Collapse of the N=28 shell closure in $^{42}$Si

B. Bastin$^2$, S. Grévy$^{14}$, D. Sohler$^3$, O. Sorlin$^{1,4}$, Zs. Dombrádi$^3$, N. L. Achouri$^2$, J. C. Angélique$^2$, F. Azaiez$^3$, D. Baiborodin$^5$, R. Borces$^6$, C. Bourgeois$^4$, A. Buta$^6$, A. Bürger$^{7,8}$, R. Chapman$^9$, J. C. Dalouzy$^1$, Z. Drouily$^5$, A. Drouard$^7$, Z. Elekes$^3$, S. Franchoo$^4$, S. Iacob$^6$, B. Laurent$^2$, M. Lazar$^6$, X. Liang$^9$, E. Liénard$^2$, J. Mazek$^2$, L. Nalpas$^1$, F. Negoita$^6$, N. A. Orr$^6$, Y. Penionzhkevich$^{10}$, Zs. Podolyák$^{11}$, F. Pougeon$^9$, P. Rousseau-Chomaz$^2$, M. G. Saint-Laurent$^3$, M. Stanoiu$^{4,6}$ and I. Stefan$^1$.

$^1$Grand Laboratoire National d’Ondes Lourdes (GANIL), CEA/DSM - CNRS/IN2P3, Bd Henri Becquerel, BP 55027, F-14076 Caen Cedex 5, France
$^2$Laboratoire de Physique Corpusculaire, 6, bd du Mal Juin, F-14050 Caen Cedex, France
$^3$Institute of Nuclear Research, H-4001 Debrecen, Pf.51, Hungary
$^4$Institut de Physique Nucléaire, IN2P3-CNRS, F-91406 Orsay Cedex, France
$^5$Institute of Atomic Physics, IFIN-HH, Bucharest-Magurele, P.O. Box MG6, Romania
$^6$CEA Saclay, DAPNIA/SPHN, F-91191 Gif-sur-Yvette Cedex, France
$^7$Helmholtz-Institut für Strahlen- und Kernphysik, Universität Bonn, Nürenballe 1-16, D-53115 Bonn, Germany
$^8$School of Engineering and Science, University of Paisley, PA1 2BE Paisley, Scotland, UK
$^9$School of Physics, University of Birmingham, Birmingham, B15 2TT, United Kingdom
$^{10}$CEA, DAPNIA/SPHN, F-91191 Gif-sur-Yvette Cedex, France
$^{11}$Institut de Physique Nucléaire, IN2P3-CNRS, F-91406 Orsay Cedex, France
$^{12}$Institut de Physique Nucléaire, IN2P3-CNRS, F-91406 Orsay Cedex, France
$^{13}$Departamento de Física Teórica, Universidad Autónoma de Madrid, E-28049 Madrid, Spain.

The energies of the excited states in very neutron-rich $^{42}$Si and $^{41,43}$P have been measured using in-beam γ-ray spectroscopy from the fragmentation of secondary beams of $^{42,44}$Si at 39 A MeV. The low $2^+$ energy of $^{42}$Si, 770(19) keV, together with the level schemes of $^{41,43}$P provide evidence for the disappearance of the Z=14 and N=28 spherical shell closures, which is ascribed mainly to the action of proton-neutron tensor forces. New shell model calculations indicate that $^{42}$Si is best described as a well deformed oblate rotor.

