Residual Interactions in Four-Quasiparticle $K^\pi = 14^-$ Isomer in ^{176}Hf†

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We have for the first time located and identified a four-quasiparticle isomer in a deformed nucleus. Its energy may be used as a test for the effective interaction between quasiparticles. We can account for the energy quite well with a simple δ-function interaction, but not with an interaction derived from Brueckner theory.

Information on the residual interaction in rare-earth deformed nuclei has come primarily from the singlet-triplet splittings of Gallagher-Moszkowski pairs in odd-odd nuclei,[1] and to a much lesser extent from similar splittings of two-quasiparticle (2-qp) states in even-even nuclei. The off-diagonal matrix elements of the residual interaction have also recently been obtained from the mixing between two-neutron and two-proton configurations[2-4] in even-even nuclei. To date, however, no attempt has been made to extract information on the residual interactions in the rare-earth region from a study of states of seniority greater than two, despite the fact that many 3-qp states are known. To begin such an investigation it is, in fact, preferable to study a 4-qp system for which the energies of the constituent 2-qp states are already known. In this case, the effects of the residual interaction may be extracted from the observed 2- and 4-qp energies without having to calculate explicitly the individual qp energies. The interactions thus deduced may then be used as a test of chosen effective interactions.

The twofold goals in the present investigation were to isolate experimentally a 4-qp state and, using its energy, to test the applicablity of a "realistic" force and a δ force as effective interactions for rare-earth deformed nuclei. We prefer to search for very high-K (≥ 12) states, since these should be rather pure because of the low density of such states even at the ~3-MeV excitation expected. An accompanying attractive feature is the fact that the large K should lead to isomerism, greatly simplifying the identification of the state.

The nucleus ^{176}Hf is a particularly favorable candidate for investigation since the lowest 2-qp excitations have been identified[2] and, furthermore, have high K so that one may expect the lowest 4-qp states to have very large K. In addition the decay of the 4-qp isomer should proceed through known[2] bands built on the lower-lying 2-qp configurations, further simplifying the observation of the isomer.

The reaction ^{176}Yb$(\alpha, 4n)^{176}$Hf at 41–50 MeV bombarding energy was used to populate high-K states in ^{176}Hf. The following experiments in which γ rays were detected by Ge(Li) detectors were performed: (a) observation of delayed γ rays in a 5-msec interval between irradiation periods of 1 msec duration; (b) search for short-lived isomers, in which the interval between beam bursts varied from 50 to 500 nsec; (c) conventional three-parameter γ-γ-t coincidence; (d) excitation function; and (e) angular distribution measurements. In addition to two previously known[2] 10-μsec isomers, a new 401 ± 6-μsec isomer was discovered at 2866.0 keV. The decay scheme of the isomer is shown in Fig. 1. All the γ rays in the figure with relative intensities greater than 0.6 were found to decay with a 401-μsec component. No other isomers with half-lives greater than a few nanoseconds were found in ^{176}Hf. It is interesting to observe that the population of the 401-μsec isomer accounts for an unusually large fraction (~30%) of the total $(\alpha, 4n)$ cross section.

The new isomer decays through two $K^\pi = 8^-$ bands which had previously been identified[2] to spin 12. The energies, branching ratios, and relative signs of the $M1$ and $E2$ matrix elements of the band members can all be accounted for in a model[2] in which there is increasing mixing between levels with increasing spin. On the basis of this model, there is little doubt that the 2827.3-keV level is the lower 13^- band member. (The higher 13^- level, not shown in Fig. 1, is found at

