Proton hole states in neutron rich nuclei near $A = 100$

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A study of proton hole states in neutron rich nuclei near $A=100$ has been carried out using the $(\vec{t},\alpha)$ reaction. Targets of ^{104}Ru and ^{110}Pd were bombarded with a beam of 17 MeV polarized tritons and the reaction α particles detected in a quadrupole-three-dipole spectrometer. Only the β decays of the residual nuclei, ^{103}Tc and ^{109}Rh, have been previously observed. The results indicate a smooth trend with Z of the proton single particle states observed in this region, except for ^{103}Tc. Examination of this nucleus indicates a strong tendency towards deformation.

[NUCLEAR REACTIONS ^{104}Ru, ^{110}Pd$(\vec{t},\alpha)$, $E=17$ MeV; measured $\sigma(\theta)$, A_y. DWBA analysis. ^{103}Tc, ^{109}Rh mass measurement.]

I. INTRODUCTION

The region of neutron rich isotopes near $A=100$ is of considerable interest because of the interplay between shell effects and the pairing force. The rapid transition in shape from spherical to deformed and back to spherical as protons are added indicates the sensitivity of these effects to a change of a few nucleons. Recent theoretical suggestions[1] indicate that the tendency towards deformation in this nuclear region may be dominated by a strong isoscalar residual interaction between particles in the $g_{9/2}$ proton orbital and the $g_{7/2}$ neutron orbital. Thus, an extensive experimental investigation of both neutron and proton degrees of freedom is necessary to understand this region.

A number of neutron transfer experiments have examined the onset of deformation[2-4] in the Mo-Ru-Pd region. In addition, several fission fragment decay-scheme studies[5-7] have probed the structure of neutron rich nuclei near $A=100$. All of these data suggest a rapid shape transition occurring in Sr and Zr, where the addition of just a pair of neutrons causes a shape transition. In Mo and Ru the transition occurs more slowly, whereas in Pd no clear evidence of a shape change is seen. Thus, the deformed region is extremely localized with a particular dependence on the number of protons present.

The present experiment involves a study of the proton hole states through the use of the $(\vec{t},\alpha)$ reaction, a reaction which has proven to be extremely valuable in establishing the character of proton hole states in the rare earth region[8,9] and in lead nuclei.[10] The focus of the present results are the nuclei ^{103}Tc and ^{109}Rh because of their location near the center of the region of rapid transition and because little is known about their properties. Both have uncertain ground state masses and no known excited states or spin assignments. Additional results using ^{100}Mo and ^{96}Zr targets are also included, although a detailed analysis of these data will appear in a separate publication.[11]

II. EXPERIMENTAL PROCEDURES

The experiments involved the use of a 17 MeV polarized triton beam from the Los Alamos Tandem Van de Graaff facility. The beam intensity averaged 30–50 nA with an average polarization of 0.75. The ^{110}Pd and ^{104}Ru targets were evaporated metal foils of 152 and 57 μg/cm^2 thickness, respectively, and had isotopic purity greater than 95%. Typical exposures were for 60 μC with the polarization direction changed at the source. Spectra at a particular angle with spin "up" and spin "down" were taken sequentially.

The reaction α particles were detected in a quadrupole-three-dipole (Q3D) spectrometer using a 1-m helical focal plane detector.[12] Complete experimental details may be found in Refs. 8–10, along with the appropriate formulas for analyzing power (A_y) and cross sections ($d\sigma/d\Omega$). (Note the Erratum to Ref. 10 mentioned in Ref. 8.) The ^{60}Ni$(\vec{t},\alpha)^{59}$Co reaction was used as an energy calibration since its known Q value is similar to that expected from the ^{104}Ru and ^{110}Pd targets.

III. DISTORTED WAVE CALCULATIONS

Distorted wave (DW) calculations were carried out using the computer code DWUCK4 of Kunz.[13] Optical model parameters from the survey of Perey[14] were tried, and a variety of triton and α potentials examined. Table I contains the final set chosen, which yielded the best fits to A_y and $d\sigma/d\Omega$. These are from the work of Refs. 15 and 16 for triton and α particles, respectively.

The spectroscopic factors C^2S are defined by

TABLE I. Optical model parameters used in $(\vec{t}, \alpha)$ distorted wave calculations. V, r_r, and a_r are the depth, radius, and diffuseness, respectively, of the real well. W, r_i, and a_i are the corresponding quantities for the imaginary well. V_{so}, r_{so}, and a_{so} are for the spin-orbit potential. A volume absorption was used for all particles.

