On the track of the one-phonon mixed symmetry state in radioactive ^{90}Sr

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1 Introduction

The main aim of the present proposal is to identify the one-phonon MSS in the unstable nucleus ^{90}Sr and to measure the magnetic moments of the first 2^+ and $2^+_{1,ms}$ using a stable beam of ^{86}Kr and the reaction $^{12}C(^{86}Kr, 2\alpha)^{90}Sr$.

States with proton-neutron mixed symmetry have been defined [1] in the framework of the interacting boson model with proton-neutron degree of freedom (IBM-2). The structure and the characteristics of these states are determined by the effective p-n correlations in the valence shell of collective nuclei. Their excitation energies are directly related to the proton-neutron symmetry energy in the valence shell. This fact is obvious in the IBM where the excitation energies of MSSs determine the parameters of the Majorana interaction to which p-n symmetric states are insensitive [1, 2].
The concept of proton-neutron mixed symmetry is formalized by the F-spin quantum number [7], which is the isospin analogue for bosons. Within this concept the fully symmetric states have $F = F_{max} = (N_\pi + N_\nu)/2$ ($N_{\pi,\nu}$ denote the proton/neutron boson numbers), while MSSs are those states with $F = F_{max} - 1$[7]. In other words, the F-spin quantum number counts the number of protons and neutrons pairs which are in phase in the quantum state. The IBM-2 states with maximum F-spin quantum number are called Full Symmetry States (FSSs). The F-spin is an approximate quantum number for low-lying collective states of heavy nuclei. The lowest states in a given nucleus are those formed by the FSSs. The M1 transitions between these states are forbidden and indeed they are observed to be small on an absolute, single-particle scale. With little modifications due to symmetry restrictions, the MSSs in the IBM-2 repeat the multiplet structure observed for the FSSs albeit at higher energy and with different decay properties. The energy difference between the FS and MS states with the same phonon number is determined by the size of the Majorana interaction in the IBM-2 [1]. The most distinct feature of MSSs (those with $F = F_{max} - 1$) is the existence of allowed F-vector ($\Delta F = 1$) M1 transitions to FSSs. This is of importance because the M1 transitions are forbidden between FSSs and can, thus, very well serve as a unique signature for MSSs.

The fundamental MSS in weakly collective vibrational nuclei, is the one-quadrupole phonon $2^+_{1,ms}$ state [1] which is the lowest-energy isovector quadrupole excitation in the valence shell. Its close relation to the 2^+_1 state is evident in the Q-phonon scheme for MSSs [9], where the wave functions of the one-quadrupole phonon excitations are well approximated by the expressions:

$$|2^+_1\rangle \propto [Q_\pi + Q\nu]|0^+_1\rangle \equiv Q_S|0^+_1\rangle \qquad F = F_{max}$$
$$|2^+_{1,ms}\rangle \propto [(Q_\pi/N_\pi) - Q\nu/N_\pi)]|0^+_1\rangle \equiv Q_m|0^+_1\rangle \qquad F = F_{max} - 1$$

where $Q_{\pi,\nu}$ denote the proton and neutron quadrupole operators and $|0^+_1\rangle$ is the ground state of a collective even-even nucleus. Within the framework of this model the following signature for one-phonon MSSs in vibrational nuclei can be expected:

- The one-phonon 2+1,ms state should be the lowest-lying MSS.
- This $2^+_{1,ms}$ state should decay to the $|2^+_1\rangle$ by a strong M1 transition with an absolute matrix element of about 1 μ_N.
- Since the $|2^+_{1,ms}\rangle$ state is a one-phonon excitation it should have collective E2 matrix elements to the ground state for both, protons and neutrons, however, with opposite signs, which might lead to partial cancellation in the total $< 0^+\|E2\|2^+_{1,ms} >$ matrix element. Thus, a small-to-weakly-collective ($\leq$ a few W.u.) E2 transition from the $2^+_{1,ms}$ state to the ground state can be expected.
- All MSSs must be expected to be very short lived, typically a few hundred femtoseconds or less, because of the strong M1 matrix elements and typical transition energies $\approx$ 1 MeV in vibrational nuclei.

