Proc. Conf. Advances in Radioactive Isotope Science (ARIS2014)
JPS Conf. Proc. **6**, 020006 (2015)
http://dx.doi.org/10.7566/JPSCP.6.020006

Properties of Intruder States in ^{34}Al and ^{34}Si

F. Rotaru[1], R. Lica[1], F. Negoita[1], S. Grévy[2], N. Marginean[1], Ph. Dessagne[3], T. Stora[4], C. Borcea[1], R. Borcea[1], S. Calinescu[1], J. M. Daugas[5], D. Filipescu[1], I. Kuti[6], L. M Fraille[7]; S. Franchoo[8], I. Gheorghe[1], R. Marginean[1], C. Mihai[1], P. Morfouace[8], J. Mrazek[9], P. Morel[5], A. Negret[1], D. Pietreanu[1], T. Sava[1], D. Sohler[6], M. Stanoiu[1], I. Stefan[8], R. Suvaila[1] and S. Toma[1]

[1]*Horia Hulubei National Institute for Physics and Nuclear Engineering, IFIN-HH, P.O.B. MG-6, 077125 Magurele, Romania*
[2]*CENBG, Université de Bordeaux, CNRS/IN2P3, Chemin du Solarium, 33175 Gradignan Cedex, France*
[3]*IPHC, Université de Strasbourg, IN2P3/CNRS; BP28, F-67037 Strasbourg Cedex, France*
[4]*ISOLDE/CERN, Geneva, Switzerland*
[5]*CEA, DAM, DIF, Bruyères-le-Châtel, F-91297 Arpajon Cedex, France*
[6]*Institute of Nuclear Research, H-4001 Debrecen, Pf.51, Hungary*
[7]*University of Madrid, Spain*
[8]*IPNO, Université Paris-Sud 11, CNRS/IN2P3, Orsay, France*
[9]*NPI, Nuclear Physics Institute, AS CR, CZ-25068 Rez, Czech Republic*

E-mail: grevy@in2p3.fr

(Received October 7, 2014)

We report on two experimental results for nuclei located in the region of the N=20 island of inversion. In the first experiment, performed at GANIL, we have discovered and studied the 0_2^+ state in ^{34}Si and made the hypothesis that it was fed by the beta-decay of a predicted isomeric 1^+ state in ^{34}Al. In the second experiment, performed at ISOLDE, we have studied the beta-decay of ^{34}Mg in order to obtain information on the structure of ^{34}Al and in particular the position of the isomeric 1^+ state.

KEYWORDS: β-decay, ^{34}Mg, ^{34}Al, ^{34}Si, E0 transition, isomer, shell model

1. Introduction

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 between the $\pi d_{5/2}$ orbital and the $\nu d_{3/2}$ and $\nu f_{7/2}$ orbitals [3], leading to a reduced 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.

2. Discovery of the O_2^+ state in ^{34}Si

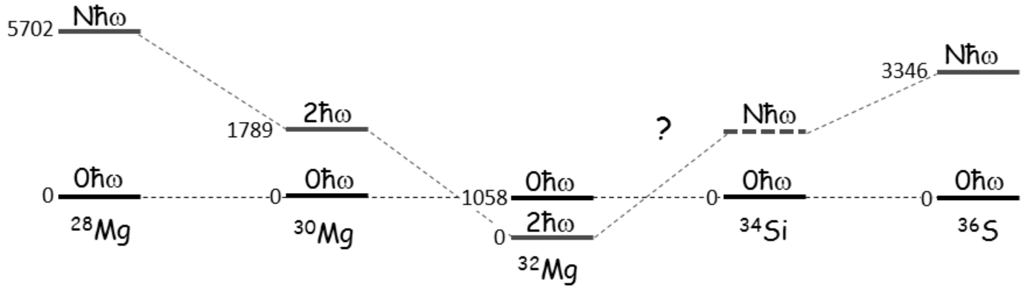

Fig. 1. Position of the first and second 0^+ states in the isotopes of Mg and in the N=20 isotones towards ^{32}Mg.

As illustrated in Fig. 1, the 0^+ state built on neutron excitations above N=20 is located around 5.7 MeV in ^{28}Mg, it has been located in ^{30}Mg 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 recently at ISOLDE at an energy of 1058 keV [5]. Therefore, 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 is observed. For the N=20 isotones, the ground state of ^{36}S at Z=16 is spherical whereas the 0^+ state built 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.

