ISSN 1547-4771, Physics of Particles and Nuclei Letters, 2021, Vol. 18, No. 3, pp. 319–322. © Pleiades Publishing, Ltd., 2021.
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PHYSICS OF ELEMENTARY PARTICLES AND ATOMIC NUCLEI. EXPERIMENT

Studying the Excitation of *K*-Isomers of ^{180,182}Hf and ^{177}Lu in (γ, α) Reactions

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Received November 11, 2020; revised November 20, 2020; accepted November 20, 2020

Abstract—The weighted average population yields of ^{180m}Hf, ^{182m}Hf, and ^{177}Lu have been measured in (γ, α) reactions at the 40 and 55 MeV boundary energies of bremsstrahlung γ quanta for the first time. The simulation is carried out as part of the TALYS-1.9 program code.

Keywords: K-isomers, activation method, gamma spectroscopy, weighted average yields, model TALYS-1.9

DOI: 10.1134/S1547477121030134

INTRODUCTION

Investigating cross sections for the excitation of high-spin isomers is urgent for understanding the mechanisms of nuclear reactions. When such isomeric states are excited, different reactions can manifest different contributions from statistical and nonstatistical reaction channels. ^{180,182}Hf isomers in this series are interesting research objects, because these *K*-forbidden isomers (ΔK= 8) are similar and have the same $I^{\pi} = 8^{-}$ and similar values of excitation energy, 1141 and 1173 keV, respectively.

Of particular interest is the study of (γ, α) reactions with the population of these nuclei. There are few data on (γ, α) reactions. The main reason for this is that their cross sections are significantly lower compared to (γ,*n*) channel due to the Coulomb barrier. At the same time, states that are often inaccessible for the (γ, n) channel can be excited in (γ, α) reactions. Also, for photonuclear reactions with the emission of alpha particles, a significant contribution of direct and semidirect processes is expected, especially when populating high-spin *K*-isomers. To date, reactions ^{184}W (γ, α)^{180m}Hf and ^{186}W (γ, α)^{182m}Hf have not been studied, but the reaction ^{181}Ta (γ, α)^{177}Lu was investigated in [1, 2] for bremsstrahlung photons with a boundary value of energy of 23 and 37 MeV, respectively. However, in [1] for E_{bd} = 23 MeV, only output ^{177}Lu with respect to reaction yield ^{181}Ta (γ, *n*)^{180}Ta was obtained.

Based on the foregoing, the goal of our work is to study the excitation of ^{180m}Hf, ^{182m}Hf, and ^{177}Lu nuclei in (γ, α) reactions for the boundary energies of bremsstrahlung γ quanta of 40 and 55 MeV.

1. EXPERIMENT AND MEASUREMENT RESULTS

The cross sections were studied by the method of induced activity on bremsstrahlung γ beams for electrons with energies of 40 and 55 MeV. Several series of irradiation and measurements were carried out. The duration of irradiation of the samples was 60–80 min.

The targets were made from metallic tungsten and tantalum of natural isotopic composition. When E_{bd} = 40 MeV, the target consisted of a rectangular tantalum strip and a square tungsten strip 0.6 × 2 × 0.011 cm in size and weighing about 220 mg and 2 × 2 × 0.0057 cm and weighing about 441 mg, respectively. When E_{bd} = 55 MeV, the sample was a square strip of tantalum and a rectangular strip of tungsten measuring 2 × 2 × 0.02 cm and weighing about 1.3 g and 1.3 × 1.5 × 0.005 cm and weighing about 186 mg, respectively. The well-studied nuclear reaction ^{181}Ta (γ, *n*)^{180}Ta was used to calculate the flux of bremsstrahlung γ quanta in both cases [3].

