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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A R T I C L E   I N F O

Article history:
Received 22 October 2007
Received in revised form 20 May 2008
Accepted 20 May 2008
Available online 23 May 2008
Editor: D.F. Geesaman

ABSTRACT

The alignment correlation terms in the β-ray angular distributions from purely spin aligned 6Li and 8B have been measured to search for the G-parity violating induced tensor term gII in the weak nucleon currents. The gII 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 gII. As a result, the induced tensor term was extracted as gII/gA = −0.28 ± 0.28 (stat.) ± 0.15 (syst.) at a 1σ (68%) level. The present data and the data in the mass A = 12 and 20 systems were 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 ζ = −(0.13 ± 0.13) × 10−3 MeV−1 and the 2-body contribution to be λ = +(0.27 ± 0.97) × 10−3 at a 1σ level.

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1. Introduction

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 axial-vector currents have not only the main terms, which are responsible for the axial-vector current and weak magnetism. The alignment correlation terms in the β-ray angular distributions from purely spin aligned 6Li and 8B have been measured to search for the G-parity violating induced tensor term gII in the weak nucleon currents. The gII 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 gII. As a result, the induced tensor term was extracted as gII/gA = −0.28 ± 0.28 (stat.) ± 0.15 (syst.) at a 1σ (68%) level. The present data and the data in the mass A = 12 and 20 systems were 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 ζ = −(0.13 ± 0.13) × 10−3 MeV−1 and the 2-body contribution to be λ = +(0.27 ± 0.97) × 10−3 at a 1σ level.

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1. Introduction

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Many β-ray correlation-type experiments of nuclei [3] and neutron [4], 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 gII 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 2Mg fII = 0.15 ± 0.12 ± 0.05 (theory) at a 90% confidence level (CL), where gA is the main coupling constant of the axial-vector current and Mg is the nucleon mass. 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 8Li and 8B have been measured by several groups [8,9]. The induced tensor term was determined as gII/gA = +0.5 ± 0.2 ± 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]. f is the second-
forbidden element matrix element of the vector current, $c$ is the Gamow–
Teller matrix element and $A$ is the mass number. If we adopt $f/Ac$
of Ref. [11], $g_{II}/g_{A}$ 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 $j_2/A^2c$, where $j_2$ is the second-forbidden matrix
element of the axial-vector current, was used to extract $g_{II}/g_{A}$ [12],
therefore the result has a large theoretical uncertainty. However,
all the highly uncertain terms contributing to the extraction of $g_{II}$
in the $\beta$–$\alpha$ angular correlation terms can be experimentally de-
termined combining with the alignment correlation terms in the
$\beta$-ray angular distribution as discussed later. In the present study,
the alignment correlation terms were measured to determine both
$g_{II}$ and the other terms in the $A = 8$ system.

2. $\beta$-ray angular correlation

The $\beta$-ray angular distribution $W(E, \theta_{j3})$ from a purely spin-
aligned nucleus has a correlation term with an alignment $A$ as
$W(E, \theta_{j3}) \propto e^{i(E_0 - E)^2[B_0(E) + AB_2(E)]P_2(\cos \theta_{j3})}$. Here, $p$, $E$
of polarization, the geometrical asymmetry and
the polarization
$\delta(0)$ and $\delta(1)$, respectively.

3. Experiment

The experimental procedure consisted of three steps, the pro-
duction of the polarized nuclei, the spin manipulation from polari-
zation to alignment and the $\beta$-ray detection. The present experi-
mental setup was an extension of $\beta$-NMR apparatus for measure-
ment of a $\beta$-ray-energy dependence of the angular distribution.
A hole was made in a dipole magnet at center axis of iron core
coil. A $\beta$-ray energy was measured by a set of plastic scintillation
counters placed just outside the dipole magnet. The detailed setup
was given in Ref. [7].

