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RECOMBINATION METHODS FOR BORON NEUTRON CAPTURE THERAPY DOSIMETRY

NATALIA GOLNIK,
PIOTR TULIK,
MIECZYSŁAW ZIELCZYŃSKI

Institute of Atomic Energy, 05-400 Otwock-Świerk, Poland

OTWOCK - ŚWIERK

Natalia Golnik, Piotr Tulik, Mieczysław Zielczyński: Recombination Methods for Boron Neutron Capture Therapy Dosimetry. The radiation effects of boron neutron capture therapy (BNCT) are associated with four-dose-component radiation field - boron dose (from the $^{10}B(n,\alpha)^{7}Li$ reaction), proton dose from the $^{14}N(n,p)^{14}C$ reaction, neutron dose (mainly fast and epithermal neutrons) and gamma-ray dose (external and from the capture reaction $^{1}H(n,\gamma)^{2}D$). Because of this, the relation between the absorbed dose and the biological effects is very complex and all the above mentioned absorbed dose components should be determined. From this point of view, the recombination chambers can be very useful instruments for characterisation of the BNCT beams. They can be used for determination of gamma and high-LET dose components and for characterisation of radiation quality of mixed radiation fields by recombination microdosimetric method (RMM). In present work, a graphite high-pressure recombination chamber filled with nitrogen, $^{10}BF_3$ and tissue equivalent gas was used for studies on application of RMM for BNCT dosimetry. The use of these gases or their mixtures opens a possibility to design a recombination chamber for determination of the dose fractions due to gamma radiation, fast neutrons, neutron capture on nitrogen and high LET particles from (n,^{10}B) reaction in simulated tissue with different content of ^{10}B.

Natalia Golnik, Piotr Tulik, Mieczysław Zielczyński: Rekombinacyjne metody dozymetryczne dla terapii borowo-neutronowej. Skutki radiacyjne terapii borowo-neutronowej (TBN) są związane z czterema składnikami dawki pochłoniętej: dawką borową (z reakcji $^{10}B(n,\alpha)^{7}Li$), dawką protonową (z reakcji $^{14}N(n,p)^{14}C$), dawką neutronową (z oddziaływania neutronów epitermicznych i prędkich z atomami tkanki) i dawką promieniowania gamma (zewnętrznego i z reakcji $^{1}H(n,\gamma)^{2}D$). Korelacja skutków biologicznych z dawką jest więc bardzo złożona i wszystkie wspomniane składniki dawki powinny być wyznaczane. Z tego punktu widzenia komory rekombinacyjne wydają się być bardzo przydatnymi detektorami w dozymetrii dla TBN. Komory te mogą być użyte do wyznaczania składowej dawki od promieniowania gamma i składowej dawki od cząstek z wysokim LET, a także - stosując rekombinacyjną metodę mikrodozymetryczną (RMM) - do oceny jakości promieniowania mieszanego. W przedstawianej pracy posłużono się wysokociśnieniową grafitową komorą rekombinacyjną - wypełnianą azotem, trójfluorkiem boru i gazem równoważnym tkance - w celu zbadania możliwości zastosowania RMM w TBN. Użycie tych gazów otwiera możliwość zaprojektowania komór rekombinacyjnych pozwalających bezpośrednio wyznaczyć składowe dawki pochłoniętej w symulowanych tkankach z różną zawartością ^{10}B.

Наталия Гольник, Пётр Тулик, Мечислав Зельчинский: Рекомбинационные методы дозиметрии в бор-захватной терапии. Радиационные последствия бор-захватной терапии (БЗТ) связаны с четырьмя составляющими поглощённой дозы: борной дозой (реакция $^{10}B(n,\alpha)^{7}Li$), протонной дозой (реакция $^{14}N(n,p)^{14}C$), нейтронной дозой (взаимодействие эпитермических и быстрых нейтронов с атомами ткани) и дозой гамма-излучения (внешнего и согласно реакции $^{1}H(n,\gamma)^{2}D$). Поэтому сопоставление биологических эффек-тов с поглощённой дозой довольно сложно, и следует определять все упомянутые составляющие дозы. С этой точки зрения может оказаться очень полезным применение рекомбинационных камер в качестве дозиметрических детекторов БЗТ. Эти камеры можно использовать для определения дозы гамма-излучения и дозы создаваемой части-цами с высоким ЛПЭ и также – применяя рекомбинационную микродози-метрическую методику (РММ) – для оценки качества смешанного излучения. В предста-вленной работе применялась графитовая камера высокого давления, наполняемая азотом, трёхфтористым бором и тканеэквивалентным газом. Использование этих газов открыло возможность запроектировать рекомбинационные камеры позволяющие непосредственно определять составляющие поглощённой дозы в симулируемых тканях с разным содержанием ^{10}B.

