Mixed-symmetry strength in ^{114}Cd

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Properties of low-spin states in ^{114}Cd have been studied with the $(n,n'\gamma)$ reaction. γ-ray angular distributions and excitation functions have been used to characterize the decays of the excited levels, and level lifetimes have been obtained with the Doppler-shift attenuation method. The one-phonon, mixed-symmetry strength is found to be concentrated in the 2_6^+ state, which exhibits a strong $M1$ transition to the first-excited 2^+ state and a weak $E2$ transition to the ground state. The data agree well with expectations of the neutron-proton interacting boson model.

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I. INTRODUCTION

In the framework of the interacting boson model [1,2], phonon excitations can be described by boson wave functions, and multiphonon excitations are described in this model as a result of the coupling between these wave functions. In the basic interacting boson model (IBM-1) [3,4], the neutron and proton bosons are not distinguishable; hence their boson wave functions are symmetric with regard to the exchange of protons and neutrons, resulting in fully symmetric states. The neutron-proton version of the interacting boson model (IBM-2) [5–7] treats the states in which neutron and proton bosons are distinguishable. Nonsymmetric or mixed-symmetry (MS) states are those with less than maximum neutron-proton symmetry. In IBM-2, nuclear states are characterized by the F spin, which is the isospin for proton and neutron bosons. By coupling the collective proton and neutron degrees of freedom in a nucleus with N_π proton pairs and N_ν neutron pairs, the F spin assumes values from $F_{max}=(N_\pi+N_\nu)/2$ to $F_{min}=(N_\pi-N_\nu)/2$. The fully symmetric states have maximum F spin, i.e., $F=F_{max}$, while MS states are those with $F<F_{max}$. The IBM-2 predicts enhanced $M1$ transitions between the MS states with $F=F_{max}-1$ and symmetric states with $F=F_{max}$ and the same number of phonons, with matrix elements of the order of $1\mu_N$. In addition, the IBM-2 predicts weakly collective $E2$ transitions between the symmetric and mixed-symmetric states following the phonon selection rule $\Delta N_{ph}=1$.

A well-known example of a mixed-symmetry state is the 1^+ scissors mode, which was first experimentally observed by Bohle *et al.* [8], who discovered a relatively large magnetic dipole strength in ^{156}Gd at about 3 MeV. Since then, this mode has been identified in a wide range of deformed nuclei, primarily in the rare-earth region, and the behavior of the 1^+ scissors mode is now well characterized [9–14].

In nearly spherical nuclei, the fundamental one-phonon 2^+ MS state, from which the scissors mode arises, is expected to lie somewhat lower in energy [6]. In recent measurements, the 2^+ MS states have been identified in the $N=52$ isotones ^{92}Zr, ^{94}Mo, and ^{96}Ru [15–21]. Moreover, the 1^+, 2^+, and 3^+ MS two-phonon states resulting from the coupling of the MS phonon and the symmetric quadrupole excitation were clearly identified in ^{94}Mo [15,16,21]. This extensive new information is a strong motivation for identifying MS states in other mass regions and exploring the systematic behavior of these excitations.

Several years ago, Garrett *et al.* [22] identified 2^+ states at 2156 and 2231 keV in ^{112}Cd, a nucleus well represented in a U(5) description of the IBM-1. These two 2^+ levels share the MS strength nearly equally; however, additional examples of MS states in this mass region have not been evident. With the goal of identifying the mixed-symmetry strength in ^{114}Cd, we have investigated the low-spin states in this nucleus with the $(n,n'\gamma)$ reaction.

The low-lying states in ^{114}Cd have been studied previously with a variety of different probes, and the spins and parities of these states are generally well characterized [23–26]. For some time, this nucleus has been regarded as exhibiting a multiphonon U(5) vibrational structure, coexisting with intruder excitations at low excitation energy [26–32]. Giannatiempo *et al.* [33] have analyzed the low-lying collective states of ^{110,112,114}Cd nuclei in the framework of IBM-2 to identify the 2^+ mixed-symmetry states in these nuclei. They suggested the 2_3^+ state at 1364 keV in ^{114}Cd as a pure one-phonon mixed-symmetry state; however, this state seems to be significantly lower in energy than expected in nearly spherical nuclei [6]. Moreover, this state, which has been studied extensively [26], is generally regarded as having an intruder structure [31]. This apparent ambiguity motivated us to search again for the lowest MS state in ^{114}Cd.

