Eur. Phys. J. Special Topics **150**, 149–153 (2007)

DOI: 10.1140/epjst/e2007-00291-7

THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS

The "island of inversion" from a nuclear moments perspective and the g factor of ^{35}Si

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Received: January 31, 2007

Abstract. This paper reviews recent results from electromagnetic moment measurements on isotopes in the island of inversion around N = 20. The obtained moments on neutron rich Na, Mg, Al and Si isotopes allow to draw conclusions on the amount of intruder components in their ground state wave function, demonstrating a gradual transition from the normal *sd*-shell region into the island of inversion, starting at N = 18 for Na, N = 19 for Mg and N = 20 for Al isotopes. A measurement of the ground state g factor of ^{35}Si (N = 21), using a polarized fragment beam at GANIL, is discussed in more detail. The magnetic moment $\mu(^{35}\text{Si}, \text{I}^{\pi} = 7/2^{-}) = (-)1.638(4)\mu_N$ is consistent with a normal ground state structure, dominated by a $\nu f_{7/2}$ neutron.

PACS. 21.10.Ky – 23.20.En – 27.30.+t

1 Introduction

In the past two decades, significant progress has been made in understanding the structure of neutron rich nuclei with about ten protons and the double of neutrons. The first mass measurement on exotic isotopes of Na with up to 21 neutrons [1] suggested a deviation from the normal shell-model structure and since then many experiments were performed to characterize the properties of these nuclei to understand the nature and origin of the changed structure. Constrained Hartree-Fock calculations suggested that the ground states of ^{31,32}Na are deformed [2], which was explained in a shell-model picture as due to an inversion of the normal shell model ground state with an intruder state that becomes the ground state [3–5]. The interplay between a reduced N = 20 shell gap and a large quadrupole-quadrupole proton-neutron interaction at proton mid-shell (between Z = 8 and Z = 20) leads to the appearance of an 'island of inversion' in which the nuclei have a ground state dominated by intruder configurations (particle-hole excitations across N = 20). The prediction of the bounderies of this island depend strongly on small changes in the shell-model parametrization, and therefore experiments are needed to investigate the transition from the normal region into the island of inversion. To probe the nuclear ground state structure, the nuclear magnetic dipole and electric quadrupole moment are very good tools. The magnetic moment, through the spin and the gyromagnetic factor, is very sensitive to which orbital is occupied by the odd nucleons. The spectroscopic quadrupole moment of isotopes with spin I $\geq$ 1 provides information on the nuclear deformation.

To measure the static moments of short-lived exotic nuclei (some milliseconds to seconds) the most appropriate methods are based on the observation of the asymmetry in the β-decay after a polarized beam is implanted in a suitable host [6,7]. Polarized beams of exotic nuclei are obtained in mainly two ways: using the reaction-induced polarization in a nuclear reaction at intermediate or relativistic beam energies [8,9] or using the collinear interaction between a radioactive ISOL-beam and a circularly polarized laser beam [10,11].

2 Structure information from moments: Present status

Since the end of the last century, a systematic study of the magnetic and quadrupole moments of isotopes in and near the island of inversion has been performed at ISOLDE-CERN (^{28,29,30,31}Na [12,13] and ^{25,27,29,31,33}Mg isotopes [14–16]) as well as at GANIL (^{31,32,33,34}Al isotopes [17–19] and ^{35}Si). In Table 1 we present the results of all moments published till now and we summarize here the major conclusions. The Na, Mg and Al isotopes have been studied

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Table 1. Isotopes near the island of inversion, for which static moments have been measured.

