

The possibility to use ‘energy plus transmutation’ set-up for neutron production and transport benchmark studies

V WAGNER¹, A KRÁSA¹, M MAJERLE¹, F KŘÍŽEK¹, O SVOBODA¹,
A KUGLER¹, J ADAM^{1,2}, V M TSOUPKO-SITNIKOV², M I KRIVOPUSTOV²,
I V ZHUK³ and W WESTMEIER⁴

¹Nuclear Physics Institute of AS CR, CZ-25068 Řež, Czech Republic

²Joint Institute for Nuclear Research Dubna, 141980, Dubna, Moscow Region, Russia

³Joint Institute of Power and Nuclear Research, NASB, Sosny, 220109 Minsk, Belarus

⁴Fachbereich Chemie, Philipps-Universität, 35032 Marburg, Germany

E-mail: wagner@ujf.cas.cz

Abstract. The set-up ‘energy plus transmutation’, consisting of a thick lead target and a natural uranium blanket, was irradiated by relativistic proton beams with the energy from 0.7 GeV up to 2 GeV. Neutron field was measured in different places of this set-up using different activation detectors. The possibilities of using the obtained data for benchmark studies are analyzed in this paper. Uncertainties of experimental data are shown and discussed. The experimental data are compared with results of simulation with MCNPX code.

Keywords. Neutron production; spallation reactions; MCNPX; accelerator driven systems; transmutation.

PACS Nos 25.40.Sc; 29.25.Dz; 28.20.Gd; 28.41.Ak

1. Introduction

There is great motivation towards improving the precision of predictions of codes used to simulate production of neutrons during spallation reactions and transport of high- and low-energy neutrons in materials. More realistic codes will help to design future accelerator driven systems (ADS). The international collaboration named as ‘energy plus transmutation’ [1,2] studies neutron production and transport inside a thick, lead target surrounded by sub-critical uranium blanket during the proton irradiation (figure 1a). The neutron field is measured using different mono-isotopic foils as activation radiochemical sensors. The acquired experimental data are used for testing the predictions of computer codes such as MCNPX [3] or DCM [4].

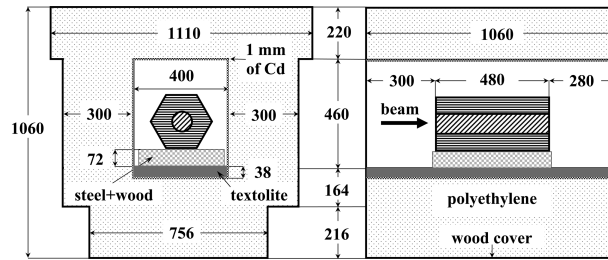


Figure 1. ‘Energy plus transmutation’: lead target, natural uranium blanket, and polyethylene shielding.

2. Experimental set-up

The ‘energy plus transmutation’ set-up was designed for transmutation studies in high-energy neutron fluxes. It consists of a cylindrical lead target (diameter 84 mm, length 480 mm) surrounded by a sub-critical uranium blanket. The target and blanket are divided into four parts. Between each section there is 0.8 cm gap for the detectors (see figure 1b). Each of these sections contains 30 identical natural uranium rods wrapped in aluminum. Each rod has diameter 36 mm, length 104 mm, and weight 1.72 kg. The blanket and target are fixed by iron and aluminum holders. The set-up is mounted on a wooden plate and placed inside a radiation shielding made of thin cadmium plates and polyethylene (see figure 1a). For detailed description, see refs [1,2].

The polyethylene layer moderates neutrons coming from the set-up. Afterwards, thermal neutrons are absorbed in cadmium. Hence, the scattering of high-energy neutrons back to the set-up should be strongly reduced. The homogenous field of epithermal and resonance neutrons should be produced inside the shielding box (see figure 2).

To measure the neutron field in the set-up, neutron activation detectors are used [5]. Radiochemical sensors are made of aluminum, gold, bismuth, yttrium, and other samples. The elements that are naturally mono-isotopic are chosen. Various nuclear reactions, (n, γ) , (n, xn) , (n, α) , and others occur in our samples and produce many radioisotopes. Their abundance is determined from the characteristic gamma spectrum they emit during the decay. Neutron capture is the dominant reaction for thermal, epithermal, and resonance neutrons. Cross-sections are very large (hundreds and thousands of barns) and the neutron absorption should be taken into account during the analysis. Other reactions have energy thresholds in the range of MeV. Cross-sections are smaller (mbarns–barns) and neutron absorption is negligible in this case. Standard location of the minimal set of the activation detectors is shown in figure 1b.