II. EXPERIMENTAL DETAILS AND RESULTS

Low-lying states of ^{114}Cd have been studied at the University of Kentucky 7-MV accelerator facility through the inelastic scattering of fast neutrons. A pulsed proton beam (pulse width ~1 ns, frequency ~2 MHz) with a beam current of about 2 μA was passed through a cylindrical gas cell with a length of 3.0 cm and a diameter of 1.0 cm, filled with tritium gas at nearly 1 atm pressure. A molybdenum foil with a thickness of 8 μm served as a window to the gas cell. Monoenergetic neutrons with an energy spread of about 60

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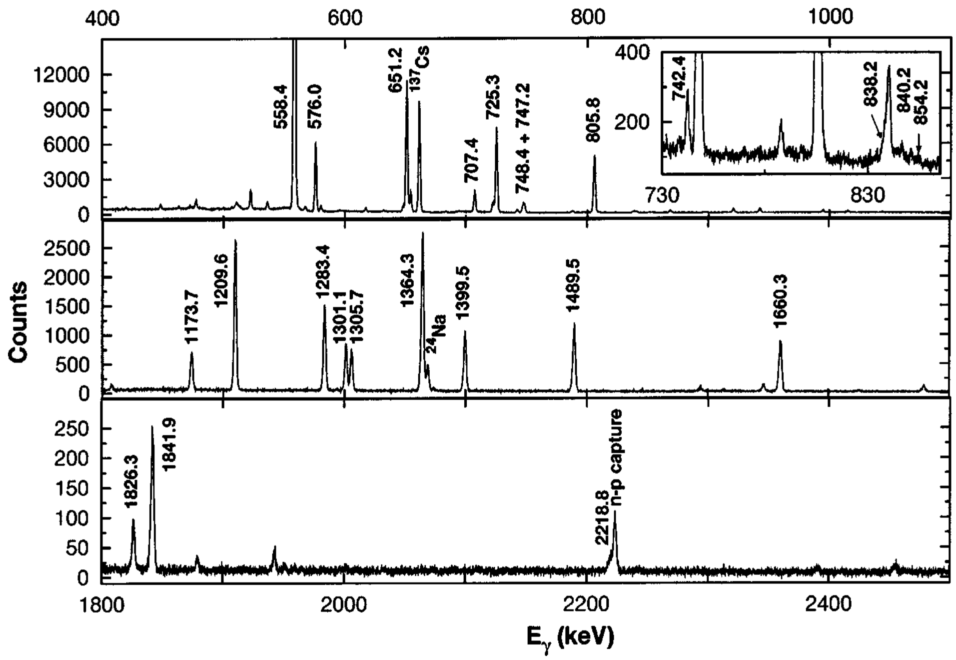

FIG. 1. γ-ray spectrum obtained in the ^{114}Cd$(n,n'\gamma)$ reaction at a neutron energy of 2.5 MeV and at a detection angle of 90°. Peaks labeled with energies in keV are from ^{114}Cd.

keV were produced through the ^{3}H$(p,n)^{3}$He reaction. The scattering sample, 13 pieces of metallic ^{114}Cd (isotopic enrichment 98.55%) totaling 47.835 g, was arranged within a cylindrical polyethelene container 1.8 cm in diameter and 3.6 cm in height. This sample was suspended in the neutron flux at a distance of 5 cm from the end of the gas cell.

The γ rays emitted in the ^{114}Cd$(n,n'\gamma)$ reaction were recorded with a Compton-suppressed HPGe detector with a relative efficiency of 55%, compared to that of a 7.6 $\times$7.6 cm^2 NaI detector. An annular BGO shield was used for Compton suppression. The HPGe and BGO detectors were at a distance of 115 cm from the scattering sample, and were further shielded by boron-loaded polyethylene, copper, and tungsten. Time-of-flight gating was implemented to suppress background radiation and improve the quality of the spectra. The neutron flux was monitored by a BF_3 proportional counter fixed at 90° relative to the axis of the incident beam and at a distance of 3.78 m from the gas cell. The neutron flux was further monitored by observing the time-of-flight spectra of neutrons in a fast liquid scintillator (NE218) at an angle of 43° relative to the incident beam axis and at a distance of 5.9 m from the gas cell. Energy and efficiency calibrations of the HPGe detector were performed with a ^{226}Ra radioactive source. More detailed descriptions of the experimental setup may be found elsewhere [34,35].

