Comparative Study of the $(p,^3He)$ and (p,t) Reactions on T=1/2 Nuclei in the 2s-1d Shell

H. Nann and B. H. Wildenthal

During the past year, work has continued on the comparative study of the $(p,^3He)$ and (p,t) reactions on T_z=1/2 nuclei in the 2s-1d shell. This study has two distinct facets, (a) investigation of the spin-isospin dependence of the interaction potential in the two-nucleon transfer reaction, and (b) test of current shell-model wave functions. The analysis is complicated by the fact that these two aspects are coupled to each other. The accuracy of the determination of the spin-isospin term in the interaction potential depends upon the reliability of the wave functions used and, conversely, a meaningful test can only be carried out with an accurate knowledge of this same spin-isospin dependent part in the interaction potential used in the DWBA analysis.

The experiments were performed using the 40 MeV proton beam from the MSU Cyclotron. The reaction products were detected in a wire-counter plastic-scintillator combination on the focal plane of the split-pole magnetic spectrograph. This equipment provides excellent particle identification and an energy resolution of about 25 to 30 keV.

We have measured angular distributions of the $(p,^3He)$ and (p,t) reactions on ^{39}K, ^{35}Cl, ^{31}P, ^{29}Si, ^{27}Al, ^{25}Mg and ^{23}Na between 4° and 55° for states up to 6 MeV excitation energy in the final nuclei. Some of the angular distributions obtained are shown in Fig. 1. We have tried to reproduce the experimental differential cross sections with microscopic DWBA calculations which employ spectroscopic amplitudes[1] extracted from available[2-5] shell-model wave functions. In all DWBA calculations the same set of optical model parameters are used. The agreement between the predicted differential cross sections and the experimental data is generally quite satisfactory. The existing discrepancies in the shapes of the angular distributions, where only one L-transfer is allowed by the selection rules, point to some contributions from two step processes[6] and not to inadequacies of the shell-model wave functions used in the analysis.

In order to elucidate the effects upon the determination of the spin-isospin dependence in the transfer interaction potential which can result from different assumptions about the nuclear wave function, different choices for wave functions of the states involved were made. The influence of the spin-isospin dependence in the interaction potential was studied by considering different choices for the exchange forces using those wave functions which simulate reality most nearly.

With these assumptions the $(p,^3He)$ and (p,t) differential cross sections for transitions to mirror final states were calculated and compared to the experimental data. The shapes of the (p,t) angular distributions are unaffected by the choice of the strength of the spin-isospin interaction potential, whereas in the $(p,^3He)$ reaction the shapes of some angular distributions are markedly influenced. Only in cases where several L-values can contribute to the transition is the shape of the angular distributions affected by the different sets of wave functions. Therefore, the more critical test of our assumptions is the comparison of the predicted magnitude of the differential cross section with the experimental data.

