Beta decay of ^{21}F

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^{21}F(β^-)^{21}Ne is re-examined. β branches are observed as follows [^{21}Ne E_x (keV), % β branch]: 0, 9.6(3.0); 351, 74.1(3.0); 1746, 16.1(1.0); 3736, 3.1(4)$\times 10^{-3}$; 3884, 4.0(4)$\times 10^{-3}$; 4525, 43(3)$\times 10^{-3}$; 4685, 77(5)$\times 10^{-3}$. The half-life was measured to be 4.158(20) s. Precision γ-ray measurements were made for the ^{21}Ne 351$\rightarrow$0 and 1746$\rightarrow$351 transitions and the ^{20}Ne 1634$\rightarrow$0 transition. Results for the γ energies are 350.725(8), 1395.131(17), and 1633.602(15) keV. logft values are calculated. Comparisons of the present results are made to the shell-model calculations of Lanford and Wildenthal and to the analog β^+ decay of ^{21}Mg to ^{21}Na. It is concluded that uncalculated Coulomb effects are a major block to the sensitivity of such comparisons.

[RADIOACTIVITY ^{21}F [from ^{19}F(t,p)]; measured I_γ, E_γ, $T_{1/2}$; deduced β and γ branching, logft values; compared with analog decay and theory.]

I. INTRODUCTION

In a continuing effort at this laboratory[1-3] to test our knowledge of the nuclear structure of the $A=21$ nuclei, and specifically ^{21}Ne,[1,2] we have re-investigated the β decay of ^{21}F ($T_{1/2}=4.2$ s), which is illustrated in Fig. 1. The last published report on the β branching of the $\frac{5}{2}^+$ ^{21}F ground state to levels of ^{21}Ne was that of Harris and Alburger.[4] Branching ratios of 29±6, 63±6, 7.6±1.0, and <0.15% were obtained to the ground state and first three excited states, respectively. In that study γ rays were detected by NaI(Tl) detectors. The Q value for ^{21}F(β^-)^{21}Ne is 5686±7 keV (Ref. 5) and there are nine further energy levels of ^{21}Ne at low enough excitation energies [$E_x<4.8$ MeV (Ref. 5)] so that an allowed ^{21}F β branch to any of them should be detectable with present day Ge(Li) γ-ray spectroscopy techniques. Therefore a search for weak branches to higher-lying states was undertaken.

Technological advances and experience since previous determinations of the ^{21}F half-life[6,7] allow considerable improvement in precision for this measurement. The same is true for the energy measurements[5] of the γ rays emitted by the first two excited states of ^{21}Ne. Accordingly, a remeasurement of these quantities was also undertaken.

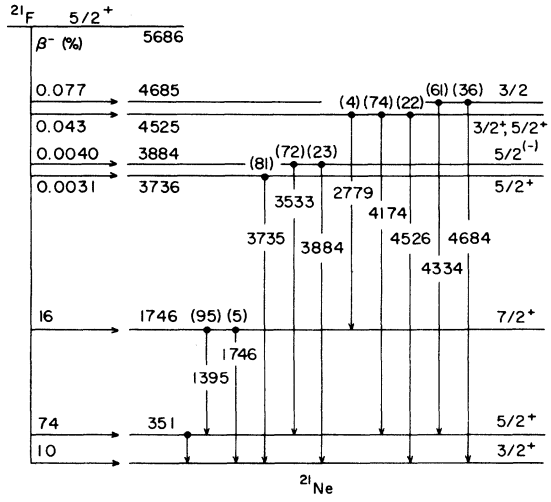

FIG. 1. Decay scheme of ^{21}F. The spin-parity assignments are from Ref. 5. The β- and γ-branching ratios (in percent) are from the present results. Only levels fed by ^{21}F(β^-)^{21}Ne are shown.

II. EXPERIMENTAL PROCEDURES AND RESULTS

A. General

^{21}F was formed via the ^{19}F(t,p)^{21}F reaction [Q = 6221±7 keV (Ref. 5)] with a triton beam of 1.0–1.8 MeV from the BNL 3.5-MV Van de Graaff accelerator. A β and/or γ detector was situated 4 m from the target chamber and on the other side of a concrete wall. The target was mounted on a "rabbit" which was shunted pneumatically between the bombard and count positions. The target consisted of a pressed pellet of BaF_2, ~3 mm thick. A typical bombard-count cycle was as follows:

0.0–3.0 s bombard,
3.0–4.0 s transfer,
4.0–8.0 s count,
8.0–9.0 s transfer. (1)

The γ detector consisted of a 5=-cm^3 ORTEC true coaxial Ge(Li) detector. For all measurements it

was separated from the BaF_2 pellet by enough material (Al, Pb, or brass) to stop the ^{21}F β rays. The β rays were detected with a 7.5-cm-diam by 5-cm-thick NE102 scintillator coupled to an RCA 8575 photomultiplier tube. Preamplified pulses from either detector were fed to an ORTEC 472 spectroscopy amplifier and then to a Northern type NS-624 4096-channel analog-to-digital converter and NS-636 memory unit.

