Monitoring of GeV deuteron beam parameters in ADS experiments at the Nuclotron (JINR, Dubna)

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Introduction: "Energy + Transmutation" collaboration

"Energy plus Trasmutation" ("E+T") is a large international collaboration (presently 15 countries), established in the Laboratory of High Energy Physics of JINR (Dubna) for investigation of different aspects of electro-nuclear technology for energy generation and long-lived nuclear wastes transmutation in the experiments on Accelerator Driven Systems (ADS) using relativistic beams of Nuclotron accelerator complex.

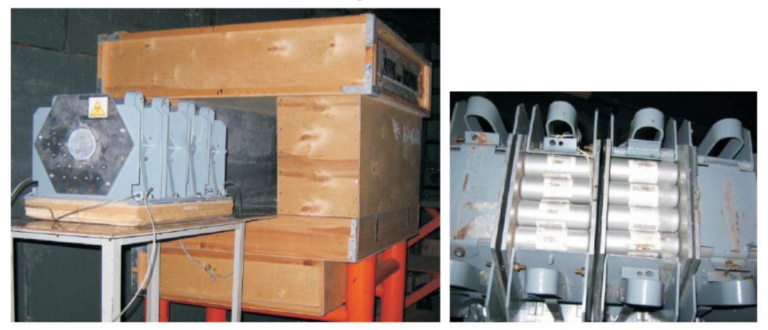
"E+T" collaboration focuses on transmutation investigation using transmutation samples and study of spatial and momentum distributions of neutrons inside and outside the targets using threshold detectors, activation samples and solid state nuclear track detectors.

Within the "E+T" collaboration a number of target systems of different geometries and composition were developed and irradiated with relativistic protons and deuterons.

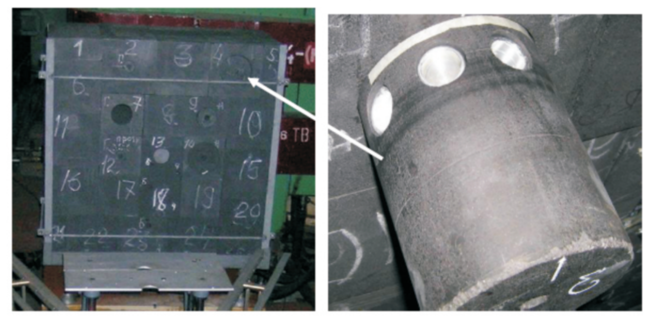
Our experimental setups:

Gamma-2: lead target in paraffin

E+T: 4 sections lead target in natural uranium blanket



Gamma-3: lead target in grafite



Quinta: 5 sections natural uranium target

Buran: massive target of depleted uranium with changeable central part (U, Th, Pb)

Experiments are planned for the year 2012

For all our measurements the development of well controlled and precise irradiation conditions are a crucial point…

The experimental techniques we use for deuteron beam monitoring in ADS experiments at the Nuclotron are:

- 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 on the target.

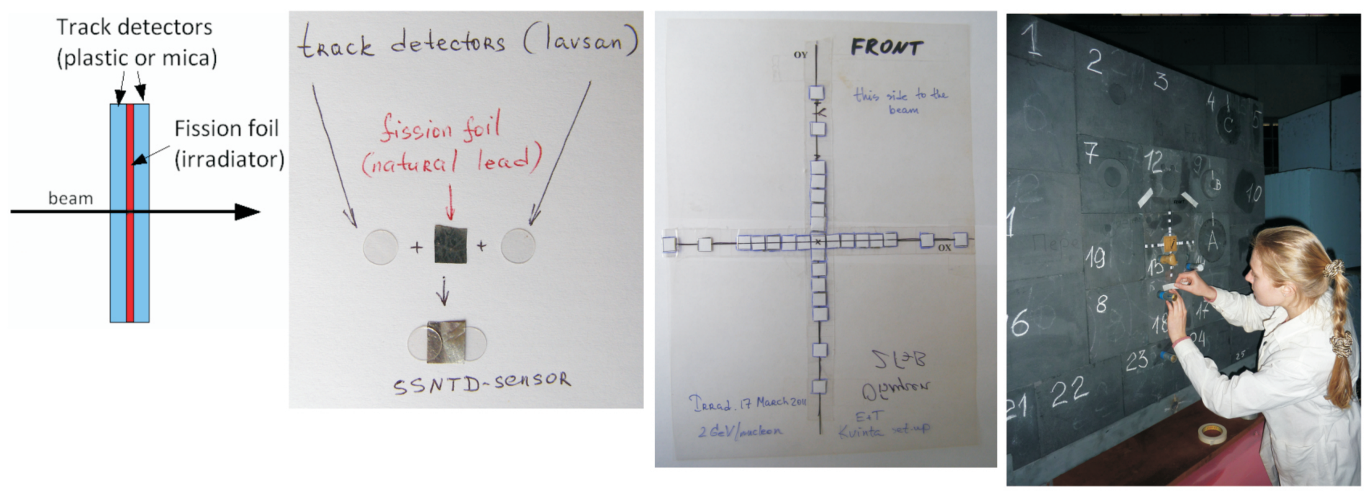
..more about "E+T" collaboration on http://e-t.jinr.ru

