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Low spin structure of the $N=Z$ odd-odd nucleus $^{46}_{23}V_{23}$

C. Frießner,[1] N. Pietralla,[1] A. Schmidt,[1] I. Schneider,[1] Y. Utsuno,[2] T. Otsuka,[2] and P. von Brentano[1]
[1]*Institut für Kernphysik, Universität zu Köln, D-50937 Köln, Germany*
[2]*Department of Physics, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*

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Low spin states in the odd-odd nucleus ^{46}V were investigated with the ^{46}Ti(p,nγ)^{46}V fusion reaction at the FN-TANDEM accelerator in Cologne. Complementary spectroscopic measurements were done, namely: γ-angular distributions, excitation functions, $\gamma\gamma$-coincidences, and $\gamma\gamma$-angular correlations. 28 states were observed, 19 for the first time. We evaluated seven new spin assignments and eight new multipole mixing ratios. In particular, the lowest $T=0$, $J=1$ quasideuteron state was identified as the 993 keV level. The data compare well to shell model calculations with the KB3 and the FPD6 forces in the full pf shell.
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Nuclei having equal numbers of neutrons and protons ($N=Z$) are particularly interesting objects. $N=Z$ nuclei are the most symmetric systems with respect to the isospin degree of freedom and thus allow us to test sensitively the isospin symmetry of the nuclear forces. The isospin symmetry leads to quasiselection rules for $M1$ and $E2$ γ transitions [1]. Due to the recent development of large detector arrays as EUROBALL [2,3], GAMMASPHERE [4], or very efficient mass separator systems, heavy $N=Z$ nuclei can be studied now up to the doubly closed shell nucleus ^{100}Sn [5]. Only in $N=Z$ nuclei can one study nuclear states with the lowest possible isospin quantum number $T=0$. The importance of nuclear states with $T=0$ is evident from the fact that the most simple proton-neutron system, the deuteron, is bound only in the lowest $T=0$ state, the $J^\pi=1^+$ ground state. Other two nucleon systems are unbound. It was discussed earlier [6] and recently confirmed [7] in shell model Monte Carlo (SMMC) calculations that the $T=0$ pairing force is particularly important for $N=Z$ nuclei. In turn the structure of $N=Z$ nuclei is particularly sensitive to certain parts of the nuclear forces as shown, e.g., by the Wigner energy [8]. Therefore, the structure of $N=Z$ nuclei is at present a very active topic of nuclear structure physics [9–18].

An important question is thus the identification of the $T=0$ states and the measurement of their properties. Particularly interesting is the complex structure of odd-odd $N=Z$ nuclei. We have investigated the low-spin structure of the $N=Z$ nucleus ^{46}V up to $E_x=3.2$ MeV. Thereby, we could considerably enlarge and correct the hitherto known [17–22] low spin level scheme of ^{46}V. Among other states, we firstly identified the lowest $T=0$, $J^\pi=1^+$ state in ^{46}V. At present, work on the high spin level schemes of ^{46}V and other $N=Z$ nuclei with $A\approx 50$ [23,24] are in progress [25] at Legnaro.

Excited states of ^{46}V were populated in the ^{46}Ti$(p,n\gamma)^{46}$V fusion reaction. The proton beam with energies of about 15 MeV was provided by the Cologne FN-TANDEM accelerator. Single γ spectra and $\gamma\gamma$-coincidence spectra of the depopulating γ cascades in ^{46}V were measured with high energy resolution. Compton-suppressed Ge-detectors were used in the COLOGNE-OSIRIS-COINCIDENCE-cube spectrometer. In order to assign spin and parity quantum numbers we measured γ-angular distributions, $\gamma\gamma$-angular correlations, and excitation functions with incident proton beam energies varying between 13 MeV and 19 MeV.