The induced activity was measured with γ spectrometers based on HPGe detectors with a detection efficiency of 15–40% compared to a NaI(Tl) detector with dimensions 3' × 3" and an energy resolution of 1.8–2 keV on γ lines of ^{60}Co. The γ spectra were processed using the Winspectrum program [4]. The detection efficiency of γ quanta from decay was deter-

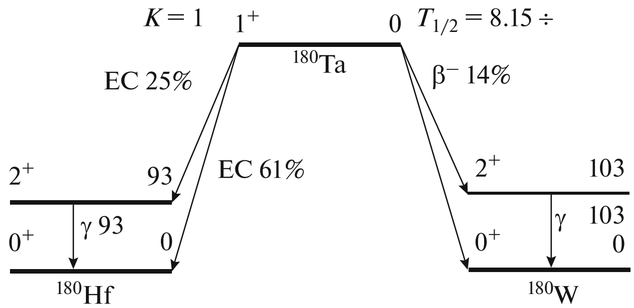

Fig. 1. Fragment of the decay scheme of ^{180}Ta.

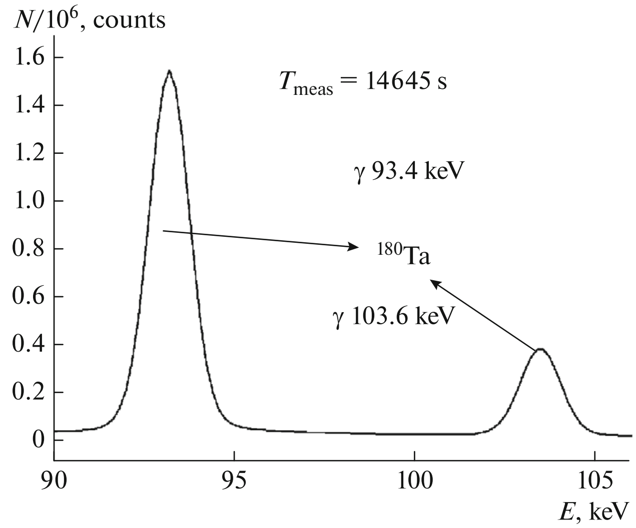

Fig. 2. Fragment of the γ spectrum of tantalum irradiated with bremsstrahlung γ quanta with $E_{\mathrm{bd}} = 55$ MeV.

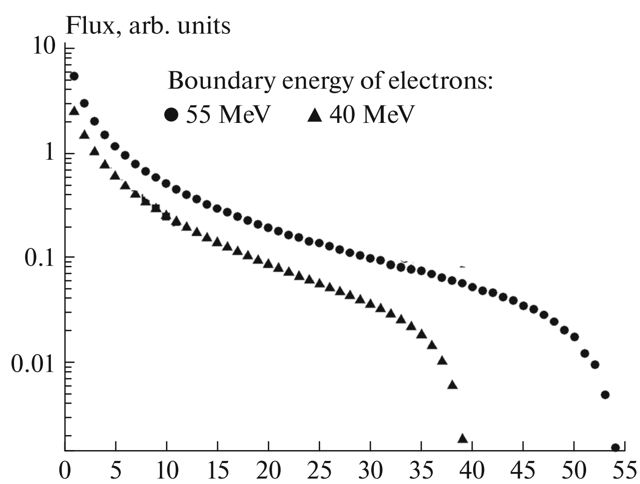

Fig. 3. Spectrum of bremsstrahlung γ quanta for different values of electron energy.

mined using standard calibration sources of ^{152,154}Eu and ^{133}Ba.

To determine the weighted average outputs ($\langle \mathrm{Y} \rangle$) reactions, fluxes of bremsstrahlung γ quanta on targets need to be known. To obtain them, we determined the intensities of the 93.3- and 103.6-keV γ lines accompanying the decay of ^{180}Ta (see Figs. 1, 2) and weighted average reaction yield of ^{181}Ta $(\gamma,n)^{180}$Ta.

