Evidence for K mixing in ^{178}Hf

C.B. Collins

The University of Texas at Dallas, Center for Quantum Electronics, PO Box 830688, Richardson, TX 75083-0688, USA

J.J. Carroll

Department of Physics and Astronomy, Youngstown State University, Youngstown, OH 44555, USA

Yu.Ts. Oganessian and S.A. Karamian

Joint Institute for Nuclear Research, Flerov Laboratory of Nuclear Reactions, Dubna, PO Box 79, 101000 Moscow, Russia

Systematics for the appearance of K-mixing levels for the pumping or spontaneous decay of multi-quasiparticle isomers in Hf isotopes are detailed in this letter. The possible location of such a level in the nuclide ^{178}Hf is discussed and an experiment is proposed to investigate its existence.

Multi-quasiparticle states in the isotopes of Hf appear as high-spin isomers that are distinguished by the combination of MeV excitation energies and long lifetimes [1]. As is typical for mid-shell isotopes, Hf nuclei have marked prolate deformations that provide a body axis upon which the total angular momentum, J can be quantized in units of $K\hbar$. Thus multi-quasiparticle states serve as the heads of rotational bands corresponding to large values of projection quantum number, K.

The Hf isomers also have angular momenta which are quite different from those of other intrinsic nuclear states. Since strong electromagnetic transitions are generally characterized by low orders of multipolarity, L and selection rules require $|\Delta J| \leqslant L$, the apparent necessity for large changes in angular momentum would seem to be the cause of the long isomeric lifetimes. However, large ΔJ transitions need not be required. The excitation energies of multi-quasiparticle states are so great that levels with similar angular momenta can be found, built upon the low-spin ground state from as many as 6–8 quanta of rotation, while still remaining below the energy of the isomers. Thus the selection rule upon ΔJ alone cannot be the cause of the isomerism.

The long lifetimes of multi-quasiparticle states of Hf result from the analogous selection rule upon K, generally accepted to be $|\Delta K| \leqslant L$ for transitions between states in different rotational bands. This is the restriction which severely hinders elec-

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tromagnetic decay of the isomers to yrast levels of similar J, but dissimilar K. While providing storage of great energy densities, the selection rule on K would also seem to vitiate otherwise attractive proposals to use concentrations of high-spin isomers for superelastic particle beam applications, (γ, γ') frequency upconversion, and the nuclear analog to the ruby laser. It is very difficult *a priori* to conceive of a trigger process or reaction which would transfer so much ΔK as would be needed to de-excite populations of high-spin isomers to freely radiating states in an efficient, controlled manner.

The key to transitions between high-spin isomers of Hf and yrast states may lie in the existence of mediating levels having mixed values of K. Those "K-mixing" levels would be described by superpositions of eigenfunctions for several different projection quanta corresponding to comparable values of J and could be reached by transitions of low multipolarity both from isomers and from members of bands built upon much lower values of K. A discussion of what type of perturbation could provide the interaction energy necessary for such a fortunate K mixing is left for later.

The first evidence for the de-excitation, or "dumping", of a multi-quasiparticle isomer through a K-mixing level seems to have been reported in 1987 and published in 1988 [2]. Populations of the 10^{15} year, two-quasiparticle isomer ^{180}Ta^{m} were dumped to the ground state in the reaction ^{180}Ta$^{m}(\gamma, \gamma')^{180}$Ta, despite a total change of $\Delta K = 8$. Identified [3] in 1990 as proceeding directly through a previously unobserved state at 2.8 MeV, the reaction was found to be excited with a surprisingly large integrated cross section of 1.2×10^{-25} cm^{2}keV. Independently, the same year the de-excitation of the 3.7 μs, four-quasiparticle isomer ^{174}Hf^{m} was reported [4] to occur as a result of *spontaneous emission* through a K-mixing level lying below the metastable state at 2.685 MeV and providing $\Delta K = 14$. The similarity of the excitation energies of the mediating levels in ^{180}Ta and ^{174}Hf, on the order of a pairing interaction, suggested an examination of the systematics of other (γ, γ') reactions that spanned large ΔK. While those reactions might have proceeded through complex cascades, they could have also benefitted from more direct transitions through K-mixing states.

