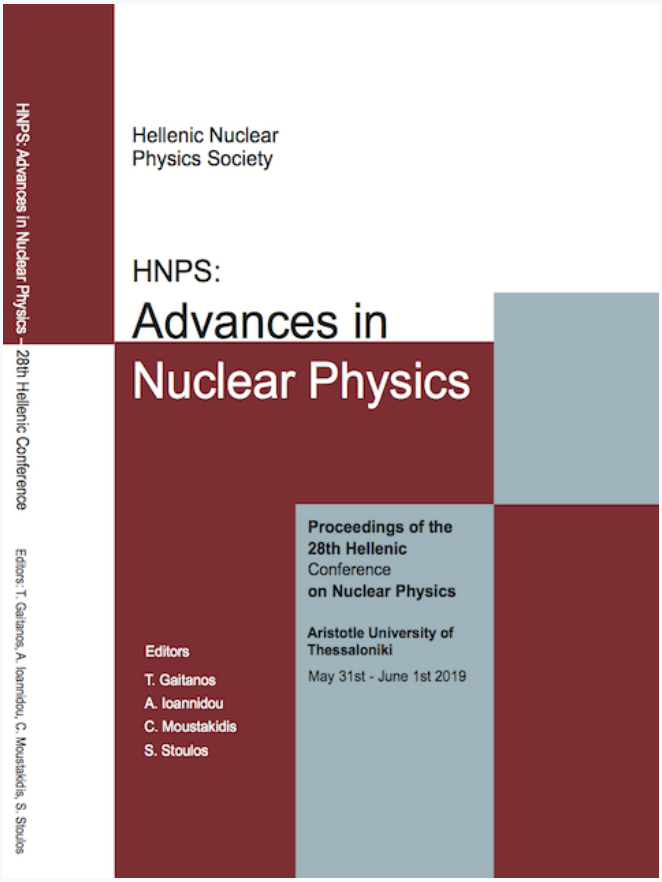
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Cross Section Measurements of (n,p) Reactions on Ge Isotopes

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Abstract *The ^{72,73}Ge(n,p)^{72,73}Ga reaction cross sections were measured at the 5.5MV HV Tandem accelerator of NCSR "Demokritos", at neutron energies 17.7 and 19.3 MeV by using the activation method. The contamination from the (n,d) and (n,np) reactions on ^{73}Ge and ^{74} Ge, leading to the ^{72}Ge and ^{73}Ge residual nuclei, respectively, has been taken into account, implementing the corresponding cross sections from TENDL–2017. A systematic investigation of the isotopic effect on all Ge isotopes is also presented, from threshold up to 20 MeV, using the present data along with existing data in literature.*

Keywords *cross section, Monte Carlo simulations, neutron activation technique, Ge*

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INTRODUCTION

Studies of excitation functions of neutron induced reactions are important both for fundamental research in Nuclear Physics as well as for applications, especially in the field of nuclear technology [1-3]. Systematics on reaction channels, such as (n,p), (n,α) and (n,2n), at different isotopes, are important for the optimization of input parameters in statistical model calculations. Germanium is a very important semi-conducting material, thus the investigation of its behavior in a neutron field is of considerable significance in several practical applications. However, little information is available in literature with many discrepancies among the existing experimental data, especially in the energy region, above ~14 MeV. In this work, natural Ge pellets were irradiated with neutron beams at NCSR "Demokritos" and the results of the (n,p) reaction cross sections are presented in this paper.

