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Study of nuclear properties for even-even nuclei (Transition probabilities B(E2)↑, deformation parameters β_2 and quadrupole moments Q_0)

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Abstract
This study investigates the electric quadrupole transition probabilities (B(E2)↑), deformation parameter (β_2), and intrinsic quadrupole moments (Q_0) for transition levels in even-even Cadmium isotopes, Cd^{98} to Cd^{130}) (Z=48). The calculations were performed for the ($0^+ \rightarrow 2^+$, $2^+ \rightarrow 4^+$, $4^+ \rightarrow 6^+$, and $6^+ \rightarrow 8^+$) transition levels by the Global Best Fit method.
The study reveals systematic trends in these nuclear parameters across the isotopic chain and with increasing transition levels. A notable finding is the comparatively lower values of B(E2)↑, β_2, and Q_0 for isotopes with neutron numbers approaching or at magic numbers, such as (N=50 for Cd^{98} and N=82 for Cd^{130}). This observation indicates a reduction in collective behavior and a tendency towards a more spherical nuclear shape in these regions, consistent with established nuclear shell effects.

Keywords: Electric quadrupole transition probabilities (B(E2)↑), deformation parameters (β_2), intrinsic quadrupole moments (Q_0), and (GBF) method.

1. Introduction
The atom is the smallest part of the elements that saves the basic features and have a minor massive central named the nucleus; this nucleus is contains of two types of separate nucleons (Neutrons and Protons) and surrounded by orbiting electrons [1].
The study of atomic nuclei, finite many-body quantum systems, seeks to understand the emergent properties arising from the complex interplay between constituent protons and neutrons. One of the most fundamental properties is the nuclear shape and its associated collective dynamics. Even-even nuclei, with their 0^+ ground states, provide a simplified yet rich canvas for exploring collective excitations, such as vibrations and rotations [2].
The nucleus in first presumed to have spherical form, and then in (1924), Wolfgang Pauli offered that an excited nucleus could found in changed forms. Then in (1936) Fritz Kalckar and Bohr proposed It possible to know the forms of the nuclei by computing "photons of a Gamma ray" emitted from of an excited nucleus.
The variation in the nuclear shape of a nucleus can be because increase in excitation energies and or the angular momenta. Such changes can be because the dynamic reaction of the nuclear system to rotation or by rearranging the orbital formation of the nucleus. The increase or decrease in proton or neutron number can lead to the variation in the nuclear shape [3].
The Cadmium (Cd) isotopic chain, with a proton number Z=48, lies just two protons shy of the magic number Z=50. This proximity to a major proton shell closure makes the Cd isotopes prime candidates for exhibiting vibrational-like behavior, as described by the liquid drop model, rather than the strong rotational patterns seen in well-deformed, mid-shell nuclei [4, 5]. These isotopes have therefore been a focal point of experimental and theoretical investigations for decades, serving as a critical testing ground for nuclear structure models.
The primary observables used to quantify nuclear collectivity and deformation are the reduced electric quadrupole transition probability (B(E2), the quadrupole deformation parameter, and the electric quadrupole moment (Q_o).

The B(E2) value for the transition from the ground state to the first 2^+ excited state is a direct measure of the dynamic collectivity of the nucleus. The quadrupole deformation parameter quantifies the degree of quadrupole deformation, while the quadrupole moment provides crucial information about the intrinsic nuclear shape in that excited state [6].

A significant development in the understanding of the Cd region was the identification of low-lying "intruder" states [7]. These are states that arise from proton-pair excitations across the Z=50 shell gap, leading to configurations with a different intrinsic deformation. The mixing between these intruder states and the normal vibrational states gives rise to the phenomenon of shape coexistence, which is now understood to be a key feature of the Cd isotopes and is essential for explaining the detailed structure, particularly the pattern of E0 transitions and the behavior of the 0^+ excited states [8].

Recent experimental efforts have utilized advanced techniques like multi-step Coulomb excitation with radioactive ion beams to probe the electromagnetic properties of more exotic, neutron-rich Cadmium isotopes [9, 10]. These experiments provide stringent tests of modern theoretical calculations, including large-scale shell-model calculations and energy density functional theories [11, 12]. The spectroscopic quadrupole moments, have been of particular interest, as their non-zero values are in direct contradiction to the simple vibrational model and provide a sensitive probe of configuration mixing [13].

