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Decay and lifetimes of levels in ^{21}Ne

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Abstract. Levels in ^{21}Ne have been studied using the reaction ^{18}O(α, n)^{21}Ne. Lifetimes have been obtained for the states at 350, 1745, 2866, 3662, 3883, 4432, 5772 and 6548 keV by the Doppler shift attenuation method. The lifetimes are generally a factor of two to four smaller than previous measurements. The major part of these differences may be accounted for by discrepancies between the Warburton and Blaugrund approaches to the stopping theory when heavy stoppers are used. The lifetimes are compared with Nilsson model calculations and with predictions of the projected Hartree–Fock model.

1. Introduction

The energy levels of ^{21}Ne are well described by the Nilsson model in which either the odd neutron is coupled to a deformed ^{20}Ne core, or a hole is coupled to a ^{22}Ne core. As regards the former description, four rotational bands have been identified corresponding to the odd neutron being in Nilsson orbits 7, 9, 5 or 14. Low-lying negative parity states arise from a $K^{\pi} = 1/2^{-}$ band corresponding to a hole in orbit 4.

The ground state band has been treated theoretically by both shell and collective model methods and, in both, difficulties were experienced in reproducing the weak E2 and M1 transition strengths deduced from previous lifetime measurements. The present experiment was thus intended to check these measurements by a similar method of Doppler shift attenuation, but using a different stopper and stopping theory. Also, the decay modes and lifetimes of higher excited states were investigated.

2. Experimental method

The Liverpool University EN tandem Van de Graaff accelerated the $^{4}He^{++}$ ions used to produce the reaction ^{18}O(α, n)^{21}Ne ($Q = -0{\cdot}7$ MeV) at bombarding energies of 5·0, 6·5, 7·5 and 9·0 MeV. The target comprised 920 μg cm^{-2} of WO_3 deposited on a thick gold backing. The oxygen was enriched to 99·3% ^{18}O. Previous papers from this laboratory describe the Ge(Li)–NaI(Tl) escape suppressed and pair escape spectrometer (Sharpey-Schafer *et al.* 1971), the data collection system (Alderson and Dawson 1970) and the method of analysis (Durell *et al.* 1971) used in the present experiment. Figures 1 and 2 show the present decay scheme and a typical spectrum.

3. Results

Eight lifetimes and seventeen limits on lifetimes were obtained for all known levels in ^{21}Ne up to and including that at 6600 keV excitation. They are listed in table 1 together with level energies and branching ratios measured in this experiment.

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The errors quoted on the lifetimes in column 7 do not contain any estimate of the inaccuracy in the stopping theory. Such inaccuracy introduces a systematic effect on the lifetimes of up to 25%. Transition strengths were calculated from measured lifetimes using the multipole mixing ratios given by Pronko *et al.* (1969) and Rolfs *et al.* (1970), and are quoted here in Weisskopf single particle units (Wu).

Table 1. Energies, branching ratios and lifetimes of levels in ^{21}Ne measured in the present experiment

