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Published in:
Physical Review Letters

DOI:
10.1103/PhysRevLett.76.376

1996

Link to publication

Citation for published version (APA):
Identification of $T = 0$ and $T = 1$ Bands in the $N = Z = 37$ Nucleus $^{74}$Rb


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(Received 28 June 1995)

The $\gamma$ decay of excited states in the $N = Z$ odd-odd nucleus $^{74}$Rb has been observed for the first time. The reaction $^{40}$Ca($^{40}$Ca, $\alpha$ pn)$^{74}$Rb at 128 MeV beam energy was used. The ground state rotational band can be interpreted as being formed from the $T = 1$ isobaric analog states of $^{74}$Kr with pairing correlations based on $^{40}$Ca and $^{40}$K. Accordingly, the $^{40}$Ca-$^{40}$K isobaric analog states of $^{40}$Rb were populated in two experiments using the reaction $^{40}$Ca($^{40}$Ca, $\alpha$ pn)$^{74}$Rb at 128 MeV beam energy. The Eurogam I array [11], consisting of 45 Compton-suppressed Ge detectors, was used to detect prompt $\gamma$ radiation in coincidence with nuclear recoils identified with the recoil separator. Recoil-$\gamma$ and twofold and higher-fold $\gamma$ events were recorded. The target consisted of 250 $\mu$g/cm$^2$ $^{40}$Ca enriched to 99.965%, evaporated onto a 10 $\mu$g/cm$^2$ carbon foil with a covering flash of gold. The second experiment was performed at the Nordball facility [12] using a 400 $\mu$g/cm$^2$ $^{40}$Ca target, enriched to 99.99% and evaporated onto a 14 mg/cm$^2$ thick gold foil. The $\gamma$ radiation was measured in 19 Compton-suppressed Ge detectors at 37°, 79°, 101°, and 143° relative to the beam axis. Efficient channel selection was possible by detecting evaporated charged particles in a 4\pi silicon ball consisting of 20 segments. Seven liquid scintillator detectors and 30 BaF$_2$ scintillators served as neutron and $\gamma$ multiplicity filters.

In the first experiment it was possible to identify the recoiling nuclei by A and Z but the statistics were not good enough to assign $\gamma$ rays unambiguously to the weak $\alpha$ pn exit channel, $^{74}$Rb. Accordingly, the $\gamma$ rays were identified from inspection of the various particle-$\gamma$ coincidences recorded in the Nordball experiment. All of the spectra with the gating conditions of 0–6 protons, 0–3 $\alpha$ particles, and 0–3 neutrons were sorted. By successively subtracting spectra with higher particle detection folds from revealed. The present study investigates the yrast states in the $N = Z = 37$ nucleus $^{74}$Rb and provides the first experimental data to test some of these predictions.

High-spin states in $^{74}$Rb were populated in two experiments using the reaction $^{40}$Ca($^{40}$Ca, $\alpha$ pn)$^{74}$Rb at 128 MeV beam energy. The Eurogam I array [11], consisting of 45 Compton-suppressed Ge detectors, was used to detect prompt $\gamma$ radiation in coincidence with nuclear recoils identified with the recoil separator. Recoil-$\gamma$ and twofold and higher-fold $\gamma$ events were recorded. The target consisted of 250 $\mu$g/cm$^2$ $^{40}$Ca enriched to 99.965%, evaporated onto a 10 $\mu$g/cm$^2$ carbon foil with a covering flash of gold. The second experiment was performed at the Nordball facility [12] using a 400 $\mu$g/cm$^2$ $^{40}$Ca target, enriched to 99.99% and evaporated onto a 14 mg/cm$^2$ thick gold foil. The $\gamma$ radiation was measured in 19 Compton-suppressed Ge detectors at 37°, 79°, 101°, and 143° relative to the beam axis. Efficient channel selection was possible by detecting evaporated charged particles in a 4\pi silicon ball consisting of 20 segments. Seven liquid scintillator detectors and 30 BaF$_2$ scintillators served as neutron and $\gamma$ multiplicity filters.

