The mean-field theories [23–27] have been developed. Neutron-rich isotopes from Si (shape coexistence, and configuration mixing observed in the vicinity of the magic number \( Z = 16 \)) to K (between \( Z = 28 \) and 38) have been studied, yielding a large set of complementary data. In parallel, elaborate shell-model calculations [18–22] and \( \beta \)-nuclear magnetic resonance technique, resulting in g-factor values and of the theoretical level scheme in the shell-model framework reveals the presence of odd-proton \( \pi_1/2 \) configurations and neutron excitation across the \( N = 28 \) shell gap in the ground state of \( ^{44}\text{Cl} \). In addition, the measured g factor strongly supports a \( 2^- \) spin assignment for the \( ^{44}\text{Cl} \) ground state.

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I. INTRODUCTION

Isotopes with extreme proton-to-neutron ratios attract a lot of attention because they exhibit nuclear properties that significantly differ from those near the valley of stability. Several regions on the nuclear chart are currently being explored (e.g., the island of inversion around \( N = 20 \), the neutron-rich nuclei around \( ^{68}\text{Ni} \), revealing vanishing magic numbers and new shell gaps.

About 15 years ago, a \( \beta \)-decay experiment suggested a new region of deformation around \( ^{44}\text{S} \) [1]. Since then, extensive experimental and theoretical studies have been performed to analyze the nuclear structure of the neutron-rich isotopes in the vicinity of the \( N = 28 \) shell closure. Various observables, such as masses [2–4], \( \beta \)-decay properties [5,6], excitation energies and level schemes [7–10], \( B(E2) \) values [11–13], spectroscopic factors [14,15], and nuclear moments [16,17], have been studied, yielding a large set of complementary data.

In parallel, elaborate shell-model calculations [18–22] and mean-field theories [23–27] have been developed.

Both the erosion of the \( N = 28 \) shell gap and the collapse of the \( Z = 16 \) subshell closure are responsible for the collectivity, shape coexistence, and configuration mixing observed in the neutron-rich isotopes from Si (\( Z = 14 \)) to K (\( Z = 19 \)). Since \( ^{44}\text{Cl} \) has three proton holes in the \( \pi(sd) \) shell, it is very sensitive to the near-degeneracy of the \( \pi_1/2 \) and \( \pi(d_1/2) \) levels and to the induced proton correlations. With one neutron hole in the \( \nu(f_7/2) \) state, \( ^{44}\text{Cl} \) is also an excellent probe for neutron excitations across \( N = 28 \).

As the nuclear g factor consists of an orbital and a spin contribution, it indicates the shell-model character of the state being studied. A measurement of the g factor can therefore provide important information on the nuclear structure of the \( N \simeq 28 \) isotopes.

This article reports on the first g-factor measurement of the \( ^{44}\text{Cl} \) ground state, using the \( \beta \)-nuclear magnetic resonance (\( \beta \)-NMR) technique at the LISE fragment separator at the Grand Accélérateur National d’Ions Lourds (GANIL). The experimental results are presented and compared to large-scale shell-model calculations. To give a correct interpretation of the \( ^{44}\text{Cl} \) g factor and ground-state structure in terms of changing single-particle orbits and enhanced correlations, the isotopic \( Z = 17 \) and isotonic \( N = 27 \) chains are discussed. This study reveals a deeper insight into the structural changes happening around the magic number \( N = 28 \).

II. EXPERIMENTAL TECHNIQUE

Neutron-rich \( ^{44}\text{Cl} \) nuclei were produced in a projectile-fragmentation reaction of a stable \( ^{48}\text{Ca} \) beam (60 AMeV) impinging on a 1212-\( \mu \)m rotating \( ^9\text{Be} \) target. The secondary beam was selected by the high-resolution fragment separator LISE at GANIL [28,29]. The polarization necessary to perform a \( \beta \)-NMR measurement was obtained by placing an angle of 2(1\(^\circ\)) on the primary beam with respect to the forward direction. To get the highest polarization [30], a selection was made in the right wing of the longitudinal momentum distribution. This configuration led to a production yield of about 2700 \( ^{44}\text{Cl} \)-ions/s for 1 \( \mu \)A of \( ^{48}\text{Ca} \). A secondary beam purity of 90% was achieved by placing a 1077-\( \mu \)m \( ^{9}\text{Be} \) wedge-shaped degrader in the intermediate dispersive plane and by adjusting the settings of the Wien filter in front of the \( \beta \)-NMR setup. The identification of the transmitted fragments was done by means of the standard energy loss versus time of flight procedure using three \( ^{3}\text{He} \) detectors along the beam path.
The characteristic $\gamma$ lines following the $\beta$ decay of the $^{44}$Cl nuclei contributed to a correct identification of the produced fragments.

