Article:

Kaneko, K., Sun, Y., Mizusaki, T. et al. (3 more authors) (2019) Large mirror asymmetry in Gamow-Teller β-decay in the A = 26 isobaric multiplet. Nuclear Physics A. pp. 107-115. ISSN 0375-9474

https://doi.org/10.1016/j.nuclphysa.2019.03.002

Large mirror asymmetry in Gamow-Teller β-decay in the $A = 26$ isobaric multiplet

K. Kaneko, [a] Y. Sun, [b,c,d] T. Mizusaki, [e] D. G. Jenkins, [f]
S. K. Ghorui, [b] S. Tazaki [g]

[a] *Department of Physics, Kyushu Sangyo University, Fukuoka 813-8503, Japan*

[b] *School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China*

[c] *Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*

[d] *China Institute of Atomic Energy, P.O. Box 275(10), Beijing 102413, China*

[e] *Institute of Natural Sciences, Senshu University, Tokyo 101-8425, Japan*

[f] *Department of Physics, University of York, Heslington, York, YO10 5DD, United Kingdom*

[g] *Department of Applied Physics, Fukuoka University, Fukuoka 814-0180, Japan*

Abstract

We investigate a striking example of mirror asymmetry in Gamow-Teller (GT) β-decay using the nuclear shell-model including isospin-nonconserving (INC) forces in the *sd*-shell region. We show that the large mirror asymmetry between ^{26}P and ^{26}Na GT β-decay can be accurately reproduced by introducing $T = 1$, $J \neq 0$ INC forces related to the $s_{1/2}$ orbit, while the usual $J = 0$ INC force, commonly adopted to describe isospin-symmetry breaking, does not work. We further show that the calculated distribution of summed GT strength for the ^{26}P β-decay is in good agreement with the experimental data. Our results support the conclusion that ^{26}P is a nucleus with proton-halo structure.

Key words: Mirror asymmetry, Gamow-Teller β-decay, Isospin-nonconserving forces, Proton halos, Large-scale shell model
PACS: 21.10.Sf, 21.30.Fe, 21.60.Cs, 27.30.+t

1 Introduction

Isospin symmetry and its breaking are of fundamental importance in nuclear and elementary particle physics [1,2]. This symmetry breaking is caused by the mass difference of up- and down-quarks and their different electromagnetic interactions [3]. As the β-decay process changes a up-quark to a down-quark, or vice versa, β-decay studies of mirror nuclei can serve as a powerful means to probe the isospin symmetry. In β-decays, the ft values are given by

$$ft = \frac{D}{|M_{fi}^F|^2 + (\frac{g_A}{g_V})^2 |M_{fi}^{GT}|^2}, \tag{1}$$

where D is a constant and g_V (g_A) is the vector (axial vector) coupling constant of the weak interaction. Here $M_{fi}^F = \langle f|\tau|i\rangle$ ($M_{fi}^{GT} = \langle f|\tau\sigma|i\rangle$, with σ and τ being the Pauli spin operator and the isospin operator, respectively) are the Fermi (Gamow-Teller) matrix elements with the initial state $|i\rangle$ and final state $|f\rangle$. Since isospin symmetry implies strict selection rules for the superallowed Fermi β-decay, its measurements have served as a fundamental test for the electroweak interaction [4–8], such as the unitarity for the up-down quark-mixing element of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. Isospin-symmetry-breaking (ISB) has been extensively studied over a wide range of nuclei [9–17]. Recently, we have investigated [18] ISB effects on binding energy and superallowed β-decay in the sd-shell nuclei using shell-model calculations with inclusion of the isospin nonconserving (INC) forces, and shown that the INC force with nonzero spin is responsible for the large ISB corrections in the superallowed β-decay.

