CONF-8405231--2

BNL-35167

INTRUDER STATES IN THE CADMIUM ISOTOPES AND A SIMPLE SCHEMATIC CALCULATION

BNL--35167

DE85 001353

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ABSTRACT

Angular correlation studies of ^{118,120}Cd at TRISTAN have allowed the discovery and identification in each nucleus of two new 0^+ states and their respective E2 decay properties. The results have been interpreted in terms of a simple schematic model based on the mixing of normal vibration-like and intruder rotation-like 2p-4h configurations.

The Cd isotopes until the very recent past were considered to be the "classic" examples of good quadrupole vibrational nuclei. Detailed studies of ^{112,114}Cd,[1,2] however, show strong deviations from the expected vibrational structure by the presence of two extra $0^+,2^+$ states as low in excitation energy as the two phonon triplet, forming a quintuplet of levels. Figure 1 shows the systematics of the low-lying states for the Cd nuclei. In ^{114}Cd, the quintuplet of levels is observed at ≈ 1.2 MeV with enormous interconnecting E2 transitions precluding the possibility of identifying the extra states as members of the three phonon group. Although it has been suggested that this type of structure is the result of the coexistence and interplay of vibrational and intruder degrees of freedom, it was only recently that a detailed quantitative explanation[3] has been offered in terms of the mixing of two such configurations for the observed structures of ^{112,114}Cd. The rotation-like intruder states are described as 2p-4h shell model states originating from the excitation of a pair of protons across the Z=50 shell gap to the next oscillator shell. In Ref. 3, two equivalent treatments are offered, one, in terms of shell model states incorporating 2p-4h excitations and the other, in terms of the IBA-2.

The key feature of the model is that ^{114}Cd (Z=48) has one proton hole boson (N_π=1) and eight neutron bosons (N_ν=8) which give rise to the vibration-like configuration, while the 2p-4h system which is approximated by three proton bosons (N_π=3) gives rise to the rotation-like configuration. Calculations[3] for the cadmium nuclei have been performed with N_π=1, N_π=3, and the resulting configurations have been mixed; the total Hamiltonian is

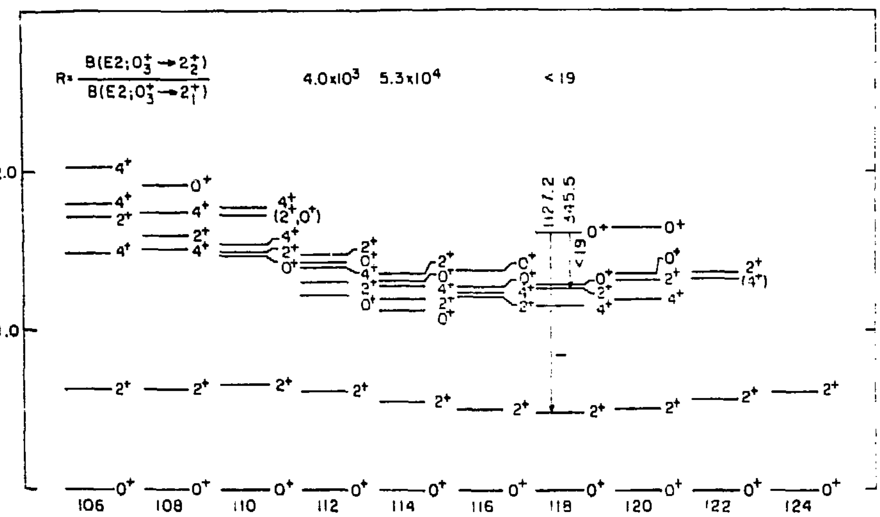
$$H = H_{vib(N_\pi=1)} + H_{int(N_\pi=3)} + H_{mix}.$$

The Hamiltonian for the vibrational and intruder states is essentially the same.

$$H_{\left\{\begin{matrix}vib\\int\end{matrix}\right\}} = \varepsilon_\pi n_{d_\pi} + \varepsilon_\nu n_{d_\nu} + \kappa Q_\pi \cdot Q_\nu$$

where $\varepsilon_\pi, \varepsilon_\nu$ are proton and neutron boson energies, respectively, and $\kappa Q_\pi \cdot Q_\nu$ is the neutron-proton interaction. The $Q_\pi \cdot Q_\nu$ interaction represents a long-range, attractive force which goes as n(n-1) where n is the number of particles and, therefore, approximately as $N_\pi \cdot N_\nu$, which is in turn proportional to N_ν across a given isotopic chain. The $Q_\pi \cdot Q_\nu$ term alone provides a "V" shaped systematics of the intruder states which decrease in excitation energy towards the midshell and rise thereafter.

