Multipole mixing ratios of transitions out of high spin gamma vibrational states in neutron rich Mo, Ru isotopes

Benjamin Brown Fenker

Vanderbilt University, Nashville TN 37235

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Abstract

Current models of nuclear structure describe nuclear states in terms of collective vibrations and rotations of a ground state. One such quadrupole vibrational band is the $\gamma-$band formed by vibrations of the short sides of a deformed nucleus. When a nucleus that is in this mode decays to its ground state, the electromagnetic radiation is predicted to be entirely quadrupole in nature. This prediction has been well documented in a wide range of nuclei. However, a recent study of neutron rich molybdenum and ruthenium isotopes found a few $\gamma-$band to ground$-$band transitions that contained almost no quadrupole radiation. This work utilizes the gammasphere detector array to examine the angular correlations in the de-excitations of the secondary fission fragments of ^{252}Cf in order to make independent measurements of these results. This work also uses the same technique to measure the multipole mixing ratios of $\gamma-$band to ground$-$band transitions originating in states with spin-parity as high as 9^+_γ. The results demonstrate that in these nuclei, electric quadrupole radiation is strongly favored in γ to ground band transitions as has been predicted by theory.

Introduction

The structure of atomic nuclei is an important testing ground for theories of the strong nuclear force. With too many constituents to solve the nuclear many−body problem in closed form and too few to employ statistical methods, developing models that accurately predict the complex nature of nuclei is a difficult theoretical challenge. Over the past century there has been an explosion of models that attempt to do this as well as experiments to test these models. Of these, the most successful models can be divided into theories that treat the constituent nucleons as individual particles and those that describe nuclei by considering collective vibrations and rotations of the nucleus as a whole.

The single particle, spherical shell model accurately predicts closed shells at N, Z = 2, 8, 20, 28, 50, 82 in analogy with electron orbitals in atomic physics [1]. When either the proton number, neutron number, or both are equal to one of these "magic numbers," the spherical shell model succeeds in predicting many properties of these nuclei such as the ground state spin and parity and the energy of the first excited level. Additionally, nuclei with neutron or proton number at or near one of these closed shells are always observed to be spherical or near-spherical in shape [2].

As protons or neutrons are added to a closed−shell nucleus, the nuclear shape transitions to oblate, prolate, or triaxial. In these instances, the spherical shell model is inadequate and collective models, such as that proposed by Bohr and Mottelson, must instead be brought to bear. Again, for nuclei that are in regions of strong deformation, these models have had a wide array of successes.

One of these success is the prediction and subsequent observation of nuclear levels that arise from a combination of nuclear vibration and rotation in deformed nuclei. These vibrational states can be characterized in terms of their symmetry axis. A state that is formed from vibrations about a nucleus' long axis is termed a β vibrational band while a γ vibrational band is formed when the short sides of the nucleus pulsate, deviating from spherical symmetry along the long axis [2]. It is the purpose of this work to study the properties of the γ vibrational bands of the neutron rich molybdenum and ruthenium isotopes in relation to the Bohr$-$Mottelson model of collective nuclear motion.

Much current experimental and theoretical interest is in transitional nuclei that exhibit soft deformations. These nuclei are especially difficult to model as they are not easily described by either category of nuclear model. One such region of interest is in the neutron$-$rich molybdenum and ruthenium isotopes, $^{104-108}$Mo and $^{106-112}$Ru[3]. This work has measured the properties of the $\gamma-$vibrational states in these neutron$-$rich isotopes in an attempt to better understand the shape and structure of these nuclei.

Electromagnetic Selection Rules

When a nucleus decays from an excited state, the angular momentum selection rule for the emitted photon is $\Delta J = |J_i - J_f| \leq L$ [4]. In practice, only the lowest two multipolarities are seen because the lifetime of the radiation increases as L increases [2]. Additionally, parity must be conserved in any electromagnetic nuclear decay producing additional selection rules. Electric radiation of multipolarity L has parity $\pi_e = (-1)^L$ and magnetic radiation has parity $\pi_m = (-1)^{L+1}$. Using these selection rules, a $\gamma-$decay from a 2^+ state into a 1^+ state permits M1, E2, or M3 radiation but only the M1 and E2 components are ever observed experimentally. Furthermore, electric multipole radiation is favored over its magnetic counterpart leading to possible ML, E(L+1) mixtures but not EL, M(L+1) mixtures. For example, in a $4^+ \rightarrow 2^+$ transition, only the E2 radiation is ever observed.

As discussed above, a $\gamma-$vibrational band is formed by vibrations of the short sides of the nucleus. A quadrupole vibration alone produces a 2^+ excited state as a band$-$head. Rotations of this state produce excited levels with increasing integer spin and positive parity. Because the γ vibrational band represents vibrations of a quadrupole state, electromagnetic radiation emitted when a nucleus decays from the $\gamma-$band to the ground$-$state rotational band is expected to be pure quadrupole. Thus, only an E2 component should be observed in $\gamma-$band to ground$-$band decays that would normally permit a M1+E2 mixing in $\Delta I = 0, 1$ transitions such as $2^+ \rightarrow 2^+$, $3^+ \rightarrow 2^+$. These predictions have been well documented

Table 1: E2/M1 admixtures in γ to ground band transitions. Reproduced from [5]

Nucleus	$2_\gamma \rightarrow 2_g$ %E2, Ave.	$3_\gamma \rightarrow 2_g$ %E2, Ave.	$3_\gamma \rightarrow 4_g$ %E2, Ave.	$4_\gamma \rightarrow 4_g$ %E2, Ave.
^{152}Sm	$99.86^{+0.12}_{-0.25}$	$98.80^{+0.61}_{-0.80}$	$96.2^{+0.9}_{-1.3}$	$99.4^{+0.6}_{-2.8}$
^{154}Gd	$99.02^{+0.29}_{-0.24}$	$99.78^{+0.20}_{-0.23}$	$97.01^{+0.19}_{-0.21}$	$95.1^{+0.9}_{-1.2}$
^{156}Gd	99.7 ± 0.1	-	-	-
^{160}Dy	99.68 ± 0.13	$98.78^{+0.50}_{-0.62}$	$95.7^{+3.3}_{-5.7}$	-
^{162}Dy	$98.0^{+2.0}_{-48} or 28^{+50}_{-19}$	-	-	-
^{164}Dy	$98.0^{+2.0}_{-18} or 26^{+55}_{-13}$	-	-	-
^{166}Er	≥ 99.77	-	-	-
^{168}Er	≥ 99.97	-	-	-
^{170}Er	≥ 99.00	-	-	-
^{172}Yb	$98.85^{+0.66}_{-0.97}$	$96.90^{+1.76}_{-4.07}$	-	-
^{178}Hf	$\geq 99 or \geq 63$	-	-	-
^{232}Th	$99.81^{+0.09}_{-0.40}$	-	-	-

in well$-$deformed, rare earth nuclei for the $\gamma-$band to ground$-$band transitions as seen in Table 1 [5][6].

A recent study of these multipole mixing rations for $\Delta I = 0, 1$ transitions in the neutron rich Mo and Ru isotopes indicated that nearly pure M1 radiation was observed in a few $\gamma-$band to ground band transitions as seen in Table 2 [1]. For example, transitions in ^{108}Mo and ^{108}Ru are observed to be almost entirely M1 radiation.

This work seeks to independently measure the case for these surprising results as well as to extend the analysis to $\Delta I = 0, 1$ transitions from higher angular momentum states of the $\gamma-$band. This analysis was accomplished by examining the angular correlation of the deexcitations of the secondary

Table 2: E2/M1 admixtures in γ to ground band transitions from [1].

Nucleus	$2_\gamma \rightarrow 2_g$ %E2, Ave.	$3_\gamma \rightarrow 2_g$ %E2, Ave.	$4_\gamma \rightarrow 4_g$ %E2, Ave.
^{102}Mo	$98.73^{+0.63}_{-0.90}$	$29.06^{+40.73}_{-10.96} or 59.01^{+12.89}_{-19.99}$	$59.01^{+12.89}_{-9.02}$
^{104}Mo	$98.11^{+0.56}_{-0.72}$	$99.80^{+0.10}_{-0.14}$	$66.22^{+33.78}_{-11.47}$
^{106}Mo	$94.64^{+2.05}_{-2.60}$	$98.95^{+0.30}_{-0.35}$	$71.91^{+8.09}_{-5.69}$
^{108}Mo	$11.47^{+1.14}_{-1.11}$	$0.34^{+1.56}_{-0.34} or 99.01^{+0.99}_{-2.9}$	$66.22^{+20.90}_{-11.47}$
^{108}Ru	$99.67^{+0.33}_{-1.98}$	$6.79^{+0.96}_{-0.91}$	$78.31^{+15.81}_{-12.09}$
^{110}Ru	$99.99^{+0.01}_{-0.08}$	$99.86^{+0.10}_{-0.17}$	$90.00^{+8.16}_{15.71}$
^{112}Ru	$99.87^{+0.11}_{-0.21}$	$99.73^{+0.21}_{-0.37}$	-

fission fragments of ^{252}Cf.

Experimental Techniques and Procedures

Experiment

The experiment for this analysis was performed at Lawrence Berkeley National Laboratory in November of 2000 using the Gammasphere detector array. Details of the procedures can be found in [1]. The Gammasphere detector array optimally consists of 110 Germanium detectors placed at 17 azimuthal and 60 different polar angles. This corresponds to 5995 unique detector pairs. In this experiment only 101 detectors were functioning. Due to Gammasphere's symmetry, the angle between any two detectors can only be one of 64 different values. For this experiment, a 62 μCi ^{252}Cf fission source was placed at the center of Gammasphere and the resulting fission fragments were fully stopped in 13 μm thick unmagnetized iron foils. A total of $\sim 4 \times 10^{11} \gamma - \gamma - \gamma$ events were recorded.

