nearly central collision of a highly relativistic proton with a heavy nucleus may act collectively with the nucleons along its path, in contrast to a peripheral collision which results in a conventional intranuclear cascade. These nucleons are rapidly ejected from the nucleus in the forward direction, carrying off most of the incident momentum and inducing a cleavage of the nucleus. Additional nucleons and clusters may be emitted from the surface of the zone of excited nuclear matter adjacent to the projectile path. Such a process would leave two fragments of the target relatively close and unaffected by the rapid event. These "spectator" fragments have almost none of the beam momentum, and because they are formed suddenly in closer proximity than would be the case for a fission process (with its stretched scission configuration), their final kinetic energies are larger than that for fission. The fast time scale of this process leads to preferential emission of the fragments at 90° to the beam, an effect which has been seen in fragment angular distributions.[7-9] Such a rapid breakup does not allow much time for the transfer of excitation energy to the newly formed fragments, accounting for the observation[2] that they are not highly excited when formed.

In summary, we have observed the breakup of a heavy nucleus by relativistic protons with the characteristics of a two-body process in which a large fraction of the target mass is missing. Moreover, the residual fragments are ejected with higher kinetic energy than expected for the fission of a mass equal to the sum of the fragment masses. The missing mass is assumed to carry with it most of the incoming energy and momentum.

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β-Ray Angular Distribution from Aligned ^{12}B and ^{12}N

Y. Masuda, T. Minamisono, Y. Nojiri, and K. Sugimoto[(a)]
Laboratory of Nuclear Studies and Department of Physics, Faculty of Science, Osaka University, Toyonaka, Osaka 560, Japan
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The coefficients $\alpha_\mp$ in the alignment-correlation terms $\mathfrak{a}\alpha_\mp EP_2(\cos\theta)$, in ^{12}B and ^{12}N decays have been determined; $\alpha_-(^{12}\mathrm{B}) = +(0.006 \pm 0.018)\%/\mathrm{MeV}$ and $\alpha_+(^{12}\mathrm{N}) = -(0.273 \pm 0.041)\%/\mathrm{MeV}$. The sign of $\alpha_+(^{12}\mathrm{N})$ was determined for the first time, by use of an NMR method and measurements on β-γ correlation in aligned ^{12}N. The $\alpha_- - \alpha_+$ result is consistent with strong conservation of vector currents without second-class currents and the $\alpha_- + \alpha_+$ result gives unique information on the time component of the axial-vector current.

Research works on β decay have recently focused on "recoil-order" experiments designed to determine the limits of validity of conserved-vector-current (CVC) theory and to search for the possible second-class currents (SCC) in the fundamental β-decay interactions. We have previously reported[1] measurements of the anisotropy coefficients α_- and α_+ in the β-ray angular distributions from aligned ^{12}B and ^{12}N. The results were compared with the available data for tests of the CVC theory in the mass-12 triad. Within the experimental uncertainty, the difference of the coefficients $(\alpha_- - \alpha_+)$, assuming $\alpha_+ < 0$, indicated no appreciable G-parity irregular component (SCC) in the nuclear weak currents. Measurements of $\alpha_\mp$ on aligned ^{12}B and ^{12}N have also been performed by Lebrun *et al.*[2] and Brandle *et al.*[2] However, the sign of α_+ has not been determined yet. It is thus essential to confirm the sign, especially since experimentally $|\alpha_-| \ll |\alpha_+|$.

In this Letter, we report the sign determination of α_+ in aligned ^{12}N decay, and data of α_- and α_+ in aligned ^{12}B and ^{12}N decays with improved accuracies. The present result confirms the previous conclusion on the SCC problem. A discussion is also given on the time component of the main (first-class) axial-vector current.

The formula for β-ray angular distribution in ^{12}B and ^{12}N decays (I^π, T, T_z: $1^+, 1, \mp 1 \to 0^+, 0, 0$) is[3]

$$W(\theta) \propto 1 \mp \mathcal{P}(p/E)(1 + \alpha_\mp E)P_1(\cos\theta) + \mathcal{A}\alpha_\mp EP_2(\cos\theta). \quad (1)$$

Here the upper sign refers to ^{12}B(β^-) decay and the lower sign to ^{12}N(β^+) decay; $P_n(\cos\theta)$ are Legendre polynomials; and p and E are momentum and energy of the β ray. The nuclear polarization $\mathcal{P}$ and alignment $\mathcal{A}$ are defined by the magnetic-substate populations; $\mathcal{P} = a_1 - a_{-1}$, $A = 1 - 3a_0$, and $a_1 + a_0 + a_{-1} = 1$. θ is the polar angle of the β-ray emission relative to the polarization (alignment) axis.

