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A POSSIBILITY OF HIGH-ENERGY BREMSSTRAHLUNG DOSIMETRY BY INDIUM ACTIVATION

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Introduction

Nowadays, the development of high-power bremsstrahlung (X-ray) sources intended for photonuclear isotope production, subcritical assembly control etc. is carried out on the basis of high-current electron linacs. The output devices of such facilities have to be exposed to the photon flux with end-point energy up to 100 MeV at an absorbed dose rate of up to 10^5 Gy/s and higher. In these circumstances, traditional methods of X-ray dosimetry appear to be of little use.

It is known that photoactivation of isomeric state in some nuclei is characterized by low energy threshold. For example, the threshold of the $^{115}In(\gamma,\gamma')^{115m}In$ reaction equals 1078 keV. The ^{115m}In isomer decays to the ground state with a half-life $T_{1/2}$=4.48 h, emitting the gamma-quantum of energy 336.2 keV, which is convenient for detection. Owing to the low reaction threshold, the natural indium (the ^{115}In abundance makes 95.8%) can be activated with practically all photons of the bremsstrahlung spectrum. This circumstance allows suggest the presence of a relationship between the specific activity of ^{115m}In and the X-ray absorbed dose.

In a number of studies, the $^{115}In(\gamma,\gamma')^{115m}In$ reaction has been used for dosimetry in γ-facilities with the ^{60}Co sources. In that case the activation of indium was realized with the quasi-monochromatic photons of energy near the reaction threshold at dose rate up to 10^2Gy/s. The present communication discusses applicability of the method to the high-energy X-ray.

1.Materials and techniques

Experimental studies were performed at NSC KIPT linacs LU-10 (the electron beam energy E_0=8…12 MeV) and LU-40 (E_0=35…95 MeV). For absorbed dose measurement, the Harwell Red 4034 (HR) detectors were used. The advantage of HR consists in the possibility of determination the photon-induced absorbed dose under mixed γ,n-irradiation.

To investigate the relationship between the specific activity of ^{115m}In and the absorbed dose in PMMA, it was suggested that the natural indium detectors together with the HRs should be exposed to X-ray under the condition of electronic equilibrium. Besides, each target incorporates a foil of natural molybdenum to check the activation regime through the yield of the reference reactions ^{92}Mo(14.84%)(γ,2n)^{90}Mo and ^{100}Mo(9.63%)(γ,n)^{99}Mo. It should be noted that in such conditions ^{90}Mo can be produced only via the mentioned reaction, while the ^{99}Mo yield can also be contributed by the ^{98}Mo(24.13%)(n,γ)^{99}Mo reaction. In its turn, apart from the photonuclear channel, ^{115m}In can also be generated in the ^{115}In(n,n′)^{115m}In reaction.

The γ-spectra of irradiated indium and molybdenum were measured with the HPGe detector, which provided FWHM of 1.3 keV at 1332 keV.

For independent analysis of the photoactivation processes and absorption of radiation energy in the detectors, we have used the simulation method based on a modified transport code PENELOPE-2008. The yield of photonuclear reactions was calculated through summation of their microyields along all the trajectories of all the above-threshold photons in the targets (the Step-By-Step method).

