In-gas-cell laser spectroscopy study of the $^{57,59,63,65}$Cu isotopes has been performed for the first time using the 244.164 nm optical transition from the atomic ground state of copper. The nuclear magnetic dipole moments for $^{57,59,65}$Cu relative to that of $^{63}$Cu have been extracted. The new value for $^{57}$Cu of $\mu(Cu) = +2.582(7)\mu_N$ is in strong disagreement with the previous literature value but in good agreement with recent theoretical and systematic predictions.

PACS numbers: 21.10.Ky, 27.40.+z, 27.50.+e, 42.62.Fi
through the reactions $^{58}\text{Ni}(p,2n)^{57}\text{Cu}$, $^{60}\text{Ni}(p,2n)^{59}\text{Cu}$ and $^{58}\text{Ni}({^3\text{He},pn})^{59}\text{Cu}$. The radioactive recoils are stopped and thermalised in 130 mbar of argon. Stable $^{63,65}\text{Cu}$ atoms are also produced by the resistive heating of a natural copper filament inside the gas cell.

The atoms are brought towards the ionization chamber of the gas cell by the gas flow where they are ionised to a Cu$^+$ state using a resonant two-step two-color laser ionization process \cite{20,21}. The ions exit the gas cell via a 1 mm exit hole and are caught by a radio-frequency sextupole ion guide before being accelerated to an energy of 40 keV. The beam is further separated according to the isotope mass-to-charge ratio by a dipole magnet. Typical production rates are about 6 ions s$^{-1}$ for $^{57}\text{Cu}$ and 1.7 · 10$^4$ or 1.7 · 10$^5$ ions s$^{-1}$ for $^{59}\text{Cu}$ using protons or $^3\text{He}$, respectively. While scanning the laser frequency, two beams are extracted and counted simultaneously at two different detection stations, $^{57,63}\text{Cu}$ or $^{59,65}\text{Cu}$, respectively. After mass separation, the radioactive isotopes ($^{57,59}\text{Cu}$) are implanted in a tape station and counted via their respective $\beta$ decay using three plastic detectors (efficiency 50\% \cite{22}) while the stable isotopes ($^{63,65}\text{Cu}$) are simultaneously counted by a channeltron electron multiplier placed after the collector chamber of the mass separator.

The laser spectroscopy is performed by scanning the frequency of the first step laser across the transition from the 3$d^{10}4s\ 2S_{1/2}$ atomic ground state to the 3$d^54s4p\ 4P_{1/2}$ atomic excited state at 244.164 nm; the ionization scheme is shown in Fig. 1. The resonances are identified by counting the number of ions extracted as a function of the applied laser frequency. The interaction of the nuclear spin $I = 3/2$; for all isotopes, and the electronic total angular momentum $J = 1/2$, for both atomic levels, yields two sub-levels with quantum numbers $F = 1, 2$ for each atomic level; the resulting hyperfine structure has four components, as visible in Fig. 2. The electronic angular momenta $J_1, J_2 = 1/2$ restrict the sensitivity of this transition to the magnetic dipole moment. This study can therefore not extract any information on the electric quadrupole moment of the copper isotopes ground states. The large splitting in both atomic levels allows for the extraction of the hyperfine parameter $A_{hf}$ for each atomic level, as detailed in \cite{19}.

Each isotope has been measured repeatedly to ensure the reproducibility of the data. In total, 34 independent measurements are available for $^{59}\text{Cu}$ and $^{65}\text{Cu}$, 68 for $^{57}\text{Cu}$ and 106 for $^{63}\text{Cu}$. The hyperfine parameters extracted for every run are consistent to each other and no systematic drift in these parameters has been observed, as shown in Fig. 3. The average value over all the measurements for each of those parameters is shown in Table I. Off-line, the pressure dependence of the resonance line width and of the center of gravity position were investigated in details and are reported in \cite{19}.

The hyperfine parameters for the atomic ground state of $^{63,65}\text{Cu}$ are known with good accuracy \cite{22} (see table I). The results from this work, $A_{hf,gs} = 5.858(10)$ GHz.
Moreover, the systematic measurement of transition (labeled C), much lower with respect to the hyperfine levels of the $3^2D_{5/2}$ level compared to the $3^2D_{3/2}$ level and the high number of independent measurements. Supported by the good agreement on the stable isotopes, the consistency of the ratio of the two hyperfine parameters and based on the precise knowledge of the magnetic moment of $^{63}$Cu, the $57,59,65$Cu are extracted, as detailed in [15], from both atomic levels. The results are given in Table 4. The signs are determined based on the ordering of the peaks considering the relative intensity of the $F = 1 \rightarrow 1$ transition (labeled C), much lower with respect to the others, as seen in Fig. 2.

