THE EXPERIMENTAL DETERMINATION OF HEAVY METAL NUCLEI FISSION REACTIONS CROSS SECTIONS AT 0.66 GeV PROTONS BEAM

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Cross sections of fission reactions of ^{197}Au, ^{207}Pb, ^{209}Bi, ^{232}Th, ^{238}U heavy metals induced by protons with energy of 0.66 GeV are presented. The protons beam was extracted from the Phasotron accelerator at JINR, Dubna, Russian Federation. Fission reactions cross sections were measured using solid state nuclear track detectors (SSNTD) and activation gamma-spectroscopy. The comparison with results from others researchers were done. The obtained results would be added in the international databases for testing of programme code for ADS-systems.

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INTRODUCTION

Since 2010 project "Energy and Transmutation of radioactive waste" carried out in Joint Institute for Nuclear Research (Dubna, RF). In the frame of the project investigations are conducting on studies of different subcritical assemblies physics characteristics driven by protons and deuterons beams with 0.6…12.0 GeV energies; multiplicities and spatial distributions of energy-time of neutron spectrum; possibility to energy production and utilization of radioactive waste studies on massive natural uranium (depleted uranium) and thorium targets based on the relativistic nuclear technologies (RNT); studies of superconductors irradiation stability in neutrons and protons beams [1].

Option of target material is significant phase for experiment calculating and optimization of central target part irradiated by relativistic ions. Commonly neutron generating target are composed of Ta, Au, Bi, Hg, W, Pb, Th, U for accelerator driven system (ADS) [2].

Because of fission reaction is one of primary decay channel it is experimental data of fission reactions cross sections for energies up several GeV per nucleon are needed for creating of full-scale ADS.

1. EXPERIMENTAL TECHNIQUE AND EXPERIMENT DESCRIPTION

1.1. EXPERIMENTAL TECHNIQUE

The solid state nuclear track detectors (SSNTD) method was chosen as a main method for fission reactions cross sections determination for this experiment.

SSNTD technique is based on correlation between the track density on a track detector and a flux density of the investigated beam.

Sensors made of track detectors placed in contact with a fission foil are irradiated by the beam. Fission fragments produced in fission reactions in fission foils form tracks on the track detectors surface. Sensor SSNTD is sketched on Fig. 1. There white section is artificial mica. The used method is described at greater length in [3].

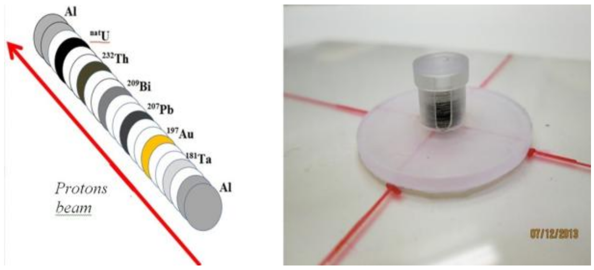

Fig. 1. Irradiated setup scheme and photo

In accordance with [3] nuclide cross section σ^i is defined:

$$\sigma^i = N_q^i / k_q^{sens} \cdot P \cdot \qquad (1)$$

There N_q^i – track density on a track detector which placed in contact with a fission foil, k_q^{sens} – calibration factor for «fission foil + SSNTD»; и P – primary particles number.

In general calibration factor determine in the following way:

$$k_q^{sens} = A^i \mu^i \varepsilon_q d_q \rho_q , \qquad (2)$$

где A^i – number of charged particles produced in the fission reaction of i-nuclides; μ^i – the fraction of charged particles reaching the detector in the fission reaction of i-nuclides; ε_q – detection efficiency of the charged particle track detectors; d_q – i-layer thickness of nuclides in the radiator, cm; ρ_q – nuclear density of i-nuclides in the radiator, nuclei/cm^3.

Calibration factors is used from [4] for this experiment.

For fission reaction μ^i determines, in accordance with [3] as:

$$\mu^i = \begin{cases} \frac{1}{2}\left(1 - \frac{d_q}{2\overline{R_0}}\right) & \text{for} \quad d_q < \overline{R_0} \\ \frac{1}{4} & \text{for} \quad d_q = \overline{R_0} \\ \frac{1}{4}\frac{\overline{R_0}}{d_q} & \text{for} \quad d_q > \overline{R_0}, \end{cases} \qquad (3)$$

where $\overline{R_0}$ – average fission fragments range.

