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# Correlations between magnetic moments and $\beta$ decays of mirror nuclei

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We examine the magnetic moments and $\beta$-decay lifetimes of light $T = \frac{1}{2}$ mirror nuclei and obtain very tight correlations between these quantities by making use of shell-model estimates for small quantities. Using the information thus obtained, we predict values for some unknown magnetic moments of heavier $T = \frac{1}{2}$ mirror nuclei. Correlations for the magnetic moments of some $T = \frac{3}{2}$ mirror nuclei are also included. The effective operators required to reproduce the data are discussed and compared to those obtained with other methods.

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## I. INTRODUCTION

The data on magnetic moments of the ground states of light mirror pairs, as well as on the corresponding superallowed $\beta$-decay lifetimes, summarized in Ref. [1], have increased in quantity and quality in recent years [2–11]. These improvements are, however, becoming more difficult to make as the mass increases and the mirror pairs fall away from the line of stability. It is thus of interest to have accurate predictions of missing information, conventionally obtained from large scale shell-model calculations [12–14]. We employ here a different method of generating these predictions [1,15] by making a novel use of shell-model estimates for *small* quantities. This results in plots that show strong linear relationships between the data for magnetic moments and Gamow-Teller $\beta$-decay matrix elements of mirror nuclei with $T = 1/2$.

When isospin is conserved the magnetic moments of mirror nuclei (in units of $\mu_N$ ) can be written as [15]

$$\mu_p = g_p J + (G_p - g_p)(S_o - S_e) + [(G_p - g_p + G_n - g_n)S_e - (g_p - g_n)J_e] \quad (1)$$

and

$$\mu_n = g_n J + (G_n - g_n)(S_o - S_e) + [(G_p - g_p + G_n - g_n)S_e + (g_p - g_n)J_e], \quad (2)$$

where $\mu_p$ and $\mu_n$ are the magnetic moments of the odd-proton and odd-neutron members of the odd-even mirror pair. The free-nucleon values of the $g$ factors are $g_p = 1.0$, $g_n = 0.0$, $G_p = 5.586$, $G_n = -3.826$. $S_{e/o}$ and $J_{e/o}$ are the contributions from the even/odd type of nucleon to the $z$ components of the total spin $S$ and total angular momentum $J$ of the mirror pair.

Because the quantities $S_e$ and $J_e$ are small [16], we rewrite Eqs. (1) and (2) in terms of corrections to the gyromagnetic ratios $\gamma_{p/n} = \mu_{p/n}/J$ in the form

$$(\gamma_p + \Delta\gamma_p) = g_p + (G_p - g_p)(S_o - S_e)/J \quad (3)$$

and

$$(\gamma_n + \Delta\gamma_n) = g_n + (G_n - g_n)(S_o - S_e)/J, \quad (4)$$

where

$$\Delta\gamma_p = -[(G_p - g_p + G_n - g_n)S_e - (g_p - g_n)J_e]/J \quad (5)$$

and

$$\Delta\gamma_n = -[(G_p - g_p + G_n - g_n)S_e + (g_p - g_n)J_e]/J. \quad (6)$$

Eliminating $(S_o - S_e)$ from Eqs. (3) and (4) we find

$$(\gamma_p + \Delta\gamma_p) = \alpha(\gamma_n + \Delta\gamma_n) + \beta, \quad (7)$$

with $\alpha = (G_p - g_p)/(G_n - g_n)$ and $\beta = g_p - \alpha g_n$.

For $T = \frac{1}{2}$ mirror pairs, the quantity $(S_o - S_e)$ is related to the Gamow-Teller matrix element for the cross-over $\beta$ decay obtained from the $ft$ value:

$$\frac{S_o - S_e}{J} = \frac{\gamma_\beta}{R}, \quad (8)$$

where

$$|\gamma_\beta| = \frac{1}{2}\sqrt{\left(\frac{6170}{ft} - 1\right)\frac{1}{J(J+1)}}, \quad (9)$$

with a sign that can be determined from systematics [1,15]. The free-nucleon value for $R$ is $R = |C_A/C_V| = 1.26$. Thus for $T = \frac{1}{2}$ mirror pairs, Eqs. (3) and (4) can be written as

$$(\gamma_p + \Delta\gamma_p) = g_p + \frac{G_p - g_p}{R}\gamma_\beta \quad (10)$$

and

$$(\gamma_n + \Delta\gamma_n) = g_n + \frac{G_n - g_n}{R}\gamma_\beta. \quad (11)$$

