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Calculations of Double Differential Cross Sections on ^{56}Fe, ^{63}Cu and ^{90}Zr Neutron Emission in Proton Induced Reactions

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In general, the deep understanding of proton-induced reactions is a crucial step for the further development of nuclear reactions theory. However there has been an interesting focus in nuclear physics. Some applications require accurate nuclear reaction data of common cross sections and especially need the data of neutron and proton induced energy-angle correlated spectra of secondary particles, as well as double differential cross sections. Double-differential nucleon-production cross-sections of ^{56}Fe, ^{63}Cu and ^{90}Zr targets, bombarded with protons are calculated based on the nuclear theoretical models. Monte Carlo calculations with the TALYS 1.6 nuclear reaction simulation code are performed. Theoretical calculated results are compared with existing experimental data in EXFOR library.

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1. Introduction

The deep understanding of nucleon-induced reactions is a crucial step for the further development of theory of nuclear reactions, in general. In addition, complete information in this field is strongly needed for a large amount of applications, such as the accelerator-driven clean nuclear power systems, which have been an interesting subject of nuclear physics [1].

The accelerator-driven system requires the nuclear reaction data of common cross sections and especially the data of neutron and proton induced energy-angle correlated spectra of secondary light particles (neutrons, protons, deuterons, tritons, helium and alpha-particles), as well as double differential cross sections, to model the performance of the target/blanket assembly and to predict neutron production, activation, heating, shielding requirements, and material damage [2].

However, double differential cross section data of charged particles, emitted due to impact of neutrons on the reactor devices, is among the fundamental values in determining nuclear heating and material damages. The choice of the proper structural materials for reactor devices depends on their radiological properties, as well as mechanical properties, compatibility with other materials and irradiation performance [3].

In some studies, especially experimental [4–6] and theoretical [1–3, 7–15, 20] the double differential cross section of charged particle emission has been investigated. Due to lack of new experimental data for proton induced reaction cross section, with energy above 20 MeV, double differential neutron emission cross-sections of ^{56}Fe, ^{63}Cu and ^{90}Zr target nuclei at 22.2 MeV (for ^{56}Fe and ^{90}Zr) and 26 MeV (for ^{63}Cu) proton incident energy are calculated, in this study, using TALYS 1.6 [16] nuclear reaction simulation code. The calculated results were compared with the existing experimental data in EXFOR [17] library.

2. Methods

In this study, double differential cross sections were calculated using nuclear reaction simulation code TALYS 1.6.

2.1. Simulation software

TALYS is a nuclear reaction simulation computer code system for the analysis and prediction of nuclear reactions. The basic objective behind its construction is the simulation of nuclear reactions that involve neutrons, photons, protons, deuterons, tritons, ^{3}He and alpha particles. TALYS integrates the optical model, direct, preequilibrium, fission and statistical nuclear reaction models in one calculation scheme and gives a prediction for all open reaction channels.

2.2. Equations for double differential cross section

The double differential cross section can be calculated by generalized master equation to get the angular momentum dependent lifetime with the Legendre expansion form [6].

In TALYS, the generalization of the exclusive spectra to angular dependent cross sections is done by means of the exclusive double-differential cross sections [16]

$$\frac{\mathrm{d}^2\sigma^{\mathrm{ex}}}{\mathrm{d}E_k\,\mathrm{d}\Omega}(i_n, i_p, i_d, i_t, i_h, i_\alpha), \tag{1}$$

which are obtained by either physical models or systematics. Integration over angles yields the exclusive spectrum [16]

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$$\frac{d^2\sigma^{ex}}{dE_k}(i_n, i_p, i_d, i_t, i_h, i_\alpha) = \int d\Omega \frac{d^2\sigma^{ex}}{dE_k\, d\Omega}(i_n, i_p, i_d, i_t, i_h, i_\alpha). \quad (2)$$

3. Conclusions

In this study, double differential neutron emission cross sections for ^{56}Fe and ^{90}Zr target nuclei at emission angles of 30°, 60°, 90°, 120° and 150° are calculated by the TALYS 1.6 code at 22.2 MeV induced energy of proton. Double differential neutron emission cross sections for ^{63}Cu target at emission angles of 18°, 33°, 90°, 147° and 162° are calculated by the TALYS 1.6 code at 26 MeV incident proton energy, according to experimental data.

