A NEUTRON SOURCE ON A BASIS OF A SUBCRITICAL ASSEMBLY DRIVEN BY A DEUTERON LINAC

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The main characteristics of a conceptual thermal neutron source based on a subcritical uranium assembly are presented. A driver for the subcritical assembly is a deuteron linac with output energy of 23 MeV and an average beam current of 1 mA. The initial neutron generation is produced in nuclear reactions as accelerated deuterons bombard a beryllium target.

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1. INTRODUCTION

One of the possible ways of increasing the safety of nuclear power production and reduce its effect on the environment lies in the development of the *ADS* (Accelerator Driven System) technologies based on powerful neutron sources. The method for initial neutron production should not deal with a chain fission reaction of actinides. At present, the most effective method for initial neutron generation is spallation reactions caused by relativistic protons in heavy metal targets [1].

Construction of high-current relativistic energy ion accelerators is a very complicated and expensive problem [2]. At the same time, many problems concerning operation and safety of "accelerator-subcritical assembly" hybrid systems can be examined by high-current ion accelerators of low energies (some tens of MeV). Prototypes for such accelerators are available in some laboratories. Both ion [3] and electron accelerators [4] are considered as drivers.

Based on a subcritical assembly driven by an accelerator, a neutron source with total exclusion of the uncontrolled chain reaction can be an effective tool for experimental neutron investigations. In particular, it may be used for experimental studies in radiation science of materials, physics of the condensed matter, magnetism, and production of radioisotopes for medicine and the industry, nuclear physics, transmutation of long-lived radionuclides, biology, etc.

In Ukraine, around 50% of the electric power is produced on the nuclear power plants. Therefore, the problems of safety and non-pollution production of nuclear power are of great importance. In view of abovementioned, the construction of an experimental facility based on a subcritical uranium assembly driven by a charge particle accelerator for neutron investigations in the NSC KIPT is promising. We suggest to use a deuteron linac with output energy of W=23 MeV and an average current of 1 mA. For construction of the deuteron accelerator it is supposed to use production facilities created in the NSC KIPT during development of a high-current proton accelerator for material science.

The channel of the deuteron linac with output energy of 14 MeV and an average current 1 mA has been already investigated numerically. The accelerator is intended for production of the medical radioisotope-generator ^{99}Mo-^{99m}Tc [5]. The permissible linear losses of beam current in this channel are examined taking into consideration the radiation purity of the accelerator [6].

Further, two more accelerating sections with an alternating-phase focusing and energy ranges of 14…19 and 19…23 MeV are added. These additional sections allow increasing of neutron yield from a conversion beryllium target.

This paper presents the conceptual scheme of the thermal-neutron source on the basis of subcritical uranium assembly driven by the deuteron linac.

2. THE CONCEPTUAL SCHEME OF THE NEUTRON SOURCE

The beryllium target is chosen as an initial neutrons converter. For low proton and deuteron energies, beryllium has rather high neutron yield and acceptable thermal and mechanical properties. The target has a shape of a thin-wall cone for maximal heat removal caused by beam energy dissipation into the cone wall [3]. A deuteron length path in beryllium is ~2.1 mm, a diameter of the cone base is ~10 cm. The outside surface of the cone is cooled with floating water, which serves as a heat coolant and a neutron moderator in the subcritical assembly. The cone target is located inside the subcritical assembly. The deuteron beam is transported to the target along a vacuum ion pipe.

Figs.1 and 2 illustrate a neutron yield δ_n from the beryllium target as a function of bombarding deuteron energy W and the energy spectrum of emitting neutrons [7]. At deuteron energy of W=23 MeV and beam current of I=1 mA, the initial neutron generation rate is $Q_0=\delta_n I \approx 2\cdot10^{14}$ neutron per second. Hence, the neutron energy cost is ~720 MeV per neutron that is approximately 20 times higher in comparison to *spallation*-processes [1]. The energy distribution of the emitting neutrons is enough complicated and causes both the stripping reactions and the formation of compound-nuclei [7]. Neutron average energy $\bar{E}_n$ grows approximately linearly with deuteron energy and at W=23 MeV makes $\bar{E}_n \approx 7.5$ MeV. This energy is much higher than average neutron energy $E_0 \approx 2$ MeV of actinide fission. Velocities of emitted fast neutrons are directed forward at a divergence angle about of 40°.

An additional multiplication of initial neutrons exists in the subcritical assembly. Thus, total neutron generation rate is $Q=Q_0/(1-k_{eff})$, and power released due to actinide fission is:

$$P_f=Q_0k_{eff}E_f/\nu(1-k_{eff})=\delta_nIk_{eff}E_f/\nu(1-k_{eff}), \quad (1)$$

where k_{eff} is the effective neutron multiplication factor, ν is the average neutron number per a fission, $E_f\approx200$ MeV is the average energy released per a fission [1].

