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EXPERIMENTAL DETERMINATION OF THE QUALITY FACTOR OF RADIATION NEAR HIGH-ENERGY ACCELERATORS

by

V.N.Lebedev, M.Zielczyn'ski and M.I.Salatskaya

Modern high-energy proton accelerators give rise to powerful secondary radiation having a very complex composition. The energy range of each component stretches from a fraction of an electron-volt to values close to the maximum energy of the accelerated protons. This variability and the pulse character of the radiation makes it extremely difficult to assess the degree of radiation hazard. In practice, in such cases it is only possible to study the components making the greatest contribution to the radiation density at places frequented by the personnel[1-3]. To estimate the contribution of very high-energy nucleons, use is generally made of various simplifying assumptions which are satisfied only to the first approximation. However, even if these assumptions are absolutely valid, an error unavoidably arises owing to the fact that the relationship between a flux of high-energy neutrons and the dose, which is recommended in ref. 4, cannot be regarded as rigorously established. A partial solution is to resort to the known experimental relationship between the density of linear energy losses (LEL) and the quality factor QF* [5,6]. Using this relationship, one can calculate the effective value of the QF of any radiation, with any energy dependence, if the LEL spectrum of this radiation is known. Knowing QF, it is not difficult to estimate the dose-equivalent in berads*). In turn, the LEL spectrum

*) Translator's note: rem ?

can be determined with a Rossi tissue-equivalent proportional counter[8,9].

* The term 'quality factor' of radiation has been recommended[7] by ICRU (International Commission on Radiological Units and Measurements) for the physically measurable parameter of the radiation, characterizing this radiation from the point of view of the expected biological effect, as distinct from the term 'relative biological effectiveness' (RBE) which it is now recommended to use only in radiobiology.

The mean LEL value can also be estimated by analysis of tracks in nuclear emulsions or on plates from track chambers[10,11]. None of these methods is, however, very suitable for rapid measurements during operation, for obvious reasons.

The recently proposed recombination method[12,13] allows us to overcome some of these difficulties and to determine the effective QF of an unknown radiation simultaneously with the measurement of the absorbed dose, without involving the LEL spectrum in the analysis. This method was thus used to determine the QF of mixed pulsed radiation near the high-energy accelerators of JINR. The results are given below.

The measurements were carried out with a double tissue-equivalent recombination chamber described in detail in ref. 14. The quantity proportional to the quality factor was the ratio of the ion currents of the two chambers, one of which was operated under a saturation regime and the other under conditions of column recombinations. In the column recombination regime, the number of recombining ions depends on the linear ion density in the particle tracks.

The results of the measurements, averaged over the entire chamber, correspond to an effective depth of 2-5 cm in the tissue, as a result of the construction of the tissue-equivalent chamber. The error arising from the fairly large (30 x 30 cm) dimensions of the chamber (nonuniformity of the radiation field, change of the spectrum within the chamber, etc.) is neglected.

The results of measurements of the effective radiation quality factor at most characteristic points within the structure of the 10 Gev proton synchrotron are shown in Figure 1. As could be expected, QF_{eff} reaches a minimum ($\lesssim 3$) in sectors directly adjacent to open rectilinear intervals of the accelerator. In these sites the main contribution to the dose comes from primary and secondary high-energy particles: relativistic protons and neutrons, mesons, and electron-photon components, exhibiting minimum specific energy losses. With increasing distance from the open sectors of the vacuum chamber, the QF increases rapidly and reaches a value of 5 in the center of the accelerator room (the mean energy of fast neutrons at this point is 0.6 Mev).[3] Opposite the windows and in the yoke of the electromagnet (which, as can be seen in Figure 1, consists of four quadrants each containing 12 oval windows 1 x 1.5 m and 12 vertical slits 0.2 m wide) the QF is 3.8, and opposite the slits it is 4.5, which is also due to diverse* contribution of the high-

* Translator's note: ?

energy component. The quality factor increases very slightly behind a thin wall (60 cm of silica brick), probably because the neutron flux, reduced on passing through the wall, is supplemented by cascade processes. Behind thick protection, in experimental rooms, the QF rises to a maximum of 6-10, in good agreement with the mean energy of fast neutrons in these places (0.4 - 0.8 Mev) if it is remembered that in a small experimental room the high-energy component is practically absent.

