Nuclear Moments and Their Dependence upon Atomic Number and Mass Number

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(Received June 27, 1933)

Nuclei are grouped into four classes depending upon whether Z and M (atomic number and mass number, respectively) are even or odd. A summary of the nuclear mechanical and magnetic moments which have been experimentally observed is given. This summary indicates similarities within each nuclear class and definite differences between classes both as to mechanical and magnetic moments and to nuclear g-factors. These results suggest a correlation between nuclear moments and the periodic table; namely, that nearly all nuclei which have large magnetic and mechanical moments lie in columns of the periodic table with Z odd, while nuclei occurring in columns for which Z is even generally have zero, or small magnetic moments and zero, or small mechanical moments. The incompleteness of the present data is emphasized.

RAPID progress has been made recently in the determination of nuclear moments from spectroscopic data, particularly so regarding the calculation of nuclear magnetic moments.[1, 2, 3] In this connection Goudsmit's paper merits particular mention for it is the first extensive attempt to calculate nuclear magnetic moments from hyperfine structure data. A still more recent paper by Fermi and Segrè[3] on nuclear magnetic moments is in excellent general agreement with Goudsmit's calculations. Other recent progress has included the determination of nuclear mechanical moments for a number of additional nuclei. Since nuclear moments are of especial interest in connection with the development of nuclear theory, it has seemed profitable at this time to attempt some organization of the data, even though these data are as yet far from complete.

All nuclei fall into four classes, depending upon whether Z (the atomic number) and M (the mass number) are even or odd. For the present it seems to be safest to adopt this system of nuclear classification since it is quite independent of any particular nuclear model. These four nuclear classes, together with a summary of the nuclear magnetic and mechanical moments which have been observed for each class, are given in Table I. The results for a number of nuclei of each class are also given. It does not seem worth while to include an exhaustive list at this time, for many of our present values are somewhat uncertain and additional results are being obtained so rapidly that no such table would long have any claim to completeness. *The experimental results that have been obtained to date indicate definite similarities within each nuclear class and differences between classes both as to nuclear mechanical and magnetic moments and to nuclear g-factors.* These similarities and differences, because of the incompleteness of the data, must not be over-emphasized; however, they may well serve as a guide in the development of certain phases of nuclear theory.

Nuclei of class I (Z even, M even) have integral mechanical moments (only zero observed) and zero (or very small) magnetic moments. From band spectra, a number of the lighter nuclei of this class up to $Z=16$ have been studied and all definitely have $I=0$. The line spectra of a number of elements up to $Z=82$ have been examined under high resolving power and in no case has any hyperfine structure for members of this class been observed. This lack of structure is particularly striking in such cases as the even isotopes of cadmium, mercury and lead where the odd isotopes (members of class III) *do* show definite structure. This lack of hyperfine structure for nuclei of class I must mean then that either $I=0$ (in keeping with the results from

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[1] Goudsmit, Phys. Rev. **43**, 638 (1933).
[2] Breit and Wills, Bull. Am. Phys. Soc. **8**, No. 2, paper 21.
[3] Fermi and Segrè, Zeits. f. Physik **82**, 729 (1933).

TABLE I. *Classification of nuclei and nuclear moments.*

Element	Atomic number Z	Mass number M	Mechanical moments ($X\ h/2$)	Magnetic moments (proton magnetons)	Nuclear g-factors
Class I	even	even	0 (band spectra)	—	—
He	2	4	0 (band spectra)	—	—
C	6	12	0 (band spectra)	—	—
O	8	16	0 (band spectra)	—	—
S	16	32	0 (band spectra)	—	—
even isotopes of Cd, Hg, Pb, Mo, W, etc.			0 from h.f.s.	—	—
Class II	odd	odd	half integral (from 1/2 to 9/2 observed)	positive varied magnitude	positive-varying from nearly zero to 4.2; I small, g large; I large, g small
Al	13	27	1/2	2.1	4.2
Tl	81	203, 205	1/2	1.8	3.6
Cu	29	63, 65	3/2	2.5	1.7
Sb	51	121	5/2	2.7	1.1
		123	7/2	2.1	0.6
Bi	83	209	9/2	4.0	0.89
Class III	even	odd	half integral (from 1/2 to 5/2 observed)	positive and negative, smaller values than class II	positive and negative—small (from +1.2 to −1.33 obs.)
Pb	82	207	1/2	0.60	1.20
Hg	80	199	1/2	0.55	1.1
		201	3/2	−0.62	−0.41
Cd	48	111, 113	1/2	−0.67	−1.33
Ba	56	137	5/2	1.0	0.4
Class IV	odd	even	integral	small	small
N	7	14	2/2	0.2 or less	$+0.2 > g > -0.2$
H	1	2	2/2	—	—