In the first experiment it was possible to identify the recoiling nuclei by A and Z but the statistics were not good enough to assign $\gamma$ rays unambiguously to the weak $\alpha$ pn exit channel, $^{74}$Rb. Accordingly, the $\gamma$ rays were identified from inspection of the various particle-$\gamma$ coincidences recorded in the Nordball experiment. All of the spectra with the gating conditions of 0–6 protons, 0–3 $\alpha$ particles, and 0–3 neutrons were sorted. By successively subtracting spectra with higher particle detection folds from
the lower-fold spectra, "pure" spectra were produced, each containing γ radiation from only one of the following isotopes: 71,73,75Br, 72,74,75,76Kr, 74,75,76,77Rb, and 77,78Sr. Figure 1(a) illustrates the "pure" spectrum in coincidence with a pn detection leading to 74Rb. Apart from previously unknown lines at 218, 303, 478, 483, 520, 528, and 575 keV assigned to 74Rb, the strongest transitions from 81Rb and 82Rb are present. They originate from αp2n and αpn channels of the <0.01% component of 48Ca in the target. The relative cross section of 73Rb was estimated to be 0.11(4)% from normalized yields of the ground state transitions in the known residual nuclei. Calculations [13] predict a total fusion cross section of 380 mb, leading to a 0.4(2) mb cross section for the formation of 74Rb. The reaction 48Ca(40Ca, αp2n)81Rb is predicted to be 120 mb, making 81Rb the most important contaminant in the "pure" αpn spectrum. Figure 1(b) presents the sum of spectra gated with the 218, 303, 483, 520, and 528 keV transitions in the nγγ matrix. The origin of the new transitions from 16O and 12C target contaminants can be ruled out from the spectrum in Fig. 1(c). It is the sum of spectra in coincidence with the 218 and 303 keV transitions in the 74Rb γγγ matrix from the Eurogam data, which contains γγγ events with one γ ray being either the 218, 265, 303, 478, 483, 520, 528, or 575 keV transition. The nuclei were observed in flight and the γ-ray energies had to be Doppler corrected and the resulting peaks are Doppler broadened. The recoil velocity is significantly lower for reactions with 40Ca compared to reactions involving 16O or 12C nuclei and would lead to broad multipeaks for the latter in Fig. 1(c). The statistics are too poor to observe angular correlations in either of the experiments. However, the Nordball data allowed us to generate 74Rb spectra at 37° + 143° and 79° + 101°. The ratios of the yields of the transitions in the two spectra were used to determine their multipolarities.

The level scheme deduced for 74Rb is presented in Fig. 2. Since, in general, low lying isomeric states are expected in odd-odd nuclei, we also looked for delayed particle-γγ coincidences. However, no isomeric γ rays were found above 50 keV in 74Rb. In addition, a second β-decaying state with T = 0 was not observed, though searched for by D’Auria et al. [14]. They reported the Fermi superallowed (0+ → 0+, T = 1) β+ decay of 74Rb. Therefore, the most intense 478 keV transition, which is consistent with E2 character, is assumed to feed the 0+ ground state. The 575 keV transition was found to be in coincidence only with the 478 keV transition. The extension of the left-hand side of the level scheme was not feasible, due to strong contaminations. On the right-hand side the other 74Rb lines were grouped on top of the 478 keV state. Up to the 1489 keV level the excitation is rather irregular. Thereafter, a sequence of states develops which follows an I(I + 1) pattern.

The excited levels in 74Rb are completely different from those of neighboring odd-odd nuclei with N ≠ Z. These nuclei develop several strongly coupled ΔI = 1 rotational bands at very low excitation energies [15]. It is interesting to note that the presumed 4+ → 2+ → 0+ ground state band (575–478 keV) is close in energy to that in the isobar 74Kr (558–456 keV). Hence, we propose that these nearly "identical" bands result from the fact that they are T = 1 isobaric analog states. Such an interpretation carries with
it certain implications concerning the pairing correlations in the odd-odd nucleus and, in particular, is consistent with the recently suggested [16] reappearance of a pairing gap in $N = Z$ odd-odd nuclei in this region.

The pairing correlations encountered most frequently are $T = 1$, $M_T = \pm 1$, i.e., neutron or proton pairs in time-reversed orbits. In an odd-odd nucleus with larger neutron excess there should be no pairing gap and the rotational bands are characterized by $K = \{\Omega_n \pm \Omega_p\}$. $\Omega_n$ and $\Omega_p$ represent the projection of the single-particle angular momenta of the “unpaired” neutron and proton on the deformation axis. The bands are spaced simply according to the summed single-quasiparticle energies of the possible combinations of orbits with $\Omega_n, \Omega_p$. The relevant energies in $^{74}$Rb in the standard Nilsson model are shown in Table I for a prolate deformation $\beta_2 = 0.3$. Note that the effect of Gallagher-Mozkowski splitting [17] and the Newby shift [18] resulting from the residual $n$-$p$ interaction has been ignored, since both typically give rise to shifts of \(\approx 200\) keV.

