THE MEASUREMENT OF NEUTRON SPECTRA IN THE INTERACTION OF 660 MEV PROTONS WITH A SUBCRITICAL NATURAL URANIUM ASSEMBLY

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Abstract- The diamond detector measurements of neutron spectra obtained in the interaction of 660 MeV protons with lead bricks as well as a subcritical natural uranium assembly (the installation of "Quinta") were carried out. In the case of lead bricks neutrons and protons contribute to the diamond detector amplitude spectrum. In the case of “Quinta” installation only neutrons give contribution to the diamond detector amplitude spectrum. Diamond detector amplitude spectra were investigated versus the angle between proton beam direction and line passing through the center of “Quinta” installation (or lead bricks) and diamond detector. The anisotropy of neutron flux versus angle has been shown. In the case of lead bricks diamond detector amplitude spectrum cover the range from 2 to 80 MeV. In the case of “Quinta” installation diamond detector amplitude spectrum was in range from 2 to 20 MeV that means neutrons to have energies in range 7.4 – 25.7 MeV. Important advantages of using diamond detector in experiments of high energy proton beam interaction with targets are its small dimensions, radiation hardness, low neutron sensitivity, ability to measure neutron spectrum. Small detector dimensions and low neutron sensitivity allow to locate an array of detectors immediately inside target and to analyze neutron fields inside the target.

Index Terms- Diamond detector, lead bricks, neutron spectra, proton beam, subcritical natural uranium assembly.

I. INTRODUCTION

One of the ways of solving fundamental problems of modern nuclear power technology is to use neutrons with energy spectrum harder than fission in extremely subcritical core made from natural uranium. This allows to involve a large set of competing inelastic processes. In this case multistage cascade processes begin to work effectively ensuring an effective fission of minor actinides. Harder neutron spectrum causes additional radiation capture reactions and also, reduces the production of long-lived radioactive materials significantly. The way to implement this task is to develop a new scheme of Electronuclear fission, based on nuclear relativistic technologies (NRT) [1]. NRT provides an extremely hard neutron spectrum in the media of quasi-endless deeply subcritical natural uranium assembly. Ion beams with energy of ~ 10 GeV are required to maximize energetic efficiency of such systems.

This article presents experimental results of measuring by diamond detector of ionizing radiation arising from the interaction of protons with an energy of 660 MeV with a lead target, and a subcritical natural uranium assembly (the installation of "Quinta" [2]). Because synthetic diamond has mechanical strength, radiation hardness, chemical inertness, small size and improved electronic properties, the diamond detector can make significant contribution to solution of modern nuclear technology problems.

The experiments on the interaction of protons with lead target of and subcritical natural uranium assembly were carried out at the synchrocyclotron-JINR protons accelerator, Dubna city [3]. The proton (P) beam in our experiment had the following parameters: an energy of 660 MeV, a modulation frequency of 250 Hz. The extracted proton beam has a microstructure: particle bunches with a duration of approximately 10 ns follow each other with an interval of about 70 ns.

II. DIAMOND DETECTOR

The detection of neutrons by the diamond detector rests on collecting the charge that is produced when recoil nuclei and products of nuclear reactions are slowing down in the diamond sensing element of the detector in the process of interaction between neutrons and carbon nuclei. When recording the neutron spectrum, the diamond spectrometer measures the total energy of products of reactions within the diamond detector. The irradiation of diamond with a flux of fast neutrons results in elastic and inelastic neutron scattering and nuclear reactions with carbon that produce new charged particles [4].

Owing to the design specifics of the diamond detector, the gamma radiation response is limited in amplitude and is discriminated easily with the lower threshold.

The energy resolution of the spectrometer is improved in the complete charge collection regime, which may be established if the diamond material is of high crystallographic quality.

The diamond detecting element of the neutron spectrometer was an electronic grade plate 4.5 × 4.5 ×0.5 mm^3 produced by Element Six. Gold contacts were deposited onto this element. The area under these contacts on the diamond plate was 16 mm^2; therefore, the sensitive detector volume was 8 mm^3. The energy resolution of the detector was no worse than 1% for fast neutrons. The diamond plate was mounted within a case with a BNC connector. The detector design

allowed for coaxial plate connection, thus providing high interference resistance.

