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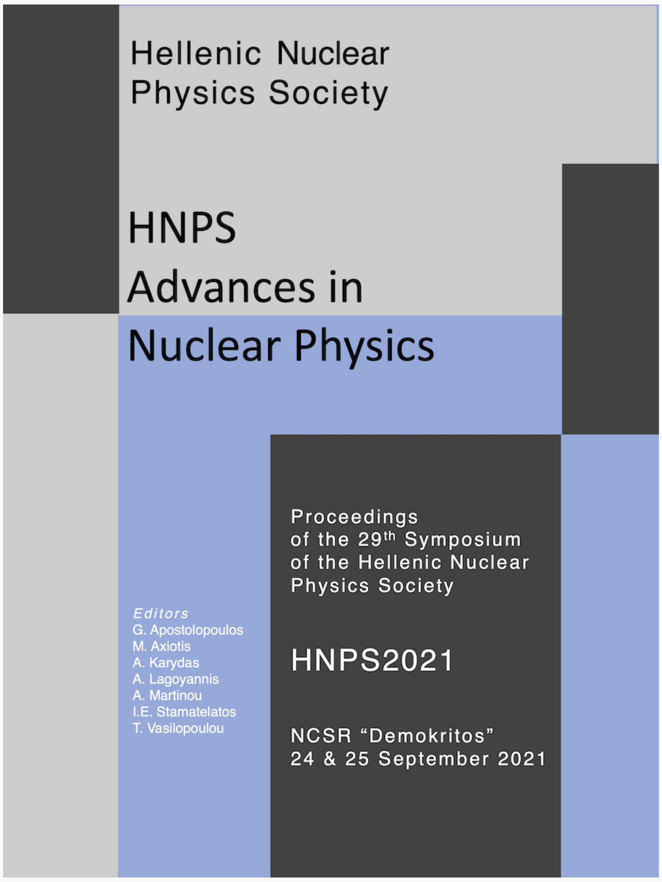

Study of the 176Hf(n,2n)175Hf cross section at 18.9 MeV

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Study of the ^{176}Hf(n,2n)^{175}Hf cross section at 18.9 MeV

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Abstract In this study measurements of experimental cross section for the ^{176}Hf(n,2n)^{175}Hf reaction were carried out, using the activation technique. The neutron beam energy at 18.9 MeV was produced via the ^{3}H(d,n)^{4}He reaction at the 5.5 MeV Tandem Van de Graaf accelerator laboratory of NCSR "Demokritos". A thin metallic foil of natural Hf was used, while for the determination of the neutron flux at the target position reference Al foils were placed in the front and the back of hafnium. The irradiation was continuous for 28 hours leading to a total neutron fluence of 10^{10} n/cm^2 and a BF_3 detector was used for monitoring the neutron flux during the irradiation. After the end of irradiation, the activity of the Hf target and the reference foils were measured off-line by two HPGe detectors. Both detector efficiencies were obtained using a calibrated ^{152}Eu source, placed in the same distance as the target and the reference foil. The ^{176}Hf(n,2n)^{175}Hf reaction has been corrected from the contribution of ^{177}Hf(n,3n)^{175}Hf. Theoretical calculations of the ^{174}Hf(n,2n)^{175}Hf, ^{176}Hf(n,2n)^{175}Hf and ^{180}Hf(n,n′γ)^{180m}Hf reaction cross-sections have also been performed using the nuclear statistical code "EMPIRE 3.2.3" and they have been compared with the data.

Keywords cross section measurements, Empire

INTRODUCTION

Neutron nuclear reactions can provide significant information in the field of nuclear physics and applications. Hafnium (Hf) is one of the rare-earth isotopes with a relative large neutron total cross-section in the thermal neutron energy region and neutron induced reactions in reactor materials could lead to the production of long-lived isomeric states of Hf isotopes. Hf is often used for reactor control rods specifically in nuclear submarines as well as in several industrial applications due to its excellent mechanical and chemical properties [1]. Thus, the study of neutron cross-sections on Hf isotopes is of great importance for basic research in Nuclear Physics as well as for nuclear applications while the existing experimental data are scarce and discrepant.

EXPERIMENTAL DETAILS

The experiment was performed at the 5.5 MV Tandem accelerator of N.C.S.R. "Demokritos". The neutron beam energy at 18.9 MeV was produced via the ^{3}H(d,n)^{4}He reaction, using a Ti-T target and a deuteron beam at 3.45 MeV. The Hf foil was irradiated along with other high purity foils (Au, Tl, Ge, and Al). The setup of the experiment is presented in Fig. 1, while the schematic representation of the target assembly is shown in Fig. 2. The neutron beam flux was monitored by a BF3 detector placed at a distance of 3 m from the neutron source.

