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Beta-Ray Angular Distribution from Aligned ^{12}B and ^{12}N, and The Validity of The G-Parity Conservation Law in Weak Nucleon Currents

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Precision alignment-correlation coefficients as a function of β-ray energy in ^{12}B and ^{12}N decays have been determined. A new upper limit is given to the G-parity violating induced-tensor current f_T as, $f_T/f_W = -(0.008 \pm 0.056)$, where f_W is the weak magnetism form factor. Also weak magnetism is discussed, as well as the time component of the main axial current.

§1. Introduction

In the past 10 years, studies on the nuclear β-decay process have focused on experiments designed to investigate the limitation of the applicabilities of various conservation laws in weak nucleon currents. Regarding the G-parity violating induced tensor current (the second class current (SCC)), the first experimentally conclusive evidence against its existence were given by us[1] in 1977 and later also by others[2] from measurements of the alignment-correlation coefficients of a pair of mirror β decays, i.e. ^{12}B and ^{12}N decays. The induced-tensor form factor f_T was shown to be small compared with the weak magnetism term[1-4] f_W, i.e. $f_T/f_W = -(0.02 \pm 0.17)$. It was our success to produce appreciable alignment for both nuclei with little nuclear polarization that principally enabled us to reach such conclusive results. Since then intensive work on the mirror decays have yielded the solid results listed in Table I.

However, in order to discuss the ultimate limitation of the validity of the G-parity conservation law in weak nucleon current and the foundation of gauge theory and current algebra, the measured precision of the correlation coefficients obtained by the year 1979 was not sufficient. More accurate values, with the errors less than a few % of the weak magnetism term were needed. Once the G-parity conservation law is guaranteed, the new precise values can open up frontiers of investigation otherwise difficult to approach. For example, the coefficients can be indispensable probes for details of nuclear structure, mesonic effects in the axial currents, the effective axial charge of the decaying nucleon in nucleus, etc.. From the experimental point of view, it was found previously that the main problems that restricted the accuracy of the previous results with the mass 12 systems to that level was first, the low production rate of the ^{12}N nuclei, and second small β-ray scattering problems caused by the materials in the vicinity of the β-ray detectors. In the present experimental setup where more accurate values were obtained, we properly solved these difficulties.

The present experimental progress is summarized in section 2. The experimental results are given in section 3. The new limit given to the induced tensor current, and other information from the new data are also given in the section 3.

§2. Beta-ray Angular Distribution and Experimental Setup

The β-ray angular distribution from the spin oriented ^{12}B and ^{12}N decays $[(I^{\pi},T,T_Z):(1^+,1,\pm1)\rightarrow(0^+,0,0)]$ have been calculated by Morita and collaborators[3] among others. The contribution of the various nucleon currents and meson exchanges have been studied theoretically in detail by many authors[4]. The angular distribution function $W(\theta)$ is given as,

$$W(\theta) = pE(E - E_0)^2B_0(E)[1 + P(B_1(E)/B_0(E))P_1(\cos\theta) + A(B_2(E)/B_0(E))P_2(\cos\theta)],$$

where p, and E are the momentum and energy of the electron, E_0 is the end point energy, P and A are the nuclear spin polarization and alignment respectively, defined

Table I. Alignment-correlation coefficients in the mass 12 system.

Experiment	α_- (%/MeV)	α_+ (%/MeV)
Osaka[a]	+(0.025 ± 0.034)	(−)(0.277 ± 0.052)
Leuvain[b]	−(0.007 ± 0.020)	
ETH[c]	+(0.024 ± 0.044)	
ETH[d]	0.01 ± 0.03	(−)(0.273 ± 0.039)
Osaka[e]	+(0.006 ± 0.018)	−(0.273 ± 0.041)
Theory		
Osaka[f]	+(0.001 ± 0.003)	−(0.269 ± 0.006)
Present Experiment	$\langle(B_2/B_0)_-/E\rangle$(%/MeV)	$\langle(B_2/B_0)_+/E\rangle$(%/MeV)
Osaka[g]	+(0.0046 ± 0.0053)	−(0.279$_5$ ± 0.010)

a) K. Sugimoto, T. Minamisono, Y. Nojiri and Y. Masuda: Invited talk and a contribution to Int. Conf. Nucl. Struct., Sept. 5-10, 1977, Tokyo, Japan; J. Phys. Soc. Japan 44 (1978) 801.
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g) For β rays in 5.0∼12.0 MeV: T.Minamisono, K.Matsuta, Y. Nojiri, and K. Takeyama: Contribution to This Conference.

