Spin-parity measurements in ^{44,46}Sc

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Assignments of natural $[\pi=(-1)^J]$ or unnatural $[\pi=(-1)^{J+1}]$ parity are made for states in ^{44,46}Sc on the basis of cross-section measurements of the polarized (d,α) reaction near zero degrees.

INTRODUCTION

It is well established[1-3] that tensor analyzing power, T_{20}, measurements near 0° or 180° using the $(\vec{d},\alpha)$ reaction on $J^\pi=0^+$ target nuclei is a good model independent method of determining whether states excited in the final nucleus have natural $[\pi=(-1)^J]$ or unnatural $[\pi=(-1)^{J+1}]$ parity. Conservation of angular momentum and parity requires that natural parity states have a T_{20} of $1/\sqrt{2}$, 0^- states have $T_{20}=-\sqrt{2}$, and unnatural parity states have analyzing powers anywhere between these two limits. Theory predicts that for a reaction dominated by compound nucleus formation, unnatural parity states, other than 0^- states, should have T_{20} values randomly distributed between the limits. Any measurement of T_{20} clearly not falling at either limit indicates an unnatural parity state. However, an unnatural parity state may accidentally have T_{20} values at the limits for some beam energies, so to establish a natural parity or 0^- state T_{20} must remain at the limit for a number of measurements at beam energies separated by more than the coherence width. In our experiment the reaction cross section was measured at 4° to the beam direction in order to avoid the problems one would encounter at 0°. In this case, T_{20} values for natural parity states are attenuated from the value of $1/\sqrt{2}$. A statistical model calculation predicts this attenuation to be approximately 5% for the conditions of our experiment.

Previous investigations of ^{44}Sc (Refs. 4—14) and ^{45}Sc (Refs. 12 and 14—24) have provided much information about the spins and parities of excited states up to a few MeV. The present study confirms many assignments already made and allows one to remove some uncertainties in other spin assignments. Some previously made assignments have been contradicted by this study.

EXPERIMENT

The targets consisted of 50 μg/cm^2 of either ^{46}Ti or ^{48}Ti evaporated onto 30 μg/cm^2 carbon backings. The experiment was performed with a polarized deuteron beam produced by the McMaster Lamb-shift polarized ion source and accelerated through an FN tandem accelerator. The reaction products were detected at 4° to the beam direction using an Enge split-pole magnetic spectrometer with a position sensitive proportional counter using delay line readout in the focal plane. The energy loss of particles was measured as they passed through the counter, thus allowing one to discriminate against the large deuteron background. Measurements of cross sections for the beam successively in $m=0$ and 1 substates relative to the beam direction were made at beam energies of 7, 8, 8.25, 8.75, 9.25, and 9.75 MeV. Each measurement lasted approximately 6 h per substate, with a beam current of 30 nA and polarization of approximately 75%. The polarization was determined with a combination of periodic quench-ratio measurements and internal consistency checks on T_{20} values for known natural-parity states. A typical spectrum is shown in Fig. 1. The spatial resolution of the counter corresponded to 12 keV full width at half maximum (FWHM) for the alphas detected. The program PFIT (Ref. 25) was used to fit the peaks to a skewed Gaussian by minimizing the χ^2 of the fit.

RESULTS

^{44}Sc

Measured values of T_{20} for ^{44}Sc are shown in Fig. 2. In Table I these results are shown along with assignments as listed by Endt and Van der Leun[26] for states below 1.8 MeV, based on a review of previous experimental data. The assignments for states above 1.8 MeV are deduced from Ref. 4. The last column lists the assignments that can be made when the data from this experiment are combined with all other known data.

