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Spectroscopy of ^{50}V with (p, nγ) reaction

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Abstract. Information on the low-lying levels up to $\sim$1·9 MeV excitation of the doubly odd nucleus ^{50}V has been obtained through the Ge (Li)–Ge (Li) coincidence study with the ^{50}Ti(p, nγ)^{50}V reaction. Branching ratios have been measured and tentative spin-parity assignments have been made. A detailed comparison with other measurements reported recently has also been made. Using the lowest seniority wave functions with $(f_{7/2})^3_p\,(f_{7/2})^{-1}_n$ configuration, energy levels and electromagnetic properties have been calculated. These have been compared with the present and earlier experimental data.

Keywords. (p, nγ) reaction; level structure; shell model calculation.

1. Introduction

The properties of low-lying levels in the odd-odd nucleus ^{50}V have been studied through transfer reactions (d, α), (^{3}He, p) and (^{3}He, d) (DelVecchio *et al* 1971, Caldwell *et al* 1972, Sourkes *et al* 1973, Smith *et al* 1973), inelastic scattering of protons and deuterons (Buhl *et al* 1969, Hansen *et al* 1968) as well as the (p, n) reaction (Blasi *et al* 1969). The spins of the first four excited states have been obtained earlier through the ^{50}Ti(p, nγ)^{50}V reaction and confirmed by other reactions. We have extended the study of the same reaction to obtain gamma transitions for the levels up to around 1·9 MeV excitation in the ^{50}V nucleus. A preliminary version of this work has been reported earlier (Gupta *et al* 1974). On the basis of this study we have obtained the branching ratios and the spins of these levels. Theoretical calculations of the levels of this nucleus have been already carried out in the shell model formalism assuming a $(f_{7/2})^3_p\,(f_{7/2})^{-1}_n$ configuration (McCullen *et al* 1965, Ginnocchio 1965). These calculations indicate that seniority is not a good quantum number for classifying wavefunctions for this nucleus. The experimental evidence presented in this paper indicates that seniority may be a good quantum number. Therefore assuming the lowest seniority wavefunctions for the ^{50}V nucleus, we have calculated the energy levels, the electric quadrupole moment and the magnetic moment of the ground state, the B(E2) and B(M1) transition rates and compared them with experimental results obtained in the present study as well as with the earlier data. Just about the time when the present experimental work was completed, very similar work was reported by Rickel and McCullen (1974). Recently two more papers have also appeared on the gamma transitions in ^{50}V by the ^{50}Ti (p, nγ) reaction (Rickel *et al* 1974 and Tomita and Tanaka 1974). Our results are generally in good agreement with those of these authors and to certain extent complement and supplement of the work of these authors.

2. Experimental procedure

The measurements were carried out using the 5·5 MeV Van de Graaff accelerator at Trombay. Proton beam currents on targets in the range of 0·2–0·3 microampere were used. We have used transmission type (~ 10 μg/cm^2 thick) targets which were prepared on thin carbon and aluminium films. All the targets were prepared by vacuum evaporation of isotopically enriched ^{50}TiO$_2$. This material was obtained from the Oak Ridge National Laboratory and its isotopic abundances were 76·4%–^{50}Ti, 2·0%–^{46}Ti, 1·8%–^{47}Ti, 17·8%–^{48}Ti and 2·0%–^{49}Ti. Gamma rays were detected using Ge(Li) detectors of 2 cc, 27 cc and 30 cc volume. The 2 cc detector has a very thin window and could detect gamma rays of energy as low as 14 keV. The energy and efficiency calibrations of detectors were done using ^{133}Ba (Marion 1968) and ^{152}Eu (Riedinger *et al* 1970) sources.

Coincidence measurements were performed using the 27 cc Ge(Li) detector and the 2 cc or the 30 cc Ge(Li) detector. Both the detectors were kept at ± 90° to the proton beam direction. The coincidence spectra were obtained at various proton energies using a fast slow coincidence system of a resolving time $2T = 400 \times 10^{-9}$ sec. By measuring the yield of the 226 keV gamma ray from the reaction $50_{\mathrm{Ti}(p,n\gamma)}$, it was observed that there are many narrow resonances of the average width ~ 10 keV (Gupta *et al* 1973). This was due to the fact that the target was quite thin. It was not possible for us to make a thick target due to an insufficient amount of the enriched isotope. Therefore, in order to have higher yield in the reaction, in the neighbourhood of the proton energy where the gamma spectra were to be obtained, the excitation function was scanned in 2·5 keV steps and the proton energy was chosen so as to work at the peak of one of the resonances in the reaction $50_{\mathrm{Ti}(p,n\gamma)}$.

