TRIGGERING OF ^{178m2}HF ISOMER EMBEDDED IN Ta MATRIX BY 30 keV ELECTRONS

A.N. Dovbnya[1]***, S.S. Kandybei***[1]***, V.I. Kirischuk***[2] [*]***, Yu.N. Ranyuk***[1]

[1]*National Science Center "Kharkov Institute of Physics and Technology", Kharkov, Ukraine;*

[2]*Institute for Nuclear Research, Kiev, Ukraine*

(Received February 5, 2013)

^{178m2}Hf isomer triggering was studied using the upgraded experimental setup developed in Kharkiv National University and installed at Kyiv Institute for Nuclear Research. The target presenting a single Ta foil of 300 μm thickness with ^{178m2}Hf isomeric activity of about 100 Bq was irradiated by 30 keV electron beam. The enhanced counting rates of all the ground-state band transitions were observed. Our data are consistent with an estimate for the triggering effect of $(2.9 \pm 0.7)\%$ and corresponding triggering cross-section can qualitatively be estimated as $\sigma_{trig} = 4.2 \times 10^{-27}$ cm^2.

PACS: 23.20.Nx; 25.20.Dc; 27.70.+q

1. BACKGROUND AND INTRODUCTION

The 16^+ 4-quasiparticle state of the nucleus ^{178}Hf, a K isomer with the excitation energy $E_e = 2.4474$ MeV and half-life $T_{1/2} = 31$ years, is considered as the most promising on the way to create gamma-ray sources controlled by low energy photons and a gamma ray laser as well. Having so high excitation energy and the longest half-life among all known highly excited nuclear isomers, ^{178m2}Hf isomer is absolutely unique nuclear isomer and the most perspective for the triggering experiments. Consequently, this isomer has become the subject of intense experimental study for possible mechanisms that could trigger its decay. Since 1998 a number of experiments have been performed, nevertheless the obtained positive results ([1]-[10]) completely exclude the negative results ([11]-[13]) and vice versa yet.

The main attention of all recently conducted experiments has been focused upon ^{178m2}Hf isomer since, first, its high excitation energy allows to propose a great variety of possible triggering mechanisms and, secondly, its longest half-life ensures the highest sensitivity of the triggering experiments. Such uniqueness of ^{178m2}Hf isomer creates an essential challenge for the triggering experiments as well. On the one hand, the production of lab-sized quantities ($\sim 10^3...10^5$ Bq) happens to be very difficult task, on the other hand, the more productive nuclear reaction is chosen, the longer cooling time (usually from 6 to 20 years) is required for the acceptable reduction of by-products activity. As a result, only one experimental group, though using very similar ^{178m2}Hf isomer target of the same origin (Los Alamos high current accelerator) and the same irradiation facility (SPring-8 Synchrotron), has really repeated the triggering experiments claiming the positive results, however failed to confirm the triggering [13]. Additional efforts of the joint Lawrence Livermore, Los Alamos and Argonne team to check the principal possibility of ^{178m2}Hf isomer triggering ([11]-[12]), just as the Sandia team to repeat the triggering experiment at the National Synchrotron Light Source of Brookhaven National Laboratory in 2005 (so called TRiggered Isomer Proof Test though confirming the triggering of ^{178m2}Hf isomer, but its results have never been published yet) have not clarified completely the situation. At the same time, taking into account the practically absolute inaccessibility of ^{178m2}Hf isomer targets and significant experimental difficulties, it is not easy to apply the new efforts to the detailed study of ^{178m2}Hf isomer triggering.

The idea of ^{178m2}Hf isomer triggering experiments is very simple and clever. The depopulation of ^{180m}Ta isomer ([14]-[15]) and excitation of ^{123m}Te, ^{125m}Te [16] and other long-lived isomers [17] with high-energy bremsstrahlung have shown that the energy stored in isomeric levels can be triggered by photons. All these experiments have reliably demonstrated that the intermediate states through which the triggering occurs can be found at the excitation energies about 2.8 MeV. It has been quite straightforward to suppose that if instead of the ground or low excited state of a nucleus some highly excited nuclear state is used then the analogous triggering effect could be reached using photons with much lower energy. Thus, photons with the energy of around 300 keV can be enough to observe ^{178m2}Hf isomer triggering. And although nuclear theory predicts lots of such highly excited isomeric states, along with ^{178m2}Hf only two

---

[*] Corresponding author E-mail address: kirisch@mpca.kiev.ua

of them were discovered till now that are long-lived ^{177m}Lu ($E_e = 970.2$ keV, $T_{1/2} = 160.5$ d) and ^{179m}Hf ($E_e = 1.1057$ MeV, $T_{1/2} = 25.1$ d). Further experiments performed with the enriched ^{180m}Ta targets and more intense bremsstrahlung sources have clearly shown that the triggering of ^{180m}Ta isomer takes place, though with more than 3 orders of magnitude less yield, even at the excitation energies a little above 1 MeV [18], hence all mentioned above long-lived and highly excited isomers can be considered as very attractive for the triggering experiments.