The weighted average yield of the above reaction was determined as a result of the convolution of the tabular values of the cross sections of this reaction for monochromatic γ quanta with a step of 1 MeV with the relative values of the spectrum of bremsstrahlung γ quanta simulated in Geant4 [5] (see Fig. 3) by the formula, b:

$$Y_{\mathrm{mon}}^{\mathrm{av}} = \frac{\sum_{i=1}^{N} \sigma_i \varphi_i}{\sum_{i=1}^{N} \varphi_i}, \quad (1)$$

where σ_i is tabular values of the reaction cross sections ^{181}Ta $(\gamma, n)^{180}$Ta for monochromatic γ quanta [3]; φ_i are the relative flux values of the bremsstrahlung gamma spectrum simulated in Geant4, reduced to the threshold response values on the monitor.

After that, the fluxes of bremsstrahlung γ quanta were calculated using the formula $\gamma/(\mathrm{cm}^2\ \mathrm{s})$:

$$F = \frac{S\lambda A}{(1 - e^{-\lambda t_{\mathrm{expos}}}) e^{-\lambda t_{\mathrm{cool}}} (1 - e^{-\lambda t_{\mathrm{meas}}}) \xi k \alpha Y_{\mathrm{mon}}^{\mathrm{av}} N_{\mathrm{A}} m p}, \quad (2)$$

where S is areas of photopeaks that accompany the decay of ^{180}Ta; α is quantum yields of γ quanta in the decay of ^{180}Ta; ξ is the efficiency of registration of γ quanta accompanying the decay of nuclei of reaction products on the monitor target; t_{irr}, t_{cool}, and t_{meas} are the times of irradiation, cooling, and measurement, respectively, s; k is the coefficients of self-absorption of γ quanta of decay; p is the absolute content of ^{181}Ta in a natural mixture; $N_{\mathrm{A}} = 6.02 \times 10^{23}$ is Avogadro's number; $Y_{\mathrm{mon}}^{\mathrm{av}}$ is the weighted average reaction yield of ^{181}Ta $(\gamma, n)^{180}$Ta calculated according to (1); m is the mass of tantalum targets normalized per unit area, g/cm^2; $A = 181$ is the mass number of tantalum atoms, Da; and λ is the decay constant of ^{180}Ta, s^{-1}. The values λ, k, α, A, and p are taken from [6]; S is taken from experimental γ spectra and ξ from calibration curves, additionally verified by simulation in Geant4.

Further, according to formula (2), using these fluxes and corrections for the difference in energy thresholds, we calculated $\langle \mathrm{Y} \rangle$ reactions (γ, α) on natural tungsten and tantalum, leading to the activation of K-isomers in $^{180.\ 182}$Hf and of the ground state of ^{177}Lu. Fragments of decay schemes ^{180m}Hf, ^{182m}Hf, and ^{177}Lu are shown in Fig. 4. To obtain weighted average settle-