3. Results

In figure 1 are shown the singles and coincidence spectra obtained. Using the thin window Ge(Li), gates were also set for the 32 + 35 keV gamma rays to remove the ambiguities in assigning the gamma transitions. In figure 1 there are extra lines present in 226 keV gate due to the Compton scattered gamma rays being detected by the other detector. The summary of the results is given in table 1 and figure 2. The measurements are in good agreement with those of Rickel and McCullen (1974), Rickel *et al* (1974) and Tomita and Tanaka (1974). We now compare the results obtained by us with the work of these authors.

3.1. 320 *keV and* 356 *keV level*

We observe a cross-over transition from the 320 keV level to the ground state. Blasi *et al* (1969) could not observe this transition in their work. Our result is in agreement with that of Tomita and Tanaka (1974) who assign 2·3±0·3% branching ratio to 320 keV transition while we have measured it to be 1·5 ± 0·2%. The cross-over transition of 129 keV from the 356 keV level to the 226 KeV level is only 0·7 ± 0·2% and has not been reported so far by other workers. In making these measurements specific care was taken to minimize and to correct for the

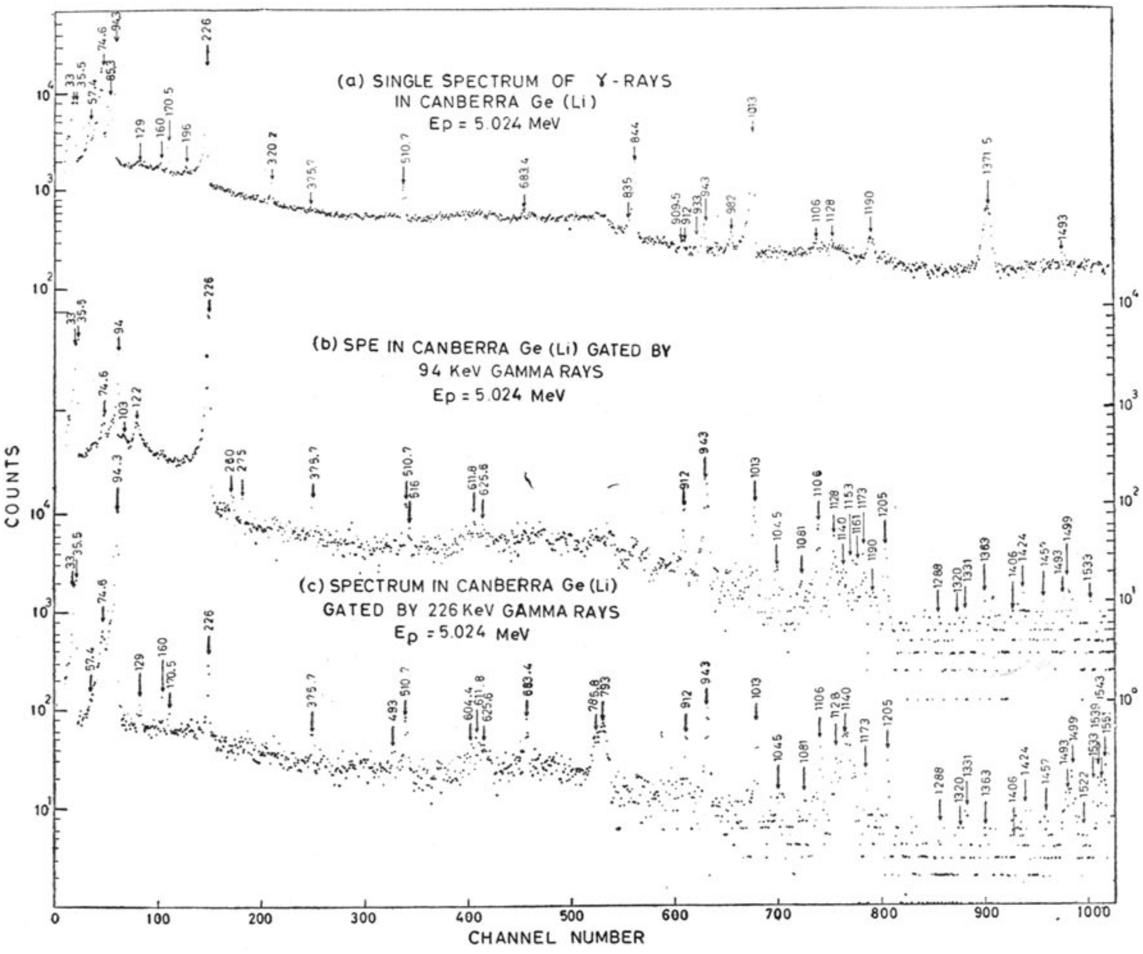

Figure 1. Singles and coincidence spectra of γ-rays in the ^{50}Ti (p, nγ) ^{50}V reaction recorded at incident proton energy E_p = 5·024 MeV. The peak positions of γ-rays are given in the figure in keV.

Table 1

Level No.	E_x (keV) present	J^{π}*	Decay gamma-rays (keV)	Branching ratios %
0	0	6^+	0	—
1	226·0±0·3	5^+	226·0±0·3	100
2	320·3±0·5	4^+	94·3±0·3 320·2±0·3	98·5±0·2 1·5±0·2
3	355·8±0·5	3^+	35·5±0·3 129±1	99·3±0·2 0·7±0·2
4	388·9±0·5	2^+	33·1±0·3	100
5	835±1	5^+	(835±1) (517±1)	67±15 37±15
