PHYSICAL REVIEW C

NUCLEAR PHYSICS

THIRD SERIES, VOLUME 56, NUMBER 2 AUGUST 1997

RAPID COMMUNICATIONS

The Rapid Communications section is intended for the accelerated publication of important new results. Manuscripts submitted to this section are given priority in handling in the editorial office and in production. A Rapid Communication in **Physical Review C** *may be no longer than five printed pages and must be accompanied by an abstract. Page proofs are sent to authors.*

Identification of excited states in the $T_z=+\frac{1}{2}$ nucleus ^{75}Rb: The quest for experimental signatures of collective neutron-proton correlations

C. J. Gross,[1,2] D. Rudolph,[1,3,*] W. Satuła,[4,5,†] J. Alexander,[6] C. Baktash,[1] P. J. Coleman-Smith,[6] D. M. Cullen,[1,‡] R. A. Cunningham,[6] J. D. Garrett,[1] W. Gelletly,[7] A. Harder,[3,§] M. K. Kabadiyski,[3] I. Lazarus,[6] K. P. Lieb,[3] H. A. Roth,[8] D. G. Sarantites,[9] J. A. Sheikh,[4,‖] J. Simpson,[6] Ö. Skeppstedt,[8] B. J. Varley,[10] and D. D. Warner[6]

[1]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6371*

[2]*Oak Ridge Institute for Science and Education, Oak Ridge, Tennessee 37831*

[3]*II. Physikalisches Institut, Universität Göttingen, D-37073 Göttingen, Germany*

[4]*Joint Institute for Heavy Ion Research, Oak Ridge, Tennessee 37831-6374*

[5]*Department of Physics, University of Tennessee, Knoxville, Tennessee 37996*

[6]*CCLRC Daresbury Laboratory, Daresbury, Warrington WA4 4AD, United Kingdom*

[7]*Physics Department, University of Surrey, Guildford GU2 5XH, United Kingdom*

[8]*Department of Physics, Chalmers University of Technology, S-412 96 Göteborg, Sweden*

[9]*Department of Chemistry, Washington University, Saint Louis, Missouri 63130*

[10]*Schuster Laboratory, University of Manchester, Manchester M13 9PL, United Kingdom*

(Received 17 April 1997)

Excited states in the $T_z=\frac{1}{2}$ nucleus ^{75}Rb were observed for the first time using the ^{40}Ca(^{40}Ca,αp) reaction at 128 MeV. Identification was achieved using events detected by the Daresbury recoil separator in coincidence with γ rays detected in the 45 element EUROGAM I Ge-detector array. Threefold events were used to build a decay scheme which consists of two rotational bands observed to $I^\pi=(\frac{45}{2}^+)$ and $I^\pi=(\frac{33}{2}^-)$. The positive parity band in ^{75}Rb behaves similarly to a negative-parity band in ^{74}Kr and contains a region of alignment at $\hbar\omega\approx 0.75$ MeV. These data, and those of ^{77}Sr, can be interpreted by treating protons and neutrons separately in a cranked shell model approach despite a recent suggestion for the presence of $T=1$ neutron-proton pairing correlations in the neighboring self-conjugate, odd-odd ^{74}Rb ground state band. Our study suggests that some experimental observables such as the energy levels and moments of inertia, may not be able to differentiate between different $T=1$ pairing phases in these $T_z=\frac{1}{2}$ nuclei. [S0556-2813(97)50208-1]

PACS number(s): 21.10.Re, 21.30.Fe, 23.20.Lv, 27.50.+e

The study of nuclei far from stability challenges our theoretical understanding of nuclear forces as well as our experimental techniques. Typically, nuclear models are based on measured properties of nuclei much closer to the line of β-stability and extrapolated towards the drip lines. The predictions based on such models have a substantial amount of uncertainty especially concerning local phenomena which appear under specific conditions of nuclear isospin, spin, or temperature. A relevant example of such an effect is the neutron-proton (np) pairing which is most often ignored in the mean-field models. Indeed, in the vicinity of the β-stability line, where protons and neutrons occupy different spatial orbitals only traditional $T=1$, $|T_z|=1$ pairing correlations are of importance. However, in $N\approx Z$ nuclei the proton and neutron Fermi levels are close and collective

*Present address, Sektion Physik der Universität München, D-85748 Garching, Germany.