B. Precision γ-ray energy measurements

The energies of the ^{21}Ne 351→0 and 1746→351 γ transitions were measured by the mixed source technique. For the 351-keV transition a ^{133}Ba source was used, while for the 1395-keV transition sources of ^{60}Co and ^{152}Eu were used. The primary calibration line from ^{133}Ba was that at 356.014(7) keV (Ref. 8) —where the number in parentheses is the uncertainty in the least significant figure. The other ^{133}Ba lines providing secondary standards were those at 276.407(3) 302.859(6), and 383.859(5) keV.[8] The primary standard for the 1395-keV γ ray was the 1408.011(14)-keV line from ^{152}Eu.[9] Secondary standards were the ^{60}Co γ rays of 1173.237(4) and 1332.501(5) keV,[8] the 1112.116(17)-keV (Ref. 9) γ ray of ^{152}Eu, and the 1633.590(100)-keV (Ref. 10) γ ray from ^{19}F$(t,d)^{20}$F$(\beta^-)^{20}$Ne (see below).

For these measurements the front face of the Ge(Li) detector was ~3 cm from the ^{21}F source. The pulse height analyzer was operated with 8192-channel conversion gain and a digital offset of 4096 channels. Because of the presence of the calibration sources, the total counting rate during the count cycle decreased by only ~15%. The energy separation between the ^{133}Ba 356-keV line and the ^{21}Ne 351-keV line, Δ(356-351), was obtained from seven different spectra. The energy difference Δ(1408-1395) was obtained from eight spectra. Each spectrum was recorded with a slightly different amplifier gain so that the position of the ^{21}F γ peak being measured varied by ~1500 channels from the lowest to highest gain. The data are illustrated in Fig. 2.

The various γ-ray sources were carefully placed so that uncertainties due to different source-detector geometries[11] could be neglected. The uncertainty due to the variation in count rate[12] was entirely negligible as was that due to any source inhomogeneities.[12]

Peak positions were determined with the program SAMPO.[13] Its use at this laboratory for precision γ-ray energy measurements has been described previously.[12,14]

For the 351-keV γ ray the average value of Δ(356-351) was found to be 5.289(3) keV. In none of the seven measurements did Δ(356-351) deviate more than 4 eV from the mean. Assuming a pos-

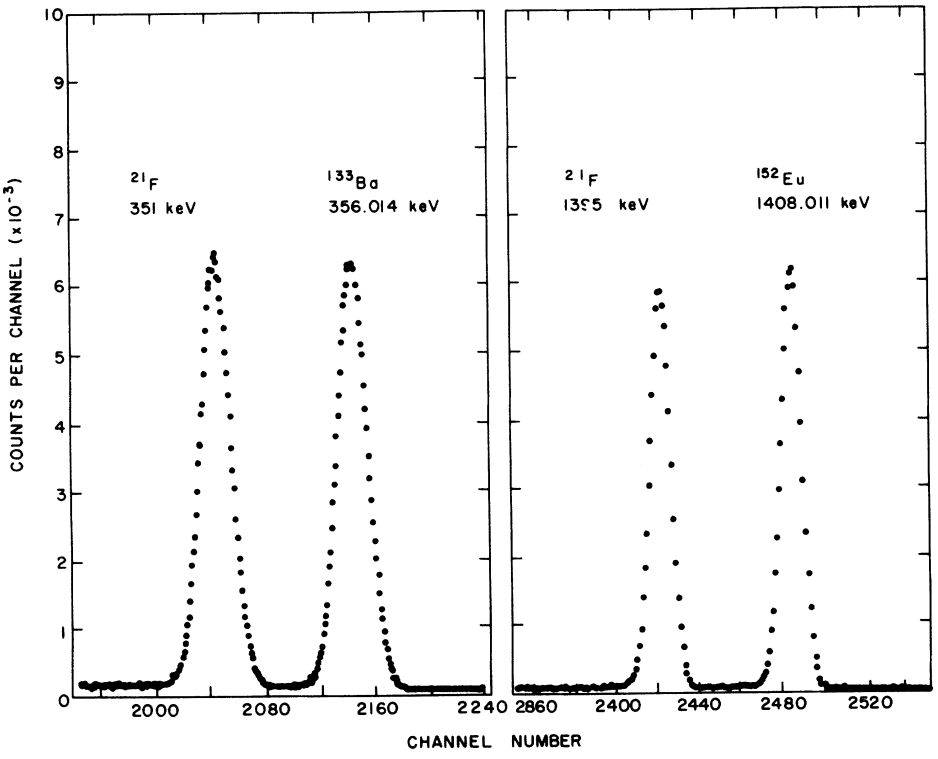

FIG. 2. Partial γ spectra illustrating the doublets ^{21}Ne 351 keV-^{133}Ba 356 keV and ^{21}Ne 1395 keV-^{152}Eu 1408 keV.

sible systematic uncertainty of ± 3 eV and combining these uncertainties with the uncertainty in the 356-keV energy, ± 7 eV, we have 350.725(8) keV for the energy of the ^{21}Ne 1 → 0 transition.