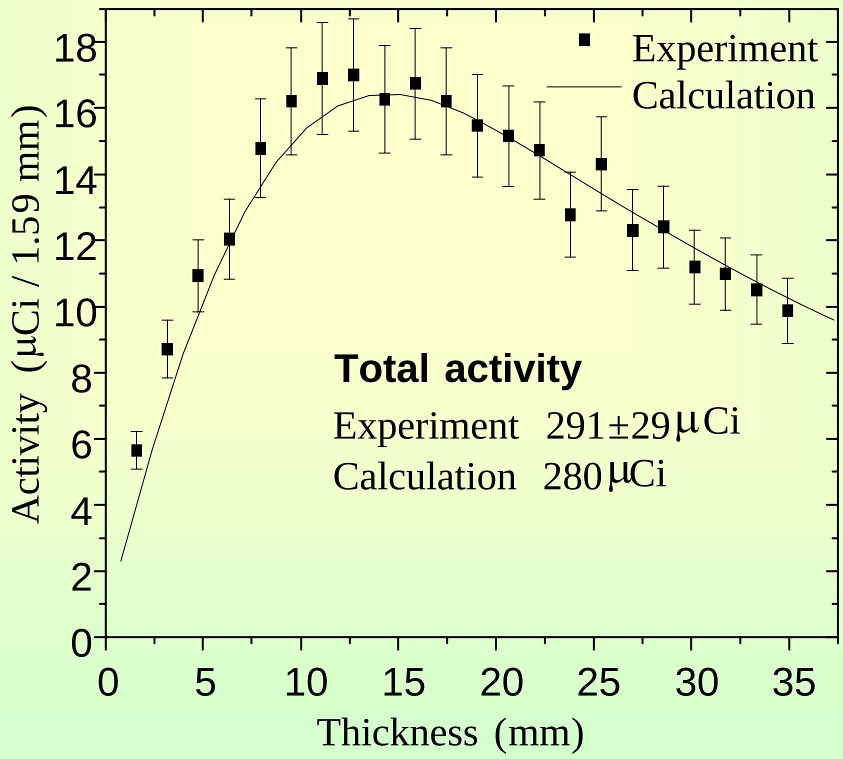

Fig.1. ^{67}Cu activity distribution in Zn-target calculated by SBSM technique

Cross sections for the reference reactions on the ^{92}Mo and ^{100}Mo isotopes (see Figs 2 and 3) were taken from the database. In the case of the $^{115}In(\gamma,\gamma')^{115m}In$ reaction the situation turned out to be more complicated. Namely, the data on its cross section, reported in different works, have shown considerable variations (see Fig.4). Therefore, we calculated the ^{115m}In yield for different variants. Then, the data obtained were compared with the experimental results.

