

# $^{61}\text{Cr}$ as a Doorway to the $N = 40$ Island of Inversion

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This paper reports on the measurement of the ground-state spin and nuclear magnetic dipole moment of  $^{61}\text{Cr}$ . The radioactive ion beam was produced at the CERN-ISOLDE facility and was probed using high-resolution resonance ionization laser spectroscopy with the CRIS apparatus. The present ground-state spin measurement  $I = \frac{1}{2}$ , differing from the previously adopted  $I = (\frac{5}{2})$ , has significant consequences on the interpretation of existing beta decay data and nuclear structure in the region. The structure and shape of  $^{61}\text{Cr}$  is interpreted with state-of-the-art Large-Scale Shell Model (LSSM) and Discrete-Non-Orthogonal Shell Model (DNO-SM) calculations. From the measured magnetic dipole moment  $\mu(^{61}\text{Cr}) = +0.539(7) \mu_N$  and the theoretical findings, its configuration is understood to be driven by 2 particle - 2 hole neutron excitations with an unpaired  $1p_{1/2}$  neutron. This establishes the western border of the  $N = 40$  Island Of Inversion (IoI), characterized by 4 particle - 4 hole neutron components. We discuss the shape evolution along the Cr isotopic chain as a quantum phase transition at the entrance of the  $N = 40$  IoI.

**Introduction.** Understanding how nuclear structure evolves at large proton-to-neutron asymmetries is one of the main quests of contemporary nuclear physics. The disappearance of a shell closure far from stability is generally accompanied by an increase in configuration mixing and collectivity, thus leading to the formation of Islands of Inversion (IoI) [1–3]. In an IoI, strong quadrupole correlations energetically favor deformed intruder configurations (*i.e.* multiparticle, multihole  $Np - Nh$  cross-shell excitations) which hence become the ground-state (*g.s.*) [4–6]. The study of these IoIs has had important consequences for our understanding of nuclear structure evolution, highlighting the need for further investigation of, *e.g.*, quadrupole correlations or the tensor force, which can drive these evolutions. To this date, four IoIs are known experimentally, associated with the neutron (sub-)shell closures at  $N = 8, 20, 28,$  and  $40$  [3].

In the  $N = 40$  IoI, collectivity rapidly develops below  $^{68}\text{Ni}$ , as a result of a narrowing of the  $N = 40$  subshell gap while emptying the proton  $f_{7/2}$  orbital [6, 7]. The chromium isotopes ( $Z = 24$ ) exhibit the strongest level of deformation in the region. Along this isotopic chain, mass measurements as well as the  $2^+$  excitation energies and transition probabilities reveal a steep increase in quadrupole correlations between  $N = 32$  and  $N = 38$  and strongly deformed *g.s.* for  $^{60,62,64}\text{Cr}$  [8–10]. While the deformation is suggested to be nearly constant from  $^{62}\text{Cr}$  onward, with a maximum achieved at  $N = 40$  [11, 12], recent mass measurements point towards a more rapid change in correlation effects in  $^{63}\text{Cr}$ , towards  $N = 40$  [13].

$^{62,64}\text{Cr}$  are understood to be members of the  $N = 40$  IoI and to share similar configurations dominated by  $4p - 4h$  neutron excitations across  $N = 40$  [11, 14]. Despite the progress made in understanding this structural evolution, questions remain about the exact nature and location of the transition into the  $4p - 4h$  regime of the  $N = 40$  IoI. The structure of  $^{61}\text{Cr}$  ( $N = 37$ ) remains to be interpreted to better understand how the  $N = 40$  IoI forms.

Despite the interest, experimental information about  $^{61}\text{Cr}$  is scarce and its structure is poorly understood. While its mass [10] and lifetime [15, 16] are known, its spin-parity  $I^\pi$  has been only tentatively assigned to be  $(\frac{5}{2}^-)$  by beta decay studies [17–19]. The high density of states at low energy and the nearly-degenerate neutron  $f_{5/2}$  and  $p_{1/2}$  orbitals in the region, make spin assignment and structure interpretation difficult both experimentally and theoretically. Furthermore, building a reliable level scheme, which is crucial to understand the excited structure of the nucleus, is impossible without measuring the *g.s.* spin  $I$  and magnetic dipole moment  $\mu$ .

