Decay of the odd-odd $N=Z$ nuclide ^{78}Y

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The odd-odd $N=Z$ nuclide, ^{78}Y has been produced in the ^{40}Ca(^{40}Ca,pn) reaction at 125 MeV. Recoiling fragments separated by their A/Q values were implanted onto the tape of a moving tape collector and transported to a shielded position between two plastic β detectors and two Ge γ-ray detectors where β-γ coincidences were recorded as a function of time. γ rays with energies of 279 (100%), 504 (90%), and 713 (40%) keV, previously identified as yrast transitions in daughter ^{78}Sr, were observed and found to decay with a half-life of 5.8 (6) s. From the relative intensities of the γ-rays, a spin and parity of 5^+ and $T=0$ are assigned to the parent state in ^{78}Y undergoing β decay. A production cross section of 4 ± 1 μb has been determined for ^{78}Y by comparison of the counting rates with those of other reaction products with known cross sections. An upper limit of 500 keV can be set for the energy of this level relative to a possible highly deformed $T=1$ 0^+ ground state. From this limit, it can be inferred that $T=1$ pn pairing is considerably quenched relative to such pairing in adjacent odd-odd $N=Z$ ^{74}Rb. Two-quasiparticle rotor model calculations have been used to account for the structure of ^{78}Y and adjacent nuclides.

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I. INTRODUCTION

There has been considerable interest in the structure of nuclides with $N\sim Z$ in the $A=80$ region. For such nuclides, nuclear structure properties dependent upon $N-Z$ are superseded by interactions which reach a maximum when $N=Z$. A most important example is the extraordinary structure for odd-odd $N=Z$ ^{74}Rb$_{37}$ [1]. In ^{74}Rb only two levels are observed below 1 MeV, a 0^+ ground state, and a 2^+ excited state at 478 keV. The energies of these $T=1$ states are nearly identical to the positions of the comparable $T=1$ states in isobaric even-even ^{74}Kr whose first 2^+ state is at 458 keV [2]. The data and interpretation of the structure of ^{74}Rb has provided ample motivation for a study of the structure and decay of the next heavier odd-odd $N=Z$ nuclide, ^{78}Y.

The single-particle orbitals are shown in Fig. 1 for nuclides with $A\sim80$ [3]. For ^{78}Y$_{39}$, the odd neutron and odd proton would be expected to occupy the 5/2+[422] orbitals and couple to give $T=0$ 5^+ and $T=1$ 0^+ states that could be isomeric. The structure of the adjacent even-even nuclide ^{78}Sr is well known to have a first excited 2^+ state at 279 keV [4]. This low energy indicates that ^{78}Y is probably considerably more deformed than ^{74}Rb. The decay of the 5^+ state would be expected to populate 4^+, 5^+, and 6^+ levels in ^{78}Sr that would, in turn, cascade through this 279-keV level, thereby providing a signature for the decay of that state in ^{78}Y. Whereas, Fermi superallowed β decay to the ground state of ^{78}Sr with a half-life of $\sim$60 ms would be expected for the decay of the 0^+ isomer.

II. EXPERIMENTAL DETAILS

The sources of ^{78}Y were produced by the bombardment of a 400 μg/cm^2 thick target of natural Ca whose isotopic composition is 97% ^{40}Ca, using a beam of ^{40}Ca with intensity as high as 2×10^{11} ions/s. That beam was accelerated to an energy of 125 MeV by the ATLAS accelerator at Argonne National Laboratory. The fragment mass analyzer (FMA) was used to separate the recoiling reaction products according to their A/Q value prior to implantation onto the tape of the moving tape collector. Although charge state 19 was calculated to be the optimum value for transmission of ^{78}Y through the FMA, that A/Q could also lead to considerable yields of nuclides with $A=74$, $Q=18$, as well. To minimize and account for such cross contamination, data were collected at both charge state 17 and charge state 18 where the most prominent interfering mass was 73.

There are almost no level structure data other than the 0^+ ground states for the odd-odd $N=Z$ nuclides with $A>58$.

