Exploration of nuclear structure beyond the limits of stability via magnetic moment measurements: ^{82}Sr and ^{90}Sr

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Abstract. Magnetic moment measurements over the last fifty years have provided considerable information on the microscopic structure of low-lying excited states of nuclei across the periodic table. At the same time there have been many developments in theoretical calculations, particularly in nuclei having either protons or neutrons or both filling orbitals at or near closed shells. Recent experimental challenges were to find means to populate states in nuclei far from stability. The development of radioactive beams has been slow and few nuclei have been accessed by that route. However, novel approaches, in particular the capture of an α particle from a ^{12}C target by stable nuclei in a beam, have opened new pathways. In this work, the region around $N = 50$, which includes the isotopes of Kr, Sr and Zr, has been investigated. The g factors of 2_1^+ and 4_1^+ states in the unstable isotopes of ^{82}Sr and ^{90}Sr were measured by the transient field technique and compared to the results of large scale shell-model calculations. In addition, the g factor of the 4_1^+ state in ^{86}Kr was measured.

1. Introduction

Over the last 28 years and 10 "International Spring Seminars on Nuclear Physics" our group has focused on the measurements of magnetic moments of short-lived states in many nuclei, from light to heavy. These nuclei exhibit behaviour ranging from single-particle excitations to collective modes. The magnetic moments have also been examined in isotopic and isotonic series of nuclei as a function of the energy and spin of their excited states. Often the results have been expected and predicted by specific models; occasionally, however, surprising results have opened new windows into the understanding of the nucleon arrangements within a given nucleus. On one hand, nuclei with neutron and/or proton numbers far from magic numbers tend to have g factors $\sim Z/A$ which are predicted for collective excitations or in the IBA model. On the other hand, the g factors of states in nuclei near closed shells are very sensitive to the details of the shell-model configurations chosen for their description. Thus, precise experimental information can guide shell-model calculations. But discrepancies between experimental observations and the theoretical results appear vividly in studies of long chains of isotopes such as, for example, in the Ca, Zr, Sn and Nd isotopes.

The advances in the field have been supported by developments and continuous improvements in both the experiments and the data analysis. The magnetic moment measurements using the transient field technique made a leap forward with the use of beam projectiles as probe ions. Nuclei in isotopic pure beams were Coulomb excited in inverse kinematics using a standard C target. That approach leads to higher detection yields of the reaction products and, ultimately, to improved statistics. It also opens the access to rare isotopes available as beams. But very few such beams of sufficient intensity have been produced so far: ^{76}Kr, $^{38,40}S$, ^{132}Te, ^{134}Te, ^{126}Sn and ^{72}Zn [1–7].

In view of the difficulties encountered in the preparation of beams of radioactive nuclei, a roundabout way was developed to access nuclei beyond stability. This opportunity ensued from the use of α-capture reactions in which specific beam ions capture an α particle from a ^{12}C target, a process which often leads to nuclei off stability. This reaction, which can be applied in the same kinematic conditions as Coulomb excitation, has been exploited in light nuclei in the Ti, Zn ,Ge region up to ^{100}Pd [8–10].

In the present work, Sr isotopes at the limits of high and low Z/N ratio, $^{82}_{38}$Sr and $^{90}_{38}$Sr, have been studied. The resulting magnetic moments obtained for these nuclei have been compared to the moments in the neighboring $_{36}$Kr and $_{40}$Zr isotopes in the same mass region which encompasses the $f_{5/2}$, $p_{3/2}$, $p_{1/2}$ and $g_{9/2}$ orbitals for protons and $g_{9/2}$, $d_{5/2}$, $g_{7/2}$, $d_{3/2}$, $s_{1/2}$, and $h_{11/2}$ for neutrons.

A compilation of the g factors of 2^+_1 states that were measured, before this work was started, in even-even nuclei from Zn to Cd is shown in Fig. 1. The results obtained in the current experiment and previous data on Kr isotopes are juxtaposed in Fig 2. At the same time important developments have taken place in the shell-model calculations describing these nuclei.

