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THE HIGH-ENERGY NEUTRON SPECTROMETRY IN MIXED UNDIRECTIONAL RADIATION FIELDS BEHIND ACCELERATOR SHIELDING

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Radiation environment on high-energy particle accelerators is as a rule initially unknown and rather complex. This complexity is caused by a wide energy range and a multicomponent character of mixed undirectional radiation fields. The main radiation components participating in the internuclear cascade inside the shielding are neutrons and charged hadrons. The contribution of charged particles leaking from the shielding to doses in mixed fields are insignificant and are usually ignored (except for the fields behind relatively thin beam stoppers in which the charged particle equivalent doses can be equal to or more than the neutron doses). The largest contribution to the equivalent doses is made by neutrons of the widest energy spectrum (from 10^{-8} to several hundreds of MeV). The shapes of the neutron spectra in the fields surrounding accelerators depend on shielding configurations and can be relatively "soft" if the shielding has splits, or "hard" behind the thick continuous shielding. The upper limit of neutron leakage energy spectra isn't formally lower than the accelerated particle energy per nucleon, but the greatest percentage of the spectra is in fact in the energy range up to several hundreds of MeV/1/. An increase in the energy of accelerated particles does not lead to serious changes in the neutron energy distribution shapes for two reasons: a weak dependence of the transverse momentum of secondaries on the beam particle energy and formation of quasi-equilibrium neutron spectra behind a rather thick continuous shielding. The neutrons with the energy above 20 MeV in a "hard" radiation field can considerably contribute to the doses received by persons working outside the shielding (up 50-60% of the total neutron equivalent doses). The measurements of the penetrating high-energy neutron component are also important for the radiation monitoring around accelerators.

For the past ten years efforts were made in Joint Institute for Nuclear Research to obtain more specific information on the differential characteristics of high-energy neutrons in mixed radiation fields around the phasotron and the synchrophasotron of proton energy 0.66 and 10 GeV respectively. The difficulty of this measurements was that common techniques allow one to obtain either hadron spectra without division into component (nuclear emulsions, threshold activation detectors), or neutron spectra under ~20 MeV (with the help of Bonner spectrometers). The hadron spectra are not adequate to determine equivalent doses in mixed fields. The multisphere Bonner spectrometer is usually used with a carbon activation detector to increase the upper limit of neutron spectra, but it does not give correct information about the shapes of the neutron spectra in the energy region above ~ 20 MeV (i.e., in general, a rate setting takes place). The errors of these spectra in the high-energy region are too big, as a rule. Besides the above-mentioned techniques have an insufficient sensibility and in many cases can't be used in fields with low level of radiation. Nevertheless the Bonner spectrometer in combination with the activation detector has been a methodical basis for neutron energy distribution measurements on accelerators for a long time and has allowed one to establish the fact that in "hard" radiation fields behind thick continuous shielding neutron spectra (in terms of $\Phi(E)xE$) have maxima in the energy range 50--150 MeV.

For adequate measurements of the neutron energy distributions in the range from ~ 20 to ~ 500 MeV in the mixed undirectional radiation fields a new technique was elaborated and a device of a very high sensitivity was designed/2,3/. The principle of operation of the device is based on dependence of the readings of the neutron counter with the plastic scintillator on the differential energy neutron flux at various thresholds of signal registration. The device, consisting of a neutron counter surrounded by a veto scintillator for charged particle rejection, is designed for measurement of fluences, maximum equivalent doses and spectra (FDS) of neutrons with energy above 20 MeV in various locations outside the shielding. The calculations of the plastic scintillator neutron-detection efficiency was performed using the Monte-Carlo code/4/. The influence of the veto counter on the neutron counter efficiency was taken into account in the calculations and led to a considerable decrease in the efficiency in the neutron energy region above approximately 100 MeV. Special rejection of counts from γ-rays was not envisaged, because the energies of γ-rays due to excitation of nuclei did not exceed ~10 MeV. On the other hand, the amount of γ-rays due to the π^0 decays is small outside a thick lateral shielding, because the main spectrum energy of neutrons inside the shielding is usually lower than the π-meson production limit. The neutron fluences and maximum equivalent doses in the FDS technique are determined by a linear combination of the device readings at specially chosen thresholds of signal registration. The unfolding of a neutron spectrum is performed by the statistical regularization method on the basis of the apparatus spectrum of signals/5/. A principle possibility of unfolding neutron spectra was established earlier by unfolding various test spectra/3/. The problem of unfolding in this case is similar to the unfolding of Bonner spectrometer spectra, but instead of counting efficiencies for moderating spheres, one uses scintillator efficiencies at different thresholds. In general, the relation between the FDS-readings N_j at the thresholds j and the neutron spectrum $\Phi(E)$ is of the form:

$$N_j = \int \Phi(E)\varepsilon_j(E)dE.$$

Here $\varepsilon_j(E)$ is the energy dependence of the neutron counter efficiency at different thresholds of signal detection expressed in MeVeee (equivalent electron energy). N_j is the result of integration of the apparatus spectrum over the corresponding channel threshold j in MeVeee. The calibration of the thresholds was carried out by means of cosmic background μ-mesons. A system of 13 algebraic equations for various thresholds over 15 MeVeee was used in computer program for unfolding neutron spectra.

The FDS technique was applied for investigations of the real radiation environment on the JINR accelerators.Figure 1 exemplifies some high-energy neutron spectra in different radiation fields. The geometries of the measurements are given in Fig.2. The spectrum errors correspond to the standard deviations from the most probable values of the spectrum. Spectra 1 and 2 in Fig.1 were formed behind a 2-meter concrete shielding with an iron stopper bombarded mainly by secondaries from the target on the 0.66 GeV proton beam (Fig.2a). Spectrum 1 is essentially more "soft" than spectrum 2 due to accumulation of low-energy neutrons in the shadow region behind the stopper from the whole shielding surface (the device placed at a distance from the shielding). A very "hard" field was obtained outside a relatively thin local stopper for a beam of ^{12}C with energy 3.65 GeV/nucleon (spectra 3 and 4). Spectrum 3 (Fig.2b) was measured at point 3 behind a 2-meter concrete wall along the beam axis/6/. The comparison of the FDS-measured fluence of neutrons with energy above ~20 MeV with the carbon activation detector data at this point allowed the conclusion that the contribution of charged particles in the total high-energy hadron fluence was about 25%. In other cases of more "soft"