by the magnetic substate populations for I = 1 as, $P = (a_+ - a_-)$ and $A = (1 - 3a_0)$, with $(a_+ + a_0 + a_-) = 1$, $[B_2(E)/B_0(E)]/E$ is the alignment correlation coefficient which is also approximated by $\alpha_\mp + O(E)$ where $O(E)$ is the higher order term dependent on E, and $[B_1(E)/B_0(E)]/E$ is the polarization-correlation coefficient. The energy dependent coefficient is given by $(B_2/B_0)_\mp/E = \pm(2/3)[a - (b_T \pm b_y)]$, where $a = g_W/g_A$, $(b_T \pm b_y) = g_T/g_A$. Here g_A, g_W and g_T are effective form factors. They are also given by use of the impulse approximation as, $g_A = (f_A \mp E_0 f_T)$, $g_W = x(f_W - f_V/2M)$, and $g_T = (f_T \pm y f_A/2M)$, where the nucleon form factors f_A, f_W, and f_T are axial vector, weak magnetism, induced tensor terms, respectively. The $\mp$ signs given are for ^{12}B (β^- emitter) and ^{12}N (β^+ emitter) decays, respectively. Here $a = -4.706(x/2M)(f_V/g_A)$ is the weak magnetism. $b_y = (y/2M)(f_A/g_A)$ is the time component which comes from the main axial-vector current, where y is dependent on the details of the nuclear structure. The factor x also includes nuclear structure effects, but this is known less dependent on its detail[3]. Koshigiri et al.[5] theoretically showed that $[(B_2/B_0)_- - (B_2/B_0)_+]/E = \Delta\alpha$ is constant for energy higher than 3 MeV. Therefore extraction of the averaged $\Delta\alpha$ from the experimental data is simple and easy. The difference contains the SCC term as, $\langle\Delta\alpha\rangle = (4/3)[-(f_T/f_A) + a]$. It is also noted that the time component is singled out as, $b_y = -(3/4)[(B_2/B_0)_- + (B_2/B_0)_+]/E$.

The experimental setup for the measurement of the alignment-correlation term is shown in fig. 1. The setup and the method used for the nuclear spin control for the production of the alignment are essentially that used in previous work[1]. Namely, in the present measurement, it was essential to measure the coefficient of a decay from the difference between the anisotropy in the β-ray distribution with positive and negative alignment of appreciable amount, in order to reject the small but not negligible asymmetry in the β-ray detection system. Also, two sets of counter telescopes placed above and below the reaction plane were needed in order to cancel a small polarization effect if it remains, the direction of which was vertical to the reaction plane, as well as to measure polarization.

One of the experimental advantages obtained from the improved techniques was a high production rate, three times the previous one for ^{12}N. This was made possible by direct cooling of the target holder by a jet of air inside the rotator. The target evaporated on a Mo ribbon stood up well under the bombardment by an intense beam