This letter reports on the first high-resolution laser spectroscopy of  $^{61}\text{Cr}$ . Its *g.s.*  $I$  and  $\mu$  are determined in a nuclear model-independent way, establishing its wave function properties. Its structure, shape, and  $Np - Nh$  content are interpreted with state-of-the-art LSSM and DNO-SM calculations, in the context of the transition into the  $N = 40$  IoI.

**Experimental techniques.** The chromium ion beams were produced at the CERN-ISOLDE facility [20]. Fission

fragments were produced by impinging a pulsed, 1.4-GeV proton beam on a thick uranium-carbide target. After diffusing out of the target, the Cr atoms were ionized using the Resonant Ionization Laser-Ion Source (RILIS) [21]. Ions were then accelerated to 30 keV and mass-selected using a high-resolution separator. The beam was cooled and bunched in a gas-filled linear Paul trap (ISCOOL) [22], before it was sent to the CRIS beam line [23, 24]. The  $^{61}\text{Cr}$  beam, at 3000 ions/s, had about  $2 \times 10^5$  ions/s of isobaric contamination, mainly from stable molecular compounds such as  $^{42}\text{Ca}^{19}\text{F}$  or  $^{45}\text{Sc}^{16}\text{O}$ .

In the CRIS setup, the ion beam was firstly neutralized using a charge-exchange cell (CEC) filled with Na vapor at 210(5) $^\circ\text{C}$ . The remaining ions were dumped using a set of electrostatic deflectors while the atom bunches were sent to the interaction region (maintained at  $2 \times 10^{-9}$  mbar to minimize non-resonant collisional ionization), where they were collinearly overlapped in space and time with three laser pulses to resonantly excite and ionize the Cr atoms. The laser-ions were then deflected towards a MagneToF single-ion detector. The frequency of the first laser step (inset Fig. 1a)) was scanned in the ion's rest-frame by tuning the velocity of the ions using a voltage scanning device [24] placed before the CEC.

The first atomic transition at 427.48 nm  $3d^5(^6S)4s\ ^7S_3 \rightarrow 3d^5(^6S)4p\ ^7P_3$ , was probed by laser light from an injection-locked Titanium:Sapphire (Ti:Sa) cavity (20 MHz linewidth), seeded by a narrowband, continuous-wave Ti:Sa laser (Sirah Matisse). Atoms in the excited  $^7P_3$  state were further excited to the  $3d^44s5s\ ^7D_4$  atomic state by an intra-cavity doubled grating Ti:Sa (6(1) GHz linewidth) exciting the 427.29-nm transition. Finally, the Cr atoms were ionized by populating an auto-ionizing state (located 4948  $\text{cm}^{-1}$  above the ionization potential), using a 785-nm transition driven by a single etalon Ti:Sa cavity (12(2) GHz linewidth). The three pulsed Ti:Sa cavities were pumped at 1 kHz by a 532-nm Nd:YLF laser. Laser frequencies were measured with a HighFinesse WS/U-2 wavelength-meter, with a  $10^{-8}$  relative accuracy. With the present Ti:Sa-only ionization scheme used both for production at RILIS and for high-resolution spectroscopy at CRIS, the overall efficiency of the experiment was improved by an order of magnitude, compared to previous schemes.

**Results.** Examples of the measured hyperfine structures (HFS) of  $^{61}\text{Cr}$  and of the two benchmark nuclei  $^{51}\text{Cr}$  and  $^{53}\text{Cr}$  are shown in Fig. 1. The background is dominated by non-resonant collisional ionization. The error bar of each data point corresponds to the statistical uncertainty. The upper excited state  $^7P_3$  has hyperfine  $A_{P_3}$  and  $B_{P_3}$  parameters well below the present experimental resolution (FWHM  $\approx 300$  MHz for  $^{61}\text{Cr}$  and 70 MHz for  $^{51,53}\text{Cr}$ ) [25–27]. Thus it is expected, as long as the nuclear  $g.s.$  spin  $I$  is smaller than the atomic  $g.s.$  spin  $J$ , to observe a one-to-one correspondence between  $I$  and the observed number of peaks in the HFS, corresponding to the num-

