Rotation of an Eight-Quasiparticle Isomer

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A $T_{1/2} = 220$ ns, eight-quasiparticle isomer, with four unpaired neutrons and four unpaired protons, has been established at an excitation energy of 6576 keV in the prolate deformed nucleus, ^{178}W. The associated rotational band has also been identified, revealing the collective properties in the presence of blocked pairing correlations, with expected quenching of the nuclear superfluidity. The band retains a small degree of rotational alignment, and has a less-than-rigid dynamic moment of inertia.

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Rotation is a characteristic feature of deformed atomic nuclei, with moments of inertia that are substantially less than rigid-body values due to pairing correlations and associated superfluidity [1,2]. Fast *collective* electromagnetic transitions connect states of a given intrinsic structure, giving regular sequences of γ-ray transitions which can be observed following heavy-ion fusion-evaporation reactions. The lowest energy rotational sequence (the *yrast* line) in an even-even nucleus is based on the fully paired ground state, at least at low spin. Collective excitations based on broken-pair two-quasiparticle configurations compete to form the yrast line at intermediate and high spins, particularly if they involve high-j nucleons with strong Coriolis effects, which can generate *alignment* [3] of intrinsic angular momentum along the collective rotation axis (perpendicular to the deformation axis). Rapid rotation [4,5] and/or multiquasiparticle excitations [6] have for some time been assumed to quench the pairing correlations and the associated superfluidity, in an analogous way to the quenching of superconductivity in metals by, respectively, magnetic fields and temperature. However, the finiteness of nuclei introduces fluctuations, and it remains a challenge to find appropriate observables to characterize the phase transition.

There is only one region of deformed nuclei, with $A \approx 180$, which offers the prospect of observing the influence of many broken pairs at low rotational frequency. In this region, the multiquasiparticle intrinsic states and their rotational bands are able to compete to form the yrast line, because both the neutron and proton Fermi surfaces are close to nucleon orbits with large projections, Ω_i, of intrinsic angular momentum on the prolate symmetry axis. Such orbits have relatively small Coriolis alignment effects. There is approximate conservation of the quantum number $K = \sum \Omega_i$, and the bandheads are frequently *isomeric*, with hindered decay and half-lives that range from nanoseconds to years [7]. The existence of K hindrance is in itself an indication of the stability of axially symmetric shapes.

To date, six- and seven-quasiparticle isomers have been discovered in ^{175}Hf [8], ^{176}Hf [9], ^{176}Ta and ^{177}Ta [10], and ^{182}Os [11], and there has been tentative identification of a nine-quasiparticle isomer in ^{175}Hf [8]. In none of these cases has an associated rotational band been identified. This may be presumed to be an experimental artifact due to the combination of the long half-lives of the isomers, their weak population, and their large angular momenta, close to the maximum available from the corresponding production reactions. The question remains as to whether there is a breakdown of collectivity for such high-seniority structures, and, if not, whether the rotational excitations can be used to characterize the nuclear fluidity. The highest-seniority (seven-quasiparticle) rotational bands have been found in ^{179}W [12], though their bandheads are not isomeric ($T_{1/2} < 1$ ns). Calculations [6,10,13,14] suggest the existence of many more multiquasiparticle isomers in the $A \approx 180$ region, but most are inaccessible with presently available (stable) beams and targets. A favorable case for further study is ^{178}W which can be formed at angular momenta over $30\hbar$ in the ^{170}Er(^{13}C$,5n$) reaction, and which is calculated [14] to contain eight-quasiparticle isomers with $K = (25 - 30)\hbar$.

In the new measurements presented here, levels in ^{178}W were populated with pulsed beams of 80 MeV ^{13}C from the ANU 14UD pelletron accelerator, incident on ^{170}Er targets. Four separate measurements were performed. In the first three, the beam was incident on a 4 mg cm^{-2} self-supporting target of ^{170}Er at the center of the CAESAR detector array, comprising six close-packed Compton-suppressed germanium γ-ray detectors. Two additional unsuppressed planar germanium detectors were included, giving enhanced sensitivity for γ-ray transitions in the 15 to 100 keV energy range.