0.968 MeV level

The angular distribution measured in the ^{44}Ca(^{3}He,t)^{44}Sc reaction[5] is consistent with assignments of $J^\pi=(5,6,7)^+$. It is observed in the ^{41}K(α,nγ)^{44}Sc reaction[6] that this level always decays to the 6^+ level at 0.271 MeV. The yield function for the latter reaction has a much steeper slope than $J=5$ yield functions. Our measurement of unnatural parity rules out an assignment of 6^+. Thus we conclude that this level can probably be assigned $J^\pi=7^+$.

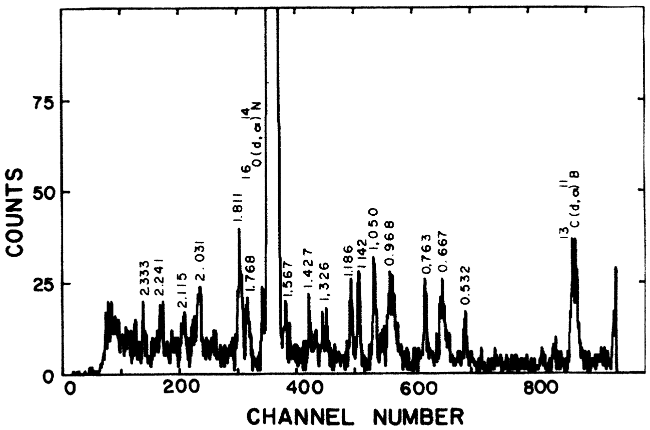

FIG. 1. Spectrum of α particles detected at 4° from the reaction ^{46}Ti($\vec{d}$,α)^{44}Sc at a bombarding energy of 8.75 MeV and for a beam polarized in the $m=1$ substate. Groups corresponding to ^{44}Sc levels are labeled by the excitation energy in MeV, while those due to target contaminants are labeled by the corresponding reaction.

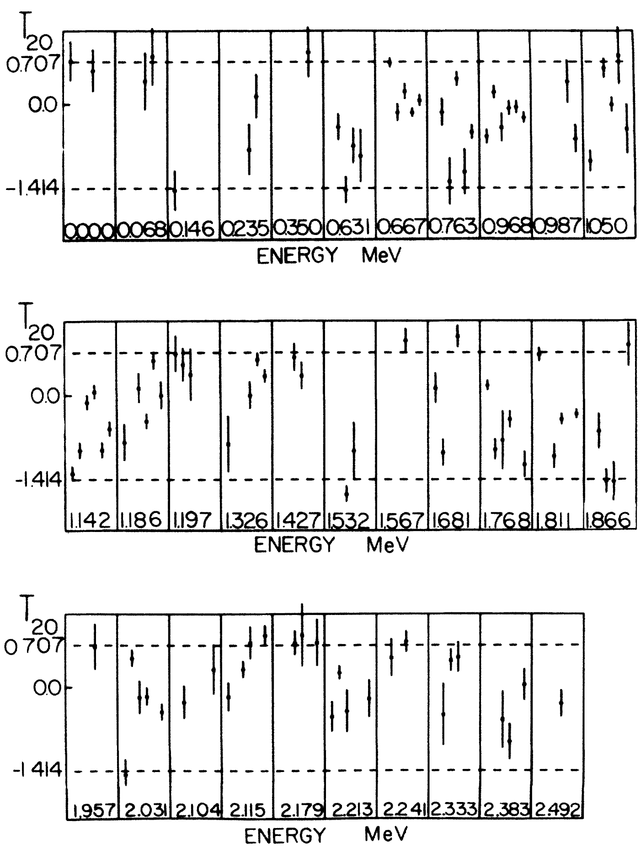

FIG. 2. Tensor analyzing powers, T_{20}, for the ^{46}Ti(d,α) reaction leading to levels of ^{44}Sc. The data for each level are grouped together and plotted from left to right in order of increasing bombarding energy. Each group is labeled by the excitation energy in MeV. The horizontal dashed lines indicate the values of T_{20} expected for natural parity (top) and 0^- (bottom).

