Magnetic Moments of Odd-A Sb Isotopes to ^{133}Sb: Significant Evidence for Mesonic Exchange Current Contributions and on Core Collective g Factors

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The magnetic moments of (double magic + 1 proton) nuclei having a "jack-knife" $j = l - s$ configuration form crucial tests for the theoretical treatment of mesonic exchange currents and core polarization effects in finite nuclei. The reported precision measurement and analysis of the magnetic moment of ^{133}Sb (^{132}Sn + one $g_{7/2}$ proton) $\mu = 3.00(1)\mu_N$ provides the first such test in medium-heavy nuclei. In addition, new data on the N dependence of the $7/2^+$ $^{123-133}$Sb ground state moments are presented. Analysis in terms of particle-core coupling indicates slightly negative collective g factors of heavy Sn core nuclei. [S0031-9007(96)02227-2]

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The magnetic moment of ^{133}Sb (double magic ^{132}Sn + one $g_{7/2}$ proton) is one of the very few experimental data capable of sensitively testing mesonic exchange current (MEC) and core polarization (CP) effects in finite nuclei. Measurement of this moment fills a critical gap between data in light nuclei $A \leq 41$ and the only equivalent moment in heavy nuclei, of ^{209}Bi (double magic ^{208}Pb + one $h_{9/2}$ proton). The large discrepancy ($+1.28\mu_N$) between the measured moment of ^{133}Sb and the Schmidt limit is reported and analyzed in terms of MEC and CP corrections. Results are comparable to data for ^{209}Bi. This Letter also reports new data and analysis on the variation of moments of the same basic $g_{7/2}$ state as neutron number N falls below $N = 82$ in the sequence $^{133-123}$Sb. Evidence is given for a small negative core collective g factor close to ^{132}Sn.

New techniques have made possible the determination of nuclear ground state moments in regions far from stability. The method of nuclear magnetic resonance on oriented nuclei (NMR/ON) uses a combination of low temperatures and high magnetic fields to achieve polarization of an ensemble of radioactive nuclei which, in these experiments, has been implanted into a pure iron foil. The angular distribution of radiation from the ensemble is given by

$$W(\theta) = 1 + f \sum_{\lambda=2}^{L} B_\lambda U_\lambda A_\lambda Q_\lambda P_\lambda(\cos\theta), \qquad (1)$$

where all symbols have their conventional meaning in the context of low temperature nuclear orientation [1]. Anisotropy of the distribution is defined as $[W(\theta)_C / W(\theta)_W] - 1$, where subscripts C and W denote normalized counting rates when the ensemble is cold (about 15 mK) and warm (about 1 K), respectively. The hyperfine field (B_{hf}) experienced by Sb nuclei in iron produces appreciable nuclear polarization below 20 mK. The quantization axis is defined by magnetization of the iron foil in an applied field B_{applied} of $\sim$0.5 T.

The polarization can be destroyed by the application of a modulated rf field applied normal to the quantization axis. As the rf frequency is varied, resonant absorption can be detected by reduction in the observed anisotropy. The technique is described in Ref. [2]. A fit to the center frequency ν_0 yields the magnetic moment of the oriented state through the relation

$$\nu_0 = \frac{|\mu|}{Ih}[B_{hf} + B_{\text{applied}}(1 + K)], \qquad (2)$$

where μ is the magnetic moment, I is the nuclear spin, and K is the Knight shift. Taking the known Korringa relaxation constant for ^{125}Sb in iron [3] and its relationship to the Knight shift, K can be estimated to be 2×10^{-3} for Sb in iron; sufficiently small to be neglected. The hyperfine field for Sb in iron has been measured by Koi *et al.* by spin-echo NMR [4]. We adopt the value $B_{hf} = +23.387(10)$ T measured for the $7/2^+$ ground state of ^{123}Sb, which has the same configuration as the isotopes studied here. Any hyperfine anomaly will be $\leq$0.1% and can be neglected.

The experiments were performed at the on-line orientation facility recently set up at the OSIRIS mass separator of the Uppsala University Neutron Research Laboratory

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at Studsvik, Sweden. The Sb activities were produced by thermal fission of neutron irradiated ^{235}U. The separated activity was implanted at 40 keV into rolled, polished, and annealed 99.99% pure Fe foils, soldered to the cold finger of the dilution refrigerator, maintained at temperatures between 11 and 15 mK. Temperatures were measured using a ^{54}Mn*Ni* nuclear orientation thermometer.