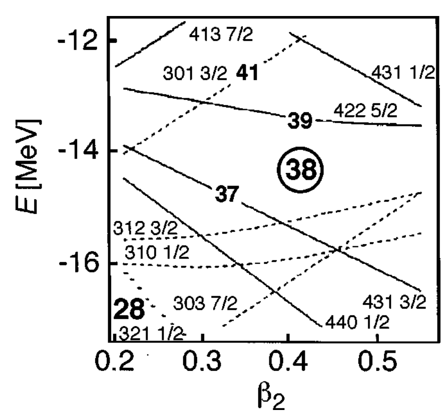

FIG. 1. Single-particle orbitals for deformed nuclei in the $N=Z=40$ region.

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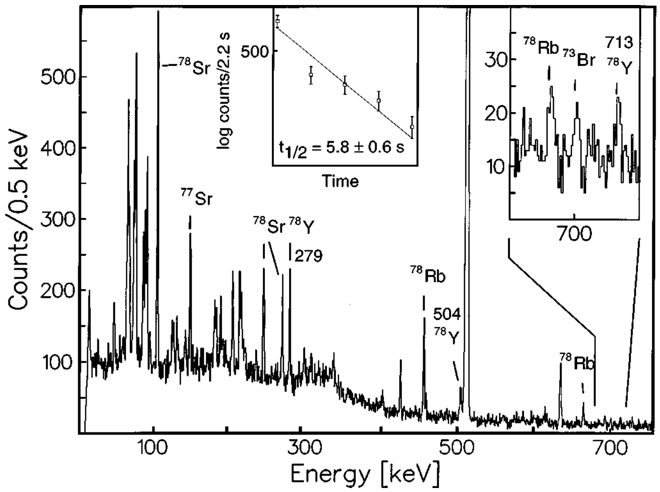

FIG. 2. The low-energy γ-ray spectrum for the decay of ^{78}Y to levels of ^{78}Sr. The inset shows the log of the sum of 279- and 504-keV peak areas taken in 2.2 s intervals ending 12 s after the end of the irradiation.

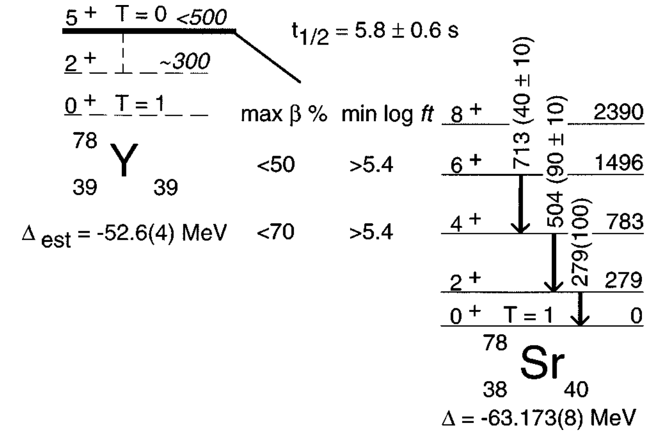

FIG. 3. The proposed decay scheme for the 5.8-s 5^+ state of ^{78}Y. The energies of the transitions and levels are given in keV.

For $^{70}Br_{35}$ whose adjacent odd-mass $T=1/2$ nuclides have low-energy $1/2^-$ and $5/2^-$ states, there is a report of a 2 s β decaying state that has not been confirmed [5]. Hence, at the outset of this experiment, equipment was in place to seek decay of a ''long-lived'' $T=0$ 5^+ isomer at the shielded counting station, as well as a ''short-lived'' $T=1$ 0^+ ground state at the point of deposit. The expected total cross section was $\sim 50\,\mu$b, with the majority populating or passing through the high-spin state.

For the measurements at $A=78$, the tape was initially moved at 3 s intervals, as our minimum half-life estimate for decay of a 5^+ state was 1 s. The recoils were collected for 2 s, the beam was deflected for 1 s while the tape moved, and then the γ rays counted for 2 s. As data accumulated and decay from ^{78}Y was detected by observation of the 279-keV γ ray, and a longer half-life value indicated, the tape cycle was lengthened to 12 s, with an 11 s collection time and a 1 s movement time.

The counting position was along a straight section of the tape. This permitted the use of thin plastic β gates and large Ge detectors on both sides of the tape, placed as close as possible to the tape. γ-ray singles, γ-γ coincidences, and β-gated singles were written to tape. The β-gated singles spectrum is shown in Fig. 2 where the peaks at 279(1), 504(1), and 713(1) keV can be noted. No other γ rays were observed with half-lives in the 4–8 s range. An inset is included that shows the time distribution of the sum of the 279- and 504-keV γ rays from which a half-life of 5.8 ± 0.6 s is extracted. As these three γ rays that were observed are well known to form the yrast cascade in daughter ^{78}Sr, the construction of the decay scheme for ^{78}Y shown in Fig. 3 was straightforward.

