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HIGH-ENERGY NEUTRON-RADIATION REFERENCE FIELD

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The technique and results of measurements performed of the neutron spectrum behind the top shielding of the U-70 experimental hall using a Bonner spectrometer based on indium and carbon activation detectors are presented. The integral characteristics of the neutron field are presented; such a field could be useful in various areas of dosimetry, radiation physics, and radiobiology, in assuring radiological safety during flights in airplanes and in space, as well as in the study of malfunctions induced in microelectronics by high-energy neutrons.

Low-energy reference neutron-radiation fields [1] were produced at the Institute of High-Energy Physics (IFVE) in the 1990s on the basis of ^{239}Pu–Be and ^{252}Cf radionuclide sources for the purpose of simulating the low-energy neutron spectra behind the shielding of the U-70 proton synchrotron at 70 GeV and for calibrating dosimetric apparatus. Subsequent measurements of the spectra showed that high-energy neutrons make a considerable contribution behind the top concrete shielding of the U-70 experimental hall [2]. This has led to the practical necessity of developing high-energy neutron fields with stable spectral characteristics for testing radiation monitoring detectors as well as for applications in other applied problems. Specifically, high-energy reference fields which were produced as part of the scientific program of the European Union "Radiological Safety of Flying in Airplanes" for simulating neutron spectra generated by cosmic rays in the atmosphere at altitude ~10 km, have been widely used at CERN since 1993.

The problem of radiological safety of flying arose after ICRP Publication No. 60 [4] was released. According to this publication the irradiation dose limit to the general public is lowered to 1 mSv/yr, as a result of which the airplane crew entered the category of professionally irradiated personnel. The conceptual changes in the system of dosimetric quantities and dose limits are also reflected in the domestic radiological safety norms (NRB-99) [5]. Aside from radiological safety problems, high-energy neutron reference fields are a tool for studying various effects, including malfunctions of electronic equipment exposed to high-energy hadrons; this problem is becoming increasingly urgent under conditions of flights in space and in the atmosphere; such fields are also a tool for experiments in modern high-energy accelerators.

At the IFVE a high-energy reference field can be created in an experimental hall behind the shielding of the U-70 proton synchrotron. The eastern section of the top shielding is most suitable for this; here, the No. 58 (RM-58 below) automated radiation monitoring system is used to monitor the dose rate of the neutron radiation. The maximum neutron dose rate 0.5–1 mSv/h in the experimental hall has been observed in this section for many years at times when the accelerator was operating. This region of the top protection is closest to the interior targets of the ring hall of the accelerator; the secondary radiation from these targets largely determines radiation conditions in the entire experimental hall. The constancy of the spectral

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TABLE 1. Specific Activity of the Activation Detectors Behind the Top Shield of the U-70 Experimental Hall Near RM-58

Detector	Specific activity, Bq/g	θ, %
Indium in a 5.08 cm in diameter cadmium-coated moderator	31	±15
Indium in a moderator with diameter, cm:		
5.08	54	±13
7.62	80	±12
10.16	98	±12
12.70	103	±12
15.24	107	±12
20.32	104	±12
25.4	82	±13
30.48	63	±13
Carbon detector (graphite)	0.365	±15

characteristics of the neutron fields near RM-58 was established from the results of studies performed over many years of the sensitivity of the individual neutron dosimeters using a passive neutron dosimeter-spectrometer [6].

In contrast to the previous studies [2, 7], where it was noticed that charged particles affect the indications of detectors, the following neutron radiation detectors were used in the present work:

1) Bonner multisphere detector based on indium activation thermal-neutron detector, insensitive to the photon and charged components of the radiation field; and

2) specially fabricated large-volume carbon activation detectors based on graphite and polyethylene; an advantage of activation detectors over other neutron detectors, for example, ^{6}LiI(Eu) with a photomultiplier, is that their indications are independent of the pulse structure of the radiation field of the accelerator.

The measurements with the Bonner spectrometer and carbon activation detectors behind the shielding of the proton synchrotron were performed at the same time that internal targets were in use and the proton beam was slowly extracted.

Measurement Procedure and Results. Thermal neutron detectors consist of 20 mm in diameter and 1 mm thick disks with mass ~2.3 g, which are placed at the center of spherical polytethylene moderators with diameters 5.08, 7.62, 10.16, 12.7, 15.24, 20.32, 25.4, and 30.48 cm. The small size and shape of an indium detector eliminate a cavity inside the sphere of the spectrometer, which makes the spherical detector isotropic as a whole. In addition, an indium detector in a 5.08 cm in diameter polyethylene sphere coated cadmium is used to measure the thermal-neutron flux density. This makes it possible to decrease the error of the cadmium-difference method, since the sensitivity function of a 5.08 cm in diameter sphere, in contrast to the ordinarily used indium detector without a moderator and with a strong resonance in the cross section of the reaction ^{115}In(n, γ) at neutron energy 1.5 eV has no resonance structure and the correction for absorption of super-thermal neutrons by cadmium is small.