Particle	V (MeV)	r_r (fm)	a_r (fm)	W (MeV)	r_i (fm)	a_i (fm)	V_{so} (MeV)	r_{so} (fm)	a_{so} (fm)
t	151.7	1.24	0.685	18.7	1.432	0.87	6.0	1.10	0.83
α	186.4	1.396	0.562	26.45	1.396	0.562			

$$d\sigma/d\Omega = N \frac{C^2 S}{2J+1} \sigma_{DW}, \quad (1)$$

where σ_{DW} is the DW calculated cross section, J is the spin of the transferred proton, and N is a normalization constant. The value of N is quite dependent on the choice of optical model parameters and varies between 10 and 50, with $N=23$ being the value prevalently used. To help determine N here, results of the $(\vec{t}, \alpha)$ reaction on ^{96}Mo (Ref. 11) and ^{96}Zr targets were compared with $(d, {}^3\text{He})$ data on the same nuclei.[17] A sum rule was also used, with Mo containing 14 particles outside of the closed $Z=28$ shell and Zr with 12 particles outside of the closed shell. A value of $N=11.6$ gave the best comparison to the $(d, {}^3\text{He})$ data and yielded 15.4 particles for ^{98}Mo and 11.5 for ^{96}Zr, close to the proper values. Although this normalization factor is rather low compared to the previously used values, it was, nevertheless, adopted here. The principal interest in the present study was to establish the systematics in this region, and therefore the absolute spectroscopic strengths were not critical. DW calculations were performed at 1 MeV intervals to correct for a strong observed Q-value effect in the magnitude of $d\sigma/d\Omega$. The resulting DW calculations are compared below with experimental values of both $d\sigma/d\Omega$ and A_y.

IV. RESULTS

Spectra of the $^{110}\text{Pd}(\vec{t}, \alpha)^{109}\text{Rh}$ and $^{104}\text{Ru}(\vec{t}, \alpha)^{103}\text{Tc}$ reactions are shown in Figs. 1 and 2, respectively. The experimental resolutions are 20 keV FWHM for the ^{109}Rh case and 15 keV FWHM for the ^{103}Tc case, the former being affected by the target thickness. (The ^{103}Tc data required better energy resolution because of the complex structure located in the ground state region.) The two spectra show marked contrast in the ground state region. At low excitation in ^{109}Rh the spectrum consists of well separated levels, all of comparable strength. In ^{103}Tc, on the other hand, the first five levels are bunched together, with the ground and first excited states only weakly excited. This is discussed in more detail below.

Angular distributions of cross sections and an-

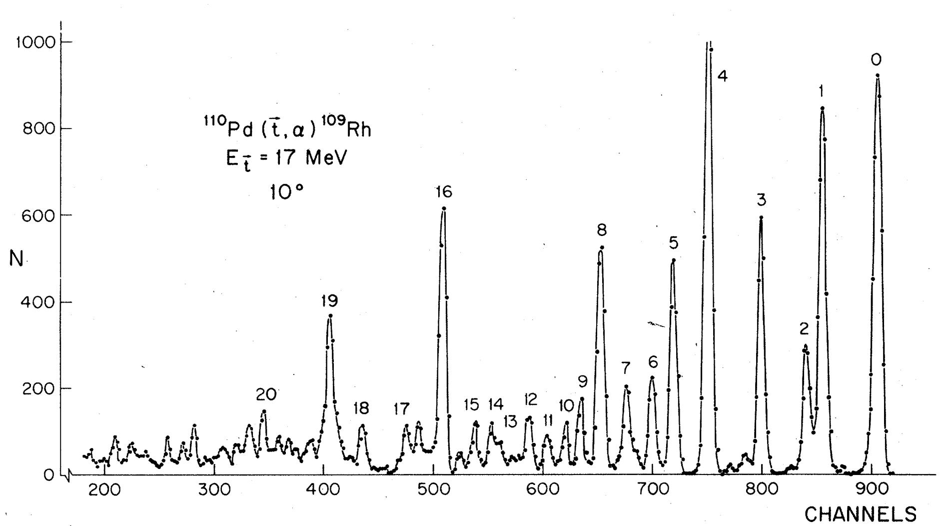

FIG. 1. Spin up spectrum of the $^{110}\text{Pd}(\vec{t}, \alpha)^{109}\text{Rh}$ reaction at 10°.

