MONITORING OF HIGH ENERGY DEUTERON BEAMS IN THE EXPERIMENTS WITH MASSIVE TARGETS

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The influence of massive uranium target (500 kg ^{nat}U) of assembly "QUINTA" on the results of high energy deuteron beam monitoring with aluminum and copper foils was investigated. In order to increase the accuracy of deuteron beam off-line monitoring, the measurements of the cross sections of fragmentation reaction $^{nat}Cu(d,x)^{24}Na$ were performed at 1.32, 2, 4 и 8 GeV deuteron energies. For the same deuteron energies the cross sections of residual nuclei ^{7}Be, ^{42}K, ^{52}Mn, ^{57}Co and ^{58}Co for $^{nat}Cu(d,x)$ reaction were measured

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INTRODUCTION

During more than 40 years, a large number of experiments on the irradiation of massive targets of heavy elements by relativistic protons and ions were performed at the Joint Institute for Nuclear Research (JINR) with Synchrocyclotron and Synchrophasotron and then superconducting accelerator "Nuclotron" beams [1 - 4]. These works have been devoted to the study of nuclear-physical processes in different extended targets (as one part of Electronuclear installation), and in uranium subcritical assemblies.

Starting from 2010 studies of neutron fields, which are generated in the 500 kg uranium target (assembly QUINTA) by relativistic particle beams, carried out at JINR in the framework of international collaboration "Energy and Transmutation RAW" [5 - 7].

The main purposes of the experiments:

- determination of the optimal energy and type of incident particles;
- determination of beam power amplification depending on the energy of the incident particles;
- determination of the influence of beam energy on the production ^{239}Pu;
- determination of reaction rates of most relevant isotope processing from the spent nuclear fuel (SNF);
- obtaining of the experimental data allowing to modify existing models and transport codes.

To solve these problems it is necessary to know the full intensity of primary accelerated particle incident on the uranium target.

Usually a standard technique of Al foil activation in the reaction $^{27}Al(a,x)^{24}Na$ for monitoring of beams of relativistic protons, deuterons and ^{12}C is used. ^{24}Na radioisotope is suitable for measurements because it has a suitable half-life (14.96 hours) and γ-radiation energy (1368.5 and 2754.0 keV). The amount of produced ^{24}Na nuclei is determined by the γ-spectra of irradiated foils. Then, using the known experimental cross sections of the corresponding nuclear reactions, the total intensity of accelerated particles that were passing through the foil is calculated.

On the other hand it is known that a large number of neutrons with energies at which the ^{24}Na is effectively produced in the reaction $^{27}Al(n,\alpha)^{24}Na$ can be generated by high-energy particle beams in massive heavy nuclei target. Thus, the cross section of reaction $^{27}Al(n,\alpha)^{24}Na$ for neutrons with an energy of 10 MeV is about 90 mb. If the monitor foil is placed near a massive target, part of neutrons produced in the target hits the monitor foil and can result in error of the total beam intensity estimation. In this case, for monitoring of the primary particle beams the activation of copper foils in the fragmentation reactions $^{nat}Cu(a,x)^{24}Na$ can be used, see, for example [8]. Use of copper foil eliminates the influence of neutrons on the monitoring result, as $^{nat}Cu(n,x)$ nuclear reactions leading to the formation of ^{24}Na are absent.

However, for deuterons, unlike protons [9], there is no experimental cross sections data for $^{nat}Cu(d,x)^{24}Na$ nuclear reaction. Therefore, in this **work**, the fragmentation nuclear reaction $^{nat}Cu(d,x)^{24}Na$ cross sections for 1.32, 2, 4 and 8 GeV deuteron energies were measured. The influence of massive uranium target (500 kg ^{nat}U) of assembly "QUINTA" on the results of monitoring of deuteron beams with aluminum and copper foils was investigated. Also, for these deuteron energies the cross sections of the residual isotopes ^{7}Be, ^{42}K, ^{52}Mn, ^{57}Co and ^{58}Co in the reactions $^{nat}Cu(d,x)$ were measured.

The measurements were performed at the Laboratory of High Energy physics, JINR, Dubna, Russia with deuteron beams of superconducting accelerator "Nuclotron".

