Aust. J. Phys., 1983, **36**, 825–30

The Spectroscopy of ${}^{19}_{8}O_{11}$ and the ${}^{18}_{7}N_{11}$ Ground State

Raymond K. Sheline

Department of Nuclear Physics, Research School of Physical Sciences, Australian National University, G.P.O. Box 4, Canberra, A.C.T. 2601. Permanent address: Department of Physics, Florida State University, Tallahassee, FL 32306, U.S.A.

Abstract

The spectroscopies of ${}^{19}O$ and ${}^{21}Ne$ (both eleven-neutron systems) are compared. The $\frac{5}{2}^+$ [211↑], $\frac{1}{2}^+$ [220↑] and $\frac{1}{2}^-$ [101↓] bands are observed in both nuclei. On the basis of these similarities ${}^{19}O$ is assumed to be a prolate rotor like ${}^{21}Ne$. If then the recently studied ${}^{18}N$ ground state is also considered to be a deformed system (a one-proton hole in the ${}^{19}O$ nucleus), both the 1^- ground state spin and the sudden change in the systematics of the two-neutron binding energies can be understood.

For the most part ${}^{19}O$ has been interpreted in terms of the shell model since it has just three neutrons beyond the doubly closed shell ${}^{16}O$. Indeed, shell model calculations for ${}^{19}O$ have been quite successful. For example, Cole *et al.* (1974) have used the Preedom–Wildenthal interaction to calculate the positive parity states in ${}^{19}O$. Attempts to describe the ${}^{19}O$ level scheme in terms of a collective model were seriously hindered by the incompleteness of the data (Lambert *et al.* 1973). However, with the most recent compilation of data (Ajzenberg-Selove 1983; see also Fortune and Bingham 1977) the band structure of ${}^{19}O$ has become more obvious. This is shown in Fig. 1 where the band structures in ${}^{19}O$ and ${}^{21}Ne$ (both eleven-neutron systems) are compared.

In contrast to ${}^{19}O$, ${}^{21}Ne$ has long been recognized (Endt and Van der Leun 1978; Andritsopoulos *et al.* 1981) as a prolate deformed nucleus with $\varepsilon \sim 0\cdot3$. The ground state rotational band is conveniently described as the Nilsson orbital $\frac{3}{2}^+$ [211↑] Coriolis coupled to the $\frac{1}{2}^+$ [220↑] band beginning at $2\cdot795$ MeV. The $\frac{1}{2}^+$ [220↑] band is predicted by the Nilsson model to have a large positive decoupling parameter a which leads to an inversion in the spin sequence (i.e. $\frac{1}{2}^+$, $\frac{5}{2}^+$, $\frac{3}{2}^+$, $\frac{9}{2}^+$, $\frac{7}{2}^+$; see Fig. 1). Only the first three members of this band are known experimentally. By using these states, the fitted values for the inverse moment of inertia $\hbar^2/2\mathscr{I}$ and the decoupling parameter a are $299\cdot3$ keV and $1\cdot106$ respectively. When these parameters are used to calculate the excitation energies of the $\frac{9}{2}^+$ and $\frac{7}{2}^+$ members of this band, the energies ($8\cdot655$ and $8\cdot941$ MeV respectively) lie outside the range of experiment in which definite high spins have been assigned. The inverted nature of the $\frac{1}{2}^+$ [220↑] band in ${}^{21}Ne$ is reflected through Coriolis coupling in the decoupled nature of the $\frac{3}{2}^+$ [211↑] ground state band. There is also evidence for the $\frac{1}{2}^-$ [101↓] Nilsson band beginning at $2\cdot789$ MeV with the expected positive decoupling parameter. The first three members of this band are reasonably well established with possible $\frac{7}{2}^-$