We present new results on the isotopes ^{131,133}Sb and improved results on ^{129}Sb. For ^{129}Sb $[T_{1/2} = 4.4h]$ we have fully on-line cold-implanted data and data from a sample implanted at room temperature. Both showed clear resonance signals with ν_0 lower than our previously reported value [5]. The weighted average value for the moment is $\mu(^{129}\mathrm{Sb}) = 2.79(2)\mu_N$. ^{131}Sb $[T_{1/2} = 23m]$ and ^{133}Sb $[T_{1/2} = 2.5m]$ can only be studied in fully on-line experiments with cold implantation. Results are shown in Fig. 1 yielding moment values $\mu(^{131}\mathrm{Sb}) = 2.89(1)\mu_N$ and $\mu(^{133}\mathrm{Sb}) = 3.00(1)\mu_N$.

Variations in linewidth, strength of resonance, and exact frequency of individual resonances reflect differing implantation and rf conditions and will be discussed in a later paper. Figure 2 shows the new results and related $7/2^+$ Sb ground state moments [6]. The smooth increase in magnetic moment as the closed shell value $N = 82$ is approached, in a direction away from the Schmidt limit value of $1.717\mu_N$, is clearly established. The measured moment value in ^{133}Sb exceeds the single-particle Schmidt limit by $1.283(24)\mu_N$. The origin of this large excess is twofold: core polarization and meson exchange currents. These are discussed in turn.

The ground state wave function, in addition to its single particle component, will have smaller components of $2p$-$1h$ and $3p$-$2h$ structure. To first order in the residual interaction, *V*, contributions to the calculated moment arise from these smaller components only when the particle-hole states are coupled to the same angular momentum as the multipolarity λ of the magnetic dipole operator, namely, $\lambda = 1$. The two possibilities at ^{132}Sn are proton $(g_{9/2}^{-1} g_{7/2})$ and neutron $(h_{11/2}^{-1} h_{9/2})$ states. Their contribution to the magnetic moment of ^{133}Sb to first and second order is given by the expression

$$\langle a \| \Delta \boldsymbol{\mu}^{(\lambda)} \| a \rangle = 2 \sum_{\alpha} T_\alpha \frac{L_\alpha}{\epsilon_\alpha} + 2 \sum_{\alpha\beta} T_\alpha \frac{(A - B)_{\alpha\beta}}{\epsilon_\alpha} \frac{L_\beta}{\epsilon_\beta}, \quad (3)$$

where Greek letters represent the particle-hole coupled states, viz. $|\alpha\rangle = |(h_\alpha^{-1} p_\alpha)\lambda\rangle$ of multipolarity λ and the following notation is introduced:

$$\begin{aligned} T_\alpha &= \langle 0 \| \boldsymbol{\mu}^{(\lambda)} \| (h_\alpha^{-1} p_\alpha)\lambda\rangle, \\ L_\alpha &= -\hat{a}^{-1} \langle (h_\alpha^{-1} p_\alpha)\lambda | V | (a^{-1} a)\lambda\rangle, \\ A_{\alpha\beta} &= \langle (h_\alpha^{-1} p_\alpha)\lambda | V | (h_\beta^{-1} p_\beta)\lambda\rangle, \\ B_{\alpha\beta} &= \langle 0 | V | (h_\alpha^{-1} p_\alpha)\lambda, (h_\beta^{-1} p_\beta)\lambda\rangle \\ &= (-)^{h_\alpha - p_\alpha + \lambda} \langle (p_\alpha^{-1} h_\alpha)\lambda | V | (h_\beta^{-1} p_\beta)\lambda\rangle, \\ \epsilon_\alpha &= \epsilon_{h_\alpha} - \epsilon_{p_\alpha}, \end{aligned} \quad (4)$$

where $\hat{a} = (2a + 1)^{1/2}$. Here a represents the valence $g_{7/2}$ proton orbital and the energy denominators ϵ_α are estimated from known spin-orbit splittings of -5.6 MeV for the proton g orbits and -5.85 MeV for the neutron h orbits. Full details of the calculation are given by Towner [7]. The residual interaction V is taken as a one-boson-exchange potential and, for finite nuclei, is multiplied by a short-range correlation function. Matrix

