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Evidence for isovector neutron-proton pairing from high-spin states in $N=Z$ ^{74}Rb

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High-spin states in the odd-odd $N=Z$ nucleus $^{74}_{37}$Rb$_{37}$ were studied using the ^{40}Ca(^{40}Ca,αnp) reaction. A previously observed odd-spin $T=0$ band has been extended to $I^{\pi}=(31^{+})$ and an even-spin $T=0$ band has been observed for the first time to $I^{\pi}=(22^{+})$; both have a $\pi(g_{9/2})\otimes\nu(g_{9/2})$ structure. A strongly coupled low-spin $T=0,K=3$ band has been interpreted as being based upon a $\pi[312]\frac{3}{2}\otimes\nu[312]\frac{3}{2}$ configuration. Cranked relativistic Hartree-Bogoliubov calculations, which are corrected for the $t=1$ np-pair field by restoring isospin symmetry, reproduce the observed spectrum. These new results provide evidence for the existence of an isovector pair field that contains a neutron-proton component with the proper strength for ensuring isospin conservation.

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Nucleon-nucleon pairing correlations are a vital component of contemporary nuclear structure models. Although proton-proton (pp) and neutron-neutron (nn) pairing is well understood, there is currently a great deal of interest in studying the more exotic neutron-proton (np) pairing modes [1–6]. Isovector np (isospin $T=1$ and z-axis projection $T_Z=0$) pairs involve correlated nucleons in time-reversed orbits coupled to spin $I=0$. This is similar to like-nucleon pp ($T=1,T_Z=+1$) and nn ($T=1,T_Z=-1$) pairs. Isoscalar ($T=0$) np pairs involve nucleons coupled to $I\neq 0$.

Medium-mass odd-odd $N=Z$ nuclei are an ideal experimental laboratory for the study of np pairing, but this pursuit is severely hampered by the difficulty in populating such systems. The advent of large, high-efficiency germanium detector arrays and their use in conjunction with light fusion-evaporation particle detectors has recently permitted studies of odd-odd $N=Z$ nuclei with $A>60$; the heaviest nucleus in which excited states are known is $^{74}_{37}$Rb$_{37}$. Work by Rudolph *et al.* [1] established a $T=1$ band to $I^{\pi}=4^{+}$ in this nucleus, and a $T=0$ band (tentatively) to $I=17$. In this work we reinterpret the known energy-level scheme of ^{74}Rb and extend it to high spins.

Frauendorf and Sheikh [7] have recently extended the classification of rotational bands in terms of quasiparticle configurations in a rotating mean field such that isovector np-pair correlations are included. In the framework of this approach, we have carried out cranked relativistic Hartree-Bogoliubov (CRHB) calculations [8], corrected for the $t=1$, np-pair field by restoring isospin symmetry (t is the isospin of the pair field, as distinct from T which is the total isospin of the states). The capability of these calculations to successfully describe the observed excitation spectrum is interpreted as new, independent evidence of the presence of strong isovector np-pair correlations, as suggested by Vogel [9] and Macchiavelli *et al.* [10] in their binding-energy analyses. Significantly, we find that no isoscalar pair field is required, in contradiction to recent work by Satula and Wyss [11].

^{74}Rb was populated in the ^{40}Ca(^{40}Ca,αnp)^{74}Rb reaction using a beam of energy 164 MeV incident upon a 0.5 mg/cm^2 enriched ^{40}Ca target, sandwiched between two 0.5 mg/cm^2 layers of gold. Prompt gamma rays were collected over a period of 36 h using the GAMMASPHERE hyperpure germanium detector array [12] at the Lawrence Berkeley National Laboratory. Events in which at least three gamma rays were detected within the 101 detectors present in this array were written to tape. The field-of-view of this detector arrangement restricts the cumulative lifetime of observed states for the above reaction to $\lesssim 2$ ns. The MICROBALL charged-particle detector array [13] was used to identify prompt alpha and proton evaporates from the compound nucleus decay.

