Parity Conservation in Strong Interactions: Reactions $B^{11}(p,p')B^{11*}{}_{2.14}$ and $F^{19}(p,\alpha)O^{16*}{}_{7.12}$†

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If parity is strictly conserved, the gamma rays emitted following the bombardment of unpolarized target nuclei by unpolarized projectiles can show no circular polarization. We look for such polarization, using an analyzer of magnetized iron, in the 2.14-Mev gamma ray from the first excited state of B^{11} formed by $B^{11}(p,p')B^{11*}$ and in the 7.12-Mev gamma ray from the fourth excited state of O^{16} formed in $F^{19}(p,\alpha)O^{16*}$. We expect this polarization to be of order $\mathfrak{R}\mathfrak{F}$, where $\mathfrak{F}$ is the amplitude of the parity-nonconserving part of the relevant wave functions and $\mathfrak{R}$ is a matrix element factor. We find that the intensity of circular polarization in the first case is less than 2.0×10^{-3} and in the second case 2.0×10^{-3}. These figures yield $\mathfrak{F}^2\lesssim1\times10^{-7}$ and $\mathfrak{F}^2\lesssim3\times10^{-8}$, respectively.

INTRODUCTION

WE continue the investigations[1] of parity conservation in strong interactions with two experiments of the second class enumerated in I, namely those experiments in which interference effects due to parity-conserving and parity-nonconserving parts (regular and irregular) of the nuclear wave functions give rise to observable effects of order $\mathfrak{F}$, the *amplitude* of the parity-nonconserving component.

The experiments are both of the sort discussed in I, namely $X(h_1,h_2\gamma)Y$ reactions where h_1 and h_2 are heavy particles and the gamma ray is emitted from a well-defined state of Y^*. There can now be no circular polarization of the gamma ray if parity is strictly conserved and both X and h_1 are initially unpolarized. Generally there will be a circular polarization of intensity of order $\mathfrak{F}$ coming from the polarization induced in Y^* by the parity-nonconserving interaction and another of order $\mathfrak{R}\mathfrak{F}$ due to the interference between the magnetic and electric transitions of the same multipolarity that are associated with the regular and irregular parts of the wave functions of Y^* and Y. $\mathfrak{R}$ is the matrix element factor discussed in I which measures the *a priori* relative intrinsic transition amplitudes of the gamma-ray transitions involving the irregular and regular components.

REACTIONS USED

It is obviously advantageous to choose reactions in which $\mathfrak{R}$ is as large as possible. In general this can be done by choosing cases in which the regular transition is $M1$ and the irregular transition is $E1$. Another consideration is of course that the analyzer for circular polarization should be efficient at the gamma-ray energy chosen. The method used in these investigations was transmission through magnetized iron and this restricted our choice to rather high photon energies. A final consideration is that the reaction should be a very prolific one. This is particularly important when the transmission method is used.

The reactions chosen were $B^{11}(p,p')B^{11*}{}_{2.14}$ and $F^{19}(p,\alpha)O^{16*}{}_{7.12}$. The 2.14 Mev first excited state of B^{11} is $\frac{1}{2}-$ and decays to the $\frac{3}{2}-$ ground state chiefly by $M1$ radiation.[2] The parity-nonconserving interaction introduces an accompanying $E1$ transition for which, following I, we say:

$$\mathfrak{R}\sim McR/3\hbar,$$

which is about 5.5 for B^{11}.

The 7.12-Mev fourth excited state of O^{16} is $1-$ and decays to the ground state by an $E1$ transition. It may therefore seem that this is not a good case to study because the irregular transition is now $M1$ and so the competition seems to be the wrong way round. However, this is not so because the regular $E1$ transition is in violation of the isotopic-spin selection rule, both states being of $T=0$. It is in fact discouraged quite strongly by this rule and its measured[3] mean lifetime is $(1.0\pm0.3)\times10^{-14}$ sec or only about 2.4×10^{-4} of a single-particle unit. However, the irregular $M1$ that, owing to the parity nonconservation, is competing with it is uninfluenced by the isotopic spin of the states and so we ascribe to it the single-particle strengths as suggested in I and find:

$$\mathfrak{R}\sim11.$$

In the bombardment of natural boron by protons the desired gamma ray is very strongly excited at proton energies of 2.6 Mev and over.[4] A thick target was used at a proton energy of 3.0 Mev in this investigation. Also very strongly excited is the first excited state of B^{10} at 0.72 Mev but these gamma rays are easily discriminated against. Gamma rays of 2.15, 1.42, and 1.02 Mev are due to transitions from the third

