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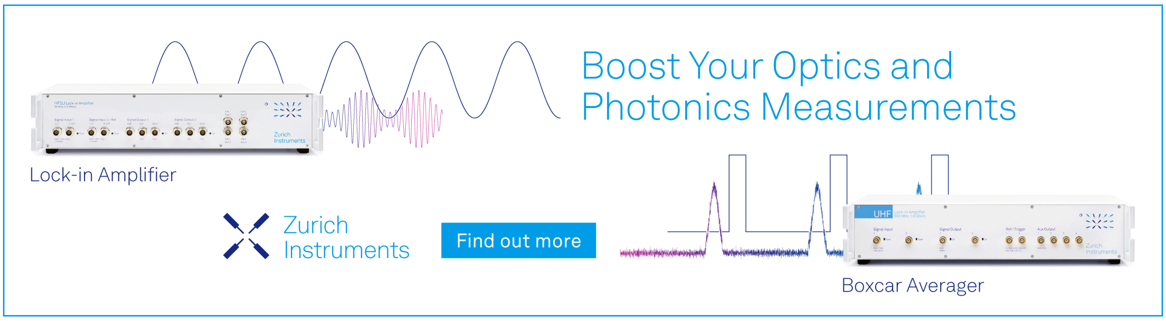

Shape coexistence at N=20 and N=28 : study of 0_2^+ states in ^{34}Si and ^{44}S

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Abstract. It is well known that the nuclear shell structure changes for the most exotic nuclei. One of the consequences of this phenomenon is the modification of the "classical" magic numbers, as experimentally observed at N = 20 and N = 28. Nevertheless, the mechanisms responsible for such changes are still under discussion and more experimental information is needed to better constrain the theoretical models. In these proceedings, we report on the discovery and the experimental study by precise spectroscopy experiments of the 0_2^+ state in ^{34}Si and ^{44}S. The ^{34}Si is located between the magic spherical ^{36}S and the deformed ^{32}Mg, member of the so-called island of inversion, whereas ^{44}S is located between the magic spherical ^{48}Ca and the deformed ^{42}Si. Therefore, the structure of these nuclei, and in particular the phenomenon of shape coexistence, is of crucial importance to understand how the intruder configurations progressively dominate the ground state structure of the most exotic nuclei at both N = 20 and N = 28.

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DISCOVERY OF THE O_2^+ STATE IN ^{34}SI

It has been shown in the last decades that the interaction between the valence protons and neutrons in neutron-rich nuclei can lead to a significant modification of the single particle energies resulting in the disappearance of the spherical magic numbers and the appearance of new ones [1]. It is in particular the case in the so called "island of inversion" centered around the N=20 ^{32}Mg [2]. It has been ascribed to the effect of the monopole part of the tensor force which act differentially between the $\pi d_{5/2}$ orbital and the $\nu d_{3/2}$ and $\nu f_{7/2}$ orbitals [3], reducing the N=20 shell gap to the profit of N=16. As a consequence, intruder configurations with neutrons located in the $\nu f_{7/2}$ orbital progressively dominate the ground state structure of the most neutron rich N=20 isotones. Nevertheless, questions remain concerning the boundary of the island of inversion and the transition between the normal ground state configuration of the spherical magic $^{36}_{16}S_{20}$ and the intruder deformed one of $^{32}_{12}Mg_{20}$ is not yet fully understood. Moreover, the relative importance between the intruder and normal configurations are still under debate and therefore it is important, from an experimental point of view, to be able to follow the evolution of the intruder configurations from the stable nuclei towards the Island of Inversion where they form the ground state of these nuclei. The 0^+ states are the good candidates for this purpose. Indeed, as illustrated on the Fig. 1, the 0^+

