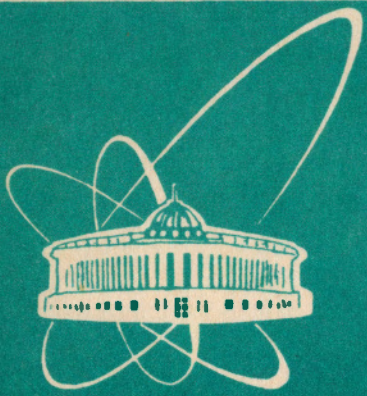

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HIGH-SPIN NUCLEAR TARGET OF ^{178m_2}Hf: CREATION AND NUCLEAR REACTION STUDIES

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1 INTRODUCTION

The present report is a review of experiments on the production, separation and investigation of the ^{178m_2}Hf isomer carried out by a wide international collaboration including the Flerov Laboratory of Nuclear Reactions (JINR, Dubna, Russia), CSNSM and IPN (Orsay, France), GSI (Darmstadt), KfZ (Karlsruhe), Mainz University and Muenchen University (Germany), Kurchatov Institute (Moscow) and FLNP JINR.

During the last few years there has been taking place an intensive development of radioactive beam facilities for the investigation of nuclear reactions and properties of radioactive nuclei by the methods of the nuclear spectroscopy on the beam. There have been already carried out experiments on the beams of such exotic nuclei as ^{8}He, ^{9}Li, ^{11}Li, ^{14}Be and others. Beams of long-lived isotopes near the β-stability line such as ^{10}Be, ^{14}C and others are obtained by the direct acceleration method. New possibilities in studying reactions with radioactive nuclei are opened by the application of heavy ion storage facilities. At the same time radioactive target technique in many cases has advantages connected with a possibility to use traditional methods and earlier built experimental setups. In this case, of course, there are some limitations for the isotope's life-time and consequently the experiments of this type have been carried out with targets of actinides and of some other isotopes close to stability. One should mention here recent experiments on the nuclear level spectroscopy using the method of the Coulomb excitation of such radioactive isotopes as ^{226}Ra and ^{231}Pa.

Several years ago there was suggested an idea [1] to use the long-lived isomer of ^{178m_2}Hf as a high-spin nuclear target. This nucleus is described in literature as a four-quasiparticle deformation-aligned yrast trap with K=16 and identified with the shell model configuration ($\pi 7/2^+$, $\pi 9/2^-$, $\nu 7/2^-$, $\nu 9/2^+$). Hence, the ^{178m_2}Hf isomer can be interpreted as an exotic in structure nucleus. Besides, its spin I=16 is much higher than all the target nuclei studied. Thus, a ^{178m_2}Hf target opens a new approach to future studies in the field of nuclear reactions with high-spin partners. Some light can be thrown on the structure hindrances in nuclear reactions, K-quantum number violation at high excitations and so on.

In this talk it is impossible to give a detailed report on all the parts of the work on the isomer production , on the target creation and on

the experiments with this target. Skipping also the chronology of the work and the authors have limited themselves by illustrating the main substantial results and by short comments.

2 PRODUCTION

The creation of a ^{178m_2}Hf target made it necessary to solve a number of problems:

- the choice of the producing reaction which is optimum with respect to both the absolute yield of accumulated nuclei and the isomeric to ground state ratio value;
- intensive long irradiations to accumulate a microweight quantity of the isomer;
- development and application of precision methods of radiochemistry and mass-separation to ensure the high purity of the ^{178}Hf nuclide both from other isotopes of Hf and from ballast elements;
- application of pure materials and methods of purity control for the successful solution of the above task;
- the technology of application and control of thin uniform layers of hafnium on carbon foils for the creation of targets which remain stable on beams of charged particles.

2.1 The choice of producing reactions

For the production of high-spin nuclei one has to use heavy particles ensuring a large enough angular momentum of reaction products. There has been measured in detail the cross section and the excitation function of the reaction ^{176}Yb (^{4}He,2n) ^{178m_2}Hf. A stack of ^{176}Yb targets (96% enrichment) was irradiated on the Alma-Ata cyclotron. The cross section of the isomer formation was determined by the γ-activity. The results are presented in fig.1.

Like it has been expected the isomer excitation function is shifted by approximately 3 MeV to the right from the calculated excitation function for the ^{178}Hf nucleus in the ground state. The isomeric ratio grows with the energy of ^{4}He ions and reaches saturation on the level of 0.07 - 0.08. The optimum energy interval is the one from 28 to 36 MeV, where the absolute cross section of the isomer formation is maximum and the isomeric ratio ($\approx$ 0.05) is not small yet. The yield of ^{178m_2}Hf in some reactions was observed in refs. [2, 3, 4, 5].

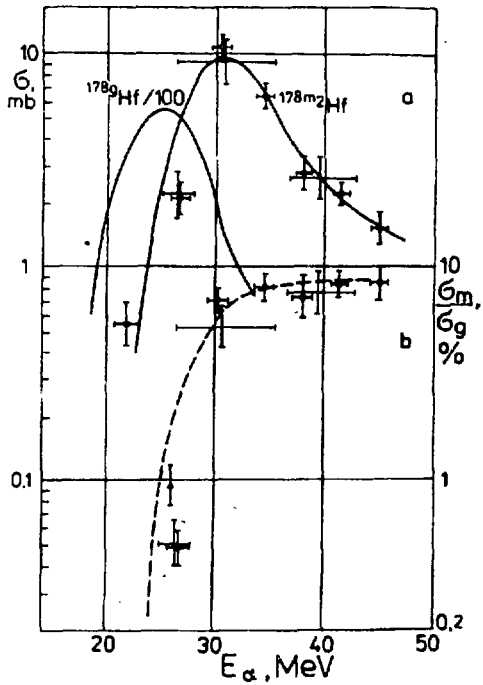

Fig. 1. Cross-sections for ^{178}Hf and $^{178m_2}Hf$ production and the isomeric to ground-state ratio versus the energy of ^4He incident ions on the ^{176}Yb target. Horizontal error bars correspond to the energy loss in the targets.

