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Nuclear Spins and Magnetic Moments of ^{71,73,75}Cu: Inversion of $\pi 2p_{3/2}$ and $\pi 1f_{5/2}$ Levels in ^{75}Cu

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We report the first confirmation of the predicted inversion between the $\pi 2p_{3/2}$ and $\pi 1f_{5/2}$ nuclear states in the $\nu g_{9/2}$ midshell. This was achieved at the ISOLDE facility, by using a combination of in-source laser spectroscopy and collinear laser spectroscopy on the ground states of ^{71,73,75}Cu, which measured the nuclear spin and magnetic moments. The obtained values are $\mu(^{71}\mathrm{Cu}) = +2.2747(8)\mu_N$, $\mu(^{73}\mathrm{Cu}) = +1.7426(8)\mu_N$, and $\mu(^{75}\mathrm{Cu}) = +1.0062(13)\mu_N$ corresponding to spins $I = 3/2$ for ^{71,73}Cu and $I = 5/2$ for ^{75}Cu. The results are in fair agreement with large-scale shell-model calculations.

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Much of the current effort in nuclear physics is focused on determining how the nuclear shell structure is changing in neutron-rich nuclei. This has been triggered by the observation of unexpected phenomena in several neutron-rich isotopes, since radioactive ion beams of such nuclei became available more than three decades ago. In the lighter elements (e.g., He, Li, Be), neutron halos and skins were observed. Around the neutron-rich ^{32}Mg region an ‘‘island of inversion’’ was discovered. In the neutron-rich region towards doubly magic ^{78}Ni, a sudden drop in the position of the first excited $5/2^-$ state in ^{71,73}Cu isotopes was observed more than a decade ago [1]. The lowering of the $5/2^-$ energy from above 1 MeV in ^{69}Cu to 166 keV in ^{73}Cu suggested that this state might become the ground state in ^{75}Cu. The migration of this level, associated with the occupation of the $\pi 1f_{5/2}$ single-particle orbital, was attributed to a strong attractive monopole interaction that becomes active when neutrons occupy the $\nu 1g_{9/2}$ orbital [2]. Such monopole interactions exist also in near-stable nuclei, but their impact on the evolution of shell structure and shell gaps in far-from-stability nuclei remained unnoticed until recently [3]. Also in other neutron-rich regions dramatic monopole shifts were observed when valence neutrons and protons are occupying orbits having their orbital and spin angular momentum, respectively, aligned and antialigned. It is now understood that one of the physics mechanisms driving these monopole shifts is the tensor part of the residual nucleon-nucleon interaction [4]. A steep lowering of the $1/2^-$ level from about 1 MeV in ^{69}Cu down to 135 keV in ^{73}Cu has also been observed [5,6]. Thus this level is also a potential ground-state candidate in ^{75}Cu. While most shell-model interactions do reproduce a lowering of the $5/2^-$ level and predict an inversion with the normal $3/2^-$ ground state somewhere between ^{73}Cu and ^{79}Cu [4,7–10], none of them reproduce the lowering of the $1/2^-$ state. Some significant physics mechanism is either omitted or seriously underestimated in each of the recently developed shell-model interactions. Therefore, experimental establishment of ground- and excited-state nuclear spins and the properties of their wave function (through spectroscopic factors, magnetic moments, transition moments, etc.) is a crucial step in the study of the shell evolution. In ^{75}Cu, two microsecond isomeric states have been observed below 130 keV [11], but their structure was never interpreted. Knowing the ground-state spin is crucial for assigning spins to these isomeric levels in order to investigate a further lowering of the $5/2^-$ and $1/2^-$ levels as the $\nu 1g_{9/2}$ gets half filled. Comprehensive understanding of the evolution of the low-energy structure is important for the development of robust nucleon-nucleon interactions that can be more widely applied in broad regions of the nuclear chart.