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[1] D. H. Wilkinson, Phys. Rev. **109**, 1603 (1958), preceding paper. This is referred to as I.
[2] D. H. Wilkinson, Phys. Rev. **105**, 666 (1957).
[3] C. P. Swann and F. R. Metzger, Phys. Rev. **108**, 982 (1957).
[4] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).

excited state of B^{10} to the ground state, from that state to the first excited state, and between the second excited state and the 0.72-Mev level, respectively. The first is negligibly weak when natural boron is used under our conditions, and the others are easily discriminated against. Other gamma rays are those of radiative capture, of which we need consider only those from $B^{11}(p,\gamma)C^{12}$ since the corresponding reaction in B^{10} is relatively weak. These capture gamma rays, chiefly of about 18 and 14 Mev, are very much weaker than those following inelastic scattering. Even though the production cross sections are known, it is not feasible to calculate the importance of these capture gamma rays because of the great importance of degradation as they filter through the iron of the analyzer. It was rather observed that if the high-energy tail of the filtered spectrum were continued into the region of the narrow counting channel of the NaI(Tl) crystal detector which was set for the 2.14 Mev gamma rays, it would represent less than 1% of the counts due to the gamma rays following inelastic scattering. This high-energy tail includes all sources of background as well as the capture gamma rays. Since these latter cannot themselves be circularly polarized without the action of parity-nonconserving interactions, despite the strong mixing of parities in the intermediate C^{12*} state due to overlapping levels, these capture gamma rays are no cause for concern.

The situation in $F^{19}(p,\alpha)O^{16}$ is not so straightforward. States at 6.14 Mev (3−) and at 6.91 Mev (2+) are strongly excited as well as the desired 1− state at 7.12 Mev. The transitions from these other states are not useful to us since they would have $\mathcal{R}<1$ (indeed the electric transitions from both these levels are enhanced over the single-particle speeds). We must therefore attempt to minimize the importance of these other transitions. It is easy to find conditions under which the 6.14-Mev gamma ray is relatively weak. Some years ago Alburger, Toppel, and the present author[5] carried out a careful survey of the gamma-ray intensities observed at 0° to the proton beam, using thin targets of fluorine. Proton energies up to 4.1 Mev were used. A three-crystal pair spectrometer was used in this work. The relative abundances of the various lines fluctuated considerably. To what degree this is due to changing transition probabilities to the various states of O^{16} and to what degree to the interplay of the angular distributions is neither known nor of importance here since the present measurements were also at 0°. For proton energies between 1.9 and 2.7 Mev there was a strong preponderance of gamma rays of 6.9 and 7.1 Mev over those of 6.1 Mev. Although the lines of 6.9 and 7.1 Mev were not resolved the one from the other, it was evident from the width of the composite line that they were present in comparable abundance. When a thick target is used with protons of 2.5 Mev, the bulk of the gamma rays comes from proton energies above 1.9 Mev. So, under these conditions, which were the ones used in the present work, we have effectively a mixture of 6.9- and 7.1-Mev gamma rays. In any case those of 6.1 Mev are strongly discriminated against by the detector. The discrimination between the 6.9- and 7.1-Mev lines is discussed later. The background at higher energies due to gamma rays from $F^{19}(p,\gamma)Ne^{20}$ and other influences was even less important here than for the $B^{11}(p,p')B^{11}$ source and for the same reasons can be ignored.