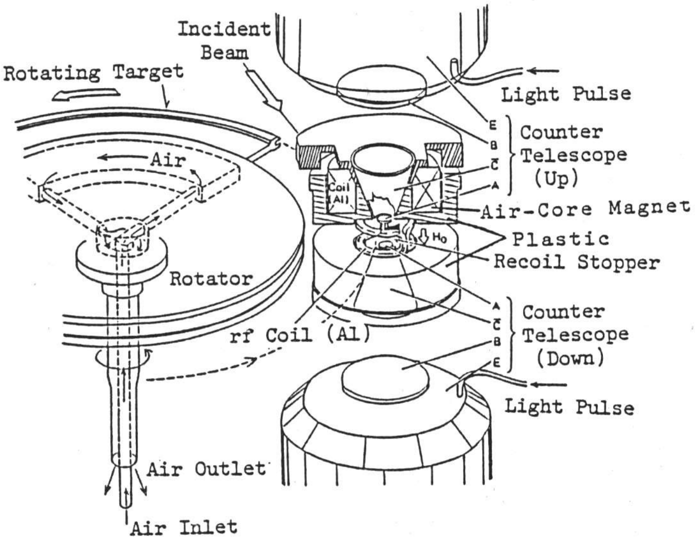

Fig. 1. Experimental setup. The principal part of the chamber wall is made of plastic. Details are given in the text. The metalic target evaporated on a molybdenum ribbon was mounted in the groove of the target holder which is cooled by a jet of air. The rotating wheel was rotated at a period of 60 msec. During the counting time the target with unwanted β emitters were hidden in the radiation shielded area.

of ^3He of 30 μA. The polarization of ^{12}B produced in $^{11}B(d,p)^{12}B$ reaction was P_0 = 0.15 at E_d = 1.5 MeV and the β-ray counting rate was 2×10^3/sec. For ^{12}N produced in $^{10}B(^3He,n)^{12}N$ reaction at $E_{^3He}$ = 3.0 MeV, P_0 = 0.25 and the counting rate was improved to 150/sec. In order to eliminate the main β-ray background scattering, the principal part of the chamber wall in the vicinity of the recoil stopper and β-ray windows was replaced by plastic, and the old magnet was replaced by an air-core magnet to apply a magnetic field of about 700 Oe for NMR. The energy-counter (160mm$^\phi$x160mm) systems were gain stabilized by use of regulated light pulses fed to the counters. The linearity of the pulse heights from the energy detector in the two counter telescopes as well as the response functions as a function of the β-ray energy was tested by use of monochromatic β rays. The β rays with a momentum spread of about Δp/p = 1 % were obtained from ^{12}B and ^{12}N nuclei where the β rays were separated by a set of magnetic β-ray separators. A main peak with energy resolution of about 8 % (HWHM) for β-rays of 10 MeV and a small low-energy tail were achieved. This shape (the response function) as a function of β-ray energy was important for the determination of the energy scale in the pulse height spectrum as well as to give small correction to the observed anisotropy. The linearity of the pulse height was also confirmed by the end point energies of the ^{12}B, ^{12}N, and ^{16}N decays, and was found sufficiently good for the present experimental purposes. As the original spin alignments produced in the reactions were small, i.e. A_0 = +0.05 for both ^{12}B and ^{12}N, alignments necessary for the correlation experiments had to be produced from the polarization. The conversion of polarization to alignment was performed by use of the NMR technique[1] in which unequal Zeeman splitting caused by nuclear quadrupole interaction eqQ with an electric field gradient superimposed on the strong magnetic interaction μH with external magnetic field H was used to induce selective rf transitions between any selective magnetic sublevels of the ^{12}B and ^{12}N nuclei (I = 1). A well defined electric field gradient was obtained in a Mg(hexagonal) single crystal in which the ^{12}B (or ^{12}N) nuclei were located in a unique site following implantation due to the kinetic energy obtained in the reaction. The principle of conversion of the polarization into alignment, and also the rf sequencing for the production of positive and/or negative alignment with, in principle, no residual polarization are illustrated in fig. 2. The amount of alignment in II are given as, $A_\pm = [\pm(3/2)P_0 - (1/2)A_0]$, while the remaining polarizations in both cases are, in principle, zero. The alignment was produced in the time section II, and during this period II, the β-ray energy spectra were observed with the up and down counter telescopes. In order to know the alignment in II, the alignment was converted back to the polarization by an rf field before III. Thus the observed alignments in II were deduced from the polarization in I and III with the help of the knowledge of the spin-lattice-relaxation time and degree of the achievement of the spin control which were also determined simultaneously during the measurements. The experimental values were $\widetilde{A} = (A_+ - A_-)$ = 0.30 and 0.51 for ^{12}B and ^{12}N, respectively.

