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Neutron-Induced Reactions Investigations in the Neutrons Energy Range up to 16 MeV

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Abstract. In this work are presented the results of study of the possibility to measure the neutron activation cross section up to 16 MeV neutron energy by the reaction $^{9}\mathrm{Be}(p,n)^{9}\mathrm{B}$ using external proton beam of cyclotron C18/18 and some (n,x) reactions. The development of the methods of the creation neutron beams in the interest region was based on the calculations using the program GEANT4. Theoretical calculations of the neutron induced reaction cross sections for the $^{\mathrm{nat}}\mathrm{Ca}(n,x)$ and $^{\mathrm{nat}}\mathrm{Zr}(n,x)$ reactions for the energy range from corresponding threshold up to 16 MeV were carried out using nuclear reaction programs EMPIRE 3.2 and TALYS 1.6.

Introduction

Nuclear data on proton-induced and neutron-induced reactions in the energy range up to 16 MeV is important to estimate the shield design and activation of low-energy cyclotron facilities for different kind of application uses.

The predictive power of the codes for the low energy region should be checked by experimental data. The experimental results can help to test the different statistical model codes and contribute to constraining the parameter set used therein. Also such studies will provide significant insight into the reaction mechanisms dominate at different energy regions.

Nearly monoenergetic neutrons can be produced by protons impinging on thin targets of the light nuclei. In current work is reported the creation of collimated quasimonoenergetic neutron beams in the energy range approximately up to 16 MeV.

The experiments will be carried out at the external proton beam of the cyclotron C18/18. In the following sections will be described the calculations for neutron-induced reactions up to 16 MeV energy range. This energy region is of interest to produce isotopes used in applied physics.

1 The Creation of Neutron Beam

The $^{7}\mathrm{Li}(p,n)^{7}\mathrm{Be}$ and $^{9}\mathrm{Be}(p,n)^{9}\mathrm{B}$ reactions are used widely as quasimonoenergetic neutron sources. The energy spectra of quasimonoenergetic neutrons has

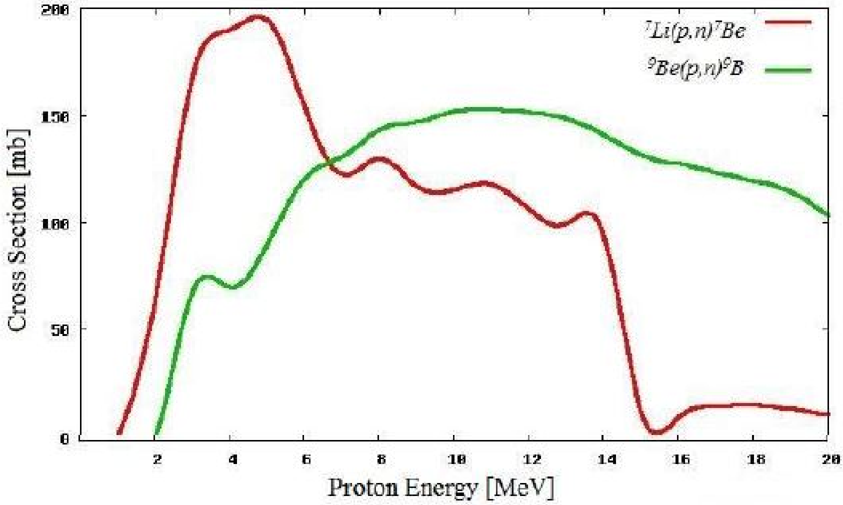

Figure 1. The dependence of the reaction cross sections via incident proton energy calculated by TALYS 1.6: red – ^{7}Li$(p, n)^{7}$Be, green – ^{9}Be$(p, n)^{9}$B.

the peak shape with maximal energy about 2 MeV lower than the proton beam energy.

As neutron source was chosen the ^{9}Be$(p, n)^{9}$B reaction because of relatively high cross section of the reaction in an investigated low energy range. The maximum cross section for ^{9}Be$(p, n)^{9}$B reaction is about 150 mb in the wide neutron energy range 8–16 MeV. Along with this, the value of melting point for ^{9}Be significantly higher than for ^{7}Li (melting point for ^{9}Be is 1287°C, for ^{7}Li is 180.54°C). This enables to use the water cooling system.