At the end of the LISE fragment separator, the $\beta$-NMR setup is installed [31]. The spin-polarized $^{44}$Cl fragments ($t_{1/2} = 0.56(11)$ s, $Q_{\beta} = 12.27(22)$ MeV [32]) are implanted in a 1-mm-thick NaCl crystal at room temperature. The stopper material is positioned in the center of a static magnetic field $B_0$ that is oriented parallel to the vertical polarization axis. $B_0$ induces a Zeeman splitting of the nuclear $m$ quantum states. The energy difference between two successive levels, $m - 1$ and $m$, is proportional to the nuclear $g$ factor $g$ and to the magnetic field strength $B_0$. It is given by

$$\Delta E = E_m - E_{m-1} = g\mu_N B_0.$$  \hfill (1)

The $\beta$ particles emitted in the $\beta$ decay of $^{44}$Cl are detected in two $\Delta E/E$ pairs of plastic scintillators placed along the polarization direction. One pair is situated above the crystal, the other below. Requiring coincidences between the upper two or the lower two detectors reduces scattering and noise events. When the implanted nuclear ensemble is spin polarized, the $m$ states have a different occupation probability, which induces an anisotropic $\beta$ decay pattern.

Perpendicular to the magnetic field, a radiofrequent (rf) field is applied in the Cu coil placed around the crystal. By varying the rf frequency $\nu$, the emitted energy $h\nu$ is matched to the energy difference between the $m$ states [Eq. (1)]. This induces an equal population of all quantum levels and a destruction of the polarization when the Larmor frequency $\nu_L = (g\mu_N B_0)/h$ is encountered. As a consequence, the $\beta$-decay pattern becomes isotropic, and a resonance is observed when the experimental asymmetry is measured as a function of the rf frequency. The experimental asymmetry is defined as

$$\text{Asymmetry} = \frac{N_{\text{up}} - N_{\text{down}}}{N_{\text{up}} + N_{\text{down}}} \simeq \frac{\nu_{\beta}}{c} A_\beta P.$$  \hfill (2)

The number of coincident events in the upper and lower detectors is given by $N_{\text{up}}$ and $N_{\text{down}}$, respectively. $A_\beta$ is the asymmetry parameter, which depends on the $\beta$-decay properties and the spin of $^{44}$Cl. $P$ is the polarization induced in the projectile-fragmentation reaction, and $\nu_{\beta}/c$, the ratio of the velocity of the $\beta$ particles to the speed of light, is assumed to be 1 because $^{44}$Cl has a high $Q_{\beta}$.

The variation of the rf frequency is performed in discrete steps, all characterized by a central frequency. In parallel to the continuous $\beta$ detection, each central frequency is applied and modulated simultaneously for several seconds up to minutes, depending on the lifetime of the nucleus. The modulation range covers at least one-half of the interval between two subsequent central frequencies and has a repetition rate of 100 Hz. After applying the last central frequency, data without an rf field are collected as a reference before starting the next scan.

### III. RESULTS

The first indication of the $^{44}$Cl $\beta$-NMR resonance was found in a broad scan, covering a 2-MHz-wide frequency range in steps of 200 kHz using a large frequency modulation of 110 kHz. A preliminary Larmor frequency $\nu_L(^{44}\text{Cl}) = 2126(110)$ kHz could be deduced. Starting from this result, four fine scans were performed, gradually reducing the scan range and the frequency modulation until an accurate $\beta$-NMR curve and a precise Larmor frequency $\nu_L(^{44}\text{Cl}) = 2096.5(2)$ kHz were obtained. Table I gives the scanned frequency range, the step between two central values, the applied frequency modulation, and the deduced Larmor frequency for the subsequent $\beta$-NMR measurements.

Two fine-scan examples with a frequency modulation of 17 kHz and 0.6 kHz, respectively, are shown in Fig. 1. The outer right point represents the data collected without an rf field. In several measurements, including the ones presented in Fig. 1, two frequencies are added on either side of the resonance region to emphasize the baseline. The $\beta$-NMR curves are fitted with a function $f(\nu)$ that includes the Lorentzian line shape and the frequency modulation $M$ [33]:

$$f(\nu) \sim \left[ \frac{1}{2} \frac{\nu - \nu_0 + M}{\Gamma} - \frac{1}{2} \frac{\nu - \nu_0 - M}{\Gamma} \right],$$  \hfill (3)

leaving the amplitude, the central frequency $\nu_0$, and the full width at half maximum of the Lorentzian profile $\Gamma$ as free parameters. The weighted mean of the five $\nu_L$ is calculated to be $\nu_L(^{44}\text{Cl})_{1T} = 2096.4(2)$ kHz.

