High spin structures in the $A \approx 40$ mass region: from superdeformation to extreme deformation and clusterization (an example of $^{28}\text{Si}$)

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Abstract. The search for extremely deformed structures in the yrast and near-yrast region of $^{28}\text{Si}$ has been performed within the cranked relativistic mean field theory up to spin $I = 20\hbar$. The fingerprints of clusterization are seen (well pronounced) in the superdeformed (hyperdeformed) configurations.

1. Introduction
A systematic search for extremely deformed structures in the $N = Z$ and $N = Z + 2$ S, Ar, Ca, Ti and Cr nuclei has been performed for the first time in the framework of covariant density functional theory in [1]. At spin zero such structures are located at high excitation energies which prevents their experimental observation. The rotation acts as a tool to bring these exotic shapes to the yrast line or its vicinity so that their observation could become possible with future generation of $\gamma$-tracking (or similar) detectors such as GRETA and AGATA. Some of the studied nucleonic configurations show the fingerprints of clusterization and nuclear molecules. The best candidates for observation of extremely deformed structures, clusterization and nuclear molecules have been identified in [1]. For example, the addition of several spin units above currently measured maximum spin of $16\hbar$ will inevitably trigger the transition to hyper- and megadeformed nuclear shapes in some of the nuclei (such as $^{36}\text{Ar}$).

This contribution extends the investigation of [1] to $^{28}\text{Si}$. Recent experimental studies and throughout analysis of previous experimental data presented in Ref. [2] provide strong indications that the $4^+$ and $6^+$ states located at 10.946 and 12.865 MeV, respectively, are superdeformed (SD).

2. The details of the calculations and the results for $^{28}\text{Si}$.
The calculations have been performed in the framework of cranked relativistic mean field (CRMF) theory [4]. The pairing correlations are neglected so the calculations could be considered as fully realistic above $I \sim 8\hbar$. There are several reasons behind this neglect of pairing (see [4] and recent review in [5]); these are the quenching of pairing by rotation (Coriolis anti-pairing effect), substantial shell gaps and blocking effect. Note that only reflection symmetric shapes are considered in these calculations. The CRMF calculations have been performed with the NL3* functional [6] which is state-of-the-art functional for nonlinear meson-nucleon coupling.
model [7] globally tested for ground state observables in even-even nuclei in [7]. The calculated configurations are labeled by shorthand [n,p] labels, where n (p) is the number of neutrons (protons) in the \( N = 3 \) intruder orbitals.

Fig. 1a shows the calculated configurations in the yrast and near yrast region. At low spin, the \([0,0]\)-obl configuration is yrast up to \( I \sim 10h \). It has an oblate shape in agreement with experimental findings [2]. The angular momentum content of this configuration is quite limited and it terminates at \( I = 12h \). The yrast line at higher spin is built by superdeformed \([1,1]_b\) configuration which terminates at spin \( I = 18h \). At higher spin, the hyperdeformed (HD) \([2,2]\) configuration becomes yrast. The transition quadrupole moments \( Q_t \) and \( \gamma \)-deformations of the yrast and excited SD and HD configurations in \(^{40}\text{Ca}\).

The \([0,0]\)-pr configuration is characterized by a substantial quadrupole and hexadecapole deformations and shows the indications of the development of neck. However, present calculations do not suggest that it could be described as a cluster of two nuclei since the maximum of the density is seen in the central part of nucleus (Fig. 2a). This configuration rather well describes both the excitation energies (compare Fig. 1a with left panel of Fig. 7 in [8]) and the moments of inertia of experimental prolate band; the latter are \( J^{(1)} \sim 4 \ h^2/\text{MeV} \) both in experiment [8] and theory.

Based on the comparison of experimental and calculated moments of inertia, the observed \({4}^+\) and \({6}^+\) SD states are most likely associated with the \([2,2]\) configuration. The calculated kinematic moment of inertia of this configuration \( J^{(1)} \sim 6.68 \ h^2/\text{MeV} \), which is nearly constant for large spin range, is only slightly above experimental one (\( J^{(1)} \sim 6 \ h^2/\text{MeV} \) [2]). Note that there are large similarities in the predictions of the properties of oblate, prolate and SD bands obtained in present CRMF calculations and the ones within the antisymmetrized molecular dynamics model of [8].
Figure 2. The self-consistent proton density $\rho_p(y, z)$ as a function of $y$ and $z$ coordinates for the indicated configurations in $^{28}$Si at specified spin values.

Note that some indications of clusterization are present in the density distribution of the SD $[1,1]b$ configuration (Fig. 2b). The HD $[2,2]$ configuration shows clear signatures of clusterization which is especially pronounced at $I = 0\hbar$ (Fig. 2c). Although the rotation somewhat hinders these signatures (Fig. 2d), they are still present at $I = 12\hbar$.

3. Conclusions
The structure of the configurations in the yrast and near yrast region of $^{28}$Si up to $I = 20\hbar$ has been studied in the CRMF theory. The signatures of clusterization are seen in superdeformed $[1,1]$ configurations, but become especially pronounced in the hyperdeformed $[2,2]$ configuration. The observation of such configurations is quite likely with future generation detectors such as AGATA and GRETA. This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under Award Number DE-SC0013037.

References
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