Ground state magnetic dipole moment of ^{35}K

T.J. Mertzimekis[1,*], P.F. Mantica[1,2], A.D. Davies[1,3], S.N. Liddick[1,2], B.E. Tomlin[1,2]

[1] *National Superconducting Cyclotron Laboratory,*
Michigan State University, East Lansing, MI 48824
[2] *Department of Chemistry, Michigan State University, East Lansing, MI 48824 and*
[3] *Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824*

(Dated: January 26, 2006)

The ground state magnetic moment of ^{35}K has been measured using the technique of nuclear magnetic resonance on β-emitting nuclei. The short-lived ^{35}K nuclei were produced following the reaction of a ^{36}Ar primary beam of energy 150 MeV/nucleon incident on a Be target. The spin polarization of the ^{35}K nuclei produced at 2° relative to the normal primary beam axis was confirmed. Together with the mirror nucleus ^{35}S, the measurement represents the heaviest $T = 3/2$ mirror pair for which the spin expectation value has been obtained. A linear behavior of g_p vs. g_n has been demonstrated for the $T = 3/2$ known mirror moments and the slope and intercept are consistent with the previous analysis of $T = 1/2$ mirror pairs.

INTRODUCTION

The magnetic dipole moment μ provides important details on orbital and spin contributions to nuclear state wave functions, mainly due to its sensitivity to the individual proton and neutron contributions. The extreme limits of the magnetic moments are represented by the so-called Schmidt values and the vast majority of the known magnetic moments fall within those extremes. One special aspect of magnetic moments can be applied to understand gross spin properties of nuclei, that is, the sum of the ground-state magnetic moments of mirror nuclei. This sum represents the isoscalar part of the magnetic moment multiplied by a factor of two, and it can be directly related to the Pauli spin expectation value, $\left\langle \sum_i \sigma_z^i \right\rangle$ or $\langle \sigma \rangle$, as illustrated in the following relation [1]:

$$\mu(T_z = +T) + \mu(T_z = -T) = $$
$$J + \left(\mu_\pi + \mu_\nu - \tfrac{1}{2} \right) \left\langle \sum_i \sigma_z^i \right\rangle \quad (1)$$

In the above, $\mu_{\pi(\nu)}$ is the free proton (neutron) magnetic moment in units of the nuclear magneton, μ_N, J is the total angular momentum and T represents the isospin. Eqn. 1 is valid *only* if isospin is a good quantum number, providing a means to test isospin symmetry breaking.

A limiting factor to test isospin symmetry is the difficulty to measure magnetic moments far from stability. Mirror nuclei lie close to the $N = Z$ line and become unstable above $A \sim 40$. As mass increases, it is more difficult to overcome the challenges of the available moment measurement techniques imposed by short lifetimes and low production rates. The situation is especially pronounced for the case of neutron-deficient nuclei with isospin $T_z = -3/2$. While mass $A = 43$ has been reached for $T = 1/2$, magnetic moments for $T = 3/2$ mirror nuclei are only known up to $A = 17$ [2]. As Z increases, Coulomb repulsion effects within the nucleus become more significant. At these higher masses, the increasing nuclear charge might have a direct effect on isospin, potentially leading to symmetry breaking.

Structural effects play an immediate role in determining the value of the magnetic moment. The reverse also holds: a measurement of the magnetic moment can reveal critical information about the structure of the nucleus under investigation. Several endonuclear effects, such as core polarization and meson current exchange [3, 4], have been found to alter the magnetic moment operator at a level which can be observed via a magnetic moment measurement. Along this line, empirical relationships have been established for either ground state [5, 6] or excited state [7] magnetic moments to overcome the lack of a firm theoretical explanation.

The present work focuses on extending the known measurements of $T = 3/2$ nuclei. Recently, we have demonstrated that significant spin polarization can be generated in single-nucleon pickup reactions at intermediate energies [8]. Spin polarization was studied in ^{37}K isotopes created as products in single proton-pickup reactions. The polarization was observed to be maximum near the peak of the fragment momentum distribution reaching a relatively large magnitude of $\sim 8.5\%$.

