PRODUCTION OF ^{178m2}Hf ON A 1.2-GeV ELECTRON ACCELERATOR

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A Ge(Li) γ-detector is used for investigations of the spectrum of γ-radiation of a tantalum plate that served as a radiator to obtain bremsstrahlung beams on the 1.2-GeV electron accelerator of the Kharkiv Institute of Physics and Technology. The plate was positioned in the electron guide of the accelerator from the moment of its start in 1966 and till its shutdown in 1990. Cascade lines arisen in the radioactive decay of ^{178m2}Hf isomer (half-life $T = 31$ yr) and other long-lived isotopes were discovered in the radiation spectrum. The number of ^{178m2}Hf nuclei in the Ta plate amounts to $(2.7 \pm 0.3) \times 10^{11}$. The obtained results are compared to data of other authors.

Study of photonuclear reactions with high-spin isomers represents an important instrument for investigation of the quasiparticle structure of the giant resonance and the phenomenon of K-mixing at high excitation energies. An interest in such reactions is also conditioned by possible applications, for example the search for effective methods of γ-pumping of a nuclear laser [1].

In 1999, a sensational information about the observation of the stimulated decay of long-lived ^{178m2}Hf isomer was published, which opened a way to the creation of a γ-laser [2]. This isomer represents a four-quasiparticle, 16^+, long-lived (31 yr) yrast trap. It is considered as the unique object for such investigations. The investigations were performed by a group of scientists under the direction of Carl Collins, the leader of the Center for Quantum Electronics, University of Texas in Dallas, USA. The essence of the investigation consisted in the acceleration of the isomer decay due to the influence of radiation produced by a dental X-ray apparatus. This work induced a chain reaction of similar investigations. Some of them didn't confirm the optimistic conclusions of work [2]. The review of these works and experiments performed in 1998–2003 is given in [3, 4].

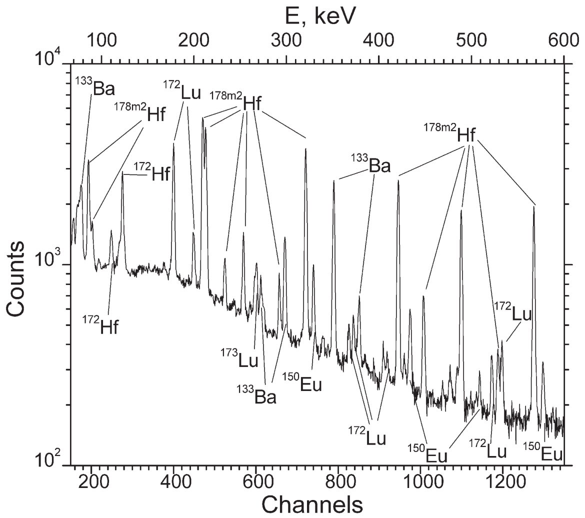
In order to investigate the phenomenon of stimulated decay of ^{178m2}Hf, one needs a microgram or even the larger number of atoms of this isomer. It doesn't occur in nature and should be produced with the help of particle accelerators or nuclear reactors.

A substantial quantity of ^{178m2}Hf was obtained in Los Alamos by means of the bombardment of Ta with protons with an energy of 800 MeV using a high-intensity accelerator (former LAMPF). The advantage of this method lies in the possibility to accumulate this isomer as a by-product from a massive tantalum block in which a proton beam is absorbed in the course of other experiments [5]. However, the isomer material produced in this way contains a high activity of other radionuclides, and radioactivity remains high even after radiochemical selection of the hafnium fraction. ^{172}Hf with a half-life of 1.87 yr represents the most problematic admixture.

The possibility of the generation of ^{178m2}Hf during the reactions of fission by medium-energy protons was systematically studied in 2002–2004 for Ta, W, and Re nuclei on the Dubna 660-MeV synchrocyclotron. However, no scheme was proposed for avoiding the parallel production of high-intensity harmful radioactivity [6].

