New Limit of the *G*-Parity Irregular Weak Nucleon Current Disclosed in β-Ray Angular Distributions from Spin Aligned ^{12}B and ^{12}N

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The angular distributions of β rays from spin aligned ^{12}B and ^{12}N were precisely remeasured using a further refined spin-manipulation technique. Our old data have also been recorrected for precisely determined systematic corrections. A nonzero *G*-parity violating induced tensor form factor f_T has been concluded as $2Mf_T/f_A = +0.22 \pm 0.05(\mathrm{stat}) \pm 0.15(\mathrm{syst}) \pm 0.05(\mathrm{theor.})$. In this result the asymmetry in the axial charges due to the binding-energy difference of the transforming nucleons is taken into account. [S0031-9007(98)06084-0]

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As was already mentioned, the *G*-parity violation can be studied from β-ray angular distributions, β-α, and β-γ correlations, and from ft-value measurements, particularly in the mass 8 and 12 systems [1]. Status of these investigations in the mid 1980s was well described in a review article [2]. Recently, an experiment on the radiative decays of the 16-MeV states in ^{8}Be was performed [3], and its results were used with the β-α correlations [4] to limit the induced tensor form factor in the mass 8 system. Here, we report our new results of the β-ray angular distributions in the mass 12 system. By the end of the 1970s, the vanishingly small value of the *G*-parity irregular induced tensor nucleon form factor f_T compared with that of the main axial vector f_A was given as $2Mf_T/f_A = -0.21 \pm 0.63$ [5–7]. Here M is the nucleon mass. This important result was obtained by measuring the β-ray energy dependence of possible anisotropies in the β-ray angular distributions from spin aligned ^{12}B and ^{12}N. Ambiguities were discussed by taking into account the off-mass shell and nuclear many-body effects [8]. The conclusion reached of a negligible induced tensor term was indeed desirable to preserve the beauty of the current algebra and gauge theories.

Still though, this conclusion did not definitely exclude a small *G*-parity violation in the axial vector component, which might be caused by possible mass and charge differences between up and down quarks [9], or any other reasons. Since 1980, to place a limit on the applicability of *G*-parity conservation, we have not only improved further the experimental technique and accumulated better counting statistics but have also experimentally and theoretically studied the possible systematic corrections in the angular correlation experiments, which might cause difficulties in analyzing the raw data of the mass 12 system. The choice of the ^{12}B and ^{12}N pair was kept because, up until now, the isospin triad in the mass 12 nuclei provides us with the best known system [5–7,10]. Parallel to this recent experimental progress, there has been an advance in the theoretical work by including the asymmetry of the axial charges in the mirror decays [11], as well as using refined nuclear structures and leptonic wave functions in describing the β decay.

One of the improvements in the experimental technique has been in the spin manipulation used for the artificial creation of alignment from the polarization produced through the nuclear reaction. Such a conversion has become reliable through a thorough understanding of the implantation processes and hyperfine interactions of ^{12}B (^{12}N) during and after implantation in a Mg crystal following their production in nuclear reactions. The most striking discovery in the implantation was that of a second location for ^{12}B (^{12}N) with minor populations of about 15%, in addition to the known main location in the crystalline unit cell in Mg [12]. With complete knowledge of the hyperfine interactions and the spin orientations of ^{12}B (^{12}N) produced by our spin manipulation technique, studies were made of the systematic corrections and uncertainties introduced in the conversion from polarization to alignment and then back again.

The angular distribution of β rays from spin oriented ^{12}B (^{12}N), for which (I^π, T, T_z) goes from $(1^+, 1, \mp 1)$ to $(0^+, 0, 0)$, can be given in a form [7]

$$W(\theta) \propto pE(E - E_0)^2[B_0(E) + PB_1(E)P_1(\cos\theta) + AB_2(E)P_2(\cos\theta)], \qquad (1)$$

where p and E are the momentum and total energy of the emitted electron, E_0 is the end point energy, and θ is the angle between the electron direction and the axis of spin orientation. The quantities P and A are the polarization and alignment, respectively, defined for an $I = 1$ state, with magnetic substate populations a_m, as $P = a_{+1} - a_{-1}$ and $A = 1 - 3a_0$, with $a_{+1} + a_0 + a_{-1} = 1$. For an accurate measurement of the ratio B_2/B_0 we observe angular distribution of β rays from spin aligned ^{12}B (^{12}N)

