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CALCULATION OF HIGH ENERGY HADRON SPECTRA AT THE CERN-CEC REFERENCE FIELD FACILITY BY THE MARS'95 AND HADRON CODES

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Abstract

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High energy spectra of neutrons, protons and pions behind the top shielding of CERN-CEC reference field facility have been calculated using the MARS'95 and HADRON Monte Carlo transport codes. The results are in a good agreement with experimental data and FLUKA simulations.

Аннотация

Ажгирей И.Л. и др. Расчет высокоэнергетических спектров адронов в опорных полях ЦЕРН-ЕС по программам MARS'95 и HADRON.: Препринт ИФВЭ 97–19. – Протвино, 1997. – 11 с., 9 рис., 6 табл., библиогр.: 9.

Высокоэнергетические спектры нейтронов, протонов и пионов за верхней защитой в опорных полях ЦЕРН-ЕС рассчитаны по Монте-Карловским программам MARS'95 и HADRON. Полученные результаты находятся в хорошем согласии с экспериментальными данными и результатами моделирования по программе FLUKA.

Introduction

The CERN-CEC reference field facility [1] was created at the H6 beam of the SPS accelerator to simulate high energy radiation fields at the altitudes of civil air flights. A number of European laboratories participated in studies of the reference fields and in calibration of dosimetric systems. The hadron spectra at different measurement positions have been calculated using the high energy transport code FLUKA [2]. An extensive comparison of the FLUKA calculations with experimental data [1,3] has shown good agreement for a neutron component of the mixed high energy radiation fields. The experimental evidence on the value of a charged fraction of the hadronic cascade is rather poor due to difficulties in data analysis and background subtraction. The comparative studies of this cascade component by different calculational methods are of interest for many applications.

This paper is devoted to the comparative study of different Monte Carlo high energy transport codes as applied to the calculation of hadron spectra at the CERN-CEC facility. Another goal was to try to obtain higher statistical accuracy of the results compared to FLUKA. This is mainly related to the charged particle spectra and fluences. A comparison with the available experimental data is presented as well.

1. Computer codes

The FLUKA Monte Carlo radiation transport code [4,5] is widely used at CERN and other institutions for radiation physics calculations as well as for the detector simulations. It describes production, interaction and transport of all essential particles in the complicated geometry for energies from several TeV down to energy of thermal neutrons. The FLUKA results are compared here with the data obtained using the MARS'95 [6] and HADRON [7,8] Monte Carlo codes developed at IHEP. The MARS code was widely used for the UNK and SSC accelerators projects and for radiation environment simulations at UKD(UNK), SDC(SSC), DIRAC(PS) and CMS(LHC) detectors projects. As regards to the HADRON program, it was developed for dosimetric purposes such as the calculation of doses in phantoms, responses of dosimetric devices, etc. The most important distinction between the programs is the use of different hadron event generators. Hadron interactions in FLUKA92 are simulated using a dual parton model above 5 GeV and a resonance model at lower energies. An intranuclear cascade model with pre-equilibrium emission is used below 300 MeV. A particle production in HADRON is described in the frames of a cascade-exciton model in a whole range of applicability, that is limited by 5-10 GeV. Special attention was paid to a correct description of hadron interactions in the energy range below 100 MeV and to the charged particles emission. Both the FLUKA and HADRON generators are exclusive ones, while an inclusive hadron event generator based on phenomenological formulae is used in MARS. Such an approach gives a possibility to use flexible tuning of a cascade tree construction algorithm providing a considerable gain in calculational efficiency depending on the kind of problem.

2. Geometry description and computational details

FLUKA calculations [2] have been carried out for a detailed description of the experimental setup construction. It is important for a correct simulation of the low-energy particle transport. At this stage of the comparison, we have restricted ourselves only with the high energy component of radiation field above 10 MeV for charged hadrons and 20 MeV for neutrons. The basic assumption was that the high energy radiation outside the shielding is strongly anisotropic and the contribution of the remote parts of facility is negligible. The calculations were performed in the geometry of the top concrete and iron shieldings shown in Fig. 1. A 205 GeV/c positive particle beam consisting of 2/3 protons and 1/3 pions hitted a copper target 50 cm long and 7 cm in diameter, which had been placed under a 80 cm thick concrete shielding or 40 cm thick iron shielding. The top shieldings were represented in simulations by parallelepipeds of 2.5 x 3 m^2 in area (see Fig. 1). In correspondence with the FLUKA input file [2], the concrete shielding with a density of 2.35 g/cm^3 was defined as a compound of elements: 51.1% O, 35.8% Si, 8.6% Ca, 2.0% Al, 1.2% Fe, 0.6% H, 0.4% C and 0.3% Na by mass. The iron shielding was composed of two 20 cm thick layers with the densities of 7.65 g/cm^3 and 7.2 g/cm^3 for the lower and upper layers, respectively. The scoring zones (measurement positions in the experiment) were represented by air cubes with a size of 50 x 50 x 50 cm^3.

