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Configuration and unusually fast decay of the $K^{\pi}=16^{-}$ four-quasiparticle isomer in ^{182}Re

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High-spin states in ^{182}Re were studied using the ^{176}Yb(^{11}B,5n) reaction at 70 MeV. The previously known four-quasiparticle isomer at 2256 keV is assigned spin and parity of 16^{-}. The rotational band built upon this multiquasiparticle state was identified and examination of the $(g_K-g_R)/Q_0$ values revealed that it arises from the $\pi(9/2^{-}[514])\otimes\nu^{3}(7/2^{-}[514],7/2^{-}[503],9/2^{+}[624])$ configuration. The decay of the 16^{-} isomer is found to be less hindered when compared to those observed for similar four-quasiparticle long-lived states in neighboring odd-odd ^{176,178,180}Ta isotopes. A possible explanation of this feature, involving a ''local'' mixing with a nearby 16^{-} collective state, is discussed.

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The rare-earth nuclei in the region near mass 180 are characterized by stable prolate-deformed, axially symmetric shape. Their single-particle spectrum is dominated by high-Ω orbitals, where Ω is the projection of the intrinsic angular momentum on the symmetry axis, in close proximity to both the neutron and proton Fermi surfaces. These unique circumstances give rise to a variety of high-seniority intrinsic configurations at relatively low-excitation energies that compete with structures formed by collective rotation for energetically favored status. Since there is approximate conservation of the quantum number $K=\Sigma\Omega_i$, the transitions depopulating the multiquasiparticle bandheads are often hindered, thus leading to nuclear isomers with a variation in half-lives that range from a few nanoseconds up to several years [1].

The identification of collective structures associated with the multiquasiparticle states is important as the in-band decay properties contain vital information about the constituent single-particle basis, thus allowing the configurations to be characterized. Furthermore, the bands themselves show interesting structure features, for example, effects associated with the reduction of the pairing correlations, which have been shown to depend on the number of blocked orbitals and their location near the Fermi surface [2].

In this Rapid Communication, we report on new results for both high-seniority intrinsic and collective structures in the deformed ($\beta_2\sim0.22$) odd-odd $Z=75$ ^{182}Re ($N=107$) nucleus. The present measurements establish spin and parity of 16^{-} for the previously known four-quasiparticle long-lived state at 2256 keV [3]. A rotational band associated with the isomer is identified and the examination of the in-band decay properties suggests that it arises from the $\pi9/2^{-}[514]\otimes\nu^{3}(7/2^{-}[514],7/2^{-}[503],9/2^{+}[624])$ configuration. The relatively fast $E2$ isomer decay is discussed in terms of a specific ''local'' mixing with a close lying collective state of the same spin and parity.

High-spin states in ^{182}Re were populated in the ^{176}Yb(^{11}B,5n) reaction with a beam energy of 70 MeV supplied by the Tandem-LINAC superconducting accelerator at the Florida State University. Gamma-ray coincidence measurements were carried out with a condition that at least two Ge detectors fired within ±100 ns of each other. In order to increase sensitivity across long-lived states, measurements with a coincidence window of ±400 ns were also performed. Gamma rays were detected with the Pitt-FSU array [4] consisting of eight Compton-suppressed Ge detectors and two twofold segmented CLOVER detectors. An additional unsuppressed planar germanium detector (LEPS) was included, giving enhanced sensitivity for γ rays below about 100 keV. Approximately 3×10^{8} twofold or higher coincidence events were recorded and written on magnetic tape.

The data were sorted off line into a variety of γ-γ and γ-LEPS matrices with different coincidence time requirements and detector combinations. Multiple projections, yielding background subtracted coincident spectra, were produced and examined with the RADWARE interactive package [5] in order to construct the level scheme. In the present data, no evidence was found for new isomers in ^{182}Re with lifetime greater than ~100 ns and, consequently, the main analysis was carried out with the prompt (±100 ns) coincidence matrices.

