Proposal to the INTC Committee

Measurement of the magnetic moment of the 2^+ state in neutron-rich radioactive ^{72,74}Zn using the transient field technique in inverse kinematics

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Abstract

We propose to measure the sign and magnitude of the g-factors of the first 2^+ states in radioactive neutron-rich ^{72,74}Zn applying the transient field (TF) technique in inverse kinematics. The result of this experiment will allow to probe the $\nu g_{9/2}$ component of the wave function of the 2^+ state and therefore constitutes a stringent test of different theories describing the interplay between collectivity and single particle structure in the region of N=40.

The experiment will benefit from the experience gained by the collaboration in several previous experiments performed at REX-ISOLDE, the measurements of the reduced transition probabilities B(E2: $0^+ \rightarrow 2^+$) in ^{74,76,78,80}Zn using Coulomb excitation on one hand side and the first application of the TF technique to study the magnetic moment of the 2^+ state in ^{138}Xe (IS415) on the other.

The ^{72,74}Zn nuclei will be Coulomb excited in the first layer of the multi-layer target, namely ^{27}Al, and then experience the transient magnetic field during their passage through a ferromagnetic Gd layer resulting in a precession of their nuclear spin. Finally they are stopped in a non-magnetic Cu layer before the γ-rays of interest are emitted. We propose to measure the rotation of the anisotropic angular correlation of the γ-rays emitted from the excited 2^+ state using four MINIBALL Cluster detectors positioned in a horizontal plane.

A total of 9 days is requested for this experiment. This includes one day for preparations and calibrations before cooling down the reaction target and 3 and 5 days, respectively, for the measurement of g(2^+) in ^{72}Zn and ^{74}Zn.

1) Physics motivation

Nuclear magnetic moments are sensitive probes of the single particle properties of the nuclear wave function. The magnetic moment operator, with its explicit dependence on protons or neutrons involved in the configuration of the state and on their angular momenta, serves as a stringent test of the proposed main configuration of the nuclear state, as well as of other admixtures. It is, therefore, necessary to study nuclear magnetic moments of nuclei that lie close to nuclear shell closures or, in general, to any place on the nuclear chart where the valence nucleons start filling a higher lying orbital in the next major shell. A good example is provided by the N = 40 region around ^{68}Ni on the neutron-rich side of the nuclear chart, where the positive parity $\nu g_{9/2}$ orbital dives into the negative parity *fp* shell. It is a long standing issue whether N = 40 has to be considered as a new (sub)shell closure or whether the peculiar effects observed in the region can be traced back to the parity change between $\nu g_{9/2}$ and the *fp* shell which prevents 1p1h states from contributing to the wave functions of positive parity states. The small B(E2) of the first 2^+ excited state in ^{68}Ni for example (compare Fig. 1) is explained as due to a pair scattering to the $g_{9/2}$ orbital [1] showing that the two particle – two hole excitations play a considerable role even at N=40.

