

Spins and Parities of Low-Lying
States in ^{77}Kr from the $^{78}\text{Kr}(\vec{d}, t)^{77}\text{Kr}$ Reaction⁺

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Abstract: The differential cross sections and vector analyzing powers for the $^{78}\text{Kr}(\vec{d}, t)^{77}\text{Kr}$ reaction leading to low-lying states of ^{77}Kr have been measured at an incident deuteron energy of 15.95 MeV. These data have been compared with distorted-wave Born approximation calculations, as well as with measurements of cross sections and analyzing powers on neighboring nuclei, in order to determine the spins and parities of these states and the spectroscopic factors for the transitions populating them. The ground state of ^{77}Kr , which had been the object of several conflicting spin assignments, has been found to have $J^\pi = 5/2^+$.

NUCLEAR REACTION $^{78}\text{Kr}(d, t)^{77}\text{Kr}$, $E_d = 15.95$ MeV. Measured $\sigma(\theta)$, $A_y(\theta)$.

DWBA analysis. Extracted J , π , S_j . Enriched target.

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1. Introduction

The spins and parities of the low-lying states in ^{77}Kr have been investigated in a number of experiments¹⁻⁵⁾, but there has unfortunately been almost no agreement of the spin assignments for these states. It is particularly disturbing that there exist three conflicting assignments for the ground-state spin and parity^{2,4,6)}. In fact, no two independent experiments have ever led to the same assignment for the ground state. In the present paper we clarify this situation.

In 1955, Thulin¹⁾ observed the β^+ decay of ^{77}Kr to states in ^{77}Br . Thulin's proposed decay scheme led to a $J^\pi=5/2^-$ assignment⁶⁾ for the ground state of ^{77}Kr when compared with the spins and parities which were accepted for states in ^{77}Br at that time. Holm et al.⁷⁾ later investigated the decay of ^{77}Kr using improved techniques and found Thulin's decay scheme to be in error. This later work restricted the ground-state spin of ^{77}Kr to $3/2^+$, $5/2^+$, or $7/2^+$. In 1971, Borchert²⁾ made an assignment of $7/2^+$ based on the strengths of observed decays to $9/2^+$ and $5/2^+$ states in ^{77}Br . This assignment for the ground state was then used by Liptak and Habernicht³⁾ to assign the spins of excited states in ^{77}Kr populated in the β^+ decay of ^{77}Rb . Shortly thereafter, Nolte and Vogt⁴⁾ proposed a level scheme for ^{77}Kr based on observations of the γ -decay of this nucleus following its formation in the $^{63}\text{Cu}(^{16}\text{O},\text{pn})^{77}\text{Kr}$ reaction. They assigned the ground state $J^\pi=5/2^+$, in conflict with the results of refs.¹⁻³⁾. Furthermore, they tentatively assigned the 67 keV first excited state $J^\pi=3/2^-$, in conflict with the tentative $5/2^-$ assignment of Liptak and Habernicht. The assignments for the ground state and first excited state are particularly interesting because these two states have been proposed as band heads of two rotational bands in ^{77}Kr 4).

In an attempt to resolve the discrepancies in the assignments for the ground state and 67 keV state, Wender⁵⁾ measured the K-shell internal conversion coefficient for the decay of the 67 keV state to the ground state. His measured value is consistent only with M1 decay, implying that these two states have the same parity, in conflict with both earlier determinations^{3,4)}.

In the present investigation we have measured the cross section and vector analyzing power for the $^{78}\text{Kr}(\vec{d},t)^{77}\text{Kr}$ reaction leading to a number of low-lying states in ^{77}Kr . The angular distribution of the cross section is a reliable indicator of the neutron orbital angular momentum l_n transferred in the reaction⁸⁾, and thus permits a determination the parity of the final state. The j -dependence of the vector analyzing power A_y in (d,t) reactions is now well established as a reliable indicator of the total angular momentum J of the final state⁹⁾. Our observations have therefore allowed us to make spin and parity assignments which are entirely independent of previous work on this nucleus.

