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MONTE-CARLO SIMULATION OF QUASI-INFINITE DEPLETED URANIUM TARGET IRRADIATED BY 1…10 GeV DEUTERON AND PROTON BEAM

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Simulation of a ~21 t depleted uranium target irradiated by 1…10 GeV proton and deuteron particles with the help of FLUKA simulation package was carried out. Neutron spectra and neutron flux in a target volume were obtained. Total number of ^{235}U (n,f), ^{238}U(n,f) reactions occurred in a target were determined. Beam particle power multiplication are calculated. The calculations were performed for the purpose of planning experiments on irradiation of a uranium target (22 tons of depleted uranium) at JINR (Dubna) within the framework of the international project "Energy and Transmutation of RAW".

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INTRODUCTION

Finding an appropriate solution for the long-term disposal of nuclear waste is one of the biggest challenges facing the nuclear industry.

The idea of using accelerators to breed fissile material has been around since the early 1950's [1, 2], however these early efforts were abandoned due to technical and economic reasons.

Renewed interest in the 1980's and beginning of the 1990's in Japan (OMEGA project) and in the USA (Brookhaven and Los Alamos) and in 1993 in CERN forced to research the ADS again.

An ADS is a type of hybrid reactor and therefore requires an external neutron source to sustain fission reactions in the sub-critical fuel assembly. This neutron source is a spallation neutron source which typically arises from a high current (mA), high energy ion beam impinging on a heavy metal target. The usefulness of an ADS depends on its energy gain G, and the production of neutrons which are used to maintain fission reactions, breed fissile material and transmute nuclear waste.

This scheme can be implemented for real electronuclear method of neutron production with its energy spectrum as hard as possible thanks to deeply subcritical, quasi-infinite (providing minimum leakage neutrons) active core based on natural (depleted) uranium or thorium bombarded powerful beam of relativistic particles. This neutron spectrum could allow the direct utilization in active core of spent nuclear fuel of nuclear power plants while producing energy. The deep subcritical active core without any moderator the size of which provides minimal leakage of neutrons and allow one to obtain maximally hard neutron spectrum inside.

The successful implementation of new method for energy generation and waste transmutation would eliminate the need for nuclear waste storage on a geologic time scale [3].

International project of Join Institute of Nuclear Research "Energy and Transmutation of Radioactive Wastes" (further is "E&T of RW") is aimed to study the basic characteristics of neutron fields inside deep subcritical quasi-infinite active core made of depleted uranium metal, the spatial distributions of core nuclei fission, the transmutation reaction rates of long lived minor actinides and fission products as well as to define optimal energy of incident beam for transmutation RAW and energy production. The previous studies have shown the need to study large targets [4 - 6]. One of the planning research in the frame of "E&T of RW" is experiments on quasi-infinite uranium target. In this article results getting from Monte-Carlo simulation with the FLUKA package [7, 8] to estimate main neutron-physical characteristics are presented.

1. SIMULATION

The model of irradiated target used in this work is shown on Fig. 1. It is a 120 cm in diameter and 100 cm long cylindrical target of ~ 21 t depleted uranium. Target has a 10 cm diameter and 20 cm long beam entrance window and is surrounded by 10 cm steel cover.

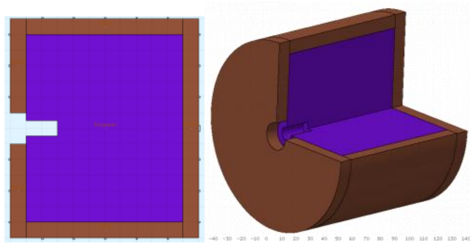

Fig. 1. Simulation target model

The simulation of irradiation with proton and deuteron with the energy 1…10 GeV were carried out. For getting a statistically significant result the number of incident particles were at least 10^6.

Fig. 2 illustrates the secondary particle fluxes in target under 4 GeV deuteron beam. The shape of secondary particle fluxes for proton and deuteron beam is the same, differ only amount.

At the energy under 8 GeV the amount of formed pions increases from 0.2 to 1% for proton and deuteron beams. The amount of secondary neutrons is stay on the same level with increasing of energy and equal to ~ 60%.

But multiplicity of neutron in a target with the increase of energy is growth for both type of impinged particles, Fig. 3.