Isotope	I^π	$\mu(\mu_N)$	$Q_s(\mathrm{efm}^2)$	Ref.
$^{27}\mathrm{Na}_{16}$	$5/2^+$	+3.984(3)	−0.72(3)	[13]
$^{28}\mathrm{Na}_{17}$	1^+	+2.420(2)	+3.95(12)	[13]
$^{29}\mathrm{Na}_{18}$	$3/2^+$	+2.457(2)	+8.6(3)	[13]
$^{30}\mathrm{Na}_{19}$	2^+	+2.069(2)	+14.6(1.6)	[12,13]
$^{31}\mathrm{Na}_{20}$	$3/2^+$	+2.298(2)	+10.5(2.5)	[12,13]
$^{31}\mathrm{Mg}_{19}$	$1/2^+$	−0.88355(15)	/	[14]
$^{30}\mathrm{Al}_{17}$	3^+	3.010(7)		[21]
$^{31}\mathrm{Al}_{18}$	$5/2^+$	3.79(5)		[17]
		3.830(5)		[18]
$^{32}\mathrm{Al}_{19}$	1^+	1.959(9)		[21]
		1.9516(22)		[18]
$^{33}\mathrm{Al}_{20}$	$5/2^+$	4.088(5)		[18]
$^{33}\mathrm{Si}_{19}$	$(3/2^+)$	(+)1.21(3)		[22]
$^{35}\mathrm{Si}_{21}$	$7/2^-$	(−)1.638(4)		this work

up to the neutron number N = 20, which was demonstrated to disappear as a magic number in this region of nuclei. Data on the N = 21 isotopes ^{33}Mg and ^{34}Al are being prepared for publication [16,19].

In this paper we first discuss which nuclear structure information has been obtained from these static moments (section 2) and then we present a new result for the N = 21 isotope ^{35}Si (section 3). Because this Z = 14 isotope has a filled $\pi d_{5/2}$ orbit, we expect it to have a rather normal shell structure. In fact, its neighbour ^{34}Si, exhibits some features of a doubly-magic nucleus [20] suggesting that Z = 14 is a sub-shell closure. By measuring its magnetic moment one can further investigate this, which is discussed in section 4.

The Na moments have been extensively discussed within the Monte Carlo Shell Model (MCSM) approach by Utsuno et al. [23]. They have shown the importance of comparing the experimental moments to predictions by the shell model, in order to understand the detailed ground state structure. Indeed, based on earlier available data (mainly binding and excitation energies), it was suggested that ^{30}Na (at N = 19) is reasonably well described by the USD shell model interaction [4]. However, comparison of the precisely measured magnetic and quadrupole moments up to ^{31}Na with calculations in the *sd* shell model showed a drastic deviation for ^{30}Na and a small deviation for ^{29}Na (illustrated in figure 1(a) and 1(b)). The calculations named "0p-0h" and "2p-2h" were made using the sdpf-interaction from [24] in which the *sd* shell part is described by the USD interaction. The "0p-0h" values are those without excitations from the *sd* to the *pf* orbits, giving indeed similar results for those with the USD interaction [18]. If two neutrons are fixed in the $f_{7/2}p_{3/2}$ orbits (named "2p-2h") the agreement for the magnetic and quadrupole moments of ^{30,31}Na is perfect, while for ^{29}Na one finds an experimental quadrupole moment in-between the 0p-0h and 2p-2h values. The ground state moments calculated with the SDPF-M

