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β decay of ^{22}F[†]

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^{22}F was produced in the ^{18}O(^{6}Li, $2p$)^{22}F reaction using 26-MeV ^{6}Li^{3+} ions. Following transfer of the target in a shuttle system, delayed γ and β rays were observed with Ge(Li) and NE102 plastic detectors. Several γ rays from ^{22}F decay were observed, decaying with a half-life of 4.23 ± 0.04 sec. γ-γ coincidence measurements have established that a 1900.0-keV transition terminates on a level in ^{22}Ne at 5523.4 keV, contrary to a previous study. The ground state of ^{22}F is of $J^\pi = 4^+$ (with 3^+ as a remote possibility) disagreeing with a previous assignment of 5^+. Accurate excitation energies are presented for seven states in ^{22}Ne. Experimental results compare favorably with full ($2s$-$1d$) basis shell-model calculations of the $A = 22$ system.

[RADIOACTIVITY ^{22}F; measured $t_{1/2}$, E_γ, I_γ, E_β, γ-γ coin., γ-β coin., deduced decay scheme, J of ^{22}F, logft, E_{levels}; compared with theory.]

I. INTRODUCTION

As part of a program of investigating the properties of neutron-rich nuclei in the ($2s$-$1d$) shell using heavy-ion compound reactions,[1] we have studied the β decay of the $T_z = 2$ nuclide ^{22}F.

A specific interest in the present case is that the $A = 22$ system is the heaviest (in the sense of numbers of particles or holes outside a closed shell) in the ($2s$-$1d$) shell for which extensive full-basis shell-model wave functions are available.[2] As more particles are added beyond the ^{16}O closed shell the dimensionality of the matrices, which must be diagonalized in a complete conventional "exact diagonalization" treatment of the shell-model problem, increases very rapidly. For $A = 22$ the dimensionalities exceed 500×500. It is clearly important to test the complete shell-model predictions as fully as possible in the heaviest systems for which they can be made to see whether—when the wave functions become of very great complexity, with hundreds of components in terms of their original basis—they retain the reliability that they possess for the lighter systems. Only by such studies can we assess the demands that must be placed on the truncation systems, if they are to be acceptable substitutes for the full calculations, and the degree to which persistence with full calculations of even greater complexity deeper into the shell might be justified.

Comparison of shell-model predictions with experiment for $A = 22$ is also of special interest because these nuclei are known to be among the most highly deformed of light nuclei. The shell model[2] is known to predict such collective features of ^{22}Ne as the large $B(E2)$ values for the ground-state band. It is then of interest to test, in the same nuclear systems, operators which are not dominated by collective effects. The comparison of theory with experiment for β-decay transition rates provides just such a test.

The theoretical level scheme[2] for the $T = 1$ states of $A = 22$ on the full $(2s$-$1d)^6$ basis is shown in Fig. 1 together with those levels of ^{22}Ne that are established experimentally to be of even parity. The correspondences indicated between theoretical and experimental states are made with varying degrees of confidence, as explained in the caption, and at various points in the discussion section of this paper.

^{22}F was first observed by Vaughn *et al.*,[3] who measured the half-life to be 4.0 ± 0.4 sec. Their decay scheme indicated β branches to the $J^\pi = 2^+$ state in ^{22}Ne at 1.27 MeV and to the $J^\pi = 4^+$ state at 3.36 MeV, suggesting $J^\pi = 3^+$ for the ^{22}F ground state. From their observed maximum β-ray end-point energy of 11.2 ± 0.6 MeV and their decay scheme, they calculated a total energy Q_β for ^{22}F of 12.5 ± 0.6 MeV.

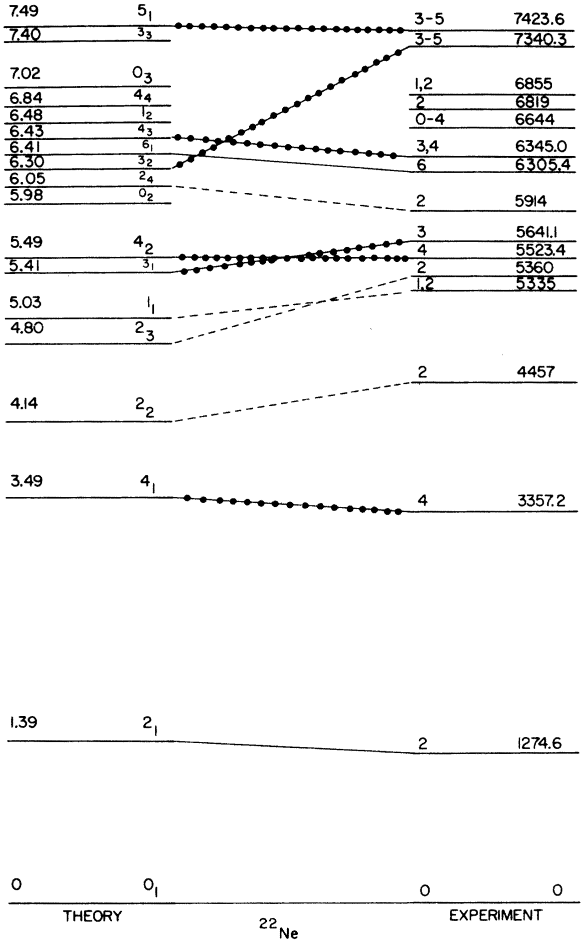

FIG. 1. Theoretical (Preedom and Wildenthal—Ref. 2) and experimental level schemes for ^{22}Ne. Only those experimental levels are shown that are established to be of even parity (within the range of the figure negative-parity states exist at 5144, 7052, 7402, and 7485 keV and states of undetermined parity at 6116*, 6241*, 6300, 6692*, 6894, 7350, and 7440 keV—the starred ones having natural parity). The experimental energies come from Endt and van der Leun (Ref. 7) or from the present work. Connections between theoretical and experimental levels through solid lines appear to be certain; those made through dotted lines are established or suggested by the present work as discussed in the text; those made through dashed lines are conjectural. Energies are in MeV to the left of the theoretical levels and in keV to the right of the experimental levels.

Using the ^{22}Ne(t, ^{3}He)^{22}F reaction, Stokes and Young[4] measured the mass excess of ^{22}F to be 2.828 ± 0.030 MeV. From this one obtains a Q_β of 10.853 ± 0.030 MeV for ^{22}F.