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with $P = 0$. The ratio is given as $B_2(E)/B_0(E)/E = \frac{2}{3}(\pm a \mp f_T/f_A - y/2M)$. The first term in the brackets is $a = -\frac{1}{2}(f_V \int \alpha \times \boldsymbol{r}/f_A \int \sigma)$, where a is the weak magnetism (WM) and f_V is the vector nucleon form factor. The third term is the time component of the axial vector divided by the space component $y = -2iM \int \gamma_5 \boldsymbol{r} / \int \sigma$. Using an experimental value of the WM, $a_{\rm exp}$, and assuming that y is symmetric under the change of the binding energies for the transforming nucleons, we extract $(f_T/f_A)_{\rm exp} = a_{\rm exp} - \frac{3}{4}[(B_2/B_0/E)_- - (B_2/B_0/E)_+]$, where the subscript $-$ $(+)$ is for ^{12}B (^{12}N) decay [5–7].

The method and experimental setup used in producing ^{12}B (^{12}N), and in creating spin alignments, were essentially the same as those used in previous work [5,10]. Namely, two β-ray counter telescopes were used one above and the other below the ^{12}B (^{12}N) catcher relative to the direction of external magnetic field H_0. Details of the counter positions, the counting system, the rotating target wheel, the way in which scattered β rays were reduced and rejected, the monitoring of pulse-height linearities against β-ray energy, and the responses of the detectors to the monochromatic β rays have been described previously [5,10]. The polarization of ^{12}B produced in the reaction ^{11}B(d, p) was $P_R = 0.10$ at $E_d = 1.5$ MeV and the β-ray counting rate in a detector assembly was $1.5 \times 10^3\ \mathrm{s}^{-1}$. For ^{12}N produced in the reaction ^{10}B(^{3}He, n) at $E_{^3\rm He} = 3.0$ MeV, we had $P_R = 0.22$ and a counting rate of $10^2\ \mathrm{s}^{-1}$. The ^{12}B (^{12}N) nuclei ejected at 40° to 75° (20° to 55°) were allowed to implant in the catcher. The magnetic field $H_0 \cong 300$ Oe for ^{12}B (600 Oe for ^{12}N) was employed parallel to P_R for maintaining and manipulating the spin orientations at room temperature in the Mg crystal with its crystalline c axis placed parallel to H_0. The size of the catcher was $0.3 \times 15 \times 20\ \mathrm{mm}^3$. As shown in Fig. 1, a pulsed-beam method was used. The target wheel was rotated at a period of 60 ms. During each beam-off counting time the target and its holder were carried away by the wheel from the catcher position to a place where they were hidden in the other side of the reaction chamber.

The majority (about 85%) of implanted ^{12}B (^{12}N) ions resided in a unique site in a crystalline unit cell (hcp) of Mg, and the rest (15%) occupied a separate site. We identified the location of the majority ^{12}N ions to be the trigonal site, where a unique field gradient is provided parallel to the crystalline c axis, with the quadrupole coupling constant $eqQ(^{12}\mathrm{N})/h = -59.3 \pm 1.7$ kHz [10,12] and the asymmetry parameter $\eta = 0$. For the majority ^{12}B ions another field gradient produced a coupling constant $eqQ(^{12}\mathrm{B})/h = -47.0 \pm 0.1$ kHz and $\eta = 0$. Since the field gradients for ^{12}B (^{12}N) in the second site are equal and perpendicular to those at the main site, the separation of the two rf transition frequencies is half of the main frequency under the present conditions. This makes it possible to manipulate the spins of the majority and the minority groups separately and reliably.