PACS numbers: 23.20.Lv; 21.60.Cs; 27.40.+z; 29.30.Kv

Magic nuclei have in common a high energy for the first excited state and a small transition probability B(E2: $0^+_1 \rightarrow 2^+_1$) compared to neighboring nuclei. This is essentially due to the presence of large shell gaps, the origins and configurations of which differ significantly along the chart of nuclides. This implies a variable sensitivity of these shell gaps with respect to the proton-neutron asymmetry. For instance, the N=20 shell closure, bound by orbitals of opposite parity, $d_{3/2}$ below and $f_{7/2}$ above, remains remarkably rigid against quadrupole deformation from $^{40}$Ca to $^{44}$Si even after the removal of six protons $^1$. This feature can be traced back to the large N=20 gap, the hindrance of $2^+$ excitations due to the change of parity across it, and to the presence of proton sub-shell gaps in the sd shells at Z=16 (~2.5 MeV) and Z=14 (~4.3 MeV) $^2,3$. Conversely, the N=28 shell closure, produced by the spin-orbit (SO) interaction and separating the orbitals of same parity $f_{7/2}$ and $p_{3/2}$, is progressively eroded below the doubly magic $^{48}$Ca nucleus in $^{46}$Ar $^4$ and $^{44}$S $^5,6$, after the removal of only two and four protons, respectively. This rapid disappearance of rigidity of the N=28 isotones has been ascribed to the reduction of the neutron shell gap N=28 combined with that of the proton subshell gap Z=16, leading to increased probability of quadrupole excitations within the $fp$ and sd shells for neutrons and protons, respectively. For the $^{44}$S nucleus, its small $2^+$ energy, large B(E2) value $^3$ and the presence of a $0^+_2$ isomer at low excitation energy $^6$ point to a mixed ground state configuration of spherical and deformed shapes. As the proton Z=14 and neutron N=28 (sub)shell gaps have been proven to be effective in $^{42}$Si and $^{48}$Ca$^2$, the search for a new doubly magic nucleus would be naturally oriented towards $^{42}$Si$^{28}$, which could be the lightest one with proton and neutron gaps created by the SO interaction.

The experimental status concerning the structure of $^{42}$Si is rather controversial. On the one hand the very short $\beta$-decay lifetimes of the $^{40,42}$Si nuclei point to deformed ground state configurations in the Si isotopic chain. On the other hand the weak two proton knock-out cross section $\sigma_{-2p}(^{44}$Si$-^{42}$Si) was given as a strong indication in favor of a "doubly magic" spherical nucleus $^8$ with a large Z=14 shell gap. However, the same authors have shown more recently $^9$ that a reduction of the Z=14 gap by as much as 1 MeV does not increase the $\sigma_{-2p}$ value significantly. Further, the newly measured atomic mass of $^{42}$Si $^{10}$ is compatible with an excess of microscopic energy as compared to a spherical liquid drop, which could be obtained either for a spherical or deformed shell closure.
The present work aimed at determining the 2\(^+\) energy of \(^{42}\text{Si}\)\(_{28}\) and the energy spectrum of the neutron-rich \(^{41,43}\text{P}\)\(_{26,28}\) isotopes to obtain a global understanding of the proton and neutron excitations at \(Z=14\) and \(N=28\) to infer whether \(^{42}\text{Si}\) can be considered as a new doubly magic nucleus or not.

The experiment was carried out at the Grand Accélérateur National d’Ions Lourds (GANIL) facility. A primary beam of \(^{48}\text{Ca}\) at 60 A-MeV impinged onto a 200 mg/cm\(^2\) C target with a mean intensity of 3.8 \(\mu\)A to produce a cocktail of projectile like fragments. They were separated by the ALPHA spectrometer, the magnetic rigidity of which was set to optimize the transmission of the \(^{42}\text{Si}\) nuclei, produced at a rate of 125 s\(^{-1}\). Fragments were guided over a flight path of about 80 m along which the time-of-flight (TOF) was determined with two microchannel plates. A thin 50 \(\mu\)m Si detector was used to determine the energy losses (\(\Delta E\)), which completed the event by event identification prior to the fragmentation in a secondary target of 195 mg/cm\(^2\) of \(^{9}\text{Be}\). This target was placed at the entrance of the SPEG spectrometer, the magnetic rigidity of which was tuned to maximize the transmission of the \(^{42}\text{Si}\) nuclei produced through a 2 proton knockout reaction. At the focal plane of SPEG, ionisation and drift chambers provided information on the \(\Delta E\) and positions of the transmitted nuclei, while a plastic scintillator was used to determine TOF and residual energies. The \(\sigma_{\gamma\gamma}(\gamma^{44}\text{Si} \rightarrow \gamma^{42}\text{Si})\) cross section is measured to be 80(10) \(\mu\)barn at 39 A-MeV. This agrees with the value of 120(20) \(\mu\)barn obtained at 98.6 A-MeV [8], after having taken into account an enhancement factor of 25\% due to the higher beam energy [11].

