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# Mirror $\beta$ Decays of $^{12}\text{B}$ and $^{12}\text{N}$ to $^{12}\text{C}_{4.44}$ [†]

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The $\beta$ decays of $^{12}\text{B}$ and $^{12}\text{N}$ to the 4.44-MeV first excited state of $^{12}\text{C}$ have been studied by means of $\beta$-$\gamma$ coincidence measurements using a $4\pi$ plastic scintillator and a NaI(Tl) detector. The ratio of $^{12}\text{N}/^{12}\text{B}$ $\beta$-ray branches to the 4.44-MeV state is found to be $1.52 \pm 0.06$ leading to $ft^+/ft^- = 1.06 \pm 0.04$ for this branch. This result removes the only severe exception to the systematic trend of positive $\delta = (ft^+/ft^-) - 1$ for mirror decays and is in agreement with a recent calculation of the binding-energy effect. In separate measurements the absolute $\beta$-ray branch of $^{12}\text{B}$ to the $^{12}\text{C}$ 4.44-MeV state is found to be $(1.27 \pm 0.06)\%$.

## I. INTRODUCTION

During the past few years extensive studies[1] have been made of mirror $\beta$ decays in order to investigate the questions of symmetry in $\beta$ decay and possible second-class currents in the weak interaction. One of the first well-established cases of asymmetry was in the $A = 12$ system, where it had been found that the $ft$ value for the $\beta^+$ decay of $^{12}\text{N}$ to the $^{12}\text{C}$ ground state is ~10% greater than the $ft$ value for the corresponding $\beta^-$ branch of $^{12}\text{B}$. More exactly, the asymmetry $\delta = (ft^+/ft^-) - 1$ is $+0.115 \pm 0.009$[2] in this case. Accumulated evidence for almost all other mirror pairs of $\beta^+$ and $\beta^-$ emitters has substantiated the conclusion that $\delta$ has a positive value. It is not yet clear whether $\delta$ increases linearly with the total decay energy, since the existing data could just as well be satisfied by the assumption of a constant value of $\delta$ averaging about $+0.10$.

Except for $A = 24$, where the measurements are exceedingly difficult and the slightly negative $\delta$ is in doubt, the only really severe exception to the systematics has been in the $A = 12$ system itself. Two measurements have been reported on the ratio of $^{12}\text{N}/^{12}\text{B}$ $\beta$-ray branches to the 4.44-MeV $2^+$ first excited state of $^{12}\text{C}$, namely $1.84 \pm 0.1$[3] and $1.72 \pm 0.15$.[4] The mean of these results led to $\delta = -0.117 \pm 0.041$[5] for this case which represented a large departure from the systematics.

The purpose of the present work was to remeasure the ratio of $^{12}\text{N}/^{12}\text{B}$ $\beta$ decays to the $^{12}\text{C}_{4.44}$ state using a technique that should be less subject to systematic errors than previous methods, as well as providing greater accuracy in the result. This technique has also allowed a more accurate value to be obtained for the absolute $\beta$-ray branch of $^{12}\text{B}$ to the $^{12}\text{C}$ 4.44-MeV state.

## II. EXPERIMENTAL PROCEDURES

In experiments on $\beta$-ray emitters using scintillation detectors in large solid-angle geometry one possible source of systematic error in the comparison of $\beta^+$ and $\beta^-$ activities results from the fact that both detectors can respond to positron annihilation radiation. As far as the $\beta$-ray detector is concerned corrections for the effects of annihilation radiation can be practically eliminated by the use of a $4\pi$ $\beta$-ray counter, as adopted in the present work. When the coincident $\gamma$ ray is of 4.44 MeV as in the present case, the effect of annihilation radiation in the $\gamma$-ray detector can be reduced to negligible proportions by the use of appropriate $\gamma$-ray absorbers.