Level	E_x (keV)	Transition	Branching ratio (%)†	E_α (MeV)	F	τ_m (fs)‡
1	350·5 ±0·1	1–0	100	5·0	0·046 ±0·002	3600 ±300§
2	1745·4 ±0·2	2–0		5·0	0·927 ±0·013	24 ±6§
		2–1			0·889 ±0·024	
3	2788·5 ±0·3	3–0		5·0	0·026 ±0·042	>5200
		3–1			0·009 ±0·014	
		3–0		6·5	0·008 ±0·067	
		3–1			0·030 ±0·006	
4	2797 ±1	4–0	100	5·0	0·960 ±0·062	<35
		4–0		6·5	0·956 ±0·041	
5	2865·5 ±0·2	5–1	41 ±2	5·0	0·936 ±0·022	27 ±5§
		5–2	59 ±2		0·840 ±0·074	
		5–1		6·5	0·939 ±0·017	
		5–2			0·914 ±0·019	
		5–1		7·5	0·930 ±0·016	
		5–2			0·909 ±0·020	
6	3662·0 ±0·4	6–1	54 ±3	6·5	0·862 ±0·024	63 ±7
		6–3	46 ±3		0·855 ±0·018	
		6–1		7·5	0·819 ±0·022	
		6–3			0·816 ±0·044	
7	3733·7 ±0·2	7–0	87 ±2	6·5	0·987 ±0·020	<25
		7–1	13 ±2		0·976 ±0·030	
		7–0		7·5	0·967 ±0·020	
		7–1			0·930 ±0·050	
8	3882·7 ±0·3	8–0	29 ±3	6·5	0·970 ±0·020	24 ±10
		8–1	71 ±3		0·958 ±0·014	
		8–0		7·5	0·911 ±0·023	
		8–1			0·917 ±0·018	
9	4432·0 ±1·0	9–2	‖	7·5	0·956 ±0·028	25 ±6
		9–2		9·0	0·936 ±0·013	
10	4523·7 ±0·5	10–0	21 ±3	6·5, 7·5, 9·0	¶	<10
		10–1	79 ±3			
11	4683·1 ±0·7	11–0	36 ±3	7·5, 9·0		<10
		11–1	64 ±3			
12	4725·0 ±1·0	12–1	‖	7·5		<10
13	5332·6 ±1·0	13–1	100	7·5, 9·0		<10
14	5429·1 ±1·0	14–1	‖	9·0		<20
		14–2				
15	5626 ±2	15–1	100	9·0		<10
16	5683·0 ±0·6	16–0	30 ±10	9·0		<10
		16–3	70 ±10			
17	5772 ±2	17–0	100	9·0	0·904 ±0·026	40 ±12
18	5821 ±3	18–0	100	9·0		<20
19	5991 ±3	19–0	100	9·0		<10
20	6030·4 ±0·5	20–2	45 ±5	9·0		<20
		20–5	55 ±5			
21	6165 ±2	21–2	100	9·0		<20

Table 1. (cont.)

Level	E_x (keV)	Transition	Branching ratio (%)†	E_α (MeV)	F	τ_m (fs)‡
22	6263 ± 2	22–5	100	9·0		<20
23	6445·9 ± 1·0	23–5	30 ± 15	9·0		<20
		23–9	70 ± 15			
24	6548 ± 2	24–2	100	9·0	0·896 ± 0·066	45 ± 30
25	6600 ± 5	25–1	100	9·0		<10

† Branching ratios measured at 50° and 130°. The results quoted are averages of data taken at the beam energies listed.

‡ The errors quoted in this column do not contain any estimate of the systematic uncertainty in the conversion of attenuation factors to lifetimes due to uncertainties in the slowing down theory.

§ Lifetimes corrected for feeding from higher excited states.

|| Intensity measurements were unreliable because gamma rays were not resolved.

¶ For brevity, attenuation factors of fully shifted gamma rays are omitted for levels above level 9.

An important discrepancy between present results and previous measurements occurs in the case of the first excited state. A lifetime of 22 ps has been obtained from recoil distance experiments (Bamberger *et al.* 1968 and Nickles 1969). The Doppler shift resulting from such a lifetime would certainly be too small to be observed in the present experiment, but data from the 5·0 MeV run showed the existence of a shift in the 350 keV line. However, at the dispersion of 1·75 keV per channel, measurement of a small shift was unreliable. To obtain an accurate value of the shift, the data were retaken with a dispersion of 0·19 keV per channel and the

