STUDY OF THE $K = 8$ AND $K = 16$ ISOMERIC STATES IN ^{178}Hf *

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In ^{178}Hf it has been found that some 2- and 4-quasiparticle states can occur lower in energy than members of the collective ground state rotational band with corresponding spin. Recent studies of these high-K isomers in the Lu, Hf, Ta, region have uncovered the existence of surprisingly large transition probabilities between the $K = 0$ ground state band and the high-K bands which should be forbidden if the K selection rule is valid. For the population of the $K^\pi=8^-$ isomer in ^{178}Hf a 2-band K-mixing model is presented which reproduces both the long lifetime of the isomer and the strong Coulomb excitation. In two scattering experiments at the Munich tandem accelerator and at the UNILAC in Darmstadt we searched for excited states built on the $K^\pi=16^+$ isomer. Micro weight quantities of 10^{15} atoms in the isomeric state have been produced by a Dubna-Orsay-GSI collaboration in order to prepare a radioactive target. In both measurements the first excited state built on the $K^\pi=16^+$ isomer has been observed at an excitation energy of 357 keV with respect to the isomeric state. The intrinsic electric quadrupole moment of $Q_0 = 8.2 \pm 1.1$ b has been derived from the experimental data within the rigid rotor model.

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1. Introduction

In prolate, axially symmetric nuclei the projection of the total nuclear angular momentum I onto the symmetry axis, K, is an approximately good quantum number. For low K-values, one has the well known rotational alignment where the angular momentum aligns to an axis perpendicular to the symmetry axis ($\gamma = 0^0$). These collective states have been commonly observed to be energetically the most favourable mode for generating spin.

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However, in ^{178}Hf it has been found [1] that some 2- and 4-quasiparticle (qp) states can occur lower in energy than members of the ground state (gs) band with corresponding spin. This is due to the occurrence, for both protons and neutrons, of many high-Ω single-particle orbitals near the Fermi-surface. The single particle angular momenta align parallel to the deformation axis leading to high K-values. In the extension of the picture suggested by Bohr and Mottelson [2], this may correspond to a situation where a rotation around the prolate symmetry axis ($\gamma = -120^0$) has become energetically favourable. Fig. 1 shows the partial level scheme for ^{178}Hf with the $K^\pi = 0^+$ gs-band, the $K^\pi = 8^-$ 2-qp band and the $K^\pi = 16^+$ band head of a 4-qp state.

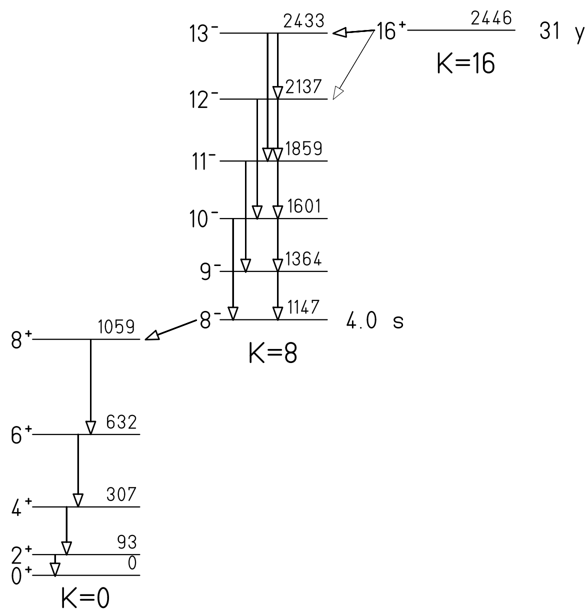

Fig. 1. Partial level scheme for ^{178}Hf.

Transitions between the two classes of quantum states are governed by the K-selection rule [3]. If the difference in K-quantum number $\triangle K$ is larger than the multipole order, L, electromagnetic transitions are forbidden. The observation of 'forbidden' transitions establishes the generally important role of K-mixing. Some admixture may be associated with *(i)* interplay between intrinsic (particle) motion and rotational motion (*e.g.* Coriolis perturbation) and *(ii)* deviations from axial symmetry. As a consequence of this, the multi-quasiparticle states with high K-values are often isomeric, decaying only by virtue of small admixtures of lower K-components and therefore tend to decay stepwise through lower-lying K-bands in order to minimize the K-forbiddenness.

Information on the K-mixing mechanism can be extracted from the surprising population of the $K^\pi = 8^-$ isomer at 1147.4 keV in ^{178}Hf. In a Coulomb excitation experiment, which is described in section 2, the nuclear shape is turned with respect to the angular momentum from a rotational aligned $K = 0$ configuration to a situation where the angular momentum is parallel to the nuclear symmetry axis.

