Search for the G-Parity Irregular Term in Weak Nucleon Currents Extracted from Mirror Beta Decays in the Mass 8 System

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Abstract

The alignment correlation terms in the β-ray angular distributions from purely spin aligned ^{8}Li and ^{8}B have been measured to search for the G-parity violating induced tensor term g_{II} in the weak nucleon currents. The g_{II} was extracted from the present alignment correlation terms, combined with the known β-α angular correlation terms and weak magnetism. This analysis permits an experimental determination of all the matrix elements necessary to extract g_{II}. As a result, the

induced tensor term was extracted as $g_{\rm II}/g_{\rm A} = -0.28 \pm 0.28(\text{stat.}) \pm 0.15(\text{syst.})$ at a 1σ (68%) level. The results in those mass systems were also analyzed under the KDR model in which medium effects including the off-shell effect and meson exchange current were taken into account. We determined the 1-body contribution to be $\zeta = -(0.13 \pm 0.13) \times 10^{-3}$ MeV^{-1} and the 2-body contribution to be $\lambda = +(0.27 \pm 0.97) \times 10^{-3}$ at a 1σ level.

Symmetry between proton and neutron in the charge space is associated with the symmetric properties of strong interactions, which are charge symmetric and charge conjugation invariant. Consequently, the process on strong interactions is invariant under the G transformation defined as the product of the charge symmetry and the charge conjugation. In the weak interaction, the G-operation invariance claims an important fundamental symmetry in the framework of the standard model, considering the effect of strong interactions on the weak processes [1]. The weak nucleon currents have not only the main terms, which are responsible for the Fermi and Gamow-Teller matrix elements, but also have additional induced terms because of the strong interactions. The induced terms are expected to hold the G symmetry, that is, the decays of a proton and a neutron in a nucleus should be symmetric. A proton and a neutron are, however, a composite particle of a different set of three quarks, (uud) and (udd), respectively, confined by gluons in a nucleon. It is well known that the axial-vector coupling constant is modified from 1 for decay of a free quark to 1.27 for a nucleon [2]. Thus the G-parity violating term may be induced

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from a small asymmetry caused by such renormalization and also the mass difference between up and down quarks.

Many β-ray correlation-type experiments of nuclei [3] and neutron [4], $\overline{\nu}p$ quasielastic scattering experiment [5] and a measurement of semileptonic-decay branching ratio of τ lepton [6] have been performed to test G-parity violation. The most precise limit has been imposed on the G-parity-violating induced tensor term g_{II} from the β-ray correlation with the nuclear spin alignment of a parent nucleus in the mass $A = 12$ system by Minamisono *et al.* [7] as $2M_n f_{\mathrm{T}}/f_{\mathrm{A}}(= g_{\mathrm{II}}/g_{\mathrm{A}}) = -0.15 \pm 0.12 \pm 0.05(\text{theory})$ at a 90% confidence level (CL), where g_{A} is the main coupling constant of the axial-vector current. So far, there was no reliable confirmation of the result of the $A = 12$ system in other mass systems.

In the $A = 8$ system, the β-delayed α angular correlation terms of the mirror pair ^{8}Li and ^{8}B have been measured by several groups [8,9]. The induced tenser term was determined as $g_{\mathrm{II}}/g_{\mathrm{A}} = +0.5 \pm 0.2 \pm 0.3$ from the correlation terms by McKeown *et al.* [9] combined with the M1/E2 transition strength of the analog γ decay [10]. The second error reflects the error from the analog-γ-decay measurement. The second-forbidden term f/Ac used in their analysis, which was determined from the E2 strength, however, disagrees with another measurement [11]. If we adopt f/Ac of Ref. [11], $g_{\mathrm{II}}/g_{\mathrm{A}}$ shifts by about -1.1. The disagreement of f/Ac introduces an additional large systematic uncertainty to the final result. In the $A = 20$ system, a theoretical prediction of a second-forbidden term j_2/A^2c was used to extract $g_{\mathrm{II}}/g_{\mathrm{A}}$ [12], therefore the result has a large theoretical uncertainty. However, all the highly uncertain terms contributing to the extraction of g_{II} in the β-α angular correlation terms can be experimentally determined combining with the alignment correlation terms in the β-ray angular distribution as discussed later. In the present study, the alignment correlation terms were measured to determine both $g_{\rm II}$ and the other terms in the $A = 8$ system.

