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Spins of ^{47}V and ^{48}V by the atomic beam magnetic resonance method

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The atomic beam magnetic resonance technique has been used to measure the spins of ^{47}V (33 min) and ^{48}V (16 days). The spin values are: ^{47}V, $I = 3/2$ and ^{48}V, $I = 4$. These results are compared with the available nuclear structure calculations. Recalculations of the level scheme of ^{47}V using the pure $f_{7/2}$ model of McCullen, Bayman, and Zamick, with revised two-body matrix elements for the residual interaction are reported. Agreement is found with the experimentally observed $15/2^-$ state of ^{47}V.

[NUCLEAR STRUCTURE ^{47,48}V; measured J, Atomic-beam magnetic resonance. ^{47}V calculated levels, Pure $f_{7/2}$ model.]

I. INTRODUCTION

One of the $1f_{7/2}$ shell nuclei not previously studied by the atomic-beam magnetic-resonance method (ABMR), ^{47}V (33 min), appears now to have a ground state which is quite different in character from all those already studied in that its spin, $I = \frac{3}{2}$, cannot be explained with the pure $f_{7/2}$ model of McCullen, Bayman, and Zamick[1] (MBZ).

In the present work the $I = \frac{3}{2}$ assignment of Rosner and Pullen[2] is confirmed by a direct measurement[3] with ABMR. Rosner and Pullen concluded, on the basis of their measurement of the angular distribution of deuterons from the ^{46}Ti(^{3}He, d) reaction that the assumption[4] of $I = \frac{5}{2}$ for the ground-state spin based on its observed β^+ decay was incorrect and that the spin-parity is either $\frac{1}{2}^-$ or $\frac{3}{2}^-$. The first possibility is eliminated by considering the known logft value for the ^{47}V-^{47}Ti (ground state) β^+ decay.

The spin of ^{48}V (16 days) was also measured[5] in this work with ABMR. This measurement confirms the spin, $I=4$, deduced[4] earlier from decay scheme studies.

The particular experimental techniques used here could also be applied to atomic hyperfine structure measurements which would yield the magnetic-dipole and electric-quadrupole moments of these nuclei.

II. EXPERIMENTAL METHOD

ABMR experiments were performed with the apparatus of Lemonick, Pipkin, and Hamilton[6] which employs six-pole focusing "A" and "B" magnets. The apparatus and its modifications[7] have been described in earlier papers. (An additional modification used in this experiment is mentioned in Sec. III.) Appropriate radiofrequency transitions induced in a homogeneous magnetic field H_c of central "C" magnet cause a beam, normally focused by the B magnet, to be defocused because of a change in sign of the atomic high field effective magnetic moment, $\mu_{eff} = g_J \mu_B m_J$. Here g_J is the electronic g factor, μ_B the Bohr magneton, and m_J the magnetic quantum number corresponding to electronic angular momentum J. Two collector surfaces are placed near the exit of the B magnet: a "beam" collector placed on the axis of the apparatus and a "flop" collector concentric to it. F/B, the ratio of the radioactivity of the two collectors, is determined for many different values of the rf frequency ν. A resonance is indicated by a peak plot of F/B as function of ν. The strength of the magnetic field H_c was precisely measured with a ^{39}K beam.

The experiment was performed at sufficently low magnetic fields (Zeeman region) so that the frequency associated with a state of total angular momentum F is, to a sufficiently good approximation, independent of the strength of the hyperfine interaction and is given by[8]

$$\nu_{\text{Zeeman}} = g_F \mu_B H_c / h ,$$

where

$$g_F \cong g_J [F(F+1) + J(J+1) - I(I+1)]/2F(F+1) . \quad (1)$$

The expression for g_F is approximate in that a term in the nuclear g factor, g_I, has been neglected, since $|g_I| \ll |g_J|$.

