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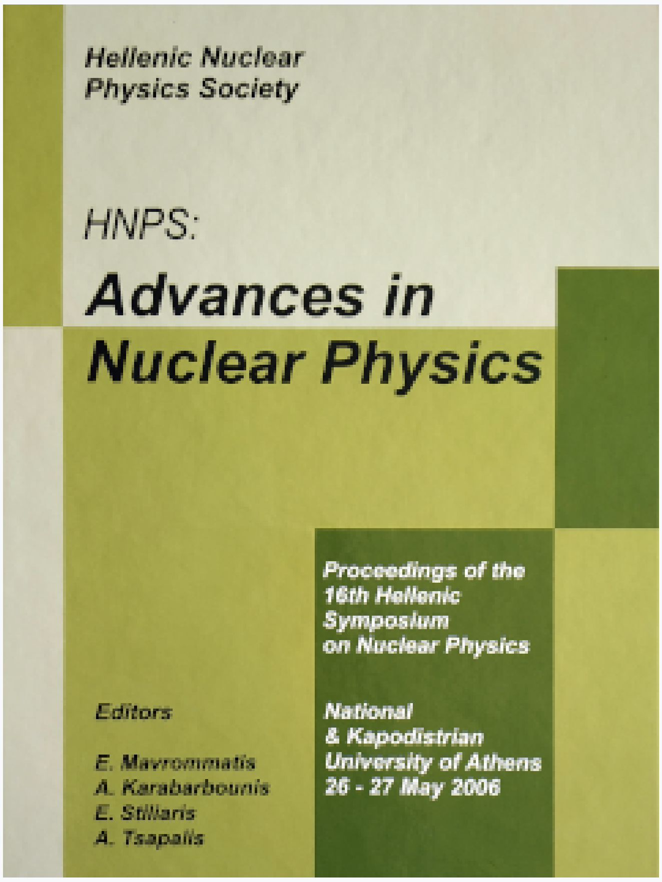

Statistical model calculations of 72,73Ge(n,p) and 72,74Ge(n,α) reactions on natural Ge

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Statistical model calculations of Ge(n,p) and Ge(n,α) reactions on natural Ge

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Systematic experimental and theoretical investigations of the ^{72,73}Ge(n,p)^{72,73} Ga and ^{72,74}Ge(n,α)^{69,71}Zn^m reaction cross sections are presented in the energy range from threshold to about 17 MeV neutron energy. The above reaction cross sections were measured from 8.8 to 11.4 MeV by using the activation method, relative to the ^{27}Al(n,α)^{24}Na reference reaction. The quasi-monoenergetic neutron beams were produced via the ^{2}H(d,n)^{3}He reaction at the 5 MV VdG Tandem T11/25 accelerator of NCSR “Demokritos”. Statistical model calculations using the code EMPIRE-II (version 2.19) taking into consideration pre-equilibrium emission were performed on the data measured in this work as well as on data reported in literature.

1. INTRODUCTION

Studies of excitation functions of neutron induced reactions are important, both in fundamental research in Nuclear Physics and for practical applications, especially in the field of nuclear technology. Furthermore, in the energy region up to 20 MeV, many reaction channels, which may proceed via different reaction mechanisms such as (n,2n), (n,p) and (n,α), are open and therefore can be simultaneously studied. The development of up to date computer codes based mainly on compound and pre-compound reaction mechanisms present many uncertainties in their parameterizations. Therefore, more experimental data are needed in order to test the reliability of the theoretical calculations and to improve the systematic development of the model parameters [1,2]. Concerning Ge, which is a very important semiconducting material, a survey of the available cross section data showed plenty of data at neutron energies arround 14 MeV and a few ones at lower and higher energies. These data reveal, in many cases, large discrepancies [2–5]. In view of these remarks, the neutron facility at the 5 MV tandem T11/25 Accelerator of NCSR “Demokritos”, has been used for the measurement of neutron induced threshold reaction cross sections on natural Ge. Investigation of (n,p) and (n,α) reaction data on ^{72,73}Ge and ^{72,74}Ge isotopes, respectively, from the present work, as well as from literature, have

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been performed to test the reliability of nuclear models and to develop systematic trends in the representation of the data.

2. EXPERIMENTAL METHOD

Quasi-monoenergetic neutron beams were produced via the ^{2}H(d,n)^{3}He reaction in the 5 MV Tandem T11/25 accelerator laboratory of NCSR "Demokritos". Detailed descriprion of the experimental setup, the targets used in the measurements, the irradiations and the neutron fluxes are given in Ref. [6,7]. The deduced cross section values of the (n,p) and (n,α) reactions of the present work are shown in Table 1.

Table 1
Cross sections determined using natural Ge samples.

