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Passage of Fast Neutrons Through the Crystal Structure of Textured CVD Diamond

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Abstract—The passage of fast neutrons through the crystal structure of a textured diamond obtained by chemical vapor deposition (CVD diamond) is studied. Neutrons with an energy of 2.45 MeV from the DD reaction and with an average energy of about 2 MeV from the ^{252}Cf isotope are used as neutron sources. The neutrons are detected by two independent methods: using proportional counters filled with ^{3}He and a paraterphenyl-based scintillation detector. The measurements show that the neutron-flux incident on the detector depends on the orientation of the target. In the case of isotropic samples containing diamond and carbon, such effects are not observed. A possible explanation for the effect is the channeling of deuterium ions and neutrons in channels of textured CVD diamond.

Keywords: DD-reaction yield, interaction of neutrons with matter, ion accelerator, neutron detector, CVD diamond

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INTRODUCTION

Earlier [1], the neutron yield in the reaction

$$\mathrm{D} + \mathrm{D} \rightarrow n(2.45\ \mathrm{MeV}) + {}^3\mathrm{He}(0.8\ \mathrm{MeV}), \qquad (1)$$

was investigated by using a textured target of diamond obtained by chemical vapor deposition (CVD diamond) [2] and a D^+-ion beam with an energy of about 20 keV from the HELIS accelerator [3], which provides a beam with a small angular divergence and small energy spread. In [1] the dependence of the neutron yield (the products of DD reactions) on the orientation of the target with respect to the deuterium-ion beam was discovered. The authors suggested that the observed increase in the neutron yield is associated with both shielding and channeling effects.

The orientation effect of an increase in the amplification coefficient of the DD reaction in a synthetic diamond was investigated by the computer simulation method [4]. It was found that as a result of the flux-peaking effect associated with channeling, the relative amplification coefficient increases by 2.2 times in the case of a parallel beam and by up to 1.2 times in the case of a D^+-ion beam with an angular divergence equal to three critical angles for channeling. Qualitative agreement with the experimental results of [1] was obtained. It was shown that the value of the neutron flux depends not only on the target orientation in the beam, but also on the direction in which the neutrons leave the target. The neutron flux along the ion-beam direction significantly exceeds the flux across the beam. One of the possible explanations of this effect is the channeling and focusing of neutrons in the structure of textured synthetic diamond. In our study, measurements are performed with the use of a ^{252}Cf neutron source and a target of textured synthetic diamond similar to that used in [1].

EXPERIMENTAL

The schemes of arrangement of the ^{252}Cf neutron source, detector, and target are shown in Fig. 1. Neutrons were recorded by using a detector based on counters filled with ^{3}He and a scintillation detector with an organic crystal. The ^{252}Cf neutron source (with an activity of 10^4 s^{-1}) was arranged at the center of a polyethylene container with dimensions of $10 \times 10 \times 10$ cm, which was surrounded by a cadmium layer with a thickness of 0.5 mm. At the face part of the container, there was a channel with a diameter of 4 mm and a length of 5 cm. The detector based on ^{3}He counters was arranged at a distance of 1 m from the ^{252}Cf neutron source (Fig. 1b). It consisted of six gas-discharge

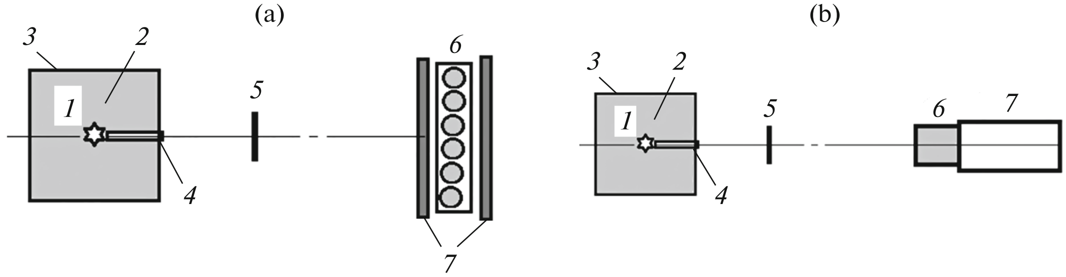

Fig. 1. Arrangement of the ^{252}Cf neutron source, detector, and target in the schemes of measurement by means of (a) a detector based on ^{3}He counters: *1*—^{252}Cf neutron source, *2*—polyethylene container, *3*—cadmium, *4*—channel of the neutron collimator, *5*—diamond target, *6*—detector, *7*—organic glass; (b) the scintillation detector: *1*—^{252}Cf neutron source, *2*—polyethylene container, *3*—cadmium, *4*—channel of the neutron collimator, *5*—diamond target, *6*—scintillator (paraterphenyl), *7*—photomultiplier tube.