The intention here is simply to indicate the high density of states likely to arise in the absence of $n$-$p$ pairing. In fact, the Nilsson orbits of Table I would give rise to a total of 72 rotational band heads below 2 MeV in $^{74}$Rb, and the coupling rules [17] for an odd neutron and proton occupying Nilsson orbits with the same $\Omega = 3/2$ imply that the ground state band should have $K^\pi = 3^+$. Even allowing for the separation induced by the isospin quantum number, the single-particle space still gives rise to a total of 36 $T = 1$ bands.

When neutrons and protons are filling identical orbits, the possibility of $n$-$p$ pairing correlations needs to be considered [7]. The last neutron and proton simply add one additional pair to the correlated ground state rather than constituting a two-quasiparticle state. The correlations can involve $T = 1$ pairs in time-reversed spatial orbitals, while $T = 0$ allows for pairing between identical orbits as well. The $T = 0$ interaction is normally assumed to be the most attractive, and this is borne out by the fact that the $N = Z$ odd-odd nuclei with $A < 40$ (except $^{34}$Cl) have a $T = 0$ ground state. It also agrees with the results of generalized Hartree-Fock-Bogoliubov calculations incorporating both $T = 0$ and $T = 1$ $n$-$p$ pairing [7,19] where $T = 0$ pairing was indeed found to dominate in $N = Z$ nuclei and to compete with $T = 1$, $M_T = \pm 1$ pairing for $N = Z + 2$. For larger $N$, inclusion of the $T = 0$ mode was unnecessary because the advantage of the larger number of like nucleon pairs rapidly outweighs that of the more attractive $T = 0$ interaction. Interestingly, $T = 1$ $n$-$p$ pairing was never found to be important in these studies.

In the 28–50 shell, however, the ground states of the heavier mass odd-odd $N = Z$ nuclei seem to favor $T = 1$, in agreement with earlier predictions [20] based on extrapolated masses and also with the behavior of the empirically determined $n$-$p$ interaction strength in both odd-odd and even-even nuclei which exhibits large attractive “spikes” at $N = Z$ which rapidly decrease with increasing mass. This behavior has recently been shown [21] to arise from, and to reflect, the gradual erosion of the Wigner spin-isospin symmetry as a result of the increasing importance of both the spin-orbit term in the nuclear potential and of the Coulomb interaction. In $^{74}$Rb the same number of either $T = 1$ or $T = 0$ $n$-$p$ pairs can be made and the favored mode will depend on the strength of the interaction. The current results thus suggest that, by the time $N = Z = 37$ has been reached (and probably considerably earlier), the trends cited above have resulted in the $T = 1$ pairs becoming the most attractive.

We turn now to the effect of increasing rotational frequency. In the standard cranked shell model (CSM) approach [22], neutrons and protons align their spins with the axis of rotation independently of each other. The residual $n$-$p$ interaction is disregarded. This approach is known to give a reasonable description of the high-spin behavior of deformed nuclei with $N > Z$. However, for particle stable nuclei with $N = Z$, the residual $n$-$p$ interaction should be explicitly considered. The model Hamiltonian consisting of a cranked deformed one-body term and a scalar two-body interaction was described in Refs. [9,23]. In this model, the interaction of the nucleons in the intruder valence subshell with the core nucleons is approximately described by the quadrupole field generated by them and the eigenstates have good parity, signature, and, most important, isospin. The deformation energy $\kappa$ is expressed in units of $G$, where $G$ is the strength of the $\delta$ interaction which is assumed here to be the two-body residual interaction. $\kappa$ is related to the usual deformation parameter $\beta_2$ via $\kappa = 51.5A^{-1/3} \beta_2$ MeV [24]. Calculated band-crossing frequencies in neighboring even-even nuclei [25] and shell model calculations in $A \approx 90$ isotopes [26] suggest $G = 1.0–1.5$ MeV.