2. Experimental Method

States in ^{77}Kr were populated using the $^{78}\text{Kr}(\vec{d},t)^{77}\text{Kr}$ reaction initiated by 15.95 MeV polarized deuterons from the Triangle Universities Nuclear Laboratory polarized-ion source¹⁰⁾ and tandem accelerator. The beam was purely vector-polarized¹¹⁾ and typically had an intensity of 40 nA at the target. The beam polarization was determined at the beginning and end of each run using the quench-ratio method¹²⁾. The 99% enriched ^{78}Kr target gas was contained in a 2.5-cm diameter cylindrical cell with 2.5- μm Havar* walls. The Kr pressure was about 1/3 atm, giving a total energy loss for deuterons reaching the center of the cell of about 110 keV. The Kr was easily recovered from the target cell by immersing in liquid nitrogen the tip of the small stainless steel storage cylinder attached to the cell.

*Obtained from Hamilton Precision Metals, Lancaster, PA.

The reaction products were detected in four E-ΔE detector telescopes arranged to form two symmetric left-right pairs at two different reaction angles. Data were taken with the deuteron spin alternately "up" and "down" relative to the reaction plane in order to minimize the effects of instrumental asymmetries. The tritons were separated from the other reaction products using a mass identification scheme. The slit systems used with the detectors limited the angular acceptance to $\pm 1.2^\circ$. The overall energy resolution for tritons was typically 60 keV and was dominated by straggling in the Kr gas and in the gas cell walls. Further details of the scattering chamber, electronics, beam integration, and dead-time correction technique have been published elsewhere.¹¹⁾

The absolute cross section scale was determined in a separate experiment in which the same detector system was used to observe 7 MeV deuterons elastically scattered at 25° from the ^{78}Kr target. At this angle the cross section differs from the Rutherford value by only about 2%, so the results of an optical model calculation are insensitive to the details of the calculation and a reliable prediction of the cross section can be made. Comparison of this prediction with our observed yields for $^{78}\text{Kr}(d,d)^{78}\text{Kr}$ was used to determine the overall normalization of the (d,t) cross section angular distributions. There was a difference in beam energy between the (d,t) and (d,d) experiments, but multiple scattering from the foils was calculated to produce a negligible change ($\leq 0.5\%$) in beam integration between these energies. Likewise, although foil-foil and foil-gas scattered deuterons could not be separated in energy from those single-scattered from ^{78}Kr , their contribution to the normalization was found to be negligible. Thus the (d,t) cross section angular distribution data are estimated to be better than 5%, with dominant uncertainties arising

from the normalization procedure and background subtraction.

A representative pulse-height spectrum for $^{78}\text{Kr}(d,t)^{77}\text{Kr}$ is shown in fig. 1. The expected positions of all known states^{3,4)} in this energy region are indicated by vertical marks. Those states which are discussed in the present work are further identified by their excitation energies. No significant evidence for contamination of the target gas was found.

3. Data Analysis

In order to guarantee the correct identification of the peaks in the ^{77}Kr spectrum, the energy scale was determined by filling the cell with ^{40}Ar and observing the tritons from the $^{40}\text{Ar}(d,t)^{39}\text{Ar}$ reaction. This spectrum was then calibrated by comparison with the published $^{40}\text{Ar}(d,t)^{39}\text{Ar}$ spectrum of Sen et al.¹³⁾.

For most of the states of interest in this experiment, at least one other ^{77}Kr state lies close enough to prevent clear resolution of the peaks in the pulse-height spectrum (see fig. 1). The peak corresponding to the ground state transition appears as a clearly distinguishable shoulder on the much larger peak corresponding to the 67 keV transition. Reliable peak sums for these two transitions could be obtained using a peak-fitting computer program¹⁴⁾ which reproduced the shape of the doublet by summing two Gaussian distributions with equal widths and a separation which was fixed at the known separation of the peaks for these two transitions. The intensities and width of the Gaussians were adjusted, as was the position of the doublet.

The reliability of the separation of the doublet into its components can be assessed in several ways. First, the shape of the doublet was accurately reproduced. Second, the resulting cross section and analyzing power distributions for the ground state do not resemble those for the 67 keV state, (see fig. 2) indicating that the program properly separated the two peaks. As a further check, the analyzing powers for the two transitions were computed from the counts in the high- and low-energy portions of the combined peak. Counts in the region where the two peaks would be expected to overlap were excluded, so the resulting analyzing powers should be those for the two single transitions.