counters SNM-18 and was equipped with a neutron moderator made of organic glass (3 cm before the detector and 3 cm behind it). The scintillation detector consisting of a paraterphenyl crystal (diameter is 2.5 cm; height is 2.5 cm), a photomultiplier tube (Hamamatsu R6094), and an analog-to-digital converter CAENDT5730 allowed the separation of signals from neutrons and gamma-ray quanta according to the pulse shape [5]. The scintillation detector was located at a distance of 13 cm from the target (Fig. 1b). The target was arranged on a rotary device at a distance of 10 cm from the ^{252}Cf neutron source.

The technique of preparation of the target from synthetic diamond is described in detail in [2]. Its thickness was 400 μm. The diamond structure is inhomogeneous and anisotropic, which is seen from the image obtained using a JEOL scanning electron microscope (Fig. 2). Crystals grow in the shape of columns oriented perpendicular to the surface; with growing thickness of the film, the "diameter" of the columns increases. The dimensions of crystallites grow from ~1 μm in a highly imperfect layer to tens and even hundreds of micrometers on the side opposite to the growth side. The diamond crystals have the [100] texture. After irradiation of the target with a deuterium-ion beam, the partial destruction of crystallites and graphitization of the surface on the growth side occur (Fig. 3) at the ion-path depth (about 1 μm).

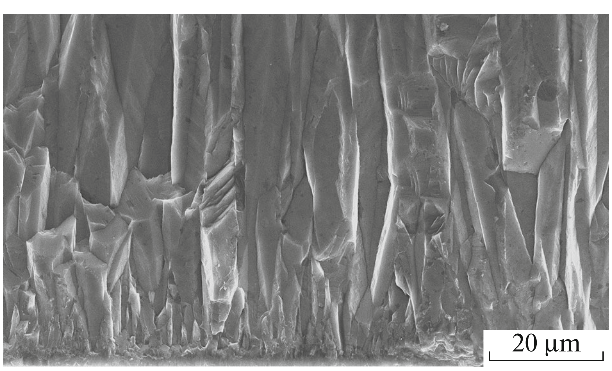

Fig. 2. Image of a polycrystalline diamond film in the transverse section obtained by using a scanning electron microscope.

EXPERIMENTAL RESULTS AND DISCUSSION

Figure 4a shows the dependence of the count of the neutron detector based on ^{3}He counters on the angle β of diamond-target rotation. It is seen that if the growth side of the target is oriented towards the neutron source, then at $\beta = 0°$, the neutron flux recorded by the detector is maximum, while at $\beta = 20°$, it is reduced by nearly 22%. If the target is arranged so that its substrate is oriented towards the neutron source, then the maximum count of the detector is observed at $\beta = 10°$. In this case, at $\beta = 20°$, the neutron-flux incident on the detector is also observed to be reduced by 22%. The dependence of the count of the paraterphenyl scintillation neutron detector on the angle β of diamond-target rotation is shown in Fig. 4b. To separate completely the signals from neutrons and gamma-ray quanta in the scintillation detector, it is necessary to establish the energy threshold. Detector calibration is performed by using gamma-ray sources; therefore, the energy unit used in such detectors is keV in the electron equivalent. In the experiment, the threshold was 150 keV in the electron equivalent. It is seen from Fig. 4b that if the target is arranged in such a way that its growth side is oriented towards the neutron source, then at $\beta = 0°$ the neutron flux recorded by the detector is maximum; while at $\beta = 30°$ it decreases by nearly 24%. At a measurement error of 4%, this provides a statistically significant result; i.e., rotation of the diamond target causes an impact to the neutron flux penetrating through it.