New spectroscopic properties could also be obtained for the $K = 16$ isomer in ^{178}Hf, which was first reported by Helmer and Reich [4]. Macroscopic quantities of this exotic isomer have recently been prepared as a target for nuclear structure experiments [5]. Two scattering experiments will be discussed in section 3 which made use of this very exotic target containing micro weight quantities of ^{178}Hf in the $K^\pi = 16^+$ isomeric state.

2. Coulomb excitation of the $K^\pi = 8^-$ isomer

In a Coulomb excitation process nuclear levels are populated primarily through multi-step collective E2 and E3 transitions. Surprisingly, the $K^\pi = 8^-$ isomer in ^{178}Hf can be populated by heavy-ion scattering at bombarding energies below the Coulomb barrier [6,7]. We performed a Coulomb excitation experiment using the Darmstadt-Heidelberg Crystal Ball, by bombarding an enriched ^{178}Hf target of 0.5 mg/cm^2 thickness with a pulsed ^{130}Te beam at three beam energies of 560, 590 and 620 MeV. Both prompt and delayed γ-rays were recorded with the Crystal Ball. The 8^- isomer at an excitation energy of 1147.4 keV with $t_{1/2}$=4 s is known to decay dominantly to the 8^+ state in the gs-band ($K = 0$) via a hindered 88.9 keV E1 transition. The population of this isomer can be identified if the delayed γ-ray cascade of $8^+ \to 6^+ \to 4^+ \to 2^+$ in the gs-band is observed (the $2^+ \to 0^+$ and the $8^- \to 8^+$ transitions are highly converted). The obtained excitation cross sections for the isomer at three bombarding energies is shown in figure 2.

The excitation of the $K = 8$ isomeric state requires an admixture of different K-quantum numbers in the participating nuclear wave functions. One can distinguish two basic cases in which the wave function of one rotational band is always assumed to be pure. The resulting coupling schemes are depict in Fig. 3.

If one includes a small $K = 8$ admixture in the wave function of the gs-band, the E3 matrix elements can be calculated from the Alaga-rule Eq.(1)

$$\langle I_f||M(E3)||I_i\rangle = \sqrt{2I_i+1}\langle I_i 3 K 0|I_f K\rangle M_{30}\,, \tag{1}$$

where M_{30} is the intrinsic E3 matrix element and the Clebsch-Gordan coefficient $\langle I_i 3 K 0|I_f K\rangle$ is calculated for $K = 8$. From the measured lifetime ($t_{1/2}$=4 s) of the 8^- state, we can estimate an upper limit of the reduced intrinsic E3 matrix element of $M_{30} \leq 0.01\ eb^{3/2}$ leading to an excitation

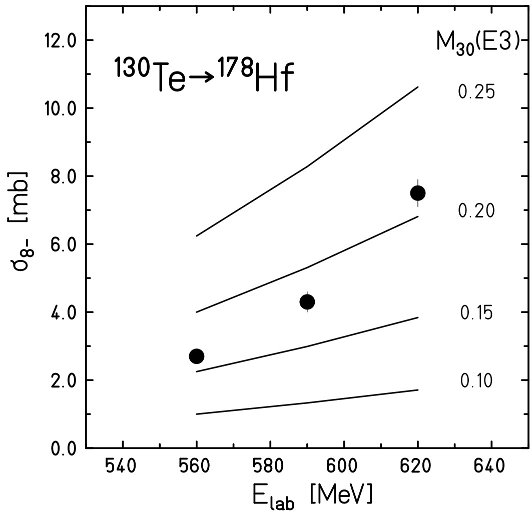

Fig. 2. Experimental excitation cross sections for the isomer at different incident beam energies compared with semi-classical Coulomb excitation calculations for various intrinsic E3 matrix elements, M_{30} $[eb^{3/2}]$.