At the first step of calculations, the spectra of secondary hadrons leaving the copper target were generated by the MARS code. These spectra integrated over the angular interval of $20 - 120°$ with respect to the beam direction are illustrated in Fig. 2. The spectra are normalized per a beam particle as in all the following cases. It can be seen that all the spectra are in the range of HADRON applicability, i.e. below 5 GeV. For HADRON calculations, the source of particles from the target was converted into the matrices of double differential cross sections in different angle intervals from 20 to 120° and energy bins from 20 MeV to 5 GeV. The coordinate Z along the target was simulated independently from the calculated distribution. To reduce the computing time, 1/E spectrum was simulated for all the particles and angles. The actual spectra were taken into account by appropriate statistical weights.

In the case of MARS, all the calculations were performed directly without intermediate steps. Particle tracking was terminated outside the scoring zones over the shielding or after decreasing their kinetic energy below the threshold. Hadron spectra in the measurement positions were scored using the track-length estimator as in the FLUKA calculations.

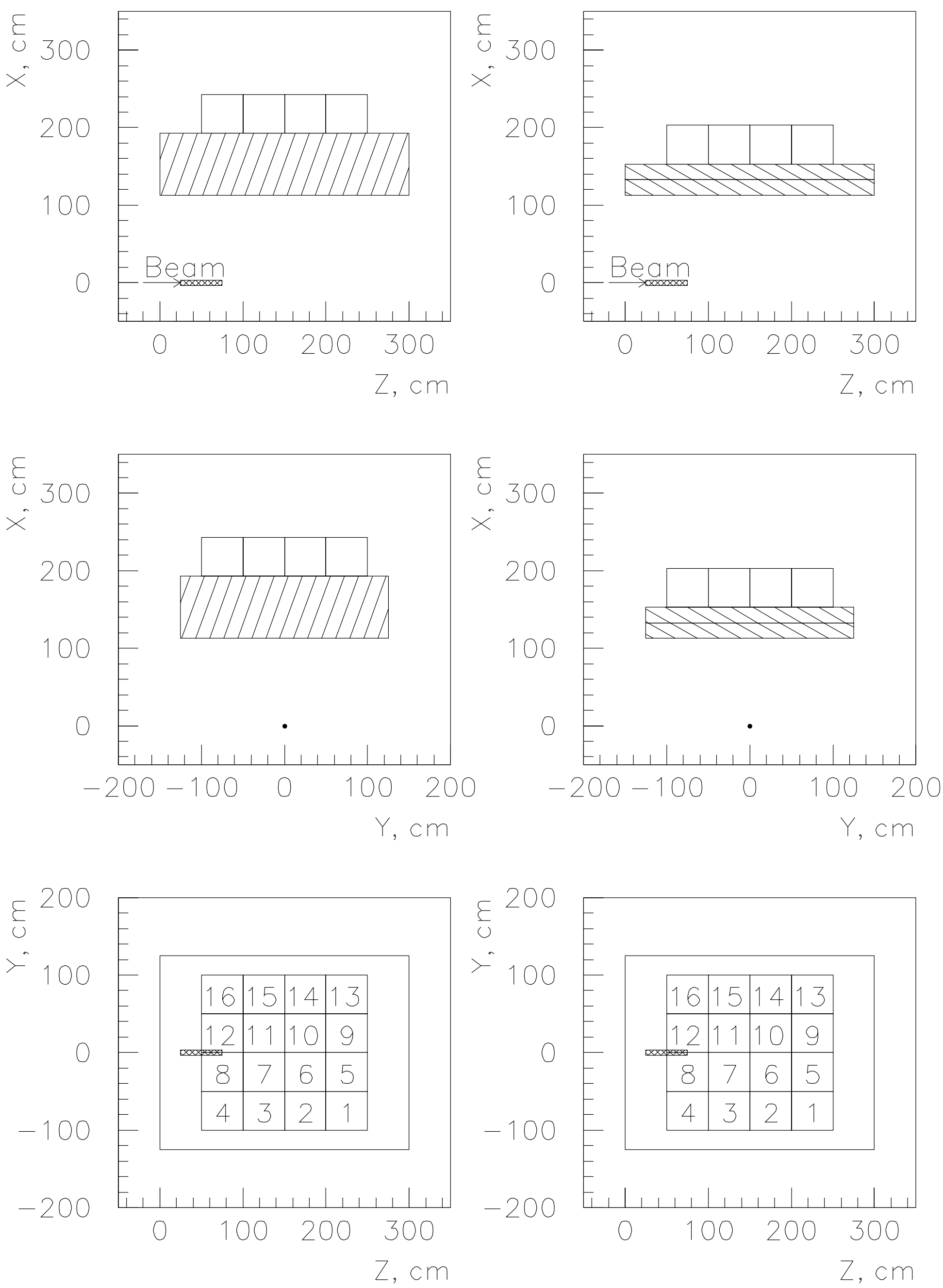

Fig. 1. Model geometry of the top concrete(left) and iron(right) shieldings of the CERN-CEC reference field facility used in MARS and HADRON calculations.

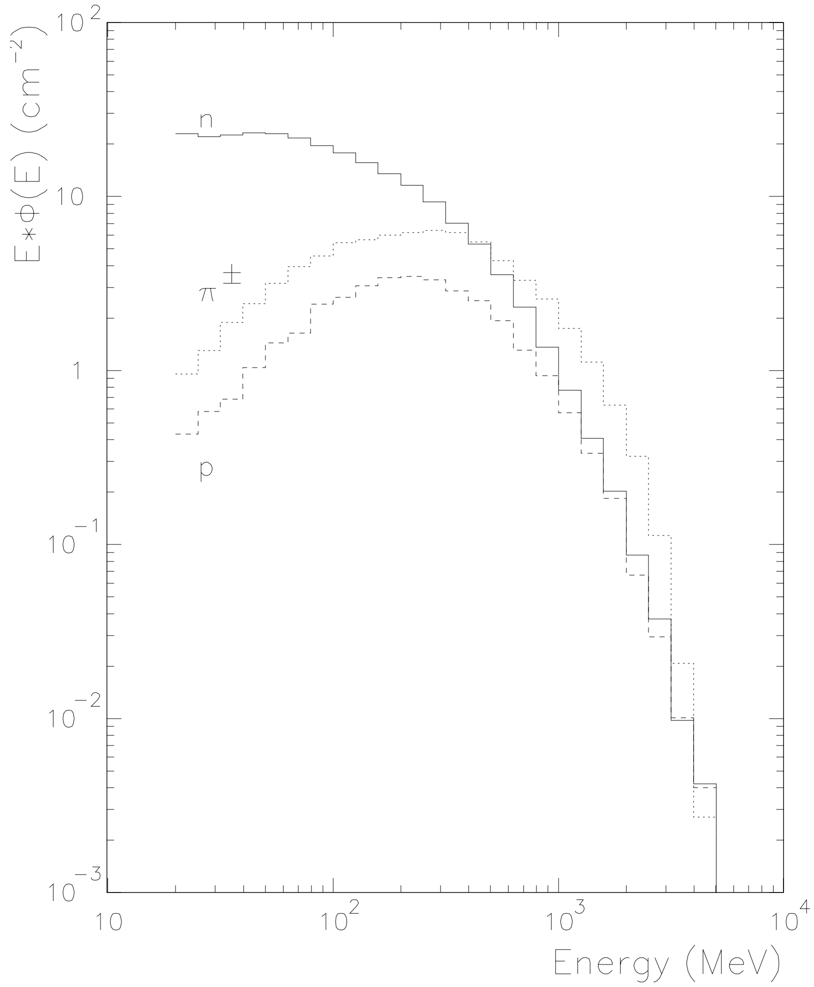

Fig. 2. Spectra of hadrons emitted in the angular interval of 20–120° from the copper target irradiated by 205 GeV/c positive particle beam (MARS calculation).

