NUCLEAR REACTIONS WITH HIGH–SPIN TARGETS*†

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Nuclear reactions ^{180}Ta$^{m}(\gamma, 2n)$ ^{178}Ta^{m,g}, ^{178}Hf^{m_2} (n,γ) ^{179}Hf^{m_2} as well as the Coulomb excitation of a ^{178}Hf^{m_2} target were newly studied. The results are promising for the progress in nuclear structure and nuclear reaction understanding.

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1. Introduction

Abundant in nature nuclei ^{176}Lu ($J^{\pi} = 7^{-}$) and ^{180}Ta^{m} ($J^{\pi} = 9^{-}$) being practically stable were used earlier as control targets to test the role of the target high-spin in nuclear reactions. Recently, a more exotic 16^{+} four-quasiparticle isomer of ^{178}Hf^{m_2} ($T_{1/2} = 31\,y$) was added to the group of high-spin targets after the development of a method [1] for producing it in microweight quantity. The investigation of electromagnetic and nuclear interactions of high-spin isomers could give an important information about structure effects in nuclear reactions because nuclear isomerism is closely related with such phenomena as single-particle orbitals alignment and deformation coexistence. Recently the interest to these processes has been enhanced due to an acute problem of the K-mixing for excited levels.

2. Photonuclear reactions on isomers

As known for decades, high-spin isomeric states are populated in the reactions (γ, n); (γ, p); $(\gamma, 2n)$ and (γ, γ') with rather low probability at the

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percent level. It can be explained within a statistical model by the spin difference of initial and final states. An additional hindrance factor coming from the K-quantum number could eventually reduce the isomeric ratio by a few orders of magnitude. The presence of special K-mixed activating states is indicated in literature [2]. They have to play the role of intermediate states for the high-K levels feeding.

In the case of a high-spin, high-K target nucleus the deexcitation cascades in the reaction product should lead both to the ground state band and to the high-spin isomeric state because spin limitations are not valid. However, the K-hindrance factor can manifest itself clearly if the K-mixing is not complete. So, measurements of isomeric ratios for the reaction on isomeric targets can serve as an informative test for the K-mixing in excited nuclei.

The reaction $^{180}\mathrm{Ta}^{m}$ $(\gamma, 2n)$ $^{178}\mathrm{Ta}^{m,g}$ was studied experimentally. In the daughter ^{178}Ta nucleus two states are known: $J^{\pi} = 7^{-}$, $\mathrm{T}_{1/2} = 2.4$ h and $J^{\pi} = 1^{+}$, $\mathrm{T}_{1/2} = 9.3$ min. It is not clear up to now which of them is the ground state, so we will use the terminology "high- and low-spin levels". The natural Ta contains $1.2 \cdot 10^{-4}$ part of $^{180}\mathrm{Ta}^{m}$ isomeric nuclei. The high sensitivity of the experiment necessary in this case was provided by intensive bremsstrahlung irradiations of the Ta target in the compact geometry on an electron beam of the MT-25 microtron at FLNR JINR. An activated Ta foil was placed just behind a 3 mm W bremsstrahlung converter. The endpoint of the bremsstrahlung spectrum was chosen to be lower than the threshold (22.1 MeV) of the $^{181}\mathrm{Ta}(\gamma, 3n)$ ^{178}Ta reaction on the major Ta isotope. For the sake of comparison, yields of the $^{181}\mathrm{Ta}$ (γ, n) $^{180}\mathrm{Ta}^{g}$, $^{174}\mathrm{Hf}$ $(\gamma, 2n)$ ^{172}Hf and of other reactions were measured too.

The endpoint energy dependencies of the measured yields are presented in Fig. 1. To avoid any model dependent transformation of the data we used the yield value defined in a conventional manner by the following equation:

$$Y = \frac{N_{\mathrm{at}}^{\mathrm{prod}}}{N_{\mathrm{at}}^{\mathrm{tar}} N_e},$$

where $N_{\mathrm{at}}^{\mathrm{prod}}$ is the reaction product number of atoms measured using the Ge-detector γ-spectrometry method, $N_{\mathrm{at}}^{\mathrm{tar}}$ is the target number of atoms and N_e is the number of electrons delivered on the bremsstrahlung target during the exposure.

Both high and low-spin states in ^{178}Ta were activated in the $(\gamma, 2n)$-reaction on $^{180}\mathrm{Ta}^{m}$. As it was measured, the $^{180}\mathrm{Ta}^{m}$ $(\gamma, 2n)$-reaction produces the high-spin state of ^{178}Ta in 75% and the low-spin state in 25% of events. The excitation function (Fig. 1) of the discussed reaction does not deviate noticeably from the regular behaviour measured for the reaction

^{174}Hf$(\gamma, 2n)$ ^{172}Hf on the zero-spin target while its absolute yield is higher by a factor of about 1.5 than that for the latter reaction. These experimental results should be considered in more detail in the frame of some theoretical models, because this is the first measurement of the isomeric-to-ground state ratio in the reaction on a high-spin isomeric target.