Events associated with the one-proton, one-alpha reaction channel were used to construct a three-dimensional array of gamma ray events and an asymmetric two-dimensional array with the requirement that all events were in coincidence with the $2^{+}\rightarrow 0^{+}$ 478 keV gamma-ray transition in ^{74}Rb. Events from detectors situated at angles $<70°$ and $>110°$ were

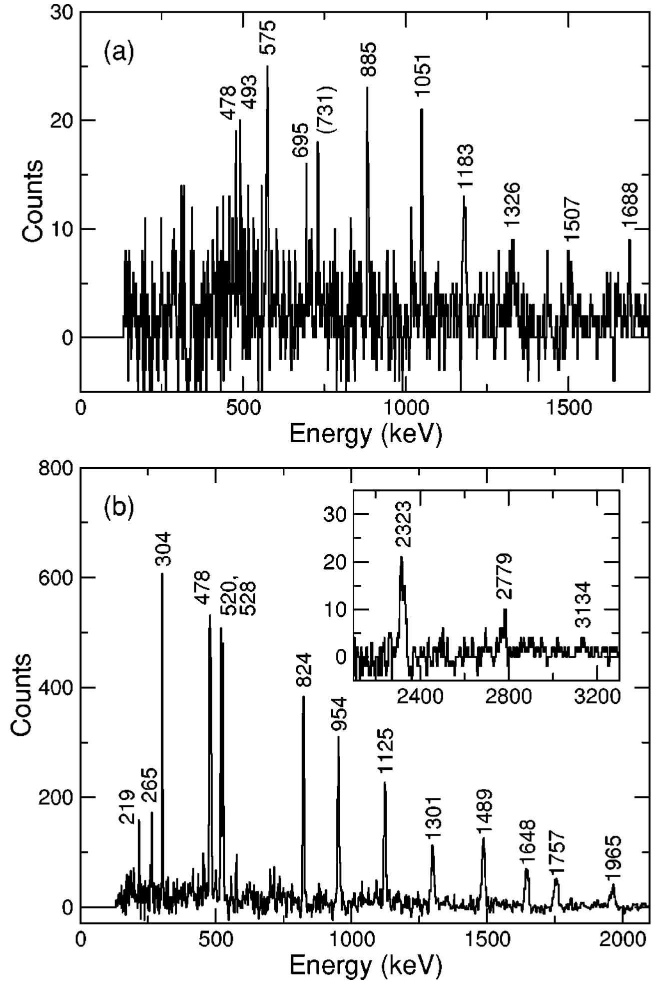

FIG. 1. (a) Gamma-ray spectrum of events in coincidence with any two of the 478, 493, and 695 keV transitions. (b) Events in coincidence with any two of the 304, 478, 483, 520, 528, 824, 1301, 2322, and 2779 keV transitions. The inset shows a region of the same spectrum from 2.1 to 3.3 MeV.

