**Title**

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# BETA-DELAYED PROTON DECAY OF $^{13}$O: A VIOLATION OF MIRROR SYMMETRY*

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## ABSTRACT

Beta-delayed protons, $E_{lab} > 1.2$ MeV, were observed following the decay of $^{13}$O, $\tau_{1/2} = 8.95 \pm 0.20$ msec. Comparison of $^{13}$O decay-rates with those of the mirror nuclide $^{13}$B indicates a 15% deviation from mirror symmetry.

Recent work [1-4] has called attention to the existence of deviations from mirror symmetry in beta-decay. In the case of the well-studied mass-12 nuclei, the magnitude of electromagnetic, second-forbidden, isospin-mixing, and binding-energy effects have been evaluated [1] and found insufficient to explain the observed deviation. This lends support to the proposal [5] that there is an induced tensor term in beta-decay. Since such a term is expected to cause the ratio $\frac{(ft)^+}{(ft)^-}$ to increase linearly [2,5] with $(W_o^+ + W_o^-)$, it is of particular interest to examine cases with large decay energies.

We have investigated the decay of $^{13}$O and compared it to that [6] of its mirror $^{13}$B, since $(W_o^+ + W_o^-)$ for these nuclei is ~ 30 MeV; this is larger than for any studied decay [2] except mass 12. $^{13}$O is a beta-delayed proton emitter

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for which all the allowed $\beta^+$- decays, except that to the ground state, lead to proton unbound levels in $^{13}N$. In the only previous study [7] of $^{13}O$ decay, protons of energy less than 5 MeV could not be detected due to a rapidly rising low energy background. Since several important beta-decay branches were consequently undetected, no detailed comparison with the mirror decays was possible.

The experimental technique was similar to that used previously [8] and will be described in detail later [9]. Briefly, a target of $N_2$ gas was bombarded with a 43-MeV proton beam from the Berkeley 88-inch cyclotron. At $\sim$ 1/2 sec intervals the gas was swept with helium into a shielded counting chamber 60 cm away. There, protons from $^{13}O$, produced by the $^{14}N(p, 2n)^{13}O$ reaction, were detected and identified in a cooled $\Delta E$-E counter telescope which fed a Goulding-Landis particle identifier. The signal from the 14 μm $\Delta E$ detector was required to be $< 1$ MeV to eliminate background coincidences between alpha-particles [10] and multiply-scattered beta-particles from the decay of $^{8}B$. Identified protons were time-sorted into four groups in a pulse height analyzer, thus providing both lifetime and energy data. In addition, the decay of a selected proton peak was recorded with a 400-channel multiscalar whose address was advanced by a quartz-crystal oscillator.

A proton spectrum from the decay of $^{13}O$ is shown in fig. 1. All peaks shown have half-lives of less than 50 msec--much less than any light delayed-proton emitter other than $^{13}O$. In a second run, all the weak peaks except those at 3.44 and 6.38 MeV were clearly observed. However, since the second run had seven times fewer counts than the illustrated run, the existence of peaks at 3.44 and 6.38 MeV cannot definitely be ruled out. These proton peaks are assumed to exist in subsequent calculations, but since the sum of their intensities amounts to only 0.7% of the total proton decays, any error from this source will be absorbed easily in our quoted uncertainties. All the remaining proton groups can be assigned to known [11] states in $^{13}N$ as is shown in fig. 2 and Table I. The widths of all assigned peaks were extracted and found compatible with the known [11] widths after correcting for the broadening due to nuclear recoil following beta-decay.

Our results for the higher energy peaks of fig. 1 can now be compared with proton resonance data. For the 8.92- and 9.52-MeV states, the fraction of proton decays that leads to the ground state of $^{12}C$ is 0.70±0.07 and 0.65±0.12, respectively. This compares well with the values of $\Gamma_{el}/\Gamma$ of 0.66 and 0.58 derived [12] from elastic and inelastic proton scattering on $^{12}C$. The energy of the decay branch of the 7.39-MeV state to the first excited state of $^{12}C$ is too low for us to observe. Therefore the total number of proton decays from this state was calculated using the decay we observed to the $^{12}C$ ground state together with the known [12-14] $\Gamma_{el}/\Gamma$ of 0.09±0.02. Similarly, the total number of decays from the 10.35-MeV level was calculated using the measured [15,16] $\Gamma_{el}/\Gamma$ of 0.27±0.02. In this case, only decay to the first excited state was observed but this is consistent with the weakness of the $\beta^+$- decay branch and the known proton branching. Arrow B in fig. 1 shows the expected location of the ground state branch. Arrows A and C indicate the predicted location of protons from the known $J\pi = 1/2-$, 10.78-MeV state. Clearly they were too weak to observe.

