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Unveiling the intruder deformed $0^+_2$ state in $^{34}$Si

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The $0^+_2$ state in $^{34}$Si has been populated at the GANIL/LISE3 facility through the $\beta$-decay of a newly discovered $1^+$ isomer in $^{34}$Al of $26(1)$ ns half-life. The simultaneous detection of $e^+e^-$ pairs allowed the determination of the excitation energy $E(0^+_2)=2719(3)$ keV and the half-life $T_{1/2}=19.4(7)$ ns, from which an electric monopole strength of $\rho^2(E0)=13.0(0.9)\times10^{-3}$ was deduced. The $2^+_1$ state is observed to decay both to the $0^+_1$ ground state and to the newly observed $0^+_2$ state (via a $607(2)$ keV transition) with a ratio $R(2^+_1\rightarrow0^+_1/2^+_1\rightarrow0^+_2)=1380(717)$. Gathering all information, a weak mixing with the $0^+_1$ and a large deformation parameter of $\beta=0.29(4)$ are found for the $0^+_2$ state, in good agreement with shell model calculations using a new sd-pf-u-mix interaction allowing np-nh excitations across the $N=20$ shell gap.

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In 1949 Mayer, Haxel, Suess and Jensen [1,2] independently gave a description of the observed shell gaps at nucleon numbers 2, 8, 20, 28, 50, 82 and 126 in terms of mean field potential including the spin-orbit interaction. With this model, these special numbers - renamed 'magic numbers'-, as well as the properties of the related nuclei observed at that time such as spin, magnetic moments, discontinuities in binding energies, and $\beta$-decay systematics could be explained. Later, other remarkable properties of magic nuclei have been found: they have a high energy $2^+$ state and a weak transition probability $B(E2;0^+\rightarrow2^+)$. The picture of immutable shell gaps persisted until the ground breaking experiments performed between 1975 and 1984 in very neutron rich nuclei close to the neutron magic number $N=20$. Although it was known since long that the ground state parity of $^{11}$Be was at odds with the naive shell model picture [3], this fact was overlooked until much later. Studies of charge radii, atomic masses and nuclear spectra in the $^{13}$Mg and $^{1}$Na isotopic chains have shown that a region of deformation exists at $N=20$ below $^{11}$Si [4]. More recently it has been found that the $B(E2)$ of $^{32}$Mg [5] is about 4 times larger than the one of $^{34}$Si [6], hereby confirming the onset of the regime of quadrupole collectivity in the region. In the framework of the shell model, the deformation in $^{32}$Mg was soon associated with two-particle-two-hole ($2p2h$) excitations across the $N=20$ shell gap [7]. These $2p2h$ configurations were referred to as intruders since they lie outside the normal model space description of the sd shell nuclei. The region of those nuclei, the ground state of which is dominantly an intruder configuration while their normal configuration ground state is found as an excited state, is called an "island of inversion". Nuclei around $^{32}$Mg were proposed first to form such an island of inversion [8–10]. It has been demonstrated in a recent evaluation of the experimental data of $^{31}$Mg and $^{33}$Mg [11] that their ground state wave function is indeed dominated by two neutrons excitations into the pd orbits. Recent theoretical works [12,13] go a bit further and propose the mixing of the normal and the intruder states for $^{32}$Mg allowing even for a normal configuration dominated ground state [12]. The major pillars to understand the inversion mechanism are the $0^+\rightarrow2^+$ states in $^{30}$, $^{32}$Mg and $^{34}$Si. Adding two neutrons to $^{30}$Mg may provoke the inversion of the normal and intruder configurations. The latter are expected to be shifted by nearly 3 MeV to become the ground state of $^{34}$Mg. Along the isotonic chain we anticipate that the transition is even more abrupt: by removing two protons from $^{30}$Si, the intruder state has to be shifted down by about 4 MeV with respect to the spherical one to become the ground state of $^{32}$Mg.