We assume that for nucleons in nuclei we may replace the free-space $g$ factors and the ratio $R = |C_A/C_V|$ by a set of effective values denoted by $\tilde{G}$, $\tilde{g}$, and $\tilde{R}$. (The effective operator may also include terms proportional to the rank-one operator $[Y^2 \otimes \sigma]^1$. But based on the previous analysis of the size of these contributions [17] for magnetic moments, they are much smaller than the terms we do consider and are not included.)

We use the linear relations of Eqs. (10) and (11) to determine the parameters $\tilde{g}$ and $(\tilde{G}-\tilde{g})/\tilde{R}$ for protons and neutrons from least-square fits to $\gamma+\Delta\gamma$ and $\gamma_\beta$. In addition we use Eq. (7) to make a fit for the parameters $\alpha$ and $\beta$. Three levels of approximations for the $\Delta\gamma$ terms are considered: (A) when the $\Delta\gamma$ are set to zero, (B) when the $\Delta\gamma$ are evaluated with $S_e^{\mathrm{SM}}$ and $J_e^{\mathrm{SM}}$ obtained with shell-model calculations with free-nucleon values for $G$ and $g$, and (C) with $S_e^{\mathrm{SM}}$ and $J_e^{\mathrm{SM}}$ together with $\tilde{G}^{\mathrm{SM}}$ and $\tilde{g}^{\mathrm{SM}}$ obtained from fits of the shell-model matrix elements to experimental magnetic moments in the $sd$-shell, discussed in the next section.

## II. CORRECTIONS FROM SHELL-MODEL CALCULATIONS

In Table I we list the 17 $T=1/2$ mirror nuclei in the mass range $11 \leqslant A \leqslant 43$ for which a complete set of data on $\gamma_p, \gamma_n$, and $\gamma_\beta$ exists, together with the values of the corrections $\Delta\gamma_p$ and $\Delta\gamma_n$ obtained from $0\hbar\omega$ shell-model calculations based on the Hamiltonians from Refs. [18–20] and free-nucleon values for the $g$ factors. We have omitted nuclei with $A \leqslant 10$ in the analysis as the various coupling constants may not have reached their fully quenched values for these nuclei [21]. For the $p$ and $fp$ shells the corrections were based, respectively, on the (8–16)CKPOT interaction [19] and the GXFP1 interaction [20]. For the $sd$ (1s0d) shell we use the recent USDB Hamiltonian [18]. The $pf$-shell calculations for $A=51$–57 were calculated with a truncated model space ($t6$) that allowed at most six nucleons to be excited from the $f_{7/2}$ orbitals to any of the $f_{5/2}$, $p_{3/2}$ or $p_{1/2}$ orbitals. To check the error from this truncation we

