First On-Line Beta-NMR on Oriented Nuclei: Magnetic Dipole Moments of the $(\nu p_{1/2})^{-1}$ $1/2^-$ Ground State in ^{67}Ni and $(\pi p_{3/2})^{+1}$ $3/2^-$ Ground State in ^{69}Cu

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The first fully on-line use of the angular distribution of beta emission in detection of NMR of nuclei oriented at low temperatures is reported. The magnetic moments of the single valence particle, intermediate mass, isotopes ^{67}Ni$(\nu p_{1/2}^{-1}; 1/2^-)$ and ^{69}Cu$(\pi p_{3/2}^{1}; 3/2^-)$ are measured to be $+0.601(5)$ μ_N and $+2.84(1)$ μ_N, respectively, revealing only a small deviation from the neutron $p_{1/2}$ single-particle value in the former and a large deviation from the proton $p_{3/2}$ single-particle value in the latter. Quantitative interpretation is given in terms of core polarization and meson-exchange currents.

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Magnetic moments in odd-mass heavy nuclei differ significantly from their single-particle (Schmidt) values. This effect occurs because, in heavy nuclei, the shell closures are such that an orbital with $j_> = l + 1/2$ may be fully occupied while the spin-orbit partner orbital with $j_< = l - 1/2$ may be unoccupied. Here j is the total angular momentum of the orbital and l its orbital angular momentum. In this situation, there is a large correction to the single-particle magnetic moment coming from the excitation in the closed-shell core of the particle-hole state $[j_<, j_>^{-1}]1^+$ made from the particle in orbital $j_<$ coupling to a hole in orbital $j_>$ with resultant angular momentum 1^+, the multipolarity of the magnetic moment operator. This correction is generally known as core polarization. For example, at the ^{208}Pb closed shell, magnetic moments of eight orbitals have been directly measured [1] or inferred. In seven of the cases (see Table I) the correction to the single-particle estimate is large, between 0.4 and 1.5μ_N. In the eighth case, that of a neutron $p_{1/2}$ orbital, the correction is very small, $\sim 0.05\mu_N$. Why, then, is the correction small for the $p_{1/2}$ orbital and large for all others?

TABLE I. Experimental magnetic moments $\mu_{\rm expt}$ and single-particle values $\mu_{\rm sp}$ and their difference $\Delta\mu$ for odd-proton (π) and odd-neutron (ν) nuclei in the Pb region.

		$\mu_{\rm expt}$	$\mu_{\rm sp}$	$\Delta\mu$
^{209}Bi	$\pi h_{9/2}$	4.11	2.62	1.49
^{209}Bi	$\pi i_{13/2}$	2.78(10)[a]	3.56	−0.78
^{207}Tl	$\pi s_{1/2}^{-1}$	1.87	2.79	−0.92
^{207}Tl	$\pi d_{3/2}^{-1}$	0.76(19)[b]	0.12	0.64
^{209}Pb	$\nu g_{9/2}$	−1.47	−1.91	0.44
^{207}Pb	$\nu p_{1/2}^{-1}$	0.59	0.64	−0.05
^{207}Pb	$\nu f_{5/2}^{-1}$	0.79(3)	1.37	−0.58
^{207}Pb	$\nu i_{13/2}^{-1}$	−1.01(3)[c]	−1.91	0.90

[a]Deduced from the magnetic moment of the 11^- state in ^{210}Po.
[b]Deduced from the magnetic moment of the $3/2^+$ state in ^{205}Tl.
[c]Deduced from the magnetic moment of the 12^+ state in ^{206}Pb.

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This question has a long history. It was first raised, we believe, in Blin-Stoyle's monograph [2] of 1957, and a quantitative response was given by Arima and colleagues [3]. One difficulty with answering this question is that there are very few examples of odd-mass heavy nuclei, with ground state spin parity of $1/2^-$, whose magnetic moments have been measured. Here we report the first measurement of the magnetic moment of ^{67}Ni ($1/2^-$), and of the neighboring nucleus ^{69}Cu ($3/2^-$). This pair of nuclei provides a unique opportunity to explore the generality of the findings in the Pb region, namely that the correction to the magnetic moment of the proton $p_{3/2}$ orbital is large, $\sim 1.0\mu_N$, while in the neutron $p_{1/2}$ orbital it is small, $\sim 0.05\mu_N$.