6	909·4±0·5	4^+	683·4±0·3	100
	909±1	7^+	909±1	100
7	1301±1	2^+	912±1 943±1	69±5 31±5
8	1332±1	1^+	945±1	100
9	1401±1	3^+	493±1 (1013±2) 1045±1 1081±1	12±4 (58±3) 16±7 14±5
10	1495±1	1^+	1106±1 1140±1	88±5 12±5
11	1517±1	2^+	1128±1 1161±1	86±5 14±5
12	1562±1	2^+	1173±1 1205±1	43±6 57±6
13	1677±1	3^+	275±0·5 375·7±0·5 1288±1 1320±1	18±5 44±7 20±7 18±7
14	1702±2	5^+	793±2	100
15	1720±3	2^+	1331±2 1363±2	56±11 44±11
16	1725±2	4^+	1499±2 1405±2	91±5 9±5
17	1760±4	3^+–5^+	..	..
18	1766±8	3^+–5^+	..	..
19	1813±2	3^+	1424±2 1457±2 1493±2	21±11 25±11 55±13

* These spin and parity assignments are based on the earlier measurements of Smith *et al* (1973), Rickel *et al* (1974), Tomita and Tanaka (1974) and our work.

coincidence summing effects which otherwise can render the measurements unreliable.

3.2. 837 *keV and* 910 *keV levels*

Rickel *et al* (1974) measured 516 keV and 836 keV transitions in their work from 836 keV level. These transitions are very weakly excited in our measurement. We observe the 683 keV transition from the 910 keV level as has been observed by others. The 910 keV level is populated by the 793 keV transition from the 1702 keV level and in a coincidence measurement selecting 901 keV in the gate, the 793 keV transition could not be detected. Combining singles and coincidence data with other gates we extracted the intensity of a 910 keV direct transition to the ground state. This data can be reconciled with the fact that there are two levels with different spins of 4^+ and 7^+ as assumed by Rickel and McCullen (1974) Rickel *et al* (1974) and Tomita and Tanaka (1974). The direct transition of 910 keV should be directly from the 7^+ state rather than from the 4^+ state. The 4^+ level at 910 keV decays by 683 keV transition.