0004-9506/83/060825$02.00

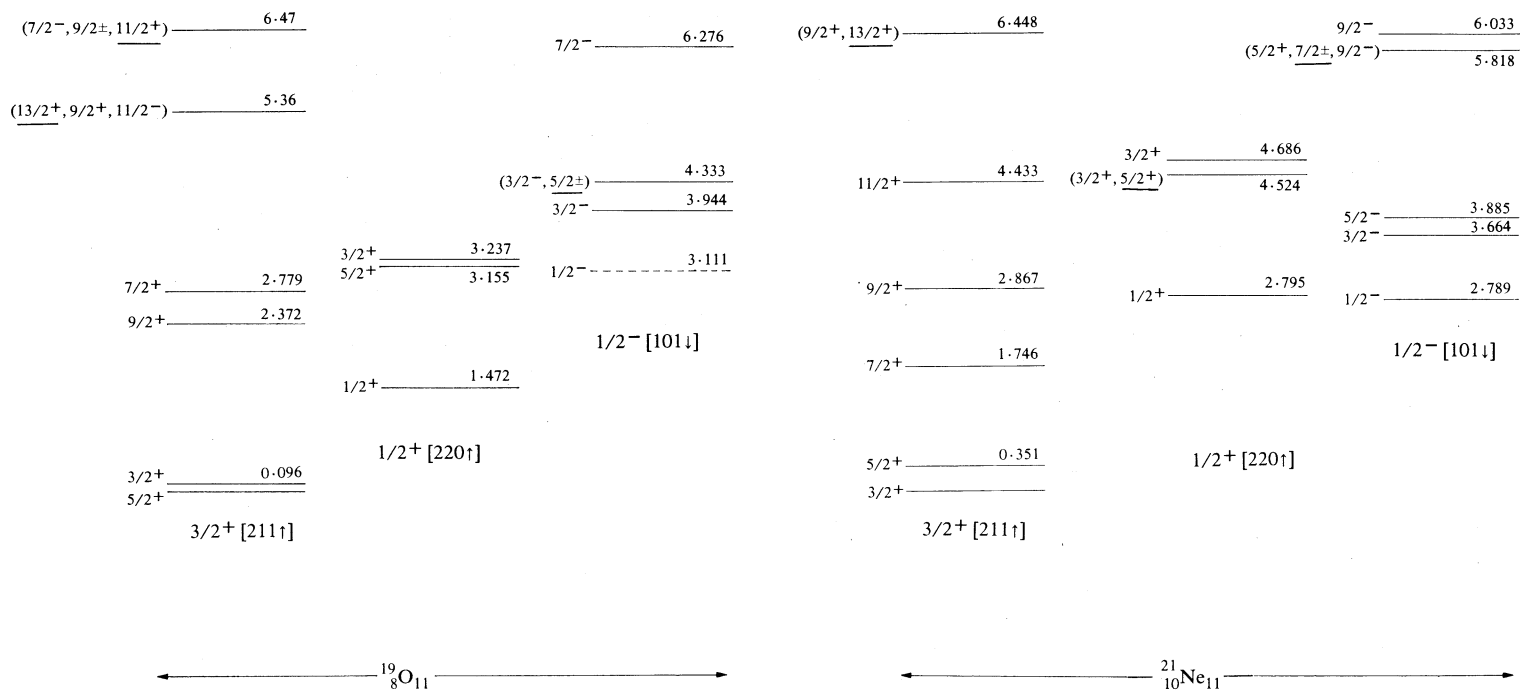

Fig. 1. Comparison of the rotational band systematics in ^{19}O and ^{21}Ne. The three lowest rotational bands are built on Nilsson orbitals $\frac{3}{2}^+[211\uparrow]$, $\frac{1}{2}^+[220\uparrow]$ and $\frac{1}{2}^-[101\downarrow]$ in each case. The $\frac{1}{2}^-$ band head has not been experimentally observed in the case of ^{19}O. Its calculated position using the rotational constants of Table 1 is shown as a dashed line. Data are taken from Ajzenberg-Selove (1983) and Fortune and Bingham (1977) for ^{19}O, and from Endt and Van der Leun (1978) and Andritsopoulos *et al.* (1981) in the case of ^{21}Ne. In those cases of multiple spin–parity assignments, the assignment used in the rotational band interpretations is underlined.