Both, ^{7}Li$(p, n)^{7}$Be and ^{9}Be$(p, n)^{9}$B reactions cross sections calculated by TALYS 1.6 [1] are shown in Figure 1.

In reality, during the interaction of protons with the beryllium target nuclei takes place not only two-particle reaction ^{9}Be$(p, n)^{9}$B. Actually, the reaction ^{9}Be(p, xn) will symbolize all reactions in which neutrons from the proton bombardment of beryllium are produced.

Table 1. All neutron emitted reactions on ^{9}Be target

Reaction	Q value, MeV	Threshold, MeV
p+^{9}Be→ n+^{9}B	-1.8504	2.0572
p+^{9}Be $\rightarrow \gamma + n$+^{9}B	-1.8855	2.057
p+^{9}Be $\rightarrow p + n$+^{8}B	-1.6645	1.85070
p+^{9}Be $\rightarrow \gamma + n + p$+^{8}B	-1.7011	1.85070
p+^{9}Be $\rightarrow p + n + 2\alpha$	-1.5727	1.74859

The list of all channels of proton-induced ^{9}Be(p, xn) reactions with neutron in final state are presented in Table 1.

Depends on targets thicknesses, the spectra of emitted neutrons are different. The target is considered to be thick if the proton is completely stopped in the target. The thickness of the beryllium target at which the proton is stopped was calculated by the program SRIM [2] and is equal 2.48 mm. The spectra of neutrons in case of thin and thick Be targets was calculated by GEANT4 [3]. In Figure 2 are shown the results of calculations in case of thick (2.5 mm) and thin (0.5 mm) beryllium targets when proton energy is 16 MeV and neutrons emitted angle is $0°$.

As seen from Figure 2 in case of the thick target the neutron flux is increasing, especially in the low-energy region.

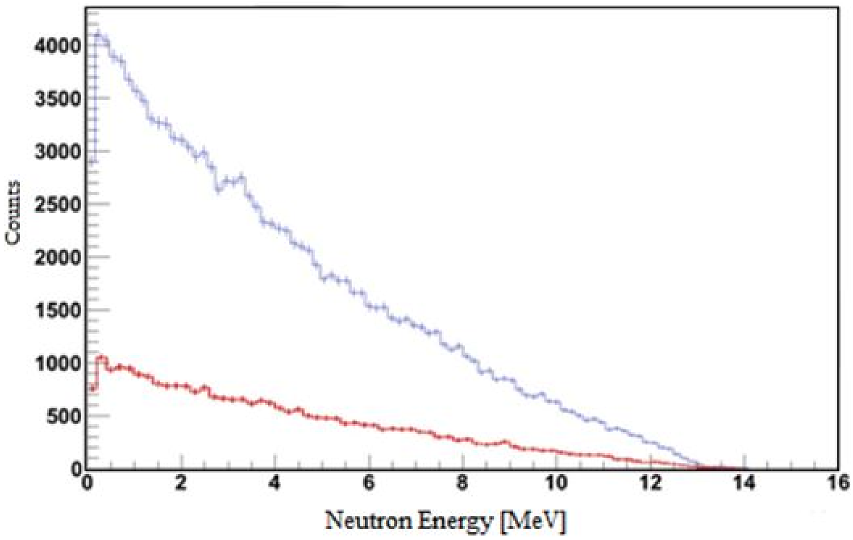

Figure 2. The spectra of all emitted neutrons under $0°$ angle: blue – 2.5 mm, red – 0.5 mm.

2 The Neutron-Induced Reaction Cross Section

It is planning to measure cross sections of the $^{\rm nat}$Zr(n, px) and $^{\rm nat}$Ca(n, px) reactions using the neutron activation method and off-line γ-ray spectrometric technique.

The low energy neutron flux will not give a contribution to the studied reaction due to the relevant thresholds. Change in the energy of the incident neutrons on the target of zirconium and calcium will be conducted by varying the energy of the incident protons on target of beryllium. Decreased the energy of the protons are planned placing on the way of the proton beam the tantalum plates which will have different thicknesses. The plate thickness are determined by the program SRIM.

Nuclear data evaluation is generally carried out on the basic of experimental data and theoretical model calculation. It is both practically and economically impossible to measure necessary reaction cross sections for all the isotopes in the periodic table.

