Spin Manipulation by Use of Nuclear Quadrupole Interactions – Quarks and Medium Effects in the Nucleus

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The alignment correlation terms in the β-ray angular distributions from the purely spin aligned mirror pair ^{12}B($I^\pi = 1^+, T_{1/2} = 20.2$ ms) and ^{12}N($I^\pi = 1^+, T_{1/2} = 11.0$ ms) were precisely measured to place a new limit on the G-parity conservation law. For the creation of the alignment, the spin manipulation technique was applied, which utilized the nuclear quadrupole interactions. The G-parity violating induced tensor coefficient was determined to be $2Mf_T/f_A = -0.15 \pm 0.12 \pm 0.05$ (theor.), which is consistent with the theoretical prediction based on QCD in which $2Mf_T/f_A$ is proportional to the mass difference between up and down quarks which constitute the nucleon. Also determined the axial charge to be $y = 4.90 \pm 0.10$ (90% CL). From the result, we have found that the nucleon mass inside the nucleus is reduced (16 $\pm$ 4)% relative to the free nucleon mass.

Key words: β-Ray Angular Distribution; Alignment Correlation Term; G Parity; Axial Charge; In-Medium Nucleon Mass Renormalization.

1. Introduction

We know well that the intrinsic process for the nucleon or the nuclear β decay is the decay of the quark inside the nucleon or the nucleus, and that the process cannot directly be seen detecting the decay of a bare quark. We may be able to expect, however, that the emitted electron in the β decay as a direct decay of the quark would carry some information about the intrinsic process of the nuclear β decay and would give us a very rare and unique chance to approach to quarks in the nucleus at very low temperature, namely with very low momentum transfer, although the β-decay process is very much disturbed by the strong and electromagnetic interactions inside the nucleus.

2. Nuclear β-Decay

Weak nuclear processes are described with the current-current-type V-A interaction as $H_I = \sqrt{1/2}$ $(V_\lambda + A_\lambda)\{\bar\psi_e\gamma_\lambda(1 + \gamma_5)\psi_\nu\}$ + h. c., where V_λ and A_λ are the vector and the axial vector currents given by $V_\lambda = \bar\psi_p(f_V\gamma_\lambda + f_W\sigma_{\lambda\rho}k_\rho + if_Sk_\lambda)\psi_n$ and $A_\lambda = \bar\psi_p\gamma_5(f_A\gamma_\lambda + f_T\sigma_{\lambda\rho}k_\rho + if_Pk_\lambda)\psi_n$, respectively. Here $k_\lambda = k_p - k_n$, $\bar\psi = \psi^+\gamma_4$ and $\sigma_{\lambda\rho} = [\gamma_\lambda, \gamma_\rho]/2i$. Along with the main vector f_V and the main axial vector f_A currents, four other currents are included in the representation.

The G transformation is defined by the product of the charge conjugation C and the charge symmetry operation, $U = \exp(i\pi T_y)$, which is the rotation about the y axis by 180° in the charge space, as $G = C\exp(i\pi T_y)$. The G parities for those six terms in the nucleon current are given by $G = +1$ for f_V, f_W and f_T terms and $G = -1$ for f_A, f_P, and f_S terms. If each current has a definite G parity, the f_S and f_T terms should vanish because they have different G parities from those of their leading terms. Adopting the CVC theory, $\partial V_\lambda = 0$, we have $f_S = 0$. Consequently only the f_T term in the axial vector current breaks G parity [1].

