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High-spin neutron-hole states in ^{50}Ti and ^{52}Cr

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Energy levels arising from the 1p7h configuration of ^{50}Ti and the 1p5h configuration of ^{52}Cr are calculated with an effective interaction which previously has been shown to reproduce the energies of intruder states in mass 53–57 nuclei. Calculated energies for yrast levels of spin up to 11 agree closely with experimental values from $(\alpha,2n\gamma)$ reactions. An effective $M1$ operator determined by a least-squares fit to data from $N = 29$ nuclei is used in the calculation of electromagnetic transition rates, and it is shown that only weak configuration mixing is required to account for transition rates which have been measured in ^{52}Cr.

[NUCLEAR STRUCTURE ^{50}Ti, ^{52}Cr; calculated 1p7h and 1p5h energy levels, effective $M1$ operator, calculated $M1$ and $E2$ transition rates.]

I. INTRODUCTION

Calculations of the spectra arising from specific $(p_{3/2}f_{5/2}p_{1/2})^{n_p}f_{7/2}^{-n_h}$ configurations relative to the ^{56}Ni closed shell (referred to below as n_p-particle, n_h-hole configurations) with a mass-independent effective interaction[1] determined by least-squares fits to empirical data, have been very successful in accounting for energy levels of mass 53–58 nuclei. In Ref. 1 it was shown that the excitation energies of "intruder" states in this mass region are reproduced, and in Ref. 2 the calculated energy levels of Fe isotopes were shown to be in good agreement with experiment. Mixing of different configurations was not explicitly included in these calculations, because the effective interaction was derived by assigning specific configurations to observed levels and therefore includes renormalizations due to configuration mixing. The success of the calculations shows that either these renormalizations are to a large extent both mass and state independent, or that actual eigenstates in this mass region have rather pure configurational structure.

To test whether the same interaction can give useful results for nuclei of mass less than 53, it has been used to generate the one-particle five-hole (1p5h) spectrum of ^{52}Cr and the 1p7h spectrum of ^{50}Ti. High-spin states in these nuclei which cannot arise from $f_{7/2}$ configurations have recently been populated by $(\alpha, 2n\gamma)$ reactions, and bands of levels up to spin 11 have been observed. In Sec. II it is shown that the energies of these levels are in excellent agreement with the predictions for yrast 1p5h and 1p7h states. Section III is a discussion of transition rates, which are calculated using an effective $M1$ operator derived from a least-squares fit to data from $N=29$ nuclei.

II. ENERGY LEVELS

A. ^{52}Cr

The lowest configuration of ^{52}Cr has four proton holes in the $f_{7/2}$ shell and gives rise to states of spin 0, 2, 4, 5, 6, and 8, with spins 2 and 4 occurring twice. The ground state and states at 1.43 MeV (2^+), 2.37 MeV (4^+), 2.77 MeV (4^+), and 3.11 MeV (6^+) are predominantly of this 0p4h configuration, being excited strongly by $l=3$ in the ^{51}V(^{3}He,d) reaction.[3] The 3.62 MeV (5^+) and 4.75 MeV (8^+) levels lie at excitation energies close to those predicted for 0p4h states. The 2.65 MeV 0_2^+ state can be assigned to the 2p6h configuration, since it is excited very weakly in neutron pickup from ^{53}Cr (Ref. 4), but is strongly excited in the ^{54}Cr(p,t) reaction with an angular distribution characteristic of $f_{7/2}{}^2$ pickup.[4] The 3.17 MeV 2_3^+ state also appears to arise from this configuration, since it is excited strongly in both ^{54}Cr(p,t) and ^{50}Cr(t,p) (Ref. 5). The 2.97 MeV 2_2^+ state is excited very weakly in both two-neutron transfer reactions, and is probably the second 0p4h 2^+. A number of levels above 3.4 MeV are excited strongly by $l=3$ in ^{53}Cr(p,d) or by $l=1$ in ^{51}V(^{3}He,d), and can therefore be assigned to the 1p5h configuration. It is clear from the one- and two-particle transfer data that the 0p4h, 1p5h, and 2p6h configurations are all important even below 4 MeV. However, the fact that most of the strength in each reaction is distributed among only a few levels suggests that configuration mixing is not strong, and gives hope that the effects of this mixing on energies can to a large extent be taken into account by using an effective interaction in calculating the levels arising from a specific configuration.