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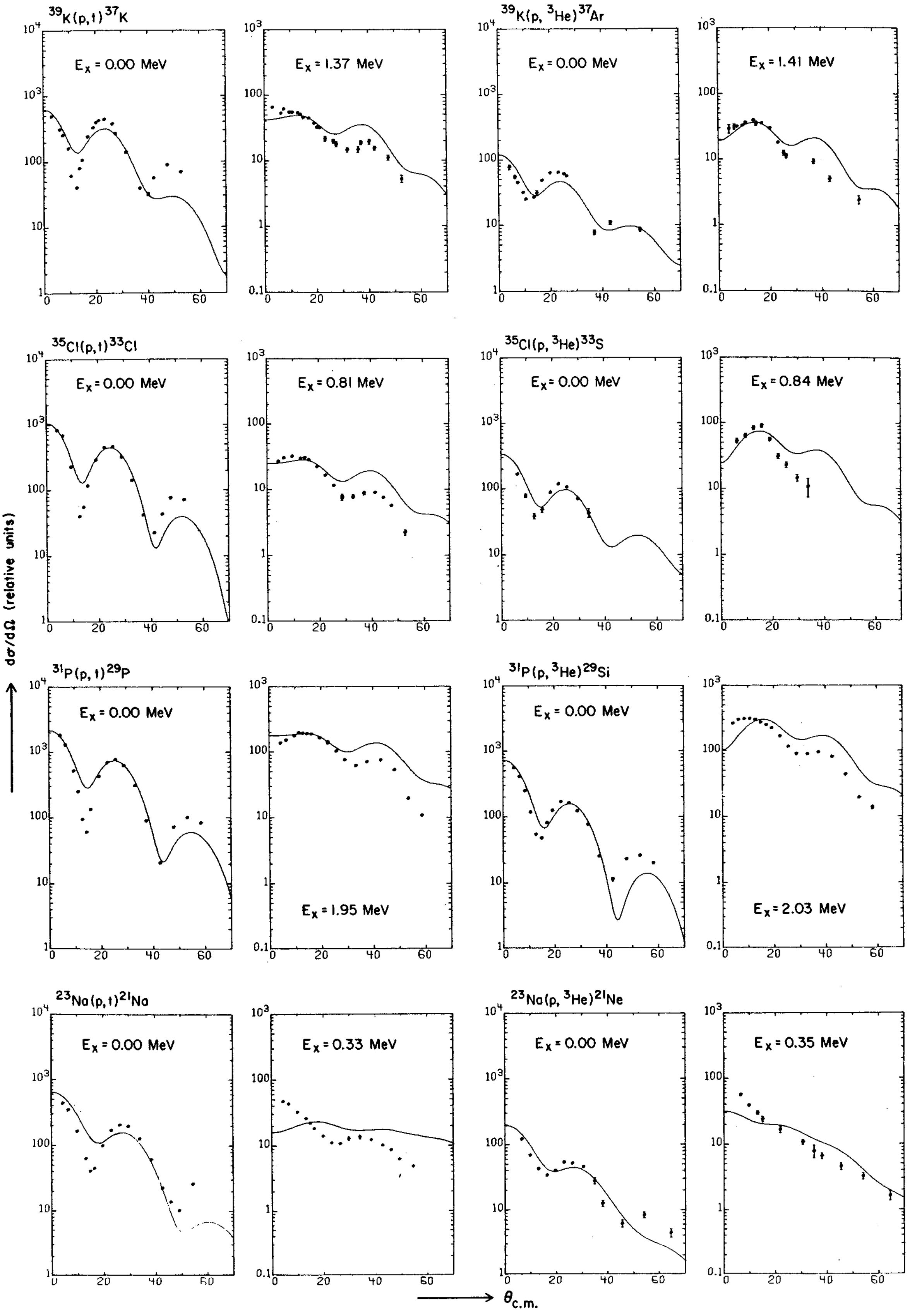
39K(p,t)37K
Ex = 0.00 MeV
Ex = 1.37 MeV
39K(p, 3He)37Ar
Ex = 0.00 MeV
Ex = 1.41 MeV
35Cl(p,t)33Cl
Ex = 0.00 MeV
Ex = 0.81 MeV
35Cl(p, 3He)33S
Ex = 0.00 MeV
Ex = 0.84 MeV
31P(p,t)29P
Ex = 0.00 MeV
Ex = 1.95 MeV
31P(p, 3He)29Si
Ex = 0.00 MeV
Ex = 2.03 MeV
23Na(p,t)21Na
Ex = 0.00 MeV
Ex = 0.33 MeV
23Na(p, 3He)21Ne
Ex = 0.00 MeV
Ex = 0.35 MeV
10^4
10^3
100
10
1
0.1
0
20
40
60
dσ/dΩ (relative units)
θc.m.

(α,d) Reaction on Odd-A Nuclei in the 2s-1d Shell

W. S. Chien, B. H. Wildenthal and H. Nann

Two-nucleon transfer in (α,d) reaction has been shown to strongly populate high-spin states.[1-3] The captured proton and neutron enter the same shell-model state and couple to the maximum angular momentum with zero isospin. The pair then couples to the target spin to give the preferentially populated state. The high spins of the strongly populated (α,d) states make configuration mixing unprobable, hence the wave functions of these levels may be relatively simple. Therefore, the high-spin levels may be well-suited for shell model studies.

We have measured the angular distributions for (α,d) reactions on ^{23}Na, ^{35}Cl, ^{37}Cl, ^{39}K, and ^{34}S targets at 40 MeV, using the alpha beam from the MSU Cyclotron. The normalization was obtained by monitoring elastically scattered α-particles with solid state detector positioned at 60°. The outgoing deuterons were detected in a resistive-wire proportional counter placed in the focal plane of an Enge split-pole magnetic spectrograph. The proportional counter was backed by a plastic scintillator which was used to identify the deuterons by time of flight measurement. Typical resolution obtained is about 80 keV.

Sample spectrum for targets ^{23}Na, ^{35}Cl, ^{37}Cl and ^{39}K are shown in Fig. 1. The dominant peak in each spectrum was assigned $13/2^+$ for ^{25}Mg(5.78 MeV) and 17.2^+ for ^{37}A(7.10 MeV) ^{39}A(5.54 MeV) and ^{41}Ca(5.24 MeV) on the basis of strength and angular distribution. In particular, the angular distributions for ^{39}K(α,d) reactions leading to levels at 3.37($11/2^+$), 3.93($13/2^+$), 3.83(15.2^+) and 5.24($17/2^+$) MeV of ^{41}Ca are shown in Fig. 2. The $(17/2)^2$ group have similar shape in angular distributions. Their J values have been previously reported[4,5,6] and confirmed by (α-α') work.[7] Further study of (α,d) reaction on odd-A nuclei in the 2s-1d shell is currently underway.