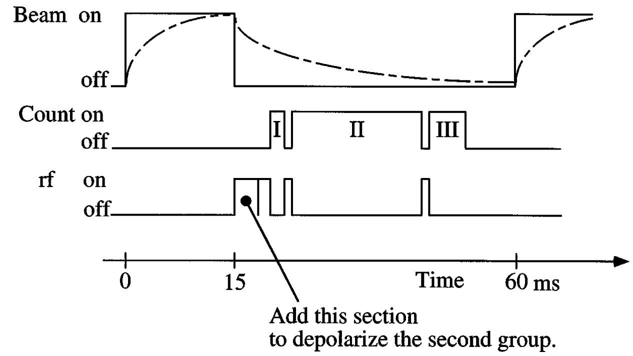

FIG. 1. The timing program employed in the pulsed-beam method. Before manipulating the polarization of the main group, the polarization of the minor group was destroyed. The method of creating alignment from polarization was the same as used before [5,10]. The broken curve shows the yield of ^{12}B (^{12}N).

We detected the alignment correlation of each majority group only, i.e., we completely destroyed the polarization of the minority group by applying a suitable rf field right after the end of the production time in each beam-count cycle as shown in Fig. 1. The spin orientation of the majority group was manipulated by use of an NMR technique, i.e., by interchanging or equalizing the populations in the substates $m = +1$ (-1) and 0 [5]. In order to carry out these procedures we made use of the fact that there is a quadrupole interaction in ^{12}B (^{12}N) that is superimposed on its magnetic interaction with H_0. For the present $I = 1$ case, the transition frequency HF between the magnetic substates $m = 1$ and $m = 0$ is higher than and well separated from the frequency LF between $m = 0$ and $m = -1$. Now, for example, if we equalize the populations of $m = 1$ (-1) and $m = 0$ by a suitable depolarizing rf, $\overline{\mathrm{HF}}$ ($\overline{\mathrm{LF}}$), before the counting region I, and interchange those of $m = 0$ and $m = -1$ $(+1)$ by an adiabatic fast passage rf, $\overrightarrow{\mathrm{LF}}$ ($\overrightarrow{\mathrm{HF}}$) before the region II; then we have either a positive or negative alignment, A_+ or A_- in region II, with $A_\pm = \pm(3/2)P_0 - (1/2)A_0$ and $P_\pm = 0$, where P_0 and A_0 are, respectively, the polarization and alignment of the majority group produced directly in the nuclear reaction. Thus, the difference between the positive and negative alignments turns out to be $\Delta A = A_+ - A_- \cong 0.26$ (0.56) for ^{12}B (^{12}N). In order to determine the value of $A_\pm$ and its relaxation time T_1^A in region II, we convert it back to a polarization before region III.

The ratio $R(E)$ of β-ray counts detected in region II by the up (down) counter with alignment A_+ to the counts with alignment A_- is given as

$$R(E) - 1 = N(E, A_+, P_+)/N(E, A_-, P_-) - 1$$
$$= (-1)^{\lambda + 1/2}\Delta P(B_1/B_0) + \Delta A(B_2/B_0), \quad (2)$$

where $\Delta P = (P_+ - P_-)$, and $\lambda = \frac{1}{2}$ and $-\frac{1}{2}$ refer to the U(up) and D(down) counters, respectively. The values of $P_\pm$ in region II were small, and $|\Delta P| < 0.5\%$. Moreover,