A spectrometer based on an indium activation detector has been used previously in low-energy reference neutron fields, as a result of which the data obtained in previous measurements [1] on the spectra as well as integral quantities [8] have been confirmed. Since the Bonner spectrometer is uninformative at neutron energies above 20 MeV (low sensitive and resolution), in the present work it was supplemented with a carbon activation detector based on the reaction ^{12}C(n, x)^{11}C with a 20 MeV threshold, to determine the high-energy neutron spectrum. The carbon detector consisted of 1869 g graphite in the geometry of a 1 liter Marinelli vessel. Each detector was irradiated the chosen point in turn at 1 m from RM-58 (to the right with respect to the beam), and the distance between the center of all detectors and the protection surface was 23 cm. The exposure time of each detector was 1 h; continual operation of the accelerator was monitored according to the RM-58 indi-

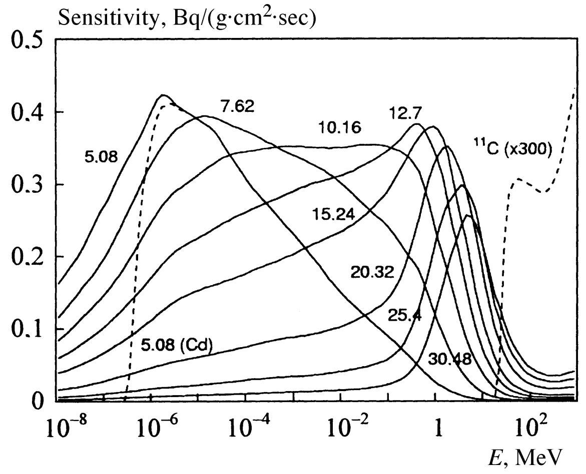

Fig. 1. Energy dependence of the sensitivity of a Bonner detector based on an indium activation detector and carbon activation detector; the numbers on the curves are the diameter of the spherical moderators, cm.

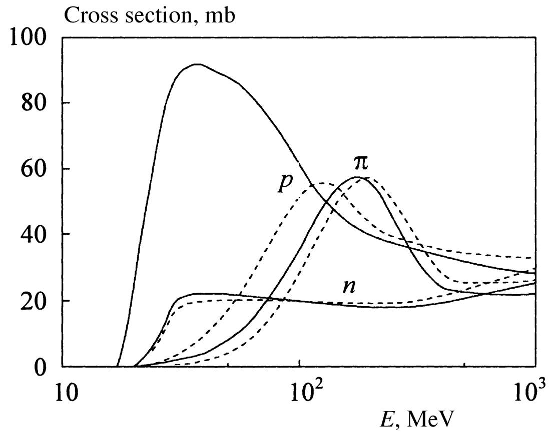

Fig. 2. Microscopic cross section for the activation of carbon by neutrons, protons, and pions (——) and the effective cross section for a bulk carbon detector (– – –).

cations. Each exposure was accompanied by monitoring with an additional carbon detector based on 880 g polyethylene in 1 liter Marinelli vessel geometry.

The activity of the detectors was determined with a semiconductor gamma spectrometer using the 1.294 MeV ^{116m}In line, formed in the reaction ^{115}In(n, γ)^{116m}In, and according to the 511 keV line of ^{11}C from the reaction ^{12}C(x, n)^{11}C. The procedure for analyzing the instrumental spectra is presented in [9]. The result of the measurements is the activity of the detectors, determined taking account of the exposure time, the computing time of the detector in the spectrometer and the time interval between the end of the exposure of the detectors and start of their calculation, as well as taking account of the coefficient of photon self-absorption in the detector. The total error of the measurements consists of the statistical errors, errors of monitoring and calibrating the gamma spectrometer, as well as the time and geometric errors. Comparing the indications of two monitors (carbon detector based on polyethylene and RM-58) showed that their ratio is constant in all exposures and

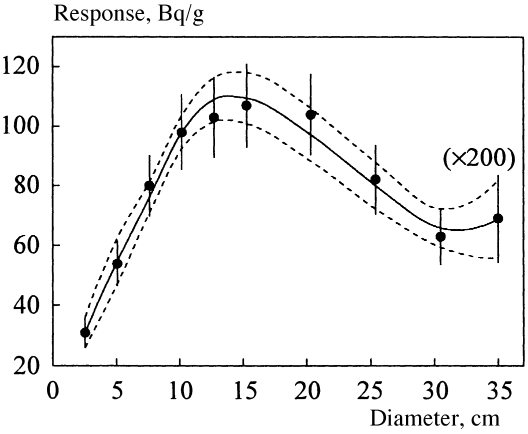

Fig. 3. Experimental (●) and computed (——) response of the detectors with an uncertainty corridor (– – –) as a function of the diameter of the spherical moderator, obtained during the reconstruction of the neutron spectrum.

equals 0.78 ± 0.03 Bq/(μSv/h). This attests to the stability of the operation of the accelerator during the measurements, which is a necessary condition for obtaining reliable data when working with activation detectors. Table 1 gives the measurement results normalized to the average activity of a polyethylene monitor 500 Bq, which corresponds to the average dose rate at the monitoring point 650 μSv/h according to RM-58.

