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МЕТОДИКА ФИЗИЧЕСКОГО ЭКСПЕРИМЕНТА

SPECTROMETRY OF LINEAR ENERGY TRANSFER AND ITS USE IN HIGH-ENERGY PARTICLE BEAMS

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A new method to determine the spectra of linear energy transfer (LET) based on the track-etch detectors has been developed. It is based on a chemically etched polyallyldiglycolcarbonate (PADC) track detector. LET spectra are measured using the track parameters measured with an automatic optical image analyzer. The method has been recently upgraded, the calibration curves have been upgraded on the base of evaluation of detectors exposed in heavier high-energy charged particle beams. The LET spectrometer has been used to determine LET spectra and integral dosimetry characteristics along the range of protons, resp. ^{12}C ions with primary energies of 205 MeV, resp. about 480 MeV/amu; and to study the importance of fragmentation and nuclear reactions in carbon and other heavier ion beams. The results obtained are analyzed and discussed, the possible advantages of this type of equipment are outlined.

Разработан новый метод определения линейной передачи энергии (ЛПЭ), основанный на трековых детекторах, химически травленных полиаллилдигликолькарбонатах. Спектры ЛПЭ определяются на основе измерения параметров треков при помощи автоматического анализатора оптических изображений образа. Методика была недавно усовершенствована, на основе облучения в пучках тяжелых высокоэнергетичных ионов получены уточненные градуировочные кривые. Спектрометр ЛПЭ был использован для определения спектров ЛПЭ и интегральных дозиметрических характеристик вдоль пробега протонов с энергией 205 МэВ и ионов ^{12}C с первичной энергией около 480 МэВ/нуклон, а также для исследования важности фрагментации и ядерных реакций в этом и других пучках тяжелых ионов. Проведен анализ полученных результатов, подчеркиваются возможные преимущества этого типа спектрометра ЛПЭ.

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INTRODUCTION

For the understanding and describing of mechanisms inducing the damage effects, it is crucial to know interactions and energy deposition of the radiation on the cellular or subcellular level. Risks from ionizing radiation depend both on the radiation quantity (absorbed dose) and on the radiation quality (spatial and time distributions of dose and energy deposition distribution on the microscopic level). Current concept of the radiation protection is based on the connection between the quality of actual radiation and physical quantity — linear energy transfer (LET). From the radiation quality factor, one can calculate dose equivalent that is the basic quantity of radiation protection dosimetry.

In the realistic fields, it is necessary for assessing the radiation quality to determine the whole spectra of linear energy transfer. There are several techniques for the purposes of measurements the LET spectra. Some of them measure directly microdosimetry spectra (tissue-equivalent proportional counters), others are based on the determination of track-structure characteristics and on the visualization of the particle's trajectory (cloud chambers, bubble chambers, nuclear emulsions, and track detectors).

One of the methods of determination of linear energy transfer is based on the chemically etched track detectors. The track detectors are sensitive to heavier charged particles and so they can be used in various applications. Compared with other methods, they have some advantages, especially in situations where: dimensions and weight of detectors are important, high LET particles have to be characterized in low LET intense radiation beams and fields, long exposure time is expected, or active devices cannot be used (e.g., in pulsed beams), and for short accelerator time-consuming experiments.

1. MATERIALS AND METHODOLOGY

1.1. Material of Detector. The method designed to determine the linear energy transfer (LET) spectra based on the track-etch detectors has been developed at the NPI [1, 2]. Our LET spectrometer is based on a polyallyldiglycolcarbonate (PADC) track detector; the chemical formula and structure of its monomer is $C_{12}H_{18}O_7$. PADC is a clear, rigid plastic with density of about 1.30 $g \cdot cm^{-3}$. This material is one of the most sensitive track detector materials and it can directly register energetic protons, alpha particles, and heavier nuclei.

The composition of the PADC is close to the tissue; however, it is not fully tissue-equivalent. Deviations from tissue- equivalence depend on the way of its dosimetric use (direct photon dosimetry, directly registered charged particles, registration of secondary particles).

In our studies, we have used three types of PADC material: Page — formerly known as Pershore — with a thickness of 0.5 mm that is available from Page Moulgings (Pershore) Ltd (England) and Tastrak 0.5 and 1 mm thick available from Track Analysis Systems Ltd (Bristol). The usual dimension of one detector is 15×15 mm.