A candidate for the 0_2^+ state in ^{34}Si has been proposed at 2133 keV in [6] but following experiments were not able to confirm this result [7–9]. 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 $^{34}_{14}Si_{20}$ has been unambiguously determined by making the hypothesis that it could be populated in the β-decay of a predicted low-lying 1^+ isomeric state in $^{34}_{13}Al_{21}$ [10].

2.1 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 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 kapton 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 mm^2, 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.

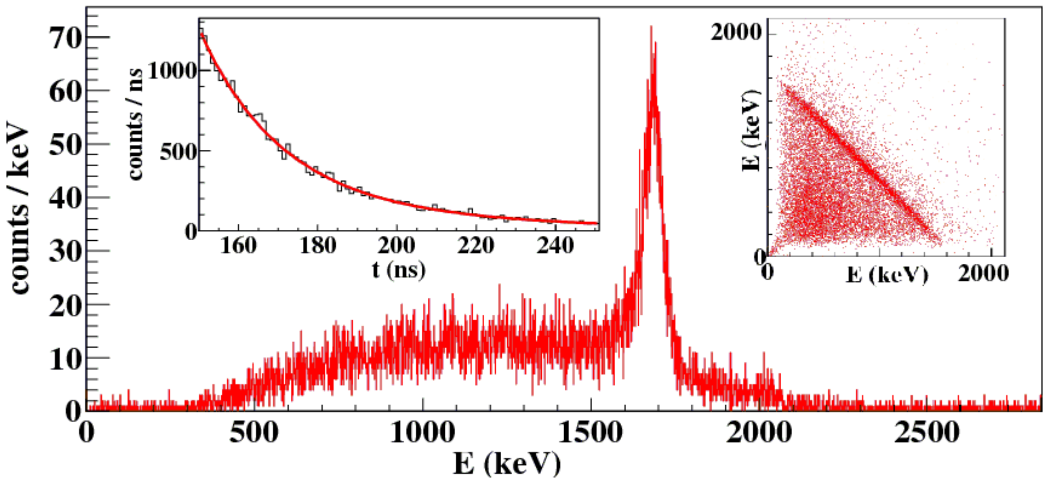

Fig. 2. insert right : Energy in one telescope versus energy in another one for a pair of electron/positron emitted in the EO decay by pair creation of the 0_2^+ state in ^{34}Si with a Si multiplicity equal to 3. Main: Sum of the two energies showing a peak at 1688(2) keV. The left inset corresponds 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.

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 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 [13–15] 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 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 the 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 I. 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
$B(E2{:}2_1^+\to0_1^+)$	17(7)	11	91(16)	85	48(6)	59
$B(E2{:}2_1^+\to0_2^+)$	61(40)	67	≤109	15	11(1)	9

2.2 *discussion*

Most of the theoretical approaches describe the 0_2^+ state in ^{34}Si as an intruder deformed state built 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. For 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 $B(E2{:}2_1^+\to0_1^+)/B(E2{:}2_1^+\to0_2^+)\sim\tan^2\theta$ (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], $\rho^2(E0)=(3Ze/4\pi)^2 sin^2\theta cos^2\theta(\beta_D^2-\beta_S^2)^2$. 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 were 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 the 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 I. 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 experimentally, 2999 in the calculation) and between ^{34}Si and ^{32}Mg (3767 keV experimentally, 3852 in the calculation) are well reproduced.

3. Study of the beta-decay of ^{34}Mg

The motivation for this second experiment was to measure the γ-rays following the β-decay of ^{34}Mg in order to extract for the first time a level scheme of ^{34}Al. First, this information is important in itself to better understand the physics of the Island of Inversion by better constraining the theoretical models. Secondly, the aim was also to determine the excitation energy of the isomeric 1^+ state of ^{34}Al and, finally, to measure the branching ratio of the 2^+ state transitions toward the two lower 0^+ states in ^{34}Si which will allow to extract the B(E2; $2^+ \rightarrow 0^+_2$) using the known B(E2; $2^+ \rightarrow 0^+_1$)=8533 e2fm4 [ref].