†On leave of absence from the Institute of Theoretical Physics, University of Warsaw, Poland.

‡Present address, Oliver Lodge Laboratory, Department of Physics, University of Liverpool, L69 38X Liverpool, United Kingdom.

§Also at Deutsches Museum, D-80306 München, Germany.

‖On leave of absence from the Tata Institute of Fundamental Research, Bombay, India.

np-pairing correlations are expected to play a significant role. In spite of the early theoretical efforts (see the review article [1] and references quoted therein) very little is known about the nature of these *np*-pairing correlations, particularly in the deformed, midmass, self-conjugate nuclei of the $A \approx 80$ region.

The properties of $N,Z \approx 40$ nuclei depend strongly on particle number (see, e.g., [2–5] and references quoted therein). The light krypton isotopes ($Z=36$) display evidence of shape coexistence, while the strontium isotopes ($Z=38$) have some of the largest known prolate deformed ground states. As we probe closer to the self-conjugate nuclei, collective *np*-pairing correlations are expected to influence the observed nuclear structure, as has recently been suggested [6] in ^{74}Rb. This result was based on the observation that the $T=1$, even-spin energy levels are similar to those in its even-even isobar, ^{74}Kr. A recent calculation by Dean *et al.* [7] suggests that the $T=1$, $J=0$ *np*-pairing correlations dominate the low-lying, even-spin states in ^{74}Rb. Whether or not this observed structure is evidence of the collective *np*-pairing correlations expected to occur along the $N=Z$ line or the more prevalent coupling of two valence $g_{\frac{9}{2}}$ particles via the two-body residual interaction, remains to be determined.

Unfortunately, the clear experimental signatures of collective *np*-pairing correlations are unknown and the search for them is the focus of this work. Our approach is to compare experimental observables with mean-field theoretical calculations which have been shown to describe these nuclei fairly well. Any systematic deviations between theory and experiment might indicate ''new'' physics and demonstrate the need to include effects such as *np* correlations.

All the calculations presented in this work have been carried out using the pairing and deformation self-consistent total routhian surface (TRS) model described in Refs. [8,9]. The model uses the traditional language of the deformed mean-field potential (Woods-Saxon type) plus residual interactions (seniority and quadrupole pairing forces), but does not explicitly contain any nonseparable *np* interaction. The *np* interaction enters into the calculations only indirectly through the parameters of the Woods-Saxon potential and through the requirement of common neutron and proton deformations. This work is part of a more systematic study of small-T_z Kr, Rb, Sr, and Zr isotopes [10], where the relatively low density of states might allow a comprehensive investigation into the possible configuration dependence of *np* correlations.

The nucleus ^{75}Rb lies just below the large deformed shell gap at $N=Z=38$. It is [11] the last proton stable even-*N* rubidium isotope and as such, is expected to play a role [12] in the extended rapid proton capture process. Before this experiment, no excited states in this nucleus have been reported. The nucleus has been observed previously through its β^+ decay and a summary of these and other data may be found in the work by Kern *et al.* [13]. The ground state of ^{75}Rb decays [13] with a half-life of (21.4 ± 1.0) s and has a spin of either $I^\pi = \frac{3}{2}^-$ or $\frac{5}{2}^-$.

The identification of γ-ray transitions in ^{75}Rb was carried out with the 45 Compton-suppressed Ge-detector array EUROGAM I [14] in coincidence with the Daresbury recoil separator [15]. The target consisted of a 250-μg/cm^2, 99.965% enriched ^{40}Ca layer evaporated onto a