3.1. Production of polarized $^8\text{Li}$ and $^8\text{B}$

The experimental procedures of $^8\text{Li}$ and $^8\text{B}$ were the same, but
several conditions were different. First the experiment of $^8\text{Li}$ is
described. The Van de Graaff accelerator at Osaka University was
used to provide the pulsed beam of deuterons at 3.5 MeV to bomb-
ard a Li$_2$O target. The $^8\text{Li}$ nuclei were produced through the nu-
clear reaction $^7\text{Li}(d, p)^8\text{Li}$. The recoil angle of the reaction products
was selected to 14°–40° to optimize the nuclear spin polarization.
The polarization of $+7.18 \pm 0.10\%$ was obtained. The direction
of polarization is defined with respect to $p_{\text{beam}} \times p_{\text{prod}}$,
where $p_{\text{beam}}$ and $p_{\text{prod}}$ are the momentum vectors of beam and reaction
product, respectively. The method of polarization measurement is
described below. The polarized $^8\text{Li}$ nuclei were implanted into Zn
single crystals. The crystals were placed in a static magnetic field
$B_0$ of 60 mT, applied parallel to the polarization direction in order
to maintain the polarization and to manipulate the spin orienta-
tion with the $\beta$-NMR technique. The $c$ axis of the single crystals
was set parallel to $B_0$.

Here the conditions of $^8\text{B}$ are summarized. The $^8\text{B}$ were pro-
duced through the nuclear reaction $^7\text{Li}(^3\text{He}, n)^8\text{B}$, where the pulsed
beam of $^3\text{He}$ at 4.7 MeV and enriched metal $^6\text{Li}$ target were
used. The selected recoil angle was $7°$–$18°$ and the polarization
of $-5.42 \pm 0.19\%$ was obtained. The catcher of polarized $^8\text{B}$ was
TiO$_2$ and the static magnetic field was 230 mT.

To determine the polarization, asymmetries of $\beta$-ray angular
distribution between $\theta_{j3} = 0°$ and $180°$ were measured. The $\beta$ ray
was detected by two sets of plastic-scintillation-counter telescopes.
The measured asymmetry included the geometrical asymmetry
which was caused by the geometrical misalignment between two
telescopes. The initial polarization, the geometrical asymmetry and
the inversion efficiency $\alpha$ of polarization were deduced using the
same test sequence program as Ref. [7]. $\alpha$ was $-85.5 \pm 0.3\%$ and
$-94.8 \pm 0.9\%$ for $^8\text{Li}$ and $^8\text{B}$, respectively. These parameters were
measured every 312 s.

3.2. Spin manipulation and spin alignment

The Larmor frequency in a static magnetic field splits into four
resonance frequencies due to the hyperfine interaction between
the electric quadrupole moment $Q$ of the implanted nucleus and
the electric field gradient $g$ at the implantation site in the crystal.
The $^8\text{Li}$ nuclei implanted in Zn are known to be located at a single
site, while the $^8\text{B}$ 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 $^8\text{B}$ implanted only in major site was manipulated [17].
The effect of the unmanipulated $^8\text{B}$ 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. Fig. 1 shows the schematic procedure of the
alignment production for $^8\text{Li}$. The nuclear spin was manipulated
by applying rf oscillating magnetic fields in $\beta$-NMR technique. Two
methods of rf application were used, i.e., the adiabatic fast pas-
sage (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 depolar-
izations and four sequential AFPs. After measuring $\beta$-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 to remove a possible systematic uncertainty due to a fluc-
The polarizations were determined from the at two intermediate steps of the alignment-production procedure. The typical counting rate of each telescope was 4 kcps for $^8\text{Li}$ and $^8\text{Bi}$ itself, $^{15}\text{O}(2.24\text{ MeV}), ^{20}\text{F}$ and $^{12}\text{N}(16.83\text{ MeV})$ for $^8\text{Br}$ run.

3.3. Beta-ray detection

The $\beta$-ray angular distribution was obtained by two sets of plastic-scintillation-counter telescopes placed at $\theta_{\beta}=0^\circ$ and $180^\circ$. The typical counting rate of each telescope was 4 kcps for $^8\text{Li}$ and 1.5 kcps for $^8\text{B}$. Each telescope consists of two thin $\Delta E$ counters with 0.5 mm and 1 mm thickness, one energy counter ($E$ counter) with 160 mm$^2 \times 120$ mm and one veto counter [7]. The veto counter eliminated the incoming $\beta$ rays scattered by the counter surface. The energy was calibrated by determining the $\beta$-ray endpoint energies for several $\beta$ emitters, which were $^8\text{Li}$ itself, $^{28}\text{Al}$ ($E_0=3.37\text{ MeV}$), $^{20}\text{F}$ ($5.90\text{ MeV}$), and $^{12}\text{B}$ ($13.88\text{ MeV}$) for $^8\text{Li}$ run, and $^8\text{B}$ itself, $^{15}\text{O}$ ($2.24\text{ MeV}$), $^{20}\text{F}$ and $^{12}\text{N}$ ($16.83\text{ MeV}$) for $^8\text{B}$ run. The response function of $E$ counter was obtained [7] using a Monte Carlo simulation with EGS4 code [18], where the distribution of the $\beta$ emitters on the catcher was taken into account by considering the kinematics of the nuclear reaction.