The γ transitions considered here are the deexcitations of the secondary fission fragments of the spontaneous fission of ^{252}Cf. In spontaneous fission, the two primary fission fragments emit, on average, 3-4 prompt neutrons on the time scale of 10^{-20} seconds, creating the secondary fission fragments. The neutron evaporation leaves the secondary fragments in a state of high spin and excitation energy. These secondary fragments then undergo prompt $\gamma-$decay on the time scale of 10^{-14} seconds and it is these γ rays that are considered here. With this brief description of the experiment, it is necessary to examine the angular correlation method and how it pertains to a study of nuclear structure. Following this will be a description of specifically how Gammasphere was used to measure angular correlations.

Angular Correlations

By measuring the unperturbed angular correlation between $\gamma-$decays in a cascade it is possible to measure the multipole mixing ratio of one or both of the transitions. The technique is described in detail in [1], [7], and [8] and summarized here as it pertains to this analysis. For a cascade depopulating levels I_1 and I_2, $I_1 \rightarrow I_2 \rightarrow I_3$, the angular correlation is defined as the probability of the second γ ray being emitted at a certain angle relative to the first γ ray. The detection of γ_1 in a certain detector defines an axis and the relative direction of that axis to the detection of γ_2 defines the angle between the two.

The angular correlation is described by

$$W(\theta) = 1 + A_2 P_2 cos(\theta) + A_4 P_4 cos(\theta)$$

where the P_i's are Legendre polynomials, θ is the angle between successive gamma rays, and the A_i's are fitting parameters that determine the mixing ratio. Once A_2 and A_4 have been fit to experimental data, they determine a mixing ratio, δ, using formulas and tables compiled by [9]. Software developed by the National Nuclear Data Center was used to aid this process. The sign convention used in this work is that of Krane and Steffen [10][11].

Alternatively, δ is defined theoretically as the ratio of reduced matrix elements

$$\delta^2 = \frac{|\langle J_f \| L' \| J_i \rangle|^2}{|\langle J_f \| L \| J_i \rangle|^2} \equiv \frac{I(L')}{I(L)}$$

Because the expression for δ contains the matrix elements of both the final and initial state, its measurement gives information about the nuclear shapes of the states involved. Oftentimes the results obtained are more easily interpreted in terms of the relative intensity of the ML, E(L+1) radiation observed. Since this analysis is concerned with M1$-$E2 mixing ratios,

$$\%E2 = \frac{100\delta^2}{1+\delta^2}$$

With these definitions, a δ value of one corresponds to an even distribution of M1/E2 radiation with larger values corresponding to higher percentage of E2 radiation and lower δ meaning a larger fraction of M1 radiation.

One further point in this discussion is that the intermediate state in a $\gamma-$cascade, I_2 above, interacts with the hyperfine field of the iron plates. It is assumed that these fields are randomly oriented and small enough so that there was no preferential orientation in the foil. If the intermediate state has a long enough lifetime to interact with the magnetic field for a sufficient length of time, then the experimentally observed angular correlation will be attenuated. The net effect of this attenuation on the correlation function, $W(\theta)$, is $A_k \rightarrow 0$. Therefore, $W(\theta)$ must be modified slightly and is given by [7]

$$W(\theta) = A_0(1 + A_2P_2cos(\theta) + A_4P_4cos(\theta))$$

The normalization parameter, A_0 is determined for each intermediate state and the details of its determination for each case will be given. It should be noted that this effect is insignificant for states with very short lifetimes, including many of the states with high spin and excitation energy considered in this work.

Angular Correlations with Gammasphere

For this analysis, each pair of gamma rays detected in coincidence was examined event by event. In each case, the angle between the two detectors recording the event was calculated. As described above, this sorts the data into 64 unique angle bins as there are only this many possible angles between pairs of detectors in Gammasphere. These bins were then further combined into 17 angle bins. Within each angle bin, a two$-$dimensional histogram was created with the x and y axes corresponding to E_1 and E_2. Since this analysis is interested in $\gamma-\gamma-\gamma$ cascades, each triple coincidence event is interpreted as three double coincidence events. For example, an event with three coincident energies, γ_1, γ_2, γ_3 would be placed in three separate histograms as three separate events, $\gamma_1 - \gamma_2$, $\gamma_1 - \gamma_3$, and $\gamma_2 - \gamma_3$. An example of histograms created in this manner is shown in Figure 1 [1][7].

Each 2$-$D histogram described above was then fit to find the number of coincidences, N_n, of the cascade of interest. This N_n must be corrected for various factors relating to Gammasphere's efficiency and response and the details are given in [1][7]. The intensity of the peak of interest is then fit as a function of the angle between γ_1 and γ_2. This gives the experimental angular correlation $W(\theta)$ which is then used to fit the coefficients A_2 and A_4.

In this analysis there are three significant backgrounds that must be considered. As seen in Figure 1, there is a smooth background and ad-

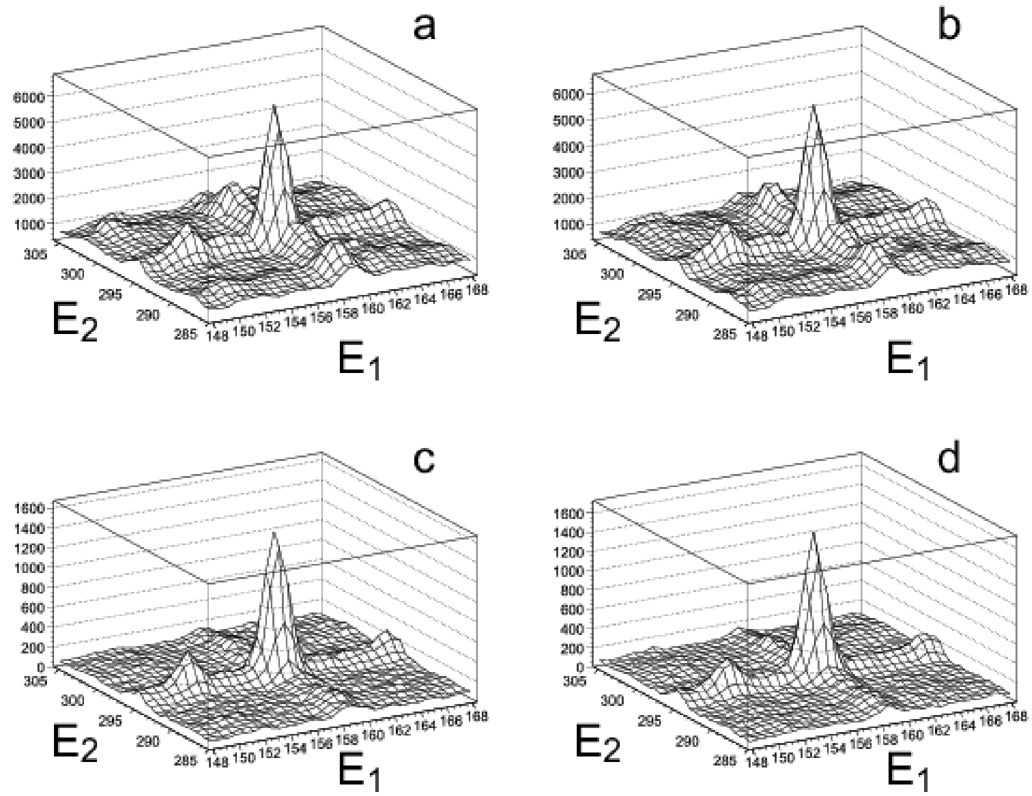

Figure 1: Two dimensional histogram showing the number of coincidences on the z−xis between energies E_1 and E_2 on the x and y axes. The histograms show the $4^+ \to 2^+ \to 0^+$ cascade in ^{148}Ce. Each column of histograms was created from coincidences with a specific angle between the two gamma−rays. The lower plots show the same data with the additional requirement that each event also be in coincidence with at least one of 9 γ rays corresponding to transitions in ^{148}Ce or in one of its fission partners, ^{100,102}Zr.

ditionally two sets of ridges parallel to the x and y axes that intersect at the peak of interest. These backgrounds and how they are handled are described in detail in [12].

In order to reduce the background further it was often necessary to employ additional restrictions on the coincidence events that are added to each histogram. This is done by requiring the cascade of interest to be in coincidence with additional transitions from the nucleus of interest or a partner nucleus. Figure 1 also demonstrates this technique. In the $4^+ \to 2^+ \to 0^+$ cascade of ^{148}Ce, the $6^+ \to 4^+$ transition in ^{148}Ce is expected to be in coincidence and can be used as an additional, triple$-$gate for these data. Additionally, low$-$lying transitions in the partner nuclei of ^{148}Ce, $^{100-102}$Zr are also expected to occur in coincidence with this cascade and can therefore also be used as triple gates. The overall effect of this is to reduce the number of total events significantly but also, and even more significantly, reduce the background and give more accurate results. With this procedure, the experimental A_2 and A_4 are obtained, which allows a determination of δ, the experimental multipole mixing ratio.

The technique described above of requiring the desired cascade to be in further coincidence with another transition is often a delicate balance between maintaining a high enough number of counts for powerful statistics while still satisfactorily eliminating background. Oftentimes, an undesired transition or pair of transitions with similar energy to those transitions of interest or to a transition used as an additional gate were discovered. Eliminating these particular backgrounds are especially difficult as they occur at the same energies as those of the cascade of interest. In these circumstances, it was even more necessary to employ judicious additional gates that eliminated this effect. Numerous examples of this technique will be given in the results section.

Results

In the molybdenum isotopes, transitions out of the gamma band from states of spin as high as 9^+_γ were measured. In most cases, the intermediate state is unattenuated or already measured in [1]. Additionally, in ^{108}Mo, the multipole mixing ratio for the $2^+_\gamma \rightarrow 2^+$ transition was measured and compared with the earlier value from [1] given in Table 2. The results as well as additional gates used are summarized later and the results for each isotope presented first.