The γ-ray excitation functions of the levels in ^{114}Cd were measured over the range of neutron energies from 1.9 to 3.8 MeV in 0.1-MeV steps. To study the angular distributions of γ rays emitted in the ^{114}Cd$(n,n'\gamma)$ reaction, spectra were recorded at 11 different angles from 40° to 150° with respect to the incident 2.5-MeV neutrons. In these experiments, the energy calibration of the HPGe detector was continuously monitored with the 661.6-, 1368.6-, and 2754.0-keV γ rays from ^{137}Cs and ^{24}Na radioactive sources. Figure 1 shows a typical spectrum of the γ rays obtained at an angle of 90° with 2.5-MeV neutrons. The 1660.3-keV transition from the 2_6^+ state at 2218.8 keV to the 2_1^+ state at 558.4 keV is clearly visible. We have also observed a new transition from this state to the ground state. This 2218.8-keV transition is weak and, unfortunately, appears as a doublet with the 2223.3-keV background γ ray from the *n-p* capture reaction. We have studied the shape of this doublet with changes in energy and angle, and found that this γ ray exhibits the expected energy threshold. Moreover, the peak position of the 2218.8-keV γ ray shifts in energy with angle, whereas that of the 2223.3-keV line does not. We have also observed a weak (compared to the 1660.3-keV transition) 854.2-keV transition from the 2_6^+ level to the intruder 2_3^+ state at 1364.3 keV. Additional, much weaker decay transitions from this level, which are listed in the data compilation [36], were not observed.

The angular distributions of the γ rays were fit to even-order Legendre polynomial expansions, and compared to theoretical predictions calculated with the code CINDY [37] to determine the multipolarities of the decay transitions. The angular distributions of the 1660.3- and 2218.8-keV γ rays emitted from the 2218.8-keV level are shown in Fig. 2. Comparisons with CINDY calculations support the spin assignment of the level as $J=2$. Because of the fast ground-state transition, we can also confirm positive parity for this level. This 2^+ assignment is in agreement with the (n,γ) work by Mheemeed *et al.* [23]. Similarly, the angular distributions of the 838.2- and 1489.5-keV transitions from the 2047.9-keV level support a $J=2$ assignment, and the fast transition from this level to the 0_3^+ state indicates positive parity. The values of the $E2/M1$ mixing ratios δ and the branching ratios of the

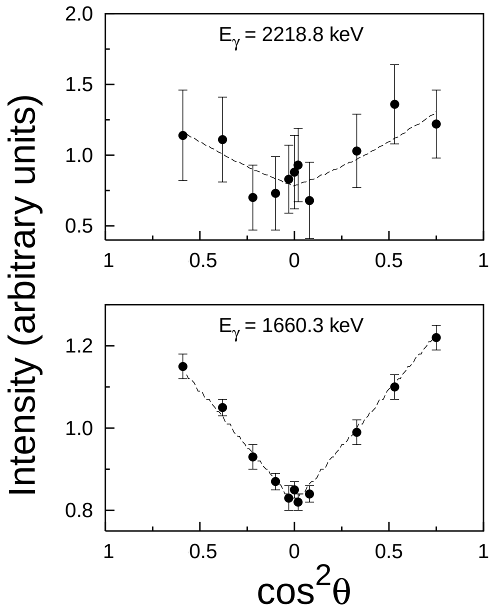

FIG. 2. Angular distributions of the 1660.3- and 2218.8-keV γ rays observed in the ^{114}Cd$(n,n'\gamma)$ reaction at a neutron energy of 2.5 MeV.

relevant transitions are given in Table I.

Lifetimes of the low-lying excited states have been extracted from the angular distribution data by considering the Doppler shifts of the γ rays with change in the angle. The position of the centroid of the γ-ray peak, $E_\gamma(\theta)$, at an emission angle θ relative to the incident neutrons can be described [38] as

$$E_\gamma(\theta)=E_0\left(1+F(\tau)\frac{v_{\text{c.m.}}}{c}\cos\theta\right), \tag{1}$$

where E_0 is the unshifted γ-ray energy and $F(\tau)$ is the Doppler-shift attenuation factor. At 2.5 MeV neutron energy, the velocity of the recoiling nucleus in the center-of-mass frame is $v_{\text{c.m.}}=(6.37\times10^{-4})c$. The observed energies of the

