Gamow-Teller strength in the $^{14}O \rightarrow ^{14}N(3.948$ MeV) beta decay

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The Gamow-Teller β decay from the ^{14}O 0^+ ground state to the 3.948 MeV 1^+ level in ^{14}N has been studied by observing γ rays from the deexcitation of the 3.948 and 2.313 MeV levels in ^{14}N. We measured a branching ratio of $(5.28 \pm 0.23)\times 10^{-4}$ relative to the superallowed Fermi decay to the 2.313 MeV level, and deduce $ft = 1446 \pm 63$. The corresponding Gamow-Teller transition strength is $B(\mathrm{GT}) = 2.73 \pm 0.12$. This value is about 40% lower than predicted by several widely used shell model calculations, and may suggest appreciable quenching by mesonic currents.

[RADIOACTIVITY ^{14}O measured I_γ, GT strength.]

I. INTRODUCTION

The recent observation of the giant $M1$ resonance in medium energy (p,n) reactions[1] has focused wider interest on the relation between the $\sigma\tau$ interaction in charge exchange reactions and the analogous Gamow-Teller (GT) matrix element obtained from the nuclear β decay of corresponding states. In a previous study of $^{14}C(^6Li, ^6He)^{14}N$ it had been observed[2] that the relative population of the final states in ^{14}N by the presumed charge exchange reaction $(^6Li, ^6He)$ disagreed significantly with expectations based on the available GT matrix elements from the $^{14}O \rightarrow ^{14}N$ β decay. The surprising $(^6Li, ^6He)$ result is fully supported by the recent $^{14}C(p,n)^{14}N$ study at 160 MeV.[1]

Hence, it becomes desirable to verify the corresponding GT matrix elements for the ^{14}O decay. The relevant Gamow-Teller β-decay branch of ^{14}O leads to the 3.948 MeV 1^+ state of ^{14}N as shown in Fig. 1. This transition is difficult to observe, because of competition from the superallowed Fermi decay to the ^{14}N 2313 keV level which is favored energetically. Only one research group has published a measurement of this weak GT branch.[3] The reliability of their reported branch $[B = (5.77 \pm 0.43)\times 10^{-4}]$ depends critically on their success in determining a nonuniform background with high accuracy. Our interest in this transition was intitially stimulated by the findings of Ref. 2 and reinforced by the recent (p,n) results, and led to several measurements by different methods yielding improved accuracy.

II. EXPERIMENTAL PROCEDURE AND RESULTS

In all measurements the radioactive isotope ^{14}O $(T_{1/2} = 70.6$ sec) was produced by the reaction $^{14}N(p,n)^{14}O$, with 8.6 – 10 MeV proton beams from the University of Pittsburgh tandem Van de Graaff. The ^{14}O β^+ decay branch of interest was detected by observing the subsequent 1635 keV γ ray from the 1635, 2313 keV decay cascade of the 3948 keV, 1^+ level in ^{14}N. The dominant 2313 keV γ line from the deexcitation of the 0^+ level to the ground state made a natural reference branch. See Fig. 1.

In the first experiment, the target used was

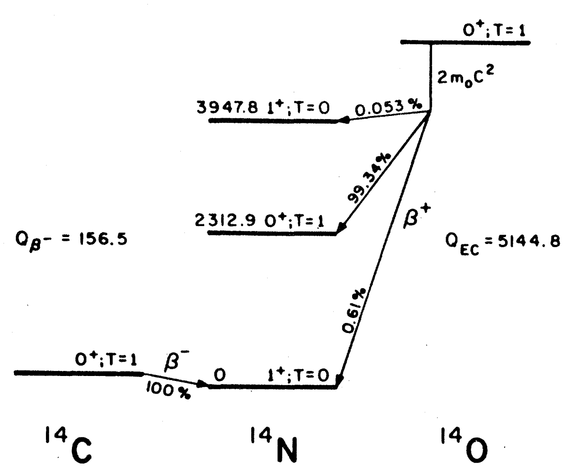

FIG. 1. Level scheme of ^{14}N and the mass 14, $T = 1$ isospin triplet.

