Spins of the 1628-, 2441-, and 2755-keV levels in ^{96}Mo determined from gamma-gamma directional and polarization directional correlations*

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γ-γ directional correlation and polarization directional correlation experiments were performed on three cascades in ^{96}Mo populated from ^{96}Tc (4.3 day). Ge(Li) detectors were used in both spectrometers. Combination of the results give unique spin-4^+ assignment to the 1628-keV level and spin-6^+ assignments to both the 2441- and 2755-keV levels in ^{96}Mo.

[RADIOACTIVITY ^{96}Tc [from ^{93}Nb(α,n)]; measured $\gamma\gamma(\theta)$ and $\gamma\gamma$(90°LP) (linear polarization correlation). ^{96}Mo deduced I. Ge(Li) detectors.]

I. INTRODUCTION

Numerous investigations of the electron-capture decay of ^{96}Tc^g to ^{96}Mo have led to the proposed decay scheme shown in Fig. 1.[1] Conflicting results for the spins of the 2441- and 2755-keV levels have been reported in the literature. In earlier reports spins of 2^+ or 3^+ [2] and 5^+ or 6^+ [3] have been assigned to the 2441-keV level, while more recently, electron and γ-ray studies seem to favor a spin assignment of 6^+.[4-8] The same situation occurs with the 2755-keV level for which spin assignments of 5^+[2-4] and 6^+[1,3,5-8] have been reported. No direct evidence has supported the above assignments since angular-correlation measurements[1,2] and conversion-coefficient data[4,6] cannot exclude spin 5^+ for these two levels. A similar situation exists for the 1628-keV level for which spin-parity of 4^+ was proposed on the basis of the systematics of "vibrational" nuclei and feeding and decay characteristics of this level.[7] Here again, the definite spin assignment cannot be made on the basis of available directional correlation[9] and conversion-coefficient data.[4,6]

In a recent in-beam study by Lederer, Jaklevic, and Hollander,[10] levels in ^{96}Mo were populated by the (α, $2n$) reaction. Their A_2(813) angular-distribution coefficient supports the 6^+ assignment to the 2441-keV state. However, due to the fact that the large error limits do not allow the sign of the A_4(813) coefficient to be established, this spin assignment cannot be considered definite. Also the small measured value for A_2(1127) and the large errors quoted for A_4(1127) give no support for their 6^+ assignment to the 2755-keV level.

Definite spin assignments to the 2441- and 2755-keV levels are important for understanding the quasirotational band structure[11] in "spherical" ^{96}Mo. If spin 6^+ could definitely be assigned to both levels, the results reported in Ref.[10] would indicate a band splitting at the 1628-keV (4^+) state. Also a relatively rapid change of the moment of inertia, reflected by the low energy of the $8^+ \rightarrow 6^+$ transition, would be indicated.

The spin-parity assignment of 6^+ for both the 2441- and the 2755-keV levels has been discussed by Barette *et al.*[1] on the basis of a series of arguments related to population and decay properties of these levels. These authors argue that the direct feeding of both levels from the 7^+ ground state of ^{96}Tc makes 5^+ assignments very unlikely. However, the 7^+ spin-parity for the ground state of ^{96}Tc was, in turn, based on the 4^+ assignment to ^{96}Tc^m, assuming the $M3$ character of the 34-keV isomeric transition. This last 4^+ spin-parity for ^{96}Tc^m was proposed[1] when the weak feeding from ^{96}Tc^m to the 5^+, 2438-keV state in ^{96}Mo was observed. The 5^+ assignment to the 2438-keV level, however, was again proposed as the most probable one only.[7] Even though all the arguments are very plausible the whole chain of reasoning is somewhat too long and relates one spin assignment to the other rather than establishes them definitely.

In order to close this chain of arguments, we have performed γ-γ directional and polarization directional correlation measurements for three cascades populated in the decay of ^{96}Tc (4.3 day). The aim of this experiment was to establish unique spin and parity assignments for the 1628-, 2441-, and 2755-keV levels in ^{96}Mo.

II. EXPERIMENTAL PROCEDURE

A. Source production

The ^{96}Tc activity was produced through the ^{93}Nb(α, n)^{96}Tc reaction using 18-MeV α particles from the Argonne National Laboratory cyclotron.