Energy Dependences of the Sensitivity of the Spectrometer. The sensitivity functions of the Bonner indium loaded spectrometer were calculated with the FANEUT program in the energy range for 10^{-8} to 20 MeV [10] and the HADRON program from 20 MeV to 1.5 GeV [11]. These data are shown in Fig. 1 in units of the specific activity per unit neutron flux density. In [8], the spectrometer was calibrated according to the flux density of cadmium neutrons of a ^{252}Cf source.

When the neutron spectrum is reconstructed using a bulk carbon detector, the absorption of neutrons in the detector, the activation of the detector by secondary particles formed in interaction between neutrons and carbon nuclei, as well as the activation of the detector by charged hadrons present at the measurement point must be taken into account. The latter factors are more important because the cross section for the production of ^{11}C on carbon by protons and pions is much larger than with neutrons. The effective cross sections for the activation of carbon by neutrons, protons, and pions under isotropic irradiation of a 1869 g detector in the Marinelli vessel geometry were calculated in [12] using the HADRON program. The results are shown in Fig. 2 in comparison with the evaluated microscopic cross sections [13], which were used in the calculations as input data. In the case of pions, the average values for π^+ and π^- were used. The energy dependence of the sensitivity of a carbon detector in units of the activity in saturation per unit neutron flux density, presented in Fig. 1, was calculated as the product of the effective cross section in cm^2 by the number of nuclei in 1 g of carbon. The contribution of the charged particles behind the accelerator shielding, equal to 5.5% according to the data of [14], was subtracted from the response of the carbon detector.

Reconstruction of a Neutron Spectrum. The neutron spectrum was reconstructed following the BON95 program [15, 16], based on parameterization and iteration methods. The program solves the equations

$$M_i = \sum_{j=1}^{n} A_i(E_j)\Phi(E_j) + \Delta M_i, \qquad i = 1, \ldots, m, \tag{1}$$

where M_i are the indications of the detectors, ΔM_i are the uncertainties including the measurements errors and the sensitivity functions $A_i(E_j) = R_i(E_j)\Delta E_j$; and $\Phi(E_j)$ is the desired neutron spectrum in the group representation.

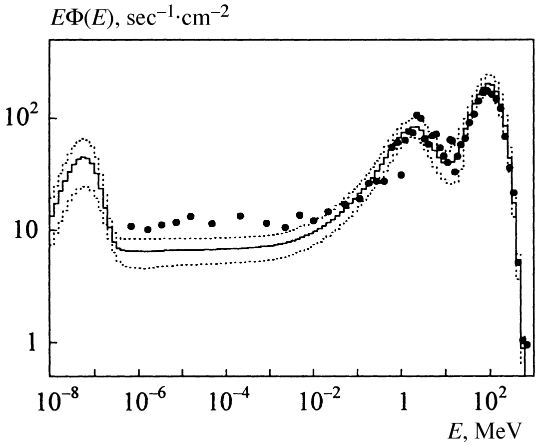

Fig. 4. Neutron spectrum behind the top shielding of the U-70 experimental hall near RM-58 (——) with an uncertainty corridor (– – –), reconstructed from the indications of a Bonner spectrometer based on an indium activation detector and carbon activation detector, in comparison with the computed spectrum of CERN's high-energy reference field (●).

The parameterization method is used to search for the initial spectrum, which is refined using an iteration procedure. The high-energy neutron spectrum is parameterized by a linear superposition of a Maxwellian peak of the thermal neutrons, $1/E$ – the intermediate-neutron "tail," the peak due to the evaporative neutrons with variable temperature and width, and a quasi-Maxwellian peak due to cascade neutrons with fixed temperature. The uncertainties of the spectrum obtained and the integral quantities are found by varying the experimental data M_i within the uncertainties ΔM_i; in this method the spectrum is reconstructed 25 times with different detector indicators $M_i' = M_i \pm \Delta M_i$. The errors of the sensitivity functions of the Bonner indium loaded spectrometer were 5% at energies below 20 MeV and 10% above 20 MeV; for the carbon detector the error was 15% [13].

