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THE CONTRIBUTION OF SECONDARY HEAVY CHARGED PARTICLES TO DOSIMETRIC QUANTITIES OF RADIOTHERAPY PROTON BEAMS USING A TRACK ETCH LET SPECTROMETER[2]

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Изучение вклада вторичных тяжелых заряженных частиц в дозиметрические характеристики радиотерапевтических протонных пучков с помощью трековых детекторов

В терапевтических протонных пучках образуются вторичные тяжелые заряженные частицы, которые вносят вклад в дозу облучения пациента. В данной работе экспериментально изучался вклад вторичных частиц с высоким значением линейной передачи энергии (ЛПЭ) в дозиметрические характеристики протонных пучков.

Метод измерения ЛПЭ с использованием трековых спектрометрических детекторов позволяет определить вклад вторичных частиц в дозиметрические характеристики протонных пучков — поглощенную дозу и эквивалентную ЛПЭ в протонном пучке с энергией 200 МэВ. Пучок протонов с энергией 80 МэВ формируется в результате замедления первичного пучка в воде, в результате чего содержит большое число вторичных низкоэнергетических нейтронов.

Если относительный вклад вторичных частиц в поглощенную дозу не превышает 1—2%, то их вклад в эквивалентную дозу для протонных пучков может достигать 20%, что несомненно должно учитываться при формировании и использовании пучков.

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The Contribution of Secondary Heavy Charged Particles to Dosimetric Quantities of Radiotherapy Proton Beams Using a Track Etch LET Spectrometer

Proton radiotherapy beams produce non-negligible number of secondary heavy charged particles, which contribute to the dose in a patient. The contribution of secondary particles with high linear energy transfer (LET) to dosimetric quantities of proton beam has been experimentally studied.

The method of the LET spectra measurement with a track etch spectrometer permits to determine the contribution of secondary particles to the dosimetric quantities of the therapeutic proton beams, absorbed dose and equivalent dose. A spectrometer of the LET was used to obtain the spectra of LET in a proton beam with the primary energy of 200 MeV. The beam of 80 MeV protons has been obtained by the slowing down primary protons in water, it should be therefore more contaminated by lower energy neutrons.

If the relative contribution of secondary heavy particles to absorbed dose does not exceed 1—2%, their contribution to equivalent dose may reach up to 20% for proton beams and undoubtedly must be taken into account during beam production and using.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna, 1999

I. INTRODUCTION

A spectrometer of the linear energy transfer (LET) based on the chemically etched polyallyldiglycolcarbonate (PADC) track etched detector (TED) has been recently developed in our laboratory /1-3/, it was already used to determine LET spectra in several radiation beams and fields /4-8/.

This paper presents, discuss and analyzes the LET spectra obtained in the detectors irradiated in beam of protons with energies of 80 and 200 MeV. The goal of experiments was to enlarge the studies already performed with the protons of energies from several tens MeV up to 1 GeV /5-7,9/.

2. EXPERIMENT

2.1. Irradiation

The irradiation has been realised in the beam of protons of the phasotron of the Laboratory of Nuclear Problems of the Joint Institute for Nuclear Research (LNP JINR), Dubna, Russia. The monitoring of irradiation conditions has been ensured through the ionisation chamber measurements. The detector sets have been irradiated perpendicularly to the beam, the proton tissue kerma was about 500 mGy. In total, four sets of detectors have been exposed. Two sets of detectors were irradiated with primary proton beam with the energy of 200 MeV and other two sets of detectors were irradiated with protons slowed down by means of water degrader to 80 MeV.

Each set contained two sheets of track detectors, the upper one was covered by one half with polyethylene (PE). In this situation there are four different " radiators " in the front of a detector sheet: no radiator (bare), 2 mm of polyethylene (PE), upper sheet of detector (bare-CR) under upper sheet of detector behind PE (PE-CR).

2.2. LET Spectrometer Based on Chemically Etched PADC TED

Polyallyldiglycolcarbonate available from Pershore Moulding, England (curing time 32 hours, thickness 0.5 mm) has been used. The detector samples have been etched in a 5N NaOH at 70°C. Each sample was before etching irradiated in a corner with ^{252}Cf fission fragments, in another one with ^{241}Am alpha particles to check exact etching conditions and to determine the bulk etching. The optimal conditions corresponded to 18 hours of etching (one-side removed layer about 17μm).