3.3 1301 *keV and* 1332 *keV levels*

We observe 912 keV and 943 keV transitions from the 1301 keV level. From 1332 keV level another transition of 945 keV could be resolved from the 943 keV transition mentioned above. The presence of 943 keV transition was confirmed by measuring the ratio of 943 + 945 keV yield to the 912 keV yield near the threshold of 1301 keV and 1332 keV levels. The 943 keV transition was not reported by Rickel and McCullen (1974) but has been measured by Rickel *et al* (1974) and by Tomita and Tanaka (1974). Our branching ratios of 69 ± 5% and 31 ± 5% agree with these latter workers who report values of 61% and 39% and 72±6% and 28±4% respectively. The 1332 keV level decays through a 945 keV transition as observed also by other workers.

3.4 1401 *keV and* 1495 *keV levels*

In our measurement the 1013 keV transition from the 1301 keV level has been marked by a strong line from the ^{27}Al (p, p′ γ) reaction. We observe a 493 keV transition not observed by others. We also observe the 1045 keV transition not reported by Tomita and Tanaka (1974) but observed by Rickel and McCullen (1974) and Rickel *et al* (1974). The branching ratio for this level has been calculated using the data of Rickel and McCullen (1974) and our data. From the 1495 keV level, a 1140 keV transition has been observed by us but not reported by other workers.

3.5 1517 *and* 1562 *keV levels*

From both these levels the transitions and branching ratios observed by us are in good agreement with the measurements of Rickel and McCullen (1974), Rickel *et al* (1974) and Tomita and Tanaka (1974).

3.6 1677 *keV level*

From the 1677 keV level we observe all the transitions reported by Rickel and McCullen (1974) and Rickel *et al* (1974) but Tomita and Tanaka (1974) do not report 275 keV and 1320 keV transitions.

3.7. 1702, 1720, 1725 *and* 1813 *keV levels*

Gamma decay of these levels have not been reported so far. The 1702 keV level has been assigned a spin of (4^+, 5^+) from the enhancement of neutron transitions at the isobaric analog resonance at the proton energy of 5·225 MeV Tomita and Tanaka (1974). From this level we observe a transition of 793 keV level to 909 keV which is in agreement with the assigned spins. At 1720 keV excitation in ^{50}V there seems to be a doublet with energies at 1720±3 and 1725±2 keV. The first of these levels decay to 356 keV and 389 keV levels by 1363 and 1331 keV transitions. On the basis of these transitions we assign it a spin of 2^+. The 1725 keV level decays by 1405 and 1499 keV transitions to 320 and 226 keV levels. We assign it a spin of 4^+ on the basis of this fact. We have not observed any transition from 1760 and 1766 keV levels. Probably they are not populated in our reaction due to higher values of spins. We observe a level at 1813 keV having 1424, 1457 and 1493 keV transitions to 389, 356 and 320 keV levels. A spin of 3^+ has therefore been assigned to this level.

On the basis of transitions observed and the earlier known data, tentative spin-parity assignments were made assuming M1 transitions to be the most probable ones. These assignments were confirmed by the work of Rickel and McCullen (1974), Rickel *et al* (1974), and Tomita and Tanaka (1974). In table 1, we have listed the branching ratios and the best spin parity assignments. The proposed decay scheme is shown in figure 2. The J^π assignments of 3^+ and 5^+