Figure 3 displays the experimental responses of detectors together with their total uncertainties, calculated taking account of the errors of the sensitivity functions. The points for a 5.08 cm in diameter cadmium-coated sphere and a carbon activation detector are presented for the diameters 2.54 and 35 cm, respectively. The agreement between the experimental and computed data, which are represented by the smooth curve in Fig. 3, attests that there are no systematic errors in the measurements and the sensitivity functions. The small value of the functional $\chi^2/m = 0.09$, obtained during the reconstruction procedure, could be an indication that the errors in the experimental data are overstated.

The reconstructed neutron spectrum in the 110-group representation is presented in Fig. 4. For comparison, the neutron spectrum CERN's high-energy reference field [16] behind the top concrete shielding, as calculated with the FLUKA92 program and normalized to the flux density of the supracadmium neutrons of the reconstructed spectrum, is also shown. Both spectra have nearly the same form in the region of the evaporative and cascade peaks, which make the main contribution to the flux density and dose rate. The irregularities in the computed spectrum are due to the structure of the cross sections for the interaction of the fast neutrons with nuclei of the elements present in concrete. The differences between the experimental and computed spectrum in the intermediate-neutron range are explained, in our opinion, by the composition of the concrete in the experiment and calculations and mainly by the hydrogen content.

We note that the reliability of computed CERN spectrum [16] has been confirmed by repeated measurements performed with different spectrometers [13, 15, 17].

The similarity of the neutron spectra of IFVE's and CERN's high-energy reference fields is of great practical importance for two more reasons. In the first place, the similarity of CERN's spectrum behind the concrete shielding and the neutron spectra generated in the atmosphere by cosmic rays had been established previously [18]. In the second place, tens of

TABLE 2. Contribution of Thermal ($E < 0.4$ eV), Intermediate-Energy (0.4 eV $\leq E < 0.1$ MeV), Fast (0.1 MeV $\leq E < 20$ MeV), and High-Energy ($E \geq 20$ MeV) Neutrons to the Fluence, Absorbed Dose, and Ambient Equivalent Dose of Neutrons, %

Functional	Neutrons			
	thermal	intermediate-energy	fast	high-energy
Fluence	11.6	12.3	32.7	43.4
Absorbed dose	0.8	1.0	30.5	67.7
Ambient equivalent dose	0.5	0.8	42.8	55.9

laboratories from Europe and the leading countries in the world with dosimeters and spectrometers of the active and passive types have participated in the experimental studies in CERN's reference fields. As a result, a great deal of information on the sensitivity of different detectors to high-energy neutrons has been accumulated; this information could also be applicable under the conditions of IFVE's reference field.

The integral characteristics of the neutron radiation behind the top shielding of the U-70 experimental hall near RM-58, which correspond to an average does rate 650 μSv/h according to the RM-58 monitor, are as follows:

Flux density, sec^{-1}·cm^{-2}	839 ± 67
Rate, μSv/h:	
absorbed dose, μGy/h	121 ± 13
ambient equivalent dose	881 ± 76
individual equivalent dose	898 ± 76
effective dose of directed radiation	928 ± 91
effective dose of isotropic radiation	725 ± 91
Average energy of the spectrum of supracadmium neutrons, MeV	52.3 ± 7.5
Average quality coefficient, Sv/Gy	7.29 ± 0.28
Ambient equivalent dose per unit fluence, pSv·cm^2	292 ± 14

Table 2 gives the contribution of thermal, intermediate-energy, fast, and high-energy neutrons to the fluence as well as absorbed and ambient equivalent neutron doses. It is evident that the high-energy neutrons (cascade peak) make the main contribution to these functionals – from 43% to the fluence and 68% to the absorbed dose.

The ambient equivalent dose rates of photons and charged particles were measured at the same point, using ^{7}LiF thermoluminescent detectors, which are insensitive to neutron radiation, in order to obtain a complete description of the radiation field near RM-58. The value obtained, 110 μSv/h, was about 11% of the total ambient equivalent dose rate. Since the quality factor for photons and charged particles is 1, their contribution to the total absorbed dose is ~48%. The evaluated integral characteristics of the mixed radiation, including neutrons, photons, and charged particles, are as follows:

Absorbed dose rate, μGy/h	231
Ambient equivalent dose rate, μSv/h	991
Average quality coefficient, Sv/Gy	4.3

In summary, the responses of the detectors in a Bonner indium loaded spectrometer and carbon activation detector measured behind the top shielding of the experimental hall of IFVE's proton synchrotron made it possible to reconstruct the neutron spectrum and determine its integral characteristics. The quite high dose rate, stability, and similarity of the measured spectrum to the neutron spectrum due to atmospheric cosmic rays make it a promising reference field for use in various domains of dosimetry, radiation physics, and radiobiology.

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