EXPERIMENTAL PROCEDURE

The cross sections of the (n,p) reactions have been experimentally determined on two natural isotopes of Germanium, namely ^{72}Ge and ^{73}Ge, at E_n=17.7 and 19.3 MeV, via the activation method, relative to the ^{27}Al(n,α)^{24}Na, ^{93}Nb(n,2n)^{92m}Nb and ^{197}Au(n,2n)^{196}Au reference reactions. The neutron beams were produced at the 5.5MV HV Tandem accelerator of NCSR "Demokritos", by means of the ^{3}H(d,n)^{4}He reaction using a Ti–tritiated target of 373 GBq activity, consisting of a 2.1 mg/cm^2 Ti–T layer on a 1mm thick Cu backing for heat dissipation purposes. The Deuterons were accelerated at 2.9 and 3.9 MeV, respectively, yielding a neutron flux of the order of ~10^6 n/sec·cm^2. A BF_3 detector and a BC501A liquid scintillator were used for the monitoring of the neutron flux. The deuteron beam current varied between 0.3 and 0.5 μA and was recorded at regular time intervals to account for the subsequent neutron beam fluctuations. The neutron production target was air cooled during the irradiations, which lasted for about 30 h.

The neutron flux was determined from the ^{27}Al(n,α)^{24}Na and ^{93}Nb(n,2n)^{92m}Nb reference reactions. For this purpose, high purity Nb foils were placed at the front and Al foils at the back of the Ge target with

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respect to the neutron beam direction. The target assembly was placed at about 2 cm from the tritiated target, thus limiting the angular acceptance to ±15°, where the produced neutrons are practically isotropic and monoenergetic. MCNP Monte Carlo simulations were used to reproduce the experimentally deduced neutron flux at the foils. The total average neutron flux obtained from the reference foils at 17.7 ± 0.2 MeV was (5.71 ± 0.28)x10^9 n/cm^2, while at 19.3 ± 0.2 MeV was (14.2 ± 0.1)x10^9 n/cm^2.

The irradiated foils were measured by a HPGe detector of 80% relative efficiency at the Institute of Nuclear and Radiological Sciences, Technology, Energy & Safety, at NCSR "Demokritos", while the reference foils were measured by a 16% relative efficiency HPGe detector at INPP. Both detection systems were properly shielded with lead blocks in order to reduce the contribution of the natural radioactivity. The targets were placed at ~10 cm away from the detector window. The characteristic gamma–rays from the de–excitation of the residual nuclei of the Ge target, namely 834.13, 2201.59, 629.97 and 297.32 keV, from both (n,p) reactions, are shown below in Fig. 1.

