First observation of mixed-symmetry states in a good U(5) nucleus

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The properties of 2^+ states at 2156 keV and 2231 keV in ^{112}Cd have been measured using the $(n,n'\gamma)$ reaction. These states have strong decay branches, determined to be almost pure $M1$, to the 2_1^+ level with $B(M1)$ values of $0.044(5)\mu_N^2$ and $0.055(5)\mu_N^2$ respectively, and are interpreted as the main fragments of the 2^+ mixed-symmetry state, the vibrational analogue of the ''scissors-mode'' state in deformed nuclei. These observations provide the first firm evidence of mixed-symmetry states in a good U(5) nucleus. [S0556-2813(96)01311-8]

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I. INTRODUCTION

The observation [1] in 1984 of a 1^+ state at $\sim$3 MeV in ^{156}Gd with a relatively large $B(M1)$ strength was immediately heralded as an example of the long-sought ''scissors-mode'' excitation. Predicted in models in which neutrons and protons are treated as separate fluids, this excitation corresponds to a scissors-type motion in which the neutrons move out of phase with the protons. These states were soon discovered in a wide range of deformed nuclei (see, e.g., [2]), and their systematics are now relatively well known.

The identification of scissors-mode states has been achieved mainly with (γ,γ') or (e,e') measurements. These reactions are selective since excited states are populated by (primarily) direct excitations from the ground state by real or virtual photon scattering. As such, levels observed in the reactions are typically of low spin with relatively large $B(\lambda)\uparrow$ values. Scissors-mode states, which have $I^\pi=1^+$ and large $B(M1;1^+\rightarrow 0^+_{\rm g.s.})$ values, fall into this category. The $(n,n'\gamma)$ reaction has also been used to extract lifetimes of the scissors-mode states in Dy nuclei, and the values determined are in general agreement with the results from (γ,γ') measurements [3].

The neutron-proton version of the interacting boson model (IBM-2) has been used extensively to explain the characteristics of scissors-mode states. The basic version of the model, IBM-1, does not distinguish between protons and neutrons, and has met with considerable success when applied to the low-lying levels in a wide range of nuclei [4]. The IBM-2 predicts states which correspond to those in the IBM-1, labeled as fully symmetric states, as well as states outside the IBM-1 model space — those of mixed symmetry. The classification of states as fully symmetric or of mixed symmetry arises from the behavior of the boson wave function under interchange of the proton and neutron labels. Fully symmetric states have the maximum value of F spin [defined as $F_{\rm max}=(N_p+N_n)/2$ where $N_p(N_n)$ is the number of proton(neutron) bosons]. Mixed-symmetry states arise when part of the boson wave function is not fully symmetric with respect to interchange of the neutron and proton labels. The lowest-lying mixed-symmetry states are $F_{\rm max}-1$ in character. In deformed nuclei, described by the SU(3) limit of the IBM, the lowest-lying mixed-symmetry state has $I^\pi=1^+$ and corresponds to the scissors mode [5]. The existence of these states has also recently been confirmed in γ-unstable [O(6)] nuclei [6].

In the vibrational U(5) limit, the lowest mixed-symmetry state has $I^\pi=2^+$. The experimental signature for this state is a large $B(M1)$ value for the decay to the 2_1^+ state with at most a small branch to the ground state, and it is expected at approximately 2 MeV of excitation [7]. As lifetime measurements in vibrational nuclei at these excitation energies and spins have been limited, small mixing ratios (δ values) for transitions from typically 2_3^+ states to 2_1^+ states have been taken as evidence for mixed-symmetry character. The first examples [8] were states in the $N=84$ isotones ^{140}Ba, ^{142}Ce, and ^{144}Nd for which small δ values ($|\delta|<0.4$) for $2_3^+\rightarrow 2_1^+$ transitions were extracted. In later measurements [9] on ^{142}Ce, a $B(M1)$ of 0.26(5) μ_N^2 for the $2_3^+\rightarrow 2_1^+$ transition was determined, in agreement with the expected value of $0.23\mu_N^2$ from IBM-2 calculations in the pure U(5) limit. However, the description of these nuclei by the IBM-2 has been questioned as it was found that there were, except for isolated cases, very small overlaps of the IBM wave functions with those of the corresponding levels in particle-core coupling model (PCM) calculations for the $N=84$ isotones [10]. In particular, in ^{144}Nd, the mixed-symmetry component of the 2_3^+ wave function was found not to be the dominant term, and the U(5) description was unable to describe, for instance, the $2_2^+\rightarrow 2_1^+$ transition. The authors of [10] note that this argues against a mixed-symmetry interpretation of the 2_3^+ states of these nuclei. In any case, while there does appear to be evidence for fragmented mixed-symmetry 2^+ states in ^{142}Ce, the low-lying level scheme cannot be explained by assuming a pure U(5) description [11].