and $\frac{9}{2}^-$ members at 5·818 and 6·033 MeV respectively. The band head of the $\frac{5}{2}^+$ [202↑] orbital has been proposed at 3·736 MeV (not shown in Fig. 1). Possible $\frac{7}{2}^+$ and $\frac{9}{2}^+$ band members are the 5·63 MeV level and the 7·99 or 8·17 MeV levels respectively. Probable members of the $\frac{1}{2}^-$ [330↑] band with a large negative decoupling parameter are the 4·726 MeV ($\frac{3}{2}^-$), 5·691 ($\frac{1}{2}^-$) and 5·334 ($\frac{7}{2}^-$) levels. Much more tentative are the levels at 7·660 ($\frac{5}{2}^-$) and 7·363 ($\frac{11}{2}^-$). (This band is also not shown in Fig. 1.)

Table 1. Rotational constants of the three lowest lying bands in ^{21}Ne and ^{19}O

Because of the different amounts of Coriolis coupling in the $\frac{3}{2}^+$ [211↑] ground state bands of ^{21}Ne and ^{19}O, the inverse moments of inertia $\hbar^2/2\mathscr{J}$ are calculated as the $J(J+1)$ weighted average of the $\frac{3}{2}-\frac{7}{2}$, $\frac{5}{2}-\frac{9}{2}$, $\frac{7}{2}-\frac{11}{2}$ and $\frac{9}{2}-\frac{13}{2}$ energy spacings

Nilsson band designation	Band head energy (keV)	$\hbar^2/2\mathscr{J}$ (keV)	a	Band head energy (keV)	$\hbar^2/2\mathscr{J}$ (keV)	a
		^{21}Ne			^{19}O	
$\frac{3}{2}^+$ [211↑]	0	146		0	163	
$\frac{1}{2}^+$[220↑]	2795	299	1·106	1472	286	1·057
$\frac{1}{2}^-$[101↓]	2789	168	0·737	3111^A	178	0·562

^{A} Calculated (see text).

The spectroscopy of ^{19}O is surprisingly similar to that of ^{21}Ne. The ground state band is described as the Nilsson orbital $\frac{3}{2}^+$ [211↑] Coriolis coupled, as in ^{21}Ne, to the inverted spin sequence of the $\frac{1}{2}^+$ [220↑] orbital beginning at 1·472 MeV. Because the $\frac{1}{2}^+$ [220↑] orbital is closer to the ground state in ^{19}O, resulting in greater interaction between the two bands, the ground state band is also inverted in ^{19}O in contrast to ^{21}Ne. However, moments of inertia of the two sets of bands in ^{21}Ne and ^{19}O are unusually similar. To demonstrate this, the inverse moments of inertia (and decoupling parameters of $K = \frac{1}{2}$ bands) are compared for ^{21}Ne and ^{19}O in Table 1 for the three bands presented in Fig. 1. If we take the fitted values of $\hbar^2/2\mathscr{J}$ and a for the $\frac{1}{2}^+$ [220↑] band in ^{19}O and calculate the $\frac{9}{2}^+$ member of this band, we obtain 7·127 MeV, exceptionally close to an observed level at 7·118 MeV (Ajzenberg-Selove 1983). Unfortunately no spin–parity has been assigned to this state and it is therefore not shown in Fig. 1.

The close agreement of the band parameters in Table 1 for ^{21}Ne and ^{19}O results for the mixed bands as they occur experimentally. Although this is quite gratifying, one may ask how similar the bands would be before mixing through Coriolis coupling. Careful three-band Coriolis coupling calculations have been made by several authors (see e.g. Ajzenberg-Selove 1983) for ^{21}Ne. Such calculations are not possible for ^{19}O since the $K = \frac{5}{2}^+$ band has not been observed. However, since Coriolis coupling effects on the energy spacings occur between the $K = \frac{1}{2}^+$ and $\frac{3}{2}^+$ bands, we can at least compare these effects in ^{21}Ne and ^{19}O. Assuming a value for $\hbar^2/2\mathscr{J}$ of $\sim$150 keV for the ground state band and that the entire energy shift is due to the coupling between the $K = \frac{3}{2}^+$ and $\frac{1}{2}^+$ bands in both ^{21}Ne and ^{19}O, one calculates the $\frac{5}{2}^+$ state to lie $\sim$285 keV below the $\frac{3}{2}^+$ state in the ground state band of ^{19}O. Thus, the ground state band in ^{19}O is inverted even more drastically than observed experimentally. By assuming that the $K = \frac{5}{2}^+$ band lies somewhere in the vicinity of 3735 keV in ^{19}O (the same as in ^{21}Ne), this $\frac{5}{2}^+-\frac{3}{2}^+$ splitting would be lessened, possibly approaching the observed value of 96 keV. With these same assumptions, it is possible to show that the decoupling parameters of the $K = \frac{1}{2}^+$ bands in ^{21}Ne and ^{19}O would both need to be increased in the unmixed bands to give the experimental situation. However, here the second order coupling with the $K = \frac{5}{2}^+$ band is crucial and goes in the opposite direction.