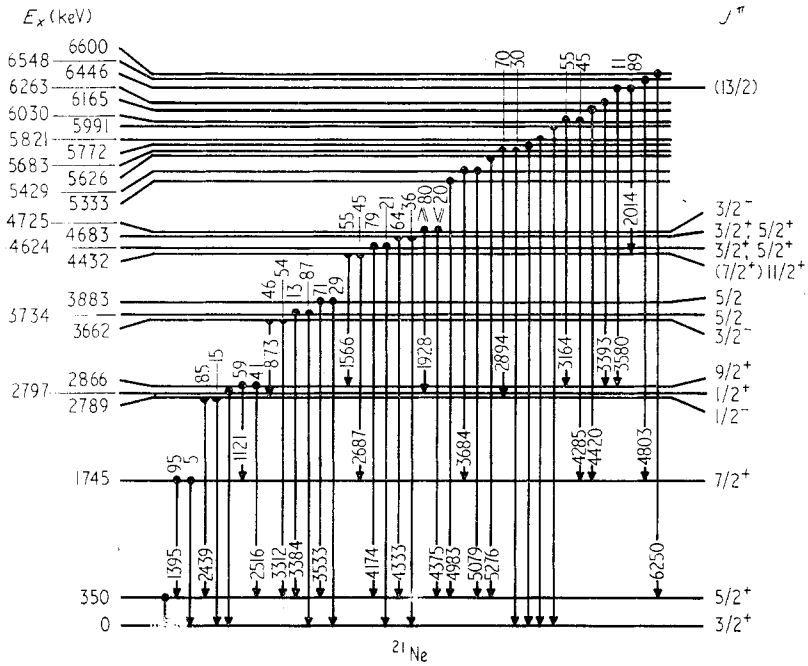

Figure 1. Decay scheme for ^{21}Ne. Data are taken from the present experiment and from Rolfs *et al.* (1970), Kuhlmann *et al.* (1970) and Howard *et al.* (1967).