The half-life and excitation energy are extremely crucial parameters for the sensitivity of triggering experiments. First, for approximately the same triggering cross-sections, while the triggering effect used to be detected as the extra counts over the spontaneous decays of the isomer, the longer half-life of the isomer the more sensitive triggering experiment. Only due to the differences in half-lives ^{178m2}Hf triggering experiments are about 60 and 450-fold more sensitive, than ^{177m}Lu and ^{179m}Hf triggering experiments, respectively. Secondly, the density of nuclear levels increases significantly at higher energies, thus the higher excitation energy of a nuclear isomer the higher probability to exist for any K-mixing nuclear states through which the triggering could proceed. As a result, ^{178m2}Hf isomer having so high excitation energy and the longest half-life is absolutely unique nuclear isomer and the most perspective for the triggering experiments.

2. ^{178m2}Hf ISOMER TRIGGERING MECHANISMS, PRODUCTION AND AVAILABLE SOURCES

The main problem of ^{178m2}Hf isomer triggering is that any available theoretical calculations cannot predict such high cross-section for the experimentally observed effect and the discrepancy is the orders of magnitude. From all the proposed mechanisms including the classical Nuclear Excitation by Electron Transition (NEET) ([7]-[8]), electronic bridges (both elastic and non-elastic ones) [19], resonant internal conversion [20] and NEET through autoionization states [21] that could explain the results of ^{178m2}Hf isomer triggering experiments the classical NEET is considered as the most probable.

The NEET effect has been studied in detail in ^{197}Au for which the energy misbalance between corresponding nuclear and atomic transitions was considered to be as small as 51 ± 2 eV. The new experiment on NEET observation in ^{197}Au conducted recently at SPring-8 [22] has clearly indicated that the energy misbalance is 40 ± 2 eV and only recently this disagreement has experimentally been resolved [23].

The last experiment on NEET observation in ^{197}Au and following theoretical calculations [24] have revealed some NEET features registered in ^{178m2}Hf isomer triggering experiments as well. ^{178m2}Hf isomer triggering experiments conducted in 2002 and 2003 at SPring-8 have clearly demonstrated that the triggering effect is recorded when the photon energies are a little higher than corresponding L edges [7]. The most reliable triggering effect in ^{178m2}Hf isomer has been observed in the experiments when the photon energy is around 6 eV above L_3 edge [8], thus it could mean that an energy misbalance for the corresponding nuclear transition (between the isomeric and intermediate levels) and atomic transition ($M_x \Rightarrow L_3$) in ^{178}Hf is about 6 eV. In both NEET cases the mentioned above energy misbalances happen to be close to the natural widths of corresponding atomic levels W_K(Au) = 52 eV and W_{L_3}(Hf) = 4.9 eV. And though it could be quite natural that NEET width should depend on the widths of the final and initial states (beam width is much narrower while the nuclear level width is negligibly small compared to the atomic shell widths), the last NEET experiment in ^{197}Au has evidently demonstrated that $W_{NEET}(^{197}\mathrm{Au}) = 14 \pm 9$ eV, thus K-shell width does not contribute to the NEET effect. At the same time, in ^{178m2}Hf isomer triggering experiments conducted in 2003 it has been observed that $W_{NEET}(^{178m2}\mathrm{Hf})$ is about 1 eV, i.e. less than L_3-subshell width in Hf as well.

The above-mentioned uniqueness of ^{178m2}Hf isomer has forced the intense search all over the world for any Ta targets irradiated by high energy projectiles many years ago, just as in the case of high current accelerator LAMPF/LANSCE at LANL [25], leading to the discovery of Ta samples irradiated by 4.5 and 1.2 GeV electrons at Erevan Synchrotron [26] and Kharkov Linac [27], respectively.

A set of Ta foils with ^{178m2}Hf isomer activity has recently been found at Kiev Institute for Nuclear Research as well. All these foils of 100 μm thickness were used as the partial energy absorbers many years ago in nuclear experiments with 100 MeV α-particles. At such energies of α-particles the original contaminant production is not very high and the most undesirable by-product ^{172}Hf, presented in significant quantities in all ^{178m2}Hf isomeric targets available yet, has not been produced at all. Now the most part of contaminants decayed completely and the total activity of the foils is presented only by ^{178m2}Hf and ^{179}Ta ($T_{1/2}$ = 664.5 d) [28]. ^{179}Ta decays exclusively by electron capture to ^{179}Hf ground state and there are no γ-rays in its spectrum that can be recorded by HPGe detector save for Hf characteristic x-rays [29]. Thus ^{179}Ta, while it can be removed by subsequent chemical processing and extraction of Hf fraction, is a minor problem for ^{178m2}Hf triggering experiments.

3. TARGET, EXPERIMENTAL SETUP AND RESULTS

Taking into account all the experience acquired during the initial ^{178m2}Hf triggering experiments with dental x-ray machine, a new experimental setup has been developed at Kharkov National University and installed at Kiev Institute for Nuclear Research allowing the irradiation of isomeric targets directly by electrons (or by x-rays when corresponding converters are used) with the energy of 1...25 keV and currents 0-150 μA. Two modifications of experimental setup, one for single γ-ray spectra measurements and another for coincidence γ-ray spectra measurements in very close geometry (as close as possible to 2π and 4π geometry, correspondingly) have been constructed.