This analysis confirmed the analyzing power results shown in fig. 2. The second excited state of ^{77}Kr at 150 keV^{3,4)} is evidently not strongly populated in the $^{78}\text{Kr}(d,t)^{77}\text{Kr}$ reaction at this energy, for we saw no evidence of a peak corresponding to this transition at any angle (see fig. 1).

The peaks corresponding to the 245 and 279 keV states are separated by about half of the experimental energy resolution, and therefore form a single peak in the pulse-height spectrum. The centroid of this peak is near the expected position of the 279 keV peak, but peak-fitting indicated a significant contribution from the transition to the 245 keV state. However, the separation of the counts from the two components was not reliable, so the data shown in fig. 3 are for the combined peak. As discussed in sect. 5, these data appear to represent contributions from two transitions.

The transitions to the 460 and 500 keV states were also unresolved in this experiment, but the peak position indicates that the dominant contribution was from the 460 keV state. The data shown in fig. 3 are for the combined peak. The peak corresponding to the 1243 keV state was relatively well resolved from other ^{77}Kr peaks, but the small strength of this transition makes the cross section, and to a lesser extent the analyzing power, subject to uncertainties in the background under the peak. This problem is most likely to affect the data for the most forward angles because the background was larger in those cases.

The cross section and analyzing power data for the five transitions are shown in figs. 2 and 3. The error bars shown include the uncertainties due to counting statistics and, for the transitions to the ground state and 67 keV state, the additional uncertainty associated with the extraction of separate peak sums for the two components of the doublet. The uncertainties in the analyzing power measurements also reflect the uncertainty in the beam polarization.

In some cases cross section measurements are shown without corresponding analyzing power data. In these instances the numbers of counts in the peaks were small and the resulting uncertainties in the analyzing power data were so large that the measurements were essentially meaningless.

4. Distorted-Wave Calculations

The spins of levels in ^{77}Kr have been assigned by comparing the experimental data with DWBA calculations performed using the code TDWUCK, which is a version of the code DWUCK¹⁵⁾. Bieszk et al.¹⁶⁾ have recently shown that distorted-wave calculations for $^{70}\text{Ge}(\vec{d},t)^{69}\text{Ge}$ at 16 MeV lead to the correct spin assignments, indicating that the deformation of the nuclei in this mass region does not interfere with the use of the j -dependence of the vector analyzing power for the determination of spins.

The DWBA calculations included corrections for the finite range of the neutron-proton interaction, but corrections for the non-locality of the potentials were not included because these corrections were not applied when the potentials were originally determined from elastic scattering data. The potential binding the neutron to the ^{77}Kr core had a radius parameter of 1.17 fm and a diffuseness of 0.75 fm (from ref.¹⁷⁾), a Thomas spin-orbit factor of 25, and a depth which was adjusted to reproduce the neutron binding energy.

The calculations shown in figs. 2 and 3 were performed with the optical model potentials shown in table 1. The deuteron potential is essentially that of Lohr and Haerberli^{18,19)}, but the magnitude of V_0 was decreased by 1.5 MeV because the deuteron energy in the present experiment is higher than those considered in refs.^{18,19)}. Several other deuteron potentials²⁰⁻²⁵⁾ were tried, but calculations using these potentials did not reproduce the data as well as

did the calculations using the potential of refs.^{18,19)}. The triton potential was that of Hardekopf *et al.*²⁶⁾ for $^{90}\text{Zr}(\bar{t}, t)^{90}\text{Zr}$ at 15 MeV. The triton potentials of refs.^{27,28)} led to less satisfactory predictions, but the predictions for the 460 keV state could be improved by increasing the magnitude of the absorptive term in the potential of ref.²⁶⁾ from 13.5 to 20 MeV. The results of the calculation with more absorption are shown by the dotted curves in the center panel of fig. 3. This change makes the prediction for the cross section slightly worse, but greatly improves the prediction for the analyzing power.

The spectroscopic factors for the transitions to the ground state and 67 keV state corresponding to the calculations shown by the solid curves in fig. 2 are given in table 2.