4. Extraction of alignment correlation term

The alignment correlation term was obtained from the ratio of counts at the positive and negative alignment sections, $R(E) = N(E, dP^+)/N(E, dP^-)$, for the up $(\theta_{\beta}=0^\circ)$ and down $(180^\circ)$ counters. $A$ and $dP$ in $R(E)$ are the alignment and the residual polarization at the alignment section. The signs given by the superscript in $A^\pm$ and $dP^\pm$ are the sign of alignment. The alignment correlation term was extracted from the well approximated formula without the influence of the beam-current fluctuation [7] as

$$R_1(E)R_2(E) = 1 \pm \frac{B_1(E)\Delta A_1+2}{B_0(E)}dP_1+2 + \frac{B_2(E)}{B_0(E)}\Delta A_1+2,$$

where the upper and lower signs are for up and down counters, respectively.

$$dP_1+2 = dP_1^+ - dP_1^- + dP_2^+ - dP_2^- \quad \text{and}$$

$$\Delta A_1+2 = A_1^+ - A_1^- + A_2^+ - A_2^-.$$

The subscript 1 and 2 for $R$, $P$ and $A$ shows the first and second alignment sections after the beam-off, respectively. $\Delta A_1+2$ was $+13.1 \pm 0.4\%$ for $^8\text{Li}$ and $+17.7 \pm 0.8\%$ for $^8\text{B}$. The alignment correlation terms extracted from the up and down counters were averaged, so that the effect of the residual polarization was canceled.

5. Corrections

The alignment correlation terms were applied the corrections for the alignment, the angular distribution and the energy spectrum. The alignment of parent nucleus is independent of the $\beta$ ray, thus the correction for alignment is independent of the $\beta$-ray energy. The others depend on the $\beta$-ray energy and are shown in Fig. 2.

The alignment was determined from the polarization change, thus the correction for alignment was related to the polarization. The $(p/E)$ term and the polarization correlation term were neglected in the polarization calculation. The correction for these terms to the alignment correlation terms was evaluated as described in Ref. [7]. The correction factor for $(p/E)$ was 0.997 for both nuclides. The correction factor for polarization correlation term was evaluated to be 0.956 ± 0.030 for $^8\text{Li}$ and 1.004 ± 0.033 for $^8\text{B}$.

The $\beta$-ray angular distribution has the $\cos\theta_{\beta}$ and $P_z(\cos\theta_{\beta})$ terms to the polarization and alignment correlated terms, respectively. The influence of the finite solid angle was corrected as a function of energy by using the Monte Carlo simulation. The correction factor $C_{\text{solid}}$ for solid angle was shown in Fig. 2. The probability of the large angle scatter of the low energy $\beta$ ray is higher than the high energy $\beta$ ray, therefore the correction at low energy becomes large.

The observed alignment correlation term at a certain energy included the contribution of lower and higher energy regions because of the distribution of the counter response function [7]. The correction factor $C_{\text{res}}$ for response function was evaluated self-consistently by using the result of the alignment correlation terms. The correction for $^8\text{B}$ was nearly 1, because the alignment correlation term of $^8\text{B}$ was almost constant above 5 MeV as shown in Fig. 3.

The $\beta$-ray angular distribution proportional to the alignment has $(p/E)^2$ term as $(p/E)^2AB_z(E)/B_0(E)P_z(\cos\theta_{\beta})$. The correction factor $C_{(p/E)^2}$ for $(p/E)^2$ term was evaluated for each energy. The correction factor $C_{\text{bc}}$ for the background in the $\beta$-ray energy spectra was negligible in the energy region higher than 5 MeV. The total correction factors $C_{\text{total}}$ are shown in Fig. 2.