For Δ(1408–1395) we found 12.880(9) keV. The maximum deviation from the mean for the eight measurements was 12 eV. From this separation energy we obtain 1395.131(17) keV for the ^{21}Ne 2 → 1 γ-ray energy.

After correcting for nuclear recoil, these γ-ray energies yield 350.728(8) and 1745.909(19) keV, respectively, for the excitation energies of the first two excited states of ^{21}Ne. The 2 → 0 crossover γ ray has an inferred energy of 1745.831(19) keV.

Previous γ-ray energy measurements yielded[5] 350.72(6) keV and 1745.6(2) keV for the first two excited states of ^{21}F. The agreement with the present, more precise results is satisfactory. On the other hand, two previous Doppler-shift studies of ^{21}Ne had yielded 1396.4(4) keV (Ref. 15) and 1396.4(3) keV (Ref. 2) for the 1395.131(17)-keV γ ray. The value of 1396.4(3) keV was obtained at this laboratory from a 0° measurement and a calculation of the Doppler shift in the ^{18}O(α,n)^{21}Ne reaction. It would appear that the uncertainty in this method was underestimated.[16]

Because of its potential use as a calibration line in this and other studies [e.g., study of ^{21}O(β$^-$)^{21}F],[3] the energy of the γ ray corresponding to the decay of the first excited state of ^{20}Ne was also measured. The ^{19}F(d,p)^{20}F(β$^-$)^{20}Ne reaction was used and all other conditions were as described for ^{19}F + t. Calibration sources of ^{56}Co and ^{228}Th were used and the ^{20}Ne 1634-keV line was measured relative to the ^{212}Bi(β$^-$)^{212}Po γ ray of 1620.735(10) keV.[17] The result of 9 separate measurements was Δ(1634–1621) = 12.867(11) keV from which we obtain 1633.602(15) keV. This γ-ray energy corresponds to an excitation energy of 1633.674(15) keV for the ^{20}Ne first excited state. The most accurate previous γ-ray energy was 1633.59(10) keV,[10] in good agreement with the present result.

C. β transitions to higher-lying states

The γ transitions from the β decay of ^{21}F to states of ^{21}Ne above 1.8-MeV excitation were searched for with a 0.6-cm thick Pb absorber in front of the 50-cm^3 Ge(Li) detector and the bombard-count cycle of Eq. (1). A total of ~30 h of data were accumulated with a triton beam current of ~0.8 μA and an energy of 2.0 MeV. Portions of the sum of all accumulated data are shown in Fig. 3. The main limitation to the sensitivity of the search for weak branches was the background from the ^{14}N(t,p)^{16}N(β$^-$)^{16}O branch to the ^{16}O 6131-keV level. The Compton distribution from the ^{16}O 6131-keV transition contributes almost all of the background apparent in Fig. 3. At the be-

