E2-2003-207

V. S. Barashenkov, H. Kumawat

U–Pb **ADS** ON THE PROTON BEAM OF **JINR** NUCLOTRON

Submitted to «Kerntechnik»

Introduction

A program of theoretical and experimental investigation of perspective abilities of the electronuclear technology and various types of accelerator driven systems [1, 2] is developing at JINR (Dubna). ADS (Accelerator Driven Subcritical systems) SAD (Subcritical Assembly in Dubna) with the neutron multiplication coefficient ($K_{eff} \simeq 0.94$) and the thermal power of several tens kW is designed on the proton beam of 660 MeV Phasotron. This set-up has a lead target and contains 354 kg U-Pu fuel MOX (75% UO_2 + 25% Pu_2), more detailed information about this set-up is presented in [3]-[5]). The construction of SAD is financially supported by the International Science and Technology Center. The design and construction is assumed to be done during 2 – 3 years. Another ADS, with small K_{eff}, having a central lead target and a blanket with natural Uranium, is used now for experiments on proton beam at JINR accelerator NUCLOTRON at energies of 1 – 2 GeV. It will be reconstructed in the nearest future with a large amount of Uranium [6]. The measurements on the NUCLOTRON beam are the first stage of the electronuclear program at JINR. Comparing the results of calculations with experimental data allows one to improve the codes which are being used to calculate the properties of ADSs and to prepare methods for the experiments with SAD.

The complete set-up on the NUCLOTRON beam will contain nine sections, each containing 210 uranium rods (342 kg of U). At present, a truncated variant is used only with four sections, each containing 30 uranium rods (for brevity it will be referred to as DSAD, i. e. Deep SAD). The goal of our paper is to analyze the abilities of this assembly by mathematical modelling.

Set-up and method of calculations

Each section of DSAD was of 10.4 cm length containing a cylindrical lead target of diameter 8 cm at its center. Every uranium rod was of 3.6 cm diameter including an aluminum cover of 0.165 cm thickness and contains 1.72 kg of natural Uranium. The average (homogeneous) density of the rod is 15.8 g/cm^3. The cross-section of every section has a hexagonal form with 16.1 cm site length, 13.1 g/cm^3 average blanket density. The section has a 0.1 cm steel cover.

On both huttends (the front and back ends of the hexagon) of every section there are closing aluminum plates of 0.45 cm thickness. The installation is placed on a multilayer support and surrounded by a radiation shielding containing 0.1 cm layer of Cadmium and a thick (of several tens cm) polyethylene layer (Figs. 1 and 2). Set-up huttends are without shielding [1]. The sections are separated by 0.8 cm empty intervals for detectors. The total weight of Uranium in one section of DSAD is 51.6 Kg.

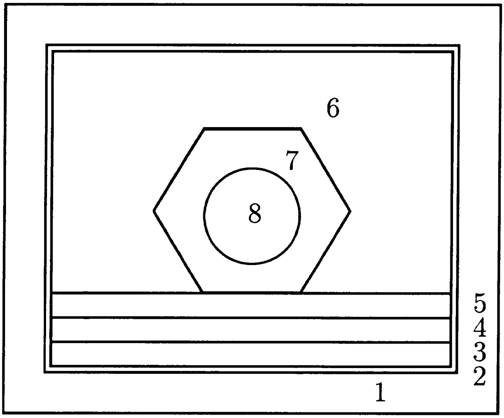

Fig. 1. Cross-section of DSAD.
1 – radiation shielding with the dimensions $\Delta X \times \Delta Y \times \Delta Z = 100 \times 110 \times 110 cm$, *, 2 – 0.1 cm cadmium layer, 3 – 3 cm layer of textolite, 4 – 9 cm wood support, 5 – 1 cm steel plate, 6 – 0.1 cm steel blanket cover, 7 – uranium blanket, 8 – lead target.*

The needle shaped proton beam is supposed to be injected into the center of the target. (The influence of space dispersion of the beam

---

[1] Comparative estimations of the set-ups with a different number of sections can be found in [7].

and its accidental experimental deviation from the target center will be also considered below).

