Shells and Shapes in the N=28 isotones

L. Caceres, Zs. Dombradi, C. Force, L. Gaudefroy, S. Grévy, F. Nowacki, D. Sohler, O. Sorlin

Shell and Shapes in the N = 28 Isotones

L. Cáceres[1*], Zs. Dombrádi[†], C. Force[*], L. Gaudefroy[**], S. Grévy[*], F. Nowacki[‡], D. Sohler[†] and O. Sorlin[*]

[*]GANIL, CEA/DSM-CNRS/IN2P3, BP5027, F-14076 Caen cedex, France
[†]Institute of Nuclear Research, H-4001 Debrecen, Pf. 51, Hungary
[**]CEA, DAM, DIF, F-91297 Arpajon, France
[‡]IReS, IN2P3-CNRS, Université Louis Pasteur, BP 28, F-67037 Strasbourg Cedex, France

Abstract. New experimental results on ^{43}S and ^{44}S reveal that these nuclei are located in a transitional region of prolate-spherical shape coexistence between the spherical ^{48}Ca and the oblate ^{42}Si. The origin of the deformation is discussed in terms of the evolution of the single particle energy levels leading to the compression of the orbitals in the *sd* and pf shells for protons and neutrons, respectively. Therefore, due to quadrupole excitations, the intruder configuration in the neutron rich S isotopes became the ground state.

Keywords: Isomeric decay, shape coexistence, quenching
PACS: 21.10.Jx, 21.10.Pc, 21.10.Re, 23.35.+g

INTRODUCTION

The shell structure and its evolution towards the limits of the nuclide chart has been one of the foremost pursuits of experimental and theoretical nuclear studies. The single particle states in conjunction with proton-neutron ($\pi\nu$) residual interaction are key ingredients in the understanding of multiparticle configuration states in the vicinity of doubly-magic nuclei. Nuclei with magic number of protons and/or neutrons have spherical shape and are expected to have large 2^+ excitation energy and small transition probability B(E2; $2^+ \rightarrow 0^+$) compared to their neighbours. However, it is known that magic nuclei far away of the valley of the stability may not fulfill these specific features. As an example, the ground state intruder configuration and E(2^+) of ^{32}Mg [1, 2] manifest the erosion of the $N = 20$ shell gap thus quadrupole excitations develop to the fp shells. On the other hand, above the $Z = 14$ sub-shell gap the $N = 20$ isotones (e.g. ^{34}Si, ^{36}S, ^{40}Ca) possess the previously mentioned characteristics of magic nuclei. In the neutron rich side, ^{48}Ca is known to be doubly-magic nuclei, while the low 2^+ excitation energy in ^{42}Si [3] at 770(19) keV has been interpreted to be originated by the combined action of the proton-neutron tensor forces leading to the compression of the single particle energy levels. Consequently, quadrupole excitations across the $Z = 14$ and $N = 28$ appear and ^{42}Si is predicted to have oblate deformation. The question that one may raise when comparing the $N = 28$ and $N = 20$ isotones is the following;

[1] caceres@ganil.fr

what are the mechanism driving the deformation in the formers? In order to understand the underlying nuclear structure in terms of deformation of the $N = 28$ isotones it is necessary at first to understand the evolution of the neutron from $N = 20 - 28$ and proton from $Z = 14 - 20$ orbitals involved in this particular region of the nuclear chard. Therefore in the next section selected experimental results which manifest this issue will be presented. In addition, in this article we review some of the most relevant experimental result which shed light to the understanding of the structure of the $N = 28$ isotones, in particular we concentrate in the ^{43,44}S cases.