3. Results and discussion

Neutron, proton and pion spectra calculated by the three Monte Carlo codes in position 6 of the top concrete and iron shieldings are shown in Figs. 3-8. The agreement is surprisingly good taking into account different physical approaches in the computer codes. One can see some systematical differences in neutron spectra where MARS gives higher fluences below 60 MeV and FLUKA shows softer spectra above 400 MeV compared with other data. But most of the differences are in the limits of statistical errors.

The comparison of integral hadron fluences in the T6 position is given in Tables 1 and 2. It can be seen that the HADRON data are obtained with higher statistical accuracy, especially for proton and pion fluences, where the typical errors are 3–5%. That was achieved mainly due to the usage of the biasing technique for the initial spectra from the target.

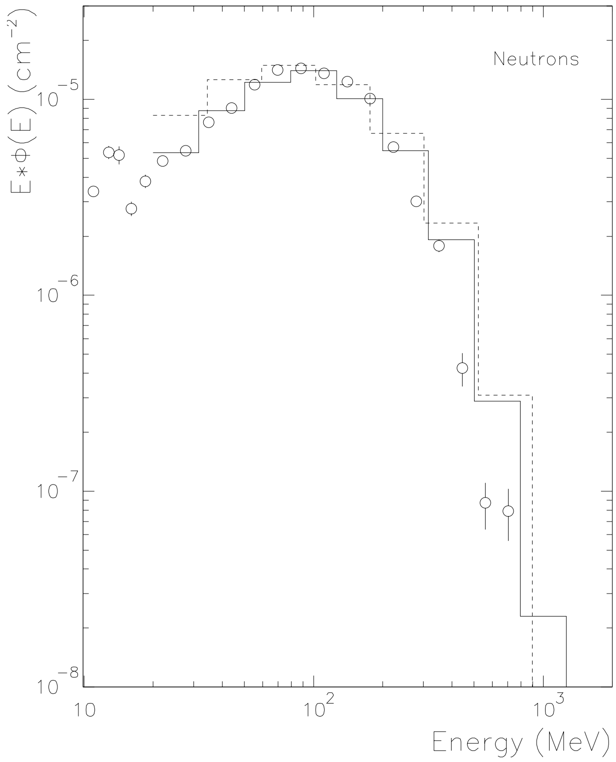

Fig. 3. Neutron spectra in position T6 above the concrete shielding calculated by the FLUKA (points), HADRON (solid histogram) and MARS (dashed histogram) computer codes.

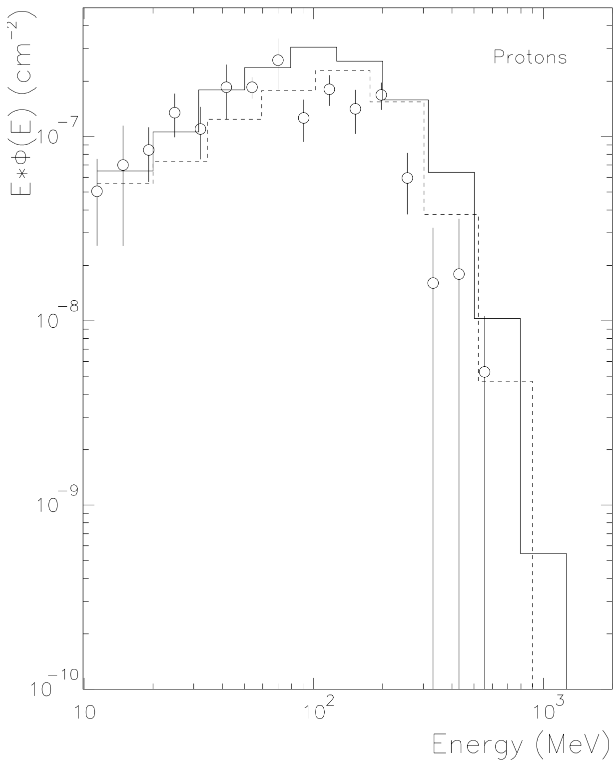

Fig. 4. The same, as in Figure 3, for protons.