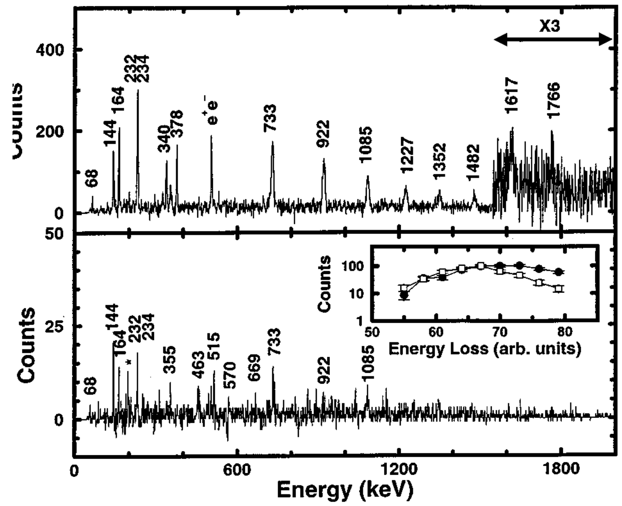

FIG. 1. (Top) A γ-ray spectrum gated by the 515 keV, $(\frac{13}{2}^+)\rightarrow(\frac{9}{2}^+)$ transition and several transitions belonging to ^{75}Rb. The large peak at 505 keV appears to be related to the 511 keV, e^+e^- annihilation radiation. We cannot rule out the possibility of a weak, 505 keV, $(\frac{7}{2}^+)\rightarrow(\frac{3}{2}^+)$ transition. The presence of such a transition could not be confirmed in other gates. (Bottom) The $A=75$ and $Z=37$ gated spectrum. γ rays marked with energies (keV) are assigned to ^{75}Rb and have been placed in a level scheme. The 198 keV transition is marked with an asterisk and could not be placed. The inset shows the γ-ray intensity (logarithmic scale) of $A=75$ recoils as a function of energy loss in the ionization chamber. Those transitions originating from Rb ions (solid symbols) should have a larger energy loss than those from known [19] Kr ions (open symbols). See Ref. [18] for discussion of procedure for obtaining these curves. The data of ^{75}Rb in the inset is produced by the sum of the yields of several γ rays.

10 μg/cm^2 carbon foil and covered with a thin ($\leqslant$ 100 μg/cm^2) layer of gold. A 128 MeV ^{40}Ca beam was used to populate ^{75}Rb via the αp evaporation channel.

The velocity filters of the recoil separator were set to permit only high-energy recoils to be accepted in an attempt to enhance detection of the α-evaporation channels, where the α particle is emitted at 180° with respect to the beam. The large recoil cone and velocity distribution resulting from α-particle evaporations reduce the efficiency of an energy sensitive, 0° device like the Daresbury recoil separator. The high γ-ray detection efficiency of EUROGAM I, which is ideal for detecting three coincident γ rays, coupled with the long time delay for recoil detection required that compromises be made in determining the electronic trigger. For these reasons, despite the high γ-ray efficiency of EUROGAM, this experiment suffered from poorer statistics than previous [16–18] recoil-γ experiments using less efficient Ge detector arrays.

Identification of γ-ray transitions in ^{75}Rb was obtained [18] using coincidence techniques between the γ rays detected in EUROGAM I, the masses detected with the position sensitive focal plane detector of the recoil separator, and the energy loss of the ions in an ionization chamber located behind the focal plane. An $A=75$, $Z=37$ gated γ-ray spectrum is shown in the lower portion of Fig. 1. The inset shows the γ-ray intensity of ^{75}Kr [19] and ^{75}Rb transitions as a function of the energy loss (Z dependent) of the mass separated $A=75$ ions in the ionization chamber.

