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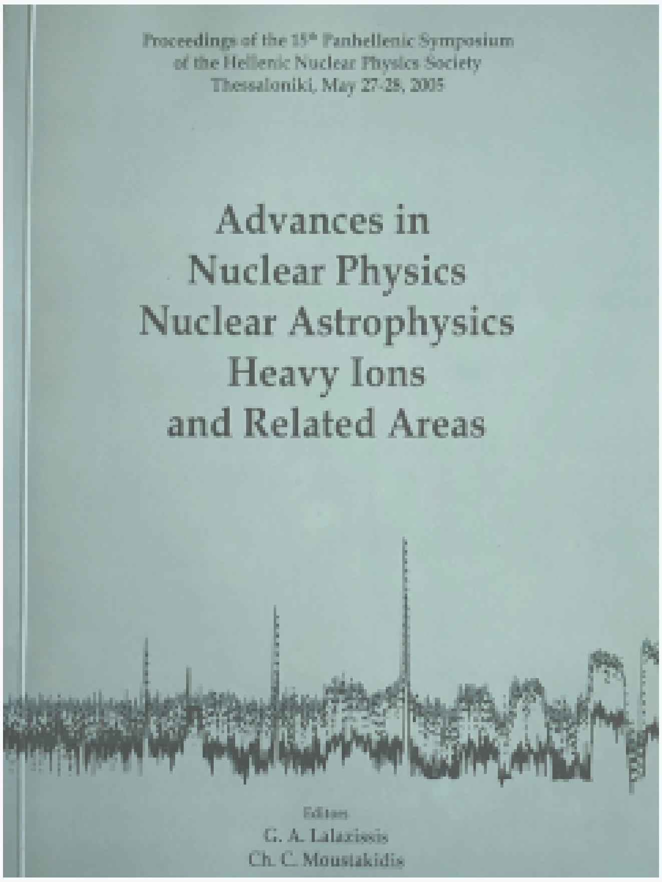

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Abstract

Cross section measurements of neutron induced reactions on isotopes of Ge and Hf have been determined at energies 8.8, 9.6, 10.6, 11.1, 11.4 MeV using the activation technique. Neutrons produced by the ^{2}H(d,n)^{3}He reaction were used to irradiate pellets of natural Ge and HfO_2. The neutron flux at the target position was determined using the ^{27}Al(n,α)^{24}Na, ^{93}Nb(n,2n)^{92m}Nb and ^{197}Au(n,2n)^{196}Au reference reactions. HPGe detectors of relative efficiency ε_r=80% and 55% were used to determine the decay of the produced unstable nuclei. The cross section values were compared with those taken from the literature.

1 Introduction

Studies of fast neutron-induced reactions are of considerable importance for testing nuclear models as well as for practical applications especially in reactor physics. At excitation energies up to 20 MeV many exit channels such as (n,p), (n,α) and (n,2n) are open, which may proceed via different reaction mechanisms as direct, compound and pre-compound ones. Statistical model calculations of neutron induced reactions are often discrepant by a factor of 2 or more comparing with the data [1]. Experimental data over a wide energy range are needed to allow for the reliable investigation of model parameters and for the development of improved models. Furthermore, in recent years, the measurement of isomeric to ground state cross section ratios for the formation of residual nuclei has attracted considerable attention. Especially, the yield to the high spin isomer in the product nucleus is strongly dependent on the level scheme and the spin distribution of the level density involved in the calculations. Apart from this primary interest, in the case of Ge isotopes there are additional technological applications related to the radiation damage on Ge detectors.