Another related, interesting observation is mirror asymmetry in Gamow-Teller (GT) β-decays of mirror nuclei. If isospin symmetry strictly held, the ft^+ value of the β^+-decay in the proton-rich nucleus should be identical to the ft^- value of the β^--decay in its mirror partner nucleus. However, mirror GT β-decays usually do not have the same ft values, and mirror asymmetry has

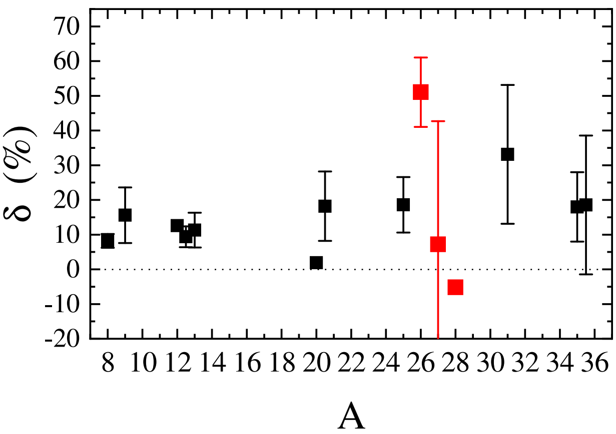

Fig. 1. (Color online) Experimental mirror asymmetry δ deduced from the ft data of $\beta^{\pm}$ transitions for mirror nuclei with $17 \leq A \leq 35$. The three data points in red denote the δ's for ^{26}P/^{26}Na, ^{27}P/^{27}Mg, and ^{28}P/^{28}Al. Experimental data are taken from Refs. [20–32].

been observed in the GT $\beta^{\pm}$-decay of mirror nuclei [19]. The extent of ISB can be quantified through the asymmetry parameter

$$\delta = \frac{ft^{+}}{ft^{-}} - 1. \tag{2}$$

Figure 1 shows the observed mirror asymmetry δ as a function of mass number A [20–32]. For most of the masses in the p and sd shells, the observed mirror asymmetry in GT β-decays are not large [22]. Large mirror asymmetry has been found for $A = 26$ when Perez-Loureiro *et al.* [21] measured Gamow-Teller transitions in the β-decay of ^{26}P and compared them with the analog transitions in the decay of ^{26}Na [33]. As seen in Fig. 1, the mirror asymmetry $\delta = (51 \pm 10)\%$ [21] is observed for the mirror β decays $^{26}\mathrm{P}\to{}^{26}\mathrm{Si}$ and $^{26}\mathrm{Na}\to{}^{26}\mathrm{Mg}$ (denoted as $^{26}\mathrm{P}/^{26}\mathrm{Na}$ mirror-pair decays hereafter). The significant mirror asymmetry was interpreted as evidence for a proton halo in ^{26}P.

Following the prediction of proton halos in ^{26,27,28}P [34], Navin *et al.* [35] measured cross sections in single-nucleon knockout reactions for these nuclei. They found that the large cross sections and narrow momentum widths for the ground state transition are evidence for proton halo structure, and pointed out that the $\pi s_{1/2}$ orbit plays an important role for the predicted proton halo structure. However, the measured cross sections for $^{27,28}\mathrm{P}+^{12}\mathrm{C}$ [36] and $^{27,28}\mathrm{P}+^{28}\mathrm{Si}$ [37] did not show proton halo structure in ^{28}P, and the calculations under-predicted the experimental data of ^{27}P [37]. The experimental mirror asymmetry of GT transition strength for $A = 27$ and 28 is small (see Fig. 1). It should be noted that the current uncertainty for $A = 27$ is very large due to the uncertainty of the logft data for ^{27}P β-decay [31].

In contrast to those of $^{27}\mathrm{P}/^{27}\mathrm{Mg}$ [31,32] and $^{28}\mathrm{P}/^{28}\mathrm{Al}$ [23], an unusually large mirror asymmetry $\delta = 51(10)\%$ in the $^{26}\mathrm{P}/^{26}\mathrm{Na}$ GT β-decays was recently reported by Pérez-Loureiro *et al.* [21] (previously measured as $\delta = 50(60)\%$ in [22]). Combining with the nearly-vanishing proton separation-energy of 0(90) keV, the authors in [21] interpreted the abrupt enhancement in δ at $A = 26$ as a signature for a proton halo in ^{26}P. The proton halo in ^{26}P was later studied theoretically by Ni and Ren [38]. The radial wave function of the proton $s_{1/2}$ orbit in the parent nucleus can have a very long tail, owing to the lack of the centrifugal barrier [39], and thus can extend into a space much larger than that of other orbitals. Therefore, the Coulomb interaction in proton-rich nuclei is generally weaker than that in their respective mirror nuclei. This leads to a large mirror asymmetry due to the difference between the radial wave functions of the initial state $|i\rangle$ and final state $|f\rangle$ in the matrix elements $M^{GT}_{fi} = \langle f|\tau\sigma|i\rangle$ in Eq. (1). Thus, the large mirror asymmetry is clearly related to the halo structure. It has been suggested [40,41] that the long tail of the radial wave function for the loosely bound proton in the $s_{1/2}$ orbit causes a reduction in the size of the interaction matrix elements. For a proton halo nucleus, the INC interaction related to the $s_{1/2}$ orbit is expected to influence the mirror asymmetry significantly.

