# Half-lives and branching ratios of some $T = 1/2$ nuclei

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Precision half-life measurements and branching ratio determinations have been carried out for some $T = 1/2$ mirror nuclei. The following results have been obtained for the half-life and for the branching ratios: $^{13}$N ($597.9 \pm 0.6$ s), $^{15}$O ($122.23 \pm 0.23$ s), $^{17}$F ($64.31 \pm 0.09$ s), $^{21}$Na [($95.8 \pm 0.2$)%], $^{23}$Mg [$11.317 \pm 0.011$ s, ($92.2 \pm 0.2$)%], $^{25}$Al [($99.16 \pm 0.04$)%], $^{27}$Si [($99.812 \pm 0.010$)%], $^{29}$P [($98.11 \pm 0.30$)%], $^{31}$S [$2.543 \pm 0.008$ s, ($98.89 \pm 0.20$)%], $^{33}$Cl ($2.507 \pm 0.008$ s), $^{35}$Ar [$1.774 \pm 0.003$ s, ($98.0 \pm 0.2$)%], $^{37}$K [$1.223 \pm 0.008$ s, ($97.8 \pm 0.2$)%], $^{39}$Ca ($0.8594 \pm 0.0016$ s, $>99.72$%).

[RADIOACTIVITY $^{13}$N, $^{15}$O, $^{17}$F, $^{21}$Na, $^{23}$Mg, $^{25}$Al, $^{27}$Si, $^{31}$S, $^{33}$Cl, $^{35}$Ar, $^{37}$K, $^{39}$Ca; measured $T = \frac{1}{2}$, branching ratios.]

## I. INTRODUCTION

Information produced through accurate $ft$ values of Gamow-Teller (GT) transitions in mirror nuclei has given some insight into the extent of the renormalization of the axial vector coupling constant in nuclear matter.[1] Such a renormalization does not occur for the case of pure vector transition as evidenced by the degree of fidelity of the conserved vector current hypothesis (CVC). However, in the case of axial vector transitions the presence of other nucleons exerts an influence on the currents and gives rise to a renormalization.

Most of the information concerning the degree of renormalization has been obtained from mirror transitions in the $A = 16$ region by what has been called a "nearly model-independent approach."[1] The result obtained for a model-dependent analysis[2] with selected data up to $A = 40$ region gives essentially the same result. The purpose of the present work is to bring accuracy to the $ft$ values which in turn may lead to a better determination of the renormalization value.

## II. EXPERIMENTAL METHOD

### $T_{1/2}$ measurements

While most of the experiments were performed using the internal proton beam of the McGill synchrocyclotron some experiments requiring low energy protons or deuterons were carried out using Van de Graaff accelerators at Université Laval (UL) or Université de Montréal (U de M). For such experiments, targets were evaporated onto 1.25 mm tantalum backings which were directly water-cooled. A pneumatic beam chopper which was programmable interrupted the beam during counting periods. Data were processed by a fast amplifier and 100 MHz discrimination before scaling. The properties of the scalars were measured where necessary. In each case, the discriminator threshold level was varied over a range such that the count rate was approximately 25–75% of the total integral count rate. Scaling was set at a rate not exceeding one-tenth of the half-life per channel, and was followed for 256, 1024, or 2048 channels.

Targets for internal beam irradiations at McGill were encapsulated in high purity low oxygen content beryllium cylinders. The beryllium was 99.87% pure and contained no given impurity (including BeO) in concentration greater than 0.02%. Targets after irradiation were transferred to a low background area by pneumatic systems. One system, 8 m long, was capable of delivering samples in 200 ms following irradiation[3] while a second system transported 15 m in about 2 s.

The data accumulation and processing techniques have been described elsewhere.[4,5] The detector was plastic (NE-102) coupled to an RCA 6342A photomultiplier tube. Data were accumulated using a fast discriminator and pileup rejector. Dead time was determined through the busy signal of the pileup rejector by use of a pulser.

### Branching ratio measurements

In most cases of $T = \frac{1}{2}$ pairs of mirror nuclei, positron decay is energetically feasible not only to the ground state of the daughter superallowed transition but also to a number of excited states.