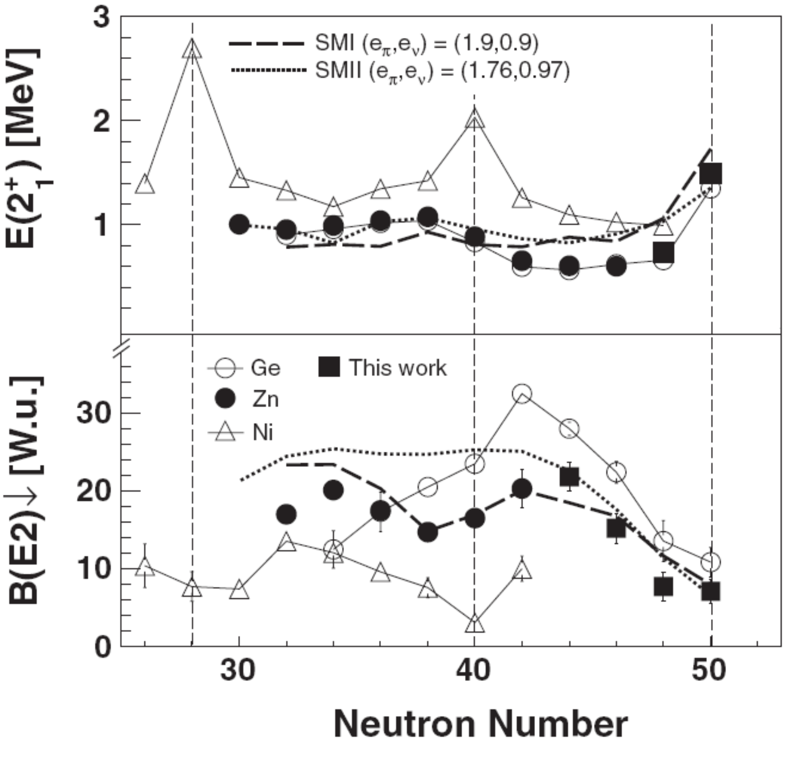

Fig. 1. Experimental E(2^+) and B(E2) values as a function of the neutron number N for the Ni, Zn and Ge isotopic chains (taken from [2]).

The Zinc isotopes have just two protons more than the semi-magic Z = 28 Nickel nuclei and one can expect that they would have similar structure, which would be reflected by the trends of particular nuclear quantities, e.g. the reduced transition probabilities B(E2) or the g factors of the first excited 2^+ and 4^+ states, denoted hereafter as g(2^+) and g(4^+), respectively. However, the spherical N=40 gap may not be strong enough to stabilize the nuclei in a spherical shape when protons are added to the ^{68}Ni core. Even with a moderate deformation, the density of Nilsson orbitals is very high thus providing many possibilities to generate 2^+ states via (parity allowed) particle-hole excitations, as deformation smears out the distinction between the negative and positive parity states below and above the N=40 spherical gap, respectively. The B(E2) is therefore expected to be large if the spherical N=40 gap is not strong enough to prevent the nuclei from deformation. This is what is observed in the chain of $_{30}$Zn isotopes as shown in Fig.1. Whereas the B(E2) value decreases when going from N=38 to N=40 in the Ni isotopic chain as expected assuming a spherical N=40 subshell closure it increases in the Zn isotopes going from ^{68}Zn to the N=40 isotope ^{70}Zn. This behaviour as well as other quantities have been compared to various shell model calculations in Refs. [2,3] demonstrating that although many different calculations are available to describe the nuclei in the ^{68}Ni region we are far from having a consistent set of calculations describing equally well the excitation energies and transition strengths in the Ge, Se, Ni and Zn isotopic chains. In particular, the excitation energies in the Zn isotopes above N=40 are clearly overestimated in all calculations and the B(E2) values can only be reproduced assuming very large effective charges. Both observations may indicate that the considered configuration space is too small and the wave functions not well understood. In such a situation additional experimental information is certainly needed.

Although the B(E2) values can hint at changes in nuclear structure, the admixture of a certain orbital in the nuclear wave function is revealed much more clearly by the gyromagnetic ratio of an individual state. In particular the measurement of magnetic moments of excited 2^+ states in the Zn isotopes around N=40 would allow to determine the importance of the $g_{9/2}$ orbital in this region. If a spherical N=40 subshell closure exists in Ni but not in Zn, one would expect to observe the larger influence of the $g_{9/2}$ neutron in the Ni isotopic chain and therefore a drop of the magnetic moment of the first excited 2^+ states above N=40 (since $g_\nu(g_{9/2})=-0.24$). For the Zn nuclei on the other hand such a decrease of $g(2^+)$ would not be expected. Recently, the g-factors of the first 2^+ states in the even-even $^{62-70}$Zn isotopes have been precisely measured by the Speidel group using the technique of projectile Coulomb excitation in inverse kinematics and transient magnetic fields [4]. Almost no dependence on the neutron number has been observed for these isotopes as shown in Fig. 2. All measured g-factors are close to the hydrodynamical limit, Z/A, observed for most of the well deformed nuclei studied so far in which the magnetic moment is dominated by the orbital motion of the protons. In the case of strong spin contributions of the valence nucleons a deviation from the Z/A line would be expected. The experimental results therefore seem to indicate that the population of the $g_{9/2}$ orbital plays only a minor role for all the isotopes studied so far.