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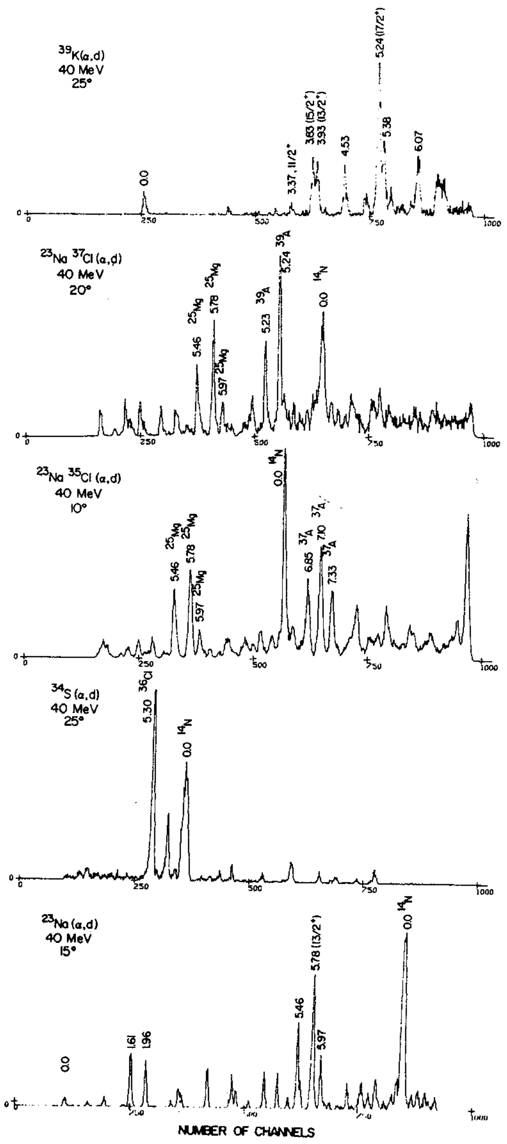