2 Experimental procedure

Cross section measurements of neutron induced reactions on natural targets of Ge and Hf have been performed at the 5.5 MV Tandem accelerator of the NCSR "Demokritos". The neutrons were produced via the $^{2}H(d,n)^{3}He$ reaction by using a cylindrical gas cell with dimensions 3.7 × 1 cm, maintained at a pressure of about 1.2 bar and air cooled during the irradiation process. The current of the deuterium beam on the gas cell was around 1 μA. The irradiated samples were pellets of 1.3 cm diameter, which have been produced by pressing the target material (high purity natural Ge and HfO_2) at a pressure of 6 tons/cm^2. High purity foils of ^{197}Au, ^{93}Nb and ^{27}Al were irradiated together with the pellets and the reference reactions $^{197}Au(n,2n)^{196}Au$, $^{93}Nb(n,2n)^{92m}Nb$ and $^{27}Al(n,\alpha)^{24}Na$ were used for the determination of the neutron flux at the target position (see Fig. 1).

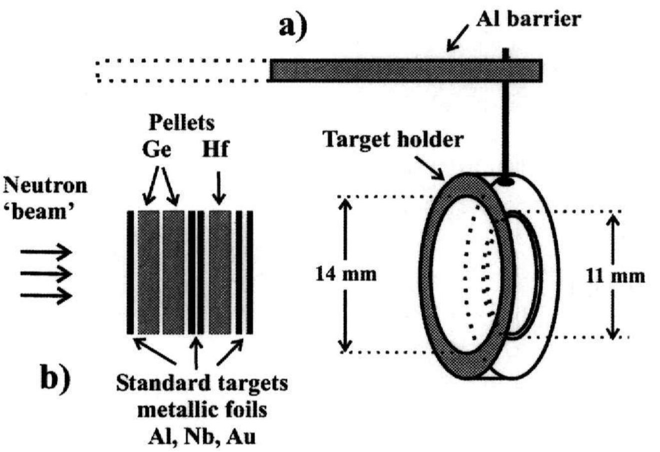

Fig. 1. Experimental setup for neutron activation measurements. In the part a) the target holder is shown, whereas in the part b) the reference foils as well as the pellets are depicted.

For the monitoring of the neutron beam flux, a BF_3 detector was used and the detected events were stored at regular time intervals of 100 s in a separate ADC during the irradiation process (Multi-Channel Scaling, MCS). The irradiated samples were placed in front of HPGe detectors of relative efficiency ε_r=80% and 55% and the decay of the residual nuclei was investigated. The cross section $\sigma(E_n)$ at an incident neutron beam energy E_n was determined by the relation

$$\sigma(E_n) = \frac{N(t_f)}{N_T\ \Phi_T\ f_c} \quad \text{where} \quad f_c = e^{-\lambda t_f} \frac{\sum_i \int_{t_i-1}^{t_i} \phi_i\ e^{\lambda t_i} dt}{\sum_i \int_{t_{i-1}}^{t_i} \phi_i\ dt} \tag{1}$$

where $N(t_f)$ is the number of the produced nuclei at the end of the irradiation time t_f, N_T is the number of the target nuclei, Φ_T is the neutron fluence and f_c is a dimensionless correction factor to account for the decay of the produced nuclei during the irradiation by using the flux data ϕ_i registered every 100 s from the MCS. The latter factor is depended on the lifetime $T_{1/2}$ ($\lambda = \ln 2/T_{1/2}$) of the decay nucleus and the irradiation time t_f. The quantity $N(t_f)$ is obtained by the relation $N(t_f) = Y/[e^{-\lambda t_1}(1 - e^{-\lambda \Delta t})\varepsilon_{abs}p]$ where t_1 is the time elapsed from the end of the irradiation, $\Delta t = t_2 - t_1$ is the time interval of activation measurement by the Ge detector, ε_{abs} the absolute efficiency of the detector in the γ ray under study and p is the decay probability of the relevant γ ray per parent decay. To determine the energy distribution and neutron flux at the target position a Monte Carlo simulation using the code MCNP4C has been performed.

3 Results

Among the possible reaction channels produced by the n irradiation, the only ones which involve reasonable lifetimes and could be observed by the activation method are presented in table 1.

Table 1
Decay data of measured reaction products.