Recently, Guratzsch *et al.*[5] have reported a study of the β decay of ^{22}F. They formed the activity in the ^{181}Ta(^{22}Ne, ^{22}F) reaction using 174-MeV ^{22}Ne ions and made the measurements with the aid of an on-line mass separator. They found a half-life of 4.24 ± 0.08 sec, and determined a maximum β end point of 5.50 ± 0.15 MeV. Using their decay scheme, they calculate a value for Q_β of 11.02 ± 0.16 MeV. Their decay scheme indicated β branches to the 5.52-MeV $J^\pi = 4^+$ state in ^{22}Ne, to the 6.35-MeV state which they identify as having $J^\pi = 6^+$, and to a new state for which they postulate an excitation energy of 7.54 MeV. On the basis of these assignments and of their calculated logft values, they assign $J^\pi = 5^+$ to the ^{22}F ground state.

This reported assignment $J^\pi = 5^+$ for the ^{22}F ground state is surprising, since the full shell-model calculations[2] give $J^\pi = 4^+$ for ^{22}F(0) with $J^\pi = 3^+$ at 0.11 MeV; the first $J^\pi = 5^+$ state comes only as the fourth excited state and at an excitation energy of more than 1 MeV. $J^\pi = 5^+$ for the ground state would therefore constitute a serious conflict with the shell model, although $J^\pi = 3^+$ would be acceptable. Also, the one-particle–one-hole configuration usually has $J = J_{\max} - 1$ for the ground state.[6] Examples of this are ^{8}Li($J^\pi = 2^+$)($p_{3/2}$), ^{36}Cl($J^\pi = 2^+$)($d_{3/2}$), ^{48}Sc($J^\pi = 6^+$)($f_{7/2}$). In this spirit one would expect ^{22}F($d_{5/2}$) to have $J^\pi = 4^+$.

In the present work we show that ^{22}F(0) is not $J^\pi = 5^+$ but is indeed, as predicted, almost certainly $J^\pi = 4^+$. $J^\pi = 3^+$ remains as a remote possibility but is extremely unlikely on the basis of the systematics of β-transition probabilities. ($J^\pi = 3^+$ also grossly violates the explicit predictions of the theoretical model[2] as to β-transition probabilities, whereas $J^\pi = 4^+$ gives an excellent account.)

II. EXPERIMENTAL METHOD AND RESULTS

^{22}F was produced via the ^{18}O(^{6}Li, $2p$)^{22}F reaction, using 26-MeV ^{6}Li^{3+} ions from one of the Brookhaven National Laboratory MP tandem accelerators. Targets of Ta$_2$^{18}O$_5$ were repetitively bombarded for 2 sec in vacuum and then transferred to a remote counting station by a pneumatic target-shuttle system. Further details of the experimental layout can be found in Ref. 1. At the counting station, singles γ rays and both β-γ and γ-γ coincidences could be studied, using 30-cm^3, 60-cm^3, and a matched pair of 70-cm^3 Ge(Li) detectors for the γ rays and a 7.5-cm-diam by 5-cm-deep NE102 plastic scintillator for the β particles. Various lead and lead/brass screens were used in front of the Ge(Li) detectors to remove β particles and low-energy γ rays and x rays.

A. Half-lives, energies, and relative intensities of decay γ rays

Delayed γ-ray singles spectra were accumulated for four 4-sec time bins, in order to measure the

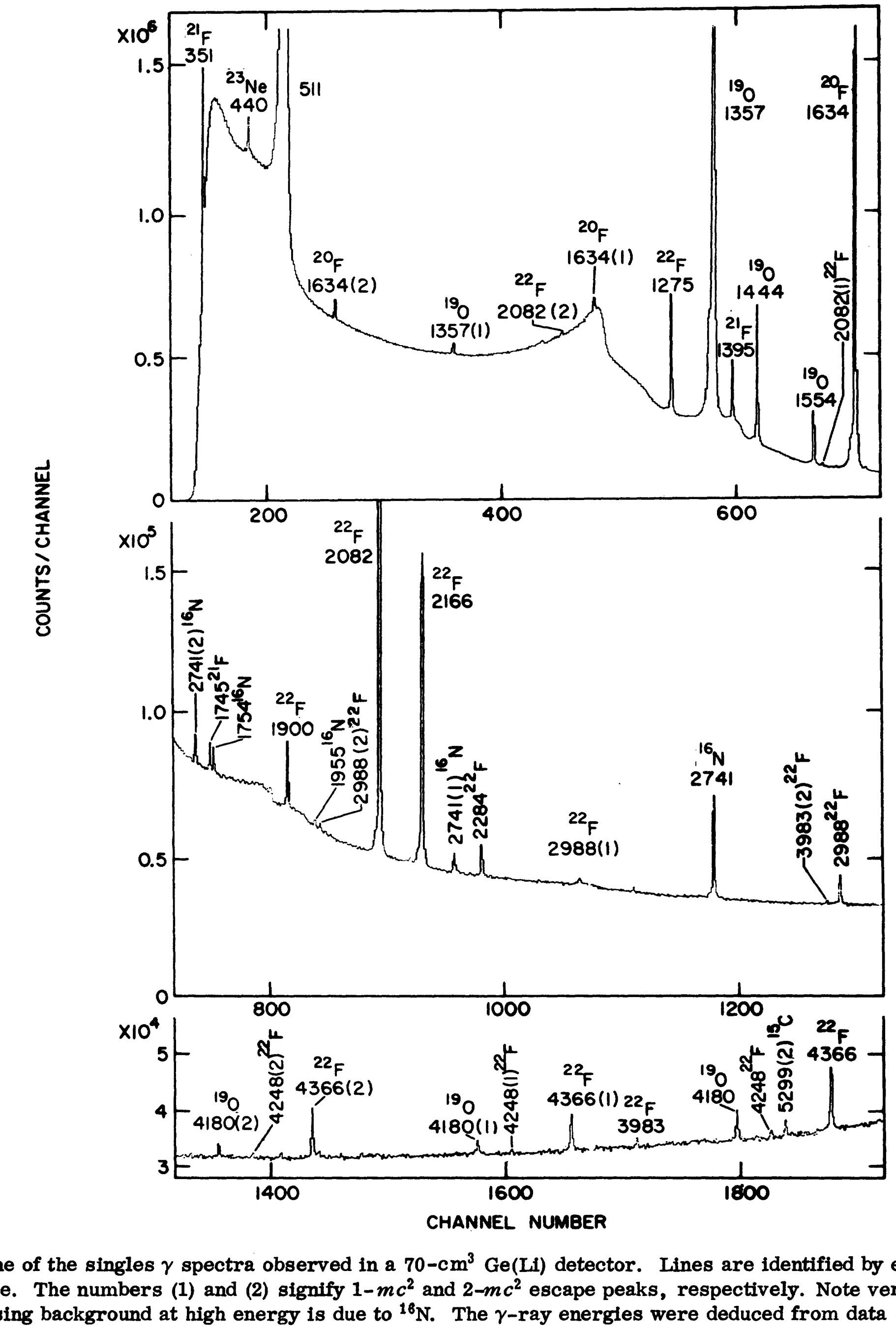

FIG. 2. One of the singles γ spectra observed in a 70-cm^3 Ge(Li) detector. Lines are identified by energy in keV and parent source. The numbers (1) and (2) signify 1-mc^2 and 2-mc^2 escape peaks, respectively. Note vertical scale changes. The rising background at high energy is due to ^{16}N. The γ-ray energies were deduced from data (not shown) taken with twice the dispersion of the data shown here.