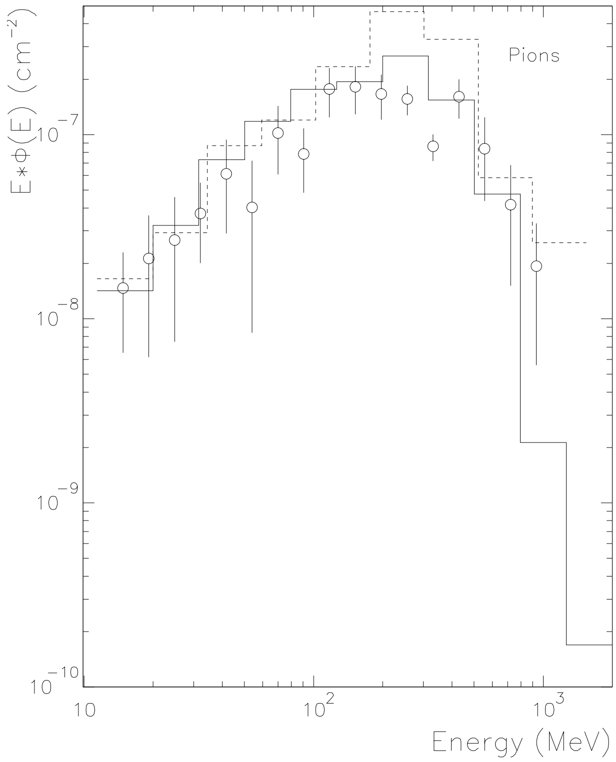

Fig. 5. The same, as in Figure 3, for pions.

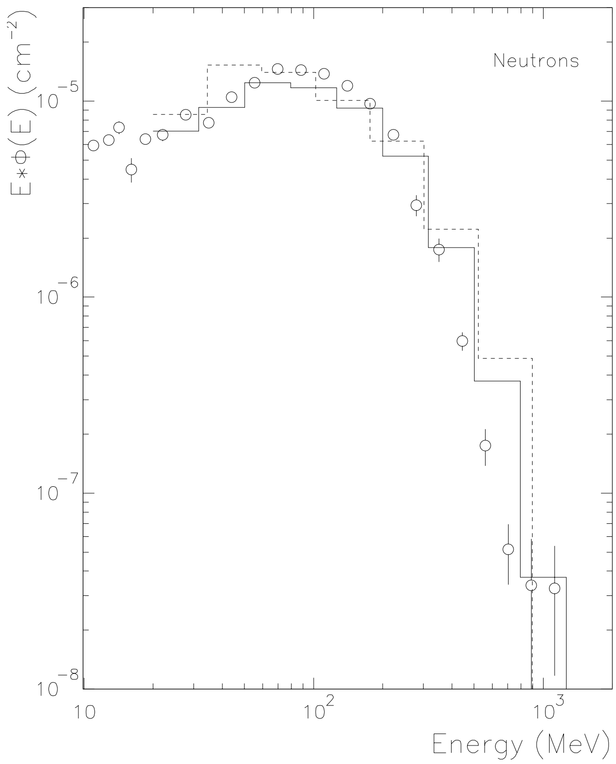

Fig. 6. Neutron spectra in position T6 above the iron shielding calculated by the FLUKA (points), HADRON (solid histogram) and MARS (dashed histogram) computer codes.

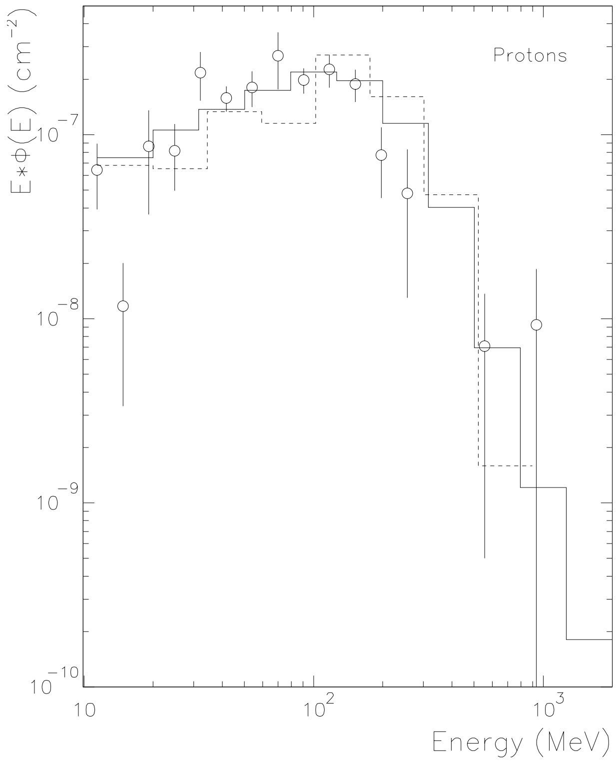

Fig. 7. The same, as in Figure 6, for protons.

