Decays of ^{21}Na, ^{23}Ne, ^{23}Mg, ^{24}Ne, and ^{31}S †

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The radioactive decays of ^{21}Na, ^{23}Ne, ^{23}Mg, ^{24}Ne, and ^{31}S have been studied using Ge(Li) and plastic scintillation detectors to measure γ and β rays. ^{21}Na, ^{23}Ne, and ^{24}Ne were formed by bombarding a neon target with 3-MeV deuterons or tritons, followed by gas transfer to a remote counting station. ^{23}Mg and ^{31}S were made in (p,n) reactions using 10-MeV protons from an MP tandem Van de Graaff together with a rabbit target-transfer facility. The following half-lives (in sec) were obtained: ^{21}Na, 22.55 ± 0.10; ^{23}Ne, 37.24 ± 0.12; ^{23}Mg, 11.36 ± 0.04; and ^{31}S, 2.605 ± 0.012. Relative β-ray intensities were derived from the measured γ-ray intensities. The various branching results are in reasonable agreement with previous work except for ^{21}Na whose measured β^+ branch of 5.1 ± 0.2% to the 350-keV state of ^{21}Ne is a factor of 2 larger than earlier reports. However, the result is in excellent agreement with an estimate by Wilkinson.

[RADIOACTIVITY ^{21}Na, ^{23}Ne, ^{23}Mg, ^{24}Ne, ^{31}S; measured $T_{1/2}$, I_γ; deduced β branches, logft.]

INTRODUCTION

During the past few years there has been a considerable amount of renewed interest in the theory of nuclear β decay. Various aspects of the β interaction have been examined by studying the systematic behavior of related cases such as the $0^+ \rightarrow 0^+$ superallowed Fermi β decays,[1] or the various examples of asymmetry in the ft values of Gamow-Teller β decay.[2] A common difficulty in all such studies based on systematics has been the frequent unreliability of experimentally determined half-lives and β-ray branching ratios which has caused some glaring and perplexing discrepancies. Renewed efforts have been made recently to recheck the "literature" values given for these β-decay properties. Greater consistency among the various laboratories doing such work is now being obtained, and many of the discrepancies in the systematics are starting to be cleared up. This is probably the combined result of using more modern equipment and techniques, greater care in taking data, and a better understanding of the problems of data analysis.

The present work was begun partly because of an outstanding discrepancy between the measured β^+ branching ratio of ^{21}Na to the 350-keV first excited state of ^{21}Ne and the value predicted by Wilkinson[3] from recent studies of the systematics of allowed Gamow-Teller β decay compared with strengths computed from shell-model wave functions.[4] Two measurements of this ^{21}Na branch have been reported, one of 2.2 ± 0.3% by Talbert and Stewart[5] and the other of 2.3 ± 0.2% by Arnell and Wernbom.[6] The mean of these results, 2.27 ± 0.20%, compares with a branch of 5 ± 1% predicted by Wilkinson[3] on the basis of theoretical wave functions,[7] where the error in the prediction comes from the width of the observed distribution of the ratio between theoretical and experimental ft values.[4] Such a large discrepancy would be very difficult to accept.

As shown below a considerably larger β^+_{350} branch has been found here for ^{21}Na agreeing with the Wilkinson estimate. Since it was thought that contaminant positron activities might have affected the previous derivations of the β^+ branch it is possible that the earlier half-life values might also have been affected. It was therefore decided to recheck the half-life of ^{21}Na.

^{23}Ne, which is produced along with ^{21}Na in the deuteron bombardment of neon, was also studied. Aside from the need to recheck its half-life there were separate reasons for measuring the relative intensities of the ^{23}Ne γ rays. In some previous work[8] on short-lived activities formed in heavy-ion reactions ^{23}Ne and ^{20}F were produced simultaneously. The analysis of the β-ray spectrum in coincidence with the 1633-keV ^{20}F γ rays depended on knowing the contribution due to the 1636-keV γ rays of ^{23}Ne. Since the 1636-keV peak due to ^{23}Ne was not resolved from the ^{20}F peak, it was necessary to use the 1636/440 γ-ray intensity ratio of ^{23}Ne from the literature, together with the observed intensity of the 440-keV peak and the detector efficiency function, to determine the ^{23}Ne contribution to the 1633-1636-keV doublet. It was therefore felt that a recheck of the ^{23}Ne γ-

ray intensities, particularly those of 440 and 1636 keV, would be desirable.