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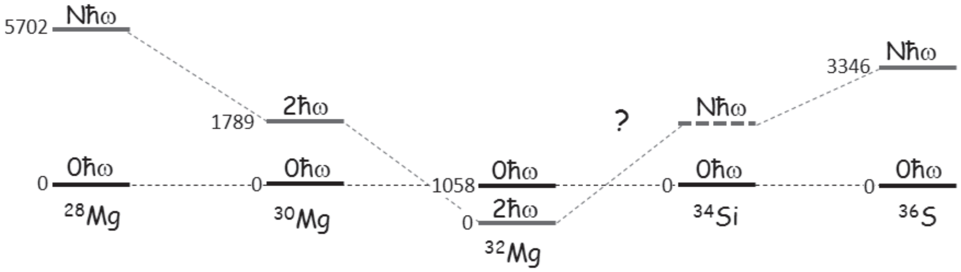

FIGURE 1. Position of the first and second 0^+ states in the isotopes of Mg and in the N=20 isotones towards ^{32}Mg.

state corresponding to neutron excitations above N=20 is located around 5.7 MeV in ^{28}Mg, it has been located recently in an experiment performed at ISOLDE around 1.8 MeV [4] and it forms the ground state of ^{32}Mg. In this nucleus, the "spherical" 0^+ state, in which the normal configurations dominate, has been observed even more recently, again at ISOLDE, at an energy of 1058 keV [5]. Therefore, we do observe a very steep decrease of the intruder configurations of 4 MeV between N=16 and N=18 and again 3 MeV from N=18 to N=20. For the N=20 isotones, the ground state of ^{36}S at Z=16 is spherical whereas the 0^+ state build on neutron excitations is located around 3.3 MeV. In between S and Mg, the observation of the 0^+_2 state in ^{34}Si would therefore represent a strong step forward to better describe the structural changes observed in this region. Being predicted to be located below the 2^+_1 state, an isomeric transition by pair creation or conversion electron is then the expected decay mode.

Many experiments tried to observe the 0^+_2 state in ^{34}Si. A candidate has been proposed at 2133 keV in [6] but following experiments were not able to confirm this result [7, 8, 9]. In [9], excited states of ^{34}Si were populated by deuteron inelastic scattering and a new candidate has been proposed at 1846 keV. In the present work, the energy of the 0^+_2 state in $^{34}_{14}\mathrm{Si}_{20}$ has been unambiguously determined making the hypothesis that this state could be populated in the β-decay of a predicted low-lying 1^+ isomeric state in the $^{34}_{13}\mathrm{Al}_{21}$ [10].

Experimental setup and results

The experiment was carried out at the GANIL facility. A primary beam of ^{36}S at 77.5 A·MeV impinged onto a 240 mg/cm^2 Be target with a mean intensity of 2 μA to produce neutron-rich fragments. They were separated by the LISE3 spectrometer [11] using an achromatic 197 mg/cm^2 Be degrader. The magnetic rigidity was set to optimize the transmission of the ^{34}Al nuclei, produced at a rate of 600 sec^{-1}, with a momentum acceptance of 1.48% and a purity of 93%. Fragments were identified on an event by event basis by means of their energy loss and time-of-flight (TOF) values. The selected nuclei were implanted in a 50 μm kapton foil tilted at 20 degrees with respect to the beam axis. Before the foil, a stack of Si detectors was used to adjust the implantation depth and a double sided strip Si detector located downstream to the implantation foil was used to control the beam centering in the transversal plane. The detectors dedicated to the registration of the decay events were surrounding the Kp foil in a very close geometry. Two Germanium clover detectors from the EXOGAM array for the γ-rays were placed left and right whereas four telescopes of large area Si detectors were used for electrons and positrons, each pair consisting in one 50x50 mm^2, 1 mm-thick Si detector followed by one 45x45 mm2, 4.5 mm-thick Si(Li) detector. The total geometric coverage was therefore 40% of 4π, providing a similar efficiency for single electron detection. The Si detectors timing signals were the unique acquisition triggers during "beam-off" periods. During the "continuous beam" runs they were considered as good β-triggers only in the absence of incident ions. Within this class of β-decay events, those having three detectors fired are plotted in the right insert in Fig. 2.