Beam position and profile determination

Using solid state nuclear track detectors (SSNTD)

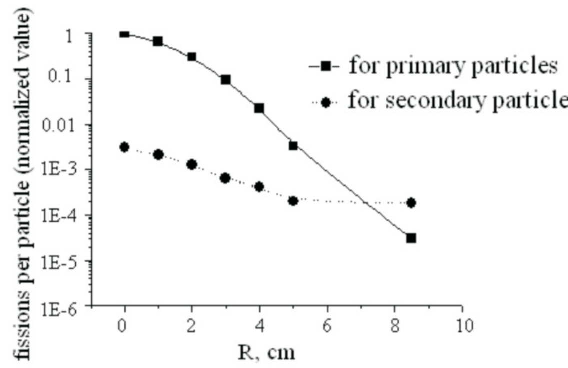
SSNTD-sensors consist of two parts: of the heavy metal that interacts with deuterons via nuclear fission (irradiator) and of the material in which fission fragments leave tracks (track detector). Natural lead (^{Nat}Pb) is used in our experiments as an irradiator, the detector materials are artificial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

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:



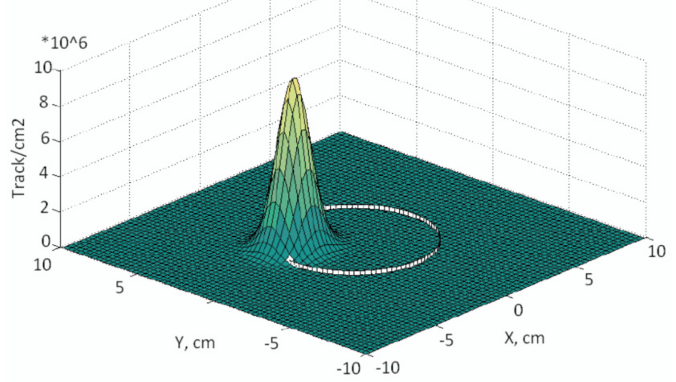
After the exposure the detectors are etched in HF or NaOH, depending on the detector type. The duration of the etching time is decided on the basis of the track population in a given sample, in order to minimize the overlapping of the track openings. To obtain an accurate measure of the track densities 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. Calculated using FLUKA code radial distributions of ^{Nat}Pb fission-rates (normalized values) induced by primary deuterons and back-scattered neutrons in E+T setup show that the beam shape is completely determined by ^{Nat}Pb(d,f) reaction:



Radial distributions of ^{Nat}Pb normalized fission rates induced by primary deuterons and secondary neutrons in E+T setup (Monte-Carlo simulation).

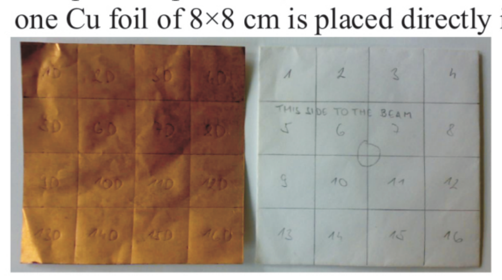
We determine the beam profile using the assumption that it has a Gaussian shape, i.e.:



It should be noted that this approximation is good for the central part of the beam, but not for its tails.

Using segmented activation Cu foils

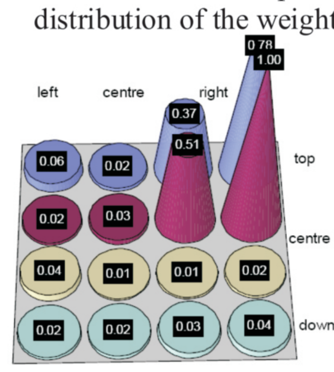
The activation foils of standard laboratory purity copper of 0.007 cm thickness are used. The copper was chosen, because in interaction with deuterons a lot of radioactive isotopes are produced, but none of them is produced by neutrons. For each irradiation one Cu foil of 8×8 cm is placed directly in front of the target faced to the beam:

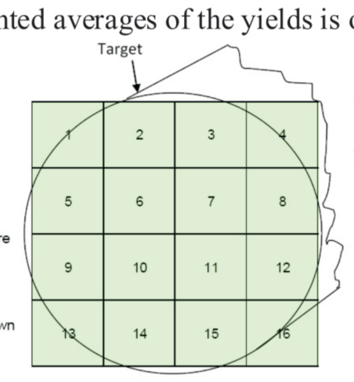


The Cu foil is after the irradiation cut into 16 pieces of 2×2 cm size and every piece is measured separately. Coaxial HPGe detector is used for gamma-measurements.

