Magnetic Moments of Even-Odd Nuclei

JACK P. DAVIDSON*
Physics Department, Washington University, St. Louis, Missouri
(Received October 22, 1951)

The deviations of nuclear magnetic moments from the Schmidt limits are interpreted in terms of a failure of L–S coupling, and a simple interpolation procedure is applied to compute the statistical weight of the components with $L=I+\frac{1}{2}$ and $L=I-\frac{1}{2}$. The results below odd N or $Z=53$ are sufficiently regular to be used to compute the magnetic moments of several odd neutron nuclei.

THE ground states of odd A nuclei are generally considered to be predominantly of the doublet type. A possible small quartet component is usually neglected. In the pure doublet approximation the wave function is

$$\Psi_I=\alpha\Psi_{L=I-\frac{1}{2}}+(1-\alpha^2)^{\frac{1}{2}}\Psi_{L=I+\frac{1}{2}} \tag{1}$$

a linear combination of pure L–S coupling states with the two possible values of orbital angular momentum $I-\frac{1}{2}$ and $I+\frac{1}{2}$, both components having the same parity. If one pure L–S coupling component can be described more or less accurately as representing a single particle interacting with a symmetrical core of even parity, the other component necessarily has a many particle character in order to obtain the same parity in both components.

In mirror nuclei ($N'=Z$, $Z'=N$) the observed symmetrical behavior of spins and moments suggests the working hypothesis

$$\alpha(N',Z')=\alpha(N,Z). \tag{2}$$

More generally we consider the possibility that

$$\alpha(N_{\text{odd}})=\alpha(Z_{\text{odd}}) \tag{3}$$

for $N_{\text{odd}}=Z_{\text{odd}}$.

The magnetic moment μ can be calculated from α and the orbital gyromagnetic ratios $g_{L=I\pm\frac{1}{2}}$. Conversely, if values are assigned to $g_{L=I\pm\frac{1}{2}}$, α can be computed from the experimental magnetic moment.

Recently Schawlow and Townes[1] predicted the magnetic moments for a group of odd neutron nuclei assuming

$$\begin{aligned} g_L&=1,\ \text{odd } Z\\ &=0,\ \text{odd } N \end{aligned} \tag{4}$$

and determining α from Eqs. (2) or (3) and the experimental values of the moments for other odd neutron and proton nuclei. This procedure reduces the calculation of α^2 to a linear interpolation between Schmidt limits associated with opposite parity.

One may accept this interpolation procedure as a useful working rule without asserting that parity is not a good quantum number. However, it seems preferable to adopt an interpolation procedure which uses only one Schmidt limit since only one of the two pure L–S components can approximate to the single particle description. The uniform model of Margenau and Wigner is adopted for the other limit (with $g_L\sim Z/A$).

In accordance with this modified interpolation procedure the quantity

$$\Delta_{\text{S-MW}}=(\mu-\mu_{\text{S}})/(\mu_{\text{S}}-\mu_{\text{MW}}) \tag{5}$$

is interpreted as α^2 or $1-\alpha^2$ depending on the location of the experimental moment μ relative to the Schmidt limits; μ_{S} is the nearby Schmidt limit while μ_{MW} is the opposite MW limit.[2] Figure 1 shows a plot of $\Delta_{\text{S-MW}}$ against the odd member of the N, Z pair. A vertical line at odd N or $Z=53$ divides the diagram into two parts: region A in which there are significant regularities and region B in which the situation is confused

TABLE I. Predicted nuclear magnetic moments for several odd-neutron nuclei. Spins have been assigned from similar odd-proton nuclei.

Number of odd neutrons	Spin	Parity	Predicted magnetic moment
3	3/2	odd	-1.59 ± 0.09
11[a]	3/2	even	-0.73 ± 0.08
15	1/2	even	-0.62 ± 0.07
19	3/2	even	0.98 ± 0.07
21	7/2	odd	-1.36 ± 0.12
23	7/2	odd	-1.17 ± 0.12
25	5/2	odd	0.87 ± 0.06
27	7/2	odd	-1.20 ± 0.12
29	3/2	odd	-0.85 ± 0.09
31	3/2	odd	-0.66 ± 0.09
33	3/2	odd	-0.10 ± 0.09
35	3/2	odd	-0.62 ± 0.09
39	1/2	odd	0.48 ± 0.07
41	9/2	even	-1.61 ± 0.14
45	1/2	odd	0.52 ± 0.07
51	5/2	even	-0.58 ± 0.11
51	7/2	even	0.83 ± 0.06

[a] Many-particle limits used.