Many studies have focused on investigates the nuclear parameters (the electric quadrupole transition probabilities (B(E2)↑), deformation parameters (β_2), and intrinsic quadrupole moments (Q_0) for transition levels in even-even isotopes. For example, [14, 15,1, 16].

The purpose of the current study is to methodically study of nuclear parameters (the electric quadrupole transition probabilities (B(E2)↑), deformation parameters (β_2), and intrinsic quadrupole moments (Q_0)) for transition levels ($0^+ \rightarrow 2^+$, $2^+ \rightarrow 4^+$, $4^+ \rightarrow 6^+$, and $6^+ \rightarrow 8^+$) in even-even Cadmium isotopes, from Cd^{98} to Cd^{130} and elucidate the dependance of nuclear parameters on the mass number and transition levels.

2. Theory

This section presents the way used to calculate the electric quadrupole transition probabilities (B(E2)↑), deformation parameters (β_2), and intrinsic quadrupole moments (Q_0).

2.1 Electric Quadrupole Reduced Transition Probability B(E2)↑

The B(E2)↑ is the transition of a particle from lower energy state to higher energy state and calculated by using Global Best Fit (GBF) Method [17].

The information of the energy E (Kev) of the 2_1^+ state according to the (GBF) Method, is completely that is essential to make a estimate for the consistent mean life time for the γ-ray, τ_γ (in ps) and hence, the B(E2)↑(e^2b^2) value. In the base of the hydrodynamic model with irrotational flow, Bohr and Mottelson [18] have derivative simple terms for the τ_γ value is given by

$$\tau_\gamma \approx 0.6 \times 10^{14} E^{-4} Z^{-2} A^{1/3} \tag{1}$$

The τ_γ value of sphere-shaped nucleus for small harmonic vibrations is,

$$\tau_\gamma \approx 1.4 \times 10^{14} E^{-4} Z^{-2} A^{1/3} \tag{2}$$

For collective rotations in axially symmetric nuclei, Grodzins [19] proposed a similar dependence but replaced $A^{1/3}$ with A. By allowing variations in the exponents of E and A [17, 20], we found that the best global fit to the available data [21] was:

$$\tau_\gamma = 1.25 \times 10^{14} E^{-4} Z^{-2} A^{0.69} \tag{3}$$

The relationship between τ_γ and B(E2)↑ is given by:

$$\tau_\gamma = 40.81 \times 10^{13} E^{-5} \left(B(E2)\uparrow / e^2 b^2\right)^{-1} \tag{4}$$

When changed to B(E2)↑, this expression go to

$$B(E2)\uparrow = 3.26\ E^{-1} Z^2 A^{-0.69} \tag{5}$$

We also presented that, the 1/E dependence is more chief than the exact A dependence. If the exponent of A is fixed as −2/3 (instead of −0.69), the revised best fitting to the information was found [22] to be,

$$B(E2)\uparrow = \frac{2.6 Z^2}{E_{\gamma_0} A^{\frac{2}{3}}} \tag{6}$$

2.2 Electric Quadrupole Moment

The electric quadrupole moment Q_0 reflects how much the nuclear charge distribution deviates from a perfectly spherical shape. A nonzero intrinsic quadrupole moment signifies that the distribution is not spherically symmetric. By convention, Q_0 is considered positive ($Q_0 > 0$) for a prolate (elongated) ellipsoid and negative ($Q_0 < 0$) for an oblate (flattened) ellipsoid [23, 24].

So electric quadrupole moment (Q_0) represented one of the important amounts to fix the nuclide form, which is in go associated to the reduced transition probability B(E2)↑ [1].

$$Q_0 = \left[\left(\frac{16\pi}{5}\right)\frac{B(E2)\uparrow}{e^2}\right]^{\frac{1}{2}} \tag{7}$$

Here, Q_0 measured in barn (b) unit.