The other activities studied in the present work included ^{24}Ne, ^{28}Mg, and ^{31}S. The ^{24}Ne investigation was made because of the availability of the gas transfer system used for the work on ^{21}Na and ^{23}Ne, and the desire to recheck the γ-ray intensity ratio in ^{24}Ne decay. On the other hand, relative γ-ray intensities in the decays of both ^{23}Mg and ^{31}S had been reported by Talbert and Stewart[5] in the same paper giving their result on the ^{21}Na γ-ray intensities.

EXPERIMENTAL METHODS

For some earlier work[9] on the decay of ^{25}Ne at the Brookhaven National Laboratory tandem Van de Graaff facility a gas target and transfer system was developed consisting of a bombardment cell, a transfer line including a liquid nitrogen trap, a remote counting cell, and appropriate valves operated by an automatic timer. This system is ideally suited to the study of a radioactive noble gas such as ^{23}Ne and was therefore adapted for use at the 3.5-MeV Van de Graaff. The cell was periodically filled with ~0.4 atm of neon and bombarded through a 0.0003-cm-thick Ni entrance window for 10 sec with a 0.3-μA beam of 3.0-MeV deuterons in order to make the activity via the ^{22}Ne$(d, p)^{23}$Ne reaction. After cutting off the beam the gas was expanded through the trap to the counting cell located in the control room and data were recorded for a specified period.

For the work on ^{23}Ne tests were made to find the most effective means of trapping out the principal contaminant activity ^{21}Na which is formed in the ^{20}Ne$(d, n)^{21}$Na reaction. This was done by measuring in a Ge(Li) detector the intensity of the 511-keV annihilation radiation line, due to the β^+ associated with ^{21}Na, relative to the 1636-keV γ ray in ^{23}Ne decay. The most effective trap consisted of a stainless-steel u tube filled with activated charcoal, dampened slightly before assembly by blowing through it, and then immersed in liquid nitrogen. Under these conditions the ratio of activities reaching the counting cell was found, after making all of the necessary corrections to the ratio of 511/1636 γ-ray peak intensities, to be ^{21}Na/^{23}Ne $= 2.4 \times 10^{-4}$. Since the isotopic abundance ratio of ^{20}Ne to ^{22}Ne is ~10 this indicates a discrimination of ~10^5 against the passage of ^{21}Na through the trap, assuming that the cross sections for the (d, p) and (d, n) reactions are comparable. Such a relatively small amount of ^{21}Na reaching the counting cell has negligible effects on the γ-ray spectrum or on the measurement of the half-life for β-ray emission in the decay of ^{23}Ne.

For the measurements of the γ-ray spectra of ^{23}Ne and ^{24}Ne, where the latter was formed in the ^{22}Ne$(t, p)^{24}$Ne reaction, the counting cell had internal dimensions of 7.5 cm diam by 2 cm high and the top and bottom were made of 1.5-mm-thick Al. This same cell was also used for the ^{23}Ne half-life measurements by placing a 5-cm-diam by 2.5-cm-high NE102 plastic scintillator next to the cell for detecting the emerging β rays. Following standard procedures[10] the counts were multiscaled after the valves had been closed so as to isolate the ^{23}Ne activity in the counting cell.

The effectiveness of the charcoal trap used in the ^{23}Ne and ^{24}Ne work suggested a way of making a source for studies of ^{21}Na. This consisted of a small flat cylindrical cell 3 cm in diam by 3 mm high filled with granular activated charcoal. The top and bottom were of 0.5-mm-thick Al and inlet and outlet tubes were attached at opposite edges of the cylinder. After bombardment of the neon target the gas was expanded through the small cell, but in this case the outlet was pumped on continuously for 15 sec in order to remove all of the ^{23}Ne activity from the system leaving the ^{21}Na sticking to the charcoal in the small cell. Of course for these experiments the large charcoal trap between the bombardment and counting cells used in the ^{23}Ne and ^{24}Ne was removed. Counting was started at the end of the 15-sec pumping period after closing the pump-out valve.