Low energy bremsstrahlung radiation has essentially been absorbed by the experimental setup wall to quite acceptable levels without noticeable decrease of ^{178m2}Hf γ-rays, even the lowest energy ones. Additionally, the target unit of the experimental setup has been heavily and rather effectively shielded against natural γ-ray background by more than 10 cm of Pb. Therefore, according to our estimates the sensitivity of ^{178m2}Hf triggering experiments must be orders of magnitude higher than in the case of the initial experiments with dental x-ray machine.

The given ^{178m2}Hf isomer triggering experiment has been conducted using as a target the Ta foil of 300 μm thickness with about 100 Bq isomeric activity which was exploited many years ago as the converter at Kharkov 1.2 GeV Linac [27]. Such target has at least two-fold advantage. First, it can be irradiated directly by electrons at maximal currents without any risk to be overheated and evaporated into vacuum. Secondly, in order to find any reasonable explanation for unexpectedly high triggering cross-section obtained in the initial ^{178m2}Hf triggering experiments it has been proposed to use the pumping radiation derived from x-ray line spectrum of a medium chosen so that one of its strong x-ray lines is resonant with the nuclear transition to the intermediate state [30]. Thus, our experiments have been performed with ^{178m2}Hf target when for the maximal efficiency of characteristic x-rays the isomer is embedded in Ta matrix.

Taking into account that the used isomeric target is rather thick, the experimental setup has been upgraded to the energy 1...30 keV and currents 0...250 μA and the triggering experiment has been carried out with 30 keV electron beam at the average current higher than 200 μA. The diameter of the beam spot at the target was about 8 mm – around the same size as the areas of two available spots each with practically the same ^{178m2}Hf isomer activity in the target. The γ-ray spectra have been acquired using 18% HPGe coaxial detector mounted on the opposite side of the target in the horizontal plane and at 180° to the horizontally incident electron beam. In our experiment GC 2018 (CANBERRA) detector with the efficiency 20% and energy resolution at γ1332 keV peak of ^{60}Co better than 1.8 keV and the standard acquisition system based on CANBERRA InSpector 2000 unit have been used. The distance from the detector front face to the target taking into account the thickness of the experimental setup wall was less than 5 mm. The acquisition rate in γ213 keV peak of ^{178m2}Hf isomer (Fig. 1) even taking into consideration its essential absorption in Ta and additional absorption in the experimental setup wall and the detector cap was around 4.3 counts/s.

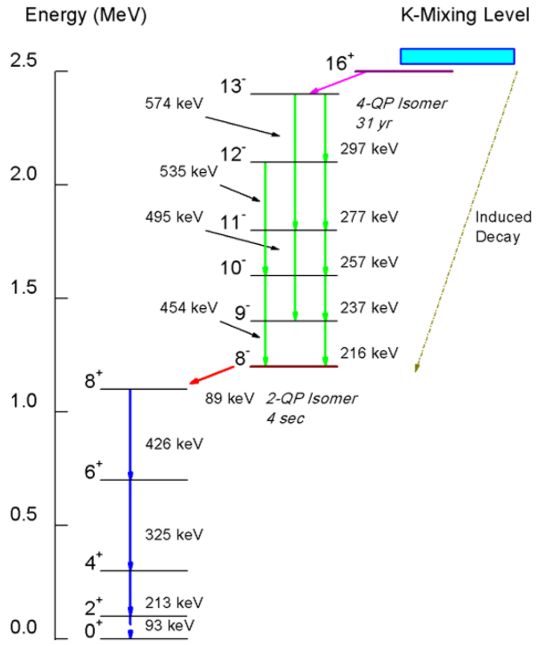

Fig. 1. *Energy level diagram illustrating the spontaneous and induced decay of the 31-yr isomer of* ^{178}*Hf*

L$_x$ lines of Hf cannot be detected in our experiment, consequently the bremsstruhlung radiation with the endpoint energy of 30 keV has been used as the beam-on monitor of electron currents at the target in all runs of measurements ensuring that the experimental luminosity remain at the expected values during the irradiations (Fig. 2,a). At the same time, bremsstruhlung radiation rate registered by the detector was low enough for x-ray coincidence detection (Fig. 2,b).

