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Title:	Concerning the Magnetic Moments of Deformed Nuclei
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Abstract:

A comparison of experimental and calculated magnetic moments of odd-A spheroidal nuclei gives strong evidence that there is a reduction of the magnitude of the effective g_s factors by ~ 1.5 units below the magnitudes for free nucleons. The seriousness of Coriolis interaction effects on μ for one class of nuclei is also illustrated.

CONCERNING THE MAGNETIC MOMENTS OF DEFORMED NUCLEI*

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Mottelson and Nilsson have given a compilation of calculated and experimental magnetic moments of the odd-mass deformed nuclei.[1] We have examined the disagreements therein with respect to two principal questions: First, is there evidence that g_s factors "quenched" or reduced in magnitude are more appropriate than the free nucleon values traditionally assumed for such calculations? Second, are there significant deviations to be associated with configuration admixture of wave function components with differing K (angular momentum projection) quantum numbers?

That class of nuclei having particularly large j values for the odd nucleon will be especially susceptible to appreciable Coriolis mixing of different K-values.[2,3] Somewhat arbitrarily we shall single out in this class states of odd parity in the 50-82 shell ($h_{11/2}$), even parity in the 82-126 shell ($i_{13/2}$), and odd parity in the >126 shell ($j_{15/2}$). We list in Table I those nuclei not falling into the above class, and hence expected to be less subject to magnetic moment corrections arising from Coriolis effects. Also excluded are $I = \frac{1}{2}$ nuclei, which need a special analysis. The nuclei are grouped in the Table according to the asymptotic quantum number Σ (projection of intrinsic spin) in order best to display the contributions of the intrinsic spin to the magnetic moment calculations; i.e. $\langle \underline{S} \cdot \underline{I} \rangle$ is positive or negative accordingly as Σ is positive or negative.

We note that the deviations are of the same sign within each group. In the final column we calculate the g_s value that would be required to give exact agreement with the experimental moment. For the calculations we used Nilsson's wave functions,[1,4] at a deformation of $\delta = 0.3$ and assumed somewhat arbitrarily a g_R of Z/A for odd-Z and a g_R of Z/2A for odd-N.

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TABLE I

Deviations of μ from Mottelson - Nilsson Theoretical values.[1]

Class	Nucleus	E_{Kev}	I	μ_{theo}	μ_{exp}	Difference $\mu_{th} - \mu_{ex}$	Calculated g_s[a]
Odd-Z $\Sigma = +1/2$	Tb^{159}	0	3/2	2.2	± 1.5[b]	.7	2.2
	Ta^{181}	482	5/2	3.7	3.3	.4	4.5
	Re^{185}	0	5/2	3.7	3.14	$.5_6$	4.1
	Re^{187}	0	5/2	3.7	3.18	$.5_2$	4.2
Odd-Z $\Sigma = -1/2$	Eu^{153}	0	5/2	0.9	1.5	-.6	3.0
	Lu^{175}	0	7/2	1.4	2.0	-.6	3.9
	Lu^{177}	0	7/2	1.4	2.0	-.6	3.9
	Ta^{181}	0	7/2	1.5	2.1	-.6	3.6
	Np^{237}	60	5/2	1.0	1.4	-.4	3.7
	Am^{241}	0	5/2	1.0	1.4	-.4	3.7
	Am^{243}	0	5/2	1.0	1.4	-.4	3.7
Odd-N $\Sigma = +1/2$	Gd^{155}	0	3/2	- .5	- .30	-.2	-2.3
	Gd^{157}	0	3/2	- .5	- .37	$-.1_3$	-2.6
	Yb^{173}	0	5/2	- .8	- .67	$-.1_3$	-2.8
Odd-N $\Sigma = -1/2$	Dy^{163}	0	5/2	1.1	.51[b]	$.5_9$	-1.7
	Hf^{177}	0	7/2	1.4	.61	$.7_9$	-1.5
	U^{233}	0	5/2	.7	.51	$.1_9$	-2.3

a. This is the g_s value required to give exact agreement with the experimental magnetic moment using Nilsson's wave functions at $\delta = 0.3$ and assuming for odd-Z that $g_R = Z/A$ and for odd-N that $g_R = Z/2A$.

b. These μ values determined by paramagnetic resonance are probably too small in magnitude because $\langle r^{-3} \rangle$ values used were too large according to calculations by B. R. Judd and I.P.K. Lindgren (University of California, Lawrence Radiation Laboratory Report 9188, May 1960, unpublished).