The error of these measurements was 30%; this was due in the first place to incomplete tissue-equivalence of the chamber material; to incomplete saturation in the chamber, operating in a saturation regime, with respect to strongly ionizing particles; to errors arising from measurements of the ion current of the chamber; and to a certain nonlinearity of the chamber characteristic in the recombination regime[15,16]. However, the error of relative measurements (deviation of the results of one and the same instrument) is very much smaller, and, as expected, does not exceed 15%. This allows one to distinguish several characteristic sectors in the accelerator room in dependence on the value of QF (Table 1).

The results of Figure 1 and Table 1 are (with the exception of one point) in good agreement with the results of an estimate made with assumptions, concerning the spectrum and composition of the radiation, which were known to be pessimistic[3].

The effective radiation quality factor in the vicinity of other high-energy accelerators has been estimated by several authors[9-11,16]. It is, however, fairly difficult to compare all known results because the geometry of the protection differs from case to case and the distributions of the measurement points with respect to the accelerator are not always fully specified. Nevertheless, we tried to generalize these data in Table 1. As can be seen from the table, the results of measurements and estimates are of roughly the same magnitude with the exception of the data for the bevatron, obtained from an analysis of the LEL spectrum, i.e. the most reliable data. It is very doubtful that all these results are erroneous, but there is no reason to ascribe a value of QF = 1.8 - 2.8 to the radiation in sectors distant from the accelerator (e.g. in the control room), strongly enriched in the soft region[26]. It may be that this is due to the presence of a large number of relativistic particles at the measurement points, although there is no direct indication of this in ref. 9.

The results of the measurement of the radiation quality factor in collimated particle beams from the JINR 680 Mev synchrocyclotron are given in Table 2.

For a beam of neutrons with a maximum energy of 680 Mev[17], the measurements were carried out in a water phantom[28]. The maximum of the absorbed dose corresponded to 24 cm of water. The QF changed negligibly with depth, and the change did not exceed the experimental error up to 1.2 m. The QF for a beam of 680 Mev protons was measured without a phantom.

Columns 3 and 4 of Table 2 give, for the sake of comparison, calculations or measurements of QF from the work of other authors, and moreover, the values of relative biological effectiveness, obtained as a rule during hard irradiation of mice and dogs.

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Table 1

Description of the sector	Effective radiation quality factor, QF_{eff}: JINR 10 Gev proton synchrotron, recomb. method (Fig.1)	JINR 10 Gev proton synchrotron, estimated from composn. of the radn.	3 Gev cosmotron	6.2 Gev bevatron	CERN 28 Gev proton synchrotron
Sectors in the immediate vicinity (2-3 m) of unscreened vacuum chamber of the accelerator	3	-			4.3-4.1-6.0-5.9 (16) (at various points)
Outer and inner ring zones along the yoke of the electromagnet (including the center of the room)	3.4-5	4.1-6.5[3]		1.8 ± 20% (9)	
Sectors behind thin (up to 60 cm) protection. (Sites which may occasionally frequented by the personnel)	5-6	4.5[3]	5[10] 8.1[11]	2.8 ± 20% (9)	13-11-8-14[16] (at various points)
Sectors behind thick protection (in the plane of the equilibrium orbit). (Sites constantly frequented by the personnel)	6-10	6.9-9.2[3]			

(Figures in brackets are reference numbers)

Table 2

Type of radiation	Effective radiation quality factor QF_{eff}		RBE-values
	680 Mev synchro-cyclotron / Recombination method	Literature data	
Neutrons $E_{m,max}$ = 680 Mev	2.7 ± 0.8	-	-
Protrons E_p = 680 Mev	1.8 ± 0.6	1.4* (18)	0.7-2** (19-24)
Dispersed radiation in experimental rooms behind thick protection	-	5.3 ± 0.5 (9) 10-13-3.6-4*** (16)	-

(Figures in brackets are reference numbers)

* for 100 - 400 Mev protons
** for 510 - 730 Mev protons (the data refer to hard irradiation)
*** measured in various sectors

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Figure 1.* Effective quality factor of the mixed radiation in the construction of the 10 Gev proton synchrotron. The values of QF_{eff} shown on the diagram below the line are taken, for comparison, from ref. 3 (a - 570 kev fore-injector. б - linear 9 Mev accelerator, B - yoke of the electromagnet, г - linear intervals, д - channels of high-energy particles, e - working targets, ж - experimental rooms)

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* Translator's note: The key to this diagram is kept in the original cyrillic to avoid confusion on the drawing.