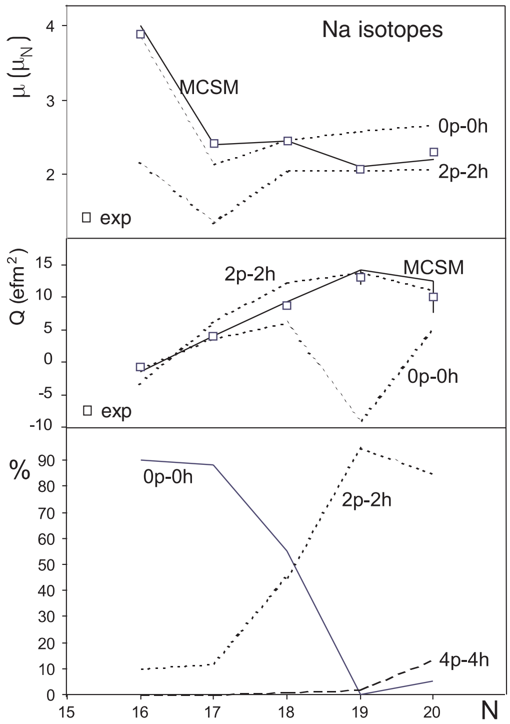

Fig. 1. (a) Magnetic dipole moments and (b) electric quadrupole moments of Na isotopes. Dashed lines represent a calculation using the sdpf-interaction with the ANTOINE code, while solid lines are results from the MCSM with the SDPF-M interaction from [23]. (c) np-nh (n = 0, 2, 4) probabilities of the Na ground states as discussed in [23].

interaction [25] in the MCSM approach, which include mixed np-nh configurations, nicely reproduce the observed values. From these calculations, for which the N = 20 shell gap was strongly reduced as compared to that in ^{40}Ca, it was found that intruder configurations already play a role in the ^{29}Na ground state (42%) and are dominating the ground states of ^{30,31}Na (see figure 1(c)). Note that in the calculations with the sdpf-interaction free-nucleon g factors were used, while in the SDPF-M calculations effective values were used. The effective charges to calculate quadrupole moments are the same in both cases ($e_\pi = 1.3e$ and $e_\nu = 1.5e$).

For the Mg isotopes, a similar conclusion was drawn recently for ^{31}Mg (N = 19), whose ground state spin $1/2^+$ and magnetic moment are not consistent with the *sd* shell model [14]. Calculations with the sdpf-interaction with two neutrons in the lowest fp orbits predict a $1/2^+$ 2p-2h state around 1 MeV and its magnetic moment is close to the observed value. The SDPF-M interaction predicts this state around 500 keV with a similar magnetic moment and also having almost pure 2p-2h nature. So both interactions seem to reproduce rather well the structure of the neutron rich Na and Mg ground states, but they need refinement in order to reproduce also the excitation energy spectra.

Finally the Al chain was investigated, as these isotopes with Z = 13 protons occur between the normal Si isotopes and the intruder-dominated Mg isotopes.

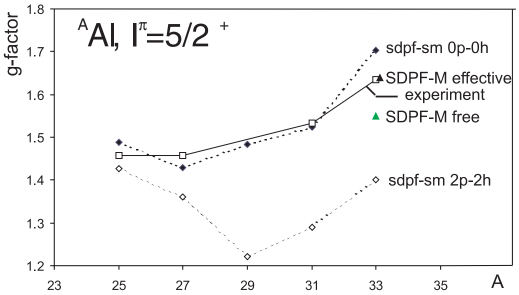

Fig. 2. Experimental g factors of the odd Al isotopes (connected by full line) compared to calculations for pure 0p-0h and 2p-2h configurations with the sdpf-interaction (dashed) and to results from the MCSM taken from [26,27] for ^{33}Al.

Calculations with the SDPF-M interaction predicted a 50% mixed normal-intruder configuration for the N = 20 ^{33}Al ground state [26], thus a gradual transition from normal to intruder dominated ground states. This is confirmed in a recent g factor measurement of the neutron-rich Al isotopes [18]. The experimental value for all odd Al isotopes is in agreement with the predictions from the USD shell model within better than 2%, except for ^{33}Al (figure 2). The experimental value is between that for a pure 0p-0h and a pure 2p-2h configuration (a state that appears below 1 MeV in the sdpf-calculations), and it agrees very well with the value predicted by the SDPF-M calculations, in particular if the same effective g-factors are used as for the Na isotopes (see figure 2).

The major conclusion from all these studies is that the transition into the island of inversion occurs gradually, both as a function of N and as a function of Z.