EVOLUTION OF π AND ν SINGLE PARTICLE ENERGY LEVELS

From the ^{40}Ca(d,τ)^{39}K reaction experiment [4] the position of the $\pi\ d_{3/2}$ single particle energy level (*SPEL*) at $N = 20$ was extracted by averaging the energy of the ground state $3/2^+$ weighted by its spectroscopic factor. In the same experiment the $\pi\ s_{1/2}$ *SPEL* was located by means of the excitation energy and spectroscopic factor of the $1/2^+$ level. The energy difference between the $3/2^+$ and $1/2^+$ states is about 2.5 MeV which can be interpreted as the spacing between the $\pi d_{3/2}$ and $\pi s_{1/2}$ orbitals. When filling the $\nu f_{7/2}$ shell towards $N = 28$, this energy spacing gets progressively reduced and even inverted up to -0.29 MeV in ^{47}K [5, 6]. The $1/2^+$ and $3/2^+$ states in ^{45}Cl have been observed in an in-beam experiment [7]. With this measurement the systematic of the K and Cl chains were completed, and it was concluded that the cross over and almost degeneracy of the $\pi\ d_{3/2}$ and $\pi\ s_{1/2}$ *SPEL* at $N = 28$ when removing protons from the *sd* shell is maintained. From the Shell Model (*SM*) point of view this effect is caused by the tensor component of the nuclear interaction which reduces the spin-orbit splitting between the spin-flip partners $\pi(d_{5/2}$-$d_{3/2})$ when filling the $\nu f_{7/2}$ shell and the central component of the monopole interaction (i.e. $V^{pn}_{d_{3/2}f_{7/2}}$ and $V^{pn}_{s_{1/2}f_{7/2}}$). In Ref. [8] Sorlin and Porquet estimated the difference between the two body matrix element responsible for the splitting of the $\pi d_{3/2}$-$\pi s_{1/2}$ to be -350 keV. The $\pi\ d_{5/2}$ orbital is deeply bound therefore it is harder to determine its evolution from $N = 20$ to $N = 28$ although it can be inferred by comparing the location of the $5/2^+$ states in ^{35}P and ^{43}P. Three $5/2^+$ levels above 4 MeV were observed in ^{35}P by means of ^{36}S(d,^{3}He)^{35}P reaction [9]. The total sum of the spectroscopic factors for these states amounts to $\approx$5.35 to be compared to the sum rule $(2J+1)C^2S = 6$ in the $d_{5/2}$ orbital. Therefore it can be concluded the existence of a large $Z = 14$ sub-shell gap at $N = 20$ as almost the full strength of the $\pi\ d_{5/2}$ is located above 4 MeV. On the other hand, the studies of the neutron rich ^{43}P [10] from a π-knockout reaction revealed that some of the $\pi\ d_{5/2}$ strength is already visible at 1 MeV indicating a possible reduction of the $Z = 14$ shell gap.

The evolution of the ν *SPEL* has been studied by Gaudefroy et al. in the ^{46}Ar(d,p)^{47}Ar transfer reaction in inverse kinematics [11]. From the Q value of the transfer reaction the authors estimate a reduction of the $N = 28$ shell gap of 330 keV from ^{48}Ca to ^{46}Ar. The quenching of the shell gap can be understood two fold taking into account that the $\pi s_{1/2}$ and $\nu d_{3/2}$ orbitals are almost degenerate at $N = 28$; on one hand due to the tensor interaction $V^{pn}_{d_{3/2}l\uparrow\downarrow}$, which it will be largest between orbitals with maximum wave function overlap (i.e. $V^{pn}_{d_{3/2}f_{7/2}}$) and on the other hand due to the density dependence of the spin-orbit interaction through the $V^{pn}_{s_{1/2}p\uparrow\downarrow}$ matrix elements as the f orbitals are located at the nuclear surface therefore its contribution is expected to be small. Extrapolating the reduction of the $N = 28$ shell gap to lighter systems will imply a quenching of about 1 MeV at ^{42}Si. This will have as consequence the development of neutron quadrupole excitations as the difference in orbital angular momentum between the occupied and valence shells is 2 units thus the net win of correlation energy is large enough to overcome the quenched gap. Therefore permanent ground state deformation will take place. Additionally the degeneracy of the $\pi\ s_{1/2}$ and $\pi\ d_{3/2}$ and the possible slight reduction of the $Z = 14$ sub-shell gap will contribute in the same manner due to the tensor and spin-orbit components of the nuclear interaction. Therefore the combine action of protons and neutrons will be responsible for the deformation in the $N = 28$ isotones. The question to be answered is how this deformation evolves from a spherical doubly-magic ^{48}Ca to an oblate ^{42}Si [3]. The best cases to address this question are the ^{43}S and ^{44}S located between the two nuclei mentioned above.

DEFORMATION IN ^{43,44}S

The B(E2;7/2$^-_2$ $\rightarrow$ $g.s.$) = 83(34) in ^{43}S was measured in an intermediate Coulomb excitation experiment [12] although no conclusion on the deformation of this nucleus could be performed. Additionally, the observation of a low lying 7/2$^-_1$ isomeric state [13] was interpreted as the proton hole in the f$_{7/2}$ orbital therefore the ground state ($g.s$) was assigned to the (p$_{3/2}$)$^{-1}$ intruder configuration. This interpretation was based on shell model calculations although could not be verified experimentally. The large difference of the reduced transition probabilities of the 7/2$^-_2$ and 7/2$^-_1$ levels to the $g.s.$, 83(34) e^{2}fm^4 and 0.403(8) e^{2}fm^4, respectively, indicates no mixing between these two states as expected if difference in deformation between the two levels occur. The g-factor measurement of the 7/2$^-_1$ state performed at GANIL by Gaudefroy et al. [14] provided the unambiguous proof of the configuration of this level. The weighted g-factor for the isomeric state extracted from the $R(t)$ function amounts to -0.317(4) and resembles to that when single neutron in the f$_{7/2}$ orbital is considered (g$_{Schmidt}$ = -0.546) probing spherical character for this level. From this experimental result it is concluded that the $g.s.$ in ^{43}S has a prolate deformation where the 7/2$^-_2$ reported on [12] belongs to the deformed band built on top of it with $\beta_2 \sim 0.3$ while the 7/2$^-_1$ isomeric state is of spherical character. The comparison of the experimental results with three different theoretical approaches further confirm this interpretation.