New techniques of fully on-line nuclear magnetic resonance on oriented nuclei (NMR/ON) make it possible to determine precisely ground and isomeric state magnetic dipole moments far from stability [4,5]. So far, the resonance effect was detected by a change in the angular anisotropy of gamma-ray emission. This method does not allow study of states with $I^\pi = 1/2^-$ for which, however, the change in the asymmetric emission of parity nonconserving beta decay can be used as a resonance detection signal. All except pure s-wave Fermi allowed beta decays from polarized nuclei exhibit appreciable forward-backwards asymmetry with respect to the polarization axis [6]. This method has been only seldom used in the past, as it requires that beta detectors be operated within the cryostat, at temperatures close to 4 K, coupled with the difficulty of separating the various overlapping beta components in a typical decay spectrum. However, in connection with on-line experiments aimed at nuclear moment measurements there is little need to analyze the observed beta spectrum quantitatively—it suffices that the isotope under study contributes a considerable component to the observed beta asymmetry. Moreover, far from stability, Q_β is often at least several MeV so that beta detectors mounted outside the cryostat can be used, accepting the scattering and energy loss produced by thin cryostat windows between source and detector [7]. Beta-NMR offers advantages for modest degrees of nuclear orientation, since beta asymmetries are proportional to the first power of the ratio $\mu B/kT$, where μ is the nuclear dipole moment of the oriented isotope, B the hyperfine field, and T the sample temperature, whereas the gamma anisotropy is proportional to the square of this quantity. Thus beta asymmetries are often larger than gamma anisotropies, so that a readily measurable resonance signal can be produced in a wider range of isotopes using beta asymmetry, especially for isotopes—often odd-neutron—with smaller magnetic moments.

Both ^{67}Ni ($T_{1/2} = 21$ s) and ^{69}Cu ($T_{1/2} = 2.85$ m) were produced at ISOLDE (CERN) in far asymmetric fission of ^{238}U induced by 1 GeV protons from the PS Booster. The standard uranium carbide/graphite target (50 gcm^{-2}) was coupled to the resonance ionization laser ion source giving enhanced element sensitivity. The yields were 7×10^5 per μC of incident protons for ^{67}Ni and 1.8×10^8 per μC for ^{69}Cu, respectively [8]. The resulting mass-separated beams, which showed excellent stability, were implanted at 60 keV into rolled, polished, and annealed 99.99% pure Fe foils soldered to the cold finger of the NICOLE dilution refrigerator. The refrigerator was maintained at a temperature between 11–12 mK, measured using a ^{54}Mn<u>Ni</u> nuclear orientation thermometer. The NICOLE cryostat is constructed with thin foil windows of less than 2 mm aluminum between the sample and room temperature. Beta spectra were observable using plastic scintillator detectors, consisting of 2.5 cm diameter discs of scintillator optically coupled to 25 mm square silicon PIN detectors, placed outside the cryostat, at room temperature, at angles of 0° and 180° to the orientation axis defined by magnetization of the iron foil in the external applied field B_{applied}.

The beta spectrum of ^{67}Ni above 600 keV is dominated by the 98% direct ground-state–ground-state, $1/2^-$-$3/2^-$, Gamow-Teller allowed transition with end point 3.56 MeV. The beta spectrum of ^{69}Cu has two major components, a 51% ground-state–ground-state, $3/2^-$-$1/2^-$, Gamow-Teller allowed beta decay with end point 2.68 MeV and a 24% ground-state to 1007.66 keV, $3/2^-$-$(1/2^-, 3/2^-)$, Gamow-Teller allowed transition, with a possible Fermi admixture, having end point 1.67 MeV.

The presence of substantial beta asymmetry, defined as $\{[(\frac{N_0}{N_{180}})_{\text{mK}}/(\frac{N_0}{N_{180}})_{1\text{ K}}] - 1\} \times 100\%$ was established by comparison of the count rate N_0/N_{180} from samples at millikelvin and 1 K temperatures. Nuclear magnetic resonance was detected and the nuclear Zeeman splitting measured by observing the variation of the asymmetry at constant millikelvin temperature as the applied rf field frequency was varied. The resulting asymmetry changes for ^{67}Ni are shown in Fig. 1. A fit to the center frequency ν_0 yields the magnetic moment of the oriented state through the resonance condition

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

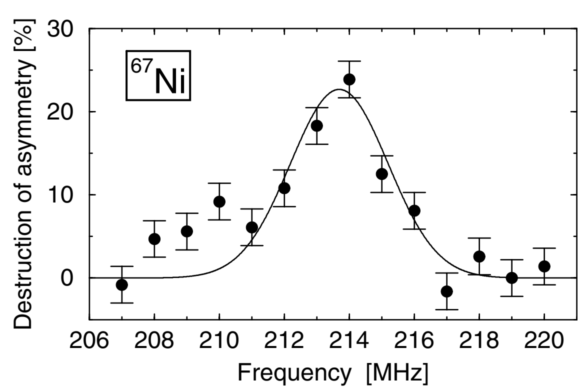

FIG. 1. Beta-NMR/ON for ^{67}Ni<u>Fe</u>.