All aforementioned $\beta$-NMR measurements were performed at a magnetic field $B_0 = 1.0001(7)$ T. During the run, the field was continuously monitored by the hall probe positioned at 7 cm behind the implantation crystal. From the measured field value, the magnetic field in the center could be calculated, relying on the field calibrations made before and after the experiment.

During the calibration process, a complete and stable hysteresis curve was measured in steps of 0.5 A. This procedure was performed in the center and at the position of the hall probe, firmly establishing the relation between both. The total error on $B_0$ consists of two contributions, added in quadrature. The statistical contribution (0.15 mT) is the smallest and originates from the linear relation between the measured and the central magnetic field. It includes the uncertainty on the hall probe readout and the errors on the slope and the intercept of the calibration function. The largest

**TABLE I.** The scanned frequency range, the interval between two central frequencies, the applied frequency modulation, and the obtained Larmor frequency for the five $^{44}$Cl $\beta$-NMR measurements, performed at $B_0 = 1.0001(7)$ T.

<table>
<thead>
<tr>
<th>Range (kHz)</th>
<th>Step (kHz)</th>
<th>Modulation (kHz)</th>
<th>$\nu_L$ (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>850–2850</td>
<td>200</td>
<td>110</td>
<td>2126(110)</td>
</tr>
<tr>
<td>1800–2300</td>
<td>30</td>
<td>17</td>
<td>2097(4)</td>
</tr>
<tr>
<td>2070–2122</td>
<td>4</td>
<td>1.6</td>
<td>2098(2)</td>
</tr>
<tr>
<td>2085–2110</td>
<td>1</td>
<td>0.01</td>
<td>2096.1(3)</td>
</tr>
<tr>
<td>2085–2110</td>
<td>1</td>
<td>0.6</td>
<td>2096.5(2)</td>
</tr>
</tbody>
</table>

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contribution (0.66 mT) is a systematic effect, linked to the fact that the field calibration around 1 T can only be reproduced with an accuracy of 0.66 mT.

From the weighted mean of the individual Larmor frequencies and the calculated magnetic field value \( B_0 \), the \( g \) factor of the \( ^{44}\text{Cl} \) ground state can be deduced: \( \left| g(^{44}\text{Cl})\right|_{\text{T}} = 0.2750(2) \).

To check this result, an extra \( \beta \)-NMR scan was performed at a different magnetic field. The experimental details and the observed Larmor frequency can be found in Table II. The \( \beta \)-NMR resonance is plotted in Fig. 2. A static magnetic field \( B_0 = 0.5001(4) \) T was applied, the error being mainly determined by the 0.36-mT divergence observed for repeated calibrations around 0.5 T. Based on the measured Larmor frequency \( \nu_L = 1047.0(5) \) kHz and the calibrated magnetic field, an independent value for the \( g \) factor of the \( ^{44}\text{Cl} \) ground state could be deduced. The result, \( \left| g(^{44}\text{Cl})\right|_{0.5T} = 0.2747(3) \), is in good agreement with the \( g \) factor observed for the double field value.

### Table II. The scanned frequency range, the interval between two central frequencies, the applied frequency modulation, and the obtained Larmor frequency for the \( \beta \)-NMR measurement performed at \( B_0 = 0.5001(4) \) T.

<table>
<thead>
<tr>
<th>Range (kHz)</th>
<th>Step (kHz)</th>
<th>Modulation (kHz)</th>
<th>( \nu_L ) (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1035–1061</td>
<td>2</td>
<td>1.5</td>
<td>1047.0(5)</td>
</tr>
</tbody>
</table>

The experimentally determined \( g \) factor of the \( ^{44}\text{Cl} \) ground state is the weighted mean of the \( g \) factors observed at 1 T and at 0.5 T and is calculated to be \( \left| g(^{44}\text{Cl})\right| = 0.2749(2) \).

