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Nuclear orientation of ^{96}Tc

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The decay of ^{96}Tc^g has been studied using low-temperature nuclear orientation. Multipole mixing ratios have been deduced for several transitions in the daughter nucleus ^{96}Mo by measuring γ-ray anisotropies following the decay of the oriented ^{96}Tc nuclei. These new mixing ratios are compared with those determined from previous measurements in light of the possible presence of a low-energy 6^+ mixed-symmetry state in ^{96}Mo. [S0556-2813(99)00508-7]

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We have completed a study of the nuclear orientation of ^{96}Tc^g ($T_{1/2}=4.3\,\mathrm{d}$) for the purpose of measuring multipole mixing ratios for γ-ray transitions depopulating low-energy, low-spin states in the daughter nucleus ^{96}Mo. The low-energy structure of ^{96}Mo, in some ways, closely resembles a vibrational nucleus, which is represented by the U(5) symmetry limit in the interacting boson model (IBM). The low-energy structure of ^{96}Mo, therefore, may be an excellent test-bed for the study of mixed-symmetry states in a near-spherical system [1]. In the U(5)-limiting symmetry, the lowest-energy mixed-symmetry state should have $I^\pi=2^+$ at an energy of ≈ 2 MeV. Recently, Garrett *et al.* [2] have reported the observation of two excited 2^+ states at 2156 and 2231 keV in ^{112}Cd which deexcite by nearly pure $M1$ transitions to the 2_1^+ state. These states have been interpreted as the first firm evidence of mixed-symmetry states in a vibrational nucleus. Candidate mixed-symmetry states in ^{96}Mo include the 2_3^+ state at 1626 keV and the second excited 4^+ and 6^+ states, which lie at 1870 and 2755 keV, respectively [3]. The β decay parent ^{96}Tc^g has a ground state spin and parity of 7^+ and a Q_{β^+} value of 2.97 MeV, with most of the β decay strength feeding the $I=6$ states at 2441 and 2755 keV. The subsequent γ transitions populate a majority of the low-energy, low-spin states in ^{96}Mo, suggesting that from a study of the angular distribution of emitted γ rays from an oriented source of ^{96}Tc^g, one can extract mixing ratios for many transitions originating from low-spin states in ^{96}Mo. These mixing ratio values may be compared to the results of IBM-2 calculations, which consider directly nuclear states that have mixed proton-neutron symmetry.

^{96}Tc^g activity was diffused into a 99.9975% pure Fe foil at 850 °C for 24 h in a H_2 atmosphere. The ^{96}Tc^g*Fe* sample was then soldered, along with a ^{57}Co*Fe* nuclear orientation thermometer, to the end of a Cu cold finger. The cold finger was loaded into the ^{3}He/^{4}He dilution refrigerator, which was part of the UNISOR Nuclear Orientation Facility [4]. The detector arrangement consisted of five Ge detectors placed at 0°, 45°, 90°, 135°, and 180° relative to the direction of the applied magnetic field. γ-ray singles data were collected as separate warm ($T>1$ K) and cold ($T<7.5$ mK) cycles over a 66 h period. Data were divided into three independent warm/cold data sets, where the ratios $W(0°)/W(90°)$, $W(180°)/W(90°)$, $W(0°)/W(135°)$, $W(180°)/W(135°)$, $W(0°)/W(45°)$, and $W(180°)/W(45°)$ were determined for each peak of interest. Some difficulty was met in the treatment of the dead time and pileup corrections, where individual warm/cold data sets could not be normalized due to changes in the pileup parametrization as the source strength

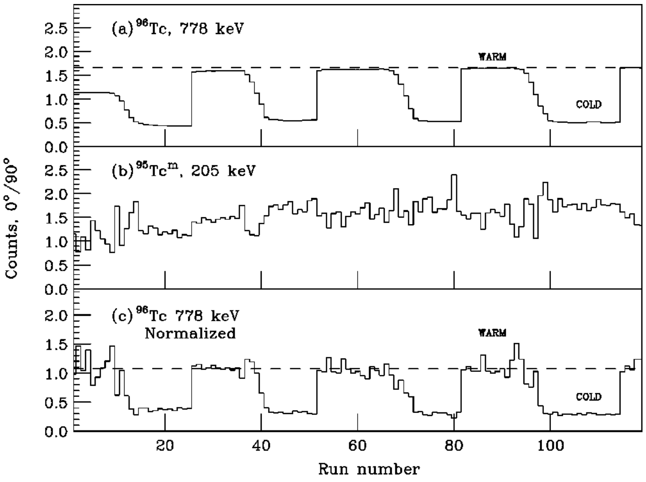

FIG. 1. The run history of the peak area ratio from the 0° and 90° detectors for the 778-keV transition in ^{96}Mo and 205-keV transition in ^{95}Mo corrected only for decay are shown in (a) and (b), respectively. Normalization of the 778-keV counting ratio with the 205-keV ratio, which exhibits no asymmetry since the parent state has $I=1/2$, produces warm and cold counting ratios for the 778-keV transition which are properly corrected for dead-time/pileup effects.