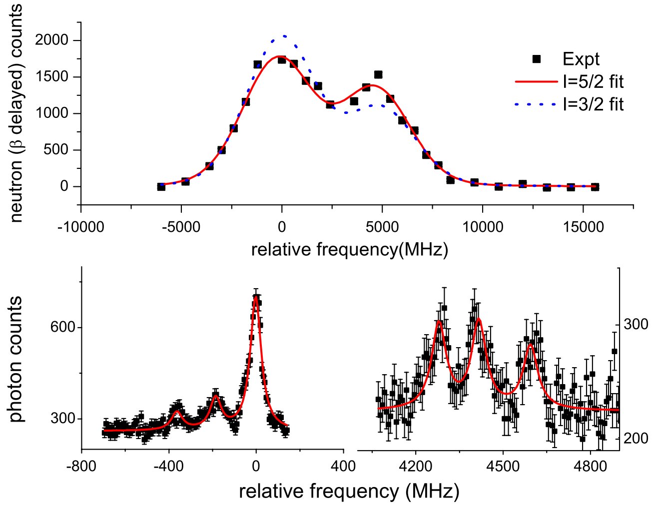

FIG. 1 (color online). In-source and collinear laser spectroscopy hfs spectra for ^{75}Cu. Top: In-source spectrum showing the best fits for $I = 3/2$ and $I = 5/2$ using the resonant ionization model [15]. Bottom: Collinear resonance fluorescence spectra of ^{75}Cu with best fit for $I = 5/2$. The left and right spectra are separated by the ground-state hfs, observed as two peaks in the upper spectrum.

This Letter reports on in-source [12,13] and collinear [14] laser spectroscopy measurements of the hyperfine structure (hfs) of neutron-rich Cu isotopes up to ^{75}Cu, from which the nuclear ground-state spins I and magnetic moments μ are determined. The radioactive ^{71,73,75}Cu isotopes were produced at the ISOLDE facility using far-asymmetric fission reactions induced by 1.4 GeV protons on a thick uranium carbide target (45 g/cm^2). The radioactive atoms diffused out of the target to a thin ionizer tube. Both target and tube were heated to approximately 2000 °C to reduce transport time. The Resonance Ionization Laser Ion Source (RILIS) was used to stepwise resonantly laser ionize the atoms within the ionizer tube. A two-step ionization scheme used the 327.4 nm $^2S_{1/2} - {}^2P_{1/2}$ transition followed by the 287.9 nm $^2P_{1/2} - {}^2D_{3/2}$ transition to an autoionizing state [12]. For the in-source spectroscopy stage of this work, the first-step RILIS laser was operated in a narrow bandwidth (1.2 GHz) mode [13], allowing the $^2S_{1/2}$ hyperfine splitting of ^{75}Cu to be resolved. The resonantly produced ^{75}Cu ions were accelerated to 30 keV and mass separated. They were implanted into the Mainz neutron long counter where their β-delayed neutron emission was detected. This provided excellent discrimination against the ^{75}Ga isobaric contamination, since the β-delayed neutron channel is absent there. The $^2S_{1/2}$ hfs was measured by recording the neutron rate as a function of the first-step laser frequency. The observed splitting in the hfs (upper section of Fig. 1) equals $A(^2S_{1/2})(I + 1/2)$, with the hyperfine A factor depending on the nuclear g factor. Fitted as described in [15] and used in [16], these data showed a preference for $I = 5/2$ and yielded a value $A(^2S_{1/2}) = 1.55(7)$ GHz. With the ^{65}Cu reference values given below, this corresponds to a moment of $0.99(4)\mu_N$. These results greatly reduced the scanning region for the high-resolution collinear laser spectroscopy measurements.