Figure 1

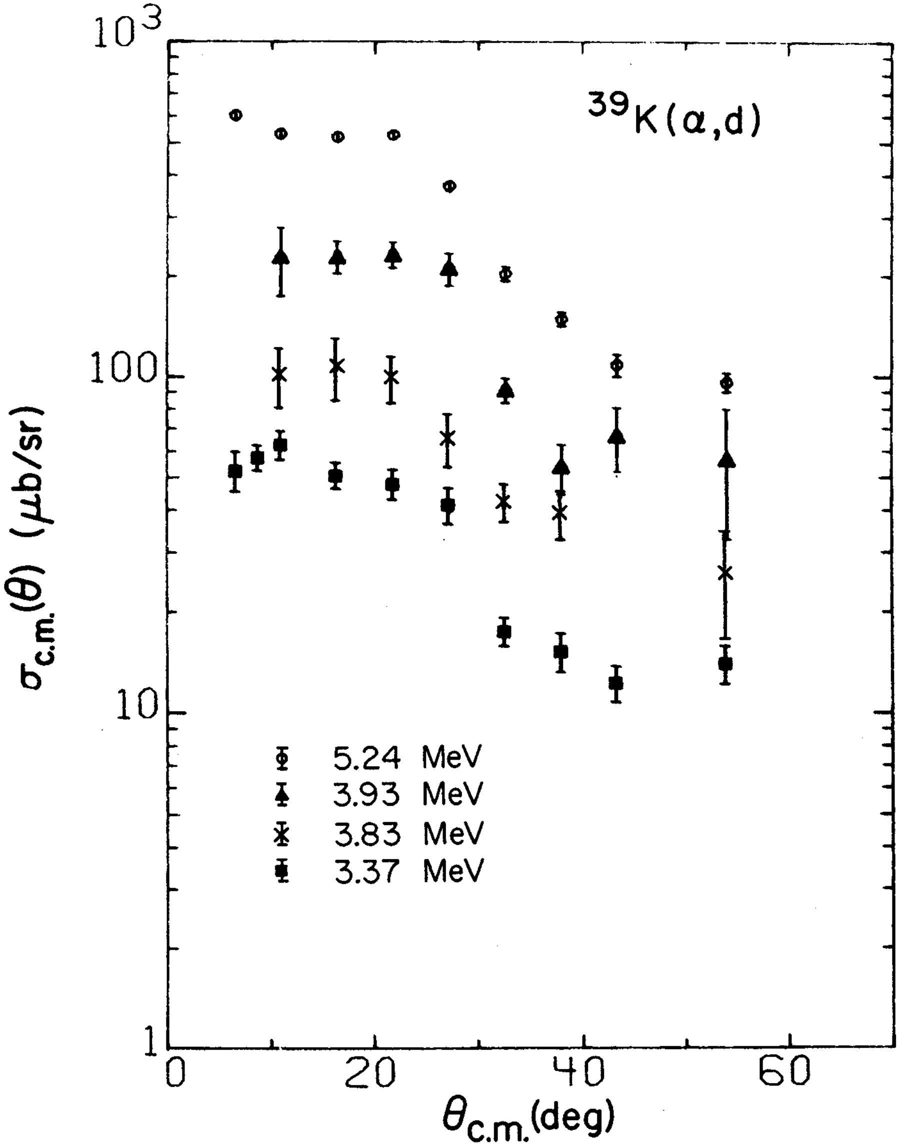

Figure 2

Levels of ^{56}Ni

H. Nann and W. Benenson

In the shell-model description, ^{56}Ni is a doubly closed shell nucleus. Therefore, the excitation and nature of levels in this nucleus are of considerable importance in nuclear structure calculations. The level structure of ^{56}Ni has been investigated by several authors with only two reactions, ^{58}Ni(p,t) ^{56}Ni[1,2] and ^{54}Fe(^{3}He,n) ^{56}Ni[3-7]. Since all these studies suffered from a lack of good energy resolution, some discrepancies exist even for low lying states. In the present study these discrepancies are shown to arise from unresolved doublets. As an example, in (p,t) experiments a spin-parity value of 4^+ was assigned to the level at 3.95 MeV, whereas a value of 0^+ was found in the (^{3}He,n) experiments. In order to resolve this type of discrepancy we measured the ^{58}Ni(p,t)^{56}Ni reaction with better energy resolution than had been previously obtained in studies of ^{56}Ni.

We have obtained angular distributions from 4° to 55° for approximately 60 resolved levels. A beam energy of 40 MeV was employed, at which energy the angular distributions displayed characteristic shapes for each L-transfer except for excitation energies greater than 6.5 MeV where only L=0 could be distinguished. This behavior is due to the low energy of the emitted tritons, which has been shown previously[8] to produce angular distributions which lack distinguishing features. The region of the T=2 state in ^{56}Ni ($\simeq$10 MeV) was repeated at 45.5 MeV beam energy to determine unambiguously the L-transfer in that region.

The triton spectra were recorded using either a position sensitive Si-semiconductor detector or a position-sensitive proportional-counter in the focal plane of the split-pole magnetic spectrograph.[9] An energy resolution of 10 and 25 keV, respectively, was obtained. A composite spectrum from the wire and Si detector is given in Figure 1. We gave considerable attention to determining the excitation energies with good accuracy. The method which was similar to that employed previously[10] does not rely on the linearity of the detector.

More details on this work can be found in a paper submitted to Phys. Rev. in July 1974.

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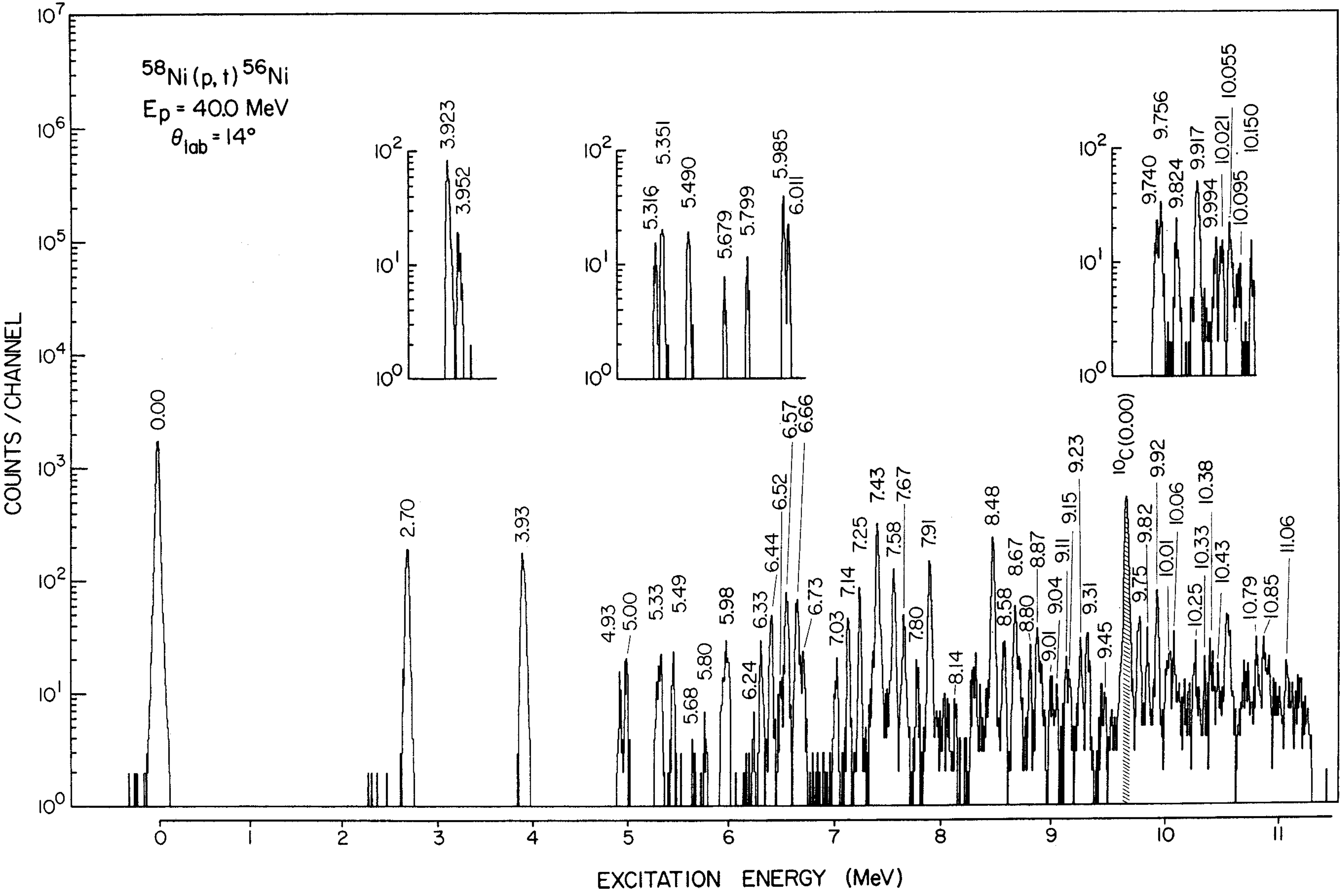