The well-type $\beta$-ray detector used for the present experiments consisted of a Pilot-B scintillator 3 in. in diameter by 2 in. thick attached to a tapered light pipe and thence to a 2-in.-diam RCA 6342 photomultiplier tube. A hole 7.1 mm diam was drilled on the axis of the scintillator to a depth of 1.0 in. so as to accept a Be target tube of 6.3-mm outside diameter and 0.45-mm wall thickness. The tube was mounted on the end of an insulated support flange such that a 1–2-mm-diam collimated beam struck the center of the target that was mounted on a 0.003-in.-thick steel backing waxed onto the end of the Be tube. After insertion of the target tube into the $\beta$-ray detector stray room light was excluded by a ring of Apiezon putty.

For the geometry of the $\beta$-ray detector described above the solid angle of the entrance hole as seen from the target is only 0.5% of $4\pi$ and thus any differential corrections for the direct escape of $\beta^-$ or $\beta^+$ particles through the hole are negligible. $\beta$ rays of high energy passing through the target backing or the wall of the Be target tube suffer an energy loss of only ~150 keV, whereas $\beta$ rays are completely absorbed only if their energies are $\lesssim 300$ keV. Since the fraction of $\beta$ rays of <500 keV in any of the $^{12}B$ and $^{12}N$ components is very small, the differential effects of $\beta$-ray absorption in the backing and target tube are estimated to be negligible. Thus, for this target-detector geometry almost all of the $\beta$ decays in the target could result in recorded events except for biasing conditions, and for the $^{12}N$ in particular it does not matter if an annihilation quantum escapes or is absorbed by the scintillator, since the absorption event is in time coincidence with a $\beta^+$ particle that is necessarily detected.

$\gamma$ rays were detected in a 5×5-in. NaI(Tl) scintillator placed at 90° to the beam and with the target on the axis of the crystal. The distance from the target to the scintillator was 7.0 cm allowing space for absorbers to be placed between the NaI(Tl) container and the Pilot-B detector. In the comparison measurements on $^{12}B$ and $^{12}N$ a Pb plate 11 mm thick was placed against the NaI(Tl) crystal and a Be plate 10 mm thick was located between the Pb and the Pilot-B crystal to reduce bremsstrahlung effects. It was calculated by standard procedures that the probability for coincidence summing of 0.51-MeV annihilation $\gamma$ rays with the 4.44-MeV $\gamma$ rays in the $^{12}N$ decay is only 0.5% for this geometry. Possible errors in this small correction, therefore, do not affect the accuracy of the measurements. The $\gamma$-ray detector and absorbers were held in fixed positions for the comparison measurements on the $^{12}B$ and $^{12}N$ decays.

The $^{12}B$ and $^{12}N$ activities were produced by the reactions $^{11}B(d, p)^{12}B$ at $E_d = 1.5$ MeV and $^{10}B(^3He, n)^{12}N$ at $E_{^3He} = 3.3$ MeV, respectively. Target materials consisted of either $^{11}B$ or $^{10}B$ powder, each enriched to about 97% and deposited onto the backing foil by a slurry method to a thickness of ~10 mg/cm$^2$. After a series of runs on $^{12}B$ a special $^3He$ ion-source bottle was installed in the 3.5-MeV Van de Graaff accelerator for the $^{12}N$ runs. Although the $^3He$ bottle had never been used with any gas other than helium, there was nevertheless.a concern that a contaminate $HD^+$ beam might be present which could make $^{12}B$ from the 3% of $^{11}B$ in the $^{10}B$ target material. Thus, in the later runs on $^{12}N$ an external gas stripper was used to convert the accelerated $^3He^+$ beam to $^3He^{++}$ which was then passed through the ana-