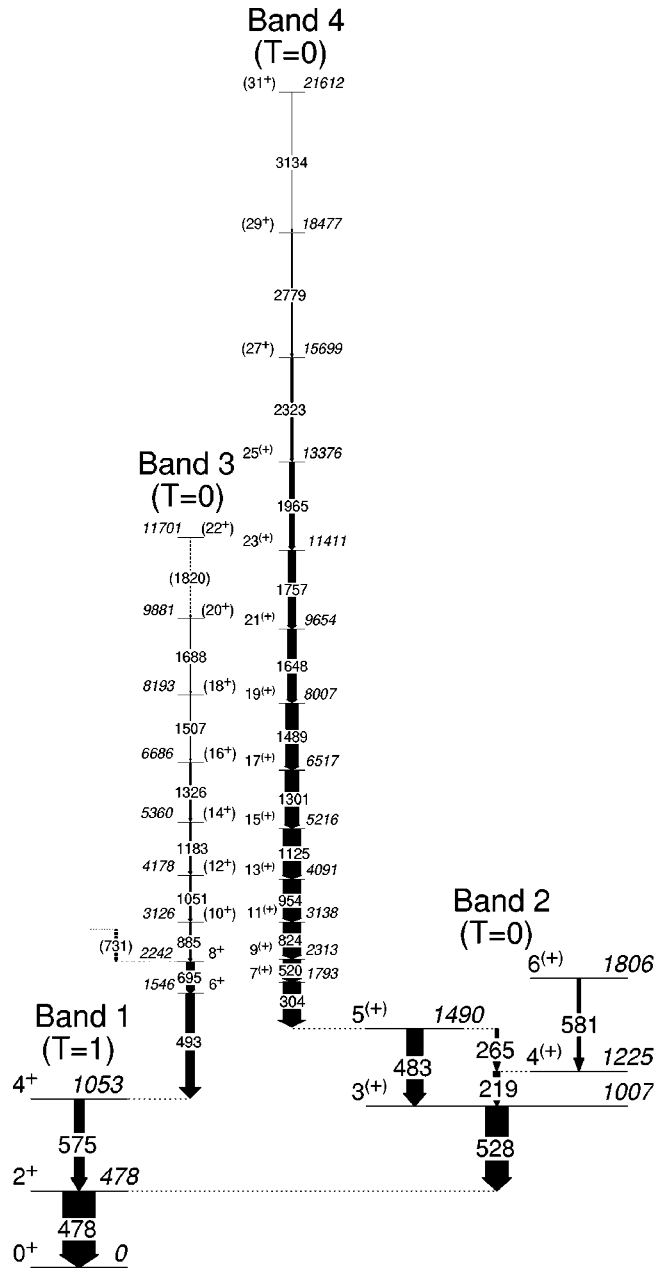

FIG. 2. Energy level scheme derived from the current analysis. Levels are labeled with assigned spin, parity, and energy. Arrow widths are proportional to gamma-ray intensity and tentatively-assigned spins and parities are bracketed. There is a change of energy scale going from bands 1 and 2 to bands 3 and 4.

incremented on the x axis, those from other angles on the y axis. Where statistics permitted, intensities of peaks in the projected spectra from each axis were measured and expressed as a directional correlation from oriented states (DCO) ratio [14], $R_{\mathrm{DCO}}=\mathrm{Int}_x/\mathrm{Int}_y$. In this manner it was possible to distinguish between $I\rightarrow I-2$ (stretched quadrupole) and $I\rightarrow I-1$ (stretched dipole) transitions.

Figure 1(a) shows events in coincidence with any two of the 478, 493, and 695 keV transitions. The 2^+ and 4^+ states at 478 and 1053 keV in band 1 of Fig. 2 are known from previous work [1]. All the other transitions in band 3 are new and in coincidence with one another.

DCO measurements (shown in Table I) indicate that the 219, 265, and 528 keV gamma rays are stretched dipole transitions, in agreement with previous work [1]. This leads to $I=3$, 4, and 5 spin assignments to the 1007, 1225, and 1490 keV states, and the interpretation of this structure as a $K=3$ band. The existence of such a $K=3$ band, built upon the $\pi[312]\frac{3}{2}\otimes\nu[312]\frac{3}{2}$ configuration, is supported by the recent observation that the lowest rotational structure in ^{73}Kr [16] is built on the $[312]\frac{3}{2}$ Nilsson orbital. In ^{73}Kr, the $[312]\frac{3}{2}$ and $[422]\frac{5}{2}$ states are in the vicinity of the Fermi level. The only negative parity combination of protons and neutrons in these states giving $I=3$ has $K=1$, but this is highly unlikely since $I=1$ and $I=2$ states have not been seen in band 2. Hence, the most plausible parity assignment for the states in bands 2 and 4 is positive. The DCO value for the 581 keV transition suggests an assignment of $I^{\pi}=6^{(+)}$ to the 1806 keV state. The similarity in energy between this and the 6^+ state (at 1782 keV) in ^{74}Kr might suggest it belongs to the $T=1$

TABLE I. Gamma rays in ^{74}Rb and their corresponding directional correlation from oriented states ratios ($R_{\rm DCO}$). The assigned spin and parity of the state deexcited and fed by each transition is given.