The log ft values shown in Fig. 3 are for decay to the 4^+ and 6^+ levels based on the assumption that all of the β decay directly populates these levels, and hence represent minimum values. It is most likely that the β decay populates a large number of higher-energy levels whose de-excitation has not been observed.

We have also included the expected structure for a lower-energy $T=1$ 0^+ ground state and $T=1$ 2^+ first excited state in ^{78}Y extrapolated from the structure of highly deformed isobaric $T=1$ ^{78}Sr. We can then estimate a maximum excitation energy for the 5^+ β decaying state, using the expected decay rate for an $M3$ transition to the 2^+ state. We base our estimate on the 4.7(3) s half-life for the 228-keV $M3$ isomer in ^{80}Y, and reason that if the 5^+ state in ^{78}Y is isomeric and were much over 500 keV then we would observe the $M3$ transition to the 2^+ level in the singles spectrum—not in the β-gated spectrum—with a 5.6 s half-life [6]. The absence of such a transition in the energy range $175 \leqslant E_\gamma \leqslant 250$ keV is the basis for the 500-keV estimate of the maximum separation of the 0^+ and 5^+ states in ^{78}Y. Because of the seventh power energy dependence of the $M3$ transition, a separation of over 300 keV between the 5^+ level and any 2^+ excited state would lead to the 5^+ level decaying almost entirely by the $M3$ channel.

Because the mass-to-charge ratio transmitted by the FMA was ~ 4, A/Q overlaps occur for masses separated by 4–5 mass units. Hence, data were collected for $A=73$, 74, 75, 76, and 77. By comparing the yields of known products, the pattern for charge-state overlaps could be determined and cross-contaminating peaks identified. The production cross section was determined by measuring the yield of the $3p$ product, ^{77}Rb. Cross sections for this reaction in this energy range have been reported by Barreto, Auger, Langevin, and Plagnol [7]. Through this method, a cross section of 4 $\pm 1\,\mu$b is obtained for the production of the 5^+ β-decaying state in ^{78}Y. Because the production cross section was much lower than expected, the entire experiment was devoted to the study of the decay of the 5^+ state. Additional experimental work will be required to determine if there is a 0^+ β-decaying state and where it would lie relative to the observed 5^+ level.

III. DISCUSSION

With the single exception of $^{58}Cu_{29}$, which has a $T=0$ 1^+ ground state, all odd-odd nuclides with $N=Z$ heavier than ^{40}Ca have a 0^+ ground state that undergoes Fermi superallowed β decay. In the $f_{7/2}$ shell, high-spin β-decaying isomers also have been identified in ^{42}Sc (616 keV, 7^+), ^{50}Mn (229 keV, 5^+), and ^{54}Co (199 keV, 7^+). These findings are quite consistent with most theoretical descriptions of the structure of odd-odd nuclides beginning with the Nordheim rules [8], expanded in the Brennan-Bernstein rules [9], treated systematically by Schiffer [10], and extended away from closed shells by the Paar parabola approach [11]. The single exception in the $f_{7/2}$ shell is $^{46}V_{23}$ where 3/2-levels exist within 100 keV of the $f_{7/2}$ ground states in both $^{45}V_{22}$ and $^{45}Ti_{23}$. In that case, the $T=0$ 7^+ state is highly elevated to 1604 keV as contrasted with only 616 keV in ^{42}Sc, and the 3^+ $T=0$ level is isomeric at 802 keV with a 1.02 ms half-life. The only other levels below 1 MeV in ^{46}V are a pair of 2^+ levels at 915 and 994 keV. Hence, it shares some features with ^{74}Rb in that the lowest energy $T=0$ state is at a high energy and has spin and parity 3^+. Attempts to account for the observed structure of ^{46}V have not been successful [12]. Because the ground states of the $Z=37$ nuclide, ^{75}Rb and $N=37$ nuclide $^{73}Kr_{37}$ are spin 3/2 states, it is possible that the structure of ^{74}Rb is not so much a consequence of strong $T=1$ pn pairing as it is the weakness of the $T=0$ interaction for low-spin states. The 915-keV energy of the $T=1$ 2^+ level in ^{46}V is as close to the 890-keV energy in adjacent $T=1$ ^{46}Ti as are the 458- and 478-keV energies in ^{74}Rb and ^{74}Kr, respectively.