The Routhians for the one-proton plus one-neutron system coupled to an axially symmetric deformed prolate core with $\kappa = 2.4G$, i.e., $\beta_2 = 0.2–0.3$, are presented in Fig. 3. The ground state in Fig. 3 at $\hbar \omega = 0$ has even-spin values and a predominant $(J = M_z = 0; T = 1)$ component with amplitude 0.83 and finite contributions from $(J = 2, M_z = 2, 0, -2; T = 1)$ configurations. $J$ denotes the intrinsic particle angular momentum, and this has to be coupled to the rotor angular momentum to obtain the total angular momentum in the laboratory frame; $M_z$ is the projection of $J$ on the rotational axis. As is evident from Fig. 3 the aligning $T = 0$

<table>
<thead>
<tr>
<th>Nilsson orbit</th>
<th>$E_{qp}^{\text{proton}}$ (MeV)</th>
<th>$E_{qp}^{\text{neutron}}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3/2^+{431}$</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>$3/2^-{312}$</td>
<td>0.349</td>
<td>0.356</td>
</tr>
<tr>
<td>$3/2^-{301}$</td>
<td>0.359</td>
<td>0.452</td>
</tr>
<tr>
<td>$5/2^-{422}$</td>
<td>0.423</td>
<td>0.346</td>
</tr>
<tr>
<td>$1/2^-{440}$</td>
<td>0.472</td>
<td>0.495</td>
</tr>
<tr>
<td>$1/2^-{310}$</td>
<td>0.965</td>
<td>0.887</td>
</tr>
</tbody>
</table>
The aligned configuration with odd-spin states ($T$ quickly lowered in energy relative to the ground state. The experimental Routhians of $\hbar \omega = 0.2G$ are shown in Fig. 3. The crossing of a $T = 0$ aligning configuration with the $T = 1$ ground state band.

The aligned configuration becomes immediately favored in energy at $\hbar \omega = 0.2G = 0.2 - 0.3$ MeV, consistent with the value of the experimental Routhians of $\hbar \omega = 0.28$ MeV. This “crossing” is diabatic since the ground state band and the aligning configuration have different isospin. The aligning configuration at $\hbar \omega = 0.2G$ is mainly comprised of the configurations ($J = 9, M_c = 9, 7, 5; T = 0$) with amplitudes 0.85, -0.36, and 0.18, respectively.

The interesting implication of the above analysis is that for odd-odd nuclei with $N = Z$, the first alignment along the yrast line is not due to the conventional breaking of two-proton or two-neutron pairs but is due to the spin alignment of an $n-p$ pair. As observed in $^{74}$Rb, the aligned configuration with odd-spin states ($T = 0$) is quickly lowered in energy relative to the ground state band with even-spin values ($T = 1$). This “crossing” of a $T = 1$ pairing ground band by a $T = 0$ pairing band at a critical spin was also predicted in earlier studies of even-even $N = Z$ sd shell nuclei [10,27,28]: The Coriolis force destroys pairs composed of two nucleons in time-reversed orbits while it reinforces the $n-p$ pairs in identical spatial orbits. In the latter case the Coriolis force has exactly the same effect on the neutron and the proton, so that they can both be aligned towards the axis of rotation without breaking the pair [8].

The crossing shown in Fig. 3 is not very sensitive to the magnitude of the deformation but depends on the two-body interaction used. With a more realistic interaction, such as the modified $\delta$ interaction, the energy spacing becomes larger with the consequence that the crossing seen in Fig. 3 will occur somewhat later. We also carried out the CSM analysis with oblate deformation since the core nucleus $^{72}$Kr may have coexisting prolate and oblate shapes in the low spin regime [4]. The crossing between the two isospin bands with $\kappa = -2.4G$ is delayed to $\hbar \omega = 1.1G$.

To conclude, we observed for the first time excited states in the heaviest $N = Z$ odd-odd nucleus $^{74}$Rb so far identified. The ground state band is proposed to consist of the $T = 1$ isobaric analog states seen in $^{74}$Kr and to exhibit $n-p$ pairing. The $T = 0$ odd-spin states become yrast at about 1.5 MeV excitation energy. Cranked shell model calculations using an axially symmetric deformed prolate core and explicitly including the residual neutron-proton interactions account for that phenomenon.

The authors wish to thank C. Baktash, R. Bark, J. D. Garrett, D. G. Sarantites, and the crew and staff of the NBITAL and the NSF for their assistance in the experiments. This work was funded by Deutsches BMFT under Contract No. 06GÖ677, the Swedish NSRC, and the U.S. DOE under Contracts No. DE-AC05-76OR05033 and No. DE-AC05-84OR21400. Eurogam is funded by EPSRC and IN2P3.

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