E_γ (keV)	$R_{\rm DCO}$	I_n^π(initial)$\rightarrow I_n^\pi$(final)
219	0.46 ± 0.03	$4_2^{(+)}\rightarrow 3_1^{(+)}$
265	0.49 ± 0.09	$5_1^{(+)}\rightarrow 4_2^{(+)}$
304	1.11 ± 0.09	$7_1^{(+)}\rightarrow 5_1^{(+)}$
483	1.81 ± 0.17	$5_1^{(+)}\rightarrow 3_1^{(+)}$
493	1.42 ± 0.43	$6_1^{+}\rightarrow 4_1^{+}$
528	0.54 ± 0.03	$3_1^{(+)}\rightarrow 2_1^{+}$
575	0.95 ± 0.05	$4_1^{+}\rightarrow 2_1^{+}$
581	1.15 ± 0.06	$6_2^{(+)}\rightarrow 4_2^{(+)}$
695	1.45 ± 0.15	$8_1^{+}\rightarrow 6_1^{+}$
1125	1.21 ± 0.08	$15_1^{(+)}\rightarrow 13_1^{(+)}$

band, but the lack of an in-band $E2$ transition (of 753 keV) to the $T=1$, $I^\pi=4^+$ state at 1053 keV contradicts this, as it should dominate over any $\Delta T=1$ $E2$ transition out of the band. Furthermore, the prompt $E2$ transition to the $4_2^{(+)}$ state at 1225 keV and energy systematics suggest that this state belongs to band 2.

The decay pattern of these states in band 2 is different from that previously observed in, for example ^{46}V [3] and ^{50}Mn [6], insofar as only the intraband $M1$ transitions are seen, whereas in the other cases only interband $M1$ transitions are observed. $M1$ and $E2$ are commonly considered to be significantly suppressed in $N=Z$ nuclei [15]. However, the transition strength depends upon the relative orientation of the orbital angular momentum and the spin of the single-particle states. In the $f_{7/2}$ shell nuclei ^{46}V and ^{50}Mn these vectors are parallel and the contributions of protons and neutrons to the transverse magnetic moment nearly cancel with one another, suppressing the intraband $M1$ transitions. In ^{74}Rb, for protons and neutrons in the $[312]\frac{3}{2}$ Nilsson orbital these contributions do not cancel because the spin and orbital angular momentum vectors are antiparallel and the $M1$ transition strength remains substantial between states of the same isospin. In the case of the neighboring state $[301]\frac{3}{2}$ there is almost complete cancellation. Hence the observation of the $M1$ is a good evidence that the low spin $K=3$ band is indeed a $\pi[312]\frac{3}{2}\otimes\nu[312]\frac{3}{2}$ configuration, and is consistent with the observation of $\nu[312]\frac{3}{2}$ as the lowest band in ^{73}Kr [16]. An estimate based on the Nilsson model for the $\pi[312]\frac{3}{2}\otimes\nu[312]\frac{3}{2}$ configuration and using the CRHB calculated values for Q_0, $\beta=0.48$, and $\gamma=-8.7°$, yields a value of $(g_k-g_R)/Q_0=0.1\ e{\rm b}^{-1}$. This compares favorably with $0.05\pm0.02\ e{\rm b}^{-1}$, derived [17] from the experimental branching ratio of the transitions from the $I^\pi=5^{(+)}$ state.