Based on $B(M1)$ values, mixed-symmetry states have been observed [12–15] in the $A\simeq 50$ region, but these nuclei do not display a spectrum which is close to vibrational [12]. Similar candidates for mixed-symmetry 2^+ states have been proposed in ^{76,78}Se [16], ^{84}Kr [17], ^{124}Te [18], ^{132,138}Xe [19,20], and ^{200}Hg [21]. In a recent survey [22] of possible U(5) nuclei, it was found that the Se isotopes could not be considered as good U(5) nuclei given the present knowledge of the level schemes and have been described [23] as having a ''deceitful'' level structure; ^{84}Kr also suffers from this same lack of knowledge [22]. The Xe isotopes and ^{124}Te are not well described by the U(5) limit [22], and appear to be more O(6) like in nature. The nucleus ^{200}Hg is also considered [21] to have a structure intermediate between U(5) and O(6).

Some of the best examples [22,24] of U(5) nuclei are provided by the Cd isotopes. The nuclei ^{110,112,114}Cd have been extensively studied by a variety of reactions, and the low-lying level schemes of these nuclei are rather well developed. Based on (p,p') to (d,d') cross section ratios, Pignanelli *et al.* [25] determined that the 2231 keV 2^+ state in ^{112}Cd had a large neutron amplitude which would be consistent with either a mixed-symmetry component or a large two-quasineutron component in the wave function. In a single-nucleon transfer study, Blasi *et al.* [26] found that this state was populated very weakly, and thus ruled out the possibility of a two-quasineutron component of the form $j_l \otimes j_T$ where j_l is the target ground state orbital and j_T the transferred orbital. While this did not rule out the possibility of a $j_l' \otimes j_T$ configuration, Blasi *et al.* [26] suggested that the 2231 keV state had a mixed-symmetry character. Gainnatiempo *et al.* [27], using the fact that a small δ value was observed for the $2_3^+ \rightarrow 2_1^+$ transition, suggested that the 2_3^+ state in ^{110,112,114}Cd could have a mixed-symmetry character. Later measurements on ^{112}Cd favored a much larger value of δ, and showed that the 2_3^+ level belonged to the intruder configuration [28,29]. Electron scattering experiments on ^{110}Cd also led to a preference for an intruder interpretation [30]. Claims [31] have also been made for mixed-symmetry states in a series of Ru isotopes, based on δ values, branching ratios, and $\log ft$ values, but must await further experiments where $B(M1)$ values can be measured for confirmation. The (p,p') and (d,d') studies of [25,32] indicated the possibility of mixed-symmetry states in some Pd isotopes, but $B(M1)$ values have not been measured. Thus, as absolute transition rates have been lacking, there has been no firm evidence for a mixed-symmetry state in what can be considered a good U(5) nucleus.