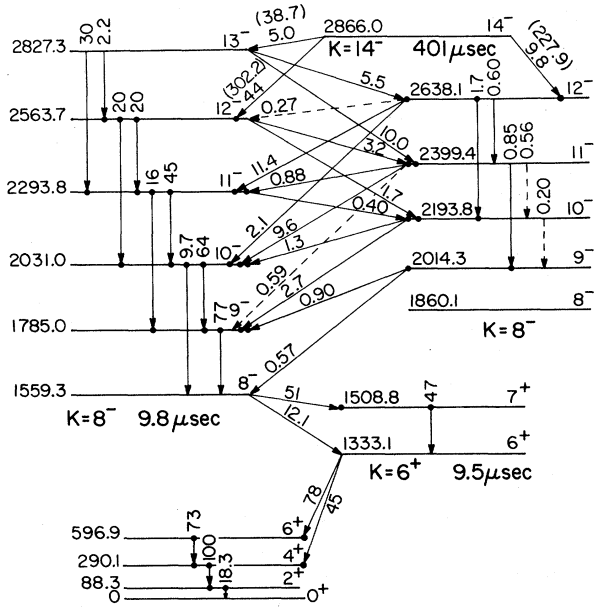

FIG. 1. Decay scheme of 4-qp $K^\pi = 14^-$ isomer in ^{176}Hf. The γ-ray relative intensities of all transitions are indicated; the energies of the transitions directly de-exciting the isomer are given in parentheses. Filled circles indicate γ rays entering and leaving a level in prompt coincidence.

2920.9 keV.)

With use of intensity-balance considerations, the total internal conversion coefficient of the 38.7-keV transition was obtained ($\alpha_{tot} = 12 \pm 2$), leading to an unambiguous $M1$ assignment. From the $M1$ character of the 38.7-keV transition and the observed decay pattern, the most likely spin and parity for the 2866-keV isomer is 14^-. The 228- and 302-keV transitions should thus be $E2$ and their conversion coefficients [$\alpha_{tot}(228) \leq 0.26$, $\alpha_{tot}(302) \leq 0.16$] are consistent with this multipolarity. The isomerism of the 2866-keV level suggests K forbiddeness, leading to a $K^\pi = 14^-$ assignment. We have also identified[5] the rotational band built on this isomer up to spin 19 and obtained an intrinsic g factor, $g_K = 0.59 \pm 02$, from intraband cascade-to-crossover ratios in the manner described in Ref. 2. This value is in excellent agreement with that expected for, and thus suggests, the 4-qp $K = 14^-$ $\{\frac{7}{2}(404)_p, \frac{9}{2}(514)_p, \frac{7}{2}(514)_n, \frac{5}{2}(512)_n\}$ configuration. (It should be noted that no 2-qp states of such high K are expected at this energy.) This is the first time a high-K 4-qp isomer has been located in a deformed nucleus.[6]

The energy of a 4-qp state composed of two protons and two neutrons may be expressed[7] in terms of the energies of the constituent 2-qp systems:

$$E(K_4) = E(K_{2p}) + E(K_{2n}) + [V(pn) - V_0(pn)] + (\hbar^2/2\mathcal{J})(K_4 - K_{2p} - K_{2n}),$$

where $E(K_4)$ is the 4-qp energy, $E(K_{2p})$ and $E(K_{2n})$ are the observed energies of the 2-qp proton and neutron states, $V(pn) - V_0(pn)$ is the difference between the qp proton-neutron interaction energies in the ground and excited states, and the last term represents the correction for the zero-point rotation energy. The p-p and n-n interactions are already included in the 2-qp energies and need not be treated explicitly. The residual interactions are given by

$$V(pn) - V_0(pn) = \sum_{i,k}{}' [\langle ik\rangle (1 - 2\nu_i^2\nu_k^2) - \langle i\bar{k}\rangle 2\nu_i^2\nu_k^2] + \sum_{i,k} V_{ik}, \quad (1)$$

where $\langle ik\rangle = \langle ik|V|ik\rangle$ is the interaction matrix element for particles in orbits i and k, ν_i^2 and ν_k^2 are the pairing fullness parameters, and the bar denotes the time-reversed orbital. The prime indicates that the first sum contains only terms in which both orbitals are occupied in the 4-qp configuration; the second sum includes all remaining terms. Since many terms are involved in the second sum, we approximate individual matrix elements by an average one, $\langle ik\rangle_{av}$. In this approximation, it can be shown[7] that

$$\sum_{i,k} V_{ik} = -\langle ik\rangle_{av} \sum_{i,k}{}' (1 - 4\nu_i^2\nu_k^2) \quad (2)$$

by noting that the number of interactions is equal in both the excited and the ground states. The prime over the sum has the same meaning as in Eq. (1).

