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Evidence for the microscopic formation of mixed-symmetry states from magnetic moment measurements

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Using the transient field technique, the magnetic moments of the second excited 2^+ states in ^{92,94}Zr have been measured for the first time. The large positive g factors, $g(2_2^+;{}^{92}\text{Zr}) = +0.76(50)$ and $g(2_2^+;{}^{94}\text{Zr}) = +0.88(27)$, which are in contrast to the known negative g factors of the 2_1^+ states, are found to be a consequence of weak proton-neutron coupling combined with the $Z = 40$ subshell closure. From their large $M1$ transition strengths to the 2_1^+ states, in earlier works an assignment to the 2_2^+ states as proton-neutron symmetric and mixed-symmetry states has been made, which are now found to be polarized in their proton-neutron content. This fact allows to identify the underlying microscopic main configurations in the wave functions, which form the building blocks of symmetric and mixed-symmetry states in this region as valence nucleons are added and shell structure changes.

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The evolution of collectivity and its underlying mechanisms is one of the most profound problems in many-body physics. It is the number of constituents and the complexity of the forces between them that make the many-body problem difficult. The strengths of the interactions are a fundamental ingredient for condensed matter systems in general, and their derivation imposes a major problem in nuclear physics. The atomic nucleus represents a system of strongly interacting particles with characteristics that make it unique among such systems: it is rather a finite-size than a mesoscopic system, it is naturally occuring, and most importantly, it is a two-component quantum fluid of protons and neutrons. Collective features are governed by the proton-neutron (pn) interaction V_{pn} in the valence shell [1,2], as recently empirically demonstrated in [3].

The fundamental vibrational one-phonon proton-neutron symmetric and mixed-symmetry states, which are briefly introduced below, are a sensitive probe of the proton-neutron interaction. When V_{pn} is sufficiently large, proton and neutron configurations are fully symmetric (FS) with respect to an exchange of the two nucleon species. Due to the two-component character of nuclei, collective states exist for which this condition does not apply, the so-called mixed-symmetry (MS) states [4–7]. MS states have been predicted within the pn version of the interacting boson model (IBM-2) [4,6,8], in which they are characterized by their F-spin quantum number. F-spin is the bosonic analog to isospin for fermions. The present work gives compelling evidence for the occurrence of weak coupling near the $N = 52$ neutron shell closure. For the first time, the dominant underlying proton and neutron configurations of collective symmetric and mixed-symmetric structures in the $A \sim 100$ mass region are experimentally identified from measuring the g factors of the lowest 2^+ states in ^{92,94}Zr.

In deformed nuclei, FS and MS states are formed by strong mixing of many proton and neutron configurations, which makes a microscopic understanding difficult. In spherical nuclei, close to magic shells, the valence space is smaller due to fewer active particles, and the number of configurations is reduced. Such nuclei are a testing ground for the underlying structure and formation of FS and MS states (see, e.g., Ref. [9]). In an even-even vibrational nucleus, the first MS state has $J^\pi = 2^+$ and is understood as a $1d$-boson state, analogous to the FS 2_1^+ state, but with an opposite relative sign for valence proton and neutron configurations, as shown below. More generally, the first excited FS and MS states in near-spherical nuclei can be attributed to quadrupole phonon excitations from the ground state [10–12]. One of the best known examples for FS and MS structures is ^{94}Mo [13]. Current experimental information on vibrational MS states has recently been reviewed [14].

A schematic understanding of MS and FS states with respect to their *pn* content was derived by Heyde and Sau [15]. These authors considered the case of only one proton pair and one neutron pair, each in a single orbital and each forming a $j = 2$ configuration with unperturbed energies E_p and E_n, respectively. These configurations correspond to d-boson configurations in the IBM-2. In a simple two-configuration mixing scheme, they are mixed by the *pn* interaction V_{pn} into final states 2_1^+ and 2_2^+,

$$|2_i^+\rangle = a_i|2_\pi^+\rangle + \epsilon_i b_i|2_\nu^+\rangle, \quad i = 1, 2 \tag{1}$$

with $\epsilon_1 = +1$ (FS) and $\epsilon_2 = -1$ (MS). For FS and MS states with good F spin, proton and neutron configurations are about equally mixed ($|a_i| \approx |b_i|$). If $|a_i| \neq |b_i|$, proton and neutron configurations will not contribute equally, and the resulting states will be dominated by one of these configurations. Following Ref. [16], this concept will be referred to as configurational isospin polarization (CIP), denoting that only valence space configurations play a role, in contrast to the full valence space in the isospin formalism.

