Large Isospin Asymmetry in ^{22}Si/^{22}O Mirror Gamow-Teller Transitions Reveals the Halo Structure of ^{22}Al

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β-delayed one-proton emissions of ^{22}Si, the lightest nucleus with an isospin projection $T_z = -3$, are studied with a silicon array surrounded by high-purity germanium detectors. Properties of β-decay branches and the reduced transition probabilities for the transitions to the low-lying states of ^{22}Al are determined. Compared to the mirror β decay of ^{22}O, the largest value of mirror asymmetry in low-lying states by far, with $\delta = 209(96)$, is found in the transition to the first 1^+ excited state. Shell-model calculation with isospin-nonconserving forces, including the $T = 1$, $J = 2$, 3 interaction related to the $s_{1/2}$ orbit that introduces explicitly the isospin-symmetry breaking force and describes the loosely bound nature of the wave functions of the $s_{1/2}$ orbit, can reproduce the observed data well and consistently explain the observation that a large δ value occurs for the first but not for the second 1^+ excited state of ^{22}Al. Our results, while supporting the proton-halo structure in ^{22}Al, might provide another means to identify halo nuclei.

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The elegant concept of isospin symmetry is of fundamental importance in nuclear and elementary particle physics. Since isospin symmetry implies strict selection rules for the superallowed Fermi β decay, its measurements have served as a test for electroweak interactions [1,2] such as the unitarity for the up-down quark-mixing element of the Cabibbo-Kobayashi-Maskawa matrix. Because of the mass difference of up and down quarks and their different electromagnetic interactions [3], this symmetry is known to be approximate. As a β-decay process changes an up quark to a down quark or vice versa, studies of nuclei with exchanged numbers of neutrons and protons, known as mirror nuclei, can be a powerful means to probe isospin-symmetry breaking. In two recent examples [4,5], evidence of a mirror-symmetry violation for the ground state in the ^{73}Br/^{73}Sr partner is reported and discussed.

If isospin symmetry would be strictly held, a pair of mirror nuclei should have identical behavior. In Gamow-Teller (GT) transitions, the reduced transition probability ft^+ value of β^+ decay in a proton-rich nucleus should be identical to the ft^- value of β^- decay in its mirror partner nucleus. The extent of isospin-symmetry breaking can be quantified through the asymmetry parameter $\delta = ft^+/ft^- - 1$. A large mirror asymmetry in ft value of GT transitions is believed to be closely related to the structure of proton-halo nuclei due to the difference between the radial wave functions of the initial state $|i\rangle$ and the final state $|f\rangle$ in the nuclear matrix element $M_{fi}^{\mathrm{GT}} = \langle f|\tau\sigma|i\rangle$. This difference appears because, when moving from tightly bound stable systems to loosely bound exotic ones, modifications to the spacing and sequence of single-particle states, as well as the contents of the corresponding wave functions, are expected. Near the driplines, a general view of the density distributions in different single-particle orbitals suggests that those with longer tails have smaller separation energies [6]. Although the tail of proton halos is usually shorter than the tails of neutron halos for the same separation energy due to the Coulomb barrier, the slope of the distributions depends strongly on the orbital angular momentum.

For most of the nuclei in p and sd shells, the observed mirror asymmetries are not large [7]. Interestingly, a large asymmetry, $\delta = -51(10)\%$, has been found for $A = 26$ extracted from the GT transitions in the β decay of ^{26}P and the analog transition in decay of its mirror nucleus ^{26}Na [8]. The extended interesting discussion is whether this large isospin asymmetry relates to the existence of a halo nucleus. Possible evidence of a proton halo of ^{26}P by β decay has been discussed but without theoretical support [8]. A quantitative explanation for the large mirror asymmetry in ^{26}P-^{26}Na was recently provided by Kaneko *et al.* [7]. The $\delta = -51(10)\%$ was accurately reproduced by shell-model calculations with inclusion of $J \neq 0$ isospin-nonconserving (INC) forces related to the $s_{1/2}$ orbit into the isospin-conserving USDA interaction [9] for the sd shell-model space [7,10].