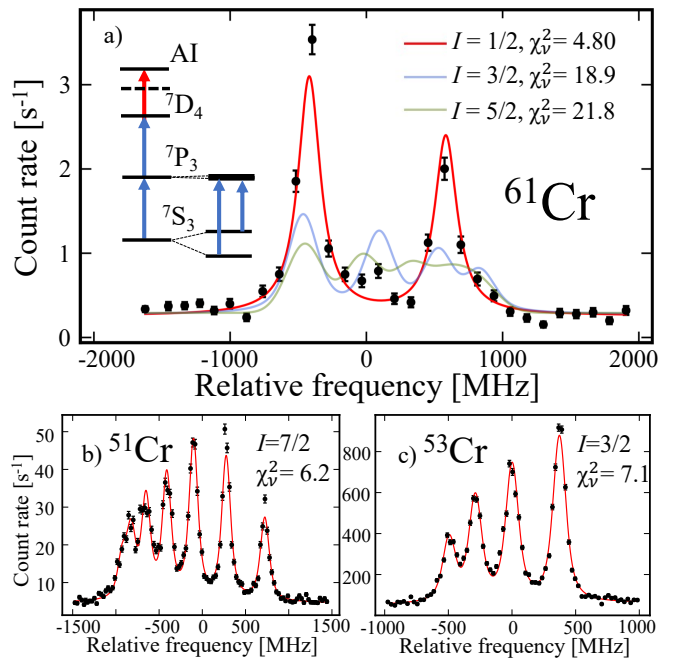


FIG. 1. Hyperfine spectrum of a)  $^{61}\text{Cr}$ , b)  $^{51}\text{Cr}$  and c)  $^{53}\text{Cr}$ : count rate in the ion detector as a function of the frequency of the first excitation step, relative to the centroid of the hyperfine structure. Black markers are experimental data while colored lines represent fits using different nuclear spin  $I$  hypothesis. The inset in a) shows a schematic of the three-step laser ionization scheme.  $\chi^2_v$  is the reduced chi-square per degree of freedom.

ber of hyperfine states  $F$ , where  $|I - J| < F < I + J$  [28]. One can observe in Fig. 1b) and c) the HFS of  $^{51}\text{Cr}$  ( $I = \frac{7}{2}$ ) and  $^{53}\text{Cr}$  ( $I = \frac{3}{2}$ ), with seven (leftmost peak being a doublet) and four peaks, respectively. The HFS of  $^{61}\text{Cr}$  Fig. 1a) displays a clear double peak structure which can only be observed with  $I = \frac{1}{2}$ . The presence of a possible  $\frac{9}{2}^+$  isomeric state in  $^{61}\text{Cr}$ , similar to the isotone nucleus  $^{63}\text{Fe}$  [32, 33], has been investigated but is not observed in our measurements.

The analysis of the HFS was performed using the SATLAS2 python package [29]. The fit function is composed of multiple Voigt functions plus a linear background, with the peak positions determined by the hyperfine Hamiltonian [28]. The fits in Fig. 1 used fixed relative peak amplitudes based on Racah intensities [28] (except for  $^{51}\text{Cr}$ , Fig. 1b)). The  $A_{P_3}$  and  $B_{P_3}$  hyperfine parameters of the  $^7P_3$  state were fixed to zero, as well as the  $B_{S_3}$  parameter of the  $^7S_3$  state (all measured to be compatible with zero within 2 MHz [25–27, 30, 31]). All the other fitting parameters (centroid and amplitude of the HFS,  $A_{S_3}$ , Gaussian and Lorentzian widths and background parameters) were left free. The red, blue, and green colored lines in Fig. 1a) shows the best fit to the data considering  $I = \frac{1}{2}$ ,  $\frac{3}{2}$  and  $\frac{5}{2}$ , respectively. Data can

only be reproduced with the  $\frac{1}{2}$  spin hypothesis.

