Mass and Beta Decay of Na^{20}†

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The β and γ spectra of Na^{20} have been measured with a wedge-gap magnetic spectrometer and a 3-cm^3 lithium-drifted germanium detector, respectively. Na^{20} was produced by a $(p,\alpha n)$ reaction on a natural magnesium target in the UCLA cyclotron. The mass excess of Na^{20} is measured to be 6863 ± 40 keV. The half-life of Na^{20} is 0.408 ± 0.006 sec. Two β branches of 11.25 ± 0.04 and 5.55 ± 0.15 MeV were observed, and their relative intensities measured to be 100 ± 2 and 9 ± 1, respectively. The more energetic β branch feeds the first excited state of Ne^{20}; the excitation energy is determined to be 1633.2 ± 1.0 keV from a study of its γ transition. The 5.55-MeV β branch establishes a link with the known delayed-α spectra from the highly excited states of Ne^{20}, and allows us to propose a decay scheme for Na^{20}. Limits on the intensities of possible unobserved β transitions are discussed.

1. INTRODUCTION

INVESTIGATION of weak β branches from short-lived isotopes is extremely difficult from a measurement of a β spectrum alone. The study of delayed-proton and delayed-α spectra, whenever such processes are energetically possible, can significantly reduce this difficulty. Conversely, these particular studies require a link to the β spectrum in order to enable one to extract β branching ratios from them.

This work, concerned with the measurement of the Na^{20} β spectrum, establishes such a link to the delayed-α measurements[1,2] from excited states of Ne^{20}, allowing us to propose a decay scheme of Na^{20} with accurate ft values. From these ft values, the $T=1$, $T_z=0$ analog state of the mass-20 triplet is unambiguously determined. In addition, the measurement of the highest endpoint energy of the Na^{20} β spectrum can determine the mass excess of Na^{20} and test the validity of the mass formula in the isobaric triplet. The first experimental value of the Na^{20} mass excess[3] has been in disagreement with more recent determinations[4,5] by more than 1 MeV. This experiment agrees with these later values and improves their accuracy.

A decay scheme of Na^{20} is constructed from the data of this measurement and those of delayed-α-particle studies.[1] On the basis of the deduced ft values, spin and parity assignments are made, confirming previous determinations.[6] From the γ-ray measurements and the systematics of $\log ft$ values of β transitions, upper limits on some unobserved β branches are discussed.

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[1] R. M. Polichar, J. E. Steigerwalt, J. W. Sunier, and J. Reginald Richardson, preceding paper, Phys. Rev. **163**, 1084 (1967).

[2] R. D. MacFarlane and A. Siivola, Nucl. Phys. **59**, 168 (1964).

[3] L. W. Alvarez, Phys. Rev. **80**, 519 (1950).

[4] P. F. Donovan and P. D. Parker, Phys. Rev. Letters **14**, 147 (1965).

[5] R. H. Pehl and J. Cerny, Phys. Letters **14**, 137 (1965).

[6] T. Lauritsen and F. Ajzenberg-Selove, in *Nuclear Data Sheets*, compiled by K. Way *et al.* (U. S. Government Printing Office, National Academy of Sciences—National Research Council, Washington 25, D. C.), NRC 61-5,6-307.

2. EXPERIMENTAL TECHNIQUES

Since the measurement of β spectra from short-lived isotopes requires the accumulation of data from many short bombardments of a given target, a number of experimental difficulties arise. Beam-intensity fluctuations during the target irradiation and the slow build up of long-lived reaction products on the target introduce normalization problems. Also, other short-lived isotopes may be produced and mask the desired activity.

Some of these difficulties are overcome by exploiting the focusing properties of a single wedge-gap magnetic spectrometer. Several detectors covering a sizable momentum range of a β spectrum (15%) can be placed along the *focal line* of the instrument. In this manner one has a way to normalize the data by partially overlapping the momentum interval analyzed in two successive runs.

The problems of extraneous half-lives can be handled by independently multiscaling the output of each of the detectors of the spectrometer. This is, of course, conveniently done in an on-line computer. After sufficient statistical accuracy is achieved in one run, the relevant data are readily accessible for the decomposition of the time spectrum into intensities and half-lives by a least-squares fitting program. Using such a system allows one to extract a normalized β spectrum from a strong "background" of competing activities.

