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Reaction Rates of Residual Nuclei Produced in ^{59}Co at the Target *QUINTA*

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In December 2013, an experiment with the natural uranium spallation target QUINTA was performed at the Joint Institute for Nuclear Research (JINR). The mass of the *QUINTA* setup is 512 kg. It consist of five hexagonal sections. The experimental samples of ^{59}Co have been irradiated in the field of secondary neutrons generated by the deuteron beam at the Nuclotron accelerator at JINR. Energy of the deuteron beam was 4 AGeV. During the experiment, samples were situated in different positions inside the assembly and after irradiation they were measured at the high-purity germanium semiconductor detectors. Experimental reaction rates of residual nuclei were determined and compared with reaction rates calculated with the MCNPX code.

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1.Introduction

In the world, 438 nuclear power reactors are in operation in December 2014 [1]. The global problem of atomic energy is radioactive waste. The radioactive waste is divided in the six main categories, e.g. actinides and long-lived fission products [2]. One of the solutions is a nuclear waste disposal. The transmutation of radioactive waste with the use Accelerator Driven Systems (ADS) is a possible solution. Europe, India and China are interested in the programs of using ADS technology. One of the European biggest project, that concentrates on the ADS is project MYRRHA [3] in Belgium.

2.Experimental

2.1 The *QUINTA* setup

Natural uranium spallation target *QUINTA* is located at the Joint Institute for Nuclear Research (JINR), Dubna, Russia. The setup consists of natural uranium. It is composed of five hexagonal sections (See *Fig. 1*), each section is 114 mm long and separated by a 17 mm air gap. The total mass of natural uranium target is 512 kg which is situated in rods. Each rod is 104 mm in length, 36 mm in diameter and 1.72 kg in mass. The first section is composed of 54 rods. Other sections have 61 rods. Each section is closed in an aluminium container with a wall thickness of 5 mm. The length of the target is 638 mm and a total mass is 538 kg including all construction materials. The *QUINTA* target is surrounded by lead bricks of 100 mm thickness on six sides. The front side of the shielding has a square window 150 x 150 mm. Plates with samples are pasted to the air gaps between sections. The target *QUINTA* stays on the rails. It is for better manipulation with the target. [4]

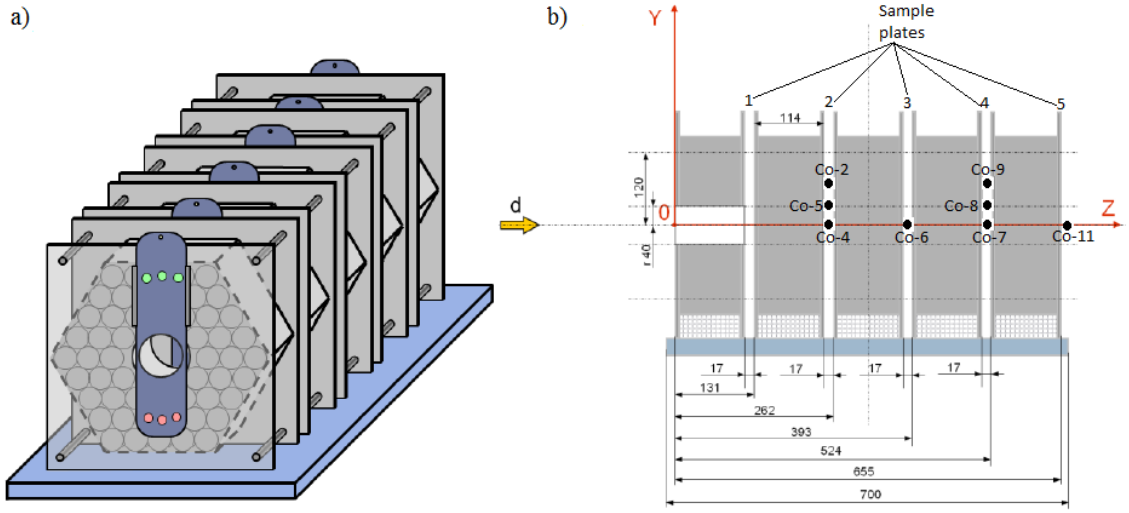

Fig. 1: *QUINTA* target a) front view [5] and b) with positions of irradiated samples.

2.2 Information about irradiation

The *QUINTA* setup was irradiated on December 7, 2013 by deuteron beam with energy 4 AGeV at the Nuclotron accelerator, which is situated at the Laboratory of High Energy Physics at JINR. Time of irradiation was 27 hours and 18 minutes. Number of deuterons was N_d=(6.11±0.6)·10^{12}. It was determined in the collaboration Energy and Transmutation of Radioactive Waste with contribution of the Czech group and group from KIPT Kharkov, Ukraine.