Fig. 1--Composite triton spectrum of the ^{58}Ni(p,t)^{56}Ni reaction.

^{64}Ni(p,t) Reaction at 40 MeV

D. H. Kong-A-Siou, H. Nann, and W. Benenson

The ^{64}Ni (p,t) reaction is part of a systematic study of Ni isotopes with (p,t) reaction. conducted at M.S.U. and at I.S.N. (Grenoble). Although the ^{62}Ni nucleus was in the past object of a larger number of experimental studies, the spin and parity of many energy-level are still undefined. The simplicity of its selection rules $S=0$, $T=1$ makes the (p,t) reaction a very useful tool for spectroscopic study, since for an even target, the total spin of final level is directly defined by the transferred angular momentum.

The experiment is realized at M.S.U. Cyclotron at 40 MeV bombarding energy. Outgoing tritons were detected with a position sensitive proportional wire-counter and nuclear emulsion states. A typical triton spectrum is shown on Figure 1. The analysis of wire counter data, used for absolute normalization, is completed. Many angular distributions show strange shapes and point to probable doublets. The analysis of the plate data with an energy resolution of about 12 keV is underway. The result will provide further test of recent shell model calculations.

Preliminary analysis allow us to assign unambiguously the spin and parity of the following levels:

0^+: 0.0, 2.047, 2.888, 4.226, 4.623, 5.450

2^+: 1.172, 2.299, 3.155, 3.253, 3.966, 4.409, 4.712, 4.781, 5.147, 5.202, 6.354

4^+: 2.333, 3.172, 3.271, 4.049, 4.884, 5.017, 5.912

3^-: 3.751, 4.655, 4.994

only 9 of these levels have had spin and parity assignments from previous works.[1,2]

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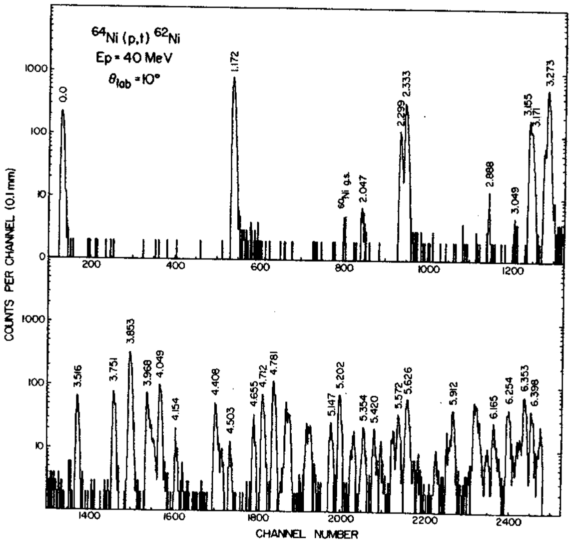


Spectroscopic Study of ^{60,61}Ni by (p,d) Reaction

D. H. Kong-A-Siou, W. S. Chien, and H. Rossner

The ^{61,62}Ni (p,d) reactions have been studied with a 40 MeV proton beam from the MSU Cyclotron. Angular distributions were measured in the focal plane of a split-pole magnetic spectrograph with a position sensitive single wire proportional counter for both reactions and also with nuclear emulsion for ^{61}Ni(p,d) reaction. The energy resolutions were respectively 45 and 10 keV FWHM. A typical spectrum of ^{61}Ni (p,d) reaction is shown on Fig. 1.

Spectroscopic factors extracted from ^{62}Ni (p,d) ^{61}Ni reaction are shown on Table 1, and are compared with results from other neutron pick-up experiments. Spin and parity were proposed to several levels in ^{61}Ni, in particular to three yet unreported $s_{1/2}$ states respectively at 3.068, 5.589, and 5.697 MeV excitation energy. The $f_{7/2}$ assignment was based on a strong j-dependence for $\ell=3$ transition observed in both ^{61,62}Ni (p,d) reactions at 40 MeV.

The ^{61}Ni (p,d) experiment was conducted to complete a recent study of ^{60}Ni nucleus by ^{62}Ni (p,t) ^{60}Ni reaction. The results will be compared with shell model predictions.

TABLE 1.--Energy levels of ^{61}Ni. Only levels with extracted spectroscopic factors are listed.

