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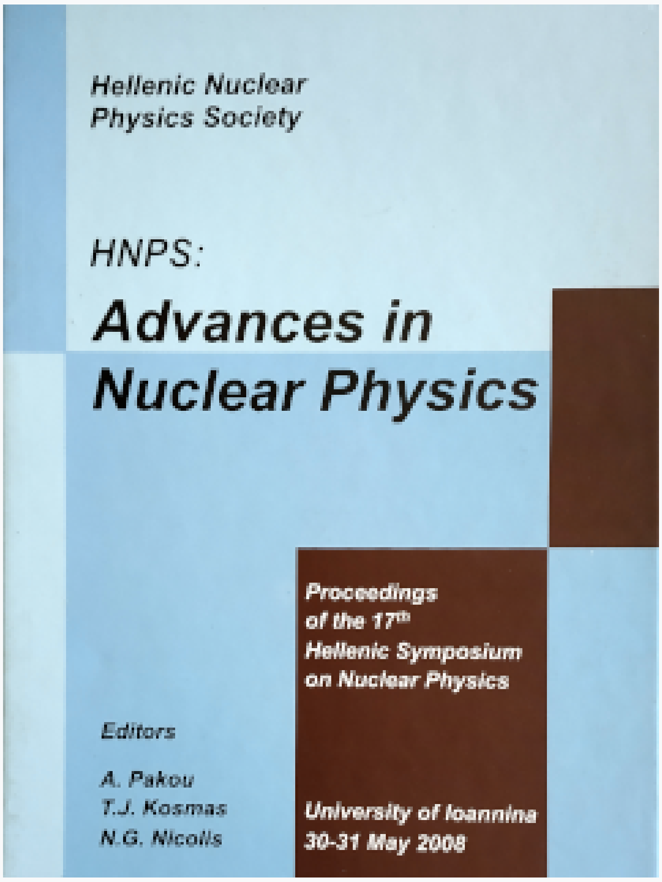

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Isomeric Cross Section Study of neutron induced reactions on Ge

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Abstract

The ^{72}Ge(n,α)^{69m}Zn, ^{74}Ge(n,α)^{71m}Zn, ^{76}Ge(n,2n)$^{75g+m}$Ge reaction cross sections have been measured from 9.6 to 11.4 MeV and studied, along with data from literature, within the frame of statistical model calculations by using the code EMPIRE-II.

Introduction

Studies of excitation functions of neutron induced reactions are of particular importance both for nuclear physics research and for practical applications, especially for nuclear technology [1]. In addition, (n,2n), (n,p) and (n,α) reactions, have generated recently new interest for the investigation of isomeric-to-ground-state cross- section ratios in the formation of residual nuclei. The experimental determination of isomeric cross sections is of fundamental importance for studying the spin dependence of the formation of metastable states [2]. Experimental and theoretical studies of isomeric-to-ground-state cross sections as a function of energy, could lead to valuable information concerning the spin distribution of the level density characterized in terms of the effective moment of inertia of the compound nucleus [3]. Several computer codes for reaction model calculations have been developed, based mainly on compound and pre-compound mechanisms which, however, present many uncertainties in their parameterizations. Therefore, more experimental data are needed to test the reliability of the theoretical calculations and to improve the systematic development of the model parameters [3]. Beyond the basic research interest, the study of neutron induced reactions on Ge isotopes at energies up to 20 MeV, is important in radiation damage of semiconductor detectors caused by fast parasitic neutrons in experiments concerning the field of particle physics.

In this work the reactions ^{72}Ge(n,α)^{69m}Zn, ^{74}Ge(n,α)^{71m}Zn and ^{76}Ge(n,2n)$^{75g+m}$Ge were chosen to be studied both experimentally and theoretically since the product nuclei have metastable states with reasonably large lifetimes for neutron activation measurements.

Experimental

The measurements were performed at the 5MV tandem accelerator of NCSR Demokritos using quasi-monoenergetic neutrons at a flux of the order of $\sim 10^6$ n/(cm^{2}sec) and in the energy region 9.6-11.4 MeV, produced by the d+d reaction by means of a D_2 gas cell and deuteron beam currents of about 1-2μA. The absolute flux of the beam was obtained with respect to the ^{27}Al(n,α)^{24}Na reference reaction, while its variation was monitored by a BF_3 detector placed at a distance of 3 m from the neutron source.