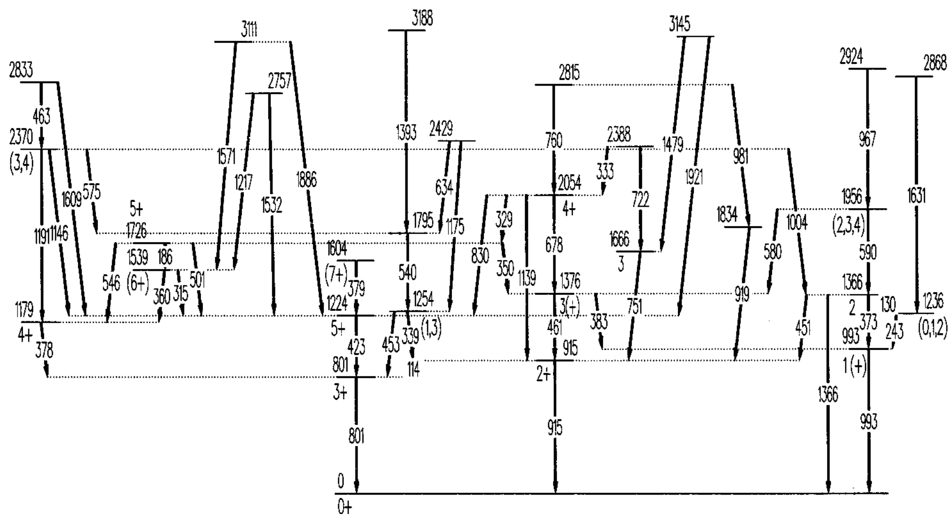

FIG. 1. Low spin level scheme of ^{46}V from the ^{46}Ti(p,nγ)^{46}V reaction at 15 MeV beam energy.

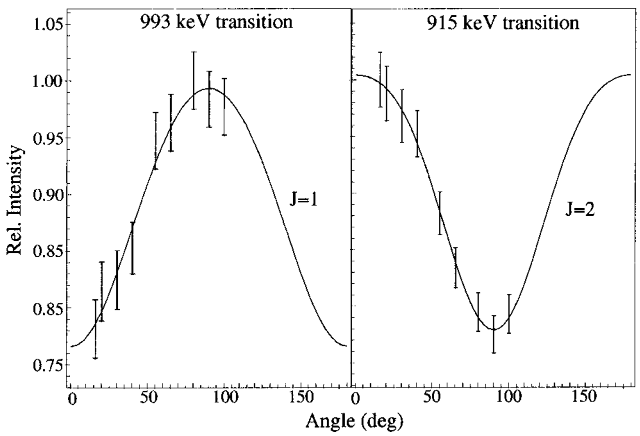

FIG. 2. Angular distribution of the 993 keV transition and the 915 keV transition from the ^{46}Ti(p,nγ)^{46}V reaction at 15 MeV beam energy. The data of the 915 keV level are in agreement with the $J=2$ hypothesis. However, the 993 keV level requires a $J=1$ spin assignment.

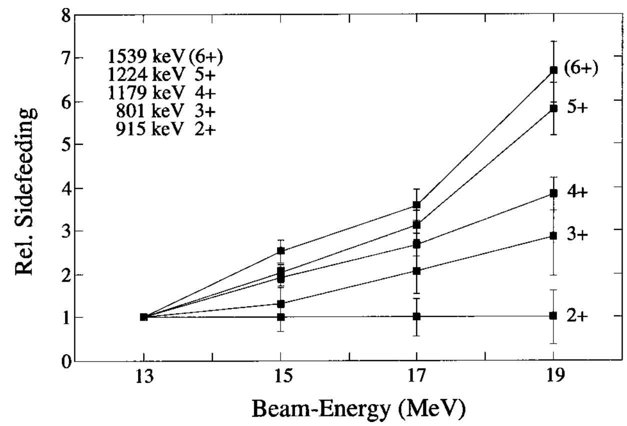

FIG. 3. Relative sidefeeding of different levels normalized to the first 2^+ level from the ^{46}Ti(p,nγ)^{46}V reaction.

