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In-Source Laser Spectroscopy of ^{75,77,78}Cu: Direct evidence for a change in the quasi-particle energy sequence in ^{75,77}Cu and an absence of longer-lived isomers in ^{78}Cu.

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This paper describes measurements on the isotopes ^{75,77,78}Cu by the technique of in-source laser spectroscopy, at the ISOLDE facility, CERN. The role of this technique is briefly discussed in the context of this and other, higher resolution, methods applied to copper isotopes in the range $^{57-78}$Cu. The data, analysed in comparison with previous results on the lighter isotopes ^{59,63}Cu, establish the ground-state nuclear spin of ^{75,77}Cu as 5/2 and yield their magnetic dipole moments as +1.01(5) μ_N and +1.61(5) μ_N respectively. The results on ^{78}Cu show no evidence for long lived isomerism at this mass number and are consistent with a spin in the range 3-6 and moment of 0.0(4) μ_N.

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I. INTRODUCTION

A compelling question in nuclear physics relates to the evolution of shell structure with neutron and proton excess. There is a growing body of evidence that the well-defined shell closures present in nuclei close to the valley of stability, do not necessarily persist in exotic nuclei with extreme ratios of N/Z. Such changes would have profound implications, not only in the field of nuclear physics but also astrophysics [1]. This has helped motivate the continuous advancement in radioactive beam facilities and experimental nuclear physics. The copper isotope chain ($Z = 29$) represents a unique opportunity to study the evolution of shell structure, with one proton outside the closed proton shell of $Z = 28$ and an isotope chain that crosses the major closures $N = 28, 50$. A series of experiments have been undertaken studying β-decay and Coulomb excitation on neutron-rich nickel and copper isotopes, which measured a rapid reduction in the energy of the $5/2^-$ and $1/2^-$ states in ^{71,73}Cu [2–4]. This could be understood by the monopole term of the residual interaction between the proton and neutron, which causes a reduction in energy of the proton $\pi f_{5/2}$ level as the $\nu g_{9/2}$ orbital is filled. A tensor type interaction predicted that the $5/2^-$ state would invert with the $3/2^-$ ground state at N=46. This motivated a series of laser spectroscopy experiments to measure the ground-state spins and moments of the neutron rich copper isotopes. Using a combination of in-source and Collinear Fast Beam Laser Spectroscopy (CFBLS) the spin of ^{75}Cu was directly measured to be 5/2 [5]. Through a comparison of the magnetic moment to shell model calculations using the JUN45 [6] and jj44b [7] interactions, this previous work concluded that the ground-state wave function is almost a pure single-particle in the $\pi f_{5/2}$ orbital. The same shell-model calculations predict that ^{77,79}Cu will have a similar single particle configuration of $\pi f_{5/2}$ for their ground states. Both of these interactions use a ^{56}Ni core and hence cannot account for particle excitations from the $f_{7/2}$ orbital, which may become important as $N = 50$ is approached. Two recent β-decay spectroscopy experiments on ^{77}Cu [8, 9] have both tentatively assigned $I^\pi = 5/2^-$ to the ground state. Although neither of these papers identified an isomeric state in ^{77}Cu, they could not rule out this possibility. Decay spectroscopy of ^{78}Cu has identified a substantial β feeding of the excited 6^+ state in ^{78}Zn [10, 11]. This result is difficult to reconcile with a 5^- ground state for ^{78}Cu assigned from the feeding of just the 4^+ and 2^+ state in ^{78}Zn [12, 13]. The recent study by Gross *et al.* [11], which combined their new observations with the theoretical analysis of Ref. [12], concluded a 6^- ground state arising from a coupling of $\pi f_{5/2} \otimes \nu g_{9/2}$. Neither studies can rule out the existence of a low energy isomeric state in ^{78}Cu, which could also explain the difference between the two results.