The 493 keV transition is assigned as an $E2$ transition on the basis of its DCO ratio. The possibility of it being a $I\rightarrow I$ dipole is rejected as this would inhibit band 3 from competing energetically with band 4. Furthermore, were the 1546 keV state actually $I^\pi=4^+$, one would expect a 1068 keV transition from this state to the 2^+ state at 478 keV to compete favorably with the 493 keV transition, but no gamma ray is observed at this energy. Energy level systematics suggest the most plausible assignment for states in band 3 is as an even-spin signature extending to $I^\pi=(22^+)$ with the quasiparticle configuration $\pi(g_{9/2})\otimes\nu(g_{9/2})$. States up to $17^{(+)}$ in band 4 had been observed in previous work [1] and we extend this structure [also assigned a $\pi(g_{9/2})\otimes\nu(g_{9/2})$ configuration] to $I^\pi=(31^+)$. A spectrum showing transitions in this band is presented in Fig. 1(b).

Prolate-oblate shape coexistence is a well known phenomenon in this mass region. The ground state band in ^{74}Kr evolves from an oblate shape in the ground state to a prolate shape at higher spin [18]. Since band 1 in ^{74}Rb is its isobaric analogue, the same behavior is expected. This is strongly supported by the similar values for the kinematic moments of inertia ($\mathfrak{I}^{(1)}$). The much larger values of $\mathfrak{I}^{(1)}$ in bands 2, 3, and 4 ($\sim$18–25 MeV^{-1} vs $\sim$6–10 MeV^{-1} in band 1) strongly suggest that these bands are prolate or near-prolate.

The method of Frauendorf and Sheikh [7] for incorporating the np-pair correlations into mean-field calculations uses the fact that the $t=1$ pair field breaks isospin symmetry. Any orientation in isospace is a legitimate intrinsic state—the y direction is chosen because the np-field does not explicitly appear for this orientation. With this choice one may carry out standard mean-field calculations that only take the pp- and the nn-pair fields into account. Here the CRHB theory of Afanasjev *et al.* [8] is employed. This uses the NL3 parametrization for the RMF Lagrangian, a Gogny D1S force for the pairing, and the Lipkin-Nogami method for an approximate particle number projection. The isospin symmetry is restored by adding the isorotational energy $T(T+1)/2J_{iso}$ to the intrinsic energy calculated via the CRHB. The isorotational energy contains the symmetry energy and the energy of the np-pair field, for which we use the experimental value of $75T(T+1)/A$ MeV [10]. Note that in order to conserve isospin, the $t=1$ np-pair field must be as strong as the nn- and pp-pair fields.

The lowest positive-parity $T=0$ configurations are generated by placing the odd proton and neutron either in the lowest $g_{9/2}$ or the lowest negative parity $N=3$ quasiparticle states [7]. The lowest $g_{9/2}$ quasiparticle orbitals, which we denote according to the standard quasiparticle picture [19] by **A**, **B**, and **C** for neutrons (**a**, **b**, and **c** for protons) have signature $\alpha=1/2$, –1/2, and 1/2, respectively. The lowest configuration is [**Aa**], which corresponds to band 4. The next highest is the combination ([**Ab**]$-$[**Ba**])/$\sqrt{2}$, corresponding to the even-spin band 3. The even-linear combination, ([**Ab**]+[**Ba**])/$\sqrt{2}$, is nonexistent because of isospin symmetry (T_y must be zero for $N=Z$ [7] nuclei). If only nn- and pp-fields were present, this symmetry argument would not apply and one would expect a doublet of even-spin bands, in contrast to the experimental data.

Placing the odd proton and neutron in the lowest negative-parity quasiparticle orbital gives a second, low-lying $T=0$ configuration of positive parity, which we assign to band 2. The projection of total angular momentum on the symmetry axis of this orbital is known to be $\Omega=3/2$ because it is observed in ^{73}Kr [16]. Therefore, band 2 should be a strongly coupled $K=3$ band, in agreement with experiment. In the CRHB calculations the lowest negative-parity orbital has $\Omega=1/2$, which points to inaccuracies in the calculated position of the single particle levels. For this reason only the calculated moment of inertia is used to construct $K=3$ band 2, with the energy difference between band 2 and band 4 taken from the experimental data. The observation of a strongly coupled and an aligned band, both starting at a similar energy of about 2Δ (where Δ is the pair gap) above the even-even $N=Z$ quasiparticle vacuum is exactly what one would expect from a $t=1$ pair field.