The β-ray angular distribution $W(E, \theta_{I\beta})$ from a purely spin aligned nucleus has a correlation term with an alignment $\mathcal{A}$ as $W(E, \theta_{I\beta}) \propto pE(E_0 - E)^2\{B_0(E) + \mathcal{A}B_2(E)P_2(\cos\theta_{I\beta})\}$. Here, p, E, E_0 and $\theta_{I\beta}$ are the β-ray momentum, energy, end-point energy and ejection angle with respect to the spin-orientation axis, respectively. The ^{8}Li and ^{8}B nuclei decay to the broad first excited state of ^{8}Be and thus the end-point energy E_0 is given by $E_0 = E_{\rm max} - E_x$. The $E_{\rm max}$ is the energy release in the β decays to the ^{8}Be ground state and E_x is the excitation energy of ^{8}Be. The alignment is defined by $\mathcal{A} = (2a_{+2} - a_{+1} - 2a_0 - a_{-1} + 2a_{-2})/2$ with the population a_m of a magnetic substate m, which is normalized to unity as $\sum a_m = 1$. The alignment correlation term, $B_2(E)/B_0(E) = K_\mp(E, 0)$, and the β-α angular correlation term, $-\frac{2}{3}p(E) = K_\mp(E, 1)$, are given [13] by the same equation except for the sign of f/Ac and j_2/A^2c terms as

$$
\begin{aligned}
K_\mp(E,s) = -\frac{E}{3M_n}\Bigg[&\frac{1}{A} \pm \frac{b}{Ac} - \frac{d_{\rm I}}{Ac} \mp \frac{g_{\rm II}}{g_{\rm A}} \\
&+\frac{(-)^s}{\sqrt{14}}\left\{\pm\frac{f}{Ac}\frac{E_0+2E}{E_0} + \frac{3}{2}\frac{j_2}{A^2c}\frac{E_0-2E}{M_n}\right\} \\
&-\frac{3}{\sqrt{35}}\frac{j_3}{A^2c}\frac{E}{M_n}\Bigg], \qquad (1)
\end{aligned}
$$

where the notations in Ref. [13] are used. The upper and lower signs refer to β decays of ^{8}Li and ^{8}B, respectively. The difference, $\delta^-(s) = K_-(E, s) - K_+(E, s)$, is given by

$$
\delta^-(s) = -\frac{2E}{3M_n}\left[\frac{b}{Ac} - \frac{g_{\rm II}}{g_{\rm A}} + \frac{(-)^s}{\sqrt{14}}\frac{f}{Ac}\frac{E_0+2E}{E_0}\right]. \qquad (2)
$$

The weak magnetism b/Ac can be determined from the analog γ-decay measurement [10] and the β-delayed α energy spectra [14] based on the Conserved Vector Current (CVC) hypothesis. Thus, the $g_{\mathrm{II}}/g_{\mathrm{A}}$ and f/Ac are separately determined from the sum and difference between $\delta^{-}(0)$ and $\delta^{-}(1)$, respectively.

The present experimental setup was an extension of β-NMR apparatus so as to measure a β-ray-energy dependence of the angular distribution. A hole was made in a dipole magnet at center axis of iron core coil. A β-ray energy was measured by a set of plastic scintillation counters placed just outside the dipole magnet. The detailed setup were shown in Ref. [7]. The experimental procedure was essentially the same as the one in Ref. [7]. The production of the purely aligned nuclei by manipulating nuclear spin is described in detail below.

The Van de Graaff accelerator at Osaka University was used to provide the pulsed beam of deuteron (^{3}He) at 3.5 MeV (4.7 MeV) to bombard a $\mathrm{Li_2O}$ (enriched metal ^{6}Li) target. The ^{8}Li (^{8}B) nuclei were produced through the nuclear reaction $^{7}\mathrm{Li}(d,p)^{8}\mathrm{Li}$ ($^{6}\mathrm{Li}(^{3}\mathrm{He},n)^{8}\mathrm{B}$). The recoil angle of the reaction products was selected to 14°-40° (7°-18°) to optimize the nuclear spin polarization, which was typically 7% for ^{8}Li and 6% for ^{8}B. The polarized ^{8}Li (^{8}B) nuclei were implanted into Zn ($\mathrm{TiO_2}$) single crystals. The crystals were placed in a static magnetic field B_0 (60 mT for ^{8}Li and 230 mT for ^{8}B) applied parallel to the polarization direction in order to maintain the polarization and to manipulate the spin orientation with the β-NMR technique. The c axis of the single crystals was set parallel to B_0. The polarization was deduced from the asymmetry of β-ray angular distribution.