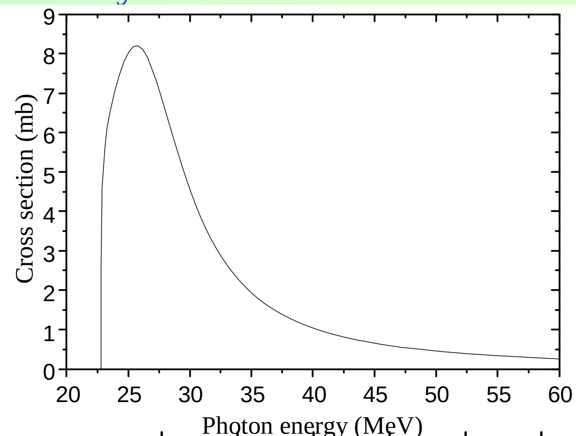

Fig.2. $^{92}Mo(\gamma,2n)^{90}Mo$ refction cross section

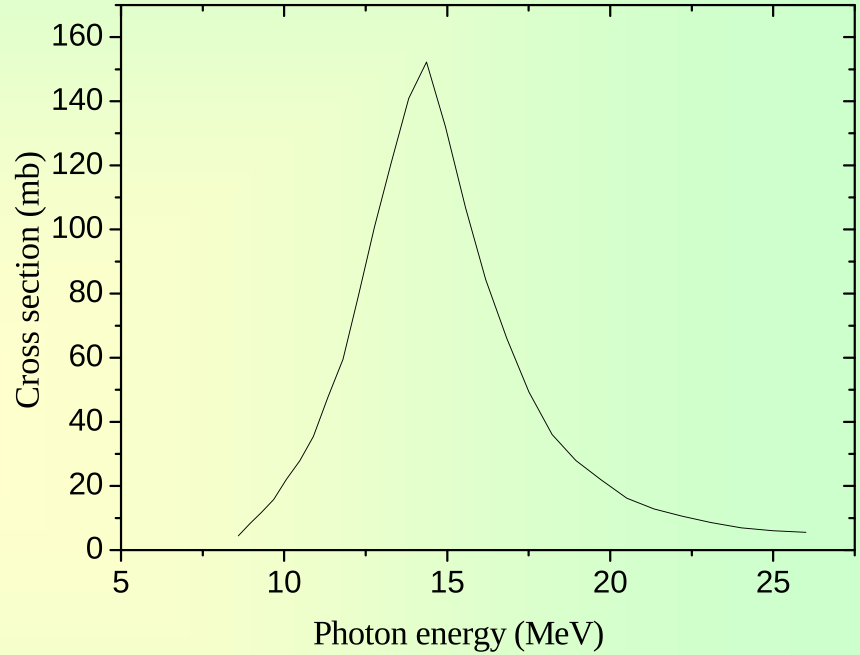

Fig.3. $^{100}Mo(\gamma,n)^{99}Mo$ refction cross section

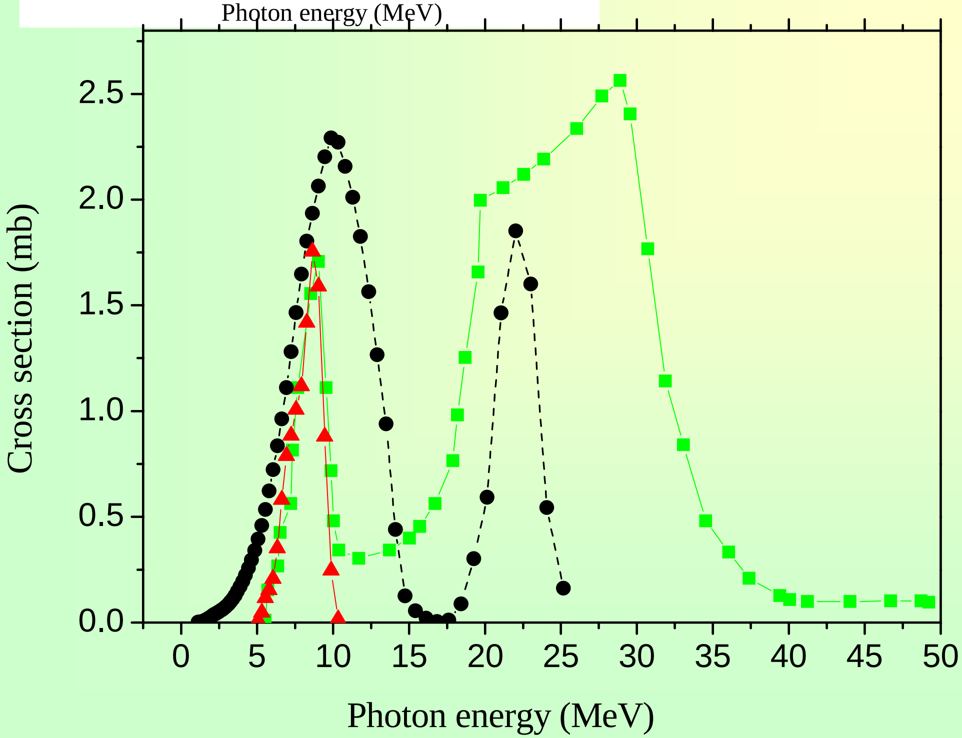

Fig.4. $^{115}In(\gamma,n)^{115m}In$ refction cross section

2.Analysis of X-ray formation

The interaction of the electron beam with the elements of accelerator output devices represents the transformation of the primary “pure” electron beam into a mixed e,X-radiation. The ratio of its component intensities in the given transverse plane is specified by the initial electron energy E_0, the thickness and atomic number of the materials in the region of radiation formation.

The basic characteristics of electron-photon radiation include the **energy coefficient of electron transmission** (E_{el}/E_{beam}) and the **energy coefficient of electron-to-photon conversion** (E_{ga}/E_{beam}). Here E_{beam} is the total of electron beam energy; E_{el}, E_{ga} are, respectively, the total energies of forward flying electrons and photons, which cross the transverse plane that passes through the given Z-coordinate. Of considerable practical use is the ratio of the mentioned coefficients (E_{ga}/E_{el}) hereinafter called as the **secondary-radiation energy factor**.

The stopping thickness of a layer of a certain material is defined as the ratio of the linear thickness of the layer (in cm) to the average range (in cm) of the electron of given energy in this material. The resulting in this way stopping thickness of the layer is dimensionless. The corresponding unit of measurement is referred to as the stopping thickness unit (stu).