To determine LET-value of a particle, the etch rate ratio V ($V=V_T/V_B$; where V_B is bulk etching rate and V_T is track etching rate) has been primarily established through the determination of track parameters. The track parameters have been measured by means of an automatic optical image analyzer LUCIA II based on a Leitz microscope /1-3/. The value of V was calculated by at least two ways of track parameters combination, the final optimisation is performed through the comparison of the removed layer thickness recalculated from V-value and that directly measured through fission fragment tracks diameter. V-spectra obtained are corrected for the critical angle of the registration and transformed to LET spectra on the basis of the heavy charged particles calibration checked through high dose electron irradiation. The spectrometer permits to establish LET of a track between 100 and 7000 MeV.cm^2.g^{-1} in tissue.

3. RESULTS; DISCUSSION

3.1. LET spectra

LET spectrometer permits to establish the distributions in LET of both the absorbed dose and the dose equivalent; quality factors from both recent ICRP Recommendations /10,11/ have been used. We have observed that there are rather important differences in absolute values of differential dosimetric quantities behind different radiators. In spite of that, there is a minimal influence of the radiator on both the absorbed dose and the dose equivalent distributions in the linear energy transfer. Typical examples of the results are obtained for a set irradiated with 80 MeV protons presented for the absorbed dose and the dose equivalent with ICRP 60 quality factors in the Figures 1 and 2. One can see there that the both spectra of differential dose quantities are quite similar for all four radiators. The same behavior was also observed for another individual set of detectors at the energy of 80 MeV and both sets irradiated with protons of the energy of 200 MeV.

More information on the contribution of particles with the different LET values to the total values can be obtained from so-called microdosimetric distributions L*D(L), resp. L*H(L). These distributions for two detectors set irradiated by 80 MeV protons for the absorbed dose as well as for the equivalent doses with both sets of quality factors are presented in Figures 3 and 4. One can see there that the absorbed dose and equivalent dose distributions of two sets irradiated are different as well as their absolute values. The set *V* exhibits clearly higher values of differential quantities, the spectrum is shifted to higher values of LET. The extent of this difference will be more discussed in the connection with integral values of dosimetric quantities.

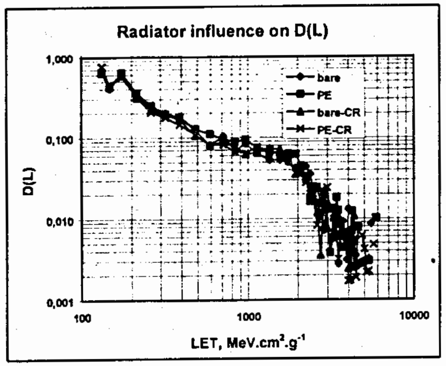

Figure 1: Radiator influence on the dose distribution in LET

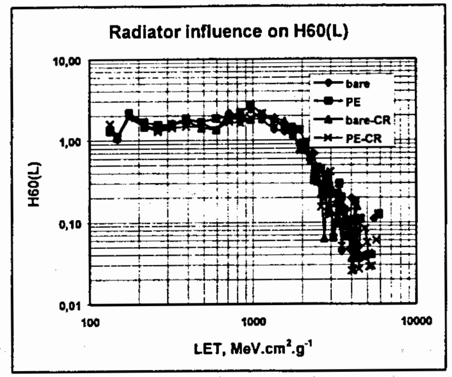

Figure 2: Radiator influence on the equivalent dose (ICRP60) distribution in LET

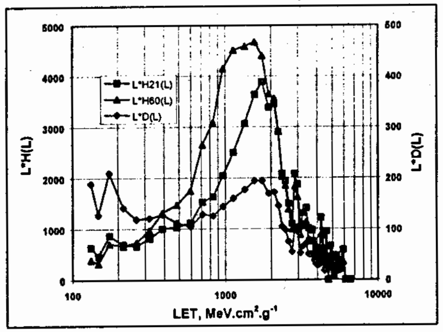

Figure 3: Microdosimetry distributions, set ***KT*** irradiated by 80 MeV protons