The second stage of this experiment used the collinear laser spectroscopy setup [14] to perform high-resolution studies which allowed both the atomic ground- and excited-state hyperfine structures of ^{71,73,75}Cu to be resolved. With the recent installation of a linear gas-filled radio frequency quadrupole Paul trap (named ISCOOL) [17,18], radioactive ions can be cooled and bunched at ISOLDE. Its application for collinear laser spectroscopy has been demonstrated in Jyväskylä (Finland) where rare isotopes with yields down to 150 s^{-1} have been studied with fluorescent photon detection on a bunched ion beam [19,20]. The ISCOOL device is located after the high-resolution separator on a high-voltage platform floated at 30 kV. A trapping potential was applied for up to 100 ms to the end plate of ISCOOL while radioactive ions were collected. Then, by fast-switching the end plate to the platform voltage, the ionic ensemble is released as a bunch with a typical time width of 25 μs. In a continuous mode, where the end plate was held at the platform voltage, a transmission efficiency through the device of 70% has been observed. The ion bunch was transported to the collinear laser spectroscopy beam line where the laser beam was overlapped in the copropagating direction. The Cu$^+$ bunch was sent through a sodium vapor cell, heated to approximately 230 °C, which neutralized the ions through charge-exchange collisions. A voltage was applied to the vapor cell for tuning the velocity of the ions and bringing them onto resonance with the laser. The resonances were located by measuring the photon yield as a function of the tuning voltage with two photomultiplier tubes (PMT). The signal from the PMT was gated so that photons were recorded only when an atom bunch was within the light collection region. This reduced the background photon counts associated with scattered laser light by a factor 4×10^3, this being the ratio of the trapping time to the temporal length in the light collection region. A dye laser was locked to a laboratory frame wave number of 15 406.9373 cm^{-1} using frequency modulation saturation spectroscopy of iodine. The fundamental wavelength was frequency doubled using an external buildup cavity.

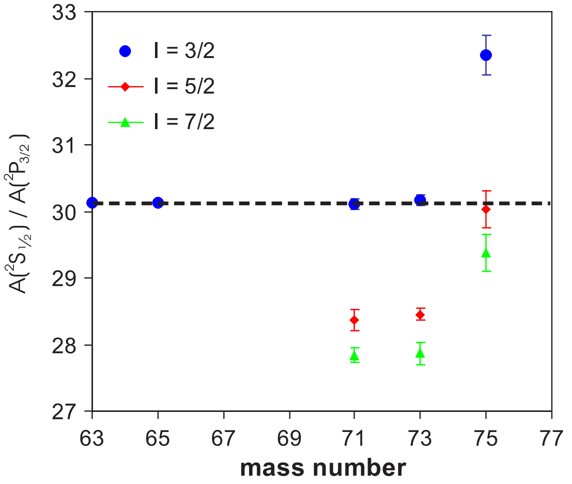

FIG. 2 (color online). Ratio of atomic g.s. and excited-state A factors deduced from a best fit to the experimental hyperfine spectra, assuming different spins for the ^{71,73,75}Cu nuclear ground states.

In the lower panel of Fig. 1 the high-resolution hfs data are shown for ^{75}Cu, scanned over the $^2S_{1/2} - {}^2P_{3/2}$ transition (324.8 nm). The number of hfs transitions and their relative splitting depends on the nuclear spin I and the atomic ground- and excited-state hyperfine parameters. Since more than three hyperfine components are observed, a nuclear spin $I = 1/2$ is excluded. The nuclear spins of the ^{71,73,75}Cu isotopes were determined by finding the best fit for their hyperfine parameters, assuming nuclear spins $I = 3/2$, 5/2, and 7/2. For each tentative spin, the fitted ratios $A(^2S_{1/2})/A(^2P_{3/2})$ are compared to those of the stable ^{63,65}Cu isotopes in Fig. 2. Ignoring the negligibly small hyperfine anomaly [21], their ratio has to be constant across the isotope chain independent of the nuclear spin. In ^{71,73}Cu the ratio for $I = 3/2$ is consistent with the stable isotope ratio. In ^{75}Cu the ratio for $I = 3/2$ deviates by 5σ from the observed trend while the ratio for $I = 5/2$ is consistent with it. A summary of A and B factors is shown in Table I. The magnetic moments are deduced relative to ^{65}Cu, using $A(^2S_{1/2}) = +6284.405(5)$ MHz and $\mu(^{65}\mathrm{Cu}) = +2.3817(3)\mu_N$ [23,24]. Quadrupole moments can be deduced from the B factors, and these will be discussed in a forthcoming paper.