In calculations aimed at describing the relative positions of the lowest 0^+ and 3^+ levels of ^{74}Rb, Rudolph *et al.* [1], neglected Gallagher-Moszkowski (GM) interactions [13] and, indeed, suggested that the effect was no more than 200 keV. But, we must note that their expectations for the ground state of ^{74}Rb were for a deformation value for $\beta_2\sim0.3$, while there is good evidence that β_2 is ~0.4 for ^{78}Y; that is, the 2^+ energy of adjacent ^{78}Sr is only 278 keV, compared with a 2^+ energy of 458 keV for ^{74}Kr. Because of the much larger deformation, it is reasonable to expect that Gallagher-Moszkowski effects are significantly larger in ^{78}Y than in ^{74}Rb [14].

The two-quasiparticle-rotor (TQRM) calculation [15] used to describe the structure of ^{80}Y in Ref. [6] has been extended to $^{74-78}$Rb, ^{78}Y, and ^{82}Y. We report here only the main results relevant for examination of properties of N close to Z nuclei in the $A=80$ region. Our approach was to determine how well the model could be used to describe systematically the known structures of the odd-odd Rb and Y nuclides with $N=Z+2$ and $N=Z+4$. Then, based on these results, use fits to the reported structure for both $N=Z$ ^{74}Rb and isotopic ^{80}Y, to extend the model to ^{78}Y.

The $N=Z+2$ ^{80}Y and ^{76}Rb low-lying, low-spin levels are well reproduced in the model. In both nuclei it has been necessary to *introduce a residual proton-neutron interaction acting between the valence particles*, modeled by a central force with Gaussian radial dependence, with spin polarization and long-range terms included [16]. The same parameters of the residual interaction were used for both nuclei.

For ^{80}Y, the best fits are for core deformation ε_2 values of ~0.37. In particular, the model is able to describe the GM energy splitting of 228 keV between the 4^- ground state and 1^- isomer in terms of the aligned (gs) and antialigned (isomer) $\pi5/2^+[422]$ $\nu3/2^-[301]$ configurations in spite of the strong configuration mixing found for the $\nu3/2^-[301]$ and $\nu3/2^-[312]$ states. The model also accounts for the 2^+ spin and parity of the lowest energy positive-parity state.

TABLE I. Energies and dominant configurations for bandheads in ^{74}Rb calculated with the TQRM without a residual proton-neutron interaction.

Energy (MeV)	J	$\vert K\vert$	Proton	Neutron
0	0	0	3/2[431]	3/2[431]
104	1	1	1/2[440]	3/2[431]
170	2	2	3/2[431]	1/2[440]
580	3	3	3/2[431]	3/2[431]
1032	4	4	3/2[431]	5/2[422]
1238	1	1	3/2[431]	5/2[422]
1697	2	2	1/2[440]	5/2[422]
1802	5	5	5/2[422]	5/2[422]

The 1^- ground state in ^{76}Rb is described by a main component of antialigned $\pi3/2^-[312]$ and $\nu5/2^+[422]$ Nilsson states in line with the suggestion by Harder *et al.* [3]. The fit to band structures built on the 1^- ground state and the 4^- state at 422 keV (aligned $\pi3/2^-[312]+\nu5/2^+[422]$) indicate an axially symmetrical core with quadrupole deformation $\varepsilon_2=0.39$ for the negative parity system. We were unable to find a positive parity band, based on a 4^+ state at 317 keV with level spacings as reported by Harder *et al.* at the same deformation as the negative parity bands. This is consistent with the interpretation suggested by Harder *et al.* The lack of experimental information on any other positive parity structure in ^{76}Rb does not permit testing the effect of the residual proton-neutron interaction in the positive parity system, as the best indication for its presence is the relative energy of a given pair of GM partner states.

Low-energy structures in the $N=Z+4$ nuclei ^{78}Rb and ^{82}Y can be well reproduced by the TQRM *without use of any residual proton-neutron interaction* [17]. Instead, a ''prolate-like'' triaxial deformation of $\gamma\sim25°$ for the core must be included to allow for the presence of all the experimentally reported band heads in the positive parity system and the measured value of the magnetic moment of the 4^- isomer at 111 keV [18]. Similarly to ^{76}Rb, the band built on the 4^+ state at 115 keV appears to correspond to a different deformation of the core than the rest of the low-lying bands.

