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Yttrium as a New Threshold Detector for Fast Neutron Energy Spectrum (>10 MeV) Measurement

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Results of two experiments with Yttrium 89 probe are presented. The experiment assembly (U/Pb model) was irradiated with Dubna NUCLOTRON for 1.6 and 2.52 GeV deuteron beam and we obtain Neutron Energy Spectrum inside whole 3D model by using threshold energy reaction. Normally in experiment like this one uses neutron activation detectors made from gold (^{197}Au), cobalt (^{59}Co), bismuth (^{209}Bi) *etc.* Detector, yttrium (^{89}Y) was proposed. Yttrium detectors give quite good results for neutron energy spectrum from 10 MeV to about 50 MeV

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I. INTRODUCTION

Investigation of physical aspects of radioactive waste transmutation, using hadron relativistic beams (proton or deuteron beams in the energy range from 0.5 GeV to 4 GeV) was undertaken within the project "Energy plus Transmutation" (1999 – 2010) in the Joint Institute for Nuclear Research (JINR), Dubna, Russia.

Normally in the experiment like this one there are used activation detectors made of gold (Au-197), cobalt (Co-59), bismuth (Bi-209) *etc.* To study the fast neutron energy spectrum we have used Yttrium-89 detectors which have the following advantages: one stable isotope - ^{89}Y, easy way to make good shape samples, several resulting isotopes (^{88}Y, ^{87}Y, ^{86}Y, ^{85}Y and ^{84}Y) with long enough half life time – few hours, obtained in the (n,xn) reactions for several threshold reactions (11.5, 20.8, 32.7, 42.1 and 54.4 MeV). In order to evaluate the fast neutron energy spectrum the detector, Yttrium-89, was irradiated with 1.6 and 2.52 GeV deuteron beam.

The neutron field was determined by help of thirty five Yttrium-89 detectors placed in specified positions (given by the radial and axial distance) inside the Pb-U-Blanket target facility. After irradiation by deuterons, the gamma activity of Yttrium-89 detectors were measured using HPGe spectrometer. Taking into account necessary corrections we have determined the isotope production per one gram of sample and per one beam deuteron – B parameter.

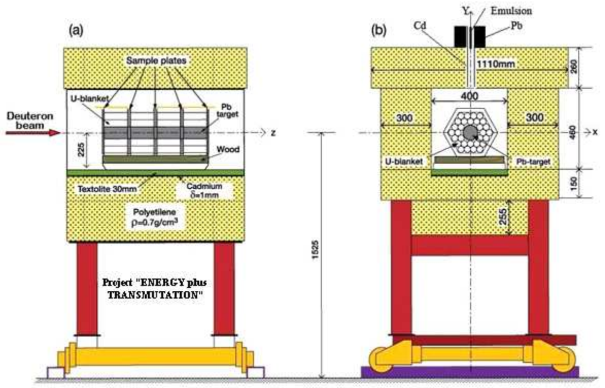

Fig. 1. (Color online) Two cross sections of the Pb-U-blanket target [1].

II. THE PB-U-BLANKET TARGET FACILITY AND EXPERIMENTAL DATA

The main part of the U-Pb blanket target is an assembly consisting of a lead cylindrical core and natural uranium cylinders [1]- the lead target has a length of 48 cm and a diameter of 8.4 cm. It is surrounded by a natural uranium blanket and divided for four identical section (Fig. 1). Each section contains 30 uranium rods. The uranium rods of 10.4 cm length, 3.6 cm diameter and 1.72 kg weight are hermetically surrounded by an aluminum cladding.

Each section contains 51.6 kg natural uranium and totally in four sections is 206.4 kg. In the gaps between the sections as well as at the front and at the back end of the setup are placed foils with detectors (Fig. 2). The

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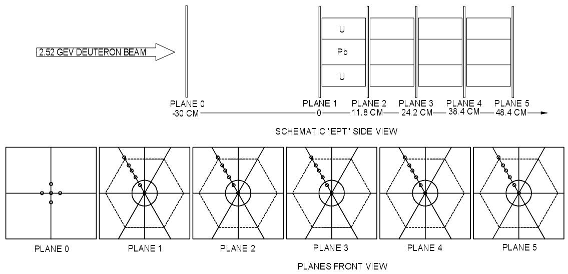

Fig. 2. Arrangement of the ^{89}Y detectors on the plastic foils for different planes in the Pb-U-blanket target [2,3].

U/Pb-assembly is inside of a massive boxes (polystyrene shielding) and placed on a mobile platform (Fig. 1).