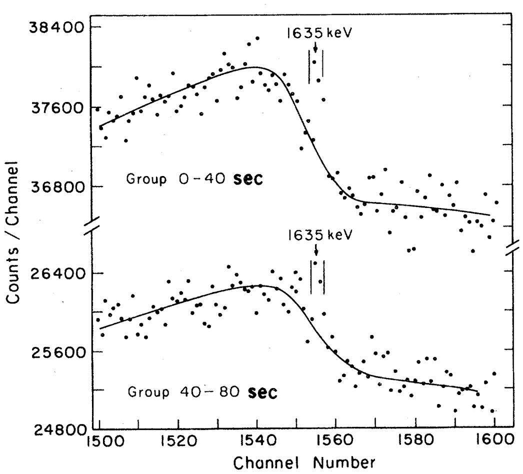

FIG. 2. Summed γ ray spectra for the 1635 keV region for two time bins (rabbit experiment). Note the use of suppressed zero. The solid lines indicate the assumed background.

melamine ($N_6H_6C_3$) resin containing approximately 20 mg/cm^2 of ^{14}N. The resin was held in a pocket made with a 8.9 μm Ta foil. The target was bombarded with 8.6 MeV protons for a period of 40 sec after which time the beam was stopped on a distant chopper and the target transported 1 m to a shielded area by a magnetically driven "rabbit."[4] After a waiting time of 10 sec spectra were accumulated in three sequential time bins, each of 40 sec, in order to permit a determination of the half-life of the observed γ peaks. The Ge(Li) detector used to measure the γ spectra was shielded with 2.54 cm of lead in order to reduce the low energy background. The efficiency of the Ge(Li) detector was determined using a ^{56}Co calibration source.[5]

Figure 2 shows the region of interest near 1635 keV for a summed spectrum obtained in this rabbit experiment. This spectrum is very similar to that reported by Ref. 3. The first two groups (0–40 and 40–80 sec) of the three sequential arrays are shown. The ratio of the total number of counts in the 1635 keV peak between both groups is (0.70 $\pm$ 0.15), in complete agreement with the expected value of 0.67 for a 70.6 sec half-life. The Compton contribution from the strong 2313 keV γ ray dominates. However, the background is not smooth because of the presence of a Compton edge from the detection of the 511 keV γ ray following single escape events from the 2313 keV γ ray. This secondary Compton edge is situated only 3–4 keV below the 1635 keV line of interest. The branching ratio obtained from this rabbit experiment is displayed in the first row of Table I.

In the second experiment, N_2 gas was used as target material. The gas was bombarded while flowing through a target cylinder of 13 cm length and 0.48 cm diameter. It then circulated from the target chamber through a 450 cm long, 0.55 mm (i.d.) plastic capillary tube to a separate "source" cell of 2.54 cm diameter and 2.54 cm length in a well-shielded counting room. A diaphragm-type compressor kept the target pressure at 3.7 atm which led to a source pressure of 2.6 atm. The typical measured gas flow was 9.0 cm^{3}atm/sec. The minimum delay before counting was about 0.6 sec.

In this experiment data were acquired continuously. The γ spectra were measured with a newer 131 cm^3 Ge(Li) detector which has a full energy peak-to-Compton ratio of 50 to 1, a little better than the Ge(Li) detector used in the first experi-

TABLE I. Summary of individual measurements for ^{14}O $\beta-\gamma$ decay. Uncertainties include statistical errors only, except for the rabbit run, where a shape uncertainty for the background was added.

Experiment	Area ratio $\frac{N(1635\text{ keV})}{N(2313\text{ keV})}$	Relative eff. ϵ (GeLi) $\frac{\epsilon(2313)}{\epsilon(1635)}$	Correction factor for cascade losses	Rel. branching ratio $\frac{\sigma(1635)}{\sigma(2313)}$
rabbit				
lead shielding = 2.54 cm	$(6.41 \pm 1.28)\times10^{-4}$	0.85 ± 0.01		$(5.45 \pm 1.10)\times10^{-4}$
circulating gas system				
lead shielding = 1.27 cm	$(6.32 \pm 0.71)\times10^{-4}$	0.82 ± 0.01	1.005 ± 0.001	$(5.21 \pm 0.59)\times10^{-4}$
2.54 cm	$(5.82 \pm 0.52)\times10^{-4}$	0.89 ± 0.01	1.004 ± 0.001	$(5.20 \pm 0.47)\times10^{-4}$
1.27 cm	$(6.47 \pm 0.37)\times10^{-4}$	0.82 ± 0.01	1.005 ± 0.002	$(5.33 \pm 0.31)\times10^{-4}$
				average: $(5.28 \pm 0.23)\times10^{-4}$

ment. Two different thicknesses of lead absorbers were used (2.54 and 1.27 cm) in different runs in order to acquire data at an optimal counting rate for our on-line computer ($\sim$ 15 000 counts/sec). A factor of 3.6 reduction of the large Compton background was achieved by gating with a NaI "anti-Compton" detector. Two Ge(Li) spectra, one ungated and the other subject to an anticoincidence requirement between the Ge(Li) and the NaI (anti-Compton detector) signals, were recorded. The (energy dependent) Ge(Li) efficiency was measured for both absorber thicknesses in the ungated mode using a ^{56}Co source, and calibrated ^{137}Cs, ^{60}Co, and ^{22}Na sources. Figure 3 shows a typical semilog, gated spectrum from this experiment. The spectrum is extremely clean with only two room background peaks visible. Figure 4 shows a linear plot of the section around the 1635 keV γ ray; assumed background is also indicated. The signal to background ratio at the peak is 14 to 100, a substantial improvement compared to the signal to background ratio of about 3 to 100 obtained in the first (rabbit) experiment. The energy of the "1635" γ ray was measured at (1634.7 $\pm$ 0.3) keV.