The detector signal was picked up by a specialized spectrometric circuit incorporating a charge sensitive preamplifier (CSPA), a spectrometric shaping amplifier, and an amplitude analyzer. The support unit, which performed interconnection functions and provided the detector bias voltage and the supply voltage for CSPA, was the basic element of the specialized circuit. The support unit also incorporated a signal shaping amplifier. The CSPA was connected to the support unit by a 50 Ω coaxial line link with a length of up to 100 m. The diamond detector was installed directly at the CSPA input terminal.

The energy scale of the circuit was calibrated in the process of detecting alpha particles from reference alpha sources from the RAS set. The 226Ra alpha spectrum was used to test the detector with an exposure of 5 min and a bias voltage of –250 V. Influence of the gamma irradiation caused by installation activation was measured after proton beam shut down. Two identical diamond detectors, named EG13 and EG19, were used in the experiments. Count rates of diamond detectors located at the distance 3 m from the target perpendicular to the proton beam direction were measured, here with lead bricks and uranium assembly were moved away from proton beam trajectory. In this case the average count rate was about 2.4 counts/sec, deviation of the number of registered events was less than 2%. Both detectors were shown to operate identically.

III. THE INTERACTION OF 660 MEV PROTONS WITH LEAD BRICKS AND A SUBCRITICAL NATURAL URANIUM ASSEMBLY

In this section the diamond detector measurements of neutron spectra obtained in the interaction of 660 MeV protons with lead bricks as well as a subcritical natural uranium assembly (the installation of "Quinta") are presented.

A. Lead target

The experiment scheme of proton beam interaction with lead target is shown in fig.1. The proton beam had an average intensity of 2×10^{10} particles/sec. Lead target consists of six lead bricks. Target dimensions: length along the beam – 30 cm, 10 cm width and 20 cm height. Detector EG13 was located on the beam line behind the lead bricks. The distance between the target center and the detector was 2.56 m. The position of the second detector was changed versus an angle between beam and direction from the target center to the detector. The particle flux was measured for 240, 600, 900 angles, wherein the distance from target center to the detector was 1.15, 1.9, and 2.25 m respectively. Fig. 2 shows detectors' count rates versus time for angles 0° and 24°. One can see that count rates of the diamond detectors EG13 and EG19 differs more than one order of magnitude. I.e. maximal count rate was achieved for the detector behind lead target (the one on the beam line).

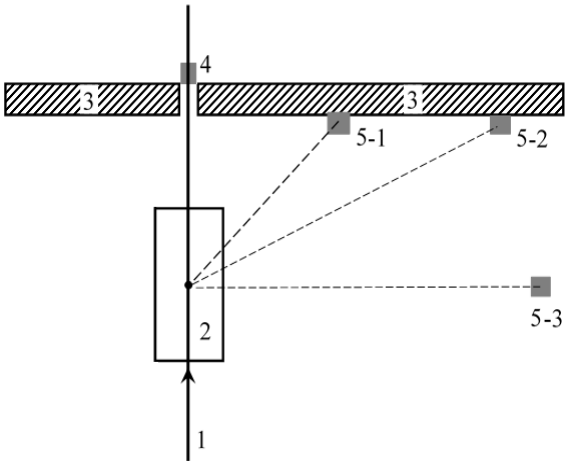


Fig. 1. The scheme of the experiment with lead target. 1 – proton beam, 2 – lead target, 3 – collimator, 4 – detector EG13 on the beam line (α=0). Locations of the detector EG19: 5-1 - α=24, 5-2 - α=60, 5-3 - α=90.

Fig. 2 shows that count rate increases with proton beam intensity rise. Fig. 3 shows pulse height spectra of diamond detectors EG13 and EG19 located as shown in fig. 1. The exposition time was 30 minutes.