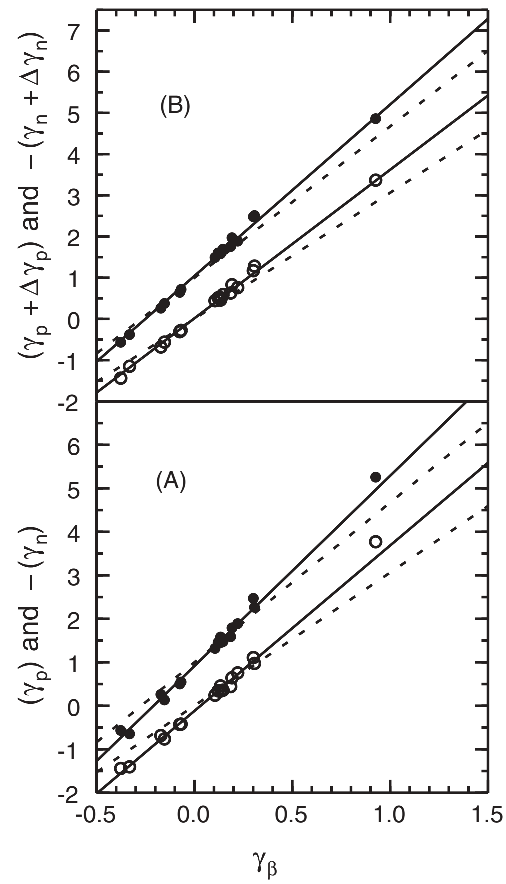


FIG. 1. (Top) $(\gamma_p+\Delta\gamma_p)$ vs $\gamma_\beta$ (solid circles) and $-(\gamma_n+\Delta\gamma_n)$ vs $\gamma_\beta$ (open circles). The lines are the result of fit (B). (Bottom) $\gamma_p$ vs $\gamma_\beta$ (solid circles) and $-\gamma_n$ vs $\gamma_\beta$ (open circles). The lines are the result of fit (A). The single-particle model using free-nucleon values for the coupling constants is shown by the dashed line.

TABLE I. Values of $\gamma_\beta$, $\gamma_p$, and $\gamma_n$ [1] obtained using data on magnetic dipole moments and $\beta$-decay lifetimes [2–8]. The contributions $\Delta\gamma_p$ and $\Delta\gamma_n$ have been estimated from $0\hbar\omega$ shell-model calculations [18–20] and free-nucleon values for the $g$ factors.

| $A, J^\pi$ | $\gamma_\beta$ | Nucleus | $\gamma_p$ | Nucleus | $\gamma_n$ | $\Delta\gamma_p$ | $\Delta\gamma_n$ |
|---|---|---|---|---|---|---|---|
| $11, 3/2^-$ | +0.192(1) | $^{11}$B | +1.7924 | $^{11}$C | −0.6427(7) | +0.1804 | −0.1864 |
| $13, 1/2^-$ | −0.331(1) | $^{13}$N | −0.6444(8) | $^{13}$C | +1.4048 | +0.2646 | −0.2586 |
| $15, 1/2^-$ | −0.376(2) | $^{15}$N | −0.5664 | $^{15}$O | +1.4390(2) | 0.0000 | 0.0000 |
| $17, 5/2^+$ | +0.221(1) | $^{17}$F | +1.8885(1) | $^{17}$O | −0.7575 | 0.0000 | 0.0000 |
| $19, 1/2^+$ | +0.926(3) | $^{19}$F | +5.2577 | $^{19}$Ne | −3.7708(2) | −0.3972 | +0.4032 |
| $21, 3/2^+$ | +0.185(6) | $^{21}$Na | +1.5909(1) | $^{21}$Ne | −0.4412 | +0.1657 | −0.1881 |
| $23, 3/2^+$ | +0.146(14) | $^{23}$Na | +1.4783 | $^{23}$Mg | −0.3576(2) | +0.2137 | −0.2377 |
| $25, 5/2^+$ | +0.137(4) | $^{25}$Al | +1.4582(5) | $^{25}$Mg | −0.3422 | +0.1459 | −0.1678 |
| $27, 5/2^+$ | +0.121(8) | $^{27}$Al | +1.4566 | $^{27}$Si | −0.3422(2) | +0.1459 | −0.1692 |
| $29, 1/2^+$ | +0.301(13) | $^{29}$P | +2.4698(4) | $^{29}$Si | −1.1106 | +0.0109 | −0.0595 |
| $31, 1/2^+$ | +0.307(11) | $^{31}$P | +2.2632(6) | $^{31}$S | −0.9759(2) | +0.2472 | −0.3044 |
| $33, 3/2^+$ | −0.075(8) | $^{33}$Cl | +0.5015(10) | $^{33}$S | +0.4292 | +0.1440 | −0.1193 |
| $35, 3/2^+$ | −0.068(7) | $^{35}$Cl | +0.5479 | $^{35}$Ar | +0.4220(13) | +0.1681 | −0.1424 |
| $37, 3/2^+$ | −0.153(7) | $^{37}$K | +0.1335 | $^{37}$Ar | +0.7633(13) | +0.2426 | −0.2027 |
| $39, 3/2^+$ | −0.171(2) | $^{39}$K | +0.2610 | $^{39}$Ca | +0.6811(1) | 0.0000 | 0.0000 |
| $41, 7/2^-$ | +0.134(2) | $^{41}$Sc | +1.5814(11) | $^{41}$Ca | −0.4557 | 0.0000 | 0.0000 |
| $43, 7/2^-$ | +0.105(2) | $^{43}$Sc | +1.3200(114) | $^{43}$Ti | −0.2428(100) | +0.1723 | −0.1992 |