5. Discussion

The cross section data for the ground state transition shown in fig. 2 are reproduced fairly well by the calculation for $\ell_n=2$, but are inconsistent with calculations for $\ell_n=3$ and $\ell_n=4$. This limits the ground state spin to $J^\pi=3/2^+$ or $5/2^+$, eliminating the previous assignments of $J^\pi=5/2^-$ and $7/2^+$. As shown in fig. 2, the predominantly negative sign of the analyzing power data indicates that the ground-state spin of ^{77}Kr is $J^\pi=5/2^+$, in agreement with the assignment of Nolte and Vogt⁴⁾. The cross section and analyzing power data for the transition to the 67 keV state are reproduced well by calculations for $J^\pi=3/2^-$, confirming the tentative assignment of Nolte and Vogt. A comparison of the cross section data for the transition to the 67 keV state with the results of the $\ell_n=3$ calculation shown in the upper left panel of fig. 2 demonstrates that the $J^\pi=5/2^-$ assignment of ref.³⁾ is clearly ruled out. The present results for the

ground state and 67 keV state reveal that these states have opposite parity, in conflict with the internal conversion measurement by Wender⁵). This conclusion is essentially independent of the analyzing power measurements.

As discussed in sect. 3, the transitions to the 245 and 279 keV states were not resolved in the present experiment, but both transitions appear to contribute to the observed peak, with the transition to the 279 keV level probably dominating. The cross section data for this doublet (upper left panel of fig. 3) are, in fact, not well reproduced by calculations with a single value of ℓ_n . Instead, they lie between the predictions for $\ell_n=3$ and $\ell_n=4$ transfers. Similarly, the analyzing power data are not well reproduced by a single calculation. The pattern of the measured values oscillates in phase with both the $J^\pi = 9/2^+$ and $J^\pi = 5/2^-$ calculations indicating that a combination of these calculations would reproduce the general features of the data. This combination was obtained using a search program which adjusted the contribution from $J^\pi = 5/2^-$ and $J^\pi = 9/2^+$ to minimize differences between theory and experiment for both cross section and vector analyzing power. This procedure provided reasonable agreement with both experimental distributions as shown in fig. 3. Nolte and Vogt assigned the 245 and 279 keV states as $J^\pi = (5/2)^-$ and $J^\pi = 9/2^+$ respectively, and the present results are consistent with their choice of spin assignments although we cannot distinguish which state might be assigned to a given spin.

The transitions to the 460 and 500 keV states were also resolved, although, as pointed out in sect. 3, the former is probably dominant in this experiment. In spite of the possibility that two transitions may contribute to this peak, the cross section data shown in the center panel of fig. 3 are well reproduced by a single calculation for $\ell_n=1$. The analyzing power data point to an assignment of

$J^\pi=1/2^-$. This is probably the correct assignment for the 460 keV state.

The 500 keV state is either very weakly populated in the present experiment, or also has $J^\pi=1/2^-$. Liptak and Habernicht³⁾ had assigned both of these states $J^\pi=(1/2^-, 3/2^-)$, which is consistent with the present results. Nolte and Vogt did not observe the 460 keV state, but assigned the 500 keV state $J^\pi=(7/2)^-$. This assignment would only be consistent with the present results if the 500 keV state is not populated significantly in the $^{78}\text{Kr}(d,t)^{77}\text{Kr}$ reaction at 16 MeV.

The cross section and analyzing power data for the transition to the 1243 keV state are shown in the right panel of fig. 3. No previous assignment has been made for this state, and the present data are not sufficient to make a reliable assignment. For this reason, no calculations are shown. The negative trend of the analyzing power is clear, however, indicating assignments of $3/2^-$, $5/2^+$, $7/2^-$, or $9/2^+$ as possibilities. The analyzing power data are, in fact, very similar to those for the $J^\pi=5/2^+$ ground state transition shown in fig. 2, but the cross section data do not appear to be consistent with a $J^\pi=5/2^+$ assignment for this state.

Additional support for the present spin assignments of $5/2^+$, $3/2^-$, and $1/2^-$ to the ground state, 67 keV state, and 460 keV state, respectively, can be obtained by comparing our data with those of Bieszk et al.¹⁶⁾ for $^{70}\text{Ge}(d,t)^{69}\text{Ge}$ at 16 MeV. Our data are in good agreement with those of ref.¹⁶⁾ for states which are known from previous work to have spins of $5/2^+$, $3/2^-$, and $1/2^-$. A summary of the present spin assignments and those from previous investigations is given in table 2.

