In-Medium Mass Renormalization of Nucleons Detected in the Axial Charges of the β Decays of Spin Aligned ^{12}B and ^{12}N

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The axial charge of the weak nucleon axial vector current extracted from the anisotropic β-ray angular distributions of spin aligned ^{12}B and ^{12}N was accounted for mainly in terms of the impulse value y_{IA} and the soft pion exchange effect term y_{exch}. The experimental value, $y = 4.66 \pm 0.06(\mathrm{stat}) \pm 0.13(\mathrm{syst})$, was enhanced by 63% from the impulse value $y_{\mathrm{IA}} = 2.85$ which includes the core polarization effect. The experimental excess of 0.54 over the theoretical value $y_{\mathrm{IA}} + y_{\mathrm{exch}} = 4.12$ is accounted for by the in-medium mass reduction from the free nucleon value, if there is such an effect, of about $(12 \pm 4)\%$ for the nucleons decaying in the $A = 12$ triad. [S0031-9007(99)08509-9]

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It was theoretically suggested by Kubodera *et al.* [1] that the time component of the weak nucleon axial vector current in nuclei carries a giant soft-pion effect, as large as about 40% of the impulse approximation (IA) value for nucleons decaying in the region of half nuclear matter density in light nuclear systems [1–5]. In fact, it has been one of the famous surprises that the early experimental works of the β-decay rate for the first forbidden $0^- \leftrightarrow 0^+$ transition in the mass $A = 16$ system [4,5] and the β-ray anisotropy coefficients for allowed $1^+ \rightarrow 0^+$ transitions in the $A = 12$ system [2,3] showed giant mesonic exchange effects of that amount although their precisions were not good enough (for reviews, see Ref. [6]). The surprises were partly because such huge mesonic exchange effects have not yet been found in other phenomena, such as the proton capture of a neutron, the photodisintegration of a deuteron, and the effective g-factors of nuclear magnetic moments which are well surveyed in Refs. [7–9].

As a matter of fact, recently, Warburton *et al.* [10] have systematically analyzed the first-forbidden β-decay rates of the nuclides in the lead region and shown that the axial charges, the time components divided by the relevant space components of the Gamow-Teller matrix elements, were enhanced by 80% compared with the IA values, which is about twice that obtained from the soft-pion exchange currents and at the same time may show its dependence on the mass of the β-decaying nucleus. To explain this additional enhancement, they proposed in-medium renormalizations of the nucleon mass [10], which are also theoretically discussed in the framework of the chiral perturbation theory [11,12].

Another explanation for this anomalous enhancement was proposed by Kirchbach *et al.* [13–17], in which the short-range exchange currents originating from the exchange of heavier mesons were taken into account. On the other hand, Warburton and Towner [17] showed by including the heavy-meson exchange currents with the short-range correlation and the hard-pion model that the numerical values of the axial-charge matrix elements are not so much different from those derived from the soft-pion exchange current. Their analyses of the β-decay rates of the nuclei in the lead region using a realistic nucleon-nucleon potential with a weaker tensor force gave values close to the experimental ones with a still unexplained excess of about 25% left over. Therefore, more precise experimental values of the light nuclei, e.g., $A = 12$, where nuclear structures and β decays are well studied are most required to give a conclusive understanding on the meson exchange mechanisms and the possible in-medium renormalization.

For such important studies, we recently redetermined a precise axial charge y of the $1^+ \rightarrow 0^+$ β decay in the $A = 12$ system [18] by use of a further improved experimental technique as $y = 4.66 \pm 0.06(\mathrm{stat}) \pm 0.13(\mathrm{syst})$. This value is 63% larger than the theoretical IA value. In parallel with this improvement, Koshigiri *et al.* [19] have theoretically investigated the axial charge matrix elements of the $A = 12$ system in detail, as will be discussed below. This theoretical work [19,20] also made advances in understanding the β-ray angular distributions from spin aligned ^{12}B and ^{12}N [designated by ^{12}B (^{12}N) hereafter] using refined nuclear structures and leptonic wave functions. In this paper, taking advantage of the present advances, we discuss this giant axial charge.