TABLE II. Result of a linear fit of Eq. (10) to the data of Table I with the three prescriptions described in the text for the even-spin correction terms. The last column gives the rms deviation between the left-hand and right-hand sides of Eq. (10).

| | $\tilde{g}_p$ | $(\tilde{G}_p - \tilde{g}_p)/\tilde{R}$ | rms |
|---|---|---|---|
| Free-nucleon | 1 | 3.67 | |
| Fit (A) | $0.910 \pm 0.027$ | $4.57 \pm 0.09$ | 0.107 |
| Fit (B) | $1.040 \pm 0.020$ | $4.26 \pm 0.07$ | 0.080 |
| Fit (C) | $1.059 \pm 0.019$ | $4.22 \pm 0.06$ | 0.093 |

performed a full-space calculation for $A = 57$. The results with free-nucleon $g$ factors for the truncated (full) space calculations are $\gamma_p = 1.682(1.676)$ and $\gamma_n = -0.512(-0.508)$. The difference is an order of magnitude smaller that the average difference between experiment and theory showing that the $t6$ truncation is adequate.

The values for $\tilde{G}^{\mathrm{SM}}$ and $\tilde{g}^{\mathrm{SM}}$ for fit (C) are obtained from a least-squares fit to magnetic moments and $M1$ $\gamma$-decay matrix elements in the $sd$ shell [22]:

$$\tilde{G}_p^{\mathrm{SM}} = 5.31 \pm 0.06, \quad \tilde{g}_p^{\mathrm{SM}} = 1.11 \pm 0.02,$$
$$\tilde{G}_n^{\mathrm{SM}} = -3.66 \pm 0.07, \quad \tilde{g}_n^{\mathrm{SM}} = -0.07 \pm 0.02. \quad (12)$$

In addition, from a fit to Gamow-Teller $\beta$-decay matrix elements in the $sd$ shell [22],

$$\tilde{R}^{\mathrm{SM}} = 0.97 \pm 0.02. \quad (13)$$

The errors on these parameters include the variation between the fits with the USDA and USDB Hamiltonians [18]. Similar results were obtained with the older USD Hamiltonian [17].

## III. RESULTS

Tables II–IV show the results of fitting the data of Table I. We note an improvement of approximately 30% in the rms obtained when the even-spin corrections are included. Figure 1 shows a plot of Eqs. (10) and (11) with assumptions (A) and (B) for the even-spin terms. Comparison of the bottom (case A without even-spin terms) and top (case B with even-spin terms) shows that the overall trend is determined by the dominant odd-spin contribution as assumed in the original work of Buck, Merchant, and Perez [1] and Buck and Perez [15]. However, the results of Tables II to IV show that the inclusion of the even-spin terms has a non-negligible effect on the linear coefficients extracted in the analysis.

TABLE III. Caption as for Table II with Eq. (10) → Eq. (11).

| | $\tilde{g}_n$ | $(\tilde{G}_n - \tilde{g}_n)/\tilde{R}$ | rms |
|---|---|---|---|
| Free-nucleon | 0 | −3.06 | |
| Fit (A) | $0.123 \pm 0.025$ | $-3.99 \pm 0.09$ | 0.097 |
| Fit (B) | $-0.011 \pm 0.016$ | $-3.70 \pm 0.05$ | 0.064 |
| Fit (C) | $-0.029 \pm 0.019$ | $-3.66 \pm 0.06$ | 0.076 |

TABLE IV. Caption as for Table II with Eq. (10) → Eq. (7).

| | $\alpha$ | $\beta$ | rms |
|---|---|---|---|
| Free-nucleon | −1.199 | 1 | |
| Fit (A) | $-1.145 \pm 0.013$ | $1.051 \pm 0.013$ | 0.060 |
| Fit (B) | $-1.147 \pm 0.013$ | $1.027 \pm 0.013$ | 0.042 |
| Fit (C) | $-1.151 \pm 0.013$ | $1.026 \pm 0.013$ | 0.045 |

Figure 2 shows the plot of $\gamma_p$ vs $\gamma_n$ from Eq. (7). For this plot the contribution of the even-spin terms has the effect of moving the points along the line resulting in essentially the same slope and the similar linear coefficients for cases (A) and (B).