Samples of high impurity natural Ge pellets doped with 12% high purity C were placed between Al reference foils and exposed to the neutron beam for about two days continuous irradiation. The induced activity of product radionuclides in both target and reference foils was measured with a HPGe detector of 56% efficiency. The characteristic γ-rays were corrected for self absorption in the target, summing effects of cascading transitions and counting geometry. The Monte Carlo code MCNP [4] was utilized to perform simulations and to test the reliability of the various corrections.

The cross section was deduced by measuring the characteristic gamma rays from the decay of the residual nuclei. The ^{72}Ge(n,α)^{69}Zn reaction leads to the formation of the unstable nucleus ^{69}Zn both in its $1/2^-$ ground state ($T_{1/2}$ = 56.4h) and its metastable $9/2^+$ ($T_{1/2}$ = 13.76h) state. The ground state of ^{69}Zn decays directly to the ground state of ^{69}Ga, while the metastable state decays to the ground state (99.967%) of ^{69}Zn emitting the characteristic 438.6 keV gamma ray which can be used for the determination of the σ_m cross section.

The ^{74}Ge(n,α)^{71}Zn reaction leads to the formation of the unstable nucleus ^{71}Zn both in its $1/2^-$ ground state ($T_{1/2}$ = 2.45m) and its metastable $9/2^+$ ($T_{1/2}$ = 3.96h) state. Due to the short lifetime of the ground state of ^{71}Zn, only the activity of the metastable state could be measured via the activation technique. Thus the σ_m could be determined by analyzing the 386.3keV transition of ^{71}Ga which is fed by the deexcitation of the metastable state of ^{71}Zn.

The high threshold ^{76}Ge(n,2n)^{75}Ge reaction leads to the formation of the unstable nucleus ^{75}Ge both in its $1/2^-$ ground state ($T_{1/2}$ = 82.78m) and its metastable $7/2^+$ ($T_{1/2}$ = 47.7s) state. The deexcitation of the metastable to the ground state in fraction 99.97%, along with its short lifetime leads to the measurement of the total cross section σ_{m+g} of the (n,2n) reaction via the 264.6keV characteristic transition of ^{75}As. A more detailed description of the experimental procedure for the data deduction is given in Ref. [5].

The neutron irradiations on natural Ge have been performed at energies 9.6, 10.6, 11.1 and 11.4 MeV. The data are presented in Figs. 1, 2 and 3 along with data from literature and theoretical predictions.

Theoretical Calculations and Discussion of the Results

Cross section calculations have been performed using the statistical model code EMPIRE-II [6] and taking into consideration appropriate pre-equilibrium effects. The effect of the different optical model potentials (OMP) has been investigated and the OMP of Koning-Delaroche [7] for neutrons and protons and that of Avrigeanu [8] for α particles, were found to better reproduce the data and were employed in the calculations.

The effect of different nuclear level density models on the statistical model calculations has been tested in the case of (n,α) and (n,2n) reactions leading to metastable states. The Gilbert-Cameron (GC) approach [9] (EMPIRE-1 black solid lines in Figs. 1, 2 and 3) fails to reproduce the data, while the microscopic Hartree-Fock-BCS (HFBCS) level densities of Demetriou & Goriely [10,11] exhibit a fair agreement with the measurements (EMPIRE-2 dashed lines in Figs. 1, 2 and 3. On the other hand, the HFBCS predictions for the (n,p) reactions on Ge isotopes tend to overestimate the data, while the GC ones reproduce the data of the (n,p) reactions on ^{70,72,73,74,76}Ge fairly well at neutron energies up to 20 MeV [12]. Further investigation was thus carried out within the Gilbert-Cameron approach focusing on the parameters which could influence the population of the isomeric states.