The polarization produced in the proton-pickup reaction may be a key factor for extending magnetic moment measurements to heavier $T_z = -3/2$ nuclei. Therefore we have employed a charge-pickup ^{36}Ar$(p,2n)$ reaction,

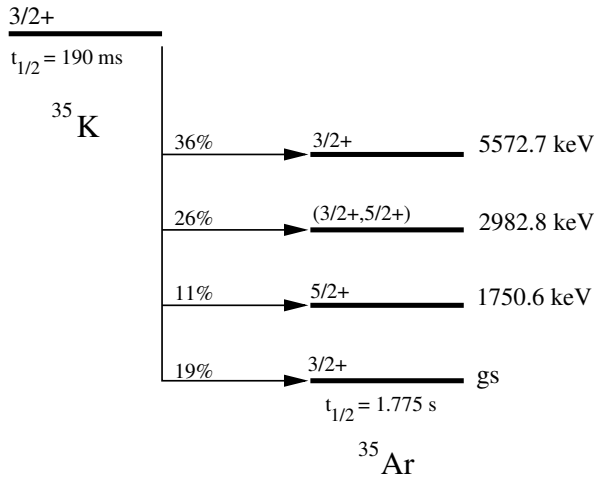*Corresponding author, email: mertzime@nscl.msu.edu

FIG. 1: Decay of ^{35}K to ^{35}Ar, where only the strongest branchings are shown [11]. The energy levels are not in scale.

where the produced ^{35}K nuclei ($J^\pi = \frac{3}{2}^+$, $t_{1/2} = 190$ ms, $Q_{EC} = 11881$ keV) are expected to exhibit considerable polarization. The effect of neutron evaporation during the reaction on the observed polarization due to two fewer neutrons with respect to ^{37}K is an open question.

A previous measurement of $\mu(^{35}$K) was attempted at GSI by Schäfer *et al.* [9] via a fast-fragmentation reaction. The experimental result suffered small polarizations and low counting statistics and a g factor, $g = 0.24(2)$, was extracted. Schäfer *et al.* also suggested that the systematics of $T = 3/2$ nuclei did *not* follow the linear behavior between the effective g factors of the proton-odd and neutron-odd nuclei of the mirror pair, γ_p and γ_n respectively, as observed in the case of $T = 1/2$ nuclei by Buck and Perez [5, 6]. We report on the asymmetry of ^{35}K nuclei produced via a $(p,2n)$ proton-pickup reaction and a more precise value of the ground state magnetic moment of ^{35}K measured using the β-NMR technique. This new value of $\mu(^{35}$K), in combination with ^{35}S mirror data [10] is used to examine the Pauli spin expectation value $\langle\sigma\rangle$ and the relation between γ_p and γ_n for $T = 3/2$ nuclei.

EXPERIMENTAL TECHNIQUE

A primary beam of ^{36}Ar was accelerated to 150 MeV/nucleon by the coupled cyclotrons at the National Superconducting Cyclotron Laboratory and impinged on a 564 mg/cm^2 Be target to create a secondary ^{35}K beam via the proton-pickup reaction ^{36}Ar(^{9}Be,^{10}Li)^{35}K. Two dipole magnets located upstream of the Be production target were used to steer the primary beam to an angle of 2° with respect to the normal beam axis. The ^{35}K nuclei were separated from the reaction products using the A1900 fragment separator [12]. The desired ^{35}K isotopes

were finally delivered to the β-NMR end station at energies around 50 MeV/nucleon and a rate of $\sim$30 pps/pnA. The main contaminant was ^{34}Ar and the implantation ratio between ^{35}K and ^{34}Ar was roughly 1:1.

The A1900 is able to deliver beams over a broad range of both angular and momentum acceptance. The full momentum acceptance of the device is 5%, while the measured angular acceptance is 60 mrad in the horizontal direction and 40 mrad in the vertical direction. In the present experiment, the full angular acceptance was selected. The rigidity of the last two dipole magnets downstream in the fragment separator were set to $B\rho_{3,4} = 1.6910$ Tm. The particle identification was achieved using standard energy loss and time-of-flight measurements.