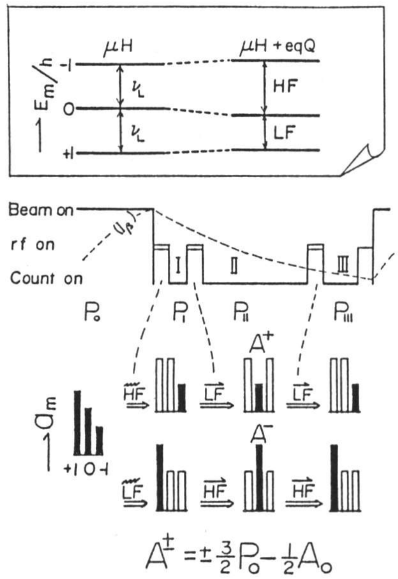

Fig. 2. Conversion of the initial polarization into alignment.

The initial polarization was converted into alignment by use of the spin control technique. Equalization in the magnetic sublevels is denoted by $\widetilde{HF}$ and $\widetilde{LF}$ for high and low frequencies. The interchange of the relevant populations by the adiabatic fast passage is denoted by $\overrightarrow{HF}$ and $\overrightarrow{LF}$.

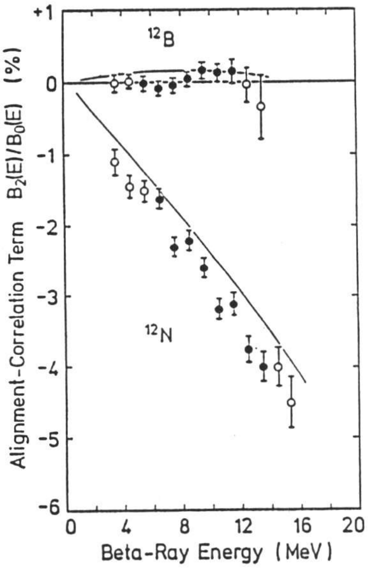

Fig. 3. Alignment-correlation terms for ^{12}B and ^{12}N.

The solid lines are theoretical ones[5)]

§3. Experimental Results and Discussion

The ratio R(E) of the β-ray counts at E is ideally given as,

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

where $\Delta P = (P_+ - P_-)$, $\tilde{A} = (A_+ - A_-)$ and $\lambda = 1/2$ or $-1/2$ refers to the U (Up) and D (Down) counters, respectively. The residual polarizations in II were shown in the present experiment to be negligibly small $|\Delta P| < 0.15$ %. Direct comparison of the experimental β-ray counts at E, $N(E,A_\pm,P_\pm)$ given as above was guaranteed to be correct for proper β-ray counts in I, II, and III for $A_\pm$ cycles, respectively. Therefore the anisotropy in the β-ray angular distribution is given as $A(B_2/B_0) = [(R^U(E) - 1) + (R^D(E) - 1)]/2$.

Present experimental results of B_2/B_0 as a function of β-ray energy are shown in fig. 3 together with the theoretical prediction given by Koshigiri et al[5)]. in which the impulse approximation with $f_T = 0$ was employed. Also the core polarization and the meson-exchange effect were taken into account in the prediction of the time component. Within the statistics, the experimental B_2/B_0 values of ^{12}B agree with the theoretical values. However the measured values of ^{12}N are lower than the theoretical ones by about 20 %.

The difference $[(B_2/B_0)_- - (B_2/B_0)_+]$ is linear dependent[9)] on E, while the sum depends slightly on E^2. From the difference, the averaged value $\langle\Delta\alpha\rangle = \langle[(B_2/B_0)_- - (B_2/B_0)_+]/E\rangle = +(0.284 + 0.011)$ %/MeV was obtained; small corrections due to decay branches, scattering problems etc. are included in the values listed in Table 2. Provided that strong CVC is valid, the weak magnetism term is obtained from the radiative decay width[6)] Γ_γ of the transition of the 15.11 MeV state of ^{12}C to the ground state. We obtained $a = +(0.2118 \pm 0.0030)$ %/MeV from $\Gamma_\gamma = (37.0 \pm 1.1)$ eV. Finally, $f_T/f_A = -(0.024 \pm 0.165)/2M$, and $f_T/f_W(CVC) = -(0.008 \pm 0.056)$ were obtained. Another "a" factor(although less accurate than the above) was obtained independently of the spectral shape factors of the mass number 12 system determined by Wu et al.[7)], and Kaina et al.[8)], i.e. $a = +(0.199 \pm 0.016)$ %/MeV. From this "a"

Table II. Typical $\langle (B_2/B_0)/E \rangle$ for β rays in 5.0 ~ 12.0 MeV and corrections.