The multiscaled lifetime data were analyzed using least-squares techniques. The deduced half-life of $^{13}O$ was 8.95±0.20 msec. Since $^{8}B$ was expected to be a contaminating activity, the small observed background was fit with half-lives ranging from 150 msec to infinity with no resulting variation in the measured $^{13}O$ lifetime. Our result agrees with the previous [7] value of 8.7±0.4 msec, so a weighted average of 8.9±0.20 msec was used for further analysis.

The ft values for $^{13}B$ decay were calculated [17] from the relative intensities of Jones et al. [6] and the recently measured [18] half-life of 17.33±0.17 msec. The results are listed in Table I. Assuming perfect mirror symmetry for these transition rates and correcting for additional observed decay branches, the half-life of $^{13}O$ was predicted to be 7.74±0.16 msec [19]. The ratio of the true half-life to the predicted one is 1.15±0.03, indicating a significant departure from mirror symmetry. It also reflects the ratio $\frac{(ft)^+}{(ft)^-}$, providing that the effects causing asymmetry are state independent [5].

Individual ft values to all observed states in $^{13}N$ were calculated from the measured proton intensities and the half-life, assuming that the ratio of the mirror ground state ft values was 1.15. The results are compared with ft values from $^{13}B$ decay in Table I; they compare well with the relevant mirror decays. However, the contrary assumption of equal ground state ft's yields a partial half-life for the ground state branch alone of 8.78±0.11 msec, a value incompatible with the observed half-life of $^{13}O$. The ratio of $\frac{(ft)^+}{(ft)^-}$ required by our results agrees well with that predicted by a linear fit [2] to $(W_o^+ + W_o^-)$ in eleven light mirror nuclei.

Allowed log ft values have been observed for all known [11] Jπ = 5/2-, 3/2-, and 1/2- levels through 10.35 MeV in $^{13}N$ and this fixes the Jπ of $^{13}O$ as 3/2- in agreement with the prediction of the simple shell model. The

$J\pi = 5/2-$, 10.35-MeV state is not predicted by intermediate coupling calculations and has been explained [20] as resulting from the excitation of two nucleons from the 1p shell into the 1d shell. The fairly high log ft value for this state gives some support to this hypothesis.

The present measurement of mirror asymmetry is consistent with the known data on masses 8 and 12, and with them accurately determines the relationship between $\frac{(ft)^+}{(ft)^-}$ values and $(W_o^+ + W_o^-)$ at high decay energies. Since asymmetries consistent with zero have been observed at low decay energies [2,4], it is now of importance to establish the form of the relationship over a range of intermediate energies.

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Table I. Beta-decay of $^{13}$O and a comparison with its mirror, $^{13}$B.

| $^{13}$N State (MeV)[a] | Jπ | Ep(c.m.) (MeV) | Relative Intensity | % of all β-decays[b] | $^{13}$O log *ft*[b] | $^{13}$B log *ft*[c] |
|---|---|---|---|---|---|---|
| g.s. | 1/2- | ——— | ——— | 88.1±3.4 | 4.10±0.02 | 4.04±0.01 |
| 3.509 | 3/2- | 1.565[d] | 100 | 10.7±3.1 | 4.52±0.13 | 4.45±0.05 |
| 7.387 | 5/2- | 1.010[e]<br>5.48±0.05 | 3.4±1.4[f]<br>0.33±0.10 | 0.40±0.19 | 5.22±0.23 | 5.33±0.09 |
| 8.92 | 1/2- | 2.56±0.05<br>6.98[d] | 1.5±0.3<br>3.5±0.3[g] | 0.54±0.16 | 4.73±0.14 | 4.59±0.08 |
| 9.52 | 3/2- | 3.12±0.05<br>7.58[d] | 0.43±0.15<br>0.8±0.1[g] | 0.13±0.04 | 5.18±0.14 | > 5.0 |
| 10.35 | 5/2- | 3.97±0.05<br>8.41[e] | 0.13±0.07<br>0.05±0.03[f] | 0.019±0.012 | 5.8 ±0.3 | ——— |
|  |  | 3.44±0.05[h]. | 0.3±0.1 | 0.030±0.016 |  |  |
|  |  | 6.38±0.05[h] | 0.46±0.10 | 0.050±0.018 |  |  |

## FOOTNOTES TO TABLE I

[a] Energies, spins, and parities taken from ref. 11, except as noted.

[b] The ground state ft was taken to be 1.15 times that of $^{13}B$.

[c] Calculated from the data of ref. 6 using a $^{13}B$ half-life of 17.33±0.17 msec.

[d] Used to determine the energy calibration.

[e] Calculated value, unobserved in this experiment.

[f] Calculated using the known ratio of the elastic and inelastic widths.

