States in ^{20}O below 6 MeV excitation via the ^{18}O(t,p) ^{20}O reaction

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(Received 14 August 1978)

Angular distributions have been measured for the ^{18}O(t,p) ^{20}O reaction at a bombarding energy of 15.0 MeV. Nine excited states below 6.02 MeV were observed. Comparison with microscopic two-particle distorted-wave Born approximation calculations yielded the following new J^{π} assignments (E_x in MeV, J^{π}): 5.382, 0^+; 5.603, 2^+; 6.02, 4^+. Tentative assignments of (1^-,2^+,3^-) and (1^-,2^+) were made to levels at 5.00 and 5.22 MeV, respectively. Spins of 2^+, 4^+, 2^+, and 0^+ to the levels at 1.674, 3.568, 4.065, and 4.446 MeV were confirmed. The experimental spectrum of states below 6 MeV is compared with the results of an $(sd)^4$ shell-model calculation using the Preedom-Wildenthal interaction matrix elements. Identification of possible core-excited states in ^{20}O is discussed.

[NUCLEAR REACTIONS ^{12}C(t, p), ^{16,18}O(t, p), E=15.0 MeV; measured $\sigma(E_p,\theta)$. ^{20}O deduced levels, J^{π}. Enriched target, DWBA analysis, shell model calculation.]

I. INTRODUCTION

Very little is presently known about the nucleus ^{20}O, as demonstrated by the paucity of experimental information contained in the most recent compilation[1] of the A=18–20 nuclei. Of the eleven known bound states, all below 6 MeV in excitation, only five have firm spin and parity assignments. In addition, no γ-ray decay measurements have been carried out on this nucleus. A meaningful comparison with model wave functions clearly requires a great deal more information.

The only convenient reactions with which to populate ^{20}O states are two-neutron transfer on ^{18}O, and of these, only the (t,p) reaction yields adequate energy resolution. Middleton *et al.*[2,3] have studied the ^{18}O(t,p) ^{20}O reaction at a bombarding energy of 10 MeV and much of what is known about ^{20}O comes from these studies. (Another study[4] at 5.5 MeV also exists.) The measured[2,3] proton angular distributions were analyzed with plane wave stripping theory and L values extracted, giving spins and parities. But plane wave theory is deficient (in fact, the above-mentioned studies sometimes gave L values in conflict with previously determined J^{π} values for states in other nuclei) and it is clear that a re-examination of this reaction is most desirable.

In this paper, we present the results of measurements of the ^{18}O(t,p) ^{20}O reaction at 15-MeV bombarding energy. The angular distributions of the outgoing protons were compared with a distorted-waves stripping calculation using two-nucleon microscopic form factors. L values were extracted for nine excited states below 6.02 MeV. It is well known[5] that the direct (t,p) reaction on a spin-zero target may populate states with only natural parity, i.e., with $\pi=(-)^L$. Furthermore, the angular distribution shapes are characterized[5] by the L transfer rather than by the microscopic configuration of the transferred neutron pair. The *magnitudes* of the cross sections, of course, do depend on the structure of the final nuclear states. Thus, L values can often be assigned with a reasonable degree of confidence. Finally, if the J^{π} of the target is 0^+, as in this case, the spin and parity of the final states are uniquely determined: $J=L$ and $\pi=(-)^J$.

II. EXPERIMENTAL PROCEDURE

Targets of $\approx$80 μg/cm^2 WO_3 on 10 μg/cm^2 carbon backings were used. Both enriched (to ~50% in ^{18}O) and natural oxygen targets were bombarded with 15 MeV tritons from the McMaster Tandem Accelerator. The triton sputter source has been described by Ashbaugh and Peng.[6] Typical beam currents obtained were 50 nA on target. The outgoing protons were detected in a resistive-wire gas proportional counter mounted on the focal plane of an Enge split-pole magnetic spectrograph. A 0.025 mm Al foil prevented helium and heavier ions from entering the detector. A typical spectrum is shown in Fig. 1. The resolution obtained was 30 keV (FWHM). The most intense lines seen in Fig. 1 are due to the ^{12}C(t,p)^{14}C reaction. At some angles certain ^{20}O levels were obscured by these contaminant peaks. Lines due to the ^{16}O(t,p)^{18}O reaction were also observed and were distinguished from ^{20}O levels by taking exposures with the enriched and natural oxygen targets. Finally, the ^{20}O identifications were con-

