PHYSICAL REVIEW C **82**, 041302(R) (2010)

Experimental determination of an $I^{\pi} = 2^{-}$ ground state in ^{72,74}Cu

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(Received 20 August 2010; published 13 October 2010)

This article reports on the ground-state spin and moments measured in ^{72,74}Cu using collinear laser spectroscopy at the CERN On-Line Isotope Mass Separator (ISOLDE) facility. From the measured hyperfine coefficients, the nuclear observables $\mu(^{72}\text{Cu}) = -1.3472(10)\mu_N$, $\mu(^{74}\text{Cu}) = -1.068(3)\mu_N$, $Q(^{72}\text{Cu}) = +8(2)$ efm^2, $Q(^{74}\text{Cu}) = +26(3)$ efm^2, $I(^{72}\text{Cu}) = 2$, and $I(^{74}\text{Cu}) = 2$ have been determined. Through a comparison of the measured magnetic moments with different models, the negative moment reveals a strong $\pi f_{5/2} \otimes \nu g_{9/2}$ component in the ground-state wave function. Consequently, a negative parity has been assigned to the ground states of ^{72,74}Cu. Large-scale shell-model calculations illustrate the strong sensitivity of the nuclear moments to configuration mixing and to the effective interaction employed.

DOI: 10.1103/PhysRevC.82.041302 PACS number(s): 21.10.Ky, 21.10.Pc, 21.10.Hw, 27.50.+e

The neutron-rich nuclei surrounding the $Z = 28$ and $N = 50$ shell closures have received a great deal of experimental and theoretical attention in the last decade. This region presents a key proving ground for the latest shell-model interactions, since it offers an attractively simple structure of the excited states in terms of particle-particle or particle-hole couplings. A compelling question in this region is related to the rapid reduction in energy of the $5/2^-$ state as the $\nu g_{9/2}$ orbital is filled in the Cu isotopes [1,2]. Given that this state remains static at approximately 1 MeV as neutrons fill the fp shell, its abrupt change at $N = 40$ garnered a great deal of interest and motivated further experimental and theoretical attention [3–17]. A major step in understanding the evolution of nuclear structure in this region was the suggestion to include the monopole term from the tensor force interaction [18,19]. This work predicted a reduction in energy of the $5/2^-$ state and an inversion with the $3/2^-$ state in the mid-shell region, which was recently confirmed to occur at $N = 46$ in the odd-Cu isotopes [20]. Effective shell-model interactions which include this effect have recently been developed in the fpg model space. Two of these interactions start from a ^{56}Ni core [21,22], while the most recent one also includes excitations of protons from the $\pi f_{7/2}$ orbit across $Z = 28$ [23]. The odd-odd Cu isotopes are an ideal testing ground for these models, as their properties are extremely sensitive to the proton-neutron interaction.

Recent beta-decay studies of ^{72}Ni [8] have tentatively assigned a spin $I = 2$ to the ground state (gs) of ^{72}Cu. Shell-model calculations, based on effective and realistic interactions, could not reproduce such gs spin [8], but placed the 2^- and 2^+ states around 400 keV. A gs spin $I = 2$ is particularly interesting since the spins of ^{71,73}Cu now have been measured as $I = 3/2$, and their magnetic moments are compatible with a leading $\pi p_{3/2}$ configuration [20]. However, a $[\pi p_{3/2} \otimes \nu g_{9/2}^3, \ \sigma = 1]$ cannot couple to spin 2, so this configuration cannot be the leading term in the gs wave function of ^{72}Cu. Alternatively it could be dominated by $[\pi f_{5/2} \nu g_{9/2}^3]_{2-}$ or $[\pi p_{3/2} \nu p_{1/2}^{-1} \nu g_{9/2}^4]_{2+}$ or a collective $[\pi p_{3/2} \otimes \nu g_{9/2}^3, \sigma = 3]$ configuration. An observable that is particularly sensitive to which configuration dominates the gs wave function is the magnetic moment.

In this article, we report on laser spectroscopy measurements which have unambiguously measured the gs spin and the nuclear moments of ^{72,74}Cu. From the results, firm conclusions are drawn about the main component in their wave functions and on the parity of their ground states. The experiment used the collinear laser spectroscopy setup [24] at the CERN On-Line Isotope Mass Separator (ISOLDE) facility for high-resolution studies to fully resolve the hyperfine structure (hfs) of ^{72,74}Cu.