The Larmor frequency in a static magnetic field splits into four resonance

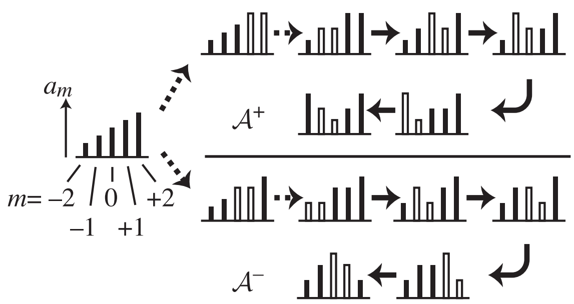

Fig. 1. Alignment production procedures for ^{8}Li ($I^\pi = 2^+$). The change of the spin orientation is shown by the population a_m of each magnetic substate m. The spin orientation was manipulated with the AFP and depolarization methods of the NMR technique, which are denoted by the solid and dashed arrows, respectively. Two open bars in each orientation show the manipulated populations by the NMR technique. The upper and lower figures show the production procedure of the positive and negative alignments, $\mathcal{A}^+$ and $\mathcal{A}^-$, respectively.

frequencies due to the hyperfine interaction between the electric quadrupole moment Q of the implanted nucleus and the electric field gradient q at the implantation site in the crystal. The ^{8}Li nuclei implanted in Zn are known to be located at a single site, while the ^{8}B nuclei in TiO_2 are located at two different sites. The quadrupole coupling constant eqQ/h has been determined for all the implantation sites [15]. The relative populations of major and minor sites of boron atoms in TiO_2 are $9:1$ [16]. The nuclear spin of ^{8}B implanted only in major site was manipulated [17]. The effect of the unmanipulated ^{8}B in minor site was negligibly small, that is, a shift of 10^{-7} for the alignment correlation terms.

The procedure of the alignment production for spin (I=2) was newly developed. Figure 1 shows the schematic procedure of the alignment production for ^{8}Li. The nuclear spin was manipulated by applying rf oscillating magnetic fields in β-NMR technique. Two methods of rf application were used, i.e., the adiabatic fast passage (AFP) and depolarization methods. The populations between the neighboring two magnetic substates can be interchanged by the AFP method and equalized by the depolarization method. The initial polarization was converted into both positive and negative alignments with ideally zero polarization by applying two depolarizations and four sequential AFPs. After measuring β-ray spectra from the aligned nuclei, the alignment was converted back into polarization to check the consistency of the spin manipulation and to measure the relaxation time of the alignment. Both positive and negative alignments were produced sequentially in each beam cycle. This timing program was used to remove a possible systematic uncertainty due to a fluctuation of a beam current [7].

The asymmetry of the β-ray angular distribution was detected by two sets of plastic-scintillation-counter telescopes placed at $\theta_{I\beta} = 0°$ and 180°. Each telescope consists of two thin ΔE counters with 0.5 mm and 1 mm thickness, respectively, one energy counter (E counter) with 160 mm$\phi\times$120 mm and one veto counter [7]. The veto counter eliminated the incoming β rays scattered by the magnet surface.

The alignment correlation term was obtained from the counting rate ratio, $R(E) = N(E, d\mathcal{P}^+, \mathcal{A}^+)/N(E, d\mathcal{P}^-, \mathcal{A}^-)$, for the up ($\theta_{I\beta} = 0°$) and down (180°) counters. $\mathcal{A}$ and $d\mathcal{P}$ in $R(E)$ are the alignment and the residual polarization when the alignment is produced. The signs given by the superscript in $\mathcal{A}^\pm$ and $\mathcal{P}^\pm$ are the sign of the alignment. The alignment correlation term was extracted from the well approximated formula as $R(E) - 1 \approx \pm B_1(E)/B_0(E)d\mathcal{P} + B_2(E)/B_0(E)\Delta\mathcal{A}$, where $d\mathcal{P} = d\mathcal{P}^+ - d\mathcal{P}^-$, $\Delta\mathcal{A} = \mathcal{A}^+ - \mathcal{A}^-$ and the upper and lower signs are for up and down counters, respectively. The alignment correlation terms extracted from the up and down counters were averaged, so that the effect of the residual polarization was canceled.

