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In-Beam Studies of ^{96}Zr and ^{98}Zr: Collective Excitations

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Introduction

Nearly two decades ago signatures of deformation in the ground state bands of ^{100}Zr and ^{102}Zr were identified, and the rapid change in the deformation of heavy zirconium nuclei noted.[1] It is now well accepted that the short-range proton-neutron interaction between the $1g_{9/2}$ and $1g_{7/2}$ spin-orbit partners plays an important role in producing ground state deformation in this region.[2] Nevertheless, recent studies of zirconium nuclei, including those in the transition region,[3-10] continue to refine our understanding of the interplay between single-particle and collective degrees of freedom. In this report we discuss some aspects of the level structures of ^{96}Zr and ^{98}Zr with emphasis on collective excitations.

Cheifitz et al.[1] first observed the rapid decrease in the energy of the 2_1^+ level as neutron pairs were added to ^{98}Zr, and measured large collectivities for the $2_1^+ \to 0_1^+$ transitions in ^{100,102}Zr. They concluded that there was a strong indication of deformation in these nuclei. From recent inelastic scattering experiments, Rychel et al.[6] obtained $0_1^+ \to 2_1^+$ transition rates for $^{90-96}$Zr which indicate that the collectivity of these transitions decreases by a factor of up to 50 compared to the same transitions in ^{100,102}Zr. They deduced further that the $2_1^+ \to 0_1^+$ transition strength in $^{90-96}$Zr is dominated by neutron matrix elements. For the $0_1^+ \to 3_1^-$ transitions, Rychel et al. obtained B(E3) enhancements of approximately 20 compared to single particle estimates for all $^{90-96}$Zr nuclei.

The monopole matrix elements provide additional information on deformation and mixing of 0^+ states. The ρ_{21}^2 value is about 0.01 for all the $^{92-98}$Zr nuclei, but increases to 0.15 for ^{100}Zr reflecting the coexistence of spherical and deformed (β = 0.35) shapes and the mixing of these states in that nucleus.[3] Recently a modest deformation of $\beta \approx 0.20$ has been deduced by Mach et al.[10] for the 0_2^+ level of ^{96}Zr by assuming that the first two 0^+ levels can be described as mixtures of $(p_{1/2})^2$ and $(g_{9/2})^2$ proton configurations, and that these configurations represent spherical and deformed structures, respectively. Using the same model and new data from Mach and Gill[9], a value of $\beta = 0.14$ can be calculated for the 0_2^+ level of ^{98}Zr. This counterintuitive decrease in the model dependent deformation for ^{98}Zr undoubtedly results from the simplifying assumption that the 0_1^+ and 0_2^+ levels are mixtures of the $p_{1/2}$ and $g_{9/2}$ proton states only. Wave functions calculated by Federman and Pittel[2] indicate that the 0_2^+ level in ^{98}Zr is highly admixed and, hence, deformed. Examination of those wave functions suggests that the admixture of deformed and spherical components is approximately the same for the two lowest 0^+ levels of ^{96}Zr and ^{98}Zr; thus, the β-values for the 0_2^+ levels of ^{96}Zr and ^{98}Zr are probably similar.

In ^{96}Zr, Molnar et al.[4] have identified 2^+ and 4^+ levels that decay most strongly to the 0_2^+ level. They proposed that these levels constitute a four-particle, four-hole band, coexisting with the spherical shell model states in ^{96}Zr. Stolzenwald et al.[7] have identified the 6^+ and 8^+ levels that belong to this band structure. They indicated that though the band might be considered the complete set of states from the $(g_{9/2})^2$ proton configuration, it is not compressed as is the analogous band in ^{90}Zr. They suggested that the level energy sequence of this band in ^{96}Zr is due to a mixture of vibrational and shell-model properties. Similarly, we have found a set of nine levels in ^{98}Zr that decay most strongly to the 0_2^+ level and appear to form a fully developed O(6) excitation structure.[5] Levels were identified that are reasonable candidates for 0^+ and 2^+ "two-phonon" states in ^{98}Zr. Juxtaposition of the excited band structures built on the 0_2^+ levels in $^{90-98}$Zr with the ground state band structures of $^{100-102}$Zr suggests a smooth change in collective character from vibrational through gamma-soft to symmetric-rotor structure for these nuclei.

In order to provide experimental information on the nature of the transitional nuclei, we have employed in-beam spectroscopy using the (t,p) reaction to study ^{96}Zr (gamma rays and conversion electrons) and ^{98}Zr (gamma rays). Photopeaks and conversion-electron multiplets belonging to these nuclei are identified by requiring coincidences with outgoing protons. The usual techniques of in-beam spectroscopy, including gamma-gamma coincidences, were used to establish level schemes for these two nuclei.