6. Conclusions

Our measurements of the cross section and vector analyzing power for the $^{78}\text{Kr}(d,t)^{77}\text{Kr}$ reaction populating the ground state and 67 keV first excited

state of ^{77}Kr lead to unambiguous spin assignments of $J^\pi=5/2^+$ and $J^\pi=3/2^-$, respectively, for these states. These results confirm the assignments of Nolte and Vogt⁴⁾, and hopefully resolve the long-standing controversy surrounding the ground state spin of ^{77}Kr . Our data for the transitions to the 245 and 279 keV states are also consistent with the $J^\pi=5/2^-$ and $J^\pi=9/2^+$ assignments of Nolte and Vogt⁴⁾. The present investigation indicates that the 460 keV state has $J^\pi=1/2^-$, and that the 500 keV state either has the same spin, or is not populated significantly in this experiment.

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Figure Captions

- Fig. 1. A representative pulse-height spectrum for the $^{78}\text{Kr}(\vec{d},t)^{77}\text{Kr}$ reaction at $\theta_{\text{LAB}} = 40^\circ$. The expected positions of peaks corresponding to all previously-reported states in ^{77}Kr are indicated by the vertical marks. The peaks corresponding to states which were investigated in the present work are labelled with the excitation energy of the state in MeV.
- Fig. 2. Cross section and vector analyzing power data for the $^{78}\text{Kr}(\vec{d},t)^{77}\text{Kr}$ reaction leading to the ground state and 0.067 MeV state of ^{77}Kr . The curves are the results of distorted-wave calculations with the indicated values of l_n and J^π .
- Fig. 3. Cross section and vector analyzing power data for the $^{78}\text{Kr}(\vec{d},t)^{77}\text{Kr}$ reaction. The data for the transition to the 0.279 MeV state probably contains a contribution from the state at 0.245 MeV. Similarly, the data for the transition to the 0.460 MeV state may include a contribution from the 0.500 MeV state. The curves are the results of distorted-wave calculations for the 0.460 MeV state are shown for two choices of the absorptive component of the triton potential.

Table 1
Optical Potential Parameters^{a)}

particle	source	V	r_o	a_o	W_s	W_d	r_w	a_w	V_{so}	r_{so}	a_{so}	r_c
d	refs. ^{18,19}	108.2 ^{b)}	1.05	0.86 ^{c)}	0	11.94	1.43	0.74	7.0	0.75	0.50	1.30
t	ref. ²⁶⁾	168.0	1.20	0.65	13.5 ^{d)}	0	1.60	0.87	6.0	1.15	0.51	1.30

a) Potential depths are given in MeV; geometrical parameters are given in fm.

b) Corrected for incident deuteron energy.

c) The value given here, from ref.¹⁹⁾, is the appropriate one, but differs from the value quoted in ref.¹⁸⁾.

d) A value of 20 MeV gave significantly better fits to the analyzing power for the 460 keV state.

Table 2
 Summary of Spectroscopic Information
 for states in ^{77}Kr

E_x (MeV)	J^π (this work)	J^π (Nolte & Vogt, ref ⁴)	J^π (Liptak & Habernicht, ref ³)	J^π (Borchert, ref ²)	J^π (Thulin, ref ¹)	S_j (this work)
0.0	$5/2^+$	$5/2^+$	$7/2^+$	$7/2^+$	$5/2^-$	0.089
0.067	$3/2^-$	$(3/2)^-$	$(5/2)^-$			0.612
0.150		$7/2^+$	$(5/2^+, 9/2^+)$			
0.245	$(5/2^-, 9/2^+)$	$(5/2)^-$	$(5/2^-)$			(0.95)*
0.279	$(9/2^+, 5/2^-)$	$9/2^+$				(2.3)*
0.460	$1/2^-$		$(1/2^-, 3/2^-)$			
0.500		$(7/2)^-$	$(1/2^-, 3/2^-)$			
1.243	$(3/2^-, 5/2^+, 7/2^-, 9/2^+)$					

* Calculated values assuming that the 0.245 MeV state is $J^\pi = 5/2^-$ and 0.279 MeV is $J^\pi = 9/2^+$.

The lack of good agreement between theory and experiment for other states investigated here makes us believe these values uncertain.