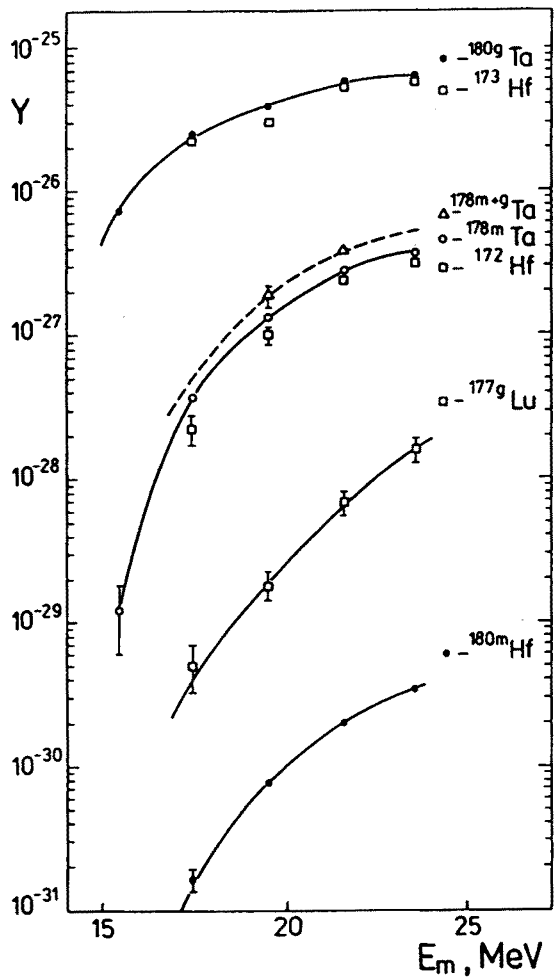

Fig. 1. Photonuclear reactions yield vs. bremsstrahlung endpoint energy taken for the target nuclei: • — ^{181}Ta, ○ — ^{180}Ta^{m}, □ — Hf isotopes. The radioactive reaction products are indicated in the figure.

The yield of the ^{178}Hf^{m_2} (γ, n) ^{177}Hf^{m_2} was tested too because this reaction is a unique case when a photonuclear reaction on a four-quasiparticle $K^{\pi} = 16^{+}$ isomeric target leading to another exotic five-quasiparticle $K^{\pi} =$

37/2$^-$ isomeric could be detected experimentally. The ^{177}Hf^{m_2} isomer ($T_{1/2}$ = 51.4 min) has decay properties convenient for the observation by the activation technique. A^{178}Hf^{m_2} target of $3 \cdot 10^{13}$ atoms on a nonactivated Be substrate was prepared using precision radiochemical methods [3]. The ^{178}Hf^{m_2} isomeric material was produced in the framework of an international collaboration as described elsewhere [1]. A lot of effort was given to find the purest Be foil as well as to clean up the ^{178}Hf^{m_2} material from both ballast activities and stable contaminants. The background conditions due to bremsstrahlung induced activation of all elements were still rather hard in this experiment.

After a series of irradiations by the bremsstrahlung with E_m = 24 MeV and induced activity measurements using γ- and e-spectrometers the yield of the ^{178}Hf^{m_2} (γ, n) ^{177}Hf^{m_2} reaction was limited to about 20% of the ^{181}Ta (γ, n) ^{180}Ta^g reaction yield. This unexpectedly low feeding probability for the ^{177}Hf^{m_2} isomeric state in the evaporation residue of the (γ, n)-reaction seems to be a significant result for the physical interpretation. It can be explained by efficient trapping of the deexcitation cascade intensity on some levels connected with the ground state band by enhanced transitions.

3. Neutron capture reaction on ^{178}Hf^{m_2} nucleus

The interest in studying the (n, γ)-reaction on a high-spin target is motivated by a possibility to get information on high-spin neutron resonances and to touch on the question of spin-dependence of the level density as well as to follow the γ-cascades and level feeding in the deexcitation of these special states. The irradiations of the isomeric ^{178}Hf^{m_2} targets were carried out on the Dubna IBR-2 and Saclay "Osiris" reactors and the 25 d lived activity of the ^{179}Hf^{m_2} isomer was detected successfully. The Cd ratio was measured and the thermal cross-section and resonance integral I_γ values were derived to be:

$$\sigma_{\text{th}} = (47 \pm 8) \text{ barns;}$$

$$I_\gamma = (1000 \pm 100) \text{ barns}$$

for the ^{178}Hf^{m_2} (n, γ) ^{179}Hf^{m_2}-reaction. It means that the ^{178}Hf^{m_2} nucleus has strong neutron resonances in the eV energy region. The major population of the m_2 state in the residual nucleus ^{179}Hf can be deduced, otherwise the total resonance integral becomes too high. The shell structure of ^{179}Hf^{m_2} state ($\pi 7/2^+$, $\pi 9/2^-$, $\nu 9/2^+$) is close to the configuration of ^{178}Hf^{m_2} target nucleus ($\pi 7/2^+$, $\pi 9/2^-$, $\nu 7/2^-$, $\nu 9/2^+$), so one could expect a successful population of the isomeric state in ^{179}Hf.