half-lives and to determine the energies and relative intensities of the γ rays resulting from the ^{22}F decay. In other, higher-statistics runs, the counting time was reduced to a single period of 6 sec per cycle, in order to maximize the accumulation of data in the search for weak γ lines. Figure 2 shows a typical singles γ-ray spectrum, accumulated for the first 6 sec following bombardment in the first mode of operation. Besides well-known lines from ^{15}C, ^{16}N, ^{19}O, ^{20}F, ^{21}F, ^{22}Na, and ^{23}Ne decay, seven transitions were observed to decay with a half-life near 4 sec, and have been assigned to the ^{22}F decay. Their energies were determined using well-known lines in the spectrum as calibrations. Table I gives the observed energies from the present experiment, along with those from previous work using Ge(Li) detectors. Decay half-lives were extracted for seven of the γ rays, using dead-time corrections obtained from the ^{19}O decay. The resulting half-lives are also shown in Table I. The mean of the seven measurements yields the value of 4.23 ± 0.04 sec for the half-life of ^{22}F. This is in good agreement with the two previous results[3,5] quoted above. Table I also shows the energies of further lines that we detected in the high-statistics run, but therefore without information as to lifetime. That of 823.5 keV is not firmly established but is included on the basis of its fitting into the established level scheme of ^{22}Ne as a transition between the 6345.0- and 5523.4-keV levels (expected energy 821.6 ± 1.2 keV). The 3983.5-keV line is seen in singles in the full energy, 1-mc^2-escape and 2-mc^2-escape peaks and also appears in coincidence with the 1274.6- and 2082.6-keV lines. It therefore represents the deexcitation via the 3357.2-keV level of a level in ^{22}Ne at 7341.1 ± 1.1 keV that may correspond to one or other of the levels reported[7] at 7336 ± 7 and 7350 ± 20 keV. The 4247.9-keV line is also seen in all three peaks in the singles spectrum. It is in coincidence with the 1274.6- but not with the 2082.6-keV line and represents the deexcitation via the 1274.6-keV level of that at 5523.4 keV (expected energy 4248.4 ± 0.8 keV). Great care was taken in establishing limits to the intensities of possible γ rays from the $J^\pi = 2^+$ states, particularly those at 4454 and 5360 keV, since such γ transitions themselves place upper limits on the direct feeding of those states in ^{22}F decay and hence reflect upon the spin of ^{22}F as will be discussed later.

The Ge(Li) counter efficiencies were determined in the exact geometry of the ^{22}F runs, with the same absorbing screens in place, by the use of a set of standard calibrated γ sources and ^{56}Co. Before translating the observed γ-line strengths into primary γ intensities a correction must be made for the contribution to the 1274.6-keV line from the decay of the ^{22}Na that is also produced in the bombardment. A special short run with a fresh target was taken to accurately establish the ratio $I_\gamma(2082.6)/I_\gamma(1274.6)$ for ^{22}F decay by counting in two time bins, as well as counting the accumulated ^{22}Na later. The contribution from ^{22}Na to $I_\gamma(1274.6)$ for this run was 0.2%. Corrections must also be made for γ summing in the Ge(Li) detectors for ^{22}F decay as well as in the construction of the efficiency calibration curves.

TABLE I. Energies (in keV) of γ-ray transitions in ^{22}Ne and their half-lives.

E_γ (present)	$T_{1/2}$ (sec)	E_γ [a]	E_γ [b]	E_γ [c]	E_γ [d]
(823.5 ± 1.2) [e]					
1274.6 ± 0.3	4.238 ± 0.042	1275 ± 3	1274.5 ± 3	1273.7 ± 0.4	
1900.0 ± 0.6	4.05 ± 0.26	1900 ± 3	1899.0 ± 5		
2082.6 ± 0.5	4.228 ± 0.038	2080 ± 3	2085.7 ± 3	2077.6 ± 1.0	2082 ± 2
2166.1 ± 0.5	4.241 ± 0.047	2165 ± 3	2170.4 ± 5	2162.9 ± 1.1	
2283.9 ± 0.7	4.46 ± 0.53	2283 ± 3			
2987.7 ± 0.9	4.10 ± 0.38	2984 ± 3	2991.1 ± 5	2992.8 ± 1.2	2991.9 ± 0.7 [f]
3983.5 ± 1.0					
4247.9 ± 1.0					
4366.1 ± 1.0	4.44 ± 0.39	4360 ± 3	4345.7 ± 15		

[a] From ^{22}F decay; Ref. 5.

[b] From the ^{19}F $(\alpha,p\gamma)^{22}$Ne reaction; W. G. Davies and J. S. Forster, private communication.

[c] From the ^{21}Ne $(n,\gamma)^{22}$Ne reaction; D. Bellman, Atomkernenergie 17, 145 (1971).

[d] From the ^{19}F $(\alpha,p\gamma)^{22}$Ne reaction; E. K. Warburton, J. W. Olness, and A. R. Poletti, Phys. Rev. 160, 938 (1967).

[e] This line is not certain.

[f] From the ^{19}F $(\alpha,p\gamma)^{22}$Ne reaction; E. K. Warburton, L. E. Carlson, G. T. Garvey, D. A. Hutcheon, and K. P. Jackson, Nucl. Phys. A136, 160 (1969).