To ascertain γ-ray transition multipolarities, directional correlation from oriented states (DCO) measurements were performed. For this purpose, events consisting of one γ ray from a detector at 145° relative to the beam direction and another from a 90° detector, were incremented into a nonsymmetrical matrix. Coincidence spectra, projected onto both axes, were then generated from which the DCO ratios, defined as the ratio of γ-ray intensity for a transition of interest deduced from the gate projected onto the 145° axis to that from the 90° projection, were extracted. Gamma rays of stretched quadrupole character were identified by DCO ratios of nearly unity when gated by a stretched $E2$ transition. Similarly, values of approximately 0.5–0.6 indicate a pure stretched dipole transition and those of approximately 0.6–

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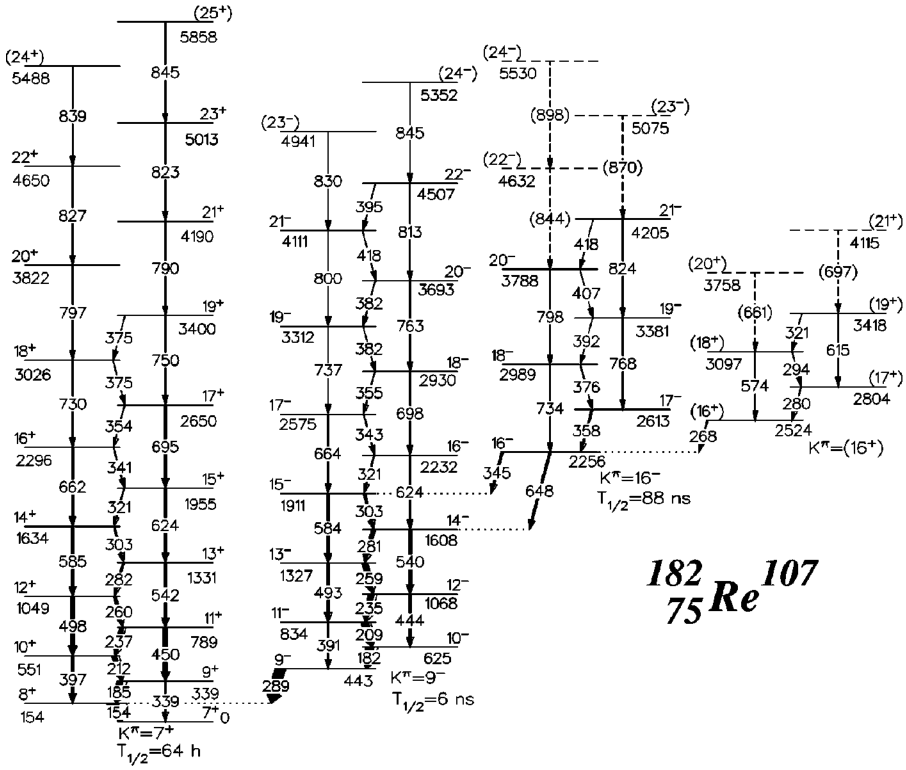

FIG. 1. Partial level scheme of ^{182}Re. The indicated half-lives are from Refs. [1, 3].

1.3 mixed dipole/quadrupole transition, the latter depending on the magnitude and sign of the mixing ratio, δ. Because the angular correlation measurements were crucial to assign multipolarity of transitions, and in particular those that depopulate the 88 ns isomer in ^{182}Re [3], the DCO ratios for γ rays of known multipolarity that are fed by the decay of the isomer were carefully examined to ensure that no significant attenuation of the initial alignment had occurred. The transition multipolarities deduced using the DCO ratios in the current work are consistent with those assigned by the angular-distribution measurements of Ref. [3]. Where appropriate, the spin and parity assignments were also aided by observation of rotational structures with both $I \rightarrow I-1$ and $I \rightarrow I-2$ transitions and the measured total electron conversion coefficients from intensity balance considerations for transitions with energies below about 200 keV.