At the exit of the beam line, the secondary beam passed through a Kapton window and traveled through air for 20 cm before being implanted into a KBr single crystal located at the center of the β-NMR apparatus. The β-NMR apparatus [13] consisted of a large dipole magnet with its poles perpendicular to the beam direction and a distance of 10 cm between them. The magnet provides the required Zeeman hyperfine splitting of the levels of the spin-polarized nuclei. Two β telescopes, each consisting of a thin ΔE (4.4 cm × 4.4 cm × 0.3 cm) and a thick E (5.1 cm × 5.1 cm × 2.5 cm) plastic scintillator, were placed between the poles of the magnet to detect the β particles emitted during the decay of ^{35}K. Two identical rf coils in a Helmholtz-like geometry were placed within the magnet and the β telescopes, with their field direction perpendicular to both the direction of the beam and the static magnetic field. The 4 mm-thick, 22 mm-diameter disc-shaped KBr single crystal was mounted on an insulated holder, between the pair of the rf coils and at a 45° angle with respect to the normal beam axis to minimize the energy loss of the emitted β particles. The spin-relaxation time of the implanted ^{35}K ions in the ionic crystal is much longer than the decay lifetime [14].

For the initial asymmetry measurements to confirm nuclear polarization of the ground state, the holding magnetic field of the dipole magnet was switched ON and OFF every 60 s, at a maximum value while on equal to 0.1 T, and the rf was always switched off [15]. The asymmetry ratio

$$R = \frac{[N(0°)/N(180°)]_{ON}}{[N(0°)/N(180°)]_{OFF}} = \frac{1 + AP}{1 - AP} \qquad (2)$$

was then deduced by the counts detected in the β scintillators, $N(0°)$ and $N(180°)$, at directions 0° and 180°, respective to the direction of the static magnetic field. The asymmetry parameter in the β decay of the ^{35}K isotopes is given as A and P is the polarization. The asymmetry ratio of the pickup ^{35}K products was determined near the center of the outgoing momentum distribution of the fragment, p_0, namely at $\frac{\Delta p}{p_0} = +0.5\%$. Two different momentum acceptance settings, 0.5% and 1%, were
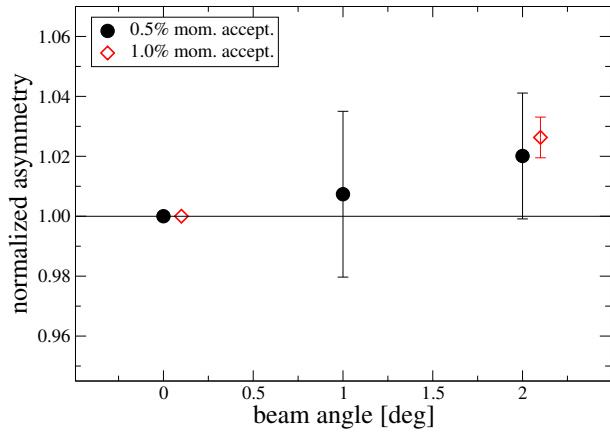
FIG. 2: (Color online) Measured asymmetry as a function of the outgoing momentum of the ^{35}K pickup products at $\Delta p/p = +0.5\%$. The open diamonds are slightly displaced to the right for clarity.
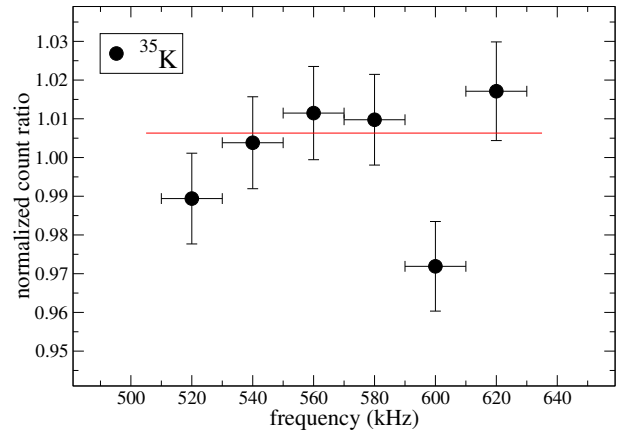

FIG. 3: (Color online) Results from the frequency scans to detect the resonance of ^{35}K fragments. The straight line is the linear fit to the offline source data. The vertical error bars correspond to statistical errors, while the horizontal ones correspond to the frequency modulation step.

employed in combination with beam angles of 1° and 2°.

