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DOSIMETRIC STUDIES OF HIGH-ENERGY (18.5 MeV) e-, γ -, n- RADIATION FIELDS: MICROTRON M-30 EXPERIMENT

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Abstract

High-energy electrons, gamma, and photo neutrons radiation are widely used for therapeutic and technological applications, but there are limited systematic studies of their dosimetric characteristics. This paper presents the experimental results of thermoluminescent (TL) method studies of such radiation fields with a maximum energy of 18.5 MeV. The radiation experiment was carried out on the M-30 microtron electron accelerator with a unique mono energy (0.15%) electron beam. Three e-, γ -, n- studies were held at the same electron fluence the M-30; the values of the dosimetric parameters of the studied materials $Y_{\gamma,n;e} = D_{\gamma,n}/D_e$, where $D_{\gamma,n}$ is the value of the intensity of the TL peaks of the dosimeters after the bremsstrahlung (γ) gamma – or photoneutron (n) irradiation, and D_e – respectively, same after the electron (e) beam was obtained. The results confirmed the general ideas about the physics of the transformation of electron radiation into beams of nuclear particles of various natures; however, the effectiveness of using doped LiF and Al₂O₃ materials for dosimetry of neutron fields requires additional studies. The results are essential for radiation technologies using beams of mixed nuclear radiation, especially for radiation therapy.

Introduction

The knowledge of the nature of damage to materials under the action of nuclear radiation of various natures: accelerated electrons (e), gamma (γ), or neutron (n) radiation, is an essential task of radiation physics. In addition to the scientific interest in studying a matter's stability in high-energy ionizing radiation, such investigations are also focused on applied applications: from the problems from the radiation safety of the population [1-6] to obtaining the regimes of radiation technologies [7, 8]. The latter has many applications in nuclear medicine, chemical and pharmaceutical production, and radiation testing of space and energy devices. An interesting possibility is modeling radiation damage caused by nuclear particles of one type, such as protons, neutrons, and with the help of others, for example, fast electrons, which requires comparing their effect on matter. Moreover, electron accelerators allow the creation of uniform fields of accelerated electrons and the realization of other radiation factors by converting electron beams into bremsstrahlung gamma radiation or neutron beams of different energies using appropriate photonuclear reactions. In this way, it is possible to create mixed nuclear radiation fields, which can also be attractive for radiation technologies. Another issue is the control of the radiation conditions of such exposure.

The thermoluminescent dosimetry (TLD), initially focused on low-energy X-ray radiation, is now widely used in medical accelerators with an energy of 6 MeV and above [9]. There is data on the use of TLD nuclear radiation of various types, intensities, and energies [10-12]. However, in some works showed the need to consider the influence of radiation defects on the linearity of the TLD signal from the absorbed radiation dose [13, 14].

This paper presents the results of TLD studies of the effectiveness of nuclear radiation of various natures (e-, γ -, n-) generated by the M-30 microtron. The peculiarity of the experiment is the use of different dosimetric materials and the constancy of their irradiation conditions.

Radiation experiment and the discussion of the results

Three irradiations were carried out at the same fluence of 10^{12} el. $\text{sec}^{-1} \text{cm}^{-2}$ that was fixed on the output window of the M-30 microtron [15] for every radiation experiment. The irradiation time was 5 min. The energy of the accelerated electrons was 18.5 MeV. Irradiation was carried out under room conditions – a temperature of 20°C. The irradiation was conducted at a distance of 1 m from the window of the M-30 output, where the electron, bremsstrahlung, and photoneutron radiation fields were formed sequentially. In the first case, the electron flow density in the irradiation field was determined by a Faraday cylinder and was $2.6 \cdot 10^8$ el. $\text{cm}^{-2}\text{sec}^{-1}$. The selected conditions must guarantee the linearity of the "dose-effect" relationship for the irradiation interval. To form bremsstrahlung radiation fields, the Ta target with a thickness of 1 mm was used, which satisfies the conditions of 0.3 radiation length for a given value of electron energy. For these irradiation conditions, the dose intensity of gamma radiation was set by a clinical dosimeter and was $3 \cdot 10^{-2}$ Gy/min. The photoneutron flux was formed using a combined converter with a bremsstrahlung Ta target and a 1 cm thick Pb material. The choice of lead as a source of neutrons was due to low thresholds of photoreactions (γ, n), which for isotopes $^{206-208}\text{Pb}$ are in the range of 6.5-8 MeV, and the conversion factor of electrons into neutrons is $10^{-3} - 10^{-4}$ [16]. Taking into account the presence of two mechanisms of photoneutron formation due to their "evaporation" (86%) and another by knocking out neutrons during direct interaction with gamma quanta (14%), their maximum energy can be up to 5 MeV, and the average energy can be estimated at 0.77 MeV for the given experimental conditions. The radiation parameters of the photoneutron flows were not determined separately, taking into account the dosimetric directionality of the experiment.