In this study we have used the calculated CRHB yrast solution for the $T=1$ band in ^{74}Kr for band 1 in ^{74}Rb as they are the isobaric analogues. We place [7] the $T=1$, $I=0$ state at $T(T+1)/2J_{iso}=1/J_{iso}$ above the $N=Z$ quasiparticle vacuum $(T=0)$. Relative to the $T=1$ band, the band head of the lowest $T=0$ band is expected at $2\Delta-T(T+1)/2J_{iso}$ ≈ 800 keV [7,10]. Experimentally, the $K=3$ band starts at 1007 keV, which is only 200 keV higher than this estimate, though 80 keV of this difference is due to the rotational energy at the band head $[(I(I+1)-K^2)/2J=K/2J\approx 80$ keV]. Band 3 must start several hundred keV higher than band 2 since they cross between $I=5$ and 7. A location of the chemical potential close to the $[312]\frac{3}{2}$ level, but somewhat removed from the $g_{9/2}$ level, would account for these energies. Hence the relative experimental energies of all bands are consistent with the assumption that only $t=1$ pair correlations are present.

Figure 3(a) shows the aligned angular momentum I_x minus a rigid-rotor reference $(i_x=I_x-20.17\omega)$. The difference in alignment of about $4\hbar$ between the strongly coupled band 2 and band 4 is the expected contribution of the $g_{9/2}$ midshell quasiparticles. The CRHB calculations agree well with the experiment, supporting our configuration assignments. In particular, they reproduce the difference in alignment between the two signatures of the $\pi(g_{9/2})\otimes\nu(g_{9/2})$ bands and the drastic change of the slope at $\hbar\omega=0.85$ MeV. This irregularity was predicted [7] and is caused by the crossing between the quasiparticle Routhians **B** (**b**) and **C** (**c**), which is well known to be the delayed first band crossing in odd-odd nuclei (where the **AB** and **ab** crossings are blocked). The alignment at $\hbar\omega=0.65$ MeV in the $T=1$ band is caused by the simultaneous crossing of **A** with **B** and **a** with **b**, which are Pauli blocked in the $T=0$, $\pi(g_{9/2})\otimes\nu(g_{9/2})$ bands. This crossing is clearly observed in the $T=1$ band of ^{74}Kr (the analogue to band 1 in ^{74}Rb). A similar crossing is expected in the $T=0$ band 2.

Figure 3(b) shows the level energies minus a rigid-rotor reference. The $\pi(g_{9/2})\otimes\nu(g_{9/2})$ structures have nearly the same energy as the $K=3$ band at low spin and are energetically favored at high spin because of the alignment of the $g_{9/2}$ protons and neutrons. Both the splitting between the two signatures and their spin dependence are well reproduced by the CRHB calculations. The agreement must be considered as satisfying because the theoretical estimate is based on a global fit of the quantity $2\Delta-T(T+1)/2J_{iso}$ to a range of nuclei, the assumption that the Fermi level lies on the $[312]\frac{3}{2}$ state and that there is no residual np-interaction in the particle-hole channel.