The measurements usually started about 2 days after irradiation and no $^{96}Tc^{m}$ activity was observed in the γ spectrum. The irradiated Nb foil (0.025 mm) was used without dissolving it, and no corrections for extranuclear perturbations were introduced. This procedure is justified by the short lifetimes of the excited states in ^{96}Mo. In addition, Nb metal has a body-centered-cubic structure.

For the directional correlation measurements the Nb foil was rolled and placed in a glass cylinder 2 mm in diameter by 5 mm in height. For the polarization directional correlation measurement, the active spot in the foil (~3-mm diam) was cut out of the foil and compressed to form a ball about 1.5 mm in diameter.

B. γ-γ directional correlations

The automated γ-$\gamma(\Theta)$ coincidence spectrometer was equipped with two true coaxial Ge(Li) detectors. The active volume and energy resolution [full width at half maximum (FWHM)] of these detectors were 25 cm^3 and 3.0 keV, and 23 cm^3 and 2.8 keV, respectively. The coincidence system of the spectrometer, which utilized a time-to-amplitude converter, had a resolving time (2τ) of about 20 nsec.

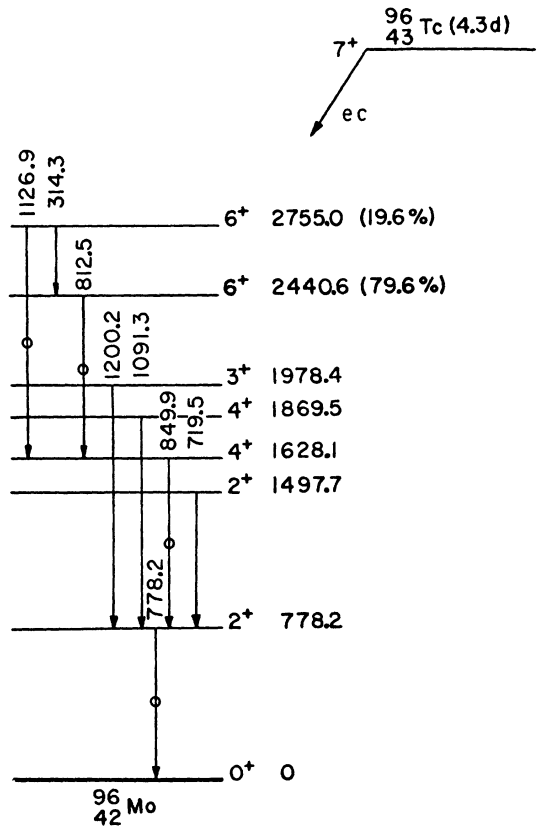

FIG. 1. Partial decay scheme of ^{96}Tc based on results reported by Barrette *et al.* (Ref. 1). Transitions involved in the present experiment are indicated by circles. Present spin assignments for the 2755-, 2441-, and 1628-keV levels are 6^+, 6^+, and 4^+ as indicated. The percentages quoted in parentheses give the relative population of the levels from the ^{96}Tc decay.

The coincidence counting rate was determined for seven different angles between the symmetry axes of the detectors. The coincidence counts were normalized, and then computer fitted to a directional correlation function of the form

$$W(\Theta) = 1 + Q_{22}B_2(1)A_2(2)P_2(\cos\Theta) + Q_{44}B_4(1)A_4(2)P_4(\cos\Theta) .$$

Numerals (1) and (2) represent the dependence on the properties of the first and the second transitions in a cascade, respectively. The finite solid-angle corrections $Q_{\lambda\lambda}$ were calculated using the method of Krane.[12] The corrections for Compton coincidence background resulting from γ rays higher in energy than those of interest were negligible and did not influence the final results.

C. Polarization directional correlations

For these measurements, the spectrometer was provided with a true coaxial Ge(Li) detector and a planar square Ge(Li) detector with dimensions 20×20×5 mm deep, which was used as a polarimeter.

The asymmetry ratio $\beta = N_\perp / N_\parallel$, where $N_\perp$ and $N_\parallel$ are the coincidence counting rates with the long axis of the detector perpendicular and parallel to the polarization plane, respectively, was measured. It can be shown that

$$\beta = \frac{1+PQ}{1-PQ} ,$$

where P is the polarization of the γ ray and Q is the efficiency of the polarimeter. The polarization P is defined in Ref. 13. Explicit expressions for the polarization directional correlation function are given by Davies and Hamilton.[14]

The efficiency of the polarimeter was determined experimentally using the known linear polarizations of γ rays emitted in well-studied γ-γ

TABLE I. Directional correlation coefficients as measured in the present experiment.