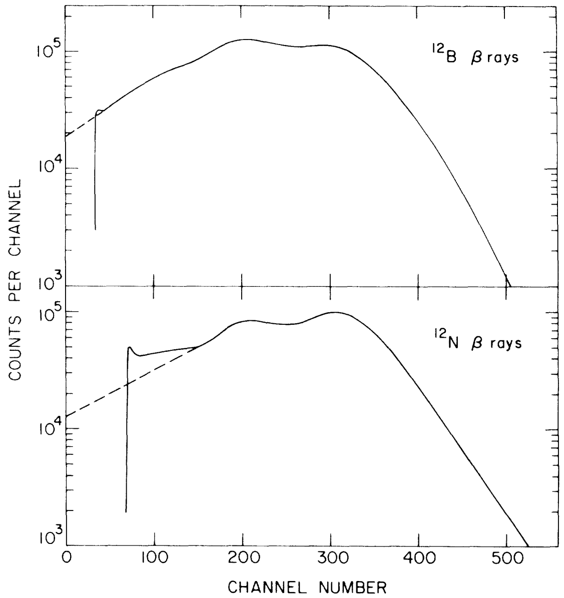

FIG. 1. $\beta$-ray singles spectra of $^{12}B$ and $^{12}N$ with biases imposed for coincidence measurements. Data points have been omitted. Experimentally determined extrapolations to zero pulse height are shown by the dashed lines. The double maxima effect in the two curves presumably results from the shape of the detector whose dimensions are less than the maximum range of the $\beta$ rays. In the $^{12}N$ curve the background yield at low energies is caused mostly by $\beta$ rays from $^{14}O$ (end point 1.81 MeV) produced in the $^{12}C(^3He, n)^{14}O$ reaction and by $^{11}C$ (end point 0.96 MeV) resulting from the $^{10}B(^3He, d)^{11}C$ reaction.

lyzing magnet to the target. Past experience had shown that this results in a contaminant-free $^3$He beam. Analysis of the data indicated no systematic differences between the results of runs using the $^3$He$^+$ and $^3$He$^{++}$ beams.

The mechanical beam chopper and electronic gating circuit have been described previously.[6] This system operates at a 60-cycle rate and provides an irradiation time of 3 msec and a counting time of 12 msec. The gating circuit can operate four different devices. In the present experiments the spectrum of $\gamma$ rays from the 5×5-in. NaI(Tl) detector in coincidence with $\beta$ rays above a selected bias level was recorded in a 256-channel pulse-height analyzer gated by pulses that had to pass through the 12-msec gate circuit during the beam-off period. A second analyzer recorded the $\beta$-ray singles spectrum above the $\beta$ bias level occurring during the 12-msec counting interval; the total number of $\beta$-ray counts in this spectrum was also recorded by a scaler.

In principle the measurements consisted of determining the number of coincident 4.44-MeV $\gamma$ rays recorded in the NaI(Tl) detector per $\beta$-ray count for the $^{12}$B and $^{12}$N activities. Since the experimental geometry was identical for the two cases the ratio of $\gamma$ rays per $\beta$ ray, suitably corrected, can lead to the ratio of branches to the 4.44-MeV state.

One of the main problems was to determine the fractions of total $\beta$-ray pulses, and of $\beta$-ray pulses corresponding to the branch to the 4.44-MeV state of $^{12}$C, that lie above a bias level that must necessarily be imposed in order to exclude noise and other background at low pulse heights. This was relatively easy to do for the total $\beta$-ray spectrum of $^{12}$B as may be seen in Fig. 1 which shows typical pulse-height spectra for $^{12}$B and $^{12}$N with biases imposed. In the case of $^{12}$B the background above the bias with the beam completely removed was only ~0.3% of the rate when the activity is being made. The shape of the spectrum at low pulse heights, as shown by the extrapolated dashed line, was measured with the bias removed, but before long-lived activities had built up. The $^{12}$N spectrum on the other hand was accompanied by a relatively stronger background due to both $^{14}$O (end point 1.81 MeV) from the $^{12}$C($^3$He, $n$)$^{14}$O reaction on carbon in the target and $^{11}$C (end point 0.96 MeV) resulting from the $^{10}$B($^3$He, $d$)$^{11}$C reaction. These background yields, which extend up to about channel 140, contributed 4–5% to the total counting rate above the bias. The correction for background $\beta$ activities was determined experimentally and the net $^{12}$N spectrum is shown by the dashed line in the figure. The scaler count corrected for the background gives the number of $^{12}$N $\beta$ rays above the bias.