Accurate nuclear data are essential for the design and analysis of nuclear systems, such as the reactor core fuel cell layouts and stored nuclear waste mixtures with other materials, as well as fuel cells. Measurement of neutron activation and improvement of nuclear database of these sections are vital to the safe operation of various nuclear systems such nuclear reactors, fusion reactors and accelerator-driven sub-critical systems. Induced neutron activation cross sections have direct application in the evaluation of the level of radiation and decay heat generation from the decay of materials that are irradiated in radiation fields with a strong neutron component.

The range of applications of neutron cross-section also covers environmental and space dosimetry, material analysis and isotope production. Besides, these practical applications, a study of neutron induced reactions (n, γ), (n, p), (n, α), $(n, 2n)$ etc. on various nuclei provides an experimental database for testing validity of the theoretical models of nuclear physics. The contributions of the direct, pre-equilibrium and the statistical compound nucleus processes, in the emission of charged particles can be estimated for a given (n, x) reaction. It should be noted that the necessary update of evaluated cross section libraries depends on the availability of accurate measurements obtainable with advanced neutron sources.

Neutron induced reaction cross-sections for structural materials (Zr, Ca, etc.) are basic data for evaluation of the processes in materials under irradiation in nuclear reactors. Neutron-induced reactions on zirconium are of a particular importance in a wide range of applications.

A number of data were reported on neutron induced reaction cross-sections for zirconium isotopes, and many of these were measured with the activation technique followed by off-line γ-ray spectrometric technique. The Experimental Nuclear Reaction Data (EXFOR) database shows significant discrepancy and gaps in the measured experimental data for many neutron threshold reactions [4]. Also it indicates that there has been scarce neutron capture (n, γ) reaction cross-section data available beyond the neutron energy of 2 MeV for many zirconium isotopes. Further, literature survey shows that most of the thermal neutron activation cross-section measurements for zirconium isotopes were made in reactors with neutron spectra and thus were not precise for thermal neutrons. On the other hand, zirconium is an important and major component of the structural materials used in traditional and advanced nuclear reactors, owing to its very low absorption cross-sections for thermal neutrons and resistance to corrosion, therefore this element need more experimental data statistic [5].

All possible channels of studied reactions taking place at irradiation of targets from natural Zr and Ca were considered.

The naturally abundances of isotopes in natural zirconium and natural calcium are presented in Table 2.

Table 2. The naturally abundances of isotopes in ^{nat}Zr and ^{nat}Ca

Element	Isotopes	Natural abundance, (%)	Element	Isotopes	Natural abundance, (%)
	^{90}Zr	51.45		^{40}Ca	96.941
	^{91}Zr	11.22		^{42}Ca	0.647
Zr	^{92}Zr	17.15	Ca	^{43}Ca	0.135
	^{94}Zr	17.38		^{44}Ca	2.086
	^{96}Zr	2.80		^{46}Ca	0.004
				^{48}Ca	0.187

The performed by nuclear program TALYS 1.6 calculations for reaction ^{nat}Zr$(n, xp)^{90m,g}$Y was shown that in the neutron energy range 10–14 MeV the neutron induced reaction cross section value is enough to carry out the measurements by using activation technique. The received values of cross sections for ^{90m}Y ($T_{1/2} = 3.19$ h) and ^{90g}Y ($T_{1/2} = 64.053$ h) are presented in the Figure 3.