This work also attempts to verify the multipole mixing ratios for ruthenium isotopes measured by Goodin in [1] as well as to extend this analysis to transitions from more excited states in the $\gamma-$band. Angular correlation measurements of gamma to ground band transitions were made in $^{108-112}$Ru. This analysis also attempted to extend these measurements to transitions from more highly excited levels in the $\gamma-$band. However, two factors limited the success of this attempt. The first was the similar nature of all the Ruthenium isotopes considered in this work. The $2^+ \rightarrow 0^+$

ground band transitions in $^{108-112}$Ru have energies of 242.1 keV, 240.7 keV, and 236.6 keV. The next ground band transitions are also within a few keV of each other, especially in the case of ^{108}Ru and ^{110}Ru. This similarity of the level schemes is shown later in Figures 11, 14, and 16 and made it difficult to distinguish between isotopes of Ruthenium, especially when considering weak transitions with few counts. Requiring cascades to be in coincidence with transitions from each isotope's most probable fission partner does little to alleviate this problem. The various ruthenium isotopes have a broad distribution when it comes to describing their fission partners. This means that, while for ^{110}Ru the most likely partner is ^{138}Xe, it is also likely to have ^{140}Xe or ^{136}Xe as fission partners. Because of these difficulties, only one angular correlation was measured for a transition higher than $4^+_\gamma \rightarrow 2^+$. The results from the ruthenium isotope angular correlation measurements are given later in Table 4.

^{102}Mo

Goodin attempted to measure the multipole mixing ratio of the $3^+_\gamma \rightarrow 2^+$ transition in ^{102}Mo using the 953.2−295.5 keV angular correlation [1]. The level scheme for ^{102}Mo used in this work is shown in Fig 2. This level scheme suggests that the 953.2 keV transition is actually a decay from an unknown band and the correct $3^+_\gamma \rightarrow 2^+$ transition has an energy of 948.8 keV. Therefore the mixing ratio for this transition presented in [1] is found to be in error. Using the correct $3^+_\gamma \rightarrow 2^+$ transition and Goodin's value

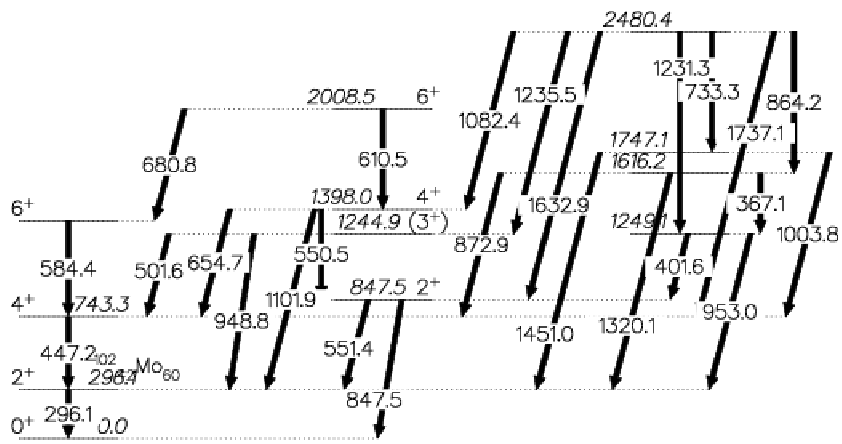

Figure 2: The level scheme of ^{102}Mo considered in this work

for the attenuation due to the $4^+ \to 2^+ \to 0^+$ cascade, the mixing ratio of the 948.8 keV $3^+_\gamma \to 2^+$ transition is found to be $\delta(E2/M1) = -7.6^{+2.7}_{-8.1}$ or $-0.32^{+0.1}_{-0.2}$. The second value is permitted given a somewhat greater than 1σ deviation from the central value for A_4.

^{104}Mo

For ^{104}Mo, angular correlations were measured for $\Delta I = 0, 1$ transitions from the $\gamma-$vibrational band up to the 9^+_γ state. This extends Goodin's analysis which measured no transitions originating higher than the 4^+_γ state. The level scheme for ^{104}Mo considered in this work is shown in Figure 3.

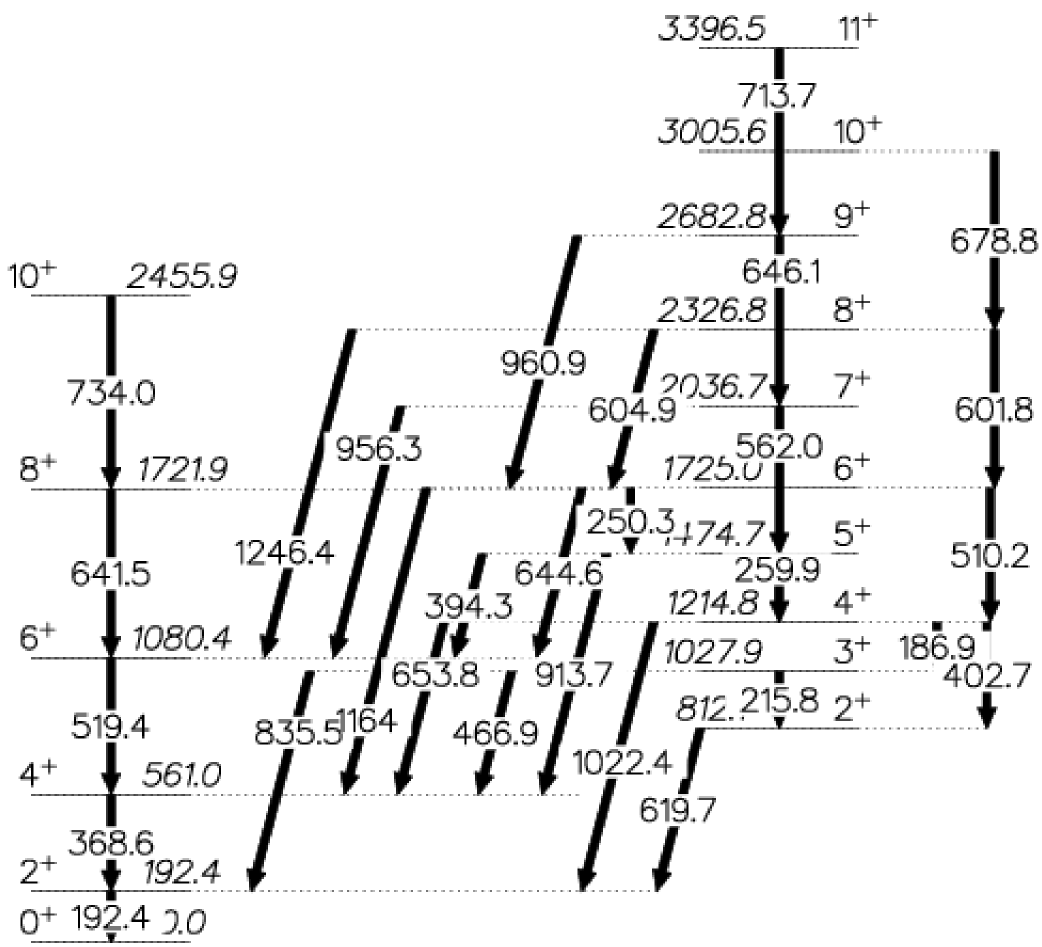

Figure 3: The level scheme of ^{104}Mo considered in this work

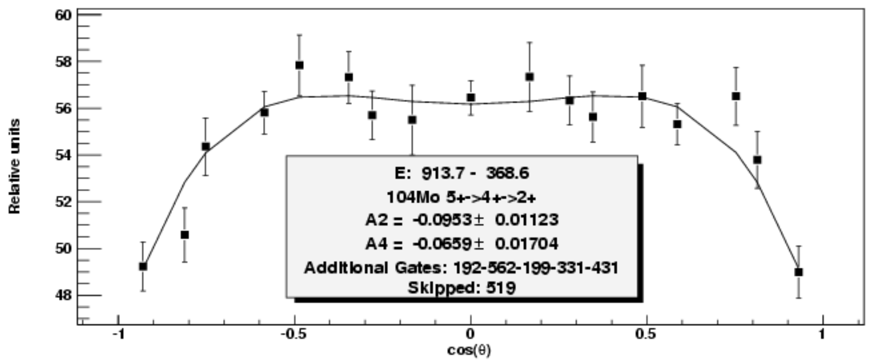

Figure 4: The angular correlation for the 913.7 keV and 368.6 keV transitions in ^{104}Mo. These A_2 and A_4 values are uncorrected for attenuation.

In this nucleus the angular correlation of the $5^+_\gamma \rightarrow 4^+$ state was measured using the 913.7$-$368.6 keV cascade. The attenuation of the intermediate 4^+ state was measured by Goodin by examining the angular correlation of the $6^+ \rightarrow 4^+ \rightarrow 2^+$ cascade. This state was found to only be weakly attenuated, with $A_0 = 1.06$ [1], and with states of higher spin having shorter lifetimes, intermediate states above 4^+ are assumed to be unattenuated. Corrected for attenuation, the A_2 and A_4 parameters for this transition are found to be $A_2 = -0.101 \pm 0.012$ and $A_4 = -0.070 \pm 0.018$. This angular correlation, which corresponds to $\delta(E2/M1) = 25.6^{+21.1}_{-8.0}$, is shown in Figure 4.