The above arrangement was used both for measuring the half-life of ^{21}Na by observing the positrons in the NE102 detector and for determining the relative γ-ray intensities in a Ge(Li) detector.

TABLE I. γ-ray intensities in the decay of ^{23}Ne normalized to a value of 33.0 for the 440-keV γ ray.

E_γ (keV)	Intensity Present	Previous I[a]	Previous II[b]	Previous III[c]
440	33.0	33.0	33.0	33.0
1636	1.00 ± 0.04	0.93	0.90	1.0
2076	0.101 ± 0.006	0.10	0.10	0.10
2542	0.027 ± 0.002	0.026	0.027	0.025
2982	0.038 ± 0.002	0.031	0.033	0.045

[a] H. Lancman, A. Jasinski, J. Kownacki, and J. Ludziejewski, Nucl. Phys. 69, 384 (1965). No errors were quoted.

[b] Deduced from decay scheme given by R. Moreh, J. Balderman, and Y. Gozez, Nucl. Phys. A107, 236 (1968). Over-all errors on relative γ-ray intensities were not quoted.

[c] Deduced from decay scheme given by J. E. Christiansson, J. Dubois, and L. Jarneborn, Phys. Scripta 5, 159 (1972). No errors were quoted.

In the latter case identical absorbers of either 1.3-cm-thick Lucite or 0.63-cm-thick Al were clamped on either side of the cell so as to completely absorb the β^+ particles in a symmetrical geometry that could be corrected for by simple calculations.

^{23}Mg and ^{31}S were both studied at the tandem Van de Graaff facility by making use of the "rabbit" target-transfer system described previously.[11] For the ^{23}Mg experiments the target consisted of a thick layer of Na_2CO_3 and the activity was made in the ^{23}Na$(p, n)^{23}$Mg reaction using a 5-nA beam of 10-MeV protons. ^{31}S was also made via the (p, n) reaction by bombarding a thick target of red phosphorus, deposited on a Ta backing, with a 1-nA beam of 10-MeV protons. In both cases the half-lives for β emission were measured with the NE102 scintillator and the γ-ray spectra were studied with a Ge(Li) detector.

RESULTS AND DISCUSSION

^{21}Na

Runs were made on the decay of ^{21}Na at β detector biases from 0.25 to 1.5 MeV. Following the procedures described previously[10] the adopted half-life of ^{21}Na based on the analysis of six runs is 22.55 ± 0.10 sec. This is in agreement with the compilation value[12] of 22.8 ± 0.2 sec. There was no evidence in the γ-ray spectrum for the 1633-keV line of ^{20}F which could be produced in the ^{22}Ne$(d, \alpha)^{20}$F reaction. Furthermore, the fitting of data over various regions of the decay curves at different biases did not suggest the presence of a ^{20}F component ($T_{1/2} \cong 11$ sec) of sufficient intensity to alter the results on ^{21}Na.

The γ-ray spectrum from ^{21}Na was recorded with a 70-cm^3 Ge(Li) detector for which the efficiency function had been accurately established with calibrated sources. This was placed 10 cm from the cell. Net areas under the 350- and 511-keV peaks were measured. In addition to correcting for γ-ray efficiency versus energy one must allow for the fact that the source of 511-keV γ rays is extended due to the penetration of the β^+ particles into the absorbers clamped on either side of the cell. Based on the mean range of the β^+ particles in the absorber the correction to the counting rate of the 511-keV line was calculated to be 0.5% for the source-detector distance used. Corrections were also made for the differences in the attenuation of 350- and 511-keV γ rays in passing through the β^+ absorbers. Summing corrections were shown to be negligible. When all factors were applied (and allowing for the two 511-keV γ rays per decay) the β^+ branching of ^{21}Na to the 350-keV state of ^{21}Ne was found from the average results of two runs using Lucite and Al absorbers to be $5.1 \pm 0.2\%$. This is more than a factor of 2 greater than the mean of the two previous measurements,[5,6] $2.27 \pm 0.20\%$.

Logft values may be derived for the ^{21}Na branches using the results presented above together with the total decay energy based on the known masses of ^{21}Na and ^{21}Ne. For all such calculations in this paper masses were taken from the 1971 tables of Wapstra and Gove.[13] The resulting logft values are 3.61 ± 0.01 for the decay of ^{21}Na to the ground state of ^{21}Ne and 4.60 ± 0.02 for decay to the 350-keV state.