1. EXPERIMENT AND METHODS

For each of the four deuteron energies two series of irradiations of the copper and aluminum foils were carried out: in the absence of the uranium target of assembly "QUINTA" and when uranium target placed in the path of the deuteron beam. In each case the copper and aluminum foils was placed at four points. Without uranium target the foils were placed: at point P1 – on the output beam window of the ion guide of accelerator and at points P2, P3, P4 – at a distance of 200, 280 and 870 cm from the output window of the ion guide, accordingly. With uranium target monitor foils were placed at the points P1, P2, P3, and at the point Pk – at the entrance to the lead shielding of uranium target, which was placed at the distance of 310 cm from the output window of the ion guide. Monitoring of total deuteron fluence passing through the copper foils was performed using aluminum foils. At each point three *Al* and *Cu* foils with size

140×140×0.03 mm were placed. This size is due to the size of large lateral dimensions of deuteron beam (5…10 cm) at the output of the accelerator ion guide. The middle foil was used for measurements. The first and third foils are used to compensate emitted ^{24}Na nuclei from the middle foil. The choice of the cross sections of $^{27}Al(d,x)^{24}Na$ reaction for different deuteron energies described in the refs [7, 10]. The cross sections equal to 16.5, 15.4, 14.6 and 14.0 mb used for 1.32, 2, 4 and 8 GeV deuteron energies, accordingly. Total eight irradiations were carried out, duration of exposures ranged from 5 to 20 hours, the total intensity of accelerated deuterons was from $1.5\cdot10^{12}$ to $3\cdot10^{13}$. After irradiation the γ-spectra of Al and Cu foils were measured by γ-spectrometer with HPGe-detector.

Earlier, in our experiments [7] the foils folded 6 times (64 layers) before starting measurements with HPGe-spectrometer. It is practically impossible to obtain the samples of identical sizes using such technique of foil preparation for measurements. Except this, it was observed that in some cases yield of ^{24}Na that was measured twice (one side of sample directed to the detector "bottom", and then another, "top") may differ by more than 10%. As an example, Fig. 1 shows the measurement error of yield of ^{24}Na for folded foils (Run December 2012, 4 and 8 GeV deuteron beam energies). All foils were measured first in the "bottom" (yield ^{24}Na I_1), and then turned over to the "top" (yield ^{24}Na I_2).

Figure shows the experimental value of $\sigma(I_1 - I_2) = \sqrt{D}$, where measurement dispersion D is $D(I_1 - I_2) = D(I_1) + D(I_2) = (\Delta I_1)^2 + (\Delta I_2)^2$. It is seen that in the confidence intervals 1σ (68.2%) were only 43.8% of all measurements, in CI 2σ (95.5%) were 68.8% of all measurements, and in CI 3σ (99.7%) were 87.5% of all measurements.

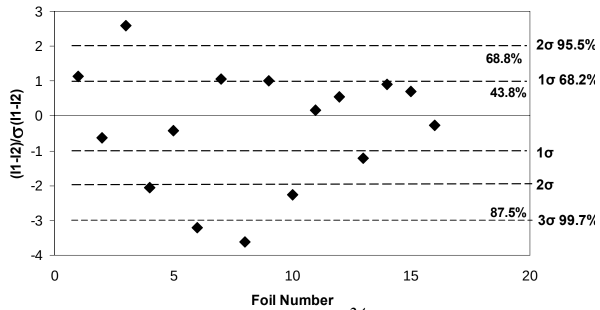


Fig. 1. Measurement error of ^{24}Na yield ("bottom", "top") for stacked foils in December 2012, the deuteron energy was 4 and 8 GeV

In March 2013 when irradiation was by deuterons with energies 1.32, 2, 4 and 8 GeV the following method for foil preparation for measurements was used. The irradiated foil was cut into squares with dimension 1…2 mm, which were carefully mixed. Then, washers with diameter 15 mm and a height of 3.3…3.4 mm were made using a mold and screw press. To improve the mechanical properties of pressed samples the foils before experiments were annealed in a vacuum furnace at 300^0C for 15 minutes. Fig. 2 shows the measurement errors of ^{24}Na yield for pressed foils in March 2013, the deuteron energies were 1.32, 2, 4 and 8 GeV. All foils were measured first in the "bottom" (yield I_1), and then turned over to the "top" (yield I_2).

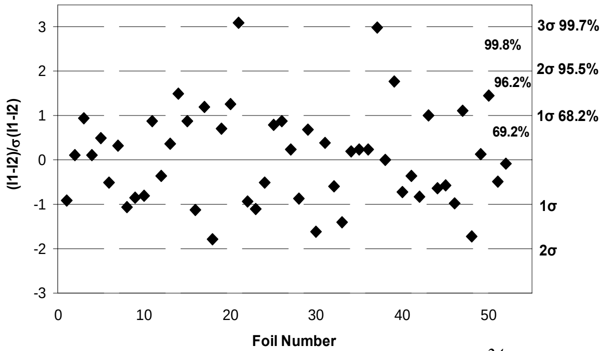


Fig.2. Measurement errors of yield of ^{24}Na ("bottom", "top") for pressed foils in December 2012, deuteron energy was 1.32, 2, 4 and 8 GeV

Note that, in this case 69.2% of all measurements fell in confidence interval 1σ, 96.2% in 2σ, and 99.8% in 3σ.