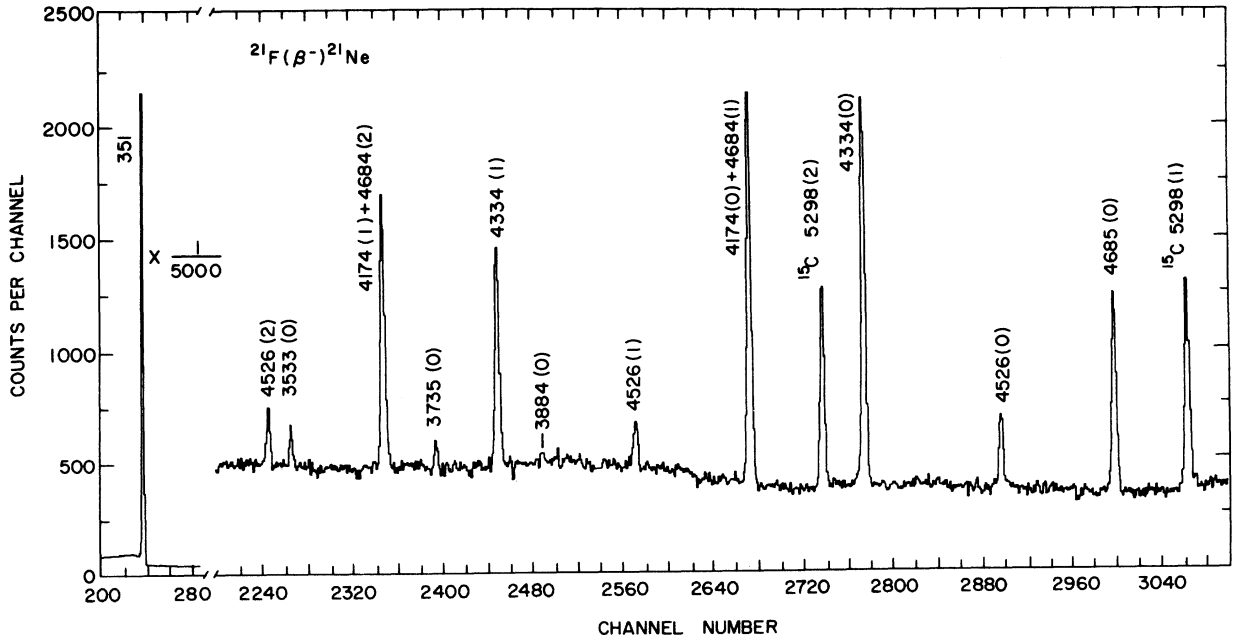

FIG. 3. Partial γ spectrum showing ^{21}F(β$^-$)^{21}Ne γ rays (identified by their energies in keV) and ^{15}C(β$^-$)^{15}N. The transitions to which the ^{21}F γ rays are assigned are listed in Table I. Full-energy, one-escape, and two-escape peaks are identified by $E_\gamma(n)$ were $n = 0$, 1, and 2, respectively.

ginning of the count cycle, ^{16}N($T_{1/2}$=7.13 s) was present with an intensity ~0.5% of that of ^{21}F. Many different targets were fabricated in our attempts to reduce the ^{14}N contamination and thus the ^{16}N activity. The figure of ~0.5% was the lowest achieved for the activity.

The ^{15}C(β^-)^{15}N branch to the ^{15}N 5299-keV level is also apparent in Fig. 3. The ^{13}C(t,p)^{15}C reaction is responsible for this activity. It could be reduced to a negligible factor but was retained since the ^{15}N 5298-keV γ ray of 5297.794(35) keV (Ref. 18) provided a convenient energy calibration standard. The ^{16}N 6129-keV γ ray, E_γ=6129.170(43) keV,[19] provided the other high-energy calibration standard. The energy calibration used these peaks and those at 351, 1395, 1634, and 1746 keV discussed in the last subsection as well as the 2614.533(14)-keV line of ^{228}Th.[17]

A γ-ray efficiency calibration was made *in situ* using sources of ^{152}Eu and ^{56}Co.[8,9] High-energy data were provided by ^{24}Al(β^+)^{24}Mg results taken[20] with the same detector and source geometry.

The energies and relative intensities of the observed ^{21}Ne γ rays are listed in Table I together with their placement in the ^{21}Ne decay scheme and the resulting level energies and γ-branching ratios. As can be seen, the γ-branching ratios are in excellent agreement with previous work[5] from other reactions. However, for the four ^{21}Ne levels not previously observed in ^{21}F(β^-), the present excitation energies are consistently higher than those listed by Endt and van der Leun. (The average of the discrepancy is 1.4 ± 0.3 keV.)

Before these γ-decay results can be converted to β-decay branching ratios it is necessary to determine the relative branch to the ^{21}Ne ground state. This we describe in the next subsection.

D. The ground state β branch

The β branching ratio of ^{21}F to the ^{21}Ne ground state was determined in a separate experiment in which β-γ coincidences were event-mode-recorded (EMR) on magnetic tape in a 2048 × 4096 channel matrix. The singles spectra were recorded simultaneously. The ratio of the branching ratios to the ^{21}Ne ground state and 351-keV level was extracted from the relation

$$\frac{f_\beta^{-1}\mathrm{BR}_{g.s.}}{\mathrm{BR}_{351}} = \frac{N_s^\beta - \epsilon_{1634}{}^{-1}N_c^\beta(1634) - \epsilon_{1395}{}^{-1}N_c^\beta(1395)/0.95}{\epsilon_{351}{}^{-1}N_c^\beta(351) - \epsilon_{1395}{}^{-1}N_c^\beta(1395)} - 1, \quad (2)$$

where N_s^β is the number of counts in the beta singles spectrum above a given discrimination bias, $N_c^\beta(E_\gamma)$ is the number of beta counts above the same discriminator setting in coincidence with the full-energy peak E_γ, and ϵ_{E_γ} is the absolute Ge(Li) efficiency for the same full-energy peak. The factor 0.95 is the branching ratio of the ^{21}Ne 1746-keV level via the 1395-keV γ ray, while the factor f_β on the left hand side of Eq. (2) corrects for the different end-point energies of the β spectra associated with the ^{21}Ne ground state and 351-keV levels.