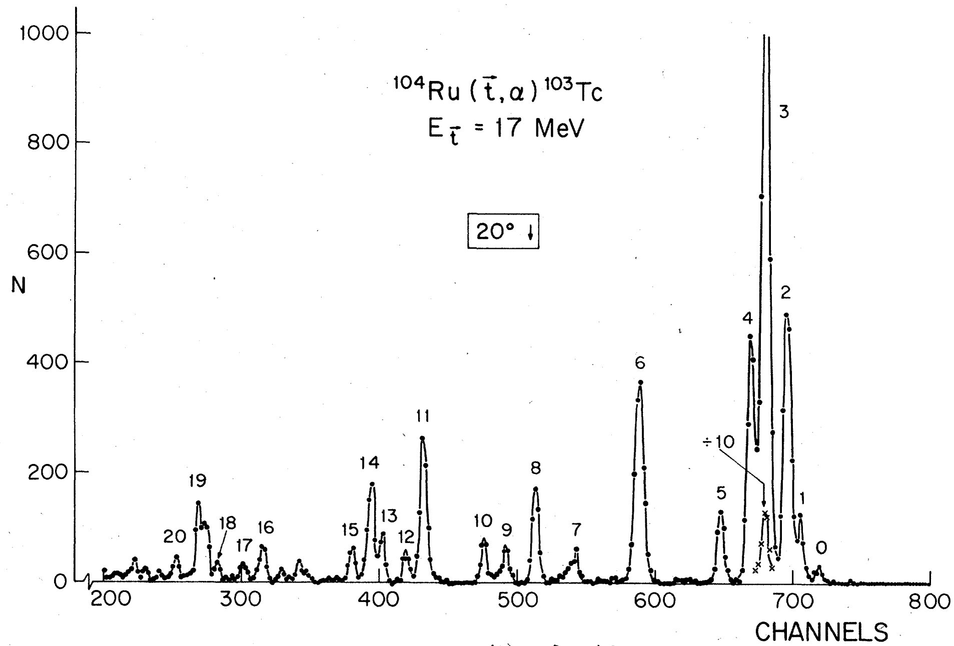

FIG. 2. Spin down spectrum of the ^{104}Ru$(\vec{t}, \alpha)^{103}$Tc reaction at 20°.

alyzing powers are shown in Fig. 3 for ^{109}Rh and in Fig. 4 for ^{103}Tc. These angular distributions are from 10° to 45° in 5° steps in the case of ^{109}Rh, but start at 15° for ^{103}Tc. All of the data were taken with the full Q3D solid angle, which gives an angular resolution of ±3° in the scattering plane. This angular resolution causes some averaging out of the structure, especially for A_y. Only levels which received significant population are shown.

The results are given in Tables II and III for the two nuclei discussed here. Listed are the excitation energies, L and J^π values as determined by the comparison of $d\sigma/d\Omega$ and A_y to DW calculations, and spectroscopic values C^2S from Eq. (1). The states for which the cross section is small or for which C^2S is small may well be populated in this reaction by a more complicated reaction process than the single one-step proton pickup assumed. Thus, assignments to such states are indicated as tentative in Tables II and III.

All of the results shown in Tables II and III are new. No excited states or spins were previously known for these nuclei. The value of the $(\vec{t}, \alpha)$ reaction is evident, given the large amount of new information obtained from the present study.

The measured ground state mass excess for ^{109}Rh is $\Delta\mu = -84\,805 \pm 40$ keV, with 20 keV of this error arising from the mass uncertainty of the target, ^{110}Pd. The systematic value quoted by Wapstra and Bos[18] is −85 110 keV. The observed value is thus 305 keV in disagreement with this number, a substantial deviation from the predicted value. Garvey *et al.*[19] predict $\Delta\mu = -85\,050$ keV, which is 250 keV different from the observed value. For ^{103}Tc, we observed $\Delta\mu = -84\,611 \pm 30$ keV, whereas Wapstra-Bos[18] give $-84\,910 \pm 100$ based on β-decay measurements. The discrepancy between our results and those reported is almost 300 keV, which is substantially greater than the quoted error. The relations of Garvey *et al.* give $\Delta\mu = -84\,670$, which is only 50 keV from the measured value for ^{103}Tc. A search was made for states with higher Q values than the level labeled "0" in Tables I and II, with negative results.

V. DISCUSSION

The A_y values observed in this experiment are quite structured and very J dependent. Values approaching −1.0 are predicted by DW calculations, but the large solid angle of the Q3D tends to wash out some of these large values. The ratios of $\frac{3}{2}^-$ to $\frac{1}{2}^-$ transfer confirm the simple $L/(L+1)$ relation suggested by Satchler.[20] Figures 3 and 4 indicate that the DW calculations satisfactorily predict the overall trend of the data both in $d\sigma/d\Omega$ and A_y, although seriously overpredicting the magnitude of A_y in a number of cases, such as for $\frac{5}{2}^-$, $\frac{5}{2}^+$, and $\frac{9}{2}^+$ transfer. The depth of the A_y minima for $\frac{3}{2}^-$ transfer also are not reproduced. The forward angle behavior of the various L transfers as observed in $d\sigma/d\Omega$ is accurately reproduced by the DW calculations. The observed angular distributions to the ground and 48 keV states in ^{103}Tc are not inconsistent with DW predictions