The details of the spectrometer operation have been published previously.[7] Four detectors (Si) with a momentum resolution of 1% were used and covered a relative momentum range of 12%. The spectrometer was calibrated to 0.1% in momentum. The targets exposed to the internal beam of the UCLA sector focused cyclotron were extracted to the spectrometer source position in 250 msec with the use of a fast, air operated, pneumatic rabbit system. The multiscaling, half-life separation, and decomposition of the Kurie plot of the β spectrum was done on-line with an SDS 925 computer.

[7] A. J. Armini, R. M. Polichar, and J. W. Sunier, Nucl. Instr. Methods **48**, 309 (1967).

3. EXPERIMENTAL RESULTS

Na^{20} was produced by the (p,αn) reaction at 45 MeV on a natural, self-supporting magnesium target. The bombardment energy, considerably above the reaction threshold of 25 MeV, was chosen to minimize the (p,n) reactions on the three magnesium isotopes Mg^{24}, Mg^{25}, and Mg^{26}.

The half-life was measured to be 408±6 msec, which is an average of over 100 independent measurements. The Kurie plot of the β spectrum associated with this half-life is shown in Fig. 1, for positron energies between 3.5 and 11.5 MeV. Above 3.5 MeV the Al^{24} (2.08-sec) and Al^{24m} (0.13-sec) contaminants were adequately separated. Below this limit, strong branches from Al^{24}, Al^{25}, Mg^{23}, and Al^{26m} could not be adequately separated from the Na^{20} activity, mainly because of their overwhelming intensity. This prevented the measurement of the superallowed transition from Na^{20} to its analog. The analysis of the Kurie plot gave three branches of allowed shape. Their endpoint energies are 11.25±0.04, 7.15 ±0.10, and 5.55±0.15 MeV. Their relative intensities are 100±2, 17±2, and 9±1, respectively.

The 7.15-MeV branch is inconsistent with the known positive-parity levels in Ne^{20}, and too strong to be a first forbidden transition. This fact prompted an investigation of the Na^{20} β spectrum through the use of another reaction. The production of Na^{20} was attempted by the (p,tn) reaction on natural sodium, with a threshold of 32 MeV. The β spectrum was severely contaminated by the 0.8-sec β activity of B^8, produced by the (p,αn) reaction on the residual mineral oil in the sodium. However carefully the target was prepared and cleaned, the relative yield of these two reactions was such that the B^8 could not be eliminated. Because of the relatively low counting rate obtained in this experiment, the half-life separation was judged too uncertain and the total β spectrum was recorded for 400 msec and analyzed. The resulting Kurie plot and its separation are shown in Fig. 2. After subtraction of the B^8 component, the remaining Na^{20} spectrum is still sufficiently accurate to definitely rule out any 7-MeV transition of intensity comparable to what had been observed from the Mg target. The reason for this 7-MeV branch and its nature must be due to an unknown contaminant of half-life very close to 0.4 sec. This contaminant is presently under further investigation. A spectroscopic analysis of the target material showed that it consisted of 99.9% Mg.

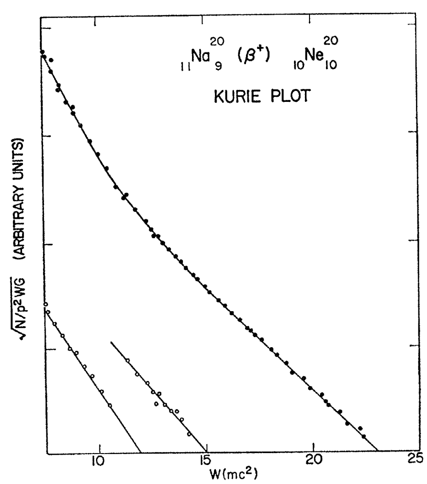

FIG. 1. The Na^{20} Kurie plot from the Mg^{24}(p,αn) reaction on natural magnesium. The branch with the $W=15$ endpoint is an unidentified contaminant.

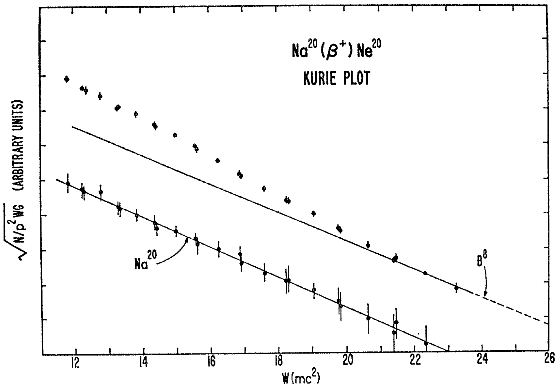

FIG. 2. The Na^{20} Kurie plot from the Na^{23}(p,tn) reaction. The extension of the B^8 contaminant spectrum at the higher energies has been omitted.