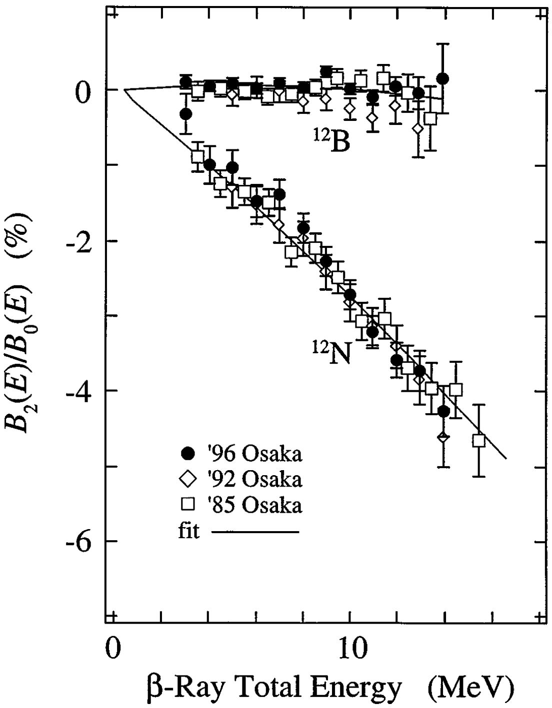

FIG. 2. Values of B_2/B_0 from aligned ^{12}B (^{12}N). Three sets of $(B_2/B_0)_{\mp}$ obtained at different times are shown (circles: 1996; diamonds: 1992; squares: 1985). A $2M(f_T/f_A)$ value is extracted from the best fit of the theoretical curve to each set of data. The solid lines are the theoretical curves with the weighted mean values given in Table II.

the effects from the ΔP term cancel out if we use the sum of the up- and down-counter results $\{R^{\mathrm{U}}(E) + R^{\mathrm{D}}(E) - 2\}/2 = \Delta A(B_2/B_0)$.

The values of the ratio B_2/B_0 obtained through Eq. (2) in the present work are shown in Fig. 2, as a function of β-ray energy, together with those measured in 1985 (open squares) and 1992 (open diamonds). The indicated errors include counting statistics and the partial systematic errors that can be included in each data point. The data were corrected at each β-ray energy for the β-decay branches, detector solid angles, response functions of the energy detectors, β-ray energy scales, relaxation times T_1 and T_1^A for P and A, the effect of the higher order term in B_1/B_0 in measuring the polarizations, and background β rays. The equal numbers of the ^{12}B(^{12}N) nuclei in the positive and negative alignment cycles were monitored by the β-ray counts in the up- and down-counter sets in each count section, in which the polarization and alignment effects were properly taken into account. Regarding the β-ray background in the ^{12}N, we made a separate run to measure the admixture of ^{12}B produced through the (d, p) reaction initiated by the admixture of 0.1% HD$^+$ in the main ^{3}He$^+$ beam, which bombarded the ^{11}B in the enriched (90%) ^{10}B target. As a typical example of the corrections and uncertainties of B_2/B_0 the present values are listed in Table I.

In order to extract $(f_T/f_A)_{\mathrm{exp}}$ and y_{exp} we have made a chi-square fit of theoretical B_2/B_0 simultaneously to the set of ^{12}B and ^{12}N data obtained in 1996. For this purpose we adopted a formulation of the angular distribution given by Eq. (1), which makes it possible to introduce higher order partial waves for leptons, and made Coulomb corrections for the finite size of nuclei [13]. The parameters for the fit were $(f_T/f_A)_{\mathrm{exp}}$, and δ_y, where δ_y is defined as $y_{\mathrm{exp}} = y_{IA}(1 + \delta_y) + y_{EC}$. The quantity δ_y represents core polarization effect and some other effects which have not been explicitly taken into account here. The impulse approximation with the Hauge-Maripuu wave functions gives $y_{IA} = 3.17$. The effect of the exchange currents is given in Ref. [14] as $y_{EC} = 1.30$. We have the experimental WM given as $2Ma_{\mathrm{exp}} = +4.02 \pm 0.03$ which was determined [15] from all the available data [16] of the transition strength of the M1-γ decay from the 15.11-MeV state of ^{12}C, $\Gamma_\gamma = 38.2 \pm 0.6$ eV.

From the fit of the two curves to the present ^{12}B and ^{12}N data, in which the asymmetry of the axial charges was not considered, we have $2M(f_T/f_A)_{\mathrm{exp}} = +0.07 \pm 0.06(\mathrm{stat}) \pm 0.15(\mathrm{syst})$, and $\delta_y = 0.02 \pm 0.02(\mathrm{stat}) \pm 0.04(\mathrm{syst})$. The previous data [10] obtained in 1985 and 1992 were also reanalyzed with the new corrections

TABLE I. Typical corrections and uncertainties for values of $B_2/B_0/E$ measured in 1996.