ANALYZER

The method of analysis for circular polarization was that of transmission through magnetized iron.[6] The analyzer was cylindrical and of length $8\frac{1}{2}$ inches. The core was of diameter about $2\frac{1}{2}$ inches and the over-all diameter was 6 inches. This magnet was saturated at a current of 3 amperes and was run during the present work at a current of 3.5 amperes. Its effective saturated length was about 7 inches. If the transmissions for the two directions of magnetization are T_+ and T_-, then we can define an efficiency for the detection of completely circularly polarized radiation as

$$\epsilon=2|T_+-T_-|/(T_++T_-).$$

For the two radiations of interest here we find: $\epsilon_{2.14}=0.13$, $\epsilon_{7.12}=0.12$.

EXPERIMENTS

The analyzer was placed at 0° to the target, which was of natural boron in the first experiment and of BaF_2 in the second. The front face of the analyzer was about 10 cm from the target. The detector was situated 10 cm from the other face of the analyzer and was coaxial with it.

Since the effect to be found was to be very small if present at all, it was most important that no aspect of the experimental situation, other than the state of polarization of the iron, should depend on the direction of magnetization. In particular, care had to be taken for an influence on the photomultiplier examining the NaI(Tl) detector. The analyzer had a complete magnetic circuit of iron and the field outside it was very weak. Nevertheless considerable precautions were taken and stringent tests applied. The crystals were mounted on long light pipes. The 3-inch right cylinder which was used for the $B^{11}(p,p')B^{11*}$ work was mounted on a light pipe of length 4 feet. The 2-inch right cylinder used for the $F^{19}(p,\alpha)O^{16*}$ experiment was mounted on a 2-foot-long light pipe. In both cases the photomultipliers were surrounded first by a mu-metal shield then by two coaxial iron pipes. In both cases lengthy procedures were adopted to check a possible residual sensitivity to the direction of magnetization of the analyzer. These consisted first of a careful examination of the peaks of various gamma-ray spectra seen under

[5] Alburger, Toppel, and Wilkinson (unpublished).

[6] S. B. Gunst and L. A. Page, Phys. Rev. 92, 970 (1953).

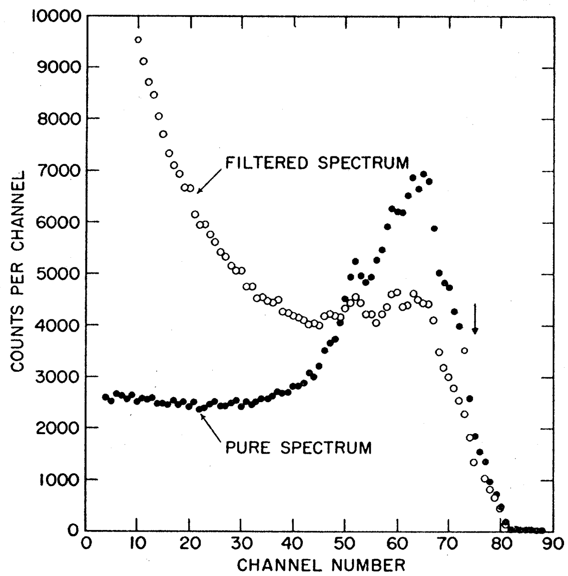

FIG. 1. Spectrum observed in the 2-inch NaI crystal at 0° to a thick target of BaF_2 bombarded by protons of 2.5 Mev. The spectrum due to gamma rays directly from the target is shown (pure spectrum) and also that observed through the analyzer of magnetized iron (filtered spectrum). The arrow shows the lower limit of the narrow counting channel used in the experiment proper. There is no normalization between the spectra.

high dispersion on a 100-channel pulse-height analyzer. The limit of sensitivity here was about 0.1% in pulse height and no such shift was observed. A more sensitive test was to set a narrow counting channel on the steeply sloping upper side of the spectrum from Cs^{137} and to count repeatedly for alternate directions of magnetization. No effect was found to a degree corresponding to a shift in gain by 0.008%.