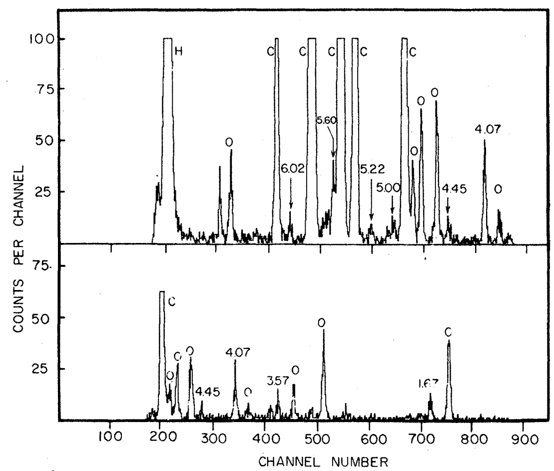

FIG. 1. Spectra for the $^{18}O(t,p)^{20}O$ reaction at a laboratory angle of 30° and 15.0 MeV bombarding energy. The two spectra shown were taken at two different values of the spectrograph magnetic field. Several peaks due to the (t,p) reaction on ^{12}C and ^{16}O contaminants in the target denoted by C and O, respectively, are also identified. H represents knock-on protons from hydrogen in the target.

firmed from the measured kinematic shifts. Calibration was carried out using the ^{14}C and ^{18}O known states and doing a linear least-squares fit to the position along the focal plane vs ejectile energy. The agreement to known states in ^{20}O was satisfactory. One new state, at 6.02 MeV, was discovered.

III. DWBA ANALYSIS

Distorted-waves predictions for the proton angular distributions were obtained using the microscopic two-particle transfer option of the code DWUCK.[7] Optical model parameters (listed in Table I) were taken from the work of Keaton

TABLE I. Optical model parameters used in DWBA analysis of the $^{18}O(t,p)^{20}O$ reaction.

Potential	Parameter	$^{18}O+t$	$^{20}O+p$
Real	V	−175	−60
	r	1.13	1.13
	a	0.69	0.57
Volume-imaginary	W_v	−15.6	0
	r_v	1.75	
	a_v	0.76	
Surface-imaginary	$4W_s$	0	34.2
	r_s		1.13
	a_s		0.50
Spin-orbit	V_{so}	0	−5.5
	r_{so}		1.13
	a_{so}		0.57
Coulomb	r_C	1.13	1.13

et al.,[8] who found good fits for the $^{12}C(t,p)^{14}C$ reaction. Angular distributions for the (t,p) reaction on the contaminants in the target were also well fitted with these parameters. Since comparisons of *absolute* cross sections with DWBA predictions probably require[5] full finite-range calculations, and since the patterns for different L values are strikingly different (see below), no attempt was made to extract absolute cross sections or to find a better set of optical model parameters, possibly more suitable for tritons on ^{18}O.

IV. RESULTS

A. $^{12}C(t,p)^{14}C$ and $^{16}O(t,p)^{18}O$ reactions

Several levels in ^{14}C and ^{18}O were observed in the present experiment (see Fig. 1). These states were used to check the DWBA predictions and the hypothesis of direct two-neutron transfer. Typical angular distributions to selected states are presented in Fig. 2. The population of the unnatural parity $J^{\pi}=2^-$ state in ^{14}C is forbidden in a direct single-step reaction and its low cross section relative to natural parity states ($\lesssim 10\%$) in-

