# Low-lying states in $^{96}$Nb from the $(t,\alpha)$ reaction

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(Received 19 October 1983)

The nuclear structure of $^{96}$Nb has been studied with the $(t,\alpha)$ reaction at 17 MeV on an isotopically enriched target of $^{97}$Mo using a quadrupole-three-dipole spectrometer. Measured angular distributions were compared with distorted-wave Born approximation calculations to assign $l$ transfer values. The results are combined with published data and shell model considerations to reassign the $3^-$ state of the low-lying $\pi(p\frac{1}{2})^1\nu(d\frac{5}{2})^{-1}$ configuration and to confirm the assignments of the spins and parities of the other levels observed.

[NUCLEAR REACTIONS $^{97}$Mo$(t,\alpha)^{96}$Nb, $E_t=17$ MeV, enriched target; measured $E_\alpha$, $\sigma(\theta)$. DWBA analysis. $^{96}$Nb deduced levels, $J^\pi$. Compared $^{96}$Nb and $^{92}$Nb using Pandya relation.]

The odd-odd $^{96}$Nb nucleus has been the subject of several investigations.[1-7] The data of these investigations have been successfully interpreted in terms of the $j$-$j$ coupling of the nuclear shell model. In the shell model, the lowest lying levels of $^{96}$Nb arise from the $\pi(g\frac{9}{2})^1\nu(d\frac{5}{2})^{-1}$ and $\pi(p\frac{1}{2})^1\nu(d\frac{5}{2})^{-1}$ configurations. These configurations give rise to states of spin and parity $2^+$, $3^+$, $4^+$, $5^+$, $6^+$, $7^+$, and $2^-$, $3^-$, respectively. The $^{97}$Mo$(t,\alpha)^{96}$Nb proton pickup reaction of the present study should strongly and selectively populate the states of these configurations.

The $^{97}$Mo$(t,\alpha)^{96}$Nb reaction was done with 17 MeV tritons from the tandem Van de Graaff accelerator at Los Alamos National Laboratory (LANL). The target was prepared at the Florida State University by vacuum evaporation from 94.24% isotopically enriched $^{97}$Mo obtained as the oxide from Oak Ridge National Laboratory. A thickness of 86 $\mu$g/cm$^2$ molybdenum on a 50 $\mu$g/cm$^2$ carbon foil was obtained. The alpha particles were momentum analyzed in the LANL quadrupole-three-dipole spectrometer[8] and detected with a 1 m helical wire proportional counter mounted in the focal plane of the spectrometer. Alpha particle spectra were recorded in 1024 energy channels at spectrograph angles of 10°, 12°, 15°, 20°, 22°, 25°, 28°, 34°, 40°, 45°, 50°, and 55° relative to the beam. A representative spectrum is shown in Fig. 1. The resolution is approximately 18 keV full width at half maximum.

Peak areas and centroids were determined by a least-squares method which fits Gaussian line shapes to the peaks. To determine excitation energies, the alpha particle spectra were calibrated with the known energies from the $^{92}$Zr$(t,\alpha)^{91}$Y reaction.[9] The excitation energies of the states in $^{96}$Nb found in this experiment are shown in Table I along with the results of previous studies. The energies determined in this experiment are in reasonable agreement with the results in other reports.

The elastic-scattered triton yield was measured with a solid state detector in the scattering chamber at 30° relative to the triton beam. The absolute differential cross sections were calculated by normalizing the yield for each peak in