In regard to the experimental studies on the $A = 12$ triad, ^{12}B-^{12}C*-^{12}N, by the end of the 1970s the Osaka [2] and ETH [3] groups had drastically improved the applicability of the conserved vector current theorem (CVC) by measuring β-ray angular distributions of spin aligned ^{12}B (^{12}N) as well as increased the probability of the nonexistence of a G-parity irregular axial vector current. Also, in 1986 the Osaka group [2] clearly extracted the axial charge of the system by obtaining a simple sum of

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the alignment-correlation coefficients which gave the axial charge as $y = (4.7 \pm 0.3)$ with rather poor precision. Recently, Minamisono *et al.* have remeasured [18] the β-ray angular distributions of the spin aligned ^{12}B (^{12}N) for which (I^π, T, T_Z) goes from $(1^+, 1, \pm 1)$ to $(0^+, 0, 0)$. In order to obtain a more precise value of the axial charge and to increase the applicability of G-parity conservation in the axial vector current, the authors improved further not only the experimental technique and counting statistics, but also studied experimentally and theoretically possible systematic corrections in the angular correlation experiments that might cause difficulties in analyzing the data of the $A = 12$ triad [2,18]. The choice of the ^{12}B (^{12}N) pair was kept because, up until then, the isospin triad in the $A = 12$ nuclei provided the best known system [2,3,18] with allowed transitions and physical observables given as the ratios of nuclear matrix elements for which nuclear model dependences are drastically reduced.

The angular distribution of β rays from spin oriented ^{12}B (^{12}N) was formulated [21] as

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

where p and E are the momentum and total energy of the emitted electron, E_0 is the end point energy of the decay, and θ is the angle between the electron direction and the axis of spin orientation. The quantities P and A are the degrees of spin 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 studied the angular distribution of β rays from spin aligned ^{12}B (^{12}N) with $P = 0$. The ratio is then given for $\beta^{\mp}$ decays as

$$B_2(E)/B_0(E)E = (2/3)(\pm a \mp f_T/f_A - y/2M). \quad (2)$$

The first term in the brackets is the weak magnetism (WM) [21], $a = -(1/2)(f_V \int \alpha \times \mathbf{r}/f_A \int \sigma)$, where f_V is the vector nucleon form factor. The second term is the induced tensor form factor divided by the form factor of the main term in the axial vector currents. The third term is the axial charge $y = -2iM \int \gamma_5 \mathbf{r}/\int \sigma$. Here M is the nucleon mass. As seen in Eq. (2), the sum of the alignment correlation coefficients in mirror decays singles out the parameter y.

Before we discuss the axial charge extracted from the data given in Ref. [18], we summarize here the experimental improvements employed at that time (1998). One of them was in the ability to manipulate the spin alignment created artificially from the polarization produced through the nuclear reaction. Such a conversion had become reliable through a thorough understanding of the implantation process and hyperfine interaction of ^{12}B (^{12}N) during and after its implantation in a Mg crystal following production in the nuclear reaction. The most striking feature found in the implantation process was the discovery of a second location for ^{12}B (^{12}N) with a minor population of about 15%, in addition to the known main location in the crystalline unit cell in Mg [22]. With a complete knowledge of the hyperfine interaction and spin orientation 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. Thus, we precisely measured the angular correlation alignment terms in the β-ray angular distributions from spin aligned ^{12}B($I^\pi = 1^+, T_{1/2} = 20.2$ ms) and ^{12}N($I^\pi = 1^+, T_{1/2} = 11.0$ ms) with spin polarizations $P = 0$. Typical values of the ratio B_2/B_0 obtained in 1996 are shown in Fig. 1 of Ref. [18] as a function of β-ray energy, together with those measured in 1985 and 1992.