Ex^a	Ex^b	$J^{\pi a}$	$J^{\pi b}$	S		
MeV				$(p,d)^a$	$(d,t)^b$	$(\zeta,\alpha)^b$
0.0	0.0	$3/2^-$	$3/2^-$	1.8	3.25	
0.067	0.0674	$5/2^-$	$5/2^-$	2.51	3.15	(3.03)
0.283	0.2829	$1/2^-$	$1/2^-$	0.49	1.14	
0.656	0.6560	$3/2^-$	$3/2^-$	0.09	0.22	
0.909	0.9086	$5/2^-$	$5/2^-$	0.09		
1.020	1.019		$1/2^-,7/2^-$			
1.118	1.1001	$3/2^-$	$3/2^-$	0.1	0.25	
	1.1325	$5/2^-$	$5/2^-$	0.18		(0.59)
1.186	1.186	$3/2^-$	$3/2^-$	0.25	0.34	
1.457	1.457	$7/2^-$	$7/2^-$	0.49	2.8	0.47
1.611	1.6111	$5/2^-$	$(5/2^-)$	0.13		
1.730	1.7304	$1/2^-,3/2^-$	$1/2^-,3/2^-$	0.06	0.09	
2.006	1.990 1.997 2.020	$(7/2^-)$	$1/2\ldots5/2$	0.09	0.60 $(\ell=3)$	
2.120	2.114	$9/2^+$	$9/2^+$	0.25	1.	0.27
	2.1224	$1/2^-$	$1/2^-$	0.021	0.08	
2.470	2.470	$7/2^-$	$(5/2^-)$	0.23		0.23
2.899	2.890 2.910	$7/2^-$	$7/2^-$	0.8	3.7	0.6
3.068	3.076	$1/2^+$		0.03		
3.306	3.30	$7/2^-$		0.98	4.7	0.9
3.657	3.64		$5/2^-,7/2^-$		1.6	
3.939	3.96	$(7/2^-)$		.12		
4.592		$7/2^-$		.18		
4.955	4.94	$7/2^-$	$(7/2^-)$	.33	0.69	
5.589		$1/2^+$		0.16		
5.697		$1/2^+$		0.12		

[a] Present experiment. Error on excitation energy is about 7 keV for $Ex \leq 3$ MeV and 15 keV above.

[b] From Nuclear Data Vol. 2(1968)B2-5-41.