The present data give center frequency 213.40(15) MHz and, integrating over the resonance line, destruction of approximately 60% of the beta asymmetry. The integrated strength of the resonance reflects the excellent implantation properties of Ni in iron. The hyperfine field of Ni in Fe is known to be $-23.4(2)$ T [9]. After allowing for the applied field $B_{\text{applied}} = +0.1$ T and incorporating the error in the hyperfine field, the magnetic moment of ^{67}Ni is

$$\mu[^{67}\text{Ni}] = +0.601(5)\mu_N\,, \tag{2}$$

where the positive sign of the moment is given by the sign of the beta asymmetry.

The results for ^{69}Cu are shown in Fig. 2. The resonance was fitted with center frequency 311.7(1) MHz and integrated destruction of approximately 40% of the beta asymmetry. The hyperfine field of Cu in Fe is measured as $-21.8(1)$ T [10], and after allowing for the applied field of 0.2 T the nuclear magnetic moment of ^{69}Cu is given as

$$\mu[^{69}\text{Cu}] = +2.84(1)\mu_N\,. \tag{3}$$

When these results are compared with the corresponding Schmidt limits we find the deviations between experimental moments and the free nucleon approximation to be

$$\nu p_{1/2}(^{67}\text{Ni}), \qquad \Delta\mu(\nu p_{1/2}) = -0.037(5)\,, \tag{4}$$

$$\pi p_{3/2}(^{69}\text{Cu}), \qquad \Delta\mu(\pi p_{3/2}) = -0.95(1)\,. \tag{5}$$

We reiterate that these results are for isotopes having major configurations [closed subshell − 1] (^{67}Ni) and [closed subshell + 1] (^{69}Cu). Only for such simple configurations can the detailed theoretical analysis presented below be carried through with confidence.

It is convenient to discuss the calculated results that follow in terms of an effective one-body magnetic moment operator:

$$\boldsymbol{\mu}_{\text{eff}} = g_{l,\text{eff}}\mathbf{l} + g_{s,\text{eff}}\mathbf{s} + g_{p,\text{eff}}[Y_2,\mathbf{s}]\,, \tag{6}$$

where $g_{x,\text{eff}} = g_x + \delta g_x$, with $x = l$, s, or p [11,12]. Here g_x is the single-particle g factor and δg_x the correction to it. Note that in the effective operator there is an additional term involving a spherical harmonic of rank 2 coupled to a spin operator to give a tensor of multipolarity 1. One reason why the correction for a $p_{1/2}$ single-particle magnetic moment is so small, is that the core-polarization correction from the 1^+ particle-hole states mentioned in the introduction is small. This was demonstrated by Arima *et al.* [3,13]. In the limit that core polarization is calculated with zero-range effective interactions a closed expression is obtained for the correction, namely

$$\delta g_l = 0, \qquad \delta g_p = -\frac{1}{2}(2\pi)^{1/2}\delta g_s\,. \tag{7}$$

This relationship between δg_s and δg_p is such that for $p_{1/2}$ orbitals the correction to the magnetic moment is identically zero. This result is exact, not just to first-order core polarization, but to all orders in the random phase approximation (RPA) theory for 1^+ particle-hole states. However, with finite-range effective interactions the relationships are only approximately true. Nevertheless, the core-polarization RPA correction, CP(RPA), of Table II, remains small for the $p_{1/2}$ neutron state, $-0.15\mu_N$, compared to $-0.49\mu_N$ for the $p_{3/2}$ proton state.

The CP(RPA) is not the only correction to consider. In second and higher orders there are further core-polarization corrections that are not part of the RPA series [11–13]. These are difficult to compute because the intermediate-state summations are slow to converge. Thus we have only computed the second-order graphs, CP(2nd), in a harmonic oscillator basis, and taken the intermediate-state summations up to $12\hbar\omega$ excitation energy, and extrapolated beyond that.