A crucial test of calculations presented in Ref. 3 is the verification of the predicted rise in energy of the intruder states. The systematics shown in Fig. 1 up to ^{116}Cd showed no clear indication of such a rise. This was the primary motivation in the experimental search for the members of the two phonon vibrational and the intruder configurations in the heavier Cd nuclei. The structures of $^{118,120}Cd$ were studied from the decay of Ag produced by fission of ^{235}U at the on-line mass separator TRISTAN at Brookhaven National Laboratory by using a fixed four-detector angular correlation system. The focus of these studies was on the discovery and identification of 0^+ states. The correlation patterns observed for ^{118}Cd[4] allowed the identification of two 0^+ states at 1286 keV and 1615 keV. These new levels are shown in Fig. 1. The data for ^{118}Cd represents the first clear evidence of the rise in energy of the intruder state in good agreement with the above-mentioned model. The energies of the two phonon states remain fairly constant throughout the shell. Although it is not possible with the available information to clearly determine the structure of the 0^+ at 1615 keV as 2p-4h, no other 0^+ states were observed between the 1286 keV and 1615 keV states, implying that the intruder state is at 1615 keV or higher. In either circumstance, the interpretation is the same; the intruder states have risen energy.



CADMIUM SYSTEMATICS

Fig. 1. Systematics of the low-lying states in the Cd nuclei. The B(E2) ratio R is given for ^{112,114}Cd along with some of the results of the present study for ^{118,120}Cd.

The structures of the cadmium nuclei are explained in terms of the mixing of rotational and vibrational configurations. The amount of mixing is therefore obviously dependent on the proximity of the two sets of states. A good signature of the amount of configuration mixing is the B(E2) ratio $R=B(E2:0^+_3 \rightarrow 2^+_2)/B(E2:0^+_3 \rightarrow 2^+_1)$. Figure 1 shows a drop in this ratio from 5.3×10^4 in ^{114}Cd to <19 in ^{118}Cd, indicating a large decrease in the mixing of the two configurations.

In order to extend the systematic study of the evolution of intruder states, a similar study was undertaken for ^{120}Cd. Two new levels were characterized as 0^+ states in ^{120}Cd at 1388 keV and 1743 keV and are shown in Fig. 1. It is interesting to note that the increase in the excitation energy of the intruder state in ^{120}Cd is not as substantial as in ^{118}Cd and clearly less than that expected from the particle number dependence of the neutron-proton interaction. One possible explanation by K. Heyde suggests the need for the inclusion of the identical boson interactions in the Q·Q interaction; i.e., $\langle \kappa Q_\pi \cdot Q_\nu + \kappa' Q_\pi \cdot Q_\pi + \kappa' Q_\nu \cdot Q_\nu \rangle$. An important consequence of the addition of $Q_\pi \cdot Q_\pi$ and $Q_\nu \cdot Q_\nu$ terms is that the predicted systematics of the intruder states acquire a parabolic shape rather than a "V" shaped systematics resulting solely from neutron-proton interactions. This means that the predicted rise in excitation energy of the intruder states will proceed more slowly across the shell.