band spectra) or that if $I \neq 0$, then the nuclear magnetic moments can be very little different from zero. It is quite important to settle this question definitely for to date there appears to be no adequate reason why all nuclei of class I should have zero mechanical moments, nor indeed is there adequate proof that such is actually the case.

Nuclei of class II (Z odd, M odd) have half-integral mechanical moments, positive magnetic moments of varied magnitude and positive nuclear g-factors. Mechanical moments from 1/2 to 9/2 have been observed and g-factors from about 4 down nearly to zero. It is interesting and possibly significant that highest g-factors have been found for nuclei where I is small (e.g., Al and Tl, where $I = 1/2$), whereas for those nuclei in which I is large (9/2), g is small (e.g., Bi and In). It is also interesting that a number of nuclei in this class have large I values. We[4] have recently investigated four nuclei of this class, Co^{59}, Cb^{93}, La^{139} and Ta^{181} and have found each to have an I value of at least 7/2, while for Co and Cb, I may well be larger.

Nuclei of class III (Z even, M odd) have half integral I values and positive and negative g-factors. In nearly every case examined to date the I values are small (1/2 or 3/2), and the g-factors are also rather small (ranging from +1.2 to −1.3), which means that the nuclear magnetic moments are small. We[4] have recently carried out experiments on some other nuclei of this class Cr^{53}, Mo^{95}, Mo^{97} and W^{183} and have found that their nuclear magnetic moments are all small. It is interesting to note that the only negative nuclear g-factors that have been found occur in this class. Nuclear g-factors in class III (as in class II) are somewhat larger in magnitude for small I values than for large I values.

Nuclei of class IV (Z odd, M even) have integral spins and small magnetic moments. According to Krönig[5] and others, N^{14}, and

[4] Grace, Phys. Rev. **43**, 762 (1933); Grace and Ballard, Grace and More, White and Anderson, Bull. Am. Phys. Soc. **8**, No. 3, papers 2, 3 and 4; Grace and McMillan, Bull. Am. Phys. Soc. **8**, No. 4, paper 54; Grace and White, Phys. Rev. **43**, 1039 (1933).

[5] Krönig, Naturwiss. **16**, 335 (1928).

according to Lewis and Ashley,[6] H^2, have spins of $(2/2)(h/2\pi)$ from band spectra. From the absence of hyperfine structure Bacher[7] has found N^{14} to have an extremely small nuclear magnetic moment. The relative abundance of the homonuclear molecule Li^6Li^6 in lithium vapor is so small that the spin of Li^6 has not yet been determined from band spectra. Li^6 shows no hyperfine structure in the spectrum of Li II where Li^7 shows very wide structure. This means for Li^6 that either $I=0$, or that if $I\neq 0$, then the magnetic moment of Li^6 can differ only very slightly from zero.

In Fig. 1 nuclear magnetic moments are plotted against mechanical moments. Most of the results are taken from Goudsmit's paper[1] in which he states that the data are only preliminary in nature. There may, therefore, be a considerable change in the numerical values of some of the magnetic moments; it seems improbable, however, that any such change will be sufficient to alter completely the general arrangement shown in Fig. 1, where the magnetic moments of classes II and III group themselves rather separately.

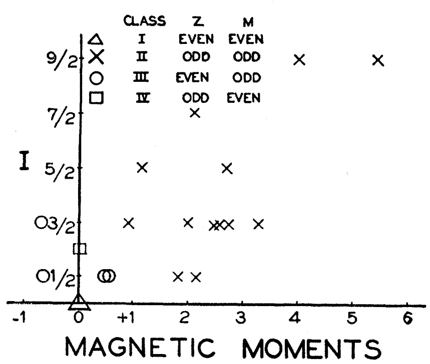

FIG. 1.

