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# Measurement of the high energy neutron flux on the surface of the natural uranium target assembly QUINTA irradiated by deuterons of 4 and 8 GeV energy

J. Adam[a,f,]* , A.A. Baldin[b], V. Chilap[c], W. Furman[a], K. Katovsky[d], J. Khushvaktov[a], V. Kumar[e], V. Pronskikh[a,g], I. Mar'in[a], A. Solnyshkin[a], M. Suchopar[f,h], V. Tsupko-Sitnikov[a], S. Tyutyunnikov[a], J. Vrzalova[a,h], V. Wagner[f], L. Zavorka[a,h]

[a]*Joint Institute for Nuclear Research, Dubna, Russia*
[b]*Institute for Advanced Studies "OMEGA", Dubna, Russia*
[c]*CPTP "Atomenergomash", Moscow, Russia*
[d]*University of Technology, Brno, Czech Republic*
[e] *G.G.S.Indraprastha University, New Delhi, India*
[f]*Nuclear Physics Institute, Rez, Czech Republic*
[g]*Fermi National Accelerator Laboratory, Batavia, IL, USA*
[h]*Czech Technical University, Prague, Czech Republic*

**Abstract**

Experiments with the natural uranium target assembly "QUINTA" exposed to 4 and 8 GeV deuteron beams of the Nuclotron accelerator at the Joint Institute for Nuclear Research (Dubna) are analyzed. The reaction rates of $^{27}Al(n,y1)^{24}Na$, $^{27}Al(n,y2)^{22}Na$ and $^{27}Al(n,y3)^{7}Be$ reactions with effective threshold energies of 5, 27, and 119 MeV were measured at both 4 GeV and 8 GeV deuteron beam energies. The average neutron fluxes between the effective threshold energies and the effective ends of the neutron spectra (which are 800 or 1000 MeV for 4 or 8 GeV deuterons) were determined. The evidence for the intensity shift of the neutron spectra to higher neutron energies with the increase of the deuteron energy from 4 GeV to 8 GeV was found from the ratios of the average neutron fluxes. The reaction rates and the average neutron fluxes were calculated with the MCNPX 2.7 code.

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*Keywords:* Accelerator driven system (ADS); uranium target-blanket; spallation neutrons; neutron spectrum; gamma spectrometry; MCNPX.

* Corresponding author. Tel.:+7(49621)62175, *E-mail address:* iadam@jinr.ru


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## 1. Motivation

At JINR, Dubna during the last two decades in the framework of the «Energy + Transmutation of Radioactive Waste (E+T RAW)» collaboration, extensive ADS studies have been carried out with high-energy proton and deuteron beams. In particular, the transmutation rates of long lived fission products (LLFP) and transuranium (LLTRU) nuclides were measured in the neutron fields generated within lead-uranium by Adam et al. (2010) and by Bhatia et al. (2012) and lead-graphite by Adam et al. (2011) targets with moderators as well as in the natural uranium target assembly (TA) QUINTA (with and without the lead blanket) by Furman et al. (2012) irradiated by deuterons of energy 1 - 8 GeV. The effective incineration of LLFP and LLTRU needs a maximally hard neutron spectrum due to the high thresholds of (n,f) and (n,xn) reactions necessary for their transmutation.

In the present work, this problem is studied with an activation method (see Adam et al. (2005)). The yields of the product nuclei in $^{27}Al(n,y_1)^{24}Na$, $^{27}Al(n,y_2)^{22}Na$, and $^{27}Al(n,y_3)^{7}Be$ reactions have effective threshold neutron energies $E_{n,th}$ = 5, 27, and 119 MeV, respectively. These three monitor reactions have been chosen for measurement of the flux of spallation neutrons produced by 4 and 8 GeV deuterons colliding with the uranium target QUINTA. The results of these measurements are compared with the calculations performed by MCNPX2.7 to estimate the ability to reproduce the whole shape of the neutron spectra.

The target assembly QUINTA consists of four identical sections of hexagonal aluminum containers with an inscribed circular diameter of 284 mm. Each one contains 61 cylindrical metallic natural uranium rods. Each rod is 36 mm in diameter and 104 mm long with a mass of 1.72 kg. It is wrapped in an Al shell. The total mass of uranium in one section is 104.92 kg. The front fifth section has the cylindrical input beam channel of diameter 8 cm that consists of 54 uranium rods. Thus the total mass of uranium in the target assembly is 512.56 kg. The uranium target is surrounded by a lead blanket 10 cm thick.

## 2. Analysis and results

The QUINTA set-up was directly irradiated by deuterons with energies 4 and 8 GeV with integral beam intensities 2.73(10)E+13 and 9.1(4)E+12 respectively. Neutrons were produced by way of spallation, fission and evaporation processes after d+Unat collisions. Al foils with diameter 21 mm and about 4.5 mm thick were placed on the surface of TA QUINTA.

The reaction rate R is defined as the number of residual nuclei produced per sample atom per incident deuteron per second. The number of produced residual nuclei ($^{24}Na$, $^{22}Na$ and $^{7}Be$) is established by measuring their emitted gamma-rays with an HPGe detector. All three measured reaction rates R together with their uncertainties and the respective calculated values with MCNPX are given in Table 1.

An analysis of the data represented in the table 1 leads to very important conclusions on the dependence of the shape of the neutron spectrum on the incident energy. While the ratio R(8GeV)/R(4Gev) for $^{24}Na$ having a low reaction threshold is less than two, for $^{22}Na$ and $^{7}Be$ product nuclei with much higher thresholds these ratios reach about 5 and 7, respectively. This gives evidence that the neutron spectrum on the surface of TA QUINTA becomes «harder» with increase of incident deuteron energy. Other essential conclusions are related to the inability of the code used to reproduce above dependence of the high energy tail of the neutron spectrum on incident energy.

Table 1. Comparison of the experimental and calculated rates of $^{27}Al(n,y1)^{24}Na$, $^{27}Al(n,y2)^{22}Na$ and $^{27}Al(n,y3)^{7}Be$ reactions obtained for 4 GeV and 8 GeV deuteron energies in units of E-29/atom/deuteron/s.

| Product nucleus | Reaction rates | $E_d$ = 4 GeV | $E_d$= 8 GeV | R(8 GeV)/R(4 GeV) |
|---|---|---|---|---|
| $^{24}Na$ | $R_1$(exp) | 7.5(4) | 12.2(5) | 1.64(12) |
| | $R_1$(calc) | 7.473 | 16.75 | 2.24 |
| $^{22}Na$ | $R_2$(exp) | 0.522(29) | 2.73(22) | 5.2(5) |
| | $R_2$(calc) | 0.71 | 1.73 | 2.43 |
| $^{7}Be$ | $R_3$(exp) | 0.069(11) | 0.47(8) | 6.8(15) |
| | $R_3$(calc) | 0.0274 | 0.0736 | 2.69 |

The measured reaction rate R for a given produced nucleus $^{Z}A$ created in the $^{27}Al(n,y)^{Z}A$ process is a convolution of energy $E_n$ of the neutron flux $\Phi$ [n/cm$^2$/MeV/deuteron/s] and the respective cross sections $\sigma_i(E_n)$ leading to the nucleus $^{Z}A$.