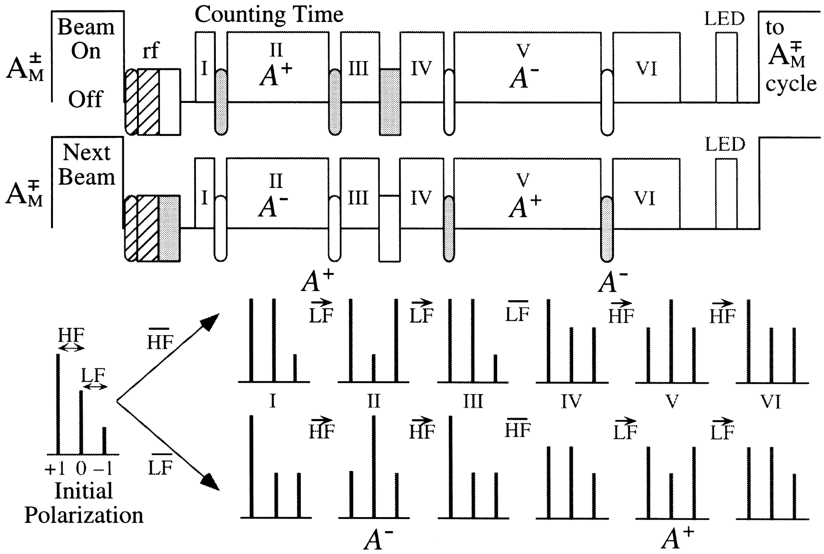

Fig. 1. Main sequence program and the change of the magnetic substate populations. The regions labelled from I to VI are the counting times. The squares and the ellipses between the counting times represent the rf for spin manipulation.

The β-ray angular distribution of ^{12}B and ^{12}N from oriented nuclei is given [2] by $W(E,\theta) \propto \left(1 + P\tilde{B}_1(E)\mathrm{P}_1(\cos\theta) + A\tilde{B}_2(E)\mathrm{P}_2(\cos\theta)\right)$, where E is the β-ray energy (endpoint energy), θ the angle between the direction of the polarization and the emitted β ray, P_i the Legendre polynomials, $\tilde{B}_1 = B_1/B_0$ and $\tilde{B}_2 = B_2/B_0$ the polarization and the alignment correlation terms. These $P = a_+ - a_-$ and $A = 1 - 3a_0$ are the degree of the nuclear spin polarization and alignment, where a_i are the magnetic substate populations with $a_+ + a_0 + a_- = 1$ for nuclear spin $I = 1$. Neglecting higher order terms in the impulse approximation (IA), the alignment correlation coefficient is simply described as $\tilde{B}_2(E)/E = 2\left\{\pm(a - f_T/f_A) - y_\mp/2M\right\}/3$, where M is the nucleon mass and the subscript $\mp$ refers to electron or positron decays. From the difference between ^{12}B and ^{12}N, f_T can be extracted as

$$\left[\frac{1}{E}\tilde{B}_2(E)\right]_{^{12}\mathrm{B}} - \left[\frac{1}{E}\tilde{B}_2(E)\right]_{^{12}\mathrm{N}} = \frac{4}{3}\left(a - \frac{f_T}{f_A} + \frac{\Delta y}{2M}\right),$$

where Δy is the possible asymmetry in the axial charge, the ratio of the time like component in the main axial vector current to the main axial vector current. On the other hand, the sum gives the axial charge as $[\tilde{B}_2/E]_{^{12}\mathrm{B}} + [\tilde{B}_2/E]_{^{12}\mathrm{N}} = -2y/3M$. The axial charge will be discussed later in this article. The first term $a = (4.04 \pm 0.03)/2M$ [3, 4] in the above equation is due to the weak magnetism and is given by the M1-γ ray decay strength of the 15.11 MeV excited state in ^{12}C to its ground state. The third term $\Delta y = 0.10 \pm 0.05$ (theor.) [3, 4], due to the binding-energy difference of the transforming nucleons, can be given with several nuclear models.

3. Experiment

The ^{12}B(^{12}N) nuclei were produced through the nuclear reaction ^{11}B(d, p)^{12}B (^{10}B(^{3}He, n)^{12}N). A deuteron beam (1.5 MeV) (^{3}He beam (3.0 MeV)), provided by the 4.7 MV van de Graaff accelerator at Osaka University was used to bombard a ^{11}B(^{10}B) enriched reaction target. The ejected ^{12}B(^{12}N) nuclei were implanted into a recoil catcher of a Mg single crystal (hcp) placed under an external magnetic field H_0. At the same time, selecting the recoil angle, a nuclear polarization of about 10% (20%) was obtained. The produced polarization was artificially converted into an alignment with, ideally, no residual polarization by the use of the spin manipulation technique. Finally, from the β-ray spectra from the aligned nuclei, the alignment correlation terms were obtained as a function of the β-ray energy.