1.050 MeV level

The angular distribution of deuterons from the ^{42}Ca(α,d)^{44}Sc reaction[7] is reproduced well by an $l=4$ distorted-wave—Born-approximation (DWBA) calculation. In the γ-decay work of Dracoulis *et al.*,[8] it was observed that this level decays only to the 350 keV (4^+) state, which would indicate $J=3,4,5$. The yield functions measured by Arnell and Selin[6] characterize this state as having spin 5. Our measurement rules out 4^+ as a possible assignment.

TABLE I. Level information for ^{44}Sc.

Energy (MeV)	J^{π} [a]	Parity[b]	J^{π}
0.0	2^+	N	2^+
0.068	1^-	N	1^-
0.146	0^-	0^-	0^-
0.235	2^-	U	2^-
0.271	6^+		6^+
0.350	4^+	(N)	4^+
0.425	3^-		3^-
0.531	3		3
0.631	4^-	U	4^-
0.667	1^+	U	1^+
0.763	3^+	U	3^+
0.829			
0.968	$(5–7)^+$	U	7^+
0.987		U	
1.006	$(3,4^-)$		$(3,4^-)$
1.050	$(3–5)^+$	U	$(3,5)^+$
1.142		U	
1.186	3^+	U	3^+
1.197	$(4^+,5^-)$	N	$(4^+,5^-)$
1.326	3	U	3^+
1.427	$(1^-–3^-)$	(N)	$(1^-,3^-)$
1.507	$(2–5)^+$		$(2–5)^+$
1.532	$(4,5)^+$	U	5^+
1.567	3^-	(N)	3^-
1.595	$(2–5)^+$		$(2–5)^+$
1.648			
1.652			
1.681	$(4–6)^-$	U	$(4,6)^-$
1.728			
1.768	2^+	U	
Above 1.8 MeV many levels among which:			
1.811		U	
1.866		U	
1.957	$(2–5)^+$	(N)	$(2,4^+)$
2.031	$(2–5)^+$	U	$(3,5)^+$
2.104	$(2–5)^+$	U	$(3,5)^+$
2.115		U	
2.179	$(2–5)^+$	N	$(2,4)^+$
2.213		U	
2.241		N	
2.333		(N)	
2.383		U	
2.492		U	

[a]References 4 and 26.
[b]Parentheses are used if the result is based on only one measurement.

1.326 MeV level

Dracoulis *et al.* argue in favor of a $J=3$ assignment to this level based on the γ-ray work.[8] Our unnatural parity measurement gives the parity as being positive if $J=3$. Therefore a 3^+ assignment is given for the 1.326 MeV level.

1.427 MeV level

This level has been assigned $J^\pi=(1^- - 3^-)$ on the basis of the γ-ray work of Dracoulis *et al.*[8] Our measurement of T_{20} suggests that this could be a natural parity state, in which case the assignment would be restricted to $(1^-,3^-)$.

1.532 MeV level

The angular momentum transfer of 4 observed in the ^{42}Ca(α,d)^{44}Sc reaction[7] allows one to make possible assignments of $J^\pi=3^+,4^+,5^+$. Poirier and Manthuruthil[9] observe branching to levels at 271 keV (6^+), 350 keV (4^+), and 642 keV in their ^{43}Ca(p,γ)^{44}Sc study. Dracoulis *et al.*[8] point out that they find no evidence that the 642 keV level really exists. Our measurement of unnatural parity rules out 4^+, allowing one to assign the level as 5^+.

1.681 MeV level

Endt and Van der Leun[26] have made an assignment of $J^\pi=(4-6)^-$ on the basis of the ^{42}Ca(α,d)^{44}Sc l transfer work of Del Vecchio *et al.*[7] Our measurement of unnatural parity rules out 5^- as a possibility.