The partial level scheme for ^{182}Re deduced from the present work is shown in Fig. 1. The placement of transitions and levels is based on the coincidence relationships, and their ordering follows from the relative intensities within a given cascade. The two-quasiparticle $K^{\pi}=7^{+}$ and 9^{-} bands were known previously up to $I \sim 15\hbar$ [3] and were extended by the current work up to $25\hbar$. A key feature of the level scheme is the state at 2256 keV which was reported by Slaughter *et al.* [3] to be long-lived [$T_{1/2}=88(8)$ ns] and was assigned $I^{\pi}=15^{+}$. While we confirm here the isomeric nature of this state, we propose different spin and parity assignments.

The DCO ratio of 0.96(8) measured for the 647.7 keV γ ray, which directly depopulates the isomer, using the 540.2 keV stretched quadrupole transition from the $K^{\pi}=9^{-}$ band as a gate, suggests that this γ ray is of either mixed dipole/quadrupole or stretched quadrupole character. The possibility that the 647.7 keV transition is mixed $E1/M2$ or pure $M2$ can be ruled out given the relatively short lifetime of the isomer. A spin value of $I=15\hbar$ for the isomer would require that both the 344.5 and 647.7 keV depopulating transitions are dipoles (assuming $\delta=0$) and the latter should be about seven times stronger because of the E_{γ}^{3} dependence of the transition rate. This is, however, in contradiction to the measured intensity ratio of $I_{\gamma}(648)/I_{\gamma}(345)=1.1(1)$. Furthermore, the nonobservation of a 929 keV transition from the 2256 keV state to the 13^{-} level of the $K^{\pi}=9^{-}$ band also favors the conclusion that the 647.7 keV transition is stretched quadrupole and, hence, a $K^{\pi}=16^{-}$ assignment is given to the isomer.

A spectrum of transitions in coincidence with the 647.7 keV γ ray is shown in Fig. 2(a). It illustrates that the 267.9 and 357.8 keV γ rays are the strongest transitions that precede the isomer in agreement with the observations by Slaughter *et al.* [3]. The DCO ratio of 0.83(6), measured for the latter transition is consistent with the $\Delta I=1$ $M1/E2$ assignment and, hence, we interpret this γ ray as the first cascade transition within the band built upon the isomer. Several more γ rays, in coincidence with the 357.8 keV transition, which are also assigned to this band, are seen in the spectrum shown in Fig. 2(b).

The DCO ratio of 1.25(12) obtained for the 267.9 keV γ ray, which depopulates the 2524 keV level, is not conclusive, since it could imply a possible $\Delta I=0$, 1, or 2 assignment. However, the intensity ratio of $I_{\gamma}(357.8)/I_{\gamma}(267.9)=1.7(2)$, deduced from a spectrum gated on transitions below the isomer, suggests that the spin of the 2524 keV state is at least one unit less than that of $I=17\hbar$ assigned to the 2613 keV level. Hence, we propose $I=16\hbar$ to the 2524 keV

