mathrm{GT})$ strengths of the analogous transitions, the MEC contributions and the combined IS-orbital contributions in the $M1$ transitions were deduced. By comparing the cumulative sums of renormalized $B^R(M1)$ and $B(\mathrm{GT})$ values, it is suggested that the MEC contributions enhance the $M1$ transition rates by a factor of $\sim$ 1.4. This is consistent with values previously determined for the pure $\Delta T=1$ transitions starting from $T=0$ even-even nuclei. The combined contributions of the IS term and the IV orbital term were deduced for the $\Delta T=0$ $M1$ transitions in ^{27}Al. The contribution becomes significant in weak $M1$ transitions with the decrease of the contribution from the IV spin term of the $M1$ operator.

ACKNOWLEDGMENTS

The authors are grateful to the accelerator group of RCNP, especially to Prof. K. Hatanaka, Prof. K. Hosono, and Prof. T. Saito, for their efforts in providing a high-quality ^{3}He beam indispensable for the realization of dispersion matching to achieve good energy resolution. One of the authors (Y.F.) acknowledges discussions with Prof. H. Ejiri (RCNP), Prof. S. S. Hanna (Stanford), Prof. K. Muto (TIT), Prof. A. Richter (TU Darmstadt), Prof. I. S. Towner (Queen's University), and Prof. K. Tamura (RCNP). The ^{27}Al(^{3}He,t)^{27}Si experiment was performed at RCNP, Osaka University under the Experimental Program No. E54. The present work was performed partly under the auspices of the U.S.-Japan cooperative science program by JSPS and NSF.

[1] F. Osterfeld, Rev. Mod. Phys. **64**, 491 (1992), and references therein.

[2] J. Rapaport and E. Sugarbaker, Annu. Rev. Nucl. Part. Sci. **44**, 109 (1994).

[3] T. N. Taddeucci, C. A. Goulding, T. A. Carey, R. C. Byrd, C. D. Goodman, C. Gaarde, J. Larsen, D. Horen, J. Rapaport, and E. Sugarbaker, Nucl. Phys. **A469**, 125 (1987).

[4] P. M. Endt, Nucl. Phys. **A521**, 1 (1990); P. M. Endt, *ibid.* **A633**, 1 (1998), and references therein.

[5] W. A. Sterrenburg and G. van Middelkoop, Nucl. Phys. **A291**, 269 (1977).

[6] E. K. Warburton and J. Weneser, in *Isospin in Nuclear Physics*, edited by D. H. Wilkinson (North-Holland, Amsterdam, 1969), Chap. 5, and references therein.

[7] P. Tikkanen, J. Keinonen, V. Karttunen, and A. Kuronen, Nucl. Phys. **A456**, 337 (1986).

[8] M. Fujiwara, H. Akimune, I. Daito, H. Ejiri, Y. Fujita, M. B. Greenfield, M. N. Harakeh, T. Inomata, J. Jänecke, S. Nakayama, N. Takemura, A. Tamii, M. Tanaka, H. Toyokawa, and M. Yosoi, Nucl. Phys. **A599**, 223c (1996).

[9] Y. Fujita, H. Akimune, I. Daito, M. Fujiwara, M. N. Harakeh, T. Inomata, J. Jänecke, K. Katori, H. Nakada, S. Nakayama, A. Tamii, M. Tanaka, H. Toyokawa, and M. Yosoi, Phys. Lett. B **365**, 29 (1996).

[10] Y. Fujita, H. Akimune, I. Daito, M. Fujiwara, M. N. Harakeh, T. Inomata, J. Jänecke, K. Katori, C. Lüttge, S. Nakayama, P. von Neumann-Cosel, A. Richter, A. Tamii, M. Tanaka, H. Toyokawa, H. Ueno, and M. Yosoi, Phys. Rev. C **55**, 1137 (1997).

[11] C. D. Goodman, C. A. Goulding, M. B. Greenfield, J. Rapaport, D. E. Bainum, C. C. Foster, W. G. Love, and F. Petrovich, Phys. Rev. Lett. **44**, 1755 (1980).

[12] I. Bergqvist, A. Brockstedt, L. Cárlen, L. P. Ekström, B. Jakobsson, C. Ellegaard, C. Gaarde, J. S. Larsen, C. Goodman, M. Bedjidian, D. Contardo, J. Y. Grossiord, A. Guichard, R. Haroutunian, J. R. Pizzi, D. Bachelier, J. L. Boyard, T. Hennino, J. C. Jourdain, M. Roy-Stephan, M. Boivin, and P. Radvanyi, Nucl. Phys. **A469**, 648 (1987).

[13] W. G. Love and M. A. Franey, Phys. Rev. C **24**, 1073 (1981).

[14] B. D. Anderson, A. R. Baldwin, P. Baumann, B. A. Brown, F. Didierjean, C. C. Foster, L. A. C. Garcia, A. Huck, A. Knipper, R. Madey, D. M. Manley, G. Marguier, M. Ramdhane, H. Ravn, C. Richard-Serre, G. Walter, and J. W. Watson, Phys. Rev. C **54**, 602 (1996).

[15] L. Zamick and D. C. Zheng, Phys. Rev. C **37**, 1675 (1988).

[16] D. Kurath, Argonne National Laboratory Report, No. ANL-7108, p. 61.

[17] M. Sakai, R. Bertini, and C. Gehringer, Nucl. Phys. **A157**, 113 (1970).