In order to extract the axial charge y_{exp} and the induced tensor term $(f_T/f_A)_{\text{exp}}$ we made a chi-square fit of Eq. (1) simultaneously to the set of ^{12}B and ^{12}N data obtained in each year. For this purpose we adopted the formulation of the angular distribution given in Ref. [21], which made it possible to introduce higher order partial waves for leptons and Coulomb corrections produced by the finite size of the nuclei. We used the experimental WM, $2Ma_{\text{exp}} = +4.02 \pm 0.03$, which was determined [23] from all the available data [24] pertaining to 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. The fitted values of y_{exp} and $(f_T/f_A)_{\text{exp}}$ for each year's data set are given in Table I. Finally, we obtained the averaged results $y_{\text{av}} = 4.66 \pm 0.06(\text{stat}) \pm 0.13(\text{syst})$ and

TABLE I. The values of y_{exp} and $2Mf_T/f_A$ extracted by the best fit to the B_2/B_0 data [18]. How the systematic errors were evaluated was described in Ref. [18]. In obtaining averaged results the total errors were used to weight the input values. The systematic error for the 1996 data was used for the final result. We obtained the averaged value $y_{\text{av}} = 4.66 \pm 0.06(\text{stat}) \pm 0.13(\text{syst})$, which is consistent with the known value, $y_{\text{exp}} = 4.7 \pm 0.3$ [2].

Year	$2Mf_T/f_A$	Stat	Error Syst	Total	y_{exp}	Stat	Error Syst	Total	Enhancement
1985	0.06	0.08	0.27	0.28	4.69	0.10	0.29	0.30	(64 ± 11)%
1992	0.29	0.11	0.24	0.26	5.04	0.13	0.25	0.28	(77 ± 10)%
1996	0.07	0.06	0.15	0.16	4.53	0.06	0.13	0.14	(59 ± 5)%
av.	0.12	0.05	0.15	0.16	4.66	0.06	0.13	0.14	(63.3 ± 5.0)%

$2M(f_T/f_A)_{\rm av} = +0.12 \pm 0.05({\rm stat}) \pm 0.15({\rm syst})$ the further analysis of which was given in Ref. [18].

According to the theoretical work [19,20], the impulse value of $y_{\rm IA}$ which includes the core-polarization effect and the soft-pion contribution $y_{\text{soft-}\pi}$ separately are evaluated in the Hauge-Maripuu model [25] to be 2.85 and 1.30, respectively. The core-polarization effect was calculated in the $(0+2)\hbar\omega$ configuration space to be -0.32 ± 0.03 by use of the M3Y interaction [26], the strength of which is consistent with the one obtained in the analysis of the magnetic form factor in the inelastic scattering of electrons on ^{12}C. Thus, the total theoretical axial charge $y_{\rm th} = y_{\rm IA} + y_{\text{soft-}\pi}$ reaches 4.15 which corresponds to an enhancement of 46%. This predicted enhancement is still 18% less than the present experimental enhancement of $(4.66/2.85 - 1) = 64\%$ as given in Table I.

The exchange current effect based on the short range correlations (src) of heavy mesons (σ, ω, and ρ) in the $A = 12$ triad was considered by Koshigiri *et al.* [19] using the hard-pion model [13–17] for the ρ-π diagrams but with the Hauge-Maripuu model [25]. They retained only the pair currents which involve the scalar meson (σ) and the exchange of vector mesons (ω and ρ) up to $O(1/M^2)$. The exchange current operators and related parameters were essentially the same as those used by Kirchbach *et al.* [16]. The numerical values cited in Table II give the contribution of the exchange current to the axial charge matrix element. For model *A* the Bonn potential parameters in the Kirchbach *et al.* paper [16] are adopted in the configuration space [27]. Model *B* uses another set of the Bonn potential parameters. Since both values are close to the soft-pion value 1.30 given above, we may take the mean value $y_{\text{hard-}\pi} = 1.27$ as the theoretical value for the mesonic effect, where we assume an uncertainty of ±0.17 that is twice as much as the difference of these two predictions. The total theoretical axial charge $y_{\rm th} = y_{\rm IA} + y_{\text{hard-}\pi} = 4.12 \pm 0.17$ does not account for the experimental $y_{\rm av} = 4.66 \pm 0.14$. A better agreement between theory and experiment, however, might be obtained by introducing still higher order graphs of exchange currents.