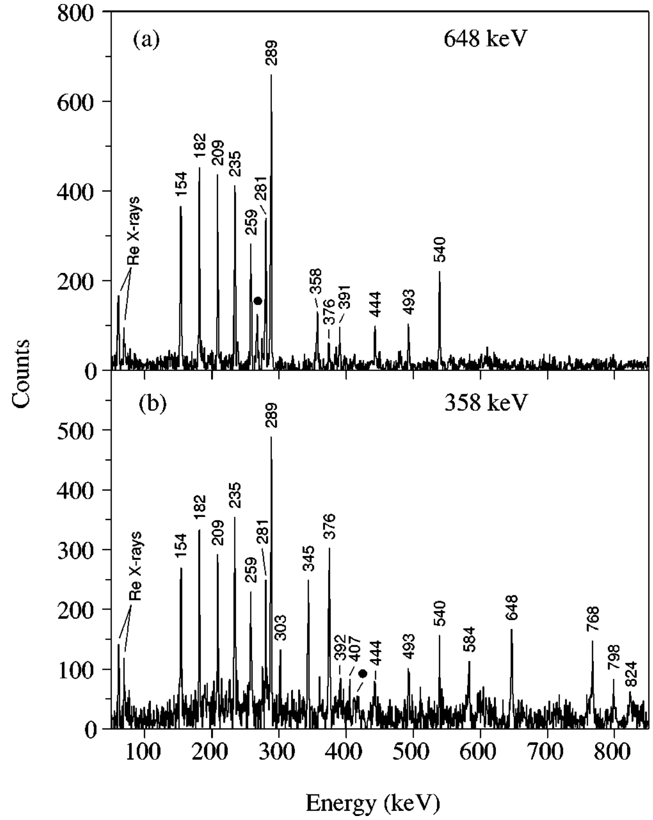

FIG. 2. Gamma-ray spectra for transitions in coincidence with the 647.7 and 357.8 keV γ rays. The filled circles correspond to the 267.9 (a) and 417.7 keV (b) γ rays.

level, although the present experimental data are not able to rule out the $I=14$ or $15\hbar$ alternatives. A rotational band, consisting of both cascade and crossover transitions built upon this state up to $I^{\pi}=(21^{+})$, is also identified in the current work, as shown in Fig. 1.

Configuration assignments to the observed structures were made by taking into account the spin and parity of the state, and the observed properties such as in-band branching ratios and alignments, considered with the orbitals expected near the proton and neutron Fermi surfaces. The experimental g_K values, deduced from the in-band branching ratios, are compared in Table I with the expectations computed using Woods-Saxon model wave functions [6] and the additivity relation $Kg_K=\Sigma g_{\Omega_i}\Omega_i$. The apparent alignments of all bands reported here are plotted in Fig. 3.

The $K^{\pi}=7^{+}$ and 9^{-} bands had been suggested by Slaughter *et al.* [3] to arise from the $\pi 5/2^{+}[402] \otimes \nu 9/2^{+}[624](\pi\nu[7^{+}])$ and $\pi 9/2^{-}[514]\otimes\nu 9/2^{+}[624] \times(\pi\nu[9^{-}])$ two-quasiparticle configurations. The g_K values deduced in the current work (see Table I) and the observed alignments (see Fig. 3) verify these assignments.

The four-quasiparticle isomer at 2256 keV had been previously assigned the $\pi^3(5/2^{+}[402],7/2^{-}[523],9/2^{-}[514]) \otimes\nu 9/2^{+}[624]$ configuration [3], obtained by coupling the $\pi^2(5/2^{+}[402],7/2^{-}[523])_{6^-}$ component to the $\pi\nu[9^{-}]$ state. However, since we propose $K^{\pi}=16^{-}$ for this bandhead level, we favor the $\pi 9/2^{-}[514] \otimes\nu^3(7/2^{-}[514],7/2^{-}[503],9/2^{+}[624])$ configuration, where the $\nu^2(7/2^{-}[514],7/2^{-}[503])_{7^+}$ pair of neutrons couples to the $\pi\nu[9^{-}]$ configuration. This assignment is supported from the observed in-band decay properties which yield $g_K=0.40(4)$ (assuming $\delta>0$) or 0.20(4) ($\delta<0$) in good agreement with the theoretical expectation of $g_K=0.38$. Note that values close to unity would be expected if the configuration includes a π^3 component (see Table I). The alignment of the band, see Fig. 3, associated with the 88 ns isomer is consistent with the presence of a single $i_{13/2}$ neutron, but it is slightly lower, at rotational frequencies below about 0.2 MeV, when compared to values observed for the $\pi\nu[9^{-}]$ band. It should be noted that the $7/2^{-}[514]$ and $7/2^{-}[503]$ neutron orbitals are expected to contribute essentially zero extra alignment. Since the configuration includes three unpaired neutrons, the reduced neutron pairing would affect the Coriolis mixing, thus leading to a smaller apparent alignment, as discussed in Ref. [2].