A precise measurement of the ground state branch is required in order to evaluate the partial half-life. Usually one determines the branching ratio by evaluating the total number of positron decays as determined through the corresponding annihilation radiation and subtracting from this number the population of the excited states as determined through the $\gamma$ decay and corresponding decay scheme. Fortunately, in the cases considered here the ground state branch is in excess of 90%. Corrections must be applied to take into account positron annihilation-in-flight[6] and finite solid angle differences associated with positron migration from the source site during slowing down in the annihilator.[7]

The experimental apparatus consisted of a spherical aluminum ball (diameter = 2.0 cm) attached to an 18% Ge(Li) detector through a dial indicator which allowed reproduction of geometry to within ±0.1 mm. Experiments carried out using the fast pneumatic probe, for targets of half-life less than 1 s, utilized a cylindrical Al annihilator positioned around the probe terminal. By placing standard sources within the annihilators in holders used for actual samples the detector was calibrated for efficiency over the range of interest to between 1% and 5%.

The accuracy of the system was tested by reproducing the experiment of Robinson, Freeman, and Thwaites[8] concerning the superallowed branch of $^{10}C$ decay. Specifically the experiment requires the ratio of a 1.022 MeV to a 0.717 MeV photon to be measured with corrections for 0.511 MeV annihilation random summing being taken into account. Our value of 1.43 ± 0.04% is in excellent agreement with the precision value of 1.465 ±0.014%.[8] Normally $\gamma$ spectra were accumulated in the multispectrum mode with spectra being taken in contiguous time intervals. These data in conjunction with half-life data served to identify contaminants in any given sample.

## III. EXPERIMENTAL RESULTS

### $^{13}_{7}N_6$

In general the $^{13}N$ activity was produced through the $(p,n)$ reaction using $^{13}C$ (97% enriched) at bombarding energies of from 10 to 13 MeV. In addition, one target using $H_2O$ and the $^{16}O(p,\alpha)^{13}N$ reaction was used. In the case of the $^{13}C$ target the powder was removed from the irradiation encapsulation prior to counting. An appropriate delay occurred prior to data accumulation. The decay was followed over many half-lives. The curve was very clean with only a low, flat background present. The result of 11 experiments using $^{13}C$ as a target and one using $H_2O$ is 597.9 ±0.6 s, in agreement with the weighted average of several results.[9] (See Fig. 1).

### $^{15}_{8}O_7$

Various targets were used in the production of $^{15}O$. The most suitable was found to be $^{15}NH_3$ which was 95% enriched. The $(p,n)$ reaction at energies of 12 to 15 MeV was employed and the gaseous activity produced was removed from the irradiation encapsulation and collected after bubbling through oil into a counting cell. In addition powdered LiF targets using the $(p,\alpha n)$ reaction were used in two experiments. The final result for all runs was 122.23 ± 0.23 s. This value is in good agreement with an average compiled result of 122.24 ± 0.16 s.[9]

### $^{17}F$

Several kinds of targets were employed in an attempt to measure the half-life of $^{17}F$: $^{18}O$ in the form of $H_2O$ (95% enriched) using the $(p,2n)$ reaction at $E_p = 18-20$ MeV; natural $W_2O_3$ using the $(d,n)$ reaction at $E_d = 2.48$ and 3.0 MeV; and Ne gas using the $(p,\alpha)$ reaction at a proton bombarding energy of 12 to 15 MeV. A delay of 30 to 60 s preceded data accumulation. The data from these reactions yielded a value of 64.31 ± 0.09 s. This result is in poor agreement with the recent compiled value[10] of 66.0 ± 0.2 s (by several standard deviations) but agrees well with a recent precision value of Alburger and Wilkinson[11] (64.50 ± 0.25 s).

### $^{21}Na$

The half-life of (22.47 ± 0.03 s) has been reported elsewhere.[12] A reanalysis of the data leads to a revised value of 22.48 ± 0.04 s, with a more conservative error. A weak branch to a 350 keV state of $^{21}Ne$ exists. Using multispectrum methods the branching ratio for four separate runs of the reaction $Mg(p,\alpha)^{21}Na$ was found to be 95.86 ± 0.23%, 96.24 ± 0.64%, 97.13 ± 0.83%, and 95.56 ± 0.26%. The average of 95.8 ± 0.2% is in poor agreement with the compilation value of 97.7 ± 0.3%[10] or with a recent value of Alburger[13] of 94.9 ± 0.2%.

### $^{23}Mg$

A reanalysis of the previously reported experimental data[12] taking into account a very weak $^{13}N$ activity arising from the 0.02% BeO content of the encapsulation, yields, together with much additional data, a value of 11.317 ± 0.011 s. This result is a half standard deviation shift from the previously reported value.