A ^{178m2}Hf source of better quality was successfully produced in the reaction ^{176}Yb(^{4}He, 2n) using a 36-MeV beam of ^{4}He ions and a chemical procedure of reprocessing of the Yb target [7]. But the problem of refinement of the isomer from stable ^{178}Hf wasn't solved yet.

It is known [8] that the ^{179}Hf(n, 2n)^{178m2}Hf reaction is characterized by the significant cross section at an energy of primary neutrons of 14 MeV. But its absolute



yield is limited by the weak intensity of present (d+T)-sources of neutrons.

An attempt was made to observe the formation of ^{178m2}Hf by means of the irradiation of natural hafnium in a reactor [9]. It was shown that a noticeable yield was observed due to the ^{178}Hf(n,n) reaction caused by neutrons – the products of nuclear fission.

The possibility of the generation of ^{178m2}Hf was investigated using a bremsstrahlung beam of the Erevan electron synchrotron with a limiting energy of 4.5 GeV [10]. The tantalum target was bombarded in 1986 for another purpose and fortunately kept safe, which provided the excellent conditions for observation of the 31-yr ^{178m2}Hf isomer. After the measurements of the spectrum and the analysis of results, which was carried out under optimal conditions as for backgrounds, a predicted value of the intensity of generation of ^{178m2}Hf on the electron synchrotron, which amounted to 3×10^9 atoms/(s $\times$ 100 μA), was obtained.

This paper contains the results of measurements of the induced activity in a tantalum radiator of the 2-GeV linear electron accelerator of the Kharkiv Institute of Physics and Technology.

The Kharkiv linear accelerator started operating in 1966. It provided a possibility to work with a bremsstrahlung beam. For this purpose, a tantalum plate (radiator) of 0.3 mm in thickness was set at the output of the accelerator on the way of the electron beam.

In September 2006, the tantalum radiator was demounted and placed on a detector for analysis of γ-radiation. The detector represented a Ge(Li) spectrometer with a working volume of 40 cm^3 and an energy resolution of 2.5 keV. Tantalum was placed directly on the detector. With the help of a special computer code, the energies and intensities of lines were obtained. The spectrum includes more than 100 of them.

Figure 1 shows a fragment of the spectrum, where the γ-lines of ^{178m2}Hf are concentrated, with 13 of 15 cascade lines from the ^{178m2}Hf decay given in the table in [11]. Two lines – 277.4-keV (1.38%) and 309.5-keV (0.019%) – didn't manifest themselves in the spectrum due to a low decay probability. There are no essential deviations of the relative intensities of the lines. The widths of the γ-lines agree with the predicted ones, which testifies to the absence of overlapping the investigated lines with one another as well as with the lines of other reactions and background lines. Two pairs of the lines represent an exclusion: the lines at 88.9 and 93.2 keV, as well as the lines at 213.4 and 216.7 keV, have partially overlapped due to the insufficient resolution of the detector. Natural background γ-lines are also present in the spectrum, which didn't influence the registration of ^{178m2}Hf. In the spectrum, we discovered the lines of ^{172}Hf (1.87 yr), ^{150}Eu(36.8 yr), and ^{133}Ba(10.5 yr) that remained in tantalum due to large decay periods, while the other radioisotopes that had shorter half-lives had time to decay. ^{172}Hf decays into ^{172}Lu that has the half-life $T = 6.7$ days. The measurements of the areas of the corresponding lines gave a possibility to determine the yield of each isotope after taking into account the decay characteristics, detector efficiency, and quantum characteristics. The corresponding parameters were taken from [11]. The number of ^{178m2}Hf nuclei was determined by means of measuring the intensities of various γ-lines. The results of measurements agree with one another within statistical errors. The error of determination of the number of generated nuclei amounts to 3–5%.