The yttrium 89 activation detectors were located on plastic foils in front of, between the sections and on rear of the Pb-U-blanket assembly in several radial positions (Fig. 2). After the end of the experiment the samples were measured by HPGe spectrometer. For the analysis of the experimental was applied the DEIMOS [4] program. Using this program one performed the gamma line energy calibrations, and determined line absolute intensity and half width of the line (FWHM) and respective errors. Finally we calibrate all the results to B parameters by the below calibration formula.

$$B = N_1 \cdot \frac{1}{m \cdot I} \cdot \frac{\Delta S(G) \cdot \Delta D(E)}{\frac{N_{abs}}{100} \cdot \varepsilon_p(E) \cdot COI(E,G)} \cdot T(t_{ira}, t_+, t_{real}, t_{live}, \lambda)$$

where: B - number of nuclei per gram of a sample material and per one primary proton, N_1 - peak area, N_{abs} - the absolute intensity of given line in percent [%], $\varepsilon_p(E)$ - detector efficiency function of energy (polynomial), COI(E,G) - cascade effect coefficient function of energy and geometry, ΔS(G), ΔS(E) - calibrations function for thickness and shape of detectors, I - total number of primary protons, $t_{1/2}$ - half life time, t_{ira} - elapsed time of irradiation, t_+ - elapsed time from the end of irradiation to the beginning of measurement, t_{real} - elapsed time of the measurement, t_{live} - "live" time of measurement, m - mass of the sample (target) in grams, λ – decay constant.

All calibrated results are presented in 3D graphs. An example of the isotope production Y-87 presented in Fig. 3 show that the Y-87 isotope production have maximum of axial distribution in the position of about 12 cm along the target [3].

III. EVALUATION OF AVERAGE HIGH ENERGY NEUTRON FLUX IN THE YTTRIUM-89 DETECTORS LOCATION INSIDE THE U/PB ASSEMBLY

To evaluate the high energy neutron field we need to know the microscope cross section for the (n,xn) re-

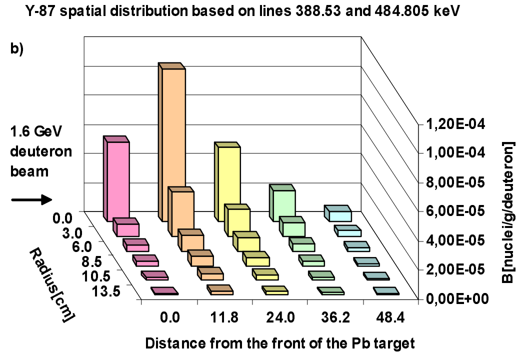

Fig. 3. (Color online) Spatial distribution (radial and axial) of Y-87 production.

action. Experimental data are available only for the cross section of ^{89}Y(n,2n) and small part (lower energies) ^{89}Y(n,3n) reactions [5] (Fig. 4). Since the nuclear data libraries are poor we have used TALYS code [6,7] for calculation of (n,xn) reactions for Y-89 cross sections [8] (Fig. 5). Using these accessible data (EXFOR) we could compare them with received from calculations (TALYS). It proved, that TALYS results are enough correct.

In general the number of yttrium isotopes (N_y) in the yttrium 89 detector of volume V_p in the chosen energy range can be expressed:

$N_y = V_p \, \overline{\Phi} \, N \, \bar{\sigma} \, t$, where $\overline{\Phi}$- average neutron flux in the chosen energy range [n/cm^2· s]

$$\overline{\Phi} = (E_2 - E_1)\, \overline{\psi} \; ; \; \overline{\psi} = \frac{\int_{E_1}^{E_2} \psi(E)\, dE}{E_2 - E_1} \, .$$

Where: $\psi(E)$ – neutron flux density [n/cm^2· s· MeV], N – number of yttrium 89 isotopes in volume unit [cm^{-3}], $\bar{\sigma}$ – average microscopic cross section for the reaction (n, xn) in the energy range (E_1 – E_2) [barns].

By choosing the first three threshold energies E1 = 11.5 MeV, E2 = 20.8 MeV and E3 = 32.7 MeV for the reactions ^{89}Y(n,2n)^{88}Y, ^{89}Y(n,3n)^{87}Y and ^{89}Y(n,4n) ^{86}Y and the fourth E4 = 100 MeV where the cross section are comparatively low.