It is known from ref. [2] that the probability of ^{178m_2}Hf formation at the capture of thermal neutrons is rather low $\approx 10^{-9}$. In the reaction ^{181}Ta(p,α) there has been achieved [3, 4] an isomeric ratio of $\approx 10^{-3} - 10^{-2}$. We have made an attempt to determine the isomer yield at the irradiation of natural Hf with the γ-quanta of the bremsstrahlung spectrum with E_{max}= 24 MeV and have obtained an estimate of the isomeric ratio on the level of 10^{-5}. In fig.2 the known data are systemized versus the maximum angular momenta of bombarding particles. With the increase of I_{max} a regular growth of the isomeric ratio is observed. Basing on fig.2 one could expect that the isomeric ratio should be rather high,

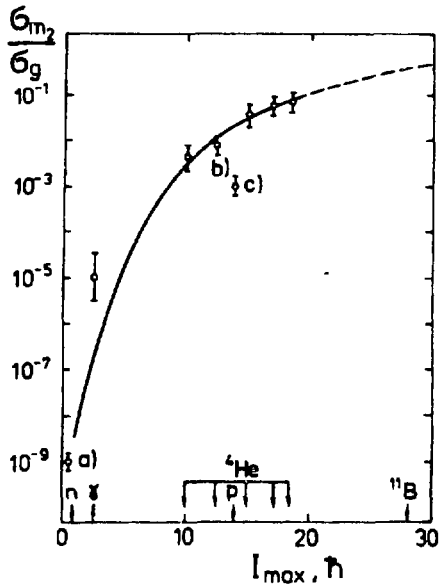

Fig. 2. Isomeric to ground state ratio (^{178m_2}Hf/^{178g}Hf) as a function of the incident particle maximum angular momentum. Literature data /2-5/ points are labelled as a), b), c).

≈ 0.3 in reactions with heavy ions of the type of ^{11}B, ^{12}C. Consequently, there have been measured the excitation functions of radioactive products in the reaction ^{12}C+^{170}Er. They are shown in fig.3. It turns out that the absolute cross section of ^{178m_2}Hf formation in the reaction ^{170}Er(^{12}C,α) is noticeably lower than in the reaction ^{176}Yb(^{4}He,2n) because of a lower probability of the charged particle emission as compared with neutrons. Since ^{178}Hf is a nucleus close to the β-stability line, when using heavy ions, it is impossible to find a reaction with no charged particle emission. Taking account of the maximum target thickness, beam power limitations and etc., one can make a conclusion that the absolute yield of ^{178m_2}Hf on a heavy ion beam will be substantially lower then in the case of ^{4}He ions. Bearing this in mind we have stopped upon the producing reaction ^{176}Yb(^{4}He,2n) in the ion energy interval from 28 to 36 MeV.

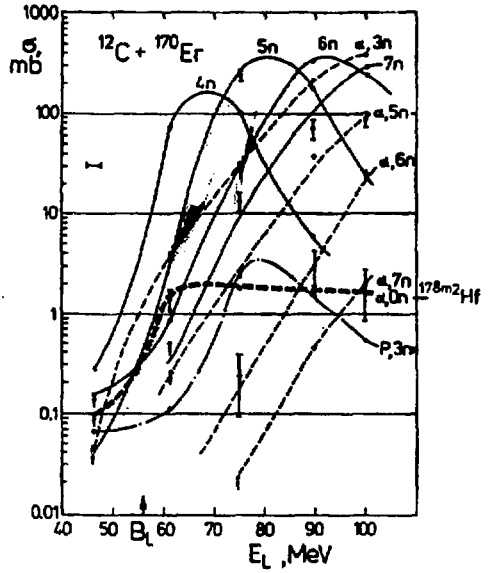

Fig. 3. Excitation functions for radioactive isotopes produced in the reaction $^{12}C+^{170}Er$. The channels are specified in the plot.

2.2 Producing runs

For the production of $^{178m_2}Hf$ isomer in the amount of hundreds of nanogramms, the FLNR U-200 cyclotron has been modified for operation in the mode of an intensive α-particle beam. The plasma-type ion source, the ion optics of the cyclotron center, the biological shielding against the cyclotron radiation and the elements of the beam extraction system using a stripper have been subjected to modifying. As a result of this the internal beam intensity on the final radius has reached 150 μA of $^4He^+$, and the extraction coefficient - about 50%. One could obtain on the target up to 150 μA of $^4He^{++}$ ions with an energy of 36 MeV. This corresponds to the thermal power of about 3 kW and brings about a serious problem of removing the heat from the target. A water cooled inclined target has been chosen and two schemed designs of it are presented in fig.4. In the first of them a layer of $^{176}Yb_2O_3$ is pressed into an Al backing and in the second - the target layer is applied via spreading layer by layer the Yb