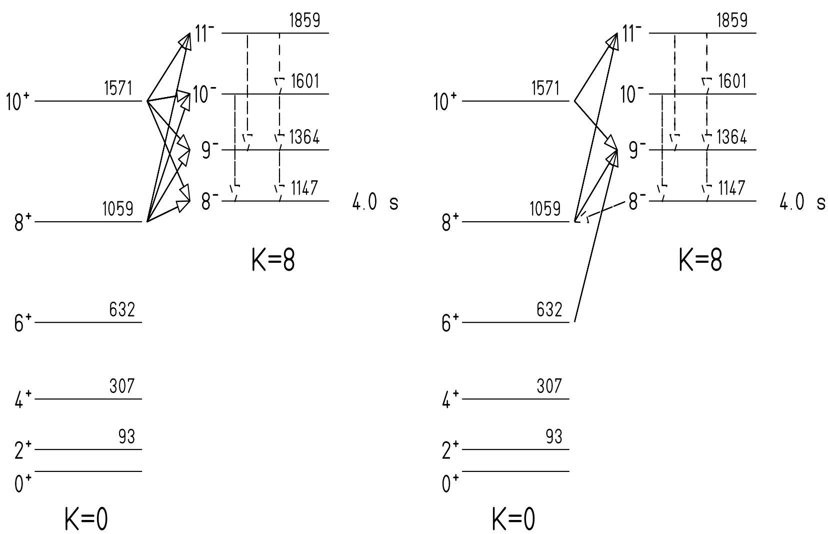

Fig. 3. Different coupling schemes relevant for the excitation of the 8^- isomer in ^{178}Hf. The E3 interband transitions are shown for a $K = 8$ admixture in the wave function of the ground state band (left) and for a $K = 0$ admixture in the wave function of the isomeric band (right).

cross section, which is too small to account for the observed population of the 8^- isomer in the mb range.

It is interesting to note, however, that in case of a $K = 0$ admixture in the wave function of the isomeric band the E3 matrix elements (using Eq. (1) with $K = 0$) for transitions from the gs-band to the even-spin members of the isomeric band vanish, while it is possible to excite the odd-spin members in the isomeric band directly from the gs-band via E3 transitions, *i.e.* $6^+ \rightarrow 9^-, 8^+ \rightarrow 11^-$, *etc.* Hence, the isomeric 8^- state can be populated by M1 and E2 transitions from higher lying levels in the band. Free from the constraint set by the the known 4 s half-life of the 8^- level, one can determine in this case an intrinsic E3 matrix element in the limit of the Alaga-rule. Fig. 2 shows a comparison of the calculated cross sections with the measured ones for the 8^- isomer in ^{178}Hf. Good agreement is obtained assuming an intrinsic E3 matrix element of $\mathrm{M}_{30} = 0.18^{+0.04}_{-0.03} eb^{3/2}$ (including systematic uncertainties).

Our interpretation shows that there is a reasonable explanation for the observed yield of the 8^- isomer by a pure Coulomb excitation process. In a future experiment with Gammasphere we hope to see the direct population of the $K = 8$ rotational band which would enable us to determine individual E3 matrix elements.

3. Nuclear structure of the $K^\pi = 16^+$ isomer

Large interest is attached to the production of exotic beams and targets for nuclear structure studies. The nucleus ^{178}Hf, with its long-lived ($t_{1/2}$ = 31 years) high-spin isomeric state $I^\pi = 16^+$ at a relative low-excitation energy (2.45 MeV), is indeed a unique probe to study nuclear phenomena in a new way. Since a few years a Dubna-Orsay-GSI collaboration has been established to produce this isomer in order to obtain micro weight quantities of it which are sufficient for target preparation. The ^{176}Yb(α,2n) reaction at a beam energy of ~35 MeV was used for the isomer production. Up to now 10^{15} isomeric atoms have been produced in several irradiations at the U-200 cyclotron in Dubna. After the chemical separation of the hafnium isotopes from the bulk of the reaction products, a target was prepared by electro-spraying a Hf-solution onto a thin carbon foil for different scattering experiments.

3.1. Inelastic scattering (d,d') experiments (Munich Tandem)

In a first experiment a mass-separated ^{178}Hf target, with an about 3% content of ^{178m2}Hf (16^+), was bombarded by proton and deuteron beams from the Munich tandem accelerator at incident energies of 22 MeV and 26 MeV [8]. Elastically and inelastically scattered ions from the target were observed at laboratory angles between 45^0 and 100^0 using the Q3D spectrograph which was equipped with a focal plane detector of 1.2 m length. Almost all peaks can be assigned to the population of the gs-band in ^{178}Hf. An additional transition at $E_x = 356.5 \pm 04$ keV was assigned to the 17^+ member of the rotational band built on the 16^+ isomeric state. There is even some weak evidence for the 18^+ state at 737 ± 2 keV. The moment of inertia deduced from the $16^+ \to 17^+$ transition is about 1.5 times larger than the moment of inertia of the gs-band in the low-spin region. The observed cross sections are in agreement with calculations assuming the same β_2 deformation as measured for the gs-band.