The experimental method used for extracting  $\mu$  was benchmarked by comparing our measurements of  $^{51,53}\text{Cr}$ , to literature values. The measured hyperfine  $A_{S_3}$  parameter for  $^{53}\text{Cr}$   $A_{S_3}(^{53}\text{Cr}) = -82.64(16)$  MHz, agrees with the literature value  $A_{S_3, lit}(^{53}\text{Cr}) = -82.5985(15)$  MHz [31]. The differential hyperfine anomaly [35] is measured to be 0.2(15)% using nuclear magnetic resonance measurements [36] and is therefore neglected in the analysis. Thus, using the precise value  $\mu_{lit}(^{53}\text{Cr}) = -0.47454(3) \mu_N$  [34], the  $\mu$  of a Cr isotope of mass  $A$  can be determined from  $\mu(^A\text{Cr}) = \mu_{lit}(^{53}\text{Cr}) \frac{A(^A\text{Cr})I(^A\text{Cr})}{A_{lit}(^{53}\text{Cr})I(^{53}\text{Cr})}$ . The measured  $\mu(^{51}\text{Cr}) = -0.933(13) \mu_N$  closely matches the literature value  $\mu_{lit}(^{51}\text{Cr}) = -0.934(5) \mu_N$  [36], further confirming the accuracy of the method. Note that, even using a spectroscopic transition with larger B parameters, no electric quadrupole moment can be extracted for  $I = \frac{1}{2}$ .

The hyperfine  $A_{S_3}$  parameter of  $^{61}\text{Cr}$  has been measured to be  $A_{S_3}(^{61}\text{Cr}) = +281.5(37)$  MHz leading to  $\mu(^{61}\text{Cr}) = +0.539(7) \mu_N$ . The value is determined by the relative position of the two peaks in Fig. 1a) while the sign is constrained by their relative amplitudes. A fit using a negative  $A_{S_3}$  leads to a reduced chi-square  $\chi^2_\nu = 10.2$ , twice as large as the one obtained with positive  $A_{S_3}$ . The value and uncertainty correspond to the  $\chi^2$ -normalized weighed average and standard deviation of four independent measurements performed over three days. The total error includes all experimental systematic errors, dominated by effects such as instabilities of the wavemeter and error on the measurement of the IS-COOL voltage. The error of a single measurement is taken as the fit error (taking into account statistical errors, experimental resolution, and line-shape distortion). The four independent measurements are all compatible within  $1 \sigma$ , with a typical uncertainty of 5 MHz.

The measured magnetic dipole moment  $\mu(^{61}\text{Cr}) = +0.539(7) \mu_N$  lies close to the single-particle value  $+0.638 \mu_N$  of a  $\nu p_{1/2}$  state, supporting a negative parity state. Assuming that  $I$  and  $\mu$  are dominated by the odd neutron, the positive sign of the moment determines a  $l - 1/2$  coupling of the occupied orbital and excludes the possibility of a  $\nu g_{9/2}$ ,  $\nu d_{5/2}$  or  $\nu s_{1/2}$  state and therefore of a positive parity. Furthermore, there are no  $I^\pi = \frac{1}{2}^+$  level observed below 500 keV in the region [37]. These arguments support a negative parity and therefore  $I^\pi = \frac{1}{2}^-$  for  $^{61}\text{Cr}$ .

*Discussion.* The ground-state spin-parity of  $^{61}\text{Cr}$  had previously been tentatively assigned ( $\frac{5}{2}^-$ ), based on its direct feeding from the beta decay of  $^{61}\text{V}$  [17] (whose spin is still not established). This assignment was supported by the beta decay study of  $^{61}\text{Cr}$  [18], based on the large feeding to the  $\frac{5}{2}^-$   $g.s.$  of  $^{61}\text{Mn}$  (now firmly established [38]) and to its first ( $\frac{7}{2}^-$ ) excited state [39]. The

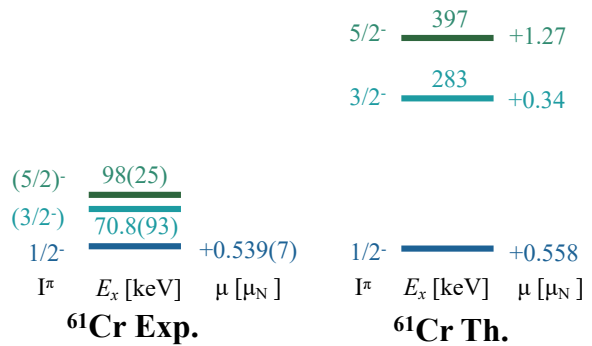


FIG. 2. Experimental and theoretical partial level scheme of  $^{61}\text{Cr}$  with spin-parities  $I^\pi$ , excitation energies  $E_x$  and magnetic dipole moments  $\mu$ . Experimental excitation energies are from Ref.[19].

measurement reported here provides the first direct spin measurement of the  $^{61}\text{Cr}$   $g.s.$ , establishing  $I^\pi = \frac{1}{2}^-$  and revising the previously adopted  $I^\pi = (\frac{5}{2}^-)$ .