This paper reports in-source laser spectroscopy on ^{75,77,78}Cu, which measured the spins and magnetic moments. This technique has been proved to be very sen-

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sitive and has allowed measurements to be performed down to yields of less than 1 atom/s [14, 15]. At the ISOLDE isotope separator facility, CERN, the technique has benefited greatly from the continuous development of the laser ion source (RILIS) [16, 17], allowing it to be applied to lead [18–20], polonium [15, 21] and copper [22, 23]. Due to the relatively low resolution of the in-source technique (limited by thermal Doppler broadening to ~ 4 GHz for Cu) previous work has not directly measured the nuclear spin of copper from the hyperfine structure. The measured nuclear moments have therefore relied on spin assignments deduced from decay data [12]. The relative intensities of the hyperfine transitions are determined by the coupling of the electronic and nuclear angular momenta and therefore can also be used for spin determination. This paper presents the first example of the measurement of the nuclear spin from the relative intensities of the hyperfine transitions using in-source laser spectroscopy. A re-evaluation of the in-source data of ^{70}Cu by Gheysen textitet al. [24] using a dressed-atom approach indicated that there was also sensitivity to the nuclear spin in the ground and isomeric states. Laser spectroscopy also allows unambiguous identification of long-lived isomeric states and can be particularly sensitive to low-lying isomers with comparable lifetimes to that of the ground state. This has been highlighted by the recent discovery of an isomer in ^{80}Ga [25]. This paper also reports on the limits for excluding isomers in ^{77,78}Cu.

II. EXPERIMENTAL DETAILS

The experiment was carried out at the ISOLDE facility, using the in-source laser spectroscopy method described in Ref [26, 27]. The pulsed beam of 1.4 GeV protons was incident upon a 46 g/cm^2 UC$_x$ target. Radioisotopes produced by spallation or fission diffused out of the 2100 °C hot target to the approximately 2000 °C hot tantalum ionizer cavity.

Two laser beams at 327.4 nm and 287.9 nm wavelength interacted with copper atoms in the ionizer cavity. The 327.4 nm photon excites the atom from the $3d^{10}4s$ ($^2S_{1/2}$) ground state to the $3d^{10}4p$ ($^2P_{1/2}$) state and the 287.9 nm photon excites the atom to the $3d^94s5s$ ($^2D_{3/2}$) auto-ionizing state. The produced ions were subsequently accelerated to 30 keV and mass separated. The first excitation step used a narrow-band laser (1.2 GHz linewidth), which was tuned across the hyperfine structure of the 327.4 nm transition. The mass-separated ions were implanted into a tape in the center of the Mainz neutron long counter [28]. The latter consists of a polyethylene matrix to moderate β-delayed neutrons to thermal energies and was filled with 50 ^{3}He tubes for efficient detection of β-delayed neutrons. The timing signals of the three rings of neutron counters were combined and fed into an eight-input multichannel scaler (module 7884 from Fast Comtec) that can handle data rates above 1 MHz. It was read out by a MPA2 DAQ from Fast Comtec. For calibration, the entire acquisition system was tested at up to two orders of magnitude higher data rates (using abundant rubidium and caesium isotopes) but showed no significant dead time effects. Selective detection of beta-delayed neutrons was used to discriminate against the high background of surface ionized isobaric gallium and rubidium ions present in the beam extracted from the separator [29]. The laser frequency was measured with an ATOS LM007 wavemeter with a long term accuracy of 0.003 cm^{-1} ($\sim$90 MHz). In order to remove systematic errors such as laser drift, the frequency settings were chosen in a random sequence rather than simply rising or falling across the search range. The measurement time per data point was between 30 and 60 s, during which time the laser frequency was constantly monitored by the wavemeter (with a 20 Hz monitoring rate). The results exhibit no evidence of drift, additionally the data set shows a consistent line shape for all measured isotopes.

III. NUCLEAR SPIN DETERMINATION WITH IN-SOURCE LASER SPECTROSCOPY.

In-source laser spectroscopy has been extensively used to measure the hyperfine structure and isotope shifts and allows nuclear-model independent determination of the moments and changes in mean square charge radius. The electron states involved in the measurement were the $3d^{10}4s$ ($^2S_{1/2}$) and the $3d^{10}4p$ ($^2P_{1/2}$). There are a total of four transitions between hyperfine levels of these states, for $I > 1/2$ (there are three transitions in the case of $I = 1/2$ and only one for $I = 0$), with a hyperfine energy splitting given by,