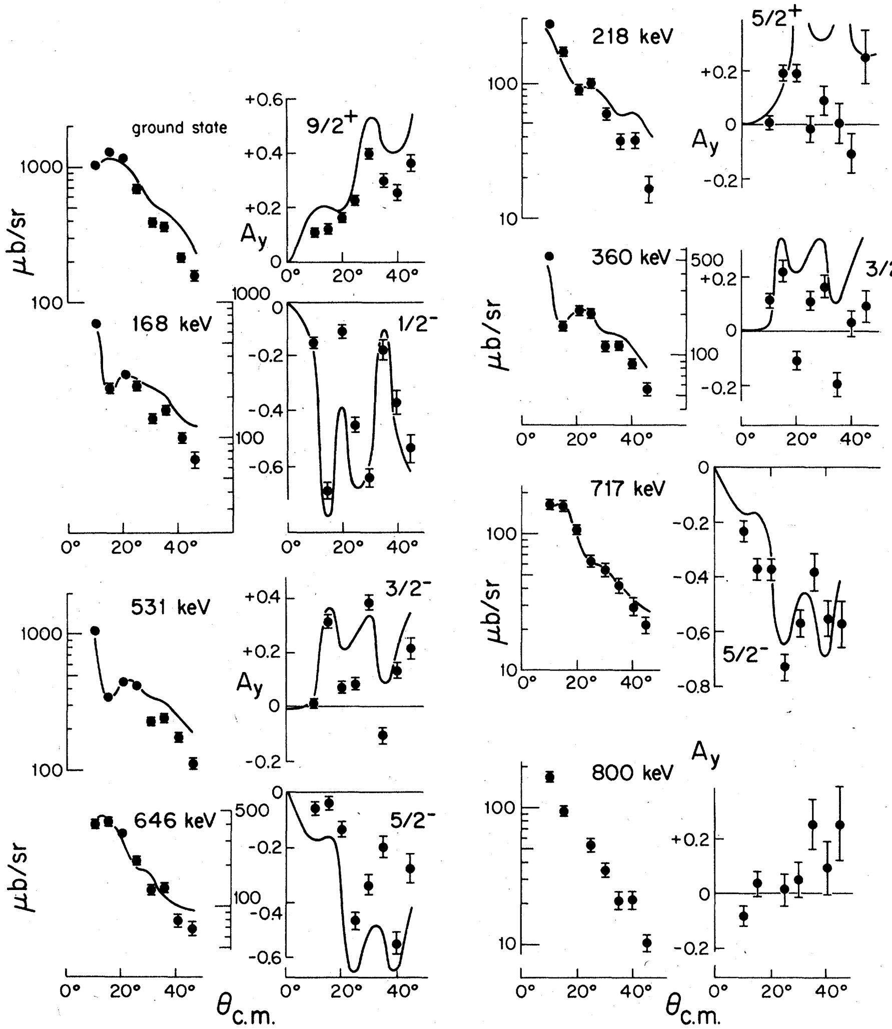

FIG. 3. Differential cross sections and analyzing powers for the ^{110}Pd($\vec{t}$, α) reaction. The solid lines are DW calculations.

of $\frac{5}{2}^+$ and $\frac{7}{2}^+$ transfer, respectively. Both of these configurations represent orbitals which have crossed the $Z=50$ shell gap. The observed A_y distributions are quite consistent with those to states with known J^π values in the Nb isotopes,[11] and thus an empirical basis for the spin assignments as well as the DW comparisons can be used.

The present results on ^{109}Rh and ^{103}Tc may be combined with other measurements of neutron rich nuclei in this region to establish the systematic behavior of proton hole states. Some (d, ^{3}He) results already exist on ^{96}Zr (Ref. 21) and ^{100}Mo (Ref. 17) as well as ($\vec{t}$, α) results.[11] In Fig. 5, we plot the dominant single particle fragment excitation energy versus the Z of the odd-proton final nucleus. The shell model suggests that the shell between $Z=28$ and 50 will be filled by the $p_{1/2}$, $g_{9/2}$, $p_{3/2}$, and $f_{5/2}$ orbitals. The $\frac{9}{2}^+$ orbital drops rapidly with Z, as would be expected for such a high degeneracy orbital since the pairing force is proportional to this degeneracy. The $\frac{1}{2}^-$ orbital rises as expected, since it is mostly filled, although a drop is seen in ^{109}Rh. The $\frac{3}{2}^-$ and $\frac{5}{2}^-$ orbitals should show slow trends with Z as these are filling more gradually. However, a substantial depression of these orbitals occurs in ^{103}Tc, where both drop below the $\frac{1}{2}^-$ state and the $\frac{3}{2}^-$ orbital lies even below the $\frac{9}{2}^+$ state. Surprisingly, two states with little proton hole strength drop below the principal proton hole states in ^{103}Tc, which is substantially different from the ^{99}Nb and ^{109}Rh situations.

In view of the unusual role of ^{103}Tc in the systematics of proton hole states versus Z, it is

