Ground state moments and spins of neutron-rich K and Al isotopes as probes for changes in nuclear structure

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Abstract. This contribution focusses on recent measurements of nuclear moments and spins using two complementary methods. The ground state magnetic moments and spins of the exotic isotopes $^{49,51}$K have been measured at the ISOLDE facility at CERN using bunched-beam high-resolution collinear laser spectroscopy. The re-inversion of the ground state spin from $I = 1/2$ in $^{47,49}$K back to the normal $I = 3/2$ in $^{51}$K has been established. At GANIL (Caen, France) the quadrupole moment of the $^{33}$Al ground state has been measured using the continuous-beam $\beta$-nuclear magnetic resonance method applied to a spin-polarized beam produced at the LISE fragment separator. The large value establishes a very mixed wave function with about equal amounts of normal and neutron particle-hole excited configurations contributing to its ground state wave function. This illustrates the transitional nature of isotopes at the border of the island-of-inversion.

1. Introduction

Static moments of nuclear ground states are ideal probes to study their wave function: the magnetic moment provides information on the nature of the unpaired single particle nature of the wave function while the quadrupole moment is also sensitive to deformation and core-polarization effects. Experimental techniques to study these properties for exotic nuclei are constantly optimized to reach out to the most exotic regions.

At ISOLDE-CERN the collinear laser spectroscopy method is used to study in a single experiment the spin, the magnetic dipole moment, the electric quadrupole moment and the mean square charge radius of long-lived isomeric states and ground states in a model-independent way [1]. In the last years, the implementation of an ion cooler-buncher [2] has lead to an improvement of the experimental sensitivity by a factor 500. This allow experiments on beams of a few $10^4$ ions/s using the bunched-beam collinear laser spectroscopy technique [3, 4]. To study the exotic potassium isotopes up to $^{51}$K, produced at less than 5000/s, a further improvement in sensitivity of almost an order of magnitude was needed. This was achieved by building a dedicated light collection region with lenses for enhancing the geometrical efficiency and dedicated shielding for reducing background photon counting [5].

Not all isotopes are produced efficiently at an ISOL-type facility and other methods are needed to study moments of nuclei produced e.g. in fragmentation reactions and selected as fast beams using an in-flight spectrometer. The $\beta$-nuclear magnetic resonance ($\beta$-NMR) method is ideally suited to study the magnetic dipole moment or electric quadrupole moment, by implanting a
polarized beam in a suitable crystal [6]. The polarized ensemble of exotic nuclei is obtained by making a proper selection in the transverse and longitudinal momentum distributions of the fragments [7, 8, 9]. With this method polarized beams of Al isotopes up to $^{34}$Al are produced at rates of a few 1000/s at the LISE fragment separator at GANIL.

In this paper we present results from both types of experiments, and we concentrate on the nuclear structure information that is deduced from the measured spin, magnetic moment or quadrupole moment.

2. Ground state spins and magnetic moments of $^{49,51}$K.

The potassium isotopes have 19 protons and the properties of the ground state of the odd-$A$ isotopes is therefore dominated by the single hole in the magic calcium isotopes. The protons occupy the positive parity $sd$ shell while the neutrons occupy the $sd$ shell below $N = 20$ and the $pf$ shell from $N = 21$ onwards. Since many years it is known that the energy difference between the $\pi 1d_{3/2}$ and $\pi 2s_{1/2}$ single particle levels is strongly decreasing from $^{40}$Ca to $^{48}$Ca, which is illustrated by the lowering of the $1/2^+$ first excited state in the odd-K isotopes. This leads to an inversion of the ground state spin from $3/2$ in $^{39-45}$K to $1/2$ in $^{47}$K [10]. The migration of the proton single particle levels has been attributed to the isospin-dependent monopole residual interaction, which is strongest between levels with the same number of nodes and changes with increasing number of neutrons occupying a certain orbit [11, 12, 13]. For the K-isotopes between $N = 20$ and $N = 28$, it is the attractive $\pi 1d_{3/2} - \nu 1f_{7/2}$ interaction that induces the lowering of the $\pi 1d_{3/2}$ level with respect to the $\pi 2s_{1/2}$ level. Beyond $N = 28$ the $\nu 2p_{3/2}$ level is filled and in these isotopes the monopole interaction between the orbits ($\pi 2s_{1/2}$ and $\nu 2p_{3/2}$) is the dominant one (as orbits with the same radial quantum number are interacting more strongly). Different theoretical models predict a different evolution of the single particle levels beyond $N = 28$ and therefore experimental data are crucial to test and improve the parametrization of the models.