From the above fingerprints its is obvious that the MSSs can be identified experimentally by their unique decay to the low-lying FSSs [1, 9]. This however, comprises a major experimental challenge because it requires full spectroscopic information, i.e. the spin-parities of these highly excited non-yrast states, their lifetimes and the branching and multipole mixing ratios of their γ-decay have to be determined. For more detailed insight in the structure of these states information on their magnetic moments is also necessary. Until recently obtaining all this information was possible for a hand-full of stable nuclei only. **No MSSs have ever been solidly identified in unstable nuclei on the basis of large absolute M1 transition rates.**

2 Physics case MSSs in the mass A≈100 region

Despite their important role for understanding the effective proton-neutron interaction in collective valence shell excitations the experimental information on MSSs is relatively scarce. Available information on MSSs of vibrational nuclei has recently been summarized in a review article [9]. Due to the experimental challenges, MSSs have been observed so far in stable nuclei only. The best examples are found in the mass A≈90 regions [9, 10, 11, 12, 13, 14, 15, 16, 17]. Among them the most significant amount of comprehensive information on MSSs is obtained for the $N = 52$ isotone ^{94}Mo [9]. The one- and two-phonon MS structures of ^{94}Mo are clearly identified on the basis of absolute transition strength [9, 18]. One-phonon MSSs are also observed in the other stable even-even $N = 52$ isotones ^{96}Ru [10, 19] and ^{92}Zr [11, 20]. The evolution of the MSSs in the $N = 52$ isotopic chain is clearly influenced by the underlying shell structure. In contrast to the cases of ^{96}Ru and ^{94}Mo, where the 2^+_3 states are identify as one-phonon MSSs [10], in ^{92}Zr the 2^+ state which carries the largest part of the $2^+ \rightarrow 2^+_1$ M1 strength is the second 2^+, however with the smaller M1 strength of $0.37(4)\mu_N^2$ [10]. This experimental observation is explained as due to the fact that in ^{96}Ru and ^{94}Mo the valence protons occupy the $\pi g_{9/2}$ orbital while ^{92}Zr lies at $Z = 40$ sub-shell closure at the upper end of the pf-shell [11]. This reduces the proton-neutron interaction and results in a different distribution of protons and neutrons contributions in the structure of one-phonon 2^+ states of ^{92}Zr. The first one-phonon state has a more pronounced neutron character and the second one-phonon state has a predominant proton contribution [11]. The reduced protonneutron interaction at the sub-shell closure results in a smaller repulsion between the proton and the neutron parts of the one-phonon configurations. This finally leads to a smaller energy separation between the one-phonon states. The fact that the MSS of ^{92}Zr is the 2^+_2 state suggest that the symmetrical two-quadrupole phonon state and the one-phonon MSS cross when going from ^{94}Mo to ^{92}Zr; however this crossing is accompanied by a breaking of the F-spin symmetry and a decrease in collectivity of the 2^+_1 state [11]. This qualitative picture is supported by the decrease of the total M1 strength between the one-quadrupole phonon states with predominant FSS and MSS character and by the increase of the strength of the E2 ground state excitation to the one-quadrupole phonon state with predominant MSS character in the $N = 52$ isotonic chain from ^{96}Ru to ^{92}Zr [10, 11].

The evolution of the MSSs in the $N = 52$ isotonic chain has been theoretically investigated in the framework of the large scale shell model [35]. The calculations describe well the observed change in the characteristics of one-phonon symmetric and mixed symmetry states when from ^{94}Mo to ^{92}Zr. The decrease in M1 strength in ^{92}Zr is explained by the fact that its symmetric one-phonon 2^+ state has predominantly neutron character while the MSS contains mostly proton excitations [35]. This phenomenon of varying contributions to the one-phonon states by the active proton and neutron particles due to subshell structure is interpreted as *configuration-isospin polarization* (CIP) [35]. Significant CIP corresponds to a breaking of the F-spin symmetry in the IBM-2, which is reflected in the small M1 transition strength, while vanishing CIP indicates a restoration of F-spin symmetry and pure FS/MS states. In other words the evolution of the MSSs of the even-even stable $N = 52$ isotones reflect the evolution of CIP, and hence p-n symmetry character, of these states: the purity of the MS character peaks in the midshell region, where CIP vanishes, before waning at the approach of the $Z = 40$ subshell closure, where CIP increases again. This process is best visible in the evolution of the g factors of the one-phonon states in the $N = 52$ isotopes [35]. According to the shell model calculations (see Fig. 1) as proton number increases the g factors of the first one-phonon state increase almost linearly, whereas the g factors of the second one-phonon state factors decrease linearly with approximately the same absolute slope [35]. As a result they cross at midshell. The available experimental information on the g factors in the region agrees well with the shell model predictions [42, 43, 44].

