Nuclear dipole moment of ^{71}Cu from online β-NMR measurements

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On-line β-NMR measurements on nuclei oriented at low temperatures of the magnetic dipole moment of ^{71}Cu($N = 42$) are reported, with the result $\mu(^{71}\mathrm{Cu}) = +2.28(1)$ nuclear magneton (n.m.). The value shows a significant difference from $\mu(^{67}\mathrm{Cu}) = +2.54(2)$ n.m., revealing asymmetry with respect to $N = 40$. This effect presents a challenge to theoretical interpretation.

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The magnetic dipole moments of odd-A Cu isotopes have been the object of considerable attention in recent years, focusing on their possessing a single odd proton outside the closed subshell at $Z = 28$. A complete sequence of measurements exists for even N isotopes between the supposedly good neutron subshell closures at $N = 28$ and 40 [1–4]. In this paper the first high precision measurement beyond the closure at $N = 40$ is reported on the 19.5 s $(\pi p^1_{3/2}; 3/2^-)$ ground state of ^{71}Cu. Preliminary reports of this result have been given elsewhere [5,6].

The experiment was performed using the NICOLE online nuclear orientation facility at the ISOLDE isotope separator, CERN, Geneva. The method of observation of nuclear magnetic resonance of polarized nuclei after online implantation and low temperature orientation has been fully described in, for example, [1,3]. Far asymmetric fission of ^{238}U by 1 GeV protons from the CERN PS Booster produced the desired isotope in a uranium carbide/graphite target which was coupled to a resonance ionization laser ion source. The resulting separated beam of isotopically pure ^{71}Cu was accelerated to 60 keV and implanted into an annealed, polished 99.99% pure Fe foil soldered to the cold finger of the NICOLE dilution refrigerator. The refrigerator temperature was varied between about 1 K and 11–12 mK, the latter being measured using a ^{54}MnNi nuclear orientation thermometer, to establish nuclear polarization.

The beta decay of ^{71}Cu is complex, with a Q_β value of 4.56 MeV. No other isotope in the decay sequence following ^{71}Cu has beta end-point energy above 2.5 MeV so the high energy beta spectrum is dominated by decay of the isotope under study. The NICOLE cryostat is designed with thin Al foil windows having less than 2 mm aluminium between the sample and room temperature. This allowed a pair of beta detectors outside the cryostat, consisting of 2.5 cm circular discs of plastic scintillator optically coupled to 25 mm square silicon PIN detectors, to be used to monitor the nuclear polarization of the implanted ^{71}Cu activity. The detectors were placed at 0° and 180° to the orientation axis, defined by magnetization of the iron foil in an external applied field B_{applied}.

Although the various components of the beta spectrum were not separated, their combined asymmetry, defined as $\{[(\frac{N_0}{N_{180}})_{\mathrm{mK}}/(\frac{N_0}{N_{180}})_{1\mathrm{K}}] - 1\}\times 100\%$, measured by taking the ratio of counts in regions set on the beta spectra in the two detectors, was large and provided ample sensitivity to allow search for nuclear magnetic resonance of the emitting polarized ^{71}Cu activity. The search was assisted by a preliminary result of in-source laser ionization experiments by Weissman *et al.* [11] calibrated on our previous resonance on ^{69}Cu, which indicated a moment for ^{71}Cu around 2.3 n.m.