$$E_F/h = \frac{1}{2}A(F(F+1) - I(I+1) - J(J+1)), \quad (1)$$

where J is the total electronic angular momentum and the quantum number F arises from the vector coupling of I and J. Since both atomic states have $J = 1/2$ the contribution from the quadrupole interaction will vanish. The A factor for each atomic state is related to the nuclear magnetic dipole moment by

$$A = \frac{\mu B_J}{hIJ}, \quad (2)$$

where μ is the magnetic moment and B_J is the electronic magnetic field at the nucleus. The small observed hyperfine anomaly in the stable copper isotopes of $^{63}\Delta^{65} = 4.7(2) \times 10^{-5}$ [30] and $^{59}\Delta^{69} = 12(17) \times 10^{-4}$ [31]) is negligible with respect to the resolution of in-source laser spectroscopy. This result permits the ratio of the A-factors for the $4p$ and $4s$ state to be held constant across the isotope chain at 0.086, which is also independent of the nuclear spin. Despite limitations in the resolution of the system, due to the Doppler width associated with the ion source (3.8 GHz) and also with possible power broadening caused by saturation of the resonant transition, the previous experiments showed that, although the closer pairs of transitions associated with the hyperfine-split $4p$ states are not resolved, fitting the energy splitting of the two doublet peaks observed can yield values of the magnetic moment to a precision of a few percent.

Although the hyperfine structure of a $^2S_{1/2} -^2 P_{1/2}$ transition is not sensitive to I, the relative intensities of the two doublets can be used to determine this observable. To a first approximation the relative intensities of the transitions are in proportion to the statistical weights $(2F+1)$ of the hyperfine split ground state, which leads, (for the present case, $F = I \pm 1/2$) to a predicted intensity ratio $(I+1)/I$ between the resolved doublets. The sensitivity diminishes with increasing I as this ratio tends to unity, and the previous examples, in ^{70}Cu, related to spins 3 and 6, hence ratios 1.33 and 1.17, while for the spins 3/2 and 5/2 the ratios are 1.67 and 1.40, making positive identification easier.

The above analysis does not take into account many effects that will considerably alter the relative intensities. The laser-atom interaction time of ∼15 ns allows at least one excitation and decay cycle to occur. This spontaneous decay of the excited state can populate the other hyperfine level of the $^2S_{1/2}$ state, optically pumping the atomic population. This will alter the relative intensities and therefore has been included in the analysis presented here. A second more subtle effect relates to the coherent excitation of the atom in an intense light field, which is required to efficiently ionize an atomic ensemble. Under such conditions, multi-photon processes cannot be ignored. Coherent effects such as coupling of hyperfine states through the continuum will further alter relative intensities as well as the profile shape [32]. The analysis presented here has used the dressed atom approach presented by Gheysen textitet al. [24] to describe the ionization process. The stable isotopes ^{63,65}Cu were measured under the same laser power conditions as the radioactive isotopes. This allowed these coherent effects to be accounted for and included in the analysis of the radioactive species. By considering these effects in the analysis as well as careful monitoring of the separation between proton pulses and their intensity and the laser intensity during the run it is possible to confidently extract the nuclear spin from the resonant ionization spectra.

IV. RESULTS

Analysis of the data on the ground states of ^{75,77,78}Cu was made using the computer code of Gheysen [24] in which the Doppler width Γ of the transition, the laser power of the resonant step P, and ionization rate I associated with the second laser step were all input parameters. The laser power was monitored during the run and did not change markedly during a measurement. The fitting routine varied the A factor and the isotope shift $\delta\nu^{A'A}$ and minimized χ^2. In addition to the data taken in this run, re-analysis of the data recorded on ^{59,63}Cu [22] was used as a double check for the ability to measure the nuclear spin from the relative intensities. All plots presented in this paper are shown relative to a central wavenumber of 30535.0 cm^{-1}. The best fit values for all parameters are given in Table I as well as those found in analyses of previous experiments.