The main difference in the low energy spectroscopies of ^{21}Ne and ^{19}O is in the failure in ^{19}O to observe the $\frac{1}{2}^-$ band head of the $\frac{1}{2}^-$ [101$\downarrow$] band. Using the band parameters from Table 1, we calculate the energy of the $\frac{1}{2}^-$ band head to be 3·111 MeV in the midst of a close lying triplet of states from 3·067 to 3·237 MeV. The shell model calculation presented in the paper by Fortune and Bingham (1977) also suggests that the $\frac{1}{2}^-$ state should occur in the vicinity of $\sim$2·9 MeV. It therefore seems probable that the failure to observe it involves an experimental difficulty. It may not have been resolved in the close lying triplet of states from 3·067 to 3·237 MeV.

All states below 5·430 MeV in ^{21}Ne have been accounted for in the band description given. The only unexplained state below 3·9 MeV in ^{19}O is the state assigned as $\frac{3}{2}^+$ at 3·067 MeV. A particularly attractive explanation for this state, from the band interpretation point of view, would be as the $\frac{1}{2}^-$ band head of the $\frac{1}{2}^-$ [101$\downarrow$] orbital. However, the data are more consistent with an explanation of this state as the $\frac{5}{2}^+$ band head of the $\frac{5}{2}^+$ [202$\uparrow$] band observed at 3·736 MeV in ^{21}Ne. It should be noted that in either case a change of spin for the 3·067 MeV state would be required.

Very little study of radiative transitions in ^{19}O has been undertaken to date. The limited study of lifetimes of states (Ajzenberg-Selove 1983) is not in very good agreement with either the shell model or the collective model. Studies of radiative transitions and lifetimes would be particularly valuable for future interpretations of ^{19}O.

If then we may assume from its spectroscopy that ^{19}O, like ^{21}Ne, is a prolate nucleus with deformation $\varepsilon \sim 0{\cdot}3$, this is not only of interest in its own right, but we may also try to interpret ambiguities in the ^{18}N ground state in terms of the prolate deformation of ^{19}O. In these considerations we think of ^{18}N as the $\frac{1}{2}^-$ [101$\downarrow$] proton hole in ^{19}O.

Recently, ^{18}N has been extensively studied. Olness *et al.* (1982) have shown conclusively, using the β^- decay of ^{18}N into ^{18}O, that the ground state (or beta decaying state) of ^{18}N must have $J^\pi = 1^-$. However, shell model calculations by these authors using the full 1 $\hbar\omega$ basis [s^4p^{11}, sd^3 and s^4p^{12}(sd) (pf) configurations] with the Chung–Wildenthal interaction (Chung 1976) for the sd shell and the Millener–Kurath (1975) interaction between the sd and the p shells have failed to reproduce the experimentally observed 1^- ground state. These shell model calculations predict a low-lying quartet of states from 0 to 155 keV with the 1^- state at 115 keV and a 2^- ground state. It should however be noted, as pointed out by Olness *et al.* (1982), that, since the shell model calculations overestimate the splitting of the $\frac{5}{2}^+$–$\frac{3}{2}^+$ doublet in ^{19}O by 110 keV, it is possible for the 2^- and 1^- states in ^{18}N to be even closer to each other when this difficulty is corrected.