The possible existence of isomers was investigated by recording the energy and time relative to the beam pulses of single γ-ray events in two regimes, one with 1 ns pulses separated by 1.7 μs and another with 6 μs wide beam bursts, separated by 160 μs. Several isomers in the submicrosecond region were identified but no particularly long-lived isomers, which would have been evident in the latter configuration, were found. All subsequent measurements were carried out with the 1 ns/1.7 μs combination.

Level-scheme information was obtained from twofold-coincidence events, recording both energy and time (relative to the beam bunches) for each γ-ray signal, within a time window of ± 0.8 μs. The coincidence information enabled the off-line construction of a variety of event matrices, including a "prompt" (± 20 ns) matrix, delayed-early (across isomer) matrices, and a matrix of prompt coincidences with the additional requirement that both events occurred *between* beam bunches. Multiple projections were made from each event matrix, yielding background-subtracted coincidence spectra, from which the ^{178}W level structure was deduced.

Gamma-ray anisotropies were obtained from singles γ-ray measurements recorded with the extra time condition that events had occurred within ± 20 ns of the beam pulse. This restriction to "prompt" events was useful for minimizing the effects of deorientation on the observed anisotropies.

The fourth measurement was carried out after the level scheme had been constructed. It involved the detection of electrons and γ rays, timed relative to the pulsed beam, to obtain conversion coefficients. The pulsed beam (with the same conditions as described above) was incident on a 1.3 mg cm^{-2} target with its plane at 30° to the beam direction. Electrons were measured with a cooled Si(Li) detector, inside a superconducting solenoid operated in lens mode [15].

The most dramatic feature of the level scheme is a new isomeric state, with $T_{1/2} = 220 \pm 10$ ns, established at 6576 keV. The isomeric state is relatively strongly populated ($\approx 2\%$ of the total for ^{178}W) because it is yrast, as indicated by its position relative to the ground-state-band sequence (extended here to spin 28) illustrated in Fig. 1. The principal decay path of the 6576 keV isomer is also shown in Fig. 1. It proceeds through a series of intrinsic states and fragments of their rotational bands, and through the known $I^{\pi} = 12^{+}$ level at 3237 keV [16–18]. Most of the γ-ray transitions below what is now identified as the 220 ns, 6576 keV isomer were reported by Krämer-Flecken [18], though with different ordering and without spin and parity assignments. The 220 ns isomer itself is presented here for the first time, together with its rotational band which is clear in the spectrum of γ rays shown in Fig. 2. A well-defined sequence of $\Delta I = 1$ and $\Delta I = 2$ transitions is evident, and confirmed by prompt γ-γ coincidence relationships. A representative time curve for transitions below the isomer is shown inset in Fig. 2.

Spin and parity assignments were made after consideration of prompt γ-ray anisotropies, total conversion