Cascades (keV)	$A_{22} \pm \Delta A_{22}$	$A_{44} \pm \Delta A_{44}$
850-778	0.109 ± 0.005	0.004 ± 0.010
813-850	0.100 ± 0.010	0.008 ± 0.013
1127-850	0.107 ± 0.010	0.003 ± 0.015

angular correlations. It was found that the polarimeter used has an efficiency $Q = 0.135 \pm 0.005$ for the energy region of interest. The results obtained with the polarimeter are not very sensitive to changes in the efficiency. A variation of 0.01 in Q would correspond to a change of only 10^{-4} in the calculated value of β.

III. RESULTS

A. Directional correlation measurements

In the present experiment the 1127-850-, 813-850-, and 850-778-keV cascades were measured. The results are presented in Table I. Multipole mixing ratios, $\delta = \langle L+1\rangle/\langle L\rangle$, were calculated from the corrected B_k and A_k coefficients. The phase convention adopted in defining the parameter δ is that of Krane and Steffen.[15] The δ values, as determined from the directional correlation experiment, are listed in column 3 of Table II.

As was mentioned previously, directional correlation and internal-conversion data are not sufficient to decide between 6^+ and 5^+ spin values for the 2441- and 2755-keV levels. Our results for the 813-850- and 1127-850-keV cascades are also consistent with both 6-4-2 and 5-4-2 spin sequences. The experimental values of the directional correlation coefficients are in good agreement with the recent results reported by Barrette *et al.*[1] The directional correlation result for the 850-778-keV cascade is in good agreement with both spin 3 and 4 for the 1628-keV level. The internal-conversion data for all three transitions (813, 850, and 1127 keV) are consistent with $E2$, $M1$, or $M1+E2$ multipolarities.[4,6]

B. Polarization correlation measurements

In order to resolve this spin assignment ambiguity, linear polarization directional correlation experiments were performed on the 1127-850-, 813-850-, and 850-778-keV cascades. All linear-polarization measurements were performed at $\Theta = 90°$, where Θ is the angle between the two γ rays. In all cases the first transition in the cascade was accepted in the polarization-sensitive detector. The experimental arrangement was similar to that described in Ref. 16. The measured asymmetries, β, are listed in Table II, together with the β values calculated for the various possible spins and mixing ratios determined by the directional correlation measurements.

IV. DISCUSSIONS AND CONCLUSIONS

For the 1628-keV level only the 4^+ spin-parity assignment is in agreement with the present results, as can be seen from Table II. The 5^- spin-parity for the 2755-keV level is in agreement with our directional correlation and polarization directional correlation results. However, the $E1+M2$ multipolarity for the 1127-keV transition as determined by our measurements assuming 5^- spin-parity for the 2755-keV state, $\delta(1127) = 0.29 \pm 0.03$, does not agree with the conversion coefficients, $\alpha_k(1127)$, as measured by Ageev *et al.*[4] and Antman *et al.*[6]

In Fig. 2 the calculated asymmetry ratio is shown as a function of δ for each of the possible spin sequences. The measured β value for the 1127-850-keV cascade is also indicated in Fig. 2. In addition, the values for the mixing ratios as obtained from the directional correlation experi-

TABLE II. Comparison between experimental results as obtained from directional correlation and polarization directional correlation experiments.

Cascades [a] (keV)	Spin sequence [b] $J^\pi_i - J^\pi_f$	$\delta = \frac{\langle L+1\rangle}{\langle L\rangle}$ [b]	Calculated β $\beta = N_\perp/N_\parallel$	Measured β
850P-778	4^+-2^+	≤ 0.02	1.046 ± 0.002	1.044 ± 0.007
	4^--2^+	≤ 0.02	0.954 ± 0.002	
	3^+-2^+	0.26 ± 0.01	0.940 ± 0.002	
	3^--2^+	0.26 ± 0.01	1.064 ± 0.003	
813P-850	6^+-4^+	≤ 0.02	1.046 ± 0.002	1.045 ± 0.007
	6^--4^+	≤ 0.02	0.956 ± 0.003	
	5^+-4^+	0.28 ± 0.02	0.944 ± 0.002	
	5^--4^+	0.28 ± 0.02	1.060 ± 0.003	
1127P-850	6^+-4^+	≤ 0.03	1.046 ± 0.002	1.048 ± 0.025
	6^--4^+	≤ 0.03	0.955 ± 0.003	
	5^+-4^+	0.29 ± 0.02	0.943 ± 0.002	
	5^--4^+	0.29 ± 0.02	1.061 ± 0.003	