In general, two-configuration mixing is an oversimplification, because there will be more than one possible $j = 2$ configuration for protons and neutrons. However, it represents a fundamental concept in quantum many-body physics, and for the microscopic understanding of the building blocks of FS and MS states, that are the CIP states with $|a_i| \ll |b_i|$ ($|b_i| \ll |a_i|$). Thus far, direct experimental tests of how protons and neutrons separately contribute to the $2_{1,2}^+$ excitation partners do not exist, and knowledge of the applicability of this simple scheme to existing nuclei is lacking. Information on nuclei that show strong CIP in low-lying states is sparse. The $Z = 40$ isotopes ^{92,94}Zr are well suited to serve as a testing ground for the CIP concept as shown in this paper, which presents the first measurements of the magnetic moments of the 2_2^+ states in ^{92,94}Zr.

In ^{94}Mo, a proton (neutron) 2^+ configuration is predominantly formed in the $\pi(g_{9/2})$ ($\nu(d_{5/2})$) orbital by breaking the proton (neutron) pair. The $T = 0$ part of the V_{pn} interaction, mixing these configurations, was found [17] to be $V_{pn}^{T=0} \simeq$ 500 keV within the shell model using a surface delta interaction (SDI). As a result, the FS 2_1^+ state has a positive g factor of $g(2_1^+; {}^{94}\mathrm{Mo}) = +0.308(43)$ [18]. In ^{92,94}Zr, because of the $\pi(p_{1/2})$ subshell closure, protons have to be excited across a gap of about 700 keV to the $\pi(g_{9/2})$ orbital, requiring different energies for the formation of proton and neutron $j = 2$ configurations. SDI shell model calculations for ^{92}Zr [19,20] yielded only $V_{pn}^{T=0} \simeq 200$ keV. Thus, ($V_{pn}^{T=0} \simeq 200$ keV) < (700 keV $\simeq E_{g9/2} - E_{p1/2}$) for ^{92}Zr, resulting in a much smaller mixture of proton and neutron configurations. Hence, the measured g factor values of $g(2_1^+; {}^{92}\mathrm{Zr}) = -0.180(10)$ and $g(2_1^+; {}^{94}\mathrm{Zr}) = -0.329(15)$ [21] may already hint to the occurence of CIP in these isotopes, as a consequence of the quantitative difference in single particle energies compared to interaction strengths. However, a proof of CIP requires the measurement of the proton content in the wave function of the 2_2^+ state.

While direct measurements of the configurations in excited states are in general difficult, g factors allow to substantiate CIP, especially when the main configurations have $j = l + s$. Negative magnetic moments are a clear signature of a neutron CIP state, while proton CIP states should have large positive magnetic moments. The systematic calculations in [16] find CIP and its decrease in the $N = 50$ region, and make strong predictions for the g factors of the CIP states (and the FS and MS states, respectively). Recently, the 2_2^+ states in ^{92}Zr [19,20] and ^{94}Zr [22] have been identified as the one-phonon MS 2^+ states on the basis of their strong M1 transitions to the 2_1^+ states. As shown here, these states are better described in terms of two-configuration mixing and CIP, as shown from the measurement of both their magnetic moments, and therefore their *pn* content. This work reports the first measurement of this kind for both CIP states.