The odd-A Cu isotopes have a simple structure, with one proton outside the $Z = 28$ closed shell. Their ground states with $I^\pi = 3/2^-$ up to ^{71}Cu are dominated by the $\pi 2p_{3/2}$ odd-proton configuration, as deduced from their measured magnetic moments [22]. The same ground-state spin-parity has been suggested for ^{73}Cu based on β-decay studies [2]. No prior spin assignment was made for ^{75}Cu. In this work we have established firm ground-state spins up to ^{75}Cu, illustrating the inversion from $I = 3/2$ to $I = 5/2$ in ^{75}Cu (upper panel of Fig. 3). With our spin 5/2 for the ^{75}Cu ground state and assuming negative parity, we can tentatively assign spins and parities to the lowest levels. The levels at 62 and 128 keV are isomeric [11] and from their half-lives and γ-decay properties the multipolarity of the 62 and 66 keV γ transitions was proposed to be most probably of mixed $E2/M1$ character. We therefore assign the level ordering $5/2^-$ (this hfs measurement), $3/2^-$, and $1/2^-$. This implies that the $\pi 2p_{3/2}$ and $\pi 1f_{5/2}$ single-particle levels are nearly degenerate at $N = 46$. It will be very interesting to study the excited states in the odd-odd Cu isotopes, where the coupling with the odd-neutron makes the level ordering very sensitive to the ordering of the proton single-particle levels.

Figure 3 also presents the calculated level schemes [25] based on an effective shell-model interaction fitted to experimental data in the region, as described in [8,9]. The calculation is performed in the fpg model space with ^{56}Ni as a core. The migration of the $5/2^-$ state in $^{69-75}$Cu and the inversion with the $3/2^-$ is correctly predicted. However, the lowering of the $1/2^-$ level is significantly underestimated in all of the available shell-model interactions for this region [4,7–10]. While the migration of the $5/2^-$ state is understood and explained in terms of the tensor interaction between nucleons in the $\pi 1f_{5/2}$ and $\nu 1g_{9/2}$ orbitals [4], the dramatic migration of the $1/2^-$ state requires an alternative mechanism. A hint can be found by comparing the experimental and theoretical magnetic moments (Fig. 4). An effective single-nucleon g_s factor ($g_s = 0.7 g_{s\,\mathrm{free}}$) is used which closely reproduces the ^{69}Cu value [26]. An increasing deviation between theory and experiment is found towards ^{73}Cu. A possible explanation could be an enhanced collectivity in the $3/2^-$ g.s. which is not properly accounted for. However, the small $B(E2)$ values for the $5/2^-$ decay to the $3/2^-$ ground states in ^{71,73}Cu [5] suggest that these ground states are not extremely collective. In the present calculation, already a significant part (30%) of the ^{73}Cu wave function contains a coupling to $\nu(2^+, 4^+)$ vibrational excitations, with 83% of the protons in the $\pi 2p_{3/2}$ orbital. The overestimation of the

TABLE I. Summary of the measured nuclear ground-state spins, magnetic moments, and hyperfine parameters. The magnetic moment of ^{71}Cu agrees well with previous β-NMR measurements $\mu = 2.28(1)$ [22].