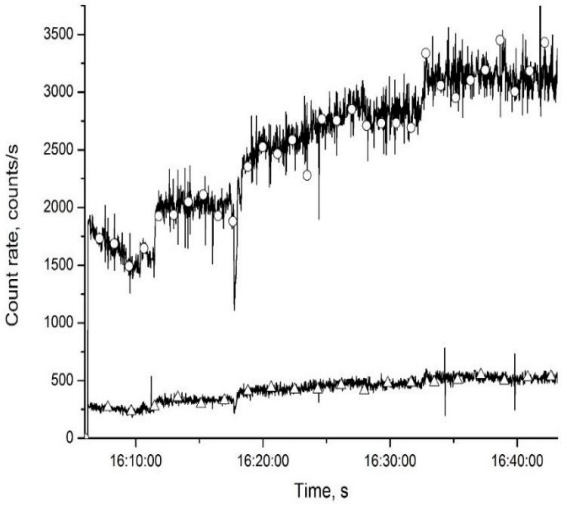


Fig. 2. Diamond detectors' count rates EG13 and EG19, α=240, located as in fig. 1 (positions 4 and 5-1).

Curves have fracture near 55 MeV, which, presumably, caused by neutrons. Also fractures of curves are shifted, and this can be explained by detector calibration curve inaccuracy.

Pulse height spectra (PHS) of diamond detector EG19 irradiated under varying angles (0°,24°,60°,90°) and distances (2.56; 1.15; 1.9; 2.25) for the case of lead target are shown in fig. 4. Pulse height spectrum curves have energies less than 80 MeV. But pulse height spectra for various angles differ. Measurements show that maximum flux was registered under angle 0°.

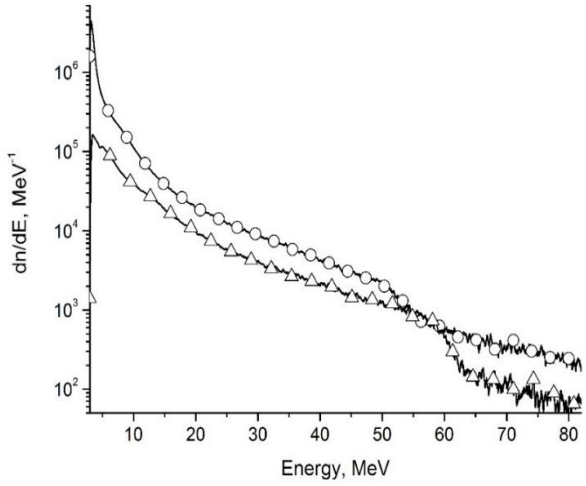


Fig. 3. Pulse height spectra measured by EG13 and EG19. EG13 is located at the distance of 2.56 m from the target center on the beam axis. EG19 is located at the distance 1.19 m from target center at the angle 24° with respect to the beam axis. Exposition time was 30 min.

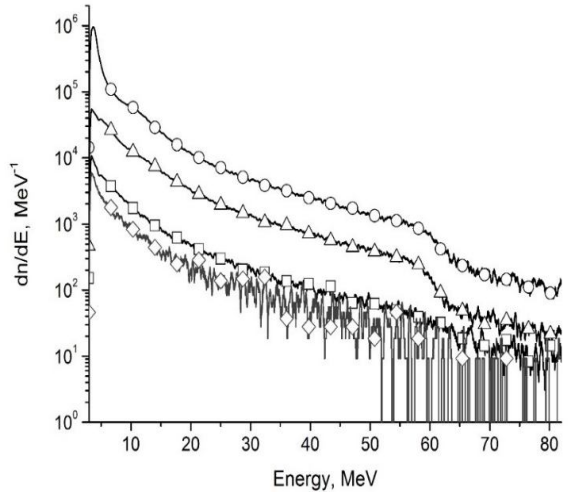


Fig. 4. Pulse height spectra of diamond detector EG19 for various angles (0°,24°,60°,90°) and corresponding distances to the lead target (2,56; 1.15; 1.9; 2.25).

Registered flux is decreasing together with angle increasing. The form of pulse height spectrum curve is also changing. At angles 0 and 24 degrees the fracture of the PHS curve is observed at 60 MeV, while at angles 60 and 90 degrees such fractures are not sighted. While changing the angle from 0 to 24 degrees the flux is dropped by more than one order of magnitude. The falling is decreasing at greater angles. For example, when angle is increasing from 60 to 90 degrees, flux is decreased by factor less than two times.