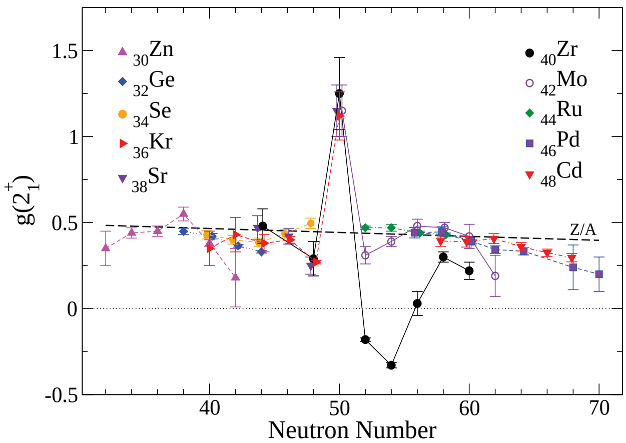

Figure 1. Compilation of all g factors of 2^+_1 states in the even Zn to Cd isotopes [11].

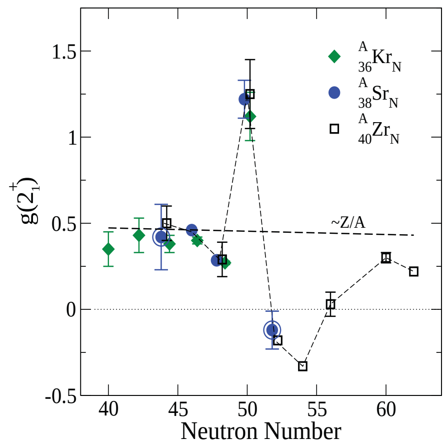

Figure 2. g factors of 2^+_1 states in even Kr, Sr and Zr isotopes. The data for $^{82}_{38}$Sr$_{44}$ and $^{90}_{38}$Sr$_{52}$ (large circles) were obtained in this work.

2. Experimental details

Beams of ^{78,86}Kr were accelerated in the K500 Texas A&M University cyclotron. Experiments were carried out with ~ 1 pnA beams at three different beam energies of 3.0, 3.1, and 3.2 MeV/u. These energies were chosen because they straddle the Coulomb barrier for the beam - target combination of ^{A}Kr - ^{12}C.

Under these conditions, both the Coulomb excitation of Kr isotopes and α-transfer reactions leading to ^{82}Sr and ^{90}Sr can occur. The latter reaction proceeds via capture by a beam ion

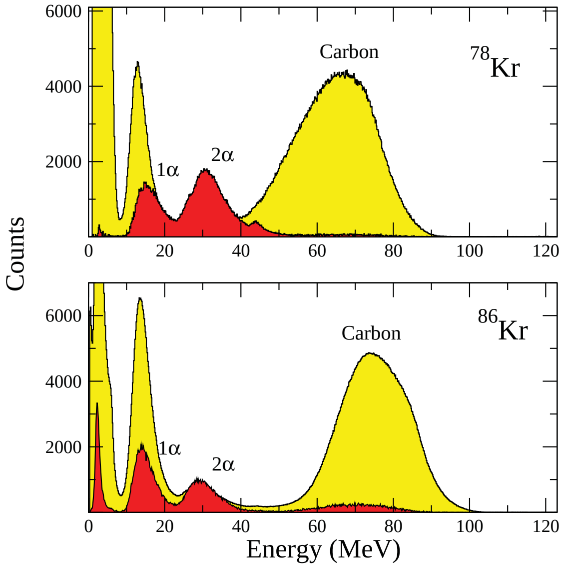

Figure 3. (light grey) Particle spectra obtained with ^{78}Kr and ^{86}Kr beams at 3.2 MeV/u. (dark grey) Particle spectra gated on γ rays belonging to ^{82}Sr or ^{90}Sr ions [11] .