The comparison of calculated results with experimental data of Biryukov et al. [18] for neutron emission double differential cross sections at incident proton energy of 22.2 MeV are given for p+^{56}Fe reaction, as shown in Figs. 1–5, respectively. There is a very good agreement between theoretical and experimental data, according to the shape of calculated curve of double differential cross sections for neutron emission from ^{56}Fe, for each angle.

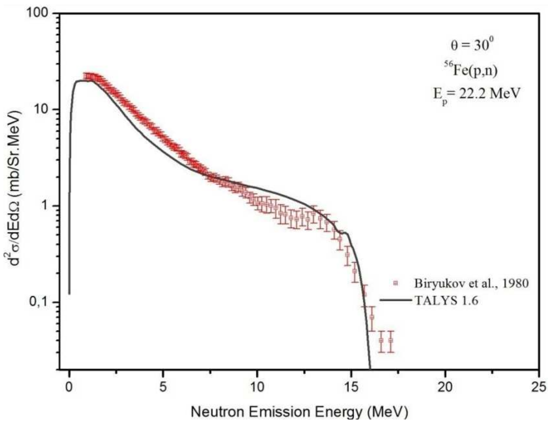

Fig. 1. Calculated double differential cross sections of neutron emission (solid line), compared with experimental data of Biryukov et al. (symbols), at incident 22.2 MeV, 30° angle, p+^{56}Fe reaction.

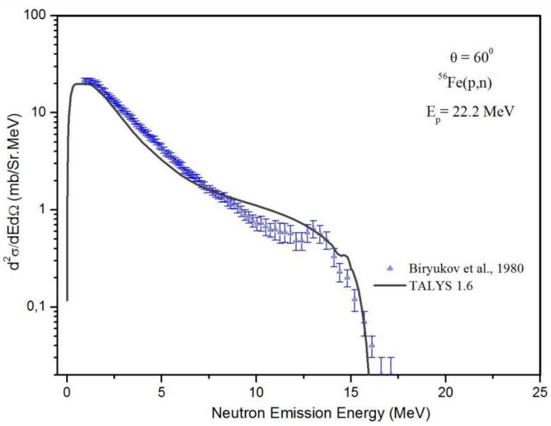

Fig. 2. Same as Fig. 1, but for the angle of 60°.

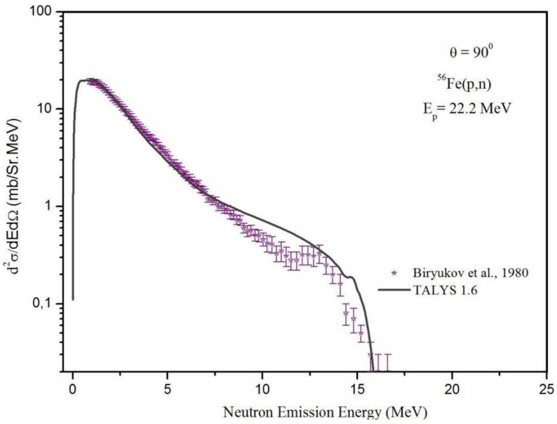

Fig. 3. Same as Fig. 1, but for the angle of 90°.