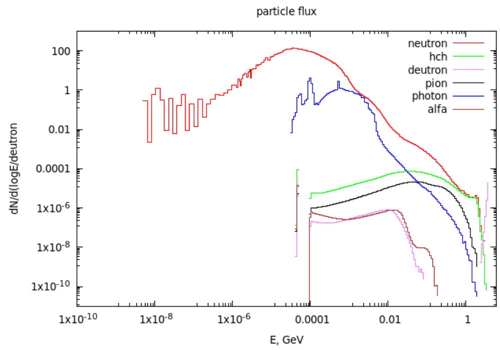

Fig. 2. Secondary particles flux

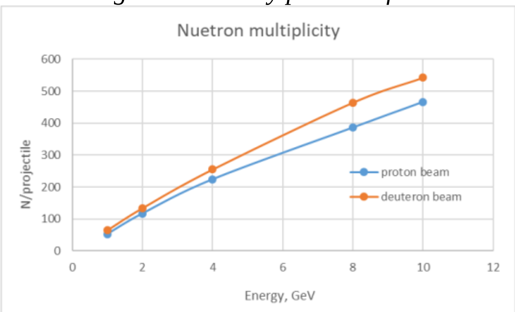

Fig. 3. Neutron multiplicity

The amount of neutron is changing linearly with the growth of energy from 50 to 470 for proton beam and from 65 to 570 for deuteron beam.

The Table 1 illustrate the number of secondary particles created in the target under proton beam with energy 1…10 GeV. Percentage of secondary particle created in target under deuteron beam almost the same.

Table 1

Secondary particles in target irradiated by proton

Secondary particles	Number of secondary particles, %				
	1 GeV	2 GeV	4 GeV	8 GeV	10 GeV
Neutrons	59.8	59.8	59.1	58.8	58.9
Photons	35.4	35.0	35.0	35.1	35.0
Protons	4.0	4.0	3.9	3.8	3.7
Alfa-particles	0.4	0.5	0.9	0.8	0.8
Deuteron	0.1	0.2	0.4	0.4	0.5
Pions	0.3	0.5	0.6	1.1	1.1

Not all secondary particles cause fission reactions.

Table 2 illustrates parts of different fission reactions of total amount of fission in a target irradiated by 1…10 GeV deuteron.

Table 2

Secondary particles in target irradiated by deuteron

Reaction	Number of reactions, %				
	1 GeV	2 GeV	4 GeV	8 GeV	10 GeV
(n, f)	84.7	85.2	84.4	82.5	80.3
(p, f)	5.3	7.2	7.7	7.7	7.9
(d, f)	9.0	4.4	2.0	1.0	1.3
(π, f)	1.0	3.2	5.9	8.7	10.2
(κ, f)	–	–	–	0.1	0.3
(*, f)	100.0	100.0	100.0	100.0	100.0

Main contribution to the total amount of fissions in the target bring secondary neutrons 70…80% for proton projectiles and 80…85% for deuteron one. Fraction of proton in a total amount of fission is from 28.3 to 8.6% with increase of impinging proton energy and from 5.3 to 7.9% for impinging deuteron energy.

With the increase of energy of projectiles, the growth contribution of (π, f) in a total amount of fission reactions is observed from 1.0 to 10.2% for proton projectiles and from 1.8 to 11.7% for deuteron respectively.

The obtained results should be taken in account under total uranium fission amount calculation and during comparison of experimental results.

2. RESULTS AND DISCUSSION

2.1. NEUTRON SPECTRA

In the target irradiated by proton and deuteron the wide spectra of neutrons are formed. On Fig. 4 neutron spectra under proton beam are presented. Secondary neutron energy spread up to the energy of incident particle. The shape of spectra in case of irradiation with deuterons is similar differ only fluxes up to 1.13 times.

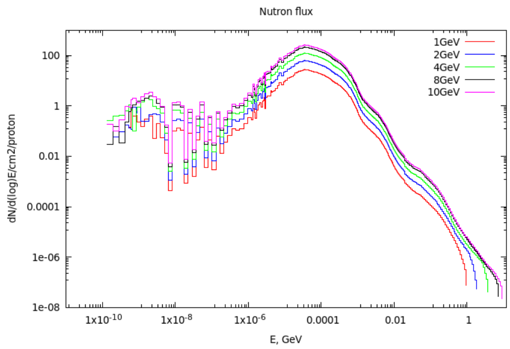

Fig. 4. Neutron spectra in target under proton beam

Radial (right) and axial (left) distribution of neutron flux under 8 GeV deuteron irradiation are presented in Fig. 5.