All samples of ^{59}Co were irradiated in the field of secondary neutrons. The samples were situated after sections 2, 3, 4 and 5 at radius 0 mm from the beam centre (See *Fig. 1b*), however after the 2nd and 4th sections, the samples were also at the positions 40 and 80 mm from beam centre. The samples have a square shape 10 x 10 mm, 1 mm thickness and a mass of about 1 g. After irradiation, the experimental samples were transported to the YaSNAPP spectroscopy laboratory and measured with the use of the high-purity germanium semiconductor detectors, manufactured by ORTEC Company with relative efficiency 32.9 % and 26 %. Measurement began 12 hours after the end of irradiation. Each sample was measured 3 times. Measured spectra were analyzed with the program DEIMOS32 [6]. DEIMOS32 is a gamma-spectroscopy software.

3.Determination of the reaction rate

Reaction rate is defined as the number of produced residual nuclei per one atom in the sample N_A and one incident deuteron per second N_D. The experimental reaction rates (R_{Exp}) were determined for each isotope from the following equation:

$$R_{Exp} = \frac{S_p \cdot C_{abs}(E) \cdot B_a}{I_\gamma \cdot \varepsilon p(E)} \frac{t_{real}}{t_{live}} \frac{1}{N_A} \frac{1}{N_D} \frac{e^{(\lambda \cdot t_0)}}{1-e^{(-\lambda \cdot t_{real})}} \frac{\lambda \cdot t_{irr}}{1-e^{(-\lambda \cdot t_{irr})}} \cdot C_{coisum} \qquad (1)$$

where S_p is the peak area; $C_{abs}(E)$ the self-absorption correction; B_a the beam intensity correction; I_γ the gamma-line intensity; $\varepsilon_p(E)$ the full-energy peak efficiency; t_{real} the real measurement time; t_{live} the live time of the measurement; λ the decay constant of produce nuclei, t_{irr} the irradiation time, t_0 the time between end of irradiation and begin of counting and C_{coisum} is the correction for true coincidence summing.

The reaction rates were calculated for the following reaction products ^{46,47}Sc, ^{48}V, ^{51}Cr, ^{52,54}Mn, ^{56,57,58,60}Co and ^{59}Fe. The reaction rates are shown in Fig. 2 a) (different sections, radius 0 mm) and Fig. 2 b) (section 2, radius 0; 40 and 80 mm). In the figures, the products of ^{59}Co are sorted according to the effective threshold energy from the lowest 4 MeV up to the highest 87 MeV (energy when the value of reaction rate is lower than 1%). Fig. 2a) shows that the reaction rates decrease with the increasing axial distance. The (n,γ) reaction rate decreased from (1.36±0.14)·10^{-26} atom^{-1}·deuteron^{-1}·AGeV^{-1} after the section two (black values) to the (3.82±0.42)·10^{-27} atom^{-1}·deuteron^{-1}·AGeV^{-1} after the section five (green values). The similar situation is illustrated in Fig. 2b) with increasing distance from the beam centre.

a) b)

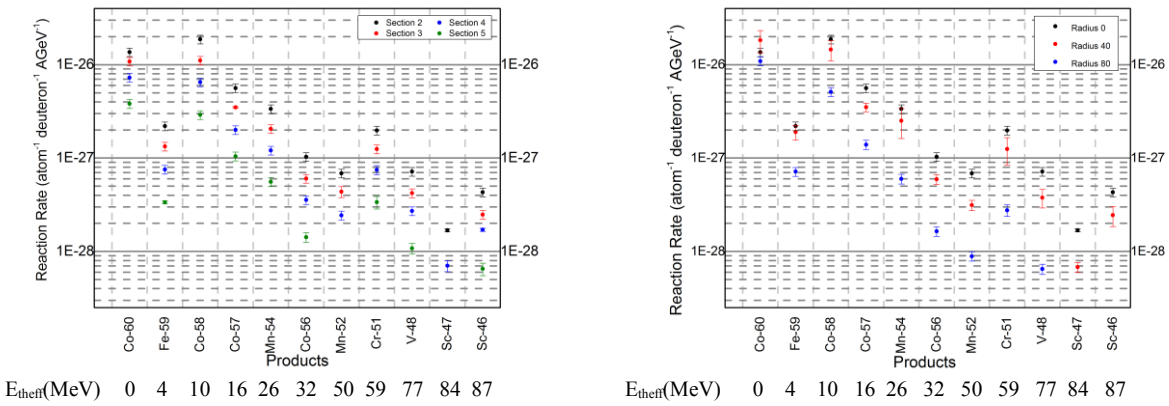

Fig. 2: Comparison of the experimental reaction rate a) at 0 mm from the beam centre in all sections, b) after section 2 at the different radius from centre.

4.Comparison of the experimental and calculated reaction rates

Calculated reaction rates were determined by folding of the simulated neutron flux and the cross section. The cross sections up to 30 MeV were taken from the data library TENDL 2012 [7]. The cross sections above 30 MeV were calculated using TALYS 1.6 code [8]. Neutron flux was simulated in the program MCNPX 2.7 [9] based on the geometry model of the *QUINTA* target. During the calculation, the ENDF/B-VII cross section library, the ABLA fission evaporation model [10] and INCL4 intra nuclear physics model [11] were used. Calculated reaction rates (R_{Cal}) were obtained from the equation:

$$R_{Cal} = \sum_j^n \sigma_i(En) \cdot \phi_i(En) \qquad (2)$$

where $\sigma_i(En)$ is the energy dependent cross section and $\Phi_i(En)$ is the neutron flux from the MCNPX code.