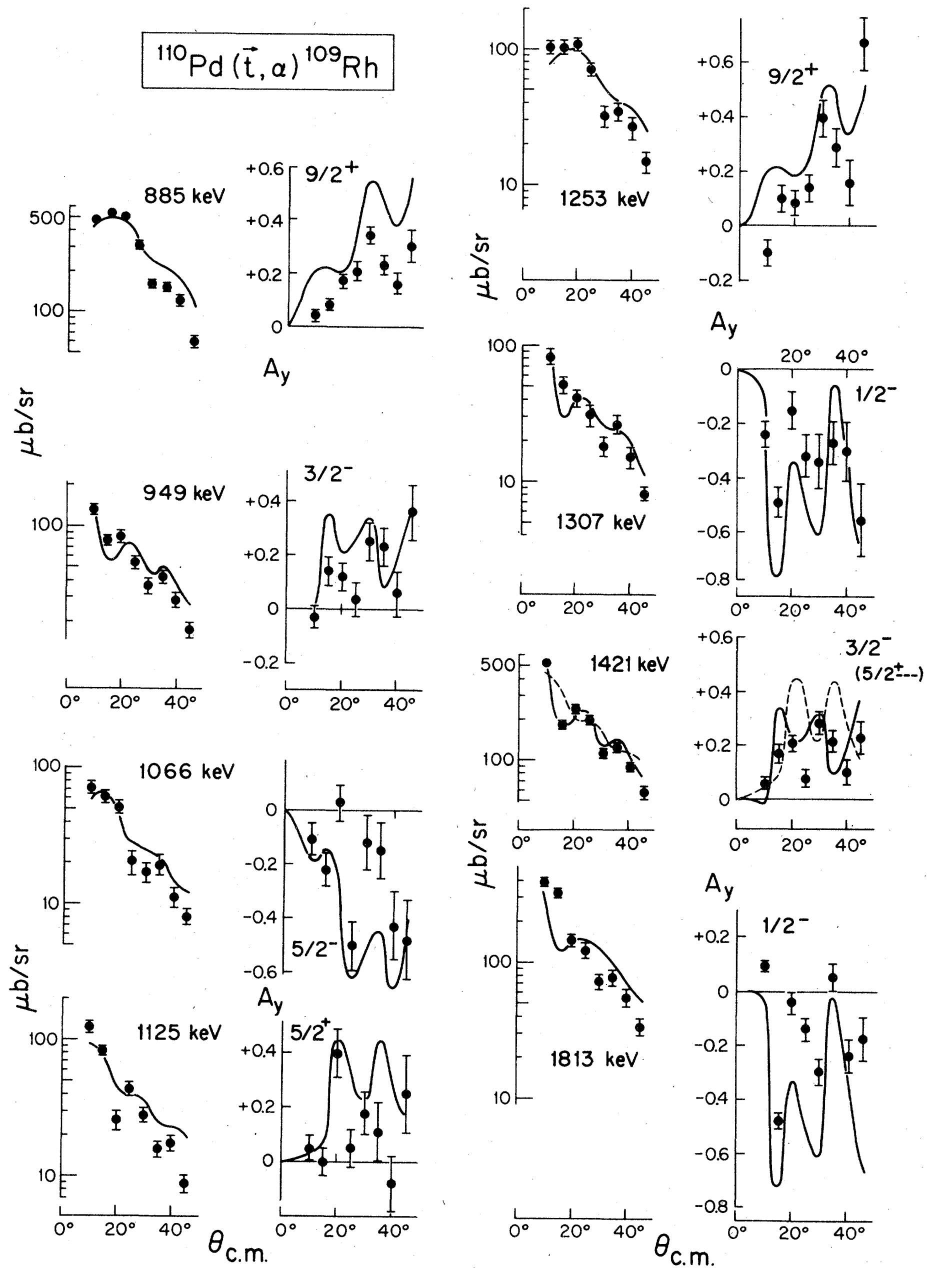

FIG. 3. *(Continued)*.

worth examining the systematics of the Tc isotopes themselves. This is done in Fig. 6, where the lowest states of each spin are plotted as a function of neutron number. Immediately obvious from this figure is the rapid compression of levels at low excitation energy as a function of increasing neutron number. Only the $\frac{1}{2}^-$ state shows a systematic trend towards increasing energy. The $\frac{9}{2}^+$ state is no longer the ground state in ^{103}Tc, with the descending $\frac{5}{2}^+$, $\frac{7}{2}^+$, and $\frac{3}{2}^-$ levels now lying below it. In general, there is a smooth trend throughout the Tc isotopes of all of the various spins. The resulting level scheme of ^{103}Tc is suggestive of a rotational nucleus with a $\frac{5}{2}^+$-$\frac{7}{2}^+$-$\frac{9}{2}^+$ sequence as well as a $\frac{3}{2}^-$-$\frac{5}{2}^-$ sequence forming. Such bands are possible in this region if deformation occurs. If one assumes a deformation parameter ϵ of about 0.3, then Nilsson orbitals of $\frac{5}{2}^+[422]$