2.3 Quadruple Deformation Parameter (β_2)

The (β_2) symbolizes to the quantity of the deviation of the nuclear form from axial symmetry and too denotes to the "nuclear quadruple deformation (Elongation or flattening)" which is calculated from equation below [3].

$$\beta_2 = \frac{4\pi}{3ZR_0^2}\left[\frac{B(E2)\uparrow e^2 b^2}{e^2}\right]^{1/2} \tag{8}$$

R_0 is the average radius nuclear calculated by using the following equation

$$R_0^2 = 0.0144\ A^{2/3}\ \text{barn} \tag{9}$$

3. Methodology

The values for the electric quadrupole transition probabilities (B(E2)↑), deformation parameters (β_2), and intrinsic quadrupole moments (Q_0) for transition levels in even-even Cadmium isotopes, (Cd^{98} to Cd^{130}) were subsequently calculated using Equations (6, 7, 8 and 9) respectively. The excitation Energy levels (E) for for the($0^+ \rightarrow 2^+$, $2^+ \rightarrow 4^+$, $4^+ \rightarrow 6^+$, and $6^+ \rightarrow 8^+$) transition levels were extracted directly from the provided experimental data [25].

Note: It is important to know that the values of B(E2)↑, β_2, and Q_0 for Cd^{126} for the($4^+ \rightarrow 6^+$, and $6^+ \rightarrow 8^+$) transition levels are not available due to the unavailability of their energy values.

4. Results and Discussion

The calculated values for the upward electric quadrupole transition probabilities (B(E2)↑), deformation parameters (β_2), and intrinsic quadrupole moments (Q_0) for transition levels in even-even Cadmium isotopes, (Cd^{98} to Cd^{130}) are systematically presented in (Table 1).

The relationships and behaviors of these calculated parameters are further illustrated and discussed through a series of conceptual figures (1, 2 and 3).

Table 1: Transition Level *li →lf*, Energy, E (KeV), Average Radius R_o^2 (b), The Electric Quadrupole Transition Probabilities B(E2)↑ (e^2b^2), Deformation Parameter β_2, and Quadrupole Moments Q_0 (b) for transition levels in even-even Cadmium isotopes, (Cd^{98} to Cd^{130}).