The proton data of Table I strongly suggest that the effective g_s factor for protons in nuclear matter is roughly ~4 instead of the free value 5.585 customarily used. Such a change would bring the proton values of Table I into remarkably good agreement.

The neutron data are fewer and scatter more. This scatter is perhaps a reflection of the relatively greater Coriolis admixture in the neutron cases, or it may reflect an inadequacy of the Nilsson wave functions themselves. The sense of each deviation does, however, indicate that the magnitude of the effective g_s factor for the neutron in nuclear matter is less than the free value ($|g_s| = 3.826$) used in the calculations. The fact that the $\Sigma = +1/2$ neutron group deviates less than the $\Sigma = -1/2$ group suggests that the effective g_R value for the odd neutron nuclei should be reduced below the Z/A value.

At first thought the reduction of the collective motion g_R factor for odd-N and not for odd-Z nuclei seems unsymmetrical and unnatural. We would point out that g_R values determined for even-even nuclei in the rare earth region show values averaging less than Z/A. Thus the effective g_R for odd-Z nuclei may be somewhat larger than for neighboring even-even nuclei, and the g_R for odd-N nuclei, somewhat smaller. A <u>rationale</u> for such a g_R shift may be provided by considerations of the pairing correlations. That is, if we add an odd neutron to a deformed even-even nucleus we block one orbital from the neutron pairing correlation, reducing the effective energy gap for neutrons and altering the population of neutron orbitals by pairs in such a way as to increase the share of rotational angular momentum carried by the neutron pairs, relative to proton pairs. Such a change would reduce g_R. The same argument for odd-Z nuclei would give an increased g_R. Bernstein and deBoer have made an analysis of magnetic properties of deformed nuclei and find evidence for g_R being lower than Z/A for both odd-Z and odd-N but lowest in the odd-N.[5]

Magnetic moment calculations for odd-odd deformed nuclei such as Eu^{154}, Tb^{160}, and Lu^{176} have shown rather satisfactory agreement.[6] It should be pointed out that these nuclei, and indeed most of the ground states of odd-odd nuclei, obey the Gallagher-Moszkowski coupling rule,[7] that the intrinsic spins of proton and neutron are parallel. In this state the proposed reductions of g_s for proton and neutron will nearly cancel. Those odd-odd nuclear states with proton and neutron spins anti-parallel, such as the long-lived isomer in Ho^{166}, should show magnetic moments shifted from calculations using free-space g_s values.

The analysis of moments of the odd-A nuclei with larger Coriolis admixtures needs to take into account important odd-diagonal contributions to the magnetic moment. For example, the calculations[8] of Marshall fitting the even parity levels of Pa^{233} give a wave function for the 87-kev level ($I = 5/2+$) of $\psi = 0.94 \, |K = 5/2\rangle + 0.34 \, |K = 3/2\rangle + .09 \, |K = 1/2\rangle$. The principal effect of this K admixture on the magnetic moment comes from an off-diagonal contribution between $K = 5/2$ and $3/2$ components. This contribution we estimate as about + 1.1 nm. The calculated moment for the pure $K = 5/2$ state at deformation $\delta = 0.2$ using Nilsson's wave functions and $g_s = 4$ is + 2.6 nm. Taking into account all components we predict a magnetic moment of 3.8 nm. for the 87-kev state in Pa^{233}. This state has a half-life of 37 millimicro seconds, and its magnetic moment may be measurable by external field attenuation of α-γ angular correlation with Np^{237}. As another example the Coriolis mixing is not expected to be as large in the 5/2+ ground state of Np^{237}, perhaps $a_{3/2} \sim 0.1$, leading to a calculated magnetic moment of around + 3.0 nm. It will be noted that our theoretical moment is the same as that of Mottelson and Nilsson,[10] the effects of lowered g_s and Coriolis mixing exactly cancelling each other. Experimental measurements are $+ 6 \pm 2.5$ nm.[9] and $\mu = 2.70$ nm.[10]

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