Neutron energy	Cross sections (mb)			
(MeV)	^{72}Ge(n,p)^{72}Ga	^{73}Ge(n,p)^{73}Ga	^{72}Ge(n,α)^{69m}Zn	^{74}Ge(n,α)^{71m}Zn
8.80 ± 0.05	7.9 ± 0.6	4.3 ± 0.8		
9.60 ± 0.05	10.5 ± 1.6	6.5 ± 0.8	1.8 ± 0.2	0.3 ± 0.1
10.60 ± 0.05	13.3 ± 1.4	6.7 ± 1.2	2.2 ± 0.1	0.7 ± 0.1
11.10 ± 0.04	14.5 ± 1.8	9.1 ± 1.8	2.6 ± 0.4	0.9 ± 0.1
11.40 ± 0.04	17.2 ± 1.8	8.0 ± 2.0	3.0 ± 0.2	1.1 ± 0.1

3. REACTION MEASUREMENTS

The cross sections of the (n,p) and (n,α) reactions on Ge isotopes derived in the present work are depicted in Fig. 1 and Fig. 2 along with data from literature [3–5,9–15] In the case of (n,p) reactions, the residual nuclei ^{72,73}Ga could also be produced by the (n,np+pn+d) reactions on ^{73}Ge and ^{74}Ge respectively. In Ref. [4], contributions from these reactions have been estimated from Qaim's systematics [8] as 4 and 3 mb respectively, and were subtracted only for the higher energy measurements at 14.7 MeV. From theoretical calculations performed with the EMPIRE-II code, at lower energies, the (n, np+pn+d) cross section drops by two orders of magnitude down to the threshold of these reactions, which opens just above 11 MeV. It is thus concluded, that in the energy range of our measurements there is no contribution from ^{73,74}Ge(n,np+pn+d) reactions. In addition, the ^{73}Ge(n,p)^{73}Ga cross section could be contaminated by the ^{76}Ge(n,α)^{73}Zn followed by β^{-} decay to ^{73}Ga. This contribution, however, is negligible in our energy range, since ^{76}Ge is the less abundant isotope in natural Ge. Furthermore, the (n,α) cross section decreases with increasing neutron number of the Ge isotopes, as indicated by both the theoretical calculations and the experimental data.

In the case of (n,α) reactions (see Fig. 2), the ^{72}Ge(n,α)^{69m}Zn cross section could be contaminated by the ^{73}Ge(n,nα)^{69m}Zn reaction, however this contamination is negligible since the cross section at the energy region of the measurements is at least two order of magnitudes lower than that of ^{72}Ge(n,α)^{69m}Zn reaction, as emerges from theoretical calculations. It should be noted that there are no experimantal data for the ^{73}Ge(n,nα)^{69m}Zn