In order to establish coincidence relationships between γ

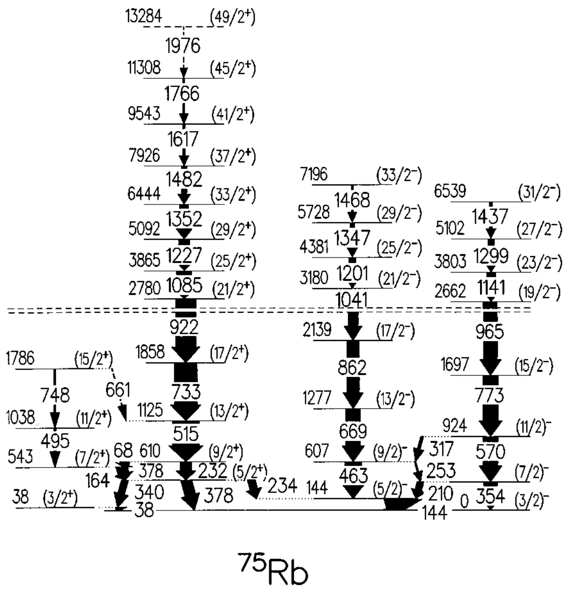

FIG. 2. Proposed level scheme deduced for ^{75}Rb. See discussion in text about the ordering of the transitions near the ground state. The dashed transitions and levels are tentative. The widths of the arrows are proportional to the relative intensities of the γ ray which were deduced from the γ-γ-γ data. Energy labels are given in keV. Note the change in energy scale at 2.5 MeV. The errors of the γ-ray energies are typically less than one keV for the intense low lying transitions and increase to some 2 keV for the transitions on top of the bands.

rays, two dimensional γ-gated ''triples'' matrices and a γ-γ-γ cube were created. The advantages of such techniques are an increase in peak-to-total ratio and a reduction in contaminant γ rays through channel selection. A disadvantage is the difficulty in determining intensities and, hence, ambiguities in the level sequences may result near the ground state. For the ground state, we assume spin $\frac{3}{2}^-$ which can be supported by (*i*) the β^+ decay work of Kern *et al.* [13] indicating negative parity for the ground state and (ii) by the Nilsson-Strutinsky calculations [20] of the bandhead energies. The calculations predict the $[431]\frac{3}{2}^+$ as the ground state configuration of ^{75}Rb with deformation $\beta_2=0.37$, $\beta_4=-0.02$. The lowest negative parity bandhead, $[312]\frac{3}{2}^-$, with deformation $\beta_2=0.39$, $\beta_4=0.01$, is predicted to be nearly degenerate with the $[431]\frac{3}{2}^+$ configuration and have an excitation energy of 0.1 MeV. A spherical configuration is predicted to lie some 0.6 MeV above the ground state. Experimentally, the position of the two lowest predicted configurations are reversed. The predicted large prolate deformations are typical of those observed in the light Rb [21] and Sr [22,23] isotopes.

The upper portion of Fig. 1 presents a sum spectrum with several gates set in the 515 keV gated ''triples'' matrix and contains transitions assigned to ^{75}Rb. This spectrum reveals one rotational band and many low-energy transitions. These transitions are organized into the left-hand side of the level scheme shown in Fig. 2. Based on systematics of neighboring odd-*A* Br [24,25] and Rb isotopes [21] and the apparent signature splitting, we tentatively assign positive parity to this band and assume the 515 keV transition is the $(\frac{13}{2}^+)\rightarrow(\frac{9}{2}^+)$ transition. Under this assumption, the multipolarity dependent Directional Correlations from Oriented States [26], or DCO ratios, of the 144-, 164-, 340-, and 378-keV transitions are consistent with stretched dipole character and those of the 515-, 733-, and 922-keV transitions with stretched quadrupole character. Although not observed, the presence of a 38-keV transition can be inferred from the coincidence relationships observed between the 164-, 232/234-, 340-, 378-, and 515-keV transitions. Its $E1$ character $(\frac{3}{2}^+)\rightarrow(\frac{3}{2}^-)$, is based on theoretical values of transition rates [27] for different multipolarities as a function of transition energy (340, 378, 38 keV) and our Nilsson-Strutinsky calculations. The ordering of the high-spin rotational band beginning with the $\frac{9}{2}^+$ state and extending to the probable $\frac{49}{2}^+$ state can be verified easily in several gates in the gated matrix and the cube. Double-gated spectra (164 kev + 234, 340, 378 keV) in the cube indicate the beginning of the unfavored positive-parity band (495- and 748-keV transitions). Since the 495- and 748-keV transitions were not observed in double gates involving the 164- and 515-keV transitions, the ordering of the 164- and 68-keV transitions is fixed.