The $^2S_{1/2}$–$^2P_{3/2}$ transition (324.8 nm) in Cu was used in order to be sensitive to the nuclear spin. The radioactive isotopes were produced using a far-asymmetric fission reaction 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 tube, both heated to approximately 2000 °C to reduce transport time. The resonant ionization laser ion source (RILIS) was used to stepwise resonantly laser ionize the Cu atoms within the ionizer tube [25]. The ions produced were accelerated through 30 kV and mass separated by the high resolution separator (HRS) before they were injected into a radiofrequency quadrupolar (RFQ) linear gas-filled Paul trap (ISCOOL) [26], which was floated at about 100 V below the ion-source acceleration potential. The application of ion cooling and bunching in collinear laser spectroscopy has been demonstrated in Jyväskylä (Finland) [27]. The ions were trapped in ISCOOL for up to 100 ms and released as a bunch with a temporal width of 25 μs. The ion bunch and laser beam were subsequently overlapped in a copropagating direction. The ion bunch was neutralized by passing it through a sodium vapour cell heated to approximately 200 °C. A continuous wave dye laser was locked to a laboratory frame wave number of 15 406.9 373 cm^{-1} and frequency doubled in an external cavity. The atomic fluorescence resonances were located by applying a scanning voltage to the vapour cell and Doppler tuning the ions before neutralization. Two photomultiplier tubes (PMTs) were then used to measure the fluorescent photon yield as a function of the tuning voltage (see Fig. 1). By placing a gate on the signal, accepting photons only when an atom bunch was within the light-collection region, the background count rate associated with scattered light was reduced by more than three orders of magnitude.

Typical fluorescence spectra for ^{72}Cu and ^{74}Cu are shown in Fig. 2. A χ^2 minimization routine was used to fit Lorentzian profiles to the data, from which the hfs A and B coefficients are obtained for different values of the nuclear spin I. The observation of 6 transitions in both ^{72}Cu and ^{74}Cu immediately excludes $I = 1$ through angular momentum considerations. The ratio of the ground- and excited-state hfs A coefficient remains constant across the Cu isotope chain and is independent of the nuclear spin [20]. This permits a comparison of different spin options for ^{72}Cu and ^{74}Cu with the stable isotopes, which is shown in Fig. 3. In both ^{72}Cu and ^{74}Cu, a nuclear spin of $I = 2$ results in a ratio that is consistent with the stable isotopes. A nuclear spin of $I = 3$ (or higher) can be excluded with a confidence level of 4σ or higher for both cases. A and B coefficients for $I = 2$, along with

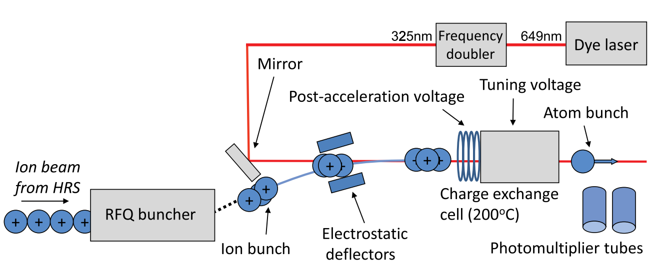

FIG. 1. (Color online) Schematic of the bunched-beam laser spectroscopy experimental setup at ISOLDE.

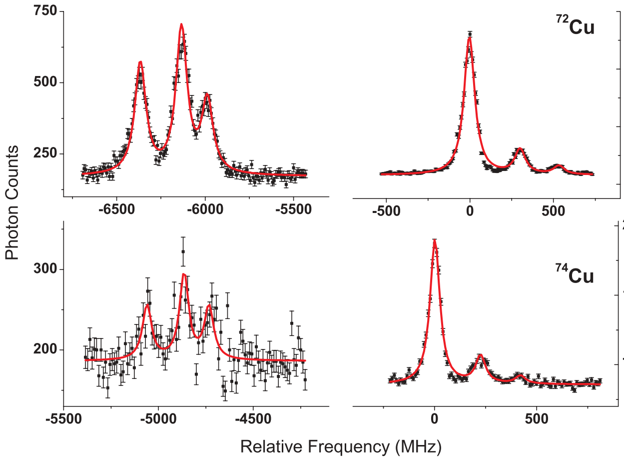

FIG. 2. (Color online) Resonance fluorescence spectra of ^{72,74}Cu measured using the bunched-beam technique that suppresses the background associated with scattered light and dark counts from the PMT.

