ON THE MRTI EXPERIENCE IN THE INTERMEDIATE ENERGY NUCLEAR PHYSICS STUDIES, PERFORMED IN EXPERIMENTAL VALIDATION OF THE ACCELERATOR-BASED LARGE-SCALE NEUTRON PRODUCTION

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1. As a matter of fact, in the former USSR studies of scientific and technical feasibility of a practical use of the spallation reaction neutron potential for the NFC purposes (mainly, novel technologies of producing the fissile materials and high-flux steady-state thermal neutron fields) have been initiated in the fall of 1948. This approach required, in particular, to develop a high-current ion accelerator technology and to establish, essentially, a new direction in the intermediate nuclear physics and accumulate the data needed for validating, even though conceptually, nuclear-technology facilities based on such proton/deuteron medium-energy accelerators.

As for the accelerator physics field, it had to advance in investigating the very possibility to build a machine providing average ion beam powers of the order of 10-100 MW. Development of a proton/deuteron linear accelerator (500 MeV, 100 rnA) began at Institute for Chemical Physics of Academy of Sciences of the USSR in 1948-49, then the works have been transferred and concentrated to a place of Oural region which one names now as Chelyabinsk-50. The project was not due to the EN problem, and in 1963 it was stopped. A perfectly operating injector PT-500 (500 keV, 150 mA dc) remained, power RF triode generators were developed, elements of the drift tube linac existed, the proton/deuteron beam dynamics in such a linac was developed.

In searching for possible new applications for the suspended linac project a rather limited nuclear physics program was started. In studying the problem of an interaction of a light ion beam (- 10^2-10^3 MeV/ion charge unit) with matter, at ICP-RTI-MRTI the detailed neutronics measurement on primary bulky targets and primitive blankets (metal natural/depleted U, Pb, Be, reactor grade graphite and their combinations), bombarded with accelerated *p*, *d*, ^{3}He, ^{4}He, ^{12}C were carried out. Also experiments were being done on thin targets of various elements (from Be to U).

Our activity aimed, in particular, at elucidating the principal properties of a spallation neutron sources and a possible role of the accelerator-based neutron production in the evolving nuclear power industry. It means a large-scale realization of nuclear transmutations : breeding of fuel, incineration of a part of radioactive waste due to nuclear power generation, tritium production [1-3].

More specifically, early in the sixties we interested in some experimental nuclear data, lacking or unreliable, mainly of integral type, which enabled to judge about target/surrounding neutron characteristics : neutron yields and spectra, neutron multiplicities per nuclear absorption of ion, fission cross-section of heavy nuclei by spallation neutrons, yields of n,γ- and n,f-reactions inside and around heavy element targets, irradiated with various light ions accelerated to energies 0.3÷8 GeV, as well as to use these data for estimating performances of the hypothetical EN breeder-transmuter and optimizing energy/current of its accelerator.

2. First of all, neutron multiplicities ν per interaction of high-energy proton (E_p = 0.4÷3.2 GeV) and deuteron (E_d = 1,48 and 7,3 GeV) with nuclei (15 elements in all : from Be up to U) were measured (some examples are presented in fig. 1). The moderation technique was used, so that neutrons of energies ≤ 15 MeV were detected, but later in experiments at the Synchrophasotron the time-of-flight (TOF) technique was supplemented and ^{6}Li/^{12}C ions as projectiles were added. These experimental results were necessary for developing/testing the cascade-evaporational model of spallation reaction and for building/testing computer codes [4], which gave integral characteristics of the high-energy radiation transport in materials of quasi-infinite target assemblies.

3. From the very beginning of our activity we were aware that lead (or Pb-Bi eutectic) was very probable substance for the primary target, albeit not the only. Therefore neutron emission from thick Pb targets (cylinders 0 10÷26×60 76 cm, bars/slabs 16x16x60 cm^3) [5] has been studied by hvo quite different experimental methods (neutron moderation and threshold solid state nuclear track detectors, SSNTD) ; sometimes, in studying shortened targets, the TOF technique was applied for the sake of check purposes. Measurements of the total yields and energy/space distributions of neutrons were done in a broad interval of kinetic energies of *p*, *d*, ^{3}He, ^{4}He, ^{12}C (fig. 2).