Finding a nucleus at the proton dripline with larger isospin breaking would be inspiring, particularly in the low-lying states from which different structural effects could be more clearly disentangled. Together with calculations, it could not only deepen our understanding of the underlying mechanism of asymmetry but also provide a pathway for further investigations of its relation to halo structure. Regarding the latter, one might address whether it is possible to use the quantity of isospin asymmetry in β-decay transitions to identify and study halo nuclei as a complementary measurement to the large total reaction cross sections and the narrow momentum distributions in breakup reactions.

^{22}Si is the lightest nucleus, with an isospin projection of $\mathrm{T}_z = -3$. Its β^+-decay daughter nucleus ^{22}Al is a candidate of proton-halo nucleus because of its extremely small proton separation energy [10,11]. Therefore, a very large isospin asymmetry is expected in the GT transition in β^+ of ^{22}Si and its mirror β^- of ^{22}O. In this Letter, we present a precise measurement of decay properties of ^{22}Si-^{22}Al and compare it to the data of β decay of ^{22}O [12]. The result is interpreted using shell-model calculations with INC forces.

The measurement of β-delayed one-proton emissions from ^{22}Si was performed at the Heavy Ion Research Facility in Lanzhou (HIRFL). A primary beam ^{28}Si was accelerated to 75.8 MeV$/u$ by HIRFL cyclotrons and then fragmented on a 1500 μm ^{9}Be target. Secondary ions were separated by the first Radioactive Ion Beam Line (RIBLL1) [13] and identified by the combination of energy loss and time of flight. The ions of ^{22}Si were finally implanted into a silicon array [14] surrounded by clover-type high-purity germanium (HPGe) detectors. The schematic layout of the detection setup can be found in Ref. [14]. The silicon array [14], which has been successfully employed in the previous β-decay experiments [14–22], was composed of two thin double-sided silicon strip detectors (DSSDs) and several quadrant silicon detectors (QSDs). DSSD1 of 149 μm thickness and DSSD2 of 66 μm served to measure energy-time-position correlations between the implantation of ^{22}Si and its decay. The 314 μm thick QSD1 placed behind DSSD2 was used for anticoincidence of the penetrating fragments and measurement of high-energy protons escaping from DSSD2, while the 1546 μm thick QSD2 was employed for β measurements. Another two QSDs were installed at the end to veto the possible disturbances from the penetrating light particles coming along with the beam. The implanted ions were identified on an event-by-event basis, and the accurate number of the implanted ^{22}Si and the subsequent decay, as well as the absolute proton and γ-ray intensities, were determined accordingly. The analysis procedures and the implantation-decay correlation have been discussed in detail in Refs. [14,17].

Figure 1 shows the charged-particle spectra within the time window of 100 ms after ^{22}Si implantation measured by

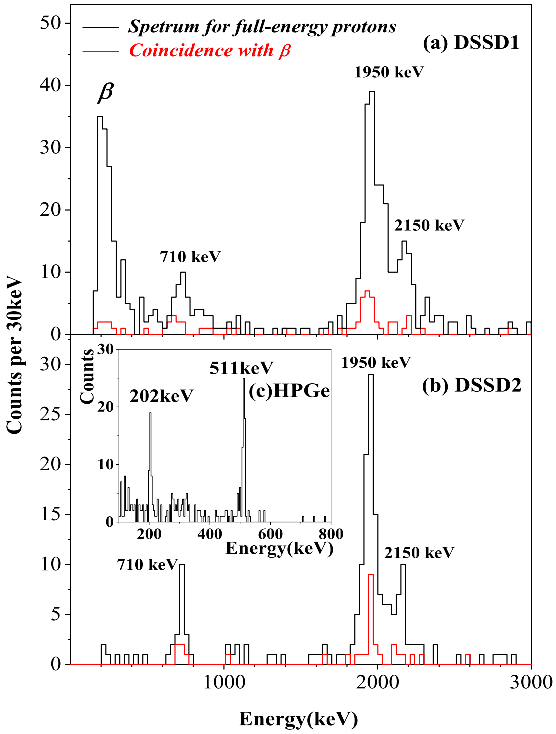

FIG. 1. Energy spectrum of β-delayed proton from ^{22}Si decay measured by (a) DSSD1 (149 μm), (b) DSSD2 (66 μm). Black line and red line represent the spectra for full-energy protons and those in coincidence with β particles detected by the downstream QSD2, respectively. Panel (c) shows the cumulative γ-ray spectrum measured by clover-type HPGe detectors in coincidence with the emitted protons from the decay of ^{22}Si.