Isotope	Abundance (%)	Reaction	Q value (MeV)	$T_{1/2}$	E_γ (keV)	I_γ (%)
^{72}Ge	27.31(0.26)	^{72}Ge(n,p)^{72}Ga	-3.21	14.10(0.02) h	834	95.63
		^{72}Ge(n,α)^{69m}Zn	1.48	13.76(0.02) h	438	94.77
^{73}Ge	7.76(0.80)	^{73}Ge(n,p)^{73}Ga	-0.81	4.86(0.03) h	297	79.8
^{74}Ge	36.73(0.15)	^{74}Ge(n,α)^{71m}Zn	0.45	3.96(0.05) h	386	93
^{76}Ge	7.87(0.07)	^{76}Ge(n,2n)^{75}Ge	-9.43	82.78(0.04) m	265	11.4
^{174}Hf	0.16(0.01)	^{174}Hf(n,2n)^{173}Hf	-8.51	23.6(0.1) h	124	83
^{176}Hf	5.26(0.07)	^{176}Hf(n,2n)^{175}Hf	-8.16	70(2) d	343	84

In figure 2 two typical spectra taken from the decay of the activated Ge and HfO_2 targets are shown.

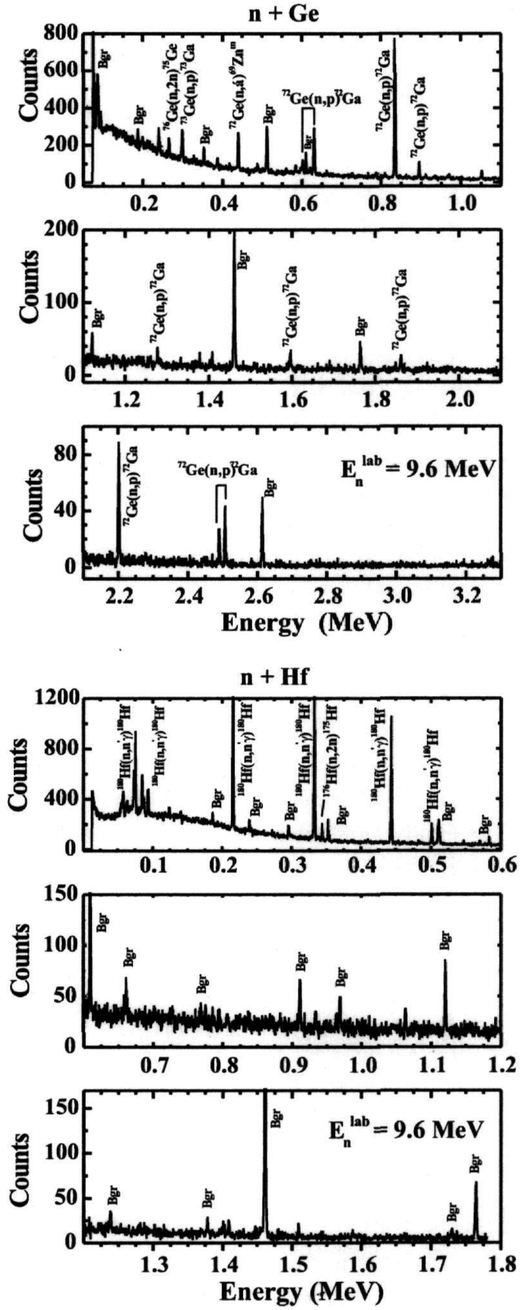

Fig. 2. Typical neutron activation spectra from isotopes of natural Ge and Hf.

The measuring time for the Ge spectrum was arround 3 h while that of HfO_2 1 h. In these spectra, the most prominent transitions from the observed reaction channels, which are also shown in Table 1, are indicated along with the

background γ-rays.
By the analysis of the γ-ray transitions deexciting the produced nuclei, the cross section of the relevant reactions were determined using the equation 1. Preliminary results of the cross section values are shown in figure 3 along with data from literature.