We defined the three average neutron fluxes $\overline{\varphi_1}$, $\overline{\varphi_2}$, $\overline{\varphi_3}$. These assumptions enabled us to write the following three algebraic equations:

$$B^{88}\, C = \bar{\varphi}_1 \, \bar{\sigma}_{11} + \bar{\varphi}_2 \, \bar{\sigma}_{12} + \bar{\varphi}_3 \, \bar{\sigma}_{13}$$

$$B^{87}\, C = 0 + \bar{\varphi}_2 \, \bar{\sigma}_{22} + \bar{\varphi}_3 \, \bar{\sigma}_{23}$$

$$B^{86}\, C = 0 + 0 + \bar{\varphi}_3 \, \bar{\sigma}_{33}$$

Where:

B^{88}, B^{87}, B^{86} – measured isotopes of ^{88}Y, ^{87}Y and ^{86}Y respectively per one gram of detector and per one beam deuteron.

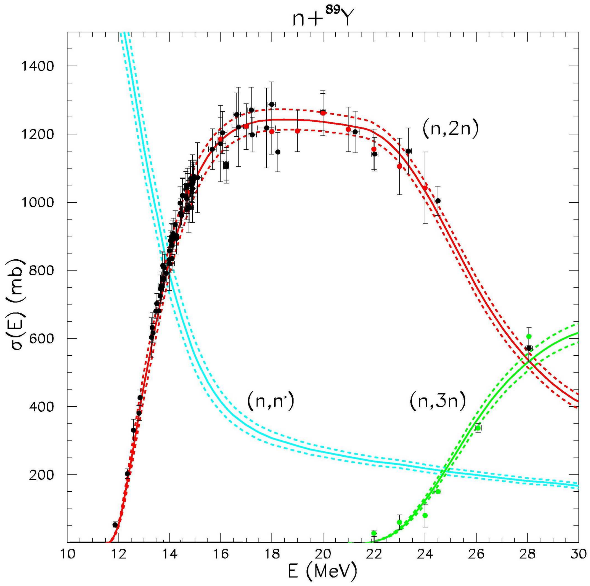

Fig. 4. (Color online) EXFOR database experimental microscopic cross sections for ^{89}Y(n,xn) reactions.

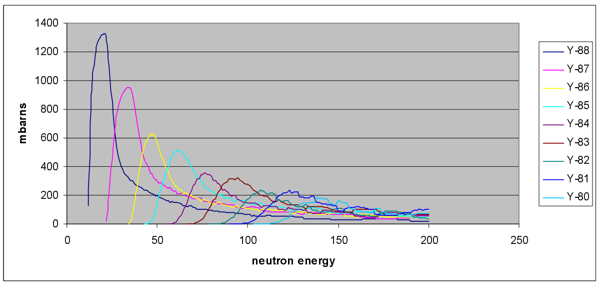

Fig. 5. (Color online) TALYS microscopic cross sections for ^{89}Y(n,xn) reactions.

C – physic constants

$\overline{\sigma_{11}} - \overline{\sigma_{33}}$ – microscopic cross section of the measured isotopes for the reaction (n, xn) in the three chosen energy ranges.

$\overline{\varphi_1}$, $\overline{\varphi_i}$, $\overline{\varphi_3}$ – unknown average neutron fluxes in the three chosen energy ranges.

Solution of the above three equations let us to evaluate the average neutron fluxes in the three energy ranges expressed in [n/cm^2·s]. Figure 6 shows an example of space neutron flux distribution in the U/Pb assembly for the neutron energy range (20.8 – 32.7) MeV for the deuteron beam of 1.6 GeV using the B parameters.

IV. MONTE CARLO METHODOLOGY CALCULATIONS FOR THE U-PB BLANKET TARGET FACILITY

Calculations of isotope production in each Yttrium-89 detectors during deuteron irradiation were performed by using Monte Carlo methodology (MCNPX 2.5 code) and EXFOR [5] data base in order to utilize the microscopic cross sections for (n,xn) reactions of yttrium to

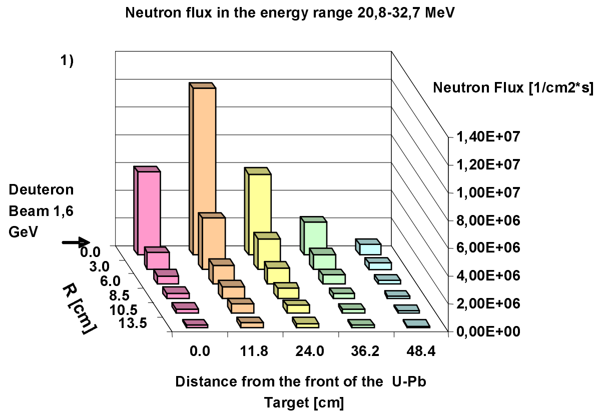

Fig. 6. (Color online) Space neutron flux distribution in the U/Pb assembly for the neutron energy range (20.8 – 32.7) MeV for the deuteron beam of 1.6 GeV.