2 Shell-model framework

In a recent work [18], we investigated the effects of the INC forces on the Coulomb displacement energy (CDE), the triplet displacement energy (TDE), and the superallowed Fermi β decay using shell-model calculations near the N=Z line. Shell-model calculations were performed employing the USDA interaction and including Coulomb and INC forces with $T = 1, J = 0$ for the sd-shell region. Together with our early work [11], we have concluded [18] that the $T = 1, J = 0$ INC force is important for the CDE and TDE in the sd-shell as well as in the fp-shell. However, including the $T = 1, J = 0$ INC force could not describe the three experiments [42–44] in the superallowed Fermi β decays for ^{31}Cl, ^{32}Cl, and ^{23}Al [45]. It was found [18] that an additional $T = 1$, $J = 2$ INC force related to the $s_{1/2}$ orbit is essential for the explanation of the superallowed Fermi β decay data. We thus expect that the $T = 1$, $J \neq 0$ INC interactions related to the $s_{1/2}$ orbit can explain the large mirror asymmetry for ^{26}P/^{26}Na.

Shell-model calculations with inclusion of the INC interaction H_{INC} in addition to the original isospin invariant Hamiltonian H_0 are performed by using the shell model code MSHELL64 [46]. The total Hamiltonian then reads

$$H = H_0 + H_{INC}. \tag{3}$$

For H_0 in (3), we employ the USDA interaction [48] with the full sd-shell model space. H_{INC} takes the form of a spherical tensor of rank two

$$H_{INC} = H'_{sp} + V_C + \sum_{k=1}^{2} V_{INC}^{(k)}, \tag{4}$$

with H'_{sp} the single-particle Hamiltonian that includes the Coulomb single-particle energies for protons and the single-particle energy shifts ε_{ls} due to the electromagnetic spin-orbit interaction for both protons and neutrons with the parameters taken from Ref. [47]. Thus the first and second terms in (4) originate from the Coulomb force, while the third term $V_{INC}^{(k)}$ represents the INC interactions. For the present calculation, the Coulomb single-particle energies for protons and the $T = 1, J = 0$ INC nuclear interaction are set to be the same as those in our previous paper [18]. The INC interaction related to the loosely bound proton $s_{1/2}$ orbit is included into $V_{INC}^{(k)}$. This interaction causes an asymmetry between the proton and neutron states. Calculations are

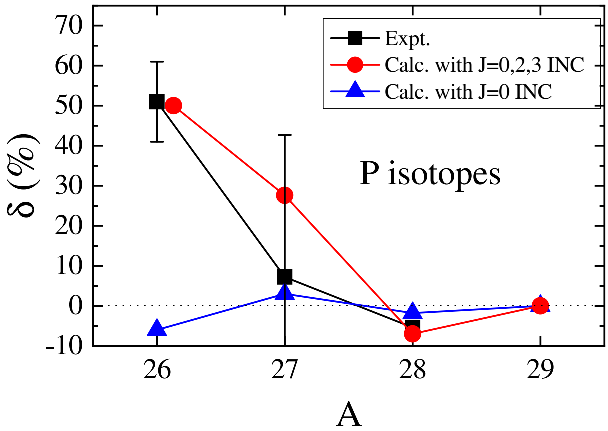

Fig. 2. (Color online) Calculated and experimental mirror asymmetries for $A = 26-29$ pairs of $\beta^{\pm}$ decays. Experimental data are taken from Refs. [21,23,31,32].

performed for all the even-mass nuclei with $T = 1$, 2 and odd-mass with $T = 1/2$, $3/2$ in the *sd* model space.