1.2. Detector's Evaluation. *Etching.* Before etching, the detectors are washed by alcohol to clean the surface from various dirtiness or contaminations. Then one corner of each sample used is irradiated with ^{252}Cf fission fragments and another one with ^{241}Am alpha particles. Parameters of tracks from these sources permit one to check the exact etching conditions.

The detectors are then etched in 5 N NaOH at a temperature of 70°C. This condition was found as the optimal for our purposes. The time of etching is usually 18 h (it corresponds to the removal of a one-sidelayer about 17 μm thick.

Determination of Track Parameters. From the knowledge of the etch rates, V_t (track etching rate) and V_b (bulk etching rate), particles that formed the tracks can be identified. The values of etching rates can be determined from the detailed investigation of the shape of the particle track.

The computational program was developed for the purposes of processing the results of track parameter measurement. It determines the ratio V_t/V_b for each evaluated track on the basis of determination of its parameters and parameters of normally incident fission fragment tracks from ^{252}Cf. To determine the L value of a particle, the etch rate ratio V $(V = V_T/V_B)$ was primarily established through the determination of track parameters. When all registered tracks are etched up to the end of their range, then the value of V is established from the smaller radius of the entrance ellipse b, angle of incidence α, the depth of track etch pit z

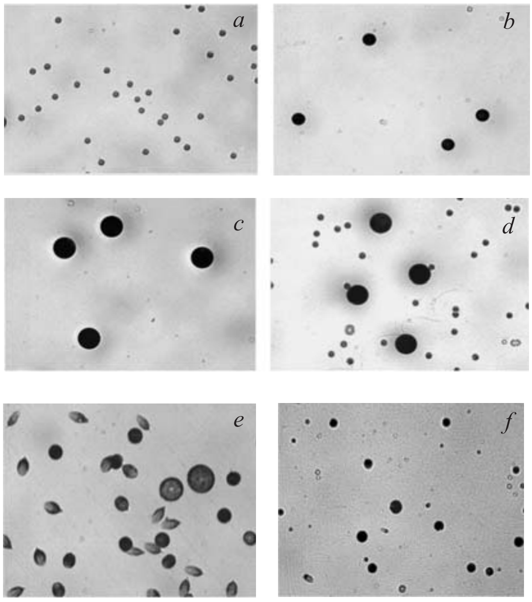

Fig. 1. Detector's surface with etched tracks; *a*) ^{16}O ions (20 keV/μm); *b*) ^{40}Ar ions (92 keV/μm); *c*) ^{56}Fe ions (402 keV/μm); *d*) blind 1 (mixture of Fe and O) from ICCHIBAN 8; *e*) ^{252}Cf fission fragments; *f*) proton induced tracks of secondary particles — plateau region

and the removed layer B as:

$$V = \frac{1 + b^2/B^2}{1 - b^2/B^2} \sin\alpha. \tag{1}$$

The track parameters are measured by means of an automatic optical image analyzer LUCIA G (Laboratory Universal Computer Image Analyzer — General). The typical track picture observed by microscope is more or less dark circles or variable ellipses. Some examples of observed tracks that correspond to different particles are shown in Fig. 1. One can see there how dimensions of tracks depend on the linear energy transfer of the particles.

Calculation of Dosimetric Characteristics. The L distributions of track numbers allow calculating the integral values of dose, D_{LET}, corresponding to particles with L above $\sim$ 7 keV/μm and, also, integral values of the «biological weighted effective dose», BWED$_L$, due to these particles. These integral values are obtained as [2]:

$$D_L = \int \frac{dN}{dL} L dL, \text{ resp.,} \tag{2}$$

$$\mathrm{BWED}_L = \int \frac{dN}{dL} L r(L) dL, \tag{3}$$

where dN/dL is the number of tracks per unit area in an dL interval; L is the value of the LET; and $r(L)$ is the biological weighting function.