For mathematical modelling we used Monte Carlo program CASCADE [8], developed at JINR . The cross-sections of hadron-nucleus interactions at energies E> 10.5 MeV were taken from [9]. For the description of low-energy neutron interactions, 26-group constants [10] were used. In the process of modelling the set-up was divided into 51 zones distinguished from each other by position, shape or its chemical composition (including 6 zones, describing the shielding and the multilayer support of the set-up). The blanket was considered as a homogeneous mixture of Uranium and Aluminum. In each variant of calculations more than 20000 cascades were sampled. The consuming time for the calculation by PC Pentium-4 with frequency 2400 MHz was about 10 hours.

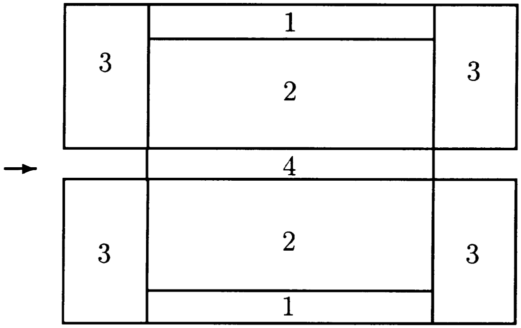

Fig. 2. *Longitudinal section of a DSAD section.*
1 – steel blanket cover, 2 – blanket, 3 – aluminum plates, 4 – lead target.

Results of modelling

Table I shows the calculated values of neutron yield in the measuring-room (i. e. taking into account the shielding and the set-up support) and the number of neutrons absorbed in (n,γ)-reactions.

Corresponding data for a "naked" set-up (without shielding and support) are also presented in brackets for comparison. All data are given for per primary proton.

The Table shows that the doubling of proton energy increases neutron yield with 85 %. The surrounding layer of polyethylene and the set-up support do not change the total neutron yield and, what is especially important, do not protect the measuring-room against γ-rays and neutron radiation. As a matter of fact, it plays a role of a converter transforming the fast neutrons into low-energy ones. In the measuring-room, there is a significant background of "cold" neutrons with energies $E_n < 2.5\cdot 10^{-8}$ MeV appearing due to the energy losses of neutrons in their collisions with light nuclei of the set-up surrounding.

The cadmium layer only prevents to return the low-energy neutron into the box, under shielding, however, such neutrons can fly out into the measuring-room. Calculations show that inside the room there is also a significant flux of fast neutrons emitted mainly by not-shielded huttends of DSAD. Safe work with DSAD demands an essential improvement of the shielding, especially on the huttends of the set-up.

Table I

The neutron yield
with proton beam of energy E(GeV)

E, GeV	1	2
Escaped neutrons		
$E_n > 2.5 \cdot 10^{-8}$ MeV	7 (21)	12 (36)
$E_n < 2.5 \cdot 10^{-8}$ MeV	13 (0)	25 (3.2)
Captured in n,γ-reactions	2.3 (0.9)	4.5 (2.1)
Summary yield	22 (22)	41 (41)

Table II contains data on the energies of created particles. Summary heat production in the set-up equals to the difference of the total produced energy E_1 and the energy losses E_2. Here $E_1 = E_o + E_f + E_{\gamma\pi}$ where E_o is the energy of the primary beam (transforming into ionization losses, recoil and residual's energies), E_f and $E_{n\gamma\pi}$ are the energies produced by fission and as γ-quanta, respectively. $E_2 = E_n + E_{ch} + E_\gamma$ where E_n and E_{ch}, E_γ are the energies of the escaped neutrons, protons and γ-quanta, respectively, in the measuring-room. As in the previous Table, the calculated results are shown separately for the shielded and the "naked" (in brackets) set-ups.

About 10% of the primary beam energy are taken away by charged particles (mainly by protons since yield of π-mesons and μ-mesons creating by their decays), is small at the considered energies. As they escape the huttends, their energies in DSAD and in the "naked" set-up are practically the same. However, the energy of the leakage neutron escaping from the side surface of the blanket is decreased significantly by the polyethylene. In γ-radiation two components can be observed: the high-energy quanta created by decays of π^o-mesons and γ-rays with the energies of several MeV emitted in (n, γ)-reactions and by the relaxation of weak-excited residual nuclei.