With this aim we have studied the ground state spins and magnetic moments of the neutron-rich $^{49,51}$K isotopes, with respectively $N = 30, 32$. From the measured hyperfine structures in the $^2S_{1/2} \rightarrow ^2P_{1/2}$ transition, a spin $I = 1/2$ is clearly established for the $^{49}$K ground state, as only three transitions are observed (figure 1) [5]. The ground state of $^{51}$K has spin $I = 3/2$ or larger, considering that four transitions are seen in the hyperfine structure. Its spin is determined by comparing the measured magnetic moment to that of the calculated $3/2^+$ ground state in different large scale shell model calculations with effective interactions for this mass region (details in [5]). The SDPF-NR [14, 15] and its recently upgraded SDPF-U interaction [16] have monopole matrix elements that were tuned by fitting experimental spectra of isotopes in this region, from O to Ca. The SDPF-MU interaction [17] is based on the recently developed monopole-based universal interaction $V_{MU}$ [13] and involves therefore fewer fitted parameters.
Calculations are performed with protons restricted to the sd shell and neutrons in the full pf shell.

A very good agreement is found between the experimental magnetic moment and all theoretical values for the calculated $I = 3/2^+$ ground states of $^{51}$K (figure 2). This establishes the re-inversion to a spin 3/2 ground state in $^{51}$K [5]. None of the magnetic moments calculated for the $^{49}$K, $I^\pi = 1/2^+$, state agrees very well with the observed value. This suggests that the $\pi 2s_{1/2}$ configuration is very likely significantly mixed with the ($\pi 1d_{3/2}^2 \nu (2^+)$)$_{1/2^+}$ configuration. Indeed, the magnetic moment of such a mixed wave function agrees with the experimental value for a 25% mixing, as illustrated in figure 3.

![Figure 2](image1.png)  
*Figure 2.* Experimental magnetic moments compared to shell model calculations (see [5] for details).

![Figure 3](image2.png)  
*Figure 3.* Calculated magnetic moment of the $^{49}$K $1/2^+$ state for a mixed wave function.

In figure 4, we compare the experimental $(3/2^+ - 1/2^+)$ energy differences with the calculated energy differences. Those calculated with the fitted interactions are better in agreement with the data than those calculated with the SDPF-MU. However, considering that the number of fitted parameters is much less in the latter, the agreement is also satisfactory. The re-inversion of the energy difference beyond $N = 28$ is somewhat overestimated with the SDPF-MU interaction. Therefore the present data, and in particular the magnetic moment of $^{49}$K, will be helpful in further investigating the role of the different components in the monopole interaction. As can

![Figure 4](image3.png)  
*Figure 4.* Experimental and calculated energy differences between the $3/2^+$ and $1/2^+$ states in odd K-isotopes. See text and ref. [5] for details.
be seen in figure 4, establishing the energy of the first excited state in $^{51}$K is crucial for further improving all of these effective interactions, which predict very different excitation energies for the $1/2^+$ state.