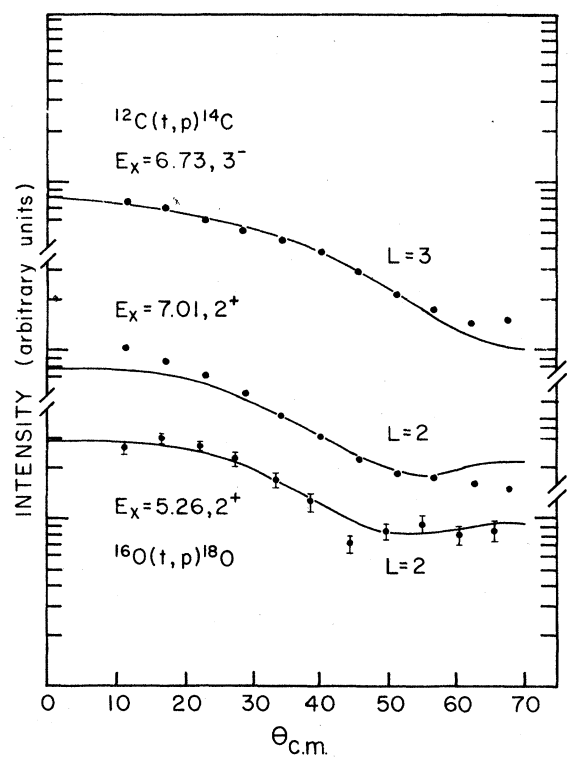

FIG. 2. Representative angular distributions for some of the excited states in ^{14}C and ^{18}O. Curves are DWBA fits using the optical model parameters in Table I.

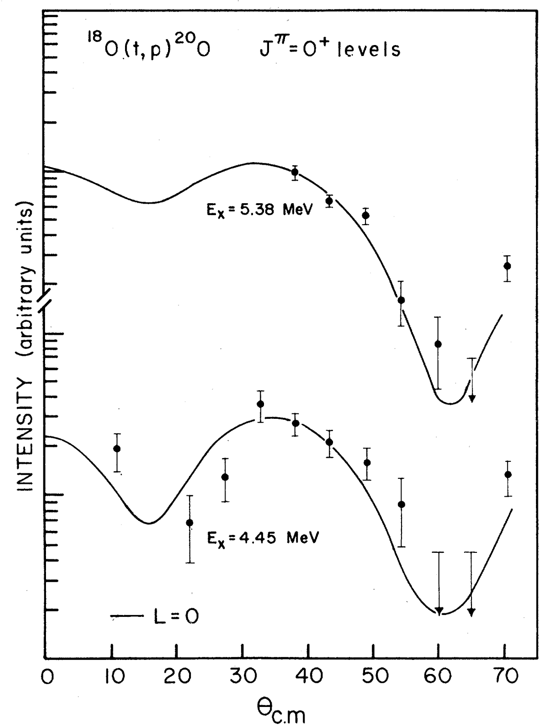

FIG. 3. Angular distributions for the $^{18}O(t,p)^{20}O$ reaction at 15.0 MeV, populating 0^+ states in ^{20}O. Curves are DWBA fits and are discussed in the text. Optical model parameters are given in Table I.

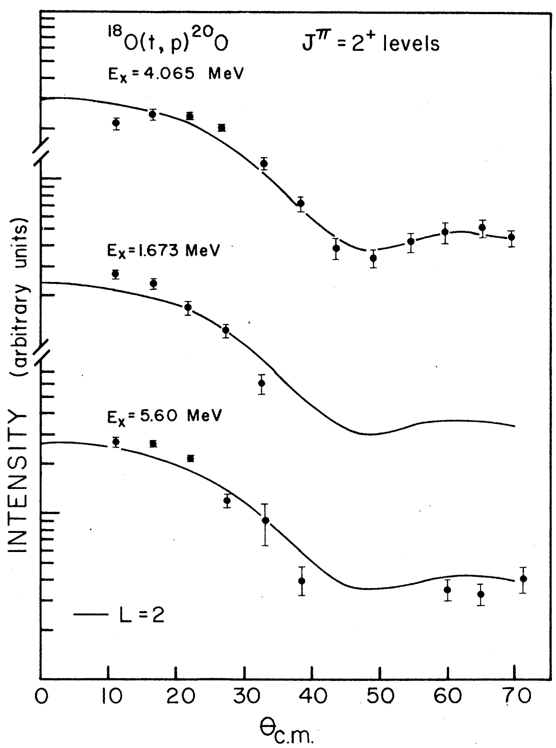

FIG. 4. Same as for Fig. 3, but for $J^{\pi}=2^+$ states.