1.768 MeV level

Poirier and Manthuruthil[9] observe branching from this level to the levels at 0 keV (2^+), 68 keV (1^-), 350 keV (4^+), and 667 keV (1^+) with a short (80 fs) lifetime.[10] This level is therefore assigned to be 2^+ since a 2^+ state can decay to these other states via $E1$, $M1$, and $E2$ transitions, whereas may other assignment would require weaker transitions to be involved. However, Coffin *et al.*[10] notice a discrepancy between the ratio of the branching ratios for the 1.768→0.068 and the 1.768→0.0 MeV transitions from their ^{41}K(α,nγ)^{44}Sc data and the same ratio measured by Poirier and Manthuruthil from their ^{43}Ca(p,γ)^{44}Sc data.[9] This could be explained by the presence of a doublet at this excitation, and if this is the case then the assignment of 2^+ based on the ^{41}K(α,nγ)^{44}Sc reaction is not valid. The branching to the observed levels could occur from two states, one with $J^\pi=0^+,1^\pm,2^\pm$ and the other with $J^\pi=2^+,3^\pm,4^\pm,5^\pm,6^+$, assuming $E1$, $M1$, or $E2$ transitions. From our data we can conclude that at least one of the two unresolved states has unnatural parity.

Higher levels

The levels at 1.957, 2.031, 2.104, and 2.179 MeV were populated in the ^{43}Ca(^{3}He,d)^{44}Sc reaction of Schwartz.[4] The angular distributions were fitted with DWBA calculations involving orbital angular momentum admixtures of $l=1,3$. The angular distribution for the 1.957 MeV state was found to be best fitted by predominantly $l=1$ transfer, while the other three states required significant admixtures of both $l=1$ and 3. Since $l=1$ transfer has significant strength in all cases, possible spins for these states are restricted to $(2-5)^+$. Our measurement of natural parity further restricts the spin assignment for the 1.957 and 2.179 MeV states to $(2,4)^+$ and the unnatural parity measurement for the 2.031 and 2.104 MeV states restricts their spins to $(3,5)^+$.

^{46}Sc

The measured T_{20}'s for ^{46}Sc are plotted in Fig. 3. Table II lists the states observed in this experiment with spins and parities as suggested by Auble[27] in a survey of the previously available data. The last column lists the assignments which can be made when the data from this experiment are combined with all other known data.

0.281 MeV level

This level has been assigned as spin $(5,6)^+$ by Yntema[15] by comparing an angular distribution of the ^{46}Ca(^{3}He,t)^{46}Sc differential cross section with DWBA calculations. Our unnatural parity measurement for this state results in a unique 5^+ assignment.

1.394 MeV level

A survey of existing data[27] gives a positive parity for this level, but no spin assignment. Our parity measurement for this level requires that its spin be odd.

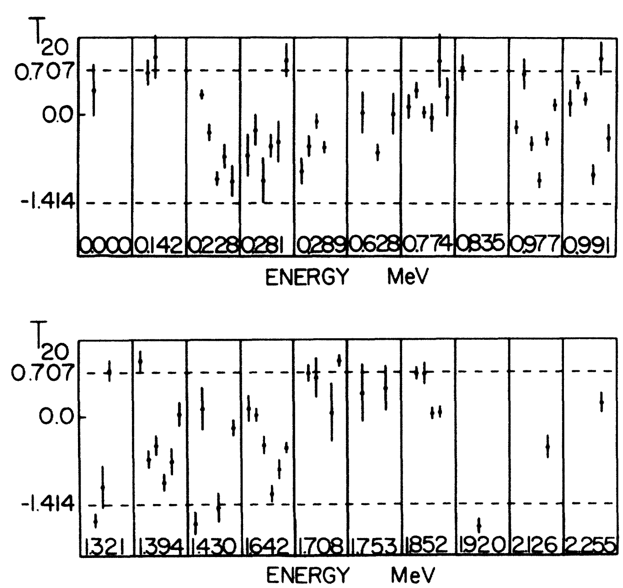

FIG. 3. Tensor analyzing powers, T_{20}, for the ^{48}Ti(d,α) reaction leading to levels of ^{46}Sc. The data for each level are grouped together and plotted from left to right in order of increasing bombarding energy. Each group is labeled by the excitation energy in MeV. The horizontal dashed lines indicate the values of T_{20} expected for natural parity (top) and 0^- (bottom).