II. EXPERIMENTAL DETAILS AND RESULTS

The fact that the mixed-symmetry 2^+ states should not have a strong branch to the ground state implies that the typical methods of identifying mixed-symmetry states, namely in inelastic photon or electron scattering measurements, are not the reactions of choice in this case. The statistical nature of the $(n,n'\gamma)$ reaction, on the other hand, ensures that all low-spin levels with excitation energies less than the incoming neutron energy will be populated [33]. Furthermore, lifetimes in the femtosecond regime can be extracted through the use [34] of the Doppler shift attenuation method (DSAM), and have been determined [35] in many medium and heavy mass nuclei. Therefore, a series of measurements, which included angular distributions, excitation functions, and $\gamma\gamma$ coincidences, was performed using accelerator-produced approximately monoenergetic neutrons obtained from the ^{3}H$(p,n)^3$He reaction at the University of Kentucky Van de Graaff facility. The scattering sample consisted of ~50 g of CdO powder enriched to 98.17% in ^{112}Cd. Two angular distribution measurements were per-

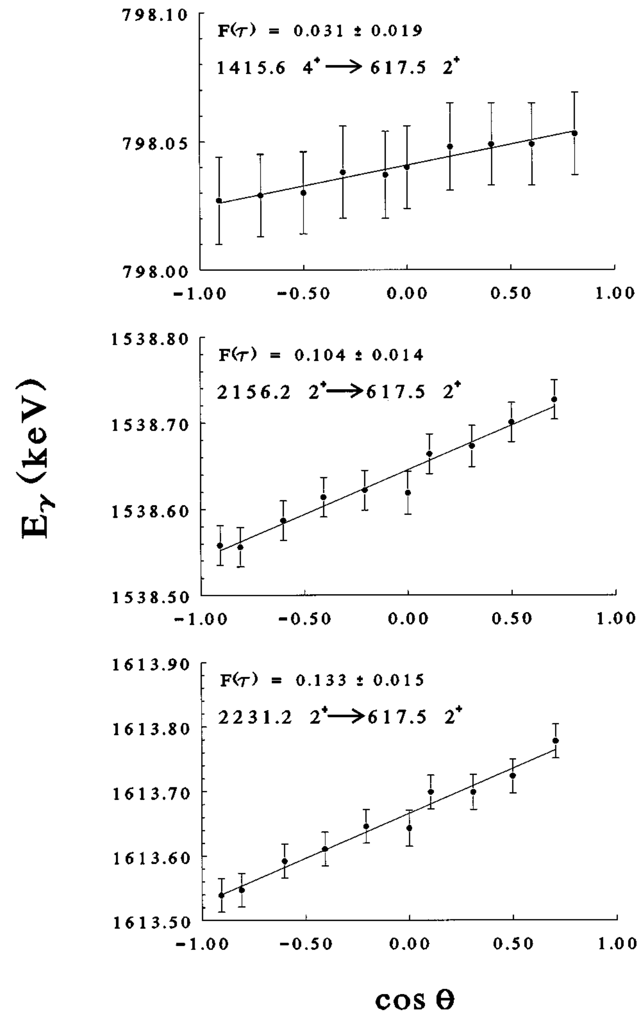

FIG. 1. Measured γ-ray energy as a function of $\cos\theta$ for selected transitions. Noted are the $F(\tau)$ values determined from linear fits to the data.

formed using 2.5 MeV neutrons. The γ-ray spectra were recorded at 10 angles for each experiment utilizing HPGe detectors (with relative efficiencies of 57% or 52%) located 1.1 m or 1.3 m from the sample. Time-of-flight gating was employed in order to reduce extraneous background events, and an annular BGO shield was used for Compton suppression. The energy calibrations were continuously monitored through the use of radioactive source spectra superimposed on the in-beam spectra.