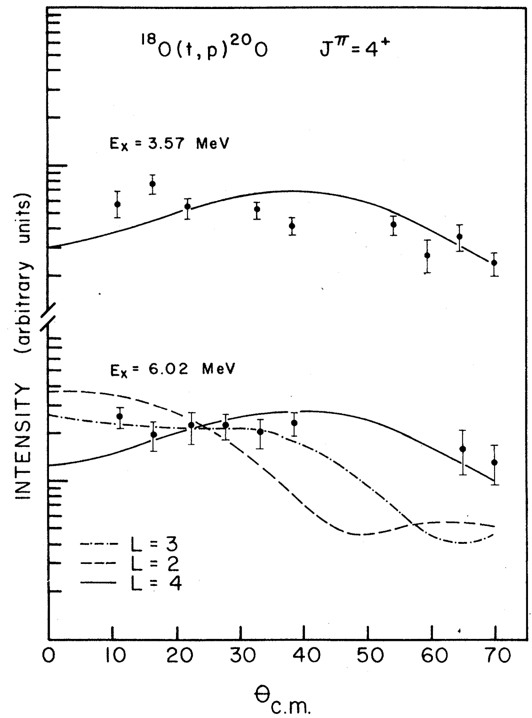

FIG. 5. Same as for Fig. 3, but for $J^{\pi}=4^+$ states.

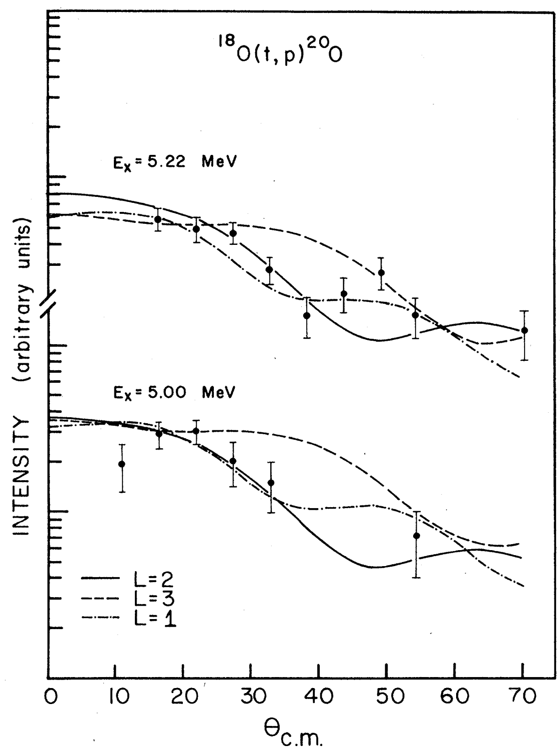

FIG. 6. Same as for Fig. 3, but for weakly populated states at 5.00 and 5.22 MeV, for which several L values give acceptable fits.

dicates that the assumption of direct transfer is reasonably valid. No new information on ^{14}C or ^{18}O bound states was obtained; all measured angular distributions were consistent with published[1] spins.

B. ^{18}O$(t,p)^{20}$O reaction

Angular distributions for the ^{20}O levels are found in Figs. 3–6, together with the DWBA predictions (Sec. III). We discuss each level in turn below. The results are summarized in Table II.

1.673 MeV level. Data were taken at forward angles only, but the shape of the angular distribution is in good agreement with $L=2$, confirming the $J^\pi=2^+$ assignment given in the compilation.[1]

3.568 MeV level. This state was rather weakly populated and was obscured by contaminants at several angles. The angular distribution is relatively structureless, but is reasonably well represented by the $L=4$ curve. Thus $J^\pi=4^+$ is assigned, in agreement with the compilation.

4.065 MeV level. The fit to an $L=2$ curve is quite good. The curve shown in Fig. 4 assumes a $(d_{5/2})^2$ transfer. Changes in the configuration of the transferred neutrons, for example, to $d_{5/2}s_{1/2}$, did not change the fit appreciably, in agreement with expectations.[5] Other L values give unacceptable fits. Thus $L=2$ and $J^\pi=2^+$, which is in agreement with the plane wave analysis.[2,3]

4.446 MeV level. The $L=0$ DWBA curve is most distinctive: It is characterized by minima at center-of-mass angles of 15° and 60°, the latter one being very deep. The angular distribution to the 4.45 MeV state is in excellent agreement with this expectation, despite its very weak population in the (t,p) reaction. A $J^\pi=0^+$ assignment given in the literature[1] is therefore confirmed.