However, several large-scale shell model calculations (which are included in Fig. 2) predict clear deviations from the Z/A behaviour for ^{72,74}Zn. In the first calculation (SM1, called LSSM I in ref. [4]), a ^{40}Ca core and the $f_{7/2}$, $p_{3/2}$, $p_{1/2}$ and $f_{5/2}$ valence orbitals have been considered. In the next three (SM2-SM4) ^{56}Ni is used as a closed shell core and all include the $f_{5/2}$, $p_{3/2}$, $p_{1/2}$ and $g_{9/2}$ valence orbitals. They however employ different effective interactions (SM2 is called LSSM II in ref. [4], for details of SM3 and SM4 see refs. [5] and [6], respectively). The huge discrepancy between the SM1 calculation, which neglects the $g_{9/2}$ orbital, and the experimental results for the heavier isotopes nicely demonstrates the importance of this orbital in particular for describing ^{70}Zn. The inclusion of the $g_{9/2}$ orbital in SM2 leads to an improved results for ^{70}Zn. However, the larger deviation of the SM2 values as compared to SM1 from the experimental results for ^{66,68}Zn shows the importance of excitations from the $f_{7/2}$ proton shell in these isotopes. The results of the third calculation SM3 indicate a large influence of the neutron $g_{9/2}$ orbital evidenced by a drastic decrease of the g-factor between ^{66}Zn and ^{68}Zn while SM4 predicts a gradual decrease from N=36 to N=44. Obviously a shell model calculation including both proton excitations from the $f_{7/2}$ orbital across Z=28 and neutron excitations to the $g_{9/2}$ orbital at the same time ($f_{7/2}$, $f_{5/2}$, $p_{3/2}$, $p_{1/2}$ active proton orbitals and $f_{5/2}$, $p_{3/2}$, $p_{1/2}$, $g_{9/2}$ active neutron orbitals) would be highly desirable. Preliminary results for ^{68,70,72}Zn obtained in this valence space [7] are included in Fig.2 as SM5. The values for ^{68,70}Zn are very close to the experimental ones and for ^{72}Zn a value around g = +0.12(6) is predicted.

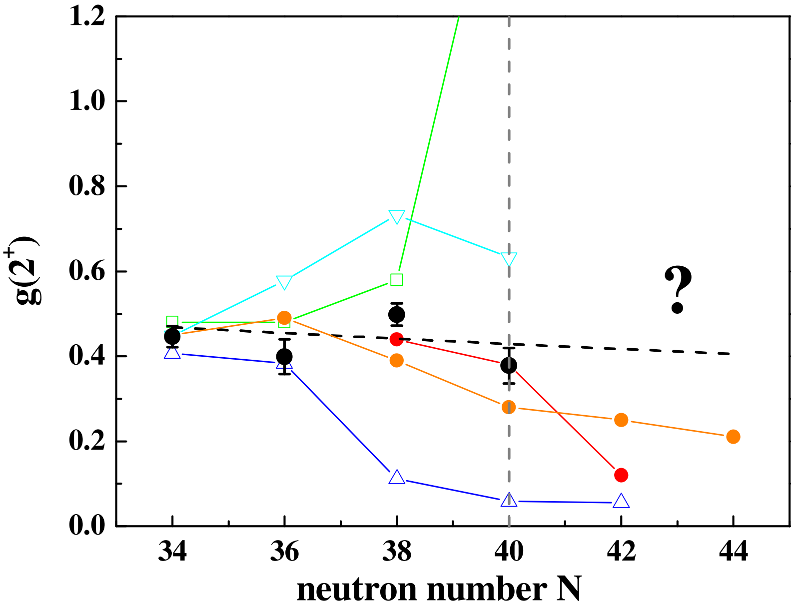

Fig. 2. Comparison between the experimental g factors (black circles with error bars, taken from [4]) of the 2^+ states in the Zn isotopes with different large bases shell model calculations (green: SM1 [4], light blue: SM2 [4], blue: SM3 [5], orange: SM4 [6], red: SM5 [7]). See text for details.