6. Systematic uncertainties

The response function could be changed due to uncertainties of the position and thickness of the catcher and the position of the beam spot on the target, because the distribution of $^8\text{Li}$ or $^8\text{B}$ on the catcher could be changed. The thickness of two crystals used...
as the catcher was 360 ± 40 μm and 250 ± 30 μm for 8Li and 100 ± 10 μm for 8B. The influence of these uncertainties was evaluated by using the Monte Carlo simulation. The reliability of the low-energy tail in the simulated response function of monoenergetic β-ray was studied experimentally [19]. The 12B and 12N were produced as a β emitter. The β-ray energy was selected by a dipole magnet. The shape and amount of tail were confirmed within the 20% statistical error. In the present experimental setup, the tail was caused mainly by the energy loss straggling in the catcher, thus this uncertainty was evaluated by changing the catcher thickness by 20%. The simple sum of the uncertainties for the simulated response function and for the catcher thickness itself was applied. The uncertainties of counter resolution and energy calibration were propagated to the systematic uncertainty of the alignment correlation term. The systematic uncertainty due to gain fluctuation of the E counters, background and pile-up were evaluated.

The statistical error in the self-consistent evaluation of Cres and Cβ/β0 was propagated to the systematic uncertainty. In the alignment determination, it was assumed that the incompleteness parameter ε of depolarization for two kinds of frequencies was same. The uncertainty due to different ε was evaluated by assuming the ratio of two ε’s was 10. The 3rd order orientation of nuclear spin was neglected in the polarization determination. The influence of the correlation term due to the 3rd order orientation, which was formulated [13] with the matrix elements determined in the present study, was evaluated self-consistently.

Each systematic uncertainty described above was less than 0.05% for 8Li and 0.04% for 8B in absolute value of the alignment correlation term at 9 MeV.

The statistical error of alignment is included in the systematic uncertainty of the alignment correlation term, because the alignment changes the alignment correlation term as a whole such as other systematic uncertainties. The error at 9 MeV was 0.08% for 8Li and 0.13% for 8B in absolute value of the alignment correlation term. However, the statistical error of the alignment was included in the statistical error of the final results such as gα/gA.

The total systematic uncertainty at 9 MeV was 5% relative to the alignment correlation term for both 8Li and 8B.

7. Results and discussions

The corrected alignment correlation terms are shown in Fig. 3. To avoid the large correction factor and systematic uncertainties, the data from 6 to 13 MeV for 8Li and from 5 to 13 MeV for 8B were used for the extraction of gα/gA. The alignment correlation terms are compared with the β–α angular correlation terms by McKeown et al. [9] in Fig. 3. The obtained difference δ(s) defined in Eq. (2) is shown in Fig. 4. The deviation of δ(s) 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(s).

7.1. Weak magnetism

The reliable evaluation of the weak magnetism b/Ac is essential to extract gα/gA. The dependence of b(Ex) and c(Ex) on the excitation energy Ex of 8Be were determined from most precise measurements of the analog-γ-transition strength from 8Be by De Braekeleer et al. [10] and of the β-delayed-γ energy spectra from 8Li and 8B by Bhattacharya et al. [14], respectively. The Ex dependence can be formulated using the R-matrix theory with four final states [20]. For c(Ex)’s of 8Li and 8B, parameters in R-matrix formalism were determined by Bhattacharya et al. The averaged c(Ex) between the mirror transitions was used in the evaluation of b/AC. The Ex dependence of b(Ex) was re-determined from the analog-γ-transition strength [10] using the same R-matrix parameters as c(Ex). The matrix elements of M′γ and Rγ in b(Ex), which were defined in Ref. [10], were rescaled so as to reproduce the data of the γ-ray-energy distribution to be M′γ = −8.71 ± 0.28 and Rγ = 1.5 ± 1.4. The b/AC as a function of a β-ray energy was de-
determined by following the procedure by De Braeckeleer et al. [10], and shown in Fig. 4.