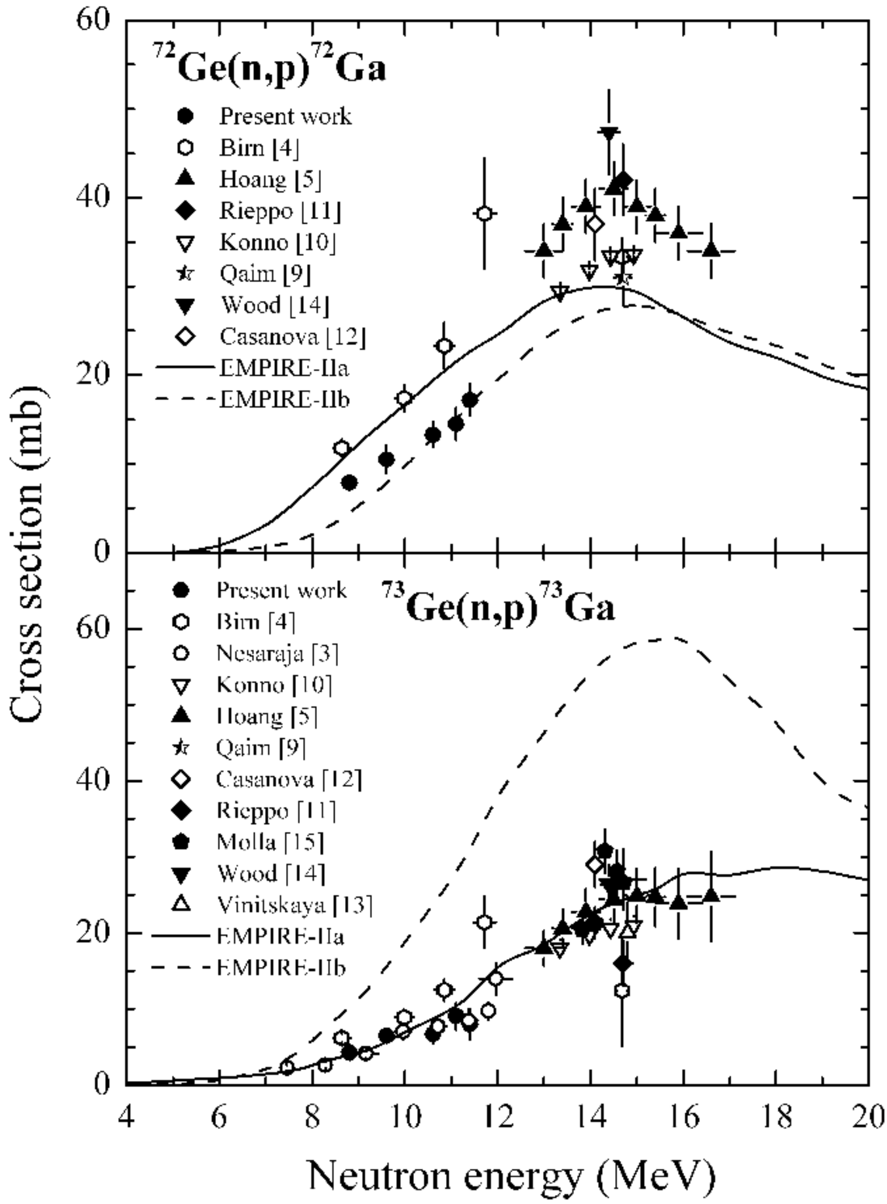

Figure 1. Cross section measurements of (n,p) reactions (•) on ^{72,73}Ge isotopes along with data from literature and comparison with theoretical predictions with the code EMPIRE-II. In the calculation labeled as EMPIRE-IIa the nuclear level density of GC [19]was used, while in EMPIRE-IIb that of Demetriou and Goriely [21] based on the Hartree-Fock-BCS [20] approximation, was applied.

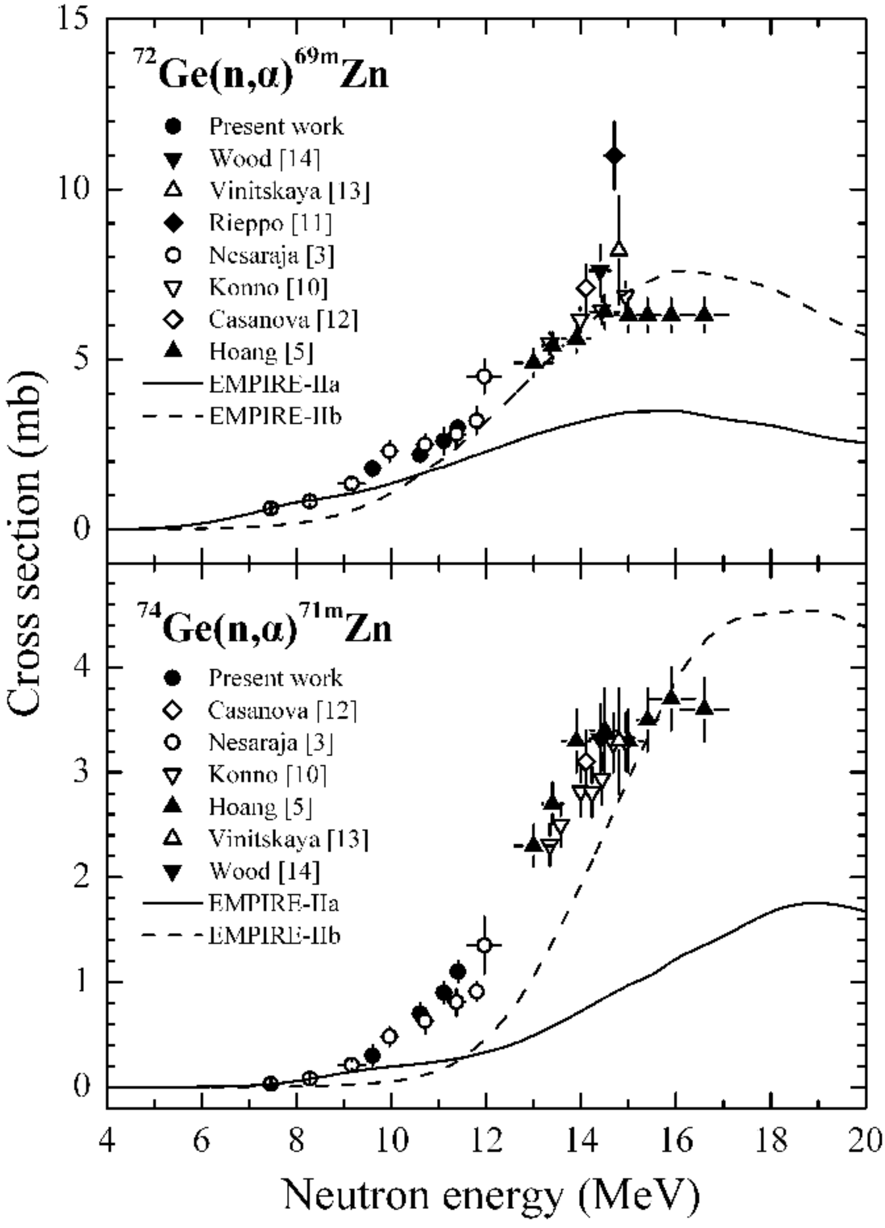

Figure 2. Cross section measurements of (n,α) reactions (•) on ^{72,74}Ge isotopes along with data from literature and comparison with theoretical predictions calculated with the code EMPIRE-II.

reaction available in the literature at any energy region.

