# MONITORING OF GeV DEUTERON BEAM PARAMETERS IN ADS EXPERIMENTS AT THE NUCLOTRON (JINR, DUBNA)

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*Abstract*

The quality of beam instrumentation is very important in the experiments on accelerator driven systems (ADS) aiming to investigate spatial and energy distribution of neutrons inside and outside the subcritical setups comprising spallation neutron sources irradiated by relativistic beams. An important source of systematic uncertainties of the experimental data is the inaccuracy of determination of the beam parameters such as total intensity of the extracted beam, beam position at the target, fraction of the beam hitting the target and beam shape.

This paper reviews the experimental techniques and measurement tools for deuteron beam monitoring used within the "Energy plus Transmutation" collaboration in the ADS experiments at the accelerator complex of Nuclotron (JINR, Russia):

- activation technique using Al monitors for measurement of the total intensity of the extracted beam;
- solid nuclear track detectors method and activation technique using segmented activation Cu foils for determination of beam profile and position at the target.

## INTRODUCTION

High-current, high-energy accelerators or cyclotrons are used to produce neutrons from heavy elements by spallation in ADS designed and investigated in order to implement safe electronuclear technology for energy generation and long-lived radioactive waste transmutation.

A large scale research program for ADS study was initiated by the Laboratory of High Energy Physics (LHEP) within the Joint Institute for Nuclear Research (JINR) in Dubna, Russia, and a large international collaboration named "Energy plus Trasmutation" ("E+T") was established carrying out the experiments using relativistic beams of Nuclotron accelerator complex of LHEP. Within the "E+T" collaboration a number of target systems of different geometries and composition were developed and irradiated with relativistic protons and deuterons.

"E+T" collaboration focuses on transmutation investigation using transmutation samples and study of spatial and momentum distributions of neutrons inside and outside the targets using threshold detectors, activation samples and solid state nuclear track detectors (SSNTD). For all mentioned measurements the development of well controlled and precise irradiation conditions are a crucial point.

This paper presents the main experimental techniques used within the "E+T" collaboration in the experiments with deuteron beams in order to determine beam position on the targets, beam shape and total intensity of the extracted beam.

## BEAM PROFILE AND POSITION INVESTIGATION

The form of spatial and momentum distribution of neutrons in the experimental setups is affected by the uncertainties of beam position and shape determination.

The beam center position and beam profile (intensity distributions along the X- and Y-axis) during the irradiation are obtained independently from solid state nuclear track detectors and from a set of segmented activation Cu foils.

### *Beam Profile and Position Determination with SSNTD*

SSNTD-sensors consist of two parts: of the heavy metal that interacts with deuterons via nuclear fission (irradiator) and of the material in which fission fragments leave tracks (track detector). Natural lead ($^{Nat}$Pb) is used in our experiments as an irradiator, the detector materials are artificial mica (Fluorophlogopite) or lavsan. The procedure for SSNTD-sensors calibration is described in [1].

Sensors of $^{Nat}$Pb foils of dimensions 0.7×0.7×0.007 cm, in contact with two track detector sheets are placed in front of the setup in contact with the target, along the X- and Y-axis, as shown in Fig. 1.

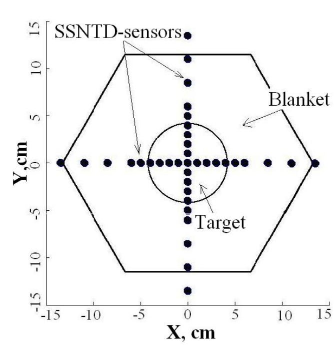


Figure 1: SSNTD-sensors positions at the front of the E+T setup.

After the exposure the detectors are etched in HF or NaOH, depending on the detector type. The duration of the etching time is decided on the basis of the track population in a given sample, in order to minimize the overlapping of the track openings. To obtain an accurate measure of the track densities the tedious method of manual track counting was chosen. We count tracks in many photomicrographs produced for each detector using an optical microscope. The distributions of the track density along the X- and Y-axis are used to obtain the beam intensity distribution on the target.

The secondary particles born in the target and the blanket also induce $^{Nat}$Pb fission. The radial distributions of $^{Nat}$Pb fission-rates (normalized values) induced by primary deuterons and back scattered neutrons in E+T setup are shown in Fig. 2.