The average count rates for angles 0°, 24°, 60°, 90° were 2365, 507, 77, 13 Hz respectively, i.e. in all cases count rate was greater than 2.4 Hz, which was observed for the case without any target at the distance about 3 m from target location. Fig. 5 shows comparison of PHSs with and without lead target. Proton beam forms monotonically decreasing PHS up to 82 MeV. In the case of lead target neutrons also contribute to the diamond detector PHS.

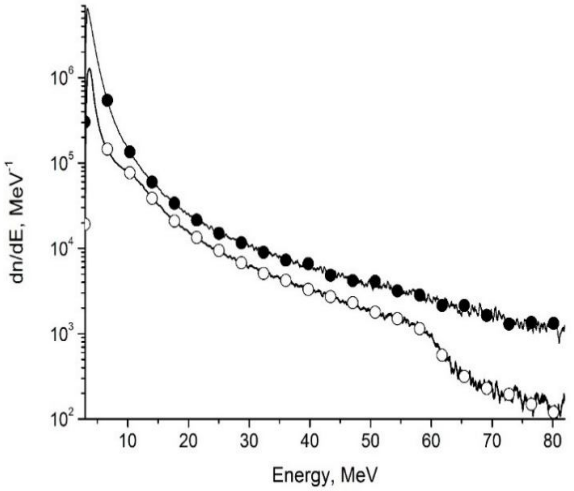


Fig. 5. PHS of diamond detector EG19 on the beam axis with (○) and without (●) lead target.

Thus, in the case of lead target the contribution to the amplitude response of a diamond detector provide protons and neutrons. The detector response spectrum was within the range of 2-80 MeV. The maximum amplitude response is fixed in the direction of α=0°. By increasing the angle between 0 and 90 diamond detector amplitude response decreases. Average count rates at angles 0°, 24°, 60°, 90° were 2365, 507, 77, 13 Hz respectively.

B. The Measurement of neutron spectra in the interaction of 660 MeV protons with a subcritical natural uranium assembly (the QUINTA setup)

In this section, a study of neutron spectra in the interaction of protons with subcritical natural uranium assembly. The QUINTA setup installed at the proton beam of the cyclotron (Laboratory of Nuclear Problems (LNP), Joint Institute for Nuclear Research). The proton beam had an average intensity of 10^{11} particles/s. It is an assembly of natural uranium, weighing 500 kg. Overall view of the QUINTA uranium target is shown in Fig. 6. The experiment scheme is shown in fig.7.

In the present study, the response spectra of the diamond detector were recorded and the spectrometer count rate was measured as a function of the angle between the proton beam and the line going through the detector and the center of the QUINTA setup. The measurements were performed at angles of 0°, 45°, and 90°.

Fig. 8 present the detector response spectra. The energy detector response spectra measured at different angles were in a qualitative agreement. The measurements showed that the neutron flux was maximized at an angle of 0°. Up to an angle of 45° degrees the neutron flux is reduced, but further up to 90° degrees remains practically unchanged. From angle 0° up to 45° degrees the neutron flux is reduced, but further up to 90° degrees remains practically unchanged.

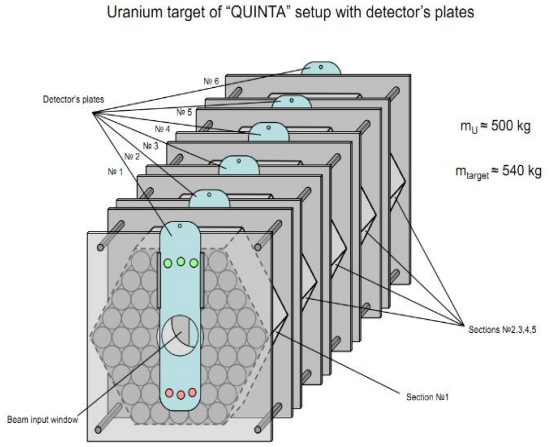


Fig. 6. Overall view of the QUINTA uranium target.