The basis of Eq. (2) is the relation between the number of singles beta counts associated with a β branch to the ith level and the number of beta counts in coincidence with a given γ-ray decay from this level:

$$N_s^\beta(i) = \epsilon_{E_\gamma}{}^{-1}N_c^\beta(E_\gamma)/\mathrm{BR}(E_\gamma), \quad (3)$$

where $\mathrm{BR}(E_\gamma)$ is the branching ratio of the ith level via the γ ray of energy E_γ. We assume that the only non-negligible contributions to the beta singles spectrum are from the branches to the first three states of ^{21}Ne and from ^{20}F(β^-)^{20}Ne(1634-keV level). This assumption was fully verified by investigations of the γ spectra, such as those already described, and the β time decay (i.e., half-life measurements). Then, the numerator of the first term on the right in Eq. (2) is the sum of the singles beta counts (above the discriminator setting) associated with the branches to the ^{21}Ne ground state and 351-keV level. The denominator is the number of singles beta counts associated with the branch to the 351-keV level and is formed by subtracting the contribution due to the cascade from the 1746-keV level from the total counts associated with the 351-keV γ ray. An advantage of this method of obtaining $\mathrm{BR}_{g.s.}$ is that it is independent of the different end-point energies of the β branches to the 351- and 1746-keV levels and the ^{20}F branch to the 1634-keV level.

The method depends on an accurate *in situ* determination of the absolute efficiency of the γ detector. This was obtained by combining a relative efficiency curve with an absolute efficiency determination for the ^{20}F 1634-keV γ ray. The relative efficiency curve was obtained from the *in situ* γ-ray singles spectra after a determination of the fluxes of 351-, 1395-, and 1634-keV γ rays was made with ^{152}Eu and ^{56}Co calibration sources[8,9] with all the γ activities at 10 cm to the γ detector and with no interposed absorbers. The absolute efficiency of the γ detector for the 1634-keV full-energy peak was made using the ^{19}F(d,p)^{20}F reaction to produce ^{20}F activity with negligible background and utilizing Eq. (3) to determine ϵ_{1634} from the ratio of $N_c^\beta(1634)$ to $N_s^\beta(1634)$. Only the beam was changed, all other

TABLE I. ^{21}Ne γ-ray energies, relative intensities, and branching ratios from ^{21}F(β^-)^{21}Ne.

Level no.	E_x [a] (keV)	E_f (keV)	E_γ [a] (keV)	Relative intensity (arbitrary units)	Branching ratio (%) (present) [b]	(previous) [c]
1	350.728(8)	0	350.725(8)	10000.000	100	100
2	1745.909(19)	0	1745.831(N)	86.4(1.5)	4.80(14)	5(1)
		351	1395.131(17)	1713(30)	95.20(14)	95(1)
7	3735.60(50)	0	3735.24(50)	0.278(26)	(81)	81(2)
		351	3384.58(N)		<17	12(2)
		1746	1989.59(N)		<17	7(1)
8	3884.29(40)	0	3883.90(N)	0.107(14)	23(5)	28(3)
		351	3533.24(40)	0.326(17)	72(5)	67(3)
		3622	262.20(N)		(4)	4(1)
10	4525.38(20)	0	4525.84(24)	1.060(33)	22(2)	21(3)
		351	4174.13(30)	3.565(65)	74(2)	76(3)
		1746	2779.40(30)	0.177(17)	4(1)	3(1)
		2789	1736.43(N)	<0.1	<2	<3
		2794	1731.13(N)	<0.1	<2	<4
11	4684.75(25)	0	4684.27(25)	3.127(109)	36.2(1.5)	36(2)
		351	4333.52(25)	5.306(135)	61.4(1.5)	60(2)
		1746	2938.62(N)	<0.10	<1.2	<5
		2789	1895.79(N)	<0.08	<1.0	<5
		2794	1890.45(30) [d]	0.203(30)	2.4(0.8)	4(2)

[a] The number in parentheses is the uncertainty in the least significant figure. An N signifies that the γ-ray energy was calculated from the level energy separation. The excitation energies have been corrected for the nuclear recoil, the γ-ray energies have not.

[b] The branching ratios in parentheses are from a previous work (Ref. 5) and were assumed.

[c] Reference 5.