DSSD1 and DSSD2. Three proton groups with total decay energies of 710 keV, 1950 keV, and 2150 keV, respectively were clearly identified with an energy resolution of 50 keV. Some protons in the energy range from 1800 to 2200 keV might originate from the decay of the daughter nucleus ^{21}Mg. This contamination is estimated to be less than 5% based on the half-life and β branching ratios of ^{21}Mg [23]. With the daughter decay and detection efficiencies for protons at different energies taken into account, absolute decay branching ratios of these three proton groups in the decay of ^{22}Si are determined as 5.3(10)%, 43.0(46)%, and 13.5(21)%, respectively.

Proton-γ coincidences were measured to establish final states of the transitions. Figure 1(c) shows the cumulative γ-ray spectrum measured by the HPGe detectors in coincidence with the emitted protons from ^{22}Si decay measured by the DSSDs. The γ-ray transition at 202 (4) keV, which is associated with the deexcitation of the first excited state in ^{21}Mg toward its ground state [24], is coincident with the proton groups at 710 (50) keV and 1950 (50) keV. Therefore, these two peaks are attributed to the proton emissions from the excited states at 905 (403) keV and 2145 (403) keV of ^{22}Al to the first excited state of ^{21}Mg.

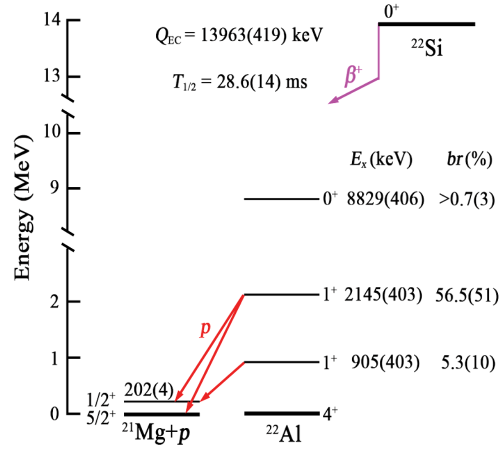

FIG. 2. Decay scheme of ^{22}Si.The transitions to 905 keV and 2145 keV are followed by the proton emissions discussed in the text, while the transition to 8829 keV is followed by a two-proton emission as discussed in Ref. [17]. All the values (except J^π) presented are deduced from this experiment.

The energies of these two states are deduced according to the proton and γ-ray energies measured in the present experiment, while the ground-state masses of ^{21}Mg and ^{22}Al are obtained from the AME2016 atomic mass evaluation [11]. The large uncertainty 403 keV of excited energies mainly originates from the 400 keV uncertainty of the ground-state mass of ^{22}Al. The configuration for the states in ^{22}Al is determined to be $I^\pi = 1^+$ as shell-model calculations show that only the isobaric analog state (0^+) and the states (1^+) in ^{22}Al can be populated from the ground state (0^+) of ^{22}Si in the β decay [17]. The third proton group is not in coincidence with the 202 keV γ-ray transition and therefore can be attributed to the decay of the 1_2^+ state of ^{22}Al directly to the ground state of ^{21}Mg. As a result, the experimental branching ratios of the first and second 1^+ states are determined to be 5.3(10)% and 56.5(51)%, respectively. The deduced decay scheme is shown in Fig. 2.

The half-life of ^{22}Si is determined to be 28.6 (14) ms in present work, with the decay-time spectrum fitted using a function of an exponential decay plus a component for the decay of its daughter nucleus ^{21}Mg, which is in good agreement with the previous experimental data of 29 (2) ms [25]. The phase-space factor f in the β decay of ^{22}Si depends on the maximum kinetic energy of β particles [26], which can be deduced from proton- and γ-decay energies, and the ground-state masses of ^{22}Si [17] and ^{21}Mg [11]. The reduced transition probability ft of β branches for the transitions to excited levels of ^{22}Al are deduced accordingly. Together with the experimental data on the β decay of the mirror nucleus ^{22}O [12], the values of asymmetry parameter δ are finalized for β-decay transitions from $A = 22$, $T_z = \pm 3$ mirror nuclei to low-lying states of their respective daughters, as shown in Table I. For the 1_1^+ excited state, the mirror asymmetry parameter is found to

TABLE I. Comparison of calculated ft values of the β decay to ^{22}Al and its mirror partner ^{22}F with the present experimental data. The numbers in parentheses, (), are experimental error bars and those into square brackets, [ ], indicate the calculations without the $J = 2, 3$ INC force.