The shielding and the set-up support weakly influence the heat production and γ-emission because creation of neutrons and γ-rays occurs inside the target and blanket and the surrounding does not influence.

For the present NUCLONRON current $\sim 5 \cdot 10^9$, the summary heat power of DSAD is only a few watt.

At present, DSAD is being used for investigation of transmutation rate of various isotopes and for comparison of the results with the corresponding data obtained in atomic reactors (MNTC project 1372). The samples are placed on the blanket top side in the center of the second section perpendicular to the direction of the proton beam (Fig. 3).

Table II

The energies of particles (MeV)
created by the primary proton with energy E [GeV]

E, GeV:	1	2
Energy generated by fission	402(394)	780 (780)
Summary energy of γ-rays	73 (62)	254 (253)
energy of γ-quanta from π^o-decays	29 (29)	126 (126)
Energy of escaped neutrons	115 (165)	274 (370)
Energy of escaped charge particles	57 (62)	221 (234)
Summary produced heat	1523 (1511)	2120 (2011)

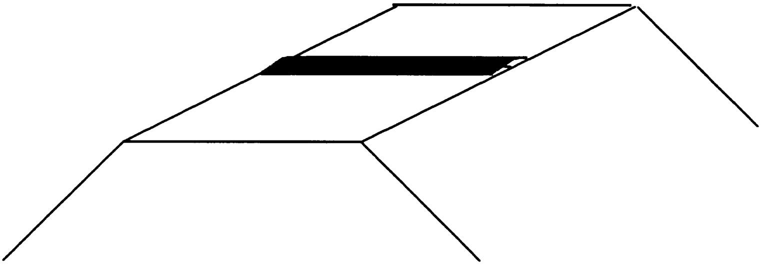

Fig. 3. *Position of the irradiated samples. The width of a container* $\Delta Z = 2.1$ *cm. Thickness of the samples* $\Delta Y = 0.15$ *cm.*

Spatial distribution of the neutrons along the length of the set-up section is given in Fig. 4. Since DSAD is put at the center of the box (Fig. 1), the spectra begins from 31.5 cm. The neutron intensity has the maximal value close to the center of the second section and about a quarter of this value at the set-up end. The average energy $E_n(Z)$ of the neutron escaping the top side is increasing smoothly (Fig. 4), due to elastic collisions, low-energy neutrons have larger scattering angles and fast particles significantly transported in forward. As we see, the neutron energy at the end of the set-up is three times larger than at its front huttend.

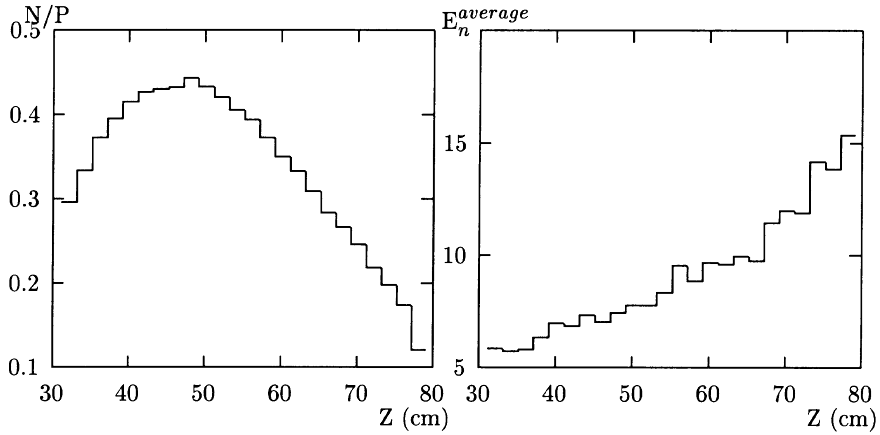

Fig. 4. *The neutron and their average energy distribution along the length of the hexagonal top side. Per primary proton and the area* $S = \Delta X \times \Delta Z = 16.1 \times 2cm^2$.

