Neutron-proton pairing correlations and deformation for $N = Z$ nuclei in pf-shell using deformed BCS and HFB approach†

E. Ha,[*1] M. -K. Cheoun,[*1] and H. Sagawa[*2]

Shell evolution by deformation is an important concept to understand the structure of neutron-rich nuclei, whose deformation can be confirmed by rotational energy spectra and the E2 transition probability extracted from the experiments. The shell evolution plays a crucial role in understanding the beta-decays in nucleosynthesis. Such features may also appear in neutron-deficient deformed nuclei, for example, $N = Z$ pf-shell nuclei. In particular, in RMF calculations, ^{68}Se and ^{72}Kr are claimed to have oblate deformations while ^{48}Cr, ^{52}Fe, and ^{64}Ge may have prolate deformations, as presented in Table 1.

In this work, we determine the most stable deformation by investigating the evolution of ground state energies along with the deformation within a framework of the deformed BCS (DBCS) and deformed HFB (DHFB) models. Specifically, ^{64}Ge is known to cause a bottle-neck on p- or α-nucleosynthesis. Then, the neutrino-proton (νp)-process, $\bar{\nu}_e + p \rightarrow n + e^+$, produces lots of neutrons which make it possible to escape the bottle-neck by ^{64}Ge (n, p) ^{64}Ga (p, γ) ^{65}Ge reaction and subsequently, bridge the waiting points. Therefore, the nuclear structure of ^{64}Ge becomes the key to understand the mechanism of these reaction.

First, we studied the evolution of single particle state (SPS) energies for $N = Z$ pf-shell nuclei by exploiting a deformed Woods-Saxon potential. Second, taking these SPS, we calculated the ground state energies of the nuclei including the pairing interactions of like- (nn and pp) and unlike-pairs(np) by the deformed BCS (or HFB) approach. The pairing correlations were found to be sensitive to the deformation parameter β_2 and the evolved Fermi energies ϵ_f.

The pairing effects of like-pairs bound the nucleus more strongly, but did not significantly change the evolution of ground state energies. In contrast, the np pairings contributed to the formation of more bound nuclei and significantly affected the pf-shell deformation. To determine the importance of $T = 0$ pairing, we introduced an enhanced $T = 0$ pairing interaction, where the $T = 0$ pairing matrices obtained by the Bruckner HF calculations were enlarged by a factor of 1.5. We found that the enhanced $T = 0$ pairing correlations, which played vital roles in the determination of nuclear deformations of sd-shell nuclei,[1)] are important in the evolution of nuclear deformation. Specifically, the oblate deformations of ^{68}Se and ^{72}Kr and prolate deformations of ^{52}Fe and ^{64}Ge could not be explained without the enhanced $T = 0$ pairing correlations in the present model. Finally, the HFB approach including pairings between different states does not provide any new effects on the nuclear structure but contributes to a more reasonable renormalization of the strength parameter for the nuclear interaction in the nuclear medium.

Table 1. Deformation parameter from the experimental $E2$ transition data[2)] and theoretical deformation parameters by Relativistic Mean Field (RMF),[3)] FRDM model,[4)] and the present results with the enhanced $T = 0$ pairing for $N = Z$ pf-shell nuclei. Empirical pairing gaps deduced from the five-point mass formula[5)] are also shown.

A	β_2^{E2}	β_2^{RMF}	β_2^{FRDM}	β_2^{ours}	Δ_p^{emp}	δ_{np}^{emp}
^{44}Ti	0.277	0.000	0.011	0.2	2.631	2.068
^{48}Cr	0.340	0.225	0.226	0.2	2.128	1.442
^{52}Fe	0.230	0.186	–0.011	0.2	1.991	1.122
^{64}Ge	0.259	0.217	0.207	0.1	1.807	1.435
^{68}Se	0.239	–0.285	0.233	–0.2	1.909	1.522
^{72}Kr	0.330	–0.358	–0.366	–0.1	2.001	1.353
^{76}Sr	0.443	0.410	0.402	0.1	1.626	0.715

In conclusion, the evolution of ground state energies is determined by the evolution of the outermost shell. The np pairing interactions significantly change the evolution of deformation. In particular, the enhanced isoscalar spin-triplet pairing is shown to play an important role in changing the shape of the pf-shell $N = Z$ nuclei such as ^{68}Se and ^{72}Kr. It is also suggested by the study of pairing gaps that the IS condensation by the enhanced $T = 0$ pairing may happen in both sd-shell and pf-shell nuclei. The state dependent pairing correlations induced by HFB model are found to rarely affect the nuclear structures as compared to the conventional BCS approach.

References
1) E. Ha, M. K. Cheoun, H. Sagawa, Phys. Rev. C **97**, 024320 (2018).
2) B. Pritychenko *et al.*, Atomic Data Nucl. Data Tables **107**, 1 (2016).
3) G. A. Lalazissis, S. Raman, P. Ring, Atomic Data and Nucl. Data Tables **71**, 1 (1999).
4) P. Möller, J. R. Nix, W. D. Myers, W. J. Swiatecki, Atomic Data and Nucl. Data Tables **59**, 185 (1995).
5) M. K. Cheoun *et al.*, Nucl. Phys. A **561**, 74 (1993); A **564**, 329 (1993); M. K. Cheoun *et al.*, *ibid.* A **587**, 301 (1995).

† Condensed from the article in Phys. Rev. C **97**, 064322 (2018)

*1 Department of Physics and Origin of Matter and Evolution of Galaxy (OMEG) Institute, Soongsil University
*2 RIKEN, Nishina Center and Center for Mathematics and Physics, University of Aizu