As pointed out in the Introduction, the present result on the ^{21}Na branch to the 350-keV state of ^{21}Ne is in excellent agreement with the $5 \pm 1\%$ branch predicted by Wilkinson.[3] Recent nuclear-structure calculations on ^{21}Ne and ^{23}Na have been carried out by Gunye[14] in the framework of Hartree-Fock projection formalism. Among his results are the calculated logft values for the β decays of ^{21}Na and ^{23}Ne to states of ^{21}Ne and ^{23}Na, respectively. The present experimental logft of 4.60 ± 0.02 for the ^{21}Na β^+ branch to the first excited state of ^{21}Ne is in better agreement with the theoretical value of 4.71 than was the previous experimental logft of 5.0. However, it is pointed out by Gunye that his calculations of logft values give only semiquantitative agreement with experiment, generally differing from experimental values by 0.2 to 0.3.

^{23}Ne

Half-life data were taken on ^{23}Ne decay at β-ray biases from 0.5 to 2 MeV. Based on the analysis of six runs the adopted half-life is 37.24 ± 0.12 sec. This differs from the mean of previous results (37.55 ± 0.10 sec) by somewhat more than the sum of the errors, the earlier measurements being 37.6 ± 0.1,[15] 37.5 ± 0.1,[16] and 38.0 ± 0.3 sec.[17]

γ-ray intensity data for ^{23}Ne are presented in Table I where the results are compared with previous measurements. The observed γ-ray peak intensities were corrected for attenuation in a 0.63-mm-thick brass β-ray absorber, for the detector efficiency function and for summing effects. The agreement of the present and previous results is good, although errors were not quoted for the earlier measurements. The decay scheme of ^{23}Ne therefore remains the same, and comparisons of the experimental and theoretical[14] logft values are unaffected by the present work.

^{23}Mg

Based on the analysis of four runs at β detector biases from 1.0 to 2.0 MeV the half-life adopted

for ^{23}Mg is 11.36 ± 0.04 sec. Data were not taken below 1.0-MeV bias because of the presence of a weak long-lived background of low-energy positrons presumably due to ^{13}N produced in the ^{13}C-$(p,n)^{13}$N reaction. The present result is substantially different from the compilation value[12] of 12.04 ± 0.09 sec representing the weighted mean of six prior measurements. But in the meantime Goss *et al.*[18] have reported a value of 11.41 ± 0.05 sec for ^{23}Mg with which the present result is in excellent agreement.

The β^+ branching ratio of ^{23}Mg to the 440-keV state of ^{23}Na was found, as in the case of ^{21}Na, by measuring the intensity ratio of the 440- and 511-keV peaks with a calibrated Ge(Li) detector. However, allowance had to be made here for the long-lived 511-keV component. This was done by recording the γ-ray spectrum for 15 sec in one section of the analyzer and again in another section after a delay of 75 sec, a procedure that was repeated often enough to acquire sufficient statistical accuracy. After making a small correction for the decay of ^{13}N ($T_{1/2}$ = 9.96 min) this component of the 511-keV peak in the first counting interval was found to be about 10% of the total. Further corrections were made as in the ^{21}Na analysis, where in this case β^+ absorbers were clamped around the rabbit line so as to make the absorption as uniform as possible.

The β^+ branching of ^{23}Mg was found to be 9.1 ± 0.4% to the 440-keV ^{23}Na state. This is in good agreement both with the 9.1 ± 0.5% result of Talbert and Stewart[5] and with a value of 8.6 ± 0.3% obtained by Gorodetzky *et al.*[19] From all measurements a mean value of 8.9 ± 0.3% is adopted and may be used to calculate logft values of 3.68 ± 0.01 for decay to the ground state of ^{23}Na and 4.39 ± 0.02 for decay to the 440-keV first excited state.