In the result of processing of the measured spectra peak area of γ-radiation with energy 1368.6 keV and 2754.0 keV (it is accompanied β^--decay of ^{24}Na) were determined. The cross section of reaction $^{nat}Cu(d,x)^{24}Na$ was determined using the following expression:

$$\sigma_{Cu} = \frac{A_{Cu}\cdot S_p^{Cu}}{\Phi\cdot N_A\cdot D_{foil}\cdot\varepsilon_p(E)\cdot I_\gamma}\times\frac{e^{\lambda t_c^{Cu}}}{1-e^{-\lambda t_{live}^{Cu}}}\times\frac{e^{-\lambda\tau}-1}{\lambda\tau}\times$$
$$\times K_B\cdot K_{COI}\cdot K_{ABS}\cdot K_G\cdot K_{NP},$$

where, A is the atomic mass; Φ is the total flux passing through the foil; N_A is the Avogadro number; D_{foil} is the foil thickness; S_p is the peak area, by what the ^{24}Na production is determined; $\varepsilon_p(E)$ is the spectrometer efficiency of γ-quanta with energy E; I_γ is the quantum yield per decay of γ-quanta with energy E; λ is the decay constant ^{24}Na; t_c is the time from the end of irradiation to starting of γ-spectrum measurement; t_{live} is the "live" time of γ-spectrum measurement; τ is the "dead" time; K_B is the coefficient that determines the course of irradiation; K_{COI} is the correction factor taking into account coincidence when γ-lines are registering; K_{ABS} is the correction factor taking into account the self-absorption of the registered radiation in the sample; K_G is the correction factor taking into account the change of geometry when measuring; K_{NP} is the correction factor taking into account the geometrical dimensions of sample.

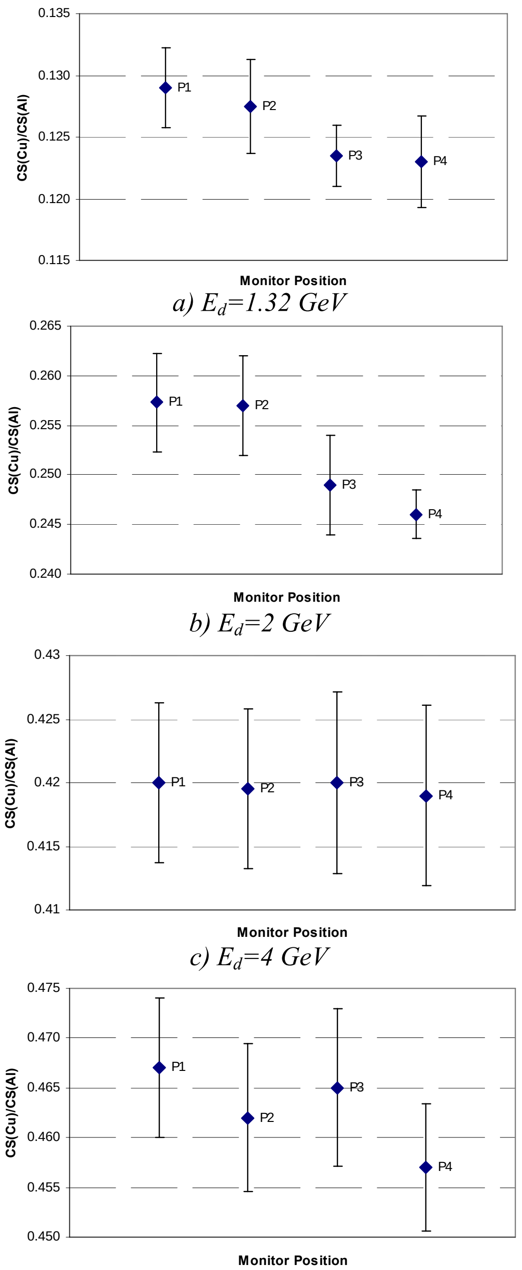
The total flux passing through the foil was measured by aluminum foil. After substituting the expression for the total flux we obtain the ratio of cross sections of ^{24}Na production in copper to aluminum:

$$\frac{\sigma_{Cu}}{\sigma_{Al}} = \frac{S_p^{Cu}}{S_p^{Al}}\cdot\frac{A_{Cu}}{A_{Al}}\cdot\frac{K_{ABS}^{Cu}}{K_{ABS}^{Al}}\cdot\frac{e^{\lambda t_c^{Cu}}}{e^{\lambda t_c^{Al}}}\cdot\frac{1-e^{-\lambda t_{live}^{Al}}}{1-e^{-\lambda t_{live}^{Cu}}}.$$

Note that for this method the total error of measurement of $^{nat}Cu(d,x)^{24}Na$ reaction cross section is formed only from the errors of the cross section of the reference reaction $^{27}Al(d,x)^{24}Na$, statistical errors of γ-peak area and errors in the self-absorption coefficients of γ-quanta in the copper and aluminum.