The energy of a γ ray emitted by a recoiling nucleus is given by

$$E_\gamma(\theta_\gamma) = E_0[1 + \beta F(\tau)\cos\theta_\gamma], \quad (1)$$

where $E_\gamma(\theta_\gamma)$ is the observed γ-ray energy at an angle θ_γ with respect to the recoil direction (taken to be the direction of the incident neutron), E_0 is the unshifted γ-ray energy, and $\beta = v/c$ with v the recoil velocity. By examining the energy of a γ ray as a function of angle, the attenuation factor $F(\tau)$ can be obtained, and the lifetime of the state can be determined [34] by a comparison with the $F(\tau)$ value calculated using the Winterbon formalism [36]. Figure 1 shows the variation of the γ-ray energy as a function of

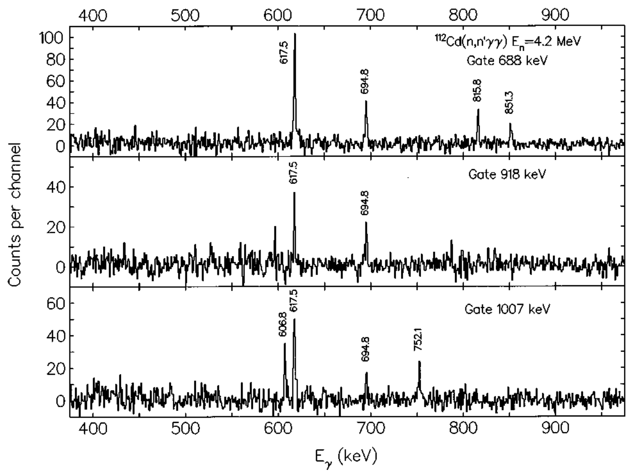

FIG. 2. Selected coincidence spectra from the ^{112}Cd$(n,n'\gamma\gamma)$ reaction performed with 4.2 MeV neutrons. The appearance of the 694.8 keV transition in the 688 keV gate and the 694.8 and 752.2 keV transitions in the 1007 keV gate are due to contributions from other γ rays.

angle for the most intense transitions from each of the states studied as well as the 798 keV $4_1^+ \rightarrow 2_1^+$ transition. Using the data shown in Fig. 1, a lifetime of 760 ± 310 fs is derived for the 4_1^+ level in excellent agreement with the tabulated value of 900 ± 80 fs [37]. The same experimental setup was also used for the excitation function measurements, spectra being recorded at neutron energies between 1.8 MeV and 4.2 MeV incremented in 100 keV steps.

For the coincidence measurements, 4.2 MeV neutrons were collimated using a lithium carbonate collimator 0.75 m in length. Three HPGe detectors were located $\simeq 4$ cm from the sample and events were recorded whenever at least two detectors registered coincident events within a 100 ns window. The events were sorted off line into a 4k$\times$4k matrix with a more stringent requirement of events in an approximately 40 ns window surrounding the beam pulse. Shown in Fig. 2 are selected coincidence gates. Especially important is the gate on the 688 keV γ ray which shows that this peak is a doublet with one member depopulating the 2156 keV level, and the other the 2121 keV level [38]. Also shown are the coincidence gates on the 918 keV and 1007 keV transitions. The use of the excitation functions and coincidence relations permit the establishment of several new transitions from the 2156 keV and 2231 keV levels; the decay schemes for these states are shown in Fig. 3, and the data are summarized in Table I. Further experimental details and results will be published elsewhere [39].

III. INTERPRETATIONS

On inspection of the decay scheme, one immediately notices: (1) the dominant decay branches of the 2156 keV (2_5^+) and 2231 keV (2_6^+) levels are to the 2_1^+ level, (2) both levels also decay to the 1469 keV intruder state, and (3) the 2231 keV level has no observable ground state transition. The observed δ values for the $2_5^+ \rightarrow 2_1^+$ and $2_6^+ \rightarrow 2_1^+$ transitions indicate that these are almost pure $M1$ in nature. Using the lifetimes of 310 ± 35 fs and 220 ± 20 fs determined for the 2_5^+ and 2_6^+ levels, respectively, the $M1$ transition probabilities are calculated to be $B(M1;2_5^+ \rightarrow 2_1^+) = 0.044 \pm 0.005 \mu_N^2$ and $B(M1;2_6^+ \rightarrow 2_1^+) = 0.055 \pm 0.005 \mu_N^2$. While these transitions are not as collective as the scissors mode states in deformed nuclei, they still reflect a significant degree of collectivity, and are comparable to the $B(M1)$ values recently observed [6] for scissors mode states in the O(6) nucleus ^{196}Pt. In addition to having a strong $M1$ transition to the 2_1^+ level, both levels have transitions to the 1469 keV intruder state. Unfortunately, these γ-ray peaks in the spectra are small, and in the case of the 687 keV transition form a doublet; thus it is difficult to get precise values for the mixing ratios. However, the angular distributions are consistent with $E2$ multipolarity and yield $B(E2)$ values of 18^{+4}_{-15} W.u. and 7 ± 3 W.u. for the 687 keV and 762 keV transitions, respectively. This observation indicates that both levels have a sizable intruder component in their wave functions. The possibility of a large $B(E2)$ value for the $2_5^+ \rightarrow 2_3^+$ transition suggests that this state can be identified as the main fragment of the second 2^+ intruder configuration.