[g] Our relative intensities agree with those of ref. 7 for the two peaks observed in that work.

[h] Weak proton groups observed in this work, but not positively attributed to $^{13}O$ decay.

## FIGURE CAPTIONS

Fig. 1. Delayed proton spectrum following the decay of $^{13}O$. The unbracketed energies were used to calibrate the spectrum. The arrows indicate the location of allowed but unobserved decays. All peak energies explicitly shown are in the center-of-mass system.

Fig. 2. Comparison of the decay schemes of the mirror nuclei $^{13}O$ and $^{13}B$. The spins, parities, and energies are taken from previous work as are the half-life and decay of $^{13}B$. The log ft values for the excited states of $^{13}O$ were obtained using the ratio of ground state ft's indicated in the figure.

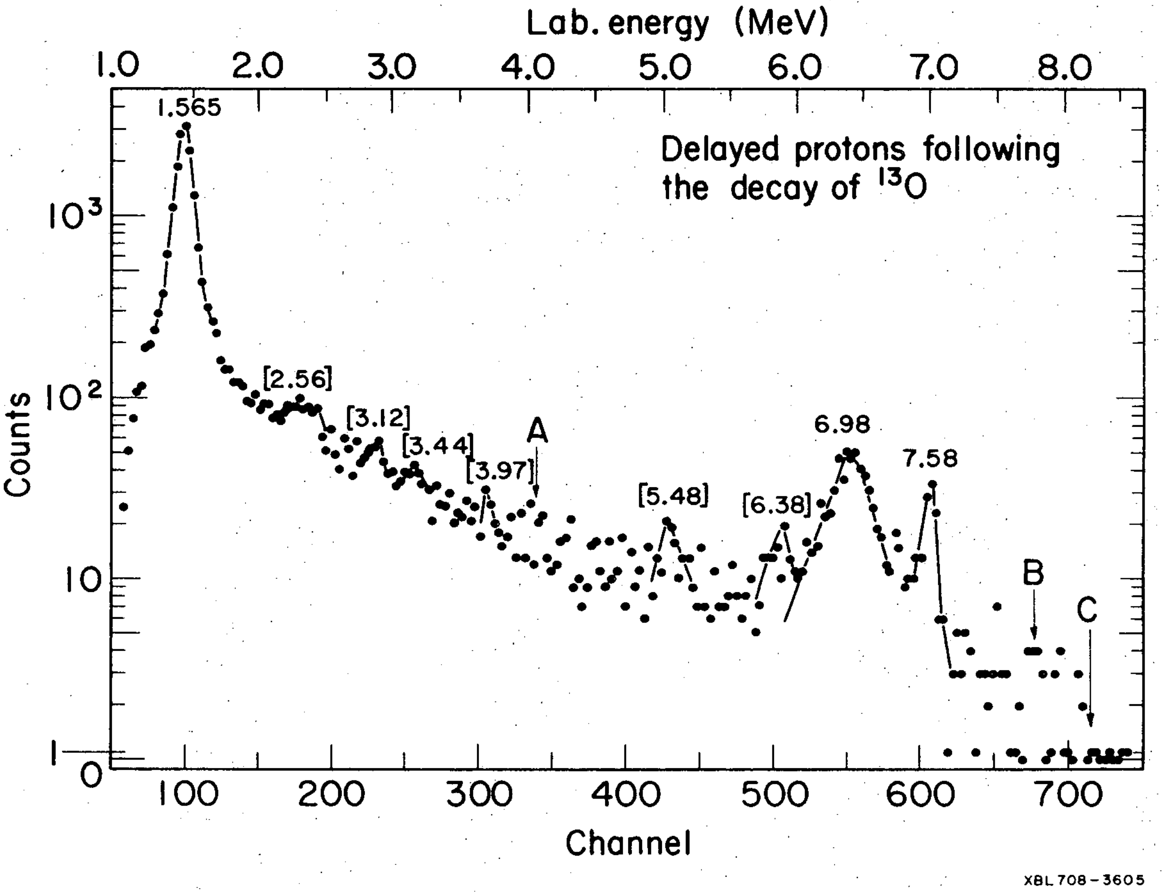
Lab. energy (MeV)
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
Delayed protons following the decay of $^{13}$O
1.565
[2.56]
[3.12]
[3.44]
[3.97]
A
[5.48]
[6.38]
6.98
7.58
B
C
Counts
$10^3$
$10^2$
10
1
0
100
200
300
400
500
600
700
Channel
XBL 708-3605