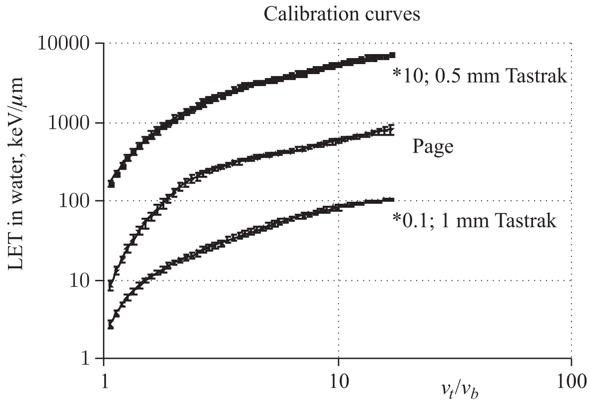

Fig. 2. Calibration curves for PADCs

The function $r(L)$ was developed on the principle to determine a single parameter estimating radiation quality for radiation therapy. The optimization of it is made so that it reproduced the RBE ratios for beams with different radiation quality; it is based on the microdosimetry approach [3–5].

To calculate these characteristics, the model of protocol was created for each detector material into which one only fills the number of tracks in individual intervals of V_t/V_b. The number of tracks is transformed to the number of tracks on 1 cm^2 and corrected with respect to the critical detection angle.

Further, it was necessary to assign values of linear energy transfer to the individual intervals of V_t/V_b. This calibration was performed by means of irradiation of detectors with various types of heavy ions with known energies (see the next chapter for details). Finally, it was necessary to assess errors of calculated integral values. These uncertainties can be divided into two parts: uncertainties in calibration curves (systematic errors) and statistical errors related to the counting of particle tracks in different energy channel. Both sources of uncertainties were combined together.

Calibration Curves. As was mentioned above, to calculate dosimetric characteristic one has to transform measured V spectra into the LET spectra. To determine the calibration curves for each PADC used, i.e., dependence $\mathrm{LET} = f(V)$, irradiation in high-energy heavier charged particle beams was performed at

• HIMAC installation (NIRS Chiba, Japan) in the framework of the ICCHIBAN programs — ICCHIBAN 2 [6], ICCHIBAN 4, and ICCHIBAN 6;

• NASA Space Radiation Laboratory (Brookhaven National Laboratory) in the framework of the ICCHIBAN NSRL program, and

• Nuclotron of the Laboratory of High Energies, JINR, Dubna.

During few years, the detectors were irradiated with various particles (up to ^{84}Kr) with LET in water from about 7 to 600 keV/μm [7, 8]. Usually for an ion beam, several absorbers were used to obtain more values of energies and LET for the same ion. All detectors irradiated were evaluated to get the values of V corresponding to the LET of a particle. Using these results, the calibration curves were obtained by means of a polynomial regression.

The calibration curves for all three materials used, Page 0.5 mm, Tastrak 0.5 and 1 mm thick, are presented in Fig. 2, together with their uncertainties. The errors of LET value range between 2 and 13 percent (average 7–8%); the higher values are for lower LET region. These curves slightly differ for each material of the detector. Threshold LET value is about 7.5, 15 keV/μm, resp. 22 keV/μm for Page, Tastrak 0.5 and 1 mm thick, resp. These threshold values correspond to the etching rate ratio $V = 1.06$ chosen with respect to the practicability and automatization of detectors evaluation.

2. RESULTS

2.1. LET Spectrometry in a Radiotherapy Proton Beam. The measurements were performed at the clinical proton beams at the Phasotron of JINR [9, 10]. The depth–dose distribution in the 205 MeV proton beam measured by means of a thin Si detector is presented in Fig. 3. The measurements of the total absorbed dose at a point of the depth–dose distribution ($D_{\rm tot}$) were performed with the thimble ionization chamber (volume 1.5 cm^3, air-equivalent material) of the KD-27012 clinical dosimeter calibrated at the reference ^{60}Co source in terms of air kerma in free air. Necessary stopping power and W/e data were taken from the last ICRU recommendations [11]. Track detectors were irradiated at various depth (0, 40, 196, 233, and 267 mm of water) using a clinical proton beam with primary energy 205 MeV. The last point is located in the Bragg peak region (see Fig. 3). The level of the absorbed dose was chosen in a way to have an optimal track density ($\sim 10^5$ cm^{-2}) in the irradiated detectors.

The LET spectrometer permits one to determine the LET distributions of dosimetry characteristics. These distributions are for absorbed dose D presented for various depths in water as $L \cdot D(L)$ in Fig. 4, normalized to the total dose at a given depth due to particles with LET above 7.5 keV/μm. The uncertainties of points presented correspond to total uncertainty. Figure 4 shows the modifications in LET distributions, because the area below a curve is proportional to the relative contribution due to particles within an LET interval. One can see there that: for depths 0 and 40 mm the secondary particles with L above 100 keV/μm dominate, and in deeper depths, the contribution of particles with L below 100 keV/μm relatively increases, being dominant in the Bragg peak region. This confirms that slowed down primary protons with energies below about 5.5 MeV [12] are directly registered.