An array of 74 BaF\(_2\) crystals, each of 9 cm diameter and 14 cm length, was arranged in two hemispheres above and below the Be target at a mean distance of 25 cm to detect \(\gamma\)-rays arising from the secondary reactions. The energy threshold of the detectors was around 100 keV. The energies of two \(\gamma\)-rays detected in coincidence in adjacent detectors were combined by add-back. The \(\gamma\)-ray energies were corrected for Doppler shifts due to the in-flight emission by the fragments. Photopeak efficiencies of 38\% at 779 keV, 24\% at 1.33 MeV and 16\% at 2 MeV were achieved for fragments with \(v/c \approx 0.3\). The energy resolution was 15\% at 800 keV and 12\% at 1.4 MeV, which includes the effects of the intrinsic resolution of the detectors and the Doppler broadening. Using the systematics of the peak widths deduced from the observation of known single peaks, doublets of \(\gamma\)-rays could also be disentangled. The time resolution of the array was 800 ps. This enabled a clean separation between neutrons or charged particles and the \(\gamma\)-rays arising from the reaction on the basis of their TOF differences.

\(\gamma\)-ray spectra obtained for the \(^{42}\text{Si}\) and \(^{41,43}\text{P}\) isotopes are shown in Fig. 1. Several other nuclei were also produced, such as \(^{38,40}\text{Si}\) and \(^{44}\text{S}\). Noteworthy is the fact that we find good agreement with their previously measured \(\gamma\) transitions, published in Refs. [3, 12]. A clear single peak is visible in the spectrum of \(^{42}\text{Si}\) at 770(19) keV on a significance level of more than 3 \(\sigma\). It can be assigned to the decay of the first excited state, namely the 2\(^+\)\(\rightarrow\) 0\(^+\) transition. The number of counts corresponds to a feeding of the 2\(^+\) state of 44\pm 10\%. In \(^{43}\text{P}\), in addition to the low energy transition at 186 keV previously reported by Fridmann et al. [8], a doublet of weak transitions is visible at 789 and 918 keV. Both transitions are in coincidence with the 186 keV transition, and are placed on top of it in the proposed level scheme (Fig. 2). In \(^{41}\text{P}\), similarly to the \(^{43}\text{P}\) case, a strong low energy transition at 172(12) keV is visible together with several slightly overlapping peaks at 420, 964, 1146 and 1408 keV. The 964 and 1408 keV transitions are in coincidence with the 172 keV transition, while the 964 keV transition is in coincidence with that at 420 keV too. In addition to coincidence relationships, intensity arguments are used in order to build the level scheme presented in Fig. 2. The

![FIG. 1: \(\gamma\)-ray spectra observed in coincidence with the \(^{42}\text{Si}\) (upper), \(^{43}\text{P}\) (middle) and \(^{41}\text{P}\) (bottom) nuclei. In the insets \(\gamma\)-\(\gamma\) coincidence spectra are presented, gated with transitions belonging to the \(^{41,43}\text{P}\) nuclei.](image-url)
Ca
categories in the those states observed around 1 MeV in the 41\textsuperscript{Ca} especially sensitive to the N=28 gap, as the 2\textsuperscript{+} states in 40\textsuperscript{Ca} are shown by dashed lines.

FIG. 2: Level schemes for 41\textsuperscript{Ca} and 42\textsuperscript{Si} in the present work. Positions of the 2\textsuperscript{+} states in 40\textsuperscript{Ca} and 42\textsuperscript{Si} are shown by dashed lines.