[d] Using the average of the result obtained from this energy (i.e., 4685 − 1890) and the value of 2793.94(40) keV obtained for the γ ray corresponding to the 2794 → 0 transition, we obtain 2794.17(40) keV for the excitation energy of the fourth excited state of ^{21}Ne. Because of the extreme weakness of the γ intensities involved we do not regard this result as definite.

experimental conditions were kept the same, in switching from measurements on ^{21}F to measurements on ^{20}F. Again, singles and coincidence data were stored simultaneously, the latter in a 2048 × 4096 matrix (EMR). The ^{20}F activity was particularly suited for this measurement because the end point for the 100% β branch to the ^{20}Ne 1634-keV level, $E_{\beta max}$ = 5392 keV, is very close to that for ^{21}F decay to the 351-keV level, $E_{\beta max}$ = 5335 keV, so that any systematic errors which depend on the difference in these end-point energies was negligible.

The final result for the ratio $BR_{g.s.}/BR_{351}$ was 13 ± 4%. The uncertainty is dominated by that in ϵ_{351} with ϵ_{1634} the only other non-negligible contributor.

E. The half-life determination

The half-life of ^{21}F was determined by multiscaling pulses from the NE102 plastic scintillator in a manner similar to that used in previous β-decay half-life determinations at this laboratory.[21-23] Pulses from the plastic scintillator above a set discriminator level were multiscaled at 0.3 s per channel for 512 channels (37 half-lives). In order to check the consistency of the method eight runs were recorded with varying β-discriminator level (1.2 to 2.3 MeV) and triton beam energy (1.67 to 1.80 MeV). The initial counting rate was kept at ~2 kHz. With this low a counting rate, gain shifts were not a problem.

The decay curves averaged ~15000 counts in the first channel with a background of long-lived activity in the last 50 channels of ~0.02% of the count in the first channel. In addition to the ^{21}F activity and activities with half-lives ≫ 4 s. ^{20}F($T_{1/2}$ = 11.00 ± 0.02 s) and ^{16}N($T_{1/2}$ = 7.13 ± 0.02 s) were also present as discussed earlier. The relative intensities of these activities were determined from γ-ray spectra taken simultaneously with the multiscaling. The relative contributions of ^{20}F and ^{16}N to the initial activity were found to be 1.65 and 0.47%, respectively, at E_t = 1.7 MeV and a beta bias of 2.3 MeV. The intensities for the other runs were comparable.

The ^{21}F half-life was determined from a least-squares fit to a function consisting of three exponential decays and a constant background with

the decay constants and relative intensities of two components (^{20}F and ^{16}N) fixed. Dead time corrections were found to be negligible. Fits were made starting in time channels 1, 14, 28, and 42. For each starting channel, the eight determinations were in good agreement. Weighted means were found for each starting channel. The four weighted means so formed were in good agreement. The weighted mean for the fits starting in channel 1 was 4.158 ± 0.006 s. To the quoted uncertainty we must add contributions due to uncertainties in the relative intensities of the ^{20}F and ^{16}N activities and other possible undetected activities, as well as other possible systematic errors. The ^{20}F activity provides the dominating uncertainty. Our estimated 7% uncertainty in the ^{20}F relative intensity contributes ± 0.012 s to that in the ^{21}F half-life. Our final value for the ^{21}F half-life is 4.158 ± 0.020 s.

The ^{21}F half-life has previously been measured with results of 4.21 ± 0.05 s (Ref. 6) and 4.34 ± 0.04 s.[7] The disagreement of these earlier measurements with the present one is typical of the general trend in β-decay half-life determinations as discussed, for example, in Ref. 23—namely that for earlier measurements the uncertainties tend to be greatly underestimated. Precautions against uncertainties due to the presence of other activities are not discussed in either of the previous[6,7] reports. Thus, the presence of ^{20}F and/or ^{16}N contaminant activities, if uncorrected for, would make the apparent ^{21}F half-life too long, in the direction observed in both of the previous results. In view of this we recommend the adoption of 4.158 ± 0.020 s as the best value for the ^{21}F half-life rather than a weighted mean of all three determinations.

III. DISCUSSION

A. The beta-decay results

The β-ray branching ratios calculated from the γ-ray intensities of Table I and the BR(g.s.)/BR(351-keV level) ratio of Sec. II D are given in Table II. The allowed logft values calculated from these β branches, the half-life of Sec. II E, 4.158 ± 0.020 s, and the Q value of 5.686 ± 0.007 MeV are also given. The theoretical logft values are those of Lanford and Wildenthal[24] as quoted by Sextro, Gough, and Cerny.[25]

The one new bit of spin-parity information provided by these new results is that the 4685-keV level has even parity since the β-decay to it is allowed. For the two highest-lying levels the comparison between experiment and theory is made assuming the 4525-keV level is the third $\frac{5}{2}^+$ level and the 4685-keV level is the second $\frac{3}{2}^+$ level.

TABLE II. ^{21}F β branches and logft values.