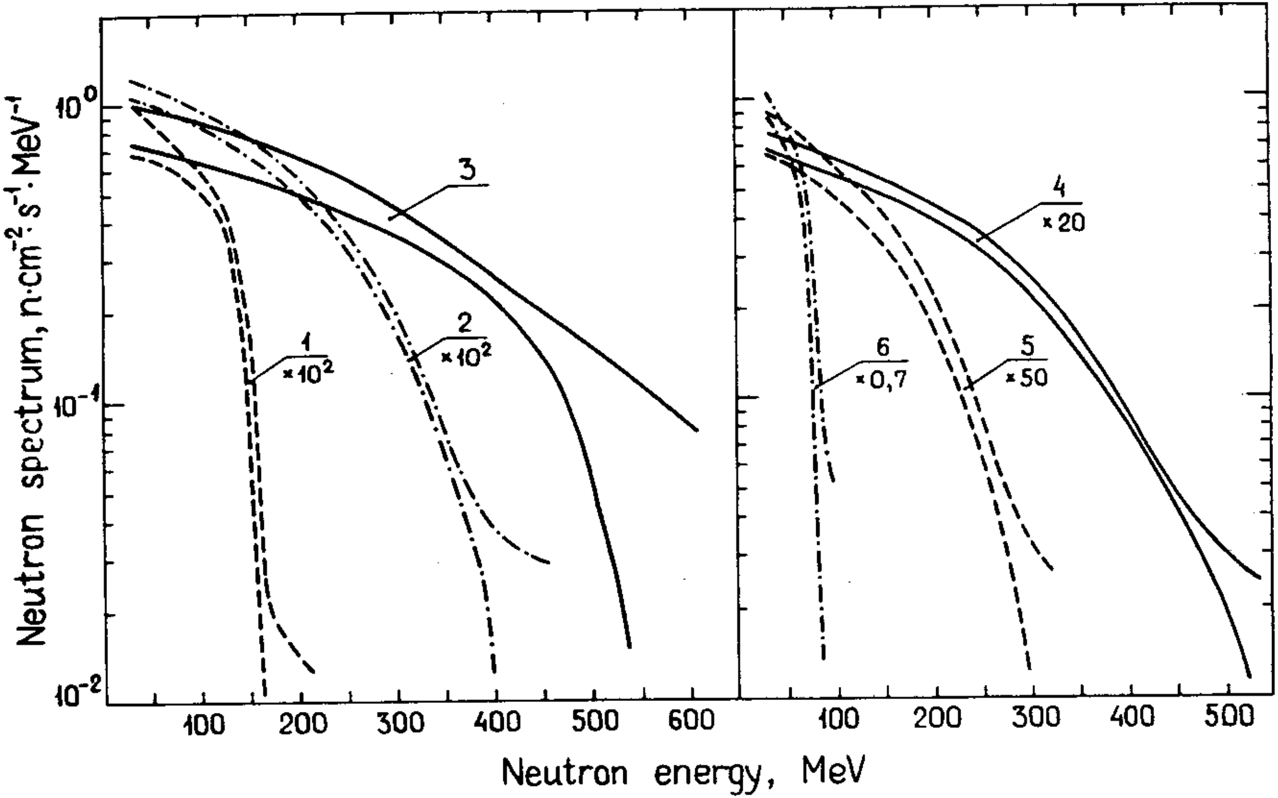

Fig.1. The neutron spectra outside the phasotron and synchrophasotron shielding. The figures in circles correspond to the numbers of measurement points which are shown in Fig.2.

fields the FDS and carbon activation techniques yield approximately equal data. It is necessary to note that the high-energy region of spectrum 3 is not so exact, because the program for the calculation of the neutron-detection efficiency/4/ does not take into account the events accompanied by π-meson production. Spectrum 5 (Fig.2c) was measured behind a 3-meter concrete side wall of the proton transport channel opposite to the target station. The proton energy was 7.1 GeV. Spectrum 6 (Fig.2d) was obtained in the tunnel under the experimental hall when a thick target was irradiated by a 3.65 GeV/nucleon α-particle beam. The concrete floor had narrow splits and this radiation field contained a lot of scattered low-energy neutrons.

Finally, Fig.1 shows wide possibilities of the FDS technique in different situations. Nevertheless all the spectra, except spectrum 6, show a generality. They have clear maxima in terms of Φ(E)xE in the energy range between 50 and 250 MeV, as it was established for the spectra measured by the Bonner spectrometer together with the carbon activation detector, but their high-energy tails fall more rapidly than in the Bonner spectra. For more "hard" spectra the maxima are shifted to higher energies. This discrepancy is perhaps caused by the inadequate interpretation of the carbon activation detector data when unfolding the Bonner spectrometer neutron spectra in "hard" fields with a considerable amount of charged particles/7/.

Since the average efficiency of the high-energy neutron registration with the given neutron counter is about several per cent and there is no own background, the FDS technique has a very high sensitivity.We used this technique for measuring the neutron background produced by cosmic rays near the earth surface in Dubna at geomagnetic latitude 57° (the height above the sea level is ~130 meters). These measurements were carried out twice in summer 1984 and autumn 1988 (when the JINR accelerators and reactors were stopped) and yielded similar results. Figure 3 shows the neutron spectrum taken within $5\cdot 10^3$ s at the air pressure 739 mm Hg in September 1988. The fluence of the high-energy neutrons was equal to $(5.5\pm 1)\cdot 10^{-3}$ neutron$\cdot$sm$^{-2}\cdot$s^{-1}.This spectrum in terms of Φ(E)xE has a weak maximum at about 50 MeV (for comparison there is a spectrum of the 1/E type), while typical neutron background spectra in the high-energy range have no such peculiarities. The most of the known neutron background spectra were measured by Bonner spectrometers with sets of moderators, the largest moderator being 12'' in diameter. Since the fluence