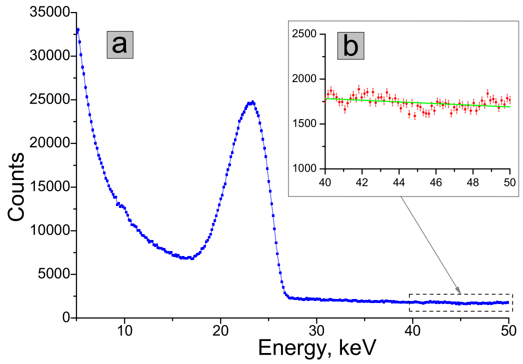

Fig. 2. *Bremsstruhlung radiation with the endpoint energy of 30 keV used as the beam-on monitor of electron currents at the target in all runs of the irradiations. (a) Due to the essential absorption of low-energy X-rays the bremsstruhlung radiation is registered by HPGe detector as a peak with the maximum at the energy about 7 keV lower than the endpoint energy. (b) Bremsstruhlung radiation rate registered by the detector was too low to produce the summing peak*

The entire series of measurements have involved a number of runs of beam-on measurements with the absolutely stable measurement geometry and the total acquisition period of about 8 hours. In order to monitor the stability of measurement geometry, several runs of beam-off measurements have been conducted before and after the irradiations, just as between the separate beam-on measurements each accumulating data over the periods from a few hours to around 20 hours. Table 1 shows the counting rates of all GSB transitions acquired in the beam-off runs conducted before and after the irradiations used to obtain the averaged values for above-mentioned counting rates.

Table 1. *The counting rates of all GSB transitions obtained in the beam-off runs conducted before and after the irradiations*

Transition	Intensity before the irradiation	Intensity after the irradiation	Averaged intensity
γ93 keV	0.208(2)	0.215(2)	0.212(4)
γ213 keV	4.27(2)	4.28(3)	4.28(2)
γ325 keV	3.77(1)	3.79(1)	3.78(1)
γ426 keV	3.01(1)	3.03(1)	3.02(1)

The accuracies of obtained counting rates are better than 1% even in the case of γ93 keV transition having the lowest intensity and reaches 0.3% for the transitions with the highest intensities. In the event when the statistical uncertainty of averaged intensity turned out to be less than the data spread obtained before and after the irradiations the latter has been taken as the uncertainty for the corresponding averaged intensity.

The beam-induced decay of the isomer has resulted in the increase of the GSB transition intensities compared to the beam-off measurements (Table 2). While any new γ-ray peaks not observed in the spontaneous decay of ^{178m2}Hf isomer have not been detected in this experiment, such result allows to use the total counting rate of mentioned above cascade transitions as a measure of the triggering effect. The total counting rates of all transitions triggered in the decay of ^{178m2}Hf isomer have been registered at the levels 11.451 ± 0.032 and 11.285 ± 0.021 decays per second for the beam-on and beam-off spectra, respectively, thus the enhancement factor can be estimated as $(1.47 \pm 0.34)\%$. Since there are two spots with practically the same ^{178m2}Hf isomer activity in the target and only one of them has been irradiated in the given experiment, the real relative triggering effect turns out to be two fold higher $(2.9 \pm 0.7)\%$.

In particular, this has resulted in the enhanced counting rates of all GSB transitions compared to the counting rates of the γ88 keV isomeric and 8^--state band transitions as well. Table 3 shows the counting rates of the γ88 keV isomeric and all 8^- band transitions (save for γ277 keV transition since its intensity is about order of magnitude lower than the intensity of the weakest transition in the list) acquired in the beam-off runs conducted before and after the irradiations used to obtain the averaged values for above-mentioned counting rates. The accuracies of obtained counting rates are better than 1% even in the case of γ534 keV transition having the lowest intensity and reaches 0.25% for the transitions with the highest intensities. In the event when the statistical uncertainty of averaged intensity turned out to be less than the data spread obtained before and after the irradiations the latter has been taken as the uncertainty for the corresponding averaged intensity.

Table 2. *The enhanced beam-on counting rates of all GSB transitions compared to the averaged beam-off counting rates*

Transition	Beam-on intensity	Beam-off intensity	Enhancement
γ93 keV	0.215(5)	0.212(4)	+0.003(6)
γ213 keV	0.215(5)	4.28(2)	+0.05(3)
γ325 keV	3.84(2)	3.78(1)	+0.06(2)
γ426 keV	3.07(1)	3.02(1)	+0.05(2)
Total GSB transition	11.45(3)	11.29(2)	+0.17(4)
Relative enhancement			+1.47(34)%

Table 3. *The counting rates of the γ88 keV isomeric and 8^- band transitions obtained in the beam-off runs conducted before and after the irradiations*

Transition	Intensity before the irradiation	Intensity after the irradiation	Averaged intensity
γ88 keV	0.674(3)	0.679(4)	0.676(3)
γ216 keV	3.52(2)	3.55(2)	3.53(2)
γ237 keV	0.433(3)	0.423(4)	0.429(5)
γ257 keV	0.791(5)	0.803(4)	0.797(6)
γ297 keV	0.417(5)	0.416(5)	0.416(4)
γ454 keV	0.565(3)	0.571(4)	0.567(3)
γ495 keV	2.034(8)	2.034(7)	2.034(5)
γ534 keV	0.253(2)	0.250(3)	0.252(2)
γ574 keV	2.114(6)	2.131(7)	2.122(8)

The beam-induced decay of the isomer has resulted in the non-enhanced beam-on counting rates of the γ88 keV isomeric and 8^- band transitions compared to the averaged beam-off counting rates (see Table 4) and the non-enhancement factor can be estimated as $(0.0221 \pm 0.0366)\%$.