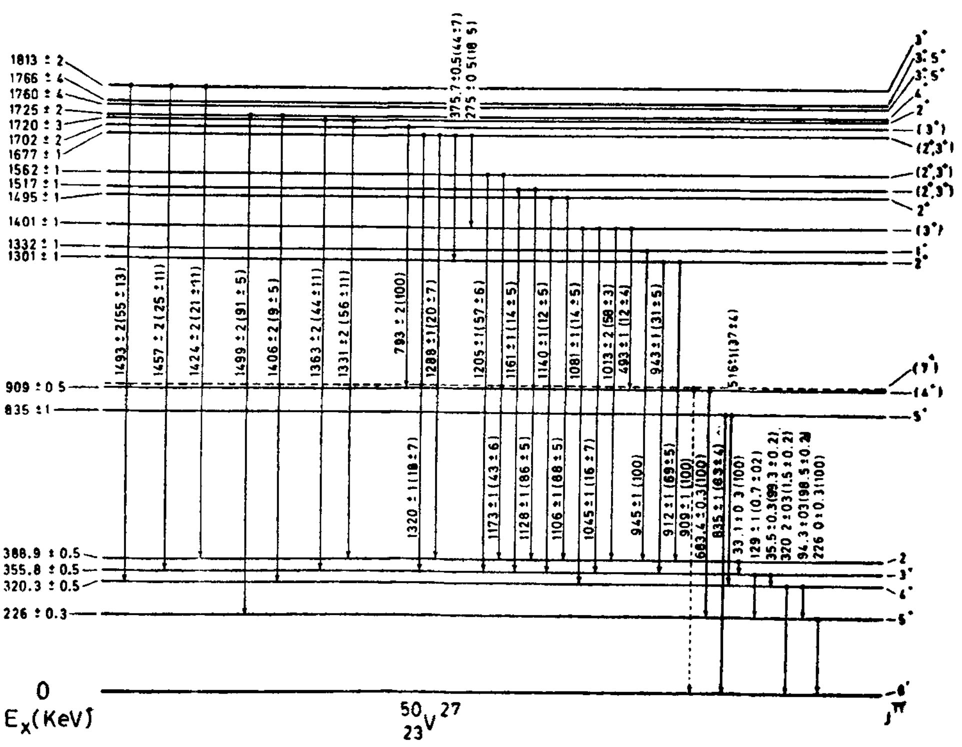

Figure 2. Decay scheme of ^{50}V as deduced from our experiment. The branching ratios are given in brackets. The doublet level at 909 (7^+) is shown as a dotted line.

to 1677 keV and 1702 keV levels respectively are in agreement with the (d, α) data of Delvecchio *et al* (1971) where the operation of certain selection rules in this transfer reaction enhances the cross-section for $J = L + 1$ transition. Using the relations given by Bohr and Mottleson (1969) for reduced transition probabilities B (M1) and B (E2) in terms of transition strengths, the ratios of reduced transition probabilities have been calculated. These have been listed in table 2. Most of the strong transitions for levels above 356 and 389 keV levels, take place through these two levels obviously due to the higher transition energies and favourable spin changes. The exceptions are the 376 and 276 keV transitions from the 1677 keV level and the 793 keV transition from the 1702 keV level. This

Table 2. Reduced transition probabilities.

E_x (keV)	Relative transition probabilities		
320	$\frac{B\,(\mathrm{E2})\ 320}{B\,(\mathrm{M1})\ 94}$	53±7	$\frac{e^2 fm^4}{(n \cdot m)^2}$
356	$\frac{B\,(\mathrm{E2})\ 129}{B\,(\mathrm{M1})\ 35{\cdot}5}$	127±36	$\frac{e^2 fm^4}{(n \cdot m)^2}$
835	$\frac{B\,(\mathrm{M1})\ 517}{B\,(\mathrm{M1})\ 835}$	0·55±0·25	
1301	$\frac{B\,(\mathrm{M1})\ 943}{B\,(\mathrm{M1})\ 912}$	0·40±0·1	
1401	$\frac{B\,(\mathrm{M1})\ 1045}{B\,(\mathrm{M1})\ 1013}$	0·26±0·14	
	$\frac{B\,(\mathrm{M1})\ 1081}{B\,(\mathrm{M1})\ 1013}$	0·20±0·09	
	$\frac{B\,(\mathrm{M1})\ 493}{B\,(\mathrm{M1})\ 1013}$	1·82±0·84	
1495	$\frac{B\,(\mathrm{M1})\ 1140}{B\,(\mathrm{M1})\ 1106}$	0·13±0·06	
1517	$\frac{B\,(\mathrm{M1})\ 1161}{B\,(\mathrm{M1})\ 1128}$	0·15±0·06	
1562	$\frac{B\,(\mathrm{M1})\ 1173}{B\,(\mathrm{M1})\ 1205}$	0·8±0·2	
1677	$\frac{B\,(\mathrm{M1})\ 276}{B\,(\mathrm{M1})\ 376}$	1·0±0·3	
	$\frac{B\,(\mathrm{M1})\ 1288}{B\,(\mathrm{M1})\ 376}$	0·12±0·04	
	$\frac{B\,(\mathrm{M1})\ 1321}{B\,(\mathrm{M1})\ 376}$	0·09±0·04	
1720	$\frac{B\,(\mathrm{M1})\ 1364}{B\,(\mathrm{M1})\ 1332}$	0·7±0·3	
1725	$\frac{B\,(\mathrm{M1})\ 1405}{B\,(\mathrm{M1})\ 1499}$	0·12±0·073	
1813	$\frac{B\,(\mathrm{M1})\ 1457}{B\,(\mathrm{M1})\ 1493}$	0·49±0·25	
	$\frac{B\,(\mathrm{M1})\ 1424}{B\,(\mathrm{M1})\ 1493}$	0·44±0·25	

seems interesting and indicates some selection rule operating which enhances these transitions over the other possible ones.