From the $\gamma\gamma$ coincidences a low spin level scheme of ^{46}V was constructed, which is displayed in Fig. 1. With respect to earlier spectroscopic work on ^{46}V [17–22] we observed 28 levels of which 19 are new and 52 γ transitions of which 40 are new.

The ground state of ^{46}V is a $T=1$, $J^\pi=0^+$ state, which forms an isospin triplet with the 0^+ ground states of the isobars ^{46}Cr and ^{46}Ti. The two lowest excited states in the neighboring nucleus ^{46}Ti are the $T=1$, $J^\pi=2^+$ state at 889 keV and the $T=1$, $J^\pi=4^+$ state at 2010 keV. From the absolute excitation energies of the 2_1^+ states in ^{46}Ti (889 keV) and in ^{46}V (915 keV) one can assign the isospin quantum number $T=1$ for the 2_1^+ state in ^{46}V. Likewise the 4_2^+ state at 2054 keV in ^{46}V is a good candidate for the $T=1$, $J^\pi=4^+$ state. Below we will give the results of a shell model calculation for ^{46}V, which supports these isospin assignments. Furthermore there should exist a low lying $T=0$, $J^\pi=1^+$ state in $N=Z$ nuclei, which can be loosely interpreted as a spin 1 deuteron coupled to the ^{44}Ti even-even core. Up to now this state was not identified. For the 915 keV and the 993 keV states the Nuclear Data Sheets (NDS) report a spin quantum number of $J^\pi=2^+$. For the 915 keV level the $J^\pi=2^+$ assignment could be confirmed. However, we can definitely assign a spin quantum number of $J=1$ to the 993 keV level: For both states a $J=0$ assignment is excluded due to the existence of a direct γ decay to the 0^+ ground state. $J=1$ and $J=2$ can be easily distinguished from the angular distribution data shown in Fig. 2, which unambiguously require the new $J=1$ assignment. There is no measurement of the parity of the $J=1$ state although from the comparison of the $T=0$, $J^\pi=1^+$, $J^\pi=3^+$ energy difference with the shell model calculation discussed below we assume the parity to be positive.

From the angular distribution data we could give two more new spin assignments $J^\pi=4^+$, $J^\pi=(6^+)$ for the levels at 1179 keV and 1539 keV. The angular distributions were fitted to an expansion in Legendre polynomials

$$\frac{d\sigma}{d\Omega}(\Theta)=A_0+A_2P_2(\cos\Theta)+A_4P_4(\cos\Theta), \qquad (1)$$

where the parameters A_k are functions of the Gaussian width σ of the m substate distribution and of the multipole mixing ratios δ:

TABLE I. Excited levels and γ transitions in ^{46}V observed in the angular distribution and excitation function data. The first column shows the level excitation energy. The second column gives the new spin and parity assignments made by these measurements. The third column displays the old spin and parity assignments from [21,22]. The fourth column shows the energy of the γ transition to the final level with spin and parity assignment given in the fifth column. The other columns are explained in the text.

E [keV]	J^π This work	J^π Other works	E_γ [keV]	J_f^π	A_0	A_2/A_0	A_4/A_0	σ	δ
801.3	3	3^{+a}	801.3	0_1^+					
915.0	2^+	2^{+a}	915.0	0_1^+	1.00(2)	0.22(2)	−0.05(2)	1.6(1)	0
993.2	$1^{(+)}$	2^{+a}	993.2	0_1^+	0.273(4)	−0.18(2)	−0.01(2)	1.0(1)	0
1179.4	4^+	-	378.1	3_1^+	0.199(3)	0.15(2)	0.09(3)	2.1(2)	9(3)
1224.4	5^+	5^{+b}	423.1	3_1^+	0.241(3)	0.25(2)	−0.06(2)	2.6(2)	0.00(5)
1539.4	(6^+)	-	315.0	5_1^+	0.025(1)	0.72(7)	0.1(1)	1.9(4)	0.8(3)

[a]From Ref. [21].
[b]From Ref. [22].