Fig. 1 summarizes the results reported earlier for a systematic investigation [5,6] of integrated cross sections and excitation energies measured for (γ, γ') processes mediating large changes of ΔK. The only known reactions starting on multi-quasiparticle levels seem to be those of ^{174}Hf^{m} and ^{180}Ta^{m}, so the others shown are for the excitation of one- or two-quasiparticle isomers from ground-state targets. Nevertheless, the trend is compelling and suggests the pervasive existence of a K-mixing level between 2.5 and 2.8 MeV in many mid-shell nuclides below $p = 82$. Moreover, the values of integrated cross section for (γ, γ') reactions occurring through such levels seem to peak in this region, notwithstanding the large ΔK between initial and final states. Such magnitudes would suggest strong transitions of low multipolarity, requiring the change in K to occur in the mediating state.

The persuasive nature of the data plotted in fig. 1 encourages the tentative conclusion that a similar K-mixing level can be expected in the ^{178}Hf system. This would be

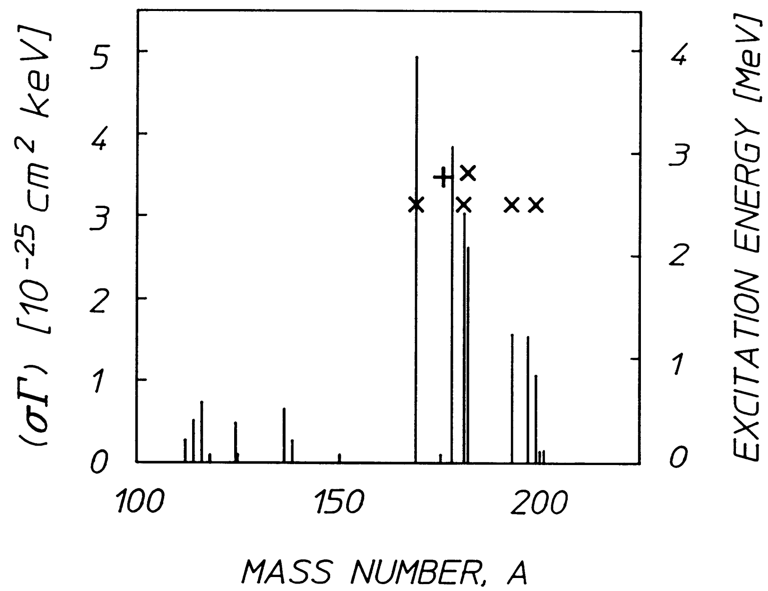

Fig. 1. Summary of systematic studies [5,6] of the excitation and de-excitation of quasiparticle isomers in (γ, γ') reactions. Measured integrated cross sections are plotted by the left-hand axis and the excitation energies for possible K-mixing levels are plotted by the right-hand axis. The $\times$ symbols indicate mediating states excited from the ground state or isomer with bremsstrahlung and the $+$ represents the level through which spontaneous decay of $^{174}\mathrm{Hf}^{\mathrm{m}}$ occurs [4]. Values of integrated cross section peak mid-shell in the mass island below $p = 82$.

particularly important for the 31 yr, four-quasiparticle isomer $^{178}\mathrm{Hf}^{\mathrm{m2}}$ since such an intermediate state could connect it to yrast states, providing the means for realizing an induced release of the stored energies. Unfortunately, few studies have been conducted for reactions involving $^{178}\mathrm{Hf}^{\mathrm{m2}}$ due to great difficulties in obtaining appropriate targets. The present objective is to attempt to estimate the parameters that would describe such a reaction, $^{178}\mathrm{Hf}^{\mathrm{m2}}(\gamma, \gamma')^{178}\mathrm{Hf}$ from the data which has recently become available [7].

Fig. 2 shows an expanded view of the data of fig. 1 for the mass island immediately below $p = 82$. Measured excitation energies of apparent K-mixing levels mediating those reactions are plotted as $\times$ and $+$ symbols by the right-hand ordinate and fall between 2.5 and 2.8 MeV, defining an interval ΔE_K within which such levels may be reasonably expected. The circles give the energies of the four- and five-quasiparticle isomers $^{174}\mathrm{Hf}^{\mathrm{m}}$, $^{175}\mathrm{Hf}^{\mathrm{m}}$, $^{176}\mathrm{Hf}^{\mathrm{m3}}$, $^{177}\mathrm{Hf}^{\mathrm{m2}}$ and $^{178}\mathrm{Hf}^{\mathrm{m2}}$, which trend to lower values with increasing mass numbers. Relevant parameters for those isomers are shown in table 1. The important detail in fig. 2 is the position of those isomers relative to the possible excitation energies of K-mixing levels. At present no direct observations of (γ, γ') reactions are available for those isotopes and thus the discussion is based on ΔE_K which bounds the likely energies of mediating states.