The transient field technique is well-suited for the measurement of magnetic moments of short-lived excited states. Experiments using this technique were carried out at the Wright Nuclear Structure Laboratory (WNSL) at Yale University using beams of ^{92,94}Zr. The beams were Coulomb excited on C target layers, while the precession of the excited nuclei traversing the subsequent magnetized Gd layer was measured. All targets were backed with sufficient amounts of Cu to stop the Zr ions, while allowing the recoiling C ions to exit from the target. The C recoils that induced Coulomb excitation of the beam were detected in PIPS Canberra silicon circular detectors or rectangular solar cells subtending angles of up to $\pm 33^\circ$ in the vertical direction. Four HPGe Clover detectors were used to detect the γ-rays.

An asymmetry ϵ in the particle-γ coincidence rate as a function of the direction of the magnetization of the ferromagnetic foil was measured, and the logarithmic slope S of the angular correlation was derived for each transition from measured anisotropy ratios. The precession angle $\Delta\theta = \epsilon/S$ is related to the g factor by

$$\Delta\theta = -g \cdot \frac{\mu_N}{\hbar} \cdot \int_{t_{\rm in}}^{t_{\rm out}} B_{TF}(v(t),\, Z) \cdot e^{-t/\tau} dt, \tag{2}$$

where B_{TF}, the transient field, is a function of both the velocity v and the atomic number Z of the projectile ion, τ is the mean lifetime of the state being considered, and $t_{\rm in(out)}$ is the mean entrance (exit) time of the ions into (out of) the Gd layer. The value of B_{TF} was derived from the Rutgers parametrization [27]. The details of the setup and analysis are given in previous papers [21,24,25] and a recent review article [26].

The experiments proved to be difficult for several reasons. At a beam energy of 275 MeV the second 2^+ states in ^{92}Zr at 1.847 MeV and ^{94}Zr at 1.671 MeV are both only weakly excited. Furthermore, because of the very short lifetimes, $\tau(^{92}\mathrm{Zr};\, 2_2^+) = 138(14)$ fs [20] and $\tau(^{94}\mathrm{Zr};\, 2_2^+) = 175(20)$ fs [22], only thin C layers can be used. The effective interaction time in the ferromagnetic layer was only ~120 fs, and beam intensities were limited to 3×10^9 particles/s. Thus, statistical errors for the states of interest outweigh systematic uncertainties in the field parametrization. In addition, relative g factors are independent of the absolute magnitude of the field strength.

Four different targets were used in a total of six one week long runs. One of them had a thick layer of C,

TABLE I. Summary of relevant nuclear parameters of the first 2^+ states of ^{92,94}Zr isotopes: level energy E_x, spin and parity J^π, mean lifetime τ, transition, branching ratio I_γ, multipolarity mixing ratio δ, $B(E2)$, $B(M1)$.

Isotope	E_x (keV)	J^π	τ (ps)	Transition	I_γ	$\delta = E2/M1$	$B(E2)\downarrow$ (W.u.)	$B(M1)\downarrow$ ($\mu_N{}^2$)	Ref.
^{92}Zr	934.5	2_1^+	6.9(5)	$2_1^+ \to 0_1^+$	100	$E2$	6.8(5)		[28]
	1847.3	2_2^+	0.138(14)	$2_2^+ \to 0_1^+$	44.6(23)	$E2$	3.4(4)		[20]
				$2_2^+ \to 2_1^+$	100.0(23)	−0.04(2)	$0.4^{+0.5}_{-0.3}$	0.37(4)	[20]
^{94}Zr	918.8	2_1^+	9.9(21)	$2_1^+ \to 0_1^+$	100	$E2$	5(1)		[28]
	1671.4	2_2^+	0.175(20)	$2_2^+ \to 0_1^+$	100(4)	$E2$	8(1)		[22]
				$2_2^+ \to 2_1^+$	76(4)	0.02(2)	0.13(26)	0.33(5)	[22]