The γ rays from Na^{20} were observed using a magnesium target. A 3.2-cm^3 lithium-drifted germanium detector with an energy resolution of 3.6 keV for the 1.33-MeV γ transition of Co^{60} was coupled to the rabbit irradiation system. A 1024-channel time-sequenced spectrum was used for the pulse-height analysis. Only one γ ray was found which had a half-life consistent with the 0.4 sec of Na^{20}. Its energy was measured to be 1633.2±1.0 keV from an external calibration with Co^{60}, Ga^{66}, and Na^{24} sources, and an internal calibration with the two standard γ transitions of Mg^{24}, present in the target from the competing Mg^{24}(p,n)Al^{24} reaction. This result is in excellent agreement with the value of 1632.6±0.8 keV reported by Alburger and Jones.[8]

4. THE Na^{20} DECAY SCHEME AND ITS DISCUSSION

The 11.25-MeV end point and the subsequent 1633.2-keV γ transition allow us to determine the mass excess of Na^{20}. The result obtained is 6863±40 keV and is in excellent agreement with the measurements of Donovan and Parker[4] and Pehl and Cerny.[5]

The necessary link to the delayed-α measurements of Polichar *et al.*[1] is established through the intensity ratio of the 11.25- and 5.55-MeV β transitions. The 5.55-MeV β branch feeds the 7.43-MeV level of Ne^{20}, which breaks up into O^{16} and the strongest delayed-α line observed

[8] D. E. Alburger and K. W. Jones, Phys. Rev. **149**, 743 (1966).

TABLE I. Combined data of this measurement and the delayed-α spectra of Polichar *et al.*[a]

Level in Ne^{20} Energy (MeV)	I^{π}		β in (MeV)[b]	Branching ratio %	Logft
1.6332±0.0010	2^+	β_0	11.25±0.04	90.0	4.89±0.05
7.43 ±0.01	2^+	β_1	5.45±0.04	8.1	4.49±0.10
7.84 ±0.03	2^+	β_2	5.04±0.05	0.38	5.51±0.13
8.74 ±0.03	1^-	β_3	4.14±0.05	0.024	6.35±0.16
9.48 ±0.02	2^+	β_4	3.40±0.05	0.11	5.27±0.11
10.28 ±0.01	2^+	β_5	2.60±0.04	1.38	3.77±0.10
10.86 ±0.02	2^+	β_6	2.02±0.05	0.097	4.40±0.13
11.28 ±0.04	2^+	β_7	1.60±0.06	0.032	4.53±0.16

[a] Reference 1.
[b] The endpoint of β_0 is the measured one. The others are deduced from the energy levels obtained in the α measurement and correspond to the transitions α_1 to α_7 of Ref. 1.

from the Na^{20} decay. Making use of the intensity ratio reported in the delayed-α measurements[1] and of the levels of Ne^{20} from which they originate, it is possible to infer the relevant β-branching ratios and to propose a complete Na^{20} decay scheme. Table I presents a summary of both experimental data, where the intensities of the α transitions[1] have been renormalized to the total β decay. The Na^{20} decay scheme is shown in Fig. 3.

The fact that only the 2^+ level of the ground-state rotational band of Ne^{20} is populated by β decay determines the spin and parity of Na^{20} to be 2^+. This result is supported by similar observations[6,8] from the analog decay of F^{20}. With the exception of the 8.74-MeV level, all the levels populated by β decay and reported in Table I have spin and parity 2^+. This is deduced from the logft values of the involved β transitions and from the α-decay selection rules. The β_3 transition feeding the 8.74-MeV level has a logft of 6.35. The transition is then