Table II gives the results of the relative-intensity measurements, and also those obtained by Guratzsch *et al.*[5]

B. γ-γ coincidence measurements

Six of the seven γ rays observed in ^{22}F decay by Guratzsch *et al.*[5] were assigned as transitions between known levels in ^{22}Ne. They postulated the existence of a new state at an excitation energy of 7535 ± 9 keV, which deexcites by emitting a 1900-keV γ ray to the $J^\pi = 3^+$ state at 5.64 MeV. The $J^\pi = 3^+$ assignment for the 5.64-MeV level has been made by Ollerhead *et al.*,[8] who showed that this state has unnatural parity. Its spin had previously been shown to be 2 or 3,[9] and (d,p) measurements indicate that it has positive parity.[7] Both the placement of the 1900-keV transition and its intensity are crucial to the assignment by Guratzsch *et al.*[5] of $J^\pi = 5^+$ to the ^{22}F ground state. If the 5.64-MeV state were to be populated directly by an allowed β transition, the ^{22}F ground state could not be $J^\pi = 5^+$. The intensity measurements of Guratzsch *et al.*[5] account for all the deexcitation strength of the 5.64-MeV state by γ-ray population from the 7.54-MeV state. Our first indication that the 5.64-MeV state must be at least partially populated directly by β rays was the observation that the relative intensity of the 1900.0-keV transition, as given in Table II, was only half as great as that reported by Guratzsch *et al.*[5] Even if the placement of this transition as terminating on the 5.64-MeV level were to be correct our data would still require direct β feeding of this state in order to account for the total intensity of the 2283.9- and 4366.1-keV γ rays.

According to the ^{22}F decay scheme of Guratzsch *et al.*,[5] the 1900.0-keV transition should be in coincidence with the 4366.1-, 2283.9-, 2082.6-, and 1274.6-keV transitions, and not in coincidence with the 2166.1-keV γ rays. We performed several sets of γ-γ coincidence measurements for the seven strongest γ rays observed in ^{22}F decay. Digital gates were set on the photopeaks and on suitable nearby background regions. 30-cm^3, 60-cm^3, and 70-cm^3 Ge(Li) detectors were used in various combinations and with various gains depending on whether attention was being directed to high- or low-energy coincident γ rays. The 1900.0-keV transition was observed to be in coincidence with only the 2166.1-, 2082.6-, and 1274.6-keV transitions, indicating that the 1900.0-keV γ ray terminates on the 5523.4-keV state in ^{22}Ne($J^\pi = 4^+$), rather than on the 5.64-MeV level. The placements for the other transitions agreed with those obtained by Guratzsch *et al.*[5] Weaker transitions also detected in the coincidence runs have already been noted.

TABLE II. Relative intensities of γ rays from ^{22}F decay.

E_γ (keV)	Relative intensity [a]	Relative intensity [b]
(823.5) [c]	(≈0.3)	
1274.6	100	100
1900.0	8.7 ± 0.4	15 ± 2
2082.6	81.9 ± 2.0	73 ± 3
2166.1	61.6 ± 1.4	62 ± 4
2283.9	5.1 ± 0.3	6 ± 2
2987.7	7.0 ± 0.3	7 ± 2
3983.5	1.2 ± 0.2	
4247.9	1.0 ± 0.2	
4366.1	11.3 ± 0.6	12 ± 2

[a] Present work.

[b] Reference 5.

[c] This line is not certain.

C. Excitation energies of ^{22}Ne states

Using the measured energies of the ^{22}F decay γ rays, and the decay scheme to be discussed below, accurate values for excitation energies of states in ^{22}Ne have been obtained. All of these values have been corrected for nuclear recoil. Table III shows the excitation energies obtained from the present experiment, along with previous results from other work, and adopted values. Where possible, other measurements using Ge(Li) detectors have been used. In the case of the 5641.1-keV state, the present value is the average of two determinations obtained from the triple cascade and the double cascade. The two differed in value by only 0.16 ± 1.7 keV.

D. β-γ coincidence measurements

In order to further clarify the origin of the various γ rays observed in ^{22}F decay, the spectra in the NE102 scintillator coincident with the photopeaks and backgrounds for each of seven γ rays were

TABLE III. Excitation energies (in keV) for ^{22}Ne states.

E_x (present)	E_x [a]	E_x (adopted)
1274.6 ± 0.3	1274.58 ± 0.03	1274.58 ± 0.03
3357.3 ± 0.5	3356 ± 2	3357.2 ± 0.5
5523.5 ± 0.7	5521 ± 4	5523.4 ± 0.7
5641.3 ± 0.8	5637 ± 4	5641.1 ± 0.8
6345.2 ± 1.0	6343 ± 3	6345.0 ± 1.0
7341.1 ± 1.1		7341.1 ± 1.1
7423.6 ± 0.9	7440 ± 20	7423.6 ± 0.9

[a] Reference 7.

recorded simultaneously. The calibration spectra coincident with the 1633.6-keV line from ^{20}F decay and the 439.9-keV line from ^{23}Ne decay were also accumulated at the same time. Data were taken in two 4-sec time bins, with β counting rates varying between 60 000 and 40 000 per sec from the beginning to the end of the counting period. β pulses were shaped to a full width of 700 nsec, and pileup rejection circuitry vetoed events if two pulses of more than 250 keV occurred with a time difference between 25 and 1000 nsec. A real-to-random ratio of 150 or greater was maintained.

In order to decrease the effects of γ-ray summing in the NE102, the scintillator was moved back 3.3 cm from the source. Rather than moving the detector further away to reduce the summing effects to a negligible value, which would severely limit the β-ray statistics, we decided to carry out the measurements at 3.3 cm and calculate numerically the effects of β-γ summing in the NE102 scintillator.

Fortunately, the strongest β-ray branch from ^{22}F decay is that to the 5523.4-keV level, whose end-point energy is very close to that from the strong ^{20}F calibration spectrum (end point = 5393 keV). Previous experiments have shown[1] that to a good approximation the shapes for β spectra may be calculated by numerically interpolating between the shapes of calibration spectra, or by simply stretching horizontally the observed ^{20}F shape to generate the expected shape for any β ray likely to be encountered in the ^{22}F decay.

The response of the NE102 scintillator to γ rays of various energies are closely approximated by stretching or compressing the measured shape for the 1836-keV γ ray from ^{88}Y decay.

Therefore, in contrast to Guratzsch *et al.*,[5] we do not present Kurie plots of the various β spectra, but show each spectrum along with a detailed calculation of the response of the NE102 to all the β rays, γ rays, and β-γ summing events coincident with the appropriate γ ray in the Ge(Li) detector. The observed spectra are shown in Fig. 3. For each spectrum the calculated solid curve is based upon the β-ray intensities and origins shown in Fig. 4. The spectra of Fig. 3 are shown in order of increasing excitation energy in ^{22}Ne.