Nuclei	Number of Neutron	Transition Level, *li →lf* [25]	Energy, E in KeV [25]	R_o^2 (b)	B(E2)↑ (e^2b^2)	β_2	Q_0 (b)
Cd-98	50	$0^+ - 2^+$	1395.1	0.306	0.202	0.128	1.424
		$2^+ - 4^+$	687.7		0.409	0.182	2.029
		$4^+ - 6^+$	198.3		1.421	0.339	3.778
		$6^+ - 8^+$	147.2		1.914	0.394	4.386
Cd-100	52	$0^+ - 2^+$	1004.1	0.310	0.276	0.147	1.668
		$2^+ - 4^+$	794.95		0.349	0.166	1.874
		$4^+ - 6^+$	296.4		0.938	0.272	3.070
		$6^+ - 8^+$	452.6		0.614	0.220	2.484
Cd-102	54	$0^+ - 2^+$	776.55	0.314	0.353	0.164	1.884
		$2^+ - 4^+$	861.3		0.318	0.156	1.789
		$4^+ - 6^+$	593		0.462	0.188	2.156
		$6^+ - 8^+$	487.43		0.562	0.208	2.378
Cd-104	56	$0^+ - 2^+$	658	0.318	0.411	0.175	2.033
		$2^+ - 4^+$	834.1		0.324	0.156	1.806
		$4^+ - 6^+$	878.1		0.308	0.152	1.760
		$6^+ - 8^+$	532.9		0.508	0.195	2.259
Cd-106	58	$0^+ - 2^+$	632.66	0.322	0.422	0.175	2.061
		$2^+ - 4^+$	861.16		0.310	0.150	1.766
		$4^+ - 6^+$	997.87		0.268	0.140	1.641
		$6^+ - 8^+$	552.53		0.484	0.188	2.205
Cd-108	60	$0^+ - 2^+$	632.97	0.326	0.417	0.172	2.047
		$2^+ - 4^+$	875.47		0.301	0.146	1.741
		$4^+ - 6^+$	1032.92		0.255	0.135	1.602
		$6^+ - 8^+$	569.31		0.463	0.181	2.159
Cd-110	62	$0^+ - 2^+$	657.76	0.330	0.396	0.166	1.996
		$2^+ - 4^+$	884.67		0.294	0.143	1.721
		$4^+ - 6^+$	937.48		0.278	0.139	1.672
		$6^+ - 8^+$	707.40		0.368	0.160	1.925
Cd-112	64	$0^+ - 2^+$	617.51	0.334	0.417	0.168	2.048
		$2^+ - 4^+$	798.04		0.323	0.148	1.801
		$4^+ - 6^+$	752.14		0.342	0.152	1.855
		$6^+ - 8^+$	713.23		0.361	0.156	1.905
Cd-114	66	$0^+ - 2^+$	558.45	0.338	0.456	0.174	2.141
		$2^+ - 4^+$	725.29		0.351	0.152	1.878
		$4^+ - 6^+$	707		0.360	0.154	1.902
		$6^+ - 8^+$	678.2		0.375	0.157	1.942
Cd-116	68	$0^+ - 2^+$	513.5	0.342	0.490	0.178	2.219
		$2^+ - 4^+$	705.95		0.356	0.152	1.893
		$4^+ - 6^+$	807.21		0.312	0.142	1.770
		$6^+ - 8^+$	798		0.315	0.143	1.780
Cd-118	70	$0^+ - 2^+$	487.77	0.346	0.510	0.179	2.264
		$2^+ - 4^+$	677.13		0.367	0.152	1.922
		$4^+ - 6^+$	771		0.322	0.143	1.801
		$6^+ - 8^+$	655		0.380	0.155	1.954
Cd-120	72	$0^+ - 2^+$	505.9	0.350	0.486	0.173	2.211
		$2^+ - 4^+$	697.8		0.352	0.147	1.882
		$4^+ - 6^+$	830		0.296	0.135	1.726
		$6^+ - 8^+$	852.5		0.288	0.133	1.703
Cd-122	74	$0^+ - 2^+$	569.45	0.354	0.427	0.161	2.072
		$2^+ - 4^+$	759.7		0.320	0.139	1.794
		$4^+ - 6^+$	848.8		0.286	0.131	1.697
		$6^+ - 8^+$	645.4		0.377	0.151	1.947
Cd-124	76	$0^+ - 2^+$	612.8	0.358	0.393	0.152	1.987
		$2^+ - 4^+$	771.9		0.312	0.136	1.770

		4^+ - 6^+	754.4		0.319	0.137	1.791
		6^+ - 8^+	534.4		0.450	0.163	2.128
Cd-126	78	0^+ - 2^+	651.91	0.361	0.365	0.145	1.916
		2^+ - 4^+	814.92		0.292	0.130	1.714
		4^+ - 6^+			--	--	--
		6^+ - 8^+			--	--	--
Cd-128	80	0^+ - 2^+	654.82	0.365	0.360	0.143	1.902
		2^+ - 4^+	784.6		0.300	0.130	1.737
		4^+ - 6^+	765.03		0.308	0.132	1.760
		6^+ - 8^+	450.43		0.523	0.172	2.293
Cd-130	82	0^+ - 2^+	1325	0.369	0.176	0.099	1.330
		2^+ - 4^+	539		0.433	0.155	2.086
		4^+ - 6^+	128		1.823	0.318	4.280
		6^+ - 8^+	138		1.691	0.306	4.122