Several new high-spin states recently have been isolated by the ^{50}Ti$(\alpha, 2n\gamma)$ reaction.[6,7] Figure 1

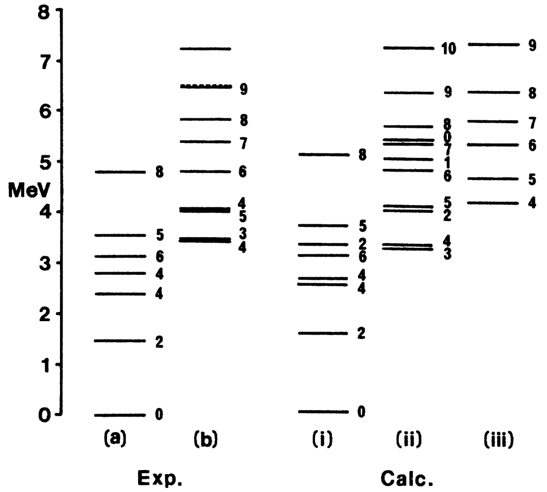

FIG. 1. Partial level scheme of ^{52}Cr from Ref. 6, showing (a) levels which are predominantly 0p4h and (b) other levels. Calculated levels are (i) 0p4h, (ii) lowest 1p5h, and (iii) second 1p5h levels with $J>3$.

gives the partial level scheme of ^{52}Cr obtained in Ref. 6. The levels are divided into those which appear to belong to the 0p4h configuration and those which arise from excited configurations. Also shown in Fig. 1 are results of calculations for the 0p4h and 1p5h configurations with the effective interaction discussed in Sec. I. The very close energy correspondence makes it clear that the levels observed above 3.4 MeV, other than the 4.75 MeV 8^+, are 1p5h states. This configuration assignment is supported by data from the ^{53}Cr(p,d) reaction,[4] which give strong $l=3$ pickup to groups of levels at 3.4 and 4.0 MeV.

For $J>2$, the lowest 1p5h state of each spin is calculated to be more than 99.5% neutron excitation. The calculation also predicts that for $J>3$ these states should be almost degenerate with a 1p5h state of spin $J-1$, a feature of the spectrum which is observed experimentally in the case of spins 4 and 5. The 7.24 and 8.22 MeV levels reported in Ref. 7 appear to be the lowest 1p5h 10^+ and 11^+ states, which the calculation places at 7.3 and 8.1 MeV. Yrast levels of spins 12, 13, and 14 are predicted to lie at 9.7, 10.35, and 12.35 MeV.

B. ^{50}Ti

The ^{48}Ca$(\alpha,2n\gamma)$ reaction[8] has been used recently to populate high-spin states lying above 6 MeV in ^{50}Ti, and a partial level scheme derived from that experiment is shown in Fig. 2. Comparison with the calculated spectrum in Fig. 2, which gives the lowest 1p7h state of each spin, clearly shows that these high-spin states have 1p7h structure. The

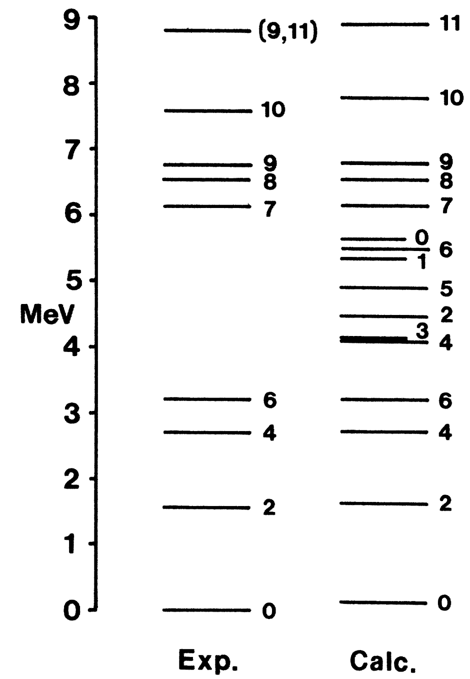

FIG. 2. Partial level scheme of ^{50}Ti from Ref. 8, and the calculated spectrum showing 0p6h and lowest 1p7h levels.

8.80 MeV level appears to be the lowest 11^+ (the second 9^+ is calculated to lie 600 keV lower), and the lowest 12^+ is predicted to lie at 11.5 MeV.

The lowest 1p7h state is calculated to be a 4^+ at 4.10 MeV, and can be associated with the (4^+) level at 4.16 MeV which has a large $l=1$ spectroscopic strength in the ^{49}Ti(d,p) reaction.[9] The calculated strengths of this 4^+ and 3^+, 2^+, and 5^+ levels lying above it are 1.05, 0.82, 0.49, and 1.05. The 5^+ is calculated to lie at 4.9 MeV, and its large strength suggests that it is the level observed at 4.895 MeV. If the empirical strengths are increased by a factor of 1.4, theory and experiment are in good agreement for the 4^+ and 5^+ levels; the strength observed at 4.18 MeV would then be 1.3, which suggests that this level, which has a tentative 2^+ assignment, could actually be a doublet consisting of the lowest 2^+ and 3^+ 1p7h levels. The 2^+ level at 4.31 MeV has very small (d,p) strength, but is excited strongly in the ^{48}Ti(t,p) reaction,[10] and is probably a 2p8h state.

