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Nuclei recoil method for measurement of fast neutron spectra on the NG-150 neutron generator INP AS RUz

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Abstract. The developed version of measuring neutron energy spectra by the deuterium recoil method with registration by a telescope of semiconductor Si-detectors is described. Model calculations have been carried out to optimize the parameters of the corresponding experimental setup. The feasibility of the proposed method using the recoil deuteron technique was demonstrated.

Key words: neutron generator, subcritical nuclear systems, nuclear recoil method, neutron cross sections, tagged neutrons, energy spectra of secondary neutrons, $\Delta E - E$ registration, semiconductor Si detector.

I. INTRODUCTION

At present, much attention is paid to the development of subcritical systems that allow increasing the neutron flux from external neutron sources depending on the composition of the system and the neutron energy [1, 2]. The main issues considered in studying neutron field enhancement using a subcritical assembly are the choice of an "external" source and the determination of the optimal composition and arrangement of subcritical systems. However, the possibilities of using systems based on natural fissile materials (such as uranium and especially thorium) have not yet been sufficiently studied. In particular, the possibility of using relatively low-energy neutron fluxes (∼2–14 MeV) for these purposes is important. Such fluxes can be obtained using (D+D) and (D+T) neutron generators [3–5].

Considerable attention is currently being paid to the development of systems using fissile materials in a subcritical state, controlled by an external high-power neutron source (ADS – Accelerator Driven Systems) [6–8].An assembly consisting of a well-optimized subcritical system and an "external" source realized by an accelerator can provide a neutron flux comparable to that of typical research reactors and, in the future, could serve as the basis for safe nuclear power. The indisputable advantages of ADS systems include not only the ability to multiply neutrons from an "external" source, but also their use for the implementation of nuclear fuel reserves, in particular, taking into account the large world reserves of thorium based in particular on the large global reserves of thorium. If a mixture of natural or slightly enriched uranium with the isotope ^{235}U is used as the initial fuel, two main processes occur when the reactor is irradiated with neutrons obtained using an accelerator. Firstly, when a neutron is captured by a ^{232}Th nucleus, a chain of β-decays occurs, leading to the formation of a ^{233}U nucleus:

$$^{232}_{90}\mathrm{Th} + n \rightarrow \gamma + ^{233}_{90}\mathrm{Th} \xrightarrow{\beta} ^{233}_{91}\mathrm{Pa} \xrightarrow{\beta} ^{233}_{92}\mathrm{U}$$

And on the main uranium isotope, ^{238}U, the following process occurs:

$$^{238}_{92}\mathrm{U} + n \rightarrow \gamma + ^{239}_{92}\mathrm{U} \xrightarrow{\beta} ^{239}_{93}\mathrm{Np} \xrightarrow{\beta} ^{239}_{94}\mathrm{Pu}$$

Both produced isotopes, ^{233}U and ^{239}Pu, can undergo fission under the action of slow neutrons, similarly to the ^{235}U isotope, i.e., they are fuel - a source of energy. Each fission reaction leads to the loss of one ^{233}U or ^{239}Pu nucleus, while each of the

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aforementioned reactions leads to the creation of such a nucleus. If the probabilities of fission and the formation of fissile nuclei are equal, then the amount of isotopes $^{233}\mathrm{U}$ or $^{239}\mathrm{Pu}$ reaches a certain equilibrium value during reactor operation, meaning the fuel is reproduced automatically. This technology ensures nuclear safety and prevents the unauthorized proliferation of nuclear materials.

It is important to know the neutron interaction cross-sections with these nuclei. Also of interest is the study of the neutron interaction cross-sections with fuel consisting of mixtures of these isotopes. A crucial aspect of experimental research in this area is monitoring the intensities and energy spectra of fast neutrons. There are also many other purely scientific and technological tasks where fairly simple and convenient methods for such measurements are needed. A special feature of neutron registration is the absence of an electric charge, and in the detector its kinetic energy must be transferred to a charged particle. Measurement methods vary depending on the neutron energy, intensity-to-background ratio, type of accompanying radiation, etc. – for example, the need for gamma-ray rejection [9] or the requirement for high sensitivity and selectivity in the presence of background [10] and other experimental features. The time-of-flight (TOF) method [11, 12], often employing pulsed neutron sources [13, 14] or tagged neutron method [15, 16], is the most common approach for measuring neutron energy. However, these methods are technically demanding. The research carried out in this work developed the methodological basis for such studies, in particular, the development of a method for measuring the energy spectra and yields of fast secondary neutrons produced by the interaction of a 14 MeV neutron flux produced by the neutron generator NG-150 of the INP AS RUz with samples of natural uranium and thorium mixtures.