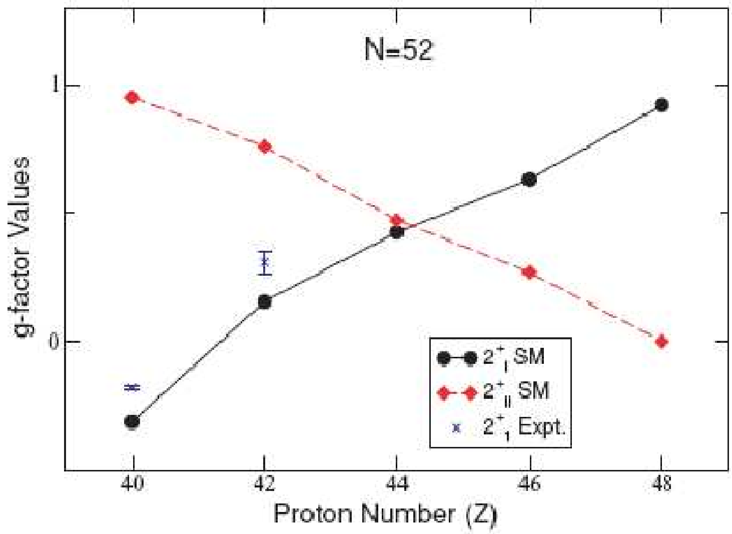

Abbildung 1: *Predicted evolution of the g factors for one-phonon states across the series of* $N = 52$ *isotones. The figure is taken from ref. [35]*

It has to be noted however, that the due to the limited experimental information on MSSs, in general, and on magnetic moments of the low-lying 2^+ states, in particular, the generic nature of the CIP phenomenon is not clear. The natural way to address this question is to identify the MSS of ^{90}Sr and to determine the g factors of its low-lying 2^+ states. ^{90}Sr lies at $Z = 38$ sub-shell closure and like ^{92}Zr it can be expected that CIP will be large, i.e. a reduce M1 strength between MS and FS, a large negative g factor for the first one-phonon state, and large positive g factor for the second one-phonon state can be expected. Following this analogy the 2_2^+ state of ^{90}Sr at 1892 keV can be consider as a candidate for the MSS. Indeed, this state decays to the 2_1^+ state with a predominantly M1 transition [45]. On the other hand the reported lifetime of 3(2) ps [41] for this state leads to a small absolute M1 strength of $0.012^{+24}_{-5}\mu_N^2$ which is too small for decay of a MSS. As far as a reduced M1 strength between MS and FS in ^{90}Sr is excepted, the large experimental uncertainty in reported lifetime [41] does not allow a definitive conclusion on the character of the 2_2^+ state to be made and prompts for a new, more precise measurement. It also has to be noted that the crucial for the CIP experimental information, namely the g factors of the low-lying 2^+ states of ^{90}Sr is also missing.

Finally, we want to emphasize that to study further the properties of MSSs in vibrational nuclei such states have to be identified in unstable, radioactive nuclei. No MSSs have ever been unambiguously identified in unstable nuclei on the basis of large absolute M1 transition rates. The main reason for this comes from the fact that determination of the lifetimes of these highly excited, off-yrast states comprises a real experimental challenge. In this respect, developing new methods for population of MSSs, in particular, those that could potentially be applied to radioactive isotopes, is extremely important. Recently, it has been shown that α-transfer reactions may be an efficient way to populate MSSs in spherical nuclei [36]. In ref. [36] analytical expression for α-transfer cross-sections have been derived for the SU(3) and U(5) dynamical limits of IBM. It turned up that the α-transfer intensities to the zero-, one- and two-phonon states depend in a unique way on the total boson number. This opens the possibility to identify MSSs by measuring the population cross-sections of excited states in α-transfer reactions. Here, we propose to use $^{12}C(^{86}Kr, 2\alpha)^{90}Sr$ reaction to populate the low-lying states of ^{90}Sr which will allow us to measure the their lifetimes and g factors. In addition, we will also be able to check whether and to what extent the α-transfer cross-sections can be used as a new signature for the assignment of mixed-symmetry character to particular excited nuclear state.