Excited $0^+$ states were searched for in $^{30}$Mg, $^{32}$Mg and $^{34}$Si for a better understanding of the inversion mechanism. Despite many experimental efforts, this quest was vain for about 30 years until the recent discovery of the $0^+_2$ states in $^{30}$Mg at 1789 keV [14] and in $^{32}$Mg at 1058 keV [15]. While the excited $0^+$ state in $^{30}$Mg could be assigned to the intruder configuration [14], the assignment of the ground state to the intruder and the
excited 0+ state to the normal configuration in 32Mg has been recently questioned [16]. Detailed spectroscopy of 34Si resulting in the discovery of a 0+ intruder state is an important step towards understanding the coexistence of the normal and intruder configurations [10]. A candidate for the 0+ state in 34Si has been proposed at 2133 keV in Ref. [17] but experiments which followed were not able to confirm this result [18–20]. In [20], a new candidate has been tentatively proposed at 1846 keV, but not confirmed by later works [18, 19, 21].

In the present work we propose to use the β-decay of 34Al to populate the 0+ state in 34Si. As 33Al occupies the boundary of the island of inversion, it exhibits normal and intruder configurations at similar excitation energies. Indeed, in the shell model calculations of [22], its ground state (J=4−) has a mixed configuration πd5/2 ⊗ νf7/2 and πd5/2 ⊗ ν(d3/2)−2(f7/2)3 while an excited state at around 200 keV (J=1−) has an intruder 2p2h configuration πd5/2 ⊗ ν(f7/2)2(d3/2)−1 leaving a hole in the neutron d5/2 orbit. Following this prediction the J=1− state would be a β-decay isomer. Its decay would mainly proceed through a Gamow-Teller transition νd3/2 → πd5/2, leading mostly to the 2p2h 0+ state in 34Si. If the 0+ state is located below the 2+ state at 3.326 MeV in 34Si, it would decay by an E0 transition through internal electron conversion (IC) and/or internal pair creation (IPF) processes. Thus, electron spectroscopy coupled to β-decay spectroscopy was used to search for the 0+ state in 34Si.

The experiment was carried out at the Grand Accélérateur National d’Ions Lourds (GANIL) facility. The 34Al nuclei were produced in the fragmentation of a 77.5 A-MeV 36S primary beam of 2 eµA mean intensity on a 240 mg/cm² Be target. The Lise3 spectrometer [23] was used to select and transport the 34Al nuclei, produced at a rate of 600 pps with a purity of 93% and a momentum dispersion of 1.48%. The produced nuclei were identified on an event by event basis by means of their energy-loss in a stack of Si detectors (labeled SiStack) and time-of-flight values referenced to the radiofrequency of the cyclotrons. The transversal alignment of the 34Al nuclei was controlled by means of a double-sided Si strip detector located downstream to a 20 degree-tilted kapton foil of 50 µm, in which the 34Al nuclei were implanted. Once the alignment was performed, the implantation depth of the nuclei was adjusted by tilting the SiStack with respect to the beam direction. Four telescopes (labeled as SiTel), each composed of a 1 mm-thick Si detector of 50x50 mm² followed by a 4.5 mm-thick Si(Li) detector of 45x45 mm², located 24 mm above and below the beam axis were used to detect electrons and positrons with a geometrical efficiency of ~40%. In addition two Ge clover detectors of the EXOGAM array, located at 35 mm on the left and right hand sides of the beam axis, were used to detect γ-rays with an efficiency of 1.6% at 1 MeV, and 0.8% at 3.3 MeV. The experiment ran in sequences of beam-on (120 ms) during which nuclei were collected and beam-off (300 ms) during which the SiTel detected the β-rays (from the β-decay) as well as e⁺e⁻ (from IPF). Note that the detection of these particles was also considered in the beam-on mode in anti-coincidence with an ion detected in SiStack. The 0+ state would decay mainly through IPF if located at a high energy E0≥Eγ below the 2+ state at 3.326 MeV. In this hypothesis, the electron and positron would share a total energy Ee−+Ee+=E0−1022 keV. The search for these events was achieved by requiring a delayed coincidence between three SiTel telescopes. Fig. 1a shows the total energy in one telescope versus the total energy in another. The oblique line corresponds to events in which the detected energy sum in two telescopes equals to 1688(2) keV (as shown in Fig. 1c). Taking into account the energy losses of the e⁺e⁻ pair in the kapton foil as well as their energy-angle correlations [24] with GEANT4 simulations [25], we deduce that the total energy of the emitted pair (Ee−+Ee+) was 9(1) keV higher, establishing a 0+ state at E0=2719(3) keV in 34Si.