Experimental data on $N=Z$ ^{74}Rb were reported and discussed in terms of competition between proton-neutron and like-nucleon pairing by Rudolph *et al.* [1], and in terms of the Monte Carlo shell model with proton-neutron pairing included by Dean *et al.* [19]. In the TQRM calculation (which included pairing only between like nucleons) of ^{74}Rb, we took into account $g_{9/2}$ Nilsson states 1/2[440], 3/2[431], 5/2[422], 7/2[413], and the $g_{7/2}$ ($d_{5/2}$) state 1/2[431] for both the odd-proton and the odd-neutron. The calculated band-head states in the positive parity system below 2 MeV for $\varepsilon_2=0.34$ and moment of inertia corresponding to the energy of the first 2^+ state of the core nucleus 600 keV (which is a reasonable expectation in the vicinity of ^{72}Kr) are given in Table I.

The main feature of this calculation is that very strongly mixed two-quasiparticle states for ^{74}Rb are obtained. The Nilsson assignments in Table I correspond to a ''dominating'' configuration, that is typically 50% or less. It is therefore understandable that rotational bands with a regular structure built on the band heads are not clearly predicted in

TABLE II. Calculated TQRM energies and main components (>5%) for the ground-state band (0^+, 2^+, 4^+) in ^{74}Rb without a residual proton-neutron interaction.

E_{exp} (MeV)	E_{cal} (MeV)	Component	$\|K\|$	Percentage
0	0	$\pi1/2[440]+\nu1/2[440]$	0	38
		$\pi3/2[431]+\nu3/2[431]$	0	52
		$\pi5/2[422]+\nu5/2[422]$	0	9
478	536	$\pi1/2[440]+\nu1/2[440]$	0	19
		$\pi1/2[440]+\nu3/2[431]$	2	11
		$\pi3/2[431]+\nu1/2[440]$	2	11
		$\pi3/2[431]+\nu32/[431]$	0	44
		$\pi5/2[422]+\nu5/2[422]$	0	7
1054	853	$\pi1/2[440]+\nu1/2[440]$	0	6
		$\pi1/2[440]+\nu5/2[422]$	2	7
		$\pi3/2[431]+\nu3/2[431]$	0	24
		$\pi3/2[431]+\nu5/2[422]$	1	17
		$\pi3/2[431]+\nu5/2[422]$	4	7
		$\pi5/2[440]+\nu1/2[440]$	2	7
		$\pi5/2[440]+\nu3/2[431]$	1	17
		$\pi5/2[440]+\nu3/2[431]$	4	7

this calculation. Also, it is plausible to assume that mutual feeding of states with very complicated structure can be reduced by cancellation of transition matrix elements and thus a reduced number of states is observed experimentally. We note that it is possible to identify 2^+ and 4^+ states which have a component of the ground state and may be interpreted as members of the ground-state band. Data on these states are summarized in Table II and illustrate the complex structure even of the lowest-lying members of the ground-state band.

The GM partner state to the ground state is predicted at about 600 keV which is lower than the lowest reported 3^+ state at 1006 keV. That calculation was performed *without any residual proton-neutron interaction*. We tested effects of different forms of this interaction [16], including the one used in ^{80}Y and ^{76}Rb, but did not observe a simple exchange of the relative position of GM partner states seen in the other cases (see, e.g., Figs. 4 and 5). It is possible that this behavior is a consequence of the complex structure of the two-quasiparticle wave functions, illustrated in Tables I and II.

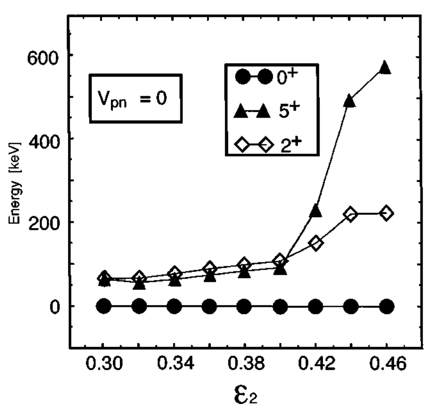

FIG. 4. The positions of the lowest 0^+, 2^+, and 5^+ energy levels in ^{78}Y as calculated with the two-quasiparticle rotor model without residual proton-neutron interactions.