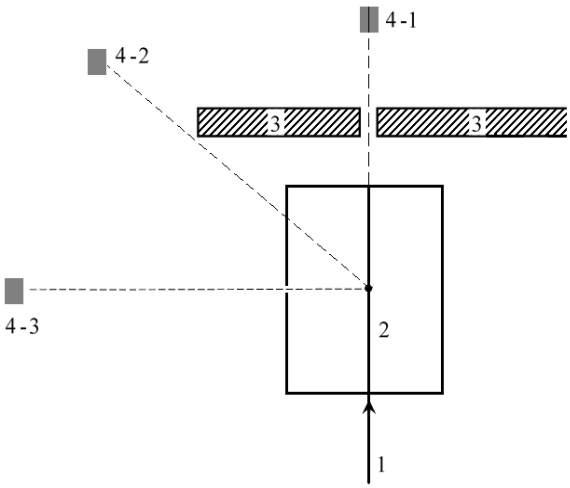


Fig. 7. The Scheme of experiment. 1-proton beam, 2- the QUINTA setup, 3- Collimator. The location of the detector: 4-1,4-2 - α=0, 4-3 α=45, 4-4 α=90.

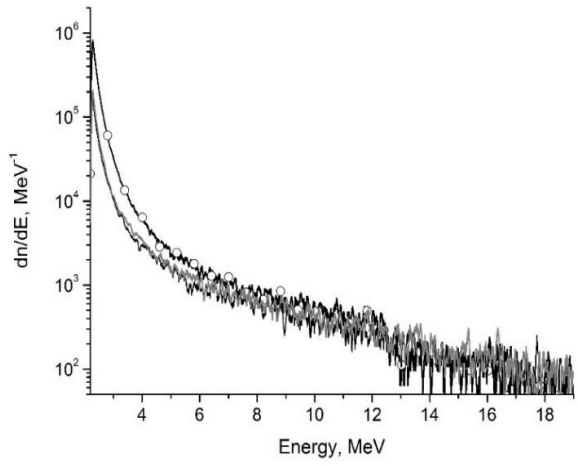


Fig. 8. PHS of diamond detector for various angles. If α = 0° the distance between the center of the installation and the detector 3.4 m (○). At angles of 45 and 90° detectors were set at a distance of 1.7 m. The bias voltage -250 V. The exposition time was 30 minutes.

Fig. 9 presents a count rate of the diamond detector during irradiation of the "Quinta" installation. The distance from the "Quinta" setup to the detector - 5 m. The bias voltage -250 V. Exposition time was 15 min.

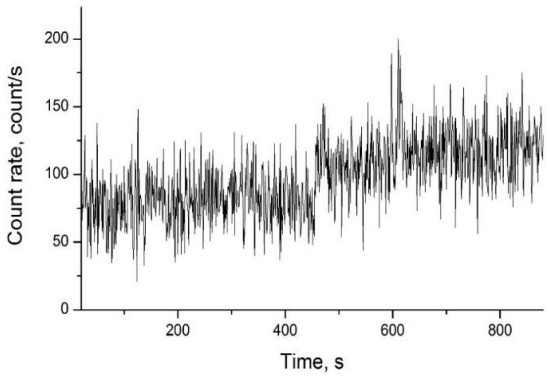


Fig. 9. Count rate of the diamond detector irradiated by the "Quinta" installation.

The neutron flux in the experiments may be estimated from Fig. 9. One can see that the count rate due to neutrons was approximately 100 counts/s. For considered energies, neutron cross section is ~0.8 barn. Taking into account the volume and the cross section of the diamond detector, calculated neutron flux is about 0.9×10^5 n / (cm^2 sec) at the detector. The detection threshold in these measurements was 2.1 MeV. As shown in fig. 8 the detector pulse height was within the range of 2.1–20 MeV.

IV. DISCUSSION

Diamond detector is promising for high energy neutron spectrometry applications due to its high radiation hardness, wide bandwidth, high mobility and low lifetime of charge carriers. Important advantages of using diamond detector in experiments of high energy proton beam interaction with targets are its small dimensions, radiation hardness, low neutron sensitivity, ability to measure neutron spectrum. Small detector dimensions and low neutron sensitivity allow to locate an array of detectors immediately inside target and to analyze neutron fields inside the target.