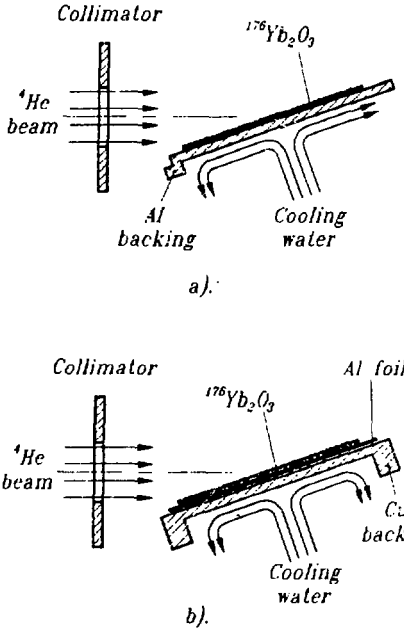

Fig. 4. Sketch of the ^{176}Yb target constructions resistant to the high-intensity ^4He ion beam, variants a) and b).

nitrate solution on a bimetallic backing and heating it. The latter is manufactured by means of the diffusion welding of a 200μ Al foil to a copper plate. Aluminium is to decrease the activation of the target due to the intensive beam and copper is to ameliorate the heat transfer. Targets of these designs could resist the $^4He^{++}$ ion current up to 100μA, although there were observed certain losses of the $^{176}Yb_2O_3$ target material during long irradiation runs. The effective beam time used for the production of the isomer $^{178m_2}Hf$ in the course of two years totals about 2000 hr. There have been produced all in all more than $5 \cdot 10^{14}$ atoms of the isomer, i.e. about 200 ng.

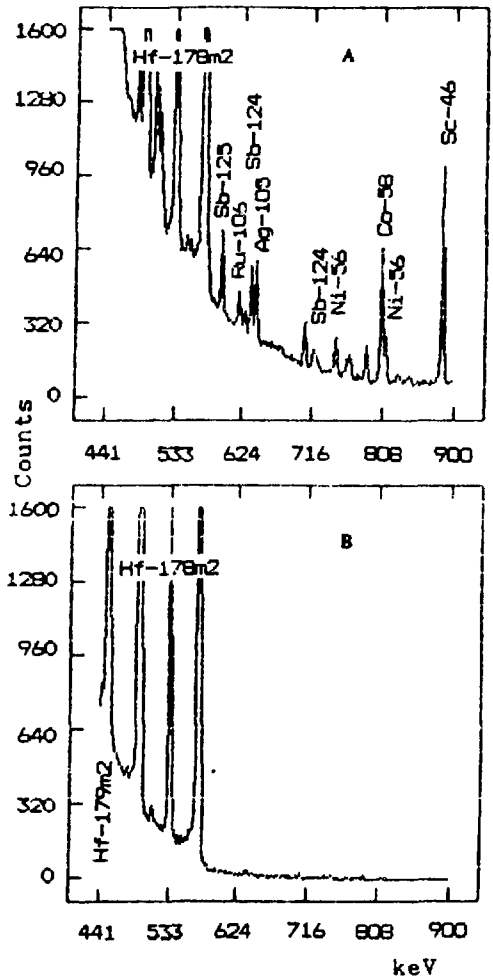

Fig. 5. Fragments of hafnium γ-spectra A – before and B – after the chemical purification.

2.3 Radiochemistry and mass-separation

The reaction ^{4}He+^{176}Yb produces, of course, not only ^{178m_2}Hf but also some other hafnium isotopes, for example ^{178g}Hf in the amount of 20÷1. The number of ^{177}Hf nuclei is also great and other isotopes are produced in less quantities. The task of creating a target from ^{178m_2}Hf makes it necessary to maximally enrich the material with this nuclide. The choice of the ^{4}He+^{176}Yb reaction has already increased the concentration of ^{178m_2}Hf by approximately one order of magnitude as compared with the reaction p+^{181}Ta [3].

To preserve this advantage it is necessary:

1. to *minimize* the share of other Hf isotopes during the production;
2. to ensure a high degree purification of Hf from weight fractions and ballast elements during the chemical treatment of the irradiated target (made of ^{176}Yb);
3. to use probably the electro-magnetic mass-separation of the produced hafnium for most radical purification from other hafnium isotopes.

At the implementation of all these requirements it is possible to increase the concentration of ^{178m_2}Hf to 0.05 i.e. to the physical limit which is determined by the isomeric ratio value in the producer reaction. The task of separating the isomer from the ground state of the same isotope has been never approached practically since it is lacking the basis of technological methods.

The initial material - the commercial isotope ^{176}Yb has the enrichment of 96%. At its application, along with the production of ^{178}Hf, a big enough number of nuclei of light hafnium isotopes including such long-lived intensive γ-activities as ^{175}Hf (70 d) and ^{172}Hf (683 d) is produced. Their presence is undesirable when the substance is used for nuclear spectroscopic measurements. On the PARIS mass-separator at the Orsay, France, there has been manufactured a high enriched isotope ^{176}Yb (99.998%). In the two long runs 7 g of ^{176}Yb oxide (96%) were subjected to mass separation and about 1 g of the oxide of high enriched isotope was obtained. The separator efficiency was about 15%. The obtained material was used for the production of ^{178m_2}Hf on the U-200 accelerator and about $3 \cdot 10^{14}$ atoms of the isomer were accumulated. This material was used in further experiments. Its isotopic content is presented in Table 1. It is seen that the yield of light Hf isotopes is substantially suppressed.

Table 1. Isotopic composition of Hf material produced by the irradiation of a superenriched ^{176}Yb target by a 36 MeV ^{4}He beam at the end of 1991. The data were taken on July 15th 1992.