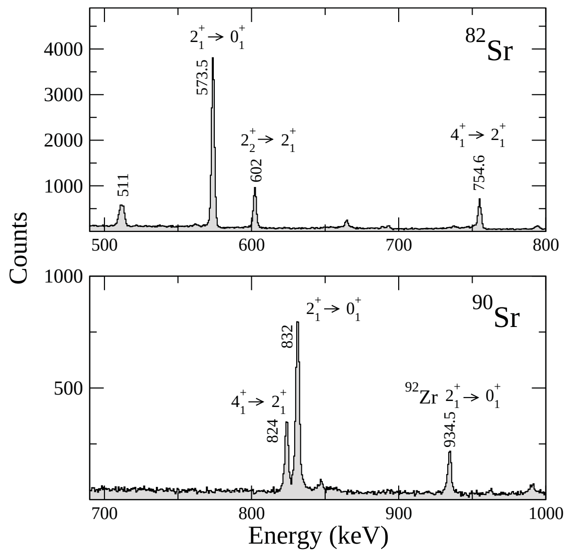

Figure 4. Partial γ spectra observed in coincidence with α particles from the α-capture reactions leading to ^{82}Sr and ^{90}Sr [11].

of an α particle from the C target, with the residual ^{8}Be breaking up immediately into two α particles, ^{12}C(^{78,86}Kr,^{8}Be)^{82,90}Sr.

The C recoils that follow Coulomb excitation reactions and the two α particles from the ^{8}Be breakup were detected in a PIPS silicon detector placed at 0° with respect to the beam. The γ rays emitted by the recoiling excited beam nuclei were detected in four germanium clover detectors located at appropriate angles where the slope of the particle-γ angular correlation is favorable.

A typical particle spectrum identifying the various particle components, is shown in light grey in Fig. 3. The dark color spectra correspond to particle spectra, mostly α particles and protons, obtained by gating on γ rays from ^{82}Sr and ^{90}Sr [11] . Spectra of γ rays from ^{82}Sr and ^{90}Sr in coincidence with the two-α particle-peak are shown in Fig. 4.

Angular correlations were measured for both Coulomb-excitation and α-transfer reactions. These latter reactions lead to nuclei with a lower spin alignment than that observed in Coulomb excitation. However, this reduction in sensitivity is compensated for by the increased α-transfer reaction cross-section.

The details of the experimental setup and of the data acquisition and analysis are extensively described in [11].

3. Results

The g factors of Coulomb-excited 2_1^+, 2_2^+ and 4_1^+ states in ^{78}Kr and the g factor of the 2_1^+ state in ^{86}Kr, measured in the present experiment, reproduce well the values obtained previously [12]. In addition, the magnetic moment of the 4_1^+ state in ^{86}Kr was measured for the first time. The g factors of the 2_1^+ and 4_1^+ states in ^{82}Sr and ^{90}Sr were obtained. The new results are listed in Table 1. The g factors of 2_1^+ states in even-even Kr, Sr and Zr isotopes are shown in Fig. 2.

Table 1. Summary of the new g factors measured in this experiment.

I^π	${}^{86}_{36}\mathrm{Kr}_{50}$	${}^{82}_{38}\mathrm{Sr}_{44}$	${}^{90}_{38}\mathrm{Sr}_{52}$
2_1^+		+0.44(19)	–0.12(11)
4_1^+	+1.03(14)	+0.53(39)	–0.02(17)

4. Theoretical calculations

The nucleus ${}^{82}_{38}\mathrm{Sr}_{44}$ is located in the middle of a major shell, $28 \leq N, Z \leq 50$. Collective models predict $g \sim Z/A$, a result which was indeed observed in this work for both the 2_1^+ and 4_1^+ states, and had been previously observed as well for ${}^{84}_{40}\mathrm{Zr}_{44}$.

The ^{86}Kr nucleus, where the neutrons fill the magic N=50 shell and the protons occupy the $p_{3/2}$ and $f_{5/2}$ shells, is amenable to relatively simple shell-model calculations (SM) described below in Section 4.1. For ^{90}Sr, a full large-space shell-model calculation was carried out and is described in Section 4.2.