The angular correlation in the $7^+_\gamma \rightarrow 6^+ \rightarrow 4^+$, 956.3$-$519.4 keV cascade in ^{104}Mo was also measured in this work. Since this weak transition makes full use of the high statistics data, multiple sets of additional gates were tested and the results compared in order to determine the set of additional gates that gave the most reliable results. In this instance, the $4^+ \rightarrow 2^+$ and $2^+ \rightarrow 0^+$ transitions in ^{104}Mo as well as transitions in the $\gamma-$band that feed the 7^+_γ state were used in a variety of combinations as additional gates. The intermediate 6^+ state is assumed to have negligible attenuation. The results from using each combination of additional gates were within one standard deviation of each other and the central value corresponded to $\delta(E2/M1) = 3.4^{+0.7}_{-0.5}$ or, although less likely, $\delta(E2/M1) = 0.25^{+0.06}_{-0.05}$. The second value is less likely because it requires a greater than 1σ deviation from the central value for A_4.

Finally, the the angular correlation was measured for the 960.9−641.5 keV cascade in ^{104}Mo. This measures the multipole mixing ratio for the $9^+_\gamma \rightarrow 8^+$ transition. Again, various combinations of additional gates were tested and the results converged on one of two values. It was found that for this transition, $\delta(E2/M1) = 0.64^{+1.79}_{-0.23}$ or $0.43^{+3.38}_{-0.19}$. The angular correlations for these results are shown in Figure 5 and Figure 6.

^{106}Mo

In ^{106}Mo, $\gamma-$band to ground−band transitions were measured extending up the $\gamma-$band to the 7^+_γ state. The level scheme for this nucleus is shown in Figure 7.

The multipole mixing ratio for the 784.4 keV, $5^+_\gamma \rightarrow 4^+$ transition was measured using the angular correlation of the 784.4−350.8 keV cascade in

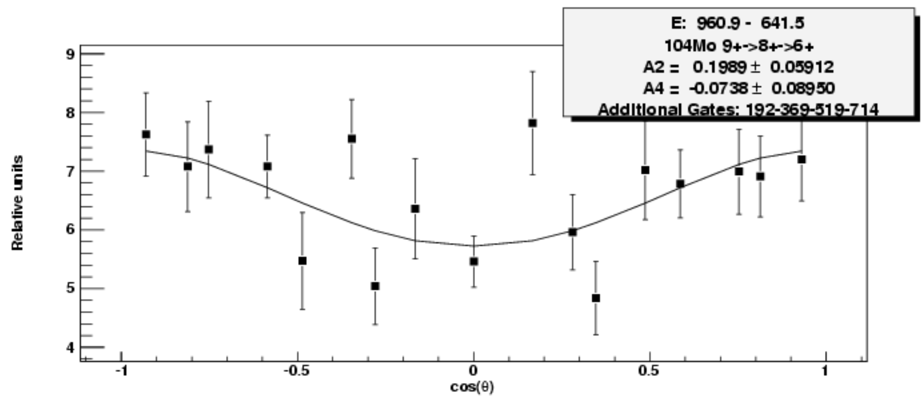

Figure 5: Angular correlation between the 960.9 keV and 641.5 keV transitions in ^{104}Mo.

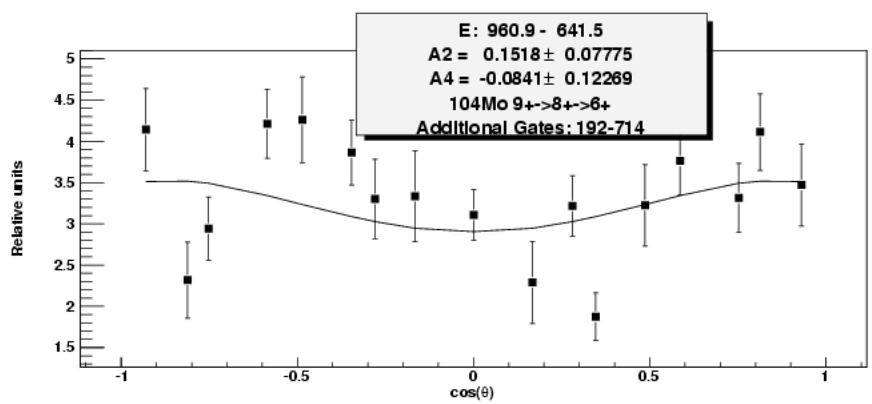

Figure 6: Angular correlation for the 960.9−641.5 keV cascade in ^{104}Mo. To be compared with Figure 5

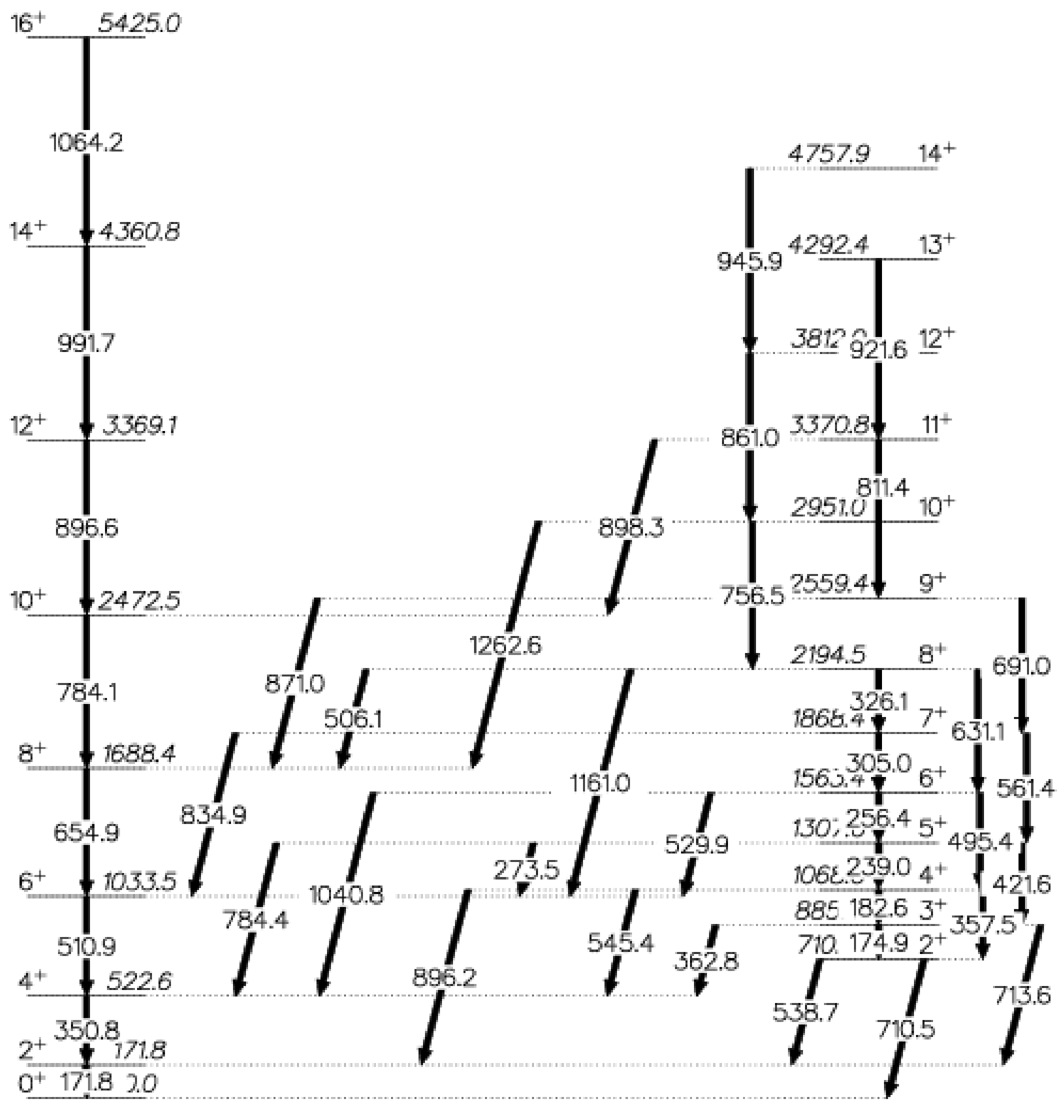

Figure 7: Level scheme for ^{106}Mo considered in this work

^{106}Mo. The attenuation for the intermediate 4^+ state was measured in [1] and this value is adopted here. For this transition, $\delta(E2/M1) = 4.14^{+0.31}_{-0.27}$. This measurement also provides an example of how multiple sets of additional gates are in close agreement, implying that this weak transition was measured accurately. This $5^+_\gamma \rightarrow 4^+ \rightarrow 2^+$ cascade feeds the 2^+ state in ^{106}Mo, which then decays to the ground state with an energy of 171.8 keV. Therefore, this transition is a suitable additional gate. Furthermore, the 5^+_γ state is populated by a 561.4 keV $7^+_\gamma \rightarrow 5^+_\gamma$ transition which can also serve as a gate. Finally, the most probable fission partner of ^{106}Mo is ^{142}Ba, and the two lowest ground band transitions from this nucleus, 359 keV and 475 keV, can also be used as additional gates. In this work, all four of these gates were used in the final analysis, but excluding the ^{142}Ba gates only alters $\delta(E2/M1)$ by 4%, well within one standard deviation. This technique was used here and with other weak transitions in order to confidently assign a multipole mixing ratio.