2. RESULTS AND DISCUSSION

Figs. 3, a, b, c, d shows the results of measuring the ratio of the cross sections σ_{Cu}/σ_{Al} for deuteron energies 1.32, 2, 4 and 8 GeV.



a) E_d=1.32 GeV

b) E_d=2 GeV

c) E_d=4 GeV

d) E_d=8 GeV

Fig. 3. The ratio of $^{nat}Cu(d,x)^{24}Na$ reaction cross section to e $^{27}Al(d,x)^{24}Na$ reaction cross-section, measured at positions P1-0, P2-200 cm, P3-280 cm, P4-870 cm – the distance from the beam output from the ion guide of accelerator NUCLOTRON

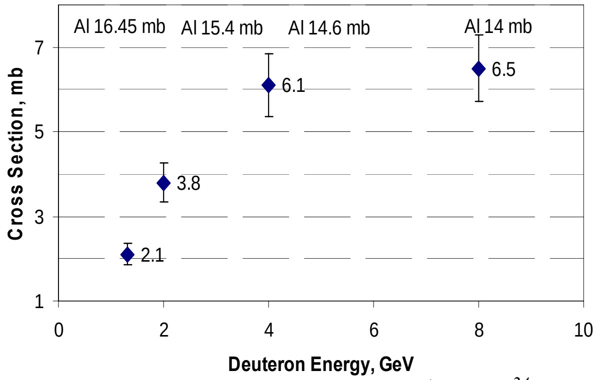


Fig. 4. The reaction cross section $^{nat}Cu(d,x)^{24}Na$ depending on the deuteron energy

The average value of the ratio of $^{nat}Cu(d,x)^{24}Na$ reaction cross section to $^{27}Al(d,x)^{24}Na$ reaction cross section for deuterons with energy 1.32 GeV is 0.125±0.004, for 2 GeV is 0.249±0.005, for 4 GeV is 0.421±0.009 and for 8 GeV is 0.464±0.11. Averaging was carried out from the results of measuring at the irradiation of foils located in the 4 positions. Fig. 4 shows the measured dependence of the reaction cross section $^{nat}Cu(d,x)^{24}Na$ on the deuteron energy. The figure shows the cross section of reference reaction $^{27}Al(d,x)^{24}N$ for all used deuteron energies.

Note the reaction cross section $^{nat}Cu(p,x)^{24}Na$ in dependence of proton energy behaves similarly. Initially, it increases almost linearly with increasing energy and then reaches a plateau near 3…4 GeV [9].

In the measured spectra of irradiated copper foils, along with γ-lines accompanying decay of ^{24}Na, γ-lines corresponding to a variety of radioactive isotopes has also been identified. For some of them figure 5 shows residual cross section dependencies on deuteron energy.

The energy dependence of the reaction cross section $^{nat}Cu(d,x)^{7}Be$ is similar to the dependence of reaction cross section $^{nat}Cu(d,x)^{24}Na$. This indicates that ^{7}Be is formed as a result of fragmentation reactions, wherein the value of cross section is approximately three times higher.

Yield of isotopes ^{42}K, ^{52}Mn, ^{57}Co, ^{58}Co decreases with increasing deuteron energy and tends to reach a plateau. The reaction cross section also decreases with increasing of number of nucleons emitted from the nucleus.

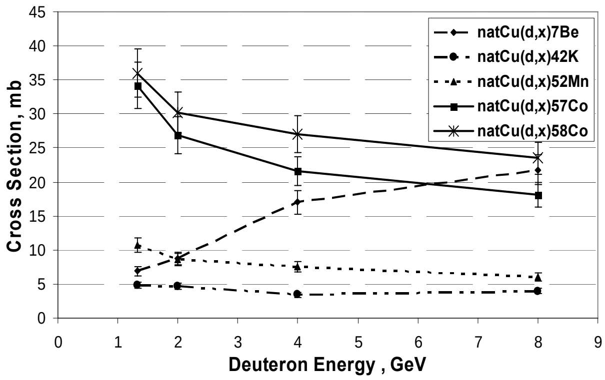


Fig. 5. The reaction cross section $^{nat}Cu(d,x)^{7}Be$, $^{nat}Cu(d,x)^{42}K$, $^{nat}Cu(d,x)^{52}Mn$, $^{nat}Cu(d,x)^{57}Co$, $^{nat}Cu(d,x)^{58}Co$ depending on the deuteron energy

To study the effect of a uranium target of assembly QUINTA on determination of total fluence of deuterons incident on the target it was measured the number of deuterons passing through the *Al* and *Cu* foils at positions P1, P2, P3 and P_K. The measurement results are shown in Table.