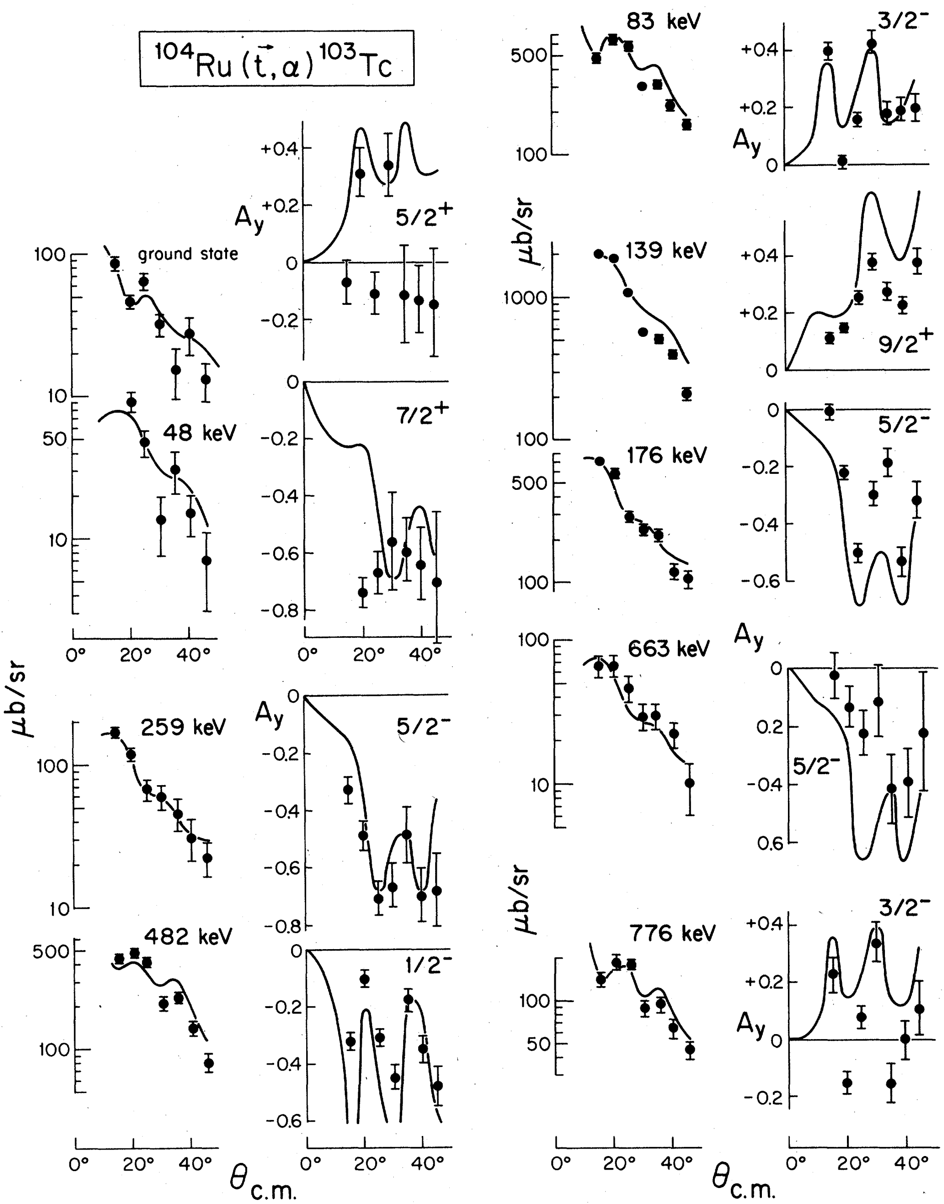

FIG. 4. Differential cross sections and analyzing powers for the ^{104}Ru$(\vec{t}, \alpha)$ reaction. The solid lines are DW calculations.

arising from the $g_{9/2}$ orbital and $\frac{3}{2}^-[302]$ arising from the $p_{3/2}$ orbital may be expected. In the study of ^{104}Mo, a deformation of 0.32 has been suggested,[7] which could produce the level scheme of ^{103}Tc observed here. However, the rotational energy parameter given by the even parity sequence is not consistent with either the negative parity band energy parameter or those of the ^{102}Mo or ^{104}Ru cores.

Many of the low lying levels of these odd proton nuclei may be interpreted as particle-vibration multiplets based on coupling of the odd proton to the even-even core. In particular, coupling an odd particle to the 2^+ state of the even core gives rise to a low-lying multiplet because of the strong collectivity in this region. A systematic study of such couplings has been done using the (t, p) reaction on odd-A targets in this region.[22] It was seen that levels in ^{105}Rh fit such a multiplet scheme to some degree, with the lowest $\frac{3}{2}^-$ and $\frac{5}{2}^-$ states identified as members of the $[2^+ \otimes \frac{1}{2}^-]_{3/2^-, 5/2^-}$ multiplet. The centroid of these multiplets has al-

