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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 comp-
lexity 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 ig-
nored (except for the fields behind relatively thin beam stop-
pers in which the charged particle equivalent doses can be
equal to or more than the neutron doses). The largest contri-
bution to the equivalent doses is made by neutrons of the wi-
dest energy spectrum (from 10^{-8} to several hundreds of MeV).
The shapes of the neutron spectra in the fields surrounding ac-
celerators depend on shielding configurations and can be rela-
tively "soft" if the shielding has splits, or "hard" behind
the thick continuous shielding. The upper limit of neutron lea-
kage 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 hund-
reds of MeV[1]. An increase in the energy of accelerated par-
ticles 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 conside-
rably contribute to the doses received by persons working out-
side the shielding (up 50-60% of the total neutron equivalent
doses). The measurements of the penetrating high-energy neu-
tron 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

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(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 te-
chniques have an insufficient sensibility and in many cases
can't be used in fields with low level of radiation. Neverthe-
less the Bonner spectrometer in combination with the activa-
tion 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 $\Phi(E) \times E$) have maxima in the energy range 50-
-150 MeV.
    For adequate measurements of the neutron energy distribu-
tions in the range from ~ 20 to ~ 500 MeV in the mixed undi-
rectional 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 depen-
dence of the readings of the neutron counter with the plastic
scintillator on the differential energy neutron flux at va-
rious thresholds of signal registration. The device, consis-
ting 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 outsi-
de the shielding. The calculations of the plastic scintilla-
tor neutron-detection efficiency was performed using the Mon-
te-Carlo code[4]. The influence of the veto counter on the
neutron counter efficiency was taken into account in the cal-
culations and led to a considerable decrease in the efficien-
cy 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 in-
side the shielding is usually lower than the π-meson produc-
tion limit. The neutron fluences and maximum equivalent doses
in the FDS technique are determined by a linear combination

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of the device readings at specially chosen thresholds of sig-
nal registration. The unfolding of a neutron spectrum is per-
formed by the statistical regularization method on the basis
of the apparatus spectrum of signals[5]. A principle possibi-
lity 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 thre-
sholds. 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 ef-
ficiency at different thresholds of signal detection expressed
in MeVee (equivalent electron energy). N_j is the result of in-
tegration of the apparatus spectrum over the corresponding chan-
nel threshold j in MeVee. The calibration of the thresholds
was carried out by means of cosmic background μ-mesons. A sy-
stem of 13 algebraic equations for various thresholds over
15 MeVee 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 exemp-
lifies 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 essential-
ly more "soft" than spectrum 2 due to accumulation of low-ener-
gy 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 re-
latively 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"

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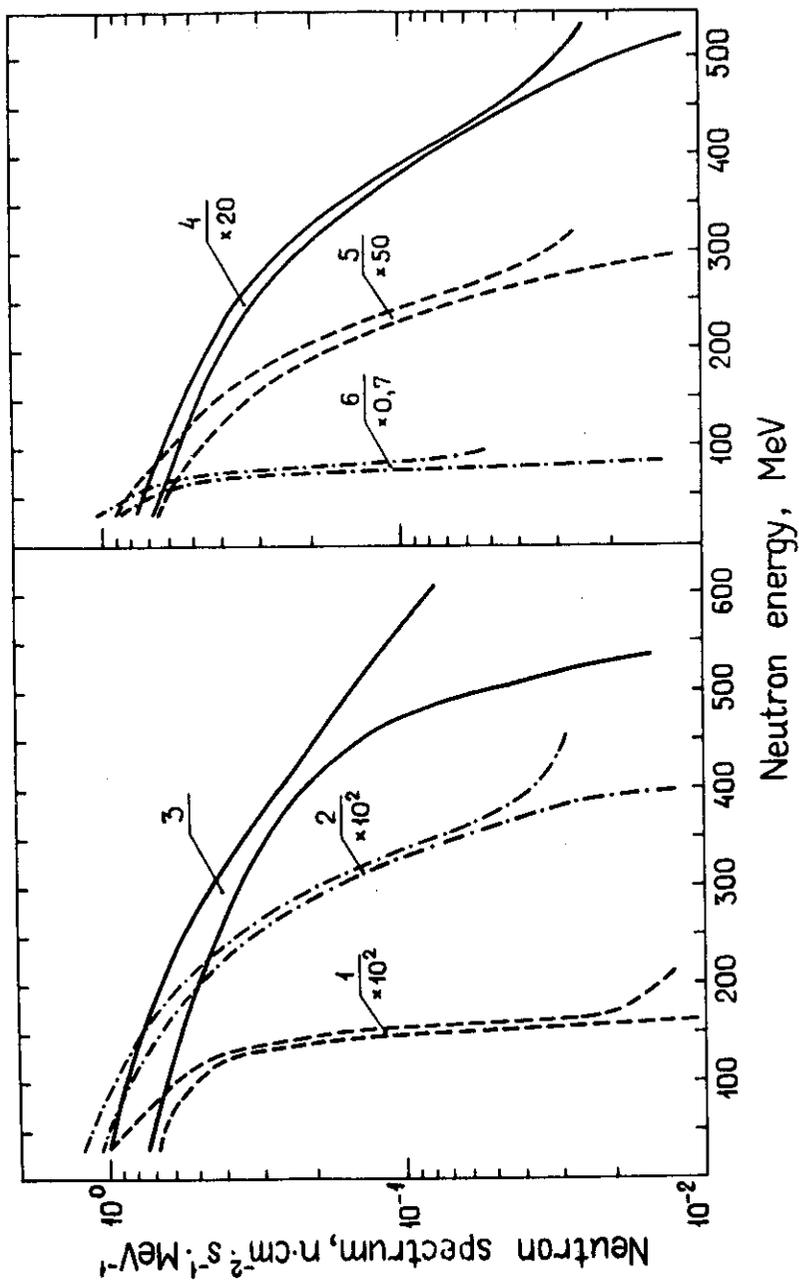
Fig.1. The neutron spectra outside the phasotron and synchrophasotron shielding. The figures in circles correspond to the numbers of measurement points which are shown in Fig.2.