This nucleus reveals a very orderly spin sequence 6, 5, 4, 3 and 2 for low-lying levels which is not reproduced by the existing shell model calculations (McCullen *et al* 1965, Ginnocchio 1965). Though the theory predicts the same spectra both for ^{50}V and its particle hole conjugate ^{46}Sc, the experimental spectra of these nuclei violate such a prediction (Rickel *et al* 1974). Instead of such a feature, the experimentally observed spectra of $^{48}_{21}\mathrm{Sc}^{27}$ (Ohnuma *et al* 1970) for low-lying levels agree with that of $^{50}_{23}\mathrm{V}^{27}$. This resemblance tempts us to believe that probably seniority is a good quantum number for each of the group. Smith *et al* (1973) conclude on the basis of the transfer reaction (^{3}He, p) that the lowest five levels and 1332 keV level are the members of the octet with the $(f_{7/2})^1_p\,(f_{7/2})^{-1}_n$ configuration indicating thereby that seniority is a good quantum number. The assumption of a pure $f_{7/2}$ configuration for ^{50}V is also supported by the studies of transfer reactions ^{49}Ti(^{3}He, d)^{50}V and ^{51}V(d, t)^{50}V (Sourkes *et al* 1973). The results of these studies show large spectroscopic factors with the $f_{7/2}$ configuration for both the odd particles for the low-lying levels of ^{50}V with small admixtures of $p_{3/2}$ orbitals in some cases. The further justification can be given by using the expression for the pairing energy E for n particles with a seniority v (Lane 1964):

$$E(j^n,\, v) = -G\frac{(n-v)}{4}\,[2j+1-n-v+2] \tag{1}$$

With such an expression the following relation can be written down.

$$E\,[(f_{7/2})^3_p\ ;\ v=3] - E\,[(f_{7/2})^3_p\ ;\ v=1] = 3G \tag{2}$$

If one assumes a reasonable value of $G = 20/A$ MeV, the seniority one state is lowered by 1·2 MeV in comparison to seniority 3 states in the proton odd group. This feature is partly exhibited by the experimental spectrum of ^{50}V.

The energy levels were calculated with $(f_{7/2})^3_p\,(f_{7/2})^{-1}_n$ configuration assuming the minimum seniority, taking the residual interaction, given by

$$V(r_{ij}) = -V_0\left[\delta(r_i - r_j) + \frac{5}{4\pi}\,V_Q r_i^2\, r_j^2\, P_2(\cos\theta_{ij})\right] \times [(1-a) + a\sigma_i \cdot \sigma_j] \tag{3}$$

Expression (3) represents a sum of a short range delta function interaction (Schwartz 1954) and a long range quadrupole-quadrupole interaction (DeShalit and Walecka 1961) with a suitable spin-spin interaction. The parameters V_0, V_Q and a were adjusted to get the experimental spin sequence and spacings for the calculated energy levels. The results are shown in figure 3 along with the experimental data on ^{50}V and the other calculations (McCullen *et al* 1965, Ginnochio 1965). The experimental and calculated spectra for ^{48}Sc are also shown in figure 3. The spectrum for ^{48}Sc is obtained satisfactorily only when a different set of parameters is used. This implies that the effective residual interaction is renormalized to different extent for different nuclei when energies are calculated with a truncated configuration space.

The same wavefunctions, which were used for the energy level calculation were also used to calculate the electromagnetic properties of some of the low-lying levels.