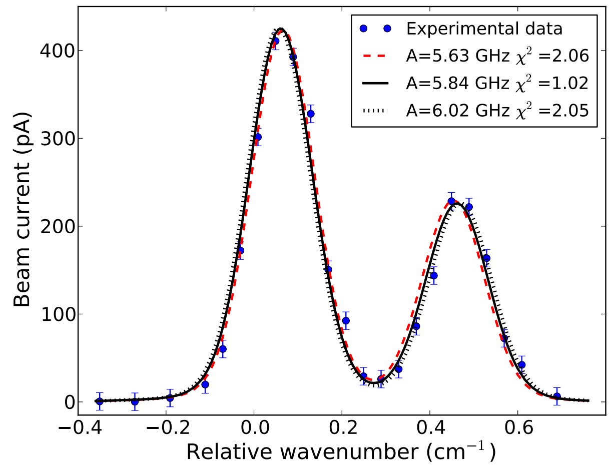

FIG. 1: (Color online) Best fit for ^{63}Cu.

Isotopes ^{59,63}Cu both have $I = 3/2$ and in Fig. 1 and Fig. 2 the best fits to the data are shown, assuming this spin value. The best fit parameters are given in Table I. The laser and ion source parameters (discussed more fully below) show that the broadening derives mainly from the ion source Doppler width, which contributes more than 80% of the total line width.

The magnetic moments were deduced from the measured A factor values, given in Table I, by using Eq. 2 and taking the ratio with a reference isotope, in this case ^{63}Cu with, $I = 3/2$, $\mu = +2.2273456(14)\ \mu_{\rm N}$ [44] and $A(^2S_{1/2}) = 5.866908706$ GHz [45]. A summary of the magnetic moments is given in Table II. The moment value for ^{63}Cu, 2.22(9) $\mu_{\rm N}$ is in full agreement with the literature value [44]. The value found for ^{59}Cu, 1.84(3) $\mu_{\rm N}$ was used in a later experiment to assist search for NMR/ON resonance in that isotope, which gave the more accurate, but consistent, moment 1.891(9) $\mu_{\rm N}$ [35]. In the present analysis and that of Ref. [22], the χ^2 hyperspace has been used to extract errors on the A factor and the isotope shift $\delta\nu^{A',63}$ with the laser parameters held at values determined by the fitting to the reference isotope ^{63}Cu. The result for ^{59}Cu was a first measurement and was subsequently found to be within 3% of the NMR/ON resonance value. The data on all isotopes ^{59,63,75,77}Cu show similar resolution of the two peaks, leading to sim-

TABLE I: Experimental in-source data best fit parameters of copper isotopes.

Isotope	I	$A(^2S_{1/2})$ (GHz)	Laser power P (W/m^2)	Ionisation rate Γ(GHz)	Doppler width D(GHz)	$\delta\nu^{A',63}$ (GHz)	$\chi^2_{\rm min}$
^{59}Cu	3/2	4.87(8)	7300	0.27	4.4	+1.14(21)	1.07
^{63}Cu	3/2	5.84(10)	7300	0.27	4.25	+0.58(8)	1.02
^{75}Cu	1/2	5.39(28)	6300	0.21	3.8		
	3/2	2.48(12)	6300	0.21	3.8		27.0
	5/2	1.60(8)	6300	0.21	3.8	−2.34(27)	4.3
	7/2	1.21(6)	6300	0.21	3.8		7.8
^{77}Cu	1/2	7.74(41)	6300	0.21	3.8		
	3/2	3.86(20)	6300	0.21	3.9		14.1
	5/2	2.55(13)	6300	0.21	3.9	−2.70(33)	5.0
	7/2	1.88(10)	6300	0.21	3.9		7.8
^{78}Cu	(6)	0.0(4)	6300	0.21	3.8	−3.03(39)	

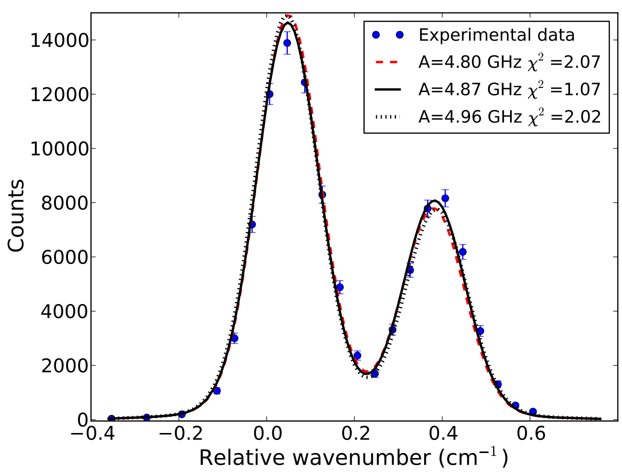

FIG. 2: (Color online) Best fit for ^{59}Cu.