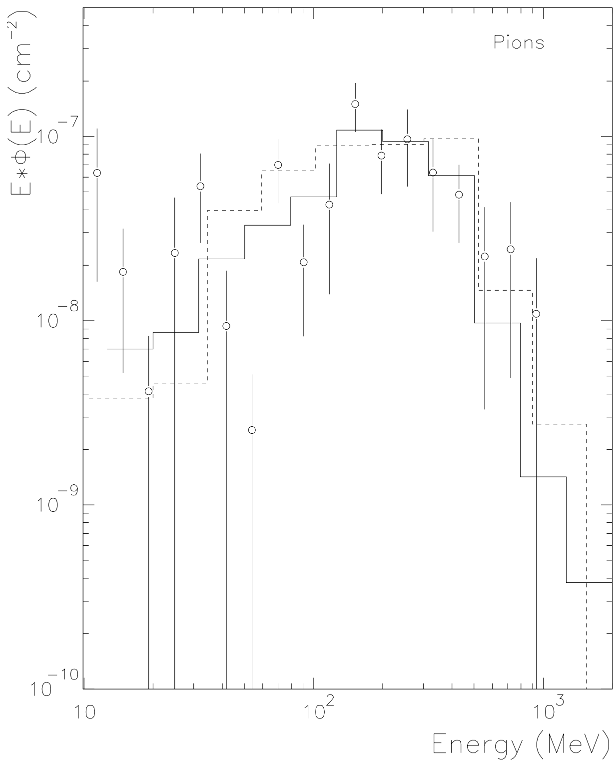

Fig. 8. The same, as in Figure 6, for pions.

Table 1. Calculated hadron fluences in the T6 position above the concrete shielding.

	FLUKA	MARS	HADRON
$\Phi_n(10^{-5}cm^{-2})$	2.62 ± 0.03	3.10 ± 0.03	2.70 ± 0.02
$\Phi_p(10^{-7}cm^{-2})$	4.67 ± 0.39	5.09 ± 0.47	6.57 ± 0.24
$\Phi_{\pi^\pm}(10^{-7}cm^{-2})$	3.78 ± 0.35	7.00 ± 0.70	4.82 ± 0.21
$\Phi_{ch}(10^{-7}cm^{-2})$	8.45 ± 0.52	12.09 ± 0.85	11.39 ± 0.32
Φ_{ch}/Φ_n (%)	3.23 ± 0.20	3.90 ± 0.27	4.22 ± 0.12

Table 2. Calculated hadron fluences in the T6 position above the iron shielding.

	FLUKA	MARS	HADRON
$\Phi_n(10^{-5}cm^{-2})$	2.81 ± 0.03	3.09 ± 0.03	2.65 ± 0.02
$\Phi_p(10^{-7}cm^{-2})$	4.74 ± 0.42	4.61 ± 0.44	4.65 ± 0.17
$\Phi_{\pi^\pm}(10^{-7}cm^{-2})$	2.09 ± 0.29	2.19 ± 0.22	1.79 ± 0.09
$\Phi_{ch}(10^{-7}cm^{-2})$	6.83 ± 0.51	6.80 ± 0.49	6.44 ± 0.19
Φ_{ch}/Φ_n (%)	2.43 ± 0.18	2.20 ± 0.16	2.43 ± 0.07

For the concrete shielding, the difference between three programs for hadron fluences reaches up to 10% for neutrons, 21% for protons and 35% for charged pions. The agreemeant for the iron shielding is much better. It may be supposed therefore that the geometrical differences do not play an important role in the observable discrepancies for the concrete shielding. The calculated values of neutron fluence are well supported by the experimental data for the ^{12}C(n,X)^{11}C reaction rate [1] measured at the T6 position. The ratios of calculated to experimental data are presented in Table 3. Taking into account a 10–15% error in beam calibration and about 15% error in the reaction cross section, one would find this agreement quite a good one.

Table 3. Ratios of calculated to measured values of ^{12}C(n,X)^{11}C reaction rate for the T6 position above the concrete and iron shieldings.