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.

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:



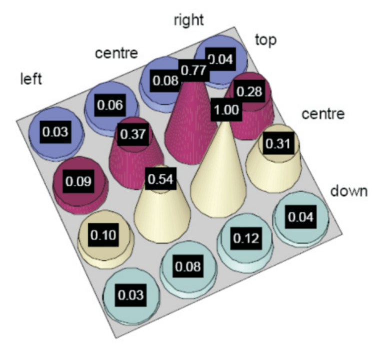


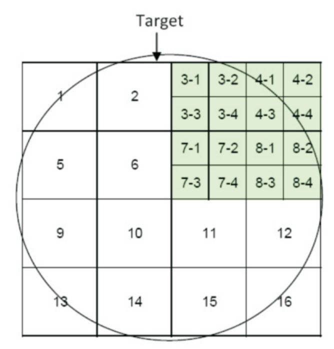
Weighted average (left) over relative yields of 19 gamma-lines in the whole Cu beam monitor and scheme of monitor position on the target (right).

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 and each of them is measured once again:





Weighted average (left) over relative yields of 11 gamma-lines in the double cut part of Cu beam monitor and scheme of monitor position on the target (right).

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.

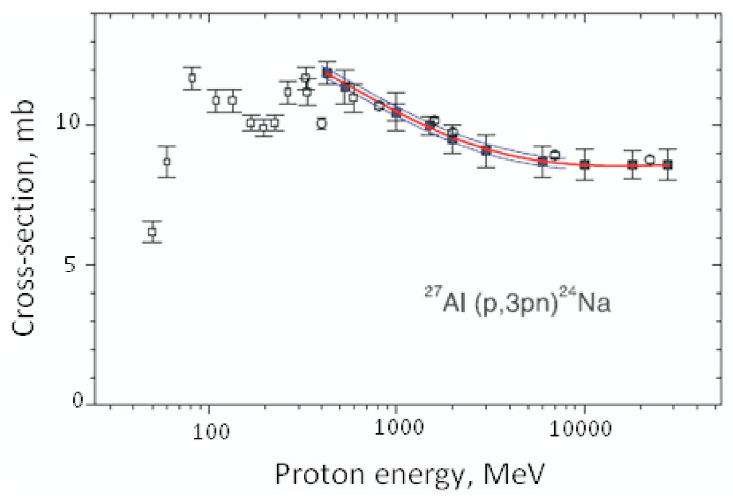
In order to check the beam direction inside the target one more copper foil can be placed behind the target.

Deuteron 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 or Cu foils) placed for the whole irradiation run at the position of a few meters upstream the target in order to avoid activation from back-scattered particles. The distance was chosen on the basis of MCNPX calculations.

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. Published data on ^{27}Al(p,2pn)^{24}Na reaction cross-sections were analyzed, evaluated and fitted with the appropriate function shown below, 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 < E_p < 7 GeV.

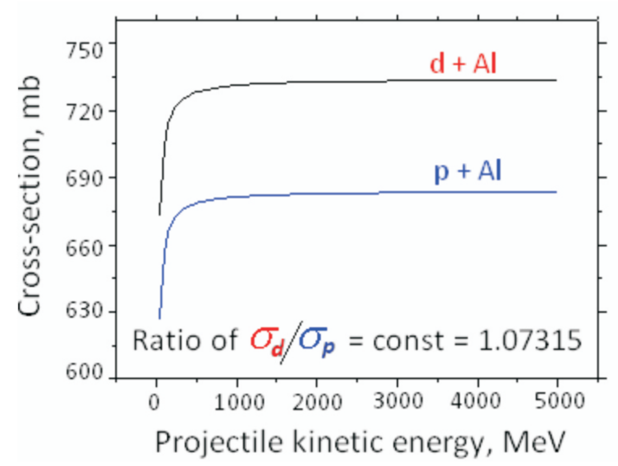


Excitation function for the monitor reaction ^{27}Al(p,3pn)^{24}Na.
The central line is the fitted function,
the two outer lines indicate ±σ uncertainty range.

[Westmeier W. et al. Radiochimica Acta V.93 (2005), p. 65-73]

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 [Banaigs J. et al., Nuc.Instr.and Met. In Phys. Res., V. 95 (1971)].

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 the figure below, yielding to a constant ratio between the inelastic cross-sections at any energy.