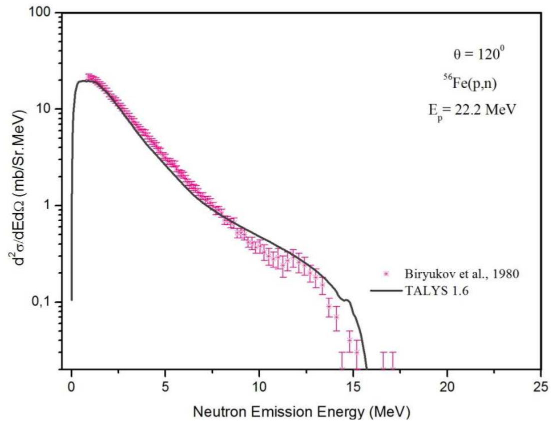

Fig. 4. Same as Fig. 1, but for the angle of 120°.

The calculated results of the double differential cross sections of neutron emission at incident proton energy of 26 MeV for p+^{63}Cu reaction are compared with neutron emission experimental data of Ahrens et al. [19] in Figs. 6–10, respectively, according to angle. The shape and the magnitude of calculated curves for neutron emission are in very good agreement with those of experimental data.

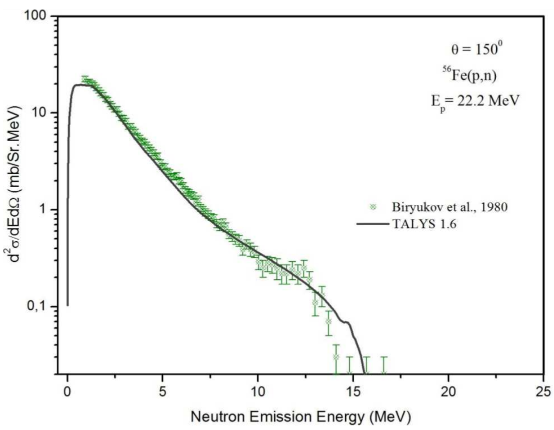

Fig. 5. Same as Fig. 1, but for the angle of 150°.

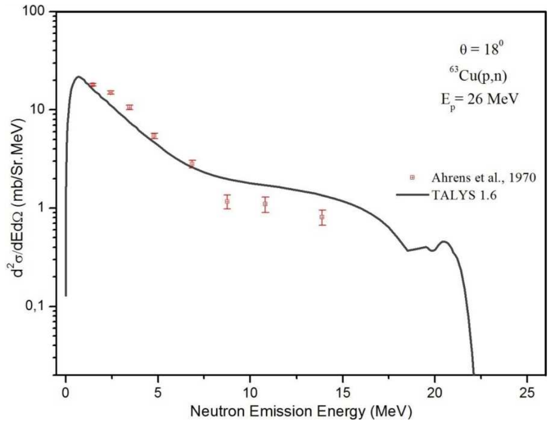

Fig. 6. Calculated double differential cross sections of neutron emission (solid line), compared with experimental data of Ahrens et al. (symbols), at incident 26 MeV, 18° angle, for p+^{63}Cu reaction.

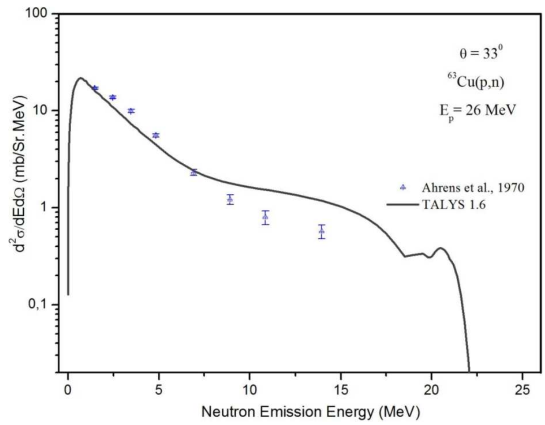

Fig. 7. Same as Fig. 6, but for the angle of 33°.