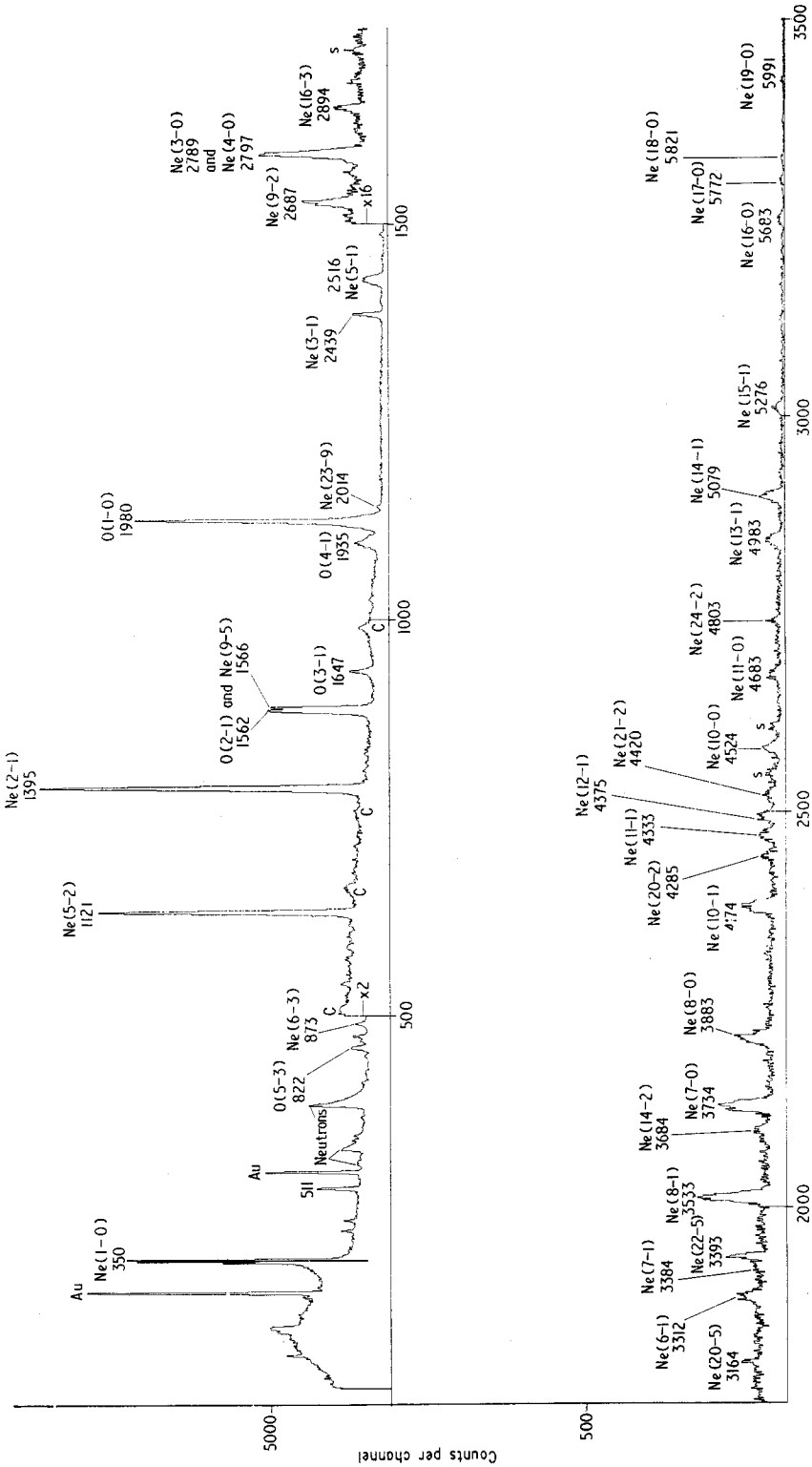

Figure 2. Escape suppressed spectrum of gamma rays from the $^{18}O(\alpha, n)^{21}Ne$ reaction taken at 90° to the beam direction. The alpha particle bombarding energy was 9·0 MeV. Peaks are labelled with their corresponding transition and energy in keV. and C and s indicate Compton edge and single escape peak respectively.

stability of the system monitored using the 122 keV gamma ray from a ^{57}Co source and the 662 keV gamma ray from ^{137}Cs. The shift observed in this experiment is displayed in figure 3. It should be pointed out that feeding of the 350 keV state from higher excited states reduces the observed Doppler shift, thus the true shift is greater than that displayed in figure 3. Such feeding was taken into account when computing

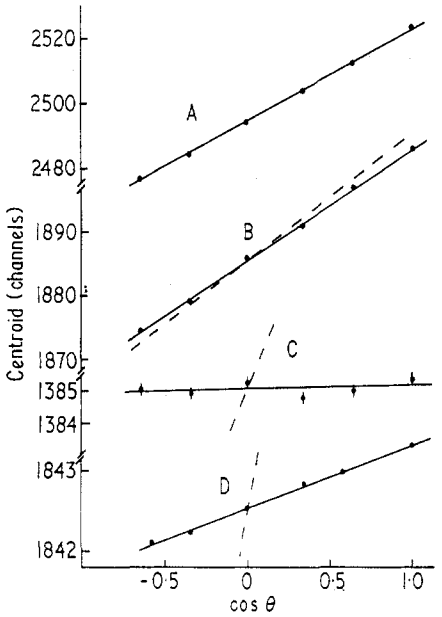

Figure 3. Centroid against cos θ plots for some ^{21}Ne gamma rays. Least squares fits to the data are shown as full lines and maximum shifts as broken lines. The dispersion is 1·746 keV per channel, except in the case of the 350 keV line where it is 0·188 keV per channel. In cases where they are appreciable, statistical errors on the values of centroids are shown as error bars. A, 4725 keV state $E_\gamma = 4375$ keV, $F = 1{\cdot}00 \pm 0{\cdot}02$ $E_\alpha = 7{\cdot}5$ MeV; B, 3662 keV state $E_\gamma = 3311$ keV, $F = 0{\cdot}86 \pm 0{\cdot}02$ $E_\alpha = 6{\cdot}5$ MeV; C, 2789 keV state $E_\gamma = 2439$ keV, $F = 0{\cdot}01 \pm 0{\cdot}02$ $E_\alpha = 5{\cdot}0$ MeV; D, 350 keV state $E_\gamma = 350$ keV, $F = 0{\cdot}046 \pm 0{\cdot}002$ $E_\alpha = 5{\cdot}0$ MeV.

the lifetime from the measured F factor, the formula used being that of Bell *et al.* (1969). The lifetime obtained was $3{\cdot}6 \pm 1{\cdot}0$ ps, which is not in agreement with the 22 ps of Bamberger *et al.* (1968). The latter result can be accounted for if part of the deuterium target were absorbed by the tantalum stopper. This absorbed deuterium would then give a disproportionately large stopped component in the gamma ray spectrum and a long lifetime would result.