Nuclide	$T_{1/2}$	Number of atoms
^{179}Hf	stab.	$2.5 \cdot 10^{14}$
$^{179m_2}Hf$	25.1 d	$7 \cdot 10^{10}$
^{178}Hf	stab.	$4.8 \cdot 10^{15}$
$^{178m_2}Hf$	31 y	$2.6 \cdot 10^{14}$
^{177}Hf	stab.	$1.8 \cdot 10^{16}$
^{176}Hf	stab.	$1.8 \cdot 10^{15}$
^{175}Hf	70 d	10^{10}
^{174}Hf	stab.	$5 \cdot 10^{10}$
^{172}Hf	1.9 y	$1.4 \cdot 10^{10}$

Remark: The radioactive nuclides were determined by γ-activity measurements using a Ge(Li) detector, while stable-isotope yields were calculated.

The preliminary separation of hafnium from the irradiated target was performed by the extraction chromatography using tri-n-octilphosphine oxide (TOPO) and high purification from the lanthanides and some other elements was achieved. However, the method cannot provide a complete hafnium purification from Fe, Sc and other metals. It is illustrated by the γ-spectrum shown in fig.5 a. Many activities are produced in the reactions on the admixtures in the target as well as at the fission of ^{176}Yb (^{4}He, f), their presence demonstrates the chemistry failure. The method was developed for the precise purification. The hafnium fraction eluted from the TOPO column, in 0.2M HF solution is passed through a column filled with the anion exchanger Dowex – 1×8, conditioned with 0.2M HF. The column was consequently washed with 0.2M HF, 5M HF, 0.01M HF and 0.5M acetic acid solutions. The Fe, Ni, Co, Cu, Al and Sc were eluted. Finally, hafnium was eluted in a few drops with a mixture of 1M CH_3COOH and 2M HCl (1÷1). The γ-spectrum of the hafnium fraction after this procedure is shown in Fig.5 b), the complete purification from all side activities is evident. This Hf material produced on a superenriched ^{176}Yb target was used later for the neutron resonance search in (n, γ)-reaction as well as in the experiment on the (p, p') and (d, d') inelastic scattering (see below). There was another group of experiments in which the mass-separation of Hf was necessary, namely for the collinear laser spectroscopy and for the implanted sources preparation. The Hf material produced on the 96% enriched ^{176}Yb target was suitable for these experiments.

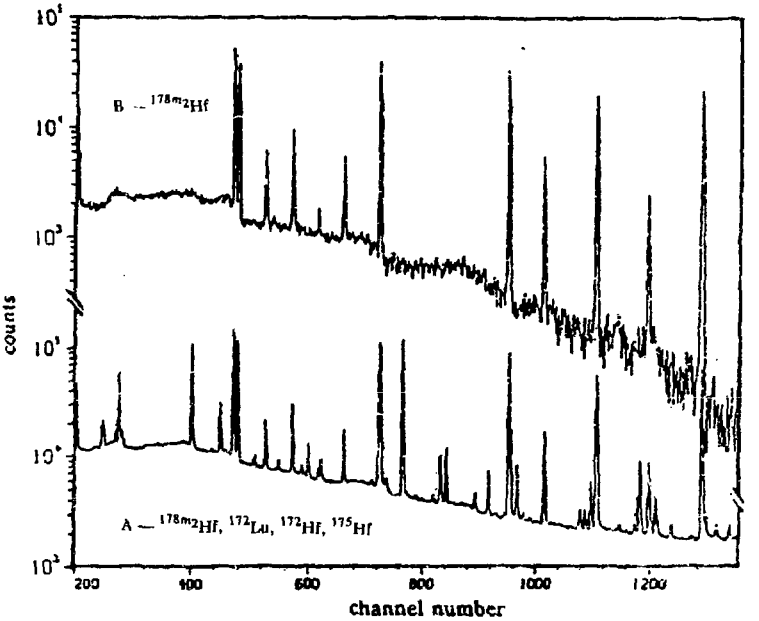

Fig. 6. γ-spectra of a hafnium fraction extracted from ^{176}Yb (96%) target irradiated with ^{4}He ions: before (A) and after (B) isotopic separation of the mass A=178.

After the chemical separation cycle described above the Hf fraction in the form of a chloride was charged into the ion source of the separator "PARIS" and separated using CCl_4 as a jet gas. Since the ^{178}Hf quantities disposable for the separation were in the range of some μg, it was reasonable to use an additional portion of Hf as a carrier. The superenriched ^{176}Hf isotope was playing a role of a carrier. It was prepared in a special run on the "PARIS" separator. There was obtained the ^{178}Hf admixture on the level of 10^{-5} g/g, thus, the addition of 25 μg of the ^{176}Hf superenriched isotope did not worsen the isomer-to-ground state ratio of the isotopically separated ^{178g}Hf–^{178m_2}Hf. Four separations of the ^{178}Hf were accomplished and the total amount of about $5 \cdot 10^{13}$ of ^{178m_2}Hf nuclei was delivered on the focal plane of the separator and used for the

laser collinear experiment, for the implantation in the Hf crystal and in the Fe foils as well as simply collected on a Cu catcher. The efficiency of the separation was between 22 and 25% with a good reproducibility. The quality of the separation is demonstrated in Fig.6 where γ-spectra before and after separation are compared. The total suppression of ^{175}Hf and ^{172}Hf$\rightarrow^{172}$Lu activities is evident.