III. ELECTROMAGNETIC TRANSITIONS

A. Effective $M1$ matrix elements

There have been several attempts to determine effective $M1$ single-particle matrix elements for $1f2p$-shell calculations which use wave functions with a fixed number of $f_{7/2}$ particles. Large shifts from the bare-nucleon values are expected, due to excitations from the $f_{7/2}$ to the $f_{5/2}$ shell which are not included in the wave functions. Kutschera, Brown, and Ogawa[11] have shown that magnetic moments of $f_{7/2}$-shell nuclei are reproduced with proton and neutron g factors which are approximately 88% and 69% of the Schmidt values, and Glaudemans, de Voight, and Steffens[12] have found effective matrix elements for $p_{3/2}$, $f_{5/2}$, and $p_{1/2}$ neutrons by a least-squares fit to data from Ni isotopes. The latter work does not, however, contain any discussion of how precisely individual matrix elements are determined.

The $N=29$ nuclei have configurational structure similar to that of the 1p5h and 1p7h states which are the topic of this paper, and might be expected to provide relevant information concerning an appropriate effective $M1$ operator. Sufficient experimental data are now available to attempt a determination of this $M1$ operator by least-squares fitting. Wave functions were generated using a ^{56}Ni core, ^{57}Ni single-particle energies, empirical energies for the $N=28\ f_{7/2}^{-n}$ hole states, and the effective neutron-proton interaction of Ref. 1. A total of 25 transition rates and 5 magnetic moments in ^{53}Cr, ^{54}Mn, ^{55}Fe, ^{56}Co, and ^{57}Ni were included in the fits. Parameters were determined by a reduced χ^2 fit using experimental errors, with a minimum accepted uncertainty of 25% for transition strengths and 5% for magnetic moments. The signs of transition amplitudes were taken to be those given by bare-nucleon matrix elements, and agreed in every case with the signs given by the best-fit parameters. The main features of the results can be summarized as follows:

(a) The available data give very low weighting to the diagonal $p_{1/2}$ and $f_{5/2}$ neutron $M1$ matrix elements, and as a result these are determined very poorly. The fit is not significantly worse, nor are the other parameters altered appreciably, if both of these matrix elements are fixed at their Schmidt values. This was done for the final fit. A measurement of the magnetic moment of the lowest $\frac{5}{2}^-$ state in the ^{57}Ni would determine the $f_{5/2}$ matrix element, but it is difficult to see how the $p_{1/2}$ matrix element can be tied down since current methods of measuring magnetic moments of excited states cannot be used for spin $\frac{1}{2}$. Transitions with large weightings of either matrix element involve the third or higher eigenstates of a particular spin, for which there can be little confidence in the calculated wave functions.

(b) The $f_{7/2}$ proton g factor is determined very precisely, and has a value of 1.39, or 84% of the Schmidt value. This is close to the g factor deduced from magnetic moments of $f_{7/2}$-shell nuclei.[11]

(c) The diagonal $p_{3/2}$ matrix element is well determined, and is equal to 47% of the Schmidt value. This is in agreement with both the ^{57}Ni magnetic moment[13] and the effective value in Ni isotopes determined by Glaudemans, deVoight, and Steffens.[12]

(d) The effective $p_{3/2} \rightarrow f_{5/2}$ matrix element $(f_{5/2} \| \underline{\mu} \| p_{3/2})$ is determined fairly precisely, the data clearly requiring a nonzero value. The fit suggests a value of about 0.7, which is consistent with the lifetime of the lowest $\frac{5}{2}^-$ state in ^{57}Ni and is about 85% of the value given by the fit to Ni data in Ref. 12.

(e) The $p_{1/2} \rightarrow p_{3/2}$ matrix element has rather small weighting. The fit gives about 35% of the bare-nucleon value, or about 80% of the value deduced in Ref. 12, and is consistent with the lifetime of the lowest $\frac{1}{2}^-$ state in ^{57}Ni.