The relevant portion of difference spectrum for the total beam-on and beam-off spectra normalized to the same period of time is presented in Fig. 3. The channel widths are $\sim$ 0.152 keV/channel. Similar difference spectra for different beam-off and beam-on spectra normalized to the same period of time are presented in Fig. 4 and Fig. 5, respectively. The reference beam-off spectrum shown above the acquired difference spectra presents the difference spectrum between the beam-on and beam-off spectra measured in the ideal case when no calibration shifts and line width broadenings are observed while the triggering effect is exactly equal to 1.47%.

Table 4. *The non-enhanced beam-on counting rates of the γ88 keV isomeric and 8^- band transitions compared to the averaged beam-off counting rates*

Transition	Beam-on intensity	Beam-off intensity	Enhancement
γ88 keV	0.673(6)	0.676(3)	-0.003(7)
γ216 keV	3.53(3)	3.53(3)	-0.005(29)
γ237 keV	0.421(9)	0.429(5)	-0.01(1)
γ257 keV	0.790(6)	0.797(6)	-0.007(9)
γ297 keV	0.427(5)	0.416(4)	+0.011(6)
γ454 keV	0.565(5)	0.567(3)	-0.002(6)
γ495 keV	2.038(9)	2.034(5)	+0.004(10)
γ534 keV	0.256(4)	0.252(2)	+0.004(4)
γ574 keV	2.15(1)	2.122(5)	+0.028(11)
Averaged enhancement			+0.022(37)

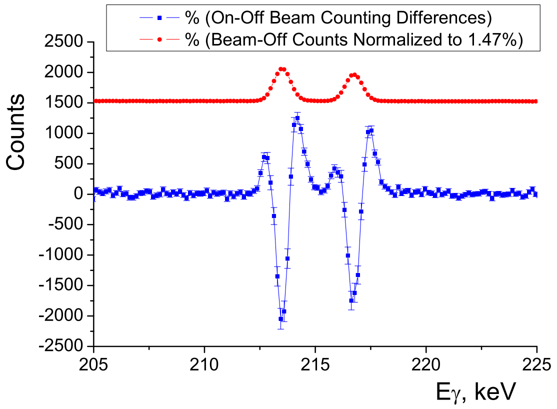

Fig.3. *The points with error bars show the difference gamma-ray spectrum between the beam-on and beam-off spectra from 205 to 225 keV normalized to the same period of time*

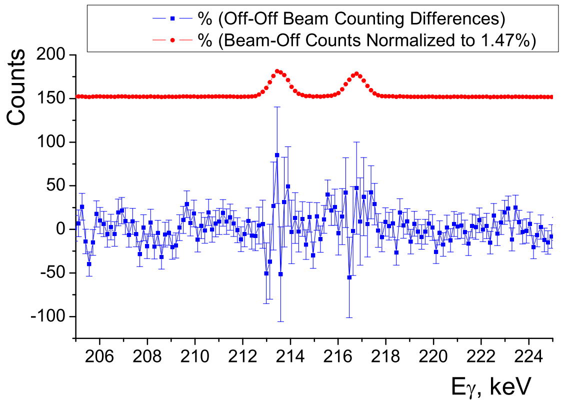

Fig.4. *The points with error bars show the difference gamma-ray spectrum between different beam-off spectra from 205 to 225 keV normalized to the same period of time*

In our experiment the line widths have significantly broadened in the beam-on spectra compared to the beam-off spectra. Such broadening has produced very strong differentiation effect in the difference spectrum not allowing to illustrate visually the ^{178m2}Hf isomer triggering in the difference spectrum as it used to be done earlier. All the reasons for the differentiation are quite clearly shown in Fig. 6.

Nevertheless, in the case of the difference spectrum for different beam-on spectra (see Fig. 5), when the relative line width broadening is not so drastic as in the event of the difference spectrum for beam-on and beam-off spectra (see Fig. 3), a slight triggering effect due to some difference in beam currents is rather visible for γ213 keV peak.

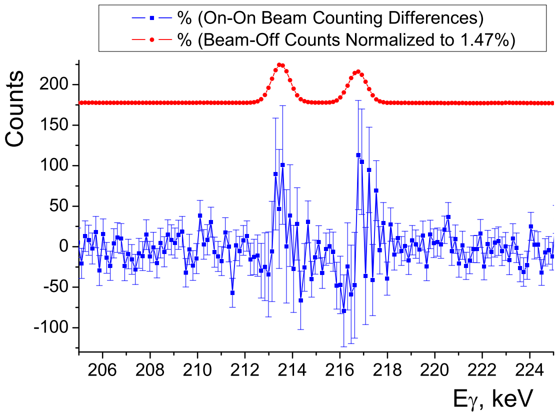

Fig.5. *The points with error bars show the difference gamma-ray spectrum between different beam-on spectra from 205 to 225 keV normalized to the same period of time when irradiation currents differ slightly*