In general if one considers the 4^+ states one would expect stronger single-particle contributions into their wave functions. Indeed, for the two Zn isotopes (^{64}Zn and ^{68}Zn) where the g(4^+) are experimentally determined [5], one observes a sign change. The negative g(4^+) value in ^{68}Zn clearly proofs the importance of the $\nu g_{9/2}$ orbital already at N=38. So it seems natural to expect deviations from Z/A also for the 2^+ g-factor in the heavier Zn isotopes. Note that only the calculation SM3 is able to reproduce the drastic decrease of g(4^+) between ^{64}Zn and ^{68}Zn, but gives higher (i.e. more positive) g(4^+) values and underestimates the strong contribution of the $\nu g_{9/2}$ orbital which is evident from the measured g factor of the 4^+ state in ^{68}Zn (see Fig. 3).

Comparing the trends in the theoretical versus experimental g factors of the 4^+ and 2^+ states raises the possibility that the g(2^+) value in ^{72}Zn may be *negative* since at N=42 the $\nu g_{9/2}$ orbital starts filling. By way of contrast with this view, it may also be the case that collectivity will prevail over single-particle contributions in the 2^+ state and that the g(2^+) will remain positive. Therefore, a g-factor measurement which is sensitive to the *sign* can serve as a stringent test of the theory and help us gain an insight into the interplay between single-particle and collective properties of the nuclei in the N=40 region.

The strength of the Transient Field (TF) technique of determination of g factors of short lived states is that it allows the sign of the g factor to be derived. Therefore, we propose to apply the TF technique to measure the sign and magnitude of the g factors of the first 2^+ states in ^{72,74}Zn. This should allow us to probe the $\nu g_{9/2}$ component of its wave function and shed more light on the interplay between collectivity and single particle structure in the region of N = 40.

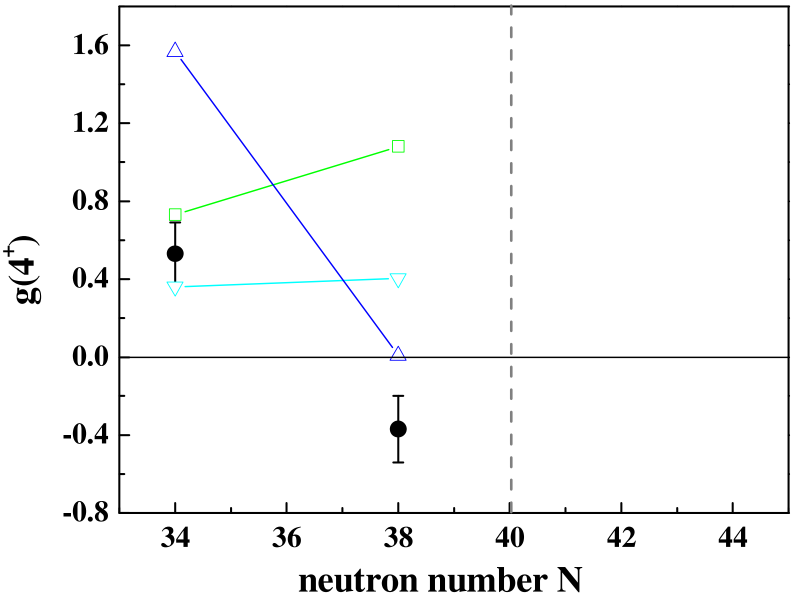

Fig. 3. Comparison between the experimental g factors of the 4^+ states in ^{64}Zn and ^{68}Zn [5] with different large bases shell model calculations (green: SM1 [8], light blue: SM2 [8], blue: SM3 [5]).

2) Experimental technique

We propose to measure the g-factors of the 2^+ states in ^{72,74}Zn using the transient field technique (TF) in combination with Coulomb excitation in inverse kinematics [9]. The transient field technique in combination with Coulomb excitation in inverse kinematics ensures high detection efficiency of coincident γ-rays due to kinematic focussing of the target ions in the beam direction and provides high spin alignment of the excited states followed by strongly anisotropic γ-angular correlations. The latter is a prerequisite to be sensitive to the spin precessions in the TF. Furthermore, the inverse kinematics implies relatively high recoil velocities of the Zn ions and therefore large transient fields.