When using the anti-Compton shield a small additional efficiency correction is required. Since the 1635 keV and the 2313 keV γ rays are in cascade a small relative decrease in the intensity of the 1635 keV γ ray will occur because of a (false) coincidence suppression by the anti-Compton shield.

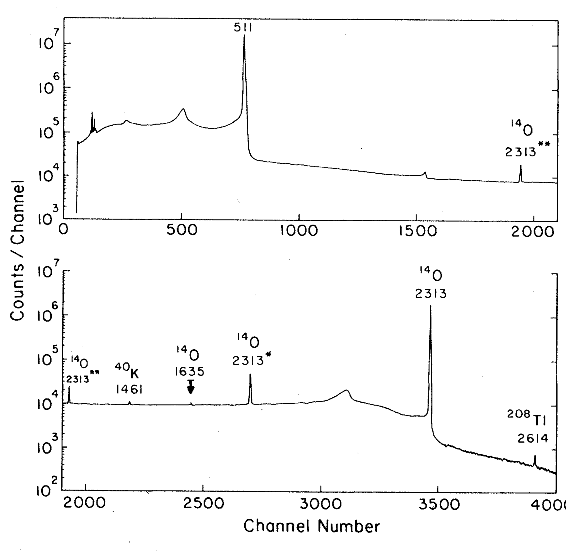

FIG. 3. Semilog plot of the γ ray spectrum obtained in the circulating gas system experiment. The energy calibration is 0.67 keV/ch. The spectrum was "hardened" with a 1.27 cm Pb absorber.

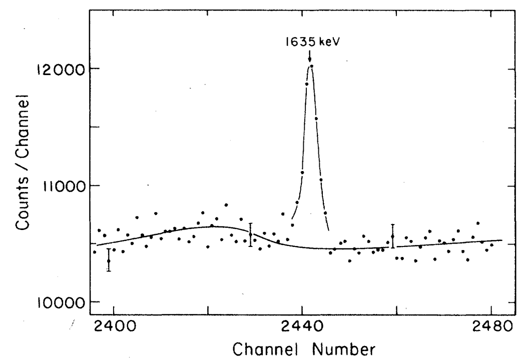

FIG. 4. Linear detail plot of the spectrum shown in Fig. 3, near 1635 keV. The bars indicate the size of statistical uncertainties.

This effect can be evaluated by considering the 2598.5 keV γ ray from the ^{56}Co calibration spectra. This γ ray is in cascade with the 846.7 keV γ ray, having then nearly the same rejection factor as the 1635 keV γ ray of interest. We found a correction factor (CF) of (1.002 $\pm$ 0.014). Another way to estimate this correction factor is to find the absolute efficiency ϵ(NaI) of the (shielded) anti-Compton detector, which is related to the CF by CF $\approx[1-(n-1)\epsilon(NaI)]^{-1}$, where n is the number of the γ rays in cascade, and ϵ the typical absolute efficiency of the NaI detector for radiation from the source cell.

We found, in this way, a typical correction factor CF $=1.004\pm0.001$. The values obtained with both methods agree very well within their uncertainties. We used the CF value from the second method to correct our results for the branching ratio. The results obtained from several runs using the circulating gas system are displayed in Table I. Combining all four results (using $1/\sigma^2$ weighting), we obtain (5.28 $\pm$ 0.23)$\times 10^{-4}$ for the branching ratio, which with 0.61% for the ground state branch yields an absolute branch for the β decay to the 3948 keV state of

$$B=(5.25\pm0.23)\times10^{-4} .$$

This value is in agreement, within their combined uncertainties, with the absolute branch previously measured by Wilson *et al.*,[3] mentioned above. Based on our experimental result the ft value for this branch is $ft=1446\pm63$. Log$f$ values were taken from Ref. 6, considering K capture and radiative losses.[7,8] The GT strength obtained, using the equation[3]

$$B(\mathrm{GT})=\frac{6163.4\pm3.8\ \mathrm{sec}}{(1.25)^2 ft} ,$$

is B(GT) $=2.73\pm0.12$.