3 Expected results

The excited states of ^{90}Sr will be populated in the α-transfer reaction $^{12}C(^{86}Kr, 2\alpha)^{90}Sr$. The α-transfer intensities to the excited states in ^{90}Sr will be measured. The lifetimes and the magnetic moments of the exited states in ^{90}Sr will be determined by a DSA method and the Transient Field technique. This experimental information will allow to:

- identify the one-phonon mixed-symmetry state in ^{90}Sr on the solid ground of measured absolute M1 transition rates
- determine the $g(2_1^+)$ and $g(2_{1,ms}^+)$ in ^{90}Sr
- check whether the CIP phenomenon is present at the $Z = 38$ sub-shell closure
- check whether the α-transfer cross-sections can be used as a new signature for the assignment of mixed-symmetry character to particular excited nuclear state

4 Experimental method

We propose to apply the well established technique of Transient Magnetic Fields (TF) in inverse kinematics [38] for the measurement of the magnetic moments of the 2_1^+ and the $2_{1,ms}^+$ states in ^{90}Sr. The slowing down of the excited ions in the rather thick targets of about 10 mg/cm^2 required by this technique will allow to deduce the lifetimes simultaneously, using the Doppler-Shift-Attenuation-Method (DSAM). Since the α transfer reaction also occurs below the coulomb barrier ^{86}Kr ions will be accelerated to 3 MeV/u which would correspond to the Coulomb barrier from Kr on carbon at 264 MeV in the lab frame.
The multilayered target will consist of a carbon layer enabling the transfer reaction and simultaneous Coulomb excitation of the xenon ions, followed by an externaly magnetized

gadolinium layer where excited ions precess in their different nuclear states under influence of the transient fields and a backing made of copper which serves as hyperfine interaction free environment where the ions will finally be stopped and decay. The scattered carbon ions as well as the alpha particles emerging from the decay of the residual ^{8}Be from the α transfer will be detected in a Si array consisting of two PIN diodes of 2cmx2cm, one above and one below the beam axis, in coincidence with the de-excitation γ rays. This configuration will ensure the maximum nuclear spin alignment when the γ detectors are placed in a plane perpendicular to the particle detector. Four EUROBALL cluster detectors with an absolute γ efficiency of 1% will be placed upstream and downstream at ± 65 degrees with respect to the beam axis for the measurement of the nuclear spin precession and particle-γ angular correlation, respectively.
The TF technique in inverse kinematics will combine high detection effiency due to the kinematic focussing of the scattered target ions and a high sensitivity to the nuclear spin precession as a consequence of the large nuclear spin alignment in the particle-γ angular correlation. In addition high velocities of the recoiling Kr and Sr ions will provide large transient fields as well as favourable conditions for the DSAM analysis. As a by-product the known lifetimes and magnetic moments in ^{86}Kr allow to exclude systematic uncertainties due to the possibility to measure the Coulomb excited Kr ions simultaneously. The combination of α transfer and transient field technique in heavy nuclei was already successfully applied in the UNILAC experiment U234 in 2008 for stable beams of $^{112,114,116}Sn$ and in transfer reactions created $^{116,118,120}Te$ in 2008 [39]. Since the transfer reaction is highly selective for low spin states basically background free γ spectra can be obtained which is a crucial requirement for the analysis in particular for the one-phonon MS state.

5 Beamtime estimate

For the quoted lifetime of 3(2) ps from [41] and the expected $g(2^{+}_{1,ms}) \approx +1.0$ an experimental value with an relative uncertainty of 20% could be obtained within one day of beamtime. Since we expect the one-phonon MSS to have rather a short lifetime of only 150 femtoseconds the proposed target will depend on this assumption. In order to increase the number of excitations a thick carbon layer would be favourable in contrast to the requirements for the nuclear spin precession. To avoid that a larger fraction of the excited nuclear states will already be decayed before entering the magnetized gadolinium the excitation layer must not exceed a critical thickness. In fig. 2 the required beamtime for a given uncertainty of the experimental g factor is compared for different target configurations. We intend to reach a relative uncertainty of 30% which corresponds to approximately 5 days of beam on a target where the excitation layer has a thickness of 0.4 mg/cm^2.