III. BEAM PRODUCTION AND DETECTION

^{48}V and ^{47}V samples were made by (p,n) reactions[9] using the Princeton FM cyclotron. A 17.5-

MeV internal proton beam was stopped in a thick (0.5 g/cm^2) natural titanium metal sheet. This target was used in the experiment without any radiochemical processing. Vanadium atomic beams were obtained from tantalum ovens which contained the cyclotron target and were heated to ~2000°C by electron bombardment. The emitted atoms, upon transiting the atomic beam apparatus, were collected on room temperature copper surfaces.

The β activity of the beam and flop collectors was measured with scintillation detectors in which 5-cm-diam, 0.025-cm-thick plastic scintillators were used. The need for high-efficiency β counting precluded effective discrimination between radioactive isotopes on the basis of their β endpoint energies. It was therefore important to use procedures which would result in atomic beams consisting of only one dominant activity. Details of the isotope and atomic beam production procedures for ^{48}V and ^{47}V are discussed below.

^{48}V

Samples of ^{48}V were made in 40-μA h cyclotron bombardments. After a bombardment, target activities were allowed to undergo radioactive decay for 10 days so as to reduce the short half-life components to negligible proportions. At the end of the 10-day period, the dominant impurity activities were expected to be (p,α) reaction[10] produced $^{44}Sc^m$, ^{47}Sc, and ^{46}Sc, with each isotope contributing of the order of 1% of the total β activity. A γ-ray spectrum of the target obtained with a Ge(Li) detector did not reveal any unexpected γ-ray lines. In order to identify the activities detected in the atomic beam experiments, a decay curve was obtained for the radioactive deposit on an atomic beam collector. Data obtained during a 76-day period were found to be in agreement with a pure exponential decay, $t_{1/2} = 16$ days.

A typical ^{48}V sample with an activity of 10 mC at the beginning of an atomic beam experiment yielded about 18 flop/beam collector pairs with a beam count rate of 300/min. Collection times for this activity varied from 15 to 60 min depending on the "age" of the oven.

^{47}V

^{47}V samples were made in 75-min bombardments with maximum cyclotron beam currents (3.7 – 4.0 μA). ^{47}V activity, about 34 mC, thus produced was only marginally adequate for the spin measurement requiring a total of 30 separate bombardments. Because of the relatively short half-life of this isotope, the activity cannot be utilized very efficiently in an off-line experiment. An additional problem was that the proportion of the total β activity due to the longer-lived isotopes, ^{43}Sc and ^{44}Sc, became quite significant during the course of an ABMR experiment. The fraction of total activity due to each of these isotopes at the end of the cyclotron bombardment was of the order of 4%. The proportion of impurity activities present during β counting of the atomic beam collectors (see Fig. 1) was determined by radioactive decay rates and the emission rates of vandium and scandium atoms from the atomic beam oven. In order to reduce the scandium content of the atomic beam, the oven was first heated to a temperature, $T \cong 1930$°C. Here a large amount of scandium but little vanadium is emitted. The oven was kept at this temperature for 12 minutes with the atomic beam shutter closed. It was then heated to the temperature range used in the vanadium atomic beam experiments which lasted for a period of 30 minutes. During this period three sets of flop/beam collectors were exposed in rapid succession (a complete cycle = 30 sec) while the rf frequency was stepped through three corresponding values. This procedure, made possible by a modification of the apparatus, allowed a more efficient use of the ^{47}V beam by eliminating air-lock pump down time, assured that the scandium impurity level was the same for all collectors, and made possible some signal averaging of the atomic beam noise. To further improve the signal-to-noise ratio and assure that all observed resonances could be attributed to ^{47}V, $(F/B)_{Sc}$ obtained for the counting period in which the 3.9-h scandium activities were dominant (Sc in Fig. 1) was