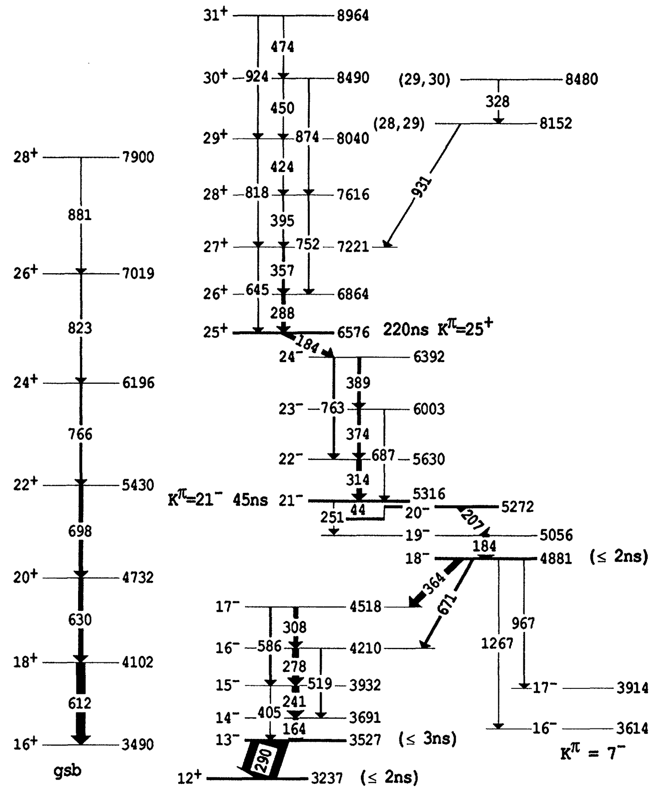

FIG. 1. Partial level scheme for ^{178}W, showing the $K^{\pi} = 25^{+}$ isomer, its associated rotational band, and its principal decay path. Part of the ground-state-band extension is included for comparison. Energies are in keV and the transition intensities are proportional to the arrow widths.

coefficients inferred from γ-ray intensity balances, and directly measured K- and L-shell conversion coefficients. Where appropriate, the apparent band structure was used to make assignments. The assignments will not be discussed in detail here, but it is useful to point out several key places where spin and parity changes occur. For example, the 44 keV transition decaying from the 5316 keV, 45 ns isomer has a total conversion coefficient of $9 < \alpha_T < 14$, leading to an $M1$ multipolarity assignment from comparison with theoretical values [$\alpha_T(M1) = 9.4$ from Ref. [19]]. The 251 keV transition, also from the 5316 keV isomer, is a very weak branch, consistent with stretched $E2$ character that competes unfavorably with the 44 keV $M1$ decay. Further, although there are two unresolved 184 keV transitions in the decay sequence (the upper one decays directly from the 220 ns isomer and the lower one depopulates the 5065 keV state), they can be separated using the time correlations available in the data because of the intervening 45 ns isomer. Intensity balances then allow the deduction of $E1$ multipolarity for the upper transition [$\alpha_T(\mathrm{exp}) = 0.04 \pm 0.10$, $\alpha_T(E1) = 0.08$] and $M1$ multi-

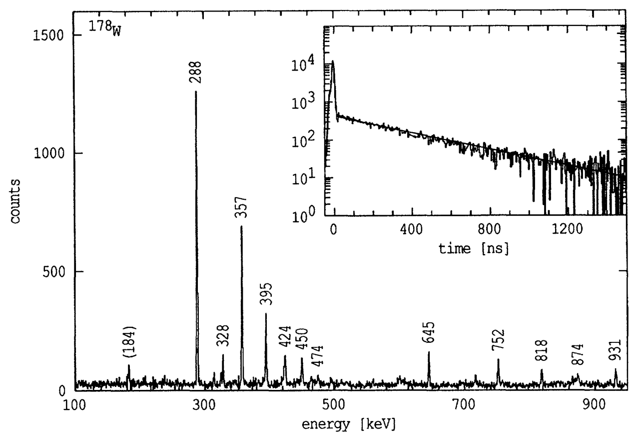

FIG. 2. Gamma-ray spectrum, showing transitions above the $K^\pi = 25^+$ yrast isomer in ^{178}W, obtained from delayed gating on the 314, 374, and 763 keV transitions below the isomer. (The 184 keV peak in parentheses is a contaminant.) The corresponding time spectrum, relative to the beam bunches, is included as an inset, with a 220 ns fitted half-life.

polarity for the lower [$\alpha_T(\text{exp}) = 0.9 \pm 0.2$, $\alpha_T(M1) = 0.88$]. Directly measured K-conversion coefficients establish an $M1$ assignment for the 207 keV transition from the 5272 keV state, and $M1$ and $E2$ assignments for the 364 and 671 keV decays, respectively, from the 4881 keV state.