Since model calculations of the isomeric states depend critically on the input level scheme of the residual nucleus, the effect of the level scheme of the product nucleus has been tested by two different ways in an attempt to increase the isomeric cross section. a) In the high energy region of the discrete, for levels of unknown J^{π} and de-excitation mode, dummy information was given in the program concerning the values of J^{π} and transition probability. Despite the fact that convenient values were tried for $\sim$10 levels, which would increase the feeding to the isomeric state, the actual effect to the cross section was irrelevant. b) In the cumulative plots of energy levels, lowering of the matching point between the discrete and the continuum (lowering of the continuum), increases considerably the isomeric cross section, while the ground state cross section remains the same. Furthermore, the sensitivity of the calculations for isomeric state production to variations of the level density parameter $\tilde{\alpha}$ has also been investigated. Since parameter $\tilde{\alpha}$ is known in literature for ^{69}Zn, ^{71}Zn and ^{75}Ge, it was varied only within its uncertainties to improve the reproduction of the isomeric cross sections.

These results are exhibited in the case of the ^{76}Ge(n,2n) reaction data in Fig.1,

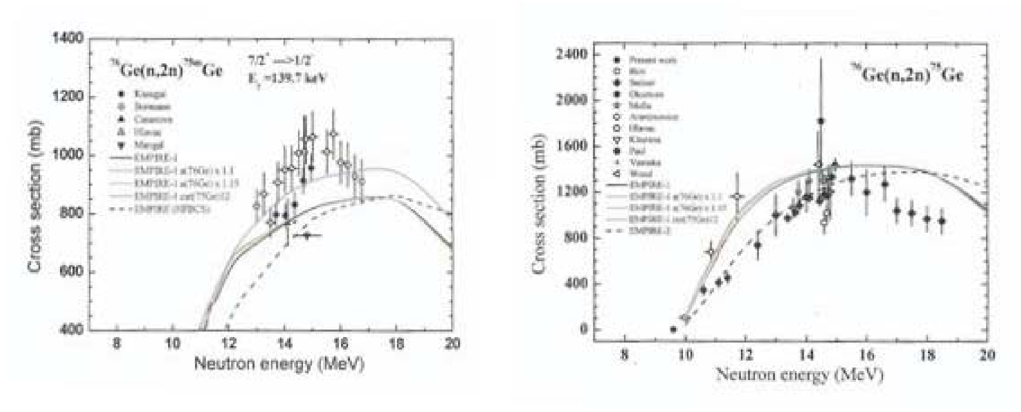

Fig. 1. Cross section measurements of ^{76}Ge(n,2n)^{75m}Ge and ^{76}Ge(n,2n)$^{75m+g}$Ge reactions along with data from literature and comparison with theoretical predictions with the code EMPIRE-II.

where the population of the ^{75m}Ge state can only be increased by lowering the continuum down to the 12^{th} state of ^{75}Ge (cut(75Ge)12 in the figure), while the population of the ground state of ^{75}Ge remains unchanged. The rise of $\tilde{\alpha}$ parameter for ^{76}Ge by 10 and 15%, does not affect the calculations for the reproduction of the isomeric cross section. Despite the efforts, the theoretical predictions of both approaches (HFBCS and GC) seem to underestimate the data for ^{75m}Ge and to overestimate them for ^{75}Ge ground state.

In the case of ^{72}Ge(n,α)^{69m}Zn reaction, by increasing the $\tilde{\alpha}$ parameter for ^{69}Zn by 10% or by decreasing the $\tilde{\alpha}$ parameter for ^{72}Ge by 7%, the population of the ^{69}Zn metastable state increases considerably and the theoretical predictions (gray lines in Fig.2) reproduce very well the experimental data in the whole energy region.

In the case of the ^{74}Ge(n,α)^{71m}Zn reaction however, major variations of the $\tilde{\alpha}$ parameter of ^{71}Zn of the order of 20% are essential for a reasonable rise of the isomeric cross section to reach the experimental values. For further improvement of the results, lowering of the continuum down to the 12^{th} or even 7^{th} discrete state of ^{71}Zn has been tried, but still the predictions tend to underestimate the data. The best fit to the isomeric cross section data has been achieved by decreasing the $\tilde{\alpha}$ parameter in ^{74}Ge by 20%. This fit though is still lower than the experimental values and in the high energy region decreases rapidly with energy, a behavior which cannot be tested due to lack of experimental data. All these results are depicted in Fig.3.

