AN ESTIMATE OF ^{47}Sc PHOTONUCLEAR YIELD IN A PRODUCTION TARGET

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^{47}Sc is considered as a promising beta-emitter for cancer immunotherapy. For its carrier-free production, the ^{48}Ti(γ,p)^{47}Sc reaction in the field of bremsstrahlung radiation of an electron accelerator can be used. On the basis of developed analytical model and a double-foil activation technique, the main characteristics of the photonuclear isotope production and optimal dimensions of a production target have been established. The measured photonuclear yield of ^{47}Sc and dominant scandium admixtures in thin foils of natural titanium in the electron energy range of 35 to 95 MeV enabled to specify the available data on the cross-section of the ^{48}Ti(γ,p)^{47}Sc reaction. Using those results, the gross and specific activity of ^{47}Sc in the cylindrical titanium targets of optimal size were calculated by a simulation technique. The comparison of capacity of the photonuclear method of the ^{47}Sc production with other techniques is carried out.

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INTRODUCTION

^{47}Sc ($T_{1/2}$=3.35 d; $\bar{E}_\beta$=162 keV; E_γ=159.4 keV) is believed as a promising beta-emitter for theragnostic ^{44}Sc /^{47}Sc pair (see e.g. [1]). The practical application of ^{47}Sc is hampered by the absence of a high-capacity technology with tolerant content of admixtures. In a number of works, the possibility of that isotope carrier-free production in the field of the bremsstrahlung radiation of an electron accelerator via the ^{48}Ti(γ,p)^{47}Sc reaction with threshold E_{th}=11.4 MeV was studied [2 - 4].

Commonly, estimation of capacity of such a technology is conducted on the ground of experimental data on the ^{47}Sc yield in a target of small size (weight) normalized to the accelerator beam current [2]. Such an approach includes the considerable uncertainties connected with the accuracy of determination of target position in a nonuniform flux of X-rays. So in Fig. 1, the distribution of the ^{47}Sc nuclei generated in a large cylindrical target from titanium with the X-ray beam having end-point energy of 40 MeV, obtained by a simulation technique, is presented. It is seen, that the reaction products are essentially nonuniformly distributed over the target volume.

It should be noted, that calculation of photonuclear yield by a Monte-Carlo method, even using a HS calculation technique [5], is borne with the considerable expenditure of time in view of a comparatively small reaction cross-section. Moreover, such an approach requires experimental checking, as the information sources give sometimes different data on the reaction cross-section. So for the ^{48}Ti(γ,p)^{47}Sc reaction, the referenced maximum of the cross-section makes about 30 [6], 13 [7], and 7 mb [8, 9], respectively.

In [10] on the basis of a simplified analytical model for the description of photonuclear isotope generation in a thick target, the principal parameters of the process have been introduced. In this work, the experimental study of those characteristics for the ^{48}Ti(γ,p)^{47}Sc reaction is conducted and the most appropriate value of the reaction cross-section are specified. Using the data obtained, an optimal size of a production target and its activation regime are determined. So the capacity of the technology is calculated, and also the yield of the Sc by-products in a target from natural titanium is measured.

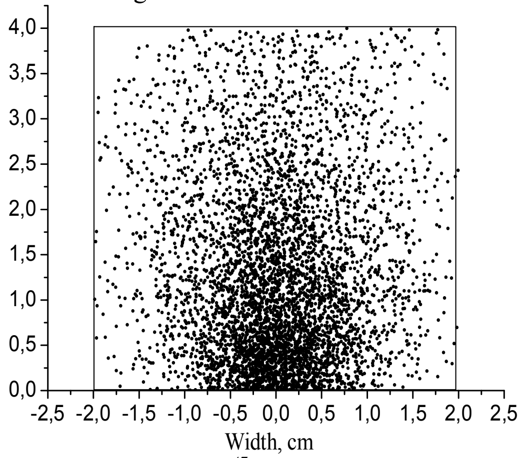

Fig. 1. Distribution of ^{47}Sc nuclei in titanium target irradiated with bremsstrahlung radiation