0.423 mg/cm^2, and the thickness of the Gd layer was 3.44 mg/cm^2. The three other targets had thicker layers of Gd, ∼4.1 mg/cm^2, and rather thin layers of C, 0.18–0.3 mg/cm^2. Kinematics for these targets were similar, and the average velocities and energies of the probe ions in the ferromagnetic foil varied between $\sim 6.0 \leqslant v/v_0 \leqslant \sim 8.5$ and $\sim 80 \leqslant E \leqslant \sim 165$ MeV, where $v_0 = e^2/\hbar$. The magnetization of each target was measured as a function of temperature between 25 K and 150 K in an AC magnetometer [23]. During the experiments, the target temperature was kept at about 60 K. Figure 1 shows sample ^{12}C-γ coincidence spectra. The average logarithmic slopes of the angular correlation obtained for the ^{92}Zr $2_1^+ \to 0_1^+$ and $2_2^+ \to 0_1^+$ transitions were 1.8(1) rad^{-1} and 1.5(1) rad^{-1} respectively. Only the $E2$ ground state transitions were measured. The relevant spectroscopic parameters required for the analysis of the data are listed in Table I.

The resulting g factors in ^{92,94}Zr are given in Table II, and are compared to theoretical predictions. g factors for the 2_1^+ states in both isotopes are in excellent agreement with previously published values [21]. For ^{92}Zr, available calculations were done within the quasiparticle phonon model (QPM) [29], and within the shell model using the SDI [19,20], and the $V_{\text{low}-k}$ interaction [16]. For ^{94}Zr, so far only the calculations within the shell model using SDI and $V_{\text{low}-k}$ presented here have yielded g factor predictions.

While all models predict a positive g factor for the 2_2^+ state, this prediction is not as trivial as one may assume from the simple two-configuration mixing scheme shown above, it is rather a result of delicate variations in the pn interactions (compare the references in [29]). The experimental results

TABLE II. Comparison of experimental g factors of 2^+ states in ^{92,94}Zr from this work, and calculated values.

$g(J^\pi)$	Exp.	SM		QPM
		SDI	$V_{\text{low}-k}$	
		^{92}Zr		
$g(2_1^+)$	−0.18(2)	−0.18	−0.31	−0.11
$g(2_2^+)$	+0.76(50)	+1.07	+0.95	+0.72
		^{94}Zr		
$g(2_1^+)$	−0.32(2)	−0.32	−0.25	−0.11
$g(2_2^+)$	+0.88(27)	+0.87	+0.98	

verify the predicted proton dominance in the wave functions of the 2_2^+ states in ^{94}Zr, with a g factor of $g(2_2^+, {}^{94}\text{Zr}) = +0.88(27)$. While the error for ^{92}Zr is large, $g(2_2^+, {}^{92}\text{Zr}) = +0.76(50)$, the consistency of the values and the very similar structure of both isotopes suggest the same proton dominance in the 2_2^+ states.

Previous shell model studies in the region [30,31] addressed weak coupling of proton and neutron configurations, however only the neutron dominated states were discussed. As pointed out in [18], level energy systematics alone do not allow to distinguish between a weak coupling scheme or rather strong, state independent coupling. The new result on g factors now proves not only the occurrence of weak coupling, but for the first time, identifies both CIP 2^+ states in ^{92,94}Zr which evolve into the FS and MS 2^+ states in the neighboring isotopes. The two CIP states in ^{92,94}Zr are therefore shown to be the underlying building blocks of the most fundamental, the lowest collective one-phonon FS and MS excitations in the $A \sim 100$ mass region, the formation of which was so far not well understood.

