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EXCITATION OF THE HIGH-SPIN ^{180}Hf ISOMER AND DEEXCITATION OF THE ^{180}Ta ISOMER IN (γ, γ') REACTIONS

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Возбуждение высокоспинового изомера ^{180}Hf
и девозбуждение ^{180}Ta^{m} в реакции (γ, γ')

В реакциях неупругого рассеяния γ-квантов изучался механизм возбуждения и девозбуждения высокоспиновых изомеров ^{180}Hf ($J^{\pi}= 8^{-}$) и ^{180}Ta ($J^{\pi}= 9^{-}$) соответственно. Получено аномально большое интегральное сечение и изомерное отношение для ^{180}Ta по сравнению с ^{180}Hf. Обсуждаются свойства уровней, влияющих на величину этих отношений.

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Excitation of the High-Spin ^{180}Hf Isomer and Deexcitation
of the ^{180}Ta Isomer in (γ, γ') Reactions

The reaction mechanism of excitation and deexcitation of the high-spin isomers ^{180}Hf ($J^{\pi}= 8^{-}$) and ^{180}Ta ($J^{\pi}= 9^{-}$) in inelastic gamma-quanta scattering was investigated. Anomalously large integral cross section and isomeric ratio for ^{180}Ta in comparison to ^{180}Hf were obtained. Level properties influencing these relations are discussed.

The investigation has been performed at the Flerov Laboratory of Nuclear Reactions, JINR.

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1. Introduction

Photo nuclear reactions at low and mean energies of γ-quanta are of important source of information on atomic nuclear structure. One of the directions in researching γ-quanta is measuring the probabilities of nucleus production in separated quantum state. Such investigations will be the most effective if the studied states are in isomeric relation with sufficiently large half-lives so that to separate the irradiation processes and measurements with time.

The great interest of investigation in (γ,γ′) reactions are connected with the next facts. Firstly, since there are not Coulomb barrier and binding energy for γ-quanta, one can obtain excited nuclei both in the region above nucleon threshold and below it. Secondly, the momentum being introduced into nucleus by γ-quantum is not varied with energy increase (it is $1\hbar$ at dipole absorption and $2\hbar$ at quadruple one).

This characteristic property of population of high spin causes to that, Isomeric Ratio (IR) is very sensitivity to the level density parameter and possibility of radiative transition. In deformed nuclei reason of isomerism and prohibition for γ-quanta may be not only high differences of isomeric and ground state spin, but and they projection on the symmetric axis (quantum number K).

The aim of the present work is to investigate the reaction mechanism leading to the excitation and deexcitation of high-spin isomers in the inelastic γ-quanta scattering, and also the properties of the levels participating in these processes. As objects of this investigation the nuclei ^{180}Hf and ^{180}Ta were chosen. These nuclei have one and the same mass number and also the same spin difference between the ground and isomeric state (ΔI=8). At the same time, their level structure is quite different (viz., the nucleus ^{180}Hf is odd-even, while ^{180}Ta is odd-odd with a great number of low-lying states with high spins).

2. Level properties of ^{180}Hf and ^{180}Ta

The level schemes and radioactive decay of ^{180}Hf and ^{180}Ta are presented in fig.1 [1]. In the nucleus ^{180}Hf there is an isomeric level with $I^{\pi}=8^{-}$ and the cause for the isomerism is the hindrance by quantum number K (the projection of the spin on the nuclear symmetry axis) for γ-transitions to the states in the ground state rotational band with K=0. The isomeric state is two-quasi particle one, arising because of the de coupling of two protons, and has the configuration p[504] p[514]. The isomeric state of ^{180}Hf decays by a weak beta-decay branch (0.3 %) to the isomeric state in ^{180}Ta ($I^{\pi}=9^{-}$) with the configuration p[514] n[624]. Because of the big difference in the spins of the isomeric and ground states (ΔI=8) and because of the absence of levels lying below the isomeric state and having close spin values, the nucleus ^{180}Ta in its isomeric state is practically stable ($T_{1/2}>10^{15}$ y). It is present in the natural Ta-isotope mixture in very small amounts (0.012 % or 4.10^{17} atoms in 1g of Ta). This opens unique possibilities to carry out different experiments using a target consisting of high-spin nuclei, for instance natural Ta-target or one enriched in ^{180}Ta. One of these experiments is to study the deexcitation of the ^{180}Ta isomer using the inelastic scattering of γ-quanta. The results of such an experiment are presented in this report. In this process, the isomer captures a γ-quant and subsequently by means of a γ-cascade by-passing the isomeric state deexcites to the ground state. This state ($I^{\pi}=1^{+}$), as one can see from fig.1, decays to ^{180}Hf (K-capture) and to ^{180}W (β-decay) with a half-life convenient for measuring (8.1 h).