Isotope	I	μ_{exp} (μ_N)	$A(^2S_{1/2})$ (MHz)	$A(^2P_{3/2})$ (MHz)	$B(^2P_{3/2})$ (MHz)
^{71}Cu	3/2	+2.2747(8)	+6002(2)	+199.6(8)	−25.3(14)
^{73}Cu	3/2	+1.7426(8)	+4598(2)	+152.4(3)	−26.5(10)
^{75}Cu	5/2	+1.0062(13)	+1593(2)	+53.0(9)	−36(2)

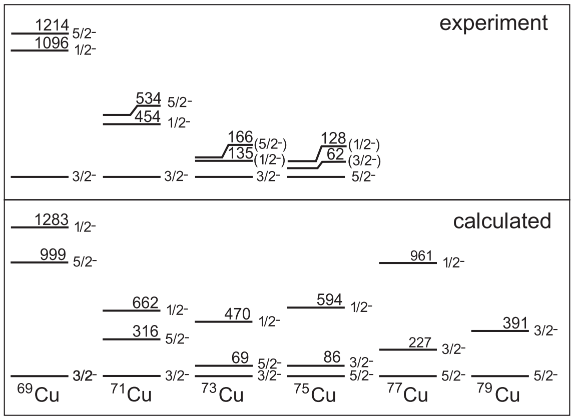

FIG. 3. Energy of the lowest levels from experiment [2,5,6] compared to large-scale shell-model calculation [25].

calculated ^{73}Cu moment is more likely related to the overestimated $1/2^-$ energy. Indeed, a lowering of the $\pi 2p_{1/2}$ single-particle energy would lower the calculated $1/2^-$ level energy, and would at the same time lead to a larger fraction of the $p_{1/2} \otimes \nu(2^+)$ configuration in the ground-state wave function. This would significantly lower the calculated magnetic moment.

The shell-model magnetic moment for ^{75}Cu compares closely with its experimental value. The ground-state wave function of ^{75}Cu is dominated by a proton in the $\pi 1f_{5/2}$ orbital (90%) yet with a significant fraction of the wave function coupled to the $\nu(2^+)$ vibrational excitations (36%). The rather collective nature of the ground state is further highlighted by the deviation from the effective Schmidt estimate of the magnetic moment (Fig. 4).

In summary the magnetic moments and spins of ^{71,73,75}Cu have been measured using a combination of collinear and in-source laser spectroscopy. A further lowering of the $5/2^-$ energy is established as it becomes the g.s. in ^{75}Cu. The g.s. spin and magnetic moment of ^{75}Cu are very well reproduced by a large-scale shell-model calculation based on a ^{56}Ni core. With a spectroscopic factor of 90% for the $\pi 1f_{5/2}$ orbit, the inversion between the $\pi 1f_{5/2}$ and $\pi 2p_{3/2}$ single-particle states in ^{75}Cu is established. Tentative spin assignments are made to the isomeric levels in ^{75}Cu, suggesting a further lowering of the $1/2^-$ energy as well. This trend is not reproduced by the current shell-model interactions. Also the calculated $3/2^-$ magnetic moments of ^{71,73}Cu are deviating progressively from the experimental value. These features together may indicate an underlying mechanism not well accounted for in the present shell-model interactions and call for further theoretical and experimental studies to investigate which are the physics mechanisms driving the evolution of the proton single-particle levels as the doubly magic ^{78}Ni is approached.

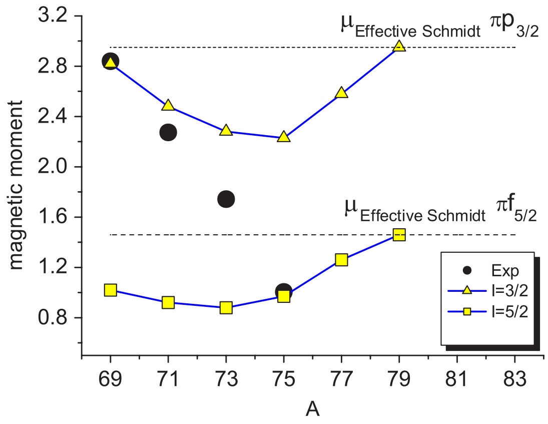

FIG. 4 (color online). Comparison of experimental $3/2^-$ and $5/2^-$ magnetic moments with shell-model calculations and effective Schmidt estimates using $g_s^{\mathrm{eff}} = 0.7 g_s^{\mathrm{free}}$ [25].

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