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1. INTRODUCTION

Boron neutron capture therapy (BNCT) is a binary bio-targeted therapy, considered as a possible way to cure some kinds of malignant tumours, which up to now cannot be successfully treated in any other way. Physical concept of the method is based on nuclear reaction that occurs when a nucleus of boron (^{10}B) captures thermal neutron, producing an α particle and lithium ion:

$$ {}^{1}_{0}n + {}^{10}_{5}B \rightarrow {}^{7}_{3}Li + {}^{4}_{2}\alpha $$

The therapy is based on physiological rather than physical, targeting of radiation. This is achieved by the administration to the patients of boron-containing compounds which have the property to accumulate selectively in the tumour tissue and much less in the immediate surrounding.

Following the accumulation of boron, the tumour area in the patient's body is externally irradiated with low-energy (epithermal) neutrons produced by a nuclear reactor. The neutrons pass some layer of tissue and slow down to thermal energies before reaching the tumour area. The boron atoms accumulated in tissue absorb thermal neutrons and then release two heavy charged particles (^{7}Li and ^{4}He) that dissipate most of their energy within the volume of a single cell. This binary process damages the involved cell, while both boron drug and thermal neutrons alone are to some extent innocuous to tumour and normal tissues. Because the boron concentrates in the tumour cells, the cancer can be destroyed, while the normal cells nearby receive the acceptable radiation dose.

Presently, BNCT is experimentally used for treatment of glioblastoma. Clinical trials of BNCT were initiated at few reactors in Europe, USA and Japan. The studies (of Phase II according to medical nomenclature) showed that the treatment was tolerated well and that the median survival was better than available best care. Results of these studies were promising enough to promote a decision about construction of a BNCT beam line at Polish research reactor MARIA.

It has been generally recommended that for BNCT to be successful, a thermal neutron fluence of about 5×10^{12} n cm^{-2} should be delivered to a tumour with ^{10}B concentration of 30 μg per gram of tissue. For clinical trials it is thought that epithermal neutrons (neutron energies between 1 eV and 10 keV) are optimum for the treatment. Epithermal neutrons thermalize at a depth of about 2.5 cm. Therefore, they can provide a maximum thermal neutron flux density at the tumour site with a minimum damage to normal tissue. Production of sufficient fluence of epithermal neutrons, with acceptably low background of high energy neutrons and of gamma radiation, requires special nuclear reactor features. As a consequence, the construction of the BNCT facilities is justified only at some of the existing reactors. Some reactors can be adapted for BNCT by use of fission converters. This is also the case of Polish research reactor MARIA in Świerk near Warsaw. The technical concept of such facility was elaborated in the Institute of Atomic Energy. At present, the facility is under construction [1].

From dosimetry point of view, the BNCT beams are very complex mixed radiation fields, because of rather broad neutron energy range, presence of gamma contamination and necessity of precise determination of several dose components. Despite of already long time experience, the dosimetric characterization of such beams is still a challenging task. Therefore, the development of measuring methods for characterisation and monitoring of the beam is of interest in all BNCT centres, both clinical and research.

This work presents the improvements of recombination dosimetric methods, which are proposed for dosimetry of BNCT beams.

2. RECOMBINATION CHAMBERS

Recombination chambers are high-pressure, tissue-equivalent ionisation chambers operated in unsaturated mode, under conditions of initial recombination of ions. Usually, such chambers contain several parallel-plate tissue-equivalent electrodes spaced by few millimetre gaps. Mostly, the chambers are filled with tissue-equivalent gas mixtures up to the pressure of some hundreds of kilopascals. The electrical charge created between the electrodes is proportional to the absorbed dose, while the shape of the saturation curve of the chamber provides information on radiation quality [2, 3, 4].