In view of the failure of the shell model to predict the ground state spin of ^{18}N, it is of interest to attempt this prediction on a collective model basis. The two Nilsson orbitals which determine the ground state in $^{18}_{7}N_{11}$ are shown in Fig. 1. For the eleven-neutron system the lowest lying Nilsson orbital is $\frac{3}{2}^+$ [211$\uparrow$], while for the seven-proton system of this doubly odd nucleus the Nilsson orbital $\frac{1}{2}^-$ [101$\downarrow$] is predicted. The coupling of these two orbitals, according to the Gallagher–Moskowski (1958) coupling rules, energetically strongly favours the triplet or the configuration

$\nu\frac{3}{2}^{+}[211\uparrow]-\pi\frac{1}{2}^{-}[101\downarrow]$ to give a 1^{-} ground state as observed experimentally. The only way this prediction could be altered is if the $K = 2^{-}$ band (expected from the opposite pairing of the proton and neutron orbitals) Coriolis coupled with the 2^{-} state of the ground state band so strongly that one had an inverted order for the 1^{-} and 2^{-} members of the $K = 1^{-}$ band. This seems very improbable, although an excited state has been observed (Putt *et al.* 1983) at 120 keV in ^{18}N (presumably the 2^{-} state) which implies moderately strong Coriolis coupling.

The probable success of the 1^{-} prediction for the ground state is further sustained by the success of the Gallagher–Moskowski coupling rules over the entire periodic table. The only known failure in the case of the ground state of ^{166}Ho results because of zero point rotation energy which lifts the 7^{+} state above the 0^{+} ground state. Furthermore, one example of the success of the Gallagher–Moskowski coupling rules is ^{20}F which can be thought of in terms of coupling a proton to ^{19}O. In this case one would be coupling the $\frac{3}{2}^{+}[211\uparrow]$ neutron orbital to the $\frac{1}{2}^{+}[220\uparrow]$ proton orbital. The triplet configuration $\nu\frac{3}{2}^{+}[211\uparrow]+\pi\frac{1}{2}^{+}[220\uparrow]$ results in the observed 2^{+} ground state spin in spite of the inverted band sequence in ^{19}O.

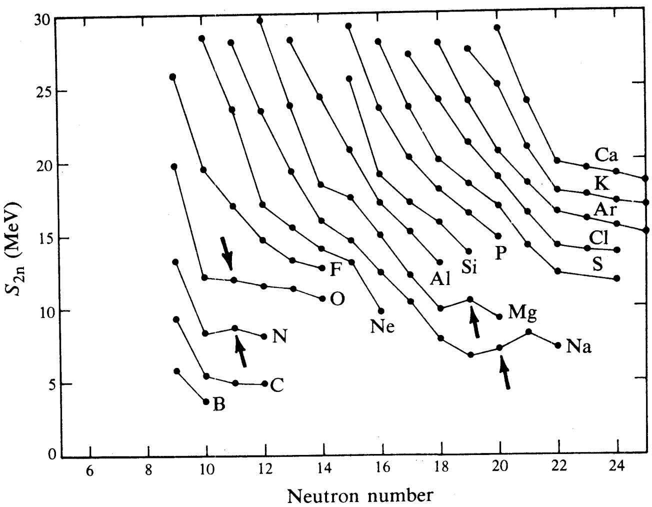

Fig. 2. Two-neutron separation energies for the isotopes of boron through to calcium plotted against neutron number. Arrows indicate the two-neutron separation energies of ^{18}N, ^{19}O, ^{31}Na and ^{31}Mg. The systematics suggest the onset of deformation as described in the text.

A systematic study of the excited state spectroscopy of ^{18}N is beyond the scope of the present paper. It is perhaps of value to point out that one would need to evaluate not only the rotational constants, but also the Gallagher–Moskowski (1958) splittings and a Newby (1962) splitting for the even and odd member spins of the expected $K = 0^{+}$ band. Finally, Coriolis coupling is expected and therefore the importance of Coriolis attenuation in these light nuclei would need to be addressed. In spite of the difficulties in making a detailed calculation of the ^{18}N excited state spectroscopy, it seems very unlikely that there could be more than two states (1^{-} and 2^{-}) in the first 155 keV rather than four as suggested in the shell model calculation (Olness *et al.* 1982).