Good agreement is found with previous moment measurements of the $^{59,65}$Cu isotopes. The measured moment of the lightest isotope $^{57}$Cu ($\mu = +2.582(7)\mu_N$) displays however a major difference with the literature value ($|\mu| = 2.00(5)\mu_N$) [14]. A careful inspection of our running conditions and of our analysis has been performed. Moreover, the systematic measurement of $^{63}$Cu, the high reproducibility of the spectra and the good agreement of each measured isotope with the established literature values confirm the accuracy of the method. The literature value in [14] is therefore questioned.

All the magnetic moments of the copper isotopes depart strongly from the Schmidt value $\mu_{Schmidt} = +3.79\mu_N$ of a single proton in a $1p_{1/2}$ orbital. In the case of the semi-magic $^{69}$Cu nucleus, the difference between the Schmidt moment and the experimental moment is very well reproduced by the shell-model calculation from Golovko et al. [12] ($\mu = +2.87(13)\mu_N$). $^{68}$Ni was taken as a closed-shell core but including effects of core polarization, meson exchange current, $\Delta$-isobars and relativistic corrections in perturbation theory. The same calculations for $^{57}$Cu using $^{56}$Ni as the core give $\mu = +2.40(18)\mu_N$ and reproduce the new measured value.

Theoretical studies considering a $^{40}$Ca core and the full $fp$-shell valence space are also in agreement with the dipole moment of $^{57}$Cu as measured in this Letter, predicting a magnetic moment of $\mu = +2.48\mu_N$ using the FPD6 interaction [13] or $\mu = +2.489\mu_N$ using the GXPf1 interaction (with effective $g$ factors $g_{ef}^{fp} = 0.9g_{free}^{fp}$, $g_{free}^{fp} = 1.1$ for protons and $g_{free}^{fp} = -0.1$ for neutrons) [10, 16]. The moments of the isotopes between $N = 28$ and $N = 40$ have also been extracted with the latter interaction and reproduce the experimental data accurately (see Fig. 2).

The new value for the magnetic dipole moment of $^{57}$Cu can also be used together with the one of its mirror partner $^{57}$Ni ($-0.7975(14)\mu_N$) [20] to extract the isoscalar spin expectation value $\langle \sum \sigma_z \rangle = 0.75(2)$ according to the formalism described in [14]. This quantity reflects the contribution from the nucleon spin to the magnetic moment. Our value is in strong disagreement with the value of $-0.78(13)$ from [14]. However, it is in reasonable agreement with the calculated values 0.71 using the
across the world making use of the gas-cell technology possibilities for the future radioactive ion beam facilities systems. This new technique opens therefore exciting topes and of isotopes from refractory elements that are spectroscopy measurements of short-lived radioactive iso-
total resonance line width. Furthermore, it allows laser temperature in-source laser spectroscopy due to a lower very stable, has a superior accuracy compared to high-
pled to a mass separator. The system is proven to be netic moment measurement of an exotic isotope using significant shell breaking than introduced in [10], unlikemeasurement of

The neutron-deficient silver, indium and tin isotopes, ap-
57
57

tings are very well suited for this type of measurement. The neutron-deficient silver, indium and tin isotopes, ap-
proaching N = 50, are expected to possess large mag-
netic dipole moments. They are therefore ideal to probe this shell closure. The in-gas-cell laser spectroscopy tech-
nique can also be improved by reducing the resonance line width further, performing the laser spectroscopy in a Laser Ion Source Trap (LIST) as recently shown in [19].

We thank the CRC team, Louvain-La-Neuve (Belgium). This work was supported by FWO-Vlaanderen (Belgium), GOA/2004/03 (BOF-K.U.Leuven), the IUAP - Belgian State Belgian Science Policy - (BriX network P6/23) and by the European Commission within the Sixth Framework Programme through I3-EURONS (Contract RII3-CT-2004-506065).

Table I: Measured hyperfine parameters $A_{hf,exp}$ for the atomic ground (gs) and excited (es) states and the deduced moments $\mu_{exp}$ using $^{65}$Cu as the reference isotope. The literature values $A_{hf,lit,gs}$ [15,22], $\mu_{lit}$ [15,14,21,22] and theoretical calculations using GXPF1 [18,16] are given for comparison; no literature is available on the atomic excited hyperfine parameter.

| $A$ | $I$  | $A_{hf,exp,gs}$ [GHz] | $A_{hf,exp,es}$ [GHz] | $\mu_{exp}$ $[\mu_N]$ | $\mu_{lit}$ $[\mu_N]$ | $\mu_{GXPF1}$ $[\mu_N]$ |
|-----|-----|------------------------|------------------------|-------------------------|-------------------------|-------------------------|
| 57  | 3/2$^-$ | 6.785(15)              | 2.834(16)              | +2.582(7)               | 2.00(5)                 | 2.489                   |
| 59  | 3/2$^-$ | 5.033(10)              | 2.069(8)               | +1.910(4)               | +1.891(9)               | 1.886                   |
| 63  | 3/2$^-$ | 5.858(10)              | 2.432(8)               | -                       | 2.2273602(13)           | 2.251                   |
| 65  | 3/2$^-$ | 6.288(17)              | 2.588(15)              | +2.387(7)               | 2.3818(3)               | 2.398                   |

FPD6 interaction [18] and 0.51 using the GXPF1 inter-
ction [10,14]. The departure of this value from 1 is an extra indication of a non-pure $p_{3/2}$ nuclear configuration (see Fig. 3 in [14]).