Finally, the most important transition defining both the spin and parity of the isomer decay sequence given in Fig. 1 is the 290 keV transition from the 3527 keV level to the $I^\pi = 12^+$ state at 3237 keV. Spin assignments were previously reported, up to the 3527 keV level, using the results of γ-ray angular distribution [16] and γ-γ angular correlation [17] measurements. We have also found new γ-ray decay branches [20] that confirm $I = 12$ for the 3237 keV level and establish a positive parity assignment. The 3527 keV state, however, had been assigned previously as $I = 14$ on the basis of γ-ray angular correlation data which were taken as evidence of quadrupole multipolarity for the 290 keV transition [17]. We make a different and firm assignment of $E1$ multipolarity, on the basis of the K-conversion coefficient for the 290 keV transition [$\alpha_K = 0.027^{+0.004}_{-0.007}$, which agrees with the theoretical value of $\alpha_K(E1) = 0.021$, and eliminates the $E2$ possibility which would have $\alpha_K = 0.068$] giving $I^\pi = 13^-$ for the 3527 keV state.

From these and other data [20], the 6576 keV isomer is found to have $I^\pi = 25^+$ and presumably $K = I = 25$. The band above the isomer is seen (Fig. 2) up to $I = 31$, and there is evidence for other intrinsic states, at 8152 and 8480 keV (see Fig. 1). The 184 keV, $E1$ transition depopulating the $K^\pi = 25^+$ isomer goes to a $K^\pi = 21^-$ rotational band and changes the K quantum number by four units, making it threefold K forbidden. Its hindrance per degree of K forbiddenness is $f_\nu = 190$, where $f_\nu = (T^\gamma_{1/2}/T^W_{1/2})^{1/\nu}$, $T^\gamma_{1/2}$ is the partial γ-ray half-life, $T^W_{1/2}$ is the Weisskopf single-particle estimate, and ν is the degree of K forbiddenness. The substantial f_ν value is typical for K-forbidden $E1$ transitions and indicates the preservation of axial symmetry, i.e., the K quantum number remains "good."

Quasiparticle-BCS calculations, with the blocking formalism of Soloviev [21], have been performed for ^{178}W. They are of the type used recently to calculate multiquasiparticle excitation energies in ^{177}Ta [10] and ^{179}W [12]. The single-particle energies corresponding to known one-quasiparticle states were adjusted to reproduce experimental energies, and all other single-particle energies were taken from the Nilsson model. Semiempirical residual interactions were included, as these were previously shown to be valuable for calculating multiquasiparticle energies in ^{176}Hf [13]. A full report on this approach applied to multiquasiparticle states in the $A \approx 180$ region is given by Jain *et al.* [14]. The calculated near-yrast energies for ^{178}W show a one-to-one correspondence with experimental intrinsic states of the same spin and parity. The lowest calculated state with $K^\pi = 25^+$ has the eight-quasiparticle Nilsson configuration $\nu\{\frac{5}{2}^-[512], \frac{7}{2}^-[514], \frac{7}{2}^+[633], \frac{9}{2}^+[624]\} \otimes \pi\{\frac{1}{2}^-[541], \frac{5}{2}^+[402], \frac{7}{2}^+[404], \frac{9}{2}^-[514]\}$ and is at 6365 keV, in good agreement with the observed state at 6576 keV. There is no lower-seniority configuration able to generate such a high K value close to the yrast line.

This configuration assignment is supported by the g factor deduced from the observed $(\Delta I = 1)/(\Delta I = 2)$ in-band γ-ray branching ratios. Using the rotational model, as discussed in Ref. [12], for example, the $K^\pi = 25^+$ band is found to have $|g_K - g_R| = 0.03 \pm 0.02$, where g_K and g_R are the intrinsic and collective g factors, and an intrinsic quadrupole moment of $Q_0 = 7\ e\,\text{b}$ has been assumed. This compares well with an estimate of $g_K - g_R = 0.05 \pm 0.05$ for the eight-quasiparticle configuration given above, assuming $g_R = 0.30 \pm 0.05$ and a quenching factor of 0.6 for the intrinsic nucleon g_s factors. Although the values of Q_0 and g_R are not known experimentally for ^{178}W, the values used here are in accordance with the systematics in this mass region [12,22].