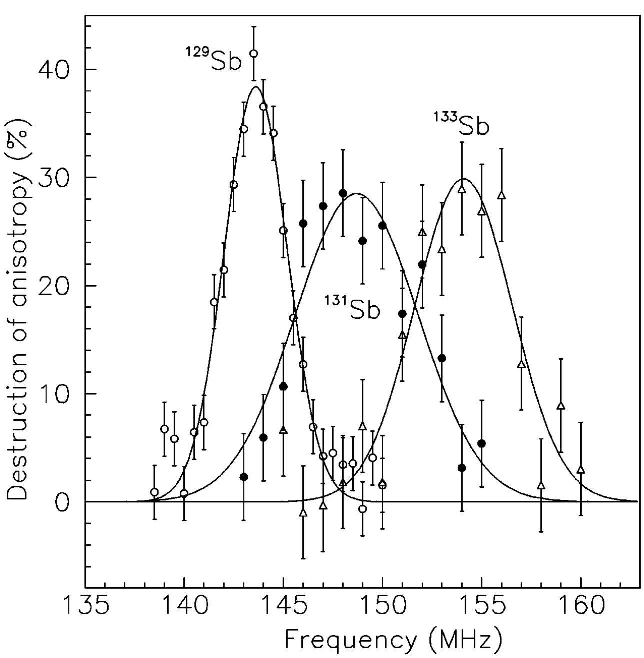

FIG. 1. NMR/ON resonance data for ^{129,131,133}Sb.

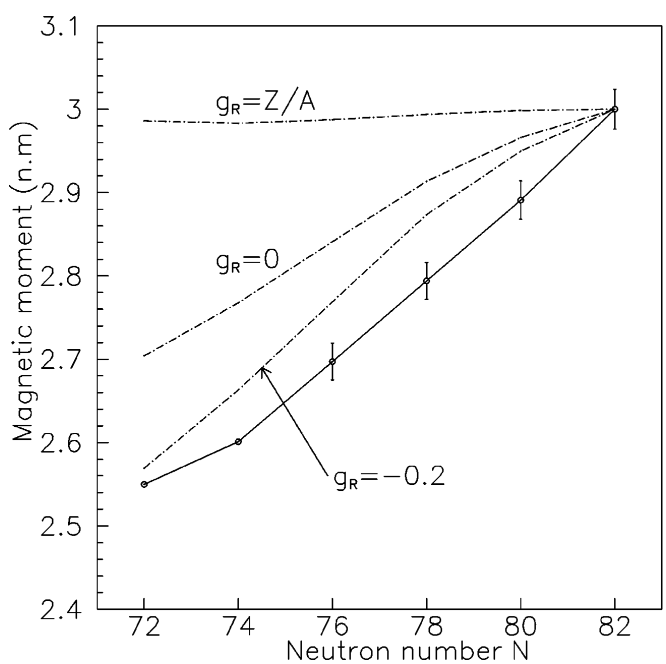

FIG. 2. Systematic variation of $\mu(\mathrm{Sb}\ g_{7/2})$ as a function of neutron number N. The broken lines show the results of particle-core coupling calculations described in the text.

elements are evaluated with harmonic oscillator radial functions of characteristic frequency, $\hbar\omega = 7.87$ MeV. The calculation, epitomized by Eq. (3), is extended to all orders in V in the random phase approximation (RPA).

The results can be expressed in terms of an effective magnetic moment operator

$$\boldsymbol{\mu}_{\rm eff}^{(\lambda)} = g_{l,{\rm eff}}\, l + g_{\rm s,eff}\, \mathbf{s} + g_{\rm P,eff}[Y_2, \mathbf{s}], \tag{5}$$

where $g_{l,{\rm eff}} = g_l + \delta g_l$, etc. There is a new term $[Y_2, \mathbf{s}]$, absent from the free-nucleon operator, which is a spherical harmonic of rank 2 coupled to the spin operator to form a spherical tensor of multipolarity 1. Results for the proton in the $g_{7/2}$ orbital in ^{133}Sb are given in Table I denoted CP(RPA). The published results for a proton in the $h_{9/2}$ orbital in ^{209}Bi are included for comparison. The very similar corrections δg_l, $\delta g_{\rm s}$, and $\delta g_{\rm P}$ for the Sn and Pb regions should be noted. In total the RPA calculation gives a correction of $+0.48\mu_N$ to the ^{133}Sb moment, only about 40% of the required amount, the main contribution arising from quenching of the spin g factor $g_{\rm s}$.