The research was conducted by the TLD dosimetry method with the selection of two types of dosimetric materials – based on $\text{Al}_2\text{O}_3:\text{C}$, type TLD 500K, after this, LS, and crystals $\text{LiF}:\text{Mg, Cu, P}$, type TLD 100H. In the latter case, materials from two manufacturers, now LiF1 and LiF2, were used, taken from kits of different readers of different systems. Three samples were selected for the LS and LiF1, LiF2 series to ensure the statistics of dosimetric experiments. TSL curves were measured under normal conditions at a heating rate of 0.5°C/sec. The phenomenon of luminescence was observed in the newly irradiated materials, especially after the action of accelerated electrons and gamma radiation. Therefore, thermally stimulated studies were carried out only after three days.

In newly irradiated materials, especially after the action of accelerated electrons and gamma radiation, the phenomenon of phosphorescence was observed, the glow (or extinction) of which lasted up to 3 days. Measurement of thermoluminescence curves during heating of samples at a rate of 0.5°C/s to 300°C was carried out after complete extinction of phosphorescence. An FEU-106 photomultiplier in the photon counting mode measured the phosphorescence and thermoluminescence outputs.

Since the illumination intensities of the samples after radiation experiments differed significantly, their studies after electron irradiation and in gamma fields were carried out using filters that had a known attenuation coefficient of the TSL signal. Typical TSL spectra of these samples are presented in Fig. 1, separately for samples of the TLD 500K (LS) and LiF1, LiF2 series. The curves are built taking into account the use of attenuating filters.