### IV. Discussion

Being an odd-proton isotope, \( ^{44}\text{Cl} \) is very sensitive to the near-degeneracy of the \( \pi(s_{1/2}) \) and \( \pi(d_{3/2}) \) levels \([9,34–36]\). Having 27 neutrons, \( ^{44}\text{Cl} \) is also an excellent probe to study the reduction of the \( N = 28 \) shell gap, which has been observed in the neighboring \( ^{43}\text{S} \) \([17]\) and \( ^{45}\text{Ar} \) \([15]\) isotones. Prior to the discussion of the \( ^{44}\text{Cl} \) ground-state structure, the preceding effects are addressed from experimental and theoretical points of view. The entire discussion is performed in the shell-model framework, and all calculations are made using the ANTOINE code \([37]\) with the most recent \( sdpf \) residual interaction \((\text{SDPF-U}) \) \([22]\). The protons are confined to the \( \pi(sd) \) orbits while the valence neutrons occupy full \( v(pf) \) shell.

The degeneracy of the \( \pi(s_{1/2}) \) and \( \pi(d_{3/2}) \) levels is to a large extent caused by the proton-neutron tensor force \([38,39]\), which works attractively on the \( \pi(d_{3/2}) \) state, lowering it in energy with respect to the \( \pi(s_{1/2}) \) level when the \( v(f_{7/2}) \) orbit is filled. When both proton levels come close together, ground-state configurations with an odd \( s_{1/2} \) proton are energetically favored as the energy gain by pairing two protons in the \( \pi(d_{3/2}) \) level overcomes the energy needed to excite a proton. As a consequence, a ground-state spin change is predicted in the odd-mass Cl isotopes, similar to the spin flip observed in the K isotopes \([40]\). Going toward \( ^{45}\text{Cl} \), a decrease of the energy difference between the normal \( 3/2^+ \) ground state and the first
whereas dash-dotted lines define strongly fragmented states. Dominating single-particle nature are indicated with a solid line, whereas dash-dotted lines define strongly mixed states. The 7/2− ground state of 43Cl originates from the odd-neutron hole in the ν(f1/2) orbital. Promoting one neutron across the N = 28 shell gap to the ν(p3/2) level gives the 3/2+ first excited state. Both configurations are also present in the level scheme of 45Ar. The lower excitation energy of the 3/2− state already indicates the weakening of the N = 28 shell gap. In addition, a collective 3/2− state appears at 535 keV.

When going to 43S, the intruder 3/2− level with a neutron configuration dominated by np-nh excitations across N = 28 is suggested to replace the single-particle 7/2− level as the ground state. An extensive discussion of this structural change can be found in Refs. [15,17,48]. Note that for the N = 27 isotones, a good agreement between the experimental and calculated g factors is obtained using the effective nucleon g factors proposed in Ref. [49] (g∗ = 1.1, g∗ = −0.1, and g∗ = 0.75g∗free).

As 44Cl is situated between 45Ar and 43S, ν(p3/2) configurations are expected to contribute to the ground-state wave function. Experimentally, this was confirmed by Riley et al., who measured the momentum distribution of the 44Cl nuclei in the single-neutron knockout reaction 9Be(45Cl, X) [50]. From the obtained results, it was concluded that the ν(p3/2) configurations play a prominent role in the 44Cl ground state and that the collapse of the N = 28 shell closure, earlier observed in 43S [17], persists in 44Cl.

Let us now combine both effects, the degeneracy of the π(s1/2) and π(d3/2) levels and the reduced N = 28 shell gap, in the odd-odd nuclei. The theoretical and (known) experimental level schemes of 46K and 45Cl are presented in Fig. 5, together with the calculated and measured ground-state g factors. The experimental data are taken from this work and Refs. [40,51], while the theoretical g factors are

![FIG. 3. Calculated and experimental level schemes of the odd-mass neutron-rich 39−45Cl27−28 isotopes.](image_url)

![FIG. 4. Experimental level schemes and known g factors of the N = 27 isotones (47Ca, 45Ar, and 43S). Nuclear states with a dominating single-particle nature are indicated with a solid line, whereas dash-dotted lines define strongly fragmented states.](image_url)

![FIG. 5. Calculated and experimental (if known) level schemes of 46K and 44Cl. The experimental spin assignments for 46K are the ones adopted in Ref. [51], and the measured ground-state (g.s.) g factors are taken from this work and Ref. [40].](image_url)
TABLE III. Main calculated wave-function components of the ground state and low-lying excited states in 46K and 44Cl. Only contributions larger than 10% are reported.