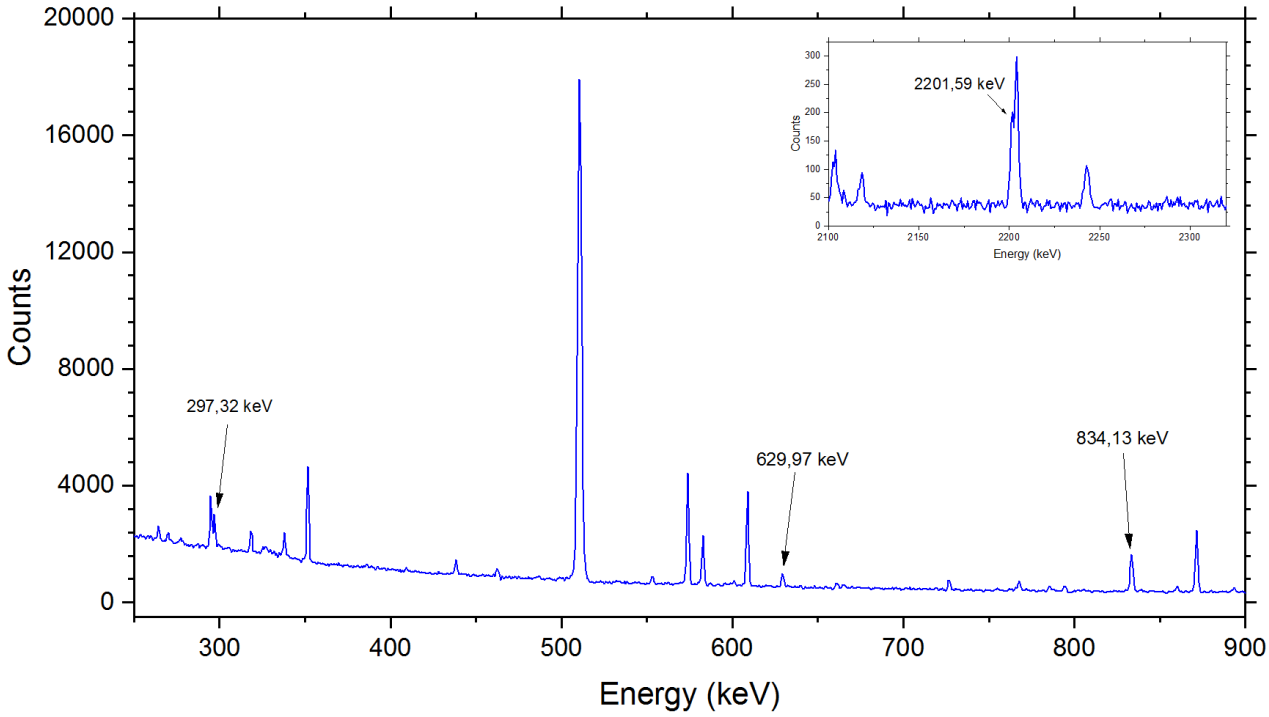


Figure 1. *Typical off-line spectrum of the 19.3 MeV run. The lines used in the data analysis are indicated by their energy.*

DATA ANALYSIS AND RESULTS

A detailed description of the data analysis is given in Ref. [6], so only the correction procedure for the contaminant reactions will be described here.

The (n,np) and (n,d) reactions on ^{73}Ge and ^{74}Ge contribute to the activities of the ^{72}Ga and ^{73}Ga residual nuclei which result from the ^{72}Ge(n,p)^{72}Ga and ^{73}Ge(n,p)^{73}Ga reactions, measured in the present work. The (n,np) and (n,d) contributions were estimated using the TENDL–2017 evaluated library and were subtracted from the obtained results. The thus determined cross sections, along with their uncertainties, are presented in Fig. 2. The solid circles are the values before the application of the corrections and the solid squares are the final cross section values after the corrections for the contaminant reactions, while the solid triangles represent previous data from our group [2]. The corrections were quite significant, especially in the ^{73}Ge(n,p) case, due to the high abundance of ^{74}Ge and low abundance of ^{73}Ge.

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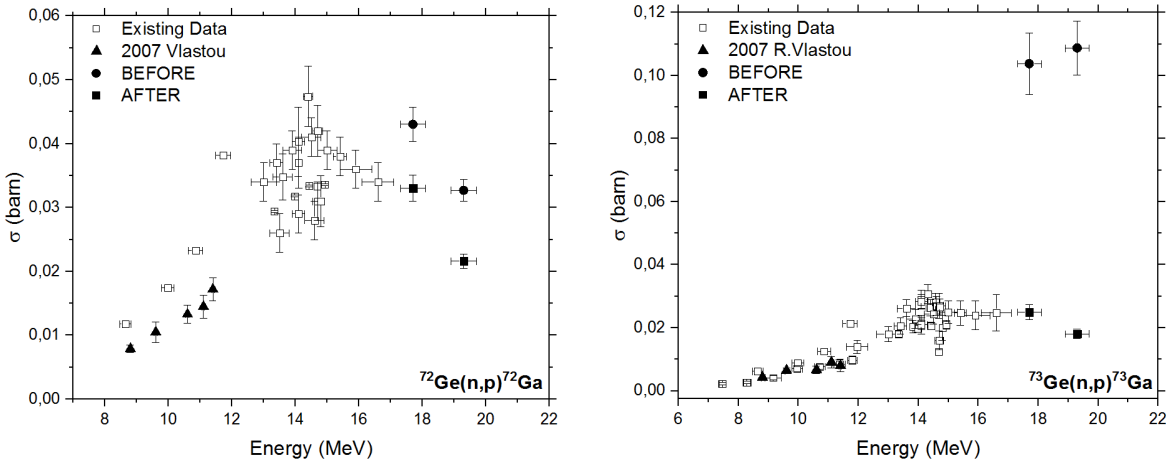