Once the asymmetry profile was established, the setting with the maximum asymmetry was selected for the magnetic moment measurement, to maximize the resonance effect during the frequency scans. The static magnetic field was switched permanently ON at a value of 0.3012 T for the NMR measurement, monitored by a Hall probe throughout the experiment. A Hewlett-Packard HP 33120A Function Generator provided the *rf* signal, which was amplified by an EIN 406L power amplifier. The coils were configured as part of a RCL circuit, with a 50 Ω resistor and a variable capacitor to match the output impedance of the *rf* source with the input impedance of the coil, thus maximizing the alternating magnetic field to the sample. The impedance of the *rf*-coil was 59 μH. The strength of the *rf* signal was monitored by measuring the voltage drop across the 50 Ω resistor by means of an AC-DC voltage probe (Pomona 6106). The oscillating field strength was maintained at ≈ 0.3 mT. The frequency scans were conducted using a frequency modulation (FM) of ± 10 kHz. The region of frequency scans was limited between 520 kHz and 620 kHz, spanning the full range around the previously measured g factor of ^{35}K [9].

Systematic asymmetries in the setup were checked before and after the run with a standard ^{22}Na source that was placed in the center of the β-NMR apparatus, at the same position with the KBr crystal.

RESULTS

Asymmetry measurements

The polarization, P, is directly related to the asymmetry ratio, R, and the asymmetry parameter, A, as shown in Eqn. 2. For a measurement of P, R is established from the data and A can be deduced from the decay scheme. However, the decay scheme of ^{35}K (Fig. 1) is inconclusive about the asymmetry parameter. From the known properties of the decay, only limits of A can be imposed. Hence, we were unable to deduce the absolute polarization of the ^{35}K fragments. The asymmetry measurements were completed for two different momentum acceptance points, as described earlier, and the results are depicted in Fig. 2.

Normalization is required to correct for systematic asymmetries existing in the setup, mainly due to the fringing magnetic field affecting the photomultipliers. The photomultiplier tubes were shielded with μ metal and soft iron shields, however, a small asymmetry ($< 1\%$) was noted in field ON/OFF measurements with unpolarized radioactive sources. Measurements at 0° produce nuclei with no polarization and can serve as normalization points for all measurements.

The data at 2° and 1% momentum acceptance present an asymmetry equal to $(2.8 \pm 0.8)\%$, produced in the charge-pickup reaction for the ^{35}K fragments. The result comes as a confirmation of the previous observation of polarization in the case of ^{37}K nuclei [8] produced in a proton-pickup reaction.

The observed asymmetry is sufficient to allow a measurement of the ground-state magnetic moment in ^{35}K using the β-NMR technique. We note that the measured

asymmetry includes the influence of the ^{34}Ar contamination in the secondary beam. ^{34}Ar β decay should show no asymmetry due to the 0^+ ground state. The decay properties ($J^\pi = 0^+$, $t_{1/2} = 844.5$ ms, $Q_{EC} = 6061$ keV) are similar to ^{35}K. Thus, the observed asymmetry ratio is reduced.

There are two additional measurements at 0.5% momentum acceptance and 1° and 2°, respectively. The experimental error is large for both measurements, crossing the no-asymmetry line and making the results inconclusive. However, an increasing trend in the asymmetry as the beam angle becomes larger is apparent, while the value at 0.5% and 2° seems to agree within statistical accuracy, with the measured asymmetry for 1% and 2°.