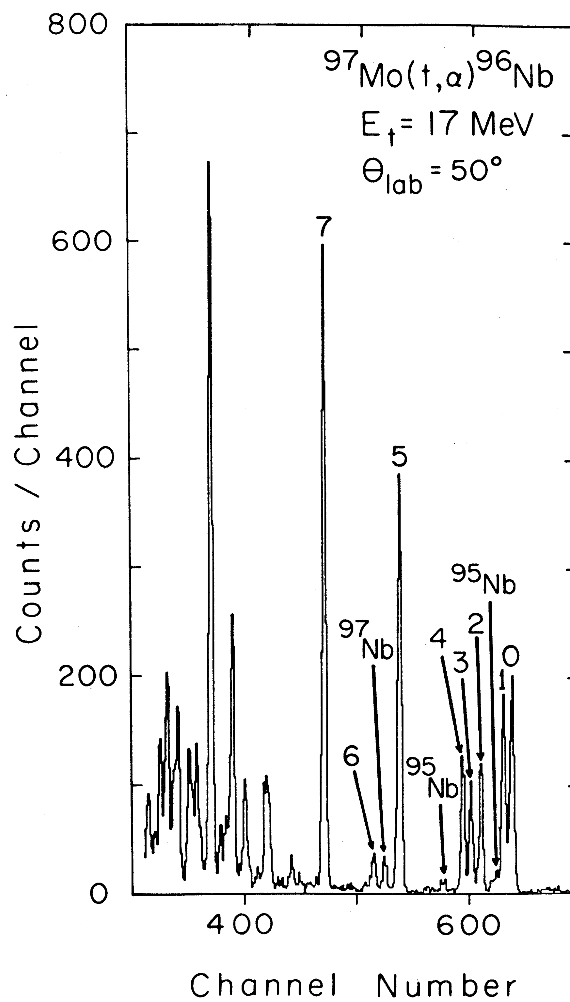


FIG. 1. Alpha particle spectrum of the $^{97}$Mo$(t,\alpha)^{96}$Nb reaction at a laboratory angle of 50° and a beam energy of 17 MeV.



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TABLE I. Excitation energies of states in $^{96}$Nb from the $^{97}$Mo(t, $\alpha$)$^{96}$Nb reaction and from previous reports together with absolute differential cross sections from the (t, $\alpha$) reaction at 17 MeV and 50°. Also listed are the spins and parities ($J^{\pi}$) assigned to these states. Peak numbers correspond to the labeled peaks in the spectrum in Fig. 1.

| | Present experiment | | Earlier measurements[a] | |
|---|---|---|---|---|
| Peak number | $E_x$[b] (keV) | $\left(\frac{d\sigma}{d\Omega}\right)_{50°}$ ($\mu$b/sr) | $E_x$ (keV) | $J^{\pi}$ |
| 0 | 0 | 102 | 0 | $6^+$ |
| 1 | 40 | 92 | 43 | $5^+$ |
| 2 | 147 | 56 | 142 | $4^+$ |
| 3 | 192 | 44 | 180 | $3^+$ |
| 4 | 230 | 62 | 233 ±5 | $7^+$ |
| 5 | 521 | 177 | 506 | $2^-$ |
| 6 | 644 | 18 | 630 | $2^+$ |
| | | | 687 | $3^-$ |
| 7 | 876 | 258 | 865 ±5 | $3^-$ [c] |

[a]Level energies and spin assignments are taken from Refs. 4 and 6. Where no error is given the energy is derived from gamma rays with errors of ±1 keV.
[b]The error is ±8 keV.
[c]Assignment made in this work.

the alpha spectra to the elastic-scattered triton yield and are shown for 50° in Table I. The computer code DWUCK was used to calculate the theoretical angular distributions.[10] Optical model parameters used in the calculations are listed in Table II.

Figure 2 shows the angular distributions for states populated in the $^{97}$Mo(t, $\alpha$)$^{96}$Nb reaction which have been assigned by Comfort, Maher, Morrison, and Schiffer[4] as the six members of the $\pi(g\frac{9}{2})^1\nu(d\frac{5}{2})^{-1}$ multiplet. The solid curves in Fig. 2 are the results of distorted-wave Born approximation (DWBA) calculations. The absolute value of the DWBA results has been normalized to fit the experimental cross sections. Each of these six states exhibits an $l=4$ angular distribution in the (t, $\alpha$) reaction. This result is consistent with proton pickup from the $\pi g\frac{9}{2}$ shell model orbital and supports the work of Comfort *et al.*

TABLE II. Optical model parameters used in the DWBA calculations for the $^{97}$Mo(t, $\alpha$)$^{96}$Nb reaction.

| | $\alpha$[a] | t[b] | p[c] |
|---|---|---|---|
| $V_R$ (MeV) | 187.3 | 154.0 | d |
| $r_R$ (fm) | 1.444 | 1.24 | 1.25 |
| $a_R$ (fm) | 0.523 | 0.672 | 0.65 |
| $W_I$ (MeV) | 22.3 | 18.62 | · · · |
| $r_I$ (fm) | 1.444 | 1.39 | · · · |
| $a_I$ (fm) | 0.523 | 0.99 | · · · |
| $r_C$ (fm) | 1.30 | 1.25 | 1.25 |
| $\lambda$ | · · · | · · · | 25.0 |

[a]Reference 11.
[b]Reference 12.
[c]Reference 13.
[d]Adjusted to reproduce the proton separation energy.