III. DISCUSSION

The absolute value of this B(GT) strength is important since the results of the $^{14}C(p,n)^{14}N$ as well as that of the $^{14}C(^6Li,\ ^6He)^{14}N$ reaction[1,2] indicate that 90% of the GT strength below 30 MeV excitation is in the 3948 keV state. Hence, the total GT strength below 30 MeV excitation, if based on our β-decay value, is $B(\mathrm{GT}) \approx 3.0$. Our value 2.73 $\pm$ 0.12 for the 3.948 MeV state can be compared with corresponding values from the shell model calculations of Vissher and Ferrel[9] who give $B(\mathrm{GT}) = 4.2$ (the smallest theoretical value we know of), and of those Cohen and Kurath[10] who give $B(\mathrm{GT}) = 4.81$.

A similar but broader comparison was made by Wilkinson.[11] He considered 20 β transitions in the $(1p)$, $(2s,1d)$ shell region, whose experimental GT strengths were accurately measured, and compared them with the corresponding strengths derived from shell model wave functions computed in the full bases of the major shell. The systematic differences that he found between the experimental rates of GT β decay and those predicted by the shell model lead him to suggest a renormalization of the axial vector constant g_A by a factor 0.897 $\pm$ 0.035 relative to its free space value. This renormalization has the effect of increasing B(GT) obtained from β decay by about 20%.

A similar analysis was made by Brown *et al.*[12] for the region $17 \le A \le 23$, reaching an identical result $[B(\mathrm{GT})_{\mathrm{expt}}/B(\mathrm{GT})_{\mathrm{th,free}} \simeq 80\%]$. This quenching of the axial vector coupling has been attributed to the effects of configuration mixing outside the shell model space considered as well as to meson exchange currents.

It is also interesting to compare the GT strength obtained from the experimental value of the β branching ratio and the one obtained from the width of the $M1$ γ decay between the 3948 and 2313 keV states. Because the 2313 keV level is the isobaric analog of the ^{14}O g.s., that $M1$ transition involves the same GT matrix element as the β decay between the ^{14}O g.s. and the 3948 keV level.

The width of the $M1$ transition in terms of the matrix element is expressed by

$$\Gamma(M1) = \frac{e^2}{3\hbar c}\frac{E_\gamma{}^3}{M_p{}^2c^4}\,|\langle f\,|\,M1\,|\,i\,\rangle\,|^2\,,$$

where only the isovector part of the $M1$ operator should be considered for the analog $M1$ transition with $\Delta T = 1$. Then, the following relation between the width of the analog $M1$ transition (eV) and the ft value (sec) for the GT transition can be obtained[13]:

$$\Gamma(M1) = \frac{129}{ft(\mathrm{GT})}E_\gamma{}^3(\mathrm{MeV})\frac{\langle T+1\ T_z 1\ 0\,|\,T\ T_z\rangle^2}{\langle T+1\ T_z+1\ 1\ -1\,|\,T\ T_z\rangle^2}$$
$$\times\left[1+0.212\frac{1+2\delta g_l}{1+\dfrac{\delta g_s}{4.71}}\frac{\langle J_f,T\,||\,l\tau||J_i,T+1\rangle}{\langle J_f,T\,||\,\sigma\tau||J_i,T+1\rangle}\right]^2 .$$

Neglecting the mesonic correction (δg_s and δg_l) and with the $l\tau$ matrix element estimated from shell model wave functions[2] as equal to -2.75 $\pm$ 0.75, a GT strength of $B(\mathrm{GT}) = 3.18 \pm 0.59$ is obtained from the most recent $\Gamma(M1)$ value[14] for this transition $[\Gamma(M1) = 0.079 \pm 0.010]$. [This strength is about 30% smaller than the value quoted in Ref. 2 which resulted from a larger, no longer accepted $\Gamma(M1)$ value.] The remaining 16% difference between this value for B(GT) and our experimental result must be compared to a 19% uncertainty associated to the GT strength from $M1$ decay (which comes predominantly from the uncertainty in the estimate of the $l\tau$ matrix element). It agrees, however, with similar discrepancies which were found by Yoro[15] when examining the $M1$ moments and β decay ft values in other $1p$ shell nuclei. Configuration mixing should affect the $M1$ and GT matrix elements in the same way but the mesonic exchange current effects need not be identical. Deviations of the g factor from its free nucleon values for the GT and $M1$ matrix elements are due to both effects, mesonic currents and truncated shell model space, but their relative difference should originate from a difference in the mesonic corrections. Yoro found this difference to be 20% of its free nucleon value.

A recent study[16] implies that $M1$ strength of up to 40% is spread to much higher excitation energies through effects of the Δ resonance on the structure of low lying states. Our new data suggest that the cause of these large discrepancies in ^{14}N does not lie in the uncertainties of the experimental β decay matrix elements.

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