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TABLE I. Measured angular distribution parameters for selected transitions in ^{96}Mo.

E_γ	I_i	I_f	A_2[a]	A_4[a]	δ	δ[b]
778	2^+_1	0^+_1	$-0.54(1)$	$-1.10(7)$		
719	2^+_2	2^+_1	$-0.56(3)$	$+0.26(25)$	$+0.13(3)$	$+0.44^{+3}_{-4}$
					or $+1.6(1)$	
1498	2^+_2	0^+_1	$-0.39(2)$	$-0.37(15)$		
848	2^+_3	2^+_1				-1.05^{+9}_{-10}
850	4^+_1	2^+_1	$-0.40(1)$	$-0.32(1)$	$-0.05(4)$[c]	
1092	4^+_2	2^+_1	$-0.40(2)$	$-0.31(2)$	$-0.05(5)$[c]	$+0.02(2)$
1200	3^+_1	2^+_1	$-0.77(1)$	$+0.38(4)$	$+0.81(2)$	$+0.39^{+15}_{-11}$
					or $+2.12(8)$	$+1.6(3)$
481	3^+_1	2^+_2	$+0.02(2)$	$+0.52(5)$	$+0.18(2)$	$-0.4(1)$
					or $-15.5(20)$	
1441	4^+_3	2^+_1	$-0.37(3)$	$-0.32(4)$	$-0.08(7)$[c]	
722	4^+_3	2^+_2	$-0.42(3)$	$-0.27(9)$	$-0.03(3)$[c]	
569	5^+_1	4^+_2	$+0.598(5)$	$+0.066(26)$	$-0.183(3)$	$-0.21(2)$
					or $-2.84(3)$	
460	5^+_1	3^+_1	$-0.38(2)$	$-0.24(2)$	$-0.04(4)$	
812	6^+_1	4^+_1	$-0.362(6)$	$-0.22(1)$	$-0.036(8)$[c]	$-0.01(3)$
1127	6^+_2	4^+_1	$-0.361(6)$	$-0.22(1)$	$-0.037(5)$[c]	$-0.03(10)$
885	6^+_2	4^+_2	$-0.29(4)$	$-0.22(8)$	$-0.10(3)$[c]	
536	6^+_2	4^+_3	$-0.35(2)$	$-0.24(2)$	$-0.10(3)$[c]	
314	6^+_2	6^+_1	$-0.386(6)$	$-0.018(14)$	$-0.11(1)$	$+0.27(5)$
317	6^+_2	5^+_1	$+0.392(4)$	$+0.025(19)$	$-0.060(5)$	
435	7^+_1	6^+_1	$-0.40(1)$	$-0.01(1)$	$+0.40(1)$	$+0.31(4)$
					or $+3.68(4)$	

[a] The errors in the A_2 and A_4 are dominated, for the most part, by statistical uncertainties. In the few cases where the statistical error is small, systematic uncertainties on the order of 1–2 % may need to be considered, but are not included in the reported error.

[b] As compiled in Ref. [3].

[c] Determined as % $M3$ mixing.

diminished during the experiment. This problem was circumvented by comparing the counting rates of the 205-keV transition in ^{95}Tc^m, which appeared as a long-lived contaminant ($T_{1/2}=61$ d) in our sample. The ground state spin of ^{95}Tc^m is 1/2, and an oriented sample would not reveal anisotropy in subsequent γ-ray transitions in the daughter nucleus. We were able, therefore, to use this background activity as a reference to make the appropriate dead time and pileup corrections, and properly normalize the individual cold and warm data sets. An example of this correction made for the 778-keV $2^+_1 \rightarrow 0^+_1$ transition in ^{96}Mo for the duration of the experiment is shown in Fig. 1.