	^{12}B		^{12}N	
	Corr. (%)	Error (%)	Corr. (%)	Error (%)
Alignment calculation	⋯	0.23	⋯	0.58
Response function[a]	−1.88	2.13	−3.81	1.89
Background[a]	<0.01	<0.01	<0.01	<0.01
HD$^+$ mixed in ^{3}He beam[a]	⋯	⋯	0.27	0.23
Branching ratio[a]	−0.81	0.03	−0.74	0.03
Solid angle of detector	3.10	0.40	3.10	0.40
p/E	−0.26	⋯	−0.22	⋯
$(B_1/B_0 - 1)$ effect in P measurement	−0.07	0.10	−2.28	0.20
Energy scaling	⋯	0.73	⋯	0.74
Diff. of numbers of ^{12}B(^{12}N) in $A_\pm$ cycles in $(2M)^{-1}$	⋯	$0.03(2M)^{-1}$	⋯	$0.15(2M)^{-1}$
Total error in $(2M)^{-1}$		$0.03(2M)^{-1}$		$0.15(2M)^{-1}$

[a]The corrections for four quantities are typical values for β rays with energy of 8 MeV.

TABLE II. The values of $2Mf_T/f_A$ and δ_y corresponding to the best fits to the B_2/B_0 data. The systematic errors in the 1996 result were evaluated from the uncertainties in Table I and the estimated errors given to the WM. In obtaining average results the total errors were used to weight the input values. Reevaluated corrections were applied to the data obtained in 1985 and 1992, which suffered large systematic uncertainties. In the results in this table the possible asymmetry in the axial charges was not taken into account. The averaged value is consistent with the known value [5–7].

Year	$2Mf_T/f_A$	Error stat	Error syst	Error total	δ_y	Error stat	Error syst	Error total
1985	0.06	0.08	0.27	0.28	0.07	0.03	0.09	0.10
1992	0.29	0.11	0.24	0.26	0.18	0.04	0.08	0.09
1996	0.07	0.06	0.15	0.16	0.02	0.02	0.04	0.05
av.	0.12	0.05	0.15	0.16	0.06	0.02	0.04	0.05

and uncertainties for which the previous experimental conditions were properly taken into account. All the results are listed in Table II. In obtaining average results the total errors were used to weight the input values. The systematic error obtained for the 1996 data is added to the final result as $2M(f_T/f_A)_{\rm av} = +0.12 \pm 0.05({\rm stat}) \pm 0.15({\rm syst})$, and $(\delta_y)_{\rm av} = 0.06 \pm 0.02({\rm stat}) \pm 0.04({\rm syst})$, i.e., $y_{\rm av} = 4.66 \pm 0.06({\rm stat}) \pm 0.13({\rm syst})$.

A possible asymmetry in the axial charge due to the binding-energy difference of the transforming nucleons can be given with different nuclear models. (A possible asymmetry in the Gamow-Teller matrix elements from the same origin as above was studied in [17].) For example, a value estimated by Guichon *et al.* [18] is equivalent to $\Delta y = (y_+ - y_-)/2 = 0.06$ in our notation. Koshigiri *et al.* [11] obtained $\Delta y = 0.10-0.13$ with the Woods-Saxon-type radial wave functions explicitly by adjusting the potential depth parameters so as to reproduce the separation energies of the relevant nucleons. The smaller value of Δy of the former authors was obtained in the estimation of the axial charge simply by taking the overlap factors which were used in the calculation of the Gamow-Teller matrix elements. Here the contribution of the exchange currents to Δy is relatively small compared with the above Δy values. This is because matrix elements of the axial charge due to the exchange currents consist of two parts coming from the core and valence nucleons, while those in the impulse approximation are due to the valence nucleons only, whose wave functions are subject to the charge asymmetry. Possible asymmetry in the weak magnetism may not be important since the main term is $(-f_V/f_A + 2Mf_W/f_A)$, where f_W is the weak magnetism form factor, and the residual orbital angular momentum term $(-f_V/f_A)\int l/\int \sigma$ which may depend on the asymmetry is only a small fraction, 4.5%, of the main term. The magnitude of Δy changes with the method by which we represent the binding energy difference of the transforming nucleons. However, if we assume the case of the Woods-Saxon-type radial wave functions for nucleons and a 50% uncertainty, we have $\Delta y = 0.10 \pm 0.05({\rm theor.})$. With this model, we have the final result $2M(f_T/f_A)_{\rm exp} = 2M(f_T/f_A)_{\rm av} + \Delta y = +0.22 \pm 0.05({\rm stat}) \pm 0.15({\rm syst}) \pm 0.05({\rm theor.})$, i.e., $0.01 < 2M(f_T/f_A)_{\rm exp} < 0.43$. Certainly, this result is consistent with and more precise than the previous limit which included zero. We conclude that there is a nonzero, although vanishingly small, amount of induced tensor interaction in the weak axial vector currents.