The operational principle of the chambers is based on the phenomenon of initial recombination of ions in the gas filling the chamber. Therefore it is possible to determine not only the absorbed dose to tissue, but also, when using the recombination microdosimetric method (RMM) [3, 5, 6], to get information about the distribution of the absorbed dose versus local ionisation density or versus restricted linear energy transfer (LET).

Recombination chambers are used mostly for radiation protection at workplaces [3, 7, 8], as they are especially suitable for determination of the ambient dose equivalent in unknown stray radiation fields. The chambers can also be applied for medical beam dosimetry, however, the RMM was not used for this purpose yet. For RMM it is necessary to measure the ionisation current at low polarising voltages, where the volume recombination becomes a limiting factor at high dose rates. Therefore, up to now only the absorbed dose and the recombination index of radiation quality [9] were measured in medical beams [10].

The information on initial recombination needed for RMM can be extracted from the ionisation current measured at low polarizing voltages, by proper separation of volume recombination and back diffusion of ions from the initial recombination. In this work, the method used for such separation was improved and extended to higher dose rates. The method was proved experimentally for tissue equivalent chamber.

As it was mentioned above, the recombination chambers are usually tissue equivalent, in order to simulate the so called standard soft tissue. However, the composition of a particular tissue, being of interest for radiation biology and radiation therapy (e.g. skin, eye, fat, brain, vein), is somewhat different. The difference becomes drastically important in case of BNCT, because even small amount of ^{10}B introduced to the tissue, changes considerably the absorbed dose, as compared to the dose measured using TE ionisation chamber of standard composition. Also the contain of nitrogen is essential for the dosimetry and especially for microdosimetry for BNCT.

It is expected that the response of the recombination chamber can be, to some extent, adjusted to the actual needs by the use of different filling gases. In this work, a chamber filled with nitrogen and $^{10}BF_3$ was used in order to investigate a possibility of using the RMM with chambers filled with different gases. In future, these gases and their mixtures with tissue-equivalent gas could be used for simulating malignant and healthy tissues subjected to BNCT, with a given content of ^{10}B.

Recombination chambers were also used for determination of neutron and photon kerma in a reactor beam. Two measuring methods were compared in this experiment - a recombination microdosimetric method, RMM (a simplified approach [3, 4, 6]) and a twin-detectors method [11], with the C-CO_2 chamber as a neutron insensitive detector [3]. Determination of kerma components by simplified RMM is based on measurements of ion collection efficiency for several values of the polarising voltage U_j, in the investigated radiation field, $f(U_j)$, and in a reference field of ^{137}Cs gamma radiation source, $f_\gamma(U_j)$. Then, the photon component, Γ, (ratio of

the photon kerma to the total kerma in tissue) can be determined by fitting the set of equations (1) to the experimental data.

$$f(U_j) = \Gamma\ f_\gamma(U_j) + \frac{1-\Gamma}{1+\dfrac{1-f_\gamma(U_j)}{f_\gamma(U_j)}\,\nu_{ef}} \tag{1}$$

where ν_{ef} is the relative local ionisation density of the neutron component (relatively to local ionisation density of ^{137}Cs gamma radiation).

For comparison, the neutron and photon components of the tissue kerma were determined by twin-detectors method using two detectors of different neutron sensitivity. Commonly, two ionisation chambers are used, for example, a tissue-equivalent ionisation chamber combined with a C-CO_2, "neutron-insensitive" chamber, operated at atmospheric gas pressure. Because the C-CO_2 chambers have also some sensitivity to neutrons, the classical method requires information about the neutron spectral fluence of the radiation field, the sensitivity of the detectors as a function of neutron energy, and the fluence-to-kerma conversion coefficients in materials of both detectors. In our method, the high-pressure C-CO_2 chamber, operated at low polarising voltages was used. Under such conditions, the recombination of the ions generated in tracks of secondary particles with high LET is considerably greater than for low-LET tracks. As a result, the relative neutron sensitivity k_U of such chambers is much lower than those operated at saturation and depends on the voltage applied. The earlier calculations and measurements [3] showed that for chambers filled with CO_2 under the pressure of few MPa the value of k_U is below 0.03 for neutron energies of up to 15 MeV supposing that the collecting electric field strength in the chamber cavity does not exceed 200 V/cm.