4.1. ${}^{86}_{36}\mathrm{Kr}_{50}$

A simple SM calculation for the 2_1^+ and 4_1^+ states in ^{86}Kr was carried out [13]. In that calculation the neutrons are inert and there are two proton holes in the $p_{3/2}, f_{5/2}$ orbital space. The Surface Delta Interaction (SDI) was used and it was assumed that the energies of the $p_{3/2}$ and $f_{5/2}$ orbitals are identical. The free-nucleon spin g factor for the proton $(g_s)_\pi = +5.586$ was used. The magnetic moments μ of the 2_1^+ and the 4_1^+ states are then given by

$$\mu(2_1^+) = \mathrm{a}^2\ \mu(f_{5/2})^{-2} + \mathrm{b}^2\mu\ [(f_{5/2})^{-1}(p_{3/2})^{-1}] + \mathrm{c}^2\mu(p_{3/2})^{-2} \text{ and}$$
$$\mu(4_1^+) = \mathrm{d}^2\mu[(p_{3/2})^{-1})(f_{5/2})^{-1}] + \mathrm{e}^2\mu(f_{5/2})^{-2}.$$

The values of the coefficients a, b, c, d, and e were obtained by matrix diagonalization resulting in

$\mu(2_1^+) = +2.0$ and $g(2_1^+) = +1.0$, and $\mu(4_1^+) = +4.0$ and $g(4_1^+) = +1.0$.

Both calculations are in agreement with the measurements.

4.2. Large-scale shell-model calculation

Calculations were carried out using the model space outside the ^{78}Ni core with the protons in the $f_{5/2}$, $p_{3/2}$, $p_{1/2}$, and $g_{9/2}$ orbitals and the neutrons in the $d_{5/2}$, $g_{7/2}$, $d_{3/2}$, $s_{1/2}$, and $h_{11/2}$ orbitals. The effective interaction for this valence space was constructed by monopole corrections of the realistic G-matrices based on the CD-Bonn potential. A standard M1 operator and the j-coupled code NATHAN were used with $g_{s\,eff} = 0.75\ g_{s\,free}$ [11, 14].

The results of the calculations are shown in Table 2. The calculations are in good agreement with the experimental values for the 2_1^+ and 4_1^+ states in ^{86}Kr and ^{92}Zr. However, the calculations over predict the magnitude of the g factor of the 4_1^+ state of ^{90}Sr. These observations suggest that proton excitations may be underestimated in the latter calculation.

5. Conclusions

New magnetic-moment measurements of 2_1^+ states in the ^{82,90}Sr nuclei, beyond the limits of stability, have been performed as well as a measurement of the magnetic moment of the 4_1^+ state in semi-magic ^{86}Kr. The new results fit well into the systematics for nuclei in this region in so

Table 2. The results of large-scale shell-model calculations for ^{86}Kr, ^{90}Sr and ^{92}Zr, using the model space outside the ^{78}Ni core with the protons in the $f_{5/2}$, $p_{3/2}$, $p_{1/2}$, and $g_{9/2}$ orbitals and the neutrons in the $d_{5/2}$, $g_{7/2}$, $d_{3/2}$, $s_{1/2}$, and $h_{11/2}$ orbitals [11, 14].

	$^{86}_{36}$Kr$_{50}$		$^{90}_{38}$Sr$_{52}$		$^{92}_{40}$Zr$_{52}$	
	Exp't	SM	Exp't	SM	Exp't	SM
$g(2_1^+)$	+1.10(5)	+1.03	–0.12(11)	–0.09	–0.18(1)	–0.24
$g(4_1^+)$	+1.03(14)	+0.99	–0.02(17)	–0.34	–0.50(11)	–0.43

far as ^{82}Sr can be considered a collective nucleus lying in the middle of a major shell, and ^{90}Sr has the characteristics of a nucleus where single-particle excitations dominate.

Large-scale shell-model calculations for the $N = 52$ isotones ^{90}Sr and ^{92}Zr suggest that the $Z = 40$ core might be more robust than the $Z = 38$ core because proton excitations play a more important role in reducing the magnitude of the magnetic moments in ^{90}Sr than in ^{92}Zr.

This work also suggests that, while waiting for the advent of radioactive beams of sufficient intensity to carry out magnetic moment measurements, the α-transfer reaction mechanism should be studied in more depth in order to establish optimum running conditions and increase the sensitivity of the experiments.

We thank Aldo Covello for his many contributions to nuclear physics over the last three decades and for providing a unique environment where the community could share ideas and thrive.

Acknowledgments

The work was supported in part by the U.S. National Science Foundation. The authors thank their collaborators from many institutions who participated in the experiment.
The support of the Texas A&M Cyclotron Institute staff is very much appreciated.

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