Resolution of the ^{179}W-Isomer Anomaly: Exposure of a Fermi-Aligned *s* Band

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The $K^\pi = \frac{35}{2}^-$, five-quasiparticle isomer in ^{179}W is shown to decay into the region of a backbend in the $\frac{7}{2}^-[514]$ band, allowing for the first time the identification of a full set of aligned-band states. Destructive interference results from level mixing in the band-crossing region. The deduced γ-ray branching ratios are used to establish the mixing matrix elements and to show that the aligned band has a high value of the K quantum number. The properties of well-defined alignment and yet also high K provide the first clear example of a Fermi-aligned s band. The anomalous decay of the isomer itself is now explained.

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The discovery of backbending [1] was pivotal to the understanding of rotating nuclei. At angular momenta in the range $(10–20)\hbar$, many nuclei suffer an abrupt change in their apparent moment of inertia, due to the partial alignment of individual particle angular momenta with the collective rotation. In the well-deformed rare-earth region of nuclei where the Fermi neutron surface is low in the shell, the alignment of two $i_{13/2}$ neutrons is of prin- cipal importance [2]. Viewed as a band-crossing phenomenon, at some critical frequency ω_c, the aligned sequence of states (the s band) becomes energetically favored, or yrast. The location of the unfavored yrare states has long been an experimental challenge, not least because the low-spin part of the s band may contain valuable spectroscopic information about its physical origins.

In this Letter we report the discovery of the full set of states of the crossing band, from well above the backbend down to a bandhead, in the odd-N nucleus ^{179}W. Here the Fermi level is near midshell for the $i_{13/2}$ neutrons. The location of the yrare s-band extension is facilitated by the strong delayed population of states in the band-crossing region. The isomer responsible, a five-quasiparticle (5-qp) excitation with $K^\pi = \frac{35}{2}^-$, was previously believed [3,4] to decay directly to a 1-qp structure, bypassing the 3-qp states and violating normal selection rules. Exposure of the crossing band, and deduction of its high K value from the analysis of the interference effects in the branching ratios, removes this anomaly.

Pulsed beams of 67-MeV ^{13}C from the Australian National University 14UD accelerator were incident on a 3.3-mg/cm^2 self-supporting ^{170}Er target placed in the center of the γ-ray array CAESAR [5] which comprised six Compton-suppressed germanium detectors. Coincidences between pairs of γ rays were recorded event by event, together with the time of each γ-ray signal relative to the beam pulses, which were 1 ns wide and 864 ns apart. This enables the highly sensitive measurement of γ-ray transitions with prompt γ-γ coincidences both in and out of beam. In addition, singles, prompt-gated γ-ray angular distributions, and beam-γ-time experiments were performed. The last enabled the measurement of half-lives down to 0.5 ns, by centroid-shift and line-shape analyses. From the high-statistics coincidence measurement ($\approx 2.5\times10^8$ Compton-suppressed events) it has been possible to identify numerous rotational sequences based on 1-, 3-, 5-, and 7-qp structures. Here we concentrate on the resolution of the fast decay of the $K^\pi = \frac{35}{2}^-$ 5-qp isomer, and the character of the s bands associated with the 1-qp rotational sequences. The other intrinsic and collective structures will be the subject of a forthcoming full report.

A partial level scheme of ^{179}W deduced from the present study is presented in Fig. 1. The negative-parity yrast rotational sequence is assigned the $\frac{7}{2}^-[514]$ Nilsson configuration at low spin [6], but changes character between $I^\pi = \frac{27}{2}^-$ and $I^\pi = \frac{31}{2}^-$ (the 598-keV transition) at a band crossing. Because of strong isomeric population into the band-crossing region, it was possible to use the sensitivity of the *delayed* γ-γ coincidences to identify unambiguously the very weak ($\sim$1%) transitions that connect with lower-lying yrare states. These lower states were located up to $I^\pi = \frac{29}{2}^-$ in earlier work [3,4] on account of their prompt feeding from compound states, but the connection with the negative-parity yrast sequence was not identified. We confirm the spin and parity assignments from our γ-ray angular distribution and intensity data. In particular, the 200-keV transition from the bandhead is assigned $E1$ character, based on conversion coefficients deduced from the intensity balance at the 1832-keV bandhead. Further, the in-band $\Delta I = 1$ transitions have negative mixing ratios (δ) which, taken with the in-band branching ratios and the high spin ($I = \frac{23}{2}$) of the bandhead, establish a three-quasineutron intrinsic structure. The two other 3-qp states [3,4] illustrated in Fig. 1 (1216 and 1632 keV) also have three-quasineutron structure, and we are able to make configuration assignments which have the $[\frac{7}{2}^-[514]\otimes\frac{9}{2}^+[624]]_{K^\pi=8^-}$ structure common to all three states, and a third quasineutron $\frac{1}{2}^-[521]$, $\frac{5}{2}^-[512]$, or $\frac{7}{2}^+[633]$ in, respectively, the $\frac{17}{2}^+$, $\frac{21}{2}^+$, or $\frac{23}{2}^-$ state. These states involve the five lowest-