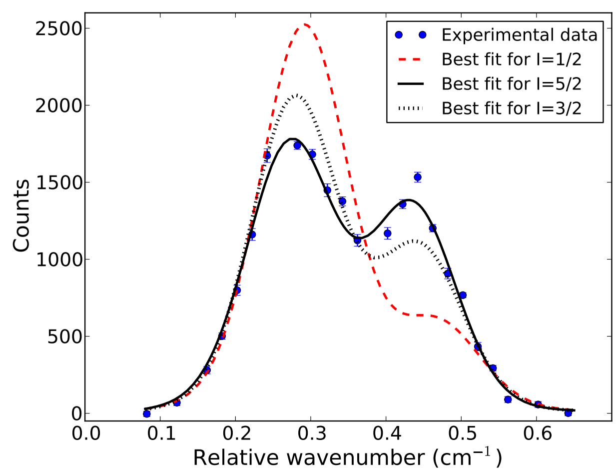

FIG. 3: (Color online) Hyperfine spectrum for ^{75}Cu showing the best fits for $I = 1/2, 3/2$ and $5/2$. A ground-state spin of $I = 5/2$ is favoured.

ilar error estimates of a few percent in all cases.

The best fits for each ground-state spin hypothesis for ^{75}Cu are shown in Fig. 3. By comparing the χ^2 values for the fits to ^{75}Cu (Table I), it is possible to exclude a ground state $I = 1/2, 3/2$ with a level of confidence of better than 5σ in both cases. A spin of $I = 7/2$ can also be excluded with a level of confidence of 3.9σ. The best fit values for these, (D = 3.8 GHz, P = 6300 W/m^2), are smaller than in previous the experiment [22] on ^{63,59,58}Cu (D = 4.5 GHz, P = 7200 W/m^2), since the nuclear mass is increased and the laser power was reduced to eliminate power broadening. When P and D were allowed to vary the best fit values changed very little from the $I = 5/2$ best fit. The $\delta\nu^{A'A}$ showed little change with change of spin, as expected with this experimental precision. A value of $A(S_{1/2}) = 1.60(8)$ GHz, was determined, which is in agreement with the high resolution measurement of 1.593(2) GHz [5].

For both ^{77,78}Cu a scan region of 30 GHz was used to search for additional hyperfine structure components associated with an isomeric state. The spectrum for ^{77}Cu is shown in Fig. 4 with best fits for ground-state spins of $I = 1/2$, 3/2 and 5/2. Again the peak intensity ratio identifies $I = 5/2$ and excludes $I = 3/2$ with a confidence of better than 5σ and $I = 7/2$ can be excluded with a confidence level of 4σ. The hyperfine splitting, $A = 2.55(13)$ GHz, is approximately 1.6 times larger than for ^{75}Cu. There was no evidence of additional hyperfine components in a wide scan of the structure, suggesting that there is no long lived isomeric state in ^{77}Cu, at least none that emits β-delayed neutrons. Given the very large energy window for β-delayed neutron emission ($Q_{\beta n} = 5.9(5)$ MeV for $Q_\beta = 10.5(5)$ MeV [46]) leading to a non-negligible probability of β-delayed neutron emission. This result corresponds effectively to a severe limit on the presence of β decaying isomers with half-

TABLE II: Experimental values of ground and isomeric state magnetic moments of copper isotopes. Results from in-gas cell laser spectroscopy are labelled as IGC Laser and from in-source laser spectroscopy as IS Laser. Results from βNMR on oriented nuclei are labelled as βNMR/ON.