	FLUKA/exp	MARS/exp	HADRON/exp
Concrete	1.07	1.27	1.10
Iron	1.10	1.21	1.04

The full set of data for neutron and charged particle fluences collected inside the volumes of the measurement grid is presented in Tables 4 and 5. Due to the symmetry in our geometrical model, we present the results only for the T1–T8 positions. The agreement is quite good excluding the MARS ratios Φ_{ch}/Φ_n, which are down to 50% lower than the other data for positions 3,4 and 7,8 (large angles relative to the beam direction and, respectively, softer spectra of cascade hadrons). These discrepancies may be caused by underestimation of charged hadron production by neutrons below approximately 100 MeV in MARS. The average charged particle fluences vary from 2 to 4.5% of the neutron fluence above 20 MeV for the concrete shielding and from 1.1 to 2.7% for the iron shielding.

Table 4. Hadron fluences on the concrete top shielding.

Position	8			7			6			5		
	FLUKA	MARS	HADRON	FLUKA	MARS	HADRON	FLUKA	MARS	HADRON	FLUKA	MARS	HADRON
$\Phi_n(10^{-5}cm^{-2})$	1.85	2.17	1.95	2.37	2.77	2.50	2.62	3.10	2.70	2.58	3.09	2.57
$\Phi_{ch}(10^{-7}cm^{-2})$	4.20	3.14	4.06	7.00	6.98	8.24	8.50	12.1	11.4	10.3	13.3	13.4
$\Phi_{ch}/\Phi_n(\%)$	2.3	1.5	2.1	3.0	2.5	3.3	3.2	3.9	4.2	4.0	4.3	5.2
Position	4			3			2			1		
	FLUKA	MARS	HADRON	FLUKA	MARS	HADRON	FLUKA	MARS	HADRON	FLUKA	MARS	HADRON
$\Phi_n(10^{-5}cm^{-2})$	1.51	1.72	1.59	1.95	2.23	2.02	2.15	2.55	2.15	2.19	2.52	2.07
$\Phi_{ch}(10^{-7}cm^{-2})$	3.50	2.49	3.46	6.10	5.15	6.53	7.30	8.66	8.19	8.20	10.2	10.2
$\Phi_{ch}/\Phi_n(\%)$	2.3	1.5	2.2	3.1	2.3	3.2	3.4	3.4	3.8	3.7	4.1	4.9

Table 5. Hadron fluences on the iron top shielding.

Position	8			7			6			5		
	FLUKA	MARS	HADRON	FLUKA	MARS	HADRON	FLUKA	MARS	HADRON	FLUKA	MARS	HADRON
$\Phi_n(10^{-5}cm^{-2})$	2.09	2.23	2.05	2.74	3.00	2.68	2.81	3.09	2.65	2.53	2.83	2.31
$\Phi_{ch}(10^{-7}cm^{-2})$	2.70	1.98	2.37	4.80	3.29	4.57	6.80	6.80	6.44	6.40	7.65	7.18
Φ_{ch}/Φ_n (%)	1.3	0.9	1.2	1.8	1.1	1.7	2.4	2.2	2.4	2.5	2.7	3.1
Position	4			3			2			1		
	FLUKA	MARS	HADRON	FLUKA	MARS	HADRON	FLUKA	MARS	HADRON	FLUKA	MARS	HADRON
$\Phi_n(10^{-5}cm^{-2})$	1.53	1.73	1.60	2.05	2.30	1.91	2.14	2.35	1.92	1.96	2.08	1.73
$\Phi_{ch}(10^{-7}cm^{-2})$	1.60	1.51	2.30	3.80	2.19	3.40	3.40	3.71	4.51	4.10	5.40	5.17
Φ_{ch}/Φ_n (%)	1.0	0.9	1.4	1.9	1.0	1.8	1.6	1.6	2.3	2.1	2.6	3.0

These values are much lower than the reported recently in [9], where the charged particle contributions of 28 and 13% were calculated for the same experimental setups. Analysis of the geometry model used in calculations [9] shows that it does not correspond to the actual geometry. The hadron spectra from the target calculated for the angular interval of 10–25° were applied in one-dimensional transport calculations for the infinite shieldings. It can be seen from the original setup drawings [1,2] and Fig. 1 that the actual angles from the target to position 6, for which the FLUKA data were used in comparison [9], are more than 50° for both shieldings. On the other hand, the procedure of transformation of the considered geometry to the one-dimensional one was not described and seems to be problematical.