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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 $\Phi(E) \times E$ 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·sm^{-2}·s^{-1}. This spectrum in terms of $\Phi(E) \times E$ 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
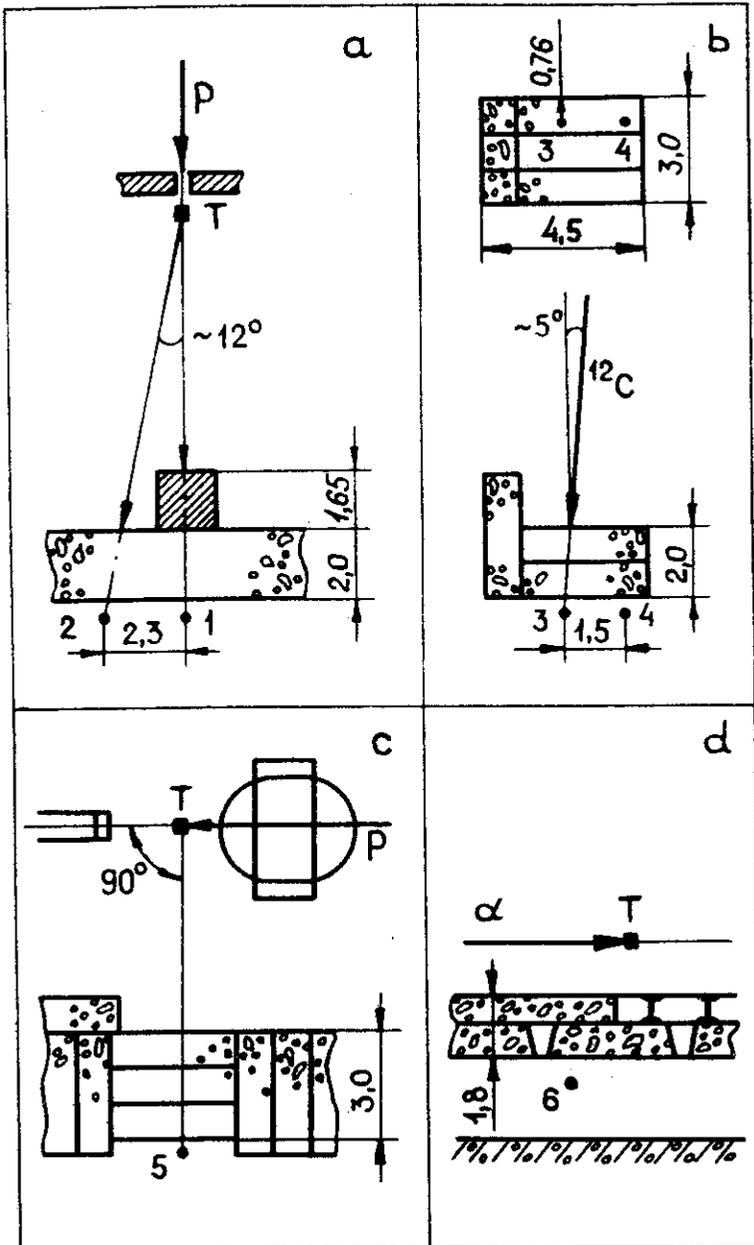
Fig.2. The location of measurement points (solid circles) and shielding configurations. All dimensions are given in meters. In Fig.2b the frontal surface of shielding is also shown.
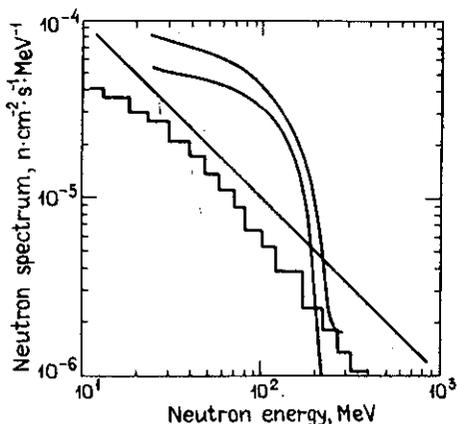
Fig.3. The high-energy background neutron spectra due to cosmic rays. The solid curves are the present measurement; the straight line is the 1/E spectrum; the histogram is spectrum/9/.

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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