3 g factor of the $7/2^-$ ground state in ^{35}Si

^{35}Si ($t_{1/2}$ = 0.78 s [28]) is expected to be a normal nucleus with $I^\pi = (7/2^-)$ [24]). Its g factor has been measured at the LISE fragment separator at GANIL using the β Nuclear Magnetic Resonance (β-NMR) method on a polarized fragment beam obtained from a one-neutron pickup reaction at intermediate energies. The experimental technique and set-up have been extensively discussed in several papers [9,17,18]. To produce this neutron rich nucleus, a ^{36}S beam at 77.5 MeV/u (typical intensity of 1.5 μA) interacted with a ^{9}Be target ($\approx$200 mg/cm^2) from which it picked up a neutron. The ^{35}Si fragments were separated from the other reaction products using the doubly-achromatic LISE fragment separator with a ^{9}Be (198 mg/cm^2) wedge degrader placed at the middle focal plane. Recently it was shown that in pickup reactions a significant amount of spin-polarization can be observed in an ensemble of fragments selected in the center of their longitudinal momentum distribution [9,29]. By closing the slits in the intermediate focal plane to (−1,+0.5)%, a fully-stripped ^{35}Si beam with a purity of 85% and a rate of 1600 ^{35}Si ions/s was selected for the β-NMR study. After implantation in a suitable crystal (Si in this case) that is placed in a sufficiently large magnetic

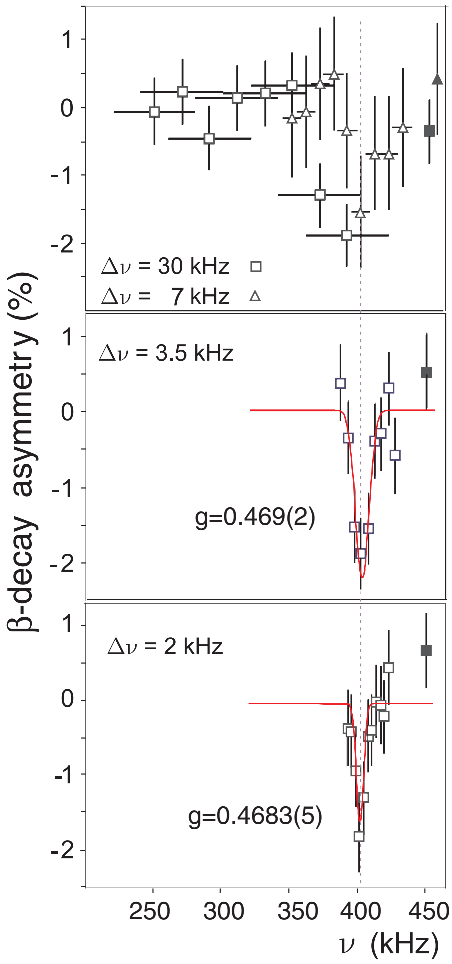

Fig. 3. NMR resonances for ^{35}Si implanted in a Si single crystal at room temperature. Filled squares are measured with the rf-field switched off.

field (B = 0.1130(2) Tesla), the spin-polarization gives rise to an asymmetry in the β-decay. By applying additionally a radiofrequency (rf) field with a frequency ν_{rf}, the polarization in the ensemble (and thus the asymmetry in the β-decay) is destroyed if the applied rf-frequency equals the Larmor frequency $\nu_L = \frac{g\mu_N B}{h}$. Thus by measuring the asymmetry in the β-decay as a function of the applied rf-frequency, one can determine the Larmor frequency as the center of the measured NMR resonance. From this the nuclear g factor is deduced.

The result from a resonance search is illustrated in the top of figure 3 using large modulations on the applied rf-frequency (30 kHz and 7.5 kHz). Two fine scans were made in the region were a breakdown of the asymmetry is observed, using respectively frequency modulations of 3.5 kHz and 2 kHz. More details about the measuring procedure, the data analysis procedure and the calibration of the magnetic field, can be found in [18]. From the fitted resonance positions, the g factor is deduced as $|g(^{35}\mathrm{Si})| = 0.468(1)$, where the error includes the uncertainty on the magnetic field.