Using the cube, the additional transitions at 463, 570, and 669 keV in Fig. 1 were found to be in coincidence with the 144-keV transition, but not with the 232/234-keV doublet nor the 340-, 378-, or 515-keV transitions. This suggests the 144-keV γ ray, and, hence, the 378-keV γ ray, to be transitions to the ground state. Based on γ-γ-γ relationships, a second strongly coupled rotational band with almost no signature splitting was established and is shown on the right-hand side of Fig. 2. Systematics of neighboring nuclei [21] support negative parity for this band.

The experimental and calculated dynamical moments of inertia, routhians, and angular momentum as a function of rotational frequency $\hbar\omega$ are presented in Fig. 3. The $J^{(2)}$ moment of inertia indicates a very broad band crossing at $\hbar\omega\approx0.75$ MeV in the positive parity band in ^{75}Rb and in the negative parity bands in ^{74}Kr. This is the broadest crossing observed in this mass region. The alignment gain associated with the crossing is some 3 $\hbar$ (not shown), a value not unexpected for the alignment of a single $g_{9/2}$ neutron pair. The negative-parity bands indicate an alignment at the highest known frequency. Unfortunately, the band is not observed beyond this band crossing which would be expected to be a double band crossing as in the yrast bands in ^{74,76}Kr [25,29].

The standard TRS calculations are able to reproduce the main experimental trends rather well. The spin alignment (I_x) in the positive parity $\pi[431]\frac{3}{2}^+$ band is well accounted for by the traditional picture involving blocking by the $g_{9/2}$ proton and the alignment of a $g_{9/2}$ neutron pair at very large deformation. The model cannot, however, fully account for the dynamics of the alignment process in this band. The calculated crossing is somewhat delayed and the yrast-yrare interaction, although large, is smaller than that observed experimentally. One should, however, point out that the cranking model is by definition not capable of properly describing the crossing region due to anomolous angular momentum fluctuations [30] at the crossing point. Moreover, our calculations predict substantial changes of the quadrupole (and hexadecapole) shape induced by the aligning $g_{9/2}$ quasiparticles. The shape changes are of the order of $\Delta\beta_2(\Delta\beta_4)\sim-0.08(-0.06)$, respectively. It might well be that the broad interaction range seen in the $J^{(2)}$ plot reflects a gradual shape change induced by $\nu g_{9/2}$ alignment.