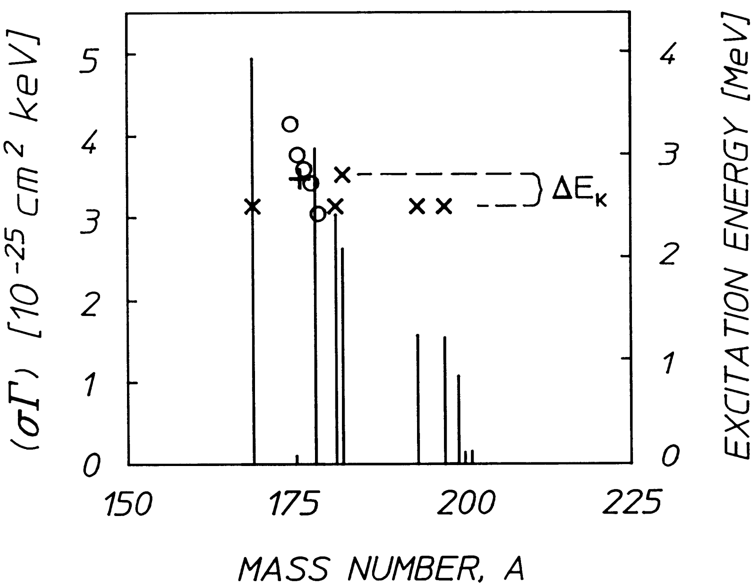

Fig. 2. Expanded view of the data of fig. 1 for the mass island below $p = 82$. Also indicated by the circles are the excitation energies of four- and five-quasiparticle Hf isomers lying between 2 and 3 MeV and having halflives longer than 1 μs. The interval ΔE_K shows the range of energy within which all possible K-mixing levels are expected to lie.

For $^{174}Hf^{m}$ and $^{175}Hf^{m}$ the isomers lie well above the upper bound of ΔE_K and it can be reasonably expected from fig. 2 that those multi-quasiparticle states would be relatively short-lived due to the availability of K-mixing states which could mediate spontaneous decay. As mentioned before, this is indeed the case for $^{174}Hf^{m}$ with a halflife of 3.7 μs. Similarly, $^{175}Hf^{m}$ has a 1.21 μs halflife. In the case of $^{176}Hf^{m3}$, the isomer lies at 2.866 MeV, slightly above the upper bound of ΔE_K. Thus, it could be expected to have a short lifetime somewhat lengthened by a small transition energy to a K-mixing level. This is supported by a measured halflife of 401 μs. The isomer

Table 1
Summary of relevant adopted properties [1] for three-, four-, and five-quasiparticle Hf isomers having excitation energies between 2 and 4 MeV and lifetimes longer than 1 μs. Parentheses indicate suggested values

Isomer	$J^{\pi} = K^{\pi}$	Number of quasiparticles [1,9]	Excitation energy (MeV)	Halflife
$^{174}Hf^{m}$	14^{+}	4	3.312	3.7 μs
$^{175}Hf^{m}$	35/2	5	3.016	1.21 μs
$^{176}Hf^{m3}$	14^{-}	4	2.866	401 μs
$^{177}Hf^{m2}$	$37/2^{-}$	5	2.740	51.4 min
$^{178}Hf^{m2}$	16^{+}	4	2.446	31 yr

$^{177}Hf^{m2}$ lies just below the upper bound of ΔE_K, possibly at a lower energy than any mediating state. In that event a long lifetime would be suggested since spontaneous decay could not occur, but this could also be the result if a K-mixing level were located little below the isomer. The measured halflife of 51 min agrees well with either possibility. Of most importance to the present discussion, the isomer $^{178}Hf^{m2}$ appears to lie below the likely position of a mediating state. This points to a long lifetime and indeed the measured value is 31 yr. Clearly the known halflives of these multi-quasiparticle Hf isomers agree well with the speculation that K-mixing levels are prevalent and lie between 2.5 and 2.8 MeV.