2.4 Control methods

In addition to the described above application of superenriched ^{176}Yb and ^{176}Hf materials the commercially supplied 99.999% Al foils and 99.9% Al bulk material as well as carbon and beryllium foils were used in the experiments. The target, the backing and the chemical fraction materials were controlled for contaminations by means of the activation analysis methods and the X-ray fluorescence method. There were used for activation the thermal neutrons, the bremsstrahlung radiation, and the α-particle beams available in Dubna. The finally obtained thin ^{178m_2}Hf targets on carbon foil backings were controlled by the back scattering of deuterons and α-particles accelerated on the Tandem at Garching and on the Van de Graaf in Frankfurt as well as by the activation. The analytical data could not be presented here, but they were significant in all the design works.

2.5 Target preparation

The creation of an isomeric hafnium target could be considered to be completed if one prepares successfully a thin homogeniuos hafnium layer on a thin carbon backing stable to the influence of charged particle beams. An additional requirement is the high efficiency of the hafnium material depositing on the foil, since ^{178m_2}Hf is available only in small quantities. The method of electrospraying [6] the hafnium nitrate from a methanolic solution or of the acetate from a glacial acetic acid was chosen. The procedure was worked out for preparing solutions stable at room temperature. Electrospraying of the methanolic and acetic acid solutions was performed with a glass capillary or with a teflon device at a voltage of 5.1 – 5.7 kV and $10 - 20$ μA current. The concentration was kept in the range of $10 - 200$ μg/ml. Many test targets of stable enriched hafnium isotopes were manufactured. The diameter of the spot was from 3 to 15 mm and the thickness - from 5 to 1500 μg/cm^2. The carbon foils with a thickness of $10 - 40$ μg/cm^2 were prepared at the GSI Darmstadt. Finally, the target from the hafnium material produced in the ^{4}He+^{176}Yb reaction was prepared with the diameter of 5 mm and the thickness of about 10^{15} atoms/cm^2 of ^{178m_2}Hf.

3 NUCLEAR REACTION STUDIES

3.1 Thermal and resonant neutron capture

Thermal neutron capture on the 16^+ isomeric state in ^{178}Hf is illustrated in fig.7. Three deexcitation channels are opened after the capture: the inelastic scattering on the levels below the 16^+ state (neutron acceleration), a high-multiplicity γ-cascade to the ground state in ^{179}Hf and a regular multiplicity γ-cascade to the isomeric state $25/2^-$ in ^{179}Hf. The experiment was performed [7] on the neutron channel of the IBR-2, FLNP, Dubna pulsed reactor in March 1992. Two identical ^{178m_2}Hf targets were prepared on high-purity quartz backings using the chemically separated hafnium material produced on the cyclotron U-200 in December 1990. This material contains only ^{178m_2}Hf, ^{175}Hf and ^{172}Hf$\rightarrow^{172}$Lu activities, the 25.1 d lived ^{179m_2}Hf activity fully decayed to the moment of neutron irradiation. Thus, good conditions were created to search for the ^{179m_2}Hf activity induced in the ^{178m_2}Hf (n, γ) reaction. The ^{178m_2}Hf prepared targets were exposed to thermal and resonant neutrons. The total fluence of neutrons was about $6 \cdot 10^{18}$ n/cm^2 during an 11 day run. One of the ^{178m_2}Hf targets was enveloped in a 0.5 mm Cd filter while the second one was exposed without a filter in order to separate the reactions induced by thermal and resonant neutrons, respectively.

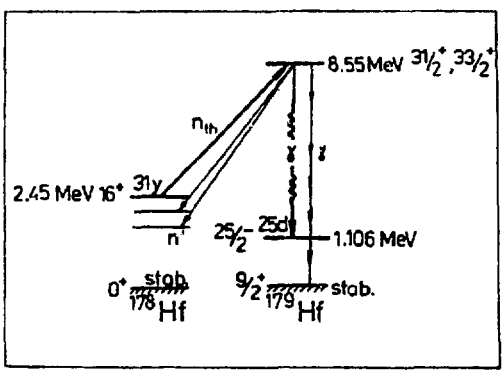

Fig. 7. Scheme of the neutron capture reaction on ^{178m_2}Hf nuclei.

After a 5-day cooling the chemical procedure of hafnium isolation by chromatographic methods was repeated. The aim of this treatment was to purify hafnium from the ^{172}Lu activity and from ballast material activities produced in the neutron irradiation. It also served to be ensure that expected γ-lines of ^{179m_2}Hf were really searched for in the hafnium fraction.

Ready hafnium fractions were investigated by the γ-spectrometry using a Ge(Li)-detector. Eight lines of ^{179m_2}Hf were observed with a high yield in the sample exposed both with and without the filter. Thus, ^{179m_2}Hf nuclei were indeed produced by the neutron irradiation of the ^{178m_2}Hf targets. The estimates for the background reactions on the stable hafnium isotopes (present in the targets) give a several order of magnitude lower yield.

The ratio of the number of atoms produced in the reaction to the number of target atoms is determined by the reaction cross section and fluence values:

$$N_{at}^{179m_2}/N_{at}^{178m_2} = \sigma_{th}\Phi_{th} + I_r c\Phi_r,$$

where c is the normalization constant of the neutron spectrum. Φ_{th} and $c\Phi_r$ were determined numerically using the ^{95}Zr and ^{97}Zr activation of a ^{nat}Zr target used as monitor. The measured values of Φ_{th}, $c\Phi_r$ and $N_{at}^{179m_2}/N_{at}^{178m_2}$ are given in table 2 for both the targets exposed with and without the Cd filter.