The data enabled, in particular, to establish a type of accelerated ion, providing the maximum neutron yield per unit of spent energy, determine the ion initial kinetic energy, up to which it would be expediently to accelerate the ion (minimization of expenditures of the primary ion kinetic energy for releasing one neutron) - with accuracy to E-dependence of RF power.

4. By the SSNTD technique, supplemented in some cases with the TOF method, the integral neutron spectra over the target surface (and over various angles) have been measured, thereby fluences of neutrons in 8 energy groups, including the tens-hundreds MeV range, and a fraction of neutrons was got in the full

spallation neutron spectrum, of which energies> 15 MeV. Some examples of the neutron data for Pb target 0 20x60 cm are presented in fig. 3.

5. On the same bulky primary Pb targets the neutron multiplication was studied in general outline in several primitive blankets : the homogeneous ones assembled of continuous metal uranium (both natural and depleted, with/without Pb core inside U) ; the heterogeneous ones made of Pb-Be-graphite/Pb-Be-water (with neutron traps in some geometries).

In searching for novel approaches to generate steady-state high-intensity thermal neutron fluxes, which are unachievable even for the high-flux fission reactors, specially designed for this aim ($\geq 7\div 8.10^{15}/cm^2.c$), we carried out a series of experiments on the total absorption assemblies composed on the Pb primary target (16x 16x60 cm^3) - a converter of proton beam power into neutrons in the MeV range, a Be blanket of $4\div 20$ cm thick (*n, 2n reaction* multiplier) and a reactor grade graphite moderator/reflector 80 cm thick [7] (fig. 4). This and all other assemblies of such a kind were driven by 0.66 GeV proton beam (or lower) of the JINR Synchrocyclotron at Dubna in 1966-1969. Now this assembly maybe of interest again.

In the first phase of the experiments, an increase of neutrons in the target assembly Pb+Be (as compared with Pb only) was determined by the moderation technique, using as thermal neutron detector 5 % solution of $MnSO_4$ in water. The number of spallation neutrons becomes 1.82 ± 0.20 as much when Be wall is 16 cm thick; the thickness of Be wall 20 cm gives the neutron rise only 3-4 % more. Such a neutron source (Pb 16x 16x60 cm^3+Be wall 16 cm thick) provides the thermal neutron flux densities in surrounding graphite moderator (in the maximum of its distribution measured along the proton beam direction, at a distance from Be wall $1\div 41$ cm) from $7.2.10^{-3}$ to $3,8.\ 10^{-3}.\ cm^{-2}.\ sec^{-1}.p^{-1}$ (± 11 %).

6. Lastly, on the total absorption metal uranium targets (3.2-3.4 ton, natural/depleted, with or without lead converter inside), irradiated by 300-660 MeV protons, the data have been obtained [8] concerning the yields of ^{239}Pu and fission energy. The data enabled to estimate performances of the EN breeding (the Pu production rate, energy spent for its production, accompanying release of energy) and to test computer codes describing the nuclear cascade in large masses of uranium.

7. In the spallation neutron fields around the same Pb cylinder, absorbing *p/d* beams of energies 1.O-3.7 GeV, the study of transuranium actinides fission has been started, some results (averaged one-group fission cross-sections) have been obtained for ^{237}Np, 235J238U, ^{232}Th [9] and quite recently ^{243}Am.

8. Some our data were used at developing and testing computer code describing the neutron multiplication and balance of energy both in homogeneous infinite/quasi-infinite U blocks (MRTI, BNL, JAERI, JINR, ORNL) and in full-scale heterogeneous target/blankets (BNL, JAERI) ; also for validating the codes HETC, describing neutronics of thick Pb cylinder, irradiated with protons of energies -- GeV (CRE Casaccia, LAHET, ORNL, KEK); for testing the high-energy cascade model of spallation reaction (ORNL, JINR, MRTI). Agreement between calculational and measured results is moderately good, as a rule, but only when the integral values are compared. In the matter of differential values such an agreement is a rarity.