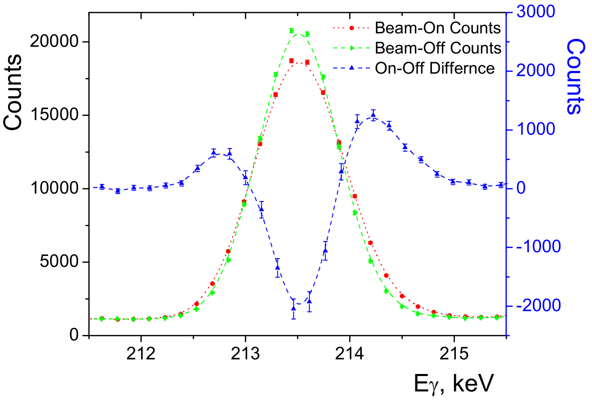

Fig.6. *Notably broadened line widths observed in the beam-on spectra compared to the beam-off spectra are a reason why the very strong differentiation is clearly seen in the difference spectrum*

4. DISCUSSIONS AND CONCLUSIONS

In the same manner to that used in the previous works we can estimate, at least qualitatively and ignoring many unknown effects including all the absorption factors, the triggering cross-section as well. The enhancement factor S can be expressed through the triggering cross-section from the relation

$$S \cdot (N/\tau) = (N/A) \cdot F \cdot \sigma_{trig}, \qquad (1)$$

where N is the number of isomeric states in the target, τ is the lifetime of the isomeric state (1.4×10^9 s), A is the area of the target, F is the number of incident electrons, and σ_{trig} is the triggering cross-section for the isomer de-excitation. N/τ is the normal decay rate of the isomeric nuclei in the target. This then gives

$$\sigma_{trig} = S \cdot [A/(\tau \times F)]\,. \tag{2}$$

As a result, for the observed triggering effect $S = 2.9\%$ with the values of $A = 0.8$ cm^2 and $F = 4 \times 10^{15}$ e/s (~ 200 μA), the cross-section estimate $\sigma_{trig} = 4.2 \times 10^{-27}$ cm^2 can be deduced.

The most part of publications in which the principal possibility of ^{178m2}Hf isomer triggering is questioned used to be based on the contrary propositions – if the size of detected triggering effect is correct or some feature of the triggering process is really recorded, then the corresponding triggering cross-sections (for γ-ray absorption, etc.) and probabilities (for NEET effect, high multipolarity transitions, etc.) turn out to be orders of magnitude higher than one could expect from the available systematics. Now that is hardly the case. In the last published work on ^{178m2}Hf isomer triggering [13] the authors has obtained the upper limit for the magnitude of the triggering effect cross-section around 7×10^{-27} cm^2 keV, which is quite comparable with the upper limit from the null experiment [12] of about 3×10^{-27} cm^2 keV. If the real photon flux of around 3.3×10^{12} photons/cm$^2/s$ used in the experiment is taken into account instead of the spectral flux density applied to produce the above-mentioned estimate, one can obtain the upper limit for the cross-section magnitude of the triggering effect expressed in cm^2 (or barns) and it turns out to be about 4.6×10^{-24} cm^2 (or 4.6 barns). It means that in our case if all the losses of electron beam and produced bremsstrahlung radiation (including the shielding of ^{178m2}Hf isomer by Ta matrix, ineffectiveness of the wide-range bremsstrahlung radiation compared to the practically monochromatic photon beam at the SPring-8 beamline, etc.) and possible multiplication effects (for instant, when a single electron with the energy ≤ 30 keV can ionize more then a single atomic shell in Hf, etc.) are taken into account, then the averaged effectiveness of electron flux happens to be at the level of around 10^{-3} and it sounds more or less realistic.

And while the branching ratios or partial probabilities for an assumed intermediate state to decay back to the isomeric level [31] can really be very high when one supposes that to bypass the isomeric level the intermediate state should decay through any well-known excited level of ^{178}Hf, for instant 13^- level of 8^- band of ^{178}Hf [31], such particular scheme for the induced decay of ^{178m2}Hf isomer can have nothing to do with the real situation. For example, the intermediate state should not necessarily be a band head state and in this case its decay by an intraband transition, the probability of which used to be higher than the probability of crossover (or interband) transitions, is quite possible. On the other hand, the intermediate state can be so-called γ-soft one presenting the mixture of practically all K-values and for such excited level the decay probabilities to any nuclear levels with the same nuclear spin and parity could have rather comparable magnitudes. Moreover, the current theoretical study of possible NEET effect for ^{178m2}Hf isomer in the frame of strict collision theory [32] indicates that the above-mentioned controversy is not as drastic as it has been considered before as well ([13], [31]).

In summary, we have repeated the initial ^{178m2}Hf isomer triggering experiments using the isomeric source not used before and the new experimental setup upgraded for this experiment. We see the evidence for the triggering of ^{178m2}Hf isomer by observing the enhanced counting rates of all ground-state band transitions. Our data are consistent with an estimate for the triggering effect of $(2.9 \pm 0.7)\%$.

Additionally, it has been demonstrated that even using rather weak isomeric source the sensitivity of our ^{178m2}Hf isomer triggering experiments is much better than in the initial triggering experiments with dental x-ray machine.