The strong dependence of isomer lifetime on the possible excitation energy of a mediating state is shown directly in fig. 3. Again, ΔE_K indicates the interval within which all measured values for possible K-mixing levels lie. This interval can be further constrained by comparing the data to lifetimes derived from single-particle widths. Since low multipolarities would be indicated for transitions between the isomers and states of mixed K, dipole radiation is considered here. Derived using the typical $1/(E_i - E_K)^3$ dependence for dipole transition widths where E_i is the isomer

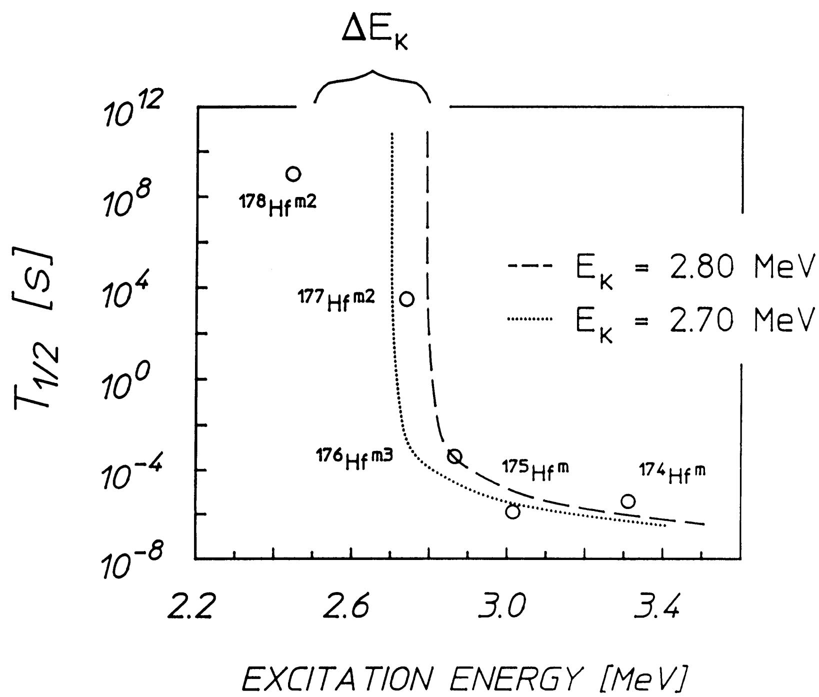

Fig. 3. Plot of halflife as a function of excitation energy for the four- and five-quasiparticle Hf isomers of fig. 2. The interval ΔE_K is shown within which all K-mixing levels are expected to lie based on previous measurements. The curves represent halflives calculated based on the assumption of the availability of dipole transitions for the de-excitation of the isomers for different choices for the energy of the mediating state and further bound the possible positions of such a level.

energy and E_K is the energy of the mediating level, the curves in fig. 3 show halflives in good agreement with the measured values. It is doubtful that a K-mixing state could lie much below the isomer $^{177}Hf^{m2}$ without affecting its 51 min lifetime. Thus, the value $E_K = 2.7$ MeV used to generate the curve passing just below that isomer represents a lower bound on the likely energy of an intermediate state of mixed K. Likewise, $E_K = 2.8$ MeV provides an upper bound for that energy since larger values produce curves which do not reproduce the lifetimes of the isomers $^{174}Hf^{m}$, $^{175}Hf^{m}$ and $^{176}Hf^{m3}$. The excellent agreement seen between halflives predicted for dipole transitions and those measured provides further evidence for a K-mixing level in $^{178}Hf^{m2}$ lying no more than about 300 keV above the isomer.

The presence of such a K-mixing level could in principle be identified in a (γ, γ') reaction study similar to those conducted previously [2,3,6], but might be most easily detected in the proposed experiment shown schematically in fig. 4a. A beam of protons of energy E_0 would be incident on $^{178}Hf^{m2}$ nuclei in a sample located within a 4π granular detector array, or "γ ball". This arrangement would provide for inelastic scattering of protons in $(p,p'\gamma)$ reactions where the γ refers to photons emitted in the decay of the excited nucleus. Many scattering events would merely excite low-lying members of the ground-state or isomeric rotational bands with a low multiplicity n of accompanying γ-rays. However, the excitation of a K-mixing state from the isomer would result in a transfer of the isomer to the yrast band with an accompanying large multiplicity of detected photons ($n \geqslant 4$), since the γ-cascade multiplicity, M_γ is