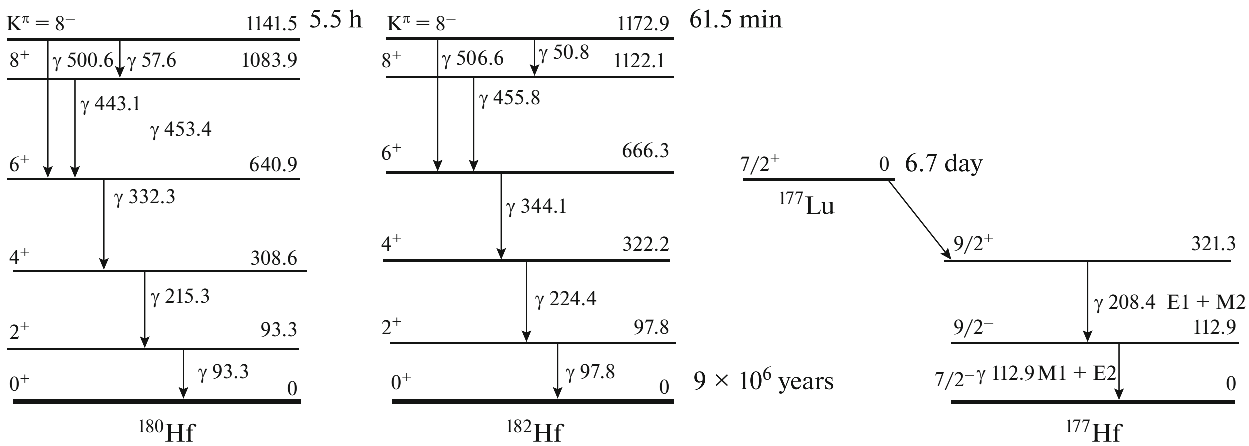

Fig. 4. Fragments of decay schemes: ^{180m}Hf, ^{182m}Hf, and ^{177}Lu

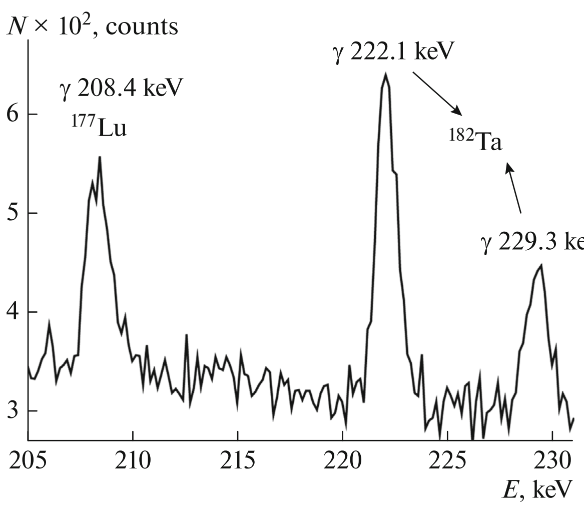

Fig. 5. Fragment of the γ spectrum of a Ta target irradiated at E_{bd} = 55 MeV.

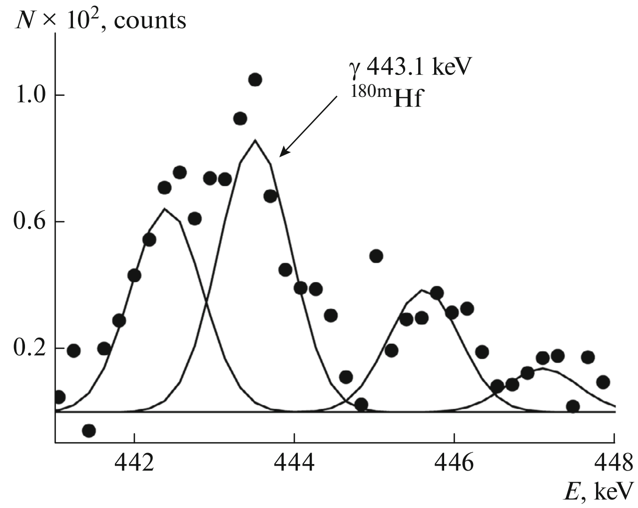

Fig. 6. Fragment of the γ spectrum of the ^{nat}W target irradiated at E_{bd} = 55 MeV (reaction ^{184}W (γ, α)^{180m}Hf).

ment yields of ^{177}Lu and isomeric states ^{180m}Hf, ^{182m}Hf, the areas of the photopeaks of the γ lines 208.4 keV, 443.2 keV and 224.4 keV were determined, respectively (see Fig. 5–7). The results are summarized in Table 1.

3. DISCUSSION

To assess the mechanisms of the studied nuclear reactions, we simulated these processes using the TALYS-1.9 program code. More details about modeling using this code are described in [7]; it takes into account the dominant statistical and preequilibrium processes.