The $V_{INC}^{(k)}$ in (4) is the INC interaction, with $k = 1$ and $k = 2$ for the isovector and isotensor component, respectively. The INC two-body matrix elements are related to those in the proton-neutron formalism [49,12] through

$$V_{abcd,J}^{(1)} = V_{abcd,J}^{pp} - V_{abcd,J}^{nn}, \tag{5}$$

$$V_{abcd,J}^{(2)} = V_{abcd,J}^{pp} + V_{abcd,J}^{nn} - 2V_{abcd,J}^{pn}, \tag{6}$$

where $V_{abcd,J}^{pp}$, $V_{abcd,J}^{nn}$, and $V_{abcd,J}^{pn}$ are, respectively, the *pp*, *nn*, and *pn* matrix elements of $T = 1$ and J. As mentioned before, this recipe has recently been successfully applied to the investigation of the CDE's, TDE's, and the isospin-breaking corrections in the superallowed Fermi transition. Based on the CDE calculation, we have further calculated a total of 122 one- and two-proton separation energies, and the results were in good agreement with the known experimental data [18].

Theoretical β-decay half-lives can be directly linked to the calculated transition matrix elements by Eq. (1), where $D = 6143.6(17)$s [6], and the free nucleon ratio of axial vector to vector coupling constants is given by $\frac{g_A}{g_V} = -1.270(3)$ [5]. A quenching factor q is usually introduced for the axial-vector coupling through $g_A^{eff} = q \cdot g_A$. In the present calculation, we take $q^2 = 0.636$.

3 Results and discussion

Figure 2 shows the comparison between theoretical mirror asymmetries δ's for the Phosphorus isotopes, calculated with the $T = 1, J = 0$ INC interaction, and the experimental ones. These correspond to mirror β-decays from the ground state to the first excited state for ^{26}P/^{26}Na, ^{27}P/^{27}Mg, ^{28}P/^{28}Al, and ^{29}P/^{29}Si. The quantum numbers for the ground states concerned are $T = 2, I = 3^+$ for ^{26}P and ^{26}Na, $T = 3/2, I = 1/2^+$ for ^{27}P and ^{27}Mg, $T = 1, I = 3^+$ for ^{28}P and ^{28}Al, and $T = 1/2, I = 1/2^+$ for ^{29}P and ^{29}Si. As seen in Fig. 2, the calculated δ's are in good agreement with the experimental data for $A = 27$ and $A = 28$. However, the calculation fails to reproduce the observed large mirror asymmetry for mass $A = 26$. Following Ref. [18], we now introduce additional isovector and isotensor $T = 1, J \neq 0$ INC interactions related to the $s_{1/2}$ orbit, parameterized as $V^{(1)}_{sdsd,J} = -V^{(2)}_{sdsd,J} = -2V_{s,J}$. For simplicity, we assume that the $V^{(1)}_{sdsd,J=2}$ and $V^{(2)}_{sdsd,J=2}$ strengths have opposite signs. We have carefully examined, and found that only the $T = 1, J = 2, 3$ INC terms are sensitive to the quantity of isospin asymmetry, while the $T = 1, J = 1$ INC term has almost no influence. The INC interactions with $J > 3$ do not enter into the discussion because the $s_{1/2}$ orbit does not involve them in the sd-shell. Therefore, we adopt only $T = 1, J = 2, 3$ terms in the present calculation. We have then chosen the parameters $V_{s,J=2} = 0.10$ and $V_{s,J=3} = 0.13$ (in MeV), so as to reproduce the experimental B(GT) for both ^{26}P and ^{28}P β-decays. The same strength for $V_{s,J=2}$ was employed in Ref. [15] in the study of mirror energy differences (MEDs) and triplet energy differences (TEDs) in the $T = 1$ analogue states of the upper fp shell.