* Washington University Fellow.

[1] A. L. Schawlow and C. H. Townes, Phys. Rev. 82, 268 (1951).

[2] In the case of P^{31} and I^{127} the observed values of μ lie nearly midway between the single-particle limits. These points are computed from Eq. (5) using μ_{S} associated with even parity in agreement with shell model parity assignments. For As^{75} odd parity is assigned in agreement with the shell model even though the even parity Schmidt limit is slightly closer. Na^{23} has a predominantly ${}^2P_{3/2}$ ground state in a region where ${}^2D_{5/2}$ ground states are the rule. In the context of d orbits for neutrons and protons outside of the O^{16} core both pure L–S components of the Na^{23} ground state must be given a many particle interpretation. Thus it seems necessary here to modify the interpolation rule; Eq. (5) is replaced by interpolation between the two MW limits. Similarly Mn^{55}, in a region where ${}^2F_{7/2}$ states are common, is predominantly ${}^2D_{5/2}$. Nevertheless Eq. (5) is used, somewhat arbitrarily, to compute the point at $Z=25$ in Fig. 1 since alternative procedures such as that used on Na^{23} yield very small values for $\Delta_{\text{S-MW}}$.

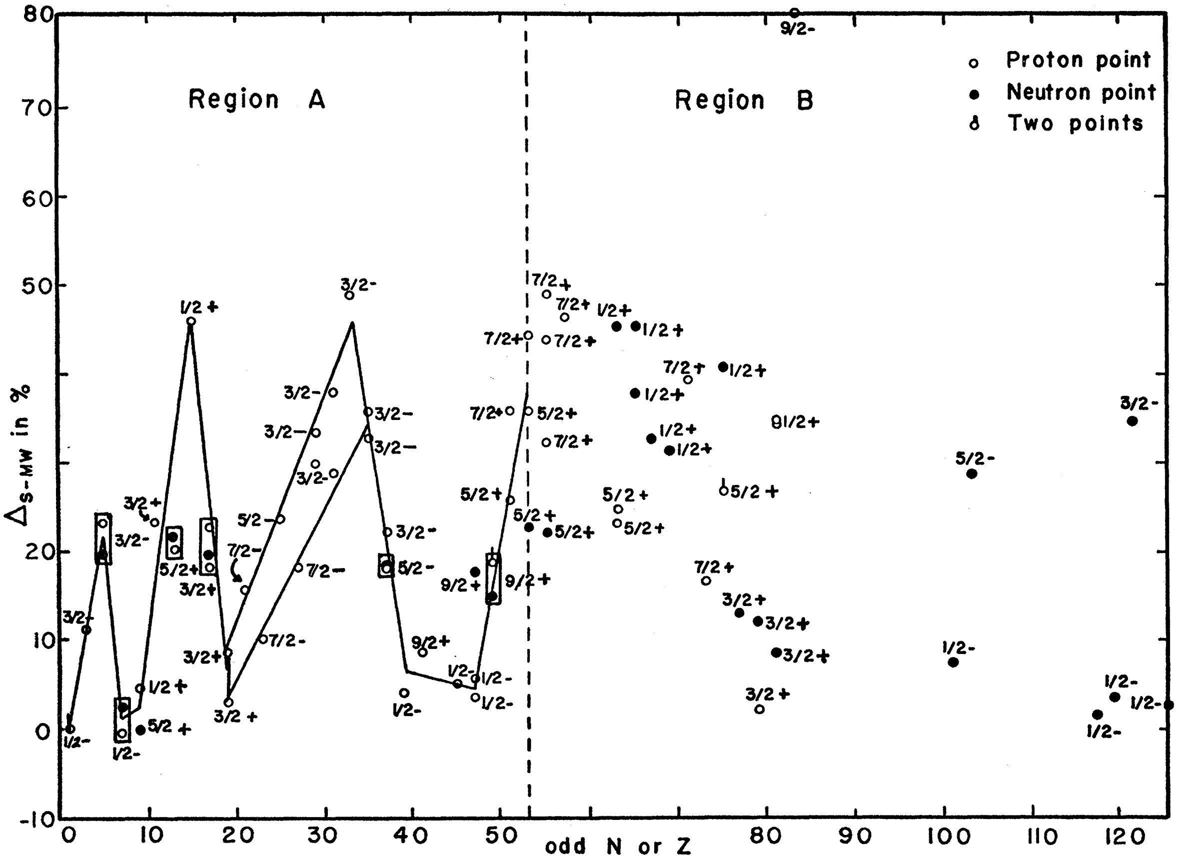

FIG. 1. $\Delta_{S-MW}=(\mu-\mu_S)/(\mu_S-\mu_{MW})$, with μ the experimental moment, μ_S the nearest Schmidt limit and μ_{MW} the opposite MW limit, plotted against the odd member of the N, Z pair. The vertical line at 53 divides the diagram into two regions: region A in which there are significant regularities and region B in which the situation is confused. The groups of points representing $N_{odd}=Z_{odd}$ with the same spin have been enclosed in boxes for emphasis. The $\pm$ signs indicate parity assignments.

and Eq. (3) apparently fails. In region A the shell structure is evident with a minimum in the graph appearing just before closed shells at 8, 20, and 50. There is, however, no indication of the closed shell at 28. Also the values of Δ_{S-MW} for $N_{odd}=Z_{odd}$ lie close together, especially when both nuclei have the same spin. Such points are enclosed in boxes for emphasis. Points for H^3 and He^3 are omitted since exchange currents are thought to account for a substantial part of the small deviations from the Schmidt limits.