Cross sections and efficiencies will be scaled to rates and efficiency from experiment U234 which was done with the proposed set-up under similar experimental conditions:

- Target : 0.4 mg/cm^2 C + 8 mg/cm^2 Gd + 1 mg/cm^2 Ta +5 mg/cm^2 Cu

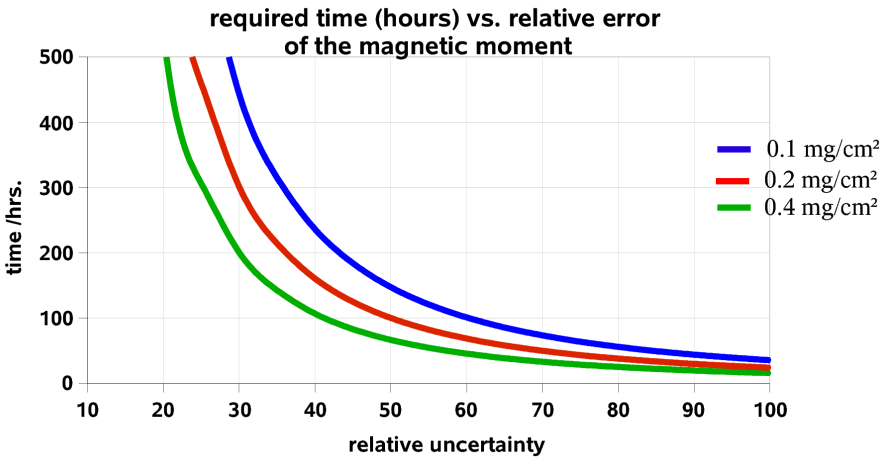

Abbildung 2: *Comparison of different target configurations with respect to the beamtime in hours which is required to measure the magnetic moment of the* $2^+_{1,ms}$ *for a given uncertainty.*

- Beam : ^{86}Kr at 3 MeV/u
- Beam intensity : 1pnA
- absolute gamma efficiency of 1% for 4 EUROBALL cluster detectors
- the cross section of $^{12}C(^{86}Kr, 2\alpha)^{90}Sr$ is approximately 1/3 of the Coulex cross section $^{12}C(^{86}Kr,^{86}Kr*)^{12}C$ with $\sigma_{tot} = 0.003b/sr$ for the proposed set-up
- according to [36] the one-phonon MSS is expected to have 1/3 of the strength from the first 2^+ state

From the calculated and estimated cross sections and the given set-up one would expect to have

- 1 ct/s or 3600 cts/h for $^{86}Kr(2^+_1 \rightarrow 0^+_1)$
- 1/3 cts/s or 1200 cts/h for $^{90}Sr(2^+_1 \rightarrow 0^+_1)$
- 1/9 cts/s or 400 cts/h for $^{90}Sr(2^+_{1,ms} \rightarrow 0^+_1)$

per cluster and field direction. In order to reach the optimum statistics for the lineshape analysis of the $(2^+_{1,ms} \rightarrow 0^+_1)$ transition a total number of 10000 counts will be required corresponding to 1 day of beam on target (with 0.5% absolute γ efficiency at the sensitive angles). Assuming g factors of $|g(2^+_1)| = 0.3$ and $|g(2^+_{1,ms})| = 1.0$ in ^{90}Sr for the given beam intensity and known slopes of the particle-γ angular correlation for α-transfer reactions of $|S| \approx 0.4 mrad^{-1}$ and the calculated and measured slope for a $(2^+_1 \rightarrow 0^+_1)$ transition for this configuration 6 days of beam on target are required to reach an accuracy of 15% for the $g(2_1^+)$ and for a 30% accuracy of the one-phonon MSS. Therefore we ask for

	15 shifts	for a 15% accuracy of the $g(2_1^+)$ in ^{90}Sr
		for a 30% accuracy of the $g(2_{1,ms}^+)$ in ^{90}Sr
	3 shifts	for the set-up with beam on target
in total :		**18 shifts**

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