The coefficients $\alpha_\mp$ are given in the notation of Morita *et al.*[4] as

$$\alpha_\mp = \pm \tfrac{2}{3}[a - (b_T \pm b_y)],$$
$$a = g_W/g_A, \quad b_T \pm b_y = g_T/g_A, \quad (2)$$

where g_A, g_W, and g_T are effective form factors which are real provided that time-reversal invariance holds. They can be related to the nucleon form factors with the impulse approximation as

$$g_A = f_A \mp E_0 f_T, \quad g_W = x(f_W - f_V/2M),$$
$$g_T = f_T \pm y(f_A/2M). \quad (3)$$

Here f_V, f_A, f_W, and f_T are vector, axial-vector, weak-magnetism, and induced-tensor form factors, respectively. M is the nucleon mass. $a = -4.706(x/2M)(f_V/g_A)$ is the weak-magnetism term and $b_y = (y/2M)(f_A/g_A)$ is the time component which comes from the main axial-vector current, where x and y are dependent on details of the nuclear structure.[4] $b_T = f_T/g_A$ is the induced-tensor term. It is noted that the elementary-particle treatment[5] essentially gives the same form as given in Eq. (2).

In the present experiment, the sign of the alignment $\mathcal{A}$ of ^{12}N was identified in order to determine the sign of α_+. The brief outline of the procedure was as follows: (a) Production of polarized ^{12}N through ^{10}B(^{3}He,n)^{12}N. (b) Conversion of $\mathcal{P}$ to $\mathcal{A}$ by use of an NMR technique on ^{12}N in a Mg single crystal. (c) Sign determination of $\mathcal{A}$ from the angular distribution of γ rays from the first excited state of ^{12}C ($I^\pi = 2^+$, 4.43 MeV) populated through the β-decay branch.

The experimental setup of the sign determination was essentially the same as in the previous work[1] as shown in Fig. 1, except for the γ-ray detector system. The rotating-target system was employed to produce polarized ^{12}N. The pulsed-beam emthod was used to separate the production from the count period. $\mathcal{P}$ was monitored by the up-down count ratio of β rays detected by the counter telescopes at $\theta = 0$ (down) and $\theta = \pi$ (up). In order to control $\mathcal{P}$ and $\mathcal{A}$ by the NMR technique, the recoil nuclei were implanted in a Mg crystal,[6] the crystal c axis of which was perpendicular to the holding magnetic field H_0 (1.4 kG). The unequal Zeeman splitting of magnetic sublevels caused by the electric-quadru-

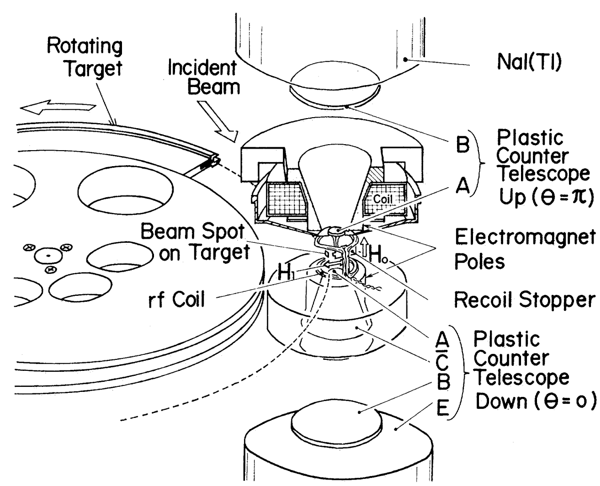

FIG. 1. Experimental setup for the sign determination. A 5-in.-diam×5-in. NaI(Tl) scintillator was set at $\theta = \pi$ (up) to detect the 4.43-MeV γ rays from ^{12}C. The counter telescope for the β-ray detection at $\theta = 0$ consisted of $AB\bar{C}E$ and the one at $\theta = \pi$ consisted of AB. The vacuum chamber, which was a part of the return yoke for H_0, is abbreviated together with other details.