3. Experimental data and main source of their uncertainties

Irradiations of the experimental set-up (usually last for a few hours) are carried out in the Laboratory of High Energies at JINR Dubna (Russia) with the GeV proton beam extracted from the accelerator Nuclotron. Four different beam energies (0.7,

Energy plus transmutation set-up

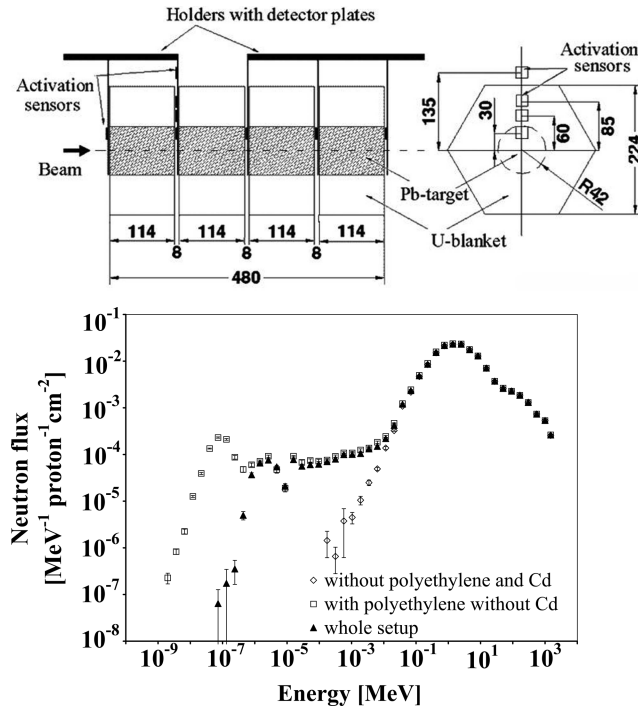


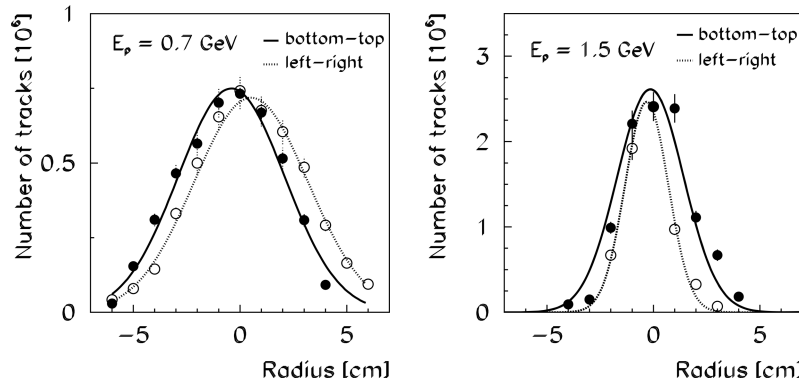
Figure 2. (a) Standard minimal set of activation sensors used during irradiation of the ‘energy plus transmutation’ set-up. (b) Example of neutron spectra inside the ‘energy plus transmutation’ set-up simulated by MCNPX code. Thermal, epithermal, and resonance neutrons are produced by polyethylene shielding neutron moderation. Thermal neutrons are absorbed by Cd layer.

1.0, 1.5, and 2.0 GeV) were used up to now. The main interest was in the spatial distribution of the neutron field inside and outside our set-up. An important source of systematic uncertainties of the experimental data is the inaccuracy of the beam definition. Parameters of the proton beam are determined by two methods. The beam integral is obtained using big activation monitors (Al and Cu foils). The beam profile and position are obtained independently from lead solid state nuclear track detectors and from a special set of segmented activation foils.

The accuracy of the beam integral determination depends mainly on the accuracy of (p, X) reaction cross-section value which in the best cases is around 6%. This systematic uncertainty affects only absolute values and not the shape of spatial distributions. The form of distribution is affected by the uncertainties of beam positions [6]. We determined beam profile using the assumption that it has a Gaussian shape. The approximation is good for the central part of the beam, but not for its tails. The obtained beam parameters are shown in table 1. It is possible to see that the proton integral was around 10^{13} protons for all experiments. The shape of the beam profile was ellipsoidal and very similar for beam energies 1.0 and 1.5 GeV. A very small fraction of the beam was outside the lead target. In the

Table 1. Beam parameters during experiments with energy 0.7, 1.0, 1.5, and 2.0 GeV.