In theoretical calculations, the cross sections are determined with a step of 1 MeV for monochromatic γ quanta; then, according to (1), the weighted average yields of the reactions under study are calculated.

The results of our calculations are shown in Table 1. As can be seen, for both boundary values of energy,

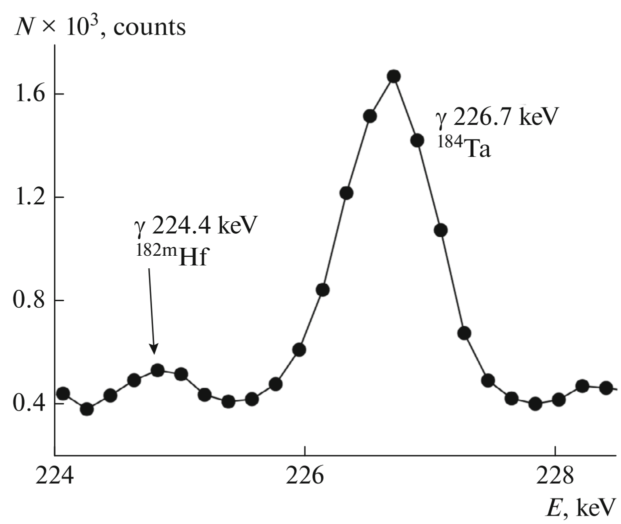

Fig. 7. Fragment of the γ spectrum the ^{nat}W target irradiated at E_{bd} = 55 MeV (reaction ^{186}W (γ, α)^{182m}Hf).

Table 1. Experimental weighted averages $\langle Y \rangle$ operating time outputs $^{180}Hf^{m}$, $^{182}Hf^{m}$ and ^{177}Lu

Reaction	E_{bd}, MeV	$\langle Y \rangle$, exp, μb	$\langle Y \rangle$, TALYS-1.9, μb
$^{184}W(\gamma, \alpha)^{180m}Hf$	40	1.0(2)	0.004
$^{184}W(\gamma, \alpha)^{180m}Hf$	55	2.5(3)	0.005
$^{186}W(\gamma, \alpha)^{182m}Hf$	40	5.7(17)	0.001
$^{186}W(\gamma, \alpha)^{182m}Hf$	55	2.8(9)	0.003
$^{181}Ta(\gamma, \alpha)^{177}Lu$	40	33(8)	0.16

agreement between the theoretical and experimental data is not achieved for either the default parameters or for their variation within reasonable limits. The theoretical yields remain below the experimental values by about 3 orders of magnitude.

Therefore, we have considered the mechanism of semidirect reactions [8]. With this approach, an α particle escapes from the nucleus in time $t \sim 10^{-21}$ s, and the formation time of the Coulomb barrier is 10^{-18}–10^{-19} s. [9.10]. After the emission of an α particle, the nucleus decays through ordinary statistical transitions. In our case, the $^{180,182}Hf$ and ^{177}Lu residual nuclei decay is the same as in the case of (γ, γ′) reactions [11]. The calculated weighted average outputs in the TALYS-1.9 code for the constant temperature and Fermi gas level density model [12], which is used by default, give quantities $\langle Y \rangle \approx 2$–$3$ μb for $^{180,182}Hf$ and, for ^{177}Lu, it is an order of magnitude larger; i.e., they are in good agreement with experiment.

CONCLUSIONS

Weighted average yields of $^{181}Ta(\gamma, \alpha)^{177}Lu$, $^{184}W(\gamma, \alpha)^{180m}Hf$, and $^{186}W(\gamma, \alpha)^{182m}Hf$ nuclear reactions have been measured for the first time at $E^{max} = 40$ and 55 MeV. The simulation results, within the framework of the TALYS-1.9 program code, demonstrate the dominance of nonstatistical semidirect processes.

FUNDING

This research has been supported by the Interdisciplinary Scientific and Educational School of Moscow University "Photonic and Quantum technologies. Digital medicine."

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