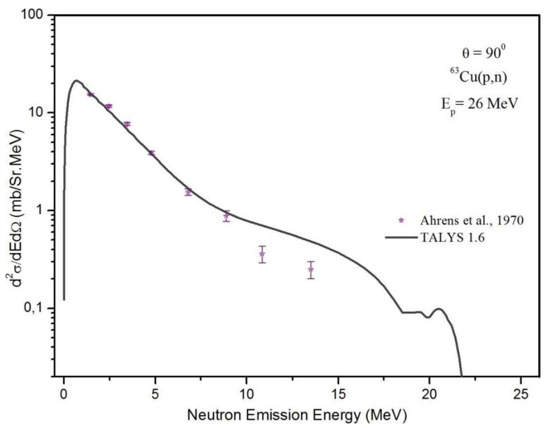

Fig. 8. Same as Fig. 6, but for the angle of 90°.

Biryukov et al. [18] (1980) measured the double differential cross sections of neutron emission for p+^{90}Zr reaction at an incident proton energy of 22.2 MeV. The comparison of calculated results and experimental data for different angles, at incident proton energy of 22.2 MeV is provided in Figs. 11–15.

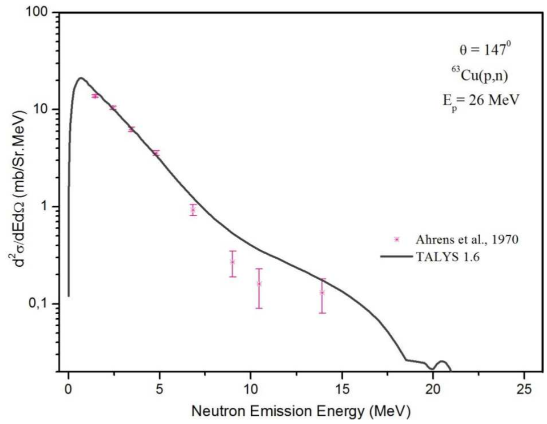

Fig. 9. Same as Fig. 6, but for the angle of 147°.

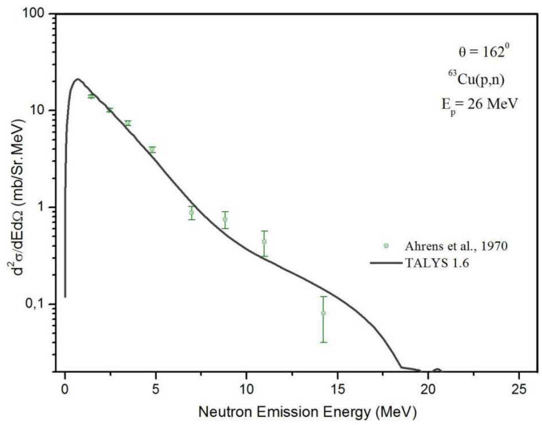

Fig. 10. Same as Fig. 6, but for the angle of 162°.

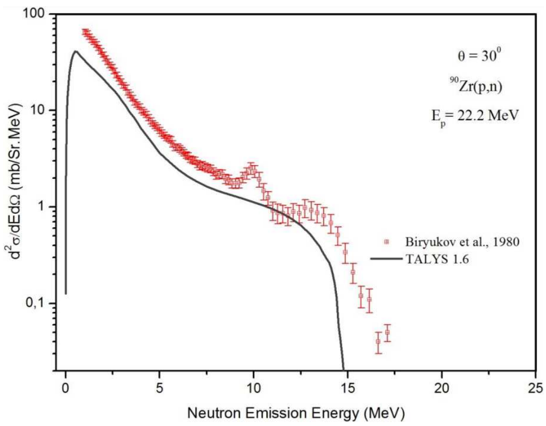

Fig. 11. Calculated double differential cross sections of neutron emission (solid line), compared with experimental data of Biryukov et al. (symbols), at incident 22.2 MeV, 30° angle, for p+^{90}Zr reaction.

The calculated double differential cross section of ^{90}Zr(p,n) reactions at 22.2 MeV, for different angles, show that the shape and the magnitude of the calculated curve for all angles are in agreement with Biryukov's experimental data.