Using Coulomb excitation methods, Lemberg (1960) measured the E2 partial lifetime of the 350 keV state to be $9{\cdot}2 \times 10^{-10}$ s giving an E2 transition strength of 50 ± 10 Wu. This value compares favourably with the 30^{+40}_{-20} Wu from our measurement, but poorly with the 5 ± 5 Wu from references (Bamberger *et al.* 1968 and Nickles 1969). The large errors on these values arise mainly from the errors in the value of the mixing ratio (Pronko *et al.* 1969) used.

4. Stopping analysis

Comparison of present lifetimes in ^{21}Ne with previous measurements by Pronko *et al.* (1969) given in columns 2 and 4 of table 2, shows that the former are smaller by factors of between 2 and 4. This led us to a closer investigation of the two experiments. First we accounted for maximum uncertainties in target composition and thickness in our data. Taken together they had an effect on the lifetimes of less than 10%. Also, from ionic stopping experiments, we expected the stopping power expressions used in the analysis to be inaccurate by only 25% at maximum. As conditions were different in the two experiments (ie different stopping material, beam energy, etc) we still needed a firm basis for a comparison. To achieve this we used the data on the experimental conditions and F factors given in Pronko *et al.* (1969) as input to our stopping theory program. The agreement of these results with our own measured lifetimes was then greatly improved as shown by column 3 and 4 of table 2. This indicated that a major discrepancy exists between the stopping theory of Warburton *et al.* (1963, 1966, 1967) used by Pronko *et al.*, and that of Blaugrund (1966) used in the present experiment. A comparison of the two theories is necessary.

Table 2. Comparison of lifetimes in ^{21}Ne computed using the Warburton and Blaugrund stopping theories

Level	Lifetimes† (fs)		
	Pronko *et al.* (1969)		Present experiment
	Warburton‡	Blaugrund§	
2	150 ±35	65 ±20	24 ±6
5	100 ±15	50 ±15	27 ±5
6	120 ±10	67 ±20	63 ±7
8	78 ±25	40 ±15	24 ±10
9	78 ±25	45 ±15	25 ±6

† The errors quoted in this table do not contain any contribution for stopping theory uncertainty.

‡ Lifetimes as quoted in Pronko *et al.* (1969).

§ Computed from data given in Pronko *et al.* (1969) using Blaugrund theory.

The Warburton approach starts from the equation for the Doppler shift attenuation factor

$$F(\tau) = \frac{1}{\tau}\int_0^\infty \exp\left(-\frac{t}{\tau}\right)\frac{v(t)}{v_1}\,\mathrm{d}t \tag{1}$$

where $v(t)$ is the velocity of the recoiling ion at time t after its production, $v_1 = v(0)$ and τ is the lifetime of the excited state.

After adoption of the particular forms of electronic and atomic stopping powers, and after integration equation (1) becomes

$$F(\tau) = \frac{(\alpha/\tau)}{(\alpha/\tau)+1}(1 - A(\text{Warburton})) \tag{2}$$

where A(Warburton) contains all the effect of atomic stopping and α is the characteristic electronic stopping time.

Blaugrund uses as his initial equation for F

$$F(\tau) = \frac{1}{\tau}\int_0^\infty \exp\left(-\frac{t}{\tau}\right)\frac{v(t)}{v_1}\overline{\cos\phi}\,\mathrm{d}t. \tag{3}$$

The $\overline{\cos\phi}$ factor is introduced to account for the effect of atomic scattering on the F factor and is a function of t. Equation (3) also reduces to the form of equation (2), but with A(Warburton) replaced by a term A(Blaugrund), and thus any discrepancy between the two theories arises in these atomic stopping terms.

Investigation shows that the lifetimes of Pronko *et al.* (1969) are almost identical to those obtained from the simple first order approximation of equation (2) neglecting A(Warburton). This lack of atomic stopping is unlikely for three reasons. First, the initial recoil velocities are well below $(c/137)\,Z_{\mathrm{neon}}^{2/3}$ and hence are in the region where atomic and electronic effects are expected to be comparable. Also in both experiments high Z stoppers are used, again enhancing atomic effects. Finally, as Blaugrund shows, the $\overline{\cos\phi}$ atomic scattering factor, omitted in the Warburton theory, is the more important part of the atomic stopping for heavy stoppers and low velocities. For these reasons we consider the Blaugrund formalism to be the more realistic of the two.