Magnetic moment of ^{35}K

The magnetic moment measurement was carried out with the same settings in the primary beam and the A1900 fragment separator that produced the asymmetry of 2.8% in the prior asymmetry measurement, i.e. 2° beam angle and 1% momentum acceptance. The resonance was found at a frequency $\nu_1 = 600 \pm 10$ kHz, after sweeping the region 520–620 kHz (Fig. 3). A statistical significance of 3σ away from the reference baseline was found for the resonance. The baseline was determined independently during the ^{22}Na source runs. The overall statistical certainty of the present measurement reaches a level of 99.7%.

From the frequency of the resonance, the corresponding g factor was deduced as 0.261(5), where the quoted error originates from the frequency modulation width. The magnetic moment can be further extracted as $\mu = gJ$, with $J = 3/2$ being the spin of the ^{35}K ground state [16]. The final result is $|\mu(^{35}\text{K})|$=0.392(7) μ_N.

DISCUSSION

The deduced spin-polarization of ^{37}K nuclei at intermediate energies was measured at 8.5% [8] and with a positive sign, confirming the fact that the picked-up proton from the production target is preferentially located at Fermi momentum and with its momentum aligned with the axis of the incident projectile. The asymmetry parameter A in Eqn. 2 is known for ^{37}K, enabling the translation of the measured asymmetry ratio R into polarization. In ^{35}K nuclei the asymmetry parameter is not known, and the asymmetry is obscured in part by the presence of ^{34}Ar contamination. It is noted that significant β asymmetry has been observed for ^{35}K fragments, suggesting that spin polarization is maintained even with evaporation of two neutrons from proton pickup products.
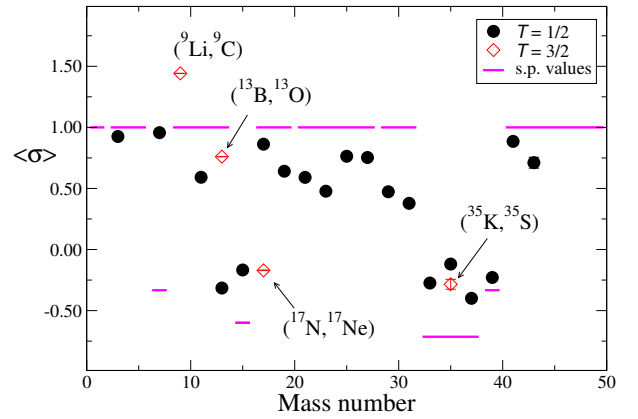

FIG. 4: (Color online) Systematics of isoscalar magnetic moments for both $T = 1/2$ and $T = 3/2$ mirror nuclei. The labels and arrows refer to the $T = 3/2$ data known to date.

The measured value of the ground state g factor, 0.261(5) falls in range with the g factor, $g = 0.24(2)$, previously measured with a much larger error. The Schmidt prediction for the g factor of a single proton in $1d_{3/2}$ is $g = 0.083$, acting as an extreme limit for the measured g factor. Previous theoretical predictions for ^{35}K include the shell-model prediction using the USD interaction, $g_{USD} = 0.122$, and an "effective" shell-model calculation $g_{USD}^{eff} = 0.243$ as quoted in Ref. [9]. The present measurement is in good agreement with the prediction employing the effective USD interaction. A configuration mixing which was suspected to exist for the $T = 3/2$ seems to be confirmed [17]. A simple Z/A collective prediction, $g_{coll} = 0.542$, doubles the experimental value, thus promoting the dominant single-particle nature in the ground state wavefunction of ^{35}K. The sign of g can not be determined directly from the current measurement. However, we assume it to be positive based on theoretical considerations for a single proton in the $1d_{3/2}$ level.