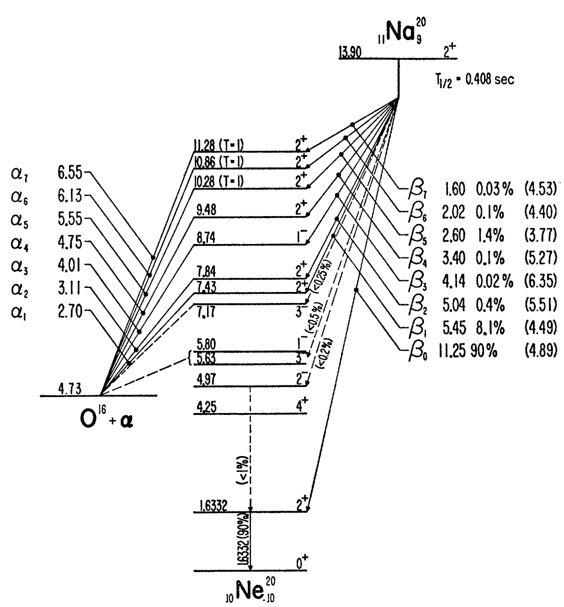

FIG. 3. The proposed Na^{20} decay scheme. The broken lines indicate unobserved transitions whose branching might be higher than 0.1% (see text and Ref. 6). The α transition energies and intensities are taken from Ref. 1.

likely to be first forbidden, in agreement with the assignment of 1^- for the 8.74-MeV level, previously inferred by Lauritsen and Ajzenberg-Selove.[6]

The 10.28-MeV level of Ne^{20} was first identified by Pearson and Spear[9] in an experiment on radiative capture of α's by O^{16}. The logft value of the deduced 2.60-MeV β transition confirms that this level is the $T=1$, $T_z=0$ analog of the mass-20 triplet. The 2.60-MeV β branch is clearly superallowed, although slower than one might expect from a comparison with the ft value of similar transitions in neighboring nuclei. This retardation may be due to some $T=0$ impurity in the 10.28-MeV level. This must be true to some extent because otherwise the isospin selection rule would forbid its α decay.

One may draw several conclusions from the data concerning the β_6 and β_7 transitions. Since both β branches are followed by α decay and have ft values which are allowed, it follows that the 10.86-MeV and 11.28-MeV states of Ne^{20} have $J^{\pi}=2^+$. If one compares the excitation of these levels relative to the lowest $T=1$ state at 10.28 MeV, one finds a close correspondence with the $T=1$ levels at 0.65 MeV and 0.99 MeV in F^{20}. It is tempting to suggest that these two pairs of levels are in fact $T=1$ isobaric analog states, which would be supported by the ft values of both β transitions involved. This would in turn suggest $J^{\pi}=2^+$ for the corresponding levels in F^{20}.

From our γ measurements, we can deduce some limits on the intensities of possible first-forbidden β transitions to negative-parity states of Ne^{20}. The first candidate for such a transition is the 2^- level at 4.97 MeV. This state is known to decay with a branching $>95\%$ by a cascade γ transition to the 1.63-MeV level. Our measurement gives a limit of log$ft>6.1$ to the corresponding β transition. This result can be compared to the value of log$ft=6.9$, reported by Alburger and Jones[7] for the analog β transition from F^{20}. From charge independence of nuclear forces, analog β transitions should have nearly equal comparative half-lives. Assuming equality, one can deduce that the branching ratio of a β transition to the $4.97(2^-)$-MeV level is $<1.6\times10^{-3}$.

The next two candidates for first-forbidden β-decay feeding are the 3^- state at 5.63 MeV and the 1^- state at 5.80 MeV. Both states are known to decay predominantly by α-particle emission[6,10] to the ground state of O^{16}. These α particles have not been observed in the work of Polichar *et al.*[1] and recent measurements[11] have placed an upper limit of 0.5% to their total intensity relative to the β decay of Na^{20}. This result gives to the corresponding β branches a log$ft>6.5$, which is in reasonable agreement with the systematics of logft values for $\Delta J=1$ first-forbidden β transitions.

[9] J. D. Pearson and R. H. Spear, Nucl. Phys. 54, 434 (1964).
[10] J. D. Pearson, E. Almqvist, and J. A. Kuehner, Can. J. Phys. 42, 489 (1964).
[11] J. E. Steigerwalt (private communication).

From our γ measurements, a β branching to the 7.03(4^-)-MeV level could be as high as 2%. This would give a $\log ft$ of 5.0 which is about three orders of magnitude too small. It is reasonable to infer, from consideration of $\log ft$ systematics, that such a transition has a probable branching ratio $<3\times10^{-5}$. Similar arguments could be used to estimate a possible β feeding of the α unstable states at 7.17(3^-), 8.90(1^-), and 9.16(3^-) MeV. Assuming a $\log ft>6.0$, the corresponding branching ratios would be <0.25, <0.06, and <0.04%, respectively. These estimates are realistic and agree with the fact that those transitions were not observed in delayed-α measurements. Along the same lines, branching to 0^+ and 4^+ states by second-forbidden transitions ought to be $<10^{-7}$. This is well below the limit of 1–2% placed upon them by our γ measurements and the estimate of <0.05% obtained for a possible β transition to the 0^+ ground state of Ne^{20}.