deduced moments, are shown in Table I. The moments were deduced relative to ^{65}Cu, using $A(^2S_{1/2}) = 6\,284.405(5)$ MHz, $B(^2P_{3/2}) = -25.9(6)$ MHz, $\mu(^{65}\mathrm{Cu}) = +2.3817(3)\mu_N$, and $Q(^{65}\mathrm{Cu}) = -19.5(4)$ efm^2 [28–30].

Considering the single-particle proton and neutron orbits that play a role in this region, there are three possible configurations of protons and neutrons that can couple to form an $I = 2$ state in a seniority 1 scheme: $(\pi f_{5/2} \otimes \nu g_{9/2})_{2^-}$, $(\pi p_{3/2} \otimes \nu p_{1/2}^{-1})_{2^+}$, and $(\pi f_{5/2} \otimes \nu p_{1/2}^{-1})_{2^+}$. Interpretation of the measured magnetic moments can help to determine which of these three options is the leading configuration of the ground state and, consequently, what its parity is. Assuming weak coupling of protons and neutrons, and using the additivity rule for moments [31], the magnitude and sign of the magnetic moment for these three configurations is calculated. For the single proton and neutron configurations, respectively the free nucleon, effective, and empirical moments are used and the results are presented in Table II. Empirical single-particle moments are taken as the experimental moments of ^{73}Cu(3/2$^-$), ^{75}Cu(5/2$^-$), ^{71}Zn(9/2$^+$), and ^{67}Ni(1/2$^-$). Empirical moments of odd-odd isotopes closely agree with

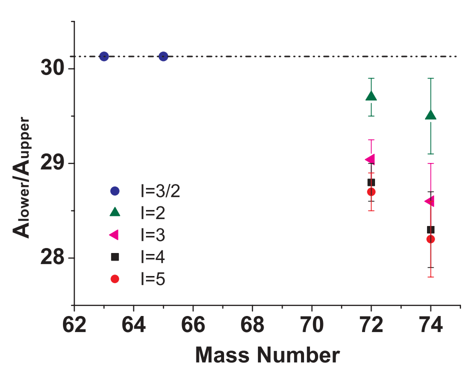

FIG. 3. (Color online) Plot of the hfs A coefficient ratio of the $^2S_{1/2}$ and $^2P_{3/2}$ states. The values for the stable isotopes ^{63,65}Cu are compared to the values obtained for ^{72,74}Cu using nuclear spin options $I = 2$, 3, 4, and 5 to fit observed spectra.

TABLE I. Summary of the measured gs hyperfine parameters of ^{72,74}Cu and deduced magnetic-dipole and electric-quadrupole moments.

Isotope	I	$A(^2S_{1/2})$ (MHz)	$A(^2P_{3/2})$ (MHz)	$B(^2P_{3/2})$ (MHz)	$\mu_{\rm expt}$ (μ_N)	Q (efm^2)
^{72}Cu	2	−2666(2)	−89.8(6)	+10(2)	−1.3472(10)	+8(2)
^{74}Cu	2	−2113(5)	−71.6(11)	+34(4)	−1.068(3)	+26(3)

their experimental values if the proposed configuration forms the leading term in the wave function. For both of the positive-parity configurations, the calculated moments have a positive sign. Therefore, the negative sign of the experimental magnetic moment rules out a positive parity gs configuration dominated by a $\nu p_{1/2}$ excited across $N = 40$. Conversely, the sign and magnitude of the calculated empirical moments for the $\pi f_{5/2} \otimes \nu g_{9/2}$ configuration closely matches the measured moments for ^{72,74}Cu and, therefore, a negative parity for both ground states is proposed.