3. METHOD OF ACCOUNT FOR VOLUME RECOMBINATION AND BACK DIFFUSION OF IONS

In contrary to the initial recombination, the volume recombination depends on the dose rate. This physical feature can be therefore used in order to distinguish between the two processes of ion recombination. Moreover, the initial recombination occurs just after formation of the charged particle track, before the ions diffuse to the distance of few hundreds nanometres. The volume recombination takes the rest of the time of ion collection in the chamber. This means that the initial and volume recombination can be considered as consecutive processes, i.e. the ions that may recombine in volume recombination are those which already escaped from the initial recombination process.

The third process, which may influence the ion collection in the chamber is the back diffusion of ions. This process strongly depends on voltage between the chamber electrodes and it may play any considerable role only below approximately 20 V. It was assumed in this work that this process occurs after the volume recombination. The assumption is made for simplicity. Generally, the correction for back diffusion of ions is small and even much more detailed consideration of the model, assuming the simultaneous volume recombination and back diffusion, causes only minor change of the final result.

With the above assumption, one can express the ion collection efficiency in an ionisation chamber as:

$$f = f_d f_V f_i \tag{2}$$

where the ion collection efficiency $f(U) = I(U)/I_S$ is the ratio of the ionisation current I, measured at the polarising voltage U, to the saturation current I_S, f_d is ion collection efficiency in the process of back diffusion of ions, f_V - the ion collection efficiency of the volume recombination and f_i the ion collection efficiency of the initial recombination of ions.

Back diffusion of ions in a parallel-plate ionisation chamber can be expressed as [12]:

$$f_d = 1 - \frac{2kT}{eU} + \frac{2}{\exp(eU/kT) - 1} \tag{3}$$

or in the form more suitable for numerical computations

$$f_d = 1 - \frac{2kT}{eU} + \frac{2\exp(-eU/kT)}{1 - \exp(-eU/kT)} \tag{4}$$

where T is the absolute temperature, k is the Boltzmann constant and e is the electron charge.

Up to now, the formula (3) was checked experimentally only for air under atmospheric pressure. We confirmed experimentally that the equation was valid also for CO_2, N_2 and tissue equivalent gas, in a broad range of gas pressure.

According to the theory of Boag [13], the ion collection efficiency of volume recombination in a parallel-plate ionisation chamber is given by:

$$f_V = \frac{2}{1 + \sqrt{1 + \frac{4aI_V}{U^2}}} \tag{5}$$

where a is a constant dependent on the chamber and its gas filling, and $I_V = I_S f_i$ is the ionisation current after initial recombination.

Taking into account that $f = f_d f_V f_i$ one has:

$$f = \frac{2 f_d f_i}{1 + \sqrt{1 + \frac{4aI_S f_i}{U^2}}} \tag{6}$$

$$\sqrt{1 + \frac{4aI_S f_i}{U^2}} = \frac{2 f_d f_i}{f} - 1 \tag{7}$$

$$1 + \frac{4aI_S f_i}{U^2} = \left(\frac{2 f_d f_i}{f}\right)^2 - \frac{4 f_d f_i}{f} + 1 \tag{8}$$

and finally:

$$f = f_d f_i - \frac{aI_S f^2}{U^2 f_d} \tag{9}$$

The constant a, can be, therefore, determined from the measurements of ion collection efficiency at different values of I_s, i.e. at different dose rates. An example of such procedure is shown in Fig. 1, where the plot of f versus $I_S f^2/U^2 f_d$ was fitted with the set of straight lines (each line corresponds to one value of the polarising voltage U, i.e. to one value of f_i). The fit was performed with the constraint of the same slope for all the lines. The slope determines the value of the parameter a, needed for correction for volume recombination. The value of f_d is known

from the eq. (3), so the crossings of lines with the abscissa in Fig. 1 determines f_i for each polarising voltage. Once determined, the value of the constant a, can be used in calculations of volume recombination for all the measurements performed with the same chamber.