The oblique line corresponds to events in which the energy sum is constant. They are interpreted as events in which a positron hits one telescope and the accompanying electron hits a second telescope while the β-trigger was given by another telescope. Therefore, these events clearly correspond to the observation of a pair creation emitted in a $0^+ \rightarrow 0^+$ transition. The peak in the energy sum of the two detectors, including the energy loss in the Si(Li) detectors behind them, is centered at 1688(2) keV. Detailed GEANT4 [12] simulations showed that the peak of energy sum is shifted down by about 9 keV due to energy losses in the foil. Including this correction with 10% error, we conclude that the energy of the E0 transition is 2719(3) keV and that it corresponds to the excitation energy of the 0^+_2 state in ^{34}Si. The lifetime of the state 0^+_2 was determined to be

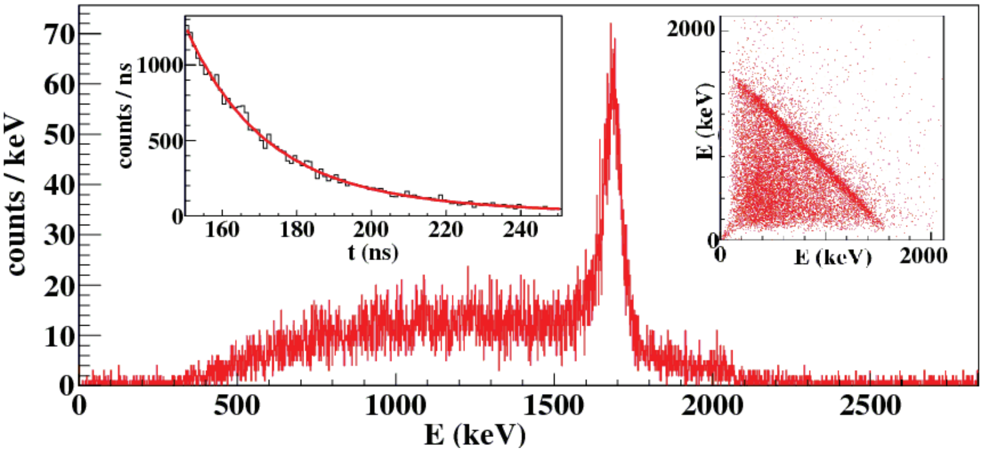

FIGURE 2. insert right : Energy in one telescope versus energy in another one for a pair of electron/positron emitted in the EO decay by pair creation of the 0_2^+ state in ^{34}Si with a Si multiplicity equal to 3. Main: Sum of the two energies showing a peak at 1688(2) keV. The left inset corresponds to the time spectra between the β-decay electron and the electron/positron. The adjustment gives a half-life of 19.4(7)ns for the 0_2^+ state.

19.4(7) ns both from Si detectors timing signals (see left inset Fig. 2) and from the γ-times (relative to the beta-triggers) of 511 keV photons, many of them following the annihilation of positrons originating from E0 transition. Based on tabulated [13, 14, 15] electronic factors Γ_{IC}=3.68x107 s^{-1} and Γ_{IPF}=2.69x109 s^{-1}, the monopole strength $\rho^2(E0,0_2^+ \rightarrow 0_1^+)$=13.0(0.9) 10^{-3} is extracted. A 607 keV gamma peak corresponding to the transition from the 2_1^+ state at 3326 keV to the 0_2^+ state is observed with a very small intensity in the gamma spectrum with a multiplicity higher than 2 for the Si detectors. This condition assures a reduction factor of about 30 for γ-rays not in coincidence with E0 pairs, due to the low probability of β and β-γ events to fire more than one Si detector. On the same spectra, we observe the known 591 keV transitions in ^{34}Si.