The obtained alignment correlation terms are shown in Fig. 2. The corrections applied at each data points were evaluated for the response of the E counter, the solid angle of the counter telescope, the higher order matrix elements and p/E term in the polarization correlation term, and the $(p/E)^2$ term in the alignment correlation term. The correction for the background in the β-ray energy spectra was negligible in the energy region higher than 5 MeV. The total correction at 9 MeV was typically 4% for ^{8}Li and 3% for ^{8}B relative to the alignment correlation term. The systematic uncertainties were evaluated for the uncertainties of the response function, the position and the thickness of the crystal for implantation, the position of the beam spot on the target, the energy calibration and the gain fluctuation of the E counters, the higher order matrix elements in the polarization term and the error in the alignment calculation. The total systematic uncertainty at 9 MeV was typically 5% relative to the alignment correlation term for both ^{8}Li and ^{8}B.

The energy dependence of the β-α angular correlation terms have been observed by Tribble *et al.* and McKeown *et al.* [8,9]. The experiment by Tribble *et al.* did not reproduce the $\cos\theta$ term in the angular correlation, which is a kinematic shift term. Since this problem was resolved by McKeown *et al.*, the McKeown's data shown in Fig. 2 were used to extract the $g_{\rm II}/g_{\rm A}$ by combining the present data. Only the alignment correlation terms have a large E^2 contribution as shown in Fig. 2. This fact clearly shows that E^2 contributions from the j_2/A^2c term and from the j_3/A^2c term contribute additively to the alignment correlation terms but are canceled each other in the β-α angular correlation terms. The obtained difference $\delta^-(s)$ defined in Eq. (2) is shown

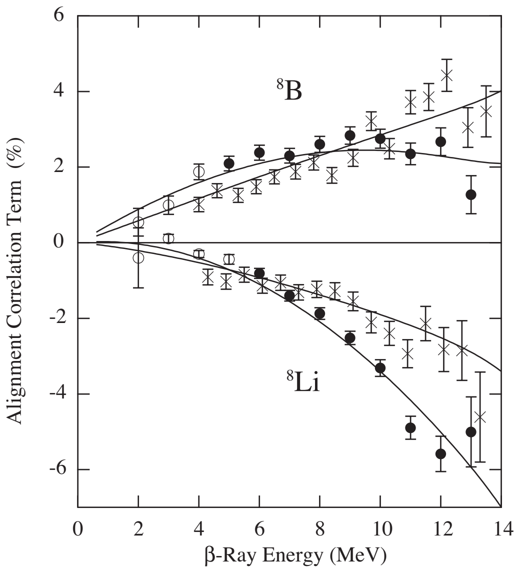

Fig. 2. Present alignment correlation terms and β-α angular correlation terms. The filled circles are the present alignment correlation terms used in the extraction of $g_{\rm II}/g_{\rm A}$. The open circles are not used to avoid large systematic uncertainties. The crosses are the β-α angular correlation terms [9]. The solid lines are the best fit curves.

in Fig. 3. The deviation of δ^- of the alignment correlation terms and the one of the β-α angular correlation terms indicates that the f/Ac term contributes measurably to δ^-. In the previous study [10], the $g_{\rm II}/g_{\rm A}$ was extracted only from $\delta^-(1)$ of the β-α angular correlation terms neglecting the f/Ac term, because the CVC prediction of f/Ac from the analog-γ-decay measurement was negligibly small. The analysis combining two angular correlation terms enables us to separate the f/Ac term from the weak magnetism b/Ac and $g_{\rm II}/g_{\rm A}$.

The reliable evaluation of the weak magnetism b/Ac is essential to extract $g_{\rm II}/g_{\rm A}$. The dependence of $b(E_x)$ and $c(E_x)$ on the excitation energy E_x of ^{8}Be were determined from measurements of the analog-γ-transition strength from ^{8}Be by De Braeckeleer *et al.* [10] and of the β-delayed-α energy spectra from ^{8}Li and ^{8}B by Bhattacharya *et al.* [14], respectively. De Braeckeleer *et al.* used a short and high pressure target cell of a ^{4}He gas without collimator between the cell and a γ ray detector to solve problems due to a long cell with a collimator at early studies [11,18]. The determination of the effective cell length with collimator was difficult, therefore there were possible problems about the absolute cross section and the angular distribution. And there was no data at forward angles due to the neutron background from the entrance window of the long cell. Recently β-delayed-α energy spectrum from ^{8}B has been measured with different techniques by Ortiz *et al.* and by Winter *et al.* [19]. These two results disagreed each other. Bhattacharya *et al.* remeasured the delayed-α spectra from ^{8}Li and ^{8}B with entirely different techniques [14]. The spectrum by Bhattacharya *et al.* agreed the one by Winter *et al.* but disagreed the one by Ortiz *et al.* The deviation of Ortiz's spectrum might be caused by a large energy dependence of an α-ray-detection efficiency due to a strong magnetic field to sweep away β rays.

