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Montanari, D., Courtin, S., Jenkins, D. G. [orcid.org/0000-0001-9895-3341](https://orcid.org/0000-0001-9895-3341) et al. (11 more authors) (2017) Search for highly excited states in 28Si. Journal of Physics: Conference Series. 012051. pp. 1-5. ISSN 1742-6596

<https://doi.org/10.1088/1742-6596/863/1/012051>

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To cite this article: D Montanari *et al* 2017 *J. Phys.: Conf. Ser.* **863** 012051

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## Search for highly excited states in $^{28}\text{Si}$

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**Abstract.** The theoretical and experimental determination of superdeformed states in nuclei in the mass region  $A \leq 40$  has been since a long time one of the major challenges of nuclear structure studies. Despite the considerable experimental and theoretical work dedicated to this topic, up to now superdeformed bands have been found in only two nuclei,  $^{36}\text{Ar}$  and  $^{40}\text{Ca}$ . While the experimental signature of the superdeformed nature of those states is irrefutable, their theoretical interpretation is still uncertain. In particular, it is not clear whether clusterisation is responsible of the onset of superdeformation. For this reason, we wanted to investigate an even lighter system,  $^{28}\text{Si}$ , where a number of theoretical calculations predict the presence of superdeformation as an effect of the cluster structure of the nucleus.

### 1. Introduction

The experimental and theoretical study of superdeformation (SD) in lighter nuclei ( $A \leq 40$ ) has been at the focus of the interest for decades and still represents one of the most important topics of nuclear structure. It is remarkable that, for  $^{40}\text{Ca}$ , an early experimental study [1] showed, more than 40 years ago, the presence of low-spin states associated to  $4p-4h$  and  $8p-8h$  configurations, which were much strongly populated than the  $0p-0h$  ground states. Subsequent experiments [2, 3] confirmed the multiparticle-multihole structure of these states and measured their large transition quadrupole moments, suggesting the presence of superdeformation in this nucleus. However, despite the considerable experimental efforts done in the past, the presence of SD bands has been only recently observed in this mass region for  $^{36}\text{Ar}$  [4] and  $^{40}\text{Ca}$  [5]. This has been made possible by the coincident detection of particle and gammas by using new-generation high-resolution high-efficiency gamma array detectors.

Under a theoretical point of view, superdeformation in these nuclei has been described by theoretical models in terms of particle-hole shell model excitations [4, 5, 6], cranked Skyrme-Hartree-Fock theory [7] and alpha-clustering configurations by using the Antisymmetrized Molecular Dynamics (AMD) [8, 9, 10].

Up to now, it remains still uncertain whether the cluster description of superdeformation in the  $A \leq 40$  mass region reflects a real microscopic structure of the involved nuclei or it is just able to reproduce data with no physical meaning behind.



For this reason, it is of particular importance to measure SD states in lighter nuclei where some theoretical calculations based on cluster assumption predict the existence of SD bands at energies higher than the particle break-up threshold [11, 12].

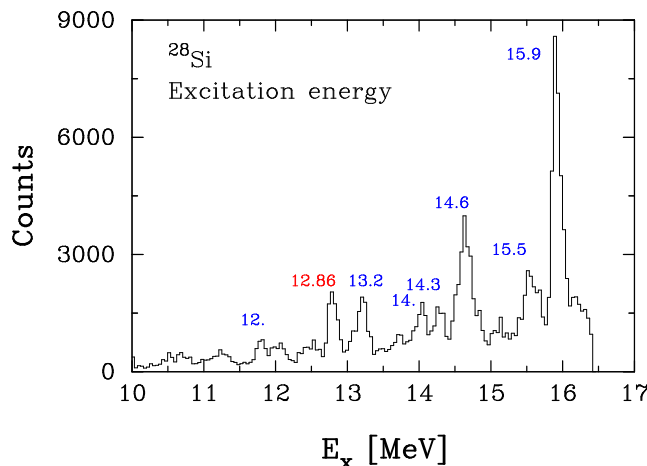
## 2. Superdeformation in $^{28}\text{Si}$

The identification of SD bands based on alpha-cluster hypothesis is still an open question for both experiments and theories. In particular for  $^{28}\text{Si}$ , a recent study [12] using the AMD model identify a SD band in  $^{28}\text{Si}$  with a strong  $\alpha$ - $^{24}\text{Mg}$  configuration, coexisting with a prolate normal deformed and an oblate ground state rotational band. Moreover, macroscopical-microscopical calculations [13] showed the onset of strongly deformed minima in  $^{28}\text{Si}$  nuclear potential at sufficiently high angular momentum and identified possible SD states.