Fig. 5 shows the spectra of neutrons irradiating the samples under study in DSAD. Though the primary proton energy was E= 2 GeV, the neutrons only with energies $E_n \leq 350$ MeV, reached the blanket top surface. There is a plateau of thermal particles and a hump of "cold" neutrons with $E_n < 10^{-8}$ MeV. Such neutrons are usually created in collisions inside the support. The low-energy neutrons created in polyethylene are detained by the cadmium layer. In the "nacked" set-up without shielding and the support the hump is absent and the curve in Fig. 5 tends to zero at low energies.

The radial neutron spectra inside the interval separating the second section of DSAD from others are plotted in Figures 6– 8. In all cases the proton energy was E=2 GeV. One can see that the spectra before and after the section are practically identical. In this region of the target, at small R, there exists a large contribution of high-energy particles with $E_n \geq 350$ MeV. The share of "cold" neutrons decreases towards the periphery of the blanket.

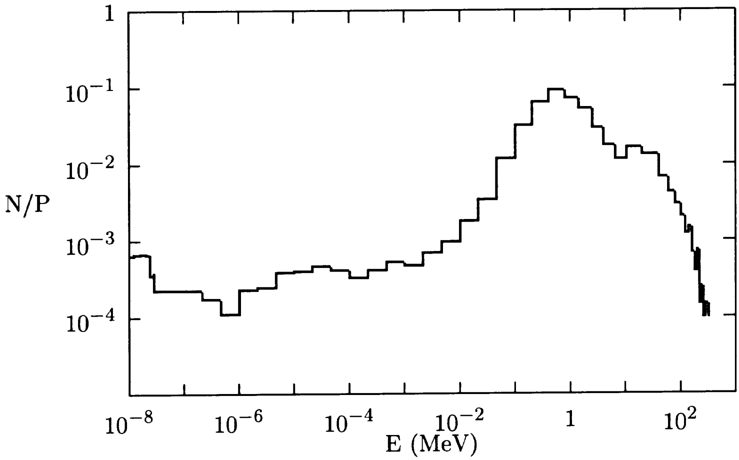

Fig. 5. *The neutron spectra on the top side of the blanket at proton bombarding energy E=2 GeV. Normalization is the same as in Fig. 4.*

A sharp decreasing of the neutron intensity at $E_n \simeq 10$ MeV attracts attention. It is masked by large contribution of slowing neutrons in the middle part of the blanket (Fig. 7) and on its periphery (Fig. 8). It is hidden in the summary spectrum integrated over all R. We do not see any physical reasons for such a fast change of spectra in the region of ten MeV. The overestimating of the calculated spectra in comparison to experimental ones in this energy region was observed also in [11]. The analysis has shown that the origin of this effect is mainly due to insufficiently correct description of decays of excited compound systems created by nuclear captures of slow cascade particles. This peculiarity is inherent almost all used now variants of the code CASCADE. At this point the code CASCADE needs an improvement in order to decrease the yield of neutrons with energies of several tens MeV.

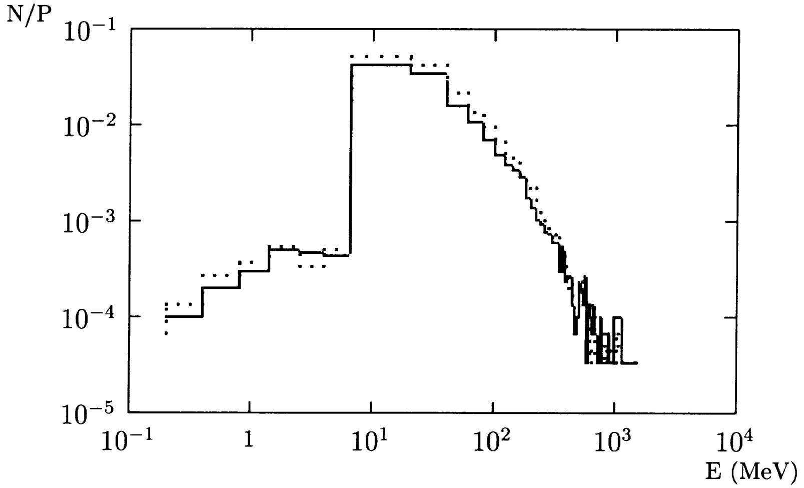

Fig. 6. *Neutron spectra inside the ring between radii* $R_1 = 0$ *and* $R_2 = 1$ *cm in the intervals before and after the second DSAD section (solid and dotted histograms). Per primary proton and the ring area.*