The beta decay of the  $\frac{1}{2}^-$   $^{61}\text{Cr}$   $g.s.$  to the  $\frac{5}{2}^-$   $^{61}\text{Mn}$   $g.s.$  corresponds to a second forbidden transition, contradicting its measured  $\log ft = 5.1(2)$  [18]. This discrepancy may stem from the overestimation of  $g.s.$  direct beta feeding due to the missing beta strength for excitation energies  $E_x > 2.5$  MeV, known as the Pandemonium effect [40]. The situation is similar for the  $^{61}\text{Mn}$  ( $\frac{7}{2}^-$ ) first excited state which should be weakly populated by direct beta feeding. It would be valuable to investigate these inconsistencies with additional beta decay data, including total absorption spectroscopy. The reported apparent direct beta feeding from  $^{61}\text{V}$  to the  $g.s.$  of  $^{61}\text{Cr}$  [17] suggests  $I^\pi = (\frac{1}{2}^-)$  or  $(\frac{3}{2}^-)$  for the  $g.s.$  of  $^{61}\text{V}$ . However, the missing beta strength and the lack of spectroscopy data on  $^{61}\text{V}$  prevent any conclusion on its possible  $g.s.$  spin and configuration. Additional spectroscopy data on this nucleus are also required.

The beta decay study of  $^{61}\text{V}$  identified two  $\gamma$  transitions feeding the  $^{61}\text{Cr}$  ground-state from low-lying excited states at 70.8(3) keV and 97.7(3) keV [19]. Based on Weisskopf estimates and the non-observation of a lifetime for these states, it is suggested that the 71 keV transition is limited to a dipole character, while the 98 keV transition would be a dipole or mixed  $M1 - E2$  transition [19]. Dipole transitions ( $M1$  or  $E1$ ) from the  $I^\pi = \frac{1}{2}^-$  state would populate  $\frac{1}{2}^\pm$  or  $\frac{3}{2}^\pm$  states while an E2 transition would populate  $\frac{3}{2}^-$  or  $\frac{5}{2}^-$  states. No low-lying  $\frac{1}{2}^+$  and  $\frac{3}{2}^+$  are observed for even- $Z$  odd- $N$  nuclei in the region, making this hypothesis unlikely. Furthermore, a low-lying triplet  $\frac{1}{2}^-$ ,  $\frac{3}{2}^-$ ,  $\frac{5}{2}^-$  is observed in several even- $Z$ ,  $N = 37$  isotones and odd- $N$ ,  $Z = 24$  isotopes, around  $^{61}\text{Cr}$ . Based on these arguments, on the present  $g.s.$   $I^\pi = \frac{1}{2}^-$  determination and on the reported multi-

polarities from Ref. [19], the tentative spin-parity assignments of  $(\frac{3}{2}^-)$  and  $(\frac{5}{2}^-)$  are proposed for the 70.8(3) keV and 97.7(3)-keV states, respectively (see Fig. 2).

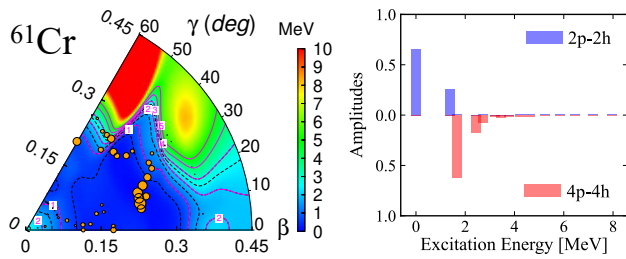


FIG. 3. Left: ground-state wavefunction of  $^{61}\text{Cr}$  expanded in the  $(\beta, \gamma)$  plane. Right: Theoretical amplitudes of the deformed neutron  $2p-2h$  (blue) and  $4p-4h$  (red) components into all the  $\frac{1}{2}^-$  states.