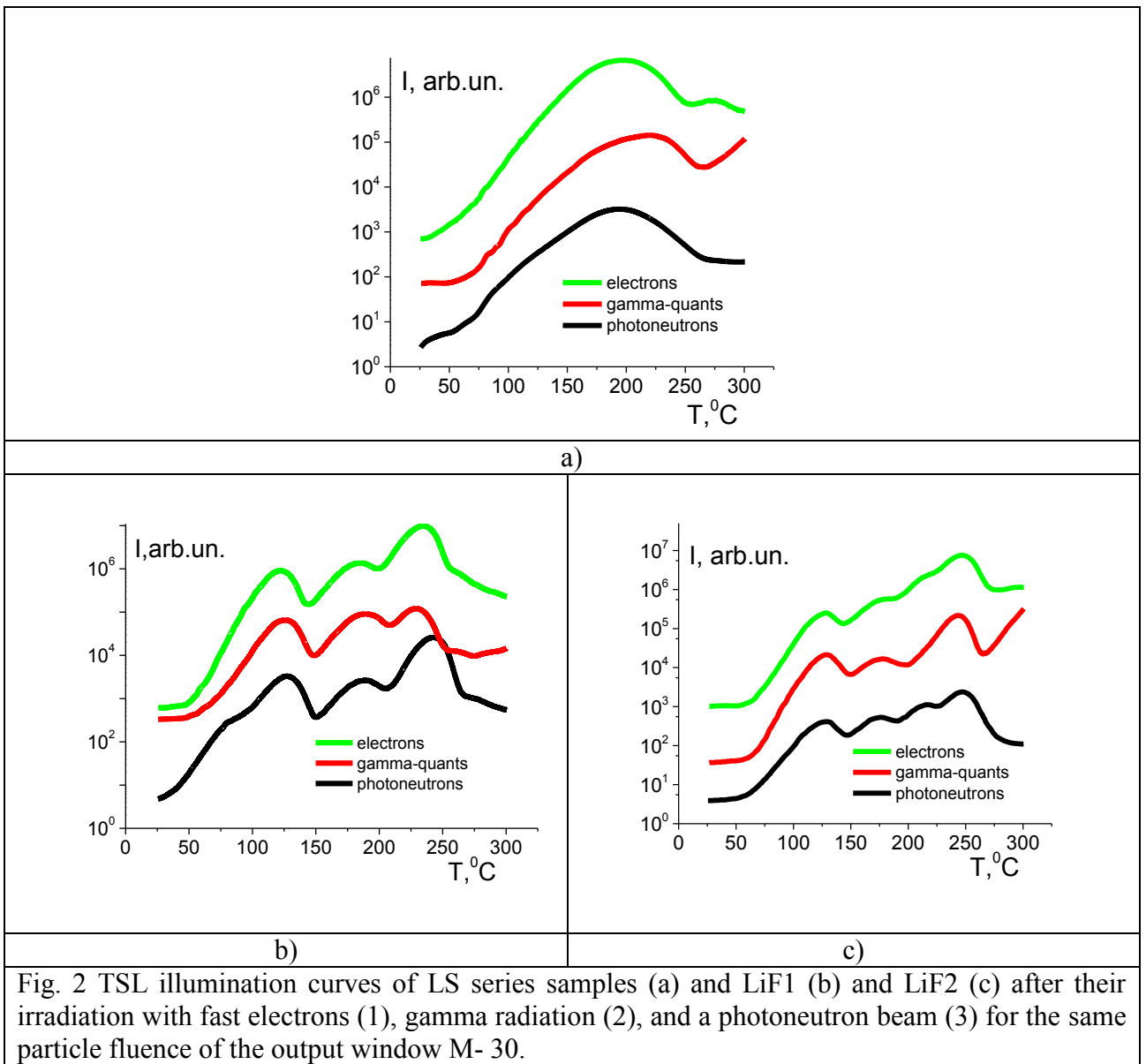


Fig. 2 TSL illumination curves of LS series samples (a) and LiF1 (b) and LiF2 (c) after their irradiation with fast electrons (1), gamma radiation (2), and a photoneutron beam (3) for the same particle fluence of the output window M- 30.

As one can be seen, the TLD 500K series samples have only one dosimetric peak, located around 200°C, the position of which does not change within 10% under the influence of nuclear particles of various types. The subject of the study was dosimetric indicators, which are determined by the ratio of the intensities of TSL signals of samples irradiated with nuclear particles of various types. In the presence of additional measurements, dosimetric indicators provide information about the ratio of absorbed radiation doses in such experiments. The subject of the study were dosimetric parameters $Y_{\gamma,e} = D_{\gamma}/D_e$, та $Y_{n,e} = D_n/D_e$, where D_{γ} is the intensity of the TLD signal after the action of bremsstrahlung gamma radiation, D_n – after the action of photoneutron radiation, and D_e – respectively, electronic. Moreover, when for TLD 500K, the specified indicators are set for only one dosimetric peak, then for LiF1 and LiF2, there are three of them. Using the TSL spectra of the materials of these series, it is possible to calculate the relative indicators $Y_{\gamma,e}$ for each of the three dosimetric peaks, respectively, $\{Y_{\gamma,e}^{(1)}, Y_{n,e}^{(1)}\}$ for low temperatures $T_1=126^{\circ}\text{C}$ and $\{Y_{\gamma,e}^{(2)}, Y_{n,e}^{(2)}; Y_{\gamma,e}^{(3)}, Y_{n,e}^{(3)}\}$ for high temperatures $T_2=183$ and $T_3=245^{\circ}\text{C}$. Such information is essential for assessing the possibility of their use for dosimetry of mixed fields of nuclear radiation. The results of such work are systematized in Table 1.

Table 1 Dependence of dosimetric indicators $Y_{\gamma,e}$, $Y_{n,e}$ of materials based on leucosapphire (TLD 500K) and lithium fluoride LiF1, LiF2 (TLD100H), obtained from the values of TSL signals of their dosimetric temperature peaks.

LS		LiF1		LiF2			
T, °C	$Y_{\gamma,e}$	$Y_{n,e}$	T, °C	$Y_{\gamma,e}$	$Y_{n,e}$	$Y_{\gamma,e}$	$Y_{n,e}$
200	0,02	0,0005	126	0,07	0,004	0,07	0,001
			183	0,05	0,002	0,03	0,0008
			245	0,01	0,003	0,02	0,0003

The analysis of Table 1 shows that for LS, the dosimetric indicator $Y_{\gamma,e}$ varies within 0.02 - 0.05 for this series. Such a spread can be explained by phosphorescence effects, which are particularly significant when samples are irradiated in electron and gamma fields. The value of the dosimetric indicator $Y_{n,e}$ is more stable. As can be seen, for all LS, the indicator $Y_{n,e}$ is 0.0005 with sufficient accuracy. Fig. 1 b) and c) show typical thermal emission spectra of dosimeters based on doped LiF. As can be seen from Table 1, they have three peaks in the range from low $T_1=126^\circ\text{C}$ to high-temperature values, such as $T_2=183$ and $T_3=245^\circ\text{C}$.