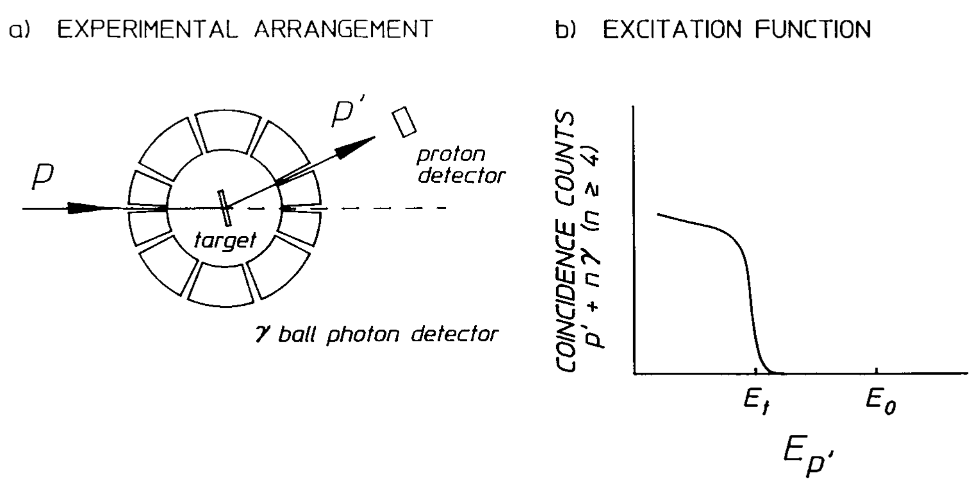

Fig. 4. (a) Schematic depicting a proposed experiment to confirm the existence of a K-mixing state in $^{178}Hf^{m2}$. Protons of energy E_0 would be incident on a sample containing $^{178}Hf^{m2}$ placed within a 4π granular "γ ball" detector. The energy of protons scattered in $(p,p'\gamma)$ reactions would be measured by the external detector while the γ ball would record photons resulting from decay of the nucleus. (b) Excitation function expected from a K-mixing level by detecting scattered protons in coincidence with a high multiplicity of γ-rays. The threshold at $E_t = E_0 - E_K$ locates the excitation energy of the mediating level.

expected to be more than 6–7. Due to the detection efficiency, $n < M_\gamma$. Thus the important aspect in the observation of a K-mixing level would be the measurement of the spectrum of inelastically scattered protons in coincidence with a high multiplicity of photons detected by the γ ball. By selecting only events satisfying this criterion it would be possible to confirm the existence of the K-mixing level in an excitation function like that depicted in fig. 4b. The location of the mediating level would be clearly marked by a threshold at an energy $E_t = E_0 - E_K$.

This article makes no attempt to estimate the probability for the actual existence of a K-mixing state. However, systematics strongly suggest that such a level may exist in $^{178}Hf^{m2}$, and at a sufficiently low excitation energy to be of great importance to proposals for the use of this isomer in superelastic particle-beam studies, gamma-ray upconversion and the nuclear analog to the ruby laser. At this point further study is needed for a definitive resolution.

Acknowledgement

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References

[1] *National Nuclear Data Center Online Evaluated Nuclear Structure Data File (ENSDF)* (Brookhaven National Laboratory, 1994).
[2] C.B. Collins, C.D. Eberhard, J.W. Glesener and J.A. Anderson Phys. Rev. C37 (1988) 2267.
[3] C.B. Collins, J.J. Carroll, T.W. Sinor et al., Phys. Rev. C42 (1990) 1813.
[4] P.M. Walker, F. Sletten, N.L. Gjorup et al., Phys. Rev. Lett. 65 (1990) 416.
[5] C.B. Collins and J.J. Carroll, these proceedings (1st Int. Gamma-Ray Laser Worksh., 1995), Hyp. Int. 107 (1997) 3.
[6] J.J. Carroll, M.J. Byrd, D.G. Richmond et al., Phys. Rev. C43 (1991) 1238.
[7] Yu.Ts. Oganessian, S.A. Karamian, Y.P. Gangrski et al., in: *Proc. Int. Conf. Nuclear Physics in Our Times* (1992).
[8] Yu.Ts. Oganessian, S.A. Karamian, Y.P. Gangrski et al., J. Phys. G: Nucl. Part. Phys. 18 (1992) 393.
[9] M.E. Bunker and C.W. Reich, Rev. Mod. Phys. 43 (1971) 348.