Table 2. Results of the experiment on ^{178m_2}Hf $(n,\gamma)^{179m_2}$Hf reaction study

target number	filter	Φ_{th}, cm^{-2}	$c\Phi_r$, cm^{-2}	$N_{at}^{179m_2}/N_{at}^{178m_2}$
1	—	$5.67 \cdot 10^{18}$	$5.75 \cdot 10^{17}$	$7.64 \cdot 10^{-4}$
2	0.5mm Cd	—	$5.94 \cdot 10^{17}$	$4.75 \cdot 10^{-4}$

Thus, the σ_{th} and I_r, values for the reaction ^{178m_2}Hf (n, γ) ^{179m_2}Hf can be deduced from the values given in the table:

$$\sigma_{th} = (51 \pm 10)\ barns;$$
$$I_r = (800 \pm 130)\ barns.$$

For a brief comment of this results one can remember that in the neutron capture reaction on ^{178m_2}Hf state with E^*=2.447 MeV and $I^\pi = 16^+$ the discrete levels in the region of E^*=8.55 MeV and I=33/2 and 31/2 are populated. The statistical-model calculations predict that the level density of this compound nucleus in mentioned region has to be 20 times higher than in the region E^*=6.1 MeV and I=1/2 populated in the neutron capture on the ground state of ^{178}Hf. Thus, one may expect a high enough thermal cross section and resonance integral values for the neutron capture on the isomeric ^{178m_2}Hf. The results of the statistical-model calculations are thus in a good agreement with our measurements.

Consequently, one can say that a nuclear reaction from one high-spin isomer to another was observed for the first time. The shell-model structure of ^{179m_2}Hf isomer is identified in literature with the configuration ($\pi 7/2^+$, $\pi 9/2^-$, $\nu 9/2^+$), i.e. not far from the structure of ^{178m_2}Hf four-quasiparticle state. The well allowed population of ^{179m_2}Hf state observed may indicate to some selection of levels similar in structure to the initial target state. However, the fractional cross-section leading to the ground state in ^{179}Hf has not yet been measured in the ^{178m_2}Hf (n, γ) reaction, and the analysis cannot be finished at the moment. The large value of the resonance integral opens up a possibility to search experimentally for high-spin neutron resonances using a prompt γ-ray multiple detector systems combined with the time-of-flight techniques.

3.2 Search for the neutron resonances

The direct observation of neutron resonances using a tiny weight (100 ng) self-radioactive ($\approx 10^6$ γ/s) target is not an easy task. Such an experiment was not performed earlier because of great difficulties of the exotic target preparation and of the problem of the background in the multidetector γ-spectrometer on the neutron beam. The target for the neutron resonance experiment was prepared using the above chemical methods from the hafnium material produced at the irradiation of the superenriched ^{176}Yb target. The hafnium fraction was deposited onto it and covered with a 30 μm Al foil of 99.999% purity. The target spot was 5 mm in diameter, the isotopic composition of the Hf material is given in Table 1.

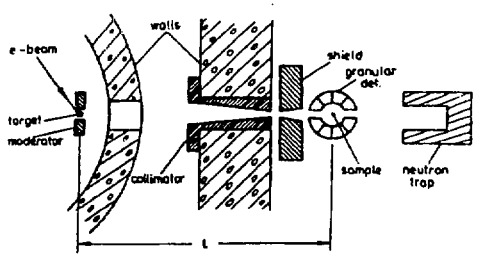

Fig. 8. Experimental set-up used for a time-of-flight study of the ^{178m_2}Hf(n,γ) reaction on a beam of resonant neutrons.

The experiment was performed on the time-of-flight base of the linear electron accelerator "Fakel" at the Kurchatov Institute in Moscow. The scheme of the experimental set-up is given in fig.8. The pulsed electron beam with an energy of 50 MeV hits a water-cooled uranium target of 35 mm thickness and generates neutron bursts of about 0.15 μs, the repetition period $\approx$3.3 ms and the total number of neutrons - about

$5 \cdot 10^9$ n/pulse. The electron beam target was surrounded by a water moderator which served as a pulsed source of resonant neutrons. The multidetector granulated NaI array "Romashka" [8] was placed at an angle of 90° to the electron beam at a distance of 10.7 m behind the concrete wall. The ^{178m_2}Hf target was placed in the vacuum chamber inside the array of the 32 NaI detectors with the total weight of about 600 kg. Two thin stilben crystals mounted near the target can be used for detecting of the neutrons and γ-quanta emitted from the target.

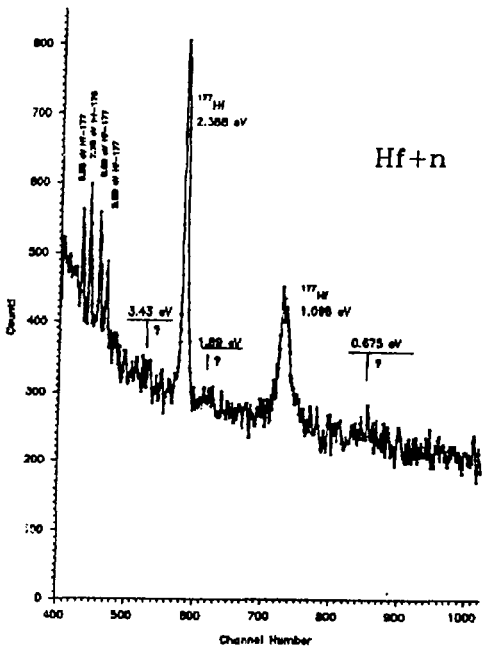

Fig. 9. Time-of-flight spectrum of (n,γ) reaction taken for the hafnium target containing ^{178m_2}Hf isomer.