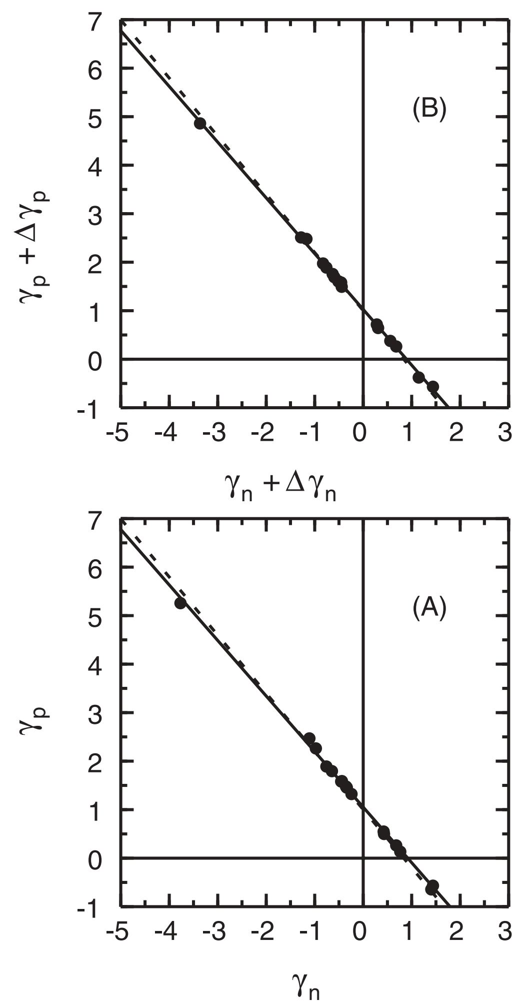


FIG. 2. (Top) $\gamma_p + \Delta\gamma_p$ versus $\gamma_n + \Delta\gamma_n$. The line is the result of fit (B). (Bottom) $\gamma_p$ versus $\gamma_n$. The line is the result of fit (A). The single-particle model using free-nucleon values for the coupling constants is shown by the dashed line.

TABLE V. Values of $\gamma_\beta$, $\gamma_p$, and $\gamma_n$ [1] obtained using data on magnetic dipole moments and $\beta$-decay lifetimes [9,23,24]. The contributions $\Delta\gamma_p$ and $\Delta\gamma_n$ have been calculated from $0\hbar\omega$ shell-model calculations [20] and free-nucleon values for the $g$ factors.

| $A, J^\pi$ | $\gamma_\beta$ | Nucleus | $\gamma_p$ | Nucleus | $\gamma_n$ | $\Delta\gamma_p$ | $\Delta\gamma_n$ |
|---|---|---|---|---|---|---|---|
| $45, 7/2^-$ | +0.082(5) | $^{45}$V | | $^{45}$Ti | 0.027[a] | +0.1753 | −0.2139 |
| $47, 3/2^-$ | +0.120(8) | $^{47}$V | | $^{47}$Cr | | +0.1050 | −0.1360 |
| $49, 5/2^-$ | +0.095(11) | $^{49}$Mn | | $^{49}$Cr | 0.1904(12)[a] | +0.1222 | −0.1595 |
| $51, 5/2^-$ | +0.102(4) | $^{51}$Mn | +1.4273(5) | $^{51}$Fe | | +0.0785 | −0.1073 |
| $53, 7/2^-$ | +0.083(14) | $^{53}$Co | | $^{53}$Fe | | +0.1053 | −0.1431 |
| $55, 7/2^-$ | +0.083(4) | $^{55}$Co | +1.3777(9) | $^{55}$Ni | | +0.0397 | −0.0708 |
| $57, 3/2^-$ | +0.146(4) | $^{57}$Cu | 1.33(3) | $^{57}$Ni | −0.532 | +0.0607 | −0.1061 |

[a]Signs for $\gamma_n$ are experimentally undetermined.