Additionally in this nucleus, the mixing ratio for the $6^+_\gamma \rightarrow 6^+$ transition was measured using the 529.9$-$510.9 keV cascade. The 6^+ state is assumed to be unattenuated and $\delta(E2/M1) = 1.14^{+0.26}_{-0.18}$ or -7^{+3}_{-13}. Even with the high statistics data available, this transition was too weak to measure definitively the mixing ratio, although multiple sets of additional gates did converge on a particular A_2 and A_4. The second mixing ratio reported above, $\delta(E2/M1) = -7^{+3}_{-13}$, requires a somewhat greater than 1σ deviation from the central value for A_4. In ^{106}Mo, the $7^+_\gamma \rightarrow 6^+$ angular correla-

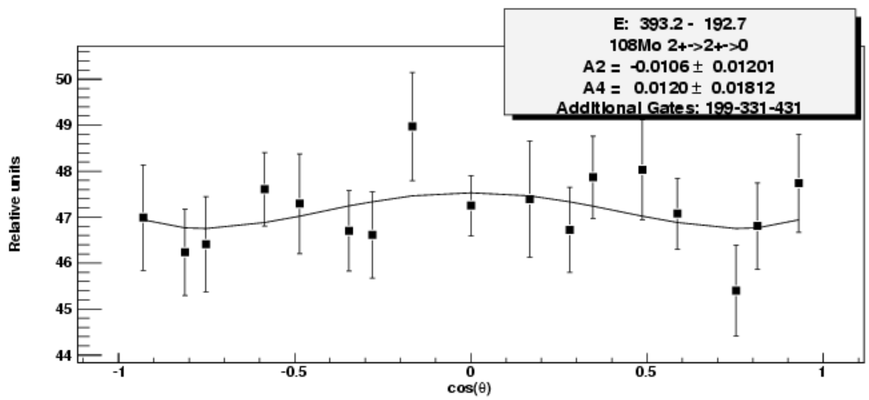

Figure 8: Angular correlation for $2^+_\gamma \rightarrow 2^+$ transition in ^{108}Mo using the additional gates from [1]. The measurement appears to be incorrect as discussed in the text.

tion was measured using the 834.9−510.9 keV cascade and is found to be $\delta(E2/M1) = 3.5^{+1.1}_{-0.7}$ or, although less likely, $\delta(E2/M1) = 0.24^{+0.10}_{-0.08}$. The second mixing ratio is less likely because it requires more than a 1σ deviation in A_4.

^{108}Mo

Goodin measured the $2^+_\gamma \rightarrow 2^+$ angular correlation using the 393.2−192.7 keV cascade. In his analysis, he used additional gates of 199 keV, 331 keV, and 431 keV. This angular correlation is show in Figure 8 and the level scheme for ^{108}Mo is given in Figure 9.

The gates that Goodin used, listed above, are low−lying transitions

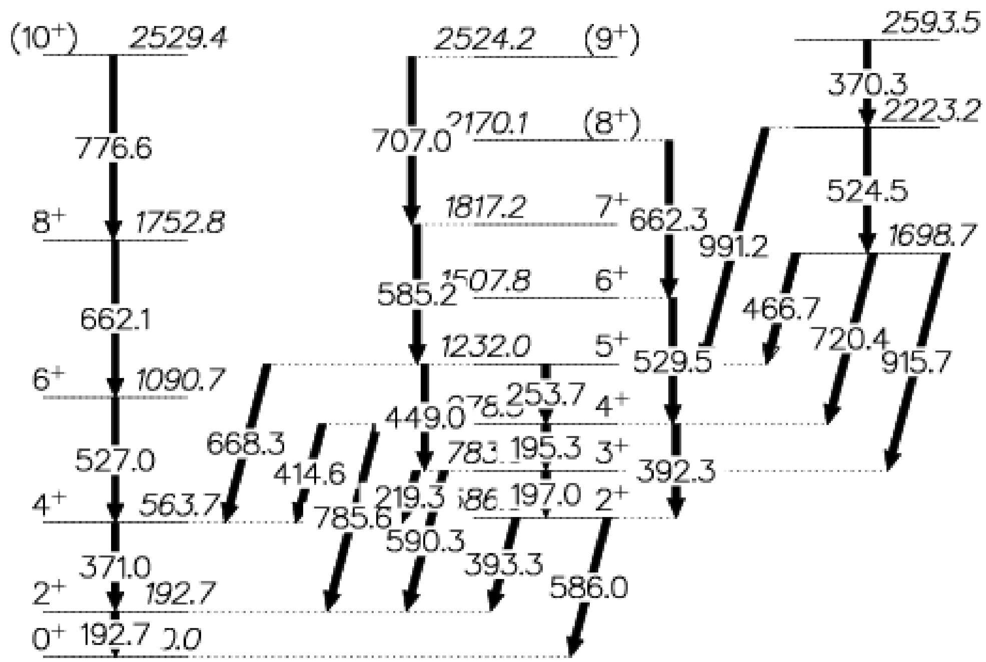

Figure 9: Level scheme for ^{108}Mo considered in this work.

in ^{144}Ba. However, ^{144}Ba is a very unlikely fission partner for ^{108}Mo as it would allow for no neutron evaporation. Furthermore, there exists a strong, 19% 393.8 keV transition in ^{144}Ba that mimics the 393.2 keV transition in ^{108}Mo. Further complicating this measurement is the $2^+ \rightarrow 0^+$ transition in ^{104}Mo with energy 192.4 keV, which mimics the 192.7 keV transition of interest. Because ^{104}Mo and ^{144}Ba are strong fission partners, these two transitions are already expected to be in coincidence, which would contaminate the ^{108}Mo data, leading to an incorrect measurement of the mixing ratio. By requiring the cascade to be in coincidence with transitions from ^{144}Ba, Goodin in fact compounded this problem and his measurement of the mixing ratio is therefore in error.

In order to accurately measure the mixing ratio for this transition, it was necessary to examine additional gates in ^{108}Mo and its true fission partner, ^{140}Ba. However, as seen in Figure 9, the 2^+_γ state is populated by a 392.3 keV transition from the 4^+_γ state. Since this transition is of similar energy to the $2^+_\gamma \rightarrow 2^+$ transition of interest, it too corrupts the measurement and additional gates must be found to avoid this transition. However, this 392 keV transition is by far the strongest transition that populates the 2^+_γ state, and any reasonable gate that eliminates this transition reduces the counts too far to make an accurate measurement of the mixing ratio.

To overcome this difficulty, the $2^+_\gamma \rightarrow 2^+$ mixing ratio was measured using the $4^+_\gamma \rightarrow 2^+_\gamma \rightarrow 2^+$, 392.3$-$393.3 keV cascade. The 529.5 keV, $6^+_\gamma \rightarrow 4^+_\gamma$ transition was required to be in coincidence because any other gate would

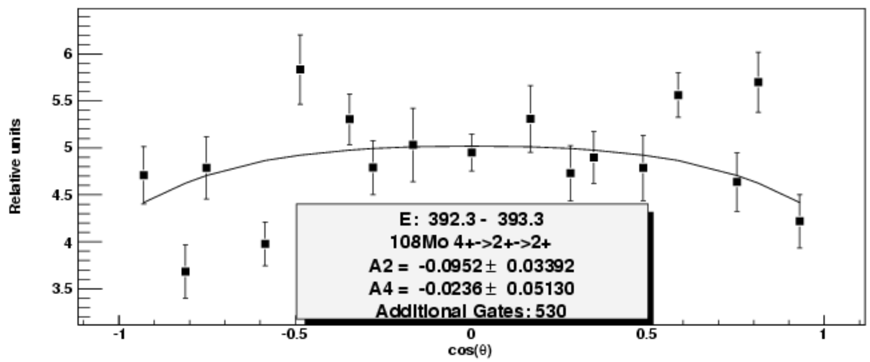

Figure 10: Angular correlation for the 392−393 keV cascade in ^{108}Mo. The value corrects Goodin's measurement show in Figure 8.

have allowed data from ^{144}Ba to enter the measurement. Because the intermediate, 2^+_γ state has a very short lifetime this measurement is assumed to be unattenuated. This angular correlation is shown in Figure 10 and results in $\delta(E2/M1) = -1.5^{+0.8}_{-3.1}$. This result is significantly different from Goodin's result and is in much better agreement with theory.

^{108}Ru

The level scheme for this isotope is shown in Figure 11. The mixing ratio for the $2^+_\gamma \rightarrow 2^+$ transition was measured in ^{108}Ru using the 465.8−242.1 keV cascade The result was found to be $\delta(E2/M1) = 22.6^{+68.0}_{-9.8}$, in good agreement with Goodin's value of $\delta(E2/M1) = 17.3^{+\infty}_{-10.8}$. For the $3^+_\gamma \rightarrow 2^+$, Goodin measured $\delta(E2/M1) = -0.27(2)$ using the 732.6−242.1 keV cas-

Table 3: Angular correlations measured in this work for molybdenum isotopes. Negative gates are shown in parentheses. Gates used to determine the attenuation of intermediate states are presented in [1] and identified with an asterisk.