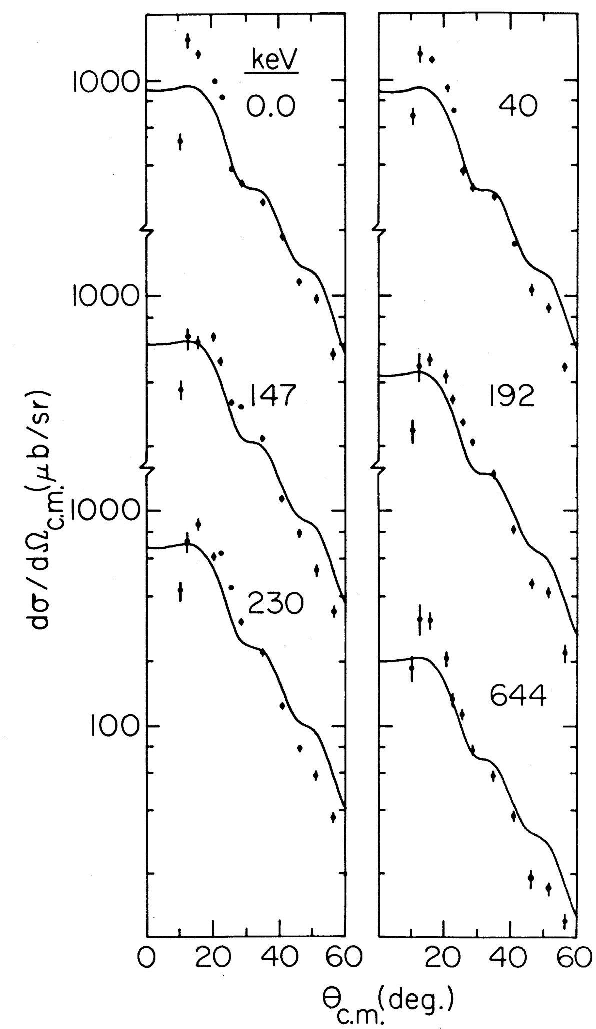


FIG. 2. Angular distributions of alphas from low-lying states observed in the $^{97}$Mo(t, $\alpha$)$^{96}$Nb reaction having $l=4$. Solid curves are the results of DWBA calculations.

The $2^-$ and $3^-$ states of the $\pi(p\frac{1}{2})^1\nu(d\frac{5}{2})^{-1}$ configuration have been previously assigned energies of 506 and 687 keV, respectively, as shown in Table I.[6] The 506 keV level is observed in the $(t,\alpha)$ reaction. There is, however, no evidence of any state at 687 keV in the proton pickup data of the present measurements. Since the $(t,\alpha)$ reaction should strongly populate both states of the $\pi(p\frac{1}{2})^1\nu(d\frac{5}{2})^{-1}$ configuration, the 687 keV level observed in other experiments is probably not the $3^-$ member of this doublet.

Two low-lying states having $l=1$ angular distributions were observed in the $(t,\alpha)$ reaction. Figure 3 shows these angular distributions along with the results of DWBA calculations. As in Fig. 2, the theoretical curves have been normalized to the experimental results. The ratio of the cross sections of the 876 to the 521 keV level, averaged over all 12 angles at which the reaction was run, is 1.35. This is very close to $2J+1$ weighted average $(\frac{7}{5})$ for the ratio expected from simple shell model considerations if the 876 and 521 keV levels are the $3^-$ and $2^-$ states of the $\pi(p\frac{1}{2})^1\nu(d\frac{5}{2})^{-1}$ configuration. The $l=1$ angular distributions are consistent with proton pickup from the $\pi p\frac{1}{2}$ shell model orbital.