9. About two years ago, in connection with the interest to a creation of safety and cleaner nuclear power industry, to mastering the Th-^{233}U NFC and more efficient reactor systems (for example, MSR with Th-^{233}U fuel and with possible adding TUA waste) we have taken up again the assembly Pb-Be-graphite. But now Be neutron multiplier is substituted for a mixture Th (80 %) + ^{237}Np (20 %) because the use of Be would be impractical in fields of very hard neutrons. A behaviour of metal Th/salt $LiF\text{-}BeF_2\text{-}ThF_4$ in the graphite moderator will be investigated in details. Besides, a possibility to apply a heavier chloride salt $PbCl_2\text{-}ThCl_3\text{-}[TUA]Cl_4$ as the primary target instead of Pb will be studied. Preliminary appraisals show, that even at moderate values of k_{eff} (0.86-0.92) current of 1 GeV protons can amount to 30-35 mA, so that one 100 MW H^+/H^- CW linac would support 3 blankets of thermal power 1.2 GW.

Unfortunately, this activity is suspended now completely owing to lack of funding.

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Table

$\langle\sigma_f\rangle$

^{237}Np	^{235}U	^{238}U	^{232}Th	
PROTON				
1.31 *0.14	**1.57 * 0.17**	**0.38 ± 0.04**	**0.14 * 0.02**	mod
1.14*0.11	**1.37 * 0.14**	**0.33 * 0.03**	**0.12 * 0.01**	SSNTD
DEUTERON				
1.32 ± 0.21	1.55 ± 0.25	0.36 ± 0.06	0.14 * 0.02	mod
1.13 * 0.23	1.35 * 0.25	0.31 * 0.05	0.12 * 0.02	SSNTD
(σ_f)				
0.84	1	***0.24***	0.09	proton
0.84	1	0.23	0.09	**deuteron**

Experimental **values** of averaged one-group fission (transmutation) cross-sections for several key **actinides** (**^{232}Th,** ^{235,238}U, ^{237}Np) [9] and ^{243}Am. A source of **spallation** neutrons is Pb target 20x60 **cm**, irradiated by 1.0-3.7 **GeV proton/deuteron** beams.

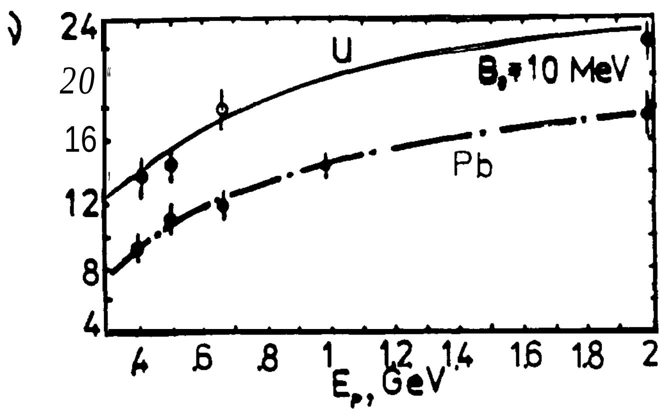
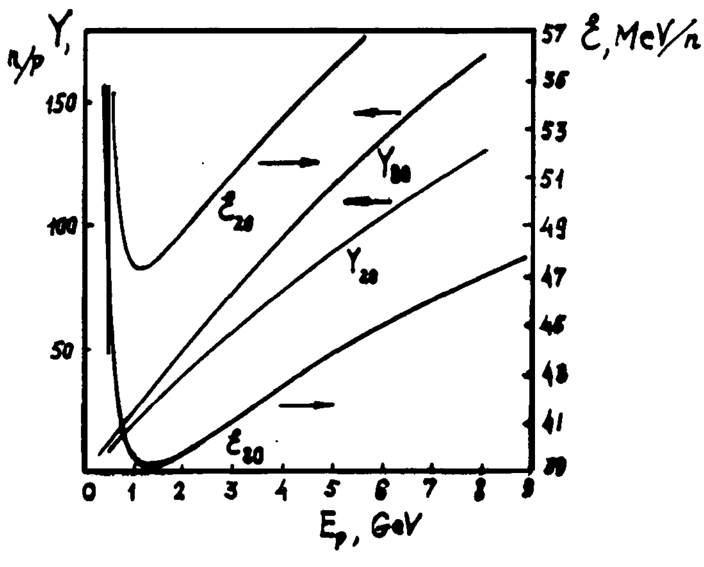