The close similarity between odd N and odd Z nuclei evident in Fig. 1 suggests using the diagram to predict magnetic moments of odd neutron nuclei for $N<53$. The results appear in Table I where the uncertainty in the predicted values is computed by assuming that the variations from the curve in Fig. 1 do not exceed $\pm 2\frac{1}{2}$ percent. The spins are taken to be the same as for the corresponding odd proton nuclei (hence for $N=51$ two values of μ are computed, one for each of the two spin values observed for $Z=51$) while parities are derived from the shell model. The predicted values of the odd neutron magnetic moments are plotted in Fig. 2 against spin in the usual manner. Finally, it should be noted that if an isotope of $_{47}$Ag should be found with spin 9/2 its magnetic moment could be calculated from the experimentally observed odd neutron point at $N=47$ with spin 9/2. A similar calculation could also be done

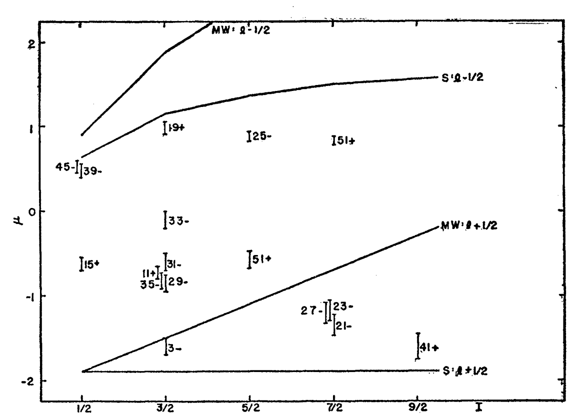

FIG. 2. The predicted values of the nuclear magnetic moment, in nuclear magnetons, for several odd neutron nuclei is plotted against the nuclear spin I. The uncertainty in the predicted values is computed by assuming that the variations from the curve in Fig. 1 do not exceed $\pm 2\frac{1}{2}$ percent. The $\pm$ signs indicate parity assignments.

for an isotope of ${}_9F$ with a spin 5/2, making use of the odd neutron point $N=9$, if such an isotope is discovered.

Unpublished work by Trigg[3] on the theory of allowed favored beta-transitions provides an independent check on the ideas and semi-quantitative relations expressed in Eqs. (1), (2), and (5). Trigg finds that the deviations from L–S coupling estimated from Eq. (5) result in values for the nuclear matrix element $|M|^2$ of the mirror nuclei beta-decay transitions such that $ft|M|^2$ is relatively constant.

Several authors[4–6] have suggested that the nucleons lose a substantial portion of their anomalous magnetic moment in complex nuclei. This effect, if it occurs, should show up most clearly just before and just after the closing of shells where the single particle picture is expected to be most reliable. However, the magnetic moments of C^{13}, N^{15}, O^{17}, F^{19}, K^{41}, Y^{89}, and Pb^{207} are all close to the appropriate Schmidt limits computed for nucleons with the observed free nucleon moments. These examples would seem to place a fairly small upper limit on the size of the suggested effect.

The author wishes to express his sincere appreciation to Professor E. Feenberg for many helpful suggestions and discussions.