Further experimental test of the neutron resonance energy position by the method of selective neutron filters was performed using the ^{10}B, Rh and

Er_2O_3 filters in addition to a Cd screen. Gold microquantity targets were used as control samples for the fluence and geometry factor monitoring. Finally, the energy position of the strong resonance of $^{178}Hf^{m_2}$ was estimated to be near 4–6 eV. In statistical model calculations the mean interresonance distance, $D \approx 4$ eV, was predicted. So the experimental result is in a good agreement with this estimate.

4. Coulomb excitation of the $^{178}Hf^{m_2}$ nucleus

In the framework of an international collaboration a few experiments with the $^{178}Hf^{m_2}$ isomeric target and charged particle beams were performed. The spectra of inelastically scattered deuterons and protons were measured using the Q3D spectrograph on the Muenchen tandem beam. The line in the spectra at an excitation energy $E^* = 353$ keV was attributed to the first level (17^+) of the rotational band built on the 16^+ isomeric state in ^{178}Hf.

The Coulomb excitation of this band using an isomeric target was proposed three years ago [4] and the experiment was recently performed successfully at Darmstadt using the ^{208}Pb ion beam with an energy of 980 MeV and intensity of about 3 electrical nA. The Coulomb excitation γ-spectra were taken in coincidences with scattered particles for the $^{178}Hf^{m_2}$ target as well as for all stable hafnium isotopes. The Doppler corrected spectra of isomeric $^{178}Hf^{m_2}$ and enriched ^{177}Hf target are compared in Fig. 2. Because the stable isotope composition of both targets was quantitatively similar, almost all peaks in spectra have the same position. So, the only evident additional peak at $E_\gamma = 354$ keV observed for the isomeric target can be attributed to the $^{178}Hf^{m_2}$ nucleus. This energy is just coinciding with the one observed earlier in the (d,d') experiment. And it serves as a reliable confirmation of the 17^+ level energy position.

The moment of inertia J of this rotational band can be deduced immediately using the equation:

$$E_I = \frac{\hbar^2}{2\mathcal{J}}[I(I+1) - I_0(I_0+1)],$$

where $\mathcal{J}_0$ is the spin value of the band basic level. In Table I the moment of inertia values deduced from the first level energy for the $K = 0$ g.s.b., $K = 8$ and $K = 16$ bands are compared. The strong increase of $\mathcal{J}$ values with a decoupling of quasiparticles is evident and it can be described in microscopical nuclear models. The electrical quadrupole moment and deformation parameter of $^{178}Hf^{m_2}$ can be determined after a quantitative treatment of the line intensities in the spectra of inelastic scattering and Coulomb excitation.

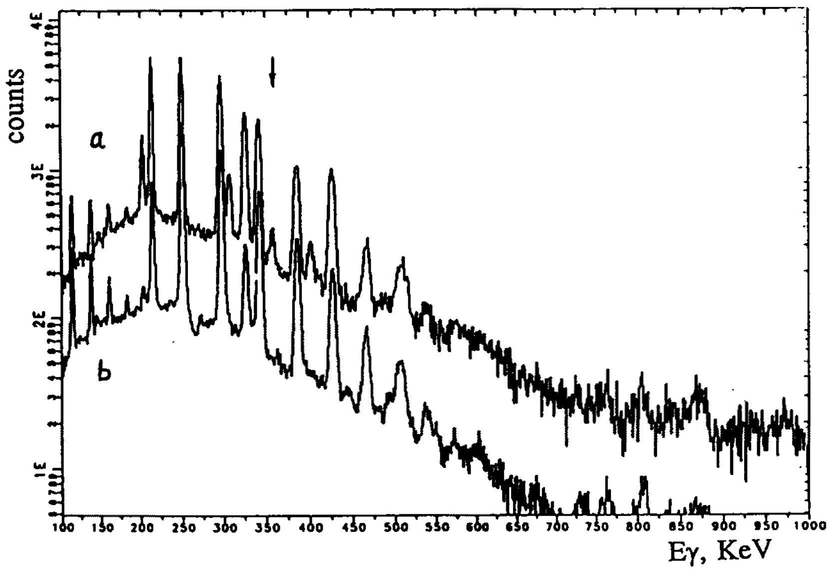

Fig. 2. γ-spectra of the Coulomb excitation of the isomeric $^{178}Hf^{m_2}$ (a) and enriched ^{177}Hf (b) targets taken with the ^{208}Pb ion beam at an energy of 980 MeV. The line attributed to the $^{178}Hf^{m_2}$ is indicated by an arrow.

TABLE I

Moments of inertia deduced from the first level energy of the bands in ^{178}Hf

K	Transition	Energy keV	J, MeV^{-1}
0	$2^+ \to 0^+$	93	32
8	$9^- \to 8^-$	217	41
16	$17^+ \to 16^+$	353	48

5. Conclusion

It was demonstrated that the studies of nuclear reactions with high-spin isomeric target can be carried out successfully despite the experimental difficulties as well as that they are fruitful in the field of nuclear structure and of nuclear reactions studies.

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