	^{22}Si → ^{22}Al $Q_{EC} = 13963$ keV					^{22}O → ^{22}F $Q_{\beta-} = 6490$ keV						
	Experiment			Calculations		Experiment			Calculations		δ (%)	
I_i^π	E_x (MeV)	br%	$\log(ft^+)$	E_x (MeV)	$\log(ft^+)$	E_x (MeV)	br%	$\log(ft^-)$	E_x (MeV)	$\log(ft^-)$	Experiment	Calculations
1_1^+	0.905	5.3 (10)	5.09 (9)	1.12 [1.69]	4.81 [4.52]	1.625	29 (4)	4.6 (1)	1.98 [1.56]	4.32 [4.56]	209 (96)	212 [−7]
1_2^+	2.145	56.5 (51)	3.83 (5)	2.43 [2.55]	3.71 [3.72]	2.572	68 (6)	3.8 (1)	2.58 [2.51]	3.72 [3.68]	7 (28)	−3.4 [10]

be 209(96)%, which is by far the largest experimental value in the low-lying states. On the other hand, we do not observe significant mirror asymmetry with the δ value of 7(28)% for the 1_2^+ excited state.

This dramatically large mirror asymmetry in GT transitions could be closely related to the structure of proton-halo nuclei. Thus, introduction of the INC forces related to the $s_{1/2}$ orbit is expected to influence the mirror asymmetry significantly. It combines two effects simultaneously. On one hand, the relation specific to the $l = 0$ orbital describes the geometrical effect for the loosely bound nuclei [27]; on the other hand, the INC forces are necessary for the physics associated with isospin-symmetry breaking in the shell-model framework [28]. As the proton separation energy of the daughter nucleus ^{22}Al is predicted to be small [10,11], we can expect that ^{22}Al may be a proton-halo nucleus. In the present calculation, we adopt the INC strength parameters for the $T = 1$, $J = 0$ channel as in Ref. [29]. For the $J \neq 0$ INC forces, the strength parameters are chosen as $V_{s,J=2} = 0.10$ MeV as in Ref. [10], and in addition, $V_{s,J=3} = 0.25$ MeV.

We first discuss the so-called mirror energy differences (MED) as an asymmetry in excitation energy defined by the differences between the excitation energies of analog states for the mirror nuclei [28,30]

$$\mathrm{MED} = E_x(I, T, T_z = -T) - E_x(I, T, T_z = T), \quad (1)$$

where $E_x(I, T, T_z)$ is the excitation energy of the states of spin I and isospin T, T_z. As shown in Table I, the excitation energies of the 1_1^+ states are quite different between the mirror nuclei ^{22}Al and ^{22}F. The MEDs estimated from experimental data are shown in Fig. 3. We can clearly see that the experimental MEDs are considerably large for the 1_1^+ state. The calculations reproduce the large MEDs very well for the 1_1^+ state, while for the 1_2^+ state the MED is a little smaller than the experimental one. When the $J = 2, 3$ INC force is switched off, both MEDs become small. Comparing the calculations with and without the $J = 2, 3$ INC force, the INC force leads to the large asymmetry of the energy as well as the GT β decay in the first excited states.

As shown in Table I, the calculated mirror asymmetries for the first and second 1^+ states in ^{22}Al and ^{22}F are $\delta = 212\%$ and $\delta = -3.4\%$, respectively, which reproduce well the difference in mirror asymmetry in the two 1^+ states, $\delta = 209(96)\%$ and $\delta = 7(28)\%$, extracted from the present experimental data. If these INC forces related to the $s_{1/2}$ orbit are switched off, the results become $\delta = -7\%$ and $\delta = 10\%$ for the first and second 1^+ state, respectively, and fail to reproduce the observed large difference in mirror asymmetries in the two states. Thus, the necessity of the $J \neq 0$ INC forces in the present shell-model calculation is evident.