The existing data for the ^{35}S nucleus may be combined to the present result to extract the Pauli spin expectation value, $\langle\sigma\rangle$, for the mirror pair at $A = 35$. Using Eqn. 1 a value $\langle\sigma\rangle = -0.284(40)$ is calculated. Fig. 4 depicts the systematics for all available $T = 1/2$ and $T = 3/2$ data for $\langle\sigma\rangle$ as a function of mass number. The ^{35}K-^{35}S value is the heaviest $T = 3/2$ mirror pair known to date and agrees with the systematics of $T = 1/2$ nuclei. The deviation of $\langle\sigma\rangle$ away from the Schmidt value is attributed mainly to core polarization effects reflected in the magnetic moments of both ^{35}K and ^{35}S.

An interesting approach to the relationship between gyromagnetic ratios and the strengths of the β-decay transitions of mirror nuclei in the region $3 \leq A \leq 43$ has been followed by Buck et al. [5, 6]. At the extreme case of only odd nucleons being active, the spin dependence of the proton and neutron magnetic mo-

TABLE I: Summary of the results of linear fits for the slope and intercept according to Buck and Perez analysis.

isospin (T)	slope (α)	intercept (β)
1/2 (th.)	-1.199	1.0
1/2 (exp.) [a]	-1.148 ± 0.010	1.052 ± 0.016
3/2 (exp.) [b]	-1.176 ± 0.087	1.063 ± 0.090
3/2 (exp.) [c]	-1.122 ± 0.096	1.001 ± 0.102

[a] Data taken from Ref. [6]
[b] The fit includes the $A = 9$ data
[c] The fit excludes the $A = 9$ data

FIG. 5: (Color online) Plot of γ_p vs. γ_n according to Ref. [6] for all the available-to-date experimental magnetic moments data for mirror nuclei. In (b), the linear fit does not include the ^{9}Li-^{9}C pair. The value for the mirror pair ^{35}K-^{35}S is the heaviest known to date. Please, note that the scale in the two plots is different and the error bars are smaller than the size of the plotted points.

ments can be eliminated and a linear relationship of the form $\gamma_p = \alpha\gamma_n + \beta J$ between mirror partners magnetic moments can be constructed. The coefficients α and β, besides being the slope and the intercept of the straight line, are directly linked to important structure quantities: $\alpha = (G_p - g_p)/(G_n - g_n)$ and $\beta = g_p - \alpha g_n$. Here, $g_p = 1$, $g_n = 0$ are the orbital magnetic moments for proton and neutron, while $G_p = 5.586$ and $G_n = -3.826$ are the corresponding spin moments. All magnetic moments are in units of the nuclear magneton. $\gamma_{p,n}$ is the magnetic moment $\mu_{p,n}$ divided by the spin, J. Linear fits of available data in mirror nuclei may be worked out to obtain the estimates of α and β.

In the original approach by Buck and Perez, only data for the case of $T = 1/2$ were included, since there were only two mirror pair moments known in $T = 3/2$ nuclei. Data for $T = 3/2$ nuclei existed only for mass $A = 9$ and mass $A = 13$, i.e. the mirror pairs ^{9}Li-^{9}C and ^{13}Be-^{13}O, respectively.

With addition of the present work and a recent measurement in $\mu(^{17}$Ne) [2] which completed the mirror pair at $A = 17$, and a remeasurement of the magnetic moment in ^{9}Li [18], the Buck-Perez analysis was applied for $T = 3/2$ nuclei (Fig. 5). Schäfer *et al.* had expressed doubts on the similarity of the behavior of $T = 3/2$ mirror nuclei with the systematics of $T = 1/2$ data, based on their less precise measurement for the ^{35}K magnetic moment. It is therefore important to examine the validity of the linear fits in $T = 3/2$ nuclei and compare the results to the slope and intercept from the $T = 1/2$ systematics.