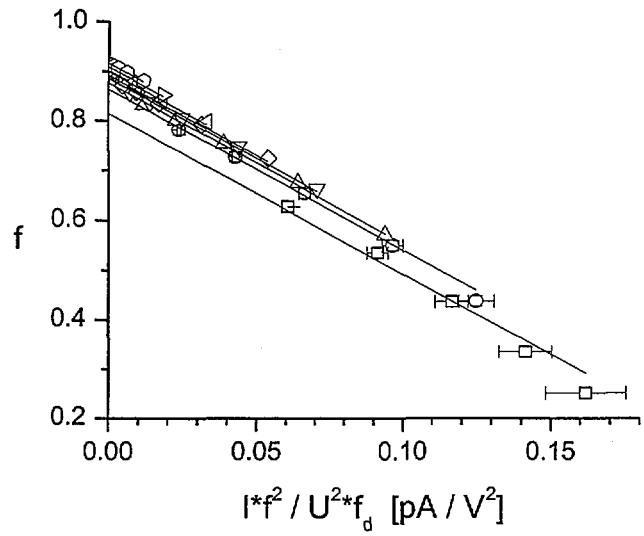

Fig. 1. Ion collection efficiency measured at different dose rates, plotted versus $I_S f^2/U^2 f_d$ and fitted with the set of straight lines which corresponds to certain values of the polarising voltage U - from 1 V (bottom line) to 12.7 V (upper line).

Figure 2 illustrates the contribution of the volume recombination and back diffusion of ions to the total recombination of ions in REM-2 chamber. It can be seen, that in agreement with theoretical predictions, the initial recombination is almost independent of polarising voltage at low electric field strength. The lines that represent the values of $f = f_d f_V f_i$ fit well all the experimental points. Therefore, even large corrections for volume recombination, up to 50% of the measured value, can be successfully introduced.

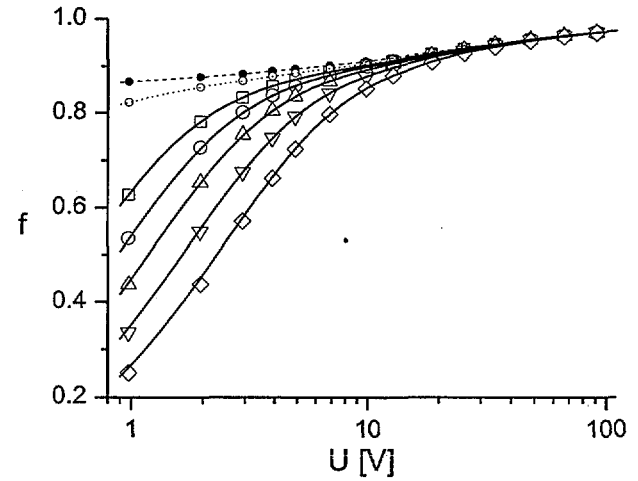

Fig. 2. Saturation curves of the REM-2 chamber, measured at different dose rates (open polygons). The values of $f_d f_i$ obtained from the fit to Eq. 9 – (the lines in Fig.1) are depicted by small open circles and dotted line, and the finally calculated values of f_i are marked by black circles and dashed line. The solid lines were generated as $f = f_d f_V f_i$ for each dose rate using the interpolated values of f_i – dashed line.

4. MEASUREMENTS

Four different recombination chambers were used in present work. Main parameters of the detectors are displayed in the Table 1.

Type	Volume [cm^3]	Geometry	Distance between electrodes [mm]	Gas	Gas pressure [MPa]	References
REM-2	1800	Parallel plate	7	Tissue equivalent	1	[4], [15]
KG2	150	Cylindrical	20	CO_2 N_2 $^{10}BF_3$	2.5 1.5 0.18	[4]
F-1	3.8	Parallel plate	1.75	Tissue equivalent	0.7	[4], [10]
G-5	7	Cylindrical	2	CO_2		[4], [16]

The methods of separation the initial recombination in presence of volume recombination, were analysed using the data collected [14] with tissue equivalent recombination chamber of REM-2 type. The chamber was irradiated at different dose rates in the reference field of ^{137}Cs gamma radiation source in calibration hall at the Institute of Atomic Energy [17].