Despite a limited statistics and the high level of background, the branching ratio for the decay of the 2_1^+ state to the 0_2^+ and 0_1^+ states has been extracted taking into account the gamma efficiencies and the relevant Si detector efficiencies : $R(2_1^+ \rightarrow 0_1^+ / 2_1^+ \rightarrow 0_2^+)$=1380(717). Therefore, a $B(E2,2_1^+ \rightarrow 0_2^+)$=61(40) e^2fm^4 is obtained, based on $B(E2,2_1^+ \rightarrow 0_1^+)$=17(7) e^2fm^4 measured in an intermediary energy Coulomb excitation experiment [16].

The total number of emitted electron-positron pairs has been estimated to be $N_{pairs}=3.10^6$ whereas the number of $2_1^+ \rightarrow 0_2^+$ transition has been extracted to be around one order of magnitude smaller. Moreover, despite the large statistics for the decay of the 0_2^+ state, no gammas are observed in coincidence with the E0 decay events, except a large number of 511 keV due to positrons annihilation. Even a very high energy gamma ray that would significantly feed the 0_2^+ state, such as the 5.33 MeV transition reported in [17] and observed also in our total gamma spectrum, would produce a peak with few tens counts. We can therefore conclude that the 0_2^+ state in ^{34}Si is predominantly directly feed in the β-decay of ^{34}Al. Furthermore, the ground-state of ^{34}Al is 4^- and therefore cannot decay into a 0^+ state with the observed probability. Consequently, an unknown long-lived low-spin β-isomer has to be supposed in ^{34}Al. Shell model calculations in [10] predict indeed an 1^+ state at less than 200 keV above the ground state. With such an energy, an E3 transition hindered also by structural differences, can be much slower than β-decay process. The experimental confirmation for the new isomer in ^{34}Al is obtained from the analysis of β-times spectra gated on γ-energies and on delayed electron detectors signals. Indeed, the fit with an exponential function of the background subtracted β-time spectra gated on 926 keV and 511 keV gamma give very different results: a period of $T_{1/2}$=54.4(5) msec is obtain in coincidence with the 926 keV transition and is in agreement with the half-life reported in [6]. On the other hand, the gate on the 511 keV line gives a smaller value of $T_{1/2}$=26(1) msec for the new 1^+ isomer in ^{34}Al. The effect of the two β-times mixture is clearly visible in the data : β-times obtained with different gates on γ-spectrum varies between 25 and 53 msec. Even after background subtraction, the β-times corresponding to the 3326 keV and other known transitions in ^{34}Si show intermediate values, suggesting that these states are populated (directly or indirectly) from both ^{34}Al ground state and isomer.

TABLE 1. Comparison between the experimental and shell model energies (in keV) and reduced transition probabilities (in e^2fm^4) for ^{34}Si, ^{32}Mg and ^{30}Mg.

	^{34}Si		^{32}Mg		^{30}Mg	
	exp.	s.m.	exp.	s.m.	exp.	s.m.
$E(0_2^+)$	2719(3)	2570	1058(2)	1282	1788.2(4)	1717
$E(2_1^+)$	3326(1)	3510	885.3(1)	993	1482.8(3)	1642
$B(E2{:}2_1^+\rightarrow 0_1^+)$	17(7)	11	91(16)	85	48(6)	59
$B(E2{:}2_1^+\rightarrow 0_2^+)$	61(40)	67	$\leq$109	15	11(1)	9