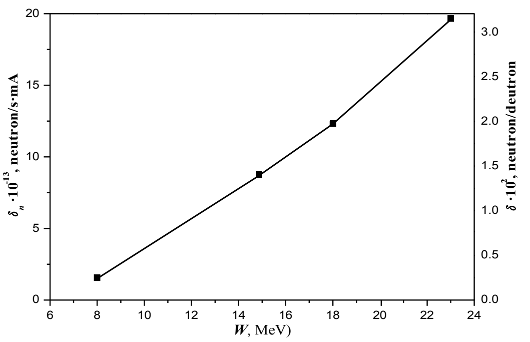

Fig.1. Total yield δ of neutrons with energy E_n>0.3 MeV as a function of incident deuteron energy W [7]

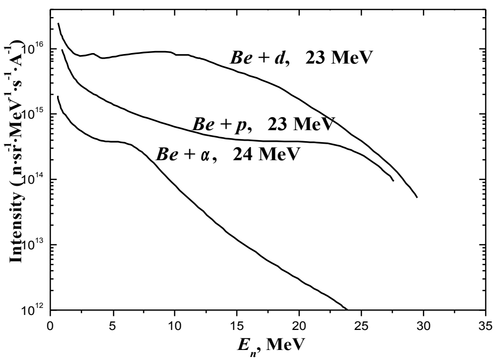

Fig.2. Energy spectra of neutrons emitted forwardly (ϑ =0°) from beryllium target bombarded by protons, deuterons and α-particles [7]

Generally, a chosen value for the multiplication factor is of $k_{eff}\leq0.98$ taking into consideration the system safety [3]. For any operation mode and experimental conditions the reactivity of the system should not increase. For chosen k_{eff} the subcritical assembly design is defined by mass m of fissile material, its enrichment factor x, power released P_f, geometry and dimensions of the fissile region, and materials for the neutron moderator, reflector, and coolant also.

The diffusion-age approximation is used to estimate the main technical parameters of the subcritical assembly and neutron field performance [8]. Preliminary calculations were performed for uranium thermal neutron subcritical assembly with k_{eff} equals 0.95 and 0.98. The fissile material is a uranium dioxide UO_2 with the isotope ^{235}U enrichment of x=20%. The initial tests of the 'accelerator-subcritical assembly' hybrid facility are supposed to be carried out with a deep subcritical assembly. Later, after experience is gained and the system reliability is improved, the multiplication factor will be increased up to the project value k_{eff}=0.98. The uranium enrichment of x=20% is restricted according to the international non-proliferation agreements. We consider only cylindrical configuration of the core region with the following spatial parameters: $H=D=2R_0$, where H stands for a height, D is a diameter, R_0 is a core radius. Such system geometry is chosen for its construction simplicity and low neutron leakage.

Fig.3 shows the dependences of uranium dioxide mass m (x=20%) on radius R_0 of the core region for the homogeneous assembly with different moderators (water, heavy water, beryllium, graphite) and the multiplication factor k_{eff}=0.98.

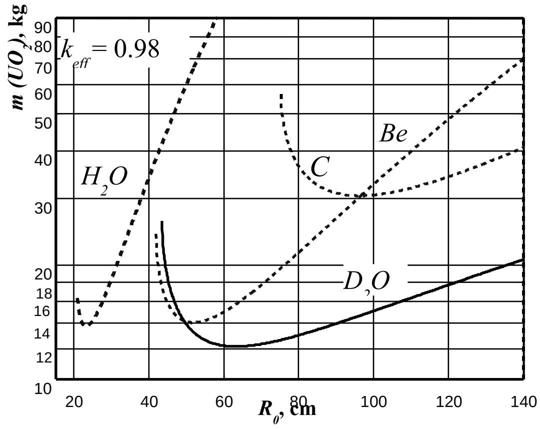

Fig.3. Uranium dioxide mass m as a function of assembly radius R_0

As one can see, Fig. 3, for each type of the moderator there is an optimal assembly radius $(R_0)_{opt}$ at which the mass of a fissile material is minimal m_{min}. The least value of m_{min} is for heavy water as a moderator, though the smallest value of $(R_0)_{opt}$ corresponds to ordinary water H_2O.

It is obvious from Fig.3 that for given k_{eff} and selected moderator a lot of assemblies may be designed for various R_0 and fissile mass m, accordingly. The optimization criterion for the assembly design should take into account the experimental usage of the neutron source, its cost, and reliability. As the main goal is to obtain the maximal thermal neutron flux Φ_m, the simulation of neutron flux as a function of the assembly radius R_0 is performed for the same moderators, Fig.4.