The parity and the composition of the gs wave function can be further investigated by comparing the measured moments to shell-model calculations. The effective interactions by Brown *et al.* (jj44b) [22] and Honma *et al.* (JUN45) [21] have been used to perform large-scale shell-model (LSSM) calculations for $^{71-75}$Cu. Both LSSM calculations start from a ^{56}Ni core with a proton and neutrons in the $f_{5/2}pg_{9/2}$ orbits. The calculated energy levels are compared to the experimentally known levels in Fig. 4. Neither interaction predicts a gs $I^\pi = 2^+$ or 2^- in ^{72}Cu or ^{74}Cu, but both correctly reproduce the inversion of the $5/2^-$ and $3/2^-$ levels in the odd-Cu chain at ^{75}Cu. The two models predict the main features of the observed low-energy-level scheme in ^{72}Cu, having a high-level density. The low-spin levels in ^{72}Cu have been observed via β-decay from ^{72}Ni [8] and the high-spin levels are seen in the decay from a suggested (6^-) isomer [32]. No data are available for ^{74}Cu. The multiplets of states arising from the coupling of $(\pi p_{3/2} \otimes \nu g_{9/2})_{(3,4,5,6)^-}$ and $(\pi p_{3/2} \otimes \nu p_{1/2}^{-1})_{(1,2)^+}$, responsible for the observed isomerism in ^{68,70}Cu [7,33,34], appear at low energy in the calculations for ^{72,74}Cu. The lowest 2^- level appears below 250 keV in both isotopes and with both interactions, while the 2^+ state appears a few 100 keV higher.

The calculated nuclear moments for the two lowest 2^+ and 2^- levels, along with their energy, are summarized in Table III for jj44b and in Table IV for JUN45. Magnetic moments have been calculated using the effective value $g_s = 0.7g_s^{\rm free}$ and for quadrupole moments the effective charges $e_\pi^{\rm eff} = 1.5e$ and $e_\nu^{\rm eff} = 1.1e$ are used for JUNE45 [21] and $e_\pi^{\rm eff} = 1.4e$ and $e_\nu^{\rm eff} = 1.0e$ for jj44b [35]. For each level, the occupancy of the leading proton configuration is given. All positive-parity states have a positive magnetic moment, in disagreement with experiment (first line in each table). With the jj44b interaction, the calculated magnetic and quadrupole moment of the lowest 2^- state in ^{72}Cu and ^{74}Cu are in rather good agreement with experiment (bold), confirming that the wave function of these levels, calculated at about 200 keV in both isotopes, is close to the gs wave function. Both are dominated by a proton in the $\pi f_{5/2}$ orbit. The leading neutron term has an odd neutron in the $\nu g_{9/2}$ level, confirming our conclusion based on the weak coupling. With the JUN45 interaction, the lowest 2^- level in ^{72}Cu is dominated by a $\pi p_{3/2}$, and its moments do not agree with the observed values. The second 2^- state, calculated at 645 keV, has moments that both agree very well with the observed values, suggesting that its wave function represents very well the observed gs. Its proton occupation in the $\pi f_{5/2}$ orbit is similar to that for the lowest 2^- from jj44b; thus, it is small differences in the neutron occupation which lead to a slightly better agreement of the moments with experiment. Note that the calculated energy of this level is about 600 keV

TABLE II. Summary of magnetic moments calculated using the additivity rule for free nucleon moments, effective moments ($g_s = 0.7g_s^{\rm free}$), and empirical moments, which are to be compared to the measured moments for ^{72}Cu[$-1.347(1)\mu_N$] and ^{74}Cu[$-1.068(3)\mu_N$].

Configuration	I	$\mu_{\rm free}$ (μ_N)	$\mu_{\rm effective}$ (μ_N)	$\mu_{\rm empirical}$ (μ_N)
$\pi f_{5/2} \otimes \nu g_{9/2}^3$	2^-	−2.13	−2.06	−1.53($\langle^{75}$Cu, ^{71}Zn$\rangle$)
$\pi p_{3/2} \otimes \nu p_{1/2}^{-1} g_{9/2}^4$	2^+	+4.43	+3.40	+2.35($\langle^{73}$Cu, ^{67}Ni$\rangle$)
$\pi f_{5/2} \otimes \nu p_{1/2}^{-1} g_{9/2}^4$	2^+	+0.380	+1.07	+0.536($\langle^{75}$Cu, ^{67}Ni$\rangle$)

TABLE III. Moments from shell-model calculations using the jj44b interaction for the lowest $I^\pi = 2^\pi$ compared to experimental moments.