For the $B^{11}(p,p')B^{11*}$ work a proton current of about 6 μa was used at a proton energy of 3.0 Mev. The spectrum observed without the analyzer was the familiar one consisting almost wholly of the 2.14-Mev line once the 0.72-Mev peak is passed. Viewed through the analyzer, this spectrum consists almost completely of a sharply-falling distribution due to degraded radiation. This fills up the trough below the full-energy peak rather completely, leaving, however, a longish plateau terminated by a clear peak due to the unmodified 2.14-Mev line and the usual rapid fall beyond. Because of the large amount of degraded radiation, it was not felt to be safe to bias the detector below the peak. The lower limit to the counting channel was accordingly set well on the high-energy side of the peak. A very narrow channel then sufficed to include almost all the residual counts. This procedure is very disadvantageous for two reasons: firstly we are obviously very sensitive to changes in gain of the system whether due to the analyzer or the normal electronics drifts; secondly we are counting the radiation very inefficiently. It was, however, considered that these disadvantages were outweighed by the advantage of staying well away from the degraded radiation. It was estimated that at most 20% of the counts in the channel could be due to degraded radiation and this possible correction was ignored.

The experiment consisted of a long series of pairs of runs with the magnetizing current in the two directions. The counting rate was maintained rather constant so that effects due to the very small possible rate dependence of the gain of the photomultiplier (less than 0.02% for a factor of two in counting rate) were negligible. Background counts were also made with no beam on the target. A total of 572 such runs was made with the beam on the target. The normalization was in terms of proton charge.

Slightly different considerations obtained for the $F^{19}(p,\alpha)O^{16*}$ experiment although they led to a very similar procedure. As we have explained, it was here necessary to make every effort to separate the 7.1-Mev line from that at 6.9 Mev. In an attempt to do this, a 2-inch instead of a 3-inch crystal was used and the light pipe was shortened to 2 feet. Both these changes encourage better resolution. The change to the smaller crystal also helps the discrimination between the gamma rays. Figure 1 shows the spectra observed at a proton energy of 2.5 Mev. The unfiltered spectrum shows the preponderance of the higher energy lines indicated much more clearly by the three-crystal spectrometer results referred to above. The first peak, at channel 52, is due to the 6.1-Mev line pair creation followed by escape from the crystal of both annihilation quanta. The final small bump around channel 78 is due to the full energy loss by the 7.1-Mev gamma ray. The detector was biased as shown by the arrow in the figure. As before, the counting channel was very narrow. It is estimated that a discrimination of at least 3:1 in favor of the 7.1-Mev line was achieved while the contribution from the degraded radiation is negligible. We shall analyze the results, neglecting all radiation but the 7.1-Mev line. Again we are in a disadvantageous experimental position which is made worthwhile by the clarification it brings to the interpretation of the results.

The experimental procedure was exactly as for the previous experiment. The total number of runs with the proton beam of about 10 μa was now 520.

TABLE I. $B^{11}(p,p')B^{11*}_{2.14}$. Study of gamma rays following inelastic proton scattering in B^{11}. N_+ and N_- are the total numbers of counts observed in each group of 52 runs for the two senses of magnetization of the analyzer.

Group	N_+	N_-	N_+/N_-
1	2 715 121	2 716 712	0.99941±0.00086
2	2 697 064	2 697 859	0.99971±0.00086
3	2 683 962	2 682 657	1.00049±0.00086
4	2 657 958	2 662 010	0.99848±0.00087
5	2 790 630	2 787 412	1.00115±0.00085
6	2 697 307	2 696 161	1.00043±0.00086
7	2 743 818	2 741 047	1.00101±0.00085
8	2 729 976	2 727 961	1.00074±0.00086
9	2 694 201	2 693 905	1.00011±0.00086
10	2 684 685	2 684 983	0.99989±0.00086
11	2 633 105	2 629 603	1.00133±0.00087

In both experiments the losses in the counting channel were quite small (about 0.05% for the first and 0.1% for the second). The fact that the counting rates for the two directions of the field were the same removed the need for applying even this small correction.