Correlation	Energies(keV)	A_2^{exp}, A_4^{exp}	Additional Gates(keV)
		^{102}Mo	
$4^+ \rightarrow 2^+ \rightarrow 0^+$	$446.5 - 296.1$	$0.107(14), 0.010(21)$	None *
$3^+_\gamma \rightarrow 2^+ \rightarrow 0^+$	$948.8 - 296.1$	$-0.305(45), -0.161(68)$	181, 333, 794
		^{104}Mo	
$6^+ \rightarrow 4^+ \rightarrow 2^+$	$519.4 - 368.6$	$0.096(6), 0.007(10)$	None *
$5^+_\gamma \rightarrow 4^+ \rightarrow 2^+$	$913.7 - 368.6$	$-0.101(12), -0.070(18)$	192, 562, 199, 331, 431, (519)
$7^+_\gamma \rightarrow 6^+ \rightarrow 4^+$	$956.3 - 519.4$	$0.075(27), -0.050(41)$	192, 369, 646, 714
$9^+_\gamma \rightarrow 8^+ \rightarrow 6^+$	$960.9 - 641.5$	$0.199(59), -0.074(90)$	192, 369, 519, 714
		$0.152(78), -0.084(123)$	192, 714
		^{106}Mo	
$6^+ \rightarrow 4^+ \rightarrow 2^+$	$511.0 - 350.6$	$0.096(6), 0.012(13)$	None *
$5^+_\gamma \rightarrow 4^+ \rightarrow 2^+$	$784.4 - 350.8$	$0.030(10), -0.049(15)$	172, 561, 359, 475
$6^+_\gamma \rightarrow 6^+ \rightarrow 4^+$	$529.9 - 510.9$	$-0.083(26), 0.052(39)$	631, 172, 351
$7^+_\gamma \rightarrow 6^+ \rightarrow 4^+$	$834.9 - 510.9$	$0.070(38), -0.077(57)$	326, 691, 172, 351
		^{108}Mo	
$4^+_\gamma \rightarrow 2^+_\gamma \rightarrow 2^+$	$392.3 - 393.3$	$-0.095(34), -0.024(51)$	530

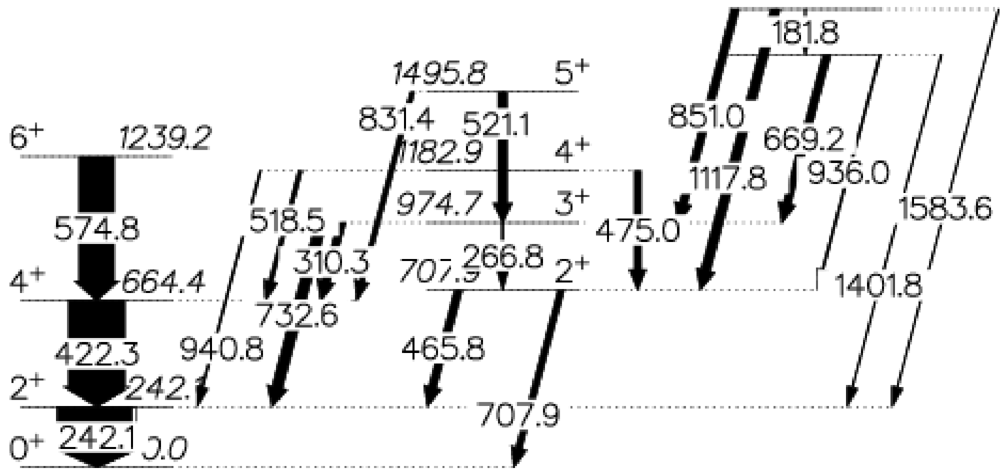

Figure 11: Level scheme for ^{108}Ru considered in this work.

cade and no additional gates. A reproduction of this angular correlation is given in Figure 12. However, to ensure that the transition measured by this angular correlation is actually the $3^+_\gamma \rightarrow 2^+$ transition, it is necessary to require additional gates on transitions feeding the 3^+_γ state. This angular correlation is shown in Figure 13. These values are corrected for attenuation as in [1] using the $4^+ \rightarrow 2^+ \rightarrow 0^+$ cascade. Using these additional gates gives $\delta(E2/M1) = -5.3^{+0.8}_{-1.0}$ or $-0.37^{+0.07}_{-0.08}$ although the second value for $\delta(E2/M1)$ requires a greater than 2σ deviation from the central value for A_2.

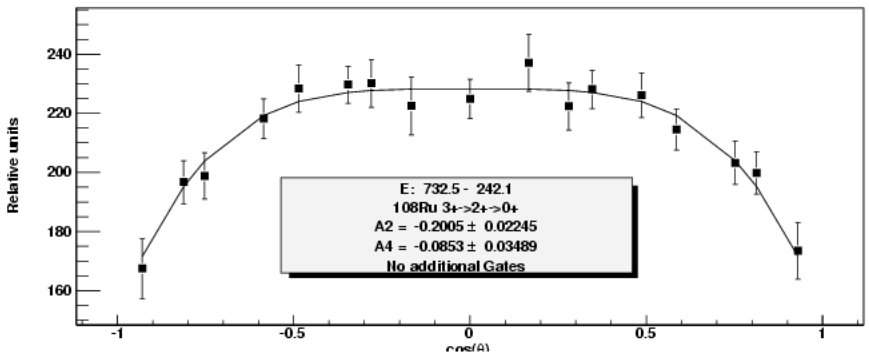

Figure 12: Angular correlation for the $3^+_\gamma \rightarrow 2^+$ transition in ^{108}Ru without any additional gates required.

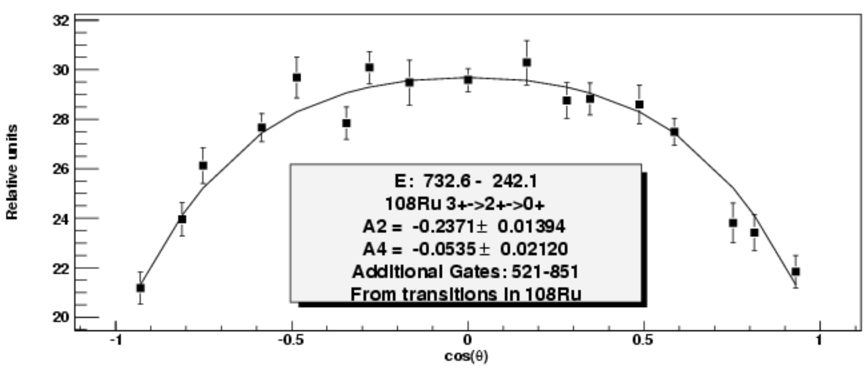

Figure 13: Angular correlation for the $3^+_\gamma \rightarrow 2^+$ transition in ^{108}Ru requiring coincidence with one of two transitions that feed the 3^+_γ state. This figure corrects the result shown in Figure 12.

^{110}Ru

In this isotope the $2^+_\gamma \rightarrow 2^+$ and $3^+_\gamma \rightarrow 2^+$ were measured independently and compared with Goodin's values using the 371.7−240.7 keV and 618.8−240.7 keV cascades respectively. In addition, the $5^+_\gamma \rightarrow 4^+$ angular correlation, which had previously not been measured, was studied using the 711.5−422.2 keV cascade. The level scheme for ^{110}Ru is shown if Figure 14. Using slightly modified additional gates from Goodin, the result obtained in this work for the $2^+_\gamma \rightarrow 2^+$ mixing ratio , $\delta(E2/M1) = 37.4^{+\infty}_{-27.5}$ is in good agreement with Goodin's value. Similarly, for the $3^+_\gamma \rightarrow 2^+$ angular correlation, the independent measurement of this work confirms Goodin's value although there is some indication of the sign of the mixing ratio being ambiguous.

Since ^{110}Ru is the most likely Ruthenium byproduct of ^{252}Cf fission, it was possible to measure one higher state that was previously unmeasured. The 711.54−422.2 keV cascade was used to measure the multipole mixing ratio of the $5^+_\gamma \rightarrow 4^+$ transition. Various combinations of additional gates from transitions in both ^{110}Ru and ^{138}Xe produced little variation in the angular correlation and a value of $\delta(E2/M1) = 12.2^{+91.5}_{-5.8}$ or 0.00 ± 0.07 is adopted here. Figure 15 shows this angular correlation.

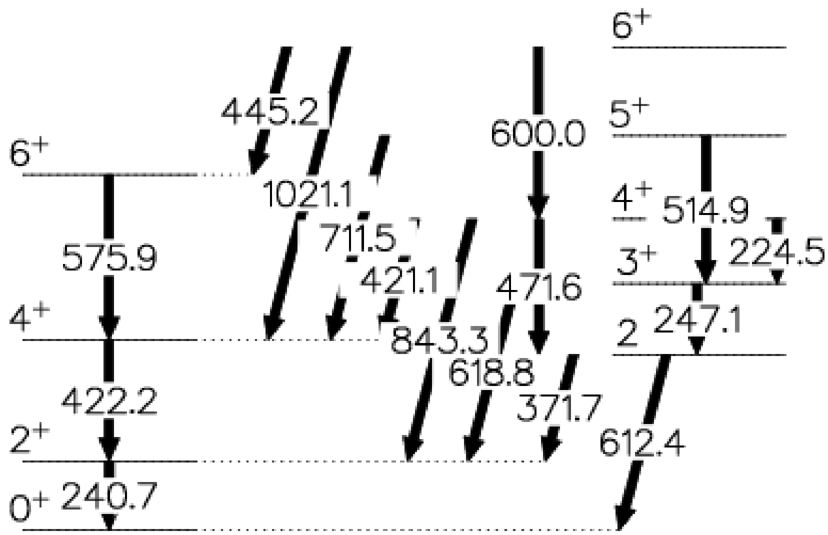

Figure 14: Level Scheme for ^{110}Ru considered in this work

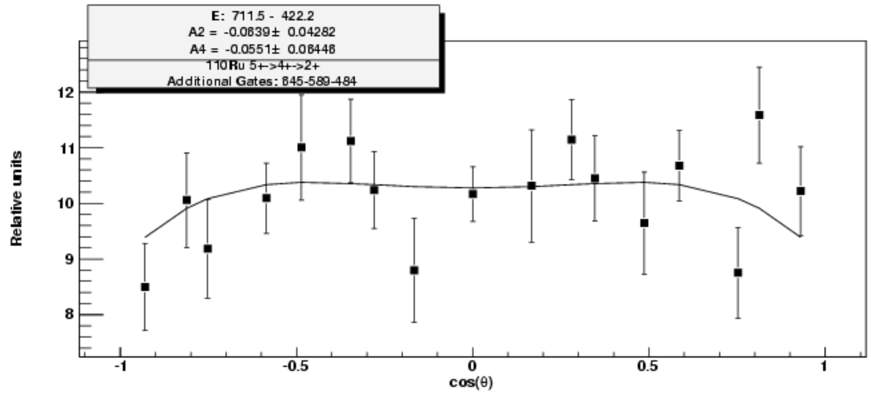

Figure 15: Angular correlation for the $5^+_\gamma \rightarrow 4^+ \rightarrow 2^+$ cascade in ^{110}Ru. Results uncorrected for attenuation.