The fits based on Eqs. (10) and (11) only give $\tilde{g}$ and the combination of parameters $(\tilde{G}-\tilde{g})/\tilde{R}$. The $\tilde{g}$ values for the orbital-$g$ factors from Tables II and III (fit C) are $\tilde{g}_p = 1.059 \pm 0.019$ and $\tilde{g}_n = -0.029 \pm 0.019$, respectively. These results are not inconsistent (the error bars just touch) with the global magnetic moment fit values from Eq. (12) of $\tilde{g}_p^{\rm SM} = 1.11 \pm 0.02$ and $\tilde{g}_n^{\rm SM} = -0.07 \pm 0.02$, respectively.

We can use the $\tilde{G}^{\rm SM}$ and $\tilde{g}^{\rm SM}$ values from Eq. (12) in $(\tilde{G}-\tilde{g})/\tilde{R}$ from fit (C) in Tables II and III to obtain $\tilde{R} = 0.99(3)$ from the proton data in Table II and $\tilde{R} = 0.98(3)$ from the neutron data in Table III. These values are nicely consistent with each other and with the earlier result $\tilde{R} = 1.00(2)$ [15]. These results are also consistent with the quenching of Gamow-Teller strength obtained from the direct comparison of calculated and experimental Gamow-Teller $\beta$-decay matrix elements with USD [14] and USDA and USDB [Eq. (13)]. The implication is that $|C_A/C_V|$ is quenched from its free-nucleon value of 1.26 to its standard-model value of unity in nuclei.

Taking $\tilde{R} = 1$ for the smaller orbital part of $(\tilde{G}-\tilde{g})/\tilde{R}$, we find from Tables II and III (fit C) $\tilde{G}_p/\tilde{R} = 5.28(6)$ and $\tilde{G}_n/\tilde{R} = -3.69(6)$. The difference $(\tilde{G}_p - \tilde{G}_n)/\tilde{R} = 8.97(8)$ can be compared to the free-nucleon value of 7.47. The nucleonic operator associated with $\tilde{G}_p - \tilde{G}_n$ and $\tilde{R}$ is the same (the isovector spin operator). Hence, the 20% enhancement of experiment over the free-nucleon value must be attributed to mesonic exchange currents [17].

## IV. PREDICTIONS FOR HEAVIER NUCLEI

For completeness we show in Fig. 3 the results for all data related to the $\gamma_p$ vs $\gamma_n$ plot. In addition to the points for the $A = 11$–$43$, $T = 1/2$ mirror pairs it includes the points for the $A = 1$ and $A = 3$ mirror pairs, the recent result for the $A = 57$ mirror pair [9], and the four $T = 3/2$ mirror pairs [10,11].

Whenever one of the quantities $\gamma_\beta$, $\gamma_p$, or $\gamma_n$ is known the remaining ones can be deduced from Eqs. (7), (10), and (11) by using appropriate values for the even-spin corrections $\Delta\gamma_p$ and $\Delta\gamma_n$ and the effective $g$ factors from Tables II to IV. As an example we use the data of Table V, approximation B for $\Delta\gamma$, and Eqs. (10) and (11) to predict values of $\gamma_p$ and $\gamma_n$ from the known values of $\gamma_\beta$ for several nuclei in the mass range $A = 45$ to 55. The results are shown in Table VI. We note that whenever $\gamma_p$ and $\gamma_n$ have in fact been measured a comparison of experimental and predicted values from Tables V and VI, respectively, gives an indication of the reliability of the method. We note here the relatively large deviation of the predicted value of $\gamma_p$ from the measured value of $\gamma_p = 1.33 \pm 0.03$ for $^{57}$Cu.