3. The static quadrupole moment of $^{33}$Al

The $^{33}$Al isotope, with 13 protons and 20 neutrons, is located at the border of the 'island-of-inversion'. From early experiments, the island-of-inversion was suggested to contain neutron-rich Na and Mg isotopes with a deformed ground state [18, 19, 20, 21, 22]. First theoretical studies suggested that the isotopes of Na and Mg with 20-22 neutrons [23] belong to the island of inversion. It was later shown that these isotopes have a ground state wave function that is dominated by the excitation of neutrons from the $sd$ shell into the $pf$ shell, across a reduced $N = 20$ shell gap (e.g. [24]). Such configurations are called 'intruder' configurations, as they appear lower in the energy spectrum than normally expected. Nuclear moments measurements on Mg isotopes with $N = 19, 20, 21$ and Na isotopes with $N = 19, 20$ have confirmed that these isotopes have an intruder ground state, with two neutrons excited into the $pf$ shell [25, 26, 27]. Thus the island-of-inversion extends down to $N = 19$ for the Na and Mg isotopes.

Measured magnetic moments of Al isotopes, occurring at the Z-border of the island-of-inversion, suggested that the ground states of $^{31,32}$Al have a normal wave function [28, 29], while $^{33}$Al($N = 20$) and $^{34}$Al($N = 21$) have a mixed ground state wave function, with a significant contribution of intruder configurations [29, 30]. This was the first signature for the island-of-inversion to extend beyond $Z = 12$.

Quadrupole moments are more sensitive to the occurrence of intruder configurations in the wave function because such configurations are related to an increased deformation. Therefore, experimental campaigns at GANIL and RIKEN were started to study this observable in order to shed more light on the wave function of these isotopes. The production of exotic Al isotopes is higher in fragmentation reactions than at ISOL-type facilities. Furthermore, using a fragmentation reaction for the production of these isotopes has the advantage that a spin-polarized ensemble can be selected [31]. By implanting spin-polarized Al-fragments into a suitable crystal with an axially symmetric electric field gradient, their quadrupole interaction frequency can be measured using the multiple-rf nuclear quadrupole resonance method. Two types of measurements have been performed: the adiabatic fast passage technique using a pulsed fragment beam [32, 33] and the continuous-rf magnetic resonance (MR) technique using the continuous implantation of a fragment beam [34]. The former technique has the advantage that if the proper magnetic resonance conditions are fulfilled, the resonance signal registers the inversion of the ensemble spin polarization. This leads to a signal with the double amplitude as compared to the continuous-rf MR method where the spin-polarization is not inverted, but simply reduced to zero. However, the full spin-inversion is only obtained if all rf-conditions are fully controlled, which is rarely the case. The continuous-rf method has the advantage that the full duty-cycle can be used, while the adiabatic technique requires a pulsed beam and therefore a duty cycle which is typically less than 50%.

The quadrupole moments of the Al isotopes have been investigated by implanting them into an Al$_2$O$_3$ (corundum) single crystal. From the ratio of the measured quadrupole frequencies, the ratio of quadrupole moments is determined. Thus all quadrupole moments are determined with respect to a reference value, which is chosen to be the stable $^{27}$Al isotope. The measured quadrupole frequency of $^{27}$Al implanted in the same crystal structure under similar conditions at 77 K is $\nu_Q = 2389(2)$ kHz [35] (used for adiabatic fast passage measurements), while the frequency at room temperature is 2402.5(1.7) kHz [36] (for measurements using the continuous-rf method). As a reference quadrupole moment for $^{27}$Al, $Q=146.6(10)$ emb is used [37].