Table II is a rather complete summary of the results that have been obtained on nuclear mechanical moments to date. It shows that there are relatively many more nuclei in class II that have large I values than there are in class III. In class II four of the nuclei with $I=1/2$ have $Z\leq 15$, while ten of those with $I=3/2$ have $Z\leq 37$. Thus most of the small I values in class II are found for elements of rather low atomic number. This is somewhat analogous to the normal states of extranuclear electrons where elements with low atomic number generally have rather low J values. In class III most of the I values have been determined for nuclei of moderately large atomic number, making the difference between classes II and III even more pronounced. Since nuclear magnetic moments depend directly upon the values of I, the smaller I values found for nuclei of class III will in part explain their smaller magnetic moments. If, however, we compare nuclei with the same I value (e.g., $I=1/2$ or $3/2$ in Fig. 1) we find that nuclei of class II have the larger magnetic moments and consequently the larger g-factors.

TABLE II. *Summary of experimental I values.*

I values	1/2	3/2	5/2	7/2	9/2
No. of nuclei in class II	6	11	9	6	3
No. of nuclei in class III	6	2	2 (?)		

The results in Tables I and II and in Fig. 1 suggest a correlation between nuclear properties and the periodic table; namely that *nearly all nuclei which have large magnetic and mechanical moments lie in those columns of the periodic table for which Z is odd, while nuclei found in columns with Z even generally have small, positive or negative (or zero) magnetic moments and rather small (or zero) mechanical moments.* There is, then, more or less of an alternation of nuclear moments throughout the periodic table as Z alternates from odd to even. While it is not our intention at this time to attempt an explanation of these suggested generalizations, yet it seems probable that their true explanation does depend upon whether the total numbers of constituent particles (such as protons and neutrons) within nuclei are odd or even.

The results on N^{14} have been interpreted by Heisenberg and others as indicating that neutrons as well as protons, within complex nuclei, may possess a mechanical moment of $(1/2)(h/2\pi)$. This suggestion may be supported by $I=2/2$ for H^2 and by the half integral I values of nuclei of class III. The small magnetic moment of N^{14} (coupled with the fact that $I=2/2$) has been interpreted by Bacher[7] on the assumption that the neutron possesses a magnetic moment of

[6] Lewis and Ashley, Phys. Rev. **43**, 837 (1933).
[7] Bacher, Bull. Am. Phys. Soc. **8**, No. 2, paper 22.

magnitude comparable with that of a proton but opposite in sign. This suggestion may find some support from the experimental result that negative nuclear g-factors have been observed only for certain members of class III (nuclei which present nuclear models would indicate contain an odd number of neutrons). If the neutron resembles the electron in having a magnetic moment which is anti-parallel to its mechanical moment, then obviously if the mechanical moments of a neutron and proton add, their magnetic moments oppose (e.g., N^{14}), while if their mechanical moments oppose, then their magnetic moments add. This possibility may explain, at least in part, the results observed in class II, where highest g-factors are observed when I is small and nuclei with high I values generally have rather small g-factors.

Landé,[8] Venkatesachar and Subbaraya[9] and others have considered the possibility of neutron shells within complex nuclei, while Venkatesachar[9] has attempted some correlation between I values and the numbers of neutrons present in incomplete outer shells. It is hoped that such a correlation might permit one to decide whether particles possess orbital angular momentum within nuclei or whether the observed I values can be quantitatively accounted for merely on the basis of their spin moments. It would, however, seem to the writer that for such a correlation we need more complete and more accurate data, for in a number of cases the present uncertainty in I amounts to as much as 2/2 and sometimes even more.

It is a great pleasure to thank Mr. A. C. Nixon of the Chemistry Department and Professor H. E. White, Mr. S. S. Ballard and Dr. E. M. McMillan of the Department of Physics for their help in the organization and presentation of the material included in this paper.

[8] Landé, Phys. Rev. **43**, 620 and 624 (1933).

[9] Venkatesachar and Subbaraya, Cur. Sci. **1**, 120 (1932).