The angular distribution coefficients A_2 and A_4 were determined for each transition from the nuclear orientation data by explicitly solving the angular distribution function

$$W(\theta)=1+B_2U_2A_2Q_2P_2(\cos\theta)+B_4U_4A_4Q_4P_4(\cos\theta). \tag{1}$$

The B_2 and B_4 coefficients were determined using $B(\mathrm{Tc}Fe)=-314(3)$ T and $g=0.727(7)$ [5] and a temperature derived from analysis of the ^{57}Co thermometer data. The deorientation coefficients (U_2, U_4) were calculated using a top-down analysis, correcting for newly deduced δ values. The Ge solid angle correction factors (Q_2, Q_4) were calculated for each detector using the prescription of Krane [6].

The resulting angular distribution coefficients and multipole mixing ratios deduced for selected γ-ray transitions in ^{96}Mo are given in Table I. Multipole mixing ratios for transitions in ^{96}Mo have been previously determined using $\gamma\gamma$ angular correlation techniques following β decay, Coulomb excitation, (n,γ), and $(n,n'\gamma)$ experiments, as well as nuclear orientation measurements, and are compiled in Ref. [3]. These δ values are also listed in Table I. To confirm that the calculated U and Q coefficients used in this analysis were reasonable, angular distribution coefficients were determined for several $\Delta L=2$ transitions in ^{96}Mo. The resulting $M3/E2$ mixing ratios (see Table I) for these transitions agree well with those determined from the previous angular correlation measurements.

The mixing ratio deduced for the 719-keV $2^+_2 \rightarrow 2^+_1$ transition is significantly different from the adopted value of $\delta(E2/M1)=+0.44^{+3}_{-4}$ [3]. The direct β feeding to the 2^+_2 state is small, and we extracted deorientation parameters of $U_2=0.6464$, $U_4=0.1690$ considering all the indirect feeding paths to this state. However, a look at the angular distribution parameters (see Table I) for the 1498-keV transition, which depopulates the 2_2^+ state to the ground state of ^{96}Mo, suggests that the calculated U coefficients for the 2_2^+ state may be in error. Recalculating the deorientation coefficients for this state assuming the 1498-keV transition is pure $E2$ (with A_2 and A_4 values of -0.597 and -1.069, respectively) results in $U_2=0.400$ and $U_4=0.070$ for the 1498-keV state. If these deorientation coefficients are used to deduce angular distribution coefficients for the 719-keV transition, $A_2=-0.86(1)$ and $A_4=+0.23(10)$. However, there is no solution for the mixing ratio using the value of A_2 deduced in this way.

We were unable to determine a multipole mixing ratio for the 848-keV $2_3^+ \rightarrow 2_1^+$ transition, as there was no evidence for this weakly fed γ ray in our singles data. For vibrational-like nuclei, the mixed-symmetry state would be a 2^+ state at an energy of ≈ 2 MeV, and the 2_3^+ state at 1626 keV in ^{96}Mo would be an excellent candidate [7]. However, it was possible, using the unique UNISOR/NOF five-detector arrangement, to unambiguously deduce the multipole mixing ratios for the 314- and 317-keV transitions from the second excited 6^+ state at 2755 keV. The values $\delta_{314}=-0.11(1)$ and $\delta_{317}=-0.060(5)$ translate into small $E2$ contributions for these two transitions. The large $M1$ contributions for the 314- and 317-keV transitions in ^{96}Mo are in agreement with the analysis of the L-conversion ratios [8] for these transitions. Our deduced sign of δ_{314}, however, is opposite to that found in the data compilation [3], which was derived from $\gamma\gamma(\theta)$ measurements following Coulomb excitation of ^{96}Mo by a ^{16}O beam [9]. We note that the δ_{314} value extracted from the Coulomb excitation data had a 100% error bar at the 1% confidence level.

The large $M1$ contribution deduced for the 314-keV and 317-keV γ rays, which depopulate the 6_2^+ state in ^{96}Mo, can be compared with results of IBM-2 calculations. Sambataro and Molnar [10] investigated configuration mixing in the Mo isotopes using the IBM-2 and the combination of $N_\pi=1$ and $N_\pi=3$ boson configurations as discussed by Duval and Barrett [11]. Dejbakhsh *et al.* [12] studied the even-even Mo isotopes in the framework of the IBM-2 for the purpose of determining effective boson numbers for these isotopes. They were able to reproduce the low-energy levels of the even-even Mo isotopes without mixing different proton boson configurations. Using the parametrizations of Dejbakhsh *et al.*, we have recalculated the low-energy levels and transition probabilities of ^{96}Mo in the IBM-2 using the code NPBOS [13]. We have also calculated multipole mixing ratios for selected transitions in ^{96}Mo. In addition, we calculated the low-energy properties of ^{96}Mo in the IBM-2 using the