5. Discussion

5.1. *The ground state rotational band*

The levels at 0, 350, 1745, 2866, 4432 and 6446 keV excitation belong to the $K^\pi = 3/2^+$ rotational band based on the odd nucleon in Nilsson orbit 7. In-band E2 and M1 strengths are listed in tables 3 and 4 respectively. They are compared with results of a Nilsson model calculation by Walsh (1970, unpublished) in which particle bands are mixed with the ground state band, the core being inert to excitations other than rotations. Bent *et al.* (1967) performed a similar K-band mixing calculation with the $K^\pi = 3/2^+$, $1/2^+$ and $5/2^+$ configurations and their results are also tabulated. In contrast, Selin (1970) gives the results of a Nilsson model calculation in which no Coriolis interaction is included. The next column gives the results of a projected Hartree–Fock calculation performed by Johnstone and Benson (1969), and the final column gives the values obtained from a simple pure $K^\pi = 3/2^+$ band calculation.

Table 3. Experimentally determined E2 transition strengths for the ground state ($K^\pi = \frac{3}{2}^+$) band of ^{21}Ne with theoretical predictions

$J_i^\pi \to J_f^\pi$	$\lvert M(\mathrm{E2})\rvert^2$ Wu					
	Present experiment	Theory				
		Walsh (1970, unpublished)	Bent *et al.* (1967)	Selin (1970)	Johnstone and Benson (1969)	Pure $K^\pi = 3/2^+$ band
$5/2^+ \to 3/2^+$	30^{+40}_{-20}	16	15	7	17	37
$7/2^+ \to 3/2^+$	30^{+10}_{-6}	22	5·7	12	7·8	16
$7/2^+ \to 5/2^+$	44^{+40}_{-20}	12	22	80	14	23
$9/2^+ \to 5/2^+$	36^{+8}_{-6}	35	23	22	12	23
$9/2^+ \to 7/2^+$	24^{+46}_{-20}	11	14	6	8	15
$11/2^+ \to 7/2^+$	30^{+10}_{-8}	—	—	13	—	28
$11/2^+ \to 9/2^+$	9^{+16}_{-6}	—	—	7	—	10
$13/2^+ \to 9/2^+$	$\geqslant 2$	—	—	24	—	30
$13/2^+ \to 11/2^+$	>0·75	—	—	8	—	8

Table 4. Experimentally determined M1 transition strengths for the ground state ($K^\pi = \frac{3}{2}^+$) band of ^{21}Ne with theoretical predictions

$J_i^\pi \to J_f^\pi$	$\lvert M(\mathrm{M1})\rvert^2$ Wu				
	Present experiment	Theory			
		Walsh (1970, unpublished)	Bent *et al.* (1967)	Selin (1970)	Johnstone and Benson (1969)
$5/2^+ \to 3/2^+$	$0{\cdot}21 \pm 0{\cdot}03$	0·11	0·007	0·017	0·11
$7/2^+ \to 5/2^+$	$0{\cdot}45^{+0{\cdot}15}_{-0{\cdot}09}$	0·13	0·14	0·53	0·15
$9/2^+ \to 7/2^+$	$0{\cdot}49^{+0{\cdot}11}_{-0{\cdot}08}$	0·22	0·23	0·14	0·21
$11/2^+ \to 9/2^+$	$0{\cdot}18^{+0{\cdot}06}_{-0{\cdot}04}$	—	—	0·21	—
$13/2^+ \to 11/2^+$	>0·16	—	—	0·30	—

The E2 transition strengths, which have enhancements typical for this region of the sd shell, are generally larger than theoretical predictions. The large errors on some results derive mainly from errors in the mixing ratios. However, for the $7/2^+ \to 3/2^+$ and $9/2^+ \to 5/2^+$ transitions the radiation is pure E2 and so errors are small. In these two cases the results of Walsh's calculation are in good agreement with experiment. Also in the case of the $7/2^+ \to 5/2^+$ transition, the value obtained by Bent *et al.* agrees within errors with experimental findings.