Resonance was sought by observing the variation of the asymmetry as the frequency of an rf field, applied at the sample through a small few-turn coil with axis perpendicular to the axis of orientation, was changed. The resulting signal is shown in Fig. 1. The rf frequency was modulated at 1 MHz and stepped by 1 MHz. Data from four sweeps across the resonance are combined in Fig. 1. A Gaussian fit of the resonance spectrum yields the center frequency ν_0 to be 250.00(14) MHz. This is related to the magnetic moment by the resonance condition between the hyperfine interaction split Zeeman levels of ^{71}Cu

$$h\nu_0 = \frac{|\mu|}{I}(B_{\mathrm{hf}} + B_{\mathrm{applied}}). \tag{1}$$

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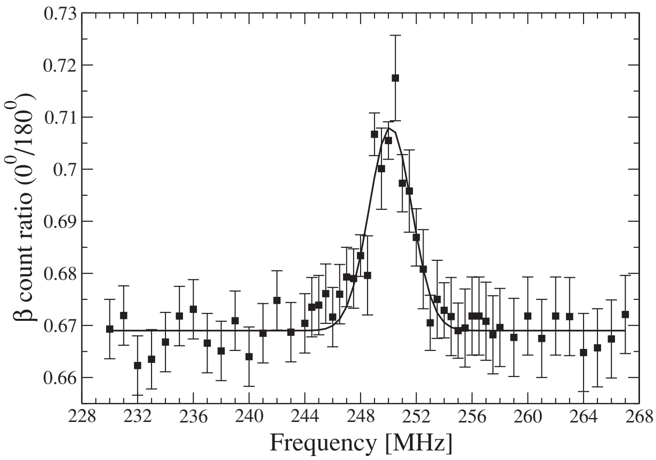

FIG. 1. β-NMR/ON for ^{71}CuFe.

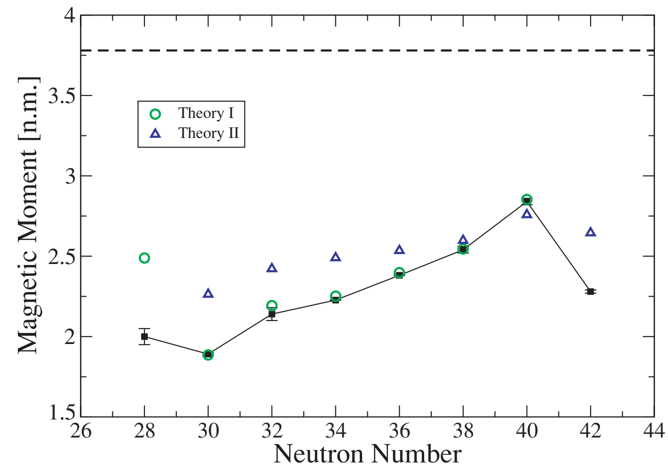

FIG. 2. (Color online) Systematics of experimental magnetic moments of odd-A Cu isotopes as a function of neutron number. The Schmidt limit is indicated by a dashed-line. Theories I and II are specified in Table I and the text.

The hyperfine field of copper in iron is known to be $-21.8(1)$ T [12] and after correction for the applied magnetic field of $+0.20(1)$ T, the resulting magnetic moment is

$$\mu[^{71}\text{Cu}] = +2.28(1)\ \text{n.m.} \qquad (2)$$

The systematic variation of magnetic moments of odd-A copper isotopes, including the present result, is given in Table I and shown in Fig. 2. The Schmidt limit value of 3.7925 n.m. is also shown. The effect of neutron subshell closure at $N = 40$ is clearly seen, resulting in a peak in the measured moments and closest approach to the Schmidt value as configuration mixing effects are at their minimum.