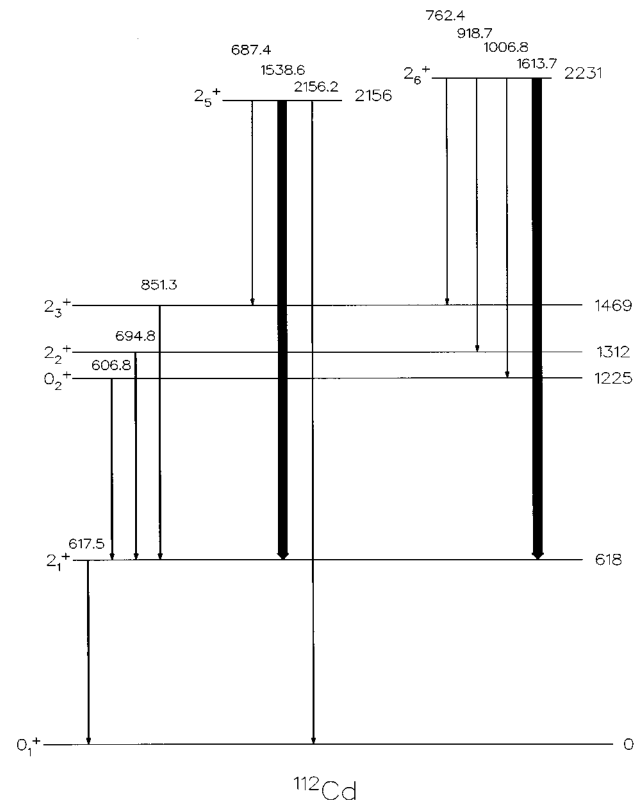

FIG. 3. Partial level scheme of ^{112}Cd showing the states interpreted as having mixed symmetry character. The width of the arrows for the 2156 keV and 2231 keV levels is proportional to the relative γ intensity. Also shown are transitions between lower-lying states observed in the coincidence spectra of Fig. 2.

The IBM-2 prediction [40] of the $B(M1;2_{\mathrm{ms}}^+ \rightarrow 2_1^+)$ value in the pure U(5) limit is

$$B(M1;2_{\mathrm{ms}}^+ \rightarrow 2_1^+) = \frac{3}{4\pi}(g_\nu - g_\pi)^2 6 \frac{N_\nu N_\pi}{N^2} \qquad (2)$$

in units of μ_N^2 which gives, using standard values of $g_\nu = 0$ and $g_\pi = 1$, $B(M1) = 0.16 \mu_N^2$ for ^{112}Cd. The sum of the

TABLE I. Measured lifetimes, relative γ-ray intensities $I_{\rm rel}$, mixing ratios (δ), and reduced transition rates.