^{21}Ne Level J^π	(keV)	β branch (%)	logft expt.	theor.[a]
$\frac{3}{2}^+$	0	9.6(3.0)	5.67(14)	5.55
$\frac{5}{2}^+$	351	74.1(3.0)	4.658(18)	4.70
$\frac{7}{2}^+$	1746	16.1(1.0)	4.721(27)	4.80
$\frac{5}{2}^+$	3736	$3.1(4) \times 10^{-3}$	7.101(56)	8.34
$\frac{5}{2}^{(-)}$	3884	$4.0(4) \times 10^{-3}$	6.844(44)	
$\frac{3}{2}^+, \frac{5}{2}^+$	4525	$43(3) \times 10^{-3}$	5.030(32)	5.21
$\frac{3}{2}^+$	4685	$77(5) \times 10^{-3}$	4.522(31)	4.44

[a]References 24 and 25.

From experimental evidence, the 3884-keV level is most probably the lowest-lying $\frac{5}{2}^-$ state. Numerous shell-model and Nilsson model calculations support this view and would place this level as a member of the $K = \frac{1}{2}^-$ 6p-1h band commencing with the $\frac{1}{2}^-$ level at 2789 keV.[26] Thus, the β decay to the 3884-keV level is probably nonunique first forbidden. Other possible first-forbidden decays are to the $\frac{3}{2}^-$ levels at 3622 and 4726 keV. Limits on β branches to these levels are 6.2×10^{-3} and 2.0×10^{-3}%, respectively, corresponding to logft values of >7.8 and >6.9, respectively. All other unobserved β decays to levels below 5-MeV excitation would be at least second forbidden and thus would not be observable with the present techniques. The next two levels above that of 4685 keV are the 4726-keV level just mentioned and a $(\frac{5}{2}^+, \frac{7}{2}^-)$ level at 5334 keV.[5] For the 5334-keV level a branching ratio of $\sim 5 \times 10^{-5}$% would correspond to logft = 4.0. Thus, observation of β-decay to this level or higher levels was also not feasible in our measurement.

The previous results[4] from this laboratory gave β branches of 29 ± 6, 63 ± 6, and 7.6 ± 1.0% to the first three levels of ^{21}Ne. The present results are in very poor agreement with $BR_{g.s.}/BR_{351}$ ~3.5 times smaller and BR_{1395}/BR_{351} ~2 times larger. Because of technological improvements in the last 10 years the present results are very much more reliable than the previous ones and we recommend adoption of the present results rather than an attempt to average the two.

B. Comparison to ^{21}Mg(β^+)^{21}Na

Assuming isospin symmetry, the β^+ decay of ^{21}Mg to ^{21}Na is the mirror of ^{21}F(β^-)^{21}Ne. Since isospin-symmetry breaking effects are not expected to be unduly large for these light nuclei, the two decays should be rather similar. The two decays are compared in Table III. The cor-

TABLE III. Comparison of $^{21}F(\beta^-)^{21}Ne$ and $^{21}Mg(\beta^+)^{21}Na$.

Level J_1^π	Excitation energy (keV) ^{21}Ne	^{21}Na	logft $^{21}F(\beta^-)$	$^{21}Mg(\beta^+)$[a]
$\frac{3}{2}^+_1$	0	0	5.67(14)	
$\frac{5}{2}^+_1$	351	332	4.66(2)	
$\frac{7}{2}^+_1$	1746	1716	4.72(3)	
$\frac{5}{2}^+_2$	3736	3544	7.10(6)	6.09(6)
$\frac{5}{2}^-_1$	3884	3863	6.84(4)	
$\frac{5}{2}^+_3$	4525	4294	5.03(3)	4.82(2)
$\frac{3}{2}^+_2$	4684	4468	4.52(3)	4.48(2)

[a]Reference 25.

respondence between ^{21}Ne-^{21}Na analogs is that of Endt and van der Leun.[5]

To date, $^{21}Mg(\beta^+)$ has only been studied by observation of the protons emitted by ^{21}Na states after formation by β^+ decay of ^{21}Mg. Thus, information on the bound levels of ^{21}Na below 2.43-MeV excitation is not available. The $^{21}Mg(\beta^+)$ logft values are from the detailed study of Sextro *et al.*[25] of the β^+-delayed proton decay of ^{21}Mg. The β^+ end point for decay of ^{21}Mg to the ^{21}Na ground state is 12.076 MeV.[5] Thus, a considerably larger range of excitation energies is available for $^{21}Mg(\beta^+)^{21}Na$ than $^{21}F(\beta^-)^{21}Ne$ and proton emission from states up to 8.97 MeV in ^{21}Na was observed by Sextro *et al.* Because of the high energy release, proton emission to excited states of ^{20}Ne is probable and decays to the first four excited states of ^{20}Ne were observed.[25] Consequently, the delayed proton spectrum is complex and its interpretation contains ambiguities. For instance, the proton peak corresponding to the decay of the $\frac{5}{2}^-$ ^{21}Na 3863-keV level, expected on the basis of mirror symmetry, would have been obscured by a strong peak corresponding to a proton branch from the ^{21}Na 5386-keV level to the ^{20}Ne 1634-keV level.