The present observation of new γ-lines in the 43\textsuperscript{P} and 42\textsuperscript{Si} is explained by an enhanced γ efficiency by about a factor of ten at 1 MeV with respect to the work of Refs. [8, 9]. Fig. 3 shows the energies of the 2\textsuperscript{+} states in the Si and Ca isotopes. The correlated increase of the 2\textsuperscript{+} energies in the 40\textsuperscript{Ca} and 34\textsuperscript{Si} nuclei at N=20 does not hold at N=28. While 2\textsuperscript{+} energies increase in Ca isotopes from N=24 to reach a maximum around 4 MeV at N=28, the 2\textsuperscript{+} energies in the Si isotopes start to deviate from those of the Ca at N=26, reaching a minimum value at N=28. The slight deviation from the Ca curve at N=26 was interpreted in Ref. [12] as an indication in favor of a reduced N=28 shell gap. However, neutron excitations occurring before the complete filling of the νf\textsubscript{7/2} shell are not especially sensitive to the N=28 gap, as the 2\textsuperscript{+} states are qualitatively due to excitations inside the f\textsubscript{7/2} shell. Conversely, in 42\textsuperscript{Si} the 2\textsuperscript{+} state comes from particle-hole excitations across the gap and therefore, the dramatic decrease of its 2\textsuperscript{+} energy leaves no doubt concerning the disappearance of the spherical N=28 shell closure at Z=14, the energy of 770 keV being one of the smallest among nuclei having a similar mass. It is worth pointing out, as shown in Fig. 2 that the decrease of the 2\textsuperscript{+} energies in the 40\textsuperscript{Ca} and 42\textsuperscript{Si} nuclei is correlated to the behavior of those states observed around 1 MeV in the 41\textsuperscript{Ca} and 42\textsuperscript{Si} isotones, which in the shell model arise from the coupling of the last proton in the s\textsubscript{1/2} or d\textsubscript{3/2} orbitals to the 2\textsuperscript{+} excitation. This provides additional support to the disappearance of the N=28 spherical gap. If the N=28 gap had persisted in the P isotopes, a sequence of levels similar to those in 47\textsuperscript{K} would have been observed. Namely two nearby 1/2\textsuperscript{+} and 3/2\textsuperscript{+} states originating from the quasi-degeneracy of the πs\textsubscript{1/2} and πd\textsubscript{3/2} orbitals and a large gap in energy (∼2 MeV) above this doublet.

The spectroscopy of the nuclei with proton number in the range of 16 to 20 and neutron number from 20 to 28 is reproduced successfully when using large scale shell model calculations in a valence space comprising the full sd-shells for protons and pf-shells for neutrons with the effective interaction SDPF-NR [17]. The remarkable features of this interaction which account for the evolution of the nuclear structure between N=20 and N=28 are: (i) the decrease of the d\textsubscript{3/2}–s\textsubscript{1/2} proton splitting by about 2.5 MeV from 39\textsuperscript{K} to 47\textsuperscript{K} as the neutron f\textsubscript{7/2} orbital is filled, (ii) the reduction of the N=28 gap by about 330 keV per pair of protons removed from the 48\textsuperscript{Ca}.

Despite these successes, a correct description of the Si isotopes cannot be straightforwardly obtained by using the monopole matrix elements of the SDPF-NR interaction derived for the Ca isotopes. This arises from the fact that the occupied and valence proton orbitals involved in both cases are somewhat different. In particular, some amount of core excitations to the πf\textsubscript{7/2} orbital, which lies just above the valence space of the Ca isotopes, is included in the neutron-pairing matrix elements V\textsuperscript{nn} of pf-shell orbits. This contribution is expected to be negligible in the Si isotopes, in which the πf\textsubscript{7/2} orbital lies at much higher excitation energy. According to the model, the configuration of the 2\textsuperscript{+} states in 36\textsuperscript{Ca}, 38\textsuperscript{Si} arises mainly from pair-breaking inside the πf\textsubscript{7/2} shell and therefore the 2\textsuperscript{+} energies scale with the V\textsuperscript{nn} values. Indeed the energy of the 2\textsuperscript{+} states in 36\textsuperscript{Ca}, 38\textsuperscript{Si} and those of the 5/2\textsuperscript{+} states in 37\textsuperscript{Na}, 39\textsuperscript{P} are overestimated by the SDPF-NR interaction up to 300-400 keV. The discrepancy is larger for 42\textsuperscript{Si}, the calculated 2\textsuperscript{+} energy of which being 1.49 MeV, instead of 770 keV. Therefore a reduction of the p\textsuperscript{f} shell V\textsuperscript{nn} matrix elements by 300 keV gives the 2\textsuperscript{+} energies of 36\textsuperscript{Ca}, 38\textsuperscript{Si} as well as the 5/2\textsuperscript{+} energies in 37\textsuperscript{Na} in agreement with their experimental values. Nevertheless the calculated 2\textsuperscript{+} energy in 42\textsuperscript{Si}, 1.1 MeV, is still larger than the experimental value. To further reduce it without changing the properties of the other N=28 isotones, the proton-neutron monopole matrix elements V\textsuperscript{pm}d\textsubscript{3/2}(fp) can be considered. Indeed the d\textsubscript{3/2} orbital is “active” in the Si isotopes whereas it is too deeply bound to play a significant role in the description of the Ca isotopes. Nevertheless, with the SDPF-NR interaction the proton d\textsubscript{3/2}–d\textsubscript{5/2} splitting in 39\textsuperscript{K} and 41\textsuperscript{K} over-estimates the experimental values, see Tab. [1] By modi-