<table>
<thead>
<tr>
<th>J^g</th>
<th>46K configuration</th>
<th>J^s</th>
<th>44Cl configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>2^-</td>
<td>71% (πd_3/2)^3(νf_7/2)^3</td>
<td>2^-</td>
<td>24% (πd_3/2)^3(νf_7/2)^3</td>
</tr>
<tr>
<td>3^-</td>
<td>35% (πd_3/2)(νf_7/2)^3</td>
<td>1^-</td>
<td>16% (πd_3/2)^3(νp_7/2)^3</td>
</tr>
<tr>
<td></td>
<td>32% (πs_1/2)(νf_7/2)^3</td>
<td>27% (πs_1/2)^3(νp_7/2)^3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>15% (πs_1/2)^3(νp_7/2)^3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4^-</td>
<td>16% (πd_3/2)(νf_7/2)^3</td>
<td>0^-</td>
<td>20% (πd_3/2)^3(νp_7/2)^3</td>
</tr>
<tr>
<td></td>
<td>61% (πs_1/2)(νf_7/2)^3</td>
<td>22% (πs_1/2)^3(νp_7/2)^3</td>
<td></td>
</tr>
<tr>
<td>5^-</td>
<td>77% (πd_3/2)(νf_7/2)^3</td>
<td>3^-</td>
<td>13% (πd_3/2)^3(νf_7/2)^3</td>
</tr>
<tr>
<td></td>
<td>22% (πs_1/2)(νf_7/2)^3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1^-</td>
<td>63% (πd_3/2)(νp_3/2)^3</td>
<td>4^-</td>
<td>10% (πd_3/2)^3(νf_7/2)^3</td>
</tr>
<tr>
<td></td>
<td>35% (πs_1/2)(νf_7/2)^3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0^-</td>
<td>64% (πd_3/2)(νp_3/2)^3</td>
<td>5^-</td>
<td>12% (πd_3/2)^3(νf_7/2)^3</td>
</tr>
<tr>
<td></td>
<td>12% (πs_1/2)(νf_7/2)^3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>29% (πs_1/2)(νp_7/2)^3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10% (πs_1/2)^3(νp_7/2)^3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A strong indication for the development of correlations and collectivity as observed in the even-odd N = 27 isotones.

Independent of the nuclear level schemes, also the g-factor values reflect the increasing number of ν(p3/2) and π(s1/2) configurations. As the ground state of 46K is dominated by (πd_3/2)^3(νf_7/2)^3 configurations, its g-factor g_{exp}^{46K} = −0.526(3) [40] can be compared to the value g_{pure} = −0.98 of a pure (πd_3/2)^3(νf_7/2)^3 state, calculated with effective nucleon g factors. For the 44Cl ground state, however, ANTOINE calculations suggest a highly fragmented wave function with (πd_3/2)^3(νf_7/2)^3 and (πs_1/2)^3(νp_7/2)^3 as main components. Because the (πs_1/2)^3(νp_7/2)^3 contribution has a g factor with a positive sign, g_{pure} = 0.28, the total value of the 44Cl g factor is reduced when both configurations are mixed. The experimentally observed value g^{44Cl} = (−0.2749(2) sign adopted from theory) confirms this argument: additional components in the wave function due to configuration mixing lower the g factor with respect to the value observed for a single-particle configuration.

An excellent agreement is observed between the experimental and calculated effective g factors of the N = 27 isotones 47Ca, 43S, 46K, and 44Cl. The measured 44Cl g factor, presented in this article, therefore strongly supports the 2^- spin assignment for the ground state of 44Cl, consistent with the conclusion drawn in Ref. [50].

In conclusion, the 44Cl ground state and g factor are very sensitive to the subtle interplay between proton configurations originating from the collapse of the Z = 16 subshell closure and neutron excitations across the reduced N = 28 shell gap. From the comparison of the 44Cl level scheme and g factor with calculated and experimental values in neighboring nuclei, it is deduced that both effects play a major role in the ground state of 44Cl.

V. SUMMARY

The g factor of the 44Cl ground state was studied for the first time, using the β-NMR technique at the LISE fragment separator at GANIL. Several measurements at two different magnetic field values were performed, leading to the final value g^{44Cl} = (−0.2749(2).

Comparison of this result with large-scale shell-model calculations using the ANTOINE code with the SDPF-U residual interaction and effective nucleon g factors favors 2^- as the ground-state spin of 44Cl. The analysis of the g-factor value and the comparison of the theoretical 44Cl level scheme with observations in the neighboring N = 27 and Z = 17 nuclei reveal the presence of odd s1/2 proton configurations and neutron excitations across N = 28 in the ground state of 44Cl.