[a] P denotes the γ ray for which the polarization was measured.
[b] Both spin sequences and mixing ratios refer to the first transition in the cascade.

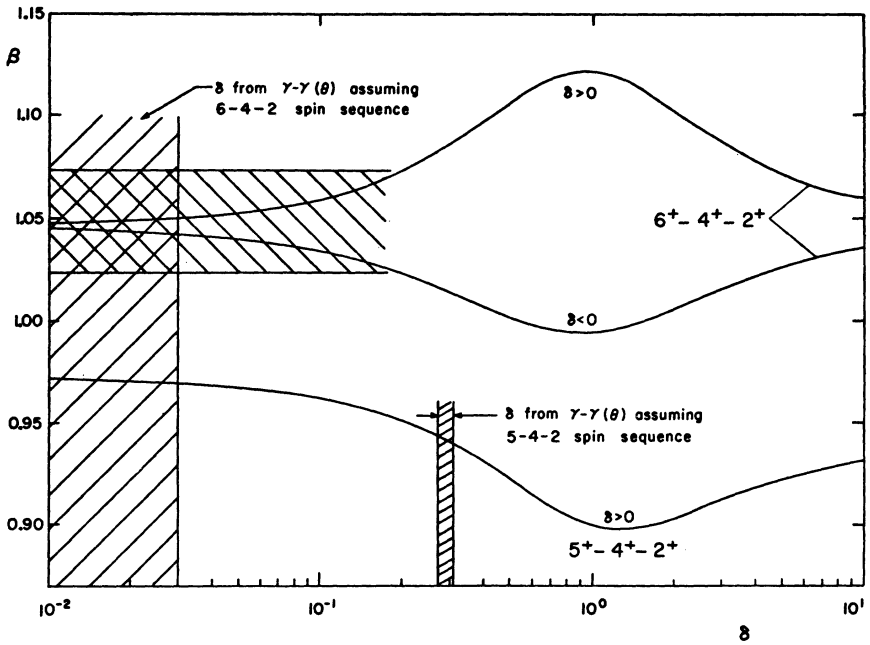

FIG. 2. Asymmetry parameter β plotted as a function of the mixing ratio δ for the spin sequences 6^+-4^+-2^+ and 5^+-4^+-2^+. Transition between 4^+ and 2^+ states is assumed to be of a pure $E2$ character. $\beta_{exp} = 1.048 \pm 0.025$, as measured for the 1127-850-keV cascade, is indicated in the figure. Hatched areas between vertical lines represent values of δ (1127) obtained from the directional correlation experiment.

ment (see Sec. III A and Table II) are indicated by hatched areas between vertical lines. As can be seen from the figure, there is agreement between the δ value measured in the polarization experiment and the value obtained from the directional correlation experiment only for the 6^+-4^+-2^+ spin sequence. Similar results are obtained for the 813-850-keV cascade where only 6^+ spin for the 2441-keV level is consistent with both experiments. These facts can also be concluded from inspection of the values quoted in Table II.

In conclusion, the combination of both the directional correlation measurements and the polarization directional correlation measurements gives a unique spin and parity assignment of 4^+ for the 1628-keV level and 6^+ for both the 2441- and the 2755-keV levels. These assignments are in agreement with the values proposed by Barrette *et al.*[1] and the tentative results of in-beam studies by Lederer, Jaklevic, and Hollander.[10] The shell-model calculation of the levels in ^{96}Mo were performed by Bhatt and Ball[17] and Vervier.[18] Neither calculation is in satisfactory agreement with the experimental level scheme of ^{96}Mo. Also, as discussed previously by Monaro, Barrette, and Boutard,[7] the collective-model predictions of Davydov and Chaban[19] do not agree with the experimental results.

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