As shown in the Fig. 1b, a half-life of T1/2(E0)=19.4±0.7 ns has been obtained for the 0+ state from the time difference between a β-ray in one of the SiTel and a pair detected in another. A consistent value of 19.2±0.8 ns was found from the time difference between a β-ray and a γ-ray of 511 keV, arising from the annihilation of the positron at rest, detected in EXOGAM. Therefore, the transition electric monopole strength ρ2(E0)0+→1+1=13.0(0.9)x10−3 is calculated using the internal conversion ΩIC=1.33×107 s−1 and internal pair creation ΩIPF=2.73×104 s−1 transition rates. These values have been obtained from the one of ref. [26] extrapolated to A=34 and corrected to take into account the atomic screening. The detailed procedure can be found in [27].

The existence of two β-decaying states in 34Al is proven in the present work by the fact that half-lives obtained when β’s are followed by 926 keV or 511 keV γ-rays differ significantly as shown in Fig. 2. The transition at 926 keV is due to the 4−→3− γ-decay, as shown in [17]. Its half-life of 54.4(5) ms agrees well with the value of 56.3(5) ms obtained in [17]. Conversely, the transition of 511 keV corresponding to the 1+→0+ β-decay has a significantly shorter half-life of 26(1) ms. The half-lives of the 4− and 1+ states in 34Al compare well with the values of 59 and 30 ms predicted by shell model calculations, a direct feeding of the 0+ state of 17% being predicted from the J=1−. As no γ-ray (except a large number of 511 keV due to positrons annihilation) was observed in coincidence with the ~2×104 e⁺e⁻ events selected in Fig. 1 (a,c) we surmise that the 0+ state is fed directly by the β-decay of the 1+ isomer of 34Al. However, an absolute direct decay-branch to the 0+ state is hard to obtain as the ratio of isomeric feeding in 34Al could not be determined. As for the direct feeding of the 2+ state in 34Si through the decay of the J=1+ isomer, the situation is more complex since all states populated in the decay of the 4− state- transition through it. Since the β-

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β-value is assigned to the β-indirectly) from concluded that the 2+ (49.8(2) ms) is shorter than the one obtained in [17], it is
deduced for the 0+ state from the time difference between a β-trigger and a e+e− pair, as shown in b).

decay lifetime in coincidence with the 2+ → 0+ transition (49.8(2) ms) is shorter than the one obtained in [17], it is concluded that the 2+ state is also fed (directly and/or indirectly) from β-decay of the isomer in 34Al. A Jπ=1+ value is assigned to the β-decaying isomer in 34Al by virtue of comparison to shell model calculations and β-decay selection rules.

Energy wise the 2+ state in 34Si could decay both to the 0+ state (located 607 keV below) and to the 0+ ground state leading to the known 3.326 MeV transition. Observation of both decay branches inform on the de-mixing of these states. Shell model predict B(E2:2+→0+)=67 e2fm4 and B(E2:2+→0+)=11 e2fm4. When weighted by the Eγ factor for E2 transitions, the expected branching to the 0+ state represents only 0.12% of the total decay of the 2+ state. To observe the weak decay branch through the 607 keV transition it was necessary to reduce the γ-background. This was achieved by requiring a multiplicity M_{S_{tot}} ≥ 2. In Fig. 3, the 607 KeV transition is seen together with the known 591 keV γ-line from the 4970 keV state in 34Si [17]. When the beta-decay of 34Al occurs to unbound states in 34Si, the emitted neutrons can react with the 34Ge nuclei contained in the Exogam detectors and excite its 2+ state at 595.8 keV, giving rise to an enlarged peak at the cor-

![FIG. 1: a) Total energy in one telescope (E_{Si}+E_{SiLi}) versus total energy in another one for events with a telescope multiplicity ≥3 and a delay of 16 ns between the β-trigger and the detected e+e− and/or e−. The oblique line corresponds to a constant energy sum of e+e− pairs emitted in the E0 decay of the 0+ state in 34Si. c) Sum of the energies in both telescopes showing a peak at 1688(2) keV. A half-life of 19.4(7)ns is deduced for the 0+ state in 34Si.](image1)