Fig. 1- Experimental data on neutron multiplicities **(Y)** and (E_ns 15 **MeV)** for **Pb/U** nuclei absorbing protons Pb target of energy 0.4-2.0 GeV.



Pig. 2- E_p-dependence of neutron yield energy cost of neutron **(*E*)** released from 0 20x60 cm **(experiment,** moderation technique) and 0 80x100 cm (calculation) under the action of protons.

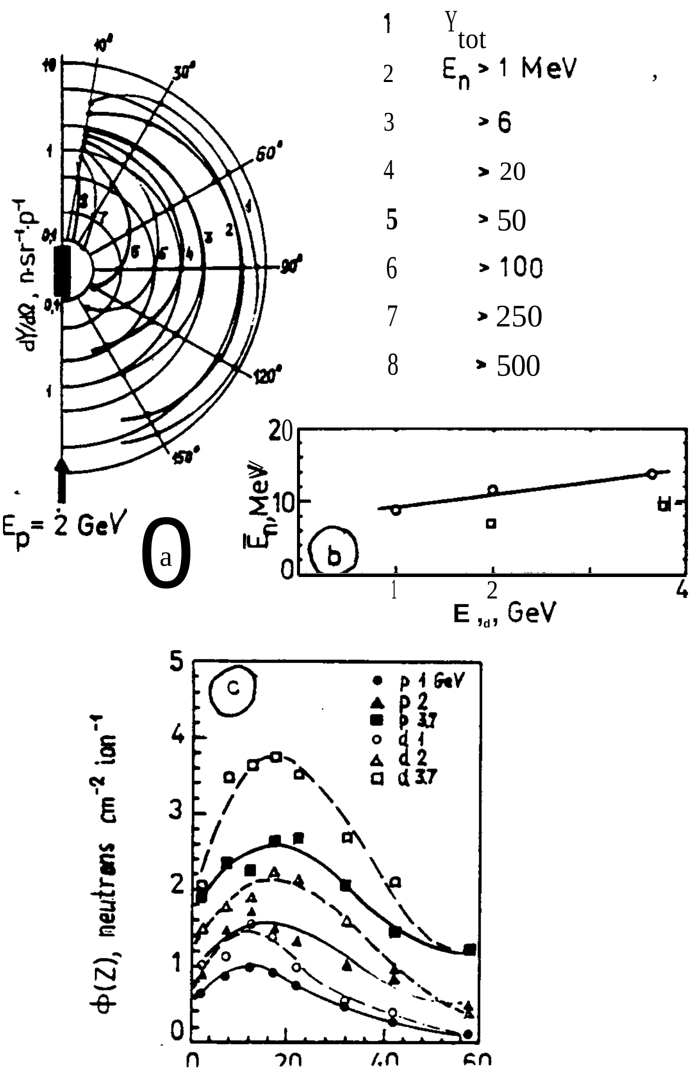


Fig. 3- The data obtained by the **SSNTD** technique for the same Pb target (Ø 20x60 cm), **bombarded with** proton/deuteron beam **($E_{p,d}$ = 1,0-3,7 GeV) [6] : a) energy/angular** distributions of **spallation** neutrons, b) mean neutron energy versus the initial **proton/deuteron** kinetic energy, c) neutron **fluences** over the target surface.