	$\langle (B_2/B_0)_-/E \rangle$	$\langle (B_2/B_0)_+/E \rangle$
Uncorrected (%/MeV)	+(0.0045±0.0050)	-(0.2733±0.0061)
Correction		
Decay Branch	0.9863±0.0005	0.9861±0.0011
Solid Angle	1.040±0.003	1.040±0.003
(p/E) Term	0.9956	0.9973
Total	1.0212±0.0031	1.0228±0.0038
Corrected (%/MeV)	+(0.0046±0.0053)	-(0.279_5±0.010)
Difference $\langle \Delta\alpha \rangle$	-(0.284±0.011) (%/MeV)	

Error	^{12}B	^{12}N
Alignment Calculation	±0.0000	±0.0015
Energy Scale	±0.001	±0.004
Scattering and Background	±0.0001	±0.0045
Counter Response	±0.0015	±0.0050

value we obtain an f_T/f_W(CVC) = -(0.09 ± 0.12). Both f_T/f_W(CVC) values are in good agreement with each other and are also consistent with the previous result that SCC is small. Therefore the present results strongly guarantee the non existence of SCC within 6 % level of the weak magnetism term; thus G-parity is conserved in weak axial currents.

Assuming f_T = 0, CVC is tested since $\langle \Delta\alpha \rangle$ = (4/3)a. We have already found that the present "a" agreed with that obtained from the radiative width. The experimental values are 13 % larger than the theoretical one which was based on the impulse approximation with the core polarization effects and meson-exchange effects included in the prediction of the time component. The discrepancy may require further core polarization and meson exchage effects in the Gamow-Teller matrix element as well as in the time component[5], and/or may also require a renormalization of the axial-vector-coupling constant to about this amount for the decaying nucleon in the nucleus of mass number 12.

Finally from the sum of the (B_2/B_0) values shown by the closed circles in fig. 3, the time component b_y can be yielded as a function of β-ray energy. The averaged value $\langle b_y \rangle$ = 3.9/2M shows a 26 % discrepancy from the predicted one ($\langle b_y(\text{theory}) \rangle$ = 3.1/2M) which was obtained by following the same averaging method for the theoretical values[5] as a function of energy as that used for the experimental ones of fig. 3. This indicates that the soft pion effect in the time component is enhanced more than 30 % of the component, and/or the core polarization effect is less than the component.

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DISCUSSION

ADELBERGER: Your beautiful experiments are now so accurate that you may have to worry about isospin violation in interpreting the results.

MINAMISONO: The isospin admixture of T=0 component in the 15.1 MeV state of ^{12}C has been studied by electron scattering, and its effect in the weak magnetism was found to be small. Theoretical estimation of the weak magnetism term will be discussed by Professor Morita.

MORITA: In fact, the magnitude of the weak magnetism affects strongly that of the incident tensor form factor. The isospin mixing in the 15.1-MeV state of ^{12}C is expected to be about 6% from the inelastic electron scattering data for the 12.7-MeV state. This is taken into account for our estimation of the weak magnetism with the gamma-decay width. This result coincides with that of the shell-model calculation with exchange current effects. For details, see our contribution.

TRIBBLE: Would you comment on the results of β-decay measurements in A=8, 19 and 20 for their implications of a Second Class Current?

MINAMISONO: As shown here, correlation-type experiments are very reliable in searching for those recoil order effects. Also, Tribble et al. studied $\beta^{\pm}$-α angular correlation in $^{8}Li \rightarrow {}^{8}Be^{*} \leftarrow {}^{8}B$. Rolin et al. and Tribble et al. studied β-γ angular correlations in mass 20 system. Calaprice studied β-decay asymmetry from polarized ^{19}Ne. Precision of their results are all similar with that of previous results on mass 12 system. Their results are in agreement with no SCC.