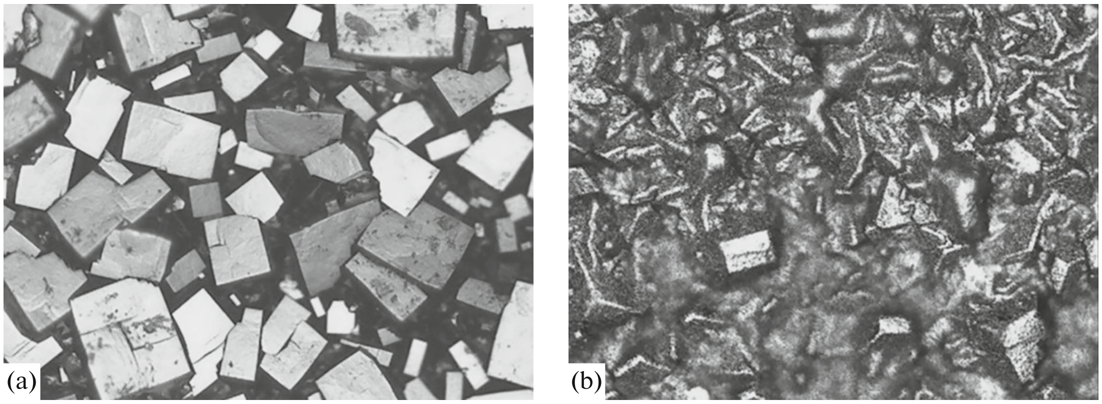

Fig. 3. Optical microphotographs of the surface of the polycrystalline diamond film before (a) and after (b) irradiation of the target by a deuterium-ion beam. The image dimensions are 500 × 370 μm.

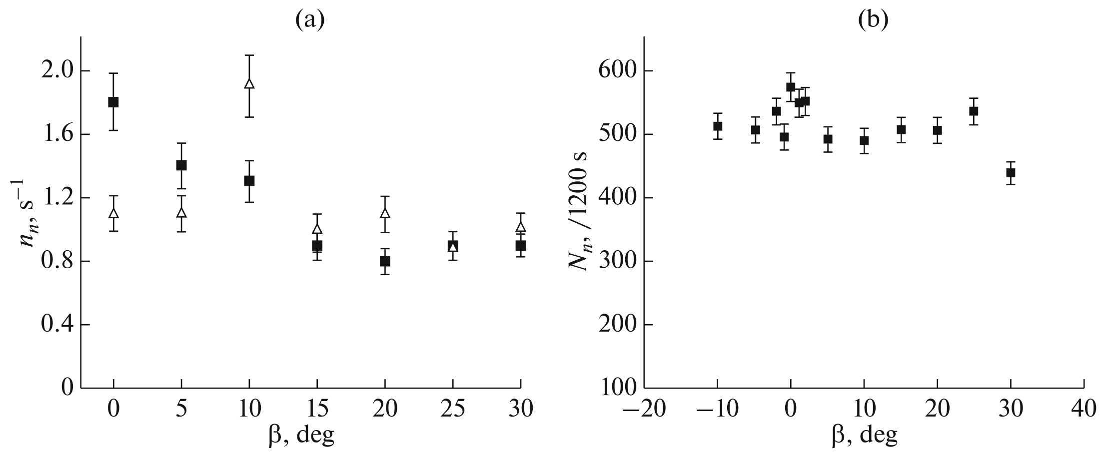

Fig. 4. Dependence of the count of the neutron detector on the angle β of rotation of the diamond target for two cases: (a) the neutron detector is based on ^{3}He counters (the target is oriented towards the neutron source by its growth side (■) and by its substrate side (Δ)); (b) the scintillation detector (time of irradiation is 1200 s; the growth side of the target is oriented towards the neutron source; the threshold of recording of recoil protons is 150 keV in the electron equivalent).

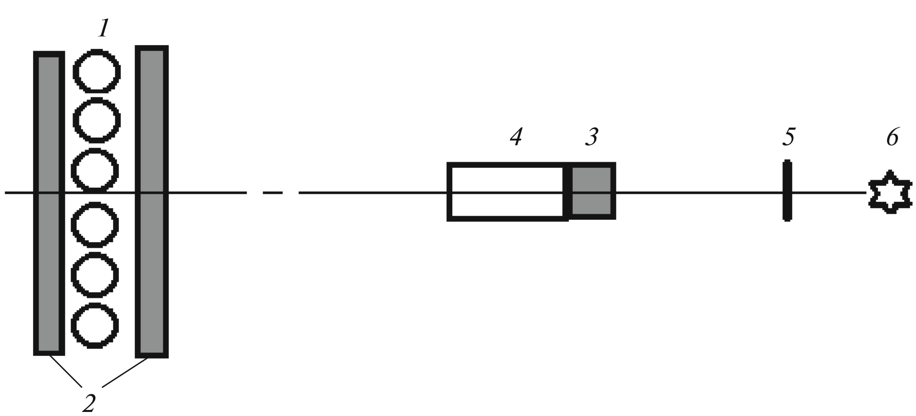

Fig. 5. Scheme of arrangement of the ^{252}Cf neutron source, detectors, and the target in the second series of measurements: *1*—detector based on ^{3}He counters; *2*—organic glass; *3*—scintillator (paraterphenyl); *4*—photomultiplier tube; *5*—diamond target; *6*—^{252}Cf neutron source.