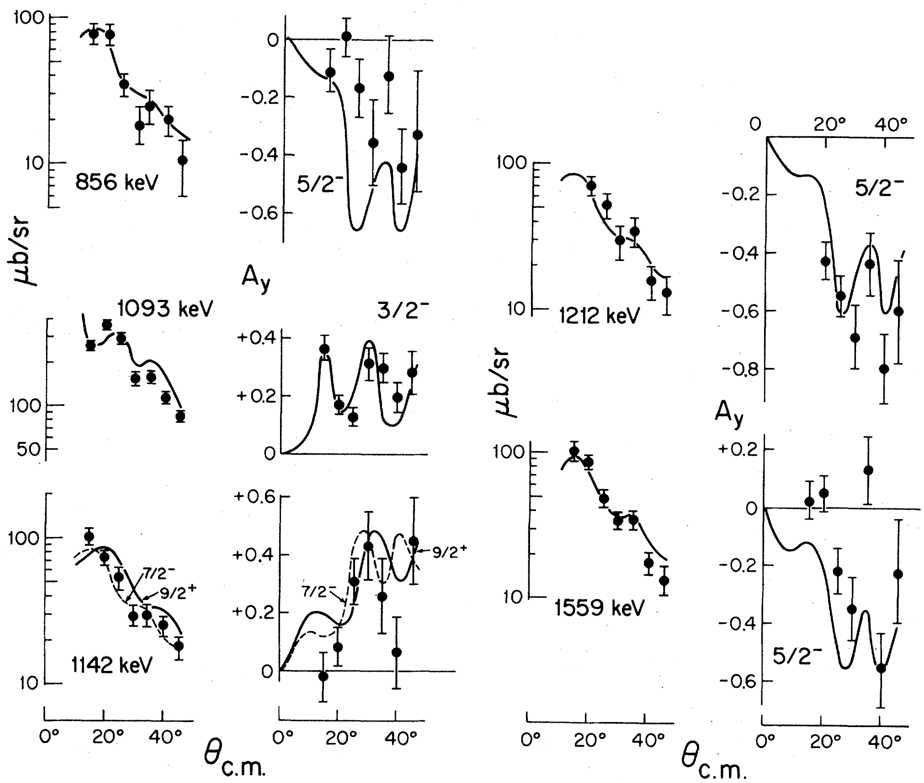

FIG. 4. *(Continued)*.

ways been observed to be depressed in energy relative to the core 2^+ energy. However, it has also been noticed that strong admixtures between single particle states and these multiplets occur. Strong mixing of the $\frac{3}{2}^-$ member of the multiplet in ^{105}Rh was noticed in a ^{104}Ru(^{3}He, *d*) study,[23] while only weak $\frac{5}{2}^-$ single particle admixtures were observed. In the present case, for ^{109}Rh, the Pd 2^+ core state lies at ~430 keV, which would suggest $\frac{3}{2}^-$ and $\frac{5}{2}^-$ levels near this energy. Indeed, a weakly populated $\frac{3}{2}^-$ state is seen at 360 keV, but no $\frac{5}{2}^-$ state is seen. The splitting of the multiplet in the

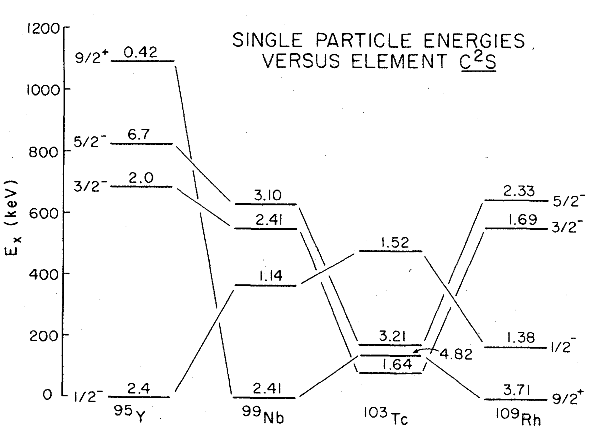

FIG. 5. Excitation energies of the strongest single-particle states observed in the (t, α) reaction as a function of Z. The numbers above the lines are the spectroscopic factors obtained in the present measurements.

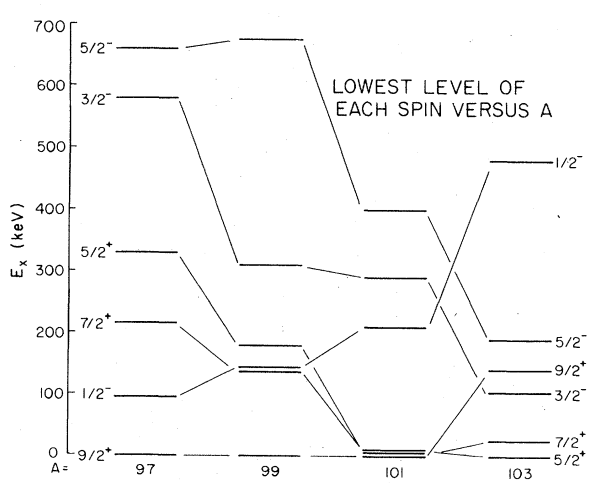

FIG. 6. Excitation energies of low-lying states in the Tc isotopes as a function of neutron number. The data are from Ref. 24. Each line represents the lowest level of each spin versus A.

TABLE II. Spectroscopic information from the $^{110}Pd(\vec{t},\alpha)^{109}Rh$ reaction measurement.

Level	E_x (keV)	L	J^π	C^2S[b]
0	0[a]	4	$\frac{9}{2}^+$	3.7
1	168 ± 3	1	$\frac{1}{2}^-$	1.4
2	218 ± 3	(2)	$(\frac{5}{2}^+)$	(0.21)
3	360 ± 3	(1)	$(\frac{3}{2}^-)$	(0.85)
4	531 ± 5	1	$\frac{3}{2}^-$	1.7
5	646 ± 5	3	$\frac{5}{2}^-$	2.3
6	717 ± 5	(3)	$(\frac{5}{2}^-)$	0.72
7	800 ± 5[c]			
8	885 ± 5	4	$\frac{9}{2}^+$	1.90
9	949 ± 5	(1)	$(\frac{3}{2}^-)$	0.19
10	1001 ± 7	(1)	$(\frac{3}{2}^-)$	0.10
11	1066 ± 10[c]	(3)	$(\frac{5}{2}^-)$	0.33
12	1125 ± 10[c]	(2)	$(\frac{5}{2}^+)$	0.11
13	1224 ± 10			
14	1253 ± 10	(4)	$(\frac{9}{2}^+)$	0.40
15	1307 ± 10	(1)	$(\frac{1}{2}^-)$	0.18
16	1421 ± 10	(2, 1)	$(\frac{5}{2}^+, \frac{3}{2}^-)$	0.44, 0.83
17	1540 ± 10			
18	1704 ± 10[c]			
19	1813 ± 10[c]	(1)	$(\frac{1}{2}^-)$	0.58
20	2055 ± 10			