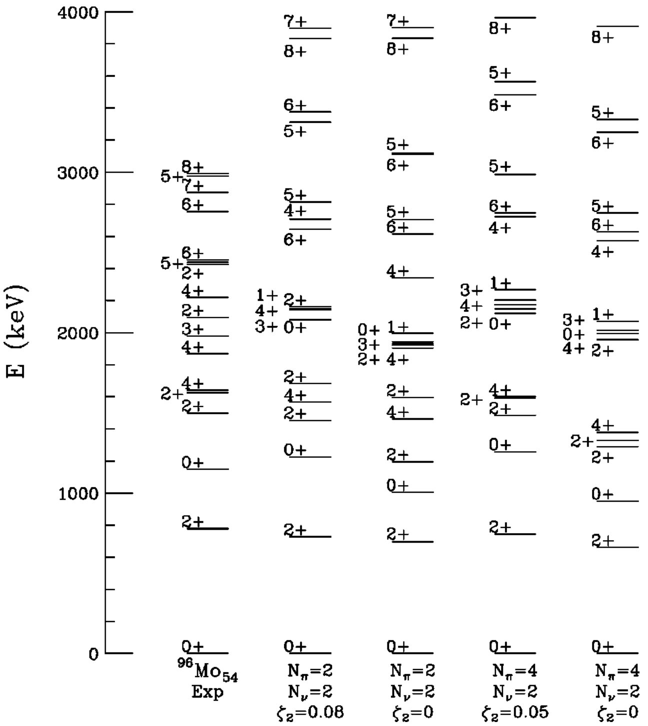

FIG. 2. Calculated low-energy levels in ^{96}Mo. The parameters of the IBM-2 Hamiltonian for $N_\pi=2(4)$, $N_\nu=2$ were: $\epsilon_\pi=0.75(0.70)$, $\epsilon_\nu=1.1(1.25)$, $\kappa=-0.09(-0.065)$, $\chi_\pi=0.4(0.4)$, $\chi_\nu=-1.2(-1.2)$, $C_{0\nu}=-0.50(-0.45)$, $C_{2\nu}=0.15(-0.10)$, $C_{4\nu}=0.0(0.0)$, and $\xi_1=\xi_3=0.035(0.035)$. The experimental levels are taken from Ref. [3].

TABLE II. Multipole mixing ratios $\delta(E2/M1)$ calculated for transitions in ^{96}Mo.

				$N_\pi=2$, $N_\nu=2$		$N_\pi=4$, $N_\nu=2$	
E_γ	I_i	I_f	$\delta(M1/E2)$	$\xi_2=0.08$	$\xi_2=0$	$\xi_2=0.05$	$\xi_2=0$
719[a]	2_2^+	2_1^+	$+0.44^{+3}_{-4}$	$+0.140$	$+0.052$	$+0.294$	$+0.498$
848[a]	2_3^+	2_1^+	-1.05^{+9}_{-10}	-0.748	-2.14	-0.510	-0.410
1200	3_1^+	2_1^+	$+0.81(2)$	$+0.990$	$+1.32$	$+1.87$	$+2.26$
			or $+2.12(8)$				
481	3_1^+	2_2^+	$+0.18(2)$	$+0.399$	$+0.876$	$+0.389$	$+0.417$
			or $-15.5(20)$				
569	5_1^+	4_2^+	$-0.183(3)$	$+0.400$	$+0.623$	$+0.722$	$+1.02$
			or $-2.84(3)$				
314	6_2^+	6_1^+	$-0.11(1)$	$+0.019$	$+0.010$	$+0.018$	$+0.008$
317	6_2^+	5_1^+	$-0.060(5)$	$+0.007$	$+0.002$	-0.002	-0.003
435	7_1^+	6_1^+	$+0.40(1)$	$+0.050$	$+0.045$	$+0.065$	$+0.052$

[a]From Ref. [3].

Dejbakhsh parameter sets with slightly modified Majorana parameters to *enhance* the effect of the mixed-symmetry states on the low-energy structure of ^{96}Mo.