E_x (keV)	τ (fs)[a]	E_γ (keV)	Placement[b]	$I_{\rm rel}$[c]	δ[d]	$B(E2)$ (W.u.)	$B(M1)$ (μ_N^2)
2156.2	310(35)	687.4	$2_5^+\to 2_3^+$	0.042(3)	<-0.4	3—22	<0.02
		1538.6	$2_5^+\to 2_1^+$	0.877(4)	$0.085^{+0.025}_{-0.022}$ ($1.91^{+0.13}_{-0.16}$)	0.06(3)	0.044(5)
		2156.2	$2_5^+\to 0_1^+$	0.079(1)		0.14(2)	
2231.2	220(20)	762.4	$2_6^+\to 2_3^+$	0.025(2)	$-1.4^{+0.8}_{-3.4}$	7(3)	0.005(5)
		918.7	$2_6^+\to 2_2^+$	0.024(2)	$0.21^{+0.20}_{-0.13}$ ($1.4^{+0.5}_{-0.5}$)	0.2(3)	0.008(1)
		1006.8	$2_6^+\to 0_2^+$	0.051(5)		5.7(8)	
		1613.7	$2_6^+\to 2_1^+$	0.900(5)	$-0.02^{+0.02}_{-0.03}$ ($2.54^{+0.24}_{-0.22}$)	0.004(9)	0.055(5)

[a]Average of all well-resolved strong deexciting transitions.
[b]The subscripts refers to the ordering of the levels as shown in Fig. 3.
[c]The branching ratios are determined from excitation function data recorded at 125°.
[d]The first solution has the smaller χ^2.

$B(M1)$ values for the 2156 keV and 2231 keV levels is $B(M1)=0.099\pm 0.007\mu_N^2$ approximately 2/3 of the IBM-2 prediction. In contrast, the 2121 keV level, the nature of which was investigated in [38], has $B(M1;2_4^+\to 2_1^+)=0.0056\pm 0.0017\mu_N^2$ approximately an order of magnitude smaller than those of the 2156 keV and 2231 keV levels. A small $B(M1)$ value of $0.004\pm 0.001\mu_N^2$ is also observed [28,37] for the $2_3^+\to 2_1^+$ transition. Results of single-nucleon transfer studies [26,41] are consistent with a mixed-symmetry interpretation, as neither the 2156 nor the 2231 keV levels were populated strongly.

The fact that both the 2156 keV and 2231 keV levels have large $B(M1;2^+\to 2_1^+)$ values and enhanced $B(E2;2^+\to 2_3^+)$ values implies that there is appreciable mixing between the second 2^+ state of the intruder configuration and the 2^+ mixed-symmetry state. Based on the O(5) selection rules [42], one would not expect such strong mixing since the second 2^+ intruder state has $\nu=2$ and the lowest mixed-symmetry state $\nu=1$. Results [38] for proposed three-phonon states were *consistent* with the O(5) selection rule, and it was found that in order to explain the $B(E2)$ values from the 2_4^+ level, a significant admixture of the mixed-symmetry state was needed. The IBM-2 calculations of [28] predict this admixture to be 33%; however, the $B(M1)$ values observed in the present work indicate that the admixed amplitude must be less than this value. Thus, the caclulation considered in [28] for the mixing of the intruder and normal configuration, which works well for low-lying states, appears to be insufficient when considering mixing between the intruder and mixed-symmetry states.

IV. CONCLUSIONS

The DSAM technique following inelastic neutron scattering has been used to determine lifetimes and other properties of 2^+ states in ^{112}Cd at 2156 keV and 2231 keV. Strong branches from these levels to the 617 keV 2_1^+ level have been found to be almost pure $M1$ transitions, with $B(M1)$ values of 0.044(5) and 0.055(5)μ_N^2 respectively. These collective $M1$ transitions are interpreted as originating from the main fragments of the lowest mixed-symmetry 2^+ state. This observation constitutes the first firm evidence of mixed-symmetry states in what can be considered a good U(5) nucleus. The identification of the 2156 keV level as the second 2^+ state of the intruder configuration needs confirmation with a more precise determination of the δ value of the 687 keV γ ray. The strong mixing between the intruder and mixed-symmetry states appears to violate the O(5) selection rules, and further theoretical work is clearly needed to unravel these interactions.

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