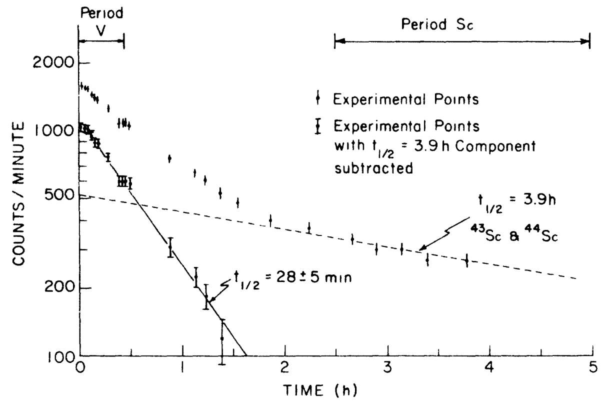

FIG. 1. Decay curve for β activity of the beam collectors in the ^{47}V experiment. The count rate shown is the sum of three typical beam collectors. Subtraction of the ^{43}Sc and ^{44}Sc contribution (dotted line) yields a straight line (solid) with $t_{1/2} = 28 \pm 5$ min in agreement with the ^{47}V half-life. The origin of the time coordinate, at the beginning of the counting period V, is 70 minutes after the end of the cyclotron bombardment.

subtracted from $(F/B)_V$ for the period in which ^{47}V was dominant (V in Fig. 1).

IV. RESULTS

High atomic beam oven temperatures produced appreciable thermal excitation of the low-lying metastable atomic states (Fig. 2). For these atomic states, half-integral and integral spin $g_F\mu_B/h$ values considered in the interpretation of the ^{47}V and ^{48}V data are given in Fig. 3. The g_J factors used here were determined by Childs and Goodman.[11] The limited range of ν/H_c in these figures corresponds to the frequency ranges used in the experiments. Excluded g_F values belong to hyperfine states which are unobservable

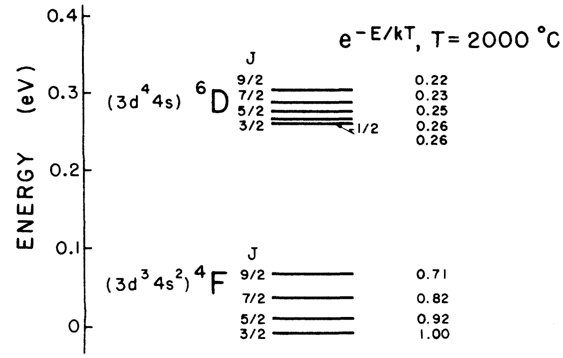

FIG. 2. Vanadium atomic energy levels below 1 eV. The Boltzmann factors for $T = 2000$ °C are shown to the right of the energy levels.