It is quite probable that such a genetic relation in the decay chain of the isotopes Hf-Ta-W with mass number A=180 plays an important role in the nucleosynthesis. In the strong fields of neutron and γ-radiation, which have existed, this relation must have manifested itself not only between the ground, but also between the isomeric states of the cited nuclei. In connection with this, the measurement of the cross sections for exciting the isomer in ^{180}Hf and deexciting the isomer in ^{180}Ta is of interest for astrophysics, too. These cross sections will allow to obtain new information necessary for calculating the abundance of these isotopes in nature, and will also help to make conclusions about the conditions in which nucleosynthesis has taken place (matter density, temperature).

3. Experiment and Data Analysis

The yields of the investigated isotopes in the ground (^{180}Ta) and isomeric (^{180}Hf) states were measured on the MT-25 microtron extracted beam of the Flerov Laboratory of Nuclear Reactions, JINR. The description

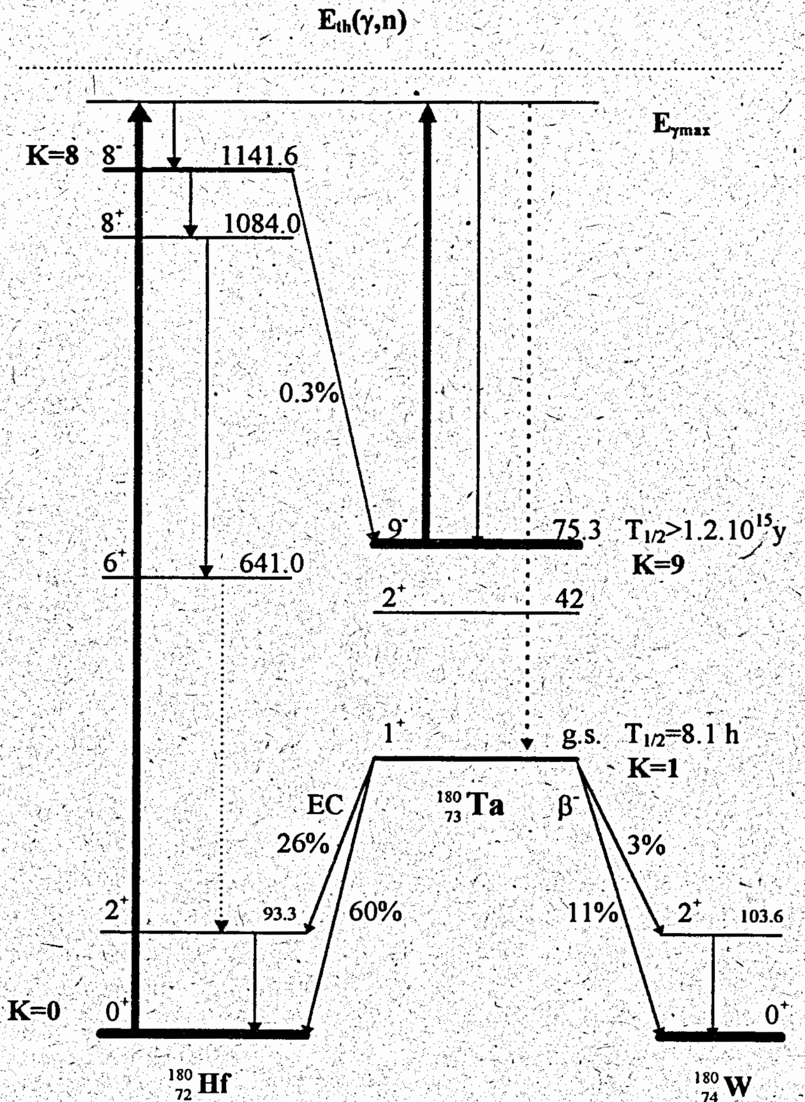

Fig.1. Schematic level diagram of ^{180}Ta and its daughter nuclei. The initial photoexcitation of ^{180}Ta begins from the 9^- isomer. The deexcitation cascade leads finally to the g.s. whose electron capture and beta decay, respectively, can be detected. For ^{180}Hf the opposite process is realised - excitation of isomeric state 8^- begins from the ground state 1^+.

of this microtron and its main characteristics are presented in the work [2]. Electron energy variation was effected in two ways: over a wide range - transition from orbit to orbit, in the energy range up to 1.8 MeV - with changing the magnetic field. The cooled device of tungsten disk 2 mm in thickness behind which there was located the aluminum electron absorber 30 mm in