By the use of spin manipulation, we were able not only to produce a large alignment compared with the small initial alignment produced through the nuclear reaction technique, but also to create both positive and negative alignments. In this technique we use NMR with a magnetic interaction between the magnetic moment μ of ^{12}B(^{12}N) and H_0, superposed on the electric interaction between a quadrupole moment

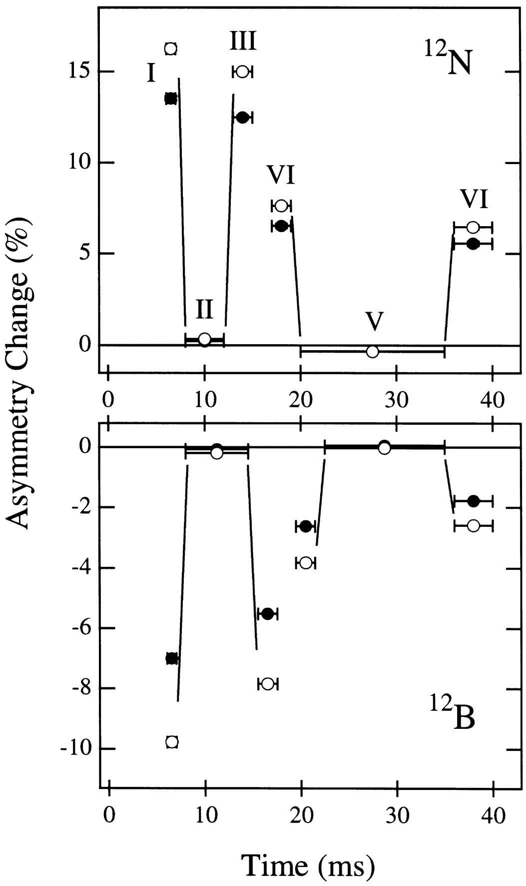

Fig. 2. Typical Result of the spin manipulation in the Main sequence program. The upper part is the result of ^{12}N and the lower part of ^{12}B. The full circles are for the polarization change in the $A^{\pm}_{M}$ cycle, and the open circles in the $A^{\mp}_{M}$ cycle. The lines in the figure schematically illustrate the change of the polarization by the spin manipulation.

Q of ^{12}B(^{12}N) and the electric field gradient q in the Mg catcher. The crystal c-axis of the Mg catcher was placed parallel to H_0. For ^{12}B and ^{12}N in the Mg crystal the asymmetry parameter of the electric field gradients is $\eta = (V_{XX} - V_{YY})/V_{ZZ} = 0$, where $V_{ij} = \mathrm{d}^2V/\mathrm{d}X_i\mathrm{d}X_j$, $|V_{XX}| < |V_{YY}| < |V_{ZZ}|$ and $V_{ZZ} = q$. The energy levels E_m are unequally split because of the quadrupole interaction $E_m = -h\nu_L m + h\nu_Q(3\cos^2\beta - 1)\{3m^2 - I(I+1)\}/12$ with $\nu_Q = 3eqQ/\{2I(2I-1)h\}$. Here, ν_L is the Larmor frequency and β the polar angle between q and H_0. The quadrupole coupling constant in Mg is known [5] to be eqQ/h = (–47.0 ± 0.1) kHz for ^{12}B and eqQ/h =(–59.3 ± 1.7) kHz for ^{12}N. In the present experimental condition, the two transition frequencies denoted by HF and LF are well separated, so that a specific transition between selected substates can be induced.

The spin manipulation was performed in accordance with the timing program named Main Sequence program illustrated in Figure 1. The $A^{\pm}_{M}$ and $A^{\mp}_{M}$ cycles for the production of the positive and negative alignment were the principal part of the experiment, in which the β-ray spectra from the aligned nuclei were measured. As shown in Fig. 1 in the $A^{\pm}_{M}$ cycle, by applying a depolarizing field $\overline{\mathrm{HF}}$ before the counting section I and sequentially applying an AFP field $\overrightarrow{\mathrm{LF}}$ before the counting section II, we obtained the positive alignment in section II. To confirm the alignment in section II, the alignment was converted back again into a polarization in the section III. Right after the counting section III, an alignment with the opposite sign was produced in counting section V. To start from the negative alignment in another beam cycle of $A^{\mp}_{M}$, we replaced the $\overline{\mathrm{HF}}$ and $\overrightarrow{\mathrm{LF}}$ rf set with the $\overline{\mathrm{LF}}$ and $\overrightarrow{\mathrm{HF}}$ rf set. Typical results of the polarization change in $A^{\pm}_{M}$ and $A^{\mp}_{M}$ as a function of time are illustrated in Figure 2. This spin manipulation yielded the actual effective alignment $\hat{A} = (A^{+}_{II} - A^{-}_{II}) - (A^{+}_{V} - A^{+}_{V})$, where $A^{\pm}_{i}$ is the alignment created in counting section i, to be 40% for ^{12}B and 85% for ^{12}N. This large effective alignment makes the experiment very efficient and reliable.