The (16^{+}) state at 2524 keV can be assigned the $\pi 9/2^{-}[514]\otimes\nu^3(7/2^{-}[503],7/2^{+}[633],9/2^{+}[624])$ configuration. The associated rotational band has greater alignment than those of the 16^{-} band, thus supporting the presence of two $i_{13/2}$ neutrons. A four-quasiparticle 16^{+} band that includes the same $i_{13/2}$ orbitals was recently reported in the neighboring odd-odd ^{178}Ta isotope [7,8]. The alignment properties of the latter band closely match those of the (16^{+}) band in ^{182}Re reported here, as illustrated in Fig. 3. In addition, the measured g_K value is in good agreement with the expectation for the suggested $\pi\nu^3[16^{+}]$ configuration.

In order to predict the excitation energies of the multiquasiparticle states in ^{182}Re, calculations were performed which treat the pairing correlations using the Lipkin-Nogami prescription and that include both effects of blocking and estimates of the residual nucleon-nucleon interactions. The calculation procedure was similar to that described in Refs. [8, 9]. The single-particle energies were taken from the Nilsson model with $\varepsilon_2=0.217$ and $\varepsilon_4=0.073$, but with the states close to the Fermi surface adjusted to reproduce approximately the experimental one-quasiparticle energies in neighboring odd-A nuclei. The predicted excitation energies, together with the experimental observations, are summarized in Table I. It is notable that the calculations show a very good agreement with the sequence of observed states. For example, in the four-quasiparticle regime, the configurations formed by coupling a pair of neutrons to the $\pi\nu[9^{-}]$ state are calculated to be energetically favored compared to those that include pairs of excited protons. The next high-K, six-quasiparticle states predicted to be low in energy are those with $K^{\pi}=24^{+}$ (at an excitation energy $E_x=4648$ keV) and 24^{-} ($E_x=5038$ keV). They are assembled from the 16^{-} and 16^{+} states by adding the $\pi^2(5/2^{+}[402],11/2^{-}[505])_{8^-}$ proton configuration. Importantly, the relatively low calculated excitation energy of the $K^{\pi}=24^{+}$ state would imply that it could decay only via a high-multipolarity ($E3$ and/or $M2$) transition to the 21^{-} and/or 22^{-} members of the 16^{-} band, or via a low-energy $E2$ transition to the 22^{+} level of the 16^{+} band, hence, isolating it as a very long-lived spin trap. These high lying six-quasiparticle states require further investigation.

The isomeric nature of the 16^{-} state arises because the depopulating transitions are K-forbidden. For a transition of multipole order, λ, the reduced hindrance factor per degree of K-forbiddenness, f_ν, where $\nu=\Delta K-\lambda$, is defined as f_ν

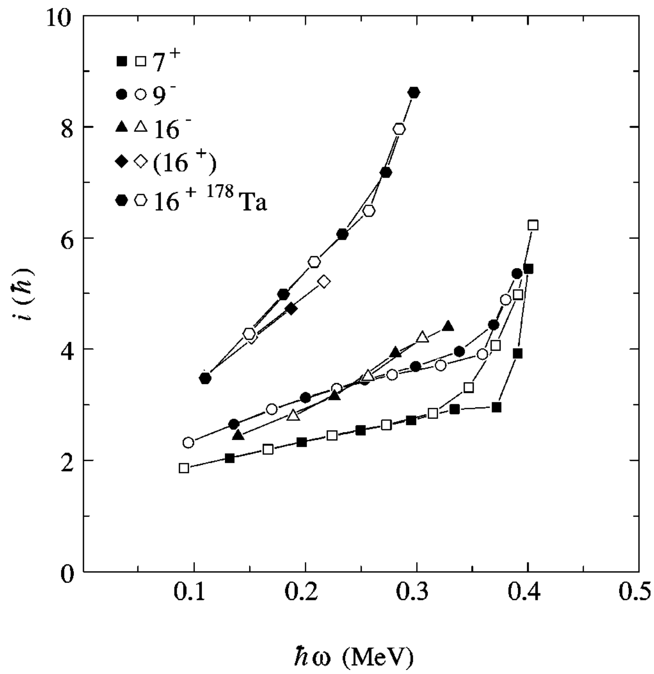

FIG. 3. Alignments for the observed bands in ^{182}Re, compared to the 16^+ four-quasiparticle band in ^{178}Ta [7,8]. Common Harris reference parameters of $\mathcal{I}_0=32\ \mathrm{MeV}^{-1}\hbar^2$ and $\mathcal{I}_1=65\ \mathrm{MeV}^{-3}\hbar^4$ were used for all bands. The open and filled symbols correspond to $\alpha=1$ and 0 signatures, respectively.