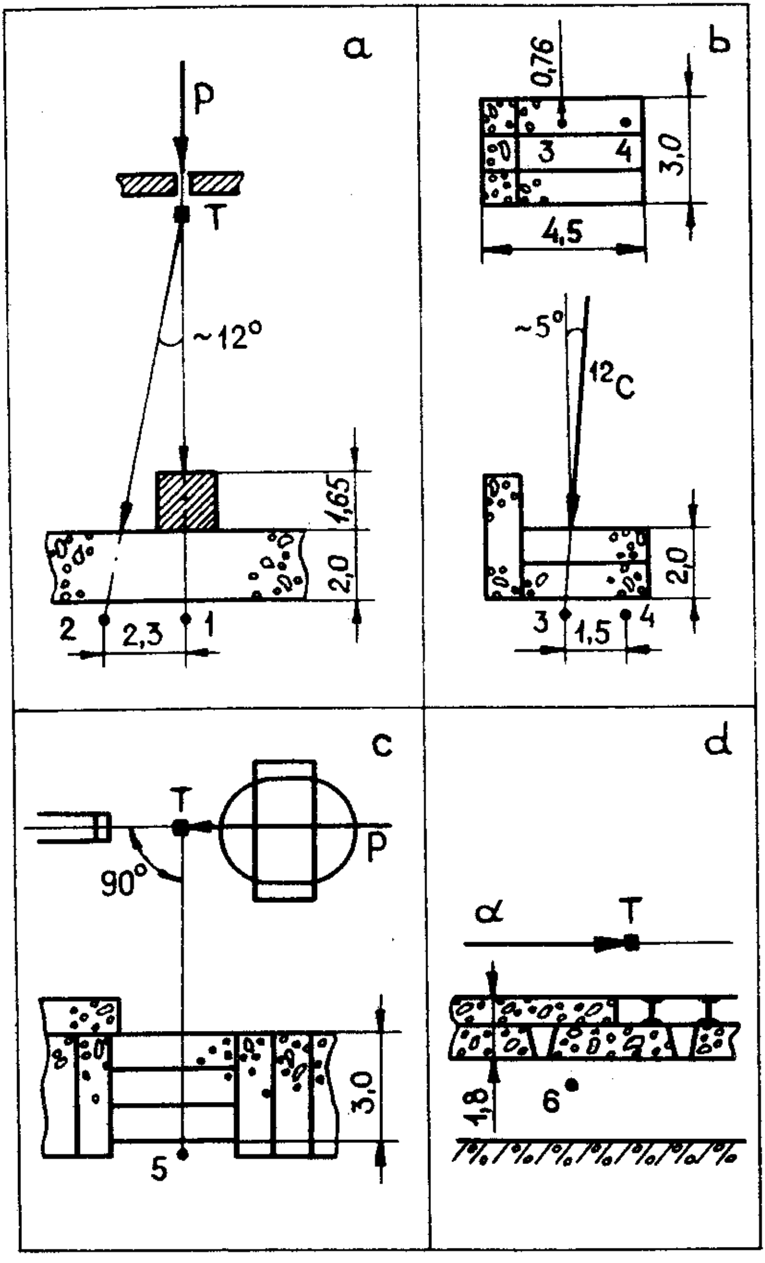

Fig.2. The location of measurement points (solid circles) and shielding configurations. All dimensions are given in meters. In Fig.2b the frontal surface of shielding is also shown.

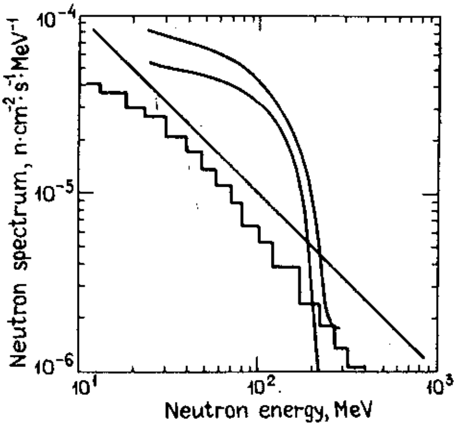

Fig. 3. The high-energy background neutron spectra due to cosmic rays. The solid curves are the present measurement; the straight line is the 1/E spectrum; the histogram is spectrum/9/.

of such neutrons is very small, an activation detector could not be used, therefore the information for unfolding the high-energy tails was missing. In recent time one sometimes uses 18'' moderators to increase the sensitivity of the multisphere technique in the high-energy range. This measurements/8,9/ displayed the behaviour in high-energy parts of the spectra similar to ours. Figure 3 also shows the spectrum/9/ obtained at the sea level at 24° latitude. The quantitative difference between two spectra is in agreement with the geographic conditions. However, the authors/8,9/ could not explain the spectrum shapes and did not take into account the 18'' moderator readings. It should be pointed out that we also consider our result as preliminary ones. Nevertheless, one can expect that this shape of the high-energy spectrum is true, because the physical laws of shaping the neutron spectra outside accelerator shielding and the neutron background spectra due to cosmic rays are, in general, quite similar.

The development of the scintillation FDS technique will promote the qualitative and quantitative understanding of accelerator radiation problems and increase the accuracy of the routine dosimetry control. We think that combining the FDS technique and the Bonner spectrometer will perhaps allow correctly unfolding neutron spectra in the whole energy range in complex radiation fields.

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