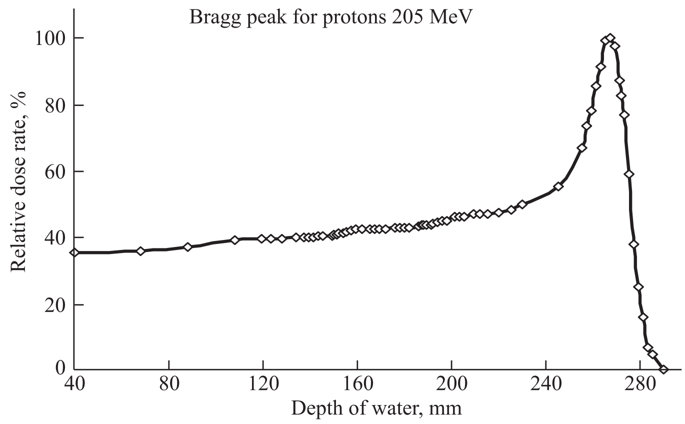

Fig. 3. Relative depth–dose distribution in 205 MeV proton beam measured with thin Si detector

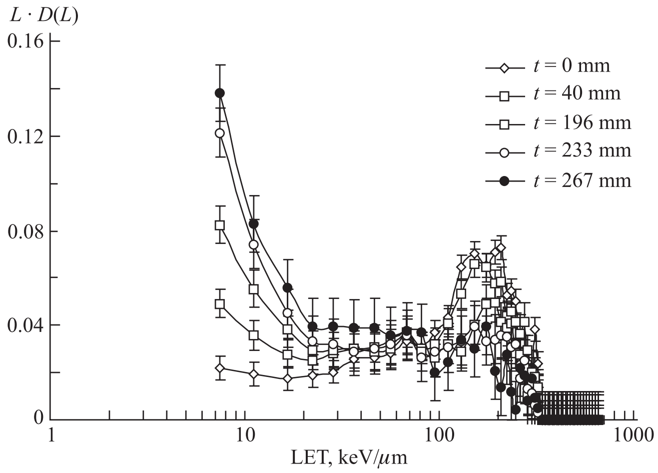

Fig. 4. $L \cdot D(L)$ distributions for different depth in water and 205 MeV proton beam, normalized at each depth to the dose due to particles with LET above 7 keV/μm

First, we calculated the contribution to absorbed doses of particles with LET higher than 7 keV/μm. This contribution is the ratio of the dose measured by track detectors, D_L, to the total dose measured by ionization chamber of the clinical dosimeter, $D_{\rm tot}$, equal to the sum of the dose from particles with L below threshold, $D_{<\rm thr}$ and D_L. This contribution regularly increases (see Fig. 5) with the depth, particularly at deeper depths. In the Bragg peak region it reaches the value above 50%. It supports the idea that the tracks of primary protons are already registered there.

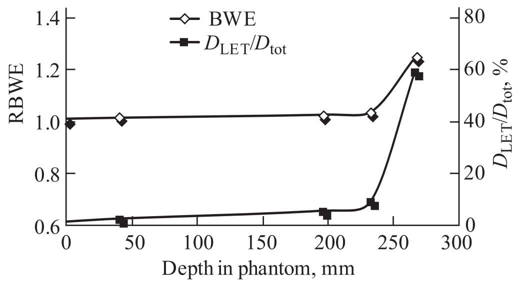

Fig. 5. $D_{\rm rel} = D_L/D_{\rm tot}$ and RBWE in 205 MeV proton beam as a function of residual proton energy

The value of relative biological weighted effectiveness RBWE in proton beam was calculated as:

$$\mathrm{RBWE} = \frac{\mathrm{BWED_{tot}}}{D_{\rm tot}}, \tag{4}$$

where $\mathrm{BWED_{tot}} = D_{<\rm thr} + \mathrm{BWED}_L$, and $D_{\rm tot} = D_{<\rm thr} + D_L$.

Their values as a function of the depth in water are also presented in Fig. 5. One can see there that RBWE values are about 1.02 at the entrance to the phantom; they increase up to 1.25 in the Bragg peak region.