Quadrupole Excitations

We have tried to identify candidates for the two-phonon 0^+ and 2^+ levels in order to characterize the nature of the suggested vibrational band in ^{96}Zr. Such states will be found near the 4^+ level at 2857 keV, among and probably mixed with shell model states. Consider first possible 2^+ levels. The 2_1^+ level decays with approximately single particle strength. The dominance of neutron matrix elements[6] indicates that a major component of its wavefunction is the $d_{5/2}s_{1/2}$ neutron configuration. We can expect to find the 3^+ level from this configuration at a low excitation energy. We identify two new levels in this work at 2439 and 2669 keV. The most intense transition from both levels is to the 2_1^+ level. Both transitions can be characterized as M1, E2, or M1/E2 multipolarity from our conversion electron data, requiring a positive parity for the two levels. However, the 2439-keV level is not populated in the beta decay of 0^- ^{96}Y (refs. 4, 12), suggesting a spin of 3 or 4 for this level. This level is a reasonable

Table 1. A summary of ρ^2- and X-values for 0^+ levels in ^{96}Zr.

0^+ level energy (keV)	Measured quantity	Value (Δ%)
1582	ρ^2_{21}	0.0107
2695	X_{312}	0.0039(22)[a]
	X_{322}	0.037-0.043(16)[b]
	ρ^2_{32}/ρ^2_{31}	9.4(28)
2925	X_{412}	0.067(40)[a]
	X_{422}	<0.119 (2 sigma)
	X_{432}	<2.8 (2 sigma)
	ρ^2_{42}/ρ^2_{41}	<3.0

[a]Statistical uncertainty only. A calibration uncertainty of 50% for $E_{e-} > 1600$ keV is not included.

[b]The lower (higher) value applies if the 1114-keV gamma ray is M1 or E2 (E1).

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candidate for the 3^+ member of the $d_{5/2}s_{1/2}$ doublet. The level at 2669 keV is populated by first forbidden unique beta decay with a log f_1t of 9.6 (ref. 10) and is close in energy to the two-phonon 4^+ level, making it a reasonable candidate for the two-phonon 2^+ level. A transition to the one-phonon 2^+ level is not observed. The enhancement of such an E2 transition would have to be greater than 1000 to compete with a single-particle M1 transition to the 2^+_1 level.

In addition to the two-phonon 0^+ state, a 0^+ state arising from the two-neutron configuration $(s_{1/2})^2$ undoubtedly exists at about 2.68 MeV also.[13] Two 0^+ levels are identified at 2695 keV (refs. 13, 14) and 2925 keV (this work and ref. 11), near the 4^+ level at 2857 keV. We have observed E0 transitions from the 2695-keV level to the 1582-keV level and the ground state, and from the 2925-keV level to the ground state. The intensity of the 1175-keV gamma-ray that depopulates the 2925-keV level is enhanced by nearly a factor of two in the 1750-keV coincidence gate compared to its singles intensity. This is consistent with an assignment of 0^+ for the 2925-keV level and a $0^+ \rightarrow 2^+ \rightarrow 0^+$ level sequence. Only upper limits are obtained for E0 transitions from the 2925-keV level to the 1582- and 2695-keV levels. X-values and ratios of ρ^2-values deduced from these data are summarized in Table 1.

Based on the evidence of a strong E2 transition to the 2225-keV 2^+ level, the level at 2695-keV is a good candidate for the two-phonon 0^+ state. There is some mixing between the levels at 2695 and 2925 keV since the strongest E2 transition from the higher level is also to the 2225-keV level. However, the E0 data do not lend themselves to a clear interpretation of either level as the two-phonon 0^+ level when discussed in terms of simple models. Since the "ground state" of the collective band has a deformation of $\beta = 0.20$, the model for spheroidal nuclei might apply: $X_{\beta 11} = 4\beta_0^2$. From this model β_0 is 0.1 for the 2695-keV level, in significant disagreement with the value of 0.20 noted above. For a quadrupole phonon vibrator model, the prediction is $X_{211} = \beta^2_{rms}$. Applying this model to the 2695-keV level gives a β_{rms}-value of 0.2, equal to the β-value for the 1582-keV level. This result implies a very unusual situation, either very large excursions of the nucleus from sphericity, or virtually none. Since the quadrupole vibrator model is normally developed for a spherical ground state, the application of the model to this situation is questionable. Taking a different view, large monopole matrix elements occur between levels that are mixtures of spherical and deformed configurations. Thus the strong E0 transition from the 2695-keV level to the 1582-keV level could indicate a more spherical character for the 2695-keV level. A comparison of the ρ^2 ratios for the two 0^+ levels could indicate that the 2925-keV level has a more deformed character than the 2695-keV level. Such a comparison is strongly dependent of the assumption that deformation, not mixing, is the most important factor in determining the intensity of the measured E0 transitions in this case. A detailed and consistent treatment of both the collective and shell model states in ^{96}Zr will be necessary to successfully explain these data.