Mass	N	I^π	$\mu_{\rm exp}$ (μ_N)	Method	Ref.
57	28	3/2-	+2.582(7)	IGC Laser	[33]
59	30	3/2-	+1.8910(9)	CFBLS	[34]
59	30	3/2-	+1.891(9)	βNMR/ON	[35]
59	30	3/2-	+1.84(3)	IS Laser	[22]
59	30	3/2-	+1.910(4)	IGC Laser	[33]
61	32	3/2-	+2.1083(5)	CFBLS	[34]
63	34	3/2-	+2.2273456(14)	NMR	[36]
63	34	3/2-	+2.22(9)	IS Laser	[22]
65	36	3/2-	+2.3816(2)	NMR	[36]
65	36	3/2-	+2.35(11)	IS Laser	[24]
67	38	3/2-	+2.54(2)	βNMR/ON	[37]
67	38	3/2-	+2.5142(6)	CFBLS	[38]
69	40	3/2-	+2.84(1)	βNMR/ON	[39]
69	40	3/2-	+2.8383(10)	CFBLS	[38]
71	40	3/2-	+2.28(1)	βNMR/ON	[40]
71	42	3/2-	+2.2747(8)	CFBLS	[5]
73	44	3/2-	+1.7426(8)	CFBLS	[5]
75	46	5/2-	+1.0062(13)	CFBLS	[5]
75	46	5/2-	+1.01(5)	IS Laser	this work
77	48	5/2-	+1.61(5)	IS Laser	this work
58	29	1+	+0.52(8)	IS Laser	[22]
58	29	1+	+0.570(2)	CFBLS	[34]
58	29	1+	+0.479(13)	IGC Laser	[41]
60	31	2+	+1.2186(5)	CFBLS	[34]
60	31	2+	+1.219(3)	NMR	[42]
62	33	1+	-0.3796(4)	CFBLS	[34]
64	35	1+	-0.2164(4)	CFBLS	[38]
66 g	37	1+	+0.2823(8)	CFBLS	[38]
68 g	39	1+	+2.55(8)(19)	IS Laser	[24]
68 g	39	1+	+2.3933(6)	CFBLS	[38]
68 m	39	6-	+1.26(7)(55)	IS Laser	[24]
68 m	39	6-	+1.1548(6)	CFBLS	[38]
70 g	41	6-	+1.58(9)(57)	IS Laser	[24]
70 m1	41	3-	-3.54(8)(34)	IS Laser	[24]
70 m2	41	1+	+1.89(4)(14)	IS Laser	[24]
70 g	41	6-	+1.3666(5)	CFBLS	[38]
70 m1	41	3-	-3.3641(15)	CFBLS	[38]
70 m2	41	1+	+1.7779(15)	CFBLS	[38]
72	43	2-	-1.3472(10)	CFBLS	[43]
74	45	2-	-1.068(3)	CFBLS	[43]
78	49	(6-)	0(4)	IS Laser	this work

lives larger than 0.1 s. Higher resolution measurements combined with a dedicated decay spectroscopy experiment would be required to completely exclude an isomeric state. The spectrum of ^{78}Cu resolved just a single resonance on a flat background (see Fig. 5), without evidence of additional structure associated with the presence of an isomeric state. In the case of ^{78}Cu there is also a large energy window for β-delayed neutron emission ($Q_{\beta n}$ = 6.2(5) MeV for Q_β = 13.0(5) MeV [46]) leading to a non-negligible probability of β-delayed neutron emission. The single peak did not show significant asymmetry, and corresponds to a small magnetic mo-

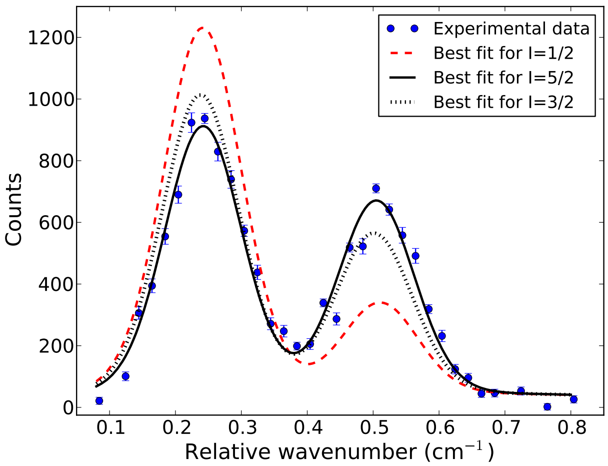

FIG. 4: (Color online) Best fits for ^{77}Cu for $I = 1/2, 3/2$ and $5/2$. A ground-state spin of $I = 5/2$ is favoured.