5.382 MeV level. No spin assignments have been made to the higher-lying states of ^{20}O, except for a tentative 0^+ assignment[1] to this state. Our backward-angle distributions show the characteristic minimum at 60° (Fig. 3) and is therefore in agreement only with the $L=0$ DWBA curve. (The forward angles were unfortunately obscured by contaminants.) Hence, we can make a definite $J^\pi=0^+$ assignment to this state. It is interesting to note that this level is populated by a factor of about 8 more strongly than the 4.45 MeV 0^+ level. Possible reasons for this will be discussed in more detail below.

5.00 MeV level. This state was rather weakly populated. If we assume direct two-neutron transfer then $L=1$, 2, or 3 assignments are all in reasonable agreement with the data. The lowest negative-parity states in ^{20}O should be of $p^{-1}sd^5$ structure and start near 6 MeV excitation. Such states can be populated only via the core-excited admixtures in the ^{18}O ground state if the reaction proceeds by a single-step direct mechanism. The weakness of this state, therefore, makes a negative-parity assignment a distinct possibility. Thus, the 1^- and 3^- assignments cannot be ruled out. We hence suggest $J^\pi=1^-$, 2^+, 3^-.

5.22 MeV level. The angular distribution to this state was similar to that of the other 2^+ states (Fig. 6) and the $L=2$ curve does indeed give a reasonable fit, but $L=1$ cannot be ruled out. In fact, the "bump" in the cross section near 50° might favor $L=1$ slightly. The $L=3$ possibility would appear to be ruled out by the low intensity around 40°. Therefore, we propose $J^\pi=1^-$, 2^+.

5.60 MeV level. The angular distribution (Fig. 3) is quite well fitted by the $L=2$ curve. No other assumption gives an acceptable fit. We thus assign $J^\pi=2^+$ to this state.

6.02 MeV level. The nearly isotropic angular distribution to this state is characteristic of high L transfer if it is populated in a direct reaction. In fact, $L=4$ gives a good fit and all lower L values are clearly unacceptable (Fig. 5). Higher L transfers are not, of course, allowed in a single-step process if two sd-shell particles are transferred. The $L=3$ curve, for example, gives the next best fit but badly underpredicts the large angle data. Thus, we assign $J^\pi=4^+$ to this new level. However, the structureless angular distribution might also be the result of compound-nuclear processes and this possibility cannot be entirely ruled out.

TABLE II. Levels in ^{20}O from the ^{18}O$(t,p)^{20}$O reaction at 15.0 MeV.

E_x (MeV)	L Previous	L Present	J^π
0	0		0^+
1.67	2	2	2^+
3.56	4	4	4^+
4.07	2	2	2^+
4.45	0	0	0^+
5.00		1,2,3	$1^-,2^+,3^-$
5.22		1,2	$1^-,2^+$
5.38	(0)	0	0^+
5.60		2	2^+
6.02		4	4^+

V. DISCUSSION AND SUMMARY

The experimental level scheme for ^{20}O as derived from a synthesis of the present and previous[1] experimental data is compared to the re-

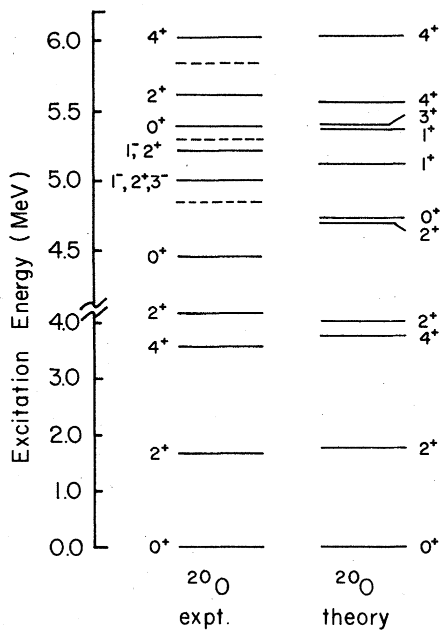

FIG. 7. Comparison of experimental and calculated levels for ^{20}O. Experimental states reported in the literature (Ref. 1) but not observed in the present work are indicated by dashed lines. Above 4 MeV in excitation, only a tentative identification of model states with those observed in the present work can be made. The unnatural parity levels ($J^{\pi}=1^+$ and 3^+) should not be observed in a direct two-neutron transfer reaction.