4. Results and Discussion

The β-ray energy spectra from the aligned nuclei were measured, and the alignment correlation terms were obtained as a function of the β-ray energy as shown in Figure 3. To extract f_T, we made a χ^2 fit of the theoretical curves for ^{12}B and ^{12}N simultaneously to a set of ^{12}B and ^{12}N data. Finally, the G-parity violating induced tensor coefficient was extracted [4] as

$$2M\frac{f_T}{f_A} = -0.15 \pm 0.12 \pm 0.05\,(\text{theor.})$$

at a 90% CL. f_T is vanishingly small and the G symmetry maintains very well. A theoretical prediction based on the QCD sum rules gives $2Mf_T/f_A$ = +0.015 ± 0.005 [6]. In its framework, the degree of violation is proportional to the mass difference between up and down quarks. This theoretical value is consistent with the experimental result. With a

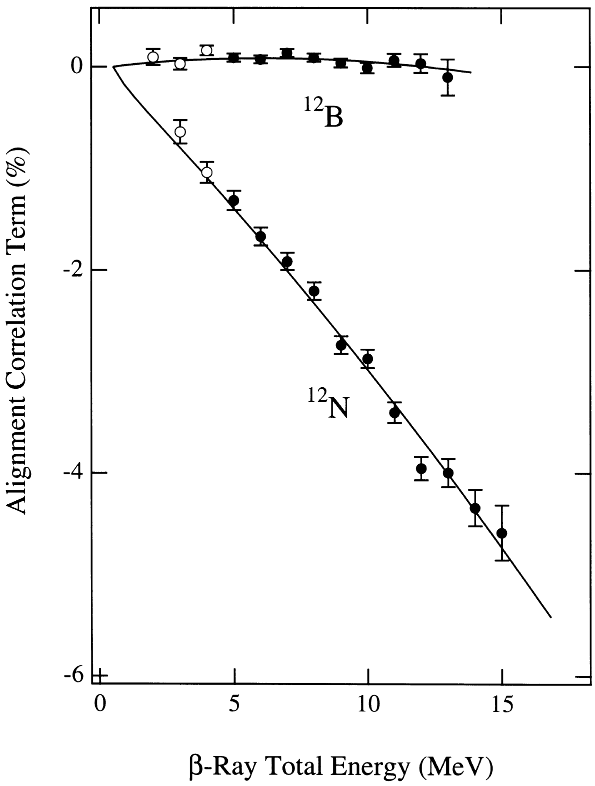

Fig. 3. Alignment correlation terms of ^{12}B and ^{12}N obtained in the year 2001. The full circles are the data used in the extraction of the final result; open circles are not because of the low energy background. The solid lines are the theoretical best fit curves to the present data.

further precise measurement and theoretical investigation, alignment correlation terms may reveal the quark degrees of freedom in nuclei. Because possible uncertainties, resulting from the lack of knowledge on the nuclear structure, may affect the result on f_T, the alignment correlation terms of a variety of mass systems have to be measured.

5. Axial Charge

Also, from the theoretical best fit to the alignment correlation terms we determined the axial charge. Theoretically, Kubodera et al. pointed out [7] that y is significantly enhanced by meson exchange effects relative to the value calculated by IA. The y value [4] from the present experiment is y = 4.90 ± 0.10, (90% CL) which shows an enhancement of as much as (72 ± 4)%. Such a huge mesonic effect has not yet been found in other phenomena. The hugeness makes it possible to perform the detailed studies on the mesonic effect inside the nucleus in spite of the lack of perfect knowledge on the nuclear structure and thus on the physics beyond that. The theoretical calculation [8, 9] based on the IA and the soft-π theorem explains well the experimental result, but there still exists an experimental excess of 26% left unexplained. If we introduce the in-medium renormalization of the nucleon mass in the nucleus [10], a mass reduction from the free nucleon of (16 ± 4)% is suggested.

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