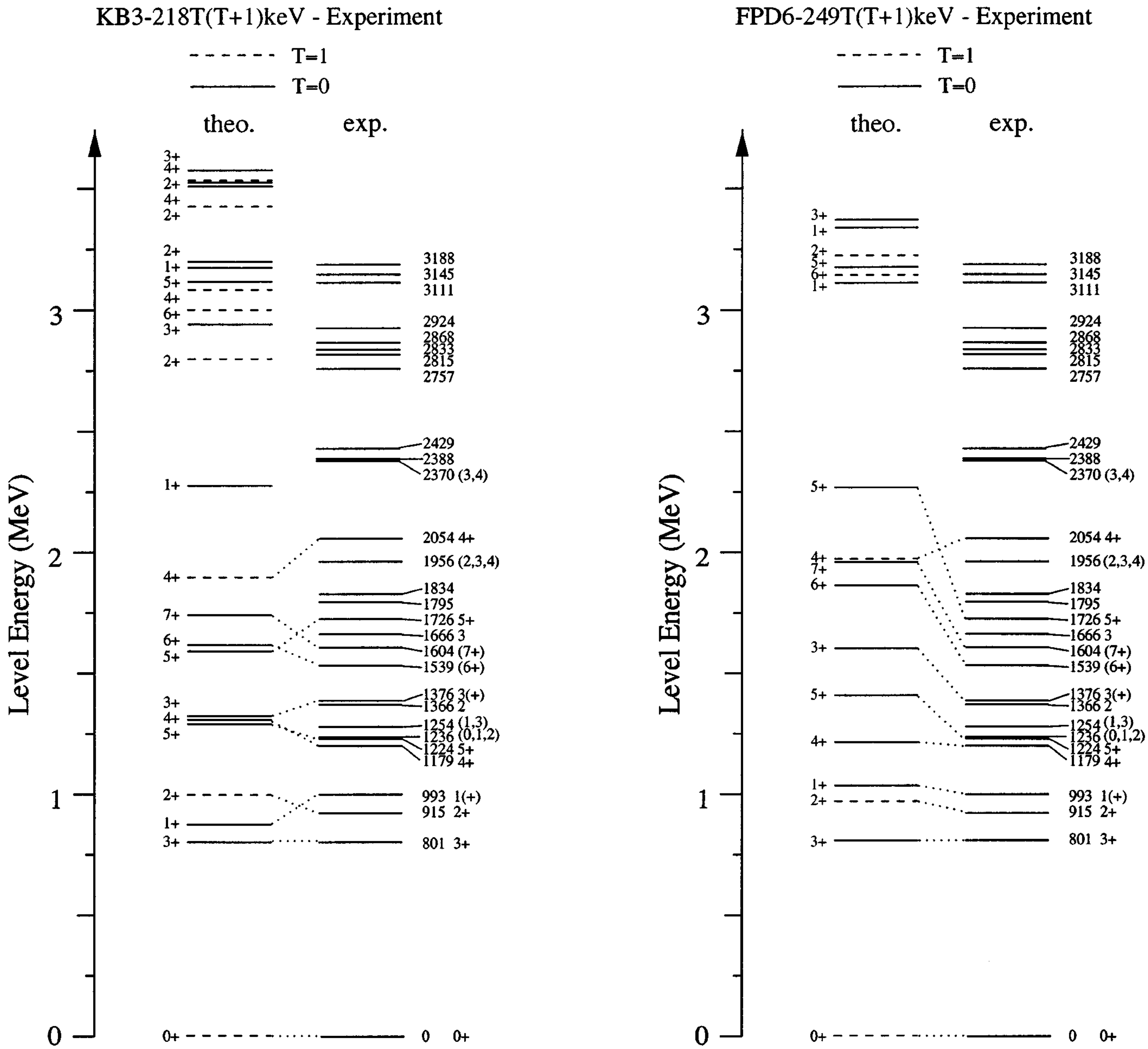

FIG. 4. Low spin level scheme of ^{46}V as populated in the $^{46}Ti(p,n\gamma)^{46}V$ reaction compared to the positive parity states of a shell model calculation with a KB3 force (left) and FPD6 force (right). The $T=1$ levels were shifted relative to the $T=0$ levels by inclusion of a fitted $T(T+1)$ term.

$$\delta^2 = \frac{T(\lambda+1, I_i \rightarrow I_f)}{T(\lambda, I_i \rightarrow I_f)}, \quad \lambda = |I_i - I_f|, \tag{2}$$

where $T(\lambda)$ denotes the transition rate of the multipolarity λ. The fitted parameters are listed in Table I.