Before comparison of the logft values of $^{21}F(\beta^-)$ and $^{21}Mg(\beta^+)$ can be made, relative proton intensities must be scaled to account for the missing decays to γ-emitting states. Sextro *et al.* did this by assuming a logft of 3.26 for the β^+ branch to the 8.970-MeV ^{21}Na analog of the ^{21}Mg ground state. This ft value results largely from the assumption of isospin symmetry with only a small ($\lesssim$10%) contribution from the Gamow-Teller matrix element. This normalization gives the ^{21}Mg logft values of Table III. For the two strongest ^{21}Mg branches the agreement with ^{21}F is satisfactory. For the weak branch to the second $\frac{5}{2}^+$ state the ft values differ by an order of magnitude. It is possible that the proton peak assigned to the decay of the ^{21}Na 3544-keV level by Sextro *et al.*[25] actually is due to decay of a higher-lying level to an excited state. If their assignment of the proton peak is correct then we have an example of a sizable breaking of isospin symmetry. Cancellation between the various contributions to the transition matrix element is usually responsible for transitions as weak as this, and the very large value of the predicted logft value (logft = 8.34) argues in favor of cancellation in this case. The Coulomb effects—of less consequence in strong transitions—can be greatly magnified when cancellation is present. Thus, such a difference in weak mirror decays is not too surprising.

With the assumption of logft = 3.26 for the β^+ decay to the ^{21}Na 8.970-MeV level, Sextro *et al.*[25] calculated that (32.6 ± 1.9)% of the ^{21}Mg β^+ decays are followed by proton emission and (67.4 ± 1.9)% of the decays are to the first three excited states. (The uncertainties attached to these percentage branching ratios are assumed to follow solely from the uncertainty of ±0.16 assigned by Sextro et al.[25] to the 2.79% branching ratio of ^{21}Mg to the ^{21}Na 8.97-MeV level.) On the other hand, if we assume strict isospin symmetry with the same logft values for the lowest three states in $^{21}F(\beta^-)$ and $^{21}Mg(\beta^+)$, we calculate partial half-lives for ^{21}Na which, with a half-life for ^{21}Mg of 122.5 ± 2.8 ms,[25] convert to branching ratios of (6.1 ± 1.9), (56.5 ± 2.7), and (26.8 ± 1.8)% for the ^{21}Na levels at 0, 332, and 1716 keV; i.e., (89.5 ± 1.0)% of the ^{21}Mg β^+ decays is to these three levels. The discrepancy between this result and the result of (67.4 ± 1.9)% from Sextro *et al.* corresponds to an average value for $\delta = (ft)^+/(ft)^- - 1$ of +0.33 ± 0.04 for the first three states of ^{21}Ne-^{21}Na. This value is larger than might be expected from the systematics of other odd-mass mirror decays.[27] The discrepancy, if any, might lie in the assumption of logft = 3.26 for the β^+ decay to the ^{21}Na 8.970-MeV level.

C. Summary

The present results revise considerably the information available on the β decay of ^{21}F. Four new β-ray branches were found and all possible allowed β branches to known states below 5-MeV excitation energy have been observed. The results for the decay to the first three states of ^{21}Ne are in much better agreement with the predictions of Lanford and Wildenthal than were the previous[4] results. Overall, the predicted results agree just about as well with either the ^{21}F or ^{21}Mg logft values as either of these agrees with each other. Unfortunately, it is just about at this level of

agreement that comparison between theory and experiment begins to test our present knowledge of the nuclear structure of the mass 21 nuclei. This raises an important topic.

The calculations of Lanford and Wildenthal do not contain a Coulomb interaction in a consistent manner and it is an implicit assumption in this calculation that mirror nuclei have identical spectra, i.e., that charge symmetry is obeyed so that, e.g., the logft values for ^{21}F$(\beta^-)^{21}$Ne and ^{21}Mg$(\beta^+)^{21}$Na are identical. As pointed out by Kelvin, Watt, and Whitehead,[27] the level of accuracy now possible in large-basis shell-model calculations is good enough so that this fiction is not tenable. They maintain that the Coulomb interaction can be introduced fairly easily in a consistent and satisfactory manner. As the present example shows, this is certainly necessary in order to fully utilize allowed β-decay results in the continuing testing of our knowledge of nuclear structure.

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