1. METHODS AND MATERIALS

1.1. A MODEL

As it is shown in [10], the volumetric distribution of specific activity produced via a photonuclear *i*-reaction, induced by a pencil electron beam with average current *I* and particle energy E_0 for the irradiation period *t,* is given by

$$\dot{A}_i(E_0, r, z) = \frac{Y_i(E_0) I}{2\pi e} \frac{[1-\exp(-\lambda_i t)]}{\delta_\gamma^2(E_0, z)} \times$$

$$\times \exp\left\{-\left[\frac{r^2}{2\delta_\gamma^2(E_0, z)} + \mu(E_i)(z-a)\right]\right\}, \qquad (1)$$

$$Y_i(E_0) = \frac{N_A}{\bar{A}} \nu_T \int_{E_{th,i}}^{E_0} n_\gamma(E) \cdot \sigma_i(E) dE, \qquad (2)$$

$$\delta_\gamma(E_0, z) = \delta_{\gamma,0} + z \cdot tg\theta_m(E_0), \qquad (3)$$

where λ_i is the decay constant, N_A is the Avogadro number, $\bar{A}$ is the average atomic mass of the target material, ρ_T is its density, ν_T is the relative content of the isotope-target nuclei, $\mu(E)$ is the linear photon attenuation coefficient of photons with energy *E* in the target material, $\delta_\gamma(E_0,z)$ – is the standard radial deviation of the photon flux density at a distance z from the converter (z=0 corresponds to its rear plain), $\sigma_i(E)$ is the reaction cross-section, $E_{th,i}$ is the threshold of the i-reaction, $n_\gamma(E)$ is the spectral density of X-rays normalized to the one beam electron, and θ_m is the most probable angle of X-ray exit from a converter.

1.2. A DOUBLE-FOIL ACTIVATION TECHNIQUE

As it is evident from Eqs. (1) - (3), that the quantities Y_i (E_0), δ_γ, and θm determine the total activity and its volumetric distribution in a target. Y_i (E_0) denotes the yield of isotope-product in a thin wide target overlapping fully the photon flux and normal to its axis (a photonuclear converter – PNC), normalized to the one beam electron and to the unit of the mass thickness of PNC. So the Y_i quantity is called as a coefficient of photonuclear conversion.

The Y, δ_γ, and θ_m values can be readily measured using a double-foil activation method [11]. It includes joint activation of two stacked foils – PNC and a small circular foil (S-target) by radius R_S~δ_γ(z), positioned normally and axially symmetrically to the radiation flux axis (Fig. 2).

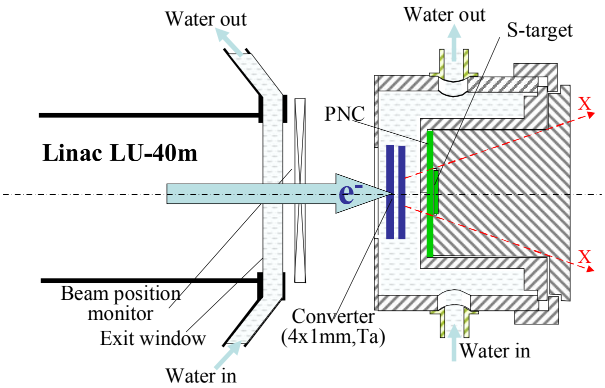

Fig. 2. Schematic of double-foil activation device at exit of LU-40 electron Linac

Electron beam of a LU-40 accelerator was ejected through an output window cooled with water [12]. On-line monitoring of the beam axis position was conducted using a beam position monitor. Via an input window (stainless steel 0.3 mm thick), the beam was injected into a target device comprises a bremsstrahlung converter (four tantalum plates each of thickness 1 mm cooled with water) followed by a pair of foils from natural titanium each of 50 µm in thickness, located axially symmetrically to the beam axis. The first foil (PNC) is by 25 mm in diameter when the second by 6 mm. Every pair of foils was activated at a specified electron energy E_0 in the range of 35…95 MeV with mean beam current of 4 µA for 30 min. After cooling, the induced γ-spectra of foils was measured using a Ge-detector. The expanded uncertainty of the activity measurement did not exceed 10%.

1.3. SIMULATION

For optimization of the target irradiation regime and analysis of the experimental results on the yield of ^{47}Sc and by-products, the calculations were performed with the use of a transport code GEANT4 and various data on the cross-section of the photonuclear reactions on the Ti isotopes.

In Fig. 3, the dependence of yield of the above-threshold photons for the ^{48}Ti(γ,p)^{47}Sc reaction on the thickness of a Ta-converter and the electron energy, is presented. It is evident, that in the E_0 span of 30 to 100 MeV the converter thickness of 4 mm is close to optimal.