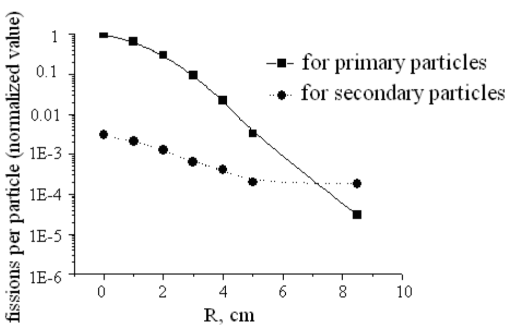


Figure 2: Radial distributions of $^{Nat}$Pb normalized fission rates induced by primary deuterons and secondary neutrons in E+T setup.

Calculation was made using FLUKA Monte-Carlo code. It is obvious that the beam shape is completely determined by $^{Nat}$Pb(d,f) reaction.

We determine the beam profile using the assumption that it has a Gaussian shape. It should be noted that this approximation is good for the central part of the beam, but not for its tails.

### *Beam Profile and Position Determination with Activation Foils*

The activation foils of standard laboratory purity copper (Cu) of 0.007 cm thickness are used. The copper was chosen, because in interaction with deuterons a lot of radioactive isotopes are produced, but none of them is produced by neutrons.

For each irradiation one Cu foil of 8×8 cm is placed directly in front of the target faced to the beam. This foil is after the irradiation cut into 16 pieces of 2×2 cm size as shown in Fig. 3a and every piece is measured separately. Since no experimental cross-sections are known for interaction of relativistic deuteron and copper, only relative comparison between the yields of produced isotopes in different foils can be made.

Coaxial high purity Germanium (HPGe) detector is used for gamma-spectrum measurements. Yields of the isotopes in each foil are normalized to the most active one and the distribution of the weighted averages of the yields is obtained (see Fig. 3).

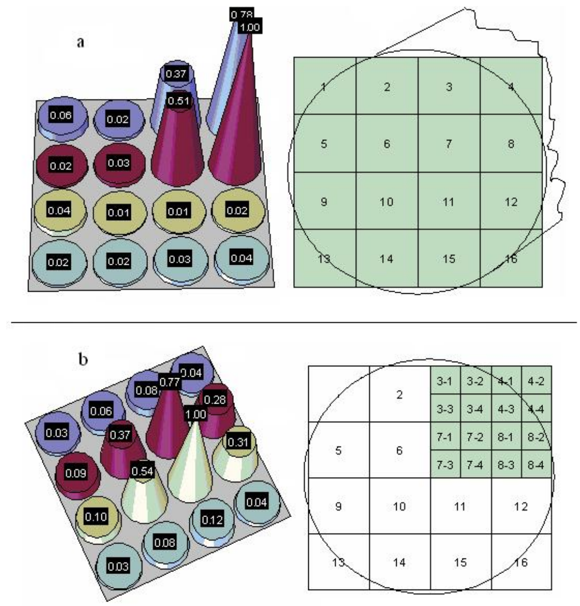


Figure 3: Weighted average (left) over relative yields of 19 gamma-lines in the whole Cu beam monitor (a), of 11 gamma-lines in the double cut part of Cu beam monitor (b) and scheme of monitor position on the target (right). Circle is a target projection, square is a Cu foil.

The gamma-lines of the following isotopes are observed: $^{58}$Co, $^{56}$Co, $^{48}$Cr, $^{52}$Mn, $^{48}$Sc, $^{44m}$Sc, $^{57}$Ni, $^{48}$V, $^{47}$Sc, $^{55}$Co, $^{48}$Cr, $^{43}$K, and $^{44}$Sc. Totally 19 lines are used for the evaluation. No one of these isotopes is visible in all foils and with similar activities; this leads to the presumption that all isotopes we use are produced by the deuterons from the beam and not by back-scattered neutrons from the target.

After the pre-evaluation the most active foils are selected for further evaluation. They are cut onto smaller pieces of 1×1 cm as shown in Fig. 3b and each of them is measured once again. The same procedure as in previous case allows to obtain precise distribution of the beam intensity on the target. The coordinates of the most active foil after all the stages of evaluation indicate the position of the beam centre on the target.

In order to check the beam direction inside the target one more copper foil can be placed behind the target.

## BEAM FLUENCE MEASUREMENT

An important source of systematic uncertainties of the experimental data is the inaccuracy of the extracted beam total intensity definition (the beam fluence). The beam fluence is obtained using big activation monitors (Al and Cu foils) placed for the whole irradiation run at the position of a few meters upstream the target in order to avoid activation from backscattered particles. The distance was chosen on the basis of MCNPX calculations [2].