Fig. 1

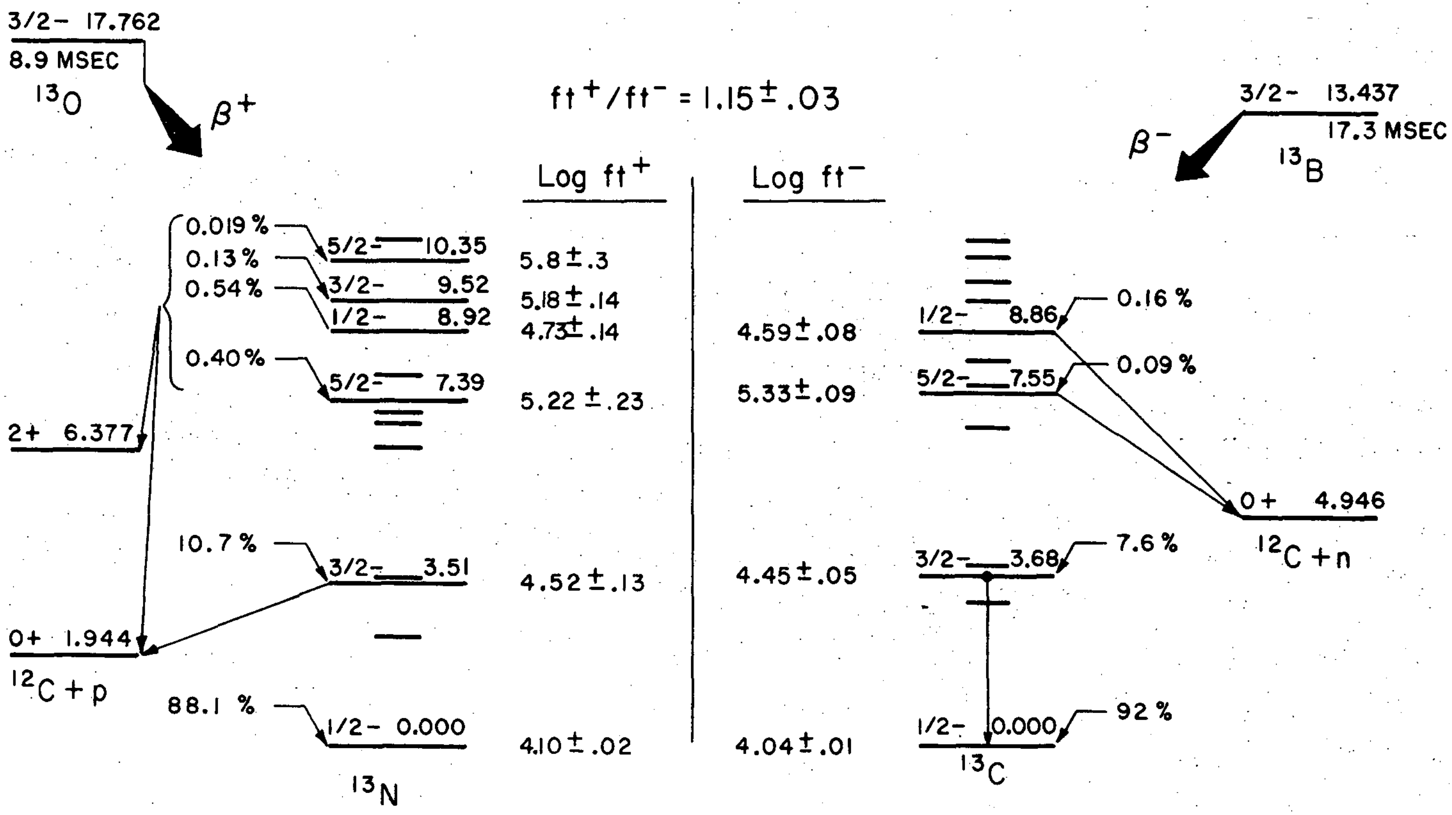
3/2- 17.762
8.9 MSEC
$^{13}$O
β+
ft+/ft- = 1.15 ± .03
3/2- 13.437
17.3 MSEC
$^{13}$B
β-
Log ft+
Log ft-
0.019 %
0.13 %
0.54 %
0.40 %
10.7 %
88.1 %
5/2- 10.35
3/2- 9.52
1/2- 8.92
5/2- 7.39
3/2- 3.51
1/2- 0.000
$^{13}$N
2+ 6.377
0+ 1.944
$^{12}$C + p
5.8 ± .3
5.18 ± .14
4.73 ± .14
5.22 ± .23
4.52 ± .13
4.10 ± .02
4.59 ± .08
5.33 ± .09
4.45 ± .05
4.04 ± .01
1/2- 8.86
5/2- 7.55
3/2- 3.68
1/2- 0.000
$^{13}$C
0.16 %
0.09 %
7.6 %
92 %
0+ 4.946
$^{12}$C + n
XBL 708-3604

Fig. 2

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