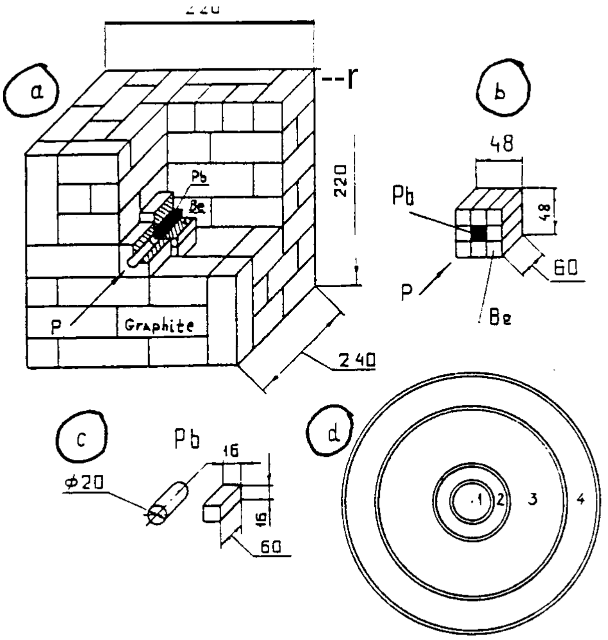


Fig. 4 - Experimental arrangement for studying multiplication of **spallation** neutrons from the Pb **primary** target in Be blanket embodied in graphite moderator-reflector [7] : a) Pb target 16x16x60 cm^3 inside Be multiplying cavity, wall thickness 16 cm, both surrounded by a graphite moderator-reflector 80 cm thick ; in the assembly **thermalized** neutron flux densities (3.8-7.2). $10^{-3}/cm^3$.s.p. (±15%) have been obtained ; b) Pb target 16x16x60 cm^3 surrounded by Be blanket-multiplier, its wall being of variable thickness or depleted U wall 8 cm thick; c) bar Pb targets 16x16x60 cm^3 and Ø10-26 cm; d) a scheme of an accelerator-driven target-blanket: **1-** Pb **(Pb-Bi)** target (a possible option is heavy chloride molten salts carrying **TUA),** 2- neutron multiplier **(Th** 80 % + TUA 20 %), 3- graphite moderator with molten salt **fuel** ('1%-^{233}U), 4- graphite reflector.

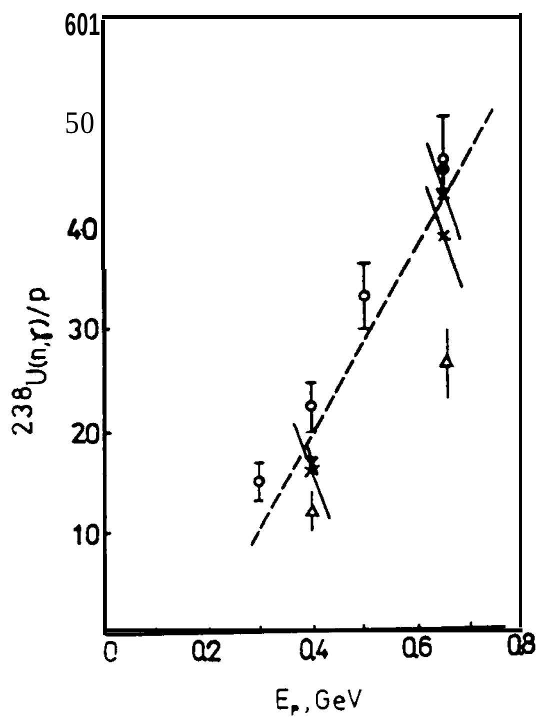


Fig. - The yields of ^{239}**Pu** (number of $^{238}U(n,\gamma)$ ^{239}U → ^{239}Np **reactions)** and fission reactions $^{235,238}U(n,f)$ in quasi-infinite metal uranium targets (both natural and depleted, 0.36 % ^{235}U), under the bombardment with protons of energies 0.3-0.66 **GeV** [8].