Similar situation is found for the ^{44}S nucleus located south of ^{48}Ca. A second 0^+ isomeric state at 1365(1) keV decaying by $E0$ transition to the 0^+ $g.s.$ was observed by Grévy et al. [15] at GANIL. By means of electron spectroscopy the half-life was extracted yielding 2.3(3) μs. The data was interpreted as an evidence of shape coexistence in this nucleus although no specific character of the deformation could be deduced. The isomeric state is located at 36 keV above the first excited state (i.e. 2^+). Consequently, it will decay by the above mentioned $E0$ transition and by a highly converted $E2$ γ-ray to the 2^+ level. Therefore a second experiment with a dedicated electron-gamma spectroscopy set-up was performed [16] where the B(E2;$0_2^+ \rightarrow 2^+$) = 42(13)e^2fm^4 was derived by means of the observed 1329 keV γ-ray from the $2^+ \rightarrow 0_1^+$ transition. In addition, the monopolar strength was measured yielding 8.7(7) mu. The large difference of the reduced transition probabilities of the 0^+ states to the 2^+ level [16, 17] indicates shape coexistance in ^{44}S. Furthermore, the mixing of the two 0^+ levels was deduced assuming two states mixing taking into account the B(E2;$0_1^+ \rightarrow 2^+$) from Ref. [17] and considering the originating 2^+ configuration of spherical character. The low value obtained ($\sim$12%) can be interpreted as a difference in deformation between these two levels. This interpretation is further supported by the measured reduced monopolar transition which is in agreement with a low mixing picture considering a change in deformation between the $g.s.$ band and the 0_2^+ state. The $\beta_2 \sim 0.26$ extracted from the $0_1^+ \rightarrow 2^+$ reduced transition probability suggests prolate deformation for the band built on top of the $g.s.$ while the 0_2^+ is most likely to be of spherical character. The experimental result are in agreement with Large Scale Shell Model calculations reinforcing the interpretation mentioned above.

SUMMARY

The large compilation of experimental results in the $N = 28$ region allows to have a more complete understanding of how the deformation changes in this region of the nuclide chard. The evolution of the proton and neutron single particle levels cause the development of quadrupole excitations across the $Z = 14$ and $N = 28$ shell gaps, thus the intruder configuration become the ground state due to the net win in energy due to correlations. Specifically, prolate-spherical shape coexistence appears at the neutron rich ^{43}S and ^{44}S manifested through low lying isomeric states. Therefore the neutron rich S nuclei are in a transitional area of deformation between the doubly-magic ^{48}Ca and the oblate ^{42}Si.

REFERENCES

1. D. Guillemaud-Mueller et al., Nucl. Phys. A426, 37 (1984).
2. T. Motobayashi et al., Phys. Lett. B346, 9 (1995).
3. B. Bastin et al., Phys. Rev. Lett. 99, 022503 (2007).
4. P. Doll et al., Nucl. Phys. A263, 210 (1976).
5. S. M. Banks et al., Nucl. Phys. A437, 381 (1985).
6. G. J. Kramer, H. P. Blok and L. Lapika, Nucl. Phys. A679, 267 (2001).
7. A. Gade et al., Phys. Rev. C 74, 034322 (2006).
8. O. Sorlin and M. -G. Porquet, Prog. Part. Nucl. Phys. 61, 602 (2008).
9. S. Khan et al., Phys. Lett. B156, 155 (1985).
10. L. A. Riley et al., Phys. Rev. C 78, 011303 (2008).
11. L. Gaudefroy et al., Phys. Rev. Lett. 97, 092501 (2006).
12. R. W. Ibbotson et al. Phys. Rev. C 59, 642 (1999).
13. F. Sarazin et al., Phys. Rev. Lett. 84, 5062 (2000).
14. L. Gaudefroy et al., Phys. Rev. Lett. 102, 092501 (2009)
15. S. Grévy et al., Eur. Phys. J 25, s01, 111 (2005).
16. C. Force et al., In preparation.
17. T. Glasmacher et al., Phys. Lett. B 395, 163 (97).