II. NUCLEAR RECOIL TECHNIQUE AND PRINCIPLE

We have analyzed the possibility of using $\Delta E - E$ telescopes with semiconductor detectors for recoil nuclei detection and neutron energy measurement(see for example [17]).

This method offers several advantages, including high energy resolution, low sensitivity to gamma-ray background, and compactness. However, it also has disadvantages, such as relatively low efficiency, a limited energy measurement range, and the presence of background reactions in the detector material and structural components.

A schematic diagram of the experimental setup for neutron energy measurement via the nuclear recoil method is shown in Figure 1. The telescope consists of one or two thin fully depleted silicon (Si) semiconductor detectors (ΔE-detectors) and a total energy loss detector (E-detector). A hydrogen-containing thin film (e.g., polyethylene or deuterated polyethylene) is placed in front of the first detector. The entire system is surrounded by a layer of carbon (graphite) to prevent the single-charged (long-range) particles, produced by neutron interactions with external structural elements, from entering the telescope. The system is placed in a vacuum chamber to eliminate energy loss of recoil nuclei in air. A charged particle can be registered by the telescope only if it produces signals in all detectors simultaneously. Therefore, the housing (or holder) of the first ΔE detector is also carefully shielded with ring-shaped graphite diaphragms to prevent charged particles generated within it by neutron interactions from passing through all the ΔE and E detectors. Graphite is used because the threshold energies for (n, p) and (n, d) reactions on carbon are relatively high (see below). At the same time, alpha particles from the (p, α) reaction on $^{12}\mathrm{C}$ have short ranges and are not registered in a three-detector telescope.

Thus, the sum of energy losses of the particle in all detectors allows us to determine the energy of the recoil particle, i.e., the neutron energy, while analysis of the two-dimensional $\Delta E_1 - E$ (or $\Delta E_2 - E$) matrix allows us to identify the type of registered particle.

If the energy of the incident monoenergetic neutrons is 14 MeV, the energies of the recoil nuclei emitted at an angle of $\sim 0^\circ$ will be: $E_p \approx E_n$= 14 MeV and $E_d \approx 0.89 \times E_n = 12.46\,\mathrm{MeV}$ for protons and deuterons, respectively. Let us consider all possible background reactions that hinder the identification and measurement of recoil nuclei, including nuclei of hydrogen isotopes (protons and deuterons):

$^{12}\mathrm{C}(n,p)^{12}\mathrm{B}$; $E_p = 0.7$ MeV ($Q = -12.6$ MeV)

$^{12}\mathrm{C}(n,d)^{11}\mathrm{B}$ ($Q = -13.7\,\mathrm{MeV}$). E_n is below the threshold energy.

$^{12}\mathrm{C}(n,\alpha)^{12}\mathrm{B}$; $E_\alpha = 7.9$ MeV ($Q = -5.7$ MeV)

$^{28}\mathrm{Si}(n,\alpha)^{25}\mathrm{Mg}$; $E_\alpha = 13.5$ MeV ($Q = -2.7$ MeV)

$^{28}\mathrm{Si}(n,p)^{28}\mathrm{Al}$; $E_p = 10.1$ MeV ($Q = -3.85$ MeV)

$^{28}\mathrm{Si}(n,d)^{27}\mathrm{Al}$; $E_d = 4.6$ MeV ($Q = -9.35$ MeV)

To determine the energy range where there is no overlap with background particles, which are products of reactions on the nuclei in the organic film converter (carbon nuclei) and the nuclei in the material of the Si detectors themselves, we performed simulation of the energy spectra of recoil protons and deuterons. It was found that the optimal telescope consists of two ΔE detectors with thicknesses of 25 and $100\,\mu\mathrm{m}$, and an E detector with a thickness of $700\,\mu\mathrm{m}$. The deuteron is the most suitable recoil nucleus, since the elastic scattering cross section of a neutron on deuterium is almost twice as large as on "ordinary" hydrogen, and deuterium is not contained in surrounding materials where background recoil nuclei can arise. So, a deuterated polyethylene film with a thickness of 20 to $30\,\mu\mathrm{m}$ should be used as the converter film. In this case, the neutron energy spectrum