Arvay and co-workers[7] have reported a gamma transition of 356 keV in the $^{96}$Zr(P,n$\gamma$e$^-$)$^{96}$Nb reaction which has $M1$ multipolarity determined from the measured internal conversion coefficient. They made no assignment of this gamma transition to the $^{96}$Nb level scheme. This $M1$ gamma transition can be assigned to a transition from a $3^-$ state at 876 keV to a $2^-$ state at 521 keV.

The energy separation between the $3^-$ and $2^-$ members of the $\pi(p\frac{1}{2})^1\nu(d\frac{5}{2})^1$ particle-particle doublet in $^{92}$Nb is 165 keV. This splittng is considerably less than the 355 keV separation observed in the present measurement for the conjugate particle-hole doublet in $^{96}$Nb.

The Pandya[14] relationship predicts that for a doublet the energy separations for particle-particle and particle-hole configurations should be identical. However, it should be noted that the true configurations $\pi(p\frac{1}{2})^1(g\frac{9}{2})^2\nu(d\frac{5}{2})^1$ and $\pi(p\frac{1}{2})^1(g\frac{9}{2})^2\nu(d\frac{5}{2})^{-1}$ are three particle-particle and three particle-hole configurations for $^{92}$Nb and $^{96}$Nb, respectively. Perhaps the existence of the more complex four-quasi particle configurations is related to the considerable difference in doublet energy separations in $^{92}$Nb and $^{96}$Nb. As previously noted[4] the Pandya relationship for the $\pi(g\frac{9}{2})^1\nu(d\frac{5}{2})^1$ and $\pi(g\frac{9}{2})^1\nu(d\frac{5}{2})^{-1}$ configurations in $^{92}$Nb and $^{96}$Nb describes the experimental situation quite successfully. In this case, however, the more simple particle-particle and particle-hole descriptions are appropriate. In order to test the Pandya relationship for the $\pi(p\frac{1}{2})^1\nu(d\frac{5}{2})^1$ and $\pi(p\frac{1}{2})^1\nu(d\frac{5}{2})^{-1}$ configuration the appropriate nuclei would be $^{90}$Y and $^{94}$Y.

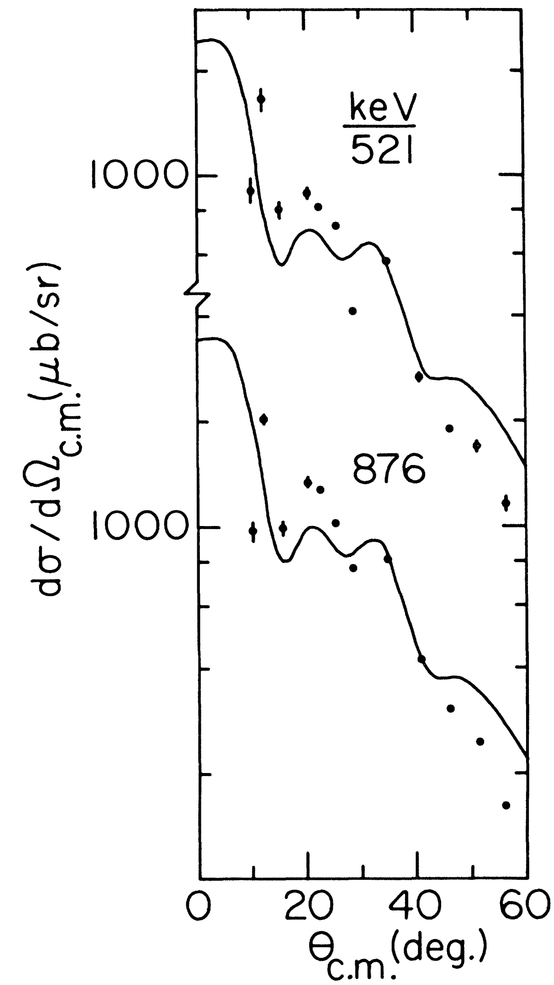


FIG. 3. Angular distributions of alphas observed in the $^{97}$Mo(t,$\alpha$)$^{96}$Nb reaction having $l=1$. Solid curves are the results of DWBA calculations.

The authors gratefully acknowledge the target preparation done by Mr. Robert Leonard and the assistance of the staff of the LANL tandem Van de Graaff facility in conducting the experiment. We also thank Mr. Harry E. Martz for his help in the data collections. This work was supported by the National Science Foundation under Contract No. PHY 82-05952.

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