More detailed conclusions can be made when much stronger isomeric source will be prepared and ready for use. In this case the increased emission of γ-rays could be detected in every separate transition supplying exclusively valuable information about possible scenarios and mechanisms of the induced acceleration of ^{178m2}Hf isomer decay. It would allow to conduct the coincidence measurements as well.

ACKNOWLEDGEMENTS

We are indebted to Prof. Valentine V. Chorny and his colleagues for their help in the development of new experimental setup and to Prof. Aleksey I. Feoktistov and Dr. Vladimir T. Kupryashkin for their help in various aspects of these measurements. Special thanks to Dr. Nikolay V. Strilchuk for the encouragement of this investigation.

References

1. C.B. Collins, F. Davanloo, M.C. Iosif, et al. Evidence for the Forced Gamma Emission from the 31-Year Isomer of Hafnium-178 // *Laser Phys.* 1999, v. 9, p. 8-11.

2. C.B. Collins, F. Davanloo, M.C. Iosif, et al. Accelerated Emission of Gamma Rays from the 31-yr Isomer of ^{178}Hf Induced by X-Ray Irradiation // *Phys. Rev. Lett.* 1999, v. 82, p. 695-698.

3. C.B. Collins, F. Davanloo, N.C. Zoita, et al. γ emission from the 31-yr isomer of ^{178}Hf induced by x-ray irradiation // *Phys. Rev. C.* 2000, v. 61, p. 054305.

4. C.B. Collins, F. Davanloo, M.C. Iosif, et al. Study of the gamma emission from the 31-yr isomer of ^{178}Hf induced by x-ray irradiation // *Phys. of Atomic Nuclei.* 2000, v. 63, p. 2067-2072.

5. C.B. Collins, A.C. Rusu, N.C. Zoita, et al. Gamma-Ray Transitions Induced in Nuclear Spin Isomers by X-Rays // *Hyperfine Interactions.* 2001, v. 135, p. 51-70.

6. C.B. Collins, N.C. Zoita, A.C. Rusu, et al. Scaling of Gamma-Ray Transitions Induced in Nuclear Spin Isomers by X-rays // *Laser Phys.* 2001, v. 11, p. 1-5.

7. C.B. Collins, N.C. Zoita, A.C. Rusu, et al. Tunable synchrotron radiation used to induce γ-emission from the 31 year isomer of ^{178}Hf // *Europhys. Lett.* 2002, v. 57, p. 677-682.

8. C.B. Collins, N.C. Zoita, F .Davanloo, et al. Accelerated γ-emission from isomeric nuclei // *Rad. Phys. and Chem.* 2004, v. 71, p. 619-625.

9. C.B. Collins, N.C. Zoita, F. Davanloo, et al. Accelerated Decay of the 31-yr Isomer of Hf-178 Induced by Low-Energy Photons and Electrons // *Laser Phys.* 2004, v. 14, p. 154-165.

10. V.I. Kirischuk, P. McDaniel, C.B. Collins, et al. // *The Proceedings of the 7th AFOSR Workshop "Isomers and Quantum Nucleonics".* Dubna, Russia, 2005, p. 99.

11. I. Ahmad, J.C. Banar, J.A. Becher, et al. Search for X-Ray Induced Acceleration of the Decay of the 31-Yr Isomer of ^{178}Hf Using Synchrotron Radiation // *Phys. Rev. Lett.* 2001, v. 87, p. 072503.

12. I. Ahmad, J.C. Banar, J.A. Becher, et al. Search for x-ray induced decay of the 31-yr isomer of ^{178}Hf using synchrotron radiation // *Phys. Rev. C.* 2005, v. 71, p. 024311.

13. J.J. Carroll, S.A. Karamian, R. Propri, et al. Search for low-energy induced depletion of ^{178}Hf^{m2} at the SPring-8 synchrotron // *Phys. Lett. B.* 2009, v. 679, p. 203-208.

14. C.B. Collins, C. D. Eberhard, J.W. Glesener, and J.A. Anderson. Depopulation of the isomeric state ^{180}Ta^{m} by the reaction ^{180}Ta$^{m}(\gamma,\gamma')^{180}$Ta // *Phys. Rev. C.* 1988, v. 37, p. 2267-2269.

15. C.B. Collins, J.J. Carroll, T.W. Sinor, et al. Resonant excitation of the reaction ^{180}Ta$^{m}(\gamma,\gamma')^{180}$Ta // *Phys. Rev. C.* 1990, v. 42, p. R1813-R1816.

16. J.J. Carroll, T.W. Sinor, D.G. Richmond, et al. Excitation of ^{123}Te^{m} and ^{125}Te^{m} through (γ,γ') reactions // *Phys. Rev. C.* 1991, v. 43, p. 897-900.

17. J.J. Carroll, M.J. Byrd, D.G. Richmond, et al. Photoexcitation of nuclear isomers by (γ,γ') reactions // *Phys. Rev. C.* 1991, v. 43, p. 1238-1247.

18. D. Belic, C. Arlandini, J. Besserer, et al. Photoactivation of ^{180}Ta^{m} and Its Implications for the Nucleosynthesis of Nature's Rarest Naturally Occurring Isotope // *Phys. Rev. Lett.* 1999, v. 83, p. 5242-5245.