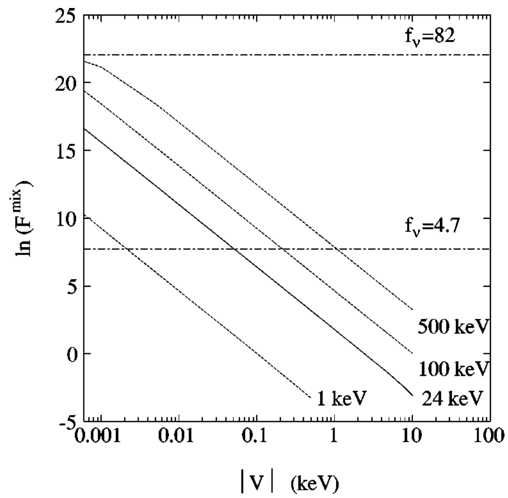

FIG. 4. Calculated hindrance factors as a function of the mixing matrix element, assuming two-state mixing (see the text for details). The solid curve represents the case of the 16^- isomer in ^{182}Re. The dashed curves are for arbitrary separations of 1, 100, and 500 keV between the initial and final states.

$=(F)^{1/\nu}$, where $F=(T^{\gamma}_{1/2}/T^{W}_{1/2})=(B^W/B^{\gamma})$ is the hindrance factor, $T^{\gamma}_{1/2}$ and B^{γ} are the partial γ-ray half-life and the γ-ray reduced transition probability, respectively, and $T^W_{1/2}$ and B^W are the Weisskopf estimates. The reduced hindrance factor obtained for the 647.7 keV $E2$ transition is $f_\nu=4.7$. It is surprisingly lower when compared to values of $f_\nu=15$, 46, and 16 observed for the equivalent decays of similar four-quasiparticle isomers in neighboring odd-odd ^{176}Ta [8,10], ^{178}Ta [7,8], and ^{180}Ta [11] nuclei, respectively.

To explain the relatively fast decay in ^{182}Re, two level mixing calculations involving the 16^- isomeric state at 2256 keV and the 16^- member of the $\pi\nu[9^-]$ band at 2232 keV were carried out. The hindrance factor for the collective $16^-\rightarrow14^-$ $K^\pi=9^-$ in-band transition was taken as $F^{col}=B^W(E2)/B^{col}(E2)$, where $B^{col}(E2)=(5/16\pi)\,Q_0^2\langle I_i 2K0|I_f K\rangle^2$ and $Q_0=6.2\,e$ b [see the footnote (b) of

TABLE I. Configurations, g_K factors and excitation energies for multiquasiparticle states in ^{182}Re.

K^π	Configuration[a]		g_K		E_x (keV)	
	π	ν	Experiment[b]	Theory[d]	Experiment	Theory
7^+	$5/2^+$	$9/2^+$	0.63(2)	0.61	0	0
9^-	$9/2^-$	$9/2^+$	0.62(2)	0.70	443	408
15^+	$5/2^+,\ 7/2^-,\ 9/2^-$	$9/2^+$		0.99		3980
15^-	$5/2^+,\ 7/2^+,\ 9/2^-$	$9/2^+$		0.82		3142
16^-	$9/2^-$	$7/2^-,\ 7/2^{-\prime},\ 9/2^+$	0.40(4)	0.38	2256	2125
			0.20(4)[c]			
16^+	$9/2^-$	$7/2^{-\prime},\ 7/2^+,\ 9/2^+$	0.35(4)	0.33	2524	2764
			0.25(4)[c]			
24^+	$5/2^+,\ 9/2^-,\ 11/2^-$	$7/2^-,\ 7/2^{-\prime},\ 9/2^+$		0.71		4648
24^-	$5/2^+,\ 9/2^-,\ 11/2^-$	$7/2^{-\prime},\ 7/2^+,\ 9/2^+$		0.67		5038