The data in Tables 4 and 5 show that all the components and particularly charged particle fluence strongly depend on the target-to-detector angle. This dependence for neutrons is illustrated in Fig. 9. The systematical decrease of a high energy tail of neutron spectrum is observed with the increase of the above angle. The same behaviour is valid for charged hadrons as well. The average hadron energies calculated by HADRON are shown in Table 6. They vary in the limits of 88-128 MeV for neutrons, 101-154 MeV for protons and 146-251 MeV for pions. Such a strong variability testifies against the equilibrium in the spectra shapes as well as in the component structure of radiation outside the considered shieldings.

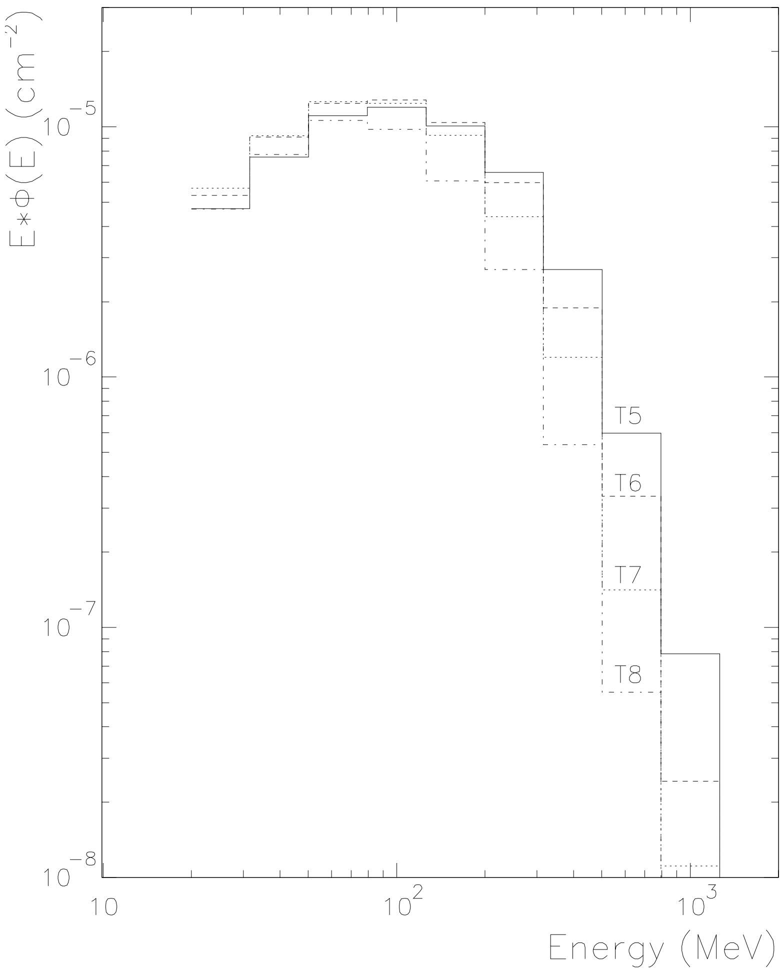

Fig. 9. Neutron spectra in positions T5–T8 above the concrete shielding calculated by HADRON.

Table 6. Average energies (MeV) of the hadron spectra calculated by the HADRON code.

Position	8		7		6		5	
	Concrete	Iron	Concrete	Iron	Concrete	Iron	Concret2e	Iron
n	94	88	104	99	115	110	128	119
p	101	101	120	114	128	130	154	150
π	167	157	189	173	203	218	227	251
Position	4		3		2		1	
	Concrete	Iron	Concrete	Iron	Concrete	Iron	Concrete	Iron
n	96	90	105	99	114	109	126	118
p	101	101	108	105	124	122	147	144
π	154	146	180	172	211	192	228	241

Conclusion

The comparison of high energy hadron spectra and fluences at the CERN-CEC reference field facility calculated by three Monte Carlo codes has shown reasonable agreement between them and with experimental data. The observable discrepancies in some data are explained by using different hadron event generators in the computer codes and by the statistical error in other cases. The presented results will be useful in analysis of the experimental data obtained with dosimetric and spectrometric devices at the CERN-CEC facility.

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