Octupole Excitations

Of continuing interest[14,15] is the search for two-phonon octupole states in nuclei, such as ^{208}Pb and ^{146}Gd, that have one-phonon octupole (3^-) states at a relatively low excitation energy. Evidence for such states has been generally inconclusive, though the coupling of one and two particles to two-phonon octupole states has been observed.[16] A recent study of ^{208}Pb suggests a $(3^- x 3^-)0^+$ assignment for the 5237-keV level in that nucleus.[15] Nazarewicz et al.[17] predict octupole deformation or softness towards octupole deformation in transitional nuclei, including N = 56 nuclei. In ^{96}Zr, the 3^- level is at 1897 keV, only somewhat higher than the 2^+_1 level, and lower than the collective 2^+_2 level. A 5^- level is also established at 3120 keV which decays mainly to the 3^- level. In addition to the octupole-octupole two-phonon states, octupole-quadrupole two-phonon states, such as the 5^- level, are to be expected nearby.[18] Positive parity neutron particle-hole states involving the $d_{5/2}$, $s_{1/2}$, $d_{3/2}$, and $g_{7/2}$ orbitals will also occur at energies similar to those of states described above. From previous discussion, it is likely that the states involving two neutrons in the $g_{7/2}$ orbital are part of the set of collective states. Thus the number of levels with spins and parities 0^+, 2^+, 4^+, and 6^+ are limited, making ^{96}Zr an attractive nucleus in which to search for the two-phonon octupole states. Signatures of octupole deformation include enhanced B(E3) transitions to the 3^- level, or fast E1 transitions from the octupole-octupole to the octupole-quadrupole two-phonon states.[18]

Three levels are identified in ^{96}Zr that have intense E1 transitions to negative parity states. Levels at 3082 and 3177 keV decay mainly to the 3^- level, while the third at 3483 keV decays mainly to the 5^- level. The level at 3082 keV has a spin and parity of 4^+ based on the depopulating E1 transition and population by the decay of higher-lying 6^+ levels. The 3176-keV level could have spins of 2 to 4. Since it is not populated strongly from the decay of the ^{96}Y

Table 2. A summary of experimental data for the proposed two-phonon octupole levels in ^{96}Zr, ratios E1 to E2 enhancements, and calculated level half-lives assuming G(E2) = 10.

Initial level	Final level	Transition	Branch (%)	G(E1)/G(E2)	Half-life (ps)[a]
3082 (4^+)	1897 (3^-)	1185 (E1)	92	9.5×10^{-5}	0.22
	2225 (2^+)	857 (E2)	4		
3176 ($(2)^+$)	1897 (3^-)	1279 (E1)	83	8.7×10^{-4}	0.019
	1582 (0^+)	1595 (E2)	7		
3483 (6^+)	3120 (5^-)	363 (E1)	93	5.6×10^{-4}	1.3
	2857 (4^+)	626 (E2)	5		

[a]Calculated assuming G(E2) = 10.

high spin isomer,[7] the lower spins are favored. We observe a gamma ray with the correct energy to be the transition from the 3176-keV level to the 1582-keV 0^+ level. On this basis we suggest a spin and parity of $(2)^+$ for the 3176-keV level. The level at 3483 keV decays by an E1 transition to the 5^- level and populated by decay of the 8^+ level at 4390 keV,[7] and thus has a spin and parity of 6^+. These three states are mixed with members of the collective band built on the 0_2^+ level, but do not form the main part of that band.

Level half-lives have not been measured for these three candidates for octupole two-phonon states. Nevertheless, by comparing E1 and E2 transition strengths, estimates of E1 strengths and level half-lives can be made. Table 2 summarizes the data, the ratio of the E1 enhancement to the E2 enhancement [G(E1)/G(E2)], and a calculation of the level half-life assuming that G(E2) is 10 single particle units. In each case the E2 transition populates a level in the collective band built on the 0_2^+ level. For each level the ratio B(E1)/B(E2) is significantly larger than 10^{-6} fm^{-2}, and a G(E1) value greater than 10^{-3} is possible. This G(E1) value compares favorably with the value of 1.1×10^{-3} for the $3_1^- \rightarrow 2_1^+$ E1 transition. An upper limit of 7 ps for the 3483-keV level half-life would result in G(E1) > 10^{-3} for that level; measurement of a half-life of this magnitude may be feasible with modern techniques. Our experiment was not sensitive enough to observe an E3 transition between the 6^+ and 3^- levels.

Levels near 3 MeV that decay to the 3^- and 5^- levels are not populated by the (t,p) reaction as strongly in ^{98}Zr, as they are in ^{96}Zr. Additionally, we have not experimentally determined the multipolarity of transitions in ^{98}Zr. However, the known 4^+ level at 2047 keV in ^{98}Zr decays by an intense E1 transition to the 3^- level (55% branch), and by E2 transitions to the 2^+ levels at 1223 and 1591 keV (20% and 18% branches, respectively). The two G(E1)/G(E2) ratios deduced from these data for the 4^+ level are 1.1×10^{-3} and 6.4×10^{-5}, again indicating the presence of fast E1 transitions and the possible influence of octupole deformation in ^{98}Zr.

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