A linear fit was performed for all available $T = 3/2$ data. The result is shown in the third row of Table I, together with the theoretical "bare" nucleon values for α and β (first row) and the values obtained by Buck and Perez for the case of $T = 1/2$ data (second row). In recent studies [19, 20], there have been strong suggestions of an existing anomaly in $A = 9$, which is responsible for the large deviation of the corresponding $\langle\sigma\rangle$ value, as can be seen in Fig. 4. The existence of such an anomaly motivated a second regression analysis on the available $T = 3/2$ data, excluding the $A = 9$ point. The resulting values for the coefficients α and β in this case are depicted in the last row of Table I.
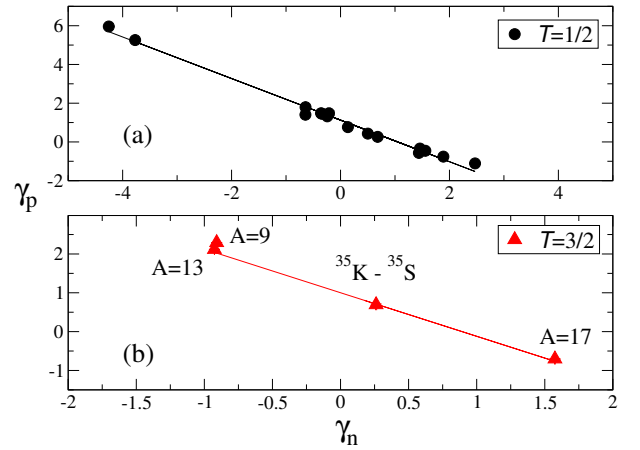
Both fits are obtained with a very good correlation coefficient ($R = 0.996$), even with a limited number of points included in the regression. The available $T = 3/2$ data exhibit a linear trend, contradicting the argument by Schäfer *et al.* about their behavior. Also, the extracted values of α and β agree with the corresponding values in the case of $T = 1/2$ nuclei. In addition, the error bars of the slope and the intercept overlap with the "bare" nucleon values. This is the first time a similarity in the regression results for the $T = 1/2$ and $T = 3/2$ is observed.

The statistical uncertainty in the $T = 3/2$ fits, however, is not sufficient to allow any judgment about the role of the $A = 9$ anomaly, as the extracted values for α and β coefficients have overlapping statistical errors.

Buck and Perez in their work [5] deduced the relations assuming that the contributions of even number particles in the nuclei account for tiny (ideally zero) contributions. If this is true, then no variation is expected between the $T = 1/2$ and $T = 3/2$ mirror pairs, since their only first-order structural difference is a pair of protons or neutrons. At this mass region, protons and neutrons occupy similar orbitals, which is still true for $T = 3/2$ nuclei. To first order, the p–n interaction is not expected to change dramatically as isospin changes. At a higher order, p–n interactions may play a role, a consideration that is not adopted in the Buck-Perez analysis. A deviation from the bare values would signify mainly the effects of meson currents in the nuclei, with an overall effect of screening the actual free nucleon current contribution in forming the bare result for the total magnetic moment of the nucleus. Therefore, it is important to improve on

the statistical uncertainties for the slope and intercept extracted from an analysis of $T = 3/2$ mirror moment data. This will require more measurements in the future.

CONCLUSIONS

A proton-pickup $(p,2n)$ reaction was employed to study the spin asymmetry in polarized ^{35}K nuclei produced from a ^{36}Ar beam at intermediate beam energies. The asymmetry measurements were carried out at various momentum acceptance settings in the A1900 fragment separator at NSCL and various beam angles. The asymmetry result obtained at $2°$ beam angle and 1% momentum acceptance was $(2.8 \pm 0.8)\%$, confirming the production of polarization in proton-pickup reactions, even with the concurrence of neutron evaporation.

At the maximum observed asymmetry setting the β-NMR technique was employed to measure the ground-state magnetic moment of the neutron-deficient ^{35}K. The extracted value, $|\mu(^{35}$K$)|=0.392(7)$, agrees with the previously known value, but is improved significantly in the precision.

The measured magnetic moment was combined with the mirror nucleus magnetic moment, $\mu(^{35}$S$)$, to extract the value of the Pauli spin expectation value, $\langle\sigma\rangle = -0.284(40)$. The result is the heaviest $T = 3/2$ mirror pair known to date and agrees well with the systematics of $T = 1/2$ nuclei. Linear fits of the existing magnetic moments of $T = 3/2$ nuclei according to the approach by Buck and Perez produced values for the slope α and intercept β. For the case of all $T = 3/2$ data, $\alpha = -1.176(87)$ and $\beta = 1.063(90)$. The extracted values agree well with the ones from $T = 1/2$ nuclei, and also overlap with the corresponding "bare" nucleon values. It is the first time such a behavior is observed for $T = 3/2$ nuclei. More magnetic moment measurements in $T_z = -3/2$ nuclei are needed for that purpose.