After the end of irradiation (~28 hours) the activities of the Hf target and the reference foils were measured off-line by three HPGe detectors (80%) characterized with ^{152}Eu sources. One of the detectors is shown in Fig. 3. The samples were placed at a 10 cm distance from the detector window. Of all five isotopes of natural Hf (^{180,179,178,177,176,174}Hf) only the ^{176}Hf(n,2n)^{175}Hf reaction could be measured in this experiment. The characteristic γ-ray from the residual nucleus ^{175}Hf, with a half-life of 70 d, is the 343.4 keV one (Iγ=84%).

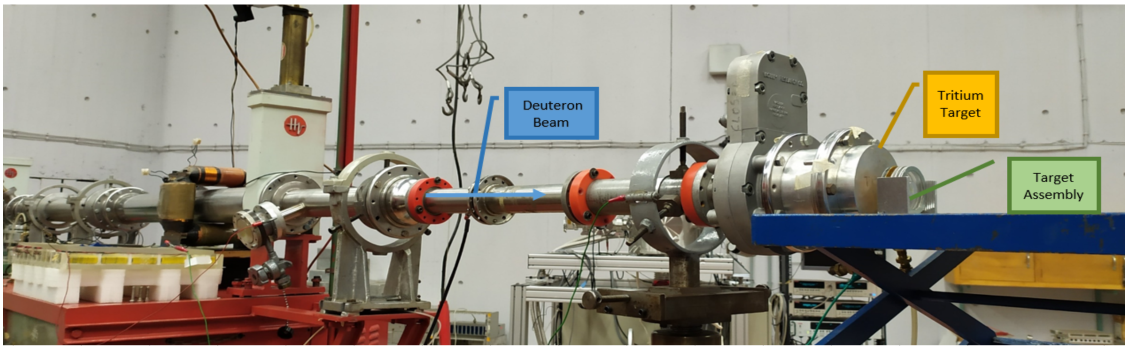

Figure 1. *The setup of the experiment*

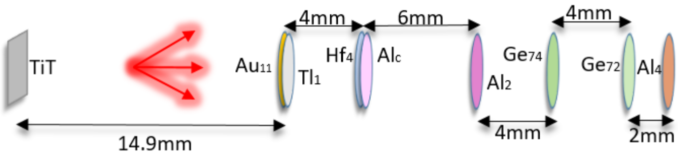

Figure 2. *Schematic representation of the target assembly*

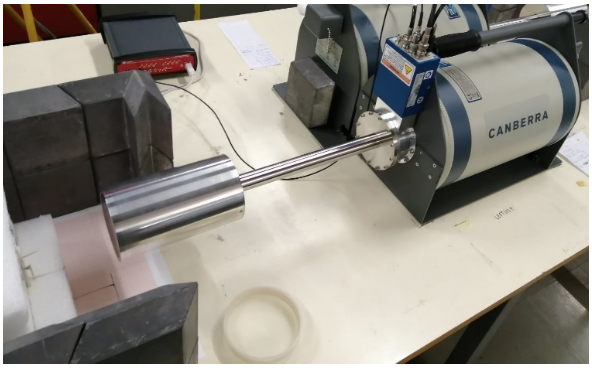

Figure 3. *One of the HPGe detectors*

Determination of neutron flux

A thin metallic foil of natural Hf was used along with reference foils of Al and Au for the determination of the neutron flux at the target position through the ^{27}Al(n,α)^{24}Na and ^{197}Au(n,2n)^{196}Au reactions. Extensive Monte Carlo simulations with MCNP5 code [2] were also used for the neutron flux determination. The results of the simulations and the experimental values of the neutron fluence at the reference foils of Au and the Al, are shown in Fig. 4 and they seem to be in very good agreement. The value of the total neutron fluence at the Hf target , as resulted from the simulations, was ~10^{10} n/cm^2.