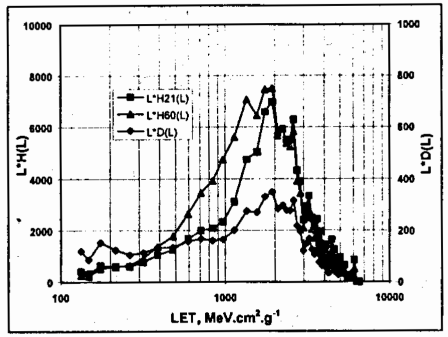

Figure 4: Microdosimetry distributions, set ***V*** irradiated by 80 MeV protons

We have observed the same behavior also in the case of sets irradiated by protons with the energy of 200 MeV. Microdosimetric distributions for these sets of detectors are presented in figures 5 and 6. One can see there that the tendencies are the same as for 80 MeV protons. Again, the sample *V* exhibits clearly higher values of differential quantities, the spectrum is also shifted to higher values of LET. The quantitative differences will be again shown and discussed more in the connection with integral values of dosimetric characteristics.

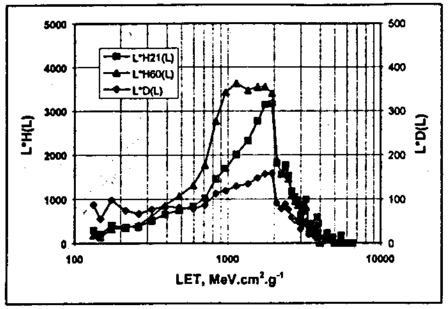

Figure 5: Microdosimetry distributions, set ***KT*** irradiated by 200 MeV protons

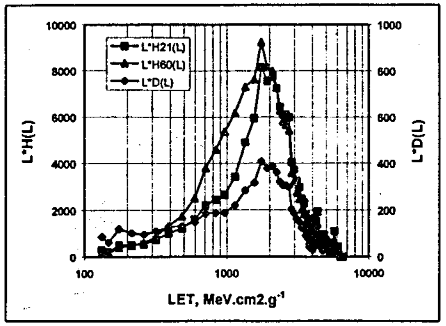

Figure 6: Microdosimetry distributions, set ***V*** irradiated by 200 MeV protons

3.2. Integral dosimetry and microdosimetry characteristics

The LET distributions in the absorbed dose and the dose equivalent enable to calculate the integral values of the dose, D, respectively. The equivalent dose, H, corresponding to the secondary particles the tracks of which are revealed. These integral values are obtained as:

$$D = \int (dN/dL) \cdot L \cdot dL; \qquad (1)$$

$$H = \int (dN/dL) \cdot L \cdot Q(L) \cdot dL; \qquad (2)$$

where dN/dL is the number of tracks in a LET interval;
L is the value of LET; and
Q(L) is the quality factor corresponding to the value of L.

The integral values of dosimetric characteristics for two sets exposed to 80 MeV protons obtained from LET distributions via the equations (1) and (2) are presented individually for each of four radiators in Table 1. One can see there that the absolute values for " bare " detectors differ substantially from other radiators. While for set ***KT*** these values are exceptionally low, for set ***V*** are exceptionally high. We do not know exactly what are the reasons for that exceptional behavior, some possibilities will be outlined below.

The integral values of dosimetric quantities for two sets exposed to 200 MeV protons are presented in Table 2, again individually for each of four radiators. Here the values for both sets of PE radiator are higher than for other radiators. Nevertheless, in this case the differences are not so pronounced particularly for the set ***V***.

Table 1: Integral values of dosimetric quantities for sets irradiated by 80 MeV protons.

Set	Radiator	D	H(21)	H(60)
		mGy	mSv	mSv
KT	bare	5.25	39.6	45.4
	PE	7.53	59.4	69.0
	bare-CR	6.74	50.3	57.6
	PE-CR	9.58	71.7	81.3
V	bare	13.88	129.7	148.4
	PE	8.12	81.8	95.1
	bare-CR	7.23	72.8	84.3
	PE-CR	6.32	61.9	72.0

Table 2: Integral values of dosimetric quantities for sets irradiated by 200 MeV protons

Set	Radiator	D	H(21)	H(60)
		mGy	mSv	mSv
KT	bare	3.59	29.3	36.3
	PE	5.27	48.2	59.8
	bare-CR	3.88	31.5	37.7
	PE-CR	3.51	28.8	35.1
V	bare	6.52	74.7	88.1
	PE	8.08	82.9	98.4
	bare-CR	7.08	83.1	96.8
	PE-CR	5.40	59.9	71.5

The average values for all radiators, except bare detector and 80 MeV protons, are presented in Table 3.