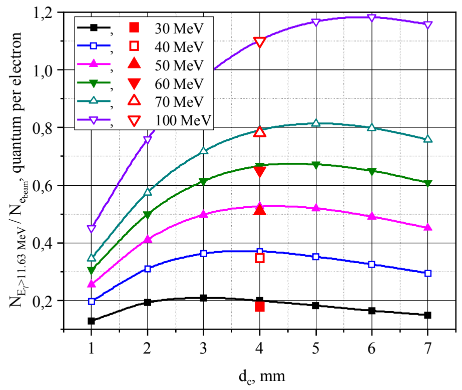

Fig. 3. Normalized yield of gammas with energy higher 11.4 MeV vs the converter thickness and electron energy (solid curves correspond to a solid converter when the separate points at d_C =4 mm correspond to its actual configuration)

The data on distribution of the photon flux density at the converter exit obtained by modelling are given in Fig. 4. It is obvious, that radial flux distribution is perfectly fitted with Gaussian.

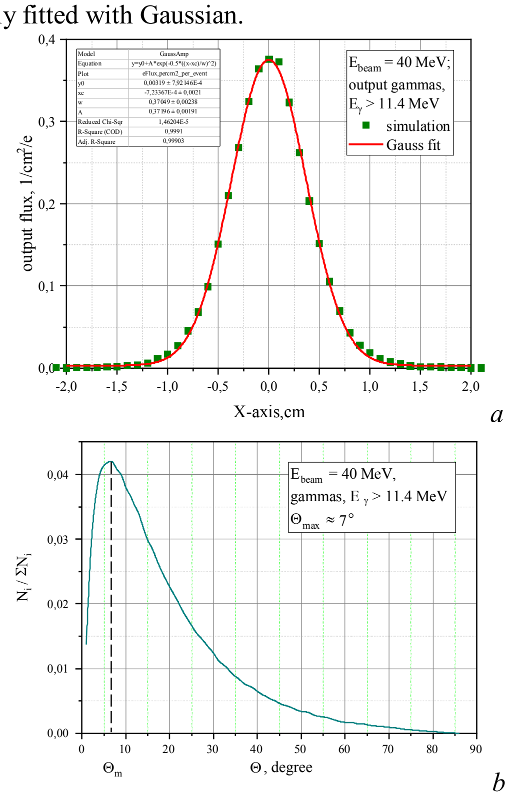

Fig. 4. Radial (a) and angular (b) distribution of the above-threshold X-rays

2. RESULTS AND DISCUSSION

2.1. In Fig. 5, the results are presented on the dependence of activity of the ^{47}Sc and ^{46}Sc isotopes in PNC from natural titanium on electron energy E_0, obtained experimentally and by simulation with the use of cross-section data given in [6] and [7]. The calculations with the [8] and [9] databases were not performed as they provide obviously underestimated results.

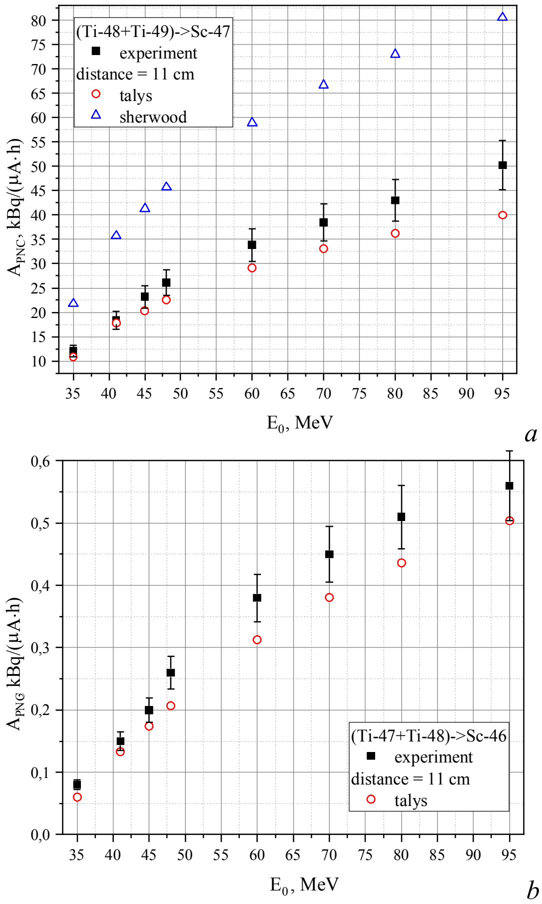

Fig. 5. Dependence of ^{47}Sc (a) and ^{46}Sc (b) activity in PNC on electron energy