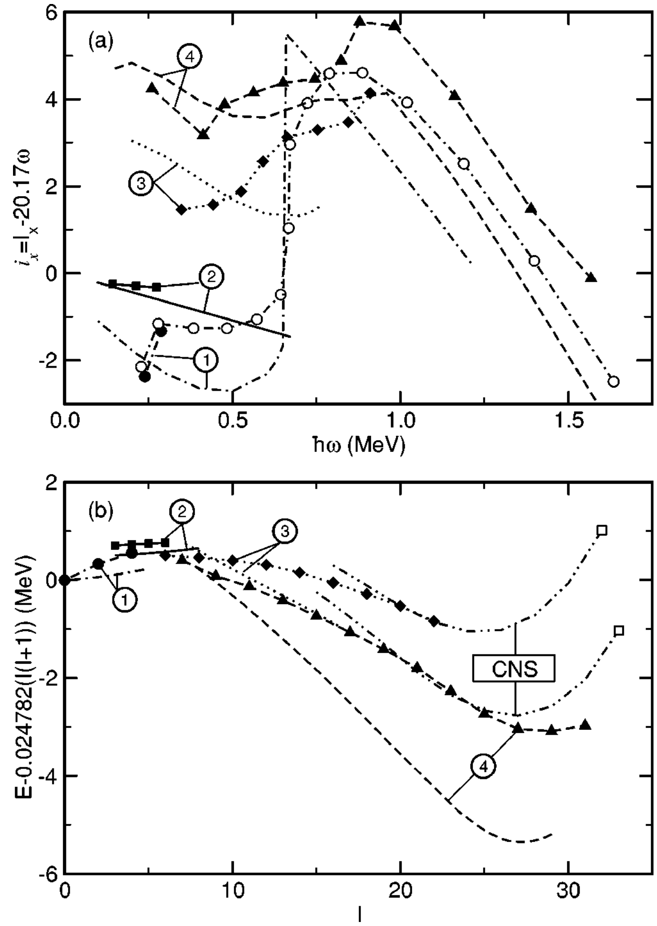

FIG. 3. Comparison between experimental data (symbols) and CRHB calculations (no symbols). Labels correspond to band numbers. (a) Aligned angular momentum (I_x) minus a rigid rotor reference versus angular frequency $(\hbar\omega)$. The $T=1$ band in ^{74}Kr [20] is shown as hollow circles and a dot-dashed line. (b) Energy E minus a rigid-rotor reference versus I. Dot-dot-dashed lines are CNS calculations adjusted to experimental band 3 at spin $I=20$.

Cranked Nilsson-Strutinsky [21] and cranked relativistic mean field (CRMF) [not shown in Fig. 3(b)] calculations [22], which assume zero pair correlations describe the region $I>20$ well, indicating that the $t=1$ pairing becomes negligible at high spin. This is consistent with CRHB, which indicates that the $t=1$ pairing becomes negligible at high spin. Similar behavior is found in ^{73}Kr [16] where unpaired calculations show excellent agreement with the experimental data at high spins, suggesting a comparable suppression of pairing.

The general agreement between the calculations and our new data suggests that there exists a $t=1$, np-pair field with a strength that conserves isospin which is quenched by rotation at high spin. The strongest evidence in support of this interpretation is that only one even-I sequence based on a $\pi(g_{9/2})\otimes\nu(g_{9/2})$ configuration is observed. It is an immediate consequence of the presence of the $t=1$ np-pair field, which restores the isospin symmetry [7]. With only $t=1$ pp- and nn-pair fields present, there are *two* even-I configurations [**Ab**] and [**Ba**] with the same energy. However, only the combination $([\mathbf{Ab}]-[\mathbf{Ba}])/\sqrt{2}$ has $T_y=0$, which is required by isospin-conserving $t=1$ pairing. Most significantly, we know that isospin is conserved so $t=1$ pairing must have as many np correlations as nn and pp in order to ensure this symmetry. The agreement between the calculations and the data is as good as for nuclei far from the $N=Z$ line. Therefore, our data are consistent with the assumption that there is no $t=0$ np-pair field present.

In summary, states in ^{74}Rb have been observed up to $I^{\pi}=(31^{+})$. Four different bands were identified and were classified as quasiparticle excitations in the presence of a substantial $t=1$ pair field at low spin, which becomes negligible at high spin $(I\geqslant 20)$. In order to reproduce the observed spectrum of states the calculations must incorporate the $t=1$ np-pair field by restoring isospin symmetry. The observation of only one even-spin $T=0$ sequence based on a $\pi(g_{9/2})\otimes\nu(g_{9/2})$ configuration, together with the energy difference between the $T=0$ and $T=1$ bands, represent the strongest evidence in favor of this interpretation. These results are consistent with the existence of an isovector pair field that contains a neutron-proton component with the proper strength for ensuring isospin conservation and no isoscalar pair field.

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