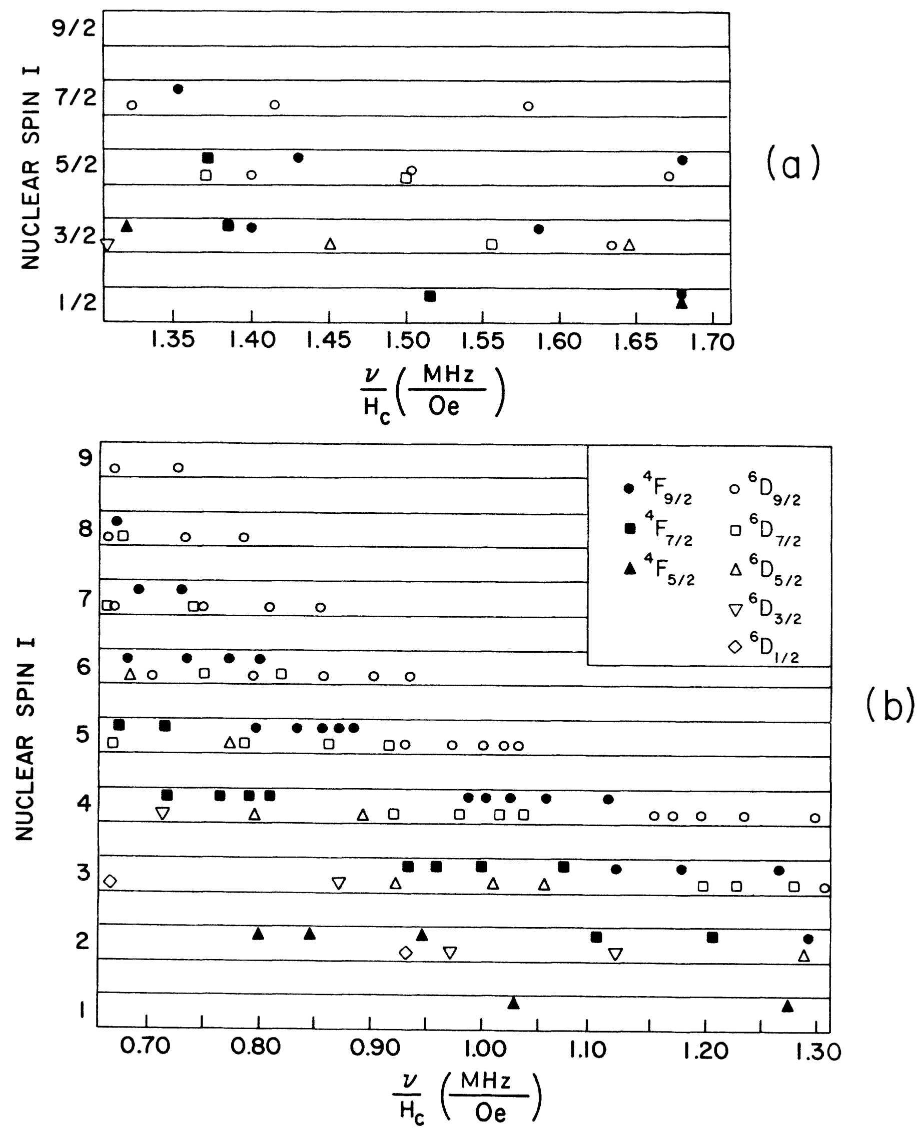

FIG. 3. (a) Half-integral I and (b) integral I $g_F\mu_B/h$ values for the states of Fig. 2.

by ABMR, namely, those with the high field effective magnetic moments all of the same sign.

^{48}V

Figure 4 shows ^{48}V ABMR data obtained at three different magnetic field values. These data are plotted with a ν/H_c scale to facilitate comparison with Fig. 3 and to make apparent the linearity between the resonance frequencies and the magnetic field. These data agree only with the expected spectrum for $I=4$. Because of the complexity of the spectra and the existence of some overlap of g_F values for different spins, a detailed discussion is presented here showing how the data lead to a unique spin assignment.

First, consider resonances observed at $H_c=0.640$ and 2.002 Oe. The broad resonance with a maximum at $\nu/H_c \cong 1.16$ MHz/Oe is inconsistent with spin assignments $I \geq 5$: For these spins no $g_F\mu_B/h$ values occur in this region of ν/H_c. Similarly, the broad resonance with a maximum at $\nu/H_c \cong 0.80$ MHz/Oe is clearly inconsistent with the spin assignments $I=1$ or 3. The asymmetry and excessive width of the two strongest resonances are easily discernible at $H_c=2.002$ Oe (see Fig. 4). These features must arise from overlapping resonances, especially in view of the data obtained at $H_c=6.982$ Oe. No overlapping resonances are expected, however, for $I=2$ in the frequency regions of the resonances under consideration. Therefore, the data are also inconsistent with an $I=2$ spin assignment.

Consider next the data at the highest magnetic field used, $H_c=6.982$ Oe. In the limited frequency region studied, two closely spaced resonances were observed which match only the $I=4$ $g_F\mu_B/h$ values.