3.2. Coulomb excitation with ^{208}Pb ions (GSI Darmstadt)

In a second experiment at the UNILAC accelerator in Darmstadt the isomeric target was used in a Coulomb excitation experiment with ^{208}Pb ions at a bombarding energy of 4.77 MeV/u [9]. The experimental set-up consisted of eight high-efficiency Ge-detectors positioned at 25^0 and 155^0 with respect to the beam direction and five position sensitive parallel-plate avalanche counters for particle detection which covered almost 80% of the relevant solid angle. The high precision of particle identification allowed for a precise Doppler correction of the measured γ-ray energies. The spectra of the isomeric target contain γ-lines which belong mostly to ^{176}Hf, ^{177}Hf and ^{178}Hf. In order to search for excited states built on the $K^\pi = 16^+$ isomeric bandhead an 'artificial' spectrum was constructed by summing up the data for the different Hf isotopes in such a way that the resulting spectrum had to reflect the intensities of major lines observed with the isomeric target. A comparison of such a spectrum with the one obtained for the ^{178m2}Hf target is shown in Fig. 4. Both spectra are almost identical except for one new transition observed with the isomeric target. The additional peak marked with a star appears at $E_\gamma = 357.4 \pm 0.3$ keV which is in good agreement with the deuteron scattering experiment. From the γ-ray intensities measured as a function of the impact parameter we were able to determine the electromagnetic multipole moments. Since only the $17^+ \to 16^+$ transition was found experimentally, the E2 matrix elements were calculated in the framework of the rigid rotor model. The best fit to the experimental data was obtained for an intrinsic quadrupole moment of $Q_0(K = 16) = 8.2 \pm 1.1$ b which agrees with the $Q_0 = 7.2 \pm 0.1$ b derived from the spectroscopic quadrupole moment obtained in the collinear laser spectroscopy experiment [10]. The large collective strength measured for the $17^+ \to 16^+$ transition suggests the existence of a complete rotational band built on the $K^\pi = 16^+$ isomeric state.

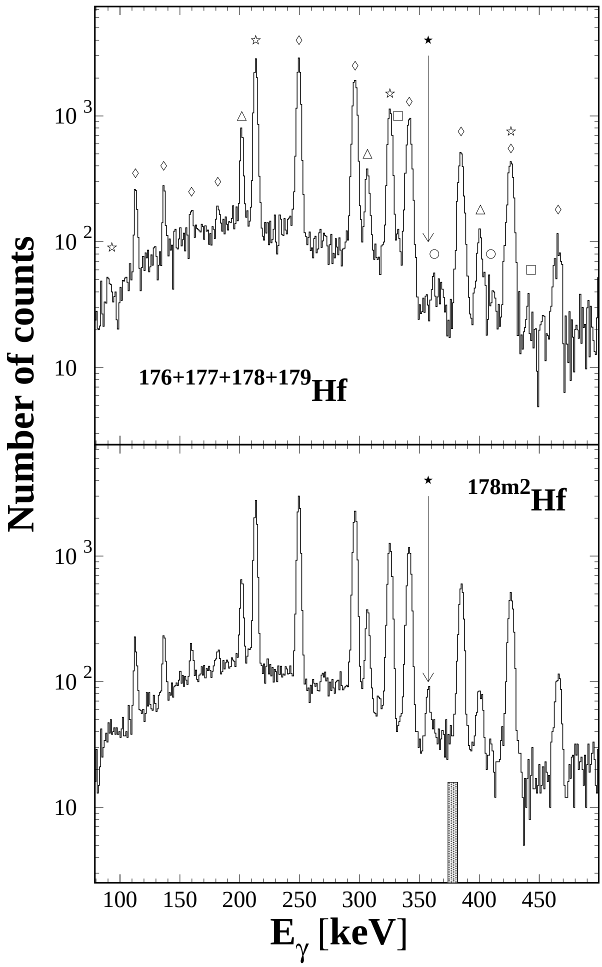

Fig. 4. The "artificial" γ -ray spectrum obtained from measurements with the ^{176}Hf, ^{177}Hf, ^{178}Hf and ^{179}Hf targets (top) and the measured spectrum obtained for the isomeric target (bottom). The $17^+ \rightarrow 16^+$ transition is marked by the full star, while the hatched area corresponds to the expected appearance of the $18^+ \rightarrow 17^+$ transition in the isomeric $K^\pi = 16^+$ band.

Based on these recent studies the rotational band associated with the $K^\pi = 16^+$ isomer in ^{178}Hf has been extended using $\alpha - \gamma\gamma$-time techniques and the incomplete fusion reaction ^{176}Yb(^{9}Be, $\alpha 3n$)^{178}Hf [11].

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