The fractions above the bias of the inner $\beta$-ray groups of $^{12}$B and $^{12}$N to the 4.44-MeV state are different from those of the total spectra because of the lower $\beta$-ray energy of the inner groups. In order to establish reliable corrections for bias the intensity of 4.44-MeV $\gamma$ rays in coincidence with $\beta$ rays can serve as a relative measure of the efficiency for detecting the inner $\beta$-ray group. Such measurements were carried out on $^{12}$B and the results are included in Fig. 2. Here, the fractions of the total $\beta$-ray spectra of $^{12}$B and $^{12}$N and the inner $\beta$-ray group of $^{12}$B, deduced from the 4.44-MeV $\gamma$-ray spectrum in coincidence and normalized so as to pass through 1.0 at zero bias, are plotted as a function of bias on the $\beta$-ray detector. As expected from the energies of the various $\beta$ groups, the efficiency for detecting the $^{12}$B $\beta$ decays to the 4.44-MeV state decreases faster with increasing bias than does the total spectrum of $^{12}$B, and the efficiency for the $^{12}$B $\beta$ decays decreases more rapidly than the $^{12}$N. Since the shapes of all three of these curves are similar, it was felt that suitable corrections for the $^{12}$N $\beta$ decays to the 4.44-MeV state could be obtained by constructing a similar curve interpolated between the two $^{12}$B curves according to end-point energy as shown in Fig. 2. What matters in the calculations is the difference in the corrections for the total and the 4.44-MeV $\beta$-ray groups. For typical runs the differences amounted to ~3% for $^{12}$B (bias at channel 40) and ~4% for $^{12}$N (bias at channel 70) and the uncertainties in these corrections were both assumed to be ±1.0%.

## III. RESULTS AND DISCUSSION

### A. Ratio of $^{12}$N/$^{12}$B $\beta$-Ray Branches to $^{12}C_{4.44}$

Examples of the $\gamma$-ray spectra of $^{12}$B and $^{12}$N in coincidence with $\beta$ rays are shown in Fig. 3. Many such runs were made on the two activities. Beam intensities of about 0.05 nA of $d$ for the $^{11}$B($d$, $p$)$^{12}$B reaction of 6 nA (particle) of $^3$He for the $^{10}$B($^3$He, $n$)$^{12}$N reaction gave total $\beta$ counting rates of ~3000 per sec. Uncertainties due to possible rate-dependent effects were thereby minimized. The intensities of $\gamma$ rays were obtained by subtracting out the bremsstrahlung background curves, as drawn in Fig. 3, and summing over the regions of the 4.44-MeV full-energy-loss peak alone or the full-energy and one-escape peaks together, as indicated by the vertical bars. Runs of 2–3 h were sufficient to give net $\gamma$-ray yields with a statistical accuracy of 1.5–3%. Subtraction of the strictly exponential bremsstrahlung background results in the expected shape of the 4.44-MeV $\gamma$-ray spectrum. Although the shape assumed for the background may not be quite correct the fact that all such curves were analyzed in the same way should minimize the background uncertainty in the ratio of yields.