One can see there that:

1. The reproducibility of the values of integral dosimetric quantities under the different radiators is not the best for both proton energies. The relative uncertainties (1 σ_{rel}) are going up to 20 %.
2. The differences between sets ***KT*** and ***V*** are really important, particularly in the case of 200 MeV protons, where the values for the dose equivalents are about twice more high for the set ***V***. The results differ also qualitatively as it could be seen in the values of quality factors which are always higher for sets ***V***.

Table 3: Average values of integral dosimetric quantities calculated from LET spectra

Dosimetric quantity	80 MeV protons		200 MeV protons	
	set ***KT***	set ***V***	set ***KT***	set ***V***
D, mGy	7.95±1.20	7.22±0.73	4.06±0.71	6.77±0.97
H(21), mSv	60.5±8.8	72.2±8.1	34.5±8.0	75.1±9.4
H(60), mSv	69.3±9.6	83.8±9.4	42.4±10.2	88.7±10.7
Q(21)	7.6±1.6	10.0±1.5	8.5± 2.5	11.1±2.1
Q(60)	8.7±1.8	11.6±1.7	10.4 ±3.1	13.1±2.5

There is another important characteristics we are studying in this type of experiments: the relative contribution of secondary particles registered by the LET spectrometer to the ionization loss energy transfer of primary protons. As mentioned above, this dose for both proton energies was about 500 mGy. One can see in the Table 3, that this relative contribution to the ionization dose is about 1.5 % in the case of 80 MeV protons, between 0.8% (set ***KT***) and 1.4 % (set ***V***) in the case of 200 MeV protons. The value for 80 MeV protons agrees well with the results of our previous studies, while the value for 200 MeV protons is more than twice lower /9/.

We do not know exactly what are the reasons for that exceptional behavior, some possibilities will be outlined in future.

4. CONCLUSIONS

1. It was found out that the LET spectra of secondary particles between 100 and 7000 MeV.cm^2.g^{-1} do not depend on the radiator, the absolute values of both differential and integral dosimetric quantities are, however, rather different both for different radiators as well as for the detector samples from different lots of fabrication.
2. These results are rather confusing, we have not usually observed such bad reproducibility and big differences in responses behind different radiators /6,8,13,14/. We suppose that three reasons could explain that: contamination of the proton beams, not unified parameters of LUCIA II equipment during the evaluation and the differences in characteristics of ***KT*** and ***V*** detectors. The following can be told about these possibilities:
   a) The beam of 80 MeV protons, being realised by slowing down in an absorber, should be more contaminated by lower energy neutrons. However, the overresponse behind PE radiator, usually seen in the case like that is more pronounced for 200 MeV protons.
   b)The choice of parameters adopted for the evaluation by means of LUCIA II equipment is not exactly known, it should be analysed more in details.

   c)The samples KT originated from older lot of fabrication. Some kind of aging could be therefore responsible for lower response obtained.
3. The method of the LET spectra measurement with a track etch spectrometer permits to determine the contribution of secondary particles with high LET to the dosimetric quantities of the therapeutic proton beams, the absorbed dose and the dose equivalent.
4. This contribution to dosimetric quantities in proton beams with the energies of 80 and 200 MeV has been established. It was obtained that these contributions for the absorbed dose of 80 MeV protons are about 1.5 %, it is in a good agreement with previous studies. In the case of 200 MeV protons this contribution is between 0.8 and 1.2%, more than twice lower than in previous studies. If the relative contribution to absorbed dose does not exceed 1 – 2 %, its contribution to the dose equivalent may reach up to 20 % for proton beams and undoubtedly must be taken into account during beam production and radiotherapy application. Using a weighting biological functions /12/ for various biological systems instead of quality factors, our results may be compared with a study of the relative biological effectiveness of proton beams.
5. The results presented in this paper complete the results already obtained in our previous studies. However, some irregularities have been observed. The possibilities of their explanation are outlined, this will be the object of future studies.

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