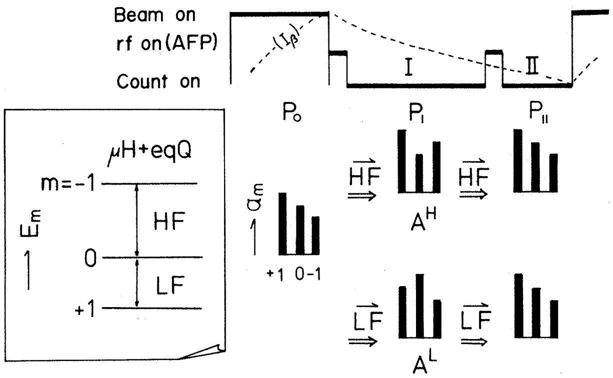

FIG. 2. Diagram to explain the conversion of the initial polarization $\mathcal{P}_0$ into a positive or a negative alignment $\mathcal{a}$ by using AFP. A time-sequence program is shown for the ^{12}N production, NMR transitions, and countings. A count period was divided into two intervals, I and II. The γ-ray distribution was measured in the intervals I.

pole interaction in Mg together with the magnetic interaction (μH_0) made it possible to induce a selective NMR transition by rf between relevant sublevels. The rf was time sequentially applied during an off-beam period following the scheme as shown in Fig. 2. Population reversal between a_{-1} and a_0 or between a_0 and a_1 was performed by the adiabatic-fast-passage (AFP) method: The frequency of the rf was swept across a resonance, and the amplitude was simultaneously modulated sinusoidally as a function of time. Two kinds of large alignments $\mathcal{a}^H$ and $\mathcal{a}^L$, opposite in sign, were alternately produced during the count interval I at each cycle by use of the rf with high (HF) and low (LF) frequencies, respectively. At the end of interval I, rf (HF or LF) was applied again for $\mathcal{a}^H$ or $\mathcal{a}^L$ cycle to monitor the degree of $\mathcal{a}$ from $\mathcal{P}$.[7] The accumulation of data was continued by repeating a pair of $\mathcal{a}^H$ and $\mathcal{a}^L$ cycles 20 times followed by a pair of normalization cycles to monitor the initial polarization $\mathcal{P}_0$. The normalization cycles consisted of one without any NMR transition and the other with polarization reversal by AFP on the double-quantum transition. In the present experiment, $\mathcal{P}_0 \cong 0.20$ and $\mathcal{a}_0 \cong 0.06$.

A 5-in.-diam×5-in. NaI(Tl) counter was placed at $\theta=\pi$ (up) to detect the 4.43-MeV γ rays, and operated during the count interval I in coincidence with the β telescope at $\theta=0$ (down). The β-γ correlation function for the oriented ^{12}N decay ($1^+ \xrightarrow{\beta} 2^+ \xrightarrow{\gamma} 0^+$) (neglecting higher-order terms[8]) is given by

$$W_\gamma(\theta_\beta=0,\theta_\gamma,\mathcal{a},\mathcal{P}) \cong 1+\tfrac{3}{4}\mathcal{P}(\cos^2\theta_\gamma-1) - \tfrac{1}{4}\mathcal{a}(\tfrac{3}{2}\cos^2\theta_\gamma-\tfrac{1}{2}), \qquad (4)$$

where $\mathcal{P}$ and $\mathcal{a}$ are for ^{12}N and $\theta_\beta(\theta_\gamma)$ is the polar angle of the β-ray (γ-ray) momentum relative to the orientation axis. In the present setup with $\theta_\beta=0$ and $\theta_\gamma=\pi$ the equation reduced to $W_\gamma(0,\pi,\mathcal{a},\mathcal{P})\cong 1-\frac{1}{4}\mathcal{a}$.

The sign of $\mathcal{a}$ was determined from

$$\Delta = 2\left(\frac{W_\gamma(0,\pi,\mathcal{a}^L,\mathcal{P}_I^L) - W_\gamma(0,\pi,\mathcal{a}^H,\mathcal{P}_I^H)}{W_\gamma(0,\pi,\mathcal{a}^L,\mathcal{P}_I^L) + W_\gamma(0,\pi,\mathcal{a}^H,\mathcal{P}_I^H)}\right), \qquad (5)$$

since $\Delta = -\frac{1}{4}(\mathcal{a}^L-\mathcal{a}^H)$. The result $\Delta=-0.101 \pm 0.036$ is in good agreement with the expected value $|\Delta|\simeq 0.12$ from $|\mathcal{a}^L-\mathcal{a}^H|\simeq 0.49$ determined from $\mathcal{P}_0$, $\mathcal{P}_I$, and $\mathcal{P}_{II}$. Thus $(\mathcal{a}^L-\mathcal{a}^H)>0$ was established. Since $(\mathcal{a}^L-\mathcal{a}^H)\alpha_+<0$ was known for the same experimental condition, $\alpha_+<0$ was concluded.[9]