The data on the ^{47}Sc yield in the both foils of the stack-targets are listed in Table 1 The results of simulation were obtained using the cross-section data of the TALYS package for the reactions ^{48}Ti(γ,p)^{47}Sc + ^{49}Ti(γ,np)^{47}Sc. The calculations showed, that the contribution of second reaction in the span E_0=35…95 MeV does not exceed 2.3%. It is seen that at the lower border of the E_0 span, the calculated and experimental data are satisfactory agreed within uncertainty of measurement. At the same time with the rise of E_0, a steady trend is observed of overestimation of experimental results as compared with ones using the TALYS database The results on the specific activity of the small S-target obtained experimentally ($\dot{A}_S^{\exp}$) and by simulation technique ($\dot{A}_S^{calc}$) are given in Table 1 also, as well as the estimates of maximum of the ^{47}Sc specific activity $\dot{A}_{\max}$, located in the front surface of the target on the axis of the radiation flux. The data was obtained with the use of Eq. (1) and experimental values of $Y_i^{\exp}$ and δ_γ.

2.2. As it follows from Eq. 1, the rate of the isotope photonuclear generation at periphery of a cylindrical target falls sharply as its diameter becomes higher than FWHM of distribution of flux density of the above-threshold photons (FWHM_γ=2.354 δ_γ), and the height of the target (H) exceeds the free range of the photons $\mu(E_i)^{-1}$, where E_i is the value of the photon energy corresponding the maximum of the reaction cross-section $\sigma_i^{\max}$. The free range of the photons with energy E_i=20 MeV in titanium makes 7.8 cm. So with due regard to the values of δ_γ listed in Table 1, a production target from titanium by FWHM_γ in diameter and up to 2 FWHM_γ high can be considered as close to optimal. The TALYS database was used in simulations as it provides a lower limit of the estimate of capacity of the photonuclear technology for the ^{47}Sc production (Fig. 6).

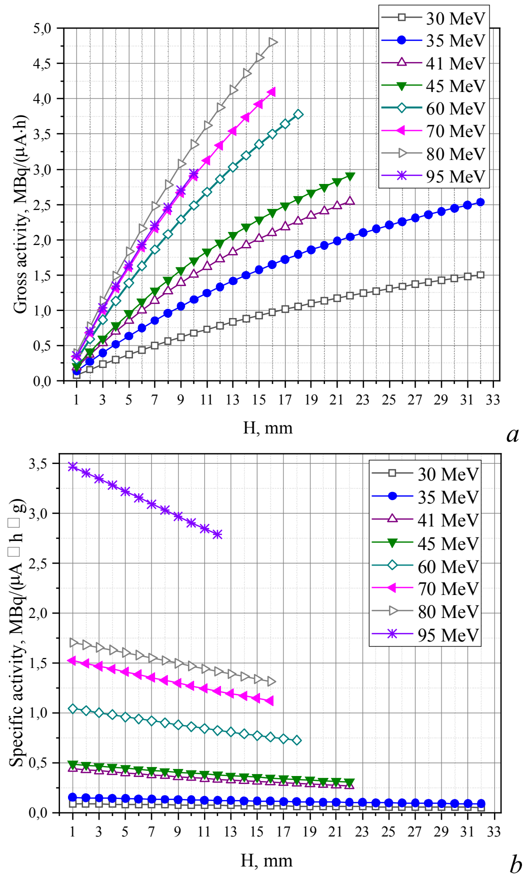

Fig. 6. Dependence of gross (a) and specific (b) activity of target from natural titanium on electron energy and target height

The measured yield of the scandium isotopes at activation of targets from natural titanium is presented in Fig. 7. It is evident, that the relative activity of ^{48}Sc ($T_{1/2}$=44 h) at EOB is ~10% of the ^{47}Sc activity and can be decreased by cooling of a target. The relative yield of ^{46}Sc ($T_{1/2}$=84 d) makes ~1%.

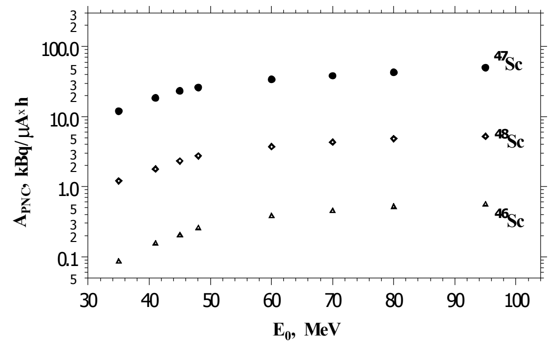

Fig. 7. Photonuclear yield of Sc isotopes in natural Ti

Table 1

Characteristics of ^{47}Sc photonuclear generation in thin targets from natural titanium