The experiment was carried out at the ISOLDE online isotope mass separator facility at CERN. The radioactive ^{34}Mg were produced by spallation of a thick UCx target induced by an intense 1.2 GeV proton beam delivered by the CERN proton-synchrotron booster (PSB). The ions were extracted in the 1^+ charge state and electrostatically accelerated to 60 keV. They were analyzed using the high resolution separator (HRS) and collected on a aluminized mylar tape. The average production yield for ^{34}Mg was around 140 atoms/μC with a very high purity. Around the collection point, 4 HPGe detectors (3 clovers and 1 coaxial), 5 LaBr3(Ce) detectors, 3 NE213 liquid scintillator detectors and a NE102 plastic scintillator were used to register the γ-rays, neutrons and β particles, respectively.

3.1 results

The beta-decay half-life of ^{34}Mg was determined using the beta-gated gamma time with respect to the proton pulse leading to $T_{1/2}$=63(1) ms, three times larger than the previously measured value determined from beta-neutron coincidences [25]. This new value is also confirmed by the beta-gated time spectra using known γ-transitions in ^{33}Al (populated in the beta-neutron decay of ^{34}Mg).

The gamma spectrum following the beta-decay of ^{34}Mg and γ-coincidence analysis led to the preliminary ^{34}Al level scheme built on top of the -presumably- 1^+ isomer, displayed in Figure 3. It is

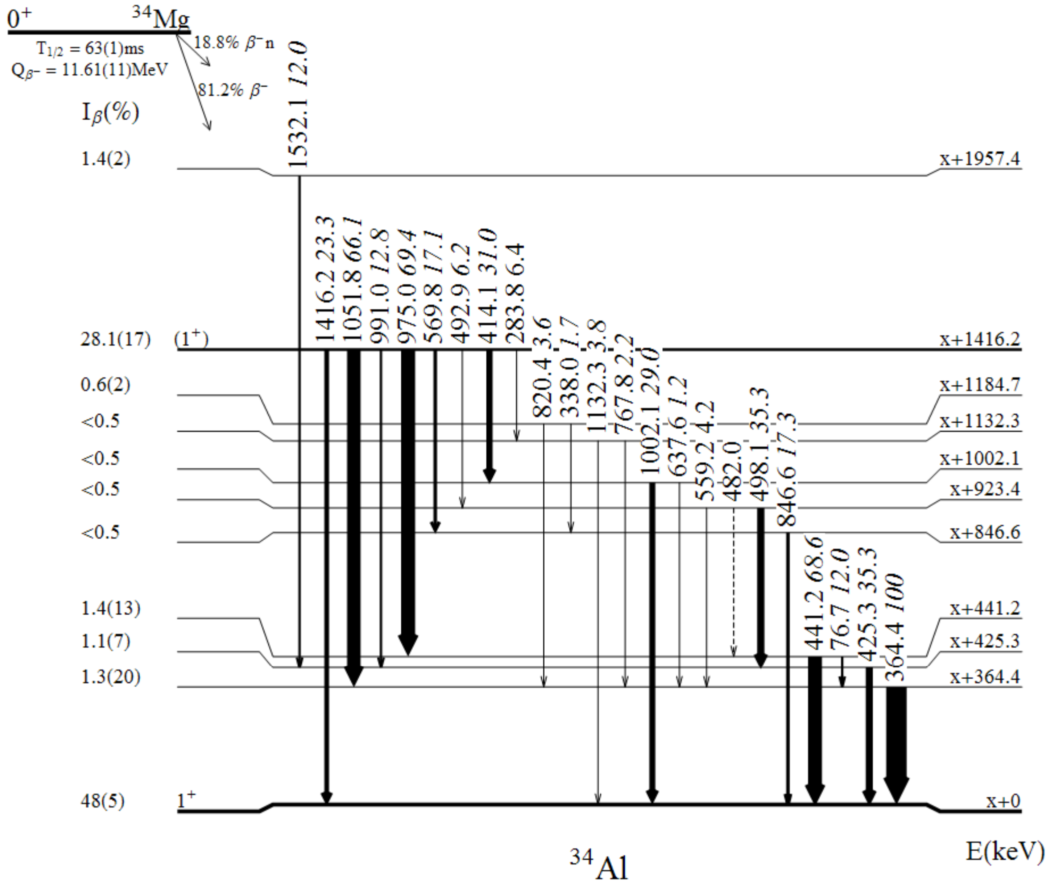

Fig. 3. level scheme above the 1^+ state in ^{34}Al deduced from the beta decay of ^{34}Mg.