A series of measurements of $\alpha_\mp$ for ^{12}B and ^{12}N were repeated by of the same experimental system and method as in the previous work.[1] The β rays were detected at $\theta=0$ and $\theta=\pi$ by the two sets of identical plastic-counter telescopes, one of which at $\theta=0$ is shown in Fig. 1. The energy spectra of β rays were obtained from the large plastic energy counters (E) of the telescopes. The method of data analysis was essentially the same as before. The energy-dependent ratio $R_\theta(E)$ of the spectra with positive $\mathcal{a}^+$ and negative $\mathcal{a}^-$ was derived separately for the counters at $\theta=0$ and $\theta=\pi$:

$$R_\theta(E)-1 = W(\theta,\mathcal{a}^+)/W(\theta,\mathcal{a}^-)-1 \cong (\mathcal{a}^+-\mathcal{a}^-)\alpha_\mp(E-\bar{E}) \mp (\mathcal{P}_{II}^+-\mathcal{P}_{II}^-)[\delta(E)-\bar{\delta}]\cos\theta. \qquad (6)$$

Here $W(\theta,\mathcal{a}^\pm)$ are the spectra normalized by respective integrated intensities. $\bar{E}$ is the mean energy of the region used for the integration. The small residual polarizations $P_{II}^\pm$ were those during main count interval (II) which was defined in Ref. 1.[10] $\delta(E)$ includes small effects due to β-decay branches and β-ray scatterings besides the term $\alpha_\mp E$, and $\bar{\delta}$ is the mean value of $\delta(E)$. $\delta(E)$ was found to be less than 5% variation in our energy region; 5–12 MeV for ^{12}B, and 7–14 MeV for ^{12}N. Since the measurement was performed with the condition $|P_{II}^+ - P_{II}^-| \lesssim 0.01$, the effect due to $\delta(E)$ was small. The $[R_\theta(E)-1]$ for

TABLE I. Experimental results of $\alpha_{\mp}$ (%/MeV).

	$\alpha_-(^{12}B)$	$\alpha_+(^{12}N)$
Previous result[a]	$+0.025 \pm 0.034$	-0.277 ± 0.048
Present result[a]	-0.001 ± 0.021	-0.267 ± 0.056
Average[a]	$+0.006 \pm 0.018$	-0.273 ± 0.037
Result	$+0.006 \pm 0.018$	-0.273 ± 0.041
Uncertainties		
Counting statistical	0.018	0.037
β-decay branch correction	0.0001	0.006
Detector solid angle	0.0003	0.011
Background	0.0001	0.001
Energy scale	0.0003	0.012

[a]Uncertainties are due to counting statistics only.

$\theta = 0$ and π was fitted with a straight line. In order to cancel further the effect due to $\delta(E)$, the slopes derived for $\theta = 0$ and π were averaged with the same weight.

It is not practical to derive the value of $(\mathfrak{A}^+ - \mathfrak{A}^-)\alpha_{\mp}$, as a function of energy, because one needs a proper production monitor which is independent of polarization and alignment for the ensemble of ^{12}B and ^{12}N. Since the ideal monitor here mentioned was not available for the present precision measurement, only the slope was derived from the experimental $[R_\theta(E) - 1]$.

The results $\alpha_{\mp}$ are shown in Table I together with the previous results,[1] and the final averaged values are $\alpha_- = +(0.006 \pm 0.018)\%/\mathrm{MeV}$ and $\alpha_+ = -(0.273 \pm 0.041)\%/\mathrm{MeV}$. Earlier reported $\alpha_{\mp}$ values[2] are in agreement with ours. We have previously reported $\alpha_{\mp}$ values from the polarization-correlation measurements[11] which were not in good agreement with the present ones; $\alpha_{\mp}$ values from the polarization correlation were larger than the present ones. In this connection, the alignment-correlation measurement is less sensitive than the polarization-correlation measurement to the disturbing effects due to β-decay branches and any small β-ray scatterings, and is more reliable, as discussed in Ref. 1.

The present $\alpha_{\mp}$ values are individually in good agreement with theoretical predictions by Morita *et al.*[3,4] with the impulse approximation without SCC; those predictions were $\alpha_- = 0.001\%/\mathrm{MeV}$ and $\alpha_+ = -0.269\%/\mathrm{MeV}$. The comparison of the $\alpha_- - \alpha_+$ value with theory is essential in search for SCC; $(\alpha_- - \alpha_+)_{\mathrm{expt}} = +(0.279 \pm 0.045)\%/\mathrm{MeV}$, and $(\alpha_- - \alpha_+)_{\mathrm{theor}} = +0.270\%/\mathrm{MeV}$. The good agreement indicates that no appreciable SCC exists: A limit on SCC can be estimated from Eqs. (2) and (3), i.e., $f_T = -(0.21 \pm 0.63) f_A/2M$, which can be compared with $f_W = -3.7 f_V/2M$.