For the background suppression a passive shielding was arranged using polyethylene and lead blocks. The detector array was shielded inside by ^{10}B layer from scattered slow neutrons. Besides, the logic selection at the tract of fast coincidences was used for the active suppression of the background. The events selection by the total energy and the multiplicity of the detectors fired could be done on the stage of detecting as well

as on the stage of the off-line processing of information. However, the suppression of the background down to the level of a hundred nanogramm target was not an easy task especially with the self-active target material.

During the 150 h run on the neutron beam there were two detector array rearrangements. The electronic system logic was reorganized repeatedly to suppress the background without a loss in the efficiency. By the end of the run the effect-to-background ratio was improved, but the statistics collected under these conditions was rather poor. The 80 h run neutron time-of-flight spectrum is presented in fig.9. The resonances of ^{177}Hf and ^{178}Hf look intensive in the spectrum, however, the background level is not low. Some small resonances existing in the spectrum can be accepted, but their attribution to ^{178m_2}Hf is not unambiguously proved. This spectrum is considered as preliminary information about the possibility of such an experiment. After the suppression of the background and a significant increase of the absolute counting rate neutron resonances on the $^{178m_2}Hf$ target can be revealed successfully.

3.3 Inelastic scattering of protons and deuterons

In reactions of inelastic scattering the band built on the 16^+ isomeric state could be revealed, and the moment of inertia and the quadrupole moment of the band could be deduced.

Just before this conference an experiment was performed on the inelastic scattering (p, p') and (d, d') on the isomeric target bombarded by the beams of the MP Tandem Accelerator at Muenchen Univ., Germany with the participation of groups from Muenchen, Darmstadt, Orsay and Dubna. The energies of the protons were 22 and 26 MeV and of the deuterons – 22 MeV, the scattering angles – 100 and 135°. A thin target on a carbon backing was prepared as described above. It contained about 10^{15} atoms of ^{178m}Hf per cm^2. The scattered particles were detected by a Q3D magnetic spectrograph in combination with a gas-filled multiparameter focal plane detector [9] of a 2 m length. The particle specy can be chosen using the twice measured ΔE signals whereas the coordinate information taken from the anodes and cathodes of two proportional counters leads to the energy resolution of detected particles of about 5 keV. The target thickness normally makes the resolution worse than the limits of the spectrograph itself.

Fig.10 shows a typical deuteron spectrum as observed in our experiment in Muenchen. The prominent peaks for excitation energies up to 400 keV can all be assigned to the population of the ground state bands in the $^{176,177,178}Hf$ isotopes. In addition nuclear states from a $^{194,195}Pt$ can be observed as a result of the Pt impurity which arose during target preparation. The only peak in the spectrum which can not be assigned to

the excitation of low-spin states in Hf- or Pt-isotopes is marked with an arrow. It was not observed in the reference spectra taken on the stable Hf isotope targets however was presented in the (p,p') spectrum on isomeric target. This state with excitation energy of 353 keV can be attributed to the $K = 16$ rotational band in ^{178}Hf, namely to $I^{\pi} = 17^{+}$ member of this band. The moment of inertia value can be evaluated immediately: $J = 48\ MeV^{-1}$, which is not far from those evaluated basing on the $16^{+} \rightarrow 14^{+}$ transition energy in the ground state band. This preliminary result has to be confirmed by the extensive analysis of the data, in particular, the cross sections measured have to be reproduced.

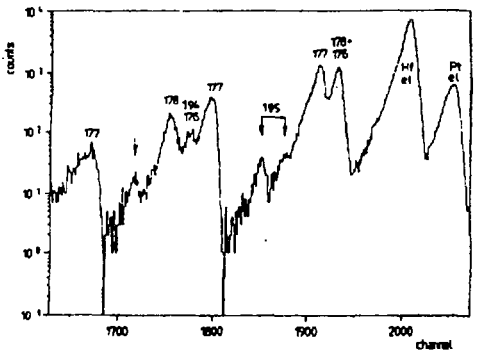

Fig. 10. Spectrum of the deuterons scattered on the $^{178m_2}Hf$ target. The incident energy - 22 MeV, the scattering angle -100°.

3.4 Coulomb excitation

At the energies of ^{4}He and of heavier ions below the Coulomb barrier, the inelastic scattering proceeds via a pure electromagnetic interaction. Thus, the experimental data interpretation is simplified, and the quadrupole moment of the band can be deduced unambiguously. The experiment could be performed in the variant of scattered particle detection (same as above in the (p,p') and (d,d') reactions) or by the coincidence technique of deexcitation γ-rays with scattered ions. A corresponding proposal is accepted by the GSI, Darmstadt.

3.5 Photonuclear reactions

The photonuclear reactions on $^{178m_2}Hf$ are of a significant interest because of the unique possibility to get information about the giant dipole

resonance built on a high-spin state of a quasiparticle nature. We have tried to observe the 51 *min*-lived activity of $^{177m_2}Hf$ induced at the irradiation of a $^{178m_2}Hf$ target by the bremsstrahlung on the electron beam with an energy of 24 *MeV* of the Dubna microtron accelerator. Precision purification of the hafnium fraction from the ballast materials was done, and the target was prepared on a pure beryllium backing. However, the activation background was not negligible. The induced activity was measured after an intensive 1.5 *h* irradiation using a Ge(Li)-detector. The line with $E_\gamma = 638$ *keV* belonging to the $^{177m_2}Hf$ decay was searched for. The satellite line of the $^{178m_2}Hf$ self-activity with an energy of 639 *keV* (added energy of the cascade transitions 213+426 *keV*) was suppressed by a 8 *mm* lead filter. However, the absolute counting rate near 638 keV was not sufficient to observe the effect. A more powerful beam is necessary to perform this experiment successfully.