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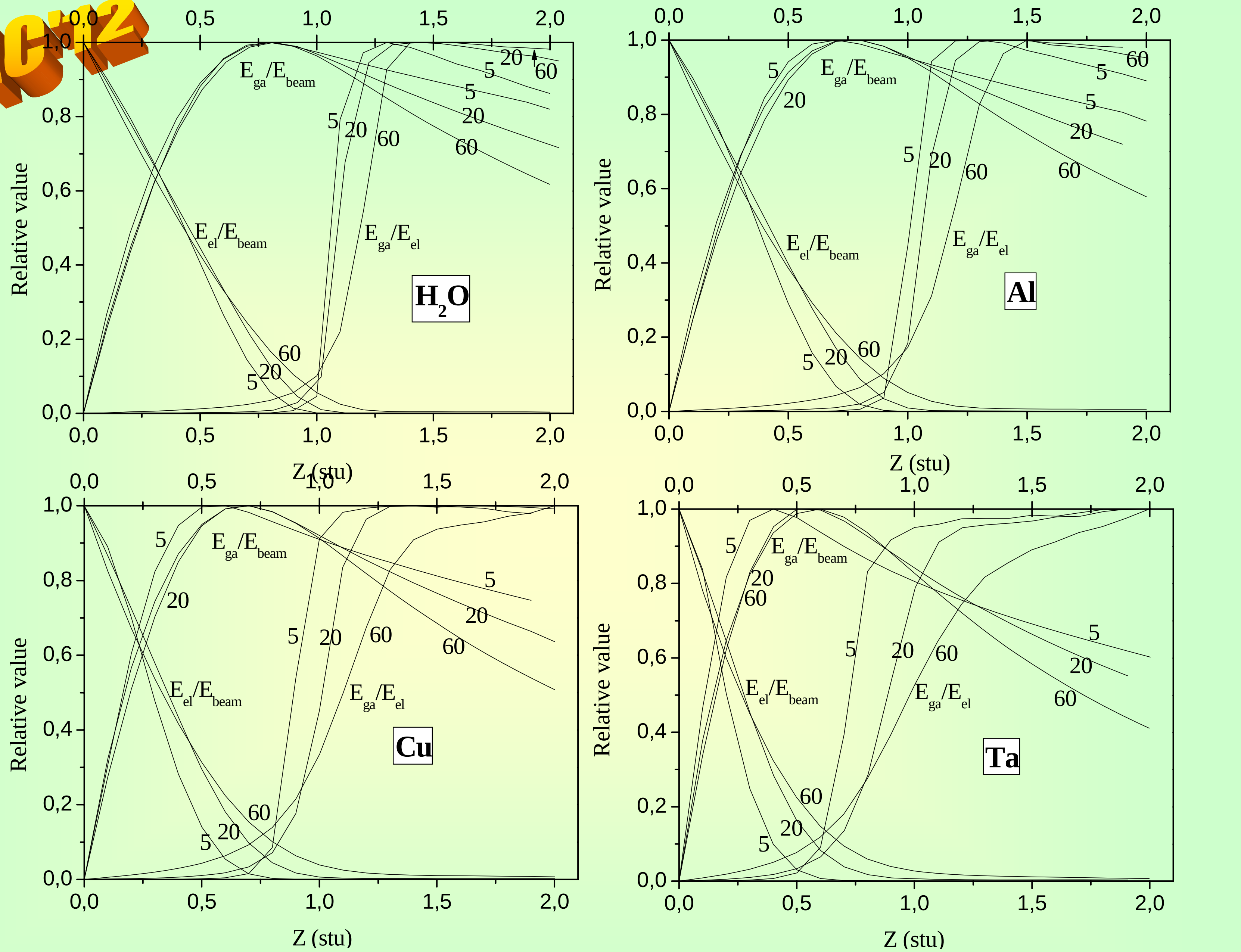

Fig.5. Normalized coefficients of transmission, conversion and the secondary radiation factor as functions of material thickness

3.Experimental conditions

For experimental studies, we have used the output device schematically shown in Fig.6. Behind the exit window of the accelerator A, there were placed successively the converter C (four stacked tantalum discs of thickness 1mm each), the aluminum electron filter of thickness l_F, and the set of three targets $T_1 \ldots T_3$. The targets were spaced at regular intervals L=10 cm one after another. The target T_4 was arranged at the same distance in the converter plane perpendicular to the beam axis. Each target was composed of an indium plate of dimensions 2x1x0.1 cm, contacting with the HR detector, and the molybdenum foil of dimensions 2x1x0.01cm. Given geometry of the output device permitted the radiation field of various intensity and composition to act upon the targets in one run. In this case, the targets T_1 and T_4 were used for evaluating the contribution of the (n,n') channel to the ^{115m}In yield. Table 1 lists the parameters of the radiation formation path and the modes of target activation.