TABLE II. Level information for ^{46}Sc.

Energy (MeV)	J^{π} [a]	Parity [b]	J^{π}
0.000	4^+	(N)	4^+
0.052	$(6)^+$		$(6)^+$
0.142	1^-	N	1^-
0.228	$(3)^+$	U	3^+
0.281	$(5,6)^+$	U	5^+
0.289	2^-	U	2^-
0.444	$(2)^+$		$(2)^+$
0.584	3^-		3^-
0.628	$(4)^-$	U	4^-
0.774	$(5)^+$	U	5^+
0.835	$(4)^+$	(N)	$(4)^+$
0.977	$(7)^+$	U	7^+
0.991	$(1)^+$	U	1^+
1.088	$(3,4)^+$		$(3,4)^+$
1.121	+		+
1.124	4^-		4^-
1.141	(+)		(+)
1.270	$(2)^-$		$(2)^-$
1.289			
1.321	2^-	U	2^-
1.394	+	U	odd$^+$
1.430	(2^-)	U	2^-
1.526			
1.642	$(3^-,4^-)$	U	4^-
1.677			
1.692	$(3^{\pm},4^-)$		$(3^{\pm},4^-)$
1.708	(2^-)	N	1^-
1.753	(+)	(N)	$(2,4,6)^+$
1.765	(+)		(+)
1.799	+		+
Above 1.8 MeV many levels among which:			
1.852	(1^+)	U	1^+
1.920	$(2,3)^+$	U	3^+
2.126	$(2)^+$	U	1^+
2.255	$(3^+,4^+,5^+)$	U	3^+

[a]Reference 27.
[b]Parentheses are used if the result is based on only one measurement

1.642 MeV level

This level has been observed to result from $l=0$ transfer in the ^{45}Sc(d,p)^{46}Sc reaction,[17] indicating a $(3,4)^-$ assignment. Angular distributions from the ^{48}Ti(p,^{3}He)^{46}Sc (Ref. 18) and ^{48}Ti(d,α)^{45}Sc (Ref. 14) reactions indicate $l=3$ transfer from a comparison with DWBA calculations, which is consistent with the above assignment. The latter authors suggest an $(sd)^{-1}(f_{7/2})^7$ configuration for this state. A previous study of the (d,α) reaction[16] showed the angular distribution for the 1.642 MeV level to be well reproduced by $l=5$ transfer with a small admixture of $l=3$. Our unnatural parity measurement rules out $J^{\pi}=3^-$ and results in a unique $J^{\pi}=4^-$ assignment.

1.708 MeV level

This level has been assigned $J^{\pi}=2^-$ on the basis of l transfer in the ^{48}Ti(d,α)^{46}Sc reaction[16] and the ^{48}Ti(p,^{3}He)^{46}Sc reaction.[18] Our measurement of natural parity contradicts this assignment. Lewis is uncertain of his $l=1,3$ transfer in the (d,α) study, and the data collected by Guichard *et al.* in the (p,^{3}He) study looks as if it could be fitted well with a pure $l=1$ angular distribution. Thus we assign this level $J^{\pi}=1^-$.

1.753 MeV level

This level has been observed to result from $l=3$ transfer in the ^{45}Sc(d,p)^{46}Sc reaction,[17] indicating a $(0-7)^+$ assignment. The fact that we observe a significant cross section for this level near 0° can be used to rule out 0^+. Our natural parity measurement further restricts the assignment to $(2,4,6)^+$.