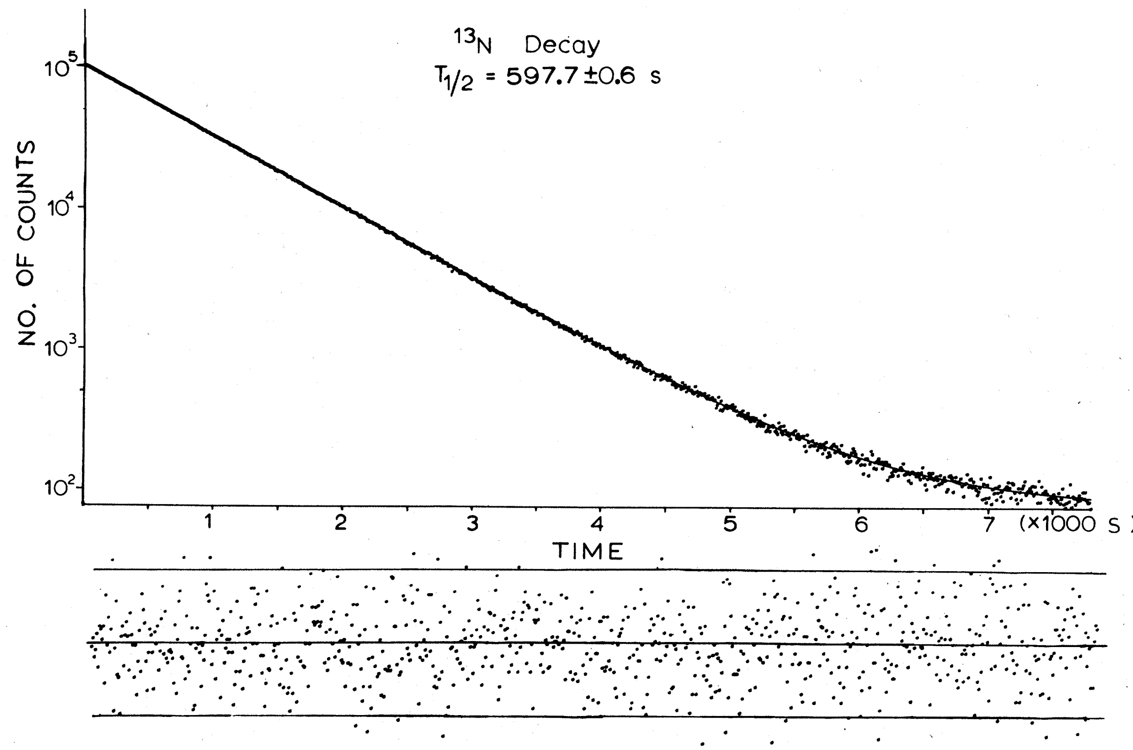


FIG. 1. Example of a decay curve obtained for the $^{13}$N activity, together with the residuals of the fit: (fit − data)/(fit)$^{1/2}$. The top and bottom lines represent the two-standard-deviation marks. In this particular case, the threshold was low (about 300 keV); $\chi^2/f = 0.9949$, corresponding to a confidence level of 53%.

The branching ratio measurement to the 440 keV level resulted in a 7.79 ± 0.15% value. This value is in considerable disagreement with a recent branching measurement of 9.1 ± 0.4%.[13] The efficiency calibration is expected to contribute only 2% to the statistical error because of the small energy separation of the 440 and 511 keV photons. No $\gamma$ rays from the 2.39 MeV level were observed. An upper limit of 0.01% has been reported for this transition.[10]

### $^{25}$Al

The half-life of $^{25}$Al has been previously measured to be 7.174 ± 0.007 s.[12] Four decay branches are allowed in $^{25}$Mg to levels at 1.965 MeV, 1.612 MeV, 0.975 MeV, and the ground state. An additional level at 0.585 MeV exists but spin differences make direct $\beta$ population unlikely. $\gamma$ rays deexciting from the 1.612 MeV level to the ground state were found to have an intensity of 0.794 ± 0.035%. Other $\gamma$-ray branches were very weak: 0.03 ± 0.01% intensity for the 585 keV $\gamma$ ray, 0.01 ± 0.01% for the 975 keV $\gamma$ ray, and 0.006 ± 0.004% for the 1965 keV $\gamma$ ray. As a result the adopted ground state branching ratio of the $\beta$ decay is 99.16 ± 0.04%. This is to be compared with the compiled value[10] of 99.14 ± 0.07% and with Jundt *et al.*[14] of 99.16 ± 0.07%.

