Shape Isomerism in 0+ states with sub-nano second half-lives

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Introduction

Low-lying 0^+ excited states in even-even nuclei may correspond to a secondary minimum in the potential energy surfaces (PES) of nuclei and may be associated with shape coexistence and shape isomerism [1-5]. Shape isomers are characterized by hindered electromagnetic decay due to shape change during a transition. Half-life of such isomeric states depend on the degree of mixing, potential barrier height and excitation energy [1]. As experimental capabilities advance, accurate and sensitive measurement of half-lives and hindrance factors at very short time scales become possible. As an example, lifetime measurement of sub-nanosecond multi-quasiparticle isomers in ^{178}W has been reported [6]. Discovery of a significant number of sub-100 ps fission (shape) isomers, with the shortest-lived isomer in ^{240}Cm having a half-life of $t_{1/2}$=10 ps, were made quite early [7].

In view of our interest in the half-life range of 100-999 ps isomers, due to the availability of experimental facilities in India, and a lack comprehensive study in this time range, we have undertaken a detailed study of the nuclear states in this range. Of particular interest are the 0+ states which might turn out to be shape isomers [1]. We have short-listed 12 such 0+ states, which fit the description of possible shape isomerism, and are discussed in the following.

All the energy level values, half-life, B(E2) (in W.u.), ρ^2(E0), $I_{(\gamma+ce)}$ and branching ratios values were taken from the ENSDF database, unless otherwise mentioned. We have also made use of XUNDL and NUBASE in these studies.

Shape Mixing

Generally, shape mixing is common to all the cases of shape coexistence. Presence of mixing becomes evident in even-even nuclei by enhanced electromagnetic decay strengths between states of coexisting bands (enhanced monopole strength ρ^2(E0) and B(E2) values) [8]. The cases under consideration are band heads of the coexisting structures in even-even nuclei. Most of the cases include significant mixing of states with different deformation, leading to enhanced branching and decay strengths between coexisting bands leading to sub-nanosecond half-lives.

Definition of a lower limit of isomeric half-life has been dictated by experimental limitations of measuring half-lives and is a question still unresolved. It's natural that the present definition of isomers continues to expand to include shorter- and shorter-lived states as experimental facilities and techniques advance. Experimentally, what can possibly differentiate between isomeric and typical excited state is the detectable delay in the decay of isomeric state vis-a-vis prompt decay [27]. Defining isomeric states to be at least 1000 times (Ex: prompt decay $t_{1/2}$: 100's fs; Isomeric decay $t_{1/2}$=100 ps or more) longer lived than the fastest transition for each nucleus individually seems reasonable.

Of the 12 cases chosen by us, the 0_2^+ intruder state at 375.14 keV with $t_{1/2}$=0.62 (21) ns in ^{184}Hg has already been interpreted as a shape isomer [5, 9, 10] and is not discussed.

Possible Candidates of Shape Isomerism

^{40}Ar: 0_2^+ state at 2120.91 keV, $t_{1/2}$=104(14) ps was identified as the band-head of super-deformed (SD) band with β~0.5 [11,12]. It lies in the A=40 SD region and decays entirely to lower-lying 2_1^+ state with a very small B(E2)=5.3(8).

^{42}Ca: Like ^{40}Ar, 0_2^+ state at 1837.31 keV, $t_{1/2}$=387(6) ps is a band-head of the SD band (β = 0.43(4)) coexisting with slightly deformed ground band [13, 14]. Decay of 0_2^+: ρ^2(E0)=0.140(12), B(E2)=55(5) (97.95% branching to 2_1^+) suggests more mixing than ^{40}Ar.

^{68}Ni: The 0_3^+ state with $t_{1/2}$=0.57(5) ns is predicted as a prolate minimum at 2511 keV energy, with triple shape coexistence in "spherical" ^{68}Ni. With B(E2)=0.00390(34), ρ^2(E0)<0.0258(to 0_2^+) and ρ^2(E0) < 0.0050 (to 0_1^+), 0_3^+ makes a good candidate for a shape isomer.

^{68}Zn: In this nucleus, the (0_2^+, 2_3^+, 4_2^+) spacing suggests large deformation compared to the ground band and a shape coexistence. Therefore, 2_3^+ and 4_2^+ excited state are likely members of the low-lying $K^{\pi}=0_2^+$ band [17]. 0_2^+ band-head at 1655.91 keV and $t_{1/2}$=96(16) ps decays visibly almost entirely to 2_1^+ yrast state with B(E2)=5.5(10), and $I_{(\gamma+ce)}$= 4.2×10^{-2}(10) for E0 transition to the ground state.

^{74}Se: 0_2^+ at 853.83 keV with $t_{1/2}$=0.75(5) ns has been interpreted as strongly deformed prolate band head with the weakly deformed ground state [18, 19]. With B(E2)=77(7) and ρ^2(E0)=0.0231(22), 0_2^+ decays mostly to 2_1^+.

^{94}Zr: Chakraborty et al. [20] established shape coexistence in ^{94}Zr [20]. The 0_2^+ state in ^{94}Zr at 1300.19 keV as the band-head of the coexisting structure with $t_{1/2}$=0.291(11) ns primarily decays to 2^+, (B(E2)=9.4(4)). E0 transition: $I_{(\gamma+ce)}$= 0.40(4).