Nowaday, electron accelerators such as CEBAF (USA) and MAMMI (Germany) in combination with developed magnetic spectrograph facilities open a possibility to study the electron scattering on the $^{178m_2}Hf$ target. Such an experiment can throw some light on the charge distribution of this exotic nuclear state.

4 HYPERFINE INTERACTIONS

4.1 Laser spectroscopy

An in-beam laser experiment [10] was performed on the PARIS mass-separator at Orsay where hafnium atoms with a 40 *keV* kinetic energy were excited by a single mode dye laser in a contralinear geometry. The hafnium tetrachloride vapor is flowed from the heated sample into the ion source chamber, in which it is decomposed and ionized. The elemental ions are extracted and accelerated by a 40 *keV* potential and finally mass separated. The selected mass is delivered into the collinear set-up, where ions are neutralized in the sodium vapors of a charge exchange cell and interact with a fixed frequency laser beam. The frequency scanning was done by changing the ion beam velocity with a tuning voltage at the charge exchange cell. The fluorescence light after passing through the filters was detected by a photomultiplier. The hyperfine structure and isotope shift were measured for stable hafnium isotopes. Signals have been recorded also at mass 178 and two almost coinciding resonances have been attributed to $^{178m_2}Hf$ (see fig.11). The pattern does not support the previous measurement of the $^{178m_2}Hf$ magnetic moment. The results are under analysis. During the next run the sensitivity will be enhanced by one order of magnitude higher.

Another approach is developed by the KfZ (Karlsruhe) group which uses a Paul trap technique for the Hf ions confinement. The experiment with mass-separated $^{178m_2}Hf$ material is promising interesting results.

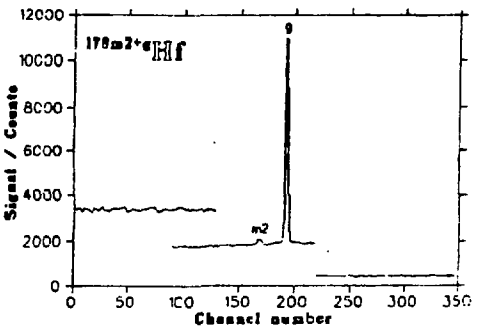

Fig.11. Photoabsorption spectrum of the neutral ^{178}Hf beam.

4.2 Nuclear orientation

The implantation of $^{178m_2}Hf$ atoms into iron foils and monocrystalline Hf samples was produced on the mass separator PARIS at Orsay. The experiment on the nuclear orientation of the implanted $^{178m_2}Hf$ nuclei was started last month at Dubna using a low temperature refrigerator and the γ-ray angular correlation technique. The magnetic and quadrupole moments of the $^{178m_2}Hf$ nucleus are expected to be measured in this experiment. Recently, new ideas [11] were proposed, such as the one to use a $^{178m_2}Hf$ source in the nuclear orientation experiment in order to estimate the P and PT parity violation in the electromagnetic decay.

5 SUMMARY

Investigations in the frame of the hafnium-178 isomer problem are a new promising scientific direction from the point of view of the development of fundamental knowledge both in the field of the nuclear structure and of nuclear reactions. The completed experiments give grounds for hopes to obtain data on the electromagnetic moments, on the mean radius and the deformation of the ^{178}Hf nucleus in the state 16^+, on the wave function structure of this state, as well as to study the influence of the target high spin on the differential cross sections of nuclear reactions, to find and investigate neutron resonances with a high spin, to obtain direct

information on the density of the levels in the earlier unaccessible region of the spin and of the excitation energy, to measure directly the parameters of a giant dipole resonance based on the high spin state and to clarify in detail the role of the structure hindrances in nuclear reactions.

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References

[1] Yu.Ts.Oganessian et al. J. of Phys. G, 1992, v.18, p.393.

[2] R.G.Helmer, C.W.Reich. Nucl. Phys., 1973, v.A211, p.1.

[3] W.Kutschera et al. Proc. 1st Intern. Conf. on Radioactive Beams, Berkeley, 1989, p.345.

[4] J.B.Wilhelmy et al. Proc. IV Intern. Conf. on Nuclei Far from Stability, Geneva 1981, p.684.

[5] J. van Klinken et al. Nucl. Phys. 1980, v.A339, p.189.

[6] Z. Szeglowski, Yu.S. Korotkin. Pribory i Tekhnika Experimenta, Moscow, 1991, N 1, p.206.

[7] Yu.Ts.Oganessian et al. JINR Rapid Communications, N3(54)-92, Dubna, 1992, p.72.

[8] H.V.Muradian. Atomnaya Energiya, Moscow 1981, v.50, p.394.

[9] R.Hertenberger et al. Nucl.Instr. and Meth., 1987, v.A258, p.210.

[10] N.Boos et al. Contribution to 6th Conf. on Nuclei Far from Stability and Conf. AMCO, Berncastel-Kues, July 1992.

[11] I.C.Girit et al. On-Line Nuclear Orientation Conf. Oak Ridge, 1991.

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