Isotope	I^π	E(keV)	Leading proton configuration	%	μ (μ_N)	Q (efm^2)
^{72}Cu	2	0			−1.3472(10)	+8(2)
	2^-	**211**	$\pi f_{5/2}$	**72**	**−1.543**	**+15**
	2^-	784	$\pi p_{3/2}$	69	−2.058	−10
	2^+	538	$\pi f_{5/2}$	79	+1.027	−24
	2^+	640	$\pi p_{3/2}$	73	+1.616	−23
^{74}Cu	2	0			−1.068(3)	+26(3)
	2^-	**208**	$\pi f_{5/2}$	**67**	**−1.418**	**+20**
	2^-	1121	$\pi p_{3/2}$	58	−1.409	+11
	2^+	517	$\pi f_{5/2}$	80	+1.098	−18
	2^+	754	$\pi p_{3/2}$	49	+0.045	+21

TABLE IV. Moments from shell-model calculations using the JUN45 interaction compared to experiment.

Isotope	I^π	E(keV)	Leading proton configuration	%	μ (μ_N)	Q (efm^2)
^{72}Cu	2	0			−1.3472(10)	+8(2)
	2^-	263	$\pi p_{3/2}$	71	−2.47	−12
	2^-	**645**	$\pi f_{5/2}$	**69**	**−1.42**	**+5**
	2^+	367	$\pi p_{3/2}$	85	+2.29	−15
	2^+	978	$\pi p_{5/2}$	81	+0.76	−25
^{74}Cu	2	0			−1.068(3)	+26(3)
	2^-	**44**	$\pi f_{5/2}$	**63**	**−1.74**	**+15**
	2^-	859	$\pi p_{3/2}$	56	−1.63	+8
	2^+	408	$\pi p_{3/2}$	53	+1.73	−14
	2^+	621	$\pi f_{5/2}$	64	+1.25	−26