Summary

In the present work, cross sections of ^{72}Ge(n,α)^{69m}Zn, ^{74}Ge(n,α)^{71m}Zn and

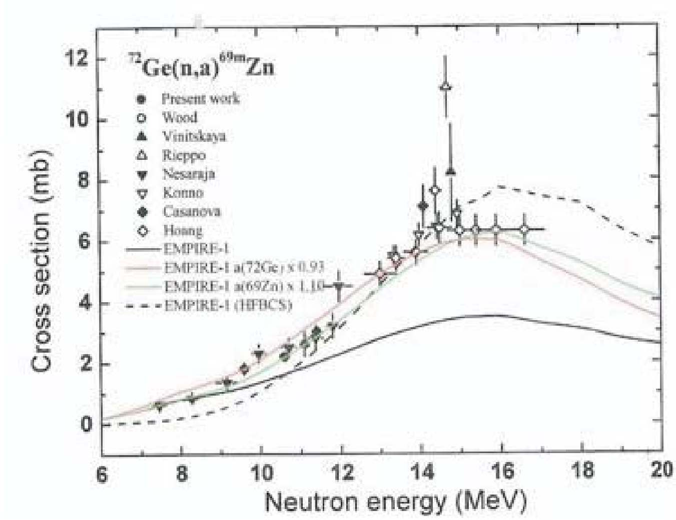

Fig. 2. Cross section measurements of ^{72}Ge(n,α)^{69m}Zn reaction along with data from literature and comparison with theoretical predictions with the code EMPIRE-II.

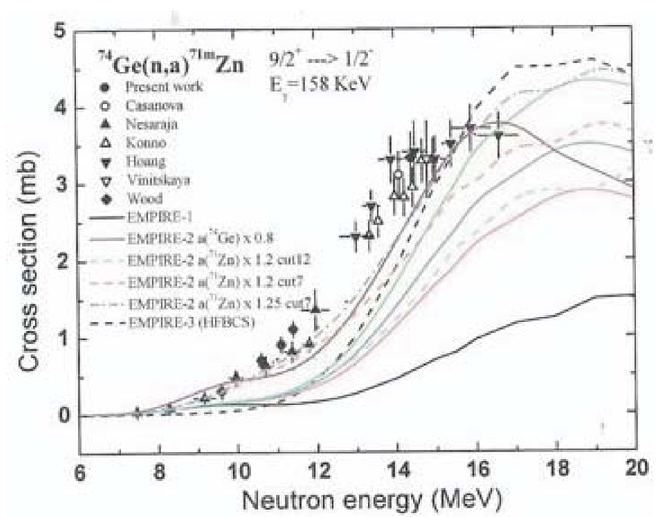

Fig. 3. Cross section measurements of ^{74}Ge(n,α)^{71m}Zn reaction along with data from literature and comparison with theoretical predictions with the code EMPIRE-II.

^{76}Ge(n,2n)${}^{75g+m}$Ge threshold reactions have been measured for neutron beam energy ranging from 9.6 to 11.4 MeV, via the activation technique. Theoretical calculations based on the Hauser-Feshbach statistical model and pre-equilibrium reaction mechanisms have also been performed applying the code EMPIRE. The statistical model calculations for the ^{72}Ge(n,α)^{69m}Zn reaction are in good agreement with the experimental data reproducing both the magnitude and the shape of the isomeric cross section by applying minor changes of the $\tilde{\alpha}$ parameter (∼10%) for ^{72}Ge or ^{69}Zn, which ly within its uncertainty. In the case of the ^{74}Ge(n,α)^{71m}Zn and ^{76}Ge(n,2n)$^{75g+m}$Ge reactions however, the theoretical predictions tend to underestimate the isomeric cross sections. Major changes in the level density parameters and the level scheme are needed in order to improve the predictions. The discrepancies of the experimental data along with the lack of data in the high energy region above 15 MeV, do not allow us to draw firm conclusions. Further theoretical investigations as well as measurements at ∼17 MeV, are planned for the near future.

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