The single-particle shell model ground state configuration of ^{71}Cu is $[\pi 2p_{3/2}]^1[\nu 1g_{9/2}]^2$, that is two neutrons outside the $N = 40$ subshell closure. Although the presence of more than one particle or hole in the closed subshell means that detailed calculations using theoretical g-factors, similar to those made and discussed for ^{69}Cu in Ref. [1] are not possible, the result may be compared with that for ^{67}Cu, $\mu[^{67}\text{Cu}] = +2.54(2)$ n.m. [2], which has two neutron holes in the same subshell. There is apparent asymmetry in the behavior of the magnetic moments either side of the subshell closure. Qualitatively, this may be the consequence of difference between the possible configuration mixing effects in the two cases as the neutron levels are filled below and above $N = 40$. Oros-Peusquens and Mantica [13] studied systematic behavior of proton single particle energies in Ni and Cu isotopes in the vicinity of ^{68}Ni in terms of the particle-core coupling model and interpreted the asymmetry with respect to the ^{68}Ni subshell closure in terms of monopole shifts. Monopole migration of single-particle levels in ^{69,71,73}Cu was observed experimentally in β-decay studies of neutron-heavy Ni isotopes, the most pronounced being the sharp lowering of the $\pi f_{5/2}$ orbital with respect to the $\pi p_{3/2}$ ground state with increasing neutron number. This feature was attributed to the monopole term of the residual proton-neutron interaction and is well reproduced in shell model [14].

TABLE I. Experimental values of $I^\pi = 3/2^-$ ground state magnetic moments of Cu isotopes [1–4,7].

Mass	N	μ_{exp} [n.m.]	μ_{thI} [n.m.]	μ_{thII} [n.m.]
57	28	2.00(5)	2.489	
59	30	+1.891(9)	1.886	2.263
61	32	+2.14(4)	2.193[a]	2.422
63	34	2.2273456(14)	2.251[a]	2.490
65	36	2.38161(19)	2.398[a]	2.535
67	38	2.54(2)	2.545	2.598
69	40	+2.84(1)	2.853[b]	2.758
71	42	2.28(1)		2.645

[a]Theoretical values taken from [8].
[b]Theoretical values taken from [1].

Shell model calculations of magnetic moments of $^{57-71}$Cu with empirical g-factors, performed in two different model spaces, are compared with the experimental data in Table I. The values in the fourth column were obtained with the GXPF1 interaction [8] in the pf-shell space, allowing six nucleons to excite from the $f_{7/2}$ orbit to the $p_{3/2}$, $f_{5/2}$, and $p_{1/2}$ orbits. The shell-model description appears quite successful except for ^{57}Cu [8]. For heavier isotopes, we need to include the $g_{9/2}$ orbit explicitly. We employed the model space consisting of the single-particle orbits $p_{3/2}$, $f_{5/2}$, $p_{1/2}$, and $g_{9/2}$, and the effective interaction was determined by modifying the realistic G-matrix interaction by a least-squares fit to 400 experimental energy data [9]. The effective g-factor $g_s^{\text{eff}} = 0.7 \times g_s^{\text{free}}$ was taken on the basis of the fitting to the available experimental magnetic moment data in this mass region. The results are shown in the fifth column. For $N = 30$–36, the calculated values are much larger than the experimental ones, indicating the importance of the ^{56}Ni core-excitation. The deviation decreases as N increases toward the $N = 40$ magic number, and at $N = 38$ and 40, the agreement between the shell-model results and the experimental data is reasonable. On the other hand, at $N = 42$, the shell-model value is much larger than the experimental one. It is expected that the two neutrons in the $g_{9/2}$ orbit give negative contribution to the magnetic moment, and in fact, the calculation shows such a decrease from $N = 40$ to 42. However, the shell-model predicts much smaller reduction, which is not enough to explain the observed value for ^{71}Cu. Considering that the present model space can reasonably take into account the excitations of neutrons across the $N = 40$ subshell gap, this result suggests the enhancement of the excitations on the proton side across the $Z = 28$ energy gap. Because of the tensor force [10], the single-particle energy gap between the $f_{7/2}$ and the $f_{5/2}$ orbits for protons decreases as the neutron $g_{9/2}$ orbit is occupied, which may be give rise to such an effect. The shell-model calculation in the extended model space including both the $f_{7/2}$ and the $g_{9/2}$ orbits is on going.

In conclusion, odd-A Cu magnetic moments together with other spectroscopic experimental information at and in the vicinity of $N = 28$ and $N = 40$ shell closures contain intriguing physics and pose a challenge to nuclear theory.

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