The studies on RMM were performed with a cylindrical graphite chamber of KG2 type. The chamber was consecutively filled with nitrogen and with BF_3, highly enriched with ^{10}B. Initial recombination in pure nitrogen is very low, therefore the high pressure of gas was used (1.5 MPa) and about 1% of air was added to the gas in the chamber cavity. BF_3, which is a relatively heavy gas, was used at relatively low pressure (0.18 MPa), comparing with other recombination chambers. The chamber was irradiated in mixed neutron - gamma radiation field of ^{239}Pu-Be source, exposed either bare or inside of a spherical filter. Additionally, the chamber was always shielded with 3 cm of lead, in order to decrease the gamma component of the radiation field. The use of the Pu-Be source makes it possible to create the radiation field with a flux of thermal, epithermal and fast neutrons which is suitable and convenient for investigations of dosimetric methods, however, the total flux is much lower than those in reactor beams. The neutron emission rate from the bare source was $2.78 \cdot 10^7$ s^{-1}. This created the radiation field with the neutron tissue-kerma rate of ca. 200 μGy/h at the distance of 0.5 m from the source. The gamma-kerma rate at this distance was equal to ca. 50 μGy/h. Paraffin and iron filters, both with the wall thickness of 10 cm, were used in order to have the radiation fields with different neutron spectra. The paraffin filter considerably moderates neutrons and increases the gamma-to-total kerma ratio more than 2 times. The iron filter slightly moderates neutrons and reduces the gamma-to-total kerma ratio by factor of about 2 [18]. The earlier results of the measurements performed in the same radiation fields with REM-2 chamber filled with tissue equivalent gas (methane + 5% of nitrogen) were used for comparison.

Two other recombination chambers of different types were used for comparison of RMM with twin-detectors technique. The first one was a tissue-equivalent, in-phantom chamber of F-1 type. The chamber has three ∅ 34 mm electrodes and the wall thickness of 0.6 g/cm^2. The second chamber was a high-pressure graphite ionisation chamber of G-5 type. This is a cylindrical chamber of 115 mm in length and 18 mm in diameter. The chamber is enclosed in

a 0.3 mm thick aluminium container. It was operated with low collecting voltage (20 V) in order to provide the conditions of strong initial recombination of ions in the high-LET particle tracks. Volumes of both chambers, hence their sensitivities, are too low to use them in the field of the Pu-Be source. Therefore, the chambers were used at the H8 channel of the reactor MARIA.

5. RESULTS AND DISCUSSION

Basic studies on RMM for different gases were performed in radiation fields of the isotopic neutron source ^{239}Pu-Be. The obtained results are shown in Fig. 3, in the form of the dose distributions versus restricted LET. The range of LET was split in this work to the following compartments: I - below 20 keV/μm, II - from 20 keV/μm to 50 keV/μm, III - from 50 keV/μm to 100 keV/μm, IV - from 100 keV/μm to 200 keV/μm and V - above 200 keV/μm. Results for different gases are arranged in rows (TE gas, nitrogen and $^{10}BF_3$ from the top to the bottom). Results for different radiation fields are shown in columns of the Fig. 3 (bare source, the source in paraffin filter and in iron filter – from the left to the right). The area of the plots in the figure is normalised to the unit dose, therefore the plotted bars represent the relative contributions of radiation with LET from certain compartments. The values of measured saturation currents, associated with certain compartments are presented in Table 2, for the KG2 chamber filled with nitrogen and $^{10}BF_3$. The measurements with TE gas were performed using the REM-2 chamber, therefore the values of the ionisation current cannot be directly compared.