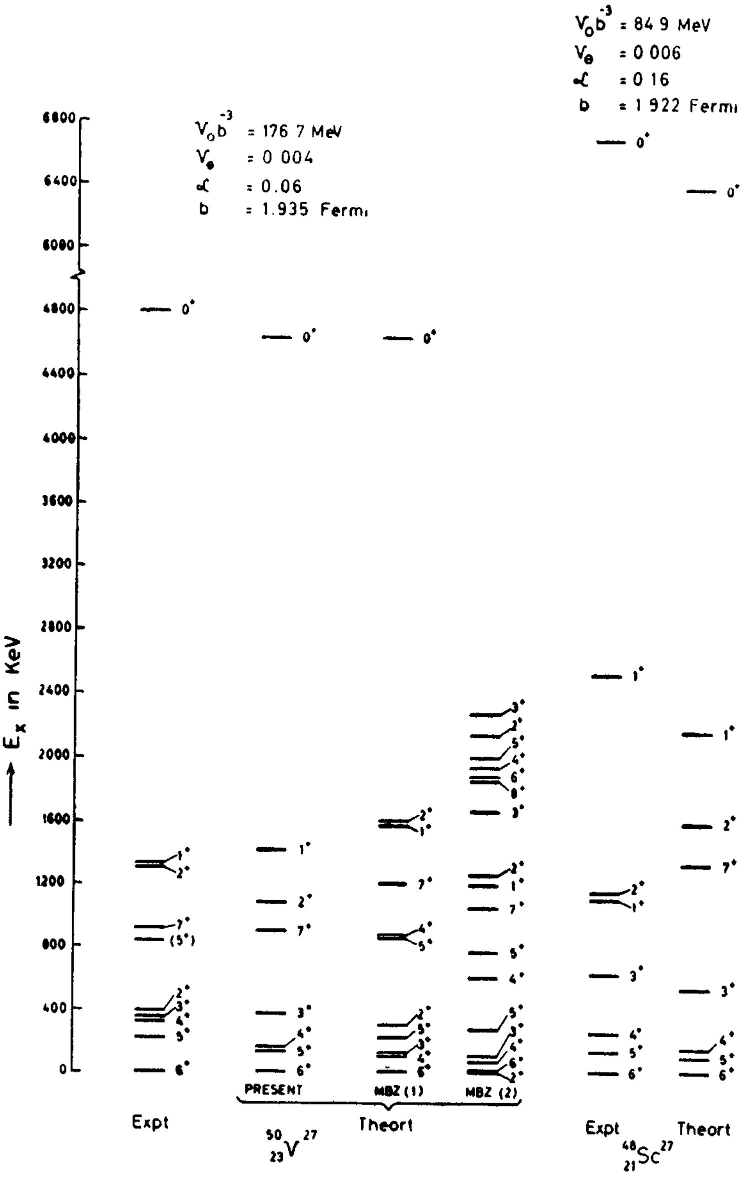

Figure 3. The comparison of experimental levels with theory. The calculation MBZ (1) is taken from McCullen *et al* (1965) and MBZ (2) is taken from Rickel and McCullen (1974). $^{48}_{21}$Sc shows a similar spin sequence as $^{50}_{23}$V and the present calculation for $^{21}_{48}$Sc is also shown for comparison. $^{21}_{48}$Sc experimental levels are taken from Ohnuma *et al* (1970). The 0^+ level at 4810 keV in ^{50}V is taken from Sherr (1967) and the 0^+ level at 6681 keV in ^{48}Sc is taken from Nolen *et al* (1967).

For the purpose of this calculation the effective 'g' factors were taken from the adjacent odd nuclei and were 1·4 nm for proton and −0·3 nm for neutron. The effective charges were assumed as 1·8 e for proton and −0·8 e for neutron (Nomura and Yamazaki 1971). The value of $\langle r^2 \rangle$ was calculated using the harmonic oscillator wavefunctions assuming the oscillator frequency ω as given by $\hbar\omega = 41\, A^{-1/3}$. The calculations are listed in table 3. Only the magnetic