thickness was served as a bremsstrahlung target. The tungsten target serves as a catcher of electrons passing through it in a time of each irradiation and which was measured with the help of the electrical charge integrator. Electron energy was determined by measuring the microtron magnetic field with the method of nuclear magnetic resonance and by measuring the frequency of accelerating electrical field. Instability of electron energy during the experiment did not exceed 50 keV.

The samples of tantalum (metallic disk 100 μm thick) and Hf (enriched isotopes - 99.3 %) were irradiated with incident energy below the neutron binding energy. The photo excitation of In serve as a monitor reaction as its cross section is known very well [3-6]. The experimental data on the yield ratios for two gamma energies are presented in Table1.

The residual activity of the irradiated samples was measured with the help of Ge(Li) detector 60 cm^3 in volume and with the resolution of 3 keV (for the line 1332 keV ^{60}Co). The detector efficiency was determined by a set of standard samples OSGI.

Table 1. The yields of ^{180m}Hf isomer and ^{180}Ta ground state related to the yield of ^{115m}In isomer.

E_0 MeV	$\frac{Y(^{180m}Hf)}{Y(^{115m}In)} \cdot 10^{-4}$	$\frac{Y(^{180}Ta)}{Y(^{115m}In)}$	σ_{int} (^{115m}In) mb.keV [6]
6.0	0.02(1)	<1	1200
6.5	0.07(2)	5.0(1.5)	2100
7.0	0.17(4)	5.0(1.2)	3200
7.5	0.35(6)	42(8)	4400
8.0	0.36(6)	1600(100)	5700

Usually, in the experiments the current of accelerated electrons was - 20 μA, irradiation time - 5 hours, and measurement time - until collecting the necessary count statistics (as a rule, of some thousands of pulses in peak of the measured γ-line) fig 2.

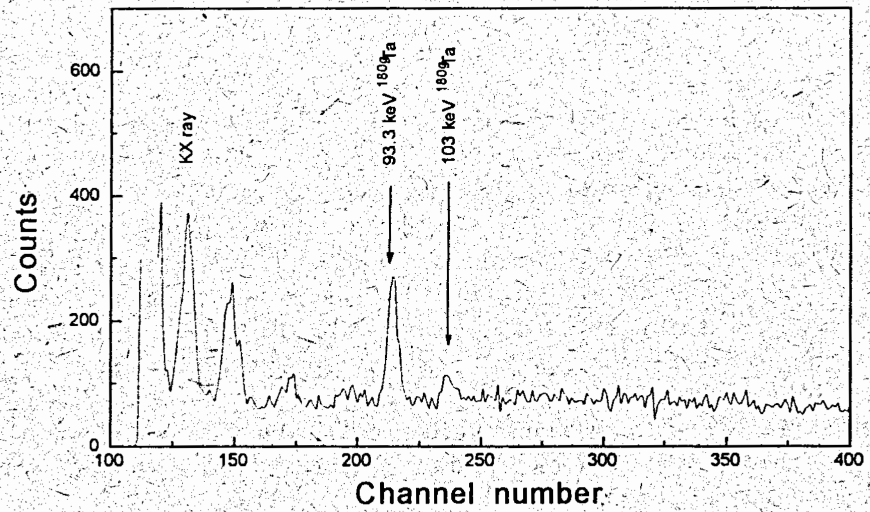

Fig.2. A γ-spectrum of ^{nat}Ta produced after the irradiation by with γ-quanta $E_\gamma = 7$ MeV.