[1] K. Sugimoto, J. Phys. Soc. Japan (suppl.) **34**, 197 (1973).
[2] W. Geithner, B. A. Brown, K. M. Hilligsøe, S. Kappertz, M. Keim, G. Kotrotsios, P. Lievens, K. Marinova, R. Neugart, H. Simon, et al., Phys. Rev. C **71**, 064319 (2005).
[3] T. Yamazaki, T. Nomura, S. Nagamiya, and T. Katou, Phys. Rev. Lett. **25**, 547 (1970).
[4] A. Arima, J. Phys. Soc. Japan (suppl.) **34**, 205 (1973).
[5] B. Buck and S. M. Perez, Phys. Rev. Lett. **50**, 1975 (1983).
[6] B. Buck, A. C. Merchant, and S. M. Perez, Phys. Rev. C **63**, 037301 (2001).
[7] T. J. Mertzimekis, A. E. Stuchbery, N. Benczer-Koller, and M. J. Taylor, Phys. Rev. C **68**, 054304 (2003).
[8] D. E. Groh, P. F. Mantica, A. E. Stuchbery, A. Stolz, T. J. Mertzimekis, W. F. Rogers, A. D. Davies, S. N. Liddick, and B. E. Tomlin, Phys. Rev. Lett. **90**, 202502 (2003).
[9] M. Schäfer, W.-D. Schmidt-Ott, T. Dörfler, T. Hild, and T. Pfeiffer, Phys. Rev. C **57**, 2204 (1998).
[10] B. F. Burke, M. W. P. Strandber, V. Cohen, and W. Koski, Phys. Rev. **93**, 193 (1954).
[11] R. B. Firestone, S. Y. Frank Chu, and C. M. Baglin, *Table of Isotopes* (John Wiley & Sons Inc., 1998), ISBN 04712-9090-4.
[12] D. J. Morrissey, B. M. Sherrill, M. Steiner, A. Stolz, and I. Wiedenhoever, Nucl. Instrum. Meth. Phys. Res. B **204**, 90 (2003).
[13] P. F. Mantica, R. W. Ibbotson, D. W. Anthony, M. Fauerbach, D. J. Morrisey, C. F. Powell, J. Rikovska, M. Steiner, N. J. Stone, and W. B. Walters, Phys. Rev. C **55**, 2501 (1997).
[14] K. Matsuta, A. Ozawa, Y. Nojiri, T. Minamisono, M. F. Fukuda, A. Kitagawa, S. Momota, T. Ohtsubo, Y. Matsuo, H. Takechi, et al., Phys. Lett. B **281**, 214 (1992).
[15] D. W. Anthony, P. F. Mantica, D. J. Morrissey, and G. Georgiev, Hyperfine Int. **127**, 485 (2000).
[16] G. T. Ewan, E. Hagberg, J. C. Hardy, B. Jonson, S. Mattsson, P. Tidemand-Petersson, and I. S. Towner, **343**, 109 (1980).
[17] R. Sherr and I. Talmi, Phys. Lett. B **56**, 212 (1975).
[18] D. Borremans, D. L. Balabanski, K. Blaum, W. Geithner, S. Gheysen, P. Himpe, M. Kowalska, J. Lassen, P. Lievens, S. Mallion, et al., Phys. Rev. C **72**, 044309 (2005).
[19] M. Huhta, P. F. Mantica, D. W. Anthony, B. A. Brown, B. S. Davids, R. W. Ibbotson, D. J. Morrissey, C. F. Powell, and M. Steiner, Phys. Rev. C **57**, R2790 (1998).
[20] Y. Utsuno, Phys. Rev. C **70**, 011303(R) (2004).