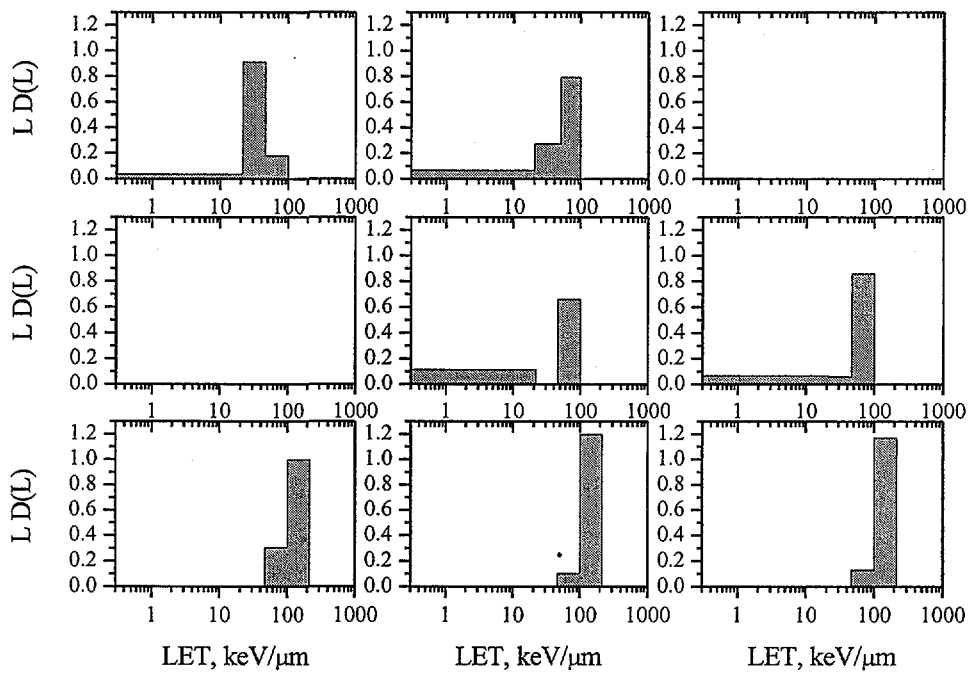

Fig. 3. Dose distributions versus restricted LET. Results for different gases are arranged in rows (TE gas, nitrogen and $^{10}BF_3$ from the top to the bottom). Results for different radiation fields are shown in columns (bare source, the source in paraffin filter and in iron filter – from the left to the right).

The use of paraffin and iron filters modifies the spectrum of the ^{239}Pu-Be source [17, 18]. The paraffin filter considerably increases the fluence of thermal neutrons and also gamma component of the absorbed dose. Because of this, in TE gas (5% of nitrogen), the source in paraffin filter gives higher contribution to the compartment III than the bare source. In nitrogen, where the neutron dose is mostly due to protons from neutron capture reaction, only the compartment III and I (gamma radiation) are seen in the dose distributions. Also the relative gamma contribution to the absorbed dose in nitrogen is higher than in TE gas because of lower contribution from fast neutrons.

In $^{10}BF_3$, the compartment IV, associated with high-LET particles from thermal neutrons capture, is the most pronounced for all the investigated radiation fields. The relative contribution of fast neutrons (associated mainly with the compartment III) decreases when the source is placed in the filters. Table 2 presents the values of partial saturation current associated with certain compartments (i.e. the products i_0D_i of saturation current and fractions of the absorbed dose associated with certain compartment). It can be seen that the ionisation current greatly increases when the paraffin filter is used. This is especially pronounced for the current associated with the compartment IV, which reflects the thermal neutron fraction. In case of the iron filter, the relative increase of the ionisation associated with the compartment IV is caused by some decrease of the ionisation due to fast neutrons, which are slowed down in iron. The filter only slightly changes the fluence of thermal neutrons, so the ionisation associated with the compartment IV remains practically the same (within the accuracy of the method) as for the bare source. The gamma dose fraction in $^{10}BF_3$ is very small (below 1%), comparing to the neutron dose and in this case cannot be determined using RMM.

Table 2. Values of partial saturation current i_0D_i [pA], associated with certain compartments of restricted LET, measured by the KG2 chamber filled with nitrogen and $^{10}BF_3$:
I - below 20 keV/μm, II - from 20 keV/μm to 50 keV/μm, III - from 50 keV/μm to 100 keV/μm, IV - from 100 keV/μm to 200 keV/μm.