The experimental excess $(y_{\rm av} - y_{\rm th})/y_{\rm IA} = 18\%$ over the theoretical value $y_{\rm th} = 4.12 \pm 0.17$ might be accounted for by some other mechanism like barionic scaling in a nuclear medium. According to the proposal of Kubodera *et al.* on the in-medium renormalization of hadron masses [11], the nucleon mass should be reduced as

$$\frac{m_N^*}{m_N} \approx \frac{m_\sigma^*}{m_\sigma} \approx \frac{m_\rho^*}{m_\rho} \approx \frac{m_\omega^*}{m_\omega} \approx \frac{f_\pi^*}{f_\pi} = \Phi(\rho), \qquad (3)$$

where m_N, m_σ, m_ρ, and m_ω are the masses of the hadrons, and f_π is the pion decay constant. Here, the asterisks refer to the renormalized values in the nuclear medium. The enhancement factor is written as

$$\varepsilon_{\rm MEC} = \frac{M_1^* + M_2^*}{M_1} = \frac{1}{\Phi(\rho)}\left(1 + \frac{M_2}{M_1}\right), \qquad (4)$$

where M_1^* is the in-medium single-particle axial-charge matrix element (IA) and M_2^* is the in-medium exchange current matrix element [11]. Here, $M_i^* = M_i/\Phi(\rho)$ where the values of M_i without an asterisk are calculated with $\Phi(\rho) = 1$. In the $A = 12$ triad, with the experimental enhancement defined by Warburton, $\varepsilon_{\rm MEC} = (4.66 \pm 0.14)/2.85 = 1.64 \pm 0.05$, and the theoretical ratio of $M_2/M_1 = 0.45 \pm 0.06$, we have $\Phi(A = 12) = 0.88 \pm 0.04$. Thus, in the present framework, the nucleons decaying in ^{12}B (^{12}N) are $(12 \pm 4)\%$ lighter than the free nucleon mass.

To check consistencies with other systems, we have the Φ value for the lead region where the observed enhancements were fairly well accounted for by the IA values plus the exchange current effects [17]. But, the amount left unexplained there, less than 25% of the experimental enhancement, could be attributed to in-medium renormalization. The experimental value of $\varepsilon_{\rm MEC} = 1.8 \pm 0.2$ and the theoretical ratio $M_2/M_1 = 0.5 \pm 0.1$ [11,17] gives $\Phi(A = 208) = 0.83 \pm 0.09$, leading to a mass reduction (from the free nucleon mass) of $(17 \pm 9)\%$ for the nucleons decaying in the nuclides in the Pb region. Also the experimental enhancements in the $A = 132$ region suggest a mass reduction of nucleons $(7 \pm 4)\%$. Such mass renormalizations are also phenomenologically in agreement with the ones evaluated from magnetic moments. For example, a renormalization of about 3% was found [28] for nuclides with $A = 16 \pm 1$ and 40 ± 1 which are one nucleon added to or removed from the doubly closed shell nuclides with $A = 16$ and 40, i.e., the renormalized unit of the magnetic moment, the nuclear magneton μ_N, was extracted from their isoscalar magnetic moments. Also, a mass reduction of $(8 \pm 3)\%$ was extracted by Yamazaki [29] from the anomalous orbital g-factors of the nuclides in the lead region.

In summary, we have accurately determined a large mesonic enhancement in the axial charge of the $A = 12$ triad. The theoretical soft-pion or hard-meson effect taken alone with the impulse (IA) value does not account for the enhancement. The experimental excess of 0.54 over the theoretical value $(y_{\rm IA} + y_{\rm exch}) = 4.12$ may suggest an in-medium nucleon-mass reduction of about $(12 \pm 4)\%$ for the mass $A = 12$ triad. In order to make sure whether

TABLE II. The theoretical enhancement of the mesonic effects in the axial charge due to the heavy mesons for ^{12}B and ^{12}N β-decays [19]. The Bonn potential parameter adopted in the Kirchbach's paper [16] is used for model *A*, and model *B* corresponds to another set of Bonn potential in the configuration space [27]. In each case, the short-range correlation was taken into account.

	Models	
	A [src]	*B* [src]
$y_{\text{hard-}\pi}$	1.357	1.186

this reduction really exists or not, more experimental and theoretical studies are encouraged.

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