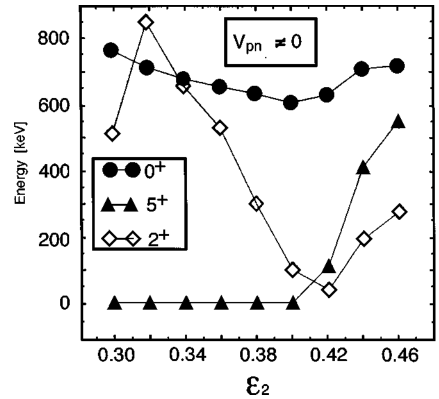

FIG. 5. The positions of the lowest 0^+, 2^+, and 5^+ energy levels in ^{78}Y as calculated with the two-quasiparticle rotor model with residual proton-neutron interactions.

Based on the results of these test calculations, it is possible to attempt to describe the structure of ^{78}Y with some confidence. The structure of the $N=Z$ ^{78}Y nucleus was calculated as a function of the core quadrupole deformation for an axially symmetric ^{76}Sr core with the energy of the first 2^+ state at 260 keV. In the positive parity system, the ground state structure is assumed to involve the coupling of a $\pi5/2^+[422]$ odd proton with a $\nu5/2^+[422]$ odd neutron. In Figs. 4 and 5, we show the lowest 0^+ and 5^+ states as a function of quadrupole deformation $0.30<\varepsilon_2<0.44$ for the calculation *without the residual proton-neutron interaction*, and *with the residual proton-neutron interaction*, respectively, employing the same parameters as used successfully for $N=Z+2$ ^{80}Y and ^{76}Rb.

We note a significant difference in the structure of the low-energy members of the ground-state band of ^{78}Y as compared to ^{74}Rb. For a ^{78}Y deformation $\varepsilon_2\sim0.4$ the $\pi5/2^+[422]$ $\nu5/2^+[422]$ configuration contributes 97, 97, and 79% to the configurations of the 0^+, 2^+, and 4^+ states, respectively, suggesting a relatively high purity for these states as contrasted with the mixing shown in Table II. This purity of wave function is likely a consequence of the rather wide gap in single-particle levels at $N=38$ as shown in Fig. 1.

More experimental data will be needed to establish the role of the residual proton-neutron interaction in ^{78}Y and, more generally, the proton-neutron pairing interaction for $N=Z$ nuclei in this region. Both calculations are consistent with the presence of a 5^+ β decaying state. That is, either the 5^+ is the ground state (in the calculations with the residual interaction) or is sufficiently close to the 0^+ ground state that an internal transition is not likely (in the calculations without the residual interaction).

IV. SUMMARY

We have investigated the decay of the highly deformed odd-odd $N=Z$ nuclide, ^{78}Y and identified a β-decaying state with a half life of 5.8(6) s. Based on the population of 4^+ and 6^+ levels in daughter ^{78}Sr, we have assigned spin and parity of 5^+ to this state and a $\pi5/2^+[422]\nu5/2^+[422]$ configuration. This fact is, in itself, distinctive, as there is no high-spin β-decaying state in isodiapheric ^{74}Rb. Indeed, the only other established high-spin β-decaying state for odd-odd $N=Z$ nuclides above ^{56}Ni is the 400-ms state in ^{94}Ag that is thought to have either 7^+ or 9^+ spin and parity [20]. Questions remain as to whether this 5^+ state is the ground state, and if not, where it lies with respect to a possible 0^+ ground state. Our data can be interpreted to limit the energy of this 5^+ state to a position no higher than 200 keV above a potential 2^+ state that would be expected to lie below 300 keV. In turn, this can be taken as an indication that $T=1$ pn pairing is significantly quenched in highly deformed ^{78}Y relative to moderately deformed ^{74}Rb. The structure for ^{78}Y that is obtained by TQRM calculations *with* pn residual interactions (that fit isotopic ^{80}Y and ^{76}Rb) shows a large GM splitting with a 5^+ ground state. Whereas the calculation for ^{78}Y level structure *without* residual pn interactions (that provided the best description of the structure of $N=Z$ ^{74}Rb) projects an isomeric 5^+ state $\sim$200 keV above a 0^+ ground state.

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