This proposal is part of our experimental program to explore the possibilities for g-factor measurements using radioactive ion beams. To study short-lived excited states there are in principle three different methods available which all take advantage of the huge Fermi contact fields produced by the inner electrons of moving ions: the TF technique at low velocity (LVTF) using post-accelerated ISOL beams, the TF technique at high velocity (HVTF) using fast beams produced in fragmentation reactions and finally the recoil-in-vacuum technique. Only very recently the first pioneering experiments employing these techniques have been successfully performed demonstrating their feasibility (LVTF: ^{132}Te@Oak Ridge [10] and IS415 at REX-ISOLDE, HVTF: ^{38,40}S@MSU [11,12] and RIV: ^{132}Te@Oak Ridge [13]). However, we are still missing a systematic comparison of their different advantages and disadvantages which would allow us to choose the optimum method for each specific case of interest in the future. In this context we performed a measurement aiming for the measurement of the 2^+ g-factor in ^{72}Zn earlier this year at GANIL (experiment E535). In that case the Zn nuclei have been produced in the fragmentation of a ^{76}Ge primary beam at intermediate energy. This direct comparison of the two techniques applied to the same nucleus will show us the way to go for future measurements in the ^{68}Ni region.

The radioactive ^{72,74}Zn ions will be produced by bombarding a UC_x target with 1.4 GeV protons. Assuming a production of $1.1\cdot10^8$/µC for ^{72}Zn and $6.9\cdot10^7$/µC for ^{74}Zn (taken from the yield data base of ISOLDE), 2 µA protons and a REX efficiency of 1%, average beam intensities of $2.2\cdot10^6$ 1/s and $1.4\cdot10^6$ 1/s for ^{72}Zn and ^{74}Zn, respectively, are expected on the secondary target. The latter will consist of a ^{27}Al layer to Coulomb excite the Zn beam ions, a Gd layer magnetized by an external field in which the excited Zn ions experience precessions during their passage through the transient field and a copper backing which serves as a stopper for the excited nuclei providing a hyperfine interaction-free environment. De-excitation γ-rays are detected by four MINIBALL Cluster detectors positioned at $\pm65^\circ$ with respect to the beam axis in coincidence with forward scattered Al ions. These Al target ions will be detected in two rectangular Si detectors positioned above and below the beam axis covering an angular range of 20°-40° degrees. This particle detector geometry has the advantage of selecting the reactions with largest spin alignment.

3) Beamtime estimate

In the following we give an estimate of the beamtime requested for the determination of the 2^+ g-factors in ^{72,74}Zn with an accuracy of about 20%. The estimate is based on the following assumptions:

- Target: 1.3 mg/cm^2 ^{27}Al + 4.0 mg/ cm^2 Gd + 1.0 mg/ cm^2 Ta + 3.5 mg/ cm^2 Cu
- Beams: ^{72,74}Zn at energies around 2.8 MeV/u with average intensities of $2.2\cdot10^6$ 1/s and $1.4\cdot10^6$ 1/s for ^{72}Zn and ^{74}Zn, respectively, on the reaction target
- γ-ray detection efficiency: 1% for each of the four MINIBALL Cluster detectors positioned at $\pm65^\circ$ and $\pm115^\circ$ with respect to the beam axis in a horizontal plane
- detection of recoiling target ions in two 20x15 mm^2 Si detectors placed 1 cm above and below the beam axis 3 cm behind the target

Taking into account the target properties and standard transient field parametrizations [9], precession angles of about 60 mrad/g are expected for the 2^+ states in ^{72,74}Zn. The average logarithmic slope of the the $2^+\rightarrow0^+$ angular distribution for a Cluster positioned at $\Theta=65^\circ$ with respect to the beam is calculated to be around 2. The statistics needed to reach a 20% accuracy of the measured magnetic moments of course depends on their absolute values. As an example we assume a realistic value of $g=0.25$. The expected precession would then be 15 mrad and roughly 5000 counts per Cluster and each of the two field directions (10000 counts in total per Cluster) would be needed. From standard Coulomb excitation calculations and assuming the particle detection geometry described above we can infer an expected γ-ray detection rate of 3100 and 2000 counts per day in the $2^+\rightarrow0^+$ line in each Cluster for ^{72}Zn and ^{74}Zn, respectively.

Consequently, the beamtime request is

- **1 day** for the beam preparation and the change from the ^{72}Zn to the ^{74}Zn beam
- **3 days** for the measurement of g(2^+) in ^{72}Zn
- **5 days** for the measurement of g(2^+) in ^{74}Zn

The total requested beamtime amounts to **9 days**.

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