RESULTS AND THEORETICAL CALCULATIONS

The cross section σ was determined using the following expression :

$$\sigma = \frac{N_P}{N_T} \cdot \frac{1}{\Phi} \tag{1}$$

Where:

- N_p : The produced nuclei ($N_p = \frac{N_\gamma}{\varepsilon \cdot I_\gamma \cdot D \cdot F \cdot f_c}$)
    - Nγ : The counts of the γ-ray peak
    - ε : The efficiency of the detector at 343.4 keV
    - Iγ : The intensity of the γ-ray peak (343.4 keV)
    - D : A correction factor relative to the time interval from the end of irradiation to the beginning and end of the measurements
    - F : The internal absorption of the 343.4 keV γ–ray in the target
    - fc : A factor that takes into account the fluctuations of the beam flux and the produced nuclei which decayed during irradiation
- N_T : The number of target nuclei ($N_T = \frac{m \cdot N_A}{A} \cdot Abundance$)
    - m : The mass of the target
    - NA : Avogadro constant
    - A : Mass number of the isotope
- Φ : Neutron flux resulted from the reference foils and MCNP simulations

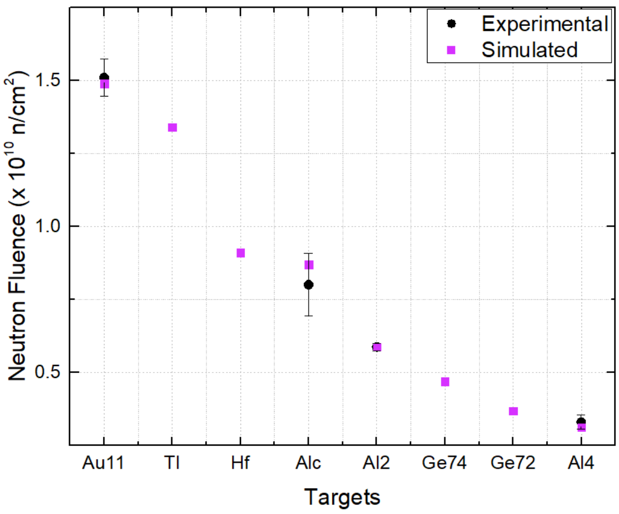

Figure 4. *Experimental fluences in the reference foils along with the simulated ones*

The desired cross section was contaminated from the ^{177}Hf(n,3n)^{175}Hf and the ^{179}Hf(n,γ)^{180}Hf reactions with the latter being negligible. The counts produced by the ^{177}Hf(n,3n)^{175}Hf reaction at the γ-energy of 343.4 keV were calculated using the cross section from ENDF/B-VIII.1 [4]. These counts, which corresponded to the 25% of the total ones, were then subtracted from the total number of counts of the 343.4 keV peak and the remaining counts were used to deduce the cross section of the ^{176}Hf(n,2n)^{175}Hf reaction. The resulted cross section value is σ=(1.33±0.34) b and is shown in Fig. 5.

Theoretical calculations based on the compound nucleus theory of Hauser-Feshbach, were perfomed in the energy range 8-20 MeV using the Empire 3.2.3 code [5] and are presented in Fig. 5 along with the experimental point and the data available in literature.
The basic input in the Empire code includes:

- Optical model parameters by F.D. Becchetti, Jr. and G.W. Greenlees [6]
- Empire level density models [7]
- Enhanced Generalized Superfluid Model (EGSM)
- Generalized Superfluid Model (GSM)
- Hartee-Fock-Bogoliubov Microscopic (HFBM)

The level density model that better describes the data is EGSM, as seen in Fig. 5. Further measurements are planned to be performed in the energy region of 15-21 MeV.

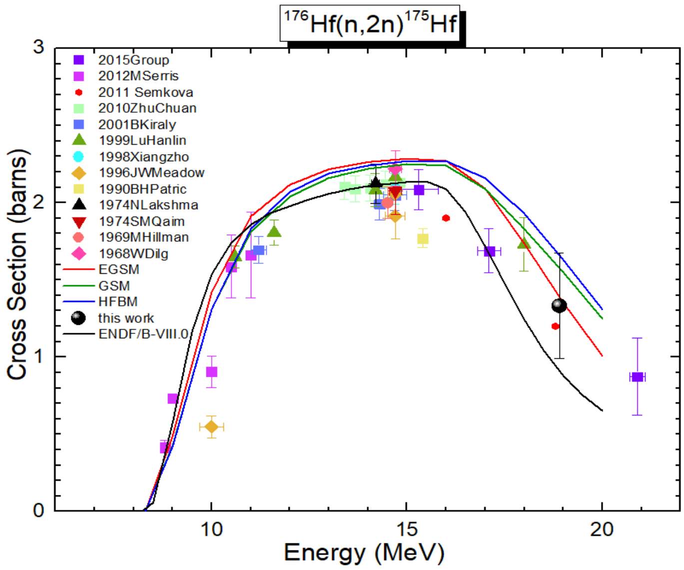

Figure 5. *Experimental point of the present work at 18.9 MeV, along with data from literature [4] and theoretical calcilations.*

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