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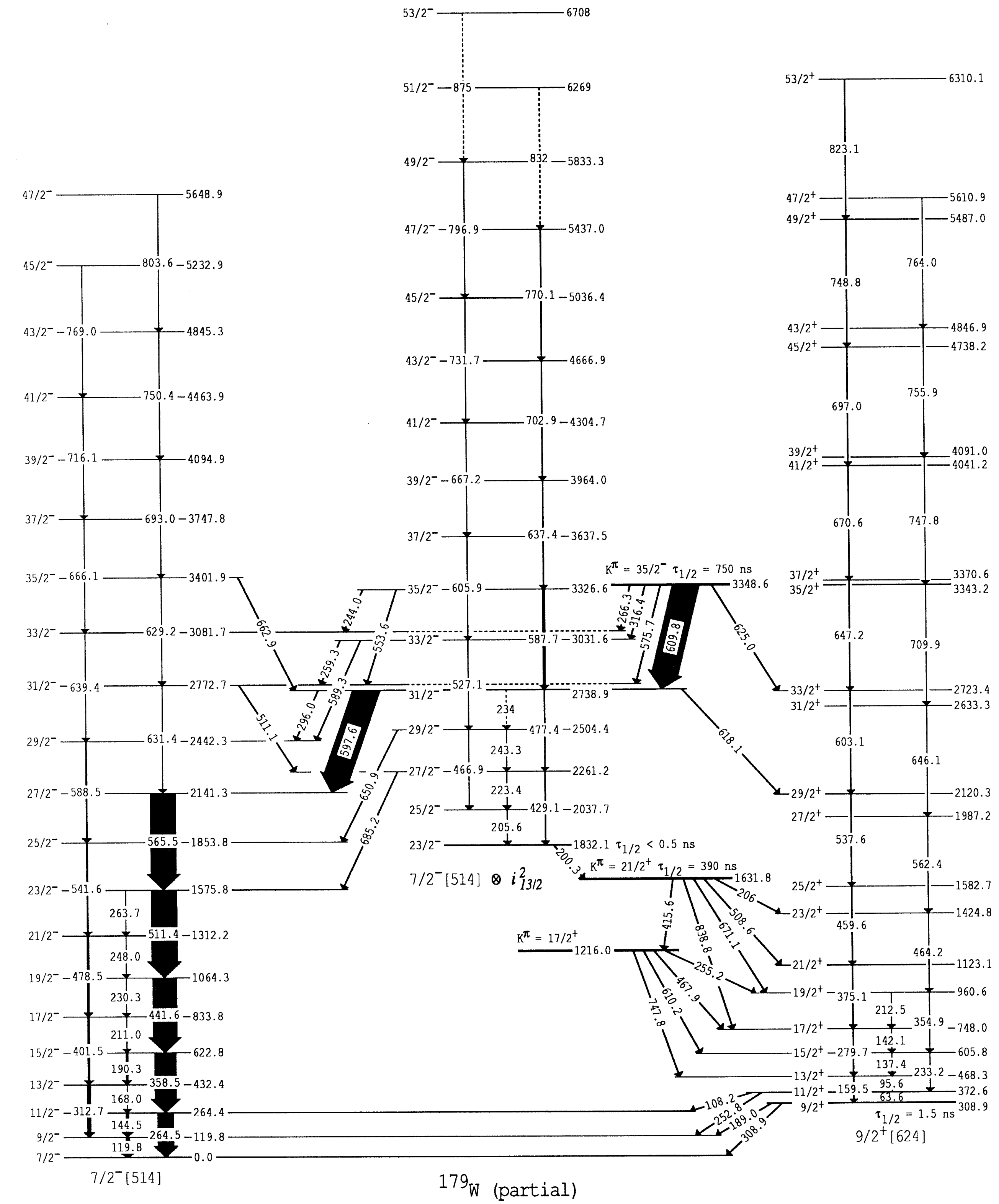

FIG. 1. Partial level scheme for ^{179}W, illustrating the positive- and negative-parity yrast sequences, the negative-parity yrare extensions, the 5-qp isomer, and their associated decays. The thicker arrows show the delayed intensity flow from the 5-qp isomer.