Contribution of the reaction $^{27}Al(n,\alpha)^{24}Na$ in the production of ^{24}Na in Al foils at positions P1 (distance to target 320 cm) and P2 (120 cm) can be neglected. At the same time, in positions P3 (40 cm) and P_K (0) neutrons emitted from uranium target exert a significant influence on the accuracy of monitoring. At the same time, in positions P3 (40 cm) and P_K (0) neutrons emitted from uranium target exert a significant influence on the accuracy of monitoring. Thus, in the P3 position the monitoring using Al leads to increasing in the total flux of about 15…20%, and in position P_K 100%.

Total fluence of deuterons with energies 1.32, 2, 4 and 8 GeV, measured at the positions P1, P2, P3 and P_K

Position	Foil	Total fluence, 1.0E+13			
		1.32 GeV	2 GeV	4 GeV	8 GeV
P1	Al	0.92±0.01	4.06±0.06	1.91±0.02	0.23±0.03
320 cm to the target	Cu	-	4.01±0.07	1.88±0.04	0.22±0.05
P2	Al	0.95±0.01	3.89±0.06	1.90±0.03	0.22±0.03
120 cm to the target	Cu	0.94±0.02	3.83±0.07	1.87±0.04	0.21±0.05
P3	Al	1.08±0.01	4.15±0.06	2.11±0.03	0.25±0.03
40 cm to the target	Cu	0.91±0.02	3.91±0.07	1.87±0.04	0.20±0.05
P_K	Al	-	-	3.27±0.03	0.45±0.07
0 cm (Entrance of the target)	Cu	-	-	1.82±0.03	0.22±0.05

CONCLUSIONS

The measured reaction $^{nat}Cu(p,x)^{24}Na$ cross sections for deuterons with energies 1.32, 2, 4 and 8 GeV allow to use copper foils for monitoring of deuteron beams during irradiation of extended targets of heavy elements. In this case, the neutrons emitted from the target, don't make an error in the results of monitoring. Using of aluminum foils is only possible when placing it at the distance of more than 1 m from the target.

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МОНИТОРИРОВАНИЕ ПУЧКОВ ВЫСОКОЭНЕРГЕТИЧНЫХ ДЕЙТРОНОВ В ЭКСПЕРИМЕНТАХ С МАССИВНЫМИ МИШЕНЯМИ

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Исследовано влияние массивной урановой мишени (500 кг ^{nat}U) установки «КВИНТА» на результаты мониторирования пучков дейтронов с помощью алюминиевых и медных фольг. Для улучшения точности off-line мониторирования пучков дейтронов, бомбардирующих протяженные мишени из тяжёлых элементов, были проведены измерения сечений реакции фрагментации $^{nat}Cu(d,x)^{24}Na$ для дейтронов с энергией 1,32; 2; 4 и 8 ГэВ. Для этих же энергий дейтронов измерены сечения выхода изотопов ^{7}Be, ^{42}K, ^{52}Mn, ^{57}Co и ^{58}Co в реакциях $^{nat}Cu(d,x)$.

МОНІТОРУВАННЯ ПУЧКІВ ВИСОКОЕНЕРГЕТИЧНИХ ДЕЙТРОНІВ В ЕКСПЕРИМЕНТАХ З МАСИВНИМИ МІШЕНЯМИ

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Досліджено вплив масивної уранової мішені (500 кг ^{nat}U) установки «КВІНТА» на результати моніторування пучків дейтронів за допомогою алюмінієвих і мідних фольг. Для покращення точності off-line моніторування пучків дейтронів, які бомбардують протяжні мішені з важких елементів, були проведені вимірювання перетинів реакції фрагментації $^{nat}Cu(d,x)^{24}Na$ для дейтронів з енергією 1,32; 2; 4 і 8 ГеВ. Для цих же енергій дейтронів виміряні перетини виходу ізотопів ^{7}Be, ^{42}K, ^{52}Mn, ^{57}Co в реакціях $^{nat}Cu(d,x)$.