The residual interactions in a 4-qp state were evaluated by use of Eqs. (1) and (2) in the following manner. The single-particle Nilsson wave functions were expanded in terms of spherical states, from which the two-particle wave functions were derived in a j-j coupling scheme. The two-body matrix elements were evaluated by use of interactions between oscillator states of the relative coordinate derived from (a) a δ interaction,

$$H(\delta) = 4\pi g(\nu/2)^{3/2}(1 - \alpha + \alpha\vec{\sigma}_1 \cdot \vec{\sigma}_2)$$

with the force strengths, $4\pi g(\nu/2)^{3/2} = 5.82$ MeV and $\alpha = 0.46$, adjusted to reproduce the splittings

of singlet-triplet pairs in odd-odd[1] and even-even[7] nuclei; and (b) a "realistic" interaction, including spin-orbit and tensor terms, obtained from the Reid potential by use of Brueckner theory in the manner described by Bertsch.[8] Details of the calculations will be published separately.[7] The average interaction, $\langle ik\rangle_{av}$, was taken as the mean of a large number of matrix elements calculated[7] for 2-qp states of odd-odd nuclei. The required pairing factors in Eqs. (1) and (2) are taken from Ref. 4.

The energies of several 4-qp states in ^{176}Hf, in addition to that of the $K^\pi = 14^-$ configuration of interest, have been calculated by use of Eqs. (1) and (2). These energies are presented in Table I, which also includes the predicted energy of a 4-qp $K^\pi = 16^+$ state in ^{178}Hf. The energies, E_0, derived from the sums of the constituent 2-qp energies without including residual p-n interactions are given in column 4 of the table. Columns 5 and 6 give the energies obtained after including p-n interactions calculated with use of the realistic and the δ-function interaction, respectively. The use of the δ force yields a calculated energy for the $K^\pi = 14^-$ state in good agreement with experiment. Furthermore, whereas the sums of 2-qp energies predict the $K^\pi = 12^+$ state to lie lowest, inclusion of the residual interactions makes the $K^\pi = 14^-$ state lowest, in accord with observation. (If the $K^\pi = 12^+$ state, or any other high-K 4-qp state, were lowest in energy, it would have received significant feeding in the experiment and its isomeric decay via 2-qp bands would have been easily detectable.) The energies calculated with use of the realistic interaction are very unsatisfactory, being too low by about 300 keV. Detailed analysis shows that this arises because the matrix elements of high-K p-n couplings calculated with the realistic interaction tend to be too large compared with the average interaction, $\langle ik\rangle_{av}$, used in Eq. (2).

Similar calculations[7] of the energies of some 3-qp states also show that the simple δ force gives better agreement with experiment than the more sophisticated realistic interaction. It would be of interest to determine the reasons for the deficiency of the realistic interaction in this mass region.

While the δ-function interaction is very successful in predicting 3- and 4-qp energies and also the splittings many Gallagher-Moszkowski pairs in odd-odd nuclei,[1,7] it is unable to account[1,7,9] for the odd-even shifts in $K=0$ bands of odd-odd nuclei. In fact, an interaction which can successfully account for the various types of data now available on deformed nuclei is yet to be found.

There is also a clear need for more data on other high-K 4-qp states and their constituent 2-qp components. A search for such configurations by means of (α, xn) reactions should be promising in the Hf region, where the orbitals near the Fermi level have large-Ω projections. Preliminary analysis of on-going experiments[6] indicates the existence of other high-K 4-qp structures in both ^{174}Hf and ^{176}Hf.

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TABLE I. Low-lying $K \geq 12$ 4-qp states in ^{176}Hf and ^{178}Hf.