The Majorana term in the IBM-2 Hamiltonian has the form

$$M_{\nu,\pi}=\xi_2(s_\nu^\dagger d_\pi^\dagger - s_\pi^\dagger d_\nu^\dagger)^{(2)}(s_\nu \tilde{d}_\pi - s_\pi \tilde{d}_\nu)^{(2)} - 2\sum_{K=1,3} \xi_K([d_\nu^\dagger d_\pi^\dagger]^{(K)}\cdot[\tilde{d}_\nu \tilde{d}_\pi]^{(K)}) \qquad (2)$$

and describes the interaction between proton and neutron bosons of unlike symmetry. For most numerical IBM-2 calculations, values for the parameters ξ_1, ξ_2, and ξ_3 have been chosen to raise the energy of these nonsymmetric (mixed-symmetry) states relative to the symmetric (normal) states. The reasoning behind this selection of Majorana parameters was to minimize the effect of nonsymmetric interactions on the low-lying portion of the calculated energy spectrum of a nucleus. The Majorana interaction in the IBM-2 Hamiltonian, however, has no microscopic basis, and the strength of the interaction can only be estimated from experimental observations.

In deformed nuclei, the lowest-lying mixed-symmetry state has $I^\pi=1^+$, and the observation of a 1^+ state at $\sim$3 MeV in ^{156}Gd [14] with a large $B(M1)$ value was the first experimental evidence for a collective state associated with the relative motion of the protons and neutrons. In vibrational nuclei, represented in the IBM-2 by the U(5) limit, the lowest-energy mixed-symmetry state is expected to have 2^+ spin parity. This state should lie at $\approx$2 MeV of excitation [1]. Evidence for such a mixed-symmetry state in each of the $N=84$ isotones ^{140}Ba (1994 keV), ^{142}Ce (2004 keV), and ^{144}Nd (2073 keV) [15] was the small multipole mixing ratio ($|\delta|<0.4$) measured for the $2_3^+\rightarrow 2_1^+$ transition. The lifetimes of the 2_5^+ (2156 keV) and 2_6^+ (2231 keV) states in ^{112}Cd, measured using the $(n,n'\gamma)$ reaction [2], provide the best experimental evidence for mixed-symmetry states at low energy in a near-spherical nucleus.

In our IBM-2 calculations, we have chosen Majorana parameters of the form $\xi_1=\xi_3\equiv b$ and $\xi_2=0$ as a modification of the parameter sets used by Dejbakhsh *et al.* [12]. This selection of Majorana parameters will depress the $I^\pi=2^+$ and other even-spin mixed-symmetry levels with respect to the $I^\pi=1^+, 3^+$ states [16]. The goal was to minimize the position of the even-spin mixed-symmetry states in ^{96}Mo and to monitor the effects of such a change on the calculated energy spectrum and, in particular, the multipole mixing ratios for transitions between states of identical spin parity. The resulting energy spectra for levels in ^{96}Mo using the Dejbakhsh parameter sets for boson configurations $N_\pi=2$, $N_\nu=2$ and $N_\pi=4$, $N_\nu=2$, and considering Majorana interactions $\xi_2\neq\xi_1=\xi_3\equiv b$ and $\xi_1=\xi_3\equiv b$, $\xi_2=0$ are shown in Fig. 2. The mixing ratios extracted from the calculated transition probabilities for selected transitions in ^{96}Mo are listed in Table II.

The results of the original calculations of Dejbakhsh *et al.* not only reproduce the energy level spectrum and relative transitions strengths in ^{96}Mo [12], but they also model well the multipole mixing ratios deduced here. The calculated energy spectrum of ^{96}Mo is clearly affected by the choice of Majorana parameters. However, there are no significant differences between the multipole mixing ratios calculated using the original Dejbakhsh parameter sets and our new parameter sets, which would enhance the role even-spin mixed-symmetry states play in the low-energy structure of ^{96}Mo. Similar results were noted by Scholten *et al.*, who calculated the properties of the vibrational nucleus ^{98}Pd using the IBM-2 [16].

Based on the results of these calculations, it is difficult to assign the 6_2^+ state in ^{96}Mo as a mixed-symmetry state. Although the multipole mixing ratio for the 314-keV γ ray suggests nearly pure $M1$ character for the $6_2^+\rightarrow 6_1^+$ transition, additional information such as measured lifetimes for the 6_2^+ and 4_3^+ states would assist greatly in determining the role states of mixed-symmetry play in the low-energy structure of ^{96}Mo.

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