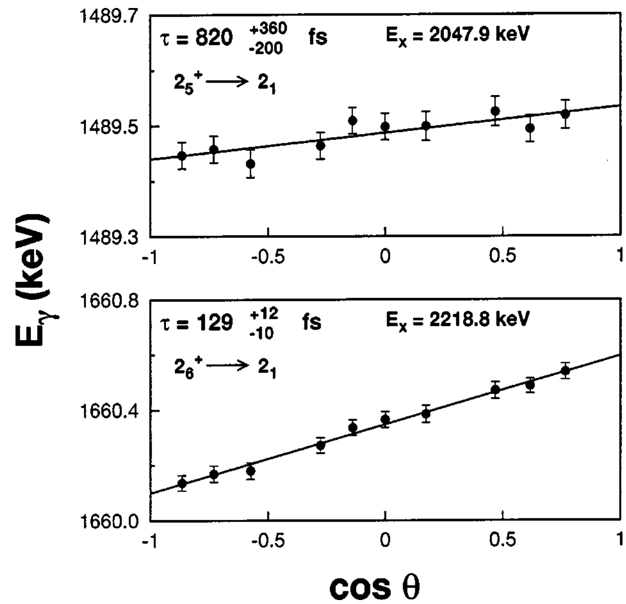

FIG. 3. Shift in γ-ray energies as a function of cos θ for the indicated transitions. The lines are linear fits to the data, from which the $F(\tau)$ values have been extracted.

1489.5- and 1660.3-keV γ rays as a function of the emission angle are shown in Fig. 3. The straight lines indicate the fits to the experimental data from which the $F(\tau)$ values have been determined. Lifetimes can be obtained by a comparison of the experimental $F(\tau)$ values of Fig. 3 with those calculated following the nuclear stopping theory of Winterbon [39,40]. The level lifetimes obtained are summarized in Table II. Casten *et al.* [26] obtained lifetimes for the 2_5^+ and 2_6^+ levels by the γ-ray induced Doppler-broadening technique. A comparison of our more precise results with their earlier measurements shows good agreement.

III. DISCUSSION

The lifetimes of all the observed 2^+ states up to 2.5 MeV are presented in Table II. As the lowest four 2^+ levels are too

TABLE I. Properties of selected transitions in ^{114}Cd.

J_i^π	J_f^π	E_γ (keV)	B.R.	$\delta(J_i^\pi \rightarrow J_f^\pi)$	$B(M1)$ μ_N^2	$B(E2)$ (W.u.)
2_5^+	0_3^+	742.4(1)	0.075 ± 0.002	$E2$		$10.0^{+3.3}_{-3.0}$
	2_2^+	838.2(1)	0.041 ± 0.003	$2.4^{+3.3}_{-1.2}$	$\leqslant 0.003$	$2.6^{+1.6}_{-1.4}$
				$0.00^{+0.29}_{-0.24}$	$0.005^{+0.002}_{-0.002}$	$3.0^{+1.2}_{-3.0}$
	2_1^+	1489.5(1)	0.884 ± 0.003	$-0.32^{+0.03\ \text{a}}_{-0.02}$	$0.017^{+0.005}_{-0.005}$	$0.34^{+0.17}_{-0.14}$
				$10.0^{+5.0}_{-0.9}$		$3.6^{+1.2}_{-1.1}$
2_6^+	2_3^+	854.2(3)	0.009 ± 0.001	$0.64^{+1.05}_{-0.53}$	$0.005^{+0.003}_{-0.003}$	$1.1^{+2.3}_{-1.1}$
	2_1^+	1660.3(1)	0.961 ± 0.002	$0.19^{+0.04\ \text{a}}_{-0.05}$	$0.089^{+0.009}_{-0.009}$	$0.50^{+0.26}_{-0.24}$
				$1.50^{+0.11}_{-0.10}$	$0.028^{+0.005}_{-0.005}$	$10.2^{+1.3}_{-1.3}$
	0_1^+	2218.8(2)	0.030 ± 0.002	$E2$		$0.107^{+0.017}_{-0.017}$

[a]Accepted values for δ.

TABLE II. Lifetimes of the low-lying 2^+ states in ^{114}Cd.

J_i^π	E_x (keV)	τ (fs)
2_1^+	558.4(1)	14700(900) [a]
2_2^+	1209.7(1)	4500(400) [a]
2_3^+	1364.3(1)	7500(600) [a]
2_4^+	1841.9(1)	940(170) [a]
2_5^+	2047.9(1)	820^{+360}_{-200} [b]
2_6^+	2218.8(1)	129^{+12}_{-10} [b]

[a]Reference [36].
[b]Present measurement.

long lived to be measured by the Doppler-shift attenuation technique, we obtained only lower limits for their lifetimes. Therefore, the values for these levels listed in the table are taken from Ref. [36]. Moreover, these lowest 2^+ levels have been well established as either vibrational phonon or intruder states [26]. We have examined two 2^+ levels as possible mixed-symmetry states. These states are well within the energy range 1.7–2.7 MeV, expected from IBM-2 calculations for 2^+ MS states [6].