Estimations show [11] that at angle 0° proton beam is significantly attenuated in the lead target. When proton beam interacts with lead target neutrons are born, which due to low cross section reach diamond detector. Because the proton flux is rather low with respect to neutron flux, the detector PHS is contributed basically by neutrons.

Measured diamond detector pulse height spectrum was applied to estimate energy spectrum of neutrons which were born by interactions of protons with sub-critical natural uranium assembly. The minimum absorbed neutron energy in the diamond detector E_{min} corresponds to an elastic process. This allows to calculate the minimum energy of the neutrons in the emission spectrum [9,10]:

$$E_1 = E_{min} \cdot (M_1 + M_2)^2 / (4 M_1 M_2) \qquad (1)$$

where M_1, M_2 are masses of the neutron and carbon nucleus, respectively. As mentioned above, the detection threshold is E_{min}=2.1 MeV, therefore, the minimum energy in the neutron spectrum is 7.4 MeV. The maximum absorbed energy corresponds to the

$^{12}C(n, \alpha_0)^9Be$ reaction. This allows to calculate the maximum energy of neutrons spectrum:

$$E_2 = E_{min} - Q, \quad (2)$$

where Q = -5,7 MeV energy of the reaction $^{12}C(n, \alpha_0)^9Be$. Thus, the range of the analyzed spectrum neutrons is 7.4-25.7 MeV.

If we suppose that neutron flux is isotropic and take into account diamond detector location, then total neutron yield can be estimated as 0.9×10^5 n/(cm^2sec) $\times 4\pi \times 2.56$ $m^2 = 7.4\times10^{10}$ n/sec. Incident proton flux was 2×10^{10} sec^{-1}. So an average neutron yield per proton per GeV was 5.6 n/(p·GeV). This value is of one order of magnitude of neutron production yield obtained in [11] (~22 n/(p·GeV). But diamond detector was registering only neutrons with energies higher than 7.4 MeV although less energetic neutrons have significant fraction.

One can notice from fig. 3, 4, 5 and 8 that PHSs for lead and ^{238}U targets are significantly different. This is caused by differences of neutron cross sections of lead and uranium-238 [12]. Lead doesn't undergo fission reaction by neutrons with energies less than 14.5 MeV and has small fission cross section when the neutron energy is in the range of hundreds of MeV. But ^{238}U undergo fission reaction with 20% probability for fast neutrons and 50% probability under irradiation by up to 1 GeV particles.

CONCLUSION

The ability of the measurement system with diamond detector to operate under irradiation origin from interaction of 660 MeV protons with lead target and natural uranium assembly has been demonstrated. In the case of lead target, the contribution to the pulse height spectrum of a diamond detector is contributed by protons and neutrons. The detector pulse height spectrum is within the range of 2-80 MeV. The maximum pulse height was reached in the direction of α=0°, and besides PHS was contributed basically by neutrons. The proton flux in this direction was low because of their absorption in the lead target. By increasing the angle between 0 and 90 diamond detector pulse height decreases. Average count rates at angles 0^o, 24^o, 60^o, 90^o were 2365, 507, 77, 13 Hz respectively.

In the case of a subcritical natural uranium assembly, the pulse height spectrum was contributed by neutrons. The detector pulse height was within the range of 2-80 MeV. It was estimated that the analyzed spectrum of neutrons of the diamond detector was in the range 7.4-25.7 MeV. The dependence of the detector pulse height spectrum was measured as a function of the angle between the direction of the proton beam and the straight line passing through the detector and the center of the installation "Quinta", and it was shown anisotropy of the neutron flux as a function of angle.

The contribution to the overall secondary activation signal was estimated: in the range of registered energies an activation background insignificant in comparison with the neutron flux.

Important advantages of using diamond detector in experiments of high energy proton beam interaction with targets are its small dimensions, radiation hardness, low neutron sensitivity, ability to measure neutron spectrum. Small detector dimensions and low neutron sensitivity allow to locate an array of detectors immediately inside target and to analyze neutron fields inside the target.

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