In this work thick radiators were used. In the context of SSNTD technique “thick” radiator means that the radiator thickness is exceeded significantly the mean free path of fission fragments in the radiator material ($d_q >> \overline{R_0}$).

This circumstance allows to reject an uncertainty caused by radiator thickness determination (as for thin foils) and to increase the total number of fission fragments. At the same time, due to the radiator thickness, we can register the only one fission fragment from the binary fission process and cannot distinguish it by using two correlated tracks. So, the fission process cannot be discriminated from the other high energy processes (such as spallation, multifragmentation and strong asymmetric fission) in which heavy and medium mass particles can be generated [5]. FLUKA [6], intranuclear cascade model and the model of the nucleon-nucleon interactions RQMD-2.4 were applied to study this effect [7]. Correction for this effect is 6…10% depending on type and energy of incident particle.

In addition, the influence of the kinematics of fission process on the track density on the track detectors has to be taking into account for the whole protons energy range. Pulse transfer effect for fission fragments can be compensated by the “sandwich-like” composition of sensors, which allows registering tracks in 4π geometry (BACK/FACE). Correction for this effect was calculating in FLUKA and it is 0.5…2%.

1.2. EXPERIMENT DETAILS

Irradiation of the setup was carried out with 0.66 GeV protons beam on the Phasotron accelerator at JINR, Dubna, Russian Federation.

In this experiment artificial mica is used. It is conditioned by low effect of recoil nuclei.

The used materials characteristics are present in Table 1.

Table 1

The used materials characteristics

The used materials	Thickness, mm	Diameter, mm
Al	1.0	6.5
^{197}Au	0.030	6.5
^{207}Pb	0.500	6.5
^{209}Bi	0.025	6.5
^{232}Th	0.070	6.5
^{238}U	0.030	6.5
Artificial mica	0.030	6.5

The studied foils was placed into plexiglass shaped location plate (height = 1 cm and diameter = 6.5 mm). Before irradiation plexiglass shaped location plate fill by foil and mica (Fig. 1). Aluminium cylindrical samples (height = 1 cm and diameter = 6.5 mm) put on upper and lowest part of plexiglass shaped location plate. These samples are applied as activation detectors for determination protons flux.

Setup was disassembled after irradiation. The SSNTD are etched in 6.8% HF solution with t = 60°C to make tracks "visible" in an optical microscope. Time etching is 10…45 min which depends on track density. To obtain an accurate measure of the track densities the tedious method of manual track counting is chosen. We count tracks in many photomicrographs produced for each detector using an optical microscope.

2. RESULTS AND DISCUSSION

In Table 2 experimental data are presented. These are used for determining of heavy metal nuclei fission reactions cross sections induced by 0.66 GeV protons beam.

Table 2

Experimental data and determinate values

Nuclide	Ratio “BACK/FACE”	Average track density, track/cm^2	Fission cross-section, mb
^{197}Au	1.60±0.07	$8.23 \cdot 10^5$	70±20
^{207}Pb	1.44±0.07	$1.55 \cdot 10^6$	120±30
^{209}Bi	1.43±0.07	$2.44 \cdot 10^6$	210±60
^{232}Th	1.22±0.05	$8.57 \cdot 10^6$	750±200
^{238}U	1.24±0.05	$1.06 \cdot 10^7$	950±260

Measured dependence of the ratio “BACK/FACE” decrease with atomic number increase is self-contained quantitativeness for verification of different theoretic models in describing of nuclei fission reactions by relativistic particles (independent of uncertainties of incident beam intensity measurement, corrections on detector efficiency etc.).

Probing uncertainties of beam monitoring adds main inaccuracy to measured result – about 10…15%. Finally it is ~ 50% from total relative measurement uncertainty.

Extended measurement uncertainty was estimated by the international standard ISO/IEC 17025:1999 and it formed 30%.

Similar data for deuterons are missed exclude several studies [8]. In the frame of project “Energy and Transmutation of radioactive waste” were determined ^{181}Ta, ^{197}Au, ^{207}Pb, ^{209}Bi, ^{232}Th, ^{238}U heavy metals nuclei fission reactions cross-sections induced by deuterons with 2, 2.94 3.5 GeV per nucleon energies [9].

In whole, obtained data on fission reactions cross sections of ^{197}Au, ^{207}Pb, ^{209}Bi, ^{232}Th, ^{238}U by 0.66 GeV protons are in good agreement with experimental data in [8, 10 - 13], and with theoretical calculation from [8] (Figs. 2, 3).