^{112}Ru

In ^{112}Ru, the multipole mixing ratio for the $2^+_\gamma \rightarrow 2^+$ transition was measured using the 287.0−236.6 keV cascade. The $3^+_\gamma \rightarrow 2^+$ angular correlation was measured from the 511.0−236.6 keV cascade. The level scheme for ^{112}Ru is shown in Figure 16. In both measurements, the attenuation of the angular correlation was measured using the $4^+ \rightarrow 2^+ \rightarrow 0^+$ cascade. The results are shown in Table 4 and confirm Goodin's earlier results although a value of $\delta(E2/M1)$ close to zero is possible for the $3^+_\gamma \rightarrow 2^+$ transition if a greater than 1σ deviation in A_4 is permitted.

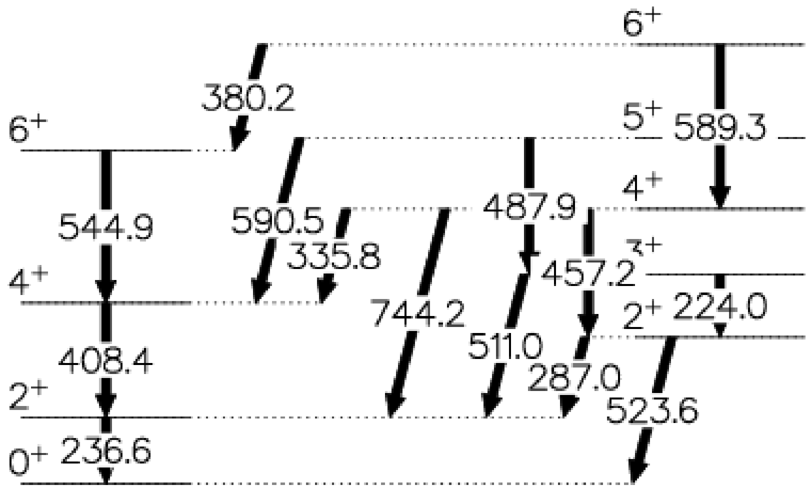

Figure 16: Level Scheme for ^{112}Ru considered in this work

Table 4: Angular correlations measured in this work for ruthenium isotopes. Gates used to determine the attenuation of intermediate states are presented in [1] and identified with an asterisk.

Correlation	Energies(keV)	A_2^{exp}, A_4^{exp}	Additional Gates(keV)
		^{108}Ru	
$4^+ \to 2^+ \to 0^+$	$422.5 - 242.1$	$0.071(6), -0.001(9)$	None *
$2_\gamma^+ \to 2^+ \to 0^+$	$465.8 - 242.1$	$-0.108(23), 0.315(34)$	267, 475, 1118
$3_\gamma^+ \to 2^+ \to 0^+$	$732.6 - 242.1$	$-0.341(20), -0.077(30)$	521, 851
		^{110}Ru	
$4^+ \to 2^+ \to 0^+$	$422.2 - 240.7$	$0.081(7), 0.006(10)$	705, 815 *
$6^+ \to 4^+ \to 2^+$	$575.9 - 422.2$	$0.090(11), 0.014(17)$	None *
$2_\gamma^+ \to 2^+ \to 0^+$	$317.7 - 240.7$	$-0.095(17), 0.242(27)$	472, 247, 484, 589
$3_\gamma^+ \to 2^+ \to 0^+$	$618.8 - 240.7$	$-0.202(15), -0.059(23)$	None
$5_\gamma^+ \to 4^+ \to 2^+$	$711.5 - 422.2$	$-0.072(49), -0.062(73)$	645, 589, 484
		^{112}Ru	
$4^+ \to 2^+ \to 0^+$	$408.4 - 236.6$	$0.084(7), -0.005(10)$	545, 651, 589, 1220, 1313 400, 723, 484 *
$2_\gamma^+ \to 2^+ \to 0^+$	$287.0 - 236.6$	$-0.052(20), 0.240(30)$	224, 457, 589, 488, 693 1220, 1313, 400
$3_\gamma^+ \to 2^+ \to 0^+$	$511.0 - 236.6$	$-0.16(2), -0.06(3)$	488, 606, 589, 1313, 1220

Discussion and Conclusions

Table 5 shows the multipole mixing ratios for transitions studied in this work. In cases where infinity is given as an error, the transition is indistinguishable from a pure quadrupole transition. The measurements of the angular correlation of transitions originating in states higher than 4^+_γ are the first ever measurements of $\gamma-$band to ground$-$band mixing of these transitions in these nuclei. Studying the properties of highly excited $\gamma-$band states offers a new and challenging testing ground for theories of nuclear structure as well as insight into intra$-$band shape changes.

Although, the absolute sign of the multipole mixing ratio is a matter of convention, the relative sign of $\delta(E2/M1)$ for $\gamma-$band to ground$-$band transitions should remain constant throughout the $\gamma-$band for a given nucleus [10]. It is clear from Table 5 that this prediction is verified for states as high as 9^+_γ in ^{104}Mo and as high as 7^+_γ in ^{106}Mo. However, the mixing ratio may experience a sign change in ^{106}Mo at the $6^+_\gamma \to 6^+$ transition. The two possible values for $\delta(E2/M1)$ in this transition have opposite signs, and although the experimental A_2 and A_4 favor the positive value for $\delta(E2/M1)$, a further analysis with higher statistics data will likely clarify the situation. Although in [1] Goodin reported two possible values of the mixing ratio for the $3^+_\gamma \to 2^+$ transition in ^{102}Mo, there was no ambiguity in the sign of $\delta(E2/M1)$ in this work. It appears that the previous measurement did not correspond to the correct transition and instead the mixing ratio for this

Table 5: The mixing ratios of $\gamma-$band to ground$-$band transitions measured in this work and in [1]. Previosly results are denoted with an asterisk. Values in parentheses represent possible mixing ratios if a greater than 1σ deviation is allowed in either A_2 or A_4.

Nucleus	A_2	A_4	$\delta(E2/M1)$	A_2^{theory}, A_4^{theory}
		$2^+_\gamma \rightarrow 2^+$		
^{102}Mo	$-0.153(11)$	$0.289(16)$	$8.8^{+3.6}_{-2.1}$	$-0.155, 0.322$ *
^{104}Mo	$-0.170(14)$	$0.343(28)$	$7.2^{+1.4}_{-1.1}$	$-0.169, 0.320$ *
^{106}Mo	$-0.225(27)$	$0.309(65)$	$4.2^{+1.2}_{-0.8}$	$-0.225, 0.309$ *
^{108}Mo	$-0.095(34)$	$-0.024(51)$	$-1.5^{+0.8}_{-3.1}$	$-0.090, 0.002$
^{108}Ru	$-0.108(23)$	$0.315(34)$	$22.6^{+68}_{-9.8}$	$-0.109, 0.326$
^{110}Ru	$-0.095(17)$	$0.242(27)$	$37.4^{+\infty}_{-27.5}$	$-0.098, 0.326$
^{112}Ru	$-0.052(20)$	$0.240(30)$	$-29.0^{+13}_{-\infty}$	$-0.051, 0.326$
		$3^+_\gamma \rightarrow 2^+$		
^{102}Mo	$-0.305(45)$	$-0.16(7)$	$-7.6^{+2.7}_{-8.1}$, $(-0.32^{+0.1}_{-0.2})$	$-0.303, -0.080$ or $-0.311, -0.008$
^{104}Mo	$-0.169(11)$	$-0.085(23)$	$22.4^{+10.2}_{-5.3}$	$-0.169, -0.081$ *
^{106}Mo	$-0.123(13)$	$-0.103(32)$	$9.7^{+1.8}_{-1.3}$	$-0.123, -0.081$ *
^{108}Mo	$-0.122(66)$	$0.07(12)$	-0.06 ± 0.08, 10^{+273}_{-5}	$-0.122, 0.0$ or * $-0.121, -0.08$
^{108}Ru	$-0.341(20)$	$-0.077(30)$	$-5.3^{+0.8}_{-1.0}$, $(-0.37^{+0.07}_{-0.08})$	$-0.343, -0.079$ or $-0.360, -0.011$
^{110}Ru	$-0.202(15)$	$-0.059(23)$	$\geq 25, \leq -50$	$-0.204, -0.082$
^{112}Ru	$-0.164(19)$	$-0.062(29)$	$19.6^{+17.6}_{-6.3}$, (-0.12 ± 0.05)	$-0.163, -0.081$ or $-0.166, -0.001$
		$5^+_\gamma \rightarrow 4^+$		
^{104}Mo	$-0.101(12)$	$-0.070(18)$	$25.6^{+21.1}_{-8.0}$	$-0.100, -0.059$
^{106}Mo	$0.030(10)$	$-0.049(15)$	$4.14^{+0.31}_{-0.27}$	$0.031, -0.056$
^{110}Ru	$-0.072(49)$	$-0.06(7)$	$12.2^{+91.5}_{-5.8}$, 0.00 ± 0.07	$-0.067, -0.058$ or $-0.071, 0.000$
		$6^+_\gamma \rightarrow 6^+$		
^{106}Mo	$-0.083(26)$	$0.052(39)$	$1.14^{+0.26}_{-0.18}$, (-7^{+3}_{-13})	$-0.077, 0.062$ or $-0.086, 0.110$
		$7^+_\gamma \rightarrow 6^+$		
^{104}Mo	$0.075(27)$	$-0.050(41)$	$3.4^{+0.7}_{-0.5}$, $(0.25^{+0.06}_{-0.05})$	$0.074, -0.047$ or $0.077, -0.003$
^{106}Mo	$0.070(38)$	$-0.077(57)$	$3.5^{+1.1}_{-0.7}$, $(0.24^{+0.10}_{-0.08})$	$0.069, -0.048$ or $0.072, -0.003$
		$9^+_\gamma \rightarrow 8^+$		
^{104}Mo	$0.199(59)$	$-0.07(9)$	$0.64^{+1.79}_{-0.23}$	
^{104}Mo	$0.152(78)$	$-0.08(12)$	$0.43^{+3.38}_{-0.19}$	