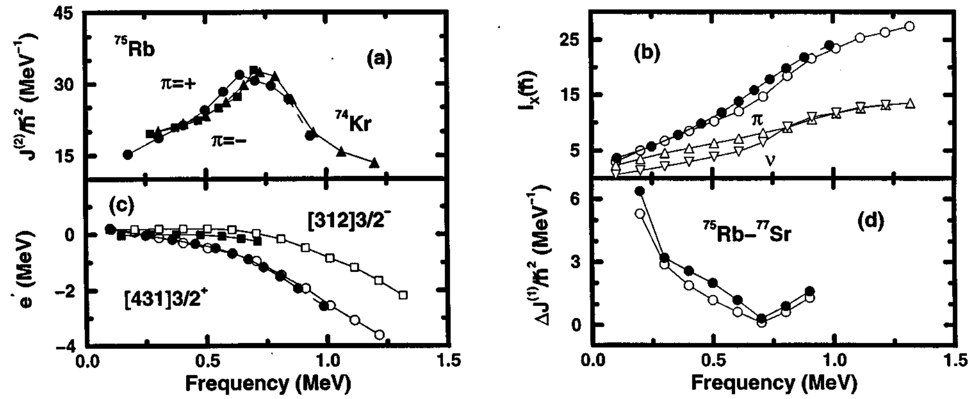

FIG. 3. (a) The dynamic ($J^{(2)}=dI/d\omega$) moment of inertia of the $[431]\frac{3}{2}^+$ (circles) and $[321]\frac{3}{2}^-$ (squares) bands in ^{75}Rb, and the negative parity, even signature band in ^{74}Kr (triangles) as a function of rotational frequency, $\hbar\omega$. Note the very broad upbend in the positive parity band in ^{75}Rb and its similarity to the negative parity band in ^{74}Kr. (b) Comparison between empirical (solid symbols) and calculated (open symbols) aligned angular momentum I_x as a function of $\hbar\omega$. The calculated proton and neutron contributions to I_x are also given. (c) Comparison between the calculated (open symbols) and measured (solid symbols) routhians for the $[431]\frac{3}{2}^+$ band (circles) and the $[312]\frac{3}{2}^-$ band (squares) in ^{75}Rb as a function of $\hbar\omega$. The $[312]\frac{3}{2}^-$ bands are strongly coupled and only one signature is shown for clarity. (d) The difference $\Delta J^{(1)}\equiv J^{(1)}(^{75}\text{Rb};\pi[431]\frac{3}{2}^+)-J^{(1)}(^{77}\text{Sr};\nu[422]\frac{5}{2}^+)$ between the experimental (solid circles) and calculated (open circles) moments of inertia $J^{(1)}$ of positive parity, positive signature bands in ^{75}Rb and ^{77}Sr. See text for more details.

The relative excitation energy of the negative parity $\pi[312]\frac{3}{2}^-$ band with respect to the positive parity $\pi[431]\frac{3}{2}^+$ band in ^{75}Rb is also fairly well reproduced although it is overestimated (over the whole frequency range) by $\Delta e^{\omega}\approx 300$ keV, see Fig. 3(c). Simultanously, the moment of inertia $J^{(1)}\equiv I/\omega$ for the negative parity bands is slightly, but systematically underestimated. The calculated negative parity bands are strongly coupled and show small, constant signature splitting at low frequencies due to slightly different deformations calculated for different signature branches. It appears that the signature splitting of the $\pi[312]\frac{3}{2}^-$ orbital is very sensitive to even small shape changes and might be easily inverted when changing the triaxiality parameter from small positive to small negative values. Similarly, rapid shape changes are predicted for the negative parity bands due to the alignment of $g_{9/2}$ quasiparticles.

Agreement of similar quality between the data and the calculations was also obtained for rotational bands [28] in the neighboring $T_z=+\frac{1}{2}$ nucleus, ^{77}Sr. Figure 3(d) shows the relative difference in moments of inertia $\Delta J^{(1)}\equiv J^{(1)}(^{75}\text{Rb};\pi[431]\frac{3}{2}^+)-J^{(1)}(^{77}\text{Sr};\nu[422]\frac{5}{2}^+)$ calculated for the data and the theory, respectively. Interestingly, both curves follow each other, indicating that the relative structural variations induced by the two additional nucleons in ^{77}Sr are properly taken into account. This suggests that the slight discrepancies between the data and the theory may have a common origin in both nuclei.

In view of the success of the standard Nilsson-Strutinsky calculations containing no explicit np correlations, it seems rather difficult to draw unique conclusions concerning the source of the rather modest disagreement between the theory and the data. Essentially all the ingredients of our model can contribute including: (i) deficiencies of the cranking approximation, (ii) deficiencies of the particle-hole mean field, and (iii) incorrectly estimating the pairing strength due to the strong influence of the Wigner energy on the odd-even mass differences around the $N\sim Z$ line. The latter is directly related to the $T=0\,np$ correlations [31,32]. Although our TRS calculations do not support any scenario involving a collective, static np-pairing phase, the np-residual interactions can emerge (a few strong matrix elements) in the band crossing region. Indeed, in the positive parity bands one can expect direct np-coupling of a blocked $\pi(\nu)g_{9/2}$ quasiparticle with the aligning pair of $\nu(\pi)g_{9/2}$ quasiparticles in the positive parity bands of ^{75}Rb(^{77}Sr). The TRS calculations predict a band crossing which occurs at higher rotational frequency than the experimental value. This would suggest that the angular momenta of the $g_{9/2}$ quasiparticles tend to couple in parallel (symmetric space-spin wave function), thus highlighting any energy lowering (frequency lowering), isoscalar component of np interaction. In the negative parity bands the np residual interactions may arise in the four quasiparticle configurations. Systematic investigation of these bands may (*i*) provide important clues to the alignment pattern yet to be observed in heavy, even-even, self-conjugate nuclei as well as (*ii*) give information about the influence of the blocked, negative parity (quasi)particle, on the possible np residual interactions. Unfortunately, the bands are only known up to the first band crossing and therefore, no conclusions may be drawn.