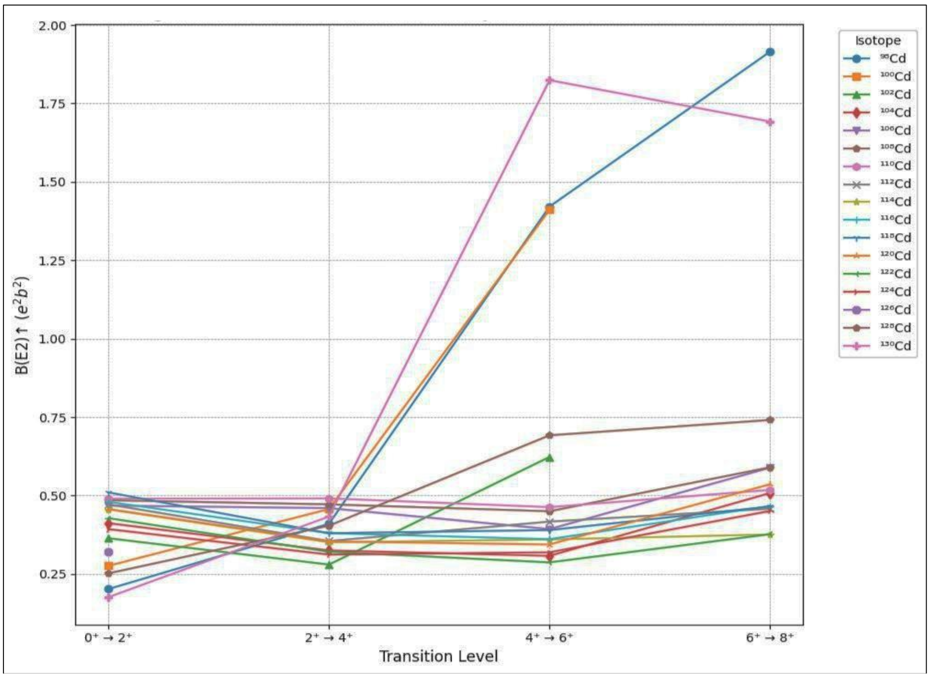

Fig 1: Conceptual representation of the variation of reduced transition probabilities with transition levels for $^{98-130}$Cd isotopes.

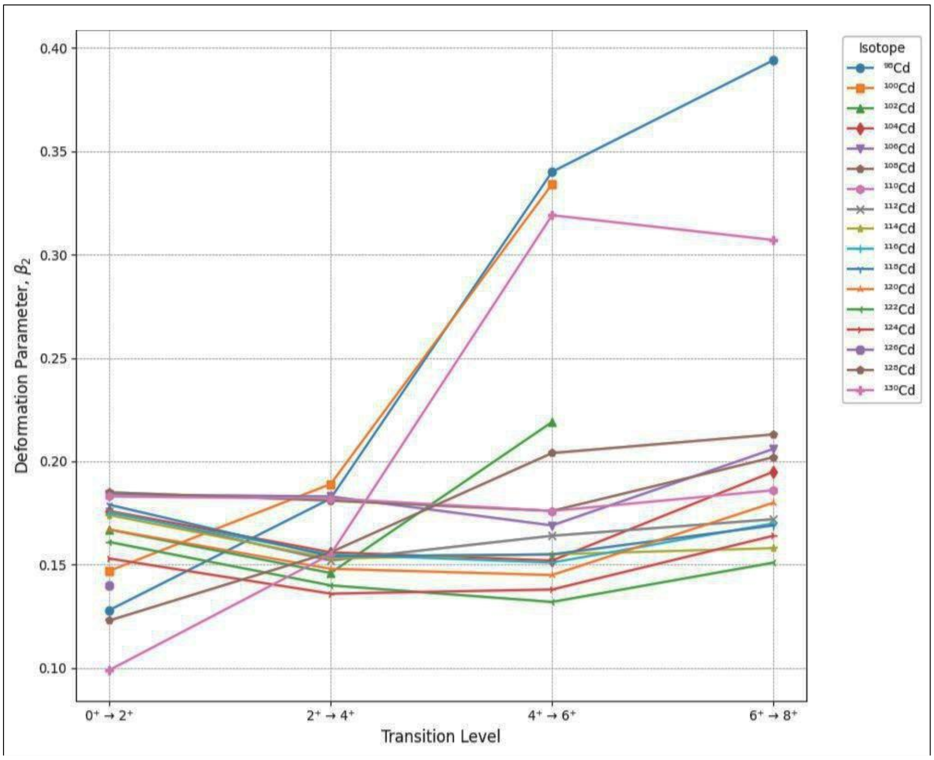

Fig 2: Conceptual representation of the variation of deformation parameter against the transition levels for $^{98-130}$Cd isotopes.