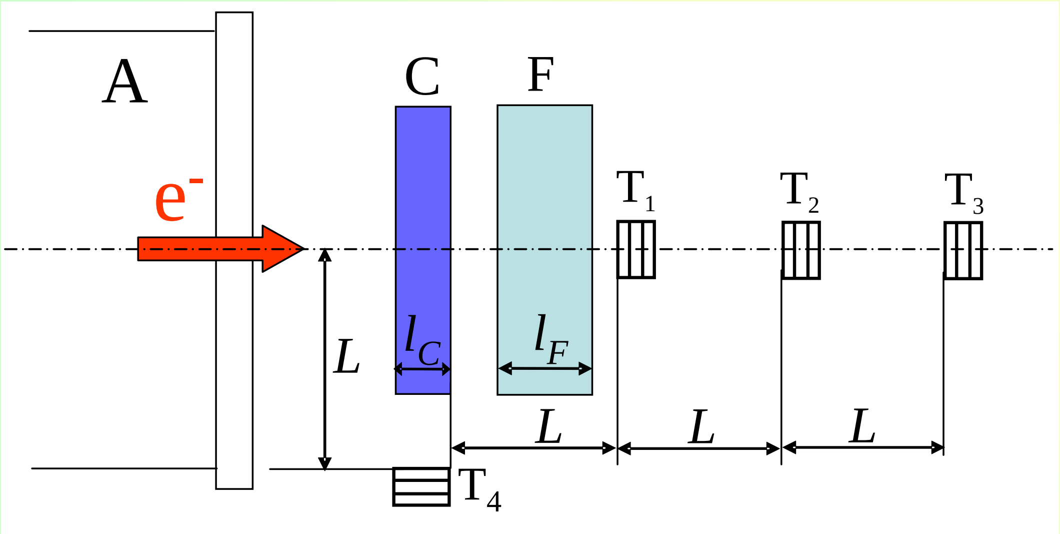

Fig.6. Schematic of experimental device

Table. Characteristics of target activation

Accelerator	E_0,MeV	l_C,cm	l_F,cm	Beam current,μA	Exposure,h
LU-10	9	0.24	1.4	20.0	0.2
LU-40	35	0.4	5	3.7	1.0
	52.5	0.4	7	4.9	0.5
	71	0.4	9	4.0	0.2

4.Results and discussion

Experimental and simulation methods were used to determine the ratio S of specific activity of the ^{115m}In isomer in indium plates to the absorbed dose in the HR detectors that were in contact with the plates. Figure 7 shows the function S(E_0) in the low-energy part of the range studied.

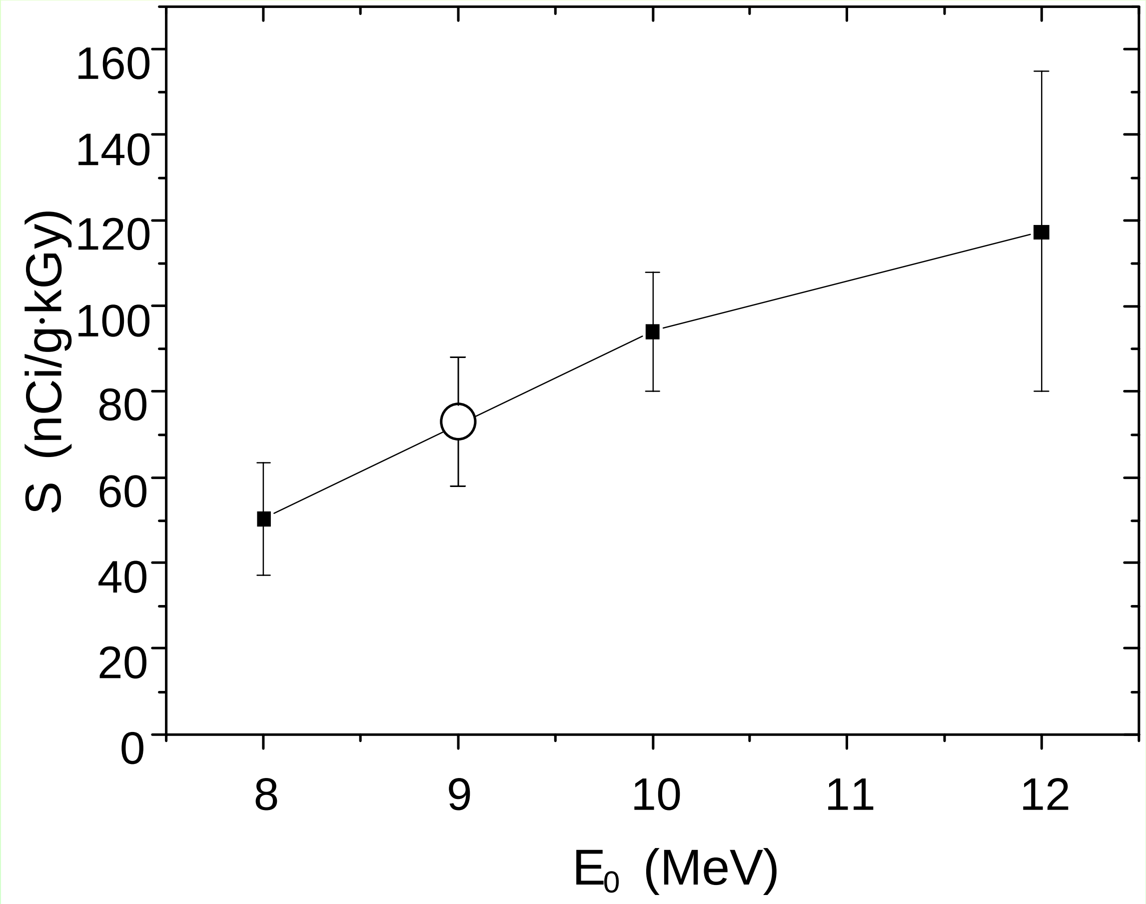

Fig.7. Ratio of specific ^{115m}In activity to the X-ray absorbed dose in PMMA (📪- experiment, ✏– calculation)