### $^{27}$Si

The half-life of $^{27}$Si has previously been measured to be 4.109 ± 0.004 s.[12] Assuming that the $\beta$ branches to the states at 1.014 MeV ($\frac{7}{2}^+$), 2.734 MeV ($\frac{5}{2}^+$), and 2.981 MeV ($\frac{3}{2}^+$) in $^{27}$Al sum up to 0.04%[10] and using the value 0.148 ± 0.007% for the main $\gamma$-ray intensity decay from the 2.21 MeV, $\frac{7}{2}^+$ state as determined from two sets of runs, the ground state feeding is established at 99.81 ± 0.01%, in agreement with the previously adopted result.[10]

### $^{29}$P

The half-life of $^{29}$P had previously been reported as 4.083 ± 0.012 s.[12] The $\gamma$ rays depopulating excited states in $^{29}$Si were measured to be 1.62 ± 0.28% (1.273 MeV), 0.20 ± 0.10% (2.028 MeV), and 0.07 ± 0.03% (2.426 MeV) with respect to the number of $\beta^+$. This leads to a ground state branching ratio of 98.11 ± 0.30%, consistent with the compilation value[10] of 98.4 ± 0.3%.

## $^{31}S$

On the basis of 12 runs performed with a proton beam of 8 MeV (U de M) and 5 runs with proton beams at 10–13 MeV (McGill) a value for the half-life of 2.543 ± 0.008 s was found. The targets were high purity (99.99%) $P_3N_5$. Because of the serious discrepancy between this result and the most precise measurement reported previously the analysis of the data was particularly rigorous. In addition to $^{14}O$ (70 s) and $^{15}O$ (122 s), a small unidentified but significant 8 ± 2 s component had to be included in the analysis in order to obtain a satisfactory fit. An attempt was made to fit the data with the previously reported most precise value of 2.605 s[13] [also from the $^{31}P(p,n)^{31}S$ reaction] but the residuals clearly demonstrated the need for an 8 s component.

Despite a total of 52 runs using the multispectrum mode of accumulation only the 1266 keV $\gamma$ ray deexciting the corresponding level in $^{31}P$ was observed. The measured intensity was 0.98 ± 0.20% and combining this value with adopted values of the intensities of other branches[10] the ground state branch is established as 98.89 ± 0.20% which agrees well with a compilation value of 98.9% and a recent precision measurement: 98.75 ± 0.06%.[13]

## $^{33}Cl$

The result of 2.507 ± 0.008 s is based on four experiments using the $^{32}S(d,n)^{33}Cl$ reaction at bombarding energies of 2 and 3 MeV (U L). The contamination from the 1.58 s component arising from the $^{32}S(d,\gamma)$ reaction was imperceptible, as expected since the $(d,\gamma)$ reaction has usually a much smaller cross section than the $(d,n)$ reactions. Nevertheless, the data were analyzed with and without omission of the first few data points, but no statistically significant difference was observed. An unidentified, but very weak 15 ± 5 s component was detected during analysis. The present result agrees well with the result of Tanihata *et al.*[15] of 2.513 ± 0.004 s. No branching ratio measurement was made for this decay.

## $^{35}Ar$

Five sets of runs with a proton beam of 10–13 MeV (McGill) and the $(p,n)$ reaction on a $CCl_4$ target gave a half-life value of 1.772 ± 0.007 s. Four sets using the same reaction on an LiCl target yielded a value of 1.772 ± 0.004 s. An 8 MeV proton beam (U de M) using the $(p,n)$ reaction on a thick LiCl pellet yielded a half-life value of 1.780 ± 0.006 s. All three results are consistent with the weighted mean; 1.774 ± 0.003 s. This value is to be compared with a published value of 1.770 ± 0.006 s.[16]

TABLE I. A summary of present half-lives and branching ratio measurements for some $T=\frac{1}{2}$ nuclei.