4. Discussion

The investigation of the reaction (γ,γ') at low energies (E_γ <6 MeV) has shown that the main role in photo-absorption and the subsequent population of isomers is played by a relatively small number of activation states with large partial width Γ_i [8,9]. For some nuclei, including ^{180}Ta, the integral excitation cross section of these states was found to be very large [10, 11]. The large cross section values may be connected with the following factors - the big number of activation states, their widths and the transition probability to the isomer (the isomeric ratio). The properties of these state are scarcely investigated, thus making it difficult to judge of the importance of any of the above factors.

A more definite conclusion can be drawn on the basis of cross sections measured for the photo excitation of isomers in the region of the neutron binding energy. At such energies level properties (density, total and partial width) are known form neutron resonance studies. The results presented here have been obtained in this energy region, too.

The fast rise of the isomeric yields with increasing the γ-quanta energy and the noticeable overrun above the values at E_γ < 6 MeV, obtained in ref. [10, 11], show that the main contribution to the integral isomer excitation cross section comes from the most highly lying states due to their high density. It this case, the isomeric yield ratio corresponds to the ratio of the integral cross sections. Because of this, on the basis of the measured isomeric yield ratios and the known value of σ_{int} for the reaction $^{115}In(\gamma,\gamma')^{115m}In$ (Table 1), we can obtain the values for the integral cross sections for exciting the ^{180}Hf isomer and deexciting the ^{180}Ta - isomer. The obtained in this way values for σ_{int} are shown in Table 2. One can see the very large, more than a factor of 10^4, difference in the reaction cross sections for ^{180}Hf and ^{180}Ta, independent of the fact that the spin difference for the isomeric and ground states is the same (ΔI=8).

The known parameters of the states of the nuclei ^{115}In, ^{180}Hf and ^{180}Ta, obtained from neutron resonance systematics [12,13], allow to estimate the total photo-absorption cross sections, which in turn allows to determine the IR. In the region of the neutron binding energy, the cross section for photo-absorption, averaged over many levels, can be represented as:

$$\sigma = \frac{\lambda^2}{8\pi} \, \frac{2 I_i + 1}{2 I_0 + 1} \, \frac{\Gamma}{D} \qquad (1)$$

where λ is the wavelength of the γ-quanta, I_0 and I_i are the spins of ground and isomeric states, respectively, Γ_i is the partial width for the gamma-transition to the ground state, D is the average distance between the levels. Assuming that the investigated nuclei have close values of $\Gamma_i \sim 10^{-2}$ eV and that the value of D is taken for one and the same excitation energy, and taking into account the changes in D for the transition to the spins of the excited levels in each nuclei, by using the relation (1) we can estimate the photo-absorption cross section for the investigated nuclei. These cross sections correspond to the known systematic [15]. The ratio of the cross sections for exciting (or deexciting) the isomers and the obtained by the above-mentioned procedure absorption cross sections, integrated over the same energy range, can be considered as IR - they are presented in Table 2. As in the case of the cross sections, the IR differ strongly for ^{180}Hf and ^{180}Ta.

Table 2. Integrated cross sections and IR at photo excitation of ^{180m}Hf and ^{180}Ta.

E_0	^{180m}Hf		^{180}Ta	
	σ_{int}	$\frac{\sigma_m}{\sigma_0} 10^{-5}$	σ_{int}	$\frac{\sigma_m}{\sigma_0}$
MeV	mb.keV		mb.MeV	
6.0	0.002(1)	0.010(5)	<2	
6.5	0.015(5)	0.07(2)	8(3)	0.20(7)
7.0	0.055(9)	0.18(3)	12(4)	0.25(8)
7.5	0.15(3)	0.30(6)		
8.0	0.20(4)	0.32(6)		

The IR for the deexcitation of ^{180}Ta is practically the same as in the case of exciting the isomers when the change in spin is not large (ΔI=3-4). The large integral cross section of deexcitation of ^{180m}Ta makes it one of the important candidates for the γ-laser.