^{24}Ne

For the ^{24}Ne measurements the neon target was bombarded with a 0.2-μA beam of 3.2-MeV tritons. Sources of ^{54}Mn and ^{88}Y, emitting γ rays of 834.81 and 898.02 keV, respectively, were superposed in order to determine the energy of 874-keV γ ray of ^{24}Ne while at the same time measuring its intensity relative to the 472-keV peak. By applying the efficiency function for the Ge(Li) detector the intensity ratio was found to be $I_{874}/I_{472} = (7.9 \pm 0.2)/100$. This differs from a previous result[20] of (8.9 ± 0.5)/100 by somewhat more than the sum of the errors. The energy of the 874-keV γ ray was found to be 874.35 ± 0.14 keV, in agreement with the previously reported[20] energy of 874.3 ± 0.3 keV.

Based on the present results and on the half-life[21] of 3.38 ± 0.02 min the logft values are 4.37 ± 0.01 for the decay of ^{24}Ne to the 472-keV first excited state of ^{24}Na and 4.41 ± 0.02 for decay to the 1347-keV level.

TABLE II. Summary of results.

Nuclide	$T_{1/2}$ (in sec, unless otherwise noted) Present	Previous	State of daughter nucleus (keV)	β branch (%) Present	Previous	Logft
^{21}Na	22.55 ± 0.10	22.8 ± 0.2 [a]	Ground	94.9 ± 0.2	97.7 ± 0.2 [b]	3.61 ± 0.01 [c]
			350	5.1 ± 0.2	2.27 ± 0.20 [b]	4.60 ± 0.02 [c]
^{23}Ne	37.24 ± 0.12	37.55 ± 0.10 [d]	e	e	e	
^{23}Mg	11.36 ± 0.04	12.04 ± 0.09 [a]	Ground	90.9 ± 0.4	91.2 ± 0.3 [f]	3.68 ± 0.01 [g]
		11.41 ± 0.05 [h]	440	9.1 ± 0.4	8.8 ± 0.3 [f]	4.39 ± 0.02 [g]
^{24}Ne	...	3.38 ± 0.02 [i]	472	92.1 ± 0.2	91.1 ± 0.5 [j]	4.37 ± 0.01 [k]
		min	1347	7.9 ± 0.2	8.9 ± 0.5 [j]	4.41 ± 0.02 [k]
^{31}S	2.605 ± 0.012	2.61 ± 0.03 [a]	Ground	98.75 ± 0.06	98.9 ± 0.1 [a]	3.71 ± 0.01 [c]
			1266	1.25 ± 0.06	1.1 ± 0.1 [a]	4.94 ± 0.02 [c]

[a] Reference 12.
[b] Mean value based on Refs. 5 and 6.
[c] Based on present measurements only.
[d] Mean value based on Refs. 15, 16, and 17.
[e] See Table I for relative γ-ray intensities.
[f] Mean value based on Refs. 5 and 19.
[g] Based on present half-life and on mean of present and previous results on β branching.
[h] Reference 18.
[i] Reference 21.
[j] Reference 20.
[k] Based on present β branches and previous half-life.

^{31}S

Runs on the decay of ^{31}S were made at β detector biases from 0.5 to 1.7 MeV. Based on the analysis of six runs the adopted half-life is 2.605 ± 0.012 sec. This compares with the compilation value[12] of 2.61 ± 0.03 sec.

The γ-ray spectrum of ^{31}S was recorded with the efficiency-calibrated Ge(Li) detector and the intensities of the 511- and 1266-keV peaks were measured. After making the necessary corrections for γ-ray efficiency and absorption the β^+ branching of ^{31}S to the 1266-keV state of ^{31}P was found to be 1.25 ± 0.06%. This is in agreement with the branch of 1.1 ± 0.1% given previously.[12] In separate runs an energy calibration source of ^{22}Na (E_γ = 1274.5 keV) was superposed and the energy of the ^{31}S γ ray was found to be 1266.2 ± 0.2 keV, in excellent agreement with a value of 1266.13 ± 0.12 keV due to Wolff, Meyer, and Endt.[22]

Logft values for the ^{31}S branches based on the present work are 3.71 ± 0.01 for decay to the ground state of ^{31}P and 4.94 ± 0.02 for decay to the 1266-keV first excited state.

Additional very weak γ rays of 2240, 3134, and 3506 keV have been reported[23] as occurring in the decay of ^{31}S. No attempt was made to confirm these lines.

A summary of the various results described in this paper is presented in Table II.

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