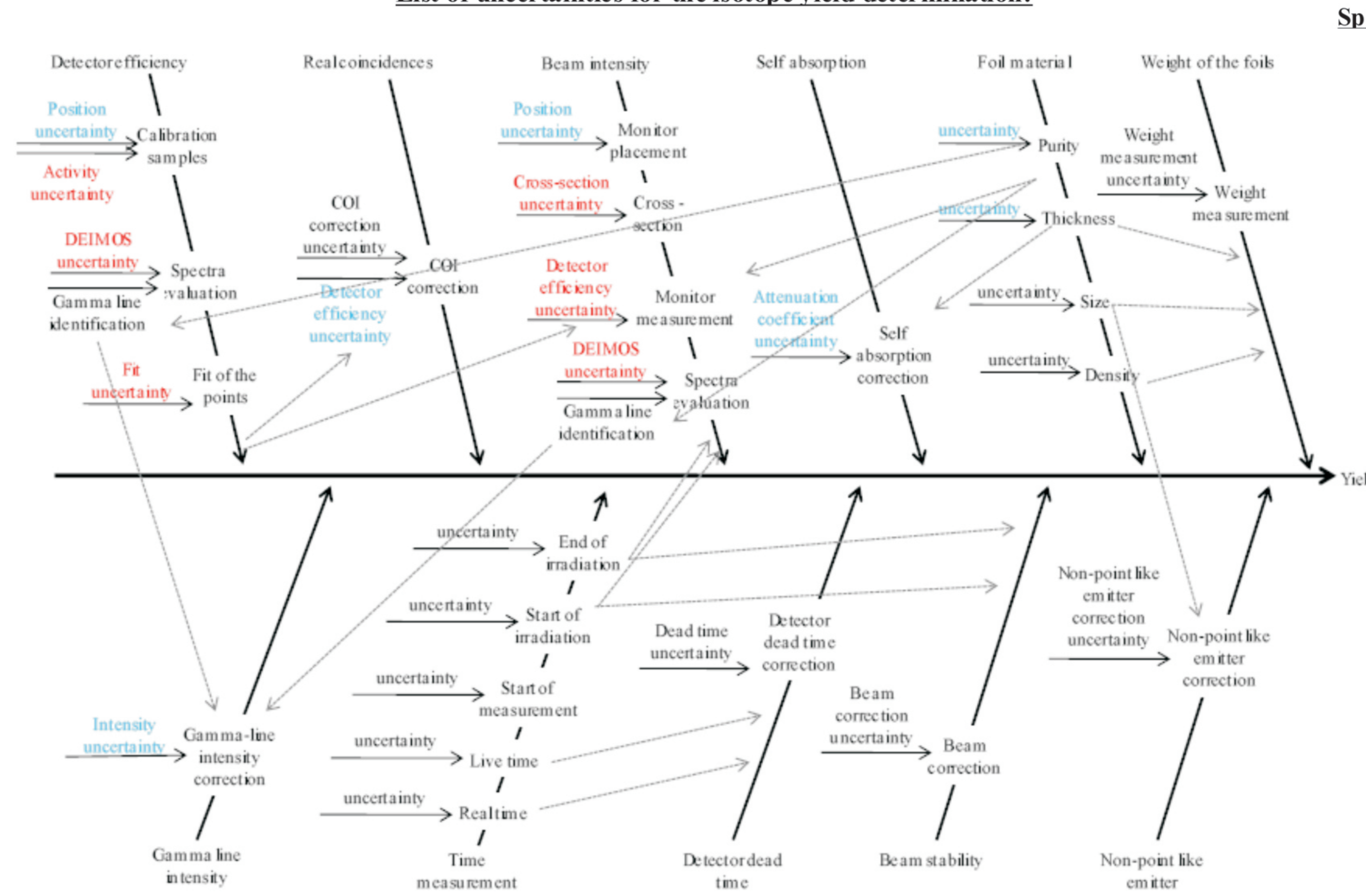


Inelastic excitation functions for proton and deuteron induced reactions on ^{27}Al.

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 σ_d for any deuteron kinetic energy E_d can be calculated as

$$\sigma_{d,Ed} = \sigma_{d,2.33} \cdot (\sigma_{p,Ed} / \sigma_{p,2.33})$$

List of uncertainties for the isotope yield determination:



Spectroscopic corrections applied for the calculation of ^{24}Na yield:

- Beam instability correction.
- Correction on decay between the end of irradiation and beginning of the measurement.
- Correction on decay during measurement.
- Correction on decay during irradiation.
- Correction on the dead-time of the detector.
- Correction on real cascade γ-γ coincidence.
- Correction on changed detector efficiency due to sample dimensions.
- Self-absorption correction.
- Square-emitter correction (geometrical correction).

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%.

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