Collective structure of even-even isotopes in the vicinity of doubly-magic nuclei

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Introduction

The collective behaviour of even-even nuclei originates from the nuclear collective motion where all the nucleons together define its properties. These collective properties depend only on the mass number of the nucleus [1]. Even-even nuclei have two possible structure configurations resulting from collective effects - vibrational and rotational structure. Mostly, nuclei in the mass region 150<A<180 are rotational in nature while those with mass number A<150 are vibrational. Observable properties of these nuclei based on which this classification is made are i) the energy of the first 2^+ state, ii) the ratio of energies of 4^+ and 2^+ excited states $E(4^+)/E(2^+)$, iii) the magnetic moments of 2^+ states, iv) electric quadrupole moments and v) the low-lying energy bands.

When nuclear properties across mass regions are studied, those in the vicinity of doubly-magic nuclei are commonly remarked as discontinuities. The general trend of properties like magnetic moments, electric quadrupole moments and separation energies is broken in the vicinity of shell closures. We report here our new observations on the even-even isotopes around doubly-magic nuclei with respect to their collective behavior and related properties.

Structural shift

Even-even isotopes of well-known doubly-magic nuclei ^{16}O, ^{24}O, ^{40}Ca, ^{48}Ca, ^{56}Ni, ^{132}Sn and ^{208}Pb have been considered for this study. The experimental data on these nuclei were taken from the ENSDF and XUNDL data files [2]. A comparison of low-lying energy levels of the isotopes, close to the doubly-magic nuclei, reveals an interesting trend as shown in Table 1. We observed that wherever the even-even isotopes of a given nuclei having mass number less than its doubly-magic isotope exhibit characteristic vibrational levels, those beyond tend to have rotational bands and vice versa. Also, even-even isotopes right next to the doubly-magic nuclei show some traits of the other structure, though one structure dominates. For example, ^{46}Ca, which is the neighbor of doubly magic ^{48}Ca, has even parity long-lived states like rotational nuclei while it is actually classified as vibrational nucleus based on its $E(2^+)$ value and trends of preceding nuclei. On the other side, ^{50}Ca has negative parity states at high energies but its $E(4^+)/E(2^+)$ value is very high indicating rotational characteristics like its succeeding even-even isotope ^{52}Ca. An analogous pattern is found

Table 1: Classification of e-e nuclei near doubly magic nuclei, based on observed low-lying energy levels.

Even-even nuclei	**Rotational levels ($0^+,2^+,4^+,6^+,8^+$...)**	**Doubly magic**	**Vibrational levels ($0^+,2^+,0^+,2^+\ 4^+,3^-,5^-$ ….)**
O	^{12}O,^{14}O	^{16}O	^{18}O,^{20}O,
	^{26}O	^{24}O	^{22}O
Ca	^{36}Ca, ^{38}Ca	^{40}Ca	^{42}Ca,^{44}Ca
	^{50}Ca, ^{52}Ca	^{48}Ca	^{46}Ca
Ni	^{52}Ni,^{54}Ni	^{56}Ni	^{58}Ni,^{60}Ni, ^{62}Ni
	^{70}Ni,^{72}Ni, ^{74}Ni,^{76}Ni	^{68}Ni, ^{78}Ni	^{64}Ni, ^{66}Ni
Sn	^{134}Sn, ^{136}Sn, ^{138}Sn	^{132}Sn	^{120}Sn,^{122}Sn, ^{124}Sn,^{126}Sn, ^{128}Sn,^{130}Sn
Pb	^{210}Pb, ^{212}Pb, ^{214}Pb	^{208}Pb	^{196}Pb,^{198}Pb, ^{200}Pb,^{202}Pb, ^{204}Pb, ^{206}Pb

in the structures of ^{14}O and ^{18}O, which flank the doubly magic nucleus ^{16}O.