sults of an $(sd)^4$ shell-model calculation[9] in Fig. 7. Preedom-Wildenthal residual two-body matrix elements for the sd shell[10] were used to generate the calculated spectra. Not all tabulated levels[1] were observed in the present work: No evidence for the states at 4.84, 5.30, and 5.83 MeV was found. If we assume that unnatural parity (notably 1^+ and 3^+) model states should not be populated in the present (t,p) reaction, then the agreement between the observed and calculated spectra below 6 MeV is in general satisfactory. Notable exceptions are: (i) we observe two 0^+ excited states below 6 MeV and only one is predicted; (ii) there are too few predicted 2^+ states; (iii) there is a 4^+ state missing in the experimental spectrum. The extra 0^+ state is a severe problem since the next model 0^+ state lies at 8.75 MeV excitation. A natural conclusion is that one or other of the two 0^+ states at 4.45 and 5.38 MeV is a core-excited state. Since $f_{7/2}$ admixtures are unlikely, the most probable configuration is $p^{-2}sd^6$. In fact, weak-coupling theory predicts[11] that the most energetically favored configuration is $^{14}C \otimes {}^{22}Ne$. Why this should be so is easy to see: The four sd-shell neutrons will want to couple to two protons in order to form an α-particle configuration and two extra neutrons. Thus structures of the form $(\pi p^{-2})\times[\nu(sd)^2\pi(sd)_{\alpha}{}^2, \gamma(sd)^2]$ are most favored.

The low-lying 4p-2h states in ^{18}O are dominantly $\pi p^{-2}\times\nu(sd)^2\pi(sd)^2$ or $^{14}C\otimes{}^{20}Ne$ in weak coupling. The ^{18}O ground state contains some 10% of this deformed configuration.[12] Thus two-neutron transfer on ^{18}O should populate 6p-2h states in ^{20}O of the type described above, albeit rather weakly.

The best candidate for the deformed 0^+ in ^{20}O is the one at 4.45 MeV since it is so weakly populated. It is only $\frac{1}{10}$ as strong as the 5.38 MeV level, and the difference in Q values cannot explain such a difference in intensity. (It is likely that the 5.38 MeV level is populated by $s^2_{1/2}$ transfer, since this is predicted to be quite strong. The ground state, unfortunately not observed in this experiment, is probably formed by $d^2_{5/2}$ transfer. If so, it should be about a factor of 4 weaker than the 5.38 MeV level.) If the 4.45 MeV state is deformed, one would expect a rotational band to be built upon it. In fact, weak coupling arguments suggest that the 2^+ should lie near 5.7 MeV and the 4^+ near 7.8 MeV—the splittings being the same as in ^{22}Ne. The 2^+ state at 5.60 MeV is then a candidate for such a state. However, it is populated with ~50% of the intensity of the 2^+ state at 4.07 MeV and the 6p-2h assignment to this state must be regarded as very tentative. If it does lie outside the $(sd)^4$ model space it would also help to resolve the problem of too few low-lying calculated 2^+ states.

As shown in Fig. 7, unnatural parity states ($J^{\pi}=1^+$ and 3^+) are predicted to exist near 5.5 MeV. Perhaps one or more of the states listed in the compilation[1] but not observed here, i.e., at 4.84, 5.30, and 5.83 MeV can be identified with these model states. However, negative parity states should also start near 6 MeV excitation.

In summary, the present (t,p) experiments have allowed new definite or tentative spin assignments to be made to five states in ^{20}O. A new $J^{\pi}=4^+$ level at 6.02 MeV has been discovered. The spins of four low-lying bound states have been confirmed. A comparison with a shell-model calculation gives quite satisfactory agreement. We suggest that the 0^+ state at 4.45 MeV and the 2^+ state at 5.60 MeV could form the start of a deformed core-excited band with dominantly 6p-2h structure. However, it is clear that more unambiguous spin and parity assignments, especially to negative-parity and unnatural-parity levels, are necessary for further comparisons with theoretical predictions to be meaningful. Perhaps γ-ray angular correlation measurements will prove to be useful in this regard.

It gives us much pleasure to acknowledge the important contributions of Dr. Y. Peng and Mr. P. Ashbaugh for the successful operation of the triton sputter source. The assistance of S. Angelo and A. Khan with the data collection is appreciated. This work was supported by the National Research Council of Canada. The shell model calculations reported were undertaken by A. P. while he was at Oxford University. He thanks Prof. K. W. Allen and Dr. D. J. Millener for their friendship and help.

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