Moreover, the dipole moments of $^{57}$Cu can be esti-
ated based on its respective mirror nucleus $^{57}$Ni [27,28]. The deduced moment $\mu = +2.49(3)\mu_N$ is again in agreement with our measurement. The magnetic moment of $^{57}$Cu and $^{57}$Ni can also be combined to calculate the magnetic dipole moment of $^{58}$Cu according to the additivity rule [13]. A value of $\mu = +0.595(2)\mu_N$ is found, in agreement with the experimental value $+0.52(8)\mu_N$ [13].

Our work brings out how good the GXPF1 interaction describes the structure near $^{58}$Ni as proven by the very sensitive reproduction of the magnetic dipole moment of the chain $^{57-69}$Cu. There is indeed no need for a more significant shell breaking than introduced in [10], unlike stated previously in [14].

To conclude, we have reported the first on-line mag-
netic moment measurement of an exotic isotope using in-gas-cell resonant ionization laser spectroscopy coupled to a mass separator. The system is proven to be very stable, has a superior accuracy compared to high-
temperature in-source laser spectroscopy due to a lower total resonance line width. Furthermore, it allows laser spectroscopy measurements of short-lived radioactive iso-
topes and of isotopes from refractory elements that are not possible using high-temperature target-ion source systems. This new technique opens therefore exciting possibilities for the future radioactive ion beam facilities across the world making use of the gas-cell technology (e.g. GANIL, NSCL, RIKEN).

The hyperfine parameter of the $3d^94s4p$ $^4P_{1/2}$ level in copper has been measured for the first time. Moreover, the known magnetic moments for $^{59}$Cu and $^{65}$Cu are well reproduced. The discrepancy with the $\beta$-NMR measurement of $^{57}$Cu questions however the correctness of the value published in [14]. Finally, a good agreement of the new measurement with recent theoretical calcula-
tions and with the prediction from the mirror nucleus $^{57}$Ni is found.

Besides, other isotopes displaying large hyperfine split-
tings are very well suited for this type of measurement. The neutron-deficient silver, indium and tin isotopes, ap-

1. M. Goeppert Mayer, Phys. Rev. 78, 16 (1950).
2. O. Sorlin and M.-G. Porquet, Prog. Part. and Nucl. Phys. 61, 602 (2008).
3. B. Bastin et al., Phys. Rev. Lett. 99, 022503 (2007).
4. L. Gaudefroy et al., Phys. Rev. Lett. 102, 092501 (2009).
5. K. Yurkewicz et al., Phys. Rev. C 70, 054319 (2004).
6. O. Perru et al., Phys. Rev. Lett. 96, 232501 (2006).
7. G. Audi et al., Nucl. Phys. A 729, 337 (2003).
8. G. Kraus et al., Phys. Rev. Lett. 73, 1773 (1994).
9. A. Lisetskiy et al., Phys. Rev. C 68, 034316 (2003).
10. M. Honma et al., Phys. Rev. C 69, 034335 (2004).
11. J. Rikovska et al., Phys. Rev. Lett. 85, 1392 (2000).
12. L. Weissman et al., Phys. Rev. C 65, 024315 (2002).
13. V. Golovko et al., Phys. Rev. C 70, 014312 (2004).
14. K. Minamisono et al., Phys. Rev. Lett. 96, 102501 (2006).
15. N. Stone et al., Phys. Rev. C 77, 067302 (2008).
16. N. Stone et al., Phys. Rev. C 77, 014315 (2008).
17. K. Flanagan et al. (2009), to be published.
18. D. Semon et al., Phys. Rev. C 85, 034316 (2003).
19. T. Ohtsubo et al., Phys. Rev. C 63, 034316 (2001).
20. Y. Kudryavtsev et al., Nucl. Instr. and Meth. B 179, 412 (2001).
21. D. Pauwels et al., Nucl. Instr. and Meth. B 266, 4600 (2008).
22. H. Figger et al., Coll. int. du CNRS 164, 355 (1967).
23. O. Lutz et al., Z. Phys. A 68, 17 (1978).
24. N. Stone, At. Data and Nucl. Data Tables 90, 75 (2005).
25. T. Ohtsubo et al., Phys. Rev. C 54, 554 (1996).
26. B. Buck et al., Phys. Rev. C 63, 037301 (2001).
27. B. Buck and S. Perez, Phys. Rev. Lett. 50, 1975 (1983).