7.2. Induced tensor term $g_{I}/g_{A}$

$f/Ac$ and $j_{3}/A^{2}c$ terms are not perfectly canceled in $\delta^{2}(s)$ because of the difference of $E_{0}$ for the mirror pair. To avoid this problem, the $\chi^{2}$ fit analysis was applied simultaneously to the four experimental correlation terms given in Fig. 3 using Eq. (1). The free parameters are $g_{II}/g_{A}$, $d_{1}/Ac$, $f/Ac$, $j_{3}/A^{2}c$, and $j_{5}/A^{2}c$. It is assumed that the $E_{0}$ dependence of all the terms except for $b(E_{0})$ is the same as $c(E_{0})$. The induced tensor term was obtained as $g_{II}/g_{A} = -0.28\pm 0.28$ (stat.) $\pm 0.15$ (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 $\beta - \alpha$ 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 $\beta - \alpha$ angular correlation terms, and 0.09 from the uncertainty of the $E_{0}$ dependence of $b(E_{0})$ and $c(E_{0})$. The $E_{0}$ dependence of the other terms may differ from that of $c(E_{0})$. The uncertainty estimated by assuming the same $E_{0}$ dependence as $b(E_{0})$ instead of $c(E_{0})$ was less than 0.01 in $g_{II}/g_{A}$. The other terms were obtained as $d_{1}/Ac = 5.5\pm 2.3$, $f/Ac = 1.0\pm 0.3$, $j_{3}/A^{2}c = -490\pm 70$ and $j_{5}/A^{2}c = -980\pm 390$. The present $f/Ac$ was the middle of the two previous CVC predictions [10,11]. At a 90% CL, we obtained $g_{II}/g_{A} = -0.28\pm 0.46$ (stat.) $\pm 0.19$ (syst.), where systematic uncertainties evaluated analytically using statistical $1\sigma$ errors 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 $0.10\pm 0.05$ in $g_{II}/g_{A}$. The charge asymmetry in the $A = 8$ system was not taken into account because the effect was small compared with the error of the present data.

To obtain the weighted mean in the $A = 8$, $12$ and $20$ systems, the results of Ref. [7] in the $A = 12$ system and Ref. [12] in the $A = 20$ system were used. In the $A = 20$ system, the theoretical prediction of $j_{2}$ was used to extract $g_{II}/g_{A}$. The value, $g_{II}/g_{A} = -0.4\pm 1.1$, including 100% uncertainty in $j_{2}$, was used. The weighted mean of the induced tensor term was obtained to be $g_{II}/g_{A} = -0.17\pm 0.16$ at a 90% CL and was slightly finite and negative. Shiomi, however, predicted a very small and positive value based on the QCD sum rule as $g_{II}/g_{A} = +0.0152\pm 0.0053$, which is proportional to the mass difference between up and down current quarks [21]. The experiment was performed for $\beta$ decay not of free nucleon but of nucleus, therefore the slight difference between the data and the prediction may indicate a renormalization in medium.

7.3. Medium effects

To incorporate medium effects such as the off-shell effect and/or the G-parity violating $\omega$ meson decay, a model was introduced by Kubodera–Delorme–Rho (KDR) [22]. In the KDR model, the G-parity violating signal is given by $\kappa = \zeta + \lambda l$, instead of $g_{II}/2M_{w}$, where $\zeta$ is the 1-body contribution including the off-shell effect and $\lambda$ is the 2-body contribution. Since meson exchange current between two nucleons depends on a nuclear structure, the $\lambda$ contribution in $\kappa$ is proportional to a matrix element $L$. Using several mass systems with different $L$, the contributions of $\zeta$ and $\lambda$ 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 [23]. Since the data of the $A = 8$ and $12$ are almost orthogonal in $\zeta$–$\lambda$ plane, the result of the $A = 8$ was crucial in determining the two KDR parameters even if the error of the $g_{II}/g_{A}$ itself was larger than the $A = 12$ system. 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 1$\sigma$ level. It is shown again that G-parity violating signals are small.

8. Summary

The G-parity violating induced tensor term, $g_{II}/g_{A}$, was extracted from the mirror $\beta$ decay of $^{8}$Li and $^{8}$B, and consistent with the G-parity conservation. The results of three mirror $\beta$ decays in the $A = 8, 12$ and $20$ systems indicated no G-parity violating signals caused by medium effects. However, in order to clarify whether there is a finite G-parity violation by medium effects at a more accurate level, systematic studies in other mass systems are desired. The $L$ of $A = 13$ system is very small such as 0.024 [22], therefore the 1-body contribution $\zeta$ will be clearly detected in the $A = 13$ system. Systematic studies in the $A = 13$ and $20$ systems [24] are in progress, where no prediction of unknown matrix elements requires to extract $g_{II}/g_{A}$.

Acknowledgements

We would like to thank R.D. McKeown at California Institute of Technology for providing their data tables and for the valuable advice. T.S. acknowledges the Special Postdoctoral Researcher Program of RIKEN for the financial support.

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Fig. 4. Difference $\delta^{2}(s)$ of the angular correlation terms. The symbols are same as Fig. 3. The shaded band shows the $1\sigma$ error of $b/Ac$. The difference of two angular correlation terms is caused by $f/Ac$. 

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