[3] G. L. Trigg, Doctor's thesis, Washington University, 1951.
[4] F. Bloch, Phys. Rev. **83**, 839 (1951).
[5] H. Miyazawa, Prog. Theor. Phys. **6**, 263 (1951).
[6] A. de Shalit, Helv. Phys. Acta **24**, 296 (1951).

PHYSICAL REVIEW VOLUME 85, NUMBER 3 FEBRUARY 1, 1952

The Disintegration of Lithium by Deuteron Bombardment*

L. M. BAGGETT† AND S. J. BAME, JR.†
Rice Institute, Houston, Texas
(Received October 25, 1951)

Thin target excitation curves for the $Li^7(d,n)$, $Li^6(d,n)$, and $Li^7(d,p)$ reactions are presented. The neutron data were taken at 90° to the deuteron beam using a BF_3-filled proportional counter in the long geometry. Resonances were observed in the $Li^6(d,n)$ reaction at 0.41 and at 2.12 Mev, in the $Li^7(d,n)$ reaction at 0.68, 0.98, and 2.1 Mev, and in the $Li^7(d,p)$ reaction at 0.75, 1.00, and 1.4 Mev. These resonances correspond to excited states in Be^8 at 22.58 and 23.86 Mev and in Be^9 at 17.22, 17.45, 17.8, and 18.3 Mev. The cross section of the resonances observed in the $Li^6(d,n)$ reactions were 9 and 41 millibarns/steradian, those for the $Li^7(d,n)$ reaction were 39, 43, and 58 millibarns/steradian, and those for the $Li^7(d,p)$ reaction were 0.230, 0.235, and 0.255 barn.

I. INTRODUCTION

THE disintegration of lithium by deuterons has been extensively studied. Recently Whaling, Evans, and Bonner[1] observed the neutrons emitted in the $Li^6(d,n)$ reactions. They detected the neutrons emitted in the direction of the deuteron beam by means of the argon recoils in a proportional counter filled with argon at atmospheric pressure and biased to count neutrons greater than 1 Mev. Whaling and Bonner[2] studied the alpha-particles from the reaction $Li^6(d,\alpha)\alpha$ and the protons from the reaction $Li^6(d,p)Li^7$. They obtained excitation functions over the energy range from 190 kev to 1600 kev using a 150 micrograms per cm^2 $Li^6{}_2SO_4$ target enriched to 95 percent Li^6. These excitation curves showed evidence for a level in Be^8 at 22.46 Mev.

The neutrons from the $Li^7(d,n)Be^8$ reaction have been studied by Bennett, Bonner, Richards, and Watt,[3] and by Whaling, Evans, and Bonner.[1] Both of these groups observed the neutrons in the direction of the deuteron beam. The beta-particles from the reaction $Li^7(d,p)Li^8$ were also studied by Bennett, Bonner, Richards, and Watt.[3] Their excitation curve indicated that a resonance might possibly exist at 1.35-Mev deuteron bombarding energy. However, their data did not extend far beyond 1.35 Mev so the evidence was not considered conclusive.

The work to be described in this paper was undertaken with the hope of expanding the knowledge of lithium disintegration by observing the neutrons from a thin target at an angle to the deuteron beam differing from that of previous observations, and by using a neutron counter that was more uniformly sensitive to neutron energies over a wide range.

II EXPERIMENTAL METHODS

The Li^7 target used in these experiments consisted of 51 micrograms per cm^2 of normal Li_2SO_4 evaporated on a silver disk. The Li^6 target was 95 micrograms per cm^2 of Li_2SO_4 enriched to 95 percent Li^6. The Li^6 was kindly loaned to us by the Isotopes Branch of the Oak Ridge National Laboratories. Since Li_2SO_4 is hygroscopic, picking up one water molecule for every Li_2SO_4 molecule, there is a 20 percent uncertainty in the weight of these targets. Since the targets were weighed immediately after evaporation, all the calculations are based on the assumption that the Li_2SO_4 had not picked up any

* Supported by the joint program of the ONR and AEC.
† Now at the Los Alamos Scientific Laboratory, Los Alamos, New Mexico.
[1] Whaling, Evans, and Bonner, Phys. Rev. **75**, 688 (1949).
[2] W. Whaling and T. W. Bonner, Phys. Rev. **79**, 258 (1950).
[3] Bennett, Bonner, Richards, and Watt, Phys. Rev. **71**, 11 (1947).