RESULTS

The experiments were analyzed in several different ways, all of which gave essentially the same result. We shall therefore present only the simplest, which was to split up the runs into a number of groups each containing a large number (26) of runs with either direction of the magnetizing current in the analyzer. The numbers of counts for each direction of magnetization for all the runs in each group were then simply totalled. Call them N_+ and N_-. The background corrections were sufficiently small and constant to be ignored. The ratio N_+/N_- for each group was then computed. Since we are dealing with very large numbers of counts, we need some assurance that our ultimate accuracy is limited by the statistics and not by drifts and other systematic effects. Indeed drifts were present, and over a period of hours the counts per unit of charge collected on the target changed by as much as 8 or 9 times the standard deviation of the individual runs. This was probably due to a combination of normal electronic drifts and changing characteristics of the targets. It was hoped that the averaging introduced by the rapid alternation of counting periods for the two magnetization directions and the subsequent grouping of runs into large units would be adequate to allow for the slow drifting and leave a result whose reliability was dependent only on the counting statistics. In order to check this the N_+/N_- values for the several groups, 11 for the boron work and 10 for the fluorine, are tested for consistency with the value unity, within the standard deviation due solely to the number of counts involved, using the χ^2 test. In both cases complete consistency is found and the value of P deriving from χ^2 is entirely satisfactory. This is a little surprising and it might have been expected that the χ^2 test would have been failed on a standard deviation due solely to numbers of counts but this is not so. It appears therefore that the extensive averaging was good enough to take care of the drifts and also, be it said, of the fluctuations in the current integrator (for which no extravagant claims are made) and to reduce them in importance below that of the statistical fluctuations.

The detailed results are presented in Tables I and II. Small changes were frequently made between the groups of runs and only their N^+/N_- values may be intercompared.

For the boron runs the average value of

$$N_+/N_- = 1.00025 \pm 0.00026.$$

The quantity χ^2, evaluated on a basis of the standard deviations due to the numbers of counts for consistency with the value unity for N_+/N_- is $\chi^2 = 10.6$. This, on 11 degrees of freedom, corresponds to $P = 0.48$.

TABLE II. $F^{19}(p,\alpha)O^{16*}{}_{7.12}$. Study of gamma rays following the (p,α) reaction in fluorine. N_+ and N_- are the total numbers of counts observed in each group of 52 runs for the two senses of magnetization of the analyzer.

Group	N_+	N_-	N_+/N_-
1	3 438 992	3 437 099	1.00055±0.00076
2	3 576 382	3 579 876	0.99902±0.00075
3	3 577 207	3 557 879	0.99981±0.00075
4	3 406 346	3 403 329	1.00089±0.00077
5	3 096 855	3 092 692	1.00135±0.00080
6	3 224 067	3 226 617	0.99921±0.00079
7	3 344 698	3 347 426	0.99919±0.00077
8	3 275 810	3 276 035	0.99993±0.00078
9	3 172 993	3 169 974	1.00095±0.00079
10	3 390 110	3 391 657	0.99954±0.00077

We may accordingly say that the difference in counting rates is zero within a standard deviation of 2.6×10^{-4}. This, together with $\epsilon_{2.14}=0.13$, represents less than 2.0×10^{-3} part of circular polarization in the gamma radiation.

For the fluorine runs the average value of

$$N_+/N_- = 1.00003 \pm 0.00024.$$

The quantity χ^2, evaluated on abasis of the standard deviations due to the numbers of counts for consistency with the value unity for N_+/N_-, is $\chi^2=10.3$. This, on 10 degrees of freedom, corresponds to $P=0.42$.

In this case the effect is zero within a standard deviation of 2.4×10^{-4}. Now $\epsilon_{7.12}=0.12$ and so we have less than 2.0×10^{-3} parts of circular polarization.

DISCUSSION

These limits on the amount of circular polarization we interpret as limits, within the standard deviations, on $\mathfrak{R}\mathfrak{F}$. They may now be taken together with the values of the matrix-element parameter $\mathfrak{R}$ derived above. They give, from the boron reaction,

$$\mathfrak{F}^2 \lesssim 1\times10^{-7};$$

and from the fluorine reaction,

$$\mathfrak{F}^2 \lesssim 3\times10^{-8}.$$

These limits are of the same order as that derived in I from an experiment in which $\mathfrak{F}^2$ itself was examined rather than $\mathfrak{F}$. It is by chance that the extra technical difficulties of the intrinsically more sensitive type of experiment just compensate for that sensitivity and give the same final accuracy as is achieved in the more obvious mode of experimentation.

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