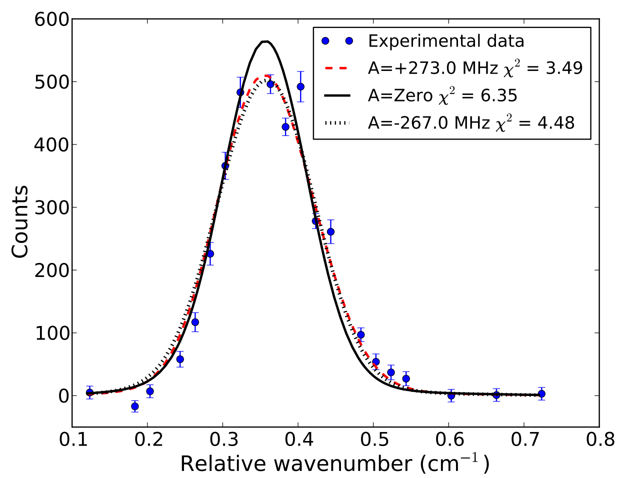

FIG. 5: (Color online) Best fit for ^{78}Cu using $I = 6$ assigned by β-decay studies [10, 11].

ment. Fits were attempted for a range of spin values between 3 and 6; all gave very small A factors with large errors. The fit results for an assumed spin of $I = 6$ (based on recent β-decay studies [10, 11]) are shown in Fig. 5.

V. DISCUSSION

The copper isotopes with one valence proton beyond the $Z = 28$ shell closure present an interesting possibility to probe the evolution of shell structure with extreme ratios of N/Z. The magnetic moment measurements reported here add to a body of data, which now provides an almost complete dataset from $N = 28$ to $N = 50$. This makes it possible to rigorously test theoretical models and answer questions on how robust shell-structure is far from stability. Magnetic moments are particularly sensitive to changes in the leading configurations of the wave function, which is possible through a comparison with shell-model calculations. Such analysis has been applied to the neutron-rich isotopes of copper ($Z = 29$) [38] and gallium ($Z = 31$) [47, 48]. In the case of gallium this comparison has demonstrated that there is an increasing contribution of the $\pi f_{5/2}$ to the ground-state wavefunction beyond $N = 42$ [47], mirroring the behaviour observed in the copper isotope chain.

The data presented here provides an independent confirmation that inversion between the $\pi p_{3/2}$ and $\pi f_{5/2}$ single-particle states occurs in ^{75}Cu. This work has also measured a spin of $I = 5/2$ for the ground state of ^{77}Cu, confirming that the inversion in spin observed at $N = 46$ is maintained at $N = 48$ for copper. The physics underlying this change can be understood in terms of the monopole component of the tensor force, resulting in an attractive residual interaction between the $f_{5/2}$ odd-proton state and the $g_{9/2}$ odd-neutron state [49, 50]. Recent shell-model calculations have also demonstrated the importance of proton excitations from the $Z = 28$ core [51]. The full sequence of measured odd-even copper isotope ground-state magnetic moments is given in Table II. Full shell-model magnetic-moment calculations undertaken by Towner [39] are impractical with more than one nucleon beyond a closed shell, however more extensive calculations of ground states and excited states can be made by truncated-space models. The most recent calculations reproduced very well the evolution of the proton, $3/2^-$ and $5/2^-$ states in the neutron rich odd-even copper nuclei when filling the $\nu g_{9/2}$ orbital [5, 38]. Application of the JUN45 and jj44b interactions have been extended to allow a comparison with the magnetic moment of ^{77}Cu and is presented in Fig. 6. In addition to shell-model calculations the results are plotted against the effective magnetic moments ($\mu_{\rm eff}$ derived from single-nucleon g-factors ($g_{\rm s} = 0.7 g_{\rm free}$), which for the $\pi p_{3/2}$ state closely reproduces the ^{69}Cu value [39].