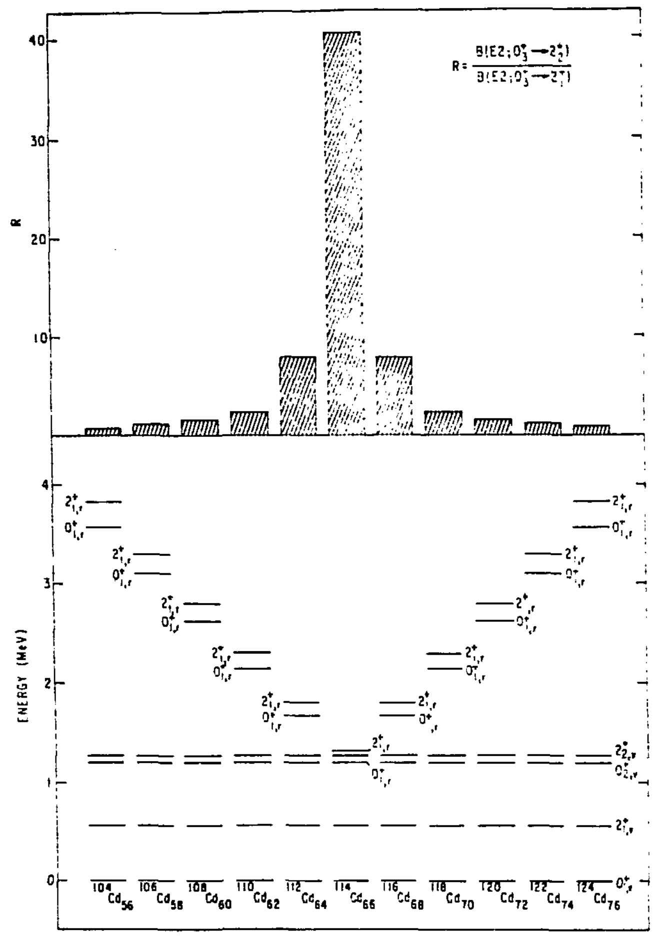


Fig. 2. The lower portion shows the excitation energies of the vibration-like (J^{π},ν) and rotation-like (J^{π},r) intruder states before mixing as a function of mass. The upper portion shows the B(E2) ratio R calculated within the schematic model using the wave functions resulting from the mixing.

In order to extend the predictions of the model presented in Ref. 3 to a wide range of Cd isotopes, a simple schematic model was constructed using ^{114}Cd as its basis. The calculated wave functions given for the 0^+ states in this nucleus show a complete admixture of intruder and vibrational states, implying degeneracy of states prior to mixing. Then keeping the vibrational states constant throughout the shell and scaling the intruder state excitation energies by $N_\pi \cdot N_\nu$, it is possible to construct the states of the two configurations before mixing as shown in the lower portion of Fig. 2. It is now possible to calculate the wave functions of $^{104-124}$Cd by using the mixing matrix elements of Ref. 3. The wave functions are

Table I. Absolute values of the wave function amplitudes for the $|0^+_3\rangle$ and $|2^+_3\rangle$ states in terms of vibration-like and the intruder, rotation-like, basis states discussed in the text.

	$0^+_3)$		$\psi(2^+_3)$		
		$\vert 0^+_1,r\rangle$	$\vert 2^+_1,v\rangle$	$\vert 2^+_2,v\rangle$	$\vert 2^+_1,r\rangle$
^{114}Cd	0.7071	0.7071	0.1056	0.5400	0.8417
^{116}Cd	0.2066	0.9784	0.0648	0.0898	0.9960
^{118}Cd	0.1085	0.9941	0.0466	0.0474	0.9989
^{120}Cd	0.0731	0.9973	0.0363	0.0322	0.9995
^{122}Cd	0.0550	0.9985	0.0295	0.0240	0.9997
^{124}Cd	0.0441	0.9990	0.0268	0.0190	0.9998

tabulated in Table 1. These coefficients are then used to calculate the ratio R shown in the top portion of Fig. 2, where the elementary matrix elements for the vibrational states are scaled by $\sqrt{N}$ which is the boson number dependence of E2 matrix elements in SU(5), and for the rotational states by N which is the boson number dependence of E2 matrix elements in SU(3).

The results of this simple calculation show a maximum for R in ^{114}Cd and a symmetric decrease away from midshell as seen in the top portion of Fig. 2. The predicted systematic trends in R show agreement with the available data. It is clear that the decrease in R is not of the magnitude observed in experiment, however, it should be noted that the schematic calculation simply exploits the particle number dependence of the $Q_\pi \cdot Q_\nu$ term. The general agreement with empirical trends shows that this schematic model embodies the most important physical effects responsible for the observed structure in the cadmium nuclei.

ACKNOWLEDGEMENT

Research has been performed under Contracts DE-AC02-76CH00016 and DE-AC02-79ER1049 with the United States Department of Energy.

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