[18] H. Ejiri and M. J. A. de Voigt, *Gamma-ray and Electron Spectroscopy in Nuclear Physics* (Clarendon, Oxford, 1989), and references therein.

[19] A. Richter, A. Weiss, O. Häusser, and B. A. Brown, Phys. Rev. Lett. **65**, 2519 (1990).

[20] C. Lüttge, P. von Neumann-Cosel, F. Meumeyer, C. Rangacharyulu, A. Richter, G. Schrieder, E. Spamer, D. I. Sober, S. K. Matthews, and B. A. Brown, Phys. Rev. C **53**, 127 (1996); (private communication).

[21] F. M. Mann and R. W. Kavanagh, Nucl. Phys. **A235**, 299 (1974).

[22] W. W. Daehnick and R. D. Rosa, Phys. Rev. C **31**, 1499 (1985).

[23] I. Towner, E. Hagberg, J. C. Hardy, V. T. Koslowsky, and G. Savard, in *Proceedings of the International Conference on the Exotic Nuclei and Atomic Masses*, ENAM95, Arles, 1995, edited by M. de Saint Simon and O. Sorlin (Editions Frontieres, Gif-sur-Yvette, 1996), p. 711; I. Towner (private communication).

[24] D. H. Wilkinson, Nucl. Instrum. Methods Phys. Res. A **335**, 172 (1993).

[25] M. Fujiwara *et al.*, Research Center for Nuclear Physics, Annual Report, 1991, p. 173.

[26] Y. Fujita, K. Hatanaka, G. P. A. Berg, K. Hosono, N. Matsuoka, S. Morinobu, T. Noro, M. Sato, K. Tamura, and H. Ueno, Nucl. Instrum. Methods Phys. Res. B **126**, 274 (1997), and references therein.

[27] C. Ellegaard, C. Gaarde, J. S. Larsen, C. Goodman, I. Bergqvist, L. Carlén, P. Ekström, B. Jakobsson, J. Lyttkens, M. Bedjidian, M. Chamcham, J. Y. Grossiord, A. Guichard, M. Gusakow, R. Haroutunian, J. R. Pizzi, D. Bachelier, J. L. Boyard, T. Hennino, J. C. Jourdain, M. Roy-Stephan, M. Boivin, and P. Radvanyi, Phys. Rev. Lett. **50**, 1745 (1983).

[28] L. Buchmann, M. Hilgemeier, A. Krauss, A. Redder, C. Rolfs, H. P. Trautvetter, and T. R. Donoghue, Nucl. Phys. **A415**, 93 (1984).

[29] T. Niizeki, H. Ohnuma, T. Yamamoto, K. Katoh, T. Yamashita, Y. Hara, H. Okamura, H. Sakai, S. Ishida, N. Sakamoto, H. Otsu, T. Wakasa, T. Uesaka, Y. Satou, T. Fujita, T. Ichihara, H. Orihara, H. Toyokawa, K. Hatanaka, S. Kato, S. Kubono, and M. Yosoi, Nucl. Phys. **A577**, 37c (1994); T. Niizeki (private communication).

[30] H. Morinaga and T. Yamazaki, *In Beam Gamma-Ray Spectroscopy* (North Holland, Amsterdam, 1976), and references therein.

[31] M. Lickert, J. Brenneisen, F. Glatz, D. Grathwohl, A. Martinez v. Remisowski, H. Röpke, J. Siefert, and B. H. Wildenthal, Z. Phys. A **331**, 409 (1988).

[32] R. Vodhanel, R. Moreh, W. C. Sellyey, M. K. Brussel, and B. H. Wildenthal, Phys. Rev. C **35**, 921 (1987).

[33] C. Rangacharyulu, G. Kuechler, A. Richter, and E. Spamer, Astrophys. J. **320**, 405 (1987).
[34] J. Jänecke, in *Isospin in Nuclear Physics*, edited by D. H. Wilkinson (North-Holland, Amsterdam, 1969), Chap. 8.
[35] N. Auerbach, Phys. Rep. **98**, 273 (1983).
[36] R. G. Thomas, Phys. Rev. **81**, 148 (1951).
[37] J. B. Ehrman, Phys. Rev. **81**, 412 (1951).
[38] S. S. Hanna, in *Isospin in Nuclear Physics*, edited by D. H. Wilkinson (North-Holland, Amsterdam, 1969), Chap. 12.
[39] P. von Neumann-Cosel, A. Richter, Y. Fujita, and B. D. Anderson, Phys. Rev. C **55**, 532 (1997).
[40] Y. Fujita, H. Akimune, I. Daito, M. Fujiwara, M. N. Harakeh, T. Inomata, J. Jänecke, K. Katori, C. Lüttge, S. Nakayama, P. von Neumann-Cosel, A. RIchter, A. Tamii, M. Tanaka, H. Ueno, and M. Yosoi, Nucl. Instrum. Methods Phys. Res. A **402**, 371 (1998).
[41] I. S. Towner and F. C. Khanna, Nucl. Phys. **A399**, 334 (1983).
[42] M. Hino, K. Muto, and T. Oda, J. Phys. G **13**, 1119 (1987).
[43] G. Morpurgo, Phys. Rev. **110**, 721 (1958); **114**, 1075 (1959).
[44] A. A. Edmonds, *Angular Momentum in Quantum Mechanics* (Princeton University Press, Princeton, NJ, 1960).