In conclusion, excited states in ^{75}Rb have been identified for the first time using recoil-γ and γ-γ-γ techniques. Two rotational bands have been observed extending to spin ($\frac{49}{2}^+$) and ($\frac{33}{2}^-$), respectively. Good agreement between the TRS calculations and experiment can be obtained without explicitly including np correlations. Minor differences associated with the band crossing region (early crossing) are not definitive proof of the presence of these correlations and if significant, most likely arise from isoscalar (i.e., noncollective) residual np interactions [7]. Assuming that the low-lying even-spin states in ^{74}Rb are indeed dominated by $T=1$, $J=0$ np pairing, the present results are somewhat surprising. However, it is possible that the $T=1$, $J=0$ np pairing may be mimicked by the $T=1$, $J=0$ like-nucleon pairing. This is because the nuclear rotation is sensitive to the angular momentum coupling, but not the T_z component of the pair's isospin. Therefore, the common high-spin observables such as alignments and moments of inertia, may not distinguish between these two couplings. Electromagnetic transition rates and g factor measurements would be a more sensitive probe of these effects. A systematic study of neighboring $T_z=+\frac{1}{2}$ nuclei is underway to see if these effects persist throughout this region of deformed nuclei.

We wish to thank the crew and staff of the Nuclear Structure Facility at Daresbury Laboratory for their excellent help in this experiment. We also thank John Green and Bob Darlington for their extraordinary efforts to provide unoxidized Ca targets. All the members of the EUROGAM collaboration deserve our recognition for their contributions to the detector array, its electronics, and our experiment. The contributions of C. J. Lister in the preparations for this experiment are gratefully acknowledged. Analysis of the data was partially carried out with the program VS by J. Theuerkauf *et al.*, View Spectra (VS), Institut für Kernphysik, Köln, Germany. EUROGAM is funded jointly by the UK EPSRC and French IN2P3. Oak Ridge National Laboratory (ORNL) is managed by Lockheed Martin Energy Research Corporation for the U.S. Department of Energy (DOE) under contract No. DE-AC05-96OR22464. This research was also supported by DOE through Contract Nos. DE-AC05-76OR00033 (Oak Ridge Institute for Science and Education), DE-FG02-96ER40963 (University of Tennessee) and DE-FG05-87ER40361 (Joint Institute for Heavy Ion Research). This work was funded in part by the German BMBF under contract No. 06GÖ667, Swedish Natural Science Research Council, and the U.S. Department of Energy under Contract Nos. DE-FG02-88ER-40406, DE-FG02-91ER-40609, and DE-FG05-93ER40770. The Oak Ridge National Laboratory Postdoctoral Research Associates Program is administered jointly by the Oak Ridge National Laboratory and the Oak Ridge Institute for Science and Education. One of us (D.M.C.) also acknowledges the support of the University of Tennessee.