1.920 MeV level

Angular momentum transfers inferred from ^{45}Sc(d,p)^{46}Sc (Ref. 17) and ^{48}Ti(p,^{3}He)^{46}Sc (Ref. 18) studies have indicated possible assignments of $2^+,3^+$. Our measurement of unnatural parity results in a unique 3^+ assignment.

2.126 MeV level

The ^{45}Ca(^{3}He,t)^{46}Sc angular distribution measured by Yntema[15] indicates possible assignment of $J^{\pi}=1^+$ or 2^+. Our measurement of unnatural parity rules out the 2^+ assignment and we assign this level as 1^+.

2.255 MeV level

The angular distribution from the ^{48}Ti(p,^{3}He)^{46}Sc reaction[18] indicates $l=4$ transfer and hence possible assignments of $3^+,4^+,5^+$ for this level. The ^{45}Sc(n,γ)^{46}Sc work of Liou *et al.*[19] indicates possible assignments of $2^+,3^+,4^+$. Our measurement of unnatural parity combined with these other results restricts the assignment to 3^+.

Shell model

Both ^{44}Sc and ^{46}Sc are odd-odd nuclei with very high level densities at low excitations. The simplest configuration expected for low energy states is a closed ^{40}Ca core with four nucleons in the $f_{7/2}$ orbital for ^{44}Sc and six nucleons in that orbital for ^{46}Sc. Since the $f_{7/2}$ orbital is well separated from other orbitals, one would expect that the major configuration for the observed states would be $f_{7/2}^n$ at low excitations. A shell model calculation restricted to this configuration would predict only positive parity states for ^{44,46}Sc since n is even in these cases. Such a calculation was performed by McCullen *et al.*[28] in 1964 for all nuclei in the $f_{7/2}$ shell. This calculation was quite successful at predicting the energy levels. Another shell model calculation based on pure $f_{7/2}$ configurations was performed by Kutchera *et al.*[29] in 1978. A shell model calculation based on fp orbits was performed for ^{44}Sc by McGrory and Halbert.[30]

Both ^{44,46}Sc have low lying negative parity states. To obtain negative parity states a nucleon must either be excited out of the sd shell into the fp shell, or be excited out of the fp shell into the $g_{9/2}$ orbital. Calculations allowing these negative parity configurations are described below.

^{44}Sc

The positive parity states have been recalculated using the shell model code OXBASH.[31] The interaction used was that of Van der Poel *et al.*[33] (VdP), which has been shown to describe the low lying positive parity states of $A=37,38$ nuclei[33–35] well. In this calculation the active orbitals were the $f_{7/2}$ and the $p_{3/2}$, with a maximum of two nucleons allowed in the p orbital. All states in this space must have positive parity. The results are plotted in Fig. 4 along with the levels that were populated in the $(\vec{d},\alpha)$ reaction. Levels not populated in the $(\vec{d},\alpha)$ reaction are shown by dashed lines. The low lying positive parity states are predicted fairly well. The level observed at 0.968 MeV could possibly correspond to one of the two 5^+ states or the 7^+ state predicted close to 1.25 MeV. One could speculate that the observed 1.050 MeV level would not be 3^+ since the 3^+ level prediction at about 0.8 MeV is needed to explain the 3^+ state observed at 0.763 MeV, and the next available predicted level of that spin appears above 1.8 MeV. Even the 3^+ level at 1.326 MeV falls far from this prediction.

A calculation by Benson *et al.*[36] in which $d_{3/2}$ holes are coupled to $(fp)^5$ states in ^{45}Ti and ^{45}Sc is very successful at predicting the low lying negative parity states, as shown in Fig. 5. Six negative parity states below 1 MeV are observed to fall fairly close to their predicted energies. The 5^- and 4^- states predicted at just about 1 MeV appear to correspond to the 1.197 and 1.006 MeV states. Since we predict positive parity for the 1.326 MeV $J=3$ state, the best candidate for the 3^- state predicted around 1.5 MeV is the state at 1.427 MeV. The state at 1.681 MeV would appear to correspond to the predicted 4^- state, since we have ruled out an assignment of 5^-, and the first 6^- state is predicted at about 2.3 MeV.