Another class of corrections are meson-exchange currents (MEC) described more fully in [11,12,14]. These produce a large positive correction for the proton $p_{3/2}$ orbital, but only a small negative correction for the neutron $p_{1/2}$ orbital. The reason is that the δg_l and δg_s values are of the same sign, giving in-phase contributions to $j = l + 1/2$ orbits and out of phase contributions to $j = l - 1/2$ orbits. A further mesonic correction to be considered is that in which the meson prompts the nucleon to be raised to an excited state, the Δ resonance, which is then de-excited by the electromagnetic field. These isobar currents give only a small correction to the magnetic moment. A more important mesonic contribution is a first-order core-polarization correction to the two-body MEC operator, MEC-CP. These terms are fourth order in meson-nucleon couplings, as are the CP(2nd) contributions, and like the CP(2nd) terms they are difficult to compute because the intermediate-state summations are slow to converge. Again we took the summation to $12\hbar\omega$ excitation energy and extrapolated beyond that. Note that the CP(2nd) and MEC-CP contributions are of opposite sign, providing some cancellation as has been pointed out by Arima *et al.* [13].

Last, there is a relativistic correction to the single-particle magnetic moment operator obtained when evaluating the operator to order $(p/M)^3$, where p is a typical nucleon momentum and M its mass. This correction has been estimated using harmonic oscillator wave functions.

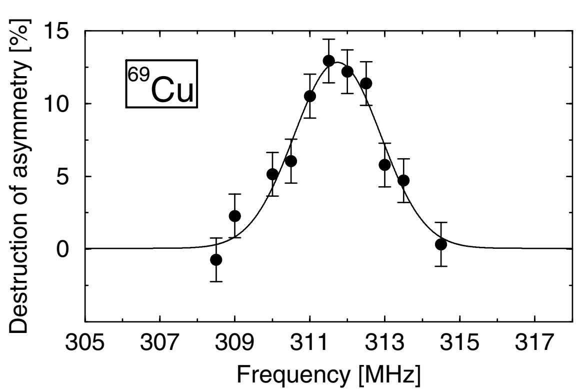

FIG. 2. Beta-NMR/ON for ^{69}CuFe.

TABLE II. Contributions to the calculated effective magnetic moment operator for a $p_{1/2}$ neutron in ^{67}Ni and a $p_{3/2}$ proton in ^{69}Cu.

	Neutron $p_{1/2}$				Proton $p_{3/2}$			
	δg_l	δg_s	δg_p	$\delta \mu$	δg_l	δg_s	δg_p	$\delta \mu$
CP(RPA)	−0.010	0.371	0.610	−0.15	0.000	−1.019	0.504	−0.49
CP(2nd)	0.191	1.150	−0.226	−0.03	−0.225	−1.448	0.334	−0.94
Isobars	0.004	0.293	−0.805	0.06	−0.002	−0.178	0.558	−0.07
MEC	−0.092	−0.241	0.051	−0.03	0.183	0.368	−0.295	0.36
CP-MEC	−0.091	−0.148	−0.169	−0.01	0.103	0.355	0.393	0.30
Relativistic	0.000	0.087	0.000	−0.02	−0.023	−0.143	−0.038	−0.10
Sum	0.001	1.513	−0.539	−0.18	0.036	−2.065	1.456	−0.94
Expt				−0.037(5)				−0.95(1)

Although this term is very sensitive to the choice of the radial wave function, depending on its second derivative, the result is small, about a 2.5% reduction to the single-particle value.

All corrections have been collated in Table II. For the $p_{3/2}$ proton in ^{69}Cu, the calculated correction to the single-particle magnetic moment is large, $-0.94\mu_N$, while for the $p_{1/2}$ neutron in ^{67}Ni it is small, $-0.18\mu_N$. For the former, the result is in good agreement with experiment, while for the latter, the correction, although small, is a factor of 4 larger than required by experiment. The same phenomenon is found in the Pb region, where for the neutron $p_{1/2}$ state the calculated [12,14,15] correction is of order $\sim 0.2\mu_N$, compared with the experimental value of $0.05\mu_N$. The small changes observed for $p_{1/2}$ nuclei are related to the absence of nearby low angular momentum negative parity orbitals. The fact that, in ^{67}Ni, even this small correction is overestimated, provides evidence for the strength of the subshell closure at $N = 40$ in ^{68}Ni.

In conclusion, these critical measurements result from the first fully on-line experiment by the beta-NMR/ON technique, and also the first experiment to use detectors external to the cryostat in the study of an isotope for which no previous data existed. Such external detection is restricted to high energy [more than ~1.5 MeV] beta decay.

The results show conclusively the need to include both meson exchange current effects and core polarization in the description of deviations from single-particle Schmidt limits.

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