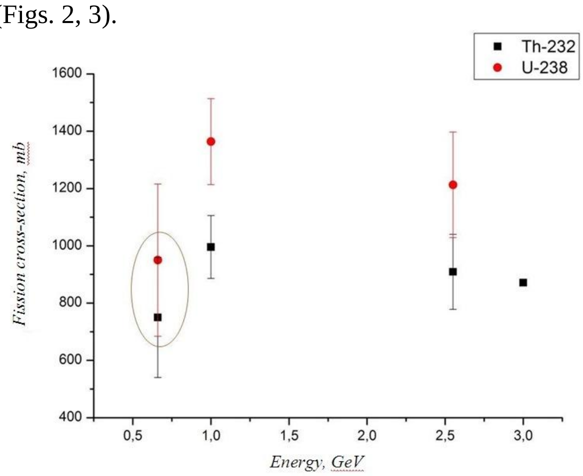

Fig. 2. Fission cross sections values of ^{232}Th, ^{238}U by protons

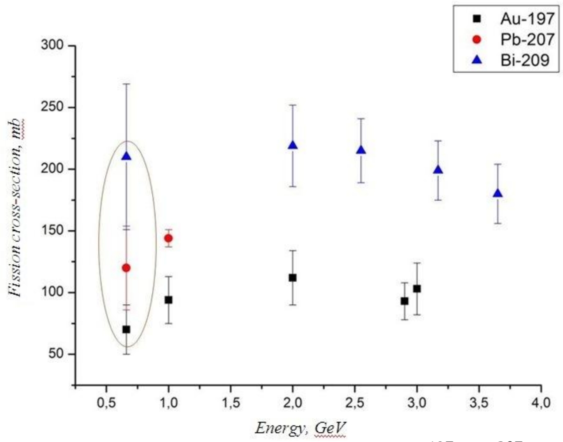

Fig. 3. Fission cross sections values of ^{197}Au, ^{207}Pb, ^{209}Bi by protons

Analysis of described experiment results and comparison with other studies confirm that the SSNTD method make it possible to obtain correct and responsible data on fission reactions cross sections for different type and energy of incident particles.

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ЭКСПЕРИМЕНТАЛЬНОЕ ИЗУЧЕНИЕ СЕЧЕНИЙ РЕАКЦИЙ ДЕЛЕНИЯ ЯДЕР ТЯЖЕЛЫХ МЕТАЛЛОВ ПРОТОНАМИ С ЭНЕРГИЕЙ 0,66 ГэВ

И. Жук, К. Гусак, А. Крюк, В. Воронко, В. Сотников, А. Жадан, А. Балдин, С. Тютюнников

Представлены экспериментальные данные по сечениям реакций деления ядер тяжелых металлов ^{197}Au, ^{207}Pb, ^{209}Bi, ^{232}Th, ^{238}U под действием протонов с энергией 0,66 ГэВ. Эксперименты проведены на пучках протонов ускорителя Фазатрон, ОИЯИ, Дубна, РФ. Для определения сечений реакций деления использована комплексная методика твердотельных трековых детекторов ядер и активационной гамма-спектрометрии. Выполнено сравнение полученных результатов с результатами других исследователей. Полученные результаты дополнят базу экспериментальных ядерных данных, что позволит протестировать компьютерные коды, применяемые при расчетах параметров ADS.

ЕКСПЕРИМЕНТАЛЬНЕ ВИВЧЕННЯ ПЕРЕТИНІВ РЕАКЦІЙ ПОДІЛУ ЯДЕР ВАЖКИХ МЕТАЛІВ ПРОТОНАМИ З ЕНЕРГІЄЮ 0,66 ГеВ

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Представлені експериментальні дані по перетинах реакцій поділу ядер важких металів ^{197}Au, ^{207}Pb, ^{209}Bi, ^{232}Th, ^{238}U під дією протонів з енергією 0,66 ГеВ. Експерименти проведені на пучках протонів прискорювача Фазатрон, ОІЯД, Дубна, РФ. Для визначення перетинів реакцій поділу використана комплексна методика твердотільних трекових детекторів ядер і активаційної гамма-спектрометрії. Виконано порівняння отриманих результатів з результатами інших дослідників. Отримані результати доповнять базу експериментальних ядерних даних, що дозволить протестувати комп'ютерні коди, що застосовуються при розрахунках параметрів ADS.