The observed difference may be the result of the different mechanism of exciting the isomer in ^{180}Hf and of deexciting the isomer ^{180}Ta. Fig.3 represents the possible paths of the (γ,γ') reaction for the two nuclei. It is probable that from the excited, after the γ-capture, levels in ^{180}Ta with spins 8^+, 9^+ and 10^+ M1 - and E2 - transitions take place to levels (with close spin values) of the rotational band built on the ground state of ^{180}Ta ($I^\pi=1^+$). The quantum number K hindrance for these nuclei may be significantly weakened due to the high level density in the odd-odd nucleus and to the mixing of levels having different K values. A similar weakening of the K - hindrance has been observed, for instance, for the transitions between the high-spin levels in the nucleus ^{174}Hf [14]. Such a path of deexcitation of the isomer can explain the high value of the IR obtained in the reaction ^{180m}Ta(γ,γ')^{180}Ta because the decay of the levels of the rotational band goes practically solely to the ground state.

In the case of the nucleus ^{180}Hf this way of populating the isomer is impossible, as from the excited, after the γ-capture, level with $I^\pi=1^-$ the isomer is reached by a long γ-cascade competing with the other decay branches at each step. Such a path of exciting the isomer is connected with

the small IR. The observed IR in the reaction ^{180}Hf(γ,γ')^{180m}Hf corresponds to the calculated one on the basis of the statistical model using the program EMPIRE [16].

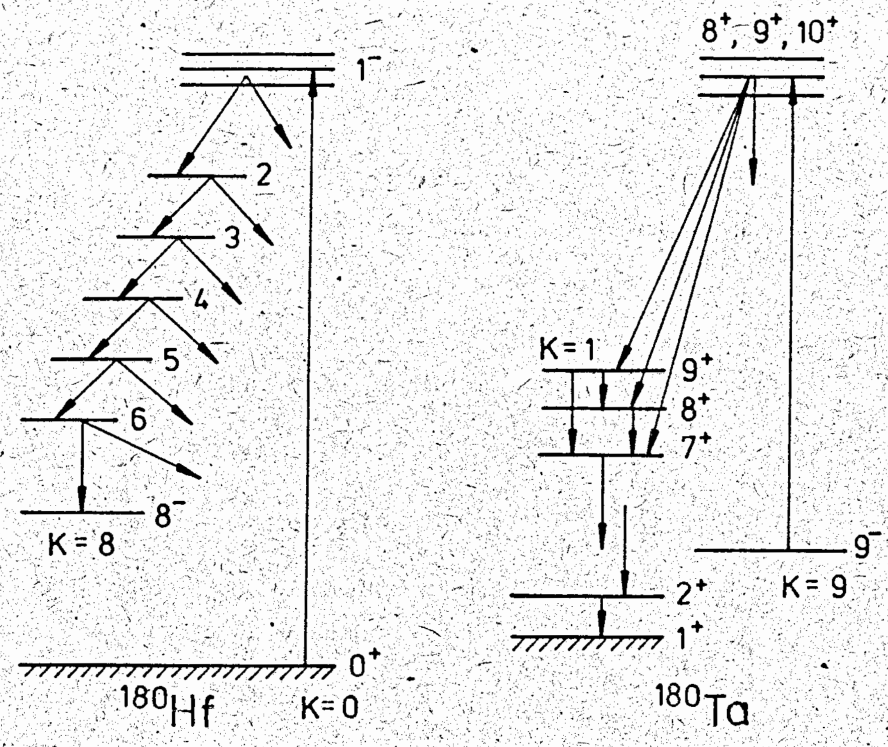

Fig.3. Excitation scheme of ^{180m}Hf and deexcitation of ^{180m}Ta at inelastic scattering of γ-quanta.

In summary, the above mentioned experiments demonstrate the large influence of the level structure of the studied nuclei on the probability of exciting the isomer - i.e. of the existence of rotational bands, the rotational transition probabilities, the hindrance according to different quantum number.

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