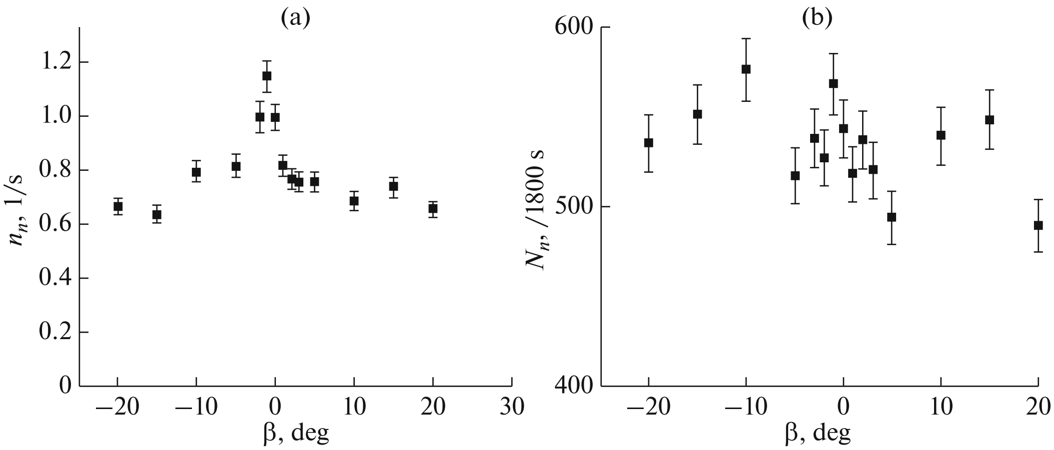

Fig. 6. Dependence of the count of the neutron detector on the angle of rotation of the diamond target in two cases: (a) the detector based on ^{3}He counters (the target is oriented towards the neutron source by its growth side); (b) the scintillation detector operating for a time of 1800 s (the target is oriented towards the neutron source by its growth side; the threshold of recording recoil protons is 150 keV in the electron equivalent).

The influence of target rotation on the counts of the scintillation detector of neutrons is less pronounced than that in the case of the detector based on helium counters. This can possibly be explained by the fact that the scintillation detector is sensitive only to fast neutrons (the threshold of recording of recoil protons in it was 150 keV in the electron equivalent), whereas the detector based on helium counters is more sensitive to slow neutrons which can be more susceptible to channeling and focusing in a diamond target.

To reduce the influence of neutrons scattered in polyethylene on the results of the experiment, a second series of measurements was carried out for the case where the ^{252}Cf neutron source was placed before the target with no polyethylene container (Fig. 5). As a target, we used textured synthetic diamond, which was not subjected preliminarily to deuterium-ion irradiation. The ^{252}Cf neutron source, target, and detectors were arranged on the same straight line in air. The distance from the source to the target was 10 cm; that from the target to the crystal of the scintillation detector was 20 cm; and that from the source to the ^{3}He detector was 128 cm.

The dependence of the count of the neutron detector based on helium counters on the angle β of target rotation for the second series of measurements is shown in Fig. 6a. It is seen that in the case where the growth side of the target is oriented towards the neutron source, the neutron flux recorded by the detector is maximum at $\beta = 0°$, while at $\beta = 20°$, it is reduced nearly to half. The influence of the target orientation on the count of the scintillation detector of neutrons is less pronounced in the case of the detector based on ^{3}He counters (Fig. 6b). However, in the region of $\beta = 0°$, the maximum of counting, which becomes reduced as the target rotates, is also observed.

CONCLUSIONS

Using two independent methods for neutron detection (the use of a detector based on ^{3}He counters and a scintillation detector), it is established that the orientation of a target made of synthetic diamond in the neutron flux influences the intensity of the neutron flux that passed through it in the direction towards the detector. This effect can possibly be explained by the peculiarities of neutron passage through the textured structure of synthetic diamond (channeling and focusing of neutrons). The technique of the experiment on neutron passage through a diamond target is not ideal, since there is a significant part of neutrons whose directions of incidence on the target are not parallel to each other, which influences detector counting. In further experiments, it is planned to provide a higher level of parallelism of the neutron flux incident on the target and avoid the outcome of scattered neutrons from the polyethylene container.

The indication on channeling of fast neutrons that confirmed in this study allows to explain the anisotropy of neutron yield from the targets, which was observed earlier in [1, 6–10].

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