Unfortunately, except for the ^{18}N ground state, no other spins and parities have been determined experimentally. Even the energies of ^{18}N excited states are controversial. It would therefore be of considerable interest to determine experimentally the energies, spins and parities of the excited states in ^{18}N.

Recently, the Q value of the reaction ^{18}O(^{7}Li, ^{7}Be)^{18}N was measured by Putt *et al.* (1983). This allowed a more accurate determination of the binding energy of ^{18}N than previously, leading to an unexpectedly large two-neutron separation energy S_{2n}. From Fig. 2, it can be seen that $S_{2n}(^{18}\mathrm{N}) > S_{2n}(^{17}\mathrm{N})$. This effect, where $S_{2n}(N) \gtrsim S_{2n}(N-1)$, involving a sudden change in the systematics of the two-neutron separation energies, has been interpreted (Thibault *et al.* 1975) as indicating a shape change from spherical to deformed as one goes from ^{27}Na and ^{28}Mg to the still more neutron-rich Na and Mg isotopes. The onset of deformation at ^{31}Na and ^{31}Mg is shown with arrows in Fig. 2. It is well known that similar effects are observed with the beginning of deformation in the well established regions of deformation. Thus the two-neutron separation energies of the nitrogen and oxygen isotopes present independent evidence for the deformation of ^{18}N and ^{19}O (arrows in Fig. 2).

An alternative explanation for the change of slope of $S_{2n}(N)$ for nitrogen and oxygen isotopes, which is difficult to eliminate, is that it might result from the neutrons filling different principal oscillator shells. It should, however, be noted that ^{18}N is experimentally $\sim 1\cdot 6$ MeV more bound than the value calculated (Garvey *et al.* 1969), as expected if ^{18}N experienced a change in nuclear structure relative to the more neutron deficient nitrogen isotopes.

Acknowledgments

Discussions with F. Barker, K. Fifield, G. Putt and particularly with M. Hotchkis who suggested the two-neutron separation plot of Fig. 2 have been particularly valuable in the preparation of this paper. The support of the National Science Foundation, and the Award of a Visiting Fellowship at The Australian National University are gratefully acknowledged.

References

Ajzenberg-Selove, F. (1983). *Nucl. Phys.* A **392**, 1.
Andritsopoulos, G., Catford, W. N., Garman, E. F., Pringle, D. M., and Fifield, L. K. (1981). *Nucl. Phys.* A **372**, 281.
Chung, W. (1976). Ph.D. Thesis, Michigan State University.
Cole, B. J., Watt, A., and Whitehead, R. R. (1974). *J. Phys.* A **7**, 1374.
Endt, P., and Van der Leun, C. (1978). *Nucl. Phys.* **310**, 1.
Fortune, H. T., and Bingham, H. G. (1977). *Nucl. Phys.* A **293**, 197.
Gallagher, C. P., and Moskowski, S. A. (1958). *Phys. Rev.* **111**, 1282.
Garvey, G. T., Gerace, W. J., Jaffe, R. L., Talmi, I., and Kelson, I. (1969). *Rev. Mod. Phys.* **41**, S1.
Lambert, M., Midy, P., and Desgrolard, P. (1973). *Phys. Rev.* C **8**, 1728.
Millener, D. J., and Kurath, D. (1975). *Nucl. Phys.* A **255**, 315.
Newby, N. D., Jr (1962). *Phys. Rev.* **125**, 2063.
Olness, J. W., Warburton, E. K., Alburger, D. E., Lister, C. J., and Millener, D. J. (1982). *Nucl. Phys.* A **373**, 13.
Putt, G. D., Fifield, L. K., Hotchkis, M. A. C., Ophel, T. R., and Weisser, D. C. (1983). *Nucl. Phys.* A **399**, 190.
Thibault, C., Klapisch, R., Rigaud, C., Poskanzer, A. M., Prieels, R., Lessard, L., and Reisdorf, W. (1975). *Phys. Rev.* C **12**, 644.

Manuscript received 14 February, accepted 24 May 1983