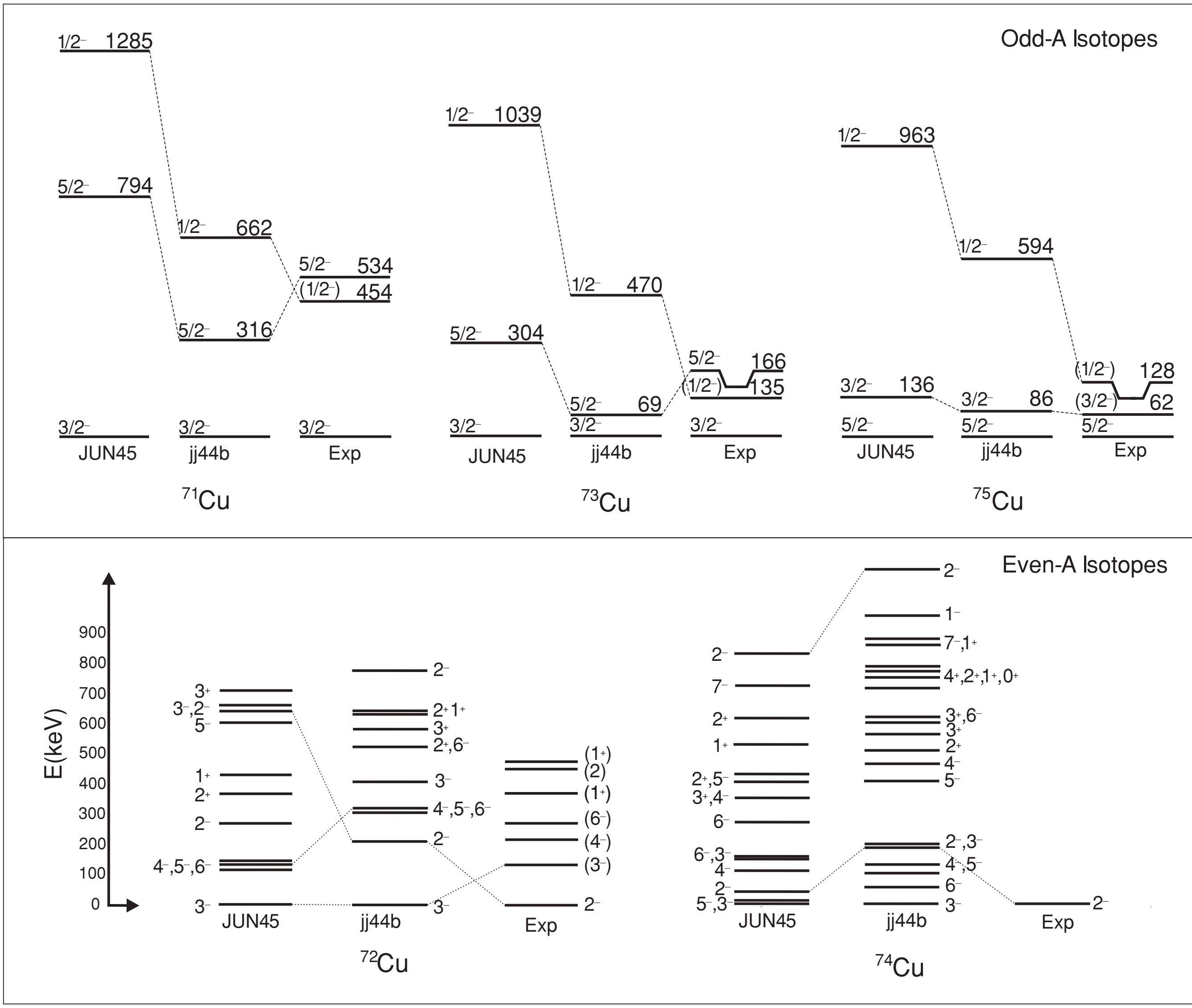

FIG. 4. Comparison of the trend in energy of the lowest states between large-scale shell-model calculations [21,22] and experiment [2,8,12,13,32].

too high, which provides information on how to improve on the relative effective single particle proton energies. In the case of ^{74}Cu, the agreement is best for the lowest 2^- state, also having a wave function dominated by protons in $\pi f_{5/2}$. In this case, the agreement is better for jj44b than for JUN45. These results show that nuclear moments are a very sensitive probe of the wave function of a nuclear state, allowing a calculated level to be assigned to an observed state.

The inferior agreement of the JUN45 ^{74}Cu moments with experiment might be associated with the $1/2^-$ state in ^{71,73,75}Cu (top of Fig. 4), which is calculated at an excessively high energy. The experimentally observed rapid decrease of the $1/2^-$ energy [16,20] is reasonably well reproduced with jj44b. Best agreement of the odd-Cu 1/2, 3/2, 5/2 energy levels with experiment has been obtained with a recently published effective interaction that includes excitations of protons across the $N = 28$ shell gap [23]. With this interaction, the steep decrease in the magnetic moments of the $3/2^-$ ground states from ^{69}Cu to ^{73}Cu is also well reproduced. It will be interesting to see how well this interaction reproduces the moments of the odd-odd Cu isotopes, in order to probe the importance of proton excitations in this region.

In conclusion, neither of the shell-model interactions nor the calculations based on the additivity rule for coupling nucleons predict an $I^\pi = 2^+$ state with a negative magnetic moment for these isotopes. Conversely, all the calculations for an $I^\pi = 2^-$ state reported in this article predict a negative magnetic moment, with a value that is in rather good agreement with the experimentally observed value. Therefore, it can be concluded that the ground states of ^{72}Cu and ^{74}Cu both have negative parity, associated with a dominant $\pi f_{5/2} \otimes \nu g_{9/2}$ configuration. This shows that, already from $N = 43$ onwards, the $\pi f_{5/2}$ level is playing a dominant role in the gs wave function of the odd-odd isotopes because of the strong $\pi f_{5/2} \nu g_{9/2}$ interaction. The LSSM calculations with effective interactions starting from a ^{56}Ni core reproduce the observed magnetic and quadrupole moments reasonably well, but fail to get the 2^{-} level as the ground state.