The parameters given by this fit, together with a neutron $f_{7/2}$ g factor of -0.38 (Ref. 11), have been used to calculate $M1$ transition strengths for the 1p5h states of ^{52}Cr and the 1p7h states of ^{50}Ti. Since the states of interest are almost exclusively neutron excitations (for $J>6$ in ^{50}Ti and $J>10$ in ^{52}Cr they are entirely so), it is not necessary to know effective matrix elements for a $p_{3/2}$, $p_{1/2}$, or $f_{5/2}$ proton; these can have only negligible effect on the calculated transition rates, and were set equal to zero. Interconfiguration $M1$ transitions discussed below were calculated with an $f_{5/2} \rightarrow f_{7/2}$ matrix element given by the bare-nucleon g factor. Effective charges for $E2$ transitions were set equal to $1.9e$ for protons and $0.9e$ for neutrons, these values being suggested by a fit to known $E2$ rates in $f_{7/2}$-shell nuclei.[11] Matrix elements of r^2 were calculated assuming harmonic oscillator radial functions, with oscillator parameter $b=1.95$ fm.

B. ^{52}Cr

The calculated decay scheme for yrast 1p5h states with $J>3$ is shown in Fig. 3. Branches to 1p5h states not shown in the diagram are less than 0.5%. The following is a discussion of the decay properties of individual levels, and of what can be deduced about configuration mixing. Experimental results quoted are from Ref. 6.

The 3415 keV 4⁺ level. The ^{53}Cr(p,d) data[4] clearly show that this is predominantly a 1p5h state. The lowest 1p5h 4^+ is calculated to have a lifetime of 76 ps, all 1p5h $\rightarrow$ 0p4h transition strengths being very weak. The lifetime of the 3415 keV state is actually about 0.5 ps, showing that its decay, which is mainly to the second 0p4h 4^+ state at 2767 keV, is dominated by configuration mixing. This mixing need not be large, however, to account for the short lifetime;

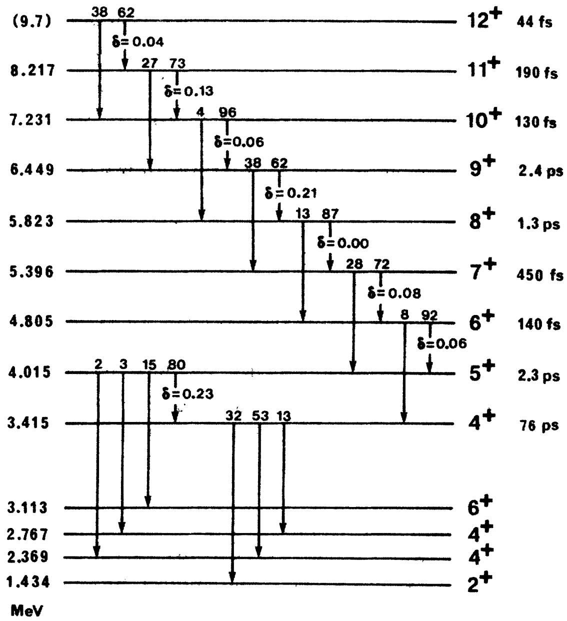

FIG. 3. Calculated decay scheme for the lowest 1p5h states with $J>3$ in ^{52}Cr. The four lowest levels shown are assumed to be 0p4h states.

0p4h→0p4h transition amplitudes are very large, being proportional to diagonal matrix elements of gJ, and with a $f_{7/2}$ proton g factor of 1.39 only 4% of the 0p4h 4_2^+ state need be mixed into the 1p5h state to give agreement with experiment.

The 4015 keV 5⁺ level. This level also is excited strongly by $l=3$ in the ^{53}Cr(p,d) reaction, and can be associated with the lowest 1p5h 5^+. Experiment shows that it decays mainly to the 3415 keV 4^+, as expected, but it also has a sizable branch to the 0p4h 5^+ at 3615 keV. Very little configuration mixing is required to give this decay; assuming a lifetime of about 1 ps (Ref. 6), a 2% 0p4h component in the predominantly 1p5h 5^+ would give a branch of 30%.

The 4805 keV 6⁺ level. This level decays mainly to the 4015 keV 5^+, as expected for the lowest 1p5h 6^+. A weaker branch which is observed to the 0p4h 6^+ at 3113 keV can again readily be understood if there is weak configuration mixing; in this case, about 0.1% of the 0p4h state mixed into the 4805 keV level would give a 30% branch. The calculated lifetime of 0.14 ps is shorter than the value of $0.8^{+1.7}_{-0.5}$ ps obtained in Ref. 6, but the experimental value has rather large uncertainties and should in any case be regarded as an upper limit.