Figure 3 shows the calculated mirror asymmetry δ for ^{26}P GT β decay as a function of $V_{s,J=3}$, with fixed $V_{s,J=2} = 0.10$ MeV and under the presence of the $T = 1, J = 0$ INC interaction. For $V_{s,J=3} = 0.0$ MeV, the calculated δ for ^{26}P/^{26}Na is 11.4%, which essentially suggests a mirror symmetry. With increasing $V_{s,J=3}$, δ increases monotonically, and the observed large mirror asymmetry $\delta = 51(10)$% is correctly reproduced at $V_{s,J=3} = 0.13$ MeV, as seen in Fig. 3 (also see Fig. 2). For $A = 27$, the calculation with the same parameter predicts a large mirror asymmetry (see Fig. 2). We note that the uncertainty of

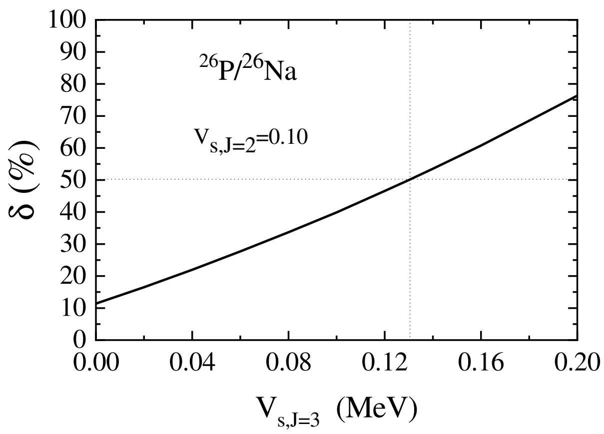

Fig. 3. Calculated mirror asymmetry for GT β-decay of ^{26}P/^{26}Na as a function of the $T = 1, J = 3$ INC force strength $V_{s,J=3}$ with fixed $V_{s,J=2} = 0.10$.

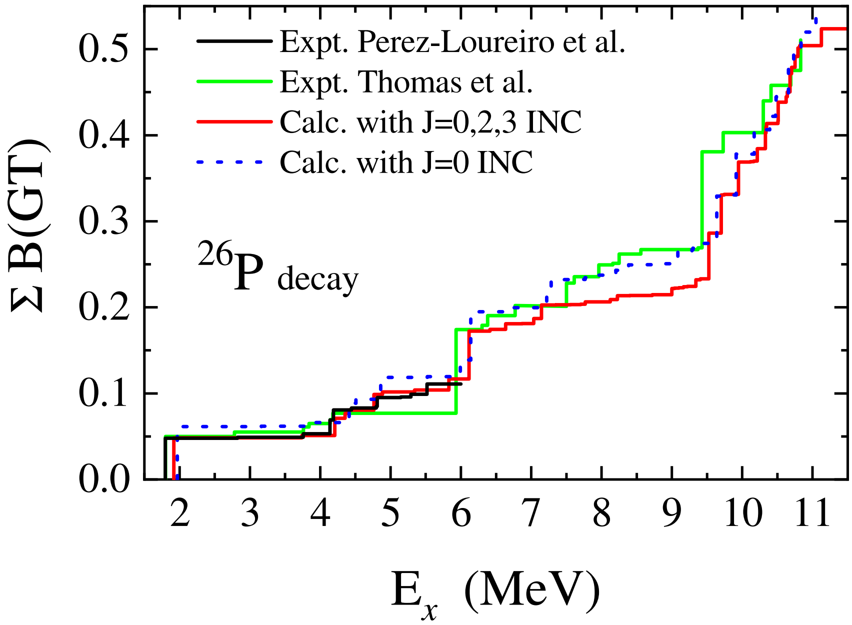

Fig. 4. (Color online) Summed Gamow-Teller strength distribution of the β^+-decay of ^{26}P up to 11.5 MeV in excitation. The calculated results are compared with two sets of experimental data in Refs. [21,22]. The quenching factor $q^2 = 0.636$ was used in the calculation.

the existing data for $A = 27$ is very large, and therefore, improved experiments are helpful to confirm our prediction. For $A = 28$, the added $T = 1, J = 2, 3$ INC term does not have any effect, and the results with and without this term are similar, which agree with the data. For $A = 29$, the predicted results with and without the $T = 1, J = 2, 3$ INC term are identical. We may thus conclude that the mirror asymmetry of the GT β decay is significantly influenced by the $T = 1, J = 2, 3$ INC interaction, and the effect is strongly structure-dependent.