The spectrum coincident with the 2166.1-keV γ ray contains many kinds of events. Shapes for β rays feeding the 5523.4-keV level, denoted

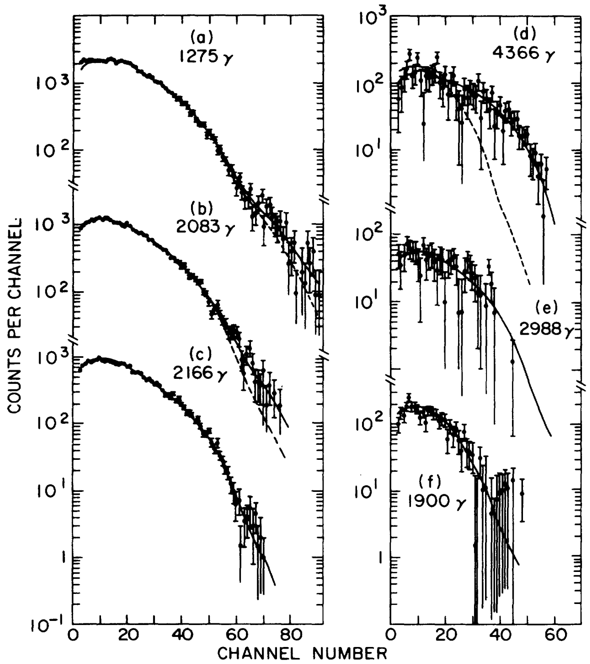

FIG. 3. The measured spectra of pulses in the NE102 detector coincident with each of six γ rays from the decay of ^{22}F. The solid curves are detailed calculations of the expected shape for the decay scheme shown in Fig. 4. The significance of the dashed curves is discussed in the text.

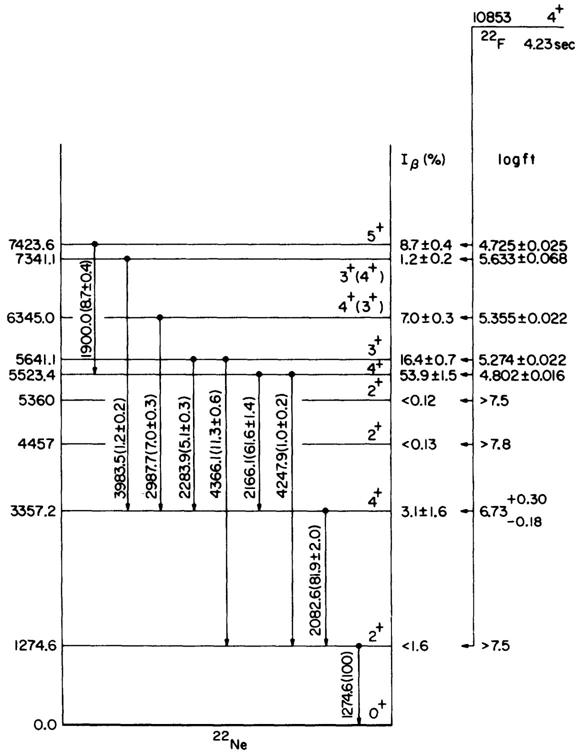

FIG. 4. ^{22}F decay scheme. Excitation energies in ^{22}Ne are in keV (see also Table III). Transitions are identified by energy in keV (see also Tables I and IV) and intensity (in parentheses) relative to the 1274.6-keV transition (see also Tables II and IV). For β branching ratios and log*ft* values see also Table IV. J^{π} values are discussed in the text.

$\beta(5523.4)$, γ rays of either 2082.6 or 1274.6 keV, denoted $G(2082.6)$ and $G(1274.6)$, respectively, and summing between $\beta(5523.4)$ and the two γ rays, denoted $\beta G(5523.4, 2082.6)$ and $\beta G(5523.4, 1274.6)$, respectively, have been computed. In addition, the triple-summing term $\beta GG(5523.4, 2082.6, 1274.6)$ has been calculated. β rays feeding the 7423.6-keV level, $\beta(7423.6)$, singles γ-ray terms $G(1900.0)$, $G(2082.6)$, $G(1274.6)$, summing terms $\beta G(7423.6, 1900.0)$, $\beta G(7423.6, 2082.6)$, and $\beta G(7423.6, 1274.6)$ have also been computed. These 13 calculated shapes have been combined to generate the expected spectrum coincident with the 2166.1-keV γ ray detected in the Ge(Li), by multiplying each calculated shape by the probability that the appropriate radiations interact (or do not interact) in the appropriate detectors [NE102 or Ge(Li)]. In general, angular-correlation effects between the γ rays detected in the Ge(Li) and those interacting in the NE102 detector have been included where the appropriate multipole-mixing ratios are known. Neglected in the calculation are summing terms involving two or more γ rays interacting in the NE102, since their magnitude is negligible except for the one term βGG mentioned above, which can produce the highest-energy pulses in the NE102 detector, for terms of this kind. The comparison between this calculation and the data is given in Fig. 3(c), showing that the observed spectrum is consistent with that expected on the basis of the decay scheme presented in Fig. 4. The calculations shown in Fig. 3(c) were carried out for a value for Q_β (the maximum possible β-ray energy to the ^{22}Ne ground state) of 10.95 MeV, since it provided the best fit to the data coincident with 2166.1-keV γ ray. After considering effects of uncertainties in inner β-ray branches and possible slight gain differences between the ^{22}F data (which decays a factor of 4 during the counting cycle) and the ^{20}F internal calibration (which does not decay by more than about 40%), we deduce a value for Q_β of 10.95 ± 0.12 MeV. This is to be compared with the more precise value of 10.853 ± 0.030 keV of Ref. 4.

Figure 3(d) is the spectrum coincident with the 4366.1-keV γ ray, compared with the expected shape assuming that the decay scheme of Fig. 4 is correct (solid curve) and the calculated shape assuming the decay scheme of Guratzsch *et al.*[5] is correct (dashed curve). This shows conclusively that the 5641.1-keV level in ^{22}Ne, which has $J^\pi = 3^+$, is fed directly by a β-ray transition, and not solely by the 1900.0-keV γ ray as contended by Guratzsch *et al.*[5] As mentioned above, our γ-γ coincidence work confirms this conclusion.

Of particular interest are possible β-ray branches to the first two excited levels of ^{22}Ne. By examining the data of Fig. 3 (b) for the spectrum coincident with the 2082.6-keV γ ray, one deduces that a β branch of $3.1 \pm 1.6\%$ to the 3357.2-keV is required to fit the data. The dashed curve for this spectrum was calculated assuming no β branch to the 3357.2-keV level. The spectrum in Fig. 3(a) coincident with the 1274.6-keV γ ray now can provide a measure of the β branch to the 1274.6-keV level. Shown in Fig. 3(a) are the best fit (solid curve) for a branch of 0.6%, and the dashed curve assuming no branch to this level. Both curves were calculated for a 3.1% branch to the 3357.2-keV level. However, because of the uncertainty in this 3.1% branch, we can assign only a $0.6^{+1.0}_{-0.6}\%$ branch to the 1274.6-keV level, viz., a branch of less than 1.6% at the 85% confidence level. The excess of counts for channels ≤ 7 in these data is due to β^+ rays and annihilation quanta from the decay of ^{22}Na.