| Nucleus | Half-life (s) | | Branching ratio (%) | |
|---|---|---|---|---|
| | Present | Previous | Present | Previous |
| $^{13}N$ | 597.9 ± 0.6 | 597.7 ± 0.24 [a] | | |
| $^{15}O$ | 122.23 ± 0.23 | 122.24 ± 0.16 [a] | | |
| $^{17}F$ | 64.31 ± 0.09 | 64.50 ± 0.25 [b] | | |
| $^{21}Na$ | | | 95.8 ± 0.2 | 97.7 ± 0.3 [c] |
| $^{23}Mg$ | 11.317 ± 0.011 | 11.26 ± 0.08 [d] | 92.2 ± 0.2 | 91.9 ± 0.4 [e] |
| $^{25}Al$ | | | 99.16 ± 0.04 | 99.16 ± 0.07 [f] |
| $^{27}Si$ | | | 99.812 ± 0.010 | 99.81 ± 0.01 [c] |
| $^{29}P$ | | | 98.11 ± 0.30 | 98.4 ± 0.3 [c] |
| $^{31}S$ | 2.543 ± 0.008 | 2.605 ± 0.012 [e] | 98.89 ± 0.20 | 98.75 ± 0.06 [e] |
| $^{33}Cl$ | 2.507 ± 0.008 | 2.513 ± 0.004 [g] | | |
| $^{35}Ar$ | 1.774 ± 0.003 | 1.770 ± 0.006 [h] | 98.0 ± 0.2 | 98.28 ± 0.05 [c] |
| $^{37}K$ | 1.223 ± 0.008 | 1.23 ± 0.02 [c] | 97.8 ± 0.2 | 98.0 ± 0.4 [c] |
| $^{39}Ca$ | 0.8594 ± 0.0016 | 0.8604 ± 0.0030 [i] | > 99.72 | > 99.88 [c] |

[a] Reference 9.
[b] Reference 11.
[c] Reference 10.
[d] G. Azuelos, J. E. Crawford, and J. E. Kitching, Phys. Rev. C 9, 1213 (1974).
[e] Reference 13.
[f] Reference 14.
[g] Reference 15.
[h] Reference 16.
[i] Reference 17.

Assuming no $\beta^+$ or $\gamma$-ray branch can be associated with the high spin 2.65 MeV level $(\frac{7}{2}^+)$ in $^{35}$Cl the measured $\gamma$-ray intensities are $1.55 \pm 0.15\%$ (1.223 MeV, $\frac{1}{2}^+$), $0.34 \pm 0.09\%$ (1.763 MeV, $\frac{5}{2}^+$), and $0.05 \pm 0.03\%$ (2.69 MeV, $\frac{3}{2}^+$). These results differ significantly from compiled values of $1.22 \pm 0.05\%$, $0.239 \pm 0.011\%$, and $0.19 \pm 0.02\%$, respectively.[10] Taking an intensity of $0.08 \pm 0.02\%$ for the decay from the 3.003 MeV level,[10] the present data yield a ground state branching ratio of $98.0 \pm 0.2\%$ as compared with $98.28 \pm 0.05\%$.[10]

### $^{37}$K

Isotopically enriched $^{40}$Ca in oxide form served as the target for $^{37}$K production through the $(p, \alpha)$ reaction at bombarding energies of 10–13 MeV. Because of a low production cross section the presence of extremely small impurities, probably associated with the trace elements in the beryllium encapsulation (< 0.02%), were detected in the analysis. A total of 21 runs produced a value of $1.223 \pm 0.008$ s, in reasonable accord with the compiled value of $1.23 \pm 0.02$ s.[10]

For this decay, only the 2.798 MeV $\gamma$-ray branch could be observed (intensity $2.22 \pm 0.21\%$). Taking the strength of one other branch at 3.605 MeV to be $0.034 \pm 0.006\%$,[10] the value of the ground state branching ratio is $97.8 \pm 0.2\%$, in good agreement with the usually accepted value of $98.0 \pm 0.4\%$.[10]

### $^{39}$Ca

Chemically pure natural potassium was used as a target for the production of $^{39}$Ca through the $^{39}$K$(p, n)^{39}$Ca reaction at bombarding energies of from 10–15 MeV. The elemental potassium was encapsulated in beryllium and irradiated through use of the fast transfer probe. A total of 17 runs yielded a half-life of $859.4 \pm 1.6$ ms, in good agreement with a recent value of Alburger and Wilkinson[17] of $860.4 \pm 3.0$ ms.

A search for $\gamma$-ray activity proved fruitless and hence only a lower limit to the ground state branch could be established; >99.72%. Other workers have established an upper limit of 0.12% for $\beta$ transitions to excited states.[10]

## IV. CONCLUSION

The data presented are summarized in Table I where they are compared with other results. In general, the branching ratio measurements are in good agreement with previous data with $^{21}$Na being the sole exception. Similarly the half-lives measured are in good accord with previous results except in the case of $^{31}$S and $^{37}$K.


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