^{96}Sr: In ^{96}Sr, it seems that an excited spherical state mixes strongly with an excited deformed state giving rise to two 0^+ states [21], one of them being 0_2^+ at 1229.28(10) with $t_{1/2}$=115(12) ps which seems to decay entirely to 2_1^+ (B(E2)=15.3(16)). Very strong E0 transition strength is observed between 0_2^+ and 0_3^+ (1464 keV) due to large shape mixing.

^{98}Zr: In case of ^{98}Zr, 0_3^+ state at 1436.17 keV is deformed (q^2 (e^2b^2) = 0.88, γ =53) differently than the ground state with $t_{1/2}$=0.72(8) ns [22]. B(E2)= 58(8) (seems to decay entirely to 2_1^+) with ρ^2=0.076(6) for decay to 0_2^+.

^{116}Sn: The proton 2p-2h intruder band-head in ^{116}Sn was first adopted to be the 0_2^+ state at 1757 keV. Later in ref. [23, 24], strong evidence suggesting the 0_3^+ state at 2027 keV to be the band-head of the intruding structure was presented. 0_2^+ state at 2027.48(3) keV with $t_{1/2}$=160(20) ps and B(E2)=0.49 (7) is a good candidate for shape isomerism.

^{188}Hg: 0_2^+ state is band-head at 824.50 keV of the coexisting structure in this nucleus [5,25,26], with $t_{1/2}$=204(45) ps and ρ^2(E0)=0.0077(+22−32) and is a good candidate for shape isomerism.

^{192}Pb: The 0_2^+ intruder and the first excited state at 768.84(23) keV with $t_{1/2}$=0.75 ns (10) in this nucleus is subject to weak E0 transition ($\rho\,^2$(E0)* 10^3=1.7(2)[28]) making it a case of shape isomer[5].

Conclusions and Future Directions

To conclude, 12 examples of probable shape isomers with sub-ns half-lives are presented. These cases differ from the 23 cases of 0^+ isomers presented in [1], which have half-lives 10 ns or more. For example, A=40 region has many 0^+ isomers which are SD and open the possibility to discover more such cases in this mass region. Their SD structure is more accessible to experiments with suitable experimental techniques and may lead to a better understanding of the structure of SD bands in heavy mass region. Observation of triple shape coexistence is a novel feature and is predicted in ^{184,188}Hg and ^{192}Pb, and it would be challenging to discover this feature in experiments. The Zr isotopes correspond to a subshell closure Z=40 and lead to particle-hole excitations at moderate excitation energy, with a distinct possibility of shape-coexistence. The Sn isotopes are known to support seniority isomers [1] and a shape coexistence in many isotopes presents a challenge to establish a link between generalized seniority and deformed structures. New measurements of BE2 and ρ^2(E0) are required in many cases and a sustained theoretical effort may lead to new breakthroughs in our understanding of the 0^+ structures and SD shapes in the light mass regions.

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References

[1] A.K. Jain, Bhoomika Maheshwari, Alpana Goel, *Nuclear Isomers: A Primer,* Springer Nature, 2021.

[2] S. Aberg, H. Flocard, and W. Nazarewicz, Ann. Rev. Nucl. Part. Sci. **40**, 439 (1990).

[3] A. N. Andreyev et al., Nature **405**, 430 (2000).

[4] E. Bouchez et al., Phys. Rev. Lett. **90**, 082502 (2003).

[5] P. Möller et al., At. Data Nucl. Data Tab, **98**, 149 (2012).

[6] M. Rudigier et al., Phys. Lett. B 801, 135140 (2020).

[7] G. Sletten et al, Phys. Lett. B **60**, 153 (1976).

[8] J.L. Wood et al., Nucl. Phys. A **651**, 323-368(1999).

[9] F. Dickmann, K. Dietrich, Z. Physik **271**,417 (1974)

[10] J. D. Cole et al., PRL **37**,18(1976).

[11] E. Bitterwolf et al, Z. Phys. A**313**, 123-132 (1983).

[12] E. Ideguchi et al, Prog. Th. Phys. Supp. **196**,427 (2012)

[13] Y. Taniguchi, Prog. Th. Phys. Supp. **196**, 433(2012).

[14] K. Hadyńska-Klek et al, PRL **117**, 062501 (2016).

[15] B.P. Crider et al., Physics Letters B **763**, 108 (2016).

[16] S. SUCHYTA et al., Phys. Rev. C **89**, 021301(2014).

[17] J.B. Gupta, J. Hamilton, Nucl.Phys. A**983**, 20 (2019).

[18] R.M. Ronningen et al, Nucl. Phys. A**261**, 439(1976).

[19] R. Budaca et al, Nucl. Phys. A **990**, 137 (2019).

[20] A. Chakraborty et al., PRL **110**,022504 (2013).

[21] S. Cruz et al., Physics Letters B **786**, 94 (2018).

[22] J. E. García-Ramos and K. Heyde, Phys. Rev. C **100**, 044315 (2019)

[23] J. L. Pore et al., Eur. Phys. J. A**53**, 27 (2017).

[24] C. M. Petrache et al., Phys. Rev. C **99**,024303 (2019).

[25] P.K Joshi et al., Int. J. Mod. Phys. E03, 757 (1994).

[26] N. Bree et al, Phys. Rev. Lett. 112, 162701 (2014).

[27] P. Walker and Z. Podolyák, Phys. Scr. **95**, 044004 (2020).

[28] P. Dendooven et al, Phys. Lett. B **226,** 27 (1989).