We performed two shell model calculations for negative parity states using the OXBASH code with the VdP interaction. One calculation was truncated to $s^3d^8f^5$ configurations and the other truncated to $s^4d^7f^5$ configurations. Neither calculation predicted the low lying negative parity states very well. In fact, no states were predicted below 500 keV. It is expected that a hole in the sd shell will deform the core of the nucleus. The Nilsson model predicts that the single-particle energies of the $f_{7/2}$ shell are quite sensitive to small deformations and this may account for the reduction in energy of the negative parity states. A shell model calculation cannot be expected to reproduce the effects of core deformation unless a much expanded configuration space is used.

^{46}Sc

Positive parity states in this nucleus were calculated using the shell model with the VdP interaction in OXBASH, with the configuration space restricted in the same way as for ^{44}Sc. The results are plotted in Fig. 6, along with the

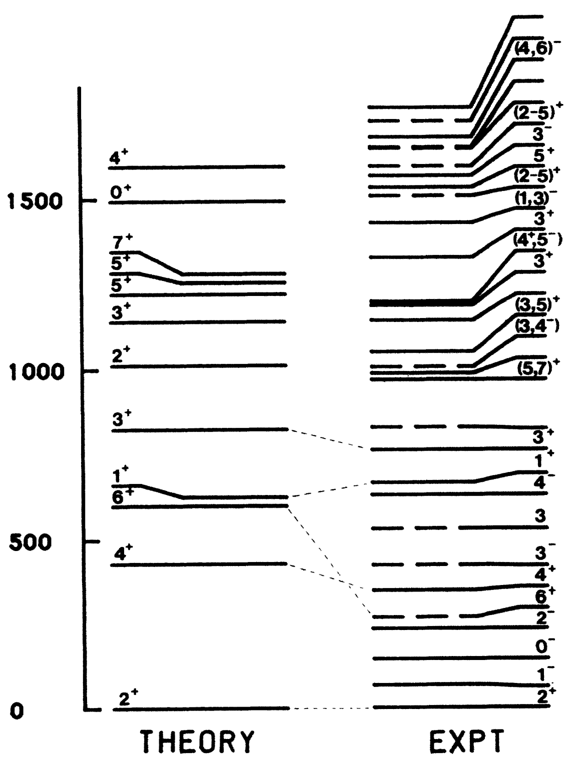

FIG. 4. Comparison of the experimental energy level spectrum of ^{44}Sc with the predicted energies of positive parity states calculated using a shell model with active $f_{7/2}$ and $p_{3/2}$ orbitals. See text for additional details.

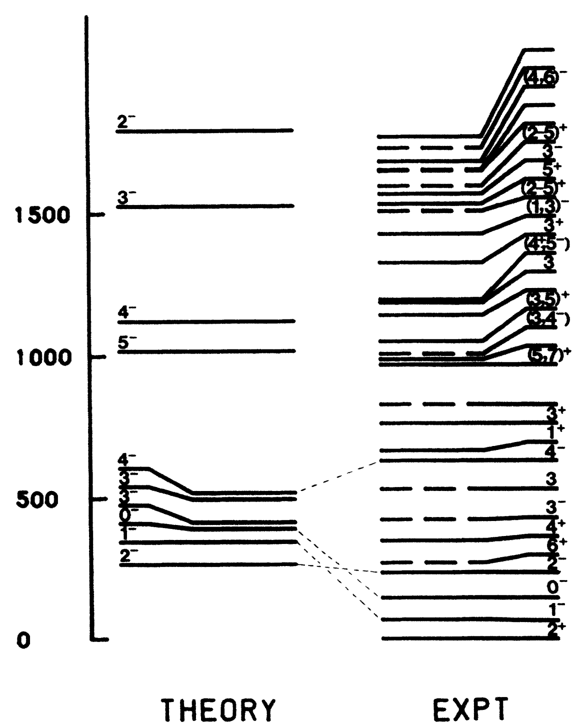

FIG. 5. Comparison of the experimental energy level spectrum of ^{44}Sc with the predicted energies of positive parity states calculated by Benson *et al.* See text for additional details.