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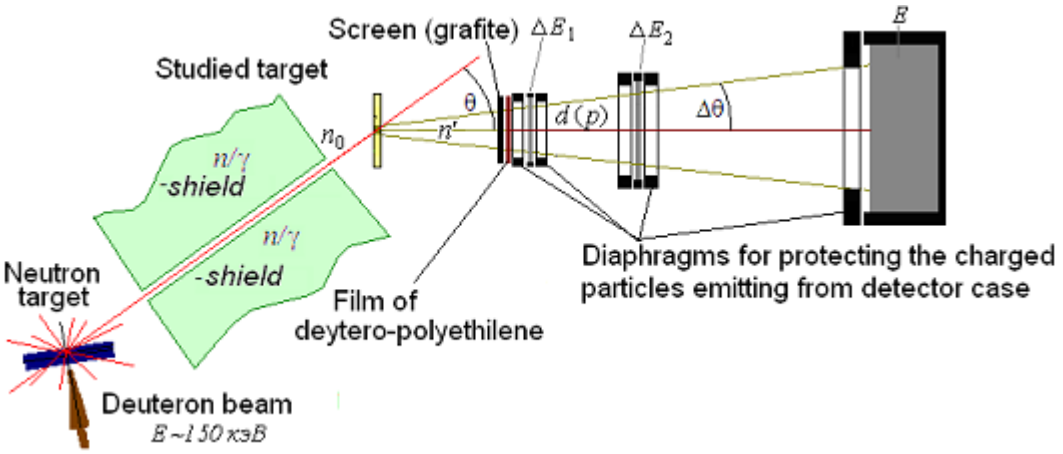


FIG. 1: Fast neutron energy measurement system using a telescope composed of semiconductor Si detectors.

can be measured in the range of 6-14 MeV without interference from background reactions. To measure the spectrum in the remaining accessible range, separate background measurements with subsequent subtraction are necessary.

The telescope aperture (angle θ), which is determined by the dimensions of the detector apertures and the distance between them, should not exceed 7° to achieve an energy resolution of $\sim$ 2–3% for recoil deuterons.

Currently, a block diagram of the spectrometer for a three-detector telescope has been developed and configured (see Figure 2). The setup includes four spectrometric chains. Each chain consists of a charge-sensitive preamplifier (PA, located in the NG-150 hall) and a linear amplifier (located in the measurement room) processing signals from two ΔE and E detectors. An all-wave ^{3}He counter of the NG-150 facility monitors the total neutron flux. The system is triggered by a triple coincident signal from the $\Delta E1$, $\Delta E2$, and E detectors, which produces two spectrometric signals from the $\Delta E2$ and E detectors by opening the linear trigger (LG). The $\Delta E2$ and E signals, delayed for time synchronization, are then fed to a custom-designed two-dimensional amplitude analyzer [18] and transferred to a PC via a USB port. The feasibility of measuring the neutron energy spectrum using this method was demonstrated employing a part of the block diagram, a part of the block diagram that enables operation of the two-detector telescope.

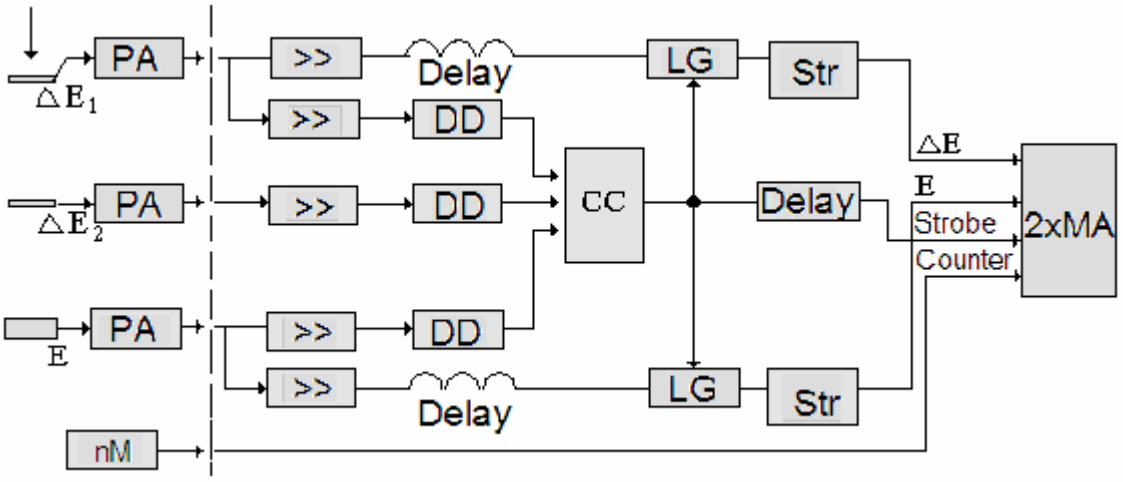


FIG. 2: Electronic block diagram for the 3-detector telescope system.

