Coulomb excitation of the $K^\pi=8^-$ isomer in ^{178}Hf

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(Received 20 April 1993)

The $K^\pi=8^-$ isomer at 1147.4 keV in ^{178}Hf was populated in a Coulomb excitation experiment with ^{130}Te ions. The measured cross section for this isomer was $2.7\pm^{1.9}_{1.4}$, $4.3\pm^{3.4}_{2.0}$, and $7.5\pm^{6.1}_{3.2}$ mb for three beam energies below the Coulomb barrier, namely 560, 590, and 620 MeV. If one assumes that the projection of the total angular momentum on the symmetry axis, K, is only an approximate quantum number, the population of this isomer can be reproduced via direct $E3$ excitations of odd spin members of the isomeric band from the ground state band.

PACS number(s): 25.70.De, 23.20.Lv, 23.20.Js, 27.70.+q

First indications for a population of the lowest $K^\pi=8^-$ isomer in ^{178}Hf by heavy ion scattering at incident energies close to the Coulomb barrier were reported by Hamilton *et al.* [1] nearly ten years ago. However, the reaction mechanism for the population of this isomer remained a puzzle. In deformed nuclei the electromagnetic transitions between states of different rotational bands are governed by both the usual spin and parity selection rules and by a supplementary selection rule for the quantum number K, which is the projection of the total nuclear angular momentum I on the symmetry axis. The K selection rule is strictly fulfilled only when the internal and rotational motions are independent of each other. Actually, there is always some coupling between these two forms of motion, and therefore the K selection rule results in small transition probabilities rather than complete forbiddenness.

To investigate the reaction mechanism for populating the $K^\pi=8^-$ isomer in ^{178}Hf, we performed a Coulomb excitation experiment using the Darmstadt-Heidelberg Crystal Ball (CB), by bombarding an enriched ^{178}Hf target of 0.5 mg/cm^2 thickness with a pulsed ^{130}Te beam ($\Delta t=74$ ns) provided by the accelerator facility at the MPI für Kernphysik. Three beam energies of 560, 590, and 620 MeV below the Coulomb barrier [2] ($V_C=634$ MeV) were used in the experiment. Both prompt and delayed γ rays were recorded with the Crystal Ball. A Pb (0.5 mm thickness) catcher was positioned 1 cm downstream from the target in order to stop the recoiling ^{178}Hf ions.

The 8^- at 1147.4 keV with $t_{1/2}=4$ s is known to decay dominantly to the 8^+ state in the ground state band via a hindered 88.9 keV $E1$ transition. The delayed γ ray cascade of $8^+\to6^+\to4^+\to2^+$ in the ground state band was used to identify the population of this isomer (the $2^+\to0^+$ and $8^-\to8^+$ transitions are highly converted and lie below the detection threshold of the CB).

A delayed time window with a width of 45 ns was set on the time spectra of the NaI detectors in between the beam pulses to distinguish the delayed isomer decay from the prompt deexcitation γ rays. Additional selection was made by utilizing the total sum energy, $E_{\rm sum}$, and multiplicity, M_γ, of γ rays obtained from the CB. The decay of the 8^- isomer could be observed in this way at all three incident energies, thereby confirming the results of Hamilton *et al.* [1] and their suggestion that the excitation of the isomer is caused by Coulomb excitation. Figure 1 shows the γ ray spectrum of the CB, where the three peaks of 426.4, 325.6, and 213.4 keV, respectively, correspond to the delayed γ rays depopulating the isomer.

The prompt γ rays were sorted out by requiring a 15 ns wide prompt time window with respect to the beam pulse. Selective gates on the total sum-energy and multiplicity correlation of the CB, i.e., $E^p_{\rm sum}=1300-4500$ keV and $M^p_\gamma=4-8$, were used in order to suppress γ rays from background reactions. Due to the limited energy resolution of the NaI detectors and Doppler broadening, the identification of discrete γ rays was limited to transi-

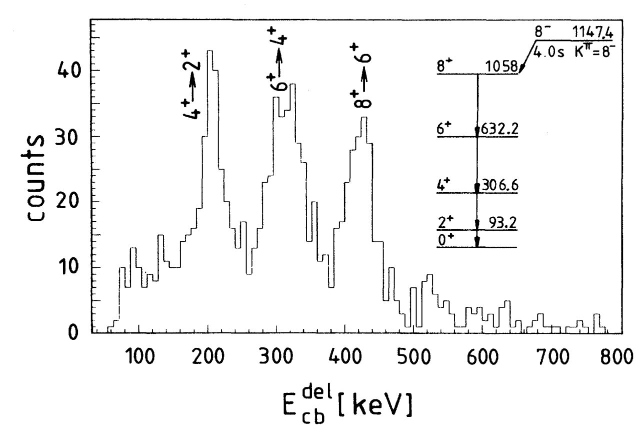

FIG. 1. Delayed γ ray spectrum of the Crystal Ball obtained at a bombarding energy of 590 MeV, demanding 850 keV $\le E^d_{\rm sum}\le 1100$ keV and $2\le M^d_\gamma\le5$. In the right corner the partial level scheme of the γ ray cascade depopulating the isomer is displayed.

tions below the $I^\pi=12^+$ state in the ground state band. Taking into account dead-time losses of the data-acquisition system and those introduced by the analysis, as well as the sum-energy vs multiplicity response of the CB, both the delayed and prompt $8^+\to6^+\to4^+\to2^+$ γ ray yields were extracted by integrating the γ ray peaks. The excitation cross section σ_{8^-} of the isomer can then be derived by

$$\sigma_{8^-}=\frac{Y_d}{Y_p(E_{\rm sum}^p,M_\gamma^p)}\sigma_p \qquad (1)$$

where Y_d and $Y_p(E_{\rm sum}^p,M_\gamma^p)$ are the delayed and prompt γ ray yields and σ_p is the excitation cross section producing the observed prompt yield.