Discussion

Most of the theoretical approaches describe the 0_2^+ state in ^{34}Si as an intruder deformed state build on 2p-2h configurations. In a single particle picture, the energy of such a state can be obtained by summing the excitation energies of the states corresponding to (1p-2h)[(2p-1h)] configurations in the (N-1)[(N+1)] isotopes, respectively. As matter of example, the 0_2^+ state in ^{36}S, described as a 2p-2h state in shell model calculations, has an excitation energy of 3346(1) keV. This value is very similar to the energy sum (3389 keV) of the 7/2$^-$ excited state in $^{35}_{16}S_{19}$ (1991.3 keV) and the 3/2$^+$ excited state in $^{37}_{16}S_{21}$ (1397.5 keV), both corresponding to the excitation of a neutron from the $d_{3/2}$ to the $f_{7/2}$ orbital above the N=20 gap. For the Si isotopes, the 3/2$^+$ excited state in $^{35}_{14}Si_{21}$ (974 keV) and the 7/2$^-$ excited state in the $^{35}_{16}S_{19}$ (1435 keV) give an energy sum of 2409 keV, to be compared to $E(0_2^+)$=2719(3) keV reported here. In this simple single particle picture, we can also extract information on the mixing and on the deformation of the 0^+ states in ^{34}Si using a two level mixing model assuming spherical and deformed configurations, as it has been done for example in [18]. Using the relation $B(E2{:}2_1^+\rightarrow 0_1^+)/B(E2{:}2_1^+\rightarrow 0_2^+)\sim\tan^2\theta$ (eq. 2 of [19]), a mixing amplitude $\cos^2\theta$=0.22(7) is deduced from the experimental B(E2) values. The magnitude of the monopole matrix element can be written as a function of the mixing amplitude and of the difference of shapes, β_S and β_D, between the two configurations before mixing [20], $\rho^2(E0)=(3Ze/4\pi)^2 sin^2\theta cos^2\theta(\beta_D^2\text{-}\beta_S^2)^2$. Using the experimental mixing amplitude in this equation, the experimental monopole strength is reproduced when deformations $\beta_D\simeq 0.22$ and $\beta_S=0$ are assumed.

As discussed in the introduction, the major pillars to understand the Island of Inversion are the $0_{1,2}^+$ states in ^{30}Mg, ^{32}Mg and ^{34}Si. A good theory should therefore be able to reproduce the shift of 3 MeV of the deformed 0^+ states in the Mg isotopes and the one of 4 MeV in the N=20 isotones. Concerning the Shell Model calculations, one of the available interactions for this region was the SDPF-U-SI [21] in which the valence protons are in the *sd* shell whereas the valence neutrons are either in the *sd* or the *pf* shells. The $sd\rightarrow pf$ neutron excitations where not considered and therefore it was not possible up to now to describe nuclei in which these excitations are important, such as in the Island of Inversion. In order to account for this type of excitations, two ingredients have to be added : -i- the off diagonal cross shell *sd-pf* matrix elements; they have been taken from the Lee-Kahana-Scott-G matrix [22] and scaled as for the description of the superdeformed states in ^{40}Ca [23] that are similarly built on multiparticles-multiholes excitations, -ii- the second ingredient are the neutron single particle energies for the *sdpf* shells on a core of ^{16}O. For the *sd* one, the standard USD [24] are used whereas for *pf* the choice was done in order to -i- reproduce the results of previous SDPF interaction in the limit of no excitation and -ii- to reproduce the energy of the 0_2^+ state in ^{30}Mg to ensure a correct slope towards ^{32}Mg. The energies of the 2_1^+ and 0_2^+ states and the associated reduced transition probabilities are compared to the experimental results in table 1. The agreement is excellent, all the energies being reproduced within 200 keV. In particular, we can notice that the steep decreases of the deformed 0^+ states between ^{30}Mg and ^{32}Mg (2846 keV experimentaly, 2999 in the calculation) and between ^{34}Si and ^{32}Mg (3767 keV experimentaly, 3852 in the calculation) are well reproduced.