Finally, a recent calculation based on the QCD sum rules gave a value of f_T/f_A [19], which is consistent with our lower limit. In the mass 8 system [3], the second class current is given by $d_{\rm II}/Ac = 0.0 \pm 0.3 \pm 0.3$ or $-0.5 \pm 0.2 \pm 0.3$. This quantity given in the elementary particle treatment is close to our $2Mf_T/f_A$, in definition and also numerically.

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[1] S. Weinberg, Phys. Rev. **112**, 1375 (1958).
[2] L. Grenacs, Annu. Rev. Nucl. Part. Sci. **35**, 455 (1985).
[3] L. De Braeckeleer *et al.*, Phys. Rev. C **51**, 2778 (1995).
[4] R. E. Tribble and G. T. Garvey, Phys. Rev. C **12**, 967 (1975); R. D. Mckeown *et al.*, Phys. Rev. C **22**, 738 (1980); **26**, 2336 (1982).
[5] K. Sugimoto *et al.*, J. Phys. Soc. Jpn. Suppl. **44**, 801 (1978); Y. Masuda *et al.*, Phys. Rev. Lett. **43**, 1083 (1979).
[6] P. Lebrun *et al.*, Phys. Rev. Lett. **40**, 302 (1978); H. Brändle *et al.*, Phys. Rev. Lett. **41**, 299 (1978).
[7] M. Morita *et al.*, Phys. Lett. **73B**, 17 (1978); M. Morita, Hyperfine Interact. **21**, 143 (1985).
[8] K. Kubodera *et al.*, Nucl. Phys. **B66**, 253 (1973).
[9] A. Halprin *et al.*, Phys. Rev. D **14**, 2343 (1976); J. F. Donoghue *et al.*, Phys. Rev. D **25**, 206 (1982).
[10] T. Minamisono *et al.*, J. Phys. Soc. Jpn. Suppl. **55**, 382 (1986); Hyperfine Interact. **78**, 77 (1993).
[11] K. Koshigiri *et al.*, Nucl. Phys. **A588**, 165c (1995).
[12] A. Kitagawa *et al.*, Hyperfine Interact. **60**, 869 (1990).
[13] M. Morita *et al.*, Nucl. Phys. **A577**, 387c (1994); K. Koshigiri *et al.*, Progr. Theor. Phys. **66**, 358 (1981).
[14] K. Koshigiri *et al.*, in *Weak and Electromagnetic Interactions in Nuclei* (World Scientific, Singapore, 1995), p. 361.
[15] K. Koshigiri *et al.*, Nucl. Phys. **A319**, 301 (1979); J. Phys. Soc. Jpn. Suppl. **55**, 1014 (1986).
[16] P. M. Endt, Nucl. Phys. **114**, 48 (1968); **114**, 69 (1968); B. T. Chertok *et al.*, Phys. Rev. C **8**, 23 (1973); U. Deutschmann *et al.*, Nucl. Phys. **A411**, 337 (1983).
[17] J. Blomqvist, Phys. Lett. **B35**, 375 (1971); D. H. Wilkinson, Phys. Rev. Lett. **27**, 1018 (1971); I. S. Towner, Nucl. Phys. **A216**, 589 (1973).
[18] P. A. M. Guichon *et al.*, Nucl. Phys. **A382**, 461 (1982).
[19] H. Shiomi, Nucl. Phys. **A603**, 281 (1996).