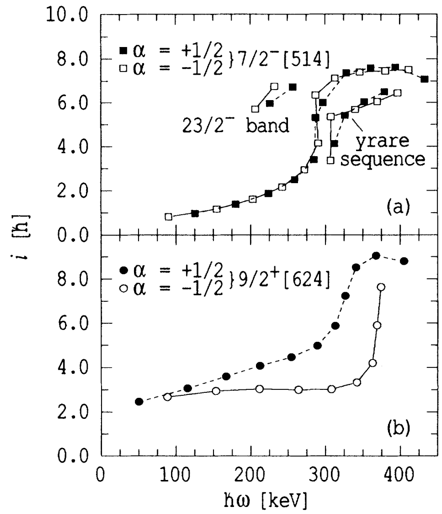

FIG. 2. Rotational-aligned angular momentum as a function of rotational frequency for bands in ^{179}W: (a) the $\frac{7}{2}^-$[514] band and associated s bands; (b) the $\frac{9}{2}^+$[624] band.

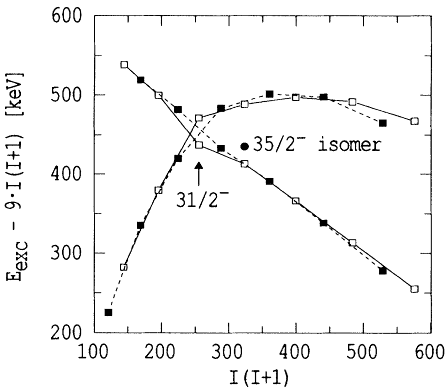

FIG. 3. Excitation energy (relative to an arbitrary perfect rotor) as a function of $I(I+1)$ for the $\frac{7}{2}^-$[514] 1-qp band and the aligned s band with which it crosses. Perturbation of the $\frac{31}{2}^-$ states is apparent. Also shown is the position of the 5-qp isomer.

lying single-quasineutron orbitals [6]. The $\frac{23}{2}^-$ level and its rotational band involve two $i_{13/2}$ neutrons, together with the $\frac{7}{2}^-$[514] neutron, as would be expected for the neutron s band associated with the $\frac{7}{2}^-$[514] 1-qp band.

We have thus located the complete set of states involved in the crossing of the $\frac{7}{2}^-$[514] band and an aligned band. In addition to the yrast states, both the high-spin yrare extension of the 1-qp band and the low-spin s-band levels down to a well-defined bandhead are now known. The aligned band has approximately constant rotational alignment ($\sim 7\hbar$) and the crossing with the $\frac{7}{2}^-$[514] band has the usual hallmarks, including backbending, as illustrated in Fig. 2(a) for both signatures, $\alpha = \pm\frac{1}{2}$. We note that the yrare extension of the $\frac{7}{2}^-$[514] band gains significant alignment ($\sim 5\hbar$) almost immediately following the yrast band crossing. Comparison with the behavior of the $\frac{9}{2}^+$[624] band [Fig. 2(b)] indicates that this yrare band crossing may involve a proton (ab) alignment, or a neutron (BC) alignment, but the currently available information from $B(M1)/B(E2)$ ratios is unable to distinguish between these two possibilities.

We now address the remarkable γ-ray branching ratios between the states in the band-crossing region. The details and effects of the band crossing can be seen in Fig. 3, which shows the sequences on an extended scale (obtained by subtracting the energy of an arbitrary perfect rotor). The $\frac{31}{2}^-$ states are obviously perturbed (by mutual repulsion) and by extrapolation would have been close to degenerate before mixing. The relative $E2$ γ-ray intensities between a number of states are given in Table I.

Most dramatic is the branching ratio from the lower $I^\pi = \frac{31}{2}^-$ level: The 477-keV in-band transition is only (1.9 ± 0.6)% the intensity of the cross-band 598-keV transition. The two $I^\pi = \frac{31}{2}^-$ levels are 33.8 keV apart, which restricts the magnitude of the mixing matrix element between the crossing bands to $|V| \leq 16.9$ keV, assuming two-band mixing. With the maximum matrix element and the same K value for both bands, the calculated branching ratio is reduced to 18% because of destructive interference, but this is still a factor of 10 larger than the experimental value. However, the high spin of the bandhead for the s band, $I = \frac{23}{2}$, is compatible with a high value of K ($\approx \frac{23}{2}$). A value of $K = \frac{23}{2}$ has a large effect on the intrinsic (unmixed) $E2$ strength for the s band through the angular-momentum-coupling coefficients, and its use in the two-band-mixing calculations then yields excellent agreement with the experimental branching ratios, because of almost complete destructive interference.