Although some candidate SD states have been identified also in previous experimental [14, 15, 16] and review articles [17], the evidence of their SD nature is still debated.

In particular, the large amount of information available in ref. [15], on the population of excited states of  $^{28}\text{Si}$  by means of  $p$ -,  $d$ - and  $\alpha$ -induced reactions, allowed the authors to measure the decay from the 12.86 MeV ( $6_{SD}^+$  candidate state) to the 10.945 MeV ( $4_{SD}^+$  candidate state). The decay probability was inferred to be quite large,  $B(E2) \geq 25$  Wu.

For this reason, we decided to study the  $^{12}\text{C}(^{20}\text{Ne},\alpha)^{28}\text{Si}$  reaction to measure the particle- $\gamma$  branch and the multipolarity of the (candidate) SD states and to locate higher-lying members of the SD band.

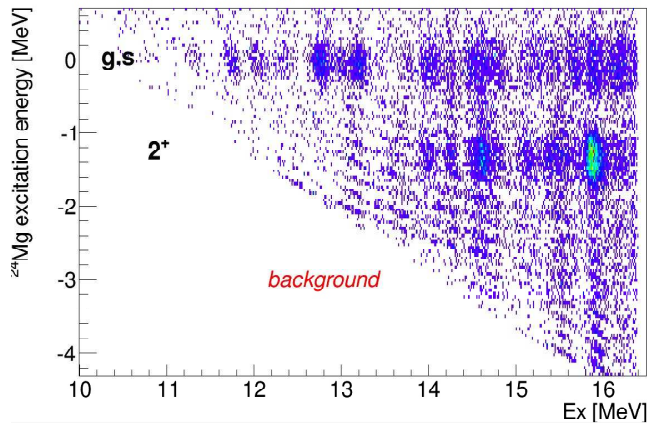


**Figure 1.**  $^{28}\text{Si}$  excitation energy spectrum. Alphas emitted in the  $^{20}\text{Ne}+^{12}\text{C}$  reaction are detected by the K600 spectrometer positioned at very small angles. The peak corresponding to the excited level of interest for this experiment is labeled in red.

## 3. The experiment and experimental results

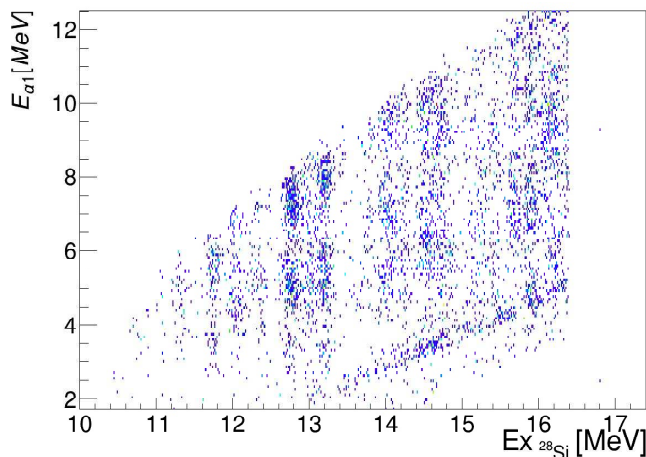
We studied the  $^{12}\text{C}(^{20}\text{Ne},\alpha)^{28}\text{Si}$  reaction at a beam energy of 50 MeV and used the K600 spectrometer at iThemba LABS (South Africa) to select the population of  $^{28}\text{Si}$  states. An accelerated beam of  $^{20}\text{Ne}$ , with an average intensity of  $\approx 50$  nA, impinged on a  $20\mu\text{g}/\text{cm}^2$  thick  $^{12}\text{C}$  target. The magnetic spectrometer consists of a set of magnetic elements, a sextupole, a quadrupole and two dipoles, used to disperse incoming charged particles around the horizontal plane. Position-sensitive multi-wire drift chambers placed at the focal plane of the spectrometer allow the detection of the position of the light reaction products, in this case  $\alpha$  particles emitted by  $^{32}\text{S}$  (here for the sake of clarity called  $\alpha_0$ ). Behind the focal plane detector, a series of two plastic scintillators are used for trigger purposes.

Particles decaying from the remaining  $^{28}\text{Si}$  ( $\alpha_1$ ) have been detected by TIARA-type Si detectors placed around the target position, while the gamma decay branch has been measured by a large NaI detector ( $300 \times 200$  mm $^2$ ).