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Beta Decay of ^{37}S†

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Radioactive ^{37}S has been prepared by the $^{37}Cl(n,p)\,^{37}S$ reaction and its decay products have been observed with a magnetic β-ray spectrometer and with NaI(Tl) crystal and Ge(Li) crystal γ-ray spectrometers. The β-ray groups have endpoint energies, relative intensities, and comparative half-lives of 4.75±0.04 MeV (5.6±0.6)%, $\log f_1t=8.01$; 1.64±0.04 MeV, 94.0%, $\log f_0t=4.38$; and 1.04±0.04 MeV, ~0.4%, $\log f_0t=5.65$. The γ rays have energies and relative intensities of 3.107±0.002 MeV (99.6%) and 3.708±0.004 MeV (~0.4%). No other γ rays were observed; an upper limit of 0.5% is placed on their relative intensity. Coincidence counting places an upper limit of 1% on the possibility of a cascade transition from the 3.107-MeV state of ^{37}Cl. Spin-parity assignments for ^{37}Cl are $\frac{7}{2}^-$ for the 3.107-MeV state and $\frac{5}{2}^-$ for the 3.708-MeV state. The ground state of ^{37}S has odd parity and probable spin $\frac{7}{2}$.

INTRODUCTION

In this investigation, NaI(Tl) scintillation crystals, a Ge(Li) crystal detector, and a magnetic β-ray spectrometer have been used in determining the energies and relative intensities of the β rays and the γ rays which are emitted in the β decay of ^{37}S. A primary purpose was to locate negative-parity excited states of the daughter $d_{3/2}$ subshell nucleus ^{37}Cl.

Previous Studies

Before this study was initiated, there had been reported[1,2] β-ray transitions to the ground state of ^{37}Cl (4.7 MeV, ~10%) and to a 3.1-MeV excited state (1.6 MeV, ~90%). Only a 3.1-MeV γ ray had been observed; cascading transitions or another β-ray transition which would produce γ rays of energy of less than 2 MeV had been reported[2] to be of less than 1% of the intensity of the 3.1-MeV γ ray. The $\log ft$ value of 7.3 for the ground-state transition was recognized as being consistent with a unique first-forbidden transition; similarly, the $\log ft$ value of 4.2 for the transition to the 3.1-MeV state was consistent with an allowed transition. In ^{37}Cl, the ground-state spin-parity was well-established[3] as $\frac{3}{2}^+$. Magnetic analysis of the charged particles from the $^{37}Cl(p,p')^{37}Cl^*$ reaction had made possible the identification of states[4,5] at 0.835 (conflicting reports), 1.72, 3.087, and 3.105 MeV. The doubtful 0.835-MeV state was not observed in the $^{37}Cl(p,p')$ reaction[5] with the use of separated isotopes of Cl, it was not observed in the $^{37}Cl(n,n'\gamma)$ reaction,[6] and it was not observed in the $^{40}Ar(p,\alpha'\gamma)$ reaction.[7]

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[1] E. Bleuler and W. Zuenti, Helv. Phys. Acta. **19**, 137 (1946); H. Murdock, N. Goldstein, and E. Goldfarb, Argonne National Laboratory, Metallurgical Laboratory, Report CF-3574, 1946, pp. 31–32 (unpublished); J. Wallace, E. Goldfarb, and C. Eggler, Argonne National Laboratory, Metallurgical Laboratory, Report No. CP-3647, 1946, pp. 11–12 (unpublished).

[2] H. Morinaga and E. Bleuler, Bull. Amer. Phys. Soc. **1**, 30 (1956).

[3] C. H. Townes, A. N. Holden, J. Bardeen, and F. R. Merritt, Phys. Rev. **71**, 644 (1947).

[4] P. M. Endt, C. H. Paris, A. Sperduto, and W. W. Beuchner, Phys. Rev. **103**, 961 (1956).

[5] J. P. Schiffer, C. R. Gossett, G. C. Phillips, and T. E. Young, Phys. Rev. **103**, 134 (1956).

[6] D. B. Nichols, B. D. Kern, and M. T. McEllistrem, Phys. Rev. **151**, 879 (1966).

[7] T. Wakatsuki, Osaka University (private communication); H. L. Scott, W. Galati, J. L. Weil, and M. T. McEllistrem, Bull. Am. Phys. Soc. **10**, 260 (1965).