Using the TSL spectra of the materials of these series, it is possible to calculate the relative indicators $Y_{n,e}$ for each of the three dosimetric peaks both around temperatures $T_1=126^\circ\text{C}$ and for high-temperature peaks at $T_2=183$ and $T_3=245^\circ\text{C}$. Such information is important for assessing the possibility of their use for dosimetry of mixed fields of nuclear radiation. Studies have shown the stability of the $Y_{n,e}$ indicator in the vicinity of 0.07 for the low-temperature peak T_1 and the tendency to decrease their value during the transition from $T_1 \Rightarrow T_2 \Rightarrow T_3$. Such a change is different for these dosimeters and reaches a value of 0.01 for LiF1 and 0.05 for LiF2. The same trends occur for $Y_{n,e}$ indicators. However, when for the LiF1 series, they change from 0.004 to 0.003, while for LiF2 dosimeters, it is more significant, so, at $T_1 \Rightarrow T_2 \Rightarrow T_3$, there are changes in $Y_{n,e}$ indicators, in the range $0,001 \Rightarrow 0,0008 \Rightarrow 0,0003$. The latter value is an order of magnitude smaller than the LiF1 series but comparable to the same value for TLD 500K. Moreover, as can be seen in Fig. 2a) there is a shift of the high-temperature peak after neutron irradiation within 40%.

It is known that electron accelerators are widely used to create gamma and neutron radiation fields [17-20]. Moreover, microtrons, as a source of monoenergetic electrons, have a better ability to focus them on the bremsstrahlung target and, therefore, the conversion efficiency into beams values of bremsstrahlung and photoneutron radiation. Experimental and theoretical results of such studies are widely presented in the literature [21]; there are data on radiation fields corresponding to the conditions of this experiment. However, as a rule, such results are obtained for radiation conditions near the bremsstrahlung target or the photoneutron converter. One can use the following formula to estimate the dose rate of gamma radiation, which creates a beam of electrons with energy E at a distance of 1 m from the accelerator [22, 23].

$$W[\text{Gr}/\text{min.}] \approx 4 \cdot 10^{-4} E^3 [\text{MeV}] I [\text{mkA}], \quad (1)$$

The formula (1) can be used to estimate the dose of gamma radiation that creates a beam of electrons with energy E at a distance of 1 m from the accelerator, which gives the value of $W \sim 0.11$ [Gr/min.]. As one can be seen, the ratio of the intensities of gamma and electron fields obtained

from estimation (1) corresponds to the order of value $Y_{g,e} = D_g/D_e$ established in the given dosimetric experiments. Carrying out such estimates for photoneutron fields is a non-simple task since there are no data on the nature of their spatial distribution from the generating target. There is also a need to consider the special nature of radiation damage during the interaction of neutrons with dosimetric material. The obtained data with sufficient reliability indicate the value of the parameter $Y_{n,e}$ of the order of $3-5 \cdot 10^{-4}$, corresponding to the order of neutron/electron conversion given in the works [24-27]. However, as these studies show, using doped lithium fluoride for dosimetry of neutron and mixed gamma-neutron fields requires separate studies, since not all of its dosimetric peaks ensure the reliability of measurements.

Conclusions

These studies show the possibilities of using TSL dosimetry to study the radiation characteristics of electron accelerators, which are widely used in medical and technological applications when generating beams of electron, gamma, and photoneutron radiation. The obtained results confirm the general ideas about the physics of transforming electron radiation into streams of nuclear particles of different natures. At the same time, the TSL dosimetry technique makes it possible to evaluate such characteristics immediately after gamma or photoneutron converters, where computer modeling of processes is effective and also at an arbitrary distance from the radiation source. Using dosimeters based on different materials in the TSL experiment demonstrates common trends in diagnosing electron and gamma radiation fields and the need for additional research to analyze neutron flows. Such features may be related to the interaction of neutrons with matter. The obtained results can be useful for proposals of new technologies using beams of mixed nuclear radiation, as well as for the problems of radiation therapy.

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