In Table I, our calculated ft-vales are compared with the experimental data for ^{26}P/^{26}Na, up to ~ 6 MeV of excitation in the daughter nuclei. Both the ft^+ and ft^- values to the first excited state are in excellent agreement with the experimental data. The observed mirror asymmetry $\delta = 51(10)\%$ is correctly reproduced, where the higher lying states may have mixings with the nearby states. Figure 4 shows the summed Gamow-Teller strength distribution of the ^{26}P decay up to 11.5 MeV of excitation, which is compared with the data from two experiments [21,22]. The calculation with the $T = 1, J = 2, 3$ INC interaction related to the $s_{1/2}$ orbit is in very good agreement with the experimental data up to 6 MeV by Pérez-Loureiro *et al.* [21]. Without the $T = 1, J = 2, 3$ INC interaction, the results overestimate the experimental summed GT strength data, which is similar to those of the theoretical calculations in Ref. [21]. The early experiment by Thomas *et al.* [22] could have missed some strengths in the 5-6 MeV range. Beyond 6 MeV, the summed Gamow-Teller strength distributions show differences between the calculations with and without the $T = 1, J = 2, 3$ INC interaction. The calculation with the

Table 1
Comparison of calculated ft values of the β-decay of ^{26}P and its mirror partner ^{26}Na with available experimental data. Data are taken from Ref. [21].

$^{26}\mathrm{P}(\beta^+)^{26}\mathrm{Si}$				
	Expt.		Calc.	
I_i^π	^{26}Si E_x (keV)	ft^+ (s)	^{26}Si E_x (keV)	ft^+ (s)
2_1^+	1797	$7.9(5) \times 10^4$	1918	7.9×10^4
3_1^+	3757	$8.7(8) \times 10^5$	3740	1.5×10^6
2_3^+	4139	$2.4(2) \times 10^5$	4354	6.9×10^5
3_2^+	4188	$3.2(2) \times 10^5$	4207	1.9×10^5
4_1^+	4445	$1.7(7) \times 10^6$	4390	1.0×10^6
4_2^+	4796	$2.1(3) \times 10^6$	4884	1.3×10^6
2_4^+	4810	$3.7(3) \times 10^5$	4763	2.1×10^5
2_5^+	5147	$5.6(20) \times 10^6$	5562	–
4_3^+	5289	$1.2(2) \times 10^6$	5343	1.7×10^6
4_4^+	5517	$3.2(3) \times 10^5$	5830	3.0×10^5

$^{26}\mathrm{Na}(\beta^-)^{26}\mathrm{Mg}$				
	Expt.		Calc.	
I_i^π	^{26}Mg E_x (keV)	ft^- (s)	^{26}Mg E_x (keV)	ft^- (s)
2_1^+	1809	$5.23(2) \times 10^4$	1870	5.24×10^4
3_1^+	3941	$7.5(2) \times 10^5$	3836	7.99×10^5
2_3^+	4332	$4.22(9) \times 10^5$	4431	4.75×10^5
3_2^+	4350	$2.16(4) \times 10^5$	4429	1.56×10^5
4_1^+	4319	$1.43(3) \times 10^6$	4260	1.81×10^6
4_2^+	4901	$1.63(7) \times 10^6$	4838	8.94×10^5
2_4^+	4835	$1.85(2) \times 10^5$	4741	1.70×10^5
2_5^+	5291	$2.0(3) \times 10^7$	5371	7.49×10^6
4_3^+	5476	$7.9(40) \times 10^7$	5476	–
4_4^+	5716	$1.71(3) \times 10^5$	5904	2.37×10^5

$T = 1, J = 2, 3$ INC interaction, which correctly describes the new data up to 6 MeV [21], underestimates the early data [22] for the 7.5-10.5 MeV range. Nevertheless, the three curves (the two calculations and the data in Ref. [22]) seem to merge at the highest excitations, showing a consistency in the total

Gamow-Teller strengths of the β^+-decay of ^{26}P summed up to about 10.5 MeV.