Figures 3(e) and 3(f) show that the β spectra coincident with the 2987.7- and 1900.0-keV γ rays are consistent with the decay scheme shown in Fig. 4.

E. Decay scheme for ^{22}F

Using the results above, a decay scheme for ^{22}F has been constructed, and is shown in Fig. 5. Appearing on this decay scheme are only the states in ^{22}Ne which are of importance for the ^{22}F decay. Logft values given in Fig. 4 as well as in Table IV have been calculated using the Q_β as determined by Stokes and Young.[4] The observed γ branching of the 5641.1-keV state agrees with the measurements of Kutschera, Pette, and Schrieder[9] and Howard *et al.*[10] Allowed β branches to the $J^\pi = 3^+$ 5641.1-keV state and the $J^\pi = 4^+$ 5523.4-keV state restrict the ^{22}F ground state to $J^\pi = 3^+$ or 4^+. Other allowed transitions are thus limited to states of $J^\pi = 2^+$, 3^+, 4^+, or 5^+.

It will be noted from Tables II and IV and from Fig. 4 that the sum of the intensities of the γ rays feeding the 1274.6-keV state, namely $94.2 \pm 2.1\%$ falls short of the 100% assigned to the 1274.6-keV γ ray. [A similar discrepancy appears in the results of Guratzsch *et al.*[5] who find a feeding intensity of $86 \pm 4\%$—after allowance for our 1% branch from the 5523.4-keV state.] This discrepancy is too large to be resolved through the upper limit of 1.6% on the direct β feeding of the 1274.6-keV level and, in any case, as will emerge from the subsequent discussion, we believe that this β feeding is effectively zero. It therefore appears that the there may remain a few percent of β feeding of other ^{22}Ne states that we have not detected although this is surprising to us in view of the effort with which we have searched. A similar, although scarcely significant, discrepancy may also arise at the 3357.2-keV state where the feeding (including the direct β feeding) is 78.0 ± 2.2% against a deexcitation of 81.9 ± 2.0%.

III. DISCUSSION

The assignment of $J^\pi = 5^+$ for the ground-state spin and parity of ^{22}F was made by Guratzsch *et al.*[5] on the basis of (i) direct β feeding of a state at 6.35-MeV in ^{22}Ne which they identified as having $J^\pi = 6^+$, and (ii) their contention that the $J^\pi = 3^+$ state in ^{22}Ne at 5.64 MeV is not populated by direct β feeding. We have shown that the 5641.1-keV state is indeed populated directly by the β decay of ^{22}F, and will now present evidence that the relevant state at 6345.0 keV in ^{22}Ne is not of $J^\pi = 6^+$.

Broude, Davies, and Forster,[11] using a Ge(Li) detector, have identified the $J^\pi = 6^+$ member of the so-called ground-state rotational band in ^{22}Ne as being at 6.30 MeV, and not at 6.35 MeV as reported by Kutschera, Pelte, and Schrieder.[9] The latter work was performed using an NaI(Tl) detector. In fact, using the adopted excitation energy of 3357.2 keV for the $J^\pi = 4^+$ member of the "ground-state rotational band," and the measured value for the $J^\pi = 6^+ \rightarrow 4^+$ transition energy of 2948 ± 3 keV,[12] the excitation energy of the $J^\pi = 6^+$ state becomes 6305.4 ± 3.0 keV. This value is about 40 keV lower in energy than the state which receives the β feeding from ^{22}F decay.

Bellmann,[13] who studied thermal neutron capture in ^{21}Ne, observed a γ ray of energy 4023.8 ± 4.3 keV, which he attributed to a transition between the 10 362-keV neutron-capture state and a state in ^{22}Ne at 6344 keV. Using the latest atomic masses,[14] and correcting for nuclear recoil, this places the state in ^{22}Ne at 6341.4 ± 4.4 keV, agreeing with the present adopted value of 6345.0 ± 1.0 keV. More importantly, Bellmann's observation of a direct transition to this state following thermal neutron capture by ^{21}Ne requires that this state must be of $J \leq 4$. This follows from the fact that the 10.36-MeV capture state (or states) is restricted to $J^\pi = 1^+$ or 2^+ since thermal neutron capture implies $l_n = 0$. We are assuming that the 4023.8-keV transition observed by Bellmann is dipole or quadrupole, or a mixture of these.

We carry out our further discussion at three levels: A. certainties, B. high systematic probabilities, and C. comparison with the theoretical model as summarized in Table IV.

A. Certainties

^{22}F shows allowed β transitions to ^{22}Ne states of $J^\pi = 3^+$ (at 5641.1 keV) and of $J^\pi = 4^+$ (at 5523.4 keV) so that its $J^\pi = 4^+$ (at 5523.4 keV) so that its J^π

TABLE IV. β decay of ^{22}F to levels of ^{22}Ne of concern in the present work. All limits are at the 85% confidence level.

E_x [a] (keV)	J	I_β [b] (rel.)	E_γ [c] (keV)	I_γ [b] (rel.)	log*ft* [b] (exp)	Calculated log*ft* [d] $J^\pi[^{22}\mathrm{F}(0)] = 4^+$
1274.58 ± 0.03	2_1	$0.6^{+1.0}_{-0.6}$	1274.54 ± 0.03	100	>7.5	
3357.2 ± 0.5	4_1	3.1 ± 1.6	2082.6 ± 0.5 [b]	81.9 ± 2.0	$6.73^{+0.30}_{-0.18}$	7.03
4454.2 ± 0.9 [e]	2_2	<0.13	3179.4 ± 0.9 [e]	<0.13	>7.8	
5360 ± 8	2_3	<0.12	4085.0 ± 8.0	<0.12	>7.5	
5523.4 ± 0.7	4_2	53.9 ± 1.5	2166.1 ± 0.5 [b] 4247.9 ± 1.0 [b]	61.6 ± 1.4 1.0 ± 0.2	4.802 ± 0.016	4.59
5641.1 ± 0.8	3_1	16.4 ± 0.7	2283.9 ± 0.7 [b] 4366.1 ± 1.0 [b]	5.1 ± 0.3 11.3 ± 0.6	5.274 ± 0.022	5.36
6345.0 ± 1.0	$4_3(3_2)$	7.0 ± 0.3	(823.5 ± 1.2 [b,f] 2987.7 ± 0.9 [b] 5069.8 ± 1.0	(≈0.3) 7.0 ± 0.3 <0.20	5.355 ± 0.022	5.69(4_3) 5.58(3_2)
7341.1 ± 1.1	$3_2(4_4)$	1.2 ± 0.2	3983.5 ± 1.0 [b] 1699.8 ± 1.4 1817.7 ± 1.3 6066.5 ± 1.1	1.2 ± 0.2 <0.2 <0.06 <0.3	5.633 ± 0.068	5.58(3_2) 5.24(4_4)
7423.6 ± 0.9	5_1	8.7 ± 0.4	1900.0 ± 0.6 [b] 4066.0 ± 1.0	8.7 ± 0.4 <0.14	4.725 ± 0.025	4.68

[a] Adopted values from Table III, others from Ref. 7.