The E_x dependence can be formulated using the R-matrix theory with four final states [20]. The $c(E_x)$'s of ^{8}Li and ^{8}B were determined by Bhattacharya *et al.* The averaged $c(E_x)$ between the mirror transitions was used in the evaluation of b/Ac. The E_x dependence of $b(E_x)$ was determined using the same R-matrix parameters as $c(E_x)$ from the analog-γ-transition strength [10]. The matrix elements of $\mathcal{M}_1^\gamma$ and R_γ in $b(E_x)$ were rescaled so as to reproduce the energy distribution of the γ ray to be $\mathcal{M}_1^\gamma = -8.71 \pm 0.28$ and $R_\gamma = 1.5 \pm 1.4$. The b/Ac as a function of a β-ray energy was determined by following the procedure by De Braeckeleer *et al.* [10], and shown in Fig. 3.

The χ^2 fit analysis was applied simultaneously to the four experimental correlation terms given in Fig. 2 using Eq. (1). The free parameters are $g_{\mathrm{II}}/g_{\mathrm{A}}$,

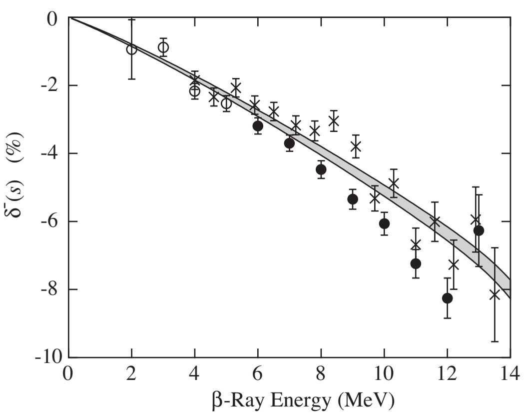

Fig. 3. Difference $\delta^{-}(s)$ of the angular correlation terms. The symbols are same as Fig. 2. The shaded band shows the 1σ error of b/Ac. The difference of two angular correlation terms is caused by f/Ac.

d_{I}/Ac, f/Ac, j_2/A^2c and j_3/A^2c. It is assumed that the E_x dependence of all the terms except for $b(E_x)$ is same as $c(E_x)$. The induced tensor term was obtained as $g_{\mathrm{II}}/g_{\mathrm{A}} = -0.28 \pm 0.28(\mathrm{stat.}) \pm 0.15(\mathrm{syst.})$, which is consistent with the G-parity conservation and the result in the $A = 12$ system [7]. The statistical error consists of 0.16 from both the alignment correlation terms and the β-α angular correlation terms, and 0.23 from the transition strength of the isovector M1 decay in determining the weak magnetism b/Ac. The systematic uncertainty consists of 0.10 from the alignment correlation terms, 0.06 from the β-α angular correlation terms, and 0.09 from the uncertainty of the E_x dependence of $b(E_x)$ and $c(E_x)$. The E_x dependence of the other terms may differ from that of $c(E_x)$. The uncertainty caused by assuming the same E_x dependence as $b(E_x)$ instead of $c(E_x)$ was less than 0.01 in $g_{\mathrm{II}}/g_{\mathrm{A}}$. The other terms were obtained as $d_{\mathrm{I}}/Ac = 5.5 \pm 1.7$, $f/Ac = 1.0 \pm 0.3$, $j_2/A^2c = -490 \pm 70$ and $j_3/A^2c = -980 \pm 280$. At a 90% CL, we obtained $g_{\mathrm{II}}/g_{\mathrm{A}} = -0.28 \pm 0.46(\mathrm{stat.}) \pm 0.19(\mathrm{syst.})$, where systematic uncertainties evaluated analytically using values with statistical 1σ error were multiplied by 1.64, while the others were already evaluated in 90% CL. In the $A = 12$ system, a possible charge asymmetry of the matrix elements in the mirror transitions was taken into account [7], which yields a shift of 0.10 ± 0.05 in $g_{\rm II}/g_{\rm A}$. The charge asymmetry in the $A = 8$ system was not taken into account because the effect is small compared with the error of the present data.