	K	Configuration[a]	E_0[b] (keV)	$E_{calc\ I}$[c] (keV)	$E_{calc\ II}$[d] (keV)	E_{exp} (keV)
^{176}Hf	14^-	$(7/2)_p(9/2)_p(7/2)_n(5/2)_n$	3158	2580	2838	2866
	14^-	$(7/2)_p(5/2)_p(7/2)_n(9/2)_n$	3353	3105	3482	e
	12^+	$(7/2)_p(5/2)_p(7/2)_n(5/2)_n$	3094	2560	2928	e
	15^+	$(7/2)_p(9/2)_p(9/2)_n(5/2)_n$	3360	3012	3190	e
	16^+	$(7/2)_p(9/2)_p(9/2)_n(7/2)_n$	3419	2697	3061	e
^{178}Hf	16^+	$(7/2)_p(9/2)_p(9/2)_n(7/2)_n$	2628	2069	2570	2430–2550[f]

[a] The single-particle orbitals are $(\frac{7}{2})_p$: $\frac{7}{2}(404)$; $(\frac{9}{2})_p$: $\frac{9}{2}(514)$; $(\frac{5}{2})_p$: $\frac{5}{2}(402)$; $(\frac{7}{2})_n$: $\frac{7}{2}(514)$; $(\frac{9}{2})_n$: $\frac{9}{2}(624)$; $(\frac{5}{2})_n$: $\frac{5}{2}(512)$.

[b] $E_0 = E(K_{2p}) + E(K_{2n})$.

[c] Evaluated with use of realistic interaction to calculate matrix elements.

[d] Evaluated with use of δ interaction to calculate matrix elements.

[e] Energy > 2866 keV. Arguments are made in the text that the 2866-keV isomer is the lowest high-K 4-qp state.

[f] Ref. 3.

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L_3 Conversion of the 2.38-keV Isomer in ^{90}Nb

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The 3.8% decrease in half-life of the 2.38-keV ^{90m}Nb isomer when Nb is converted from metal to a fluoride complex is one of the largest reported chemical effects on the internal conversion process. We present experimental and theoretical evidence that this effect is not due, as had been conjectured, to the "switching off" of L_3 conversion through increased L_3 binding energy.

Perturbations of nuclear decay rates (λ) due to changes in chemical environment[1] are typically 0.01–0.1%; for low-energy isomers the effects are attributed to altered valence-electron population and to the related change in electron density at the nucleus. The very large $\Delta\lambda$ of 3.8% observed[2,3] when the environment of ^{90m}Nb is changed from metallic Nb to a fluoride complex cannot be understood on this basis. This effect was seen by perturbing the decay chain ^{90}Mo(5.7 h) $\rightarrow$ ^{90m}Nb(18.8 sec) $\rightarrow$ ^{90g}Nb(14.6 h) through dissolution of activated Nb foils in acid, and a 1.9% effect was seen similarly for Nb/Nb_2O_5. However various workers[4-6] have prepared the 18.8-sec isomer directly and find no significant differences in half-lives measured for various chemical states; there exists no such measurement for the pair Nb/Nb(fluoride complex), but for the pair Zr/Zr(fluoride complex) the reported[6] upper limit on $\Delta\lambda$ is 0.18%.

The transition energy $E_\gamma = 2.38 \pm 0.36$ keV inferred[2] from energy balance of γ rays in ^{90}Mo decay has a large uncertainty and may lie above or below the L_3 binding energy of Nb. Olin[3] suggested that if in the metal $E(L_3) < E_\gamma$, and in the fluoride complex $E(L_3) > E_\gamma$, a large change in λ would result from the "switching off" of L_3 conversion. Smend, Borchert, and Langhoff[8] evaluated theoretical conversion coefficients for $E_\gamma = 2.38$ keV, and found that α_{L_3} contributed 3.8% of the total decay rate; they used the threshold value of α_{L_3} given by O'Connell and Carroll.[7]

In an attempt to clarify this situation we have performed measurements to determine whether or not L_3 conversion occurs in the free Nb atom. For comparison with theory we have computed α_{L_3} to within 10 eV of threshold.

The principle of our experiment is to determine the intensity ratio L/K of L and K vacancies created in ^{90m}Nb decay (Fig. 1), through measurement of the LX/KX x-ray intensity ratio. However at $Z \sim 40$, L-shell fluorescence yields