While core polarization corrects the nuclear wave function, by contrast, meson exchange currents correct the magnetic moment operator. Modifications arise because nucleons in nuclei interact through the exchange of mesons which can be disturbed by an electromagnetic field. Since meson exchange requires at least two nucleons, the correction leads to two-body magnetic-moment operators. In a (closed-shell-plus-one valence nucleon) nucleus, computation of this correction requires evaluation of the two-body matrix elements between the valence nucleon and one of the core nucleons, summed over all nucleons in the core. The results can be expressed in terms of an equivalent one-body operator acting on the valence nucleon alone.

The details of the two-body MEC operators are described in [7]. For consistency, the same mesons, coupling constants, masses, and short-range correlations are used in the construction of the MEC operators as are used in the one-boson-exchange potential V. The resulting g-factor corrections for ^{133}Sb are given in Table I. Once again, the similarity with results for the proton $h_{9/2}$ orbital should be remarked. The total correction amounts to $+0.52\mu_N$, about 40% of the required amount, but here the main contribution is an enhancement of the proton orbital g factor g_l.

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-isobar resonance, which is then deexcited by the electromagnetic field—the so-called isobar current. In Table I we see that isobar currents contribute a further 6% to the correction of the ^{133}Sb moment. Relativistic corrections to the one-body moment operator to order $(p/M)^3$, where p is a typical nucleon momentum and M its mass, also give a contribution to the magnetic moment. This has been estimated using harmonic oscillator wave functions. Although this term is very sensitive to the choice of wave function through involving a second derivative, it results in a small reduction of about 2% in the calculated moment (see Table I).

There are other second-order core-polarization corrections, CP(2nd), not contained in the RPA series that are difficult to compute because there are no selection rules to limit the number of intermediate states to be summed. Shimizu [8] has explored a closure approximation to estimate these terms. A further correction to the same order in meson-nucleon couplings is a core-polarization correction to the two-body MEC operator, MEC-CP. Fortunately, as Arima *et al.* [9] have pointed out, the latter terms largely cancel the former. In Table I we quote the results of Arima *et al.* [9] for the proton $h_{9/2}$ state outside the ^{208}Pb core. No calculations are available for a ^{132}Sn core. However, we can obtain an estimate of the CP(2nd) and MEC-CP terms by using the calculated g factors δg_l, $\delta g_{\rm s}$, and $\delta g_{\rm P}$ from the ^{208}Pb core and applying them at the ^{132}Sn core. Based on the similarity of these g factor corrections in the CP(RPA) and MEC calculations this procedure seems reasonable. Nevertheless, it is indeed fortunate that there is strong cancellation between CP(2nd) and MEC-CP such that the net contribution from these terms to the magnetic moment of ^{133}Sb is only of order 5%.

The final result of the calculation is in very satisfactory agreement with experiment, with the orbital g factor enhanced to $g_l = 1.138$ and the spin g factor $g_{\rm s}$ quenched to $0.651 g_{\rm s}^{(\rm free)}$.

TABLE I. Contributions to the effective magnetic-moment operator for a g proton in the Sn region and a h proton in the Pb region.

	Proton $g_{7/2}$				Proton $h_{9/2}$			
	δg_l	$\delta g_{\rm s}$	$\delta g_{\rm P}$	$\delta\mu$	δg_l	$\delta g_{\rm s}$	$\delta g_{\rm P}$	$\delta\mu$
CP(RPA)	0.008	−1.312	0.517	0.48	0.005	−1.167	0.481	0.45
MEC	0.185	0.581	−0.240	0.52	0.187	0.560	−0.346	0.72
Isobars	−0.004	−0.399	0.513	0.08	−0.003	−0.452	0.484	0.12
Rel	−0.023	−0.144	−0.038	−0.03	−0.024	−0.152	−0.041	−0.05
CP(2nd)[a]	−0.150	−1.030		−0.18	−0.150	−1.030		−0.32
MEC-CP[a]	0.122	0.352		0.34	0.122	0.352		0.46
Sum	0.138	−1.952	0.752	1.21	0.106	−2.227	0.578	1.36
Expt.				1.28				1.49

[a]Estimate from Ref. [9].