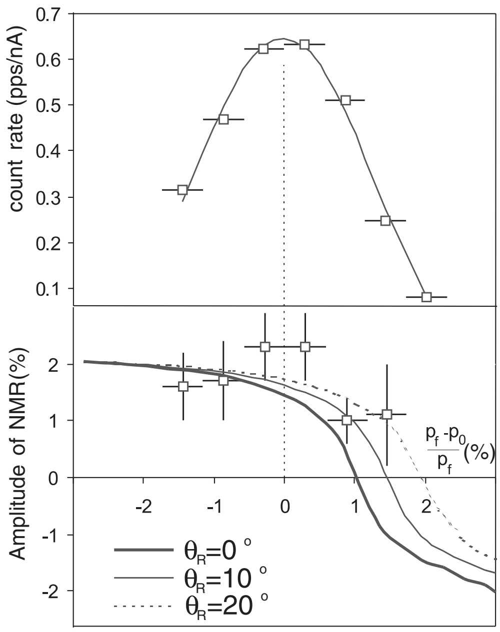

Fig. 4. (a) The yield distribution of ^{35}Si fragments produced by one-neutron pick-up on a ^{36}S beam. (b) The corresponding amplitude in the NMR resonance measured for each ensemble.

The amplitude of the measured resonances is ≈2% and proportional to the amount of polarization that is produced in the nuclear reaction. We have measured the NMR-amplitude for different selections in the longitudinal momentum distribution of the ^{35}Si fragments, shown in figure 4. The result agrees remarkably well with the predicted trend of the polarization from a kinematical model [9], which assumes that the polarization is produced by the pick-up of one neutron, while the evaporation of the two protons (S → Si) is considered not to modify the trend line of the polarization. In this calculation the only parameter is the angle θ_R which defines the average position where the nucleon has been picked-up from the target (see e.g. [9]). A good agreement is found for θ_R close to the grazing angle (around 10° in this case). The calculated polarization has been scaled by a factor 0.029 to match the maximum amount of asymmetry that is observed.

4 g factors of N = 21 isotones

The ground states of the odd N = 21 isotones from Ca (Z = 20) to Si (Z = 14) are expected to be dominated by one neutron in the $\nu f_{7/2}$ orbital, resulting in a $I^\pi = 7/2^-$ ground state. The ^{35}Si ground state magnetic moment, $\mu_{exp}(7/2^-) = (-)1.638(4)\mu_N$ deduced from our measured g factor, is indeed within 15% of the Schmidt value for a $\nu f_{7/2}$ neutron (−1.91). The magnetic moment of the less exotic isotones, shown in figure 5, are very similar and they all deviate about 16% from the Schmidt value. This suggests that none of the isotones has a 100% pure $\nu f_{7/2}$ configuration, contrary to what is predicted by the shell model. Indeed, for the Ca isotopes with a closed Z = 20 shell, one expects a magnetic moment equal to

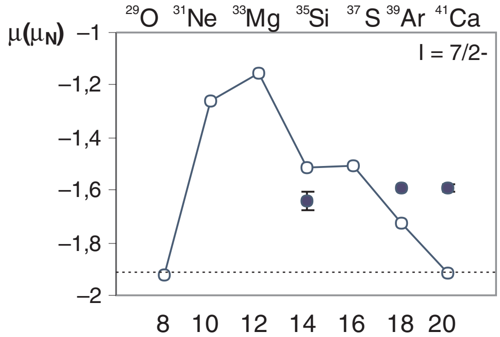

Fig. 5. Magnetic moments of N = 21 $7/2^-$ (ground) states compared to free-nucleon values in the $sdpf$-model space without excitations from sd to fp. The Schmidt line for a $\nu f_{7/2}$ is shown as a dashed line.