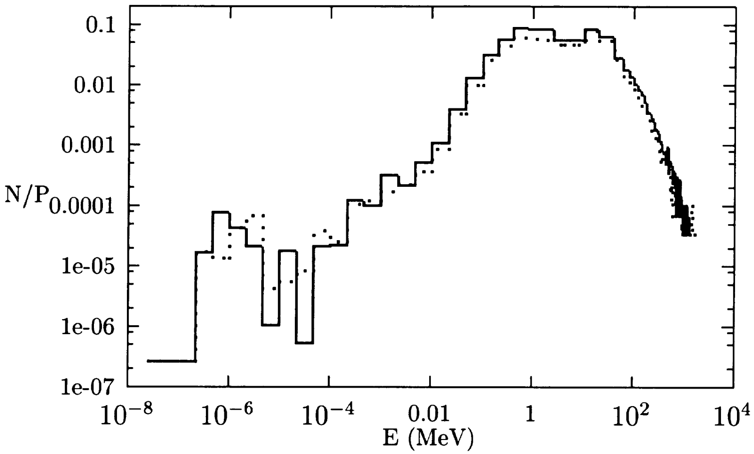

Fig. 7. *Neutron spectra inside the ring with* $R_1 = 4$ *and* $R_2 = 5$ *cm before and after the second DSAD section. Designations are the same as in Fig. 6.*

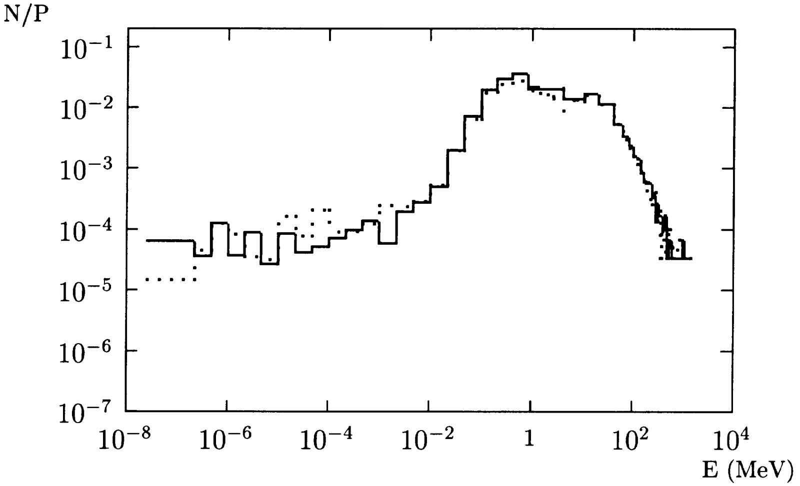

Fig. 8. *Neutron spectra inside the ring between radii* $R_1 = 10$ *and* $R_2 = 11$ *cm in the intervals before and after the second DSAD section. Designations are the same as in Fig. 6.*

We also have considered the influence of space spreading of the primary proton beam and its displacement with respect to the target center. It was supposed that the beam spreading was of Gaussian form and 90% of protons were inside the circle with the radius of 2.5 cm. Displacing from the target center is $\Delta X = -1.5$ cm. In limits of statistical errors (about 20000 cascades have been simulated), the data of Tables I and II and the neutron spectra in the most important region of present experiment, on the top surface, remain unchanged.

Conclusion

Though energy production in ADSS DSAD is very small, the neutron multiplication of this set-up is enough for the experimental investigations of various aspects of electronuclear processes. However, our mathematical experiments with various modifications of DSAD have shown that its construction is too complicated (see the more detailed description of DSAD in [6]). In particular, the multilayerness of the set-up support, thick aluminum plates on the section huttends are unnecessary. These and other details make a theoretical description and interpretation of measurements difficult. Due to its specific construction, it is difficult to compare results obtained by means of DSAD with other ADSs. Modelling of the DSAD properties, has shown also that the shielding, is being used now, does not protect the measuring-room against neutrons and γ-rays and need to reconstruct.