The $K^\pi = 25^+$ eight-quasiparticle isomer in ^{178}W is the highest-seniority intrinsic nuclear excitation with an associated rotational band and a well-defined bandhead. There is evidently no breakdown of collectivity above the eight-quasiparticle state, but with four unpaired neutrons and four unpaired protons occupying orbitals close to the Fermi surfaces, both neutron and proton pairing gaps are expected to be severely reduced [14], even at low rotational frequency. It might be supposed that static pairing no longer plays a significant role. This should be reflected in the moment of inertia, but the

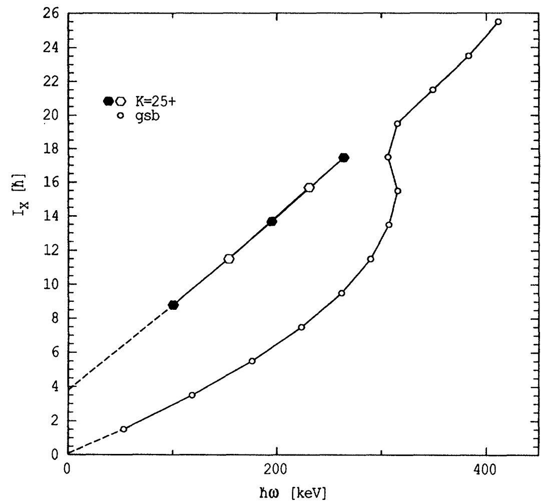

FIG. 3. Total aligned angular momentum for the $K^\pi = 25^+$ band and the ground-state band in ^{178}W, as a function of rotational frequency.

kinematic and dynamic moments of inertia ($\Im^{(1)}$ and $\Im^{(2)}$) are found to differ (see below) contrary to the simple expectation for classical rigid-body rotation, with no alignment contribution from individual nucleons [5,23].

A useful representation of the alignment is that given by Shimizu *et al.* [5], illustrated for ^{178}W in Fig. 3. The "apparent alignment" is obtained from the extrapolation of the rotation-axis component of angular momentum, I_x, to zero frequency. For the $K = 25$ band, this yields a small alignment of about $4\hbar$, which may be ascribed [24] to Coriolis effects on the $h_{9/2}$, $\frac{1}{2}^-[541]$ proton that contributes to the eight-quasiparticle configuration. With nonzero alignment, the kinematic moment of inertia, $\Im^{(1)} = \hbar I_x/\omega$, is large at the bandhead ($87\hbar^2$ MeV^{-1}) and decreases with rotational frequency. The dynamic moment of inertia, $\Im^{(2)} = \hbar dI_x/d\omega$, is obtained from the gradient in Fig. 3, and is well defined for the $K = 25$ band, with $\Im^{(2)} = 51\hbar^2$ MeV^{-1}. Although considerably larger than the ground-state-band value ($29\hbar^2$ MeV^{-1}), it is significantly less than the rigid-body moment of inertia of $85\hbar^2$ MeV^{-1}. Pashkevich and Frauendorf [25] calculated shell effects in the absence of pairing correlations and found rigid-body moments of inertia *on average*, across a major shell, but greater than rigid values are predicted in the lower half of a shell, and less than rigid values in the upper half of a shell. In the present case, $^{178}_{74}$W$_{104}$ is midshell for neutrons and upper shell for protons, and, in the absence of pairing correlations, a less than rigid moment of inertia is to be expected. A calculation specific to the $K^\pi = 25^+$ eight-quasiparticle band in ^{178}W would be valuable.

In summary, an eight-quasiparticle $K^\pi = 25^+$ yrast isomer has been found. Its excitation energy, spin, and parity are in agreement with blocked-BCS model calculations. The observed eight-quasiparticle rotational band provides a view of low-frequency nuclear rotation with blocked pairing correlations. Small residual alignment remains, and the dynamic moment of inertia falls short of the rigid-body value.

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