Negative-Parity Band in ^{48}V

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The electromagnetic decays of levels in ^{48}V have been studied via the reaction ^{34}S(^{16}O, *pn*)^{48}V at incident ion energies of 30–36 MeV. Spins, parities, and branching and mixing ratios were obtained from angular distribution, excitation function, γ-γ, and n-γ coincidence measurements. Six, and possibly seven, members of a very pure rotational negative-parity band were identified. This band is based on a 1^- low-lying core excited state with probable configuration $(\pi d_{3/2})^{-1}(\pi f_{7/2})^4(\nu f_{7/2})^5$.

A systematic study of nuclei in the $1f_{7/2}$ shell populated in heavy-ion–induced reactions is currently underway in this laboratory. The odd-odd cross-conjugate nucleus ^{48}V was the first to be studied since a knowledge of its properties is quite important for a proper understanding of the forces coming into play in this shell. In this Letter we report evidence for a negative-parity band built on a low-lying core excited state. This band has amazing regularity indicating the presence of a rigid structure with a rather large deformation.

The levels in ^{48}V were populated via the reaction ^{34}S(^{16}O,pn)^{48}V. The ^{16}O beam from the Université de Montréal EN tandem Van de Graaff accelerator was typically 150 nA in the 5^+ charge state. Targets enriched to 85.6% in ^{34}S were made by evaporation of ~ 500 μg/cm^2 of CdS onto thick nickel backings. The beam energy was varied between 30 and 36 MeV in steps of 2 MeV. Several exit channels were open at these bombarding energies, the most important being pn, $2pn$, $2p$, αp, αn, and $2n$ in roughly decreasing order of importance. The γ rays emitted in the decay of ^{48}V were identified through high-resolution γ-γ and n-γ coincidence measurements using two Ge(Li) and one NE213 detectors. The angular distributions of the decay γ rays were measured at seven angles in the horizontal plane.

TABLE I. Experimental results for the negative-parity band in ^{48}V.

E_x(keV)	E_γ(keV)	J_i^π	J_f^π	Branching ratios(%)	δ^d	a_2/a_0	a_4/a_0	W(0)/W(90)
518.6	98.0 ± 0.2	1^-	1^+	29 ± 2	0.0 ± 0.02	.04 ± .01	-	
	210.4 ± 0.2	1^-	2^+	71 ± 2	$-0.09 \leq \delta \leq 0.02$	-.09 ± .02	-	
744.9	226.3 ± 0.2	2^-	1^-	93 ± 2	0.02 ± 0.04	-.29 ± .01	-	
	324.2 ± 0.5	2^-	1^+	3 ± 1	a	a		
	436.7 ± 0.5	2^-	2^+	5 ± 2	a	a		
1055.7	310.8 ± 0.2	3^-	2^-	91 ± 3	$-0.02 \leq \delta \leq 0.07$	-.32 ± .02	-	
	537.2 ± 1.0	3^-	1^-	9 ± 3	$-0.03 \leq \delta \leq 0.15$	.45 ± .06	-.38 ± .08	
1557.6	501.9 ± 0.2	4^-	3^-	71 ± 7	0.12 ± 0.04	-.51 ± .04	.07 ± .04	
	812.7 ± 1.0	4^-	2^-	29 ± 7	b	b		1.42 ± 0.25
2062.5	504.9 ± 0.2	5^-	4^-	70 ± 7	-0.07 ± 0.07	-.17 ± .04	-	
	1006.3 ± 1.0	5^-	3^-	30 ± 7	b	b		1.34 ± 0.21
2779.4	716.9 ± 1.0	6^-	5^-	69 ± 10	c	c		0.46 ± 0.18
	1221.8 ± 1.5	6^-	4^-	31 ± 10	b	b		1.39 ± 0.18
3586.0	806.6 ± 1.0	(7^-)	6^-	68 ± 15	c	c		0.42 ± 0.23
	1523.5 ± 1.6	(7^-)	5^-	32 ± 15	e	e		

[a] Intensity of γ rays too weak to yield meaningful data.

[b] Difficult to analyze because of interference of other γ rays and Doppler shift effect; however, the ratio $W(0)/W(90)$ is consistent with stretched quadrupole transitions.

[c] Same as b, but with stretched dipole transitions.

[d] Mixing ratio defined as in Rose and Brink (Ref. 1).

[e] Masked by ^{42}Ca $2^+ \rightarrow 0^+$ 1524.2-keV transition. Branching ratios obtained from γ-γ total projection spectrum.