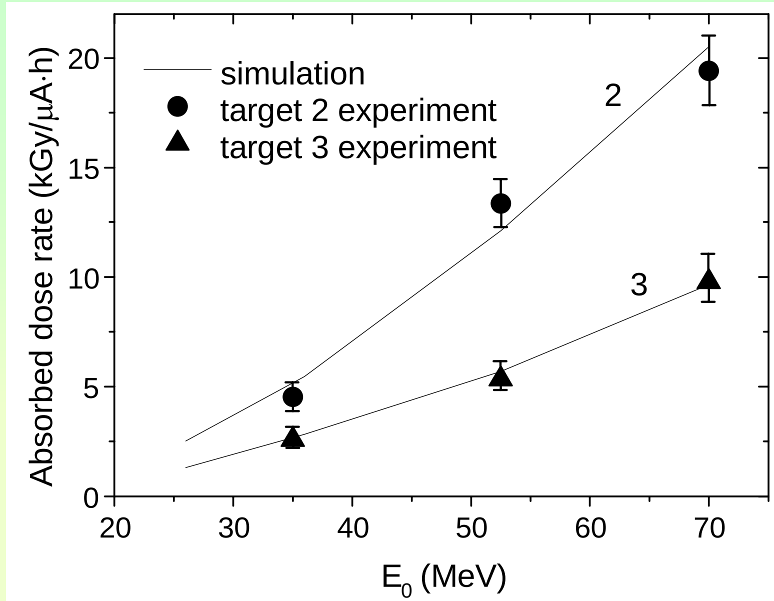

Fig.8. X-ray absorbed dose in PMMA as a function of electron energy

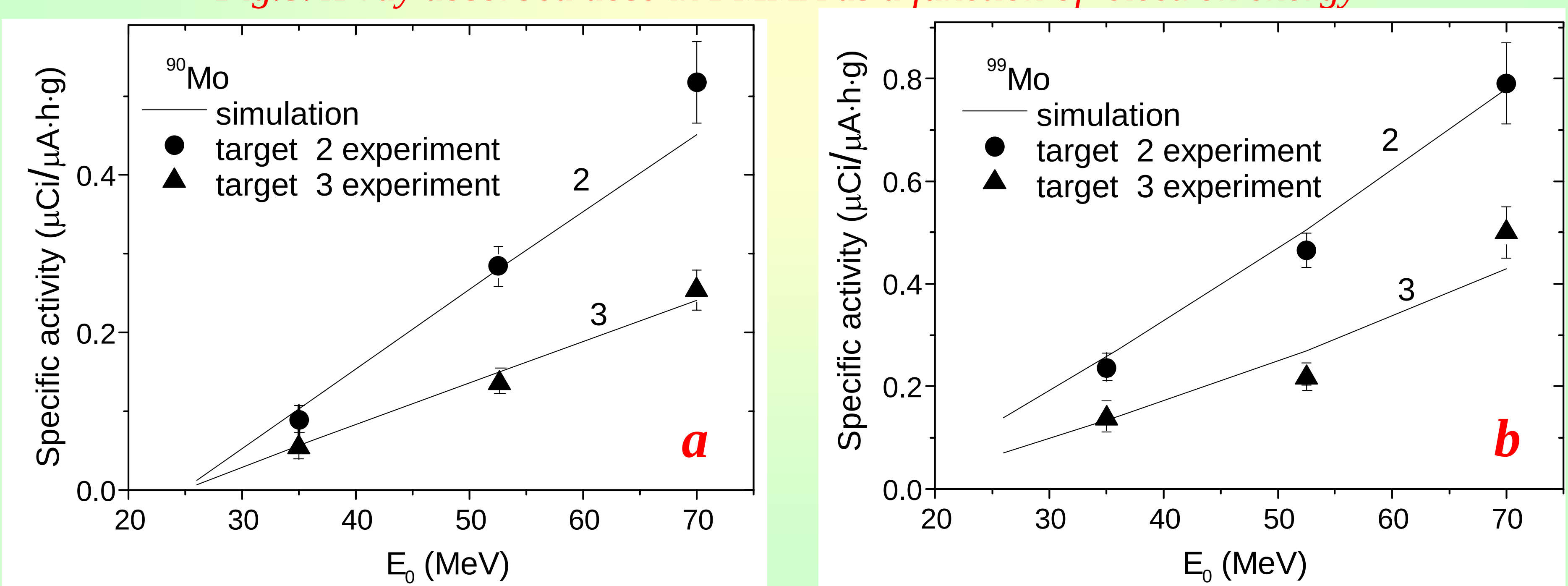

Fig.9. Yields of ^{90}Mo (a) and ^{99}Mo (b) versus electron energy.