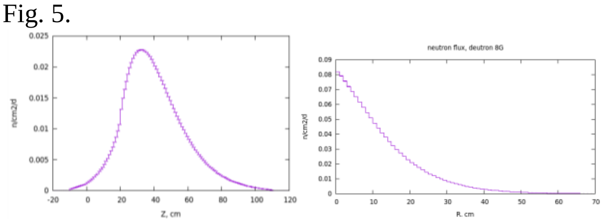
Fig. 5. Neutron distribution in the target

The highest neutron flux is formed on the way of beam on the distance of 40 cm along Z axis, in radial direction decreases exponentially to the zero. 3D representation of neutron flux in the target irradiated by 10 GeV deuteron beam is presented in Fig. 6.

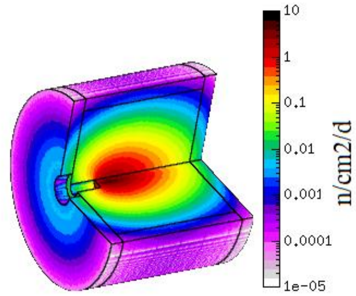

Fig. 6. Neutron flux in target under 10 GeV d beam

2.2. URANIUM FISSION

Using the obtained data of neutron flux in the target the total number of $^{235}U(n,f)$, $^{238}U(n,f)$ reactions occurred in the target are calculated. The proper cross-section data for neutron energy up to 20 MeV were token from FLUKA file – there are 260 grouped cross-section data. The cross-sections above 20 MeV were retrieved from ENDF database by A. Patapenka [9].

Total amount of U^{235}(n,f) fission differs from 1.58 to 14.97 for proton beam and from 1.79 to 17.30 for deuteron beam in 1…10 GeV energy interval. Total amount of U^{238}(n,f) fission differs from 14.61 to 137.72 for proton beam and from 16.86 to 155.31 for deuteron beam in 1…10 GeV energy interval. The maximum fissions are occurred under 2…4 GeV particle beam.

Specific number of U^{235}(n,f), U^{238}(n,f) reactions (relative to beam energy) are presented on Figs. 7 and 8 respectively.

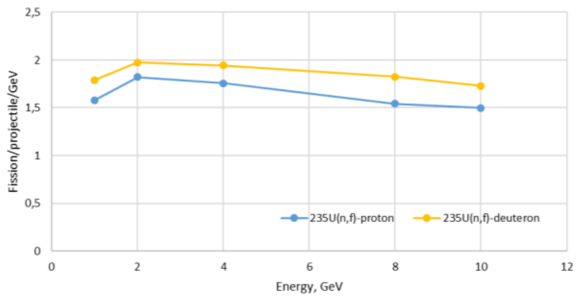

Fig. 7. U-235 fission in the target

While total number of uranium fission growth linearly with the increase of energy, specific amount on fission remain almost constant.

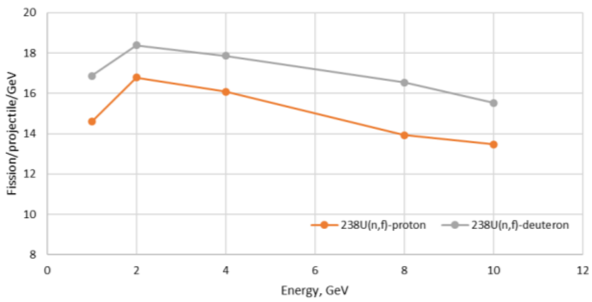

Fig. 8. U-238 fission in the target

As it is seen from the Figs. 7, 8 the amount of fission reactions increases for ~ 12…14% for deuteron beam compared to proton beam.

2.3. BEAM POWER GAIN

One of the parameter of ADS which should be estimated is power gain, G. The beam particle multiplication was calculated by the following expression according to [10].

$$G = (E_p + n_f \cdot E_f) / E_p,$$

where E_p is the accelerated particle energy (GeV); *nf* is the uranium fission numbers in the uranium assembly per one accelerated particle; *Ef* is the fission energy which is equal to 0.197 GeV.

Getting the result of uranium fission in a target under 1…10 GeV proton and deuteron beams allow us to estimate a beam particle multiplication. Fig. 9 illustrates obtained result.