A specially developed program, `WIN_EDE` [19], designed for neutron generator experiments, generates a two-dimensional $\Delta E \times E$ or $\Delta E \times (E + \Delta E)$ event matrix on the PC display. Using the standard $\Delta E - E$ method (see, e.g., [20]), the program separates loci corresponding to different types of detected particles. The energy distribution of recoil deuterons is then constructed by projecting the deuteron locus onto the $E + \Delta E2$ axis, and a corresponding neutron energy spectrum is obtained via a kinematic transformation. If the energy loss of a deuteron in the $\Delta E1$ detector (typically thin) is significant, the summation of $\Delta E1$ and $\Delta E2$ signals is added to the block diagram. Figure 3 shows a screenshot of the two-dimensional $\Delta E - E$ spectrum

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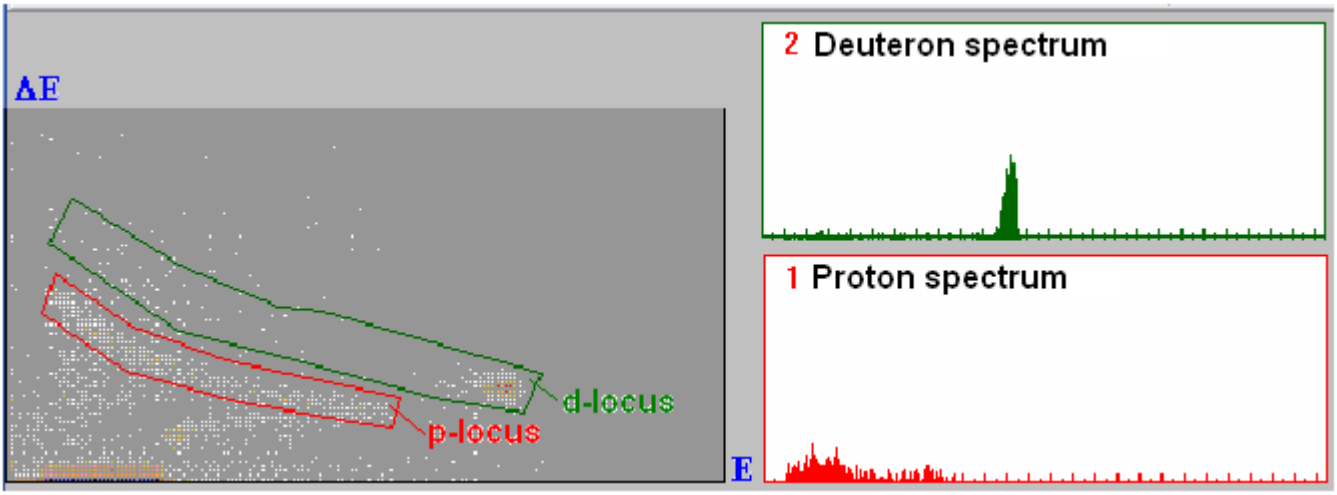


FIG. 3: Screenshot of the PC-EDE program showing the two-dimensional $\Delta E - E$ spectrum (left) and the energy spectra of recoil protons and deuterons (in arbitrary units).

of charged particles registered by the two-detector telescope ($W_{\Delta E}$ = 50 μm, W_E = 700 μm) – left panel. The corresponding energy spectra are shown on the right. A 20 μm thick deuterated polyethylene foil was used during irradiation with a neutron flux of $E_n = 14.1$ MeV . The recoil deuteron peak is clearly resolved.

III. SUMMARY AND CONCLUSION

In conclusion, the recoil deuteron method can be used to measure the spectra of secondary fast neutrons when studying the yields and angular distributions using D+T neutron fluxes from a neutron generator. The practical application of this method can be enhanced by upgrading the electronics to a faster system, incorporating fast discriminators with tracking thresholds and coincidence circuits with a resolution time no worse than ~ 10 ns.

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