The IBM-2 offers a simple schematic way of understanding this phenomenon. While in other regions F-spin breaking was attributed to different proton and neutron deformations [32], for this discussion a system was chosen which is made of only one proton and one neutron boson with different initial energies

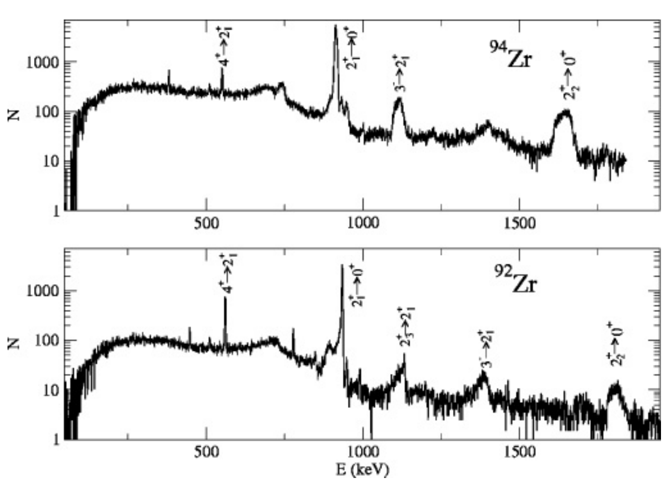

FIG. 1. Particle-γ coincidence spectra for ^{92}Zr (bottom panel) and ^{94}Zr (top panel) beams of 275 MeV.

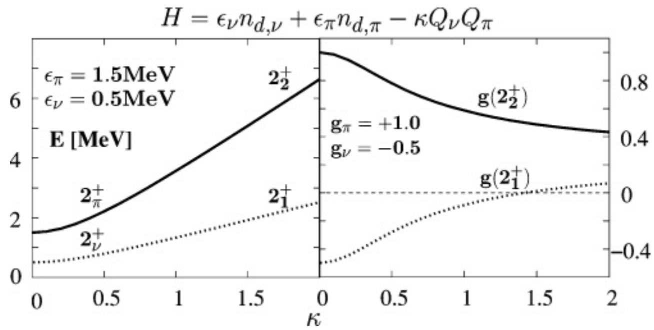

FIG. 2. Schematic IBM-2 calculation showing the dependence of energies (left) and g factors (right) of the lowest 2^+ states as a function of the pn interaction strength. Proton and neutron boson numbers were chosen $N_\pi = N_\nu = 1$.

ϵ_ρ ($\rho = \nu, \pi$), and g factors that correspond to neutron and proton excitations. The evolution of the $2^+_{1,2}$ energies and g factors as a function of V_{pn} (here given by the $Q_\pi Q_\nu$ strength parameter κ) are shown in Fig. 2. Parameters $\chi_{\pi,\nu}$, inherent in $Q_{\pi,\nu}$, were set to zero to maintain spherical symmetry. For small pn interaction strengths, the proton CIP state has a large positive g factor, while the neutron CIP state has a negative g factor. Increasing the interaction brings both values closer, as the proton and neutron configurations get more equally mixed, restoring F-spin.

Recent data from the Lexington group [22] show that the 2^+_2 state in ^{94}Zr has a larger $E2$ strength to the ground state than the 2^+_1 state (see Table I), which is the only known case of this kind. The schematic IBM-2 calculations of g factors yield such an inversion of $B(E2)$ values for small V_{pn}. This result is due to the larger effective charge of the proton CIP state, but already for $\kappa \approx 0.3$ the effect vanishes. None of the shell model calculations reproduce that effect, but predict the $E2$ strength of the 2^+_2 state to be about equal to that of the 2^+_1 state. The predictions for magnetic moments appear to be robust. As previously seen in QPM calculations [29], only a fine tuning in the quadrupole quadrupole interaction may yield a huge difference in the prediction of properties of CIP states. Therefore, a small correction to the shell model interaction may be sufficient to explain the $B(E2)$ inversion on a microscopic level. An experimental confirmation of the lifetime of the 2^+_1 state should be carried out, as well as a search for other examples.

To summarize, magnetic moments of the 2^+_2 states in ^{92,94}Zr were measured for the first time and are shown to have a positive sign, opposite to that of the corresponding 2^+_1 states. This observation sustains the concept of CIP. The $2^+_{1,2}$ states in both isotopes are identified with the building blocks of FS and MS states in near-spherical nuclei in the region, e.g., in ^{94}Mo. These nuclei lie at the onset of collectivity and these results fill an important gap in the understanding on how these collective states emerge from the underlying microscopic structure.

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