We now explore the physical origin of the large difference in mirror asymmetry for the first and second 1^+ states. The ft value of a pure GT transition relates to the nuclear matrix element through

$$ft = \frac{D}{(\frac{g_A}{g_V})^2_{\mathrm{eff}} |M_{\mathrm{GT}}|^2}, \quad (2)$$

with D and $(g_A/g_V)_{\mathrm{eff}}$ being coupling constants [2], which are fixed values in our calculation. The mirror asymmetry δ can then be expressed through nuclear matrix elements as

$$\delta = \frac{ft^+}{ft^-} - 1 = \frac{|M_{\mathrm{GT}}^-|^2}{|M_{\mathrm{GT}}^+|^2} - 1 = \frac{\Delta |M_{\mathrm{GT}}|^2}{|M_{\mathrm{GT}}^+|^2}, \quad (3)$$

where the deviation $\Delta|M_{\mathrm{GT}}|^2$ is defined as $\Delta|M_{\mathrm{GT}}|^2 = |M_{\mathrm{GT}}^-|^2 - |M_{\mathrm{GT}}^+|^2$. The quantity $\Delta|M_{\mathrm{GT}}|^2$, and therefore δ, should vanish if exact isospin symmetry holds.

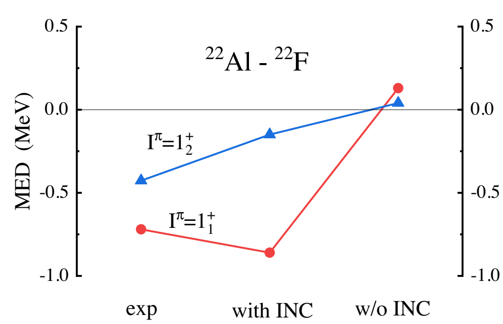

FIG. 3. Comparison of calculated MED with experimental data for the first (red circles) and second (blue triangles) excited 1^+ states in mirror nuclei ^{22}Al and ^{22}F.

From Eq. (3), it is clear that the mirror asymmetry parameter δ is a ratio determined by (a) the difference of the squared nuclear matrix elements of the β^- decay and β^+ decay of the mirror pair, and (b) the squared matrix element of the β^+ decay of the proton-rich side. For a nonzero δ, the numerator is necessarily nonzero, which means isospin-symmetry breaking in a naive picture. To describe isospin-symmetry breaking in shell-model calculations, the introduction of INC forces into the effective interactions is required [28,29]. Moreover, the actual magnitude of δ depends also on $|M^+_{\rm GT}|$ in the denominator. Thus, (a) is a necessary condition for nonzero δ, but for a large δ value, the denominator must be sufficiently small, which is determined by (b).

The $|M^+_{\rm GT}|^2$ and $|M^-_{\rm GT}|^2$ are estimated from the experimental log ft values using Eq. (2) and shown in Table II. $\Delta|M_{\rm GT}|^2$ are obtained as 0.065 and 0.037 for the 1^+_1 and 1^+_2 states, respectively, which are small but nonzero, thus satisfying the necessary condition (a). However, these two values are not much different, which suggests that the quantity $\Delta|M_{\rm GT}|^2$ alone is insufficient to explain the observed large difference in mirror asymmetries shown in Table I. Therefore, it is possible that what causes the large difference in δ would be the difference in $|M^+_{\rm GT}|^2$ for the two 1^+ states.

For the transition ^{22}Si → ^{22}Al, one sees that, with inclusion of the INC force in the calculations, as shown in Table II, $|M^+_{\rm GT}|^2$ is reduced for the 1^+_1 state but enhanced for the 1^+_2 state, which clearly makes the difference between the two 1^+ states. We can thus conclude that the differences in $|M^+_{\rm GT}|^2$ caused by the $J = 2, 3$ INC force contribute decisively to the explanation of the experimental mirror asymmetries for the two 1^+ states. We note also that the difference in the quantity $\Delta|M_{\rm GT}|^2$ in the numerator, though small, makes a non-negligible contribution to the final results.