Allowing no SCC, the present $a = \frac{3}{4}(\alpha_- - \alpha_+) = (0.209 \pm 0.034)\%/\mathrm{MeV}$ can be compared, in a model-independent way, with data so far obtained for CVC tests in the mass-12 system referring to the quantity, $a = g_W/g_A$: Comparison of the present result with "a" from the spectral shape factor; $a = (0.180 \pm 0.045)\%/\mathrm{MeV}$[12] and $a = (0.184 \pm 0.017)\%/\mathrm{MeV}$,[13] and the one from the analog γ transition; $a = 0.21\%/\mathrm{MeV}$.[14] The mutual agreements among the various "a" values are fairly good. Thus the present result supports the strong CVC with absence of SCC.

The sum singles out the time component,[15,16] $b_y(\mathrm{expt}) = -\frac{3}{4}(\alpha_- + \alpha_+)_{\mathrm{expt}} = +(3.73 \pm 0.64)/2M$, which is in good agreement with the prediction without meson-exchange current by Morita *et al.*[4]; $b_Y(\mathrm{theor}) = +3.6/2M$. This indicates a rather small effect of the meson-exchange currents in this particular nuclear system. It is noted that the time component is found to be as large as the *WM* term.

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[(a)]Present address: Institute for Nuclear Study, University of Tokyo, Tanashi-shi, Tokyo 188, Japan.

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Anomalous Analyzing Powers for Strong $(p_{\rm pol},t)$ Ground-State Transitions and Interference between Direct and $(p,d)(d,t)$ Sequential Process

K. Yagi, S. Kunori, Y. Aoki, K. Nagano, and Y. Toba
Institute of Physics and Tandem Accelerator Center, The University of Tsukuba, Ibaraki 300-31, Japan

and

K.-I. Kubo
Department of Physics, Tokyo Metropolitan University, Tokyo 158, Japan
(Received 19 May 1979)

Strong ground-state (p,t) transitions in nuclei of neutron number ≈ 50–82 are found to show anomalous analyzing powers which cannot be reproduced by direct one-step distorted-wave Born-approximation calculations at all. The anomalies are explained as an interference between $(p,d)(d,t)$ sequential processes and the one-step process. The cross section of the sequential processes is as large as that of the one-step process in the $L = 0$ (p,t) reactions. The neutron-number dependence of the anomalies is interpreted.

Angular distributions of cross sections $\sigma(\theta)$ for (p,t) and/or (t,p) transitions between 0^+ ground states $(0_g{}^+)$ of medium- and heavy-mass nuclei are known to have diffractive patterns[1] which can be explained by a direct transfer of two neutrons in a $^1S_0$ state on the basis of the first-order distorted-wave Born-approximation (DWBA) theory.[2] In addition to the cross sections $\sigma(\theta, 0_g{}^+)$, vector analyzing powers $A(\theta, 0_g{}^+)$ for the same transitions have been analyzed so far by the method of the first-order DWBA[3] because anomalous analyzing powers $A(\theta, 0_g{}^+)$ which are far beyond the predictions by this method have not been reported in two-neutron transfer experiments. In the present Letter, however, we report anomalous angular distributions of $A(\theta, 0_g{}^+)$ for (p,t) which cannot be reproduced by the first-order DWBA calculations at all.

The experiment was performed by using a 22.0-MeV polarized proton beam accelerated with the University of Tsukuba 12-UD Pelletron. The experimental procedures were the same as those used in the recent studies of the $(p_{\rm pol},t)$ reactions[4,5] except for the following two points. The angular acceptance of the magnetic spectrograph was reduced from $\Delta\theta = 3.0°$ to $\Delta\theta = 1.5°$ and angular distributions of $A(\theta, 0_g{}^+)$ and $\sigma(\theta, 0_g{}^+)$ were measured in 2° or 1.5° steps around $\theta \approx 20°$. The ground-state transitions to nuclei of ^{98}Ru, ^{102}Pd, ^{108}Pd, ^{114}Cd, ^{116}Sn, ^{120}Te, ^{126}Te, ^{128}Te, and ^{142}Nd were measured.

As reported in previous papers,[4-6] the $A(\theta, 0_g{}^+)$ for the nine nuclei of $N \approx 50$–82 show quite similar angular distributions over an angular range of 25°