	Nitrogen				$^{10}BF_3$			
Compartment	I	II	III	IV	I	II	III	IV
Bare ^{239}Pu-Be	not measured				0	0	14.4	47.1
^{239}Pu-Be in paraffin	1.55	0	1.60	0	0	0	31.8	373.3
^{239}Pu-Be in iron	0.36	0.06	0.82	0	0	0	5.2	46.0

The comparison of the RMM with twin-detectors technique was focused on determination of photon component of the beam. In such measurements, one has to remember that in BNCT beams, the value of k_U can be considerably influenced by activation of the chamber elements by thermal neutrons. In case of the measurements at the H8 channel of the MARIA reactor, the ionisation current of the F-1 chamber, measured immediately after closing the reactor channel constituted 3.7% of the current at the open channel and decreased to the half of its initial value after 160 s. This roughly corresponds with decay of activated aluminium ($T_{1/2} = 2.3$ min,

$E_\beta = 2.87$ MeV). This activation was taken into account by an appropriate modification of the classic equations of twin-detectors method. The following set of equations was proposed:

$$i_T(1-\beta_T) = A_T(h_T\dot{K}_\gamma + k_T\dot{K}_n)$$
$$i_U(1-\beta_U) = A_U(h_U\dot{K}_\gamma + k_U\dot{K}_n) \quad (10)$$

where indices T and U concern the tissue-equivalent and hydrogen-free ionisation chambers, respectively, h is the relative sensitivity of a detector to gamma radiation, k is the relative sensitivity of a detector to fast neutrons (relatively to the sensitivity to gamma radiation of the reference ^{137}Cs radiation source) and A is the calibration factor of the chamber. β_T and β_U denote the contributions of β particles to the ionisation current of the chambers T and U, respectively.

The values of the above coefficients for the chambers F1 (T) and G5 (U) are equal to: $h_T = h_U = 1.0 \pm 0.015$; $k_T = 1.03 \pm 0.05$; $k_U = 0.01 \pm 0.002$; $\beta_T = 0.037 \pm 0.005$; $\beta_U = 0.015 \pm 0.01$.

The value of the gamma component of the tissue-kerma K, obtained from the measurements by twin-detectors technique was equal to $K_\gamma/K = 0.878 \pm 0.007$. The uncertainty of the results is mostly due to uncertainty of the relative neutron sensitivity k_T of the chamber F1.

Measurements with F1 chamber and application of the simplified RMM (eq. 1) resulted in values of $\nu_{ef} = 16$ and $\Gamma = K_\gamma/K = 0.877 \pm 0.009$.

Comparison of the obtained values of K_γ/K shows that both methods gave the same result, within 0.1% of the measured value, while the uncertainty of each of the methods was estimated as being about 1%.

6. CONCLUSIONS

In summary, we arrive at the following conclusions:

(1) The recombination microdosimetric method can be used also when the recombination chamber is filled with a gas different from tissue-equivalent mixtures, investigated up to now.

(2) The use of graphite chamber filled with nitrogen and $^{10}BF_3$ makes it possible to measure dose components due to neutron capture reaction on ^{14}N and ^{10}B. In combination with measurements with a TE recombination chamber, also determination of the fast neutron component becomes possible.

(3) It was shown that the influence of volume recombination in the chamber can be taken into account using the formula proposed in this work. The accuracy of the formula was improved, comparing with the earlier approach [14] thanks to better method of fitting the experimental data. The formula was, for the first time, successfully applied to the data measured with the chambers filled with different gases at different gas pressures. This opens the possibility to use the RMM at high dose rates, such as used in BNCT, when the volume recombination is considerably high.

(4) Gamma component of tissue-kerma in the reactor beam was successfully determined using both the simplified RMM and twin detectors technique with a high-pressure C-CO_2 chamber as a "neutron insensitive" detector. However, any measurements of dose or kerma components in radiation fields with high flux of thermal neutrons creates some special

problems, which usually can be neglected in most of fast neutron radiation fields. Among them, there is the problem of activation of metal parts of the detectors, solved here for the chambers used in twin-detectors technique. It is also important to keep the appropriate atomic composition of the gas in tissue-equivalent (or quasi tissue-equivalent) ionisation chambers. This especially concerns the proportion of hydrogen and nitrogen in the gas.

(5) The properties of recombination chambers mentioned above are serious advantages of this type of detectors, used as LET-spectrometers, which can be applied for monitoring of the radiation quality in BNCT beams.

(6) Most likely, the finally optimised recombination detector for BNCT will contain some addition of nitrogen and $^{10}BF_3$ to the TE gas mixture. Using the method developed here for separation of initial and volume recombination, it will be possible to perform the measurements in the BNCT beams at therapeutic dose rates.

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