In fact all the observed data are consistent with $I=4$. The three broad resonances observed at $H_c=0.640$ Oe and at $H_c=2.002$ Oe match the three groups of $I=4$ $g_F\mu_B/h$ values associated with the $^4F_{7/2}$, $^4F_{9/2}$, and $^6D_{9/2}$ states. Contributions from the $^6D_{7/2}$ and $^6D_{5/2}$ states are negligible as discussed below. The asymmetry of the observed resonances arises from the greatly differing strengths and unequal spacing of the unresolved components. The strengths of the resonances depend on the atomic beam "optics" and hence on μ_{eff}. In this experiment, optimum focusing of atoms having the most probable velocity occurred when $|\mu_{eff}| \cong 3\mu_B$. This focusing condition explains the relative weakness of the resonances associated with the hyperfine states $F=\frac{9}{2}$ and $F=\frac{11}{2}$ (for these states the maximum value of $|\mu_{eff}|$ is limited, in the A or B magnet, to $\frac{1}{2}g_J\mu_B$ and $\frac{3}{2}g_J\mu_B$, respectively).

The relative amplitudes of the $^4F_{9/2}$ and $^6D_{9/2}$ resonances in Fig. 4 agree with the ratio of the Boltzmann factors for the two states (0.31). This is expected from the similarity of the g_J values and the equality of the angular momenta and can be used to rule out a significant contribution to the resonance signal from the $^6D_{7/2}$ state resonances,' which overlap the $^4F_{9/2}$ resonances in the low magnetic field region.

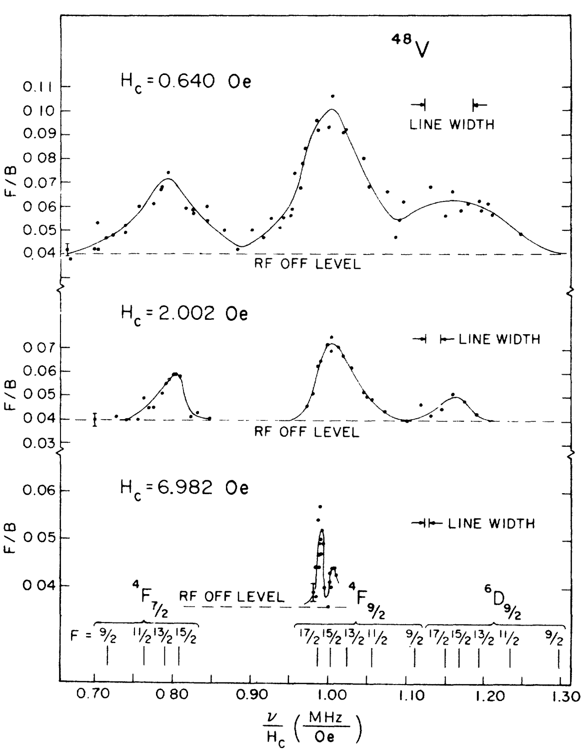

FIG. 4. Observed ^{48}V Zeeman resonances. The expected positions of the $^4F_{7/2}$, $^4F_{9/2}$, and $^6D_{9/2}$ state resonances for $I=4$ are shown near the ν/H_c scale. The rf amplitude was adjusted to optimize F/B.

^{47}V

Figure 5 shows the result of a spin search from which a preliminary spin assignment was obtained. For each spin value in the figure, one or more frequencies (given in the figure caption) were applied to the rf loop. These frequencies correspond to the expected strong $^4F_{9/2}$, and where indicated $^4F_{7/2}$, resonances. For the $I=\frac{3}{2}$ resonance, the half-life of the flop collector was determined and found to be in agreement with that of ^{47}V.