Acknowledgements

We have a pleasure to express our thanks to Ms. V. Lobanova for the preparation of Figures. One of the authors (VSB) is thankful to the International Science and Technological Center for its financial support. Another author (HK) is thankful to the Homi Baba Research Center for its financial support.

References

[1] V.S. Barashenkov. Electronuclear technology – sourses and perspective. JINR preprint P2-2003-144, Dubna, 2003.

[2] S. A. Bznuni, V.S. Barashenkov, V.M.Zhaikonyan et al. Perspective electronuclear systems. Elem. Part Atom. Nucl. 2003, v. 34, p. 977.

[3] V.S. Barashenkov, A.Polanski, I.V. Puzynin J. Comput. Meth. in Ssc.& Engen. 2002, v. 2, p. 5.

[4] V.S.Barashenkov, A.Polanski, I.V.Puzynin. Proc. of X Intern. Conf. on Emerging Nuc. Energy Systems. Petten, Netherlands, 2000, p. 429.

[5] V.Gudowski, A.Polanski, I.V.Puzynin. CD ROM Proc. Joint Meetting on Acceler. Nucl. Appl. in New Millennium, Reno,USA, 2001.

[6] M.I.Krivopustov et al. Kerntechnik 2003, v.68, p. 48.

[7] V.S.Barashenkov, V. Kumar, H. Kumawat, V. A. Lobanova. JINR E9-2003-55, Dubna, 2003.

[8] V.S.Barashenkov. Comp. Phys. Comm. 2000, v. 126, p. 28.

[9] V.S.Barashenkov, H. Kumawat, 2003, Kerentechnik (submitted).

[10] L. P. Abagan et al. Group constants for reactor and shielding calculations , Energoatomizdat, Moscow, 1981 (in Russian).

[11] Yu. V. Trebukhovsky, Yu. E. Titarenko, V. F. Batiaev et al. Duble-differential neutron spectra from Pb, W, Zr, Cu, Al and Na irradiated by protons with energies 0.8, 1.0 and 1.6 FeV. ITEP preprint 3-2003, Moscow, 2003.

Received on November 11, 2003.

Барашенков В. С., Кумават Х. E2-2003-207
Электроядерная установка U–Pb
на протонном пучке нуклотрона ОИЯИ

На основе программного комплекса Монте-Карло КАСКАД выполнено математическое моделирование спектров нейтронов, выхода и энергий частиц, генерируемых электроядерной установкой в экспериментах по трансмутации различных изотопов в пучке протонов с энергиями 1–2 ГэВ. Изучено влияние пространственной дисперсии и возможных отклонений протонного пучка относительно центра свинцовой мишени. Показано, что используемая в настоящее время полиэтиленовая радиационная защита не препятствует проникновению в экспериментальный зал интенсивного потока нейтронов и γ-излучения.

Работа выполнена в Лаборатории информационных технологий ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна, 2003

Barashenkov V. S., Kumawat H. E2-2003-207
U–Pb ADS on the Proton Beam of JINR Nuclotron

The neutron spectra, yields and energies of particles generated by a uranium electronuclear setup which is used now in Dubna for research on transmutation of various isotopes with a 1–2 GeV proton beam, are analyzed by means of mathematical modelling on the basis of a Monte Carlo code CASCADE. Influence of a space dispersion of the proton beam and its possible deviation from the center of a lead target is investigated. It is shown that the polyethylene radiation shielding that is being used now, does not protect the measuring room from neutrons and γ-rays.

The investigation has been performed at the Laboratory of Information Technologies, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna, 2003

Макет *Т. Е. Попеко*

Подписано в печать 26.11.2003.
Формат 60 × 90/16. Бумага офсетная. Печать офсетная.
Усл. печ. л. 0,93. Уч.-изд. л. 0,95. Тираж 415 экз. Заказ № 54198.

Издательский отдел Объединенного института ядерных исследований
141980, г. Дубна, Московская обл., ул. Жолио-Кюри, 6.
E-mail: publish@pds.jinr.ru
www.jinr.ru/publish/