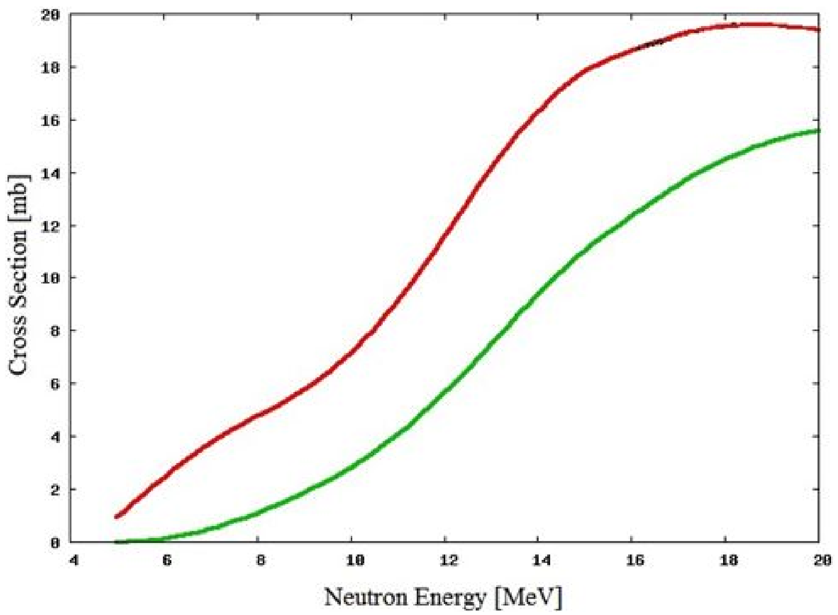

Figure 3. The ^{nat}Zr$(n, xp)^{90m,g}$Y reaction cross-section in dependence of proton energy: calculated by TALYS 1.6: green - ^{90m}Y, red - ^{90g}Y.

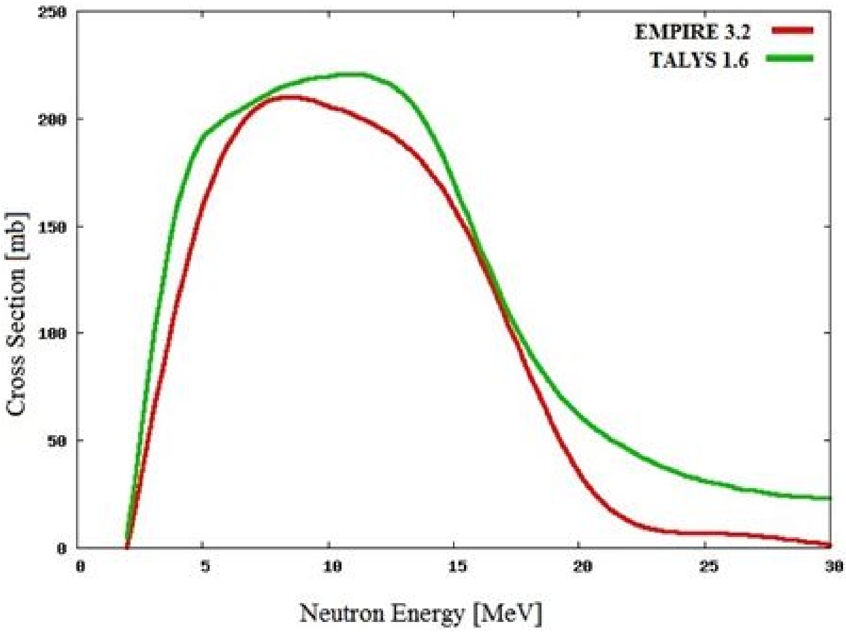

Figure 4. The ^{nat}Ca$(n, \alpha)^{37}$Ar reaction cross-section dependence of proton energy: red - EMPIRE 3.2, green - TALYS 1.6.

The values calculated by nuclear programs TALYS 1.6 [1] and EMPIRE 3.2 [6] of cross-section for the reaction ^{nat}Ca$(n, \alpha)^{37}$Ar ($T_{1/2} = 35.04$ d) are presented in Figure 4.

As can be seen from Figure 4, the calculations carried out for both programs are in good agreement and indicate that in the neutron energy range $8 - 15$ MeV the reaction cross-section reaches a value about 220 mb. Thus, our studies provide a basis to claim that by the extracted proton beam of cyclotron C18/18 can be obtained neutron beams for the investigation of neutron-induced nuclear reactions.

3 Summary

It was shown that by the proton beam of the cyclotron C18/18 is possible to obtain neutron beams by the reaction ^{9}Be$(p, n)^9$B. The obtained neutron beams can be used for experiments on neutron-induced nuclear reactions on ^{nat}Zr and ^{nat}Ca. The cross-sections for these reactions were calculated using the TALYS 1.6 and EMPIRE 3.2 nuclear programs. Based on the obtained values of the cross-sections are planned to carry out the experiment to measure the cross sections of reactions ^{nat}Zr(n, x) and ^{nat}Ca(n, x) using the method of activation analysis.

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