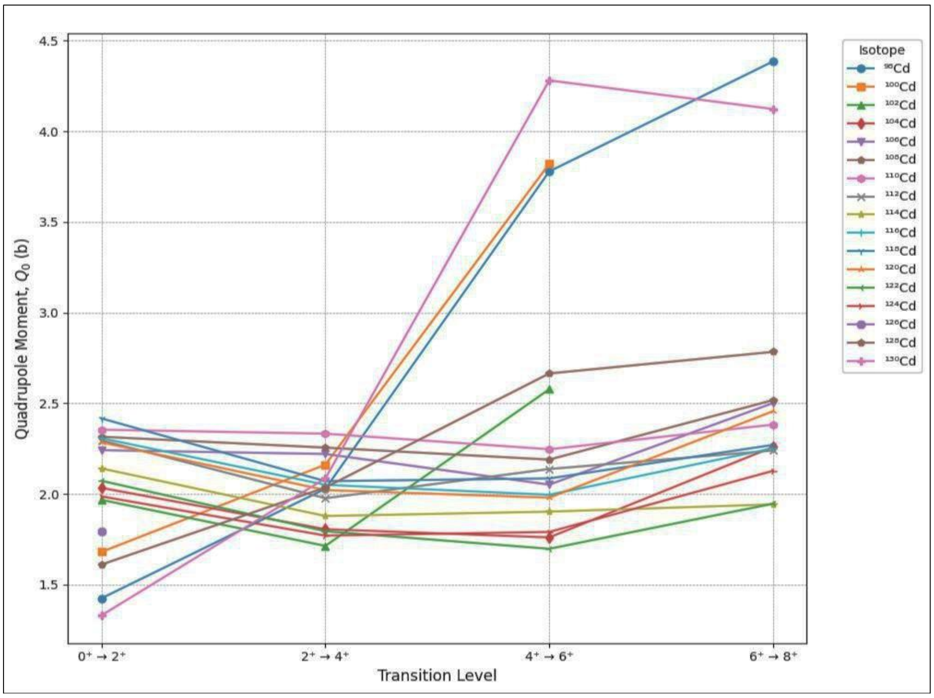

Fig 3: Conceptual representation of quadrupole moment change with respect to the transition levels for $^{98-130}$Cd isotopes.