	Beam energy (GeV)	Beam integral (10^{13})	Beam integral on the lead target (10^{13})	Fraction of beam outside the target (%)
1	0.7	1.47(5)	1.04(8)	<27
2	1.0	3.30(15)	3.15(14)	<6
3	1.5	1.14(6)	1.10(5)	<6
4	2.0	1.25(6)	1.07(10)	<20
	FWHM (vertical) (cm)	FWHM (horizontal) (cm)	Position (vertical) (cm)	Position (horizontal) (cm)
1	5.91(21)	Same	-0.4(9)	0.2(2)
2	4.1(3)	2.5(3)	0.2(2)	0.0(2)
3	3.7(5)	2.4(5)	0.1(2)	0.3(2)
4	5.4(3)	3.8(3)	0.3(2)	-1.4(2)

**Figure 3.** Examples of beam profiles for beam energy 0.7 GeV (left side) and 1.5 GeV (right side) determined by track detectors.

case of 0.7 GeV the beam was circular and very wide, and touched the uranium blanket. The beam was well centered in these three experiments. The examples of different beam profiles are shown in figure 3. In the 2 GeV experiment, the beam was elliptical, wide, and shifted from the center for more than 1 cm.

As can be seen from simulations, the accuracy of experimental data is not so much influenced by uncertainties of the beam profile width, but it significantly depends on the uncertainties in the beam position. The uncertainty of the beam position is around 3 mm. That means there are uncertainties in neutron field up to 10% [6].

Activities of radiochemical sensors are measured with HPGe detectors. The net peak areas are determined by analyzing γ -ray spectra using the code DEIMOS [7].

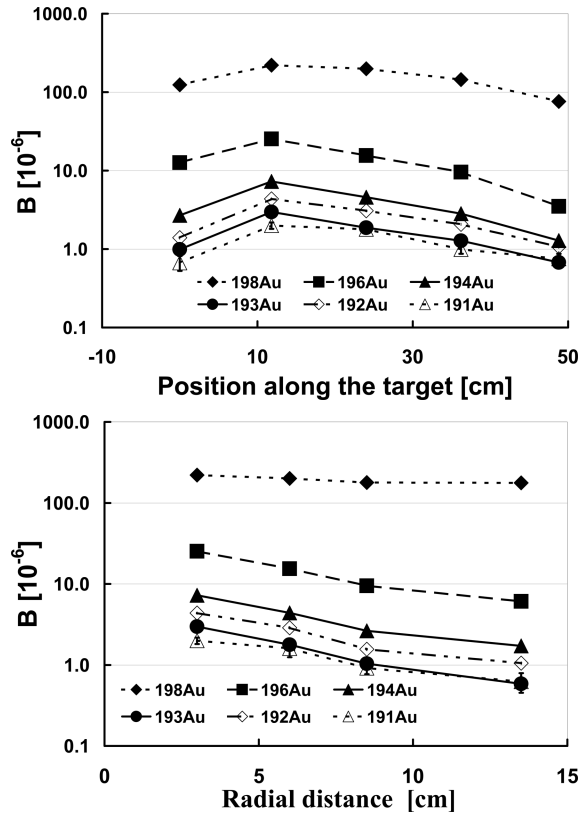


Figure 4. Example of experimental B -values obtained during 1.5 GeV irradiation. The lines are drawn to guide the eyes. Statistical errors in the points are not visible at this scale. Longitudinal distributions are plotted in the upper figure and the radial ones in the lower figure.

The minimal available error of gamma line area determination is around 0.5%. It is mainly done by not exactly Gaussian shape of gamma lines (they are fitted by Gaussian curves). Corrections for gamma line intensity, possible coincidence effects (coincidence summing and background contribution), detector efficiency, beam instability, measurement geometry, dead time, decaying during irradiation, measurement and time between irradiation and measurement are applied to receive the total number of nuclei of a given isotope produced in the activation sample during the whole period of irradiation. The uncertainty of the number of produced nuclei is not smaller than 2%. This number is then normalized to 1 g of activation sensor and to 1 primary proton to obtain the so-called B -value. Some results are given in figure 4.