transition is negative. However, the mixing ratio of the $2^+_\gamma \rightarrow 2^+$ transition in this nucleus was measured by Goodin as $\delta(E2/M1) = 8.8^{+3.6}_{-2.1}$, and this value appears to be correct. The sign change between these two gamma vibrational states is a new result and warrants further investigation as it implies that the nuclear shape of the two vibrational states are significantly different. In ^{108}Mo, the situation is similar with a possible sign change between the $3^+_\gamma \rightarrow 2^+$ and $2^+_\gamma \rightarrow 2^+$ transitions. However, $\delta(E2/M1)$ for the $3^+_\gamma \rightarrow 2^+$, as measured by Goodin, could either take on a positive or negative value, requiring more data in order to make a concrete determination. Although this analysis does suggest a second possible value of the mixing ratio for the $3^+_\gamma \rightarrow 2^+$ transition in ^{108}Ru, it is decidedly negative to give a sign change in this isotope as well. In ^{110}Ru, a possible change of $\delta(E2/M1)$ is not determined in this study. However, there is a sign change for the $2^+_\gamma \rightarrow 2^+$ transition between ^{110}Ru and ^{112}Ru and again a sign change between the $2^+_\gamma \rightarrow 2^+$ and $3^+_\gamma \rightarrow 2^+$ transitions in ^{112}Ru.

With the exceptions noted above, this analysis confirms the prediction that the relative sign of delta remains constant for gamma$-$band to ground band transitions in a given nucleus. Some of the possible sign changes listed are the result of only tentative assignments for the sign of the mixing ratio. Further analysis of the multipolarity of the radiation emitted in the gamma to ground band transitions is likely to remove these ambiguities. The most compelling observations of this analysis are the consistency of the sign of the mixing ratio for gamma$-$band to ground band transitions up to $9^+_\gamma \rightarrow 8^+$ in ^{104}Mo and up to $7^+_\gamma \rightarrow 6^+$ in ^{106}Mo respectively. These positive results provide strong verification of the prediction that the sign of $\delta(E2/M1)$ should remain constant in a given excitation band.

This work was motivated by the surprising observation that a few decays in ruthenium and molybdenum isotopes that should have been entirely quadruple contained almost no quadrupole radiation as seen in Table 2. Table 6 compares these earlier findings with those of the present study. In the $3^+_\gamma \rightarrow 2^+$ transition in ^{102}Mo, the mixing was not determined definitively within 2.3σ. However, the large E2 value for $\delta(E2/M1)$ is clearly favored. In ^{104}Mo, the nature nature of the gamma−band to ground−band transitions was measured throughout the γ band. In transitions as high as $7^+_\gamma \rightarrow 6^+$, this study demonstrates that the transition is almost entirely pure quadrupole. In the $7^+_\gamma \rightarrow 6^+$ transition, the data do allow entirely dipole radiation, although this would require a somewhat larger than 1σ deviation in fitting parameters A_2 and A_4. The highest transition measured in this nucleus, $9^+_\gamma \rightarrow 8^+$, has a central value for the percentage of E2 radiation observed well below the theoretical predictions, although the large experimental uncertainties allow for almost entirely quadrupole radiation for this transition. If the central value given here is correct it could suggest a possible intra−band shape change in this nucleus as the mixing ratio contains information about the nuclear shape.

In ^{106}Mo for transitions as high as $7^+_\gamma \rightarrow 6^+$, the multipole mixing ratio favors almost entirely E2 radiation. In the transitions from highly excited

Table 6: Percentage of electric quadrupole radiation observed in gamma−band to ground−band transitions in ruthenium and molybdenum isotopes measured here and by [1].

Transition	%E2	Previously Measured [1]
	^{102}Mo	
$2^+_\gamma \to 2^+$	-	$98.7^{+0.6}_{-0.9}$
$3^+_\gamma \to 2^+$	$98.3^{+1.2}_{-2.3}$, $(9.3^{+12.0}_{-4.7})$	$29.1^{+40.7}_{-11.0}$, $59.0^{+12.9}_{-20.0}$
$4^+_\gamma \to 4^+$	-	$59.0^{+12.9}_{-9.0}$
	^{104}Mo	
$2^+_\gamma \to 2^+$	-	$98.1^{+0.6}_{-0.7}$
$3^+_\gamma \to 2^+$	-	99.8 ± 0.1
$4^+_\gamma \to 4^+$	-	$66.2^{+33.8}_{-11.5}$
$5^+_\gamma \to 4^+$	$99.8^{+0.1}_{-0.2}$	-
$7^+_\gamma \to 6^+$	$92.0^{+2.3}_{-2.7}$, $(5.88^{+2.89}_{-2.04})$	-
$9^+_\gamma \to 8^+$	$29.1^{+56.5}_{-14.5}$, $15.6^{+78.0}_{-10.2}$	-
	^{106}Mo	
$2^+_\gamma \to 2^+$	-	$94.6^{+2.0}_{-2.6}$
$3^+_\gamma \to 2^+$	-	98.9 ± 0.3
$4^+_\gamma \to 4^+$	-	$71.9^{+8.1}_{-5.7}$
$5^+_\gamma \to 4^+$	$94.6^{+0.6}_{-0.7}$	-
$6^+_\gamma \to 6^+$	$56.5^{+9.7}_{-8.6}$, $(98.0^{+1.8}_{-3.9})$	-
$7^+_\gamma \to 6^+$	$92.5^{+3.0}_{-3.8}$, $(5.5^{+4.9}_{-3.0})$	-
	^{108}Mo	
$2^+_\gamma \to 2^+$	$69.2^{+26.3}_{-36.3}$	$11.5^{+12.4}_{-9.0}$
$3^+_\gamma \to 2^+$	-	$99.0^{+1.0}_{-2.9}$, $0.36^{+1.6}_{-0.36}$
$4^+_\gamma \to 4^+$	-	$66.2^{+20.9}_{-11.5}$
	^{108}Ru	
$2^+_\gamma \to 2^+$	$99.8^{+0.2}_{-0.4}$	$99.7^{+0.3}_{-2.0}$
$3^+_\gamma \to 2^+$	$96.6^{+1.0}_{-1.3}$, $(13.8^{+4.9}_{-4.0})$	$6.8^{+1.0}_{-0.9}$
$4^+_\gamma \to 4^+$	-	$78.3^{+15.8}_{-12.1}$
	^{110}Ru	
$2^+_\gamma \to 2^+$	$99.9^{+0.1}_{-0.9}$	$100_{-0.1}$
$3^+_\gamma \to 2^+$	≥ 99.8	$99.9^{+0.1}_{-0.2}$
$4^+_\gamma \to 4^+$	-	$90.0^{+8.2}_{-15.7}$
$5^+_\gamma \to 4^+$	$99.1^{+0.8}_{-1.6}$, $0.01^{+0.63}_{-0.01}$	-
	^{112}Ru	
$2^+_\gamma \to 2^+$	$98.3^{+0.1}_{-0.3}$	$99.9^{+0.1}_{-0.2}$
$3^+_\gamma \to 2^+$	$99.7^{+0.2}_{-0.3}$, $(1.4^{+0.8}_{-0.9})$	$99.7^{+0.2}_{-0.4}$

states, the data were insufficient to justify a singular result for $\delta(E2/M1)$. However, in each case the data do allow a strong E2 transition, with this result being preferred in the $7^+_\gamma \rightarrow 6^+$ case as discussed above. This primarily confirms the theoretical prediction of quadrupole radiation being strongly favored in gamma to ground band transitions. In ^{108}Mo, this work corrected Goodin's value for the mixing ratio and subsequently found his result of an almost entirely M1 admixture to be in error. As seen in Table 6, this study obtains a value that strongly favors E2 radiation, again in agreement with theory.

The ruthenium isotopes studied in this work also exhibit a high percentage of electric quadrupole radiation in their gamma−band to ground−band transitions. In, ^{108}Ru, the mixing ratio for the $3^+_\gamma \rightarrow 2^+$ transition is corrected from the previously measured value, which was in error as discussed above. The mixing ratio obtained in this work implies a greater than 96% fraction of E2 radiation, bringing the result in close agreement with theory. However, a low E2 percentage is also allowed by the data but requires more than 2σ deviation in A_4. In the other cases seen in Table 6, the results are in excellent agreement with theory, with well above 90% admixture of E2, electric quadrapole radiation in every case.

It is the conclusion of this study that the surprising results found in [1] are for the most part erroneous for a variety of reasons. This study tested these measurements under more ideal additional gates that ensured the results obtained were reliable. This procedure has produced results that show a strong preference for E2 over M1 radiation in $\gamma-$band to ground-band transitions in neutron rich molybdenum and ruthenium isotopes. It has overturned the earlier results that suggested a possible large M1 admixture in a few of these nuclei. Furthermore, it has extended this analysis to transitions from higher spin states and observed that the E2/M1 admixture remains constant throughout the $\gamma-$vibrational band. Although a few results concerning these transitions should be considered tentative, the overall trend clearly favors a high percentage of electric quadrupole radiation. Additionally, this study has confirmed the prediction that the multipole mixing ratio should have a consistent sign throughout the gamma$-$band for a given nucleus. Again, this prediction is confirmed with a few exceptions possible that are the result of tentative sign assignments for the mixing ratio. Each of these two results correspond to the first systematic study of high spin states in the $\gamma-$vibrational band of transitional nuclei and have provided a new and challenging test for models of nuclear structure.

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