The work performed with archives testifies to the fact that, during the first years of its operation, the Kharkiv accelerator was used as a source of bremsstrahlung radiation. This time interval amounts to $\sim$ 5 yr (1966–1970). On the whole, it worked for 10 000 h at an electron energy of above 1 GeV and a current of 0.3 μA.

Work [10] gives the total and averaged cross sections for the ^{181}Ta(γ, p2n) ^{178m2}Hf reaction, in which ^{178m2}Hf was generated. In what follows, we present the technique for the calculation of these cross sections.

Let's use the concept of "equivalent" photons, whose number is evaluated by the relation

$$n_q = n_e t/2, \qquad (1)$$

Comparison of the obtained results for ^{178m2}Hf nucleus

Number of atoms	σ, MeV· barn	$\bar{\sigma}$, cm^2	Source
$(5.9 \pm 0.2) \times 10^{11}$	0.033	3.0×10^{-29}	Our data
$(1.57 \pm 0.08) \times 10^{8}$	0.0255	2.55×10^{-29}	[10]

where n_q denotes the number of equivalent photons, n_e is the number of electrons that passed through the target, and t is the target thickness in radiation units.

According to (1), the intensity of bremsstrahlung radiation summed over 5 years amounts to $\sim 4.5 \cdot 10^{18}$ "equivalent" photons.

As for the ^{181}Ta(γ, p2n)^{178m2}Hf reaction, we can state that its effective threshold is approximately equal to 50 MeV, while the cross section represents a constant value in the range 50 MeV – 1.050 GeV.

In the "rectangular" approximation, the spectrum of bremsstrahlung photons can be presented as

$$n_\gamma \sim 1/E_\gamma, \tag{2}$$

and the relation between the cross section of the photonuclear reaction and the yield is

$$\sigma_\gamma = \sigma_q/(\ln E_0 - \ln E_{\rm th}), \tag{3}$$

where σ_q stands for the yield per an equivalent photon, E_0 is the electron energy, and $E_{\rm th}$ is the effective threshold of the reaction.

In Table, we present the obtained results compared with those in [10].

As one can see from Table, the obtained cross sections agree well with one another.

An important quantity that characterizes the suitability of a nuclear reaction for the isomer production and is important for the comprehension of the mechanism of a nuclear reaction is the isomer ratio σ_m/σ_g, where σ_m is the cross section of the generation of an isomer, while σ_g is the cross section of the generation of a nucleus in the ground state. This ratio was indirectly determined in [10] and amounts to

$$\sigma_m/\sigma_g = 0.032, \tag{4}$$

where σ_m is the cross section for the Ta→ ^{178m2}Hf reaction and σ_g is the cross section for the Ta→ ^{178}Hf reaction.

The main result of the given paper is the fact that we have managed to find and to investigate a Ta plate that now includes $(2.7 \pm 0.1) \times 10^{11}$ atoms of ^{178m2}Hf, that can be used in future for the experimental study of the deexcitation of high-spin isomers, and have obtained the cross sections of the production of ^{178m2}Hf.

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НАПРАЦЮВАННЯ ^{178m2}Hf НА ПРИСКОРЮВАЧІ ЕЛЕКТРОНІВ НА ЕНЕРГІЮ 1,2 ГеВ

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Р е з ю м е

За допомогою Ge(Li) γ-детектора досліджено спектр γ-випромінювання танталової пластини, що слугувала радіатором для отримання пучка гальмівного випромінювання на прискорювачі електронів на енергію 1,2 ГеВ Харківського фізико-технічного інституту. Пластина перебувала в електронопроводі прискорювача з моменту його запуску у 1966 р. і до зупинки у 1990 р. У спектрі випромінювання виявлено каскадні лінії радіоактивного розпаду ізомеру ^{178m2}Hf (період піврозпаду $T = 31$ рік) та інших довгоживучих ізотопів. Кількість ядер ^{178m2}Hf у пластині Ta становить $(2,7 \pm 0,3) \cdot 10^{11}$. Отримані результати порівняно з даними інших авторів.