The values of RBWE obtained in our measurements correlate well with the results of recent studies of radiobiological effectiveness. Paganetti [13] calculated relative biological effectiveness for 160 MeV protons using a Monte-Carlo approach and obtained for the Bragg peak region the value about 1.2–1.3 for the inactivation of V79 cells after the total dose 2 Gy. Tang et al. [14] studied the survival fraction of the Chinese hamster ovary cells in the beam of

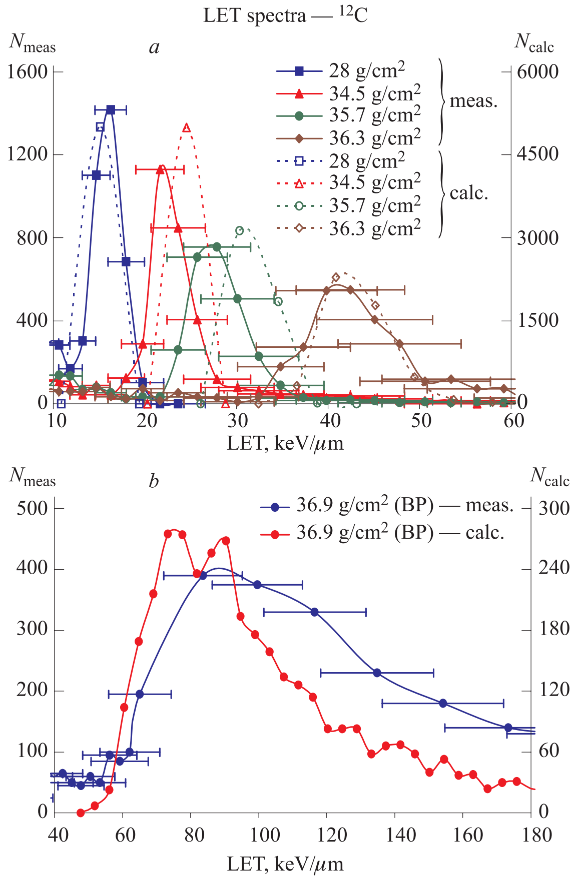

Fig. 6. Track number distributions in LET measured with LET spectrometer and calculated with SRIM code

65 MeV protons. They found a RBE of 1.19 for the surviving level 0.1. Similar results were obtained in measurements with the Chinese hamster V79 cells at the JINR Phasotron, where it was found that the RBE increases from 1.02 at the beam entrance to 1.23 at the Bragg peak [15]. So, the RBWE values obtained from track detectors are close to radiobiological measurements.

2.2. Dosimetry and Microdosimetry Studies in ^{12}C Beam. The experiment in carbon beam with primary nominal energy 500 MeV/amu was performed at the Nuclotron, JINR, Dubna [16]. The track detectors (Page) were exposed at several positions in the beam — at the entrance, behind the 28.1 and 32.3 g/cm^2 thick plexiglass (PMMA) plates, and at several positions in the Bragg peak region (from 34.6 to 38.6 g/cm^2). The beam intensity was about $5 \cdot 10^4$ ions/pulse (to obtain an optimal track density); the detectors were irradiated with one pulse — this corresponds to the dose at the entrance about 80 μGy.

The examples of LET spectra of absorbed dose determined by the LET spectrometer in various depths (at the entrance, before, at and behind the Bragg peak (BP)) in the plexiglass for carbon ion beam are presented in Fig. 6.

One can see the shifting of the spectra towards higher values of LET with the increasing depth in plexiglass as particles are slowing down; the spectra are also getting broader due to the energy and angular straggling, particularly in the BP region. The passage of carbon ions through the PMMA (density 1.17 g/cm^3) was also simulated by means of the SRIM program [17]. A rather good agreement of measured and calculated spectra was observed (considering the uncertainties) for the peak of carbon ions up to the Bragg peak region.

From the LET spectra, dosimetric characteristics can be calculated (see Eqs. (1) and (2)). The values of *relative biological weighted efficiency (RBWE)* was found to range from 1.07 at the beam entrance up to about 3 at the depth of 36.3 g/cm^2 (immediately before the Bragg peak). In the Bragg peak, *RBWE* falls to value of about 2. This should be taken into account during the therapy planning.