The excitation cross sections of states in the ground state band in ^{178}Hf, $\sigma_p(I^\pi)$, were calculated with the semiclassical Coulomb excitation code [3] using the reduced matrix element [4] $\langle 0\|M(E2)\|2\rangle=2.20$ e b and the rigid rotor model for the other matrix elements in the ground state band. In accordance with the conditions used to obtain the prompt γ ray yields, we estimated the corresponding prompt excitation cross section σ_p by summing up $\sigma_p(I^\pi)$ from $I^\pi=10^+$ to 18^+. The small side band excitations and Coulomb-nuclear interference effects were neglected, since the inaccuracy of the calculations was estimated to be small compared to the experimental uncertainties. Using Eq. (1) we obtained the excitation cross sections for the isomer at the three bombarding energies shown in Fig. 2 The systematic uncertainty in the absolute values of the cross sections amounts to about $^{+70}_{-45}\%$.

In a Coulomb excitation process, nuclear levels are populated primarily through multistep collective $E2$ and $E3$ transitions. If one assumes that the projection of the total angular momentum I on the symmetry axis, K, is a good quantum number, a direct transition from the $K=0$ ground state band to the $K=8$ isomeric state and to the rotational states built on it is forbidden. However, an admixture of different K components in the nuclear wave functions could allow for direct transitions to the isomer band in ^{178}Hf. Indeed, measurements of log ft values [5], $E2/M1$ mixing ratios [6–8], and g factors [9] all suggest a strong mixing of the wave function of the 8^- isomeric state. If one includes a small $K=8$ admixture in the wave function of the ground state band, the $E3$ matrix elements can be calculated from the Alaga rule [10]

$$\langle I_f\|M(E3)\|I_i\rangle=\sqrt{2I_i+1}\langle I_i 3K0|I_fK\rangle M_{30}\ , \qquad (2)$$

with $K=8$. 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 $M_{30}\le0.01$ e b$^{3/2}$ leading to an excitation 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

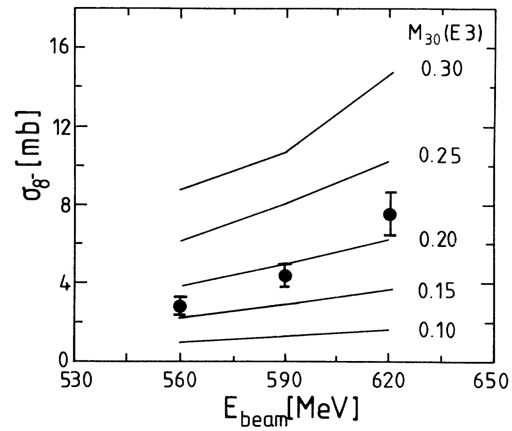

FIG. 2. Experimental excitation cross sections for the isomer at different incident beam energies compared with the semiclassical Coulomb excitation calculations for various intrinsic $E3$ matrix elements, M_{30} [e b$^{3/2}$]. The error bars correspond to statistical uncertainties only (see text).

isomeric band, the $E3$ matrix elements [using Eq. (2) with $K=0$] for transitions from the ground state 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 ground state band via $E3$ transitions, i.e., $6^+\to9^-$, $8^+\to9^-$, $8^+\to11^-$, 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 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. Figure 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 $M_{30}=0.18^{+0.04}_{-0.03}$ e b$^{3/2}$ (including systematic uncertainties). If one includes the population due to $E1$ transitions which have been estimated in the extreme limit of an octupole deformed nucleus, the M_{30} matrix element should be smaller by about 30%. The obtained matrix element also explains the result of a Coulomb excitation experiment with ^{16}O ions, mentioned in Ref. [1], in which no feeding of the isomer was observed. The population of the 8^- state in this reaction is a factor of 40 smaller than that of the highest excited state (10^+) in the ground configuration. For the heavy ion experiment discussed in [1] the calculated isomeric component of the direct 8^+ population is 0.2%, which is a factor of 4 smaller than reported by Hamilton *et al.*

Although the value of the obtained matrix element is compatible with known $E3$ matrix elements in this mass region, alternative excitation scenarios, such as through highly excited intermediate states, may be present. Our interpretation mainly shows that there are reasonable ways to explain the observed yield of the 8^- isomer by a pure Coulomb excitation process, but the role of other likely K admixtures in the isomeric band has to be considered. In future experiments with EUROBALL arrays one may have a chance to observe the direct population of the rotational states built on the 8^- isomer. This will enable a model-independent determination of individual $E3$ matrix elements which would allow more light to be shed on the excitation path of the 8^- isomer.

We thank H. Folger for the preparation of the target and the accelerator staff of the Max-Planck-Institut for providing a stable ^{130}Te beam. This work has been supported in part by the Bundesminister für Forschung und Technologie (BMFT) under Contract No. 06HD133I.

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