FIG. 3: Energies of the 2\textsuperscript{+} states measured in the Ca and Si isotopes. Present result for 42\textsuperscript{Si} -770(19) keV– brings evidence for the the collapse of the N=28 shell closure at Z=14.
TABLE I: Proton $d_{3/2}-d_{5/2}$ splitting in $^{39}\text{K}$ and $^{47}\text{K}$

|   | $^{39}\text{K}$ | $^{47}\text{K}$ |
|---|----------------|----------------|
| experiment | 6.74 [2] | 4.84 [19] |
| shell model [17] | 7.4 | 5.92 |
| shell model (this work) | 7.18 | 4.93 |

fying adequately the $V_{p,n}^{\alpha}(fp)$ matrix elements, the $d_{3/2}$-$d_{5/2}$ splitting can be better adjusted in the K isotopes (Tab. 3) and therefore the $2^+$ energies in $^{36,38,40,42}\text{Si}$, as well as the level schemes of $^{41,43}\text{P}$, agree nicely with the experimental data shown in Figs. 2 and 3. This modification leads to a decrease of the $d_{3/2}$-$d_{5/2}$ splitting by 1.94 MeV from $^{34}\text{Si}$ to $^{42}\text{Si}$ which results in an enhanced collectivity. $^{42}\text{Si}$ becomes clearly an oblate rotor up to $J=8^+$; with a calculated $2^+$ excitation energy of 810 keV and an intrinsic quadrupole moment $Q = -87$ e fm$^2$ corresponding to a quadrupole deformation $\beta = 0.45$. The doubly magic ($N=28$, $Z=14$) component is only 20% of the ground state wavefunction with an average 2.2 neutrons above $N=28$ and 1.2 protons above $Z=14$; the percentage of the closed proton configuration ($0d_{5/2}$)$^6$ being 33%. With a present $Z=14$ gap of 5.8 MeV, our measured $\sigma_{-2\ell}$($^{44}\text{Si}$)$^{42}\text{Si}$ cross section agrees with the one calculated with a similar gap in Ref. [3].

The resulting shell model description of the $N=20$ to $N=28$ region south of Ca isotopes is the following: as compared to the $^{34}\text{Si}$ and $^{48}\text{Ca}$ nuclei, major changes in the energies of the proton and neutron orbitals are occurring towards $^{42}\text{Si}$. The complete filling of the neutron $f_{7/2}$ shell from $^{34}\text{Si}$ leads to a shrinkage of the $sd$ orbitals, with a proton $SO$ splitting $d_{3/2}$-$d_{5/2}$ reduced by about 1.94 MeV. This reduction is compatible with what is accounted for by tensor forces, which act attractively (repulsively) between the proton and neutron orbits $d_{3/2}$-$f_{7/2}$ ($d_{5/2}$-$f_{7/2}$) as described in Ref. [10, 12, 20]. Simultaneously, as depicted in Ref. [3] the removal of protons from $^{48}\text{Ca}$ induces a compression in energy of the four neutron $fp$ orbits and hence a reduction of the N=28 gap by about 1 MeV in $^{42}\text{Si}$ (from an initial value of 4.8 MeV in $^{48}\text{Ca}$) due to the combined effects of the proton-neutron tensor force and the density dependence of the SO interaction. The overall picture would be that the mutual actions of the proton-neutron tensor forces in $^{42}\text{Si}$ induce the reduction of the neutron N=28 gap and limit the size of the proton Z=14 gap. In addition, particle-hole excitations between occupied and valence orbitals which are separated by $\Delta \ell, j=2$ for both protons (sd) and neutrons (fp) naturally favor quadrupole correlations that generate collectivity through mechanisms related to Elliott’s SU(3) symmetry [20]. The combined effects of the compression of the proton and neutron orbitals, plus the quadrupole excitations, produce a rich variety of behaviors and shapes in the even N=28 isotones; spherical $^{48}\text{Ca}$: oblate non-collective $^{46}\text{Ar}$; coexistence in $^{44}\text{Si}$, and two rotors, oblate $^{42}\text{Si}$ and prolate $^{40}\text{Mg}$. This variety of shapes is also globally supported by mean field calculations, relativistic or non-relativistic.