[1] A. L. Goodman, Adv. Nucl. Phys. **11**, 263 (1979).
[2] W. Nazarewicz, J. Dudek, R. Bengtsson, T. Bengtsson, and I. Ragnarsson, Nucl. Phys. **A435**, 397 (1985).
[3] P. Bonche, H. Flocard, P. H. Heenen, S. J. Krieger, and M. S. Weiss, Nucl. Phys. **A443**, 39 (1985).
[4] *Nuclear Structure of the Zirconium Region*, edited by J. Eberth, R. A. Mayer, and K. Systemich (Springer-Verlag, Berlin, 1988).
[5] A. Petrovici, K. W. Schmid, and A. Faessler, Nucl. Phys. **A605**, 290 (1996).
[6] D. Rudolph *et al.*, Phys. Rev. Lett. **76**, 376 (1996).
[7] D. J. Dean, S. E. Koonin, K. Langanke, and P. B. Radha, Phys. Lett. B (in press).
[8] W. Satuła, R. Wyss, and P. Magierski, Nucl. Phys. **A578**, 45 (1994).
[9] W. Satuła and R. Wyss, Phys. Rev. C **50**, 2888 (1994).
[10] D. Rudolph *et al.*, Phys. Rev. C **56**, 98 (1997).
[11] M. F. Mohar, D. Bazin, W. Benenson, D. J. Morrissey, N. A. Orr, B. M. Sherrill, D. Swan, and J. A. Winger, Phys. Rev. Lett. **66**, 1571 (1991); A. Jokinen *et al.*, Z. Phys. A **355**, 227 (1996).
[12] S. E. Woosley, in Proceedings of the Accelerated Radioactive Beams Workshop, Parksville, Canada, edited by L. Buchmann and J. M. D'Auria (TRIUMF Report No. TRI-85-1, 1985), p. 4.
[13] B. D. Kern, K. S. Toth, D. M. Moltz, J. Lin, F. T. Avignone, III, H. Noma, and G. A. Leander, Phys. Rev. C **28**, 2168 (1983).
[14] C. W. Beausang *et al.*, Nucl. Instrum. Methods Phys. Res. A **313**, 37 (1992); P. J. Nolan, Nucl. Phys. **A520**, 657c (1990).
[15] A. N. James, T. P. Morrison, K. L. Ying, K. A. Connell, H. G. Price, and J. Simpson, Nucl. Instrum. Methods Phys. Res. A **267**, 144 (1988).
[16] C. J. Lister, P. J. Ennis, A. A. Chishti, B. J. Varley, W. Gelletly, H. G. Price, and A. N. James, Phys. Rev. C **42**, R1191 (1990).
[17] W. Gelletly, M. A. Bentley, H. G. Price, J. Simpson, C. J. Gross, J. L. Durell, B. J. Varley, Ö. Skeppstedt, and S. Rastikerdar, Phys. Lett. B **253**, 287 (1991).
[18] P. J. Ennis, C. J. Lister, W. Gelletly, H. G. Price, B. J. Varley, P. A. Butler, T. Hoare, S. Ćwiok, and W. Nazarewicz, Nucl. Phys. **A535**, 392 (1991).
[19] S. Skoda, J. L. Wood, J. Eberth, J. Busch, M. Liebchen, T. Mylaeus, N. Schmal, R. Sefzig, W. Teichert, and M. Wiosna, Z. Phys. A **336**, 391 (1990).
[20] J. A. Sheikh and W. Nazarewicz (unpublished).
[21] L. Lühmann, K. P. Lieb, C. J. Lister, J. W. Olness, H. G. Price, and B. J. Varley, Europhys. Lett. **1**, 623 (1986); A. Harder *et al.*, Phys. Lett. B **374**, 277 (1996); Phys. Rev. C **55**, 1680 (1997).
[22] C. J. Lister, B. J. Varley, H. G. Price, and J. W. Olness, Phys. Rev. Lett. **49**, 308 (1982).
[23] P. Lievens, L. Vermeeren, R. E. Silverans, E. Arnold, R. Neugart, K. Wendt, and F. Buchinger, Phys. Rev. C **46**, 797 (1992).
[24] N. Martin, C. J. Gross, J. Heese, and K. P. Lieb, J. Phys. G **15**, L123 (1989).
[25] J. Heese, N. Martin, C. J. Gross, W. Fieber, K. P. Lieb, A. Kuhnert, K.-H. Maier, and X. Sun, Phys. Rev. C **41**, 1553 (1990).
[26] K. S. Krane, R. M. Steffen, and R. M. Wheeler, At. Data Nucl. Data Tables **11**, 354 (1973).
[27] K. E. G. Löbner, *The Electromagnetic Interaction in Nuclear Spectroscopy*, edited by W. D. Hamilton (North-Holland, Amsterdam, 1975), p 149.
[28] C. J. Gross *et al.*, Phys. Rev. C **49**, R580 (1994).
[29] C. J. Gross *et al.*, Nucl. Phys. **A501**, 367 (1989).
[30] I. Hamamoto and W. Nazarewicz, Phys. Lett. B **252**, 533 (1990).
[31] N. Zeldes, *Handbook of Nuclear Properties*, edited by D. Poenaru and W. Greiner (Clarendon, Oxford, 1996), p. 13, and references therein.
[32] W. Satuła, D. J. Dean, J. Gary, S. Mizutori, and W. Nazarewicz, Phys. Lett. (in press).