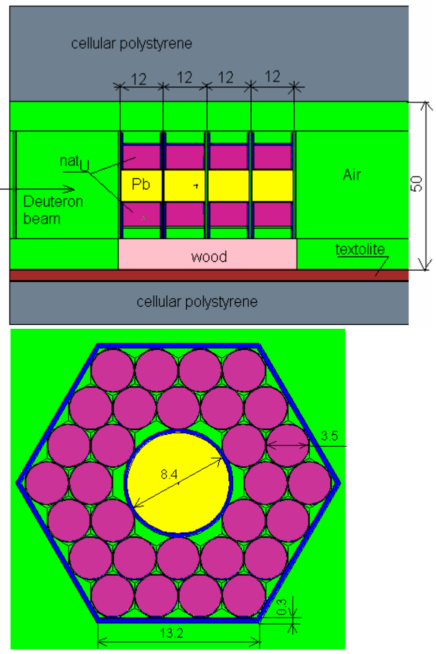

Fig. 7. (Color online) Axial and radial cross section of the U-Pb-Blanket target facility simulation.

the code. Number of simulations were equal 10^6. The data are normalized to one source deuteron. Axial and radial cross section of the U-Pb-Blanket target facility simulation are presented in Fig. 7. The neutron flux was calculated using evaluated data base ENDF. Using this neutron flux and TALYS or EXFOR cross sections we calculate number of Yttrium isotopes. Number of (n,2n) reaction in detector 89Y was calculated using definition,

$$n = \int_{E\,\min}^{E\,\max} \varphi(E)\sigma(E)\rho dE\ .$$

$E_{\min}$, $E_{\max}$ - means threshold energy and 100 MeV correspondingly,

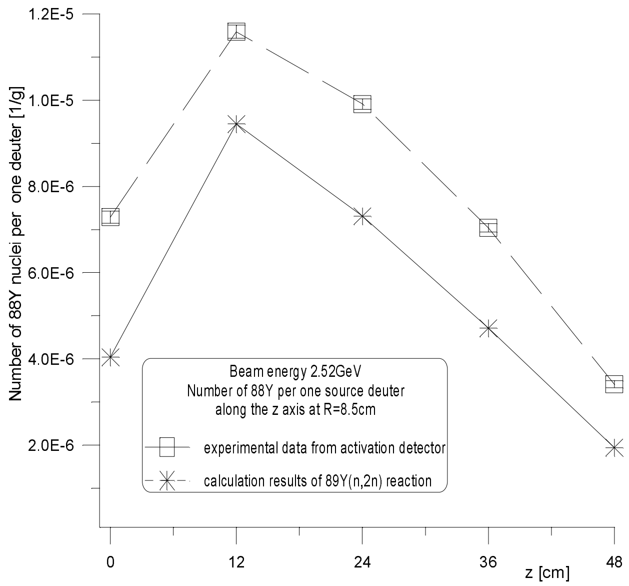

Fig. 8. Comparison of experimental and computational axial distribution of isotope Y-88 production at radial distance equal to 8.5 cm for the beam energy of 2.52 MeV.

φ(E) was calculated using MCNPX code in detector,

σ(E) cross section for (n,2n) reaction. It was obtained from EXFOR data from range (1 – 100 MeV) and interpolated, ρ – density of ^{89}Y.

We must add that we used EXFOR data base only in the case of the reaction (n,2n) and TALYS code for other reactions.

An example of comparison of experimental and computational axial distribution of isotope Y-88 production at radial distance equal to 8.5 cm for the beam energy of 2.52 MeV is presented in Fig. 8.

V. CONCLUSIONS AND REMARKS

Y-89 is a very good threshold detector for fast neutron energy spectrum measurement and easy for analyses.

Shape of spatial distribution of Y-88, Y-87 and Y-86 isotopes of the yttrium-89 detectors in the U/Pb assembly produced by the neutrons generated in the assembly irradiated by the relativistic deuteron beam of 1.62 GeV and 2.52 GeV energies in general reflects the shape of the evaluated average high energy neutron fluxes in the yttrium-89 detectors but with small aberration for the deuteron of higher energy 2.52 GeV .

It is assumed that the main contribution to the value B error comes from statistical error, ΔN_1. But it is possible that additional contribution comes from the number of deuteron beam calculation (10% – 30%).

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