Transitions to the 2_1^+ state have been observed from the 2_5^+ and 2_6^+ levels at 2047.9 and 2218.8 keV, respectively. As noted earlier, we have observed the ground-state transition from the 2_6^+ level, but we do not observe the 2_5^+ ground-state transition reported earlier [36]. The primary decay of the 2_5^+ level is the 1489.5-keV transition. In addition, another weak transition of 838.2 keV from the 2_5^+ level has been observed in this study. Considering the 1489.5-keV transition as the strongest from the 2_5^+ level, and as representing 100% intensity, we have calculated the sensitivity limit of our detection system and have found that we could have observed a transition directly to the ground state with a peak intensity as low as 1.4%. This intensity limit is significantly below the value of 7.6% reported in Ref. [36]. Interestingly, we have observed a 2047.8-keV transition with a threshold around 3250 ± 50 keV in the excitation function measurements. Hence we conclude that the 2047.8-keV transition is a decay from a level above 3 MeV.

Transition strengths of several levels have been calculated from the level lifetimes, the branching ratios, and the $E2/M1$ multipole mixing ratios δ of the γ rays. Table I displays the information obtained in our experiments and used in the calculation of transition strengths. Unfortunately, the angular distribution data for the 1489.5- and 1660.3-keV transitions exhibit two solutions for δ, with more or less equal χ-squared fits to the statistical model calculations [37]. We compare our results with those from previous work (see Table III). We should note that our values are generally in excellent agreement with those obtained by Demidov and co-workers [41,42] from $(n,n'\gamma)$ measurements with reactor fast neutrons. They also experienced a similar ambiguity in selecting unique values of the mixing ratios for the 1660.3-keV transition. In γ-γ directional correlation measurements following the (n,γ) reaction, Hungerford and Hamilton [43] have determined the mixing ratios of the 1489.5- and 1660.3-keV transitions. By combining these values with the internal conversion coefficients measured by Mheemeed *et al.* [23], Hungerford and Hamilton determined the $E2$ contributions of these transitions to be between 0.7% and 44% for the 1489.5-keV transition, and (24 ± 21)% for the 1660.3-keV transition. Clearly, these data strongly support our choice of the smaller value of δ in each case. Accepting our lower values of δ's, we calculate the $M1$ transition strengths to be $B(M1;2_5^+\to2_1^+)=(0.017\pm0.005)\mu_N^2$ and $B(M1;2_6^+\to2_1^+)=(0.089\pm0.009)\mu_N^2$, respectively.

Figure 4 displays the partial level scheme relevant to this work; it appears quite similar to that observed in ^{112}Cd [22]. It is clear that for both the 2_5^+ and 2_6^+ states, the largest decay branches are predominantly $M1$ transitions to the 2_1^+ state. But both levels also decay to intruder states. The $B(E2)$ value of $10.0^{+3.3}_{-3.0}$ W.u. for the transition from the 2_5^+ state to the intruder 0_3^+ state suggests the presence of a sizable intruder component in the wave function of the 2_5^+ state. This value is in reasonable agreement with the accepted value of 17 ± 5 W.u. [36]; however, since the angular distribution was measured at 2.5 MeV incident neutron energy, it was not affected by contributions from the 742.9-keV γ ray, known to arise from a state at 2701 keV [23]. The 838.2-keV γ ray forms a doublet with the strong 840.2-keV transition from the 2204.5-keV level, and the 854.2-keV γ-ray peak is small. Hence, it is difficult to obtain precise values of δ in these cases.

According to the IBM-2 for nuclei in the U(5) limit, the $M1$ transition strength from the one-phonon 2^+ MS state $(2_{1,ms}^+)$ to the one-phonon fully symmetric (2_1^+) state can be calculated [44] as

$$B(M1;2_{1,ms}^+\to2_1^+)=\frac{3}{4\pi}(g_\nu-g_\pi)^2 6\frac{N_\nu N_\pi}{N^2}\mu_N^2. \quad (2)$$

TABLE III. Comparison of results for $E2/M1$ mixing ratio from different experiments.