DECAY OF THE 0_2^+ STATE IN ^{44}S

The region of N=28 has been very intensively studied in the last 15 years, in particular at the GANIL laboratory. In this region two effects have to be considered to understand the evolution of the shell structure. First, the addition of neutrons in the $f_{7/2}$ orbital from ^{40}Ca towards ^{48}Ca leads to a compression of the $s_{1/2}$ and $d_{3/2}$ proton orbitals. This effect can be illustrated by the relative position of the 1/2$^+$ and 3/2$^+$ states in the odd-A $^{39-47}$K isotopes. Second, the removal of *sd*-protons from ^{48}Ca leads to a reduction of the N=28 gap itself by almost 300 keV per pair of protons. This reduction has been experimentally measured between ^{49}Ca and ^{47}Ar in a (d,p) transfer reaction at GANIL [25]. These two effects combined together finally leads to a well deformed ^{42}Si as it has been illustrated by our measurement at GANIL of its 2^+ energy at 770(19) keV [26]. This experiment has been

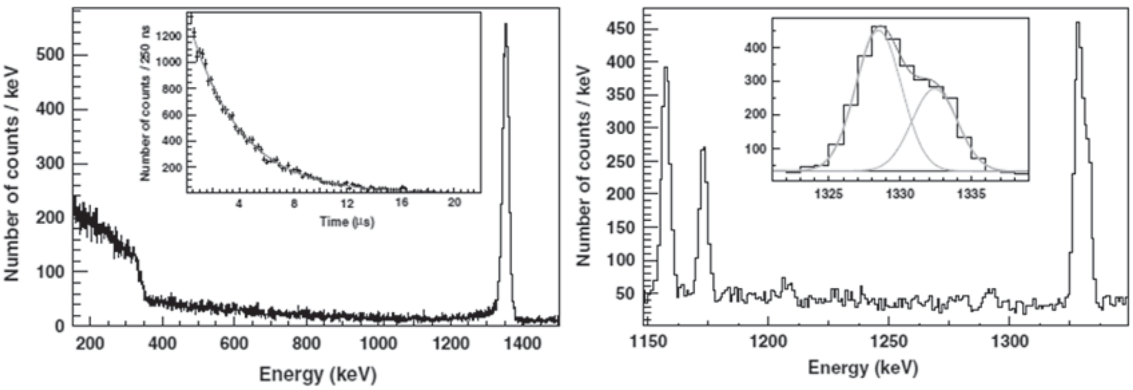

FIGURE 3. Left : Energy in one telescope. The peak correspond to the conversion electron emitted in the EO decay $0_2^+ \rightarrow$g.s. in ^{44}S. The insert corresponds to the time spectrum between the implantation of ^{44}S and the decay by the EO transition. Right : Delayed energy spectrum in the Ge detectors in which a peak at 1329 keV is observed. The insert shows its deconvolution from the 1332 keV transition arising from ^{60}Co.

repeated recently at RIKEN using the new RIBF facility which gives a spectacular gain in the production rate and the GANIL results have been confirmed. Moreover, the statistics was large enough to observe without ambiguity the 4^+ state at 1.4 MeV above the 2^+ and therefore the ratio E(4^+)/E(2^+) has been extracted. This ratio is increasing in the neutron-rich Si isotopes towards N=28, being close to the limit for a rigid rotor in ^{42}Si [27], confirming the strong deformation of this isotope.

In between the spherical ^{48}Ca and the well deformed ^{42}Si, shape coexistence is therefore expected to take place in ^{44}S. It has predicted by different theoretical approaches, shell model calculations [28] or mean field theories, see [29, 30] for example. In 2004, indeed, we observed at GANIL a low lying 0_2^+ state at an excitation energy of 1.36 MeV [7]. This observation has been interpreted as a first indication of shape coexistence. To go farther and obtain the mixing of the 0^+ states and better characterize the deformation, we have performed an isomer spectroscopy experiment with an experimental setup similar to the one described above for the ^{34}Si. Nevertheless, since the 0_2^+ is, contrary to the case of ^{34}Si, located few tens of keV above the 2^+ (1329 keV), it can therefore decay either by E0($0_2^+ \rightarrow 0_1^+$) or E2($0_2^+ \rightarrow 2_1^+$) transitions. For the E0, both internal pair creation and internal conversion have been observed, this latest being the most important decay channel.