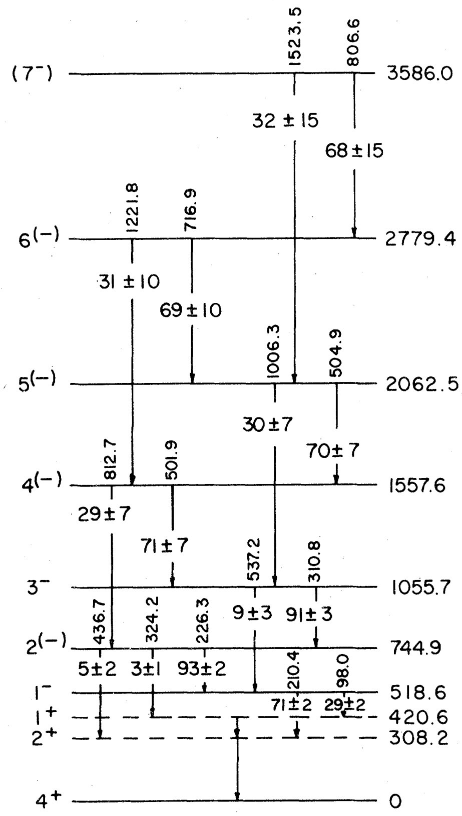

FIG. 1. Partial level scheme of ^{48}V showing the negative-parity band and its modes of decay.

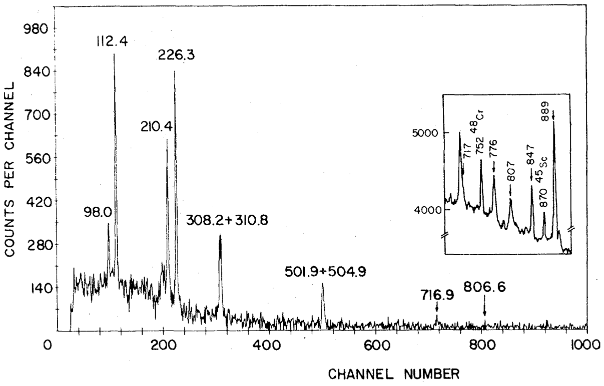

FIG. 2. γ-γ coincidence spectrum resulting from a gate placed on the (308.2 + 310.8)-keV transitions. In the inset we display part of the total γ-γ projection spectrum showing the weak transitions between the upper members of the band.

The energies of the coincident γ rays and their time distribution were recorded event by event on magnetic tape by means of an on-line computer. The results of the analysis are summarized in Table I and Fig. 1. The levels at 2062.5, 2779.4, and 3586.0 keV have not been reported previously.

The members of the negative-parity band have been definitely established up to $J = 6$ on the basis of the following arguments:

(i) Each one of the γ rays proposed to be a member of the γ-ray cascade is in coincidence with all the other members. Figure 2 shows, as an example, the resulting coincidence spectrum with the gate set on the (308.2 + 310.8)-keV transitions. Further evidence for the weaker 717- and 807-keV γ-ray transitions is given in the inset of Fig. 2 which shows part of the total γ-γ projection spectrum. These γ rays are also quite prominent in the n-γ spectrum.

(ii) The relative intensities of the γ-ray transitions in the singles spectra show a gradual decrease with increasing spin. This feature is consistent with a statistical picture of the de-excitation process of the compound nucleus.[2]

(iii) In the coincidence spectra, the relative intensities of all the transitions following a gate transition are equal within statistics, while those of the transitions preceding the gate transition are in the same proportion as in the singles spectra.

(iv) In addition, excitation functions have been measured for bombarding energies ranging from 30 to 36 MeV. The results display the systematic variation with spin expected from a statistical deexcitation mechanism,[2] e.g., over the above energy range the intensity of the 505-keV $5^- \rightarrow 4^-$ transition increases by a factor of ~2.5 while that of the 226-keV $2^- \rightarrow 1^-$ transition increases by only 15%.

Prior to the beginning of our work only the ground and first two excited states had definite spin and parity assignments. The allowed values of J and δ presented in Table I are based on a χ^2 analysis of the measured γ-ray angular distributions. All spin combinations yielding up to octupole-hexadecapole γ-ray admixtures and consistent with the excitation-function results have been considered. Further details[3] on this type of analysis will be given in the general context of spin assignments following heavy-ion-induced reactions. It was difficult to obtain a complete angular distribution for the weaker dipole and quadrupole transitions because of interference from other γ rays and Doppler-shift effect. However, the ratio of their intensities at 0° and 90° with respect to the beam axis was consistent with stretched $(J \rightarrow J - 1)$ dipole and $(J \rightarrow J - 2)$ quadrupole transitions, respectively (see Table I). The results for the first four states are in agreement with recent work by Samuelson *et al.*[4] who used the reaction ^{48}Ti(p,n)^{48}V and analyzed their data with the statistical compound-nuclear computer code MANDY.