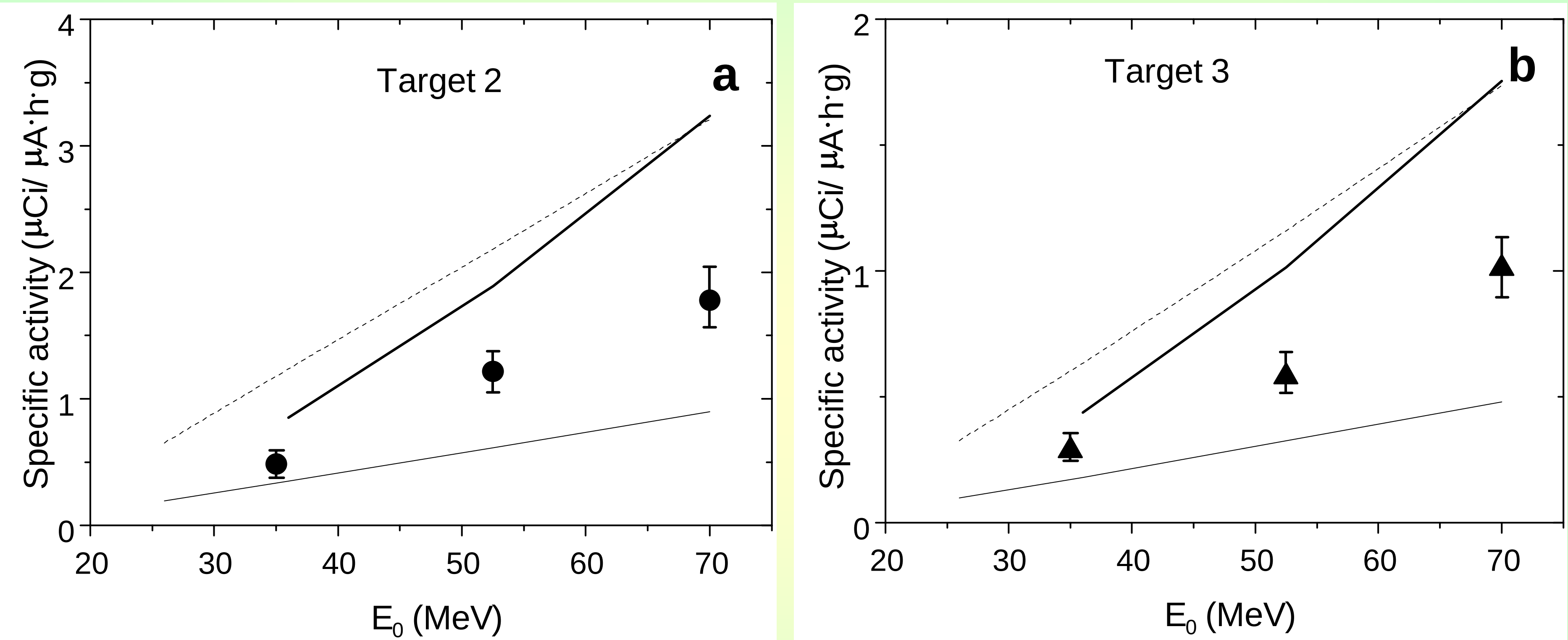

Fig.10. ^{115m}In yield versus electron energy: a) target T2; b) target T3
(●,🖮 - experiment; ---, —, — -calculations with the different cross section data)

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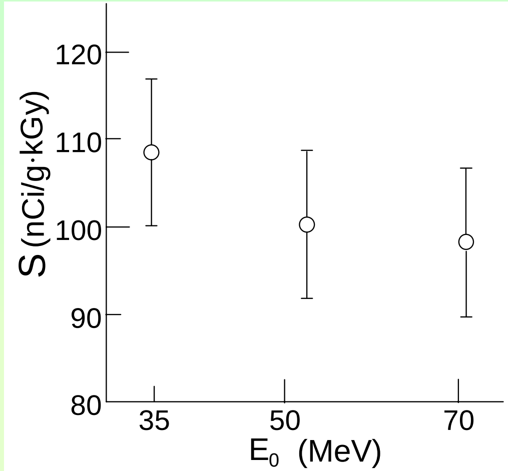