This structural transition is also substantiated by the trends of E(2^+) and E(4^+)/E(2^+) values as shown in Fig. 1 and Fig. 2 respectively. Typically, E(2^+) values of vibrational nuclei lie within 1-2 MeV, while those of rotational nuclei lie above or below this range. The sharp peaks in Fig. 1 denote the doubly-magic nuclei. Clearly, there is a gradual shift in the collective nuclear structure of even-even isotopes as the neutron number value passes through the doubly-magic number. This can also be observed in the E(4^+)/E(2^+) values which steadily increase or decrease when there is a structure shift from rotational to vibrational as seen in Fig 2.

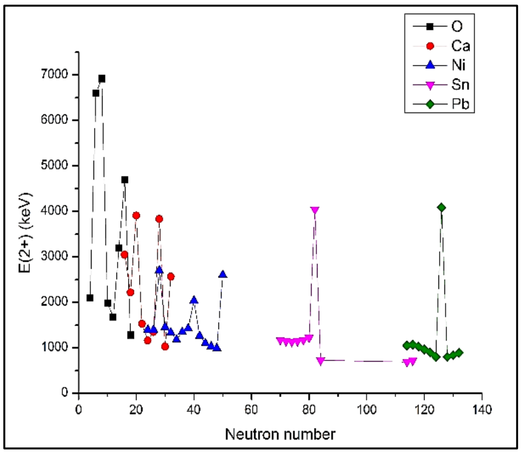

Fig. 1: E(2^+) vs Neutron number for even-even isotopes in the vicinity of doubly magic nuclei.

The structural shift supports the claim of ^{24}O as a doubly-magic nuclei as there is an observed increase in the E(2^+) value from ^{22}O [3]. The E(2^+) and E(4^+)/E(2^+) trends are also in agreement with the classification of ^{78}Ni as doubly-magic [4]. A change in structure is also observed in the vicinity of the semi-magic neutron number 40 in Ni isotopes. Beyond ^{68}Ni in which E(2^+) is about 2 MeV, ^{70}Ni,^{72}Ni and ^{74}Ni have positive parity states marking rotational behaviour. In case of Sn and Pb isotopes, the lower mass even-even nuclei are vibrational in nature. There is a steep rise in the E(2^+) value following which the nuclei show rotational characteristics. The shift is sharp in case of Sn isotopes while it is gradual in case of Pb isotopes. The change is very clearly observed in heavier nuclei as their deformations are more pronounced. The observed level structures and E(2^+) values of these nuclei can be explained theoretically by the levels from which nucleon pairs are broken to form excited states [1].

The E(4^+)/E(2^+) ratio is around 1.6 for vibrational nuclei. Rotational nuclei have very large values of this ratio in lighter nuclei and values less than 1.6 in heavier nuclei. A prominent observation in this study was that, as seen in Fig. 2, the doubly-magic nuclei had the least value of E(4^+)/E(2^+) compared to its other isotopes.

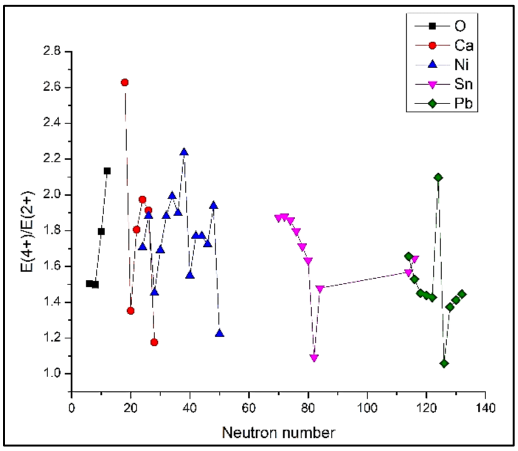

Fig. 2: E(4^+)/E(2^+) vs neutron number. The sharp drops are doubly-magic nuclei.

Thus, it is evident that the change in collective nuclear structure of even-even isotopes, in the vicinity of doubly magic nuclei, is a consistent trend across the nuclear landscape. Currently there are no detailed theoretical explanations to comprehend this trend. As this phenomenon is near the shell closure, we hope that our observations would lead to further experiments which could fill the gaps in the existing data, thereby enabling deeper insights into the collective behaviour and a better understanding of the connection between independent particle and collective behaviours.

References

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