We got additional information for spin values from the excitation function. The beam energy was varied from 13 to 19 MeV in steps of 2 MeV. The sidefeeding for the interesting levels was normalized to the sidefeeding at 13 MeV beam energy and to the sidefeeding of the 915 keV level with known spin quantum number $J=2$. The result is displayed in Fig. 3. The spin assignments for the levels at 1179 keV and 1224 keV are confirmed and furthermore the $J=3$ isomer at 801 keV is verified by the excitation function measurement. With the $\gamma\gamma$-angular correlation method, described, e.g., in [26], we could give five more new spin assignments, and six more new multipole mixing ratios were evaluated. Especially a 4_2^+ state was found at 2054 keV, which is a good candidate for the $T=1$ $J^\pi=4^+$ isobaric analogue state of the 4_1^+ state of ^{46}Ti. The (6^+) assignment for the 1539 keV level is ambiguous. From the angular distribution data and the $\gamma\gamma$-angular correlation data a 6^+ assignment is the most probable hypothesis. But from both data a spin 4 and a spin 5 hypothesis cannot be excluded. However, from the sidefeeding data (Fig. 3) only a spin 5 and 6 is possible, where $J=6$ is more favored, again. Positive parity quantum numbers are assigned for the states at 1179 keV, 1539 keV, 1726 keV, and 2054 keV, respectively,

TABLE II. Comparison of experimental branching and multipole mixing ratios with the KB3 and FPD6 shell model calculations. The first column shows the level excitation energy. The second and third columns give the spin, parity, and the proposed isospin assignments. The fourth column shows the energy of the γ transition to the final level with spin, parity, and isospin assignments given in the fifth and sixth columns. Columns seven through nine compare the experimental branching ratios with KB3 and FPD6 shell model calculations. Columns ten through twelve compare the experimental multipole mixing ratios with the shell model calculations.

Level	I^π	T_i	E_γ	I_f^π	T_f	Branching ratio			Multipole mixing ratio δ		
[keV]	$\hbar$		[keV]	$\hbar$		Expt.	KB3	FPD6	Expt.	KB3	FPD6
915	2_1^+	1	114	3_1^+	0	≥0.2	5	0.07			
			915	0_1^+	1	100(15)	100	100	$E2$	$E2$	$E2$
1179	4_1^+	0	378	3_1^+	0				6_{-2}^{+3},9(3)[a]	2.8	0.51
1366[b]	2	0	130	(0,1,2)	0	1.0(2)					
			373	1_1^+	0	100(15)			0.00(4)		
			451	2_1^+	1	32(5)					
			1366	0_1^+	1	38(6)					
1376	$3_2^{(+)}$	0	383	1_1^+	0	1.6(4)	0.1	5×10^{-5}	$E2$	$E2$	$E2$
			461	2_1^+	1	100(15)	100	100	0.02(3)	1×10^{-3}	4×10^{-4}
1539	(6_1^+)	0	315	5_1^+	0	100(16)	100	100	$1.9_{-0.3}^{+0.4}$,0.8(3)[a]	1.5	0.31
			360	4_1^+	0	72(12)	66	9	$E2$	$E2$	$E2$
1666[b]	3	0	751	2_1^+	1				−0.01(4)		
1726	5_2^+	0	186	6_1^+	0	3(1)	2	20			
			350	3_2^+	0	100(15)	100	100	$E2$	$E2$	$E2$
			501	5_1^+	0	20(3)	150	38	$0.9_{-0.2}^{+0.3}$	0.87	0.06
			546	4_1^+	0	8(2)	17	13			
2054	4_2^+	1	329	5_2^+	0	9(3)	24	13			
			678	3_2^+	0	100(17)	100	100	0.08(4)	5×10^{-4}	4×10^{-5}
			830	5_1^+	0	10(4)	6	6	0.02(6),7_{-2}^{+6}[c]	0.02	6×10^{-3}
			1139	2_1^+	1	14(3)	10	7	$E2$	$E2$	$E2$