To further understand the small GT transition matrix element for the 1^+_1 state and the large one for the 1^+_2 state, we compare the occupation numbers in their wave functions. The initial state $|i\rangle$ in ^{22}Si has the dominant ground-state configuration with proton occupation number 5.4 in $\pi d_{5/2}$ orbital. The selection rule of GT transitions requires neutron occupations in d orbitals of the final state in ^{22}Al.

TABLE II. Comparison of calculated $|M_{\rm GT}|^2$ values of the β decay to ^{22}Al and its mirror partner ^{22}F with the present experimental data. The numbers in parentheses, (), are experimental error bars and those in square brackets, [ ], indicate the calculations without the $J = 2$, 3 INC force.

	^{22}Si → ^{22}Al		^{22}O → ^{22}F	
	Experiment	Calculations	Experiment	Calculations
I^π_i	$\|M^+_{\rm GT}\|^2$	$\|M^+_{\rm GT}\|^2$	$\|M^-_{\rm GT}\|^2$	$\|M^-_{\rm GT}\|^2$
1^+_1	0.0310 (58)	0.0587 [0.1138]	0.096 (20)	0.1831 [0.1059]
1^+_2	0.563 (61)	0.7449 [0.7193]	0.60 (12)	0.7196 [0.7948]

Our calculation indicates that the final 1^+_1 state $|f\rangle$ in ^{22}Al has proton occupation numbers of 3.605, 1.156, and 0.230 and neutron occupation numbers of 0.714, 0.249, and 0.037 for the $d_{5/2}$, $s_{1/2}$, and $d_{3/2}$ orbitals, respectively. On the other hand, the 1^+_2 state of ^{22}Al has proton occupation numbers of 4.089, 0.525, and 0.386 and neutron occupation numbers of 0.673, 0.168, and 0.159 for the $d_{5/2}$, $s_{1/2}$, and $d_{3/2}$ orbitals, respectively. Comparing the occupation numbers for the two 1^+ states, one finds a clear structural difference: the 1^+_1 state has a larger s-orbit occupation but small $d_{3/2}$ occupation. In contrast, the 1^+_2 state has a reduced s-orbit occupation but enhanced $d_{3/2}$ occupation. For 1^+_2, the larger occupation in $\nu d_{3/2}$ results in a larger $M^{\rm GT}_{fi}$ for the $\pi d_{5/2} \to \nu d_{3/2}$ transition, as seen in Table II, and thus a smaller δ. Therefore, the structural differences of the two 1^+ states in ^{22}Al are the ultimate source for the significantly different values of δ.

We stress that, in the present calculation for the large ^{22}Si/^{22}O mirror asymmetry in GT decays, it is crucial to introduce a nonzero-spin INC force related to the $s_{1/2}$ orbit in the shell-model Hamiltonian, with the strength properly adjusted. The introduction of this force describes the effects of the loosely bound $s_{1/2}$ state under isospin-symmetry breaking in the shell-model framework, leading to a correct description of the large difference in mirror asymmetry between the two 1^+ states. Indeed, for the 1^+_1 state, the INC force enhances the $\pi s_{1/2}$ occupation number and reduces the $\pi d_{5/2}$ occupation number for ^{22}Al, and the reduction of the $\pi d_{5/2}$ component leads to a decrease in the GT transition $\pi d_{5/2} \to \nu d_{5/2}$.

In summary, we performed β-decay spectroscopy of ^{22}Si, which is the lightest nucleus with an isospin projection $T_z = -3$. The properties of β-decay branches for the transitions to the low-lying states of ^{22}Al were measured, and the reduced transition probabilities were determined. Combined with the data on the β decay of the mirror nucleus ^{22}O, we found mirror asymmetry of $\delta = 209(96)\%$ in the transition to the first 1^+ excited state of the respective daughters. This is by far the largest value of asymmetry observed in the low-lying states. The data can be accurately reproduced by the shell-model calculations with an INC $T = 1$, $J = 2$, 3 interaction related to the $s_{1/2}$ orbit, demonstrating that this dramatically large mirror asymmetry is attributed to the significant proton occupation and loosely bound nature of the wave functions of the $s_{1/2}$ orbit, which suggests that ^{22}Al is a proton-halo nucleus. This Letter also demonstrates quantitatively the connection between large mirror asymmetry in Gamow-Teller transitions and proton-halo structure, which might provide another means to study halo nuclei.

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