To confirm the $I=\frac{3}{2}$ spin assignment indicated by the above data, a more detailed study of the Zeeman resonances was made at three magnetic field values. The results are shown in Fig. 6. These data agree only with the expected spectrum

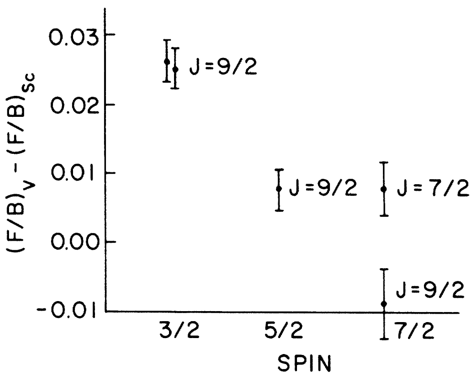

FIG. 5. Results of ^{47}V spin search. Magnetic fields and $^4F_{9/2}$ state resonance frequencies used to check for $I=\frac{3}{2}$, $\frac{5}{2}$, and $\frac{7}{2}$ resonances are: 1.123 Oe, (1.782 and 2.149) MHz; 1.182 Oe (1.523 and 1.691) MHz; 1.216 Oe, (1.277, 1.317, and 1.378) MHz. The magnetic field and the $^4F_{7/2}$ state resonance frequency used in an additional check for $I=\frac{7}{2}$ were 0.917 and 0.794 MHz. (In this case all the F states have the same resonance frequency).

for $I=\frac{3}{2}$ as is discussed below.

All resonances shown in Fig. 6 are inconsistent with spins $I \geq \frac{9}{2}$ since no $g_F\mu_B/h$ values for these spins occur in this region of ν/H_c. Similarly, the broad resonance which has a maximum at $\nu/H_c \cong 1.59$ MHz/Oe is clearly inconsistent with $I=\frac{5}{2}$ and $I=\frac{1}{2}$. The strong resonance at $\nu/H_c \cong 1.40$ MHz/Oe observed at three values of the magnetic field, while verifying the linear dependence of resonance frequencies on magnetic field, is inconsistent with an $I=\frac{7}{2}$ spin assignment. For $H_c = 1.976$ Oe, this resonance deviates by about a linewidth from the nearest $I=\frac{7}{2}$ frequency. Moreover, the nearest $I=\frac{7}{2}$ frequencies correspond to the states $^4F_{9/2}$, $F=2$ and $^6D_{9/2}$, $F=3$, which are both poorly focused; also, the second state has a relatively small Boltzmann factor.

The consistency of the data with the $I=\frac{3}{2}$ spin assignment will now be discussed. The lowest frequency resonance for $H_c = 0.889$ Oe is in agreement with the $g_F\mu_B/h$ values of the $^4F_{9/2}$, $F=6$ and the $^4F_{7/2}$, $F=4$ states. For the same magnetic field value, the higher frequency resonance in agreement with the $g_F\mu_B/h$ value for the $^4F_{9/2}$, $F=5$ state. Near this $g_F\mu_B/h$ value there are $g_F\mu_B/h$ values of three other states: $^6D_{7/2}, F=5$; $^6D_{9/2}$, $F=6$; and $^6D_{5/2}$, $F=3$. On the basis of the ^{48}V results, only the $^6D_{9/2}$, $F=6$ state resonance is expected to be strong enough to be observable. This resonance is, in fact, observed as a small "shoulder" on the high frequency side of the $^4F_{9/2}$, $F=5$ resonance.

The data obtained at $H_c = 1.976$ Oe show the $^4F_{9/2}$, $F=6$ state and the $^4F_{7/2}$, $F=4$ state resonances resolved.