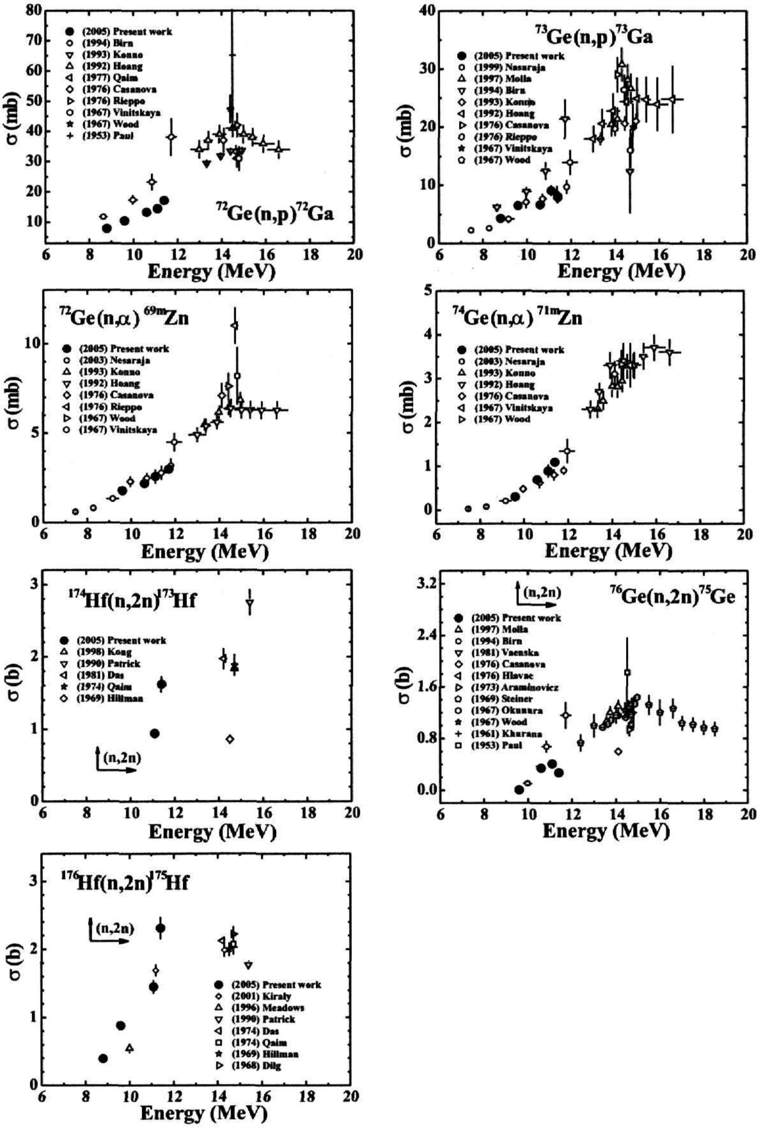

Fig. 3. Cross sections of the neutron induced reactions on Ge and Hf.

In the case of Ge, one (n,2n) and two (n,α) and (n,p) reaction channels on various isotopes could be measured, while for Hf only the (n,2n) reactions on ^{174,176}Hf could produce reliable results. In the case of ^{174}Hf(n,2n)^{173}Hf reaction

at energies below 10 MeV the cross section seems to drop rapidly so that the 124 keV γ ray is very weak to deduce reliable cross section values. Moreover, in the case of ^{180}Hf(n,n′ γ) reaction which can, in principle, be measured via the activation method, the cross section does not correspond to monoenergetic neutrons, since it is contaminated by the low energy part of the neutron beam. The threshold of this reaction is low enough so that it can be populated by the parasitic neutrons which have a continuous energy distribution and thus contribute to the investigated cross section. For the Ge case, we note considerable agreement between the cross section data of the present work and those taken by Nesaraja *et al.* [2], while the data by Birn *et al.* [3] lie slightly above. For the Hf isotopes, cross section measurements were systematically investigated in the energy range from threshold to 12 MeV for the first time.
Additional experimental points at energies above 15 MeV are planned to be measured in the near future, while statistical model calculations are in progress by using the code EMPIRE-II.

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