[a]The first δ is evaluated from the $\gamma\gamma$-angular correlation data, the second comes from the angular distribution data.
[b]No correspondent state in the shell model calculation; probably negative parity.
[c]The $\gamma\gamma$-angular correlation data give two possible multipole mixing ratios for this transition; the first is more probable.

from nonzero multipole mixing ratios δ and from the observed γ decays.

Altogether seven new unambiguous spin assignments are made, especially for the lowest five states two spin values are new. Furthermore eight new multipole mixing ratios were given. The spin and parity assignments are included in Fig. 1. Tentative assignments from decay branches and from ambiguous correlation data are also implied with parentheses in Fig. 1. With these new assignments we were able to compare the experimental branchings and the multipole mixing ratios with the shell model calculations discussed below.

The data are compared to shell model (SM) calculations of the positive parity states of ^{46}V in the full pf shell without truncation. Two different parametrizations of the nucleon-nucleon residual interaction were considered: the KB3 interaction, adopted from [27] and the FPD6 interaction taken from [28]. The KB3 interaction is based on the Kuo-Brown G matrix [29] with modifications of the monopole and some other parts [27], while the matrix elements of the FPD6 interaction is calculated by the OBEP-type functions, whose parameters are chosen so that experimental data of light pf-shell nuclei can be reproduced well. We considered the doubly closed-shell nucleus ^{40}Ca as an inert core. The Hamiltonian matrix in the full pf shell was diagonalized without any truncation using the code OXBASH [30]. The calculated excitation energies for the $T=0$ and $T=1$ levels below 3 MeV are compared to the data in Fig. 4. The relative position of the lowest states with $T=0$ and $T=1$ are adjusted to the experimental value by using an additional $T(T+1)$ term to the Hamiltonian.

Figure 4 shows that both calculations lead to similar results and the measured ordering of the lowest excited levels is well reproduced. Above 1.2 MeV the experimental data have additional levels as compared to the calculations, which however contain only positive parity states. This may indicate that there are low lying states with negative parity as it is known in the neighboring odd-odd nucleus ^{48}V [31]. For all predicted positive parity states below 2 MeV we have identified a corresponding level in the experiment. So presumably the other observed levels below 2 MeV have negative parity. Between 2 and 3 MeV both calculations predict an interesting gap in the positive parity level scheme of approximately 1 MeV. Actually only three levels of unknown parity were observed between 2.1 and 2.7 MeV. Table II shows a comparison of the experimental branching ratios and multipole mixing ratios with the calculated values from the shell model. The branching ratios were reproduced quite well with both forces. The KB3 calculation reproduces well the measured $E2/M1$ multipole mixing ratios. In particular $\Delta T=1$ transitions are of dominant $M1$ character as it is expected from the known quasiselection rules concerning $N=Z$ nuclei [1]. This gives further support for the proposed isospin assignments from Table II.

In summary we studied the odd-odd $N=Z$ nucleus ^{46}V with the ^{46}Ti(p,n) reaction. The level scheme was extended by 19 new levels to 28 states and by 40 new γ transitions to 52 γ transitions. From excitation function, angular distribution, and $\gamma\gamma$-angular correlation measurements seven new unambiguous spins and eight multipole mixing ratios were assigned. Shell model calculations, including their γ transitions, reproduce the low lying positive parity levels quite well. In particular it was possible to identify the 993 keV level as the $J=1$, $T=0$ quasideuteron state, both in experiment and from the shell model.

After this paper was submitted an experiment on high spin states in ^{46}V, done at Copenhagen, came to our attention [32].

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