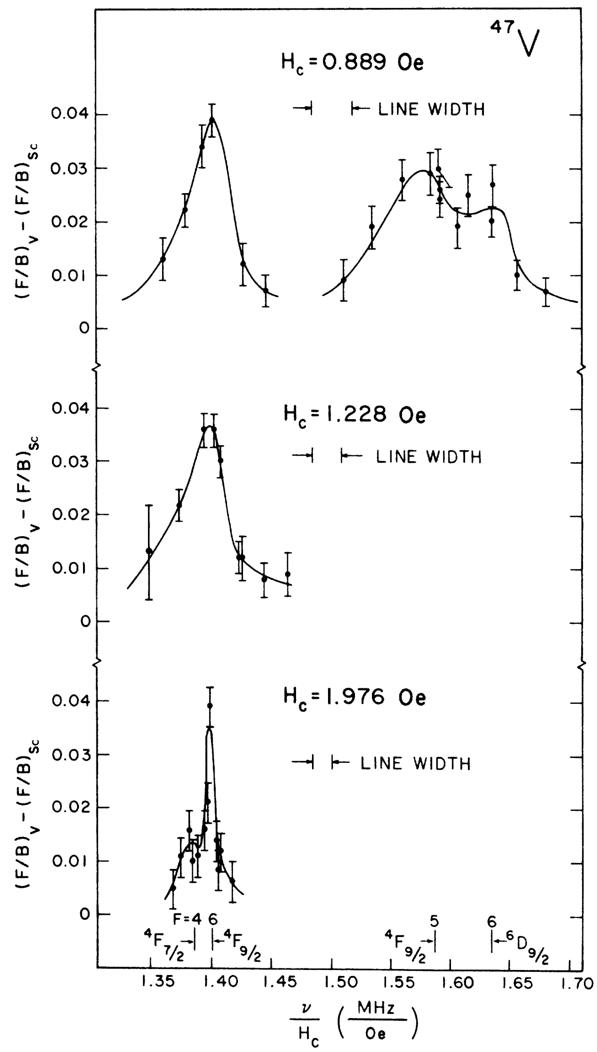

FIG. 6. Observed ^{47}V Zeeman resonances. The expected positions of the $^4F_{7/2}$, $^4F_{9/2}$, and $^6D_{9/2}$ state resonances for $I=\frac{3}{2}$ are shown near the ν/H_c scale. The rf amplitude was adjusted to optimize F/B.

V. DISCUSSION

The shell model calculations of MBZ using only $f_{7/2}$ particles have been unusually successful when used in the calculation of nearly 20 ground state magnetic moments[12] and prediction of ground state spins.[12,13] This model fails, however, to predict the $I=\frac{3}{2}$ ground state of ^{47}V. The spectrum for this nucleus in the framework of this model $[(\pi f_{7/2})^3(\nu f_{7/2})^4$ configuration$]$ has been calculated by Ginocchio[14], by Brut,[15] and as part of the present work. The two-body matrix elements for the residual interaction used in Ginocchio's calculations were identical to that of MBZ and were obtained from a poorly known ^{42}Sc spectrum. Brut's calculation avoided some of the uncertainties associated with the ^{42}Sc spectrum by obtaining the two-body

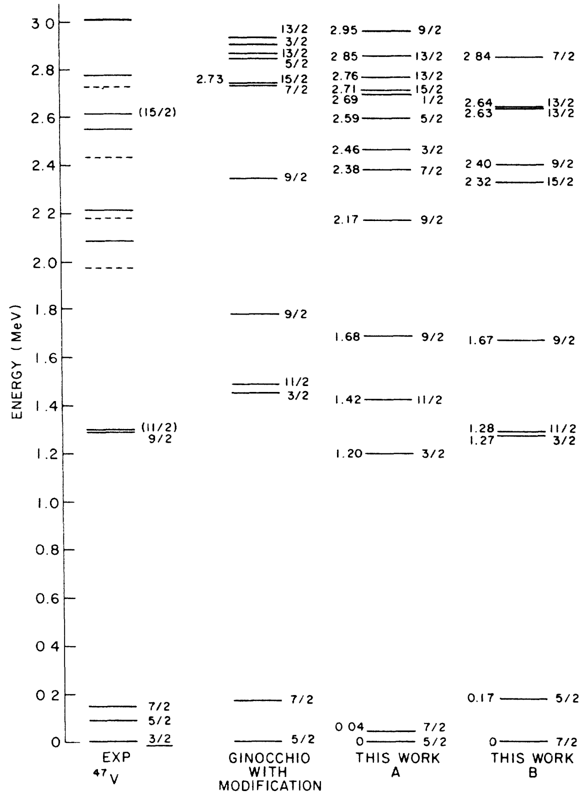

FIG. 7. Experimental and calculated negative parity energy levels of ^{47}V below 3 MeV. The two spectra, A and B, were calculated in this work with the use of the two-body matrix elements listed in columns A and B of Table I. The experimental negative parity levels are taken from the paper of Blasi *et al*. (Ref. 19) except that the assignment $\frac{9}{2}^-$ for the lower of the two states near 1.3 MeV is from Thompson *et al* (Ref. 20). Dashed lines indicate levels of unknown parity.