On the other hand, the Hartree–Fock calculation greatly underestimates all the transition strengths. However, it is perhaps interesting to note that all these Hartree–Fock results are a factor of 3 less than observation. Such a discrepancy is possibly associated with an incorrect choice of a normalization constant, such as effective charge, resulting from attempts to fit to the low strengths implied by previous measurements.

In attempts to produce a physically meaningful picture of a nucleus the more simple the model we apply the better. To this end we have calculated E2 transition strengths assuming a pure $K^\pi = 3/2^+$ band when the ratios of strengths are equal to simple ratios of Clebsch–Gordan coefficients. Knowledge of the absolute transition rate of the first excited state is then used to normalize the set. This was obtained by assuming that the ground state band intrinsic quadrupole moment of ^{21}Ne is the same as that for ^{20}Ne. The first excited state transition strengths in the two nuclei are then directly related. Using the value of 23·1 Wu (Skorka *et al.* 1966) for the ^{20}Ne transition leads to 37 Wu for ^{21}Ne. The transition strengths obtained with this normalization are listed in the final column of table 3. As can be seen, they compare as favourably with experiment as do the other theories.

The M1 transition strengths in table 4 do not depend so critically on the mixing ratios and should consequently provide a good test of the various theories. In fact with one exception, the theories agree amongst themselves, but are at odds with experiment in every case.

5.2. *The $K^\pi = \frac{1}{2}^-$ hole state band*

Kuhlmann *et al.* (1970) propose the 2789, 3662 and 3883 keV states as candidates for the first three members of the $K^\pi = 1/2^-$ hole state band obtained by promoting a particle from Nilsson orbit 4 to 7. Further evidence for this assignment comes from the inhibited E1 strengths of transitions from these states to the ground state band as measured in the present experiment. Benson and Flowers (1969) predicted such inhibitions when studying ^{19}F. The low lying negative parity states of ^{19}F can

be considered as a $p_{1/2}$ hole coupled to the ground state band of ^{20}Ne. They described such states by physically acceptable shell model wavefunctions composed of states in which only one type of nucleon, a proton in their case, is excited from the core. A consequence of this is that the E1 matrix elements between these states and positive parity states vanish if the positive parity states contain no core excitation.

In ^{21}Ne the states in question are formed by coupling a $p_{1/2}$ neutron hole to the $K^\pi = 0^+$ ground state band of ^{22}Ne. The E1 transition strengths of decays from these states to the $K^\pi = 3/2^+$ band of ^{21}Ne are given in table 5. In general they are inhibited by a factor of ten more than the average for light nuclei as given in Skorka *et al.* (1966). The exception is in the case of the 3883 to 350 keV transition where the transition is three or four times stronger than the rest. Although the 3883 keV level is the most likely candidate for the $5/2^-$ member of the band, it must be remembered that it has no definite parity assignment as yet.

Table 5. E1 transition strengths in ^{21}Ne for $K^\pi = \frac{1}{2}^-$ to $K^\pi = \frac{3}{2}^+$ cross-band transitions

$J_i^\pi \to J_f^\pi$	Transition	$\lvert M(\mathrm{E1})\rvert^2 \times 10^{-4}$ (Wu)
$1/2^- \to 3/2^+$	3–0	$\leqslant 1{\cdot}7$
$3/2^- \to 5/2^+$	6–1	$3{\cdot}0 \pm 0{\cdot}4$
$5/2^- \to 3/2^+$	8–0	$2{\cdot}7^{+1{\cdot}9}_{-0{\cdot}8}$
$5/2^- \to 5/2^+$	8–1	9^{+6}_{-3}

6. Conclusions

Present data on lifetimes of lower excited states in ^{21}Ne suggest stronger transitions than previous measurements, bringing them more into line with theoretical predictions, especially those of the simple rotation model. However, to obtain more realistic comparisons with theory it will be necessary to have greater accuracy in the values of mixing ratios involved. Most of the higher levels above 4·5 MeV excitation had lifetimes too short for measurement in the present experiments.

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