![FIG. 2: β-decay time spectra obtained in coincidence with the 926 keV (in black) and 511 keV (in red) γ-rays of 34Si giving different half-lives corresponding to the 4+ ground state [54.4(5) ms] and the 1+ isomeric state [26(1) ms] in 34Al.](image2)

![FIG. 3: Part of the gamma energy spectrum following the implantation of 34Si nuclei. The main peak corresponds to the known 591 keV transition in 34Si. Peaks at 607 keV and 596 keV correspond to the 2+→0+ decay and the (n,n’γ) reactions on the 74Ge nuclei of Exogam detectors, respectively.](image3)

Describing a weak signal to noise ratio obtained for the 607 keV peak, a ratio R(2+→0+/2+→0+)=1380(717) has been extracted for the decay of the 2+ state to the 0+ and 0+ states taking into account the γ efficiencies at 607 keV and 3.326 MeV and the Si detector efficiencies with the related uncertainties. A value of B(E2:2+→0+)=61(40) e2fm4 is deduced using the measured value of B(E2:2+→0+)=17(7) e2fm4 [28] determined via Coulomb excitation.

Information on the mixing and deformation of the 0+ states in 34Si can be obtained using a two level mixing model assuming spherical βs and deformed βd configurations, as it has been done for example in [29]. Using the relation B(E2:2+→0+)/B(E2:2+→0+)=tan^2θ [30], a weak mixing ratio of cos^2θ=0.78(9) is deduced from the experimental B(E2) values. We remind here that the maximum mixing ratio would lead to cos^2θ=0.5. The magnitude of the electric monopole matrix element can be written as a function of the mixing ratio and the differ-
Thus the image of coexistence between a closed-shell $0^+$ and the two configurations before mixing [31], $\rho^2(\text{E0})=(32e/\pi^2)^2\sin^2\theta \cos^2(\beta_3^2-\beta_5^2)^2$.

Using the experimental value of the mixing ratio, the experimental electric monopole strength is reproduced when deformation parameters of $\beta_3=0.29(4)$ and $\beta_5=0$ are taken.

We compare now the experimental results with the shell model calculations performed with the code ANTOINE [33] using the effective interaction SDPF-U-MIX which is an extension of SDPF-U-SI [34]. The SDPF-U-SI interaction was designed for 0ω calculations of very neutron-rich sd nuclei around $N=28$ in a valence space comprising the full sd(pf)-shell for the protons(neutrons), i.e. this interaction was defined with a core of 28O. Its single particle energies (SPE’s) and monopoles (neutron-proton sd-pf and neutron-neutron pf-pf) were fixed by the spectra of 35Si, 41Ca, 47K and 49Ca. In order to allow for the mixing among different np-nh neutron configurations across $N=20$, it is necessary to add to SDPF-U-SI the following new ingredients: a) The off-diagonal cross shell sd-pf matrix elements, which are taken from the Lee-Kahana-Scott G-matrix [35] scaled as in ref. [36]; b) The neutron SPE’s on a core of 28O: For the two sd-shell orbits we use always the USD values [37], while for the pf-shell orbits we have no experimental guidance at all. Nonetheless, for any particular set of pf-shell SPE’s, the neutron-neutron sd-pf monopoles must be chosen such as to reproduce the spectrum of 35Si and the $N=20$ gap. We have anchored our choice to the energy of the first excited $0^+$ state in 39Mg, because this guarantees that in our isotopic course toward $N=20$ the descent of the intruder states proceeds with the correct slope. Indeed, at 0ω SDPF-U-MIX and SDPF-U-SI produce identical results. The results of the calculations performed with this new SDPF-U-MIX interaction are gathered in Table I.

| $34\text{Si}$ | $32\text{Mg}$ | $30\text{Mg}$ |
|--------------|--------------|--------------|
| exp. s.m. | exp. s.m. | exp. s.m. |
| E(0+) | 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^+→0^+) | 17(7) | 11 | 91(16) | 85 | 48(6)* | 59 |
| B(E2;2^+→0^+) | 61(40) | 67 | <10(9) | 15 | 11(1)f | 9 |

$a$: [15]; $b$: [17, 20]; $c$: [28]; $d$: [5]; $e$: [32]; $f$: [14]

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