A clear and consistent systematic trend is observed in the calculated values of B(E2)↑, β_2, and Q_0 across the Cadmium isotopic chain. A particularly notable finding is the comparatively lower values of B(E2)↑, β_2, and Q_0 for isotopes with neutron numbers approaching or directly at magic numbers, specifically ^{98}Cd (N=50) and ^{130}Cd (N=82).
For ^{98}Cd (N=50), the $0^+ \rightarrow 2^+$ transition exhibits B(E2)↑ = 0.202 e²b², β_2 = 0.128, and Q_0 = 1.425 b. These values are among the lowest observed in the entire isotopic chain, indicating a relatively spherical shape and reduced collectivity. As the neutron number increases and moves away from N=50 towards the mid-shell region, such as for ^{114}Cd (N=66), the values of B(E2)↑, β_2, and Q_0 generally increase. For instance, the $0^+ \rightarrow 2^+$ transition for ^{114}Cd shows B(E2)↑ = 0.456 e²b², β_2 = 0.174, and Q_0 = 2.141 b, which are significantly higher than those for ^{98}Cd.
This increase signifies a rise in collective behavior and nuclear deformation. Conversely, as the neutron number approaches N=82, for ^{130}Cd, the values decrease significantly once more. For ^{130}Cd (N=82), the $0^+ \rightarrow 2^+$ transition yields B(E2)↑ = 0.176 e²b², β_2 = 0.099, and Q_0 = 1.330 b, making it the most spherical nucleus in the studied range for this specific transition. This systematic variation in B(E2)↑, β_2, and Q_0 values, showing distinct minima at N=50 and N=82 and maxima in the mid-shell region, provides quantitative empirical evidence for the "valleys of deformation" associated with nuclear shell closures. This pattern directly supports the hypothesis that magic numbers lead to more spherical and less collective nuclear shapes, while nuclei far from magic numbers tend to be more deformed.
For most isotopes within the Cadmium chain, particularly as the neutron number moves away from the magic numbers (N=50 for Cd-98 and N=82 for Cd-130) towards the mid-shell (e.g., around Cd-114, Cd-120, and Cd-122) the calculated values of B(E2)↑, β_2, and Q_0 generally tend to decrease as the transition level increases (i.e., from $0^+ \rightarrow 2^+$ to $6^+ \rightarrow 8^+$). This observation is consistent with a common trend where higher excitation energies often correspond to reduced collective strength, clearly indicates a transition from spherical to more deformed shapes.
This systematic shape evolution across the isotopic chain supports the idea of varying collective modes rather than a consistent vibrational character. The peak deformation observed in the mid-shell Cadmium isotopes aligns with expectations for nuclei exhibiting more pronounced collective behavior.
However, a significant and unexpected phenomenon is observed for the magic number nuclei, ^{98}Cd (N=50) and ^{130}Cd (N=82). For these specific isotopes, the B(E2)↑, β_2, and Q_0 values for higher transition levels (specifically $4^+ \rightarrow 6^+$ and $6^+ \rightarrow 8^+$) are remarkably higher than their corresponding $0^+ \rightarrow 2^+$ values, and often exceed values for the same transition levels in other, non-magic isotopes. For example, in ^{98}Cd, the $0^+ \rightarrow 2^+$ transition has B(E2)↑ = 0.202 e²b², β_2 = 0.128, and Q_0 = 1.425 b. In stark contrast, the $6^+ \rightarrow 8^+$ transition shows significantly higher values: B(E2)↑ = 1.915 e²b², β_2 = 0.394, and Q_0 = 4.386 b. A similar pattern is evident for ^{130}Cd, where the $0^+ \rightarrow 2^+$ transition has B(E2)↑ = 0.176 e²b², β_2 = 0.099, and Q_0 = 1.330 b, but the $4^+ \rightarrow 6^+$ transition yields B(E2)↑ = 1.824 e²b², β_2 = 0.319, and Q_0 = 4.281 b, and the $6^+ \rightarrow 8^+$ transition is B(E2)↑ = 1.692 e²b², β_2 = 0.307, and Q_0 = 4.123 b. These higher-spin states in magic nuclei exhibit substantial deformation, contrasting sharply with their relatively spherical ground states. This anomaly, where magic nuclei exhibit significantly increased deformation at higher excitation energies or spins, is a crucial finding. It directly contradicts the general expectation of decreasing collectivity with increasing excitation and the trends observed in other GBF applications. This observation indicates a more complex nuclear structure at higher spins in these "spherical" nuclei, potentially pointing towards shape coexistence or the onset of rotation.

5. Conclusion

A clear systematic trend was observed: the values of B(E2)↑, β_2, and Q_0 are comparatively lower for isotopes with neutron numbers approaching or at magic numbers (N=50 for ^{98}Cd and N=82 for ^{130}Cd). This finding indicates a reduction in collective behavior and a strong tendency towards a more spherical nuclear shape in these regions, which is consistent with established nuclear shell effects. Furthermore, the study revealed an intriguing and unexpected phenomenon: for the magic number nuclei (^{98}Cd and ^{130}Cd), the values of B(E2)↑, β_2, and Q_0 for higher transition levels (specifically $4^+ \rightarrow 6^+$ and $6^+ \rightarrow 8^+$) were significantly higher than their respective ground state ($0^+ \rightarrow 2^+$) values. This suggests the emergence of substantial deformation at higher excitation energies or spins in these nuclei, which are otherwise considered spherical in their ground states.

When the neutron number moves away from the magic numbers (N=50 for Cd-98 and N=82 for Cd-130) towards the mid-shell the calculated values of B(E2)↑, β_2, and Q_0 generally tend to decrease as the transition level increases (i.e., from $0^+ \rightarrow 2^+$ to $6^+ \rightarrow 8^+$). And clearly indicates a transition from spherical to more deformed shapes.

This research significantly contributes to the understanding of nuclear structure and the evolution of collectivity and deformation across an isotopic chain. The systematic quantification of B(E2)↑, β_2, and Q_0 provides valuable empirical data that can inform and constrain more sophisticated microscopic nuclear models. The findings for Cadmium isotopes, particularly the observed shape evolution from spherical near magic numbers to more deformed in the mid-shell, add crucial empirical evidence to the ongoing debate regarding their collective character.

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