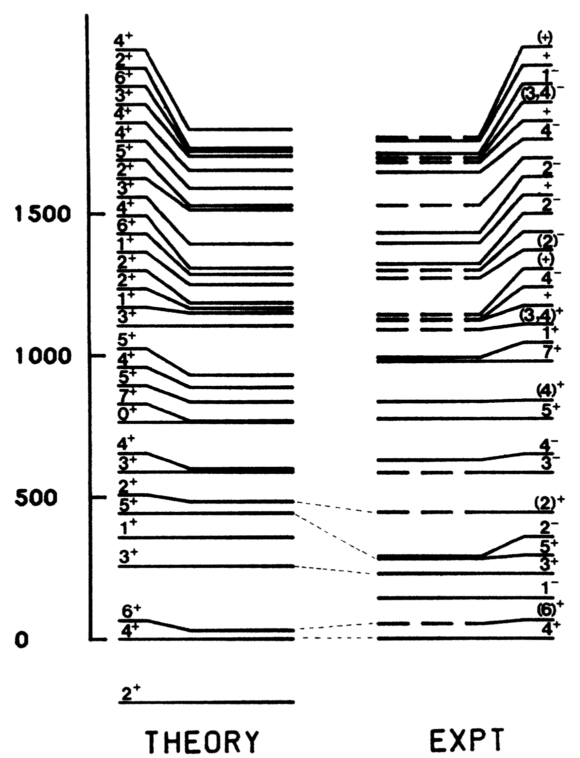

FIG. 6. Comparison of the experimental energy level spectrum of ^{46}Sc with the predicted energies of positive parity states calculated using a shell model with active $f_{7/2}$ and $p_{3/2}$ orbitals. See text for additional details.

levels that were populated in this experiment, those not populated in the $(\vec{d},\alpha)$ reaction being shown by dotted lines. The most noticeable fault of the calculation is the prediction of a 2^+ level well below all other levels. The lowest known 2^+ level in this nucleus lies at 0.444 MeV and corresponds much better to the second shell model 2^+ state. Three more low lying shell model states, the lowest 0^+ state and the second 3^+ and 4^+ states, are also not matched by experimentally observed states. It seems that the shell model calculation produces several extra energy levels not seen in experiment, but other than this discrepancy the shell model state agree fairly well in energy with the experimentally observed levels.

We attempted to calculate the negative parity states for this nucleus using the VdP interaction in OXBASH. Once again, the calculated levels did not describe the data very well.

It is interesting to speculate what contributions of two hole configurations are present in low lying positive parity states for these nuclei. We were not able to perform a calculation which included these configurations, but the calculations which we did perform agree fairly well without any two hole admixtures. Core deformations produced by one hole states may reduce single particle energies enough to allow these configurations to contribute at low excitations, but the extra deformation caused by bringing out another nucleon may not reduce the two hole configurations to the same extent. The fact that there are no positive parity states unaccounted for by our calculations for both nuclei below 1 MeV supports this suggestion.

CONCLUSION

T_{20} measurements for 32 states in ^{44}Sc and 20 states in ^{46}Sc using the ^{46,48}Ti$(\vec{d},\alpha)^{44,46}$Sc reactions have allowed us to make more restrictive assignments of J^{π}. The shell model code OXBASH has been used with a configuration space restricted to active $f_{7/2}$ and $p_{3/2}$ orbitals to predict the positive parity states of these nuclei, but was found to be inadequate at predicting the negative parity states when a small configuration space with $(sd)^{-1}$ components was used.

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