Our calculations have demonstrated clearly that the large asymmetry is caused by the $T = 1, J = 2, 3$ INC interaction related to the $s_{1/2}$ orbit. The origin of the large asymmetry for ^{26}P β-decay could be related to its proton halo nature. Our calculated proton separation energy reproduces very well the experimental data 0 (90) MeV, which was already shown in Fig. 3 of Ref. [18]. The proton halo produces significant differences in the radial wave functions between the mirror nuclei. The δ value is largely enhanced because the overlap between the radial wave functions of the loosely-bound proton $s_{1/2}$ orbit and the well-bound neutron $s_{1/2}$ orbit is much smaller than the unity which is obtained in the usual shell-model calculations. Thus, including the $T = 1, J = 2, 3$ INC interaction related to the $s_{1/2}$ orbit in the calculation is essential to account for the observed large δ in ^{26}P/^{26}Na. We stress that our adopted INC interaction in the third term of Eq. (4), which is explicitly related to the $s_{1/2}$ orbit, may be conceptually different from the nuclear INC force in other shell-model calculations. As we have demonstrated, the one in this article effectively includes two effects needed to account for the large mirror asymmetry, namely the INC force in the usual sense that breaks isospin symmetry *and* the loosely-bound nature in the wave functions of the $s_{1/2}$ orbit.

4 Summary

We have investigated the question of mirror asymmetry in GT β-decay using the ^{26}P GT β-decay to ^{26}Si as an example. Through quantitative shell-model calculations including the INC forces in the *sd*-shell region, we found that the $T = 1, J = 2, 3$ INC interaction related to the $s_{1/2}$ orbit is responsible for the large mirror asymmetry. This nonzero-spin INC interaction acts in the states discussed in Refs. [40,41], where the long tail of the radial wave function for the $s_{1/2}$ orbit causes a reduction in the size of the interaction matrix elements. Our shell-model calculation reproduces well the summed Gamow-Teller strength distribution of the ^{26}P decay experimentally observed up to 6 MeV by Pérez-Loureiro *et al.* [21] as well as the mirror asymmetry for the decay to the first excited state, and supports the conclusion that the large mirror asymmetry is closely related to the proton halo structure in ^{26}P. For this nucleus, remeasurement of GT β-decay beyond 6 MeV is much desired. The predicted mirror asymmetry ($\delta \sim 28\%$, see Fig. 2) for ^{27}P/^{27}Mg decays awaits experimental confirmation.

Communication with the experimental group at the University of Hong Kong (J. Lee and X.-X. Xu), during the course of preparation for manuscript submission, is acknowledged. This work was partially supported by the National

Key Program for S&T Research and Development (No. 2016YFA0400501) and by the National Natural Science Foundation of China (No. 11575112).

References

[1] W. Heisenberg, Z. Phys. **77**, 1 (1932).

[2] E. Wigner, Phys. Rev. **51**, 106 (1937).

[3] G. A. Miller, A. K. Opper, and E. J. Stephenson, Annu. Rev. Nucl. Part. Sci. **56**, 253 (2006).

[4] J. C. Hardy and I. S. Towner, Phys. Rev. C **71**, 055501 (2005).

[5] J. C. Hardy and I. S. Towner, Nucl. Phys. News **16**, 11 (2006).

[6] J. C. Hardy and I. S. Towner, Phys. Rev. C **79**, 055502 (2009).

[7] I. S. Towner and J. C. Hardy, Phys. Rev. C **77**, 025501 (2008).

[8] W. Satula, J. Dobaczewski, W. Nazarewicz, and M. Rafalski, Phys. Rev. Lett. **106**, 132502 (2011).

[9] W. E. Ormand and B. A. Brown, Nucl. Phys. **A491**, 1 (1989).

[10] P. E. Garrett *et al.*, Phys. Rev. Lett. **87**, 132502 (2001).

[11] K. Kaneko, Y. Sun, T. Mizusaki, and S. Tazaki Phys. Rev. Lett. **110**, 172505 (2013).

[12] M. A. Bentley and S. M. Lenzi, Prog. Part. Nucl. Phys. **59**, 497 (2007).

[13] A. P. Zuker, S. M. Lenzi, G. Martinez-Pinedo, and A. Poves, Phys. Rev. Lett. **89**, 142502 (2002).