The variation of $g_{7/2}$ ground-state magnetic moments in the odd-mass Sb nuclei moving away from ^{133}Sb can shed light on the interplay between single-particle to collective contributions to the moment and give information on the nature of the collective nuclear magnetism through the collective g factor g_R. This picture assumes that the intrinsic single-particle parameters, e.g., the quenched spin g factor and the enhanced orbital g factor, will change only slowly over the limited interval $123 < A < 133$ for the Sb nuclei. This assumption is based on results of our earlier calculations of odd-A Sb and In nuclei [10].

Magnetic dipole moments are mainly modified, up to second order, by the admixture of (collective + single-particle) configurations. Using perturbation theory, an analytic expression can be obtained for the moment when a $|2^+ \otimes j'; j\rangle$ component is admixed into a $|j\rangle$ single-particle configuration [11]. For $j' = j$ we get

$$\mu(j) = \left(1 - \frac{3}{j(j+1)} \frac{\alpha^2}{1+\alpha^2}\right)\mu_{\rm sp}(j) + \frac{3}{2(j+1)} \frac{\alpha^2}{1+\alpha^2}\, \mu(2_1^+)\,, \tag{6}$$

where α is the collective admixture amplitude given by

$$\alpha = \sqrt{\frac{\pi}{5}}\, \xi_2 \frac{\langle j \| \hat{Y}_2 \| j \rangle}{\sqrt{2j+1}} \tag{7}$$

in terms of the quadrupole-core coupling strength ξ_2 and $\mu(2_1^+) = 2 g_R \mu_N$. Even though the single-particle contribution decreases with α, it can often occur that this effect is compensated by an increasing collective part, resulting in a rather flat variation of $\mu(j)$ with neutron number moving away from closed shell (see, e.g., Fig. 6(b), Ref. [11]).

In the particle-core coupling calculations, normalization of the calculation is achieved through accepting the g_l factor from the ^{133}Sb single particle plus mesonic calculation (as described above) and choosing g_s to fit the moment of ^{133}Sb, neglecting the g_P term. The change in g_s is small. This value of g_s is then used throughout. The quadrupole coupling strength ξ_2 is estimated from $B(E2)$ rates in neighboring nuclei. Octupole effects are small.

The resulting magnetic moments contain contributions from both single-particle and core terms, the size of the latter being determined by the choice of the collective g factor g_R. The value of g_R from collective motion is often taken to be Z/A, however, the calculated N dependence found using this value is strongly at variance with the measurements, as illustrated in Fig. 2.

Also shown are calculations taking $g_R = 0$ and -0.2. It is clear that the data support a negative value of g_R. This result points along the same lines as work of Sambataro and Dieperink [12], who approximated the 2_1^+ state in even-even Sn isotopes by a single neutron d-boson excitation. More microscopically, their predicted negative g factors of the very light ($N = 52, 54$) Sn nuclei can be related to a dominant presence of a $(\nu d_{5/2})^2$ configuration and that of heavy Sn nuclei to a significant contribution of a $(\nu h_{11/2})^2$ configuration.

In summary, a series of precise nuclear magnetic dipole moments in heavy Sb isotopes up to and including ^{133}Sb are reported. The magnetic moment of the pure [^{132}Sn + one $g_{7/2}$ proton] configuration in ^{133}Sb (the first such measurement between ^{41}Sc and ^{209}Bi) has been analyzed to show that the core-polarization RPA series terms and the lowest-order mesonic exchange currents provide the bulk of the renormalization of the magnetic moment. Other terms are collectively less than 10% of the single-particle Schmidt value and represent a measure of the uncertainty in the theoretical calculation.

The variation of the magnetic moments of the $g_{7/2}$ ground states of $^{123-133}$Sb has been interpreted as evidence for core contributions with negative collective g factors supporting microscopic calculation.

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