matrix elements from the work of Dieperink and Brussard[16] who used a least-squares fitting procedure on some low-lying experimental levels of masses 40 to 48. Since then, extensive experimental work[17] on the ^{42}Sc spectrum has led to substantial revisions of the two-body matrix elements. The recent results found in a review article by Schiffer and True[18] were used in calculations of the ^{47}V spectrum based on the theoretical model of MBZ. Table I gives the matrix elements used in the present calculations and, for comparison, those used by MBZ and Ginocchio. The ^{47}V results are shown in Fig. 7 together with the spectrum of Ginocchio modified by the addition of one level. This 2.73-MeV level, with spin-parity $\frac{15}{2}^-$, was obtained in the calculations of the present study.

It is seen that in the newly calculated ^{47}V spectra the lowest $\frac{3}{2}^-$ state is lower than in the spectrum of Ginocchio; however, the gross disagreement with the experimental ground state remains. This is in

TABLE I. Two-body matrix elements, $V_I = \langle (1f_{7/2})^2 I | V_{12} | (1f_{7/2})^2 I \rangle$, used in this work (A and B) compared with those of MBZ and Ginocchio (C).

I	V_I (MeV) A^{a,b}	B^c	C^d
0	0	0	0
1	0.62	1.21	1.035
2	1.59	1.79	1.509
3	1.50	2.07	2.248
4	2.82	2.63	2.998
5	1.52	2.09	1.958
6	3.24	2.96	3.400
7	0.62	0.33	0.617

^{a}Reference 17.

^{b}P. M. Endt and C. van der Leun, Nucl. Phys. A214, 1 (1973).

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^{d}Reference 1.

qualitative agreement with the calculation of Brut. In general, no drastic modification of the calculated spectrum results from the use of the new two-body matrix elements in agreement with similar calculations[21] on other $1f_{7/2}$ nuclei.

It is interesting to note that the calculated position of the $\frac{15}{2}^-$ state agrees well with the experimental results of Blasi, Fazzini, Giannatiempo, Huber, and Signorini.[19] These investigators were led to the erroneous conclusion that the $f_{7/2}$ model does not correctly predict this $\frac{15}{2}^-$ state because of its omission in Ref. 14.

Pasquini and Zuker[22] have shown that the shell model prediction for the energy of the lowest $\frac{3}{2}^-$ state of ^{47}V is reduced to ~200 keV when the model space is enlarged to include the $(1f_{7/2})^6(2p_{1/2}2p_{3/2}1f_{5/2})$ configurations. A low-lying $\frac{3}{2}^-$ state for ^{47}V has also been obtained by Malik and Scholz[23] in their calculations using the Bohr-Mottelson strong-coupling model, including the Coriolis coupling between bands. Unlike the shell model calculations, however, these calculations do not predict a $\frac{15}{2}^-$ level below 3 MeV in disagreement with the experimental results of Blasi, *et al.*

The measured spin $I = 4$ for the ^{48}V ground state is in satisfactory agreement[13] with the pure $f_{7/2}$ calculation, by Lawson,[21] of the level scheme for this nucleus.

Note added in proof. W. Kutschera, B. A. Brown, and K. Ogawa have also recently recalculated the ^{47}V spectrum using improved two-body matrix elements (to be published in La Rivista del Nuovo Cimento). Their calculations are in agreement with those given in this work. [R. Sherr (private communication).]

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