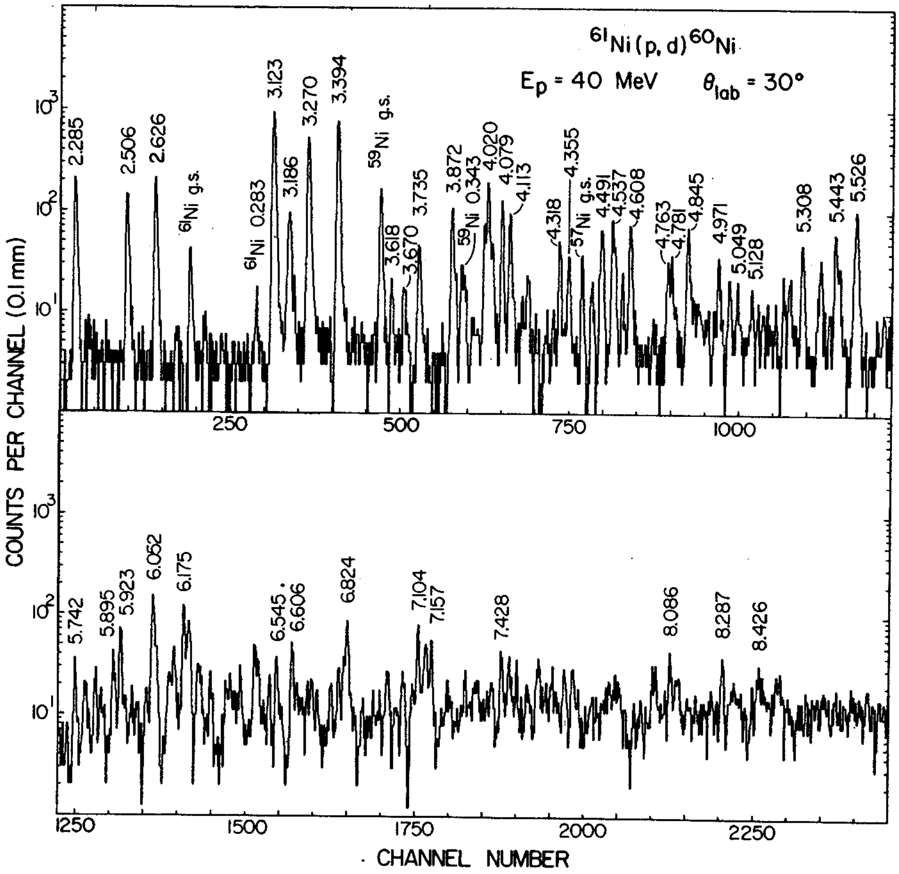

⁶¹Ni(p, d)⁶⁰Ni
Ep = 40 MeV θlab = 30°
COUNTS PER CHANNEL (0.1 mm)
CHANNEL NUMBER
10³
10²
10¹
250
500
750
1000
1250
1500
1750
2000
2250
2.285
2.506
2.626
⁶¹Ni g.s.
⁶¹Ni 0.283
3.123
3.186
3.270
3.394
⁵⁹Ni g.s.
3.618
3.670
3.735
3.872
⁵⁹Ni 0.343
4.020
4.079
4.113
4.318
4.355
⁵⁷Ni g.s.
4.491
4.537
4.608
4.763
4.781
4.845
4.971
5.049
5.128
5.308
5.443
5.526
5.742
5.895
5.923
6.052
6.175
6.545, 6.606
6.824
7.104
7.157
7.428
8.086
8.287
8.426

Figure 1

A Study of the (p,d) Reaction on the Germanium Isotopes

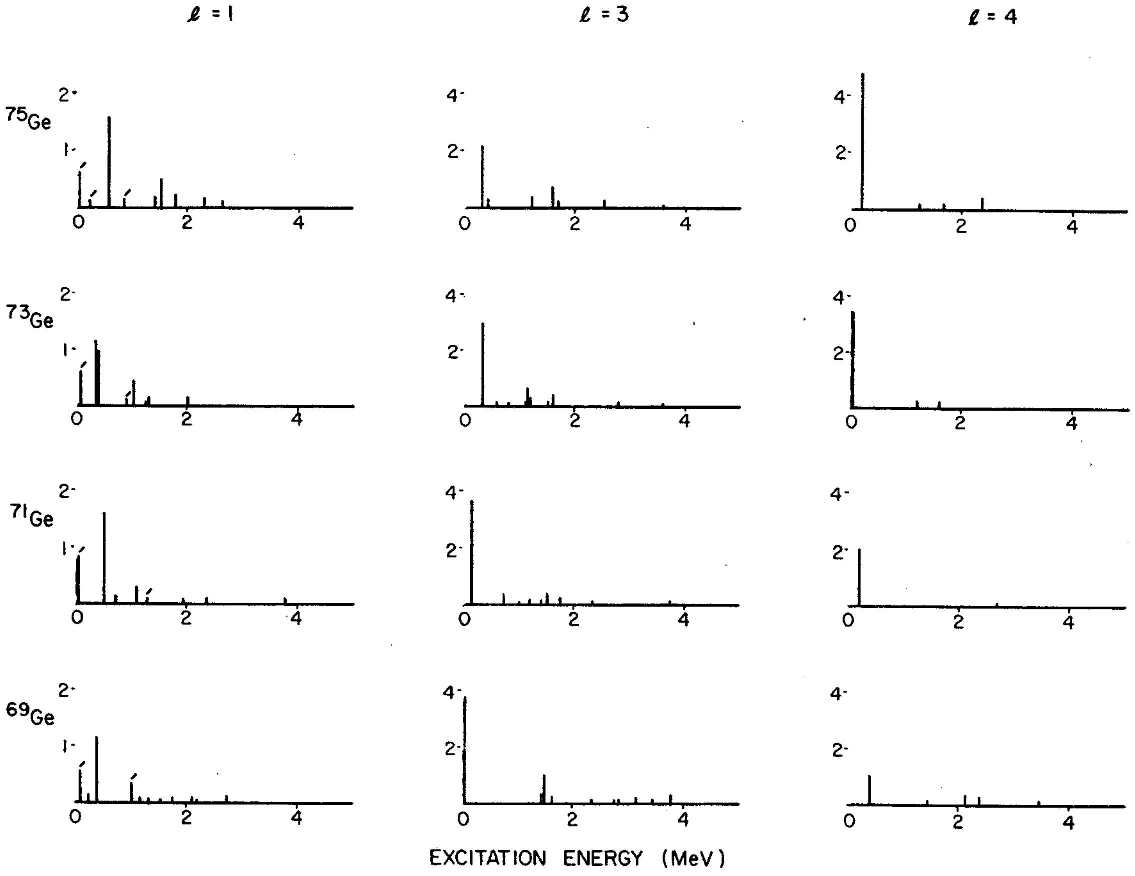
D. L. Show, B. H. Wildenthal and J. A. Nolen

We have just completed a study of the (p,d) reaction on ^{70,72,73,74,76}Ge. We used the 35 MeV proton beam from the MSU Cyclotron to bombard isotopically enriched targets of about 175 µg/cm^2 thickness. The deuterons were analyzed in the Enge split-pole magnetic spectrograph and detected on photographic emulsions which were 25 µm thick. Using the high resolution techniques developed at this laboratory a resolution of about 8 keV FWHM was obtained for most of the spectra. Angular distributions were taken between 6° and 60° in the lab.

The angular distributions were analyzed by using the DWBA. Calculations were done with the computer code DWUCK using the proton parameters of Becchetti-Greenlees and deuteron parameters determined from the adiabatic model of Johnson and Soper. An excitation energy calibration was done using the known characters of the spectrograph and the states in the germanium nuclei which have well known energies. This process yields excitation energies with an uncertainty of about 1.5 keV/MeV excitation.