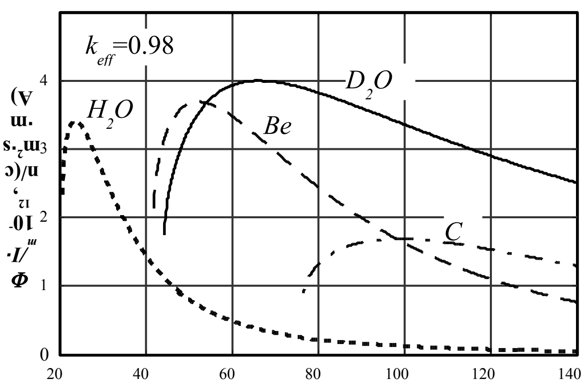

Fig.4. Maximal neutron flux Φ_m versus assembly radius R_0

The characteristic feature of curves in Fig.4 is that the peak value for the neutron flux Φ_m corresponds to the least fissile material mass m_{min} approximately. This fact can also be derived from the analysis of released power P_f coupled with an average neutron flux $\bar{\Phi}$ in the assembly and mass xm_u of the isotope ^{235}U by an expression:

$$P_f = xm_u E_f \sigma_f \bar{\Phi} N_A / A, \qquad (2)$$

where m_u is the uranium mass, σ_f is the average neutron fission cross-section of ^{235}U, N_A denotes Avogadro constant, A stands for an uranium mass number.

Comparison of Eqs.(1) and (2) yields:

$$\bar{\Phi} = \delta_n I k_{eff} A / \nu (1-k_{eff}) xm_u \sigma_f N_A. \qquad (3)$$

The main parameters of the subcritical assemblies corresponded to k_{eff}=0.98 and different moderators and optimized for the maximal neutron flux Φ_m production, are given in Table. Here, the released power P_f and neutron flux Φ_m are averaged over time and reduced to the beam current I. As the duty factor of the deuteron linac is 2%, the pulsed values of P_f and Φ_m are 50 times higher.

Moderator	ρ , g/cm^3	m_{min}, kg (UO_2)	m_{min}, kg (^{235}U)	m_{mod}, kg	R_{opt}, cm	(Φ_m/I)·10^{-12}, n/(cm^2·s·mA)	kW/mAP_f/I,
H_2O	1,0	13.7	2.4	78	23.3	3.5	125
D_2O	1,11	12.2	2.12	1770	63,3	4	125
Be	1,85	14.1	2.45	1630	52	3,7	125
C	1,67	30.5	5.31	9480	96,7	1.7	125

Parameters of the subcritical assemblies optimized

Note: ρ_{mod} is the moderator specific density

According to the Table, the uranium masses for maximal neutron fluxes Φ_m in assemblies with H_2O, D_2O and Be as the moderator differ slightly. However, the core volume and the moderator mass increase considerably if H_2O is replaced by D_2O or Be. As a result, if ordinary water H_2O is chosen as the moderator, the volume in the core for the experimental samples location is limited essentially. The total power P_f released in the source depends only on the beam current I and k_{eff}, Eq.(1), and does not depend on the moderator. But power density released in the assembly is proportional inversely to the core volume. Therefore, the thermo-hydraulic requirements for cooling are stronger for ordinary water H_2O than for D_2O or Be being the moderator.

The expenses to construct the subcritical assembly increase essentially in the case of heavy water or beryllium being the moderator and reflector due to their high cost. Moreover, the toxicity of beryllium compounds and activation of heavy water due to tritium production as a result of neutron absorption by deuterium should also be mentioned. The assembly with ordinary water being the moderator and coolant, and graphite as the reflector has the lowest cost.

One of possible arrangements of fissile material in the assembly is to use thin cylindrical fuel elements of uranium dioxide in a zirconium alloy can. The geometry of the fuel element should be optimized to obtain the maximal neutron flux taking into account the locations and dimensions of the beryllium target, diagnostic probes, and channels for irradiated samples.

In summary, it is necessary to note that experience gained in developing, designing and operation of low power ‘accelerator-subcritical assembly’ hybrid systems may prove useful in construction of high-power *ADS* installations for advanced technologies in nuclear industry.

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НЕЙТРОННЫЙ ИСТОЧНИК НА ОСНОВЕ ПОДКРИТИЧЕСКОЙ СБОРКИ, УПРАВЛЯЕМОЙ УСКОРИТЕЛЕМ ДЕЙТРОНОВ

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Приведены результаты исследований основных характеристик концептуальной схемы источника тепловых нейтронов на основе подкритической урановой сборки, управляемой линейным ускорителем дейтронов с энергией 23 МэВ и средним током 1 мА. Генерация первичных нейтронов обусловлена ядерными реакциями при бомбардировке бериллиевой мишени ускоренными дейтронами.

НЕЙТРОННЕ ДЖЕРЕЛО НА БАЗІ ПОДКРИТИЧНОЇ ЗБІРКИ, ЩО КЕРУЄТЬСЯ ПРИСКОРЮВАЧЕМ ДЕЙТРОНІВ

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Наведені результати досліджень основних характеристик концептуальної схеми джерела теплових нейтронів на базі підкритичної уранової збірки, що керується лінійним прискорювачем дейтронів з енергією 23 МеВ та середнім струмом 1 мА. Генерація первинних нейтронів зумовлена ядерними реакціями внаслідок бомбардування берилієвої мішені прискореними дейтронами.