*Interpretation.* We performed theoretical calculations within LSSM diagonalizations and further interpreted our results with the recently-developed Discrete Non-Orthogonal Shell-Model (DNO-SM) approach [41]. Within these frameworks, the valence space is composed of the  $pf$ -shell for protons and the  $1p_{3/2}$ ,  $0f_{5/2}$ ,  $1p_{1/2}$ ,  $0g_{9/2}$ , and  $1d_{5/2}$  orbitals for neutrons, on top of an inert  $^{48}\text{Ca}$  core. The interaction is the LNPS Hamiltonian [6] with minor adjustments [42], which has shown to be extremely successful for the description of collectivity and the IoI at  $N=40$  [7, 9, 12, 43, 44]. We recall that using the same valence space, the DNO-SM allows diagonalization of the same LNPS effective interaction in a relevant deformed Hartree-Fock (HF) states basis from the potential energy surface represented in a  $(\beta, \gamma)$  plane. The diagonalization was then performed after rotational symmetry restoration using angular-momentum projection technique.

The theoretical spectroscopic results are compared to experiment in Fig. 2. The calculations reproduce the  $I^\pi = \frac{1}{2}^-$   $g.s$  and support the  $\frac{1}{2}^- - \frac{3}{2}^- - \frac{5}{2}^-$  states sequence proposed in this work. The calculations also produce close-lying  $\frac{3}{2}^- - \frac{5}{2}^-$  excited states but slightly overestimate their excitation energies. With two excited states lying within less than 100 keV,  $^{61}\text{Cr}$  displays the highest level density of the isotopic chain at low excitation energies.

For the calculation of  $\mu$ , we use bare orbital  $g_i^{\pi, \nu}$  and spin  $g_s^{\pi, \nu}$  factors. These bare  $g$ -factors values (shown in Fig. 2) reproduce the  $\mu$  measurement within  $2\sigma$  and confirms its  $I^\pi = \frac{1}{2}^-$  nature. It should be noted that in the shell-model framework, effective operators, and in particular spin operators renormalized (quenched) to the model space, should be used to account for external contributions, similar to two-body currents used in *ab-initio* calculations. A recent survey on the impact of two-body currents on  $\mu$  shows that its contribution is nucleus-

to-nucleus dependent with sizeable variations, pointing to a probable minor contribution in the present case [45]. A more general study of these effective operators, beyond the scope of the present paper, should be undertaken in the future.

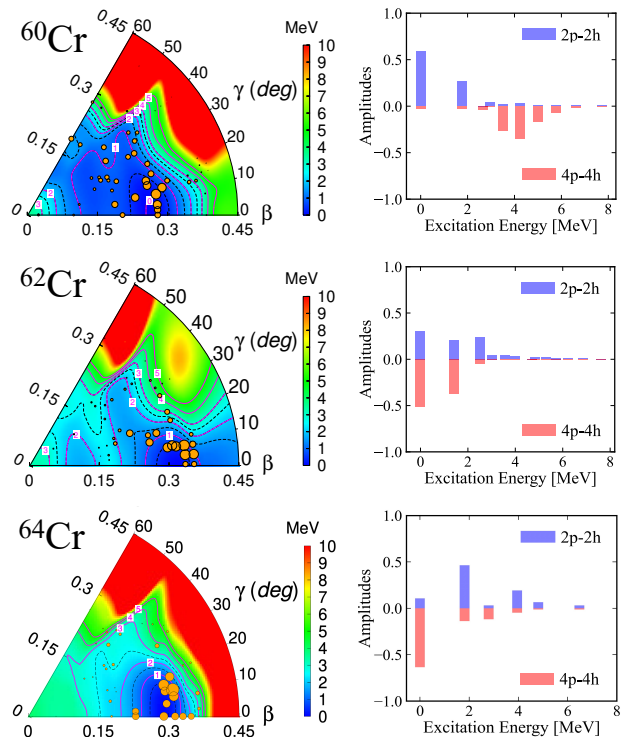


FIG. 4. Same as Fig 3 for ground-state wavefunctions of  $^{60,62,64}\text{Cr}$ .