2.3. Fragmentation Processes in Heavy Charged Particle Beams. Energy of particles passing through the matter (absorber) decreases due to inelastic losses, they can also interact with nuclei, and they may undergo a nuclear fragmentation. For higher depths the role of nuclear processes increases. The effect of both these processes is demonstrated in Fig. 7 for C ions and also in Fig. 8 for some other heavier particles [18]. One can see there that:

• The main peak shifts to higher values of LET behind an absorber.

• At the same time, some tracks with lower LET appear, they correspond to fragments and/or products of nuclear interactions of primary particles.

The importance of the nuclear processes of heavier ions used in radiotherapy consists in the fact that they diminish the number of primary ions and they produce additional ionization before and also behind the Bragg peak region. Nuclear fragmentation of heavier ions also modifies the radiation field behind a shielding. Heavy nuclei represent an important part of galactic cosmic radiation; the knowledge of fragmentations is important for radiation protection of astronauts.

The increasing importance of fragmentation processes with the increasing depth in the plexiglass for ^{12}C ions is shown graphically in Fig. 7. We made an attempt to distinguish the contribution from primary carbon ions and from fragments to the total dose [19]. These contributions are presented in Table 1.

One can see there that the primary nuclei have in the beginning enough energy to produce fragments and so the flux and the energy deposition of fragments increase, up to the depth of about 34.5 g/cm^2, where contribution of fragments comprises about 30% of the absorbed

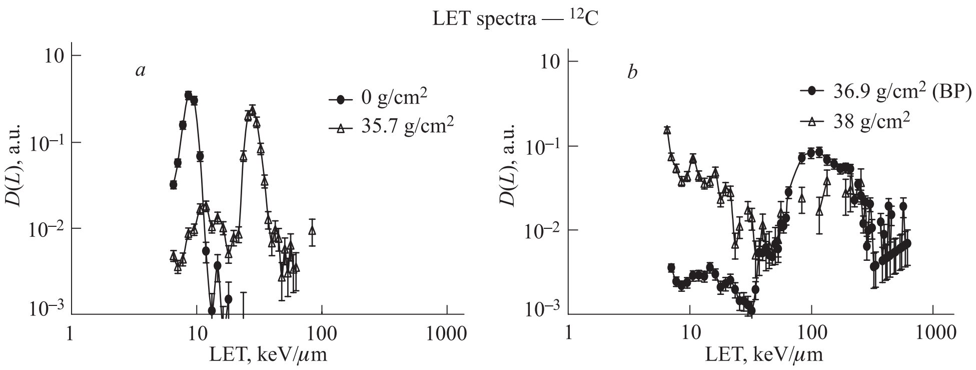

Fig. 7. Track distributions in LET (with statistical uncertainties)

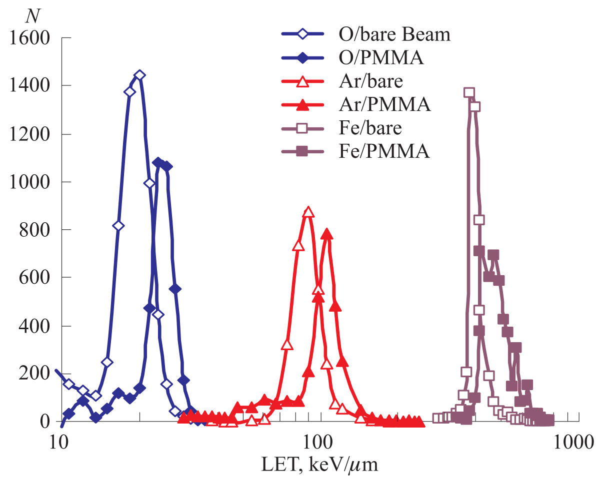

Fig. 8. LET spectra of various ions (^{16}O, ^{40}Ar, ^{56}Fe) in Page PADC

Table 1. **Relative contribution to the dose from primary ^{12}C ions (480 MeV/amu)**

Depth, $g \cdot cm^{-2}$	Dose from prim. particles, a.u.	Dose from fragments, a.u.
0	97.4 ± 5.6	2.3 ± 0.6
28	82.1 ± 4.8	17.9 ± 1.0
32.1	80.3 ± 5.1	19.7 ± 0.9
34.5	69.5 ± 4.6	30.5 ± 1.3
35.1	75.3 ± 5.5	24.7 ± 1.2
35.7	77.1 ± 5.2	22.9 ± 0.9
36.3	80.3 ± 4.6	19.7 ± 1.0

dose. With the increasing depth, especially closer to and in the BP region, the ionization losses (LET) and also energy deposition of primary ions rapidly increase, while the fragments production becomes relatively less important.