The accuracy of the beam fluence determination depends mainly on the accuracy of (d,X) reactions cross-section value.

In the “E+T” experiments using proton beams a sustainable procedure for beam fluence monitoring has been developed [3]. Published data on $^{27}Al(p,3pn)^{24}Na$ reaction cross-sections were analyzed, evaluated and fitted with the appropriate function shown in Fig. 4, in order to find a well defined cross-section value with a small uncertainty for every relevant proton energy in the range of 0.5 GeV $\leq E_p \leq$ 7 GeV.

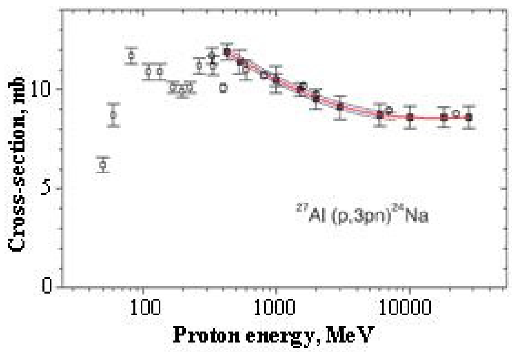


Figure 4: Excitation function for the monitor reaction $^{27}Al(p,3pn)^{24}Na$. The central line is the fitted function, the two outer lines indicate ±σ uncertainty range.

For determination of the deuteron beam fluence from the induced $^{24}Na$ activity the cross-section for the $^{27}Al(d,3p2n)^{24}Na$ reaction for the used deuteron kinetic energy has to be defined. This cross-section, however, is known only for deuterons of kinetic energy 2.33 GeV as 15.25 ±1.50 mb [4].

Deuteron cross-sections for the other energies are deduced from the known cross-sections for proton-induced reactions. The excitation functions for the inelastic reaction cross-section of protons and deuterons on $^{27}Al$ are shown in Fig. 5, yielding to a constant ratio between the inelastic cross-sections at any energy.

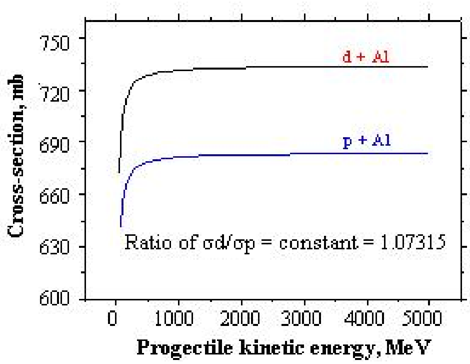


Figure 5: Inelastic excitation functions for proton and deuteron induced reactions on $^{27}Al$.

It is therefore assumed that cross-sections for the individual reaction channels leading from $^{27}Al$ to $^{24}Na$ in proton and deuteron induced reactions will also run parallel. With this assumption the cross-sections for the deuteron-induced reaction ($\sigma_d$) for any deuteron kinetic energy $E_d$ can be calculated as $\sigma_{d,Ed} = \sigma_{d,2.33} \cdot (\sigma_{p,Ed} / \sigma_{p,2.33})$.

After the irradiation the monitor foils are measured with HPGe detectors. The measured isotope is $^{24}Na$ ($T_{1/2}$=15.02 h), the activity is determined using gamma-lines of the energies 1368.6 keV (line intensity is 100 %) and 2754.1 keV (line intensity is 99.9%).

The measured activities at the end of irradiation are corrected for decay during the irradiation according to the known beam-burst profile, for decay between the end of irradiation and start of measurement and for decay during the measurement. The detailed description of all spectroscopic corrections applied for the calculation of $^{24}Na$ yield is given in [5].

The minimum uncertainty of deuteron fluence measurement using activation foils is 10% due to the uncertainties in cross-section determination as well as to the corrections that have to be applied for the gamma spectrum analysis.

## CONCLUSIONS

The experimental systematic uncertainties in the ADS experiments at the Nuclotron depend strongly on the accuracy of the beam parameters determination. The beam fluence uncertainty affects the accuracy of the absolute values of the experimental data. The accuracy of beam position determination affects also tendencies in spatial distributions of neutrons inside the targets. The overall systematic uncertainties of the experimental data due to the inaccuracy of determination of deuteron beam parameters are >10%.

## REFERENCES

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