The main purpose of our experiments is to study neutron production in the set-up consisting of the lead target and uranium blanket. Other parts can influence the neutron field also. Polyethylene box and wood parts are very good moderators. Different holders and detectors can also absorb and scatter neutrons and they can

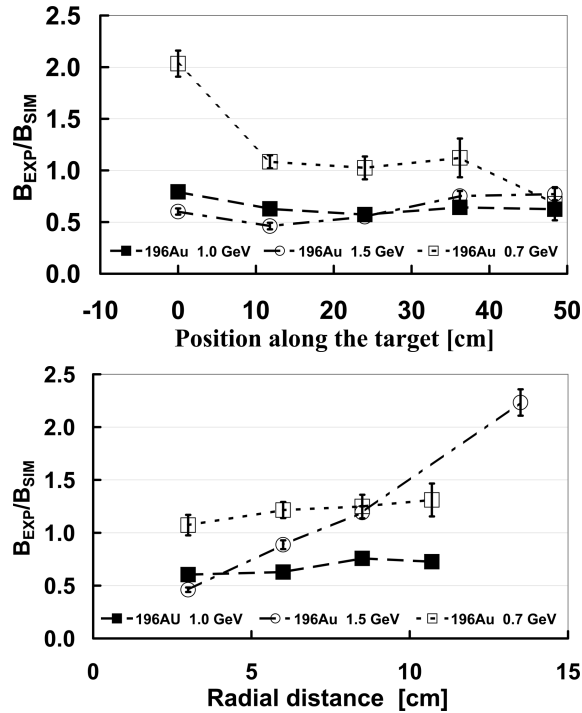


Figure 5. Ratios of the experimental and simulated ^{196}Au B -values for different beam energies (0.7, 1.0, and 1.5 GeV). The lines are drawn to guide the eyes, only statistical errors are shown. The longitudinal distributions are plotted in the upper figure and the radial ones in the lower figure.

produce asymmetries in our neutron field. Such sources of experimental uncertainties have reasons in complex analysis of the above-mentioned influences which was done by Majerle *et al* [6] using MCNPX code.

Homogeneity of the thermal, epithermal, and resonance neutron field inside the shielding can be seen from the production of ^{198}Au isotope by (n, γ) reaction (see figure 4). Production of this isotope is more or less the same in all measured places of our set-up. The spatial distribution of production rates for (n, γ) reaction is homogenous and is completely due to the polyethylene shielding (see spectra in figure 2). The vast majority of low-energy neutrons ($E < 0.1$ MeV) come from polyethylene shielding. The lead target and blanket determine only the total number of neutrons going to the polyethylene.

On the other hand, the influence of the polyethylene shielding on the neutron spectrum is negligible in the MeV energy range. It is possible to study neutron production of high-energy neutrons ($E > 0.1$ MeV) from the lead target with uranium blanket without any disturbance [6].

As follows from the simulation, other parts of our set-up (metal holders, plastic holders, wood, etc.) have negligible influence on neutron field. The detectors influenced only thermal, epithermal, and resonance neutron field in the close neighborhood of the sample (influence of absorption).

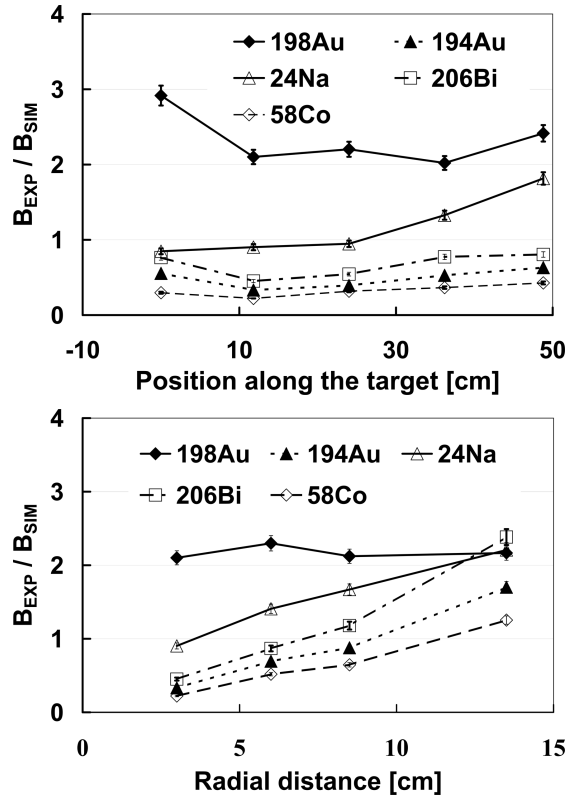


Figure 6. Example of ratios of the experimental and simulated B -values for 1.5 GeV experiment. The lines are drawn to guide the eyes, only statistical errors are shown. Longitudinal distributions are plotted in the upper figure and the radial ones in the lower figure.