Table 3

No.	Property	Experiment	Calculation	References
1	Quadrupole moment of g.s.	(±) 0·4	+0·013 barns	Lederer *et al* 1968
2	Magnetic moment of g.s.	3·348	3·30 nm	Lederer *et al* 1968
3	*B*(E2) for 226 keV level	110±20	19·4 e^2fm^4	Tammer *et al* 1956 Gagg *et al* 1956
4	E2–M1 multiple mixing amplitude	0·035±0·96	−0·0027	Gupta *et al* 1973
5	$\frac{B(\mathrm{E2})\ 320}{B(\mathrm{M1})\ 94}$ for 320 keV level	54±7	0·009 $e^2fm^4/(nm)^2$	Present work
6	$\frac{B(\mathrm{E2})\ 129}{B(\mathrm{M1})35{\cdot}5}$ for 356 keV level	127±36	0·013 $e^2fm^4/(nm)^2$	Present work

moment is of the right order of magnitude; other quantities differ considerably indicating substantial admixtures in the wavefunctions of components other than of $f_{7/2}$ orbitals. It must be mentioned here that the assumption of the pure $(1f_{7/2})^3_p\ (1f_{7/2})^{-1}_n$ configuration for some of the lowlying levels of ^{50}V is not fully justified, because as mentioned earlier the spectroscopic factors determined from the transfer reactions ^{51}V(d, t)^{50}V and ^{49}Ti (^{3}He, d)^{50}V (Sourkes *et al* 1973) show small but significant admixures due to $p_{3/2}$ orbitals. These admixtures can affect the gamma ray transition probabilities substantially. This indicates the need for carrying out further theoretical calculations including configuration mixing.

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References

Blasi P, Maurenzig P R, Taccetti N and Ricci R A 1969 *Phys. Lett.* **28 B** 555
Bohr A and Mottleson B R 1969 *Nuclear Structure* (W A Benjamin Inc.) Vol. 1. 382
Buhl W F, Kovard D, Comfort J R, Hansen D and Pullen D J 1969 *Nucl. Phys.* **A 131**))
Caldwell T, Hansen D and Pullen D J 1972 *Nucl. Phys.* **A198** 529
DelVecchio R, Dachnick W W, Dittmer D L and Park Y S 1971 *Phys. Rev. C3* 1989
DeShalit A and Walecka J D 1961 *Nucl. Phys.* **22** 184
Gagg L W, Gear E H and Wolicki E A 1956 *Phys. Rev.* **104** 1073
Ginnocchio J N 1965 *Nucl. Phys.* **63** 449
Gupta S K, Saini S, Kailas S, Kerekatte S S and Kanetkar L J 1973 *Proc. Nucl. Phys. Soli State Phys. Symp.* **16B** 35
Gupta S K, Saini S and Kanetkar L J 1974 BARC-768 55
Hansen D, Dorenbusch W and Belote T 1968 *Nucl. Phys.* **A118** 41
Lane A M 1964 *Nuclear Theory* (Pairing force correlations and collective motion) W A Benjamin Inc. 23

Lederer C M, Hollander J M and Perlman I, 1968 *Table of Isotope* Sixth edition, John Wiley and Sons

Marion J B 1968 *Nuclear Data* **A4** 301

McCullen J D, Bayman R F and Zamick L 1965 *Phys. Rev.* **134 B** 515

Nolen Jr. J A, Schiffer J P, Williams N and Ehreustein D Von *Phys. Rev. Lett.* **18** 1140

Nomura T and Yamazaki T 1971 *The structure of* $f_{7/2}$ *Nuclei* ed. R A Ricci, Editrice Compositori—Bologna 436

Ohnuma H, Erskine J R, Schiffer J P, Nolen Jr. J A and Williams N 1970 *Phys. Rev.* *C***1** 496

Rickel D G and McCullen J D 1974 *Phys. Rev.* *C***9** 1446

Rickel D G, Robertson N R, Nelson R D, Williams J R and Tilley D R 1974 *Nucl. Phys.* **A232** 200

Riedinger L L, Johnson N R and Hamilton J H 1970 *Phys. Rev.* *C***2** 2358

Temmer G M and Heydenberg N P 1956 *Phys. Rev.* **104** 967

Tomita Y and Tanaka S 1974 *Nucl. Phys.* **A232** 417

Schwartz C 1954 *Phys. Rev.* **94** 94

Sherr R 1967 *Phys. Lett.* **24 B** 321

Smith A J W, Meyer-Schützmeister L, Braid T H, Singh P P and Hardie G 1973 *Phys. Rev.* *C*7 1099

Sourkes A, Ohnuma H, and Hintz N 1973 *Nucl. Phys.* **217** 438