The excitation energies, ℓ-values, and spectroscopic factors which we obtain in the present work are generally in agreement with the results of previous (d,p) and (p,d) experiments. However, we are able to resolve some previous ambiguities with our much improved resolution. In addition, we observe many states and their characters about which nothing was previously known. The figure shows the distribution of spectroscopic strengths for the odd isotopes for $\ell=1$, 3, and 4. For the $\ell=1$ cases, those states marked with dash marks are assumed to be $1/2^-$ states. We see that most of the $\ell=4$ strength is concentrated in a single state at or near the ground state. The $\ell=3$ transitions are characterized by a strong transition to a low lying state, and fairly weak transitions to a cluster of states near 1.5 MeV. The $\ell=1$ plot shows a strong transition to a low lying $1/2^-$ state, a stronger transition to a $3/2^-$ state near 500 keV, and another weak $1/2^-$ state near 1 MeV.

Our results indicate that the prospects for a shell model calculation in this region are not good. The active space must include the $1f_{5/2}$, $2p_{3/2}$, $2p_{1/2}$, and $1g_{9/2}$ orbits. In addition, we see sufficient $\ell=2$ strength to indicate that inclusion of the $2d_{5/2}$ orbit is highly desirable. At the present time this is too large an active space for the available computer size and time.



The Structure of ^{180}Ta

T. L. Khoo and C. H. King

For a Gallagher-Moszkowski pair in odd-odd nuclei, there are very few known exceptions to the rule[1] that the spin triplet state lies lower. One apparent exception is ^{180}Ta. The expected ground state configuration of this nuclide, based on the configurations of neighboring odd nuclei,[2] is $7/2{\downarrow}[404]p\ \ 9/2{\uparrow}[624]n$, which yields states of either $K=8^+$ or 1^+. The Gallagher-Moszkowski rule would imply that the $K=1^+$ state is lower, but the ground state is thought to be $K=8^+$.[3]

We are presently engaged in an investigation of the low-lying structure of ^{180}Ta to find out whether the Gallagher-Moszkowski rule is actually violated, and if so, what is the reason for the violation. The properties of ^{180}Ta are very poorly known with only two levels identified to date.[3] It is possible that the long-lived 8^+ state is not in fact the ground state. However, if it is the ground state, there are several possible reasons why it may be depressed below its $K=1^+$ partner. For example, there should exist nearby another two-quasiparticle $K=8^+$ intrinsic state, based on the $7/2[514]n\ 9/2[514]p$ coupling. Such high spin two-quasiparticle states are known to mix strongly in nearby even-even nuclei.[4] This mixing could cause an anomalous depression of the 8^+ state. A similar effect can result from Coriolis mixing between bands. This mixing is particularly strong for intrinsic states based on the $i_{13/2}$ neutron orbital such as the 9/2[624].

Because of the limited information available on the structure of ^{180}Ta, we plan a series of transfer reaction experiments. To date we have performed angular distribution measurements for the ^{181}Ta(p,d) reaction with 35 MeV protons from the MSU Cyclotron, detecting the outgoing deuterons on a position-sensitive silicon surface-barrier detector in the focal plane of the Enge split-pole spectrograph. We are still in the process of analyzing this data. We intend to measure soon such reactions as ^{181}Ta(^{3}He,α), ^{182}W(p,^{3}He), and ^{179}Hf(^{3}He,d).

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^{40}Ar(p,d)^{39}Ar Reaction

P. T. Debevec,* W. S. Chien, R. E. Segel** and J. Tonn**

The ^{40}Ar(p,d)^{39}Ar reaction is being studied to investigate the distribution of $d_{3/2}$ pickup strength. The strength is divided among the analogue state, the anti-analogue state, and the hole state. The splitting between the analogue state and the anti-analogue state depends only on the isovector monopole of the $f_{7/2}d_{3/2}{}^{-1}$ interaction (≡b). A survey of the excitation energies of all states whose wave functions may be approximated by the configuration $[(f_{7/2})^n_{J_pT_p} \times (d_{3/2})^{-m}_{J_hT_h}]JT$ has shown that many-particle many-hole states with $T<T_p + T_h$ are predicted to be *too low* in the spectrum when values of b consistent with the ^{40}Ca spectrum are used. Conversely, states with one $f_{7/2}$ particle or one $d_{3/2}$ hole, and many-particle many-hole states with $T=T_p + T_h$ are predicted to be within 300 keV of the observed position. The anomalous position of the state with $T<T_p + T_h$ also appears to be the case in ^{39}Ar, as the anti-analogue state (a state also observed in ^{37}Cl(^{3}He,p)^{39}Ar) is predicted to be at 2.38 MeV and is in fact observed to lie at 3.38 MeV. It is expected that the spectroscopic factors of the ^{40}Ar(p,d)^{39}Ar reaction will illuminate the source of this failure of the effective interaction.

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