the Schmidt value, as illustrated by a calculation with the sdpf-interaction [24] in figure 5. In this calculation one neutron is fixed in the fp shell and no excitations of protons from sd to pf are considered. If one allows up to two protons and three neutrons in the $f_{7/2}p_{3/2}$ orbits, the calculated value for ^{41}Ca changes from −1.915 to −1.845, in better agreement with the experimental value. This suggests that Z = 20 is not a very good magic number. A similar conclusion was drawn from the mean square charge radii of the odd Ca isotopes between N = 20 and N = 28 [30]: excitations of protons across the Z = 20 shell gap are needed to explain them. In the present sdpf-interaction the gap between the $\pi(sd)$ and $\pi(fp)$ single particle levels is yet too large to allow the necessary amount of particle-hole excitations across Z = 20.

With decreasing proton number, the calculated magnetic moments start deviating from the Schmidt line due to coupling of the odd neutron with proton excitations in the sd orbits. Thus the magnetic moment of these odd isotones is very sensitive to possible sub-shell closures in the proton sd shell. The fact that the experimental magnetic moment of ^{35}Si is 8% closer to the Schmidt line than the one calculated with the sdpf-interaction, suggests that the proton collectivity is smaller than calculated. This supports the earlier evidence for ^{34}Si being a doubly-magic nucleus. However, from the magnetic moment we can not conclude whether a more substantial Z = 14 or Z = 16 sub-shell closure is present. Indeed, the magnetic moment equals the Schmidt value if the protons are blocked in the $d_{5/2}$ orbital. By including also the $\pi s_{1/2}$ orbit in the calculation (allowing proton excitations across Z = 14), the value changes little, from −1.915 to −1.86, which is not enough to reproduce the experimental value. Thus mainly excitations of protons to the $\pi d_{3/2}$ orbital (across Z = 16) are needed to account for the experimental value $\mu_{exp} = -1.638\mu_N$. However, when including this orbital in the model space, the calculated value, $\mu(\pi(sd)\nu(fp)) = -1.51$, deviates more from the Schmidt value than the experimental one. To be in agreement with the experimental value, the $\pi(d_{5/2} - d_{3/2})$ splitting needs to be increased a little, which can lead to a larger Z = 16 sub-shell gap (but does not exclude an increase of the

Z = 14 sub-shell gap as well). A measurement of the ^{37}S g factor could confirm this.

For the isotones below Si, starting at Z = 13, the N = 20 shell gap is known to be reduced due to the changing $d_{5/2}d_{3/2}$, $d_{5/2}f_{7/2}$ and $d_{5/2}p_{3/2}$ monopoles when the $\pi d_{5/2}$ orbit is being emptied. The spin/parities of the lowest excited states in the next odd isotone, ^{33}Mg, will be very useful to further investigate the proton-neutron monopoles in this region. A tentative assignment $I^{\pi} = 3/2^{+}$ is made for the ^{33}Mg ground state spin, based on a β-decay study [31]. The positive parity would mean that this nucleus has a $1p1h$ intruder ground state. A measurement of the g factor can confirm or reject this [16].

5 Conclusions

A systematic study of the magnetic moments of ground states of isotopes with Z = 11, 12, 13, 14 and neutron numbers between N = 16 and N = 21, has revealed that the transition from the normal shell model region towards the island of inversion occurs gradually. The g factor of the ^{35}Si isotope with N = 21 neutrons is consistent with a rather pure $\nu f_{7/2}$ ground state structure, thus confirming the suggested doubly-magic character of ^{34}Si and clearly placing this isotope outside the island of inversion.

This work has been supported by the European Community FP6 - Structuring the ERA - Integrated Infrastructure Initiative-contract EURONS No. RII3-CT-2004-506065. PH is grateful to the IWT-Vlaanderen (Institute for the Promotion of Innovation through Science and Technology in Flanders) for providing a scholarship. This work was supported also by INTAS 00-463, the IUAP project No. p5-07 of OSCT Belgium and by the FWO-Vlaanderen. DLB acknowledges support from the Bulgarian Science Fund VUF06/05.

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