Figure 2. *Cross section measurements of (n,p) reactions on ^{72,73}Ge isotopes, as explained in the text, along with data from literature.*

Cross sections of (n,p) reactions on elements with several stable isotopes reveal a decreasing behavior with increasing neutron number in the target nucleus. This isotopic effect has been previously observed in Ge [1,2] and in other elements with a series of isotopes, such as Zr [3], Ti [4] and Cr [5]. In Fig. 3, the systematic (n,p) reaction data on Ge isotopes from the literature and the present work, are presented. The solid line in this figure represents the cross sections from ENDF and is found to be in good agreement with the experimental data. The isotopic effect of decreasing cross section with increasing neutron excess from ^{70}Ge to ^{76}Ge is clearly demonstrated. It can be explained in terms of increasing domination in the competition between proton and neutron emission as the number of neutrons in the isotope increases. The difference in the cross sections smears out with increasing neutron energy, since the Q–value effect becomes less important. In addition, the energy threshold of the (n,p) reactions increases in the heavier isotopes due to the Q–value effect, while the odd-even isotope ^{73}Ge has a slightly lower threshold than the even-even ^{72}Ge isotope, which could be attributed to the pairing energy. Finally, the maxima of the excitation functions are shifted to higher energies as the neutron number increases.

SUMMARY

Cross sections of (n,p) threshold reactions on ^{72,73}Ge were measured at 17.7 and 19.3 MeV via the activation technique. Systematic trends attributed to Q-value effects have been observed. Further measurements are planned in the near future to cover the full energy range from ~15 to ~20 MeV. In addition, theoretical calculations based on the Hauser–Feshbach statistical theory will be performed taking into account pre–equilibrium emission, using the EMPIRE and TALYS codes.

Acknowledments

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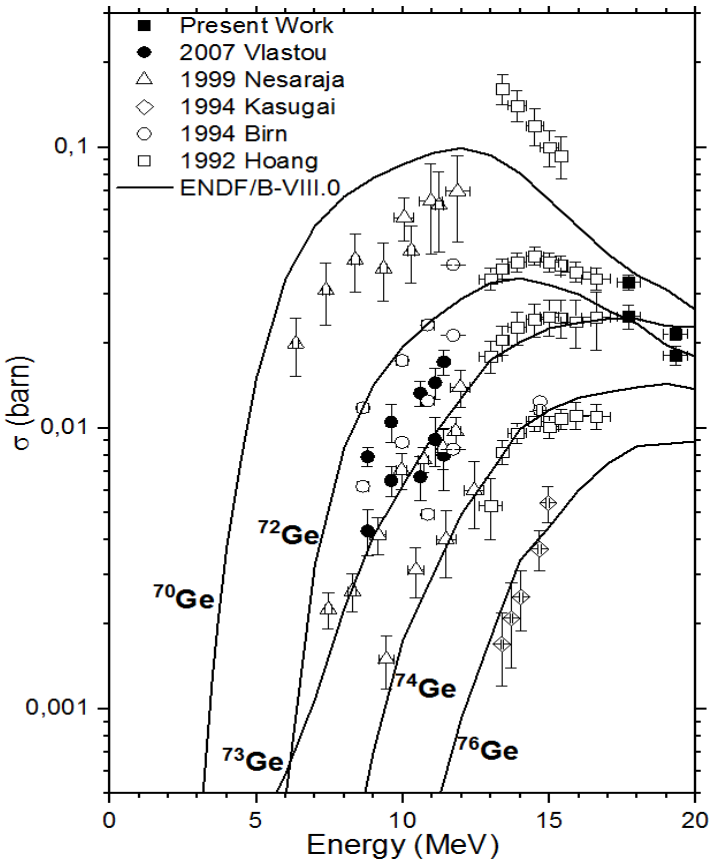


Figure 3. *Cross–section data of the (n,p) reactions on Ge isotopes along with ENDF values (solid line). The black squares are the data of the present work, while the black circles are the data from previous work of our group [2].*

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