The calculation shows the maximal beam power multiplicity equal to ~ 4.5 for proton beam and ~ 5 for deuteron beam in the range of energy 1…10 GeV.

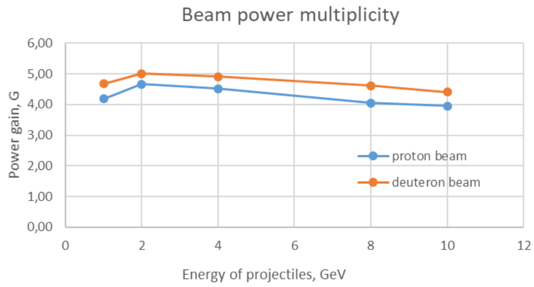

Fig. 9. Beam power multiplicity

SUMMARY

The Monte-Carlo simulation of a quasi-infinite depleted uranium target irradiated by 1…10 GeV proton and deuteron particles with the help of FLUKA package was carried out. Spectra of secondary particles generated in target are obtained. The fluxes of secondary particles in case of deuteron irradiation is ~15% higher than under the proton one.

The part of generated neutron is lasted almost the same with the growth of energy, amount of neutron is increase lineally.

Total number of ^{235}U(n,f), ^{238}U(n,f) reactions occurred in a target are calculated. With increase of beam energy the amount of fission is growth but the specific number of fission reactions is stay almost constant with slight increase at the 2…4 GeV projectile beam.

Beam particle power multiplications were determined. Based on the obtained result we can summaries that the optimal beam energy of projectiles is in 2…4 GeV range. Such results are in a good agreement with the MCNPX simulation in [11]. But such conclusion need to have experimental improvement. Obtained result will be taken into account during experiment preparation.

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МОНТЕ-КАРЛО МОДЕЛИРОВАНИЕ ОБЛУЧЕНИЯ КВАЗИБЕСКОНЕЧНОЙ МИШЕНИ ИЗ ОБЕДНЁННОГО УРАНА ПУЧКАМИ ПРОТОНОВ И ДЕЙТРОНОВ С ЭНЕРГИЕЙ 1…10 ГэВ

В.А. Воронко, В.В. Сотников, О.В. Бухал, К.В. Гусак, И.В. Жук

Методом Монте-Карло с помощью программного кода FLUKA проведено моделирование облучения квазибесконечной урановой мишени протонами и дейтронами с энергией 1…10 ГэВ. Представлены основные нейтронно-физические характеристики системы мишень плюс ускоритель. Получены спектры вторичных частиц, формирующихся в мишени, подсчитаны количества реакций ^{235}U (n,f), ^{238}U (n,f), протекающих в мишени при бомбардировании протонами и дейтронами указанных энергий. Определены коэффициенты усиления мощности пучка. Расчеты выполнены с целью планирования экспериментов по облучению урановой мишени (22 т обеднённого урана) в ОИЯИ (г. Дубна) в рамках выполнения Международного проекта «Энергия и трансмутация РАО».

МОНТЕ-КАРЛО МОДЕЛЮВАННЯ ОПРОМІНЕННЯ КВАЗІНЕСКІНЧЕНОЇ МІШЕНІ ІЗ ЗБІДНЕНОГО УРАНУ ПУЧКАМИ ПРОТОНІВ І ДЕЙТРОНІВ З ЕНЕРГІЄЮ 1…10 ГеВ

В.О. Воронко, В.В. Сотников, О.В. Бухал, К.В. Гусак, І.В. Жук

Методом Монте-Карло за допомогою програмного коду FLUKA проведено моделювання опромінення квазінескінечної уранової мішені протонами і дейтронами з енергією 1…10 ГеВ. Представлені основні нейтронно-фізичні характеристики системи мішень плюс прискорювач. Отримано спектри вторинних частинок, що формуються в мішені, підраховані кількості реакцій ^{235}U(n,f), ^{238}U(n,f), що протікають в мішені при опроміненні протонами і дейтронами зазначених енергій. Визначено коефіцієнти посилення потужності пучка. Розрахунки виконані з метою планування експериментів з опромінювання уранової мішені (22 т збідненого урану) в ОІЯД (м. Дубна) в рамках виконання Міжнародного проекту «Енергія і трансмутація РАВ».