[a]Protons (π): $5/2^+$: $5/2^+[402]$, $7/2^+$: $7/2^+[404]$, $7/2^-$: $7/2^-[523]$, $9/2^-$: $9/2^-[514]$, $11/2^-$: $11/2^-[505]$; neutrons (ν): $7/2^-$: $7/2^-[514]$, $7/2^{-\prime}$: $7/2^-[503]$, $7/2^+$: $7/2^+[633]$, $9/2^+$: $9/2^+[624]$.

[b]Values correspond to weighted averages of the branching ratios for the 9^+ to 15^+ states in the 7^+ band, the 11^- to 15^- states in the 9^- band, the 18^- to 21^- states in the 16^- band, and the (18^+) and (19^+) states in the (16^+) band. A collective gyromagnetic factor of $g_R=0.3$ and $\delta>0$ are assumed. Note that a positive sign of δ was unambiguously determined for the $\Delta I=1$ transitions within the $\pi\nu[7^+]$ and $\pi\nu[9^-]$ bands from the angular distribution measurements of Ref. [3]. A quadrupole moment of $Q_0=6.2\,e$ b, taken as the average from the values measured for the $K^\pi=2^+$ and 7^+ bands in ^{182}Re [1], was used.

[c]The same as (b), but assuming $\delta<0$.

[d]Calculated values using Woods-Saxon wave functions [6], $g_s=0.7g_s^{free}$ and deformation parameters $\beta_2=0.222$ and $\beta_4=-0.048$. To account for a Coriolis mixing effect an empirical value of $g_\Omega=0.08$ for the $7/2^+[633]$ and $9/2^+[624]$ ($i_{13/2}$) quasineutrons [13] was used.

Table I]. A value of $F^{forb}=3.7\times10^{9}$ (corresponding to $f_{\nu}=82$, which is one of the largest values in the region [12]) was assumed for the fivefold K-forbidden $16^{-}\rightarrow14^{-}$ interband transition. These were combined according to their relative contributions to the transition rate $F^{mix}=(\alpha^{2}/F^{col}+\beta^{2}/F^{forb})^{-1}$, where α and β are the mixed amplitudes in the wave function of the 16^{-} isomeric state at 2256 keV $(\psi_{16^{-}}=\alpha\phi_{9^{-}}+\beta\phi_{16^{-}},\alpha^{2}+\beta^{2}=1)$. Figure 4 shows the calculated F^{mix} values as a function of the magnitude of the mixing matrix element, $|V|$. To reproduce the half-life of the 16^{-} isomer a value of $|V|\approx51$ eV is required, yielding the squared amplitude of the low-K $(K=9)$ components in the isomeric state wave function at a level of $\alpha^{2}\sim4.6\times10^{-6}$. It is worth noting that a similar value of $|V|=24$ eV, as well as negligible low-K admixtures, were also reported by Walker *et al.* [13] in studing the decay of the $K^{\pi}=35/2^{-}$ isomer in ^{179}W, although it is appreciated that the situation there is more subtle. As illustrated in Fig. 4 (the dashed curves), such a ''local mixing'' scenario is rather sensitive to the energy separation between the initial and final states. There are already indications that the reduced hindrance values tend to decline as the isomers approach a region of high level density where further mixing occurs [14].

In summary, a previously known four-quasiparticle isomer in ^{182}Re is assigned spin and parity of 16^{-}. A rotational band built upon this state has been identified and the examination of the in-band decay and alignment properties suggest that the $\pi(9/2^{-}[514])\otimes\nu^{3}(7/2^{-}[514],7/2^{-}[503],9/2^{+}[624])$ configuration is involved. An unusually fast decay of the isomer is interpreted in terms of a ''local'' mixing $(|V|\approx51\,\text{eV})$ with a low-K collective 16^{-} level.

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