In the last few years our detectors have been exposed also to other heavier ions. An example (^{16}O, ^{40}Ar, and ^{56}Fe ions) is presented in Fig.8. We have tried to estimate the contribution of fragments to the absorbed dose also in these cases. Without the absorbers there would be theoretically no secondary particles; nevertheless, we measured that the fragments and secondary particles contribute to the absorbed dose a few percent (3–9%). It may originate from the fragmentation and nuclear reactions in the air or in the ion-conduit. The relative contributions of fragments to the absorbed dose measured with the LET spectrometer are summarized in Table 2. The measured data are also compared with the ones obtained by means of simulation (for broad monoenergetic beams) using the PHITS code [20]. Most of the data are in quite good agreement (when the uncertainties are taken into account); nevertheless, for 440 MeV/amu ^{40}Ar ions behind PMMA, 130 MeV/amu ^{56}Fe ions behind the PMMA, and 1 GeV/amu ^{56}Fe ions behind the aluminum we measured higher values. Some discrepancies may be caused by simplification in our simulations (e.g., simpler geometry of

Table 2. **Relative contribution from fragments to the absorbed dose**

Ions and primary energies	Depths, g/cm^2	Dose from fragments, %	
		PHITS	LET spectrometer
^{16}O, MeV/amu	10.0	18.6	16.3 ± 1.3
^{16}O, MeV/amu	54.0 (Al)	31.0	34.4 ± 1.9
^{40}Ar, MeV/amu	5.25	22.0	30.2 ± 1.7
^{40}Ar, MeV/amu	9.00	35.3	34.4 ± 2.2
^{56}Fe, MeV/amu	0.35	4.0	11.5 ± 0.7
^{56}Fe, MeV/amu	5.00 (H_2O)	33.0	34.3 ± 2.1
^{56}Fe, MeV/amu	5.00 (Al)	10.6	13.3 ± 1.5
^{56}Fe, GeV/amu	10.0 (Al)	15.5	21.2 ± 1.8

the experiments); the detectors could register also some tracks originating from interactions in surrounding material, not only those created in the absorber or in the detector itself.

The production of fragments depends on the material of the absorber. From Table 2 one can see that for iron ions the contribution to the absorbed dose is higher behind the water than behind the aluminum absorber, both with a thickness of 5 g/cm^2. This is in agreement with results published in [21], where the fragmentation of 1 GeV/amu iron ions was investigated in lead, aluminum, and PMMA target.

The relative absorbed dose from fragments also depends on the energy and atomic number of primary ions; with the increasing energy and Z of the primary ion the fragment production also increases.

CONCLUSIONS

The main conclusions that can be drawn from the results of our studies can be summarized as follows:

1. TED-based LET spectrometry permits one to characterize both quantitative and qualitative characteristics in heavier high-energy charged particles potentially usable in ion radiotherapy. In some cases, the method permits one to acquire the characteristics only very difficult to obtain with other types of radiation detectors.

2. When the method is used for the detection and dosimetry of directly registered particles, it is able to acquire full and complex information on the radiation quantity and quality. Minimum detectable absorbed doses are in such cases below 0.1 mGy. When secondary particles are registered (like for high-energy protons before the Bragg peak region), minimum measurable dose increases to about 1 mGy.

Further studies related to the development of the method and the appreciation of radiation quality and quantity would be concentrated on:

1. Comparison of experimental results obtained with properly chosen calculations. Some of such calculations to be performed would be:

a) Contributions of secondary particles to the absorbed dose in bremsstrahlung photon and high-energy proton, respectively, therapy beams. Collaboration in this direction has already started [23].

b) The importance of fragmentation and other nuclear processes in the energy deposition in heavier particles therapy beams. Further calculations by means of PHITS code (Iwase et al., 2002) will continue, we have started to collaborate also with teams using another code for this purpose — SHIELD HIT [23].

2) For further improvement of the experimental procedure it would be useful:

a) To refine further the procedure assuring regular check of the quality of delivered materials.

b) To search for other materials with, when possible, better and more reproducible quality for LET spectrometry. Some steps in this direction have already been started (USA, France, Japan).

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