The $\gamma$-ray yields from the coincidence data, together with the total scaler $\beta$ count, were corrected for the long-lived background and for the $\beta$ bias factors according to Fig. 2. The final set of $^{12}$N-$^{12}$B comparison measurements consisted of four separate runs on each activity from which the adopted result is

$$\left(\frac{\beta-\gamma}{\beta}\right)_{^{12}\mathrm{N}} \Big/ \left(\frac{\beta-\gamma}{\beta}\right)_{^{12}\mathrm{B}} = 1.52 \pm 0.06\,.$$

The over-all error includes the estimates of errors due to statistics, background subtraction in the analysis of the $\gamma$-ray spectra, the $\beta$-ray bias corrections, and the long-lived background correction in the $\beta$-ray count.

The present result agrees just within the errors with the earlier but less accurate value of 1.72 ± 0.15,[4] but it is outside the combined errors when compared with the value 1.84 ± 0.1 reported by Peterson and Glass.[3] From the present ratio of branches and the most recent values[7] for the half-lives and decay energies of $^{12}$B and $^{12}$N the calculated ratio of $ft$ values is

$$\left(\frac{ft^{+}}{ft^{-}}\right)_{^{12}\mathrm{C}_{4.44}} = 1.06 \pm 0.04\,.$$

Thus, the present measurement gives the value $\delta = +0.06 \pm 0.04$ which removes the previous strong conflict[5] of this case with the systematics of positive $\delta$ averaging about +0.10.

Early calculations by Blin-Stoyle and Rosina[8] of various nuclear structure effects had resulted in an asymmetry for the $A = 12$ ground-state decay that was too small to account for the experimental results. This discrepancy had led to a revival[1] of the idea of second-class currents in the weak interaction. However, there have been several more recent calculations of nuclear structure effects in the $A = 12$ ground-state decay, all of which are in reasonable agreement with experiment. With the use of better wave functions Blomqvist[9] found over-all asymmetries of +0.112 and +0.159 based on two different methods. By taking into account the whole spectrum of parent states in the $A = 12$ system Wilkinson[5] obtained $\delta = +0.098$ (Method B) for the $A = 12$ ground state. Finally, Laverne and Do Day[10] have made a calculation that takes into account the Coulomb interaction and the electromagnetic spin-orbit term. Different deformations were found and they obtained $\delta = +0.085$.

Wilkinson also calculated[5] the nuclear structure asymmetry for the $A = 12$ $\beta$-ray branch to the first excited state of $^{12}$C. The result (Method B) was $\delta = +0.048$ which is in good accord with the present experimental result. Thus, it would appear that the $\beta$-ray branches to both the ground and first excited states of $^{12}$C can now be explained without invoking some other type of fundamental asymmetry.

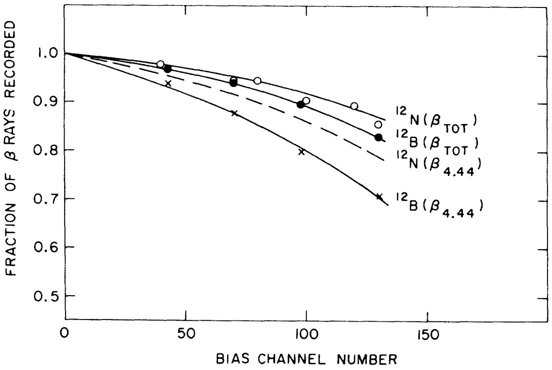

FIG. 2. Fraction of $\beta$ rays recorded as a function of bias on the detector. Solid curves are based on $^{12}$B and $^{12}$N $\beta$-ray singles spectra, and on $^{12}$B $\beta$ rays in coincidence with 4.44-MeV $\gamma$ rays. The dashed curve is for $^{12}$N $\beta$ rays in coincidence with 4.44-MeV $\gamma$ rays and was constructed by interpolation between the two adjacent curves.