Results

The energy spectrum obtained in the Si(Li) detectors is reported on the left part of Fig. 3. A single peak at 1365 keV corresponding to the $0_2^+ \rightarrow 0_1^+$ decay by internal conversion is observed. The internal pair creation process gives rise to the continuous part of the spectrum up to 343 keV corresponding to the remaining part of the energy after the pair creation (1365-1022). This $0_2^+ \rightarrow 0_1^+$ transition is delayed, as illustrated by the time spectrum displayed on the left insert of Fig. 3, the half-life being 2.6μs. Concerning the E0 decay, part of the energy spectrum obtain in the Ge detectors is displayed on the right part of Fig. 3 (with a zoom in the insert). The peak at 1329 keV corresponds to the delayed $2_1^+ \rightarrow 0_1^+$ transition which follows the E2 transition between the 0_2^+ and the 2_1^+, this latest being too small (35 keV) to be detected with the present experimental setup.

The monopole strength between the 0^+ states is extracted from the half-life and an extremely small value of 8.7(7) mu is obtained, pointing towards a small mixing between the 0^+ states. As in the study of ^{34}Si, by combining the known B(E2:$0_1^+ \rightarrow 2_1^+$) [31] and the branching ratio for the decay of the 0_2^+ towards the 2_1^+ and the ground state, a B(E2:$0_2^+ \rightarrow 2_1^+$) of 42(13) e^{2}fm^4 has been extracted. Gathering all this information and using a two levels mixing model, a small mixing of $\cos^2(\theta)$=0.88(5) is obtain for the 0^+ states and a deformation parameter β_2=0.27 for the ground state is deduced assuming that the 0_2^+ is spherical.

Discussion

The above results have been compared to shell model calculations using the SDPF-U-SI [21] interaction and both the energies and B(E2) values are well reproduced, as it can be seen from table 2. Moreover, a deformed band build on the 0_1^+ ground state is predicted [18]. It is characterized by strong B(E2) transitions up to the 6^+ state and nearly constant intrinsic and quadrupole

TABLE 2. Experimental and shell model values for the excitation energies, in MeV, and reduced transition probabilities B(E2), in e^2fm^4, of ^{44}S.

E	2_1^+	0_2^+	2_2^+	B(E2)	$2_1^+ \rightarrow 0_1^+$	$2_1^+ \rightarrow 0_2^+$
exp.	1.329(1)	1.365(1)	2.335(39)	exp.	63(18)	8.4(26)
SM	1.172	1.137	2.140	SM	75	19

moments corresponding to an prolate deformation with β +0.25. On the contrary, no deformed structure being built on the 0_2^+ state and the calculated 2_2^+ state having small quadrupole moments, the 0_2^+ state is deduced as originating from the spherical configuration. Therefore, in agreement with the phenomenological approach, the emerging picture for the structure of ^{44}S corresponds to a spherical-prolate shape coexistence, the deformed 0^+ being the ground state [18].

CONCLUSIONS

In this paper, we have reported on the discovery and the study of two 0_2^+ states, one in ^{34}Si (at N=20), and another one in ^{44}S (at N=28). These two regions are known to have a modified shell structure due to the proton-neutron interaction that modify the position of the single particle orbitals as compared to the valley of stability. In both, it results in deformed configurations which dominate the ground state structure of the most neutron-rich N=20 and N=28 isotopes, ^{32}Mg and ^{42}Si respectively. In between the spherical and deformed regions, shape coexistence takes place and can be characterized by the study of the 0_2^+ states. In these works, we have proved that for both ^{34}Si and ^{44}S, the configurations have a very small mixing leading to spherical-deformed shape coexistence.

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