19. V.I. Kirischuk, N.V. Strilchuk and V.A. Zheltonozhsky // *The Proceedings of the II International Conference "Frontiers of Nonlinear Physics".* Nizhni Novgorod, Russia, 2005, p. 477.

20. F.F. Karpeshin, M.B. Trzhaskovskaya, J. Zhang. Prospect of triggering the ^{178m2}Hf isomer and the role of resonance conversion // *Eur. Phys. J. A.* 2009, v. 39, p. 341-348.

21. I.N. Izosimov. Triggering of Nuclear Isomers via Decay of Autoionization States in Electron Shells (NEET) // *Laser Phys.* 2007, v. 17, p. 755.

22. S. Kishimoto, Y. Yoda, Y. Kobayashi et al. Nuclear excitation by electron transition on ^{197}Au by photoionization around the K-absorption edge // *Phys. Rev. C.* 2006, v. 74, p. 031301(R).

23. V. Kirischuk, A. Savrasov, N. Strilchuk and V. Zheltonozhsky. Precise energy measurements of the first-excited state in ^{197}Au // *Europhys. Lett.* 2012, v. 97, p. 32001.

24. A.Ya. Dzyublik. Photo-induced nuclear excitation by electron transition // *JETP Lett.* 2011, v. 93, p. 547-551.

25. S.A. Karamiana, J. Adama, D.V. Filossofov, et al. Accumulation of the ^{178m2}Hf isomeric nuclei through spallation with intermediate-energy protons of tantalum and rhenium targets // *JETP Lett.* 2002, v. 489, p. 448-468.

26. S.A. Karamian, J.J. Carroll, J. Adam, N.A. Demekhina. Production of the ^{178m2}Hf isomer using a 4.5-GeV electron accelerator // *JETP Lett.* 2004, v. 530, p. 463-472.

27. I.G. Goncharov, A.M. Dovbnya, Yu.M. Ranyuk, et la. LONGLIVING ^{178m2}Hf, ^{172}Hf, ^{150}Eu AND ^{133}Ba ISOTOPES PHOTOPRODUCTION STUDDING // *Problems of Atomic Science and Technology* 2007, v. 48, p. 22-25.

28. V.I. Kirischuk // In preparation.

29. R.B. Firestone, et al. *Table of Isotopes*, Eighth Edition. New York: "John Wiley and Sons", 1996.

30. C.B. Collins, F.W. Lee, D.M. Shemwell, et al. The coherent and incoherent pumping of a gamma ray laser with intense optical radiation // *J. Appl. Phys.* 1982, v. 53, p. 4645-4651.

31. M.R. Harston, J.J. Carroll. Limits on Nuclear Excitation and Deexcitation of ^{178}Hf^{m2} by Electron–Nucleus Coupling // *Laser Phys.* 2005, v. 15, p. 487-491.

32. A.Ya. Dzyublik. // In preparation.

ТРИГГЕРИНГ ИЗОМЕРА ^{178m2}Hf, ВНЕДРЁННОГО В Ta-МАТРИЦУ ПРИ ОБЛУЧЕНИИ 30 кэВ ЭЛЕКТРОНАМИ

А.Н. Довбня, С.С. Кандыбей, В.И. Кирищук, Ю.Н. Ранюк

Используя усовершенствованную экспериментальную установку, разработанную в Харьковском национальном университете и собраную в Киевском Институте ядерных исследований, изучался триггеринг изомера ^{178m2}Hf. В качестве мишени использовалась танталовая фольга толщиной 300 мкм с ^{178m2}Hf активностью около 100 Бк, которая облучалась электронным пучком с энергией 30 кэВ. Наблюдалось увеличение интенсивности всех переходов основной полосы. По полученным данным эффект триггеринга состовляет $(2.9 \pm 0.7)\%$ и качественная оценка сечения триггеринга соответсвует $\sigma_{trig} = 4.2 \times 10^{-27}$ см^2.

ТРІГГЕРІНГ ІЗОМЕРУ ^{178m2}Hf, ВБУДОВАННОГО В Ta-МАТРИЦЮ ПРИ ОПРОМІНЕННІ 30 кеВ ЕЛЕКТРОНАМИ

А.М. Довбня, С.С. Кандибей, В.І. Кирищук, Ю.М. Ранюк

Використовуючи вдосконалену експериментальну установку, розроблену в Харківському національному університеті та зібрану в Київському Інституті ядерних досліджень, вивчався тріггерінг ізомеру ^{178m2}Hf. В якості мішені використовувалась танталова фольга товщиною 300 мкм з ^{178m2}Hf активністю близько 100 Бк, яка опромінювалась пучком електронів з енергією 30 кеВ. Спостерігалося збільшення інтенсивності всіх переходів основної смуги. За отриманими даними ефект тріггерінга становить $(2.9 \pm 0.7)\%$ і якісна оцінка перетину тріггерінга відповідає $\sigma_{trig} = 4.2 \times 10^{-27}$ см^2.