worth mentioning that all of the 22 gamma transitions in ^{34}Al reported in this experiment are observed for the first time [26, 27]. The delayed gamma transition $1^+ \rightarrow 4^-$ was not observed, most likely as a result of a small excitation energy of the isomer. The absence of γ-rays (such as 124 keV) that were previously shown to be fed in the β-decay of the ^{34}Al 4^- ground state [6], is the proof that the 4^- state is not populated in the beta-decay of ^{34}Mg (not even indirectly despite the large number of excited states found in ^{34}Al that could have a small gamma branch to the 4^- state). Therefore, none of the available information can help to decide which of the 4^- and 1^+ states is the ground state of ^{34}Al. In addition to the level scheme of ^{34}Al, the subsequent beta-decay of the 1^+state in ^{34}Al revealed several new γ-transitions in ^{34}Si.

4. Conclusions

We have reported on new experimental results obtained at GANIL and ISOLDE. The newly observed 0_2^+ state in ^{34}Si represents a strong step forward to better understand the structural changes observed in the region of the N=20 island of inversion and it allowed us to propose a new version of the SDPF-U interaction taking into account the *sd* $\rightarrow$ *pf* neutron excitations. In the second experiment, we measured for the first time the γ-rays following the β-decay of ^{34}Mg and proposed a detailed level scheme located above a proposed 1^+ state.

References

[1] O. Sorlin and M.-G. Porquet, Prog. Part. Nucl. Phys. **61**(2008)602.
[2] E. K. Warburton *et al.*, Phys. Rev. C **41**(1990)1147.
[3] T. Otsuka *et al.*, Phys. Rev. Lett. **87**(2001)082502; Phys. Rev. Lett. **95**(2005)232502; Phys. Rev. Lett. **104**(2010)012501.
[4] W. Schwerdtfeger *et al.*, Phys. Rev. Lett. **103**(2009)012501.
[5] K. Wimmer *et al.*, Phys. Rev. Lett. **105**(2010)252501.
[6] S. Nummela *et al.*, Phys. Rev. C **63**(2001)044316.
[7] S. Grevy *et al.*, Eur. Phys. J. A **25**(2005)s1-111.
[8] W. Mittig *et al.*, Eur. Phys. J. A **15**(2002)157.
[9] N. Iwasa *et al.*, Phys. Rev. C **67**(2003)064315.
[10] P. Himpe *et al.*, Phys. Lett. B **658**(2008)203.
[11] R. Anne *et al.*, Nucl. Instr. and Meth. A**257**(1987)215
[12] S. Agostinelli *et al.*, Nucl. Instr. and Meth. A**506**(1997)250
[13] A. Passoja and T. Salonen, report JYFL RR-2/86(1986)
[14] E. L. Church and J. Weneser, Phys. Rev. **103**(1956)1035.
[15] D. H. Wilkinson *et al.*, Nucl. Phys. A**133**(1969)1.
[16] R.W. Ibbotson *et al.*, Phys. Rev. Lett. **80**(1998)2081.
[17] L. K. Fifield *et al.*, Nucl. Phys. A **440**(1985)531.
[18] C. Force *et al.*, Phys. Rev. Lett. **105**(2010)102501.
[19] H. Mach *et al.*, Phys. Lett. B**230**,(1989)21.
[20] J. L. Wood *et al.*, Nucl. Phys. A **651**,(1999)323.
[21] F. Nowacki and A. Poves, Phys. Rev. C **79**,(2009)014310.
[22] S. Kahana, H. Lee and C. Scott, Phys. Rev. C **79**,(1969)956.
[23] E. Caurier, *et al.*, Phys. Rev. C **75**,(2007)054317.
[24] B. A. Brown and B. H. Wildenthal, Annu. Rev. Nuc. Part. Sci. **38**(1988)29.
[25] M.Langevin et al., Nucl. Phys. A**414**(1984)151.
[26] M.Gelin, PhD thesis, Univ. de Caen (2007)
[27] B.V.Pritychenko *et al.*, Phys. Rev. C **63**,(2001)047308