As a further example we use the data on $A = 51, 55$, and 57 in Table V to predict the values of $\gamma_p$ and $\gamma_n$ using Eq. (7). The values of $\alpha$ and $\beta$ are taken from Table IV, fit (B). This gives $\gamma_n = -0.310 \pm 0.010$ ($^{51}$Fe) , $\gamma_n = -0.270 \pm 0.011$ ($^{55}$Ni), and $\gamma_p = +1.698 \pm 0.012$ ($^{57}$Cu). The relatively large deviation between our

TABLE VI. Values of $\gamma_p$ and $\gamma_n$ deduced from the data of Table V, using Eqs. (10) and (11) and using methods (A) and (B).

| $A, J^\pi$ | Nucleus | $\gamma_p(A)$ | $\gamma_p(B)$ | Nucleus | $\gamma_n(A)$ | $\gamma_n(B)$ |
|---|---|---|---|---|---|---|
| $45, 7/2^-$ | $^{45}$V | +1.285(30) | +1.214(30) | $^{45}$Ti | −0.204(26) | −0.102(26) |
| $47, 3/2^-$ | $^{47}$V | +1.458(41) | +1.446(41) | $^{47}$Cr | −0.356(35) | −0.321(35) |
| $49, 5/2^-$ | $^{49}$Mn | +1.344(52) | +1.323(52) | $^{49}$Cr | −0.256(45) | −0.204(45) |
| $51, 5/2^-$ | $^{51}$Mn | +1.376(28) | +1.395(28) | $^{51}$Fe | −0.284(23) | −0.283(23) |
| $53, 7/2^-$ | $^{53}$Co | +1.279(63) | +1.288(63) | $^{53}$Fe | −0.208(55) | −0.177(55) |
| $55, 7/2^-$ | $^{55}$Co | +1.279(28) | +1.353(28) | $^{55}$Ni | −0.208(23) | −0.249(23) |
| $57, 3/2^-$ | $^{57}$Cu | +1.577(28) | +1.603(28) | $^{57}$Ni | −0.460(23) | −0.445(23) |

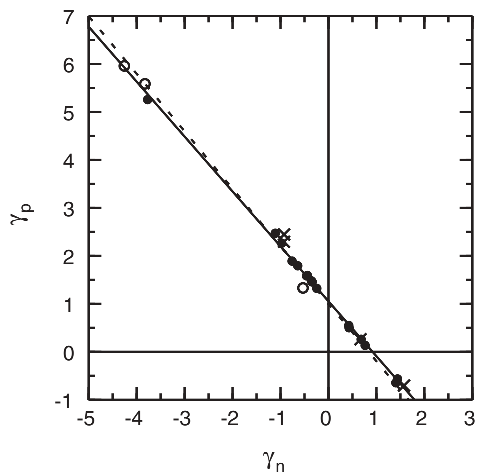


FIG. 3. $\gamma_p$ versus $\gamma_n$. Points are shown for the $A = 11$–$43$, $T = 1/2$ mirror pairs (solid circles); the $A = 57$, $T = 1/2$ mirror pair [open circle near (-1,1)]; the $A = 1$ and $A = 3$, $T = 1/2$ mirror pairs (open circles on the upper left-hand side); and the $A = 9$, 13, 17, and 35, $T = 3/2$ mirror pairs (crosses). The line is the result of fit (A).

results and experiment for $^{57}$Cu has also been noted above.

## V. CONCLUSIONS

In conclusion we have extended previous analyses of the linear correlations found between the magnetic dipole moments and $\beta$-decay lifetimes of light $T = \frac{1}{2}$ mirror pairs. This has been done by explicitly including the contributions $S_e$ and $J_e$ to the total spin and total angular momentum generated by the even type of nucleon in these odd-even nuclei. The inclusion of these contributions via a $0\hbar\omega$ shell model has led to improved linear fits. The results we present can be used to make predictions. For example, if the $\beta$-decay matrix element is known for a heavy $T = \frac{1}{2}$ mirror pair, then Fig. 1 and Tables II and III can be used to predict the odd-proton and odd-neutron magnetic moments. If the magnetic moment of one member of a mirror pair is known, then Fig. 2 and Table IV can be used to predict the other member. This can be used for any $T$ value as illustrated by the results for $T = \frac{3}{2}$ shown in Fig. 3.

## ACKNOWLEDGMENTS

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