The 518.6-keV state was assigned $J^\pi = 1^-$ according to the following arguments. Our results for this state rule out $J=0$ and $J \geqslant 3$, and in conjunction with the mean lifetime[5] of the level ($\tau = 3.92 \pm 0.09$ nsec) $J^\pi = 2^-$ could also be rejected since it would lead to unacceptable $M2$ strengths [>190 Weisskopf units (W.u.)]. Dorenbusch *et al.*[6] have populated this level in the reaction ^{47}Ti(^{3}He, d)^{48}V. Their deuteron angular distribution was fitted with a pure $l_p = 3$ component ($J^\pi = 5^+$ or 6^+). However, their distribution could have also conceivably been fitted with $l_p = 2$ ($0^- \leqslant J^\pi \leqslant 5^-$). Thus the 518-keV state could be assigned $J^\pi = 1^-$. Further support for this assignment comes from recent work on the reaction ^{46}Ti(^{3}He,p)^{48}V by Smith *et al.*[7] These authors found a large number of 1^+ and 2^+ states but failed to observe the 518-keV level. In addition, if this low-lying state were to have positive parity one would expect it to have particle configurations similar to the ground and first two excited states thus giving rise to rapid $M1$ decay. On the other hand, a negative parity with a particle configuration of $(\pi d_{3/2})^{-1}(\pi f_{7/2})^4 \times (\nu f_{7/2})^5$ would yield j-forbidden $E1$ decays in agreement with the observed long lifetime of the level. The observed $E1$ strengths are $(5.28 \pm 0.12) \times 10^5$ W.u. and $(1.45 \pm 0.05) \times 10^{-5}$ W.u. for the 98- and 210-keV γ-rays, respectively. The corresponding values for $M1$ transitions would have been $(2.46 \pm 0.23) \times 10^{-3}$ W.u. and $(0.61 \pm 0.03) \times 10^{-3}$ W.u., respectively.

The parity of the higher states shown in Fig. 1 was inferred from the fact that the band follows extremely well the $J(J+1)$ rule expected of a rigid rotor (Fig. 3). This behavior gives strong support to the interpretation of the band as being a rotational band built on a core excited state. The parity of these states should eventually be measured, for example, by a γ-ray linear polarization measurement. However, the complex γ-ray singles spectrum necessitates the use of an expensive Ge(Li) polarimeter which is not at present available in our laboratory. The lifetime measurements of the higher lying states of this band are currently in progress in our laboratory. Preliminary results on the 744.9-keV state ($\tau \sim 25$ psec) and on the 1055.7-keV state ($\tau \approx 5$ psec) indicate that the $E2$ transition strengths of the decay γ rays of these levels could be as high as 18 and 24 W.u., respectively. Unfortunately, the values of δ are close to zero and the errors, even though small, then lead to a rather large range of $E2$ strengths. It is interesting to note that the 537-keV $3^- \rightarrow 1^-$ transition strength is of the order of 30 W.u. if $E2$ and 1337 W.u. if $M2$, clearly indicating that the 1055- and 518-keV states have the same parity.

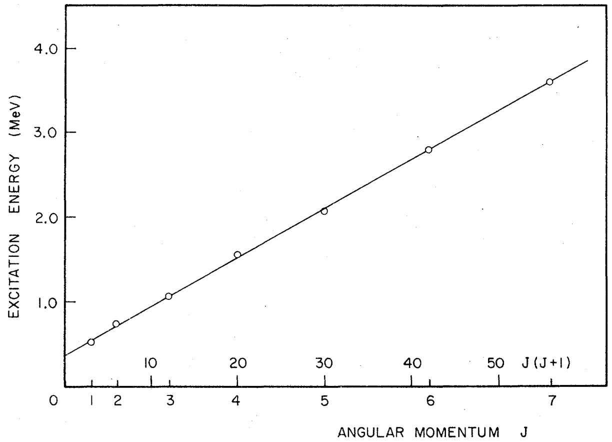

FIG. 3. Excitation energies of the members of the negative-parity band versus $J(J+1)$.