The comparison was performed for reactions (n,γ), (n,p), (n,2n) and (n,3n) (See Fig. 3 a, b, c, d) at radius 0 mm from the beam center. Calculated values are black and experimental values are red. Simulation of MCNPX 2.7 was carried out for the samples at radius 0 mm from beam center. The complete simulation and results will be carried out in the near future. The experimental results for (n, γ) reaction are in a good agreement with the calculated values only with one standard deviation. However, the experimental results of the other reactions are not in a good agreement with calculated values.

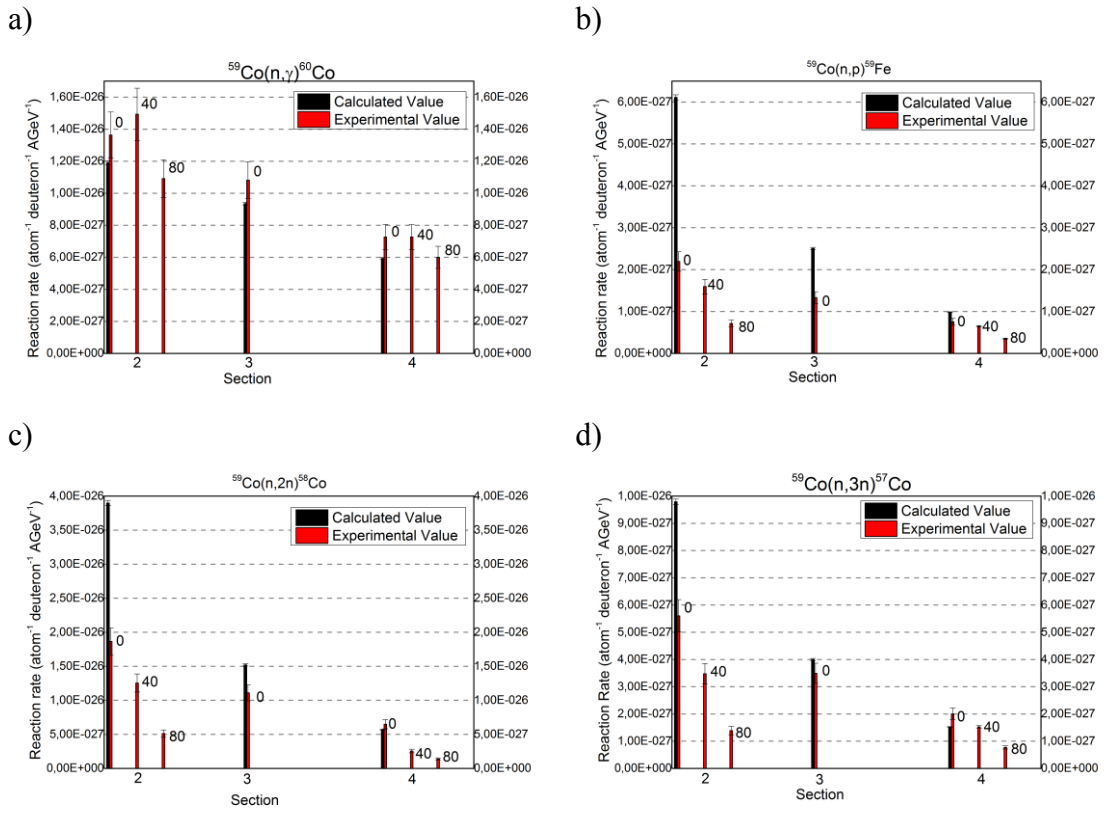

Fig. 3: Comparison calculated and experimental reaction rates in reactions a) (n,γ), b) (n,p), c) (n,2n) and d) (n,3n) from 0 mm from the beam centre.

5. Conclusion

Interaction of the secondary neutrons with ^{59}Co nuclei has been experimentally investigated. Secondary neutron field has been generated as a results of irradiation of the massive uranium target *QUINTA* at the JINR Nuclotron accelerator with the 4 AGeV deuteron beam. Experimental samples were situated in ten different positions of the neutron field. The maximum reaction rate was found after section 2 at a radius 0 mm. With the increase in radius as well as the longitudinal distance, the reaction rates decrease. The experimental reaction rates were compared with simulated ones using MCNPX 2.7 code. The reaction (n,γ) had good agreement within one standard deviation, other results of reaction rates were not in good agreement. This can be caused either by inappropriate determination of cross sections or imperfect simulation of neutron flux at higher energies. The results will be compared with the data from the MCNPX 2.6 code in the near future. The calculated values of reaction rates will be available for all positions.

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