[b] Present work.

[c] Calculated from E_x values in column 1, unless otherwise indicated.

[d] Reference 2 using $(g_A/g_V)^2 = 1.565$.

[e] See footnote f of Table I.

[f] This line is not certain.

must be 3^+ or 4^+. [We note for discussion under C. the rather high logft (≈6.7) for the $J^\pi = 4^+$ state at 3357.2 keV which we must hope will find an explanation within the framework of the theoretical model.] By the same argument the states at 6345.0, 7341.1, and 7423.6 keV are limited to $J^\pi = 2-5^+$.

B. Probabilities

The β decay of ^{22}F to the three lowest $J^\pi = 2^+$ states (2_1, 2_2, and 2_3) at 1274.6, 4454, and 5360 keV has log$ft > 7.5$, 7.8, and 7.5, respectively.[15] Thus we establish, with high probability, that ^{22}F cannot have $J^\pi = 3^+$.

The γ decays of the ^{22}Ne states at 6345.0, 7341.1, and 7423.6 keV are all predominately to states of $J^\pi = 4^+$. If these former states were of $J^\pi = 2^+$ and if we hypothesized the high $B(E2)$ value of 50 e^2fm^4 [8.7 Weisskopf units (W.u.)][16] for their $E2$ transitions to the respective $J^\pi = 4^+$ states the experimental upper limits on what would then be the missing $M1$ transitions to the $J^\pi = 2^+$ first excited state would be $B(M1) < (1.9\times10^{-4})$, (1.5×10^{-3}), and $(6.3\times10^{-6})\mu_N^2 < (1.1\times10^{-4})$, (8×10^{-4}), and (3.5×10^{-6}) W.u. These numbers are all such that we can reject the $J^\pi = 2$ hypothesis with good confidence[17] and restrict serious consideration to $J = 3$, 4, or 5 for the three states in question.

C. Model

As we have already noted, the model predicts $J^\pi = 4^+$ for the ^{22}F ground state but with a $J^\pi = 3^+$ first excited state at 110 keV so either of these might well have been right *a priori*. $J^\pi = 3^+$ or 4^+ are indeed the only possible experimental choices but the large logft limits on the three β transitions to the $J^\pi = 2^+$ states very strongly favor $J^\pi = 4^+$. For $J^\pi = 3^+$ the model predicts the allowed transition to 2_1 should in fact be rather slow (log$ft = 6.11$)[18] although some 25 times faster than our experimental upper limit; the discrepancies in speed between experiment and the model for the transitions to 2_2 and 2_3 would however be much greater, namely >600 and >150, respectively. (Theoretical logft values are 4.96 and 5.28, respectively.) In view of other excellent successes of the model in $A = 22$ and its essential freedom from major error, such gross discrepancies, particularly on two theoretically quite strong transitions could scarcely be tolerated and we have little doubt but that ^{22}F is of $J^\pi = 4^+$. This is confirmed by other comparisons with the model now to be presented for the various ^{22}Ne states of relevance in order of increasing excitation. Unless remarking to the contrary, we are assuming that ^{22}F is of $J^\pi = 4^+$.

TABLE V. Theoretical $B(M1)$ and $B(E2)$ values of relevance to the discussion in the text. Other $B(E2)$ values of relevance are given in Ref. 2.

Transition	$B(M1)$ (μ_N^2)	$B(E2)$ (e^2 fm^4)
$2_3 \to 0_1$		3.75
$4_4 \to 2_1$		3.74
$3_1 \to 2_1$	4.04×10^{-2}	
$3_1 \to 4_1$	9.15×10^{-2}	
$3_2 \to 2_1$	3.96×10^{-2}	
$3_2 \to 3_1$	0.387	
$3_2 \to 4_1$	0.205	
$3_2 \to 4_2$	1.76×10^{-2}	
$4_3 \to 4_1$	0.354	
$4_3 \to 4_2$	1.01	
$4_4 \to 3_1$	2.48×10^{-2}	
$4_4 \to 4_1$	2.56×10^{-2}	
$4_4 \to 4_2$	2.78×10^{-3}	
$5_1 \to 4_1$	2.36×10^{-3}	
$5_1 \to 4_2$	0.640	

3357.2 keV. We noted above the rather slow allowed β transition to this state (log$ft = 6.73^{+0.30}_{-0.18}$). It is therefore most pleasing to find that the theoretical speed for 4_1 is not only also low (logft = 7.03) but is in excellent agreement with experiment. [The theoretical speed for the discarded $J^\pi = 3^+$ possibility for ^{22}F is also low (log$ft = 6.18$) and, for a weak transition, would also have to be said to be in acceptable agreement with experiment.] We therefore confirm that this is the theoretical 4_1 state.

5523.4 keV. Agreement between experimental (log$ft = 4.802 \pm 0.016$) and theoretical (log$ft = 4.59$) β-decay rates is good if this is the theoretical 4_2 state. (The $J^\pi = 3^+$ possibility for ^{22}F also provides an acceptable prediction—log$ft = 5.00$).

This is the first state of ^{22}Ne for which we can test a prediction of the model as to γ decay. We have detected the 4247.9-keV $E2$ transition to the first excited state, 2_1, with a branching ratio of 0.016 ± 0.003 relative to the 2166.1-keV transition to 4_1. The model predicts a branch of 0.018 in excellent agreement with our experimental number. In view of these agreements with the predictions of the model we take it that this is the theoretical 4_2 state.

5641.1 keV. Agreement between experimental (logft = 5.274 ± 0.022) and theoretical (logft = 5.36) β-decay rates is good if this state is the model's 3_1. (The $J^\pi = 3^+$ possibility for ^{22}F gives the prediction log$ft = 6.66$, which could scarcely be found acceptable.)