**Figure 2.** Bi-dimensional matrix showing the correlation between  $^{24}\text{Mg}$  and  $^{28}\text{Si}$  excitation energies. Despite a quite consistent background level, the population of  $^{24}\text{Mg}$  at the ground and  $2^+$  state is clearly visible.

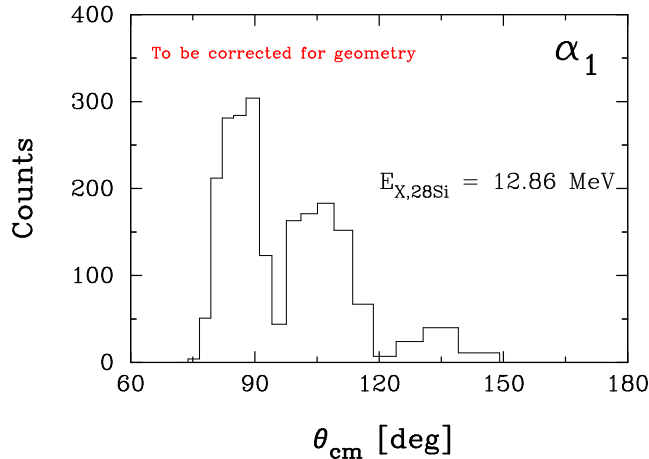
The measure of the position on the focal plane of  $\alpha_0$  emitted by the compound  $^{32}\text{S}$  allows the reconstruction of their kinetic energy and hence of the excitation energy spectrum of  $^{28}\text{Si}$ . This is shown in Fig. 1, where it is clearly visible that the 12.86 MeV state (labeled in red in the figure) is quite strongly populated. The fields of the magnetic elements of the K600 spectrometer have



**Figure 3.**  $\alpha_1$  kinetic energy vs  $^{28}\text{Si}$  excitation energy. The bump-like structures visible on the y axis, in correspondence to each excited level of  $^{28}\text{Si}$ , reflect the angular distribution of the  $\alpha_1$ .

been set in order to allow the detection of the  $\alpha_0$  particles corresponding to an excitation energy window between  $\approx 10$ -17 MeV. A two dimensional plot of the excitation energy of  $^{24}\text{Mg}$  vs the excitation energy of  $^{28}\text{Si}$  is represented in Fig. 2. The excitation of  $^{24}\text{Mg}$  has been obtained by measuring the energy released by alpha particles emitted by  $^{28}\text{Si}$  and by adding it to the energy of alpha particles emitted by  $^{32}\text{S}$  plus the kinetic energy of the recoil ( $^{24}\text{Mg}$ ) reconstructed by imposing the conservation of linear momentum. In this figure, two peculiar ridges are clearly visible and they correspond to the population of the ground state and of the first  $2^+$  state of  $^{24}\text{Mg}$ . By selecting the ground state ridge and by putting a gate around the 12.86 MeV state of Fig. 1, one can plot the kinetic energy of alpha particles emitted by  $^{28}\text{Si}$ . This kinetic energy, with suitable kinematics calculations, can be transformed into the angular distribution of alpha particles. The bi-dimensional plot of Fig. 3 shows the coincidence between  $\alpha_0$ , i.e.  $^{28}\text{Si}$  excitation energy, and  $\alpha_1$ , by requiring the population of  $^{24}\text{Mg}$  at the ground state. It can be noticed that at each excited level of  $^{28}\text{Si}$  corresponds a bump-like structure on the y axis. These bumps reflect the angular distribution of the  $\alpha_1$  particles. Through suitable fit procedures, they allow us to extract the spin removed by the  $\alpha$  decay of  $^{28}\text{Si}$  and therefore to assign spin and multipolarity to the selected excited state of  $^{28}\text{Si}$ . An example of such a distribution is shown

in Fig. 4 where the kinetic energy of the  $\alpha_1$  emitted by the 12.86 MeV state of  $^{28}\text{Si}$  is plotted. This preliminary spectrum is not corrected by the geometrical acceptance of the Si detectors.



**Figure 4.** Angular distribution of alphas emitted by  $^{28}\text{Si}$  populating the ground state of  $^{24}\text{Mg}$ . The angular distribution has been obtained by kinematics calculations. The spectrum is not corrected by the geometry of the detector.

On the gamma detection side, we are able to obtain gamma spectra in coincidence with every peak of Fig. 1. Indeed, it is of particular interest to study the gamma decay associated to the transition from the 12.86 MeV ( $6_{SD}^+$  candidate) state to the 10.945 MeV ( $4_{SD}^+$  candidate) state, and to compare its intensity to the more probable particle decay branch. Further analysis efforts are being done in order to take out this meaningful result.

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