For the sake of completeness, apart from the present measurements in Figs. 1 and 2, data from the literature are also presented. Considerable agreement can be noted between our measurements and the data by Nesaraja et al [3] for the ^{73}Ge(n,p)^{73}Ga and the ^{72,74}Ge(n,α)^{69,71m}Zn reactions, while the data by Birn et al [4] lie slightly above for both (n,p) reactions studied. The systematic trends of the excitation functions from all these reactions are discussed in the next section along with predictions from theoretical calculations.

4. THEORETICAL CALCULATIONS AND DISCUSSION

Statistical model calculations based on the Hauser-Feshbach theory, taking into account pre-equilibrium effects for the residual nuclei in the continuum were performed using the code EMPIRE-II (version 2.19) [16] and the predictions along with data points for the ^{72,73}Ge(n,p)^{72,73}Ga and ^{72,74}Ge(n,α)^{69,71}Zn^{m} reactions are shown in Fig. 1 and Fig. 2 respectively. The influence of the pre-equilibrium reaction mechanism on the predictions increases progressively with increasing neutron energy and varies from 7 to 10% at the neutron energy of 14 MeV, depending on the Ge isotope studied. Among the input parameters (masses, discrete levels, optical potentials, nuclear level densities, gamma-ray strength functions) entering in statistical model calculations applied at neutron beam energies up to 20 MeV, the optical model potential (OMP) and the Nuclear Level Density (NLD) play a dominant role. After a survey in the predictions resulted by the various OMPs it was decided to use the OMP of Koning-Delaroche et al.[17] for protons and neutrons and for α particles that of Avrigeanu et al. [18]. As level density model for nucleon induced reactions with compound nucleus excited up to 20 MeV was chosen that of Gilbert-Cameron, (GC), [19] since it assures the most accurate description of data in the above energy region. As can be seen from Fig. 1, the predictions taken by the use of GC level density provide a good description of the data in the whole energy region, while in the case of (n,α) reactions the GC approach fails at energies above 10 MeV. At this point it should be noted that efforts are being carried out to improve the parametrization of the GC level density to optimize the predictions. In order to test the sensitivity of the calculations to different nuclear level densities, microscopic level densities relying on the frame of the Hartree-Fock-BCS [20,21] approach were used, and the data are shown in Fig. 1 and Fig. 2, as dashed lines. In the case of (n,α) reactions, where the GC approach fails to reproduce the data, the results of HFBCS calculations seem to follow the general behavior of the data excitation function rather well. On the other hand, the HFBCS predictions for the (n,p) reactions are not very promising. In the case of ^{72}Ge they tend to underestimate the data, especially in the high energy region, while in ^{73}Ge overestimate the experimental points by a factor of 2 in the whole energy range. It is obvious, that further investigation is needed, in order to draw firm conclusions for the simultaneous representation of both (n,p) and (n,α) reactions on Ge isotopes.

5. SUMMARY

In the present work, cross sections of (n,p) threshold reactions on ^{72,73}Ge and (n,α) reactions on ^{72,74}Ge were measured in the neutron beam energy region 8.8 to 11.4 MeV, via the activation technique. Theoretical calculations based on the Hauser-Feshbach statistical theory and pre-equilibrium reaction mechanisms have also been performed applying the code EMPIRE-II. The calculated cross section values resulting from the optical model potential of Koning [14] for neutrons and protons and the nuclear level density of Gilbert and Cameron [17], reproduce the data of the (n,p) reactions on ^{72,73}Ge fairly well at neutron energies up 20 MeV, however they fail to reproduce the data in the (n,α) reaction channel. The utilization of the microscopic nuclear level density of HFBCS is acceptable in the case of ^{72,74}Ge(n,α) reactions, while in the other (n,p) reactions there is no a clear trend. From the findings of this work, it can be concluded that the excitation functions of the (n,p) and (n,α) reactions on Ge isotopes are helpful for the investigation of reliable parameter sets entering nuclear model studies in the medium heavy mass region and that further theoretical investigations are necessary in an attempt to reproduce both (n,p)and (n,α) reactions via statistical model calculations.

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