The 5396 keV 7⁺ level. As expected, if it is the lowest 1p5h 7^+, this level decays mainly to the 4805 keV 6^+ with a sizable branch to the 4015 keV 5^+. The calculated lifetime is 0.45 ps, while experiment gives $0.21^{+0.17}_{-0.13}$ ps.

The 5823 keV 8⁺ level. The calculation suggests that this level should have a lifetime of 1.3 ps, and should decay mainly to the 5396 keV 7^+ with a weak branch to the 4805 keV 6^+. The strong branch has been observed, and the lifetime measured as $1.5^{+0.9}_{-0.6}$ ps. No branch has been observed to the 0p4h 8^+ at 4748 keV, and if this is assumed to be less than 20% an upper limit of 0.02% can be put on the 0p4h component in the 1p5h state.

The 6449 keV 9⁺ level. It is suggested in Ref. 6 that there may be two levels in the vicinity of 6.45 MeV: a 9^+ at 6449 keV which decays to the 4748 keV 0p4h 8^+ and a level at 6451 keV which decays to the 5823 keV 1p5h 8^+. However, the authors state that both transitions may arise from a single level. The calculation gives the second 1p5h 8^+ almost degenerate with the lowest 9^+, but predicts that this should decay almost 100% to the 5396 keV 7^+ with a branch of less than 1% to 5823 keV. It therefore seems likely that both observed transitions originate from the 9^+. Small 1p5h admixtures in the 0p4h 8^+ level can account for the 9^+→4748 keV transition; for example, a component of less than 1% of the second 1p5h 8^+ would give a 50% branch.

The calculated $E2/M1$ ratios for the 1p5h 8→7, 7→6, and 6→5 transitions are not in agreement with the values deduced in Ref. 6, but it is clear that there are large errors in the empirical ratios. The values given for the 8→7 and 7→6 transitions, together with the measured lifetimes, give $E2$ transition strengths of about 3000 and 300 Weisskopf units, respectively.

C. ^{50}Ti

The calculated decay scheme for yrast 1p7h states with $J>6$ is shown in Fig. 4. Experimental-

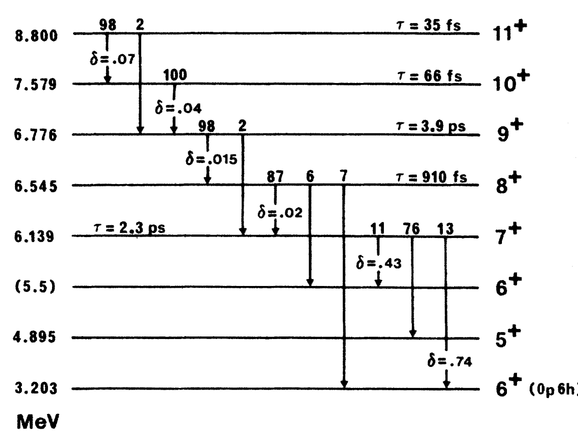

FIG. 4. Calculated decay scheme for the lowest 1p7h states with $J>6$ in ^{50}Ti.

ly,[8] an 11 → 10 → 9 → 8 → 7 cascade of $M1$ transitions is observed, followed by a 2937 keV transition with $E2$ admixture from the 7^+ to the 0p6h 6^+. The calculation accounts for the strong $M1$ decays, giving small $E2/M1$ ratios and very weak cross-over transitions. The strong 2937 keV transition can be explained if the 3203 keV 6^+ has a small 1p7h admixture. A 5% component of the lowest 1p7h 6^+ could (with most favorable phase) give a $7^+ \rightarrow 6^+$ branch of 80% rather than the 13% shown in Fig. 4, and an $E2/M1$ amplitude ratio of $\delta = 1.6$; this component would, however, cause the 6545 keV(8^+) → 3203 keV(6^+) branch to be 65%, so it appears that the 6^+ must have components of other than the lowest 1p7h state.

The lowest 12^+ state, which to date has not been isolated, is calculated to have a lifetime of about 50 fs and to decay mainly to the second 11^+ at about 10.6 MeV. Branches to yrast 1p7h states should be less than 5%.

IV. SUMMARY

These calculations have shown clearly that the high-spin states recently isolated in ^{50}Ti and ^{52}Cr are 1p7h and 1p5h states with a neutron hole in the $f_{7/2}$ shell. The excellent agreement between calculated and experimental energies is additional proof that the effective interaction which has been derived for calculations in this mass region can give very useful results even though configuration mixing is not explicitly taken into account. Calculated decay properties of 1p5h states in ^{52}Cr are generally in good agreement with experiment, only very weak mixing of 0p4h and 1p5h states being required to account for the few points of disagreement.

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