Comparison of the measured quadrupole moments of the less exotic Al isotopes to shell model calculations with and without excitations of neutrons from the $sd$ to the $pf$ shell, revealed a
normal sd wave function for the isotopes of $^{31}$Al [38] and $^{32}$Al [39], in agreement with the conclusion from the magnetic moments measurements. That is illustrated in figure 5, where the experimental quadrupole moments of the odd-Al isotopes are compared to shell model calculations. The SDPF-M calculations have been performed with the Monte Carlo Shell Model code, with protons restricted to the sd shell and neutrons occupying the full pf shell. The SDPF-NR calculations are performed with the ANTOINE shell model code, with protons and neutrons both restricted to the sd shell. Note that these calculations give a similar result as with the USD-interactions, shown in [40]. The effective charges are respectively 1.1e for protons and 0.5e for neutrons, as used by De Rydt et al. [38]. A similar result is found when the isospin-dependent effective charges are used, as can be seen in the paper by Shimada et al. [40].

The quadrupole moment of the $^{33}$Al ground state could be measured recently using the adiabatic fast passage $\beta$-NMR method at GANIL. Although the obtained value has a rather large error bar (figure 5), the deviation of the experimental value from the SDPF-NR value (restricting neutrons to the sd shell) is clear and from the good agreement with the SDPF-M value a mixing with intruder configurations in its ground state has been confirmed [40]. A new measurement using the continuous-rf NMR method, also performed at GANIL, allowed to measure the quadrupole resonance frequency with a much higher precision, resulting in a ratio of the $^{33}$Al to $^{31}$Al quadrupole moment with a precision of less than 2%. The measured resonances from this experiment are shown in figure 6. The results from this work will be published soon [41].
4. Conclusion
In this presentation we have shown some recent results from measurements of nuclear moments and spins, and how these observables are good tests for the nuclear ground state wave functions and shell model calculations.

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References
[1] Neugart R and Neyens G 2006 Nuclear Moments Lect. Notes Phys. vol 700 (Berlin Heidelberg: Springer-Verlag) pp 135-189
[2] Mane E et al. 2009 Eur. Phys. J. A 42 503
[3] Vingerhoets P et al. 2010 Phys. Rev. C 82 064311
[4] Flanagan KT et al. 2009 Phys. Rev. Lett. 103 142501
[5] Papuga J et al. 2013 submitted to Phys. Rev. Lett.
[6] Neyens G 2003 Rep. Prog. Phys. 66 633 and 1251
[7] Okubo H et al. 1994 Phys. Lett. B 335 29
[8] Borremans D et al. 2002 Phys. Rev. C 66 054601
[9] Turzo K et al. 2006 Phys. Rev. C 73 044313
[10] Tuchard F et al. 1982 Phys. Lett. B 108 169
[11] Otsuka T et al. 2001 Phys. Rev. Lett. 87 082502
[12] Otsuka T et al. 2005 Phys. Rev. Lett. 95 232502
[13] Otsuka T et al. 2010 Phys. Rev. Lett. 104 012501
[14] Retamosa J et al. 1997 Phys. Rev. C 55 1266
[15] Nummela S et al. 2001 Phys. Rev. C 64 054313
[16] Nowacki F and Poves A 2009 Phys. Rev. C 79 014310
[17] Utsuno Y et al. 2012 Phys. Rev. C 86 051301(R)
[18] Thibault C et al. 1975 Phys. Rev. C 12 644
[19] Lunney D et al. 2006 Eur. Phys. J. A 28 129
[20] Motobayashi T et al. 1995 Phys. Lett. B 346 9
[21] Pritychenko BV et al. 2000 Phys. Rev. C 63 011305(R)
[22] Warburton EK, Becker JA and Brown BA 1990 Phys. Rev. C 41 1147
[23] Brown BA 2001 Prog. Part. Nucl. Phys. 47 517
[24] Kello V et al. 1999 Proc. Int. Conf. on Exotic Nuclei and Atomic Masses (ENAM98) (AIP Conf. Proc. vol 455) ed BM Sherrill et al. (New York: AIP) p 50
[25] De Rydt M et al. 2009 Phys. Lett. B 678 344
[26] Kameda D et al. 2007 Phys. Lett. B 647 93
[27] Shimada K et al. 2012 Phys. Lett. B 714 246
[28] De Rydt M et al. 2013 in preparation