To summarize, the energies of excited states in the $^{42}\text{Si}$ and the $^{41,43}\text{P}$ nuclei have been measured through in-beam $\gamma$-ray spectroscopy. The low energy of the $2^+_1$ state in $^{42}\text{Si}$, 770(19) keV, together with the level schemes of $^{41,43}\text{P}$ provide evidence for the disappearance of the N=28 shell-closure around $^{42}\text{Si}$. It is ascribed to the combined action of proton-neutron tensor forces leading to a global compression of the proton and neutron single particle orbits, added to the quadrupole symmetry between the occupied and valence states which favors excitations across the Z=14 and N=28 shell gaps.

This work benefits from discussions with A. Navin, J. Tostevin and L. Gaudefroy. The authors are thankful to the GANIL and LPC staffs. We thank support by BMBF 06BN109, GA of Czech Republic 202/040791, MEC-DCH (Spain) BFM2003-1153, and by the EC through the Eurons contract RII3-CT-3/2004-506065 and OTKA T38404-T42733-T46901. RB, AB, ML, SI, FN and RC, XL acknowledge the IN2P3/CNRS and EPSRC support.

* corresponding author: grevy-at-in2p3.fr

[1] R.W. Ibbotson et al., Phys. Rev. Lett. 80, 2081 (1998).
[2] P. Doll et al., Nucl. Phys. A 263 210 (1976).
[3] C. E. Thorn et al., Phys. Rev. C 30, 1442 (1984).
[4] L. Gaudefroy et al., Phys. Rev. Lett. 97 092501 (2006).
[5] T. Glasmacher et al., Phys. Lett. B 395 163 (1997).
[6] S. Grévy et al., Eur. Phys. J. A 25 s01-111 (2005).
[7] S. Grévy et al., Phys. Lett. B 594 252 (2004).
[8] J. Fridmann et al., Nature 435 922 (2005).
[9] J. Fridmann et al., Phys. Rev. C 74 034313 (2006).
[10] B. Jurado et al., submitted to Phys. Lett. B.
[11] J. Tostevin, private communication.
[12] C.M. Campbell et al., Phys. Rev. Lett. 97, 112501 (2006).
[13] J. Retamosa et al., Phys. Rev. C 55 1266 (1997).
[14] P. D. Cottle et al., Phys. Rev. C 58 3761 (1998).
[15] O. Sorlin et al., Eur. Phys. J. A 22 173 (2004).
[16] A. Gade et al., Phys. Rev. C 74, 034322 (2006).
[17] E. Courrier et al., Nucl. Phys. A 742 14 (2004).
[18] X. Liang et al., Phys. Rev. C 74 014311 (2006).
[19] G. J. Kramer et al., Nucl. Phys. A 679 267 (2001).
[20] T. Otsuka et al., Phys. Rev. Lett. 95, 232502 (2005).
[21] G. A. Lalazissis et al., Phys. Rev. C 60 014310 (1999).
[22] S. Péru et al., Eur. Phys. J. A 9 35 (2000).
[23] R. Rodríguez-Guzmán et al., Phys. Rev. C 65 024304 (2002).
[24] T.R. Werner et al., Nucl. Phys. A 597 327 (1996).
[25] P.-G. Reinhard et al., Phys. Rev. C 60 014316 (1999).
[26] Elliott et al., Proc. R. Soc. London Ser. A 245 128 (1956)