The relatively close agreement between theory and experiment observed at $N = 46$ is already lost by $N = 48$. The ground state of ^{75}Cu is predicted by both interactions to have a wave function dominated by a single particle $\pi f_{5/2}$ but also has a significant contribution (36%) due to the coupling of the $p_{1/2}$ state with the $\nu(2^+)$ vibrational excitations. This collective contribution to the wave function is expected to reduce as $N = 50$ is approached with 15% contribution in ^{77}Cu and zero contribution in ^{79}Cu. This reduction in the collectivity of the ground-state wave function is reflected in the increase in the magnetic moment towards the $\mu_{\rm eff}$ value. The measured moment of ^{77}Cu is therefore surprisingly larger than the $\mu_{\rm eff}$ for $N = 50$. The energy spacing between the $p_{3/2}$ and $f_{5/2}$ is expected to increase as $N = 50$ is approached [50] making it unlikely that there is an increased contribution from the $p_{3/2}$ orbital in the ground-

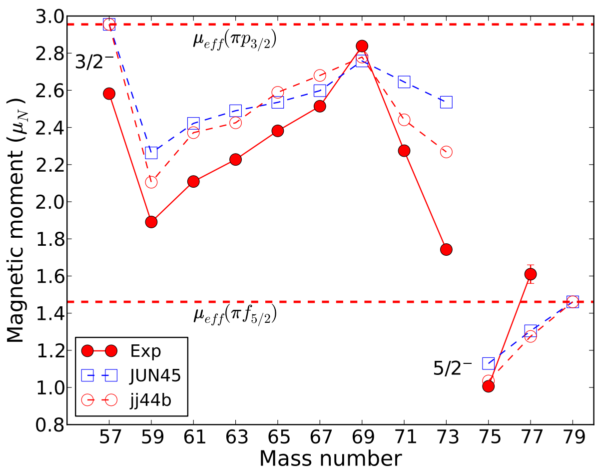

FIG. 6: (Color online) Comparison of experimental magnetic moments with shell-model calculations. The effective magnetic moments are shown as a dashed line and are calculated from the effective Schmidt estimates using $g_s = 0.7g_{\text{free}}$.

state wave function of ^{77}Cu. Both interactions (JUN45 and jj44b) use a ^{56}Ni core for the model space and therefore cannot account for particle-hole excitations across $Z = 28$. The repulsive nature of the residual interaction between $\pi f_{7/2}$ and $\nu g_{9/2}$ orbital may be much stronger than previously predicted, which would favour particle-hole excitations across $Z = 28$. The recent calculations by Sieja and Nowacki [51] used a ^{48}Ca core for the model space. Their calculations converged with a $4p4h$ (4 particle 4 hole) excitation and agreed closely with the moments and low energy level structure of ^{71,73,75}Cu. They conclude that the $Z = 28$ shell is reduced by 0.7 MeV as the $\nu g_{9/2}$ is filled. The magnetic moment of ^{77}Cu reported here agrees closely with their calculations, suggesting that the $Z = 28$ shell closure does indeed begin to quench as $N = 50$ is approached. Therefore extending these measurements to ^{79}Cu would provide critical information on the evolution of the $Z = 28$ shell closure. An extension of the shell-model calculations by Sieja and Nowacki to the neutron deficient copper isotopes, would allow the evolution of the $Z = 28$ shell closure from ^{57}Cu to ^{77}Cu to be studied, which would be extremely interesting.

VI. SUMMARY

The spins and magnetic moments of ^{75,77}Cu have been measured using in-source laser spectroscopy. A collapsed hyperfine structure of ^{78}Cu was observed, allowing an upper limit on the magnitude of the magnetic moment to be made. This paper reports the first application of the dressed-state analysis by Gheysen *et al.* [24] to determine the spin of rare isotopes. The spin of ^{75}Cu reported here represents an independent confirmation of the ground-state inversion between $I = 3/2$ and $I = 5/2$. The magnetic moments deduced from in-source laser spectroscopy have been compared to the results from more precise techniques and show close agreement. A comparison of the magnetic moment of ^{77}Cu with theoretical calculations suggests that there is significant shell quenching as $N = 50$ is approached. No evidence for long-lived isomerism was observed in the hyperfine structure of ^{77,78}Cu.

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