Unfortunately, the accuracy of the present ex-

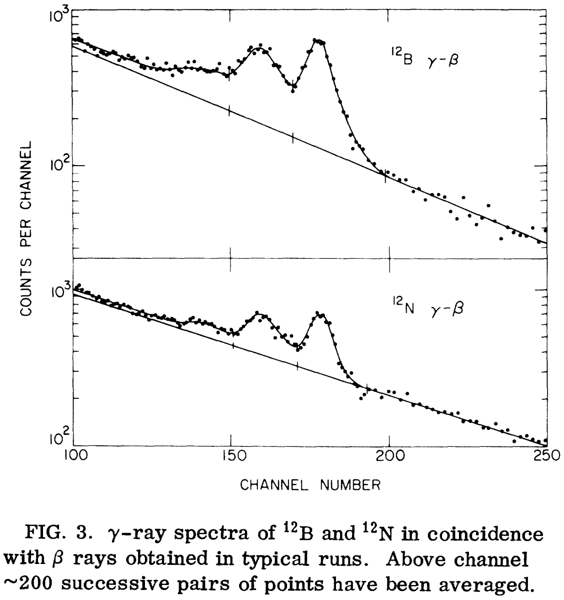

FIG. 3. $\gamma$-ray spectra of $^{12}$B and $^{12}$N in coincidence with $\beta$ rays obtained in typical runs. Above channel ~200 successive pairs of points have been averaged. The background under the 4.44-MeV peaks is due to $\beta$-bremsstrahlung coincidences and is relatively more intense in the $^{12}$N spectrum (despite the larger $\beta_{4.44}$ branch) because of the higher energy of the $^{12}$N $\beta$ rays. An exponential shape was assumed for this background. Vertical bars indicate the regions used for summing peak areas.

perimental result is not as sharp as one would like in order to make a really significant comparison with theoretical calculations. It should also be pointed out that in none of the other cases calculated by Wilkinson, i.e., $A = 8$, 9, and 13 is there close agreement between experiment and the calculation of the binding-energy effect. Wilkinson therefore concluded that, in spite of the good agreement in the case of the $A = 12$ ground state, the asymmetry must in general be due to a fundamental weak-interaction effect or to some other unknown nuclear structure effect.

### B. $^{12}$B $\beta$-Ray Branch to $^{12}C_{4.44}$

Although in principle the data obtained in the above $^{12}$B-$^{12}$N ratio measurements could also be used to derive absolute values for the $\beta$-ray branches to the 4.44-MeV state of $^{12}$C the accuracy would be limited by the large corrections for the thick absorbers that were required to reduce the summing effect in the $^{12}$N data. Separate experiments were therefore carried out on $^{12}$B to determine this absolute $\beta$-ray branch. The geometry was the same as above except that a single Pb absorber $\frac{1}{8}$ in. thick was used to keep $\beta$ rays out of the NaI(Tl) crystal. This resulted in a total correction for absorption of the 4.44-MeV $\gamma$ rays in the Pb and the Pilot-B scintillator of (19.7 ± 2.0)%. Corrections for the fractions of counts above the $\beta$-detector bias (total $\beta$ rays and $\beta$ decays to the 4.44-MeV state) were made as described above. The number of 4.44-MeV $\gamma$ rays was calculated from the area under the full-energy-loss peak in the coincidence spectrum, corrected for absolute photopeak efficiency.[11]

From the analysis of four coincidence runs the absolute $\beta$-ray branch of $^{12}$B to $^{12}C_{4.44}$ was found to be (1.27 ± 0.06)%. The corresponding $\log ft$ value is 5.12 ± 0.02. The present result is consistent with the previously adopted branch[7] of (1.33 ± 0.09)%. By combining the present results for both the $^{12}$N/$^{12}$B branching ratio and the $^{12}$B absolute branch, the $^{12}$N branch to the $^{12}C_{4.44}$ state is deduced to be (1.93 ± 0.12)% and its $\log ft$ value is 5.14 ± 0.03. These results compare with the previously quoted[7] branch of (2.3 ± 0.2)% and $\log ft$ value of 5.06 ± 0.04 for the decay of $^{12}$N to the 4.44-MeV state.

## ACKNOWLEDGMENT

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