Fig.11. Ratio S of specific ^{115m}In activity to the absorbed dose in PMMA

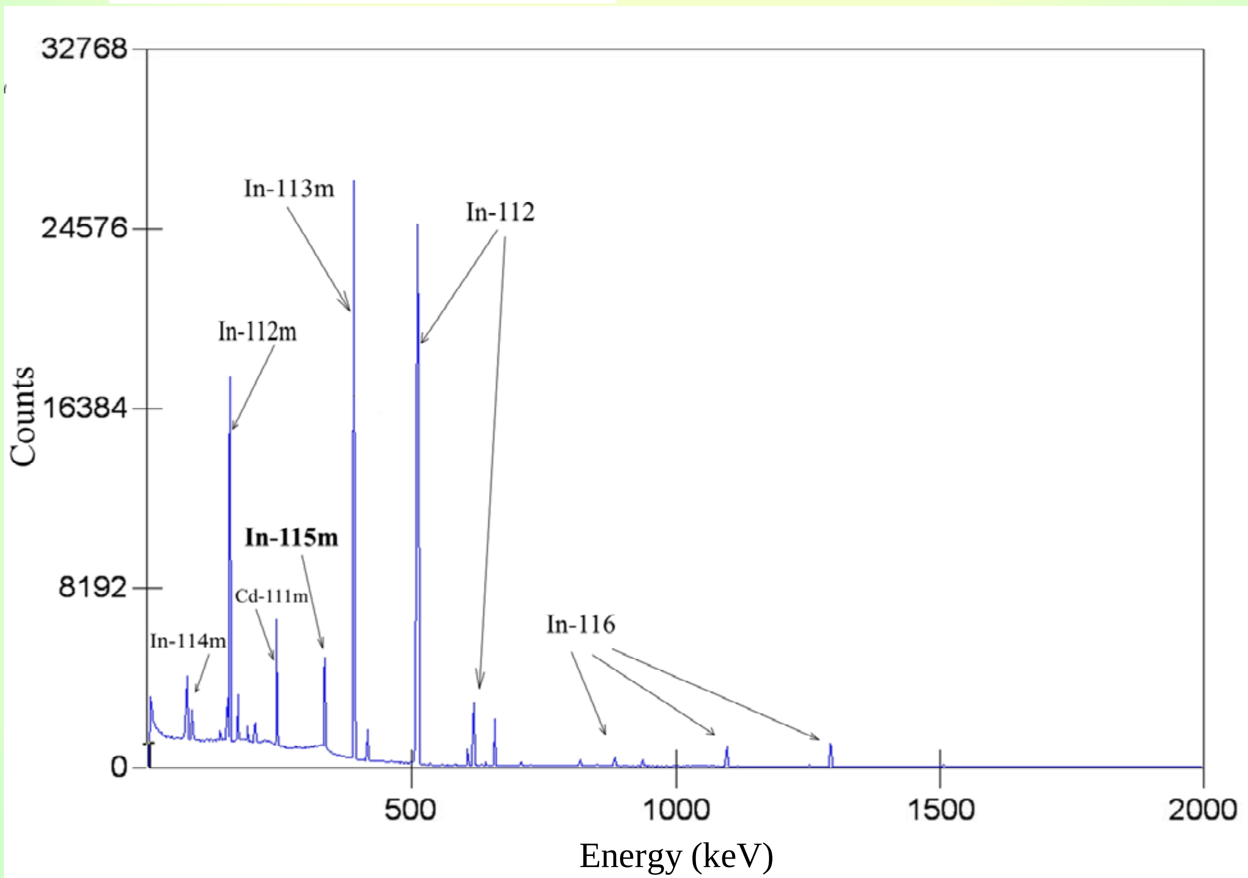

Fig.12. Measured gamma-ray spectrum of activated In detector (E_0=71MeV)

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Conclusion

The undertaken studies have demonstrated that the $^{115}In(\gamma,\gamma')^{115m}In$ reaction can be used for dosimetry of X-ray with the end-point energy up to 70 MeV and higher. The advantages of the proposed approach include: the ease of realization, the linearity with respect to the photon fluence, the independence from the dose rate, ambient conditions (pressure, temperature, neutron background) and on the state of indium (solid or liquid), and eventually, the reusability of the detectors. The calculated ratio of specific activity of ^{115m}In to absorbed dose in PMMA (sensitivity of the method) increases from 50 up to ~ 110 nCi/g·kGy in the electron energy range 8 - 12 MeV. As the experiments have shown, with a further energy increase up to 71 MeV, the value of the ratio varies only slightly.

The highest X-ray absorbed dose value measured by the proposed technique is determined by the boiling temperature of indium and makes no less than 2 MGy (at adiabatic exposure). The safe level of the In activity can be readily provided by the appropriate choice of the detector mass.

Simulation based on the transport code PENELOPE-2008 makes it possible to calculate with a reasonable accuracy the absorbed energy (dose) of electron/photon radiation, and also, the yield of photonuclear reactions, provided the description of their cross sections is correct. At the same time, none of the available data on the $^{115}In(\gamma,\gamma')^{115m}In$ reaction cross section has provided the calculated isomer yield which would be in agreement with the experimental results. So that more accurate measurement of this cross section is necessary.