[14] K. Kaneko, T. Mizusaki, Y. Sun, S. Tazaki, and G. de Angelis, Phys. Rev. Lett. **109**, 092504 (2012).

[15] K. Kaneko, Y. Sun, T. Mizusaki, and S. Tazaki, Phys. Rev. C **89**, 031302(R) (2014).

[16] Y. H. Lam, N. A. Smirnova, and E. Caurier, Phys. Rev. C **87**, 054304 (2013).

[17] N. A. Smirnova, B. Blank, B. A. Brown, W. A. Richter, N. Benouaret, and Y. H. Lam, Phys. Rev. C **93**, 044305 (2016).

[18] K. Kaneko, Y. Sun, T. Mizusaki, S. Tazaki, and S. K. Ghorui, Phys. Lett. B **773**, 521 (2017).

[19] D. H. Wilkinson, Phys. Rev. Lett. **27**, 1018 (1971).

[20] N. A. Smirnova and C. Volpe, Nucl. Phys. **A714**, 441 (2003).

[21] D. Pérez-Loureiro *et al.*, Phys. Rev. C **93**, 064320 (2016).

[22] J.-C. Thomas *et al.*, Eur. Phys. J. A **21**, 419 (2004).

[23] P. M. Endt, Nucl. Phys. **A521**, 1 (1990); **A633**, 1 (1998).

[24] G. Nyman *et al.*, Nucl. Phys. **A510**, 189 (1990).

[25] F. Gete *et al.*, Phys. Rev. C **61**, 064310 (2000).

[26] D. Tilley *et al.*, Nucl. Phys. **A564**, 1 (1993); **A636**, 249 (1998).

[27] M. Domsky *et al.*, Phys. Rev. C **49**, 1867 (1994).

[28] H. O. U. Fynbo *et al.*, Nucl. Phys. **A677**, 38 (2000).

[29] G. Audi *et al.*, Nucl. Phys. **A624**, 1 (1997).

[30] W. Trinder *et al.*, Phys. Lett. B **459**, 67 (1999).

[31] E. McCleskey *et al.*, Phys. Rev. C **94**, 065806 (2016).

[32] M. Shamsuzzoha Basunia, Nuclear Data Sheets **112**, 1875 (2011).

[33] G. F. Grinyer *et al.*, Phys. Rev. C **71**, 044309 (2005).

[34] B. A. Brown and P. G. Hansen, Phys. Lett. B **381**, 391 (1996).

[35] A. Navin, *et al.*, Phys. Rev. Lett. **81**, 5089 (1998).

[36] H. Y. Zhang *et al.*, Nucl. Phys. **A707**, 303 (2002).

[37] Z. H. Liu *et al.*, Phys. Rev. C **69**, 034326 (2004).

[38] D.-D. Ni and Z.-Z. Ren, Chin. Phys. C **41**, 114104 (2017).

[39] C. R. Hoffman, B. P. Kay, and J. P. Schiffer, Phys. Rev. C **89**, 061305(R) (2014).

[40] K. Ogawa, H. Nakada, S. Hino, and R. Motegi, Phys. Lett. B 464, 157 (1999).

[41] C. Yuan, C. Qi, F. Xu, T. Suzuki, and T. Otsuka, Phys. Rev. C **89**, 044327 (2014).

[42] D. Melconian, *et al.*, Phys. Rev. Lett. **107**, 182301 (2011).

[43] M. B. Bennett, *et al.*, Phys. Rev. Lett. **116**, 102502 (2016).

[44] V. E. Iacob, *et al.*, Phys. Rev. C **74**, 045810 (2006).

[45] R. J. Tighe, *et al.*, Phys. Rev. C **52**, R2298 (1995).

[46] T. Mizusaki, N. Shimizu, Y. Utsuno, and M. Honma, code MSHELL64 (unpublished).

[47] L-L. Andersson *et al.*, Phys. Rev. C **71**, 011303 (2005).

[48] B. A. Brown and W. A. Richter, Phys. Rev. C **74**, 034315 (2006).

[49] W. E. Ormand, Phys. Rev. C **55**, 2407 (1997).

[50] National Nuclear Data Center, http://www.nndc.bnl.gov/.