4. Comparison of experimental data with MCNPX simulations

The obtained experimental data are used for testing computer simulation codes. One of the most suitable codes for ADS is MCNPX. The geometry of the set-up was accurately described in MCNPX 2.4.0 code and simulations were performed using MCNPX [6].

We compared the experimental B -values with the results of MCNPX simulations. The simulations follow the basic trends of the measured data quite well. Nevertheless, the quantitative agreement is not perfect for all experiments. The spatial distributions of neutron field are described very well for thermal, epithermal, and resonance neutrons. Trends of the experimental data obtained during irradiation by lower energy beam protons (0.7 and 1.0 GeV) are described very well for threshold reactions also. Ratios of experimental and simulated data are constant in these cases (see figure 5). For threshold reactions, MCNPX predicts faster decrease in isotope production with growing radial distance in the case of the experiment with 1.5 GeV beam energy.

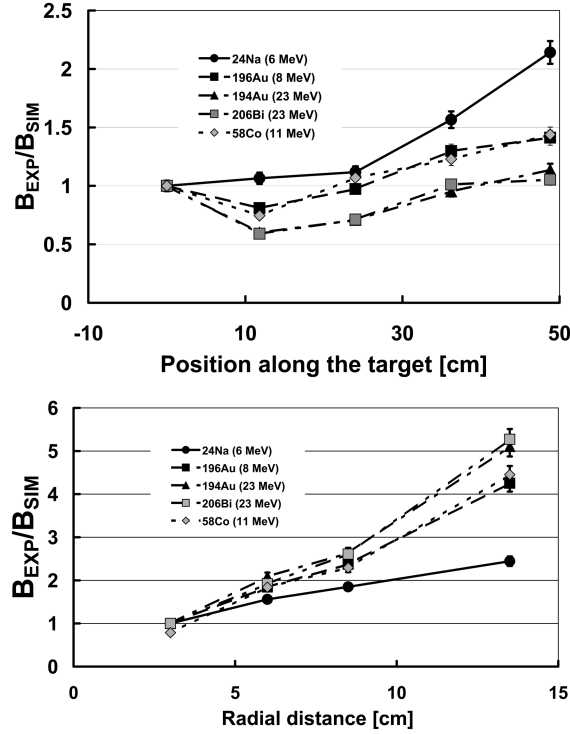


Figure 7. Normalized ratios of the experimental and simulated B -values for beam energy 1.5 GeV. The clear dependency on threshold energy is seen. Values of threshold energies are shown. The lines are drawn to guide the eyes. Statistical errors in the points are not visible at this scale. Longitudinal distributions are plotted in the upper figure and the radial ones in the lower figure.

We analyzed the dependency of the ratio between the experiment and simulation on the reaction threshold (neutron energy) for the data obtained with 1.5 GeV protons more accurately. The ratios of the experimental and simulated B -values for (n, γ) reaction (production of the ^{198}Au isotope) and threshold reactions are shown in figure 6. The ratios do not change for the longitudinal and radial distributions in the case of capture reaction. The discrepancies between experimental and simulated data increase with the radial distance in the case of threshold reactions.

We made a detailed analysis of this phenomenon on the reaction threshold. We assumed that the absolute value of the ratio is done by the inaccuracy of used cross-section library and we normalized the ratio of experimental and simulated B -value for the first position of spatial distribution to one (see figure 7). We can see very good dependencies on threshold energy mainly for radial direction. The discrepancies between experimental and simulated data increase with threshold energy of the reaction (neutron energy) (see figure 7).