[a] $Q = 8995 \pm 20$ keV gives an atomic mass excess of −84 805 ± 40 keV. Systematics (Wapstra and Bos) gives −85 110 ± 100 keV (Ref. 18).
[b] From $d\sigma/d\Omega = 11.6(2J+1)^{-1}(C^2S)\sigma_{DW}$.
[c] Group is broad and probably contains unresolved states.

TABLE III. Spectroscopic information from the $^{104}Ru(\vec{t},\alpha)^{103}Tc$ reaction measurement.

Group	E_x (keV)	L	J^π	C^2S[b]
0	0[a]	(2)	$(\frac{5}{2}^+)$	(0.11)
1	48 ± 3	(4)	$(\frac{7}{2}^+)$	(0.52)
2	83 ± 3	1	$\frac{3}{2}^-$	1.6
3	139 ± 3	4	$\frac{9}{2}^+$	4.8
4	176 ± 3	3	$\frac{5}{2}^-$	3.2
5	259 ± 3	(3)	$(\frac{5}{2}^-)$	0.73
6	482 ± 5	1	$\frac{1}{2}^-$	1.5
7	663 ± 5[c]	(3)	$(\frac{5}{2}^-)$	0.34
				0.47
8	776 ± 5	(1)	$(\frac{3}{2}^-)$	
9	856 ± 5[c]	(3)	$(\frac{5}{2}^-)$	0.40
10	922 ± 5			
11	1093 ± 5	1	$\frac{3}{2}^-$	0.68
12	1142 ± 5	(4)	$(\frac{9}{2}^+)$	0.22
13	1212 ± 5	(3)	$(\frac{5}{2}^-)$	0.39
14	1247 ± 5			
15	1299 ± 5			
16	1559 ± 10	(3)	$(\frac{5}{2}^-)$	0.48
17	1620 ± 10[c]			
18	1692 ± 10			
19	1745 ± 10[c]			
20	1820 ± 10			

[a] $Q = 9048 \pm 30$ keV gives an atomic mass excess of −84 622 ± 30 keV. Wapstra and Bos give −84 910 ± 100 keV (Ref. 18).
[b] From $d\sigma/d\Omega = 11.6(2J+1)^{-1}(C^2S)\sigma_{DW}$.
[c] Group is broad and probably contains unresolved states.

Ag isotopes is ~100 keV with the $\frac{3}{2}^-$ member lowest, so one would expect a $\frac{5}{2}^-$ state at about 460 keV in ^{109}Rh. It may be too weak to be observed in the present experiment. In the case of ^{103}Tc, it is much more difficult to determine the multiplet position because of the deviation of core 2^+ energies: 358 keV in ^{104}Ru and 296 keV in ^{102}Mo. The multiplet $[2^+ \otimes \frac{9}{2}^+]_{5/2^+ \to 13/2^+}$ is also expected in the low lying spectrum and is probably the principal origin of the low-lying $\frac{5}{2}^+$ and $\frac{7}{2}^+$ states seen in this region, with some mixing of single-particle configurations from above the $Z = 50$ shell gap occurring in order for the (t,α) reaction to populate these states. Such states would be populated[25] by a multistep process with a cross section of the order of 100 μb/sr. Thus, some of the states observed in this study could have no one-step reaction strength at all. However, in most cases the data representations achieved suggest that the one-step mechanism assumed does dominate.

VI. SUMMARY AND CONCLUSIONS

The $(\vec{t},\alpha)$ reaction has proven to be an ideal tool for the study of the neutron rich odd-proton nuclei ^{103}Tc and ^{109}Rh. Their masses and a large number of spin assignments are now determined.

Examination of the systematics of proton hole states in these two nuclei and a comparison with adjacent elements and isotopes indicate that ^{103}Tc may be deformed and belong to a rather sharp deformation region which exists near $A=100$. The existence of this deformation region is known from fission fragment decay studies and (t,p) reaction studies. The region is known to have a very abrupt transition with only a few nucleons making a difference between spherical and deformed character. This illustrates an important interplay between collective pairing forces and single-particle forces, where in a very localized nuclear region, the dominance of one degree of freedom over the other changes back and forth. Application of models such as the interacting boson fermion approximation (IBFA)[26] may be difficult in this region because of such effects. The importance that a neutron-proton interaction may have in the structure of this region has been considered.[1] In addition, the interacting boson approximation (IBA) formalism that couples an odd particle to an IBA-2 core,[27] in which the differences between neutron and proton degrees of freedom are treated explicitly, may also lead to an understanding of the complex behavior of the nuclei near $A=100$. This particular nuclear region remains a serious challenge to existing nuclear theories.

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