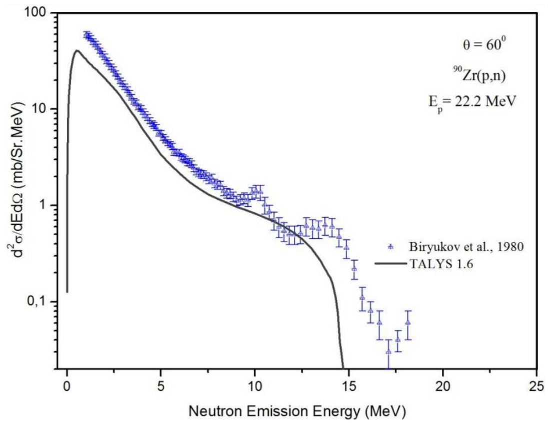

Fig. 12. Same as Fig. 11, but for the angle of 60°.

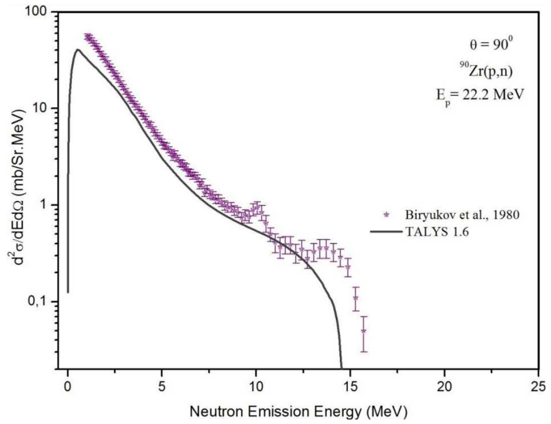

Fig. 13. Same as Fig. 11, but for the angle of 90°.

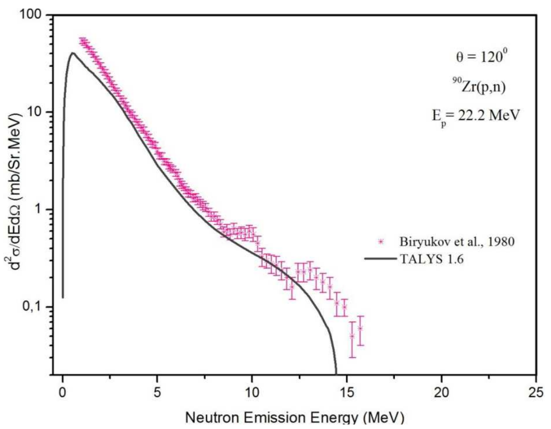

Fig. 14. Same as Fig. 11, but for the angle of 120°.

As shown in all figures, the fluctuations of the double differential cross sections become smoother and the calculated results agree better with experimental data for ^{56}Fe, ^{63}Cu and ^{90}Zr target nuclei. However, it can be seen that the double differential cross section increases with the increasing excitation energy [20]. Generally, the theoretical calculations provide a good description of

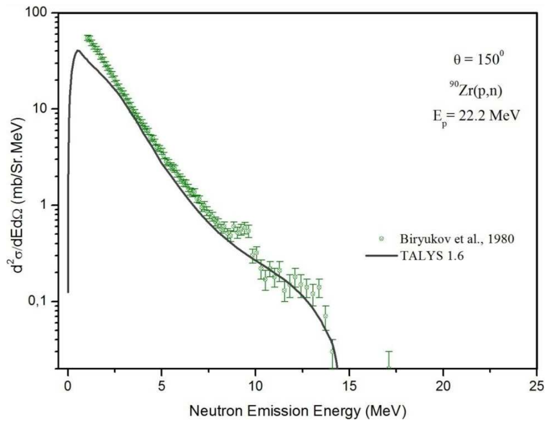

Fig. 15. Same as Fig. 11, but for the angle of 150°.

the shapes and magnitude of the double differential cross sections for neutron emission, in agreement with the experimental data. These calculated data enrich the nuclear library because there are no new experimental data for target nuclei, considered in this study. The calculated data can be used in different applications, if necessary.

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