Additional insight into the nature of the low-lying states is provided by inspection of the wave function contents. The theoretical occupations support the  $I^\pi = \frac{1}{2}^-$  and  $\mu$  being carried by an unpaired  $\nu p_{1/2}$  neutron. The remaining orbital occupancies reveal an intruder configuration with a strong population of  $\nu g_{9/2}$  and  $\nu d_{5/2}$  intruder orbitals of 1.65 neutrons, suggesting the deformed character of the state. Transfer reaction data to experimentally confirm these findings would be of high interest. In the left panel of Fig. 3, we show the  $\frac{1}{2}^-$  wavefunction expanded in the  $(\beta, \gamma)$  plane. It shows strongly-deformed triaxial components centered around  $(\beta, \gamma) \sim (0.23, 20^\circ)$  of mainly  $2p-2h$  nature. Interestingly, when extracting the overlaps between the deformed neutron  $2p-2h$  and  $4p-4h$  fixed configurations and the physical states (right panel of the same figure), the  $2p-2h$  probability amplitude is dominant in  $^{61}\text{Cr}$ , while the  $4p-4h$  deformed configuration is not present at the location of the ground-state, but mostly concentrated in a single excited state around 2 MeV.

With one additional neutron,  $^{62}\text{Cr}$  has recently been shown to exhibit a complex low-lying structure with the

occurrence of three rotational bands [46] and its *g.s.* dominated by  $4p - 4h$  configurations, which defines the  $N = 40$  IoI. In view of these characteristics, it is therefore interesting to assess the evolution of the deformation entering the  $N = 40$  IoI. For that, we perform the same theoretical treatment for  $^{60,62,64}\text{Cr}$  isotopes. One observes, in Fig. 4 (left panel), a clear evolution from a mildly collective wave function in  $^{60}\text{Cr}$ , to stronger collective and axial regimes in  $^{62}\text{Cr}$  and  $^{64}\text{Cr}$  with an intermediate triaxial regime developing in  $^{61}\text{Cr}$ . Such shape transitions are often qualified as quantum phase transitions [47, 48]. The underlying mechanism associated with these transitions is connected to the  $Np - Nh$  content of the involved wave functions: the  $2p - 2h$  probability amplitude (right panel) is the strongest in the  $^{60}\text{Cr}$  *g.s.* but becomes progressively suppressed due to the  $4p - 4h$  emergence which dominates in the *g.s.* of  $^{62,64}\text{Cr}$ . In [12],  $^{64}\text{Cr}$  was discussed to be the most collective chromium isotope in the IoI at  $N = 40$  with strongly dominating  $4p - 4h$  components. From the present scenario, we can infer that  $^{61}\text{Cr}$  is the first chromium isotope where  $4p - 4h$  components appear in the low-lying excited spectrum as well as the last Cr having a ground-state dominated by  $2p - 2h$  configurations. This feature hence enables  $^{61}\text{Cr}$  to be placed at the western entrance to the  $4p - 4h$  IoI regime.

In conclusion, the ground-state spin and nuclear magnetic dipole moment of  $^{61}\text{Cr}$  were measured for the first time using the CRIS experiment at the CERN-ISOLDE facility. Our measurement establishes  $I^\pi = \frac{1}{2}^-$  as the spin-parity of  $^{61}\text{Cr}$ , instead of  $I^\pi = (\frac{5}{2})^-$  as previously adopted in the literature and is used to re-evaluate the level scheme of  $^{61}\text{Cr}$ . This measurement also highlights the need of additional decay spectroscopy and transfer reaction data in the region, especially for  $^{61}\text{Cr}$  and  $^{61}\text{V}$ . State-of-the-art LSSM calculations reproduce the experimental findings. The  $^{61}\text{Cr}$  ground-state is interpreted, following the DNO-SM wave-function analysis, to have a triaxial shape and to be dominated by a  $2p - 2h$  neutron intruder configuration coupled to an unpaired  $\nu 1p_{1/2}$  neutron. Within the isotopic chain,  $^{61}\text{Cr}$  is understood to make the transition between the  $2p - 2h$  and the  $4p - 4h$  regime. In addition, the associated shape evolution (going from axial to triaxial to axial as we move from  $^{60}\text{Cr}$  to  $^{61}\text{Cr}$  to  $^{62}\text{Cr}$ ) is interpreted as a quantum phase transition at the entrance of the  $N = 40$  IoI.

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