E_γ (keV)	δ (Present work)	δ [a] $(n,n'\gamma)$	δ [b] (n,γ)
1489.5 (1)	$-0.32^{+0.03}_{-0.02}$, [c] $10.0^{+5.0}_{-0.9}$	$-0.29^{+0.05}_{-0.05}$	$-0.90\leqslant\delta\leqslant-0.09$
1660.3 (1)	$0.19^{+0.04}_{-0.05}$, [c] $1.50^{+0.11}_{-0.10}$	$0.17^{+0.06}_{-0.06}$, $1.5^{+0.2}_{-0.2}$	$0.56^{+0.34}_{-0.20}$

[a]References [41,42].
[b]Reference [43].
[c]Accepted values for δ.

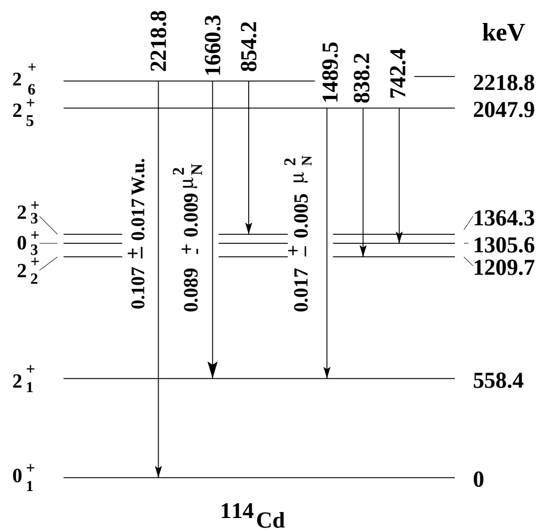

FIG. 4. Partial level scheme of ^{114}Cd relevant to this work. $E2$ strength is given in W.u.; $M1$ strengths are in μ_N^2. Transition and level energies are in keV.

Considering ^{100}Sn as the inert core, the neutron and proton boson numbers are $N_\nu=8$ and $N_\pi=1$. With standard boson g factors, $g_\nu=0$ and $g_\pi=1$, the calculated value for ^{114}Cd is $B(M1;2^+_{1,ms}\to 2^+_1)=0.14\mu_N^2$. As noted earlier, the experimentally observed $B(M1)$ strengths of the transitions from the 2_5^+ and 2_6^+ levels to the first-excited state are $(0.017\pm0.005)\mu_N^2$ and $(0.089\pm0.009)\mu_N^2$, respectively. Hence, it can be concluded that the mixed-symmetry strength in ^{114}Cd is fragmented between the 2_5^+ and 2_6^+ levels at 2047.9 and 2218.8 keV in ^{114}Cd. If we sum these transition strengths, the measured $B(M1)$ from the one-phonon mixed-symmetry state to the first-excited state is $(0.106\pm0.010)\mu_N^2$. This approaches the value predicted by the IBM-2, and is comparable to that observed in ^{112}Cd, $0.099\mu_N^2$. However, most of the mixed-symmetry strength in ^{114}Cd is concentrated in a single state, the 2218.8-keV level. This behavior is in contrast with ^{112}Cd, where the strength is shared nearly equally between the states at 2156 and 2231 keV.

The ground-state transition of the 2218.8-keV level has a $B(E2)$ of only 0.107 ± 0.017 W.u. While this value is much smaller than, for example, the $B(E2)$ values of the ground-state transitions in the $N=52$ isotones, it is similar to that observed in ^{112}Cd.

IV. SUMMARY AND CONCLUSIONS

Inelastic neutron scattering experiments have been performed on ^{114}Cd to identify the lowest mixed-symmetry state in this nucleus. The properties of the 2^+ states around 2 MeV have been examined through γ-ray angular distribution and excitation function measurements, and the Doppler-shift attenuation method has been employed to determine the lifetimes of these states. The 2_5^+ state at 2047.9 keV and the 2_6^+ state at 2218.8 keV have been found as the main fragments of the one-phonon mixed-symmetry state, with most of the strength concentrated in the latter. The $M1$ transitions from these levels to the 2_1^+ state indicate that these states are the largest fragments of the one-phonon mixed-symmetry state originating from the isovector quadrupole excitations in the valence shells of ^{114}Cd. The energies of these states are very similar to those observed for MS states in ^{112}Cd. Strong $E2$ transitions from the 2_5^+ level to the intruder state are indicative of mixing of intruder components in the wave function of this level.

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