Combining the present result with the ones in the $A = 12$ system [7] and in the $A = 20$ system [12], the induced tensor term was obtained as $g_{\rm II}/g_{\rm A} = -0.17 \pm 0.16$ at a 90% CL. In the $A = 20$ system, the theoretical prediction of j_2 was used to extract $g_{\rm II}/g_{\rm A}$, and the value, $g_{\rm II}/g_{\rm A} = -0.4 \pm 1.1$, including 100% uncertainty in j_2 was used for the weighted mean. Shiomi predicted $g_{\rm II}$ based on the QCD sum rule as $g_{\rm II}/g_{\rm A} = +0.0152 \pm 0.0053$, which is proportional to the mass difference between up and down current quarks [21]. Although the error is still large, the present experimental $g_{\rm II}/g_{\rm A}$ deviates from the very small theoretical limit a little beyond the error in the opposite direction. This may indicate an enhancement of $g_{\rm II}/g_{\rm A}$ by a renormalization in nuclear medium. The off-shell effect of the order of $B/M_n \sim 10^{-2}$ [22], where B is the binding energy, may be responsible for the deviation as large as -0.17.

A model was introduced by Kubodera-Delorme-Rho (KDR) [23] to incorporate medium effects such as the off-shell effect and/or the G-parity violating ω meson decay. In the KDR model, the G-parity violating signal is given by $\kappa = \zeta + \lambda L$ instead of $g_{\rm II}/2M_n$, where ζ is the 1-body contribution including the off-shell effect and λ is the 2-body contribution. The two KDR parameters ζ and λ are defined as $\zeta = (g_{\rm II} + g'_{\rm II})/2M_n$ and $\lambda = \frac{m_\pi^3 g_{\pi NN}}{24\pi M_n^2}\left(\frac{g'_{\rm II}}{2M_n} - \frac{g_{\omega NN}F_\omega}{g_{\pi NN}m_\omega^2}\right)$, where $g'_{\rm II}$ and F_ω are the coupling constants of the off-shell current and the G-parity violating decay of $\omega \to \pi e\nu$, respectively. Since meson exchange current between two nucleons depends on a nuclear structure, the λ contribution in κ is proportional to a matrix element L. Using several mass systems with different

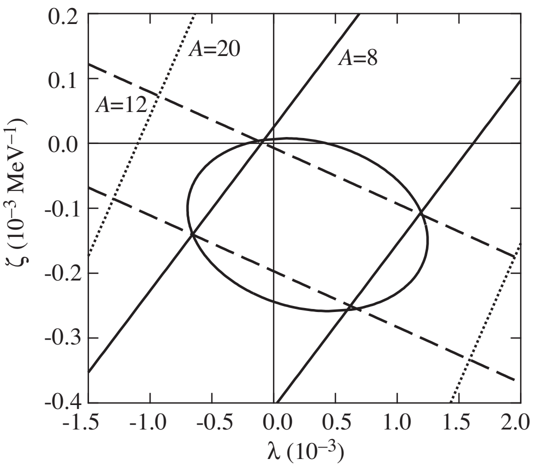

Fig. 4. Constraints on the KDR parameters. The solid slopes are the present result in the $A = 8$ system. The dashed and dotted slopes are the results in the $A = 12$ [7] and 20 [12] systems, respectively. The parameters are limited in the area between parallel lines. The ellipse shows a 1σ contour of the combined data.

L, the contributions of ζ and λ can be separated. The L values without the short range correlation are -0.252, 0.086 and -0.433 in $A = 8$, 12 and 20 systems, respectively [24]. Since the data of the $A = 8$ and 12 are almost orthogonal in ζ-λ plane, the result of the $A = 8$ was crucial in determining the two KDR parameters even if the error of the $g_{\rm II}/g_{\rm A}$ itself was larger than the $A = 12$. From the $A = 8, 12$ and 20 data, we derived the two KDR parameters to be $\zeta = -(0.13 \pm 0.13) \times 10^{-3}$ MeV^{-1}, $\lambda = +(0.27 \pm 0.97) \times 10^{-3}$ at a 1σ level as shown in Fig. 4. It is shown again that G-parity violating signals are small. However, in order to clarify whether there is a finite G-parity violation in the weak nucleon current due to the renormalization caused by medium effects, systematic studies in other mass systems are desired. The L of $A = 13$ system is very small such as 0.024 [23], therefore the ζ will be clearly detected in the $A = 13$ system. Systematic studies in the $A = 13$ and 20 systems [25] are in progress, where no prediction of unknown matrix elements requires to extract $g_{\rm II}/g_{\rm A}$.

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