This work has been supported by the German Ministry for Education and Research (BMBF) under Contract No. 06MZ215, the UK Science and Technology Facilities Council (STFC), the FWO-Vlaanderen (Belgium), EU Sixth Framework through No. Eurons-506065, BriX IAP Research Program No. P6/23 (Belgium), the Helmholtz Association of German Research Centres (VH-NG-037 and VH-NG-148), the Max-Planck Society and NSF grant PHY-0758099. M. Kowalska was supported by the EU (MEIF-CT-2006-042114). We would like to thank the ISOLDE technical group for their support and assistance during this project.

[1] S. Franchoo *et al.*, Phys. Rev. Lett. **81**, 3100 (1998).
[2] S. Franchoo *et al.*, Phys. Rev. C **64**, 054308 (2001).
[3] A. M. Oros-Peusquens and P. F. Mantica, Nucl. Phys. A **669**, 81 (2000).
[4] N. A. Smirnova, A. De Maesschalck, A. Van Dyck, and K. Heyde, Phys. Rev. C **69**, 044306 (2004).
[5] A. F. Lisetskiy, B. A. Brown, M. Horoi, and H. Grawe, Phys. Rev. C **70**, 044314 (2004).
[6] A. Lisetskiy, B. Brown, and M. Horoi, Eur. Phys. J. A **25**, 95 (2005).
[7] J. Van Roosbroeck *et al.*, Phys. Rev. Lett. **92**, 112501 (2004).
[8] J.-C. Thomas *et al.*, Phys. Rev. C **74**, 054309 (2006).
[9] C. Guénaut *et al.*, Phys. Rev. C **75**, 044303 (2007).
[10] S. Rahaman *et al.*, Eur. Phys. J. ST **150**, 349 (2007).
[11] N. J. Stone *et al.*, Phys. Rev. C **77**, 014315 (2008).
[12] I. Stefanescu *et al.*, Phys. Rev. Lett. **100**, 112502 (2008).
[13] I. Stefanescu *et al.*, Phys. Rev. C **79**, 044325 (2009).
[14] N. Patronis *et al.*, Phys. Rev. C **80**, 034307 (2009).
[15] S. V. Ilyushkin *et al.*, Phys. Rev. C **80**, 054304 (2009).
[16] J. M. Daugas *et al.*, Phys. Rev. C **81**, 034304 (2010).
[17] B. Cheal *et al.*, Phys. Rev. Lett. **104**, 252502 (2010).
[18] T. Otsuka, T. Suzuki, R. Fujimoto, H. Grawe, and Y. Akaishi, Phys. Rev. Lett. **95**, 232502 (2005).
[19] T. Otsuka *et al.*, Phys. Rev. Lett. **104**, 012501 (2010).
[20] K. T. Flanagan *et al.*, Phys. Rev. Lett. **103**, 142501 (2009).
[21] M. Honma, T. Otsuka, T. Mizusaki, and M. Hjorth-Jensen, Phys. Rev. C **80**, 064323 (2009).
[22] B. Brown and A. Lisetskiy (private communication).
[23] K. Sieja and F. Nowacki, Phys. Rev. C **81**, 061303 (2010).
[24] A. Mueller *et al.*, Nucl. Phys. A **403**, 234 (1983).
[25] U. Köster *et al.*, Nucl. Instrum. Methods B **160**, 528 (2000).
[26] E. Mané *et al.*, Eur. Phys. J. A **42**, 503 (2009).
[27] P. Campbell *et al.*, Eur. Phys. J. A **15**, 45 (2002).
[28] Y. Ting and H. Lew, Phys. Rev. **105**, 581 (1957).
[29] J. Ney, Z. Phys. A **196**, 53 (1966).
[30] P. Raghavan, At. Data Nucl. Data Tables **42**, 189 (1989).
[31] G. Neyens, Rep. Prog. Phys. **66**, 633 (2003).
[32] H. Mach, in *Proceedings of the International Symposium on Nuclear Structure Physics* (World Scientific, Singapore, 2001; Göttingen, Germany, 2001), p. 379.
[33] L. Weissman *et al.*, Phys. Rev. C **65**, 024315 (2002).
[34] K. Blaum *et al.*, Europhys. Lett. **67**, 586 (2004).
[35] P. Vingerhoets *et al.* (to be published).