Table I also lists the calculated matrix elements that reproduce each of the experimental branching ratios. The small uncertainties and good agreement between in-

TABLE I. $E2$ branching ratios and interactions between the $K^\pi = \frac{7}{2}^-$ and $\frac{23}{2}^-$ crossing bands in ^{179}W.

I_i	E_γ (keV)	I_γ (rel.)	$B(E2)$ ratio	$\lvert V\rvert$[a] (keV)
$\frac{35}{2}$	587.7	100	0.08(3)	$16.4^{+0.3}_{-0.8}$
	553.6	6(2)		
$\frac{35}{2}$	662.9	100	1.1(4)	$16.5^{+0.4}_{-1.3}$
	629.2	83(30)		
$\frac{33}{2}$	589.3	100	0.45(11)	$17.5^{+1.1}_{-0.9}$
	527.1	26(6)		
$\frac{31}{2}$	597.6	100	0.06(2)	$16.8^{+0.1}_{-0.3}$
	477.4	1.9(6)		

[a]The two-band-mixing interaction strength is assumed to be spin independent. Note that for $I = \frac{31}{2}$, the two levels are 33.8 keV apart, and the interaction must thus be ≤ 16.9 keV.

dependent estimates of the mixing strength provide strong support for this interpretation. The "uncertainty" in the K quantum number deduced for the aligned band, $K \approx \frac{23}{2}$, may also be obtained using the energy-level perturbations to define the mixing matrix element, $16.0 \leq |V| \leq 16.9$, and the branching ratios to define the effective K value. In such a way, we find an uncertainty of just one unit, $K = \frac{23}{2} \pm 1$.

The pertinent question is whether such a high (and apparently localized) K value is consistent with an aligned band. For quasiparticles in a rotating nucleus, Frauendorf [7] has delineated three different situations which will develop, with a dependence on deformation and rotational frequency, as a function of the Fermi level. The first is one of deformation alignment where the intrinsic spin j precesses predominantly about the deformation (z) axis so that the projection K is a good quantum number. The second is the now familiar rotation alignment alluded to in the introduction which involves precession around the rotation (x) axis with a well-defined alignment i but with a low, nonsharp, K. The third he has named *Fermi alignment.* There, precession is localized at an intermediate axis with the resulting characteristics of *approximately* well defined i and K and, in the limit, with $j^2 = i^2 + K^2$. Just as a 2-qp deformation-alignment configuration may have two different couplings, with $K = |\Omega_1 \pm \Omega_2|$, so also are there two possible Fermi-alignment couplings [8], one with high K and one with low K. The high-K coupling is immediately identifiable with the present case if we associate the components from the two $i_{13/2}$ neutrons, nominally the $\frac{7}{2}^+[633]$ and $\frac{9}{2}^+[624]$ orbitals, with $j = 12$, $K' = 8$, and $i \approx 7$.

Returning to the decay of the $\frac{35}{2}^-$ isomer, by taking into account the high K value for the $\frac{31}{2}^-$ state to which it decays, the 610-keV $E2$ transition has a hindrance per degree of K forbiddenness, f_ν, of 10, which compares well with other K-forbidden $E2$ decays [9]. The weakness of the 576-keV 1% $E2$ branch from the isomer can be understood as arising from destructive interference of the transition matrix elements, in a way similar to that described above for the decays of the lower $\frac{31}{2}^-$ level. A detailed analysis of the isomer strengths in ^{179}W will be given in a later full report of this work, but we note that the results may have implications for the supposedly anomalous decay branches found from multiquasiparticle isomers in ^{182}Os [10] and ^{174}Hf [11].

In summary, the fast decay of the $K^\pi = \frac{35}{2}^-$ isomer in ^{179}W has been explained as an essentially normal decay to an intermediate s-band state of $K \approx \frac{23}{2}$. The s band, which causes backbending in the $\frac{7}{2}^-[514]$ band, has unusual characteristics, namely, well-defined alignment and, simultaneously, a high value of K. These features are interpreted as the first experimental evidence for a Fermi-aligned $i_{13/2}^2$ structure.

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