For the $(3_1 \to 2_1)/(3_1 \to 4_1)$ branching ratio we find experimentally 2.2 ± 0.3. The theoretical branching ratio, including [illegible] $E2$ components, is 3.3 in quite good agreement with experiment. In view of these agreements with the prediction of the model we take it that this is the theoretical 3_1 state.

6345.0-keV state. This is the first of our states whose association with the model is not effectively unambiguous. We have the experimental possibilities $J^\pi = 2$, 3, and 4^+ with $J^\pi = 2^+$ most unlikely on account of the γ decay as noted above. The $J^\pi = 4^+$ assignment for ^{22}F leaves 3_2 and 4_3 as possible model assignments. Before making detailed comparison with the model we should favor $J^\pi = 4^+$ on account of the absence of a branch to the first excited state: $(6345.0 \rightarrow 1274.6)/(6345.0 \rightarrow 3357.2) < 0.03$ against an $E_\gamma{}^3$ ratio of 4.9. The model's value for the above branching ratio is 0.0015 if the state is 4_3. The theoretical expectation for the above branching ratio if the state is 3_2 is 0.94. It therefore seems that this state must be 4_3.

The theoretical $4_3 \rightarrow 4_2$ transition is very strong giving the theoretical expectation $(6345.0 \rightarrow 5523.4)/(6345.0 \rightarrow 3357.2) = 0.059$. Experimentally we indeed have an indication of a line at 823.5 ± 1.2 keV (expected energy 821.5 ± 1.2 keV) in the relative intensity of about 0.05 but we cannot regard it as definitely established. (The theoretical expectation for this branching ratio for 3_2 is 0.002.)

Agreement with the experimental β-decay strength ($\log ft = 5.355 \pm 0.022$) is acceptable for the 4_3 assignment which predicts $\log ft = 5.69$ as it would also have been for the 3_2 assignment with the theoretical $\log ft = 5.58$.

7341.1-keV state. The allowed β decay suggests $J^\pi = 3, 4, 5^+$ with the model assignments 3_2, 4_4, or 5_1. The last possibility would give the expectation that the dominant decay be to 4_2 at 5523.4 keV (see following discussion of the 7423.6-keV state) rather than to 4_1 at 3357.2 keV so we set it aside leaving 3_2 and 4_4. [Note that if we were wrong in our 4_3 assignment to the 6345.0-keV state 4_3 would come into play for the present state. We should, however, incline to reject it because it would lead to the prediction: $(7341.1 \rightarrow 5523.4)/(7341.1 \rightarrow 3357.2) = 0.27$ against the experimental limit of <0.050.] Consider the possible branch $(7341.1 \rightarrow 1274.6)/(7341.1 \rightarrow 3357.2)$ for which we have the experimental value <0.25. 3_2 predicts 0.68 for this ratio which contradicts experiment but not so badly as 4_4 which has the theoretical expectation of 1.32 for this ratio. The 3_2 assignment does not conflict with the above experimental limit of 0.050 on the relative branch to the 5523.4-keV state for which it predicts 0.008. Nor is there conflict with the experimental limit $(7341.1 \rightarrow 5641.3)/(7341.1 \rightarrow 3357.2) < 0.17$ for which ratio 3_2 expects 0.15. The 4_4 alternative does not conflict with these experimental limits: The model predicts 0.010 for the former limit and 0.075 for the latter.

We therefore favor 3_2 for the 7341.1-keV state and note the good agreement between the experimental ($\log ft = 5.633 \pm 0.068$) and theoretical ($\log ft = 5.58$) β-decay rates. This preference over 4_4 is slightly strengthened by the latter's somewhat poorer agreement with the β-decay rate (theoretical $\log ft = 5.24$) and by the theoretical ordering of the 3_2 and 4_4 levels.

Note that association of 3_2 with any unassigned state of lower excitation is unlikely because we should then expect a strong β transition to that state and we do not see it. Similarly we cannot associate 3_3 with the 7341.1-keV state because its β transition would be too weak (theoretical $\log ft = 7.08$).

7423.6-keV state. The allowed β decay suggests $J^\pi = 3, 4, 5^+$; the most likely model assignments are 3_3, 4_4, or 5_1 with 3_2 also to be considered. We immediately eliminate 3_3 on account of its unacceptably large $\log ft$ value (7.08 as compared with the experimental 4.725 ± 0.025). The striking feature about the γ decay of this state is its strong favoring of the lower energy transition to 4_2 over the higher energy to 4_1: Experimentally $(7423.6 \rightarrow 3357.2)/(7423.6 \rightarrow 5523.4) < 0.016$, whereas the simple $E_\gamma{}^3$ factor gives about 10. The 5_1 prediction for this ratio is 0.050 (including $E2$ components). 4_4 predicts 91 for this ratio and 3_2 predicts 114. 5_1 is therefore uniquely successful in predicting that the branching ratio should, against the odds, be very small. It is also very successful in predicting the β-decay rate (theoretical $\log ft = 4.68$) and we therefore adopt 5_1 as the assignment. (3_2 and 4_4 would also be less satisfactory from the β-decay point of view since their theoretical $\log ft$ values are 5.58 and 5.24, respectively.)

SUMMARY

In very brief summary it may be said that there is no sign in the present study of any marked deterioration in the accuracy of the shell model's account of these complicated nuclei as compared to that which it offers for the simpler ones nearer the beginning of the shell. The very large scale computational efforts are justified and must obviously be extended deeper into the shell by some means in a manner that will preserve the full activity of all the ($2s$-$1d$)-shell basis states.

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[15] Our limits for the β transitions to 2_2 and 2_3 derive from the absence of γ transitions from those states to 2_1. These transitions are expected (Ref. 2) to dominate the respective decays by factors of 20 and 8.9 over the ground-state transitions. [We gather in Table V the theoretical $B(M1)$ values used in our discussion and also those relevant theoretical $B(E2)$ values that have not been previously published (Ref. 2).] Experimentally these respective ratios are (Ref. 9) ≥ 19 and ≥ 9. The respective $E2/M1$ relative amplitudes (absolute) in the dominant transitions are (Ref. 9) $0.08 + 0.02$ and 0.25 ± 0.08, as compared with the theoretical expectations of 0.059 and 0.21.

[16] The model (Ref. 2) finds good agreement with experiment on such $E2$ transition strengths as have been measured in $A = 22$. In ^{22}Ne the highest $B(E2)$ value predicted is 66 $e^2\,\mathrm{fm}^4$ and the average of the five strongest is 52 $e^2\,\mathrm{fm}^4$. 50 $e^2\,\mathrm{fm}^4$ therefore seems to be a reasonable "high" value to use in the present context.

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[18] The theoretical $\log ft$ values quoted in this paper use $(g_A/g_V)^2 = 1.565$.