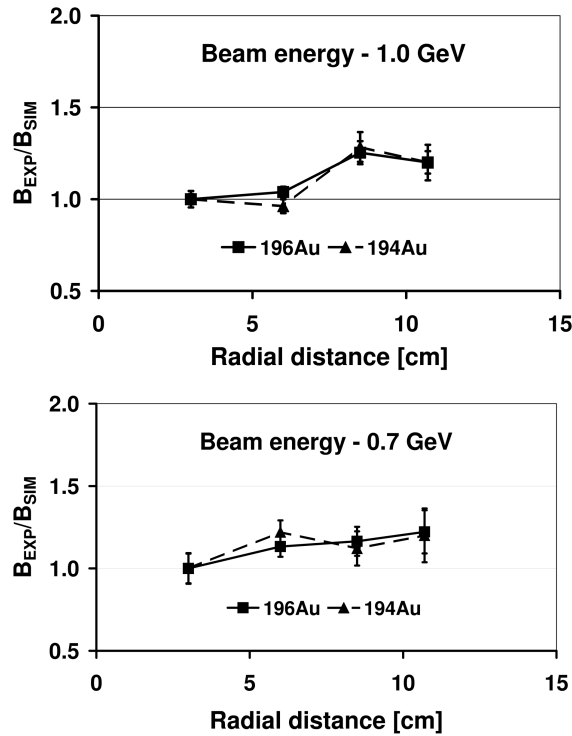


Figure 8. Normalized ratios of experimental and simulated B -values for beam energies 1.0 GeV (upper figure) and 0.7 GeV (lower figure). The radial distributions are plotted. The lines are drawn to guide the eyes, only statistical errors are shown.

The same radial distributions are shown for beam energies 0.7 GeV and 1.0 GeV (see figure 8). There is very small increase of discrepancy between experiment and simulation (only $\sim 20\%$) for both beam energies.

We simulated only the reactions caused by neutrons. The contribution of proton reactions in the activation samples is not included [6]. Primary and secondary protons are focused in forward angles and their contribution may be the reason for the discrepancies of the longitudinal spatial distribution inside and near the lead target. The determined discrepancies between experiment and simulation for radial distribution cannot be explained by proton reactions.

The observed discrepancies between experiment and MCNPX simulation have clear physical dependencies on neutron energy. This may be the reason why such discrepancies are visible only for the experiment with the highest beam energy 1.5 GeV. Highest beam energy means that more high energy neutrons are produced in this experiment.

We hope to understand observed features after the analysis of the experiment with 2 GeV proton beam. New experiments with higher beam energies are planned. More detailed systematic analysis and comparison of complex sets of data measured with different beam energies are also necessary.

5. Conclusions

The experimental systematic uncertainties depend mainly on the accuracy of the beam parameter determination. The beam integral uncertainty affects only the accuracy of the absolute values of the determined data, but the accuracy of beam position determination affects also tendencies in spatial distributions of neutron field. The overall systematic uncertainties of the experimental data are $\sim 10\%$.

The observed differences between experimental and simulated data are bigger and cannot be explained with the uncertainties of experimental data. The differences between simulation with different INC models are in the range of 30% (see [6]). The discrepancies caused by different libraries of high energy neutron cross-sections are also bigger than our experimental uncertainties. This is the reason why we hope to validate existing codes using the ‘energy plus transmutation’ set-up.

Acknowledgments

The authors thank the technical staff of the Laboratory of High Energies of JINR Dubna headed by Prof. A D Kovalenko for providing reliable operation of the Nuclotron Accelerator. This work was supported by the Czech Committee for Collaboration with JINR Dubna, GACR (202/03/H043) and IRP AVOZ 10480505.

References

- [1] M I Krivopustov, D Chulten, J Adam *et al*, *Kerntechnik* **68**, 48 (2003)
- [2] M I Krivopustov, J Adam, A R Balabekyan *et al*, JINR Preprint E1-2004-79
- [3] Group X-6: MCNPX2.3.0 – Monte Carlo N-Particle Transport Code System for Multiparticle and High Energy Applications, LANL, Los Alamos, New Mexico (2002)
- [4] V S Barashenkov, *Comp. Phys. Comm.* **126**, 28 (2000)
- [5] A Krasa, F Krizek, V Wagner *et al*, JINR Preprint E1-2005-46
- [6] M Majerle, J Adam, S R Hashemi-Neshad *et al*, *Proceedings of WP-ADS-EET 2006*, Jaipur, India, Jan. 23–25, 2006 (this proceedings)
- [7] J Frana, *J. Radioanal. Nucl. Chem.* **257(3)**, 583 (2003)