It should also be pointed out that all the γ-ray transitions occurred within the negative-parity band; none was observed to a number of other neighboring states whose parity is believed to be positive. This is not surprising since the positive-parity states appear to be fairly well accounted for on the assumption of a pure $f_{7/2}$ nucleon configuration.[8] In addition, transitions from the members of the negative-parity band based on a $(\pi d_{3/2})^{-1}$ configuration to the positive-parity states whose configurations are expected to be mainly $(\pi f_{7/2})^3(\nu f_{7/2})^{-3}$ would entail $M2$ transitions which are expected to be retarded.

The variation of the excitation energy E_x of the members of the negative-parity band as a function of $J(J+1)$ is very well reproduced by the relation $E_x = E_0 + (\hbar^2/2\mathscr{J})J(J+1)$ with $E_0 = 405$ keV and $\hbar^2/2\mathscr{J} = 56.7$ keV, the largest deviation being $\simeq 2\%$ for the 5^- state. This is rather surprising since one might have expected some band mixing. The purity of the band seems to indicate that the nucleus in its 518-keV state must have a rather rigid structure corresponding to a rather large deformation. Taking $\delta = 0.06$ for the 226-keV $2^- \rightarrow 1^-$ transition, we obtain for the intrinsic quadrupole moment $Q_0 = 0.79$ b, for the deformation $\beta = 0.24$, and a rather large value of 0.78 for the quantity $(g_K - g_R)$.

No theoretical predictions on the negative-parity states of ^{48}V have yet been published. It might be interesting to undertake SU(3) calculations to try to understand the appearance of core excited states at such low excitation energies (also known[9] to exist in other nuclei of the $1f_{7/2}$ shell) and in particular to try to find out why they appear to be so pure, as in ^{48}V.

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$\Delta I = \frac{1}{2}$ Rule for Nonleptonic Decays in Asymptotically Free Field Theories

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The effective nonleptonic weak interaction is examined assuming the Weinberg-Salam theory of weak interactions and an exactly-conserved-color gauge symmetry for strong interactions. It is shown that the octet part of the nonleptonic weak interaction is more singular at short distances than the $\underline{27}$ part. The resulting enhancement of the octet term in the effective local weak Lagrangian, together with suggested mechanisms for the suppression of matrix elements of the $\underline{27}$ operator, may be sufficient to account for the observed $|\Delta I| = \frac{1}{2}$ rule.

The purpose of this paper is to discuss the effectively local form of nonleptonic weak interactions in models in which weak interactions are described by a Weinberg-Salam–type gauge theory[1] and strong interactions by an exactly-conserved-color gauge-symmetry group,[2] and to comment on the origin of the $\Delta I = \frac{1}{2}$ (or octet) rule observed in strangeness-changing decays.

Our discussion is based on the operator-product expansion of the product of two weak currents. In an asymptotically free field theory,[3] it is possible to compute the short-distance behavior of coefficient functions in the operator-product expansion; we find that the $\Delta I = \frac{1}{2}$ part of the interaction is more singular at short distances. This is much as anticipated by Wilson.[4] (See also Mathur and Yen[5]; however, our conclusions differ substantially from theirs.)

In the following, we shall use the 't Hooft–Feynman gauge to describe both the weak bosons and the color gluons. In the 't Hooft–Feynman gauge, effects of (unphysical) Higgs scalar fields may be neglected, since they are of order $(m/m_W)^2$ compared to the W exchange, where m is a characteristic mass scale of hadrons and m_W the mass of the charged vector meson W.

It is useful to consider first the case of free quarks. The effective nonleptonic weak interaction is of the form

$$-f^2 \int d^4x\, D_F(x; m_W^2)\, T[j_{\mu N}^\dagger(x) j_S{}^\mu(0)], \tag{1}$$

where $j_{\mu N}$ and $j_{\mu S}$ are strangeness-conserving and -changing charged currents:

$$j_{\mu N} = (\bar{\mathcal{P}}\cos\theta - \bar{\mathcal{P}}'\sin\theta)\gamma_\mu(1-\gamma_5)\mathfrak{N} + \dots \tag{2}$$

and

$$j_{\mu S} = (\bar{\mathcal{P}}\sin\theta + \bar{\mathcal{P}}'\cos\theta)\gamma_\mu(1-\gamma_5)\lambda + \dots . \tag{3}$$

In Eq. (2), $\mathcal{P}'$ denotes the fourth quark field associated with the proposal of Glashow, Iliopoulos,