E_0, *MeV*	δ_γ, *mm* (exp)	$Y_i^{exp}\cdot 10^5$, *cm²/g*	$Y_i^{calc}\cdot 10^5$, *cm²/g*	$\dot{\bar{A}}_S^{exp}$, *MBq/(g·μA·h)*	$\dot{\bar{A}}_S^{calc}$, *MBq/(g·μA·h)*	$\dot{\bar{A}}_{max}^{calc}$, *MBq/(g·μA·h)*
35	6.4	0.99	0.89	0.20	0.19	0.21
40	4.3	1.51	1.47	0.62	0.54	0.71
45	4.4	1.92	1.68	0.76	0.59	0.98
48	4	2.15	1.87	1.03	0.73	1.16
60	3.5	2.80	2.41	1.63	1.22	1.96
70	3.1	3.18	2.73	2.31	1.72	2.84
80	3.3	3.56	2.99	2.81	1.96	3.63
95	2.2	4.14	3.29	5.51	2.63	7.31

The spectra of the Ti foils activated at various electron energies are presented in Fig. 8.

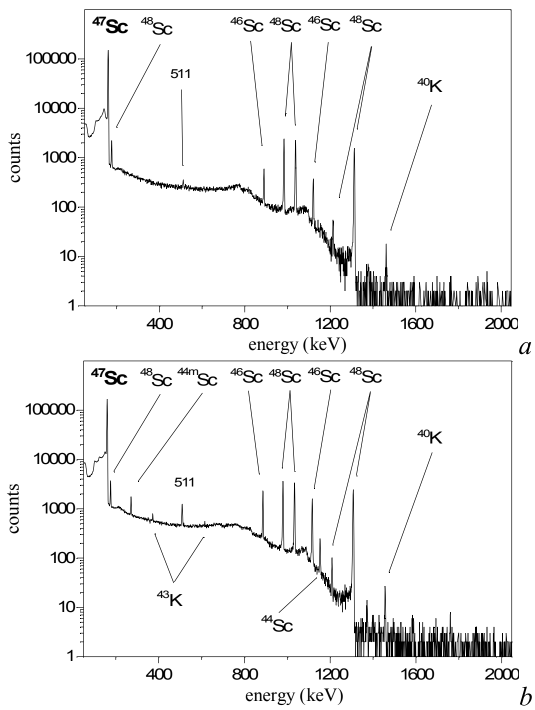

Fig. 8. Spectra of Ti foils:
E_0= 35 MeV (a), E_0= 80 MeV (b)

CONCLUSIONS

The obtained experimental results on the yield of ^{47}Sc via the ^{48}Ti(γ,p)^{47}Sc reaction show that the most applicable data on the maximum of the reaction cross-section (~13 mb) provides the TALYS database with possible underestimation of about 10 to 15%.

In the electron energy (E_0) span of 35 to 95 MeV, the gross activity of ^{47}Sc rises approximately proportional to E_0, when the specific activity ~E_0^3. The relative yield of the main Sc by-products in natural titanium at EOB makes ~10% (^{48}Sc) and ~1% (^{46}Sc) to the activity of ^{47}Sc and can be decreased considerably by usage of a target enriched in ^{48}Ti. At activation of such a target by 11 mm in diameter and 22 mm in height (the weight is 7 g) with an electron beam having routine parameters (40 MeV; 0.3 mA), one can provide the ^{47}Sc capacity of up to 1 GBq/h at a low content of by-products. Application of a more powerful machine [13] enables to increase the capacity of the technology by up to an order of values. The ^{47}Sc specific activity, obtained with due regard to the profile of the X-ray flux, appears much higher (up to by order of values) than the estimates resulting from activation of the small experimental targets [2]. At the same time, the experimentally determined yield of the scandium by-products in natural titanium turned out lower by orders of values than that obtained elsewhere by simulation [4].

The comparative characteristics of various methods of the ^{47}Sc production are listed in Table 2.

Table 2

Comparative characteristics of ^{47}Sc production methods

Reaction	Beam characteristics	Target characteristics	Sc-47 yield, GBq/day	By-products	Rel. yield, %	Ref.
^{47}Ti(n,p)^{47}Sc	E_n>1 MeV Φ_n=5.8·10^{14}, n·cm^{-2}·s^{-1}	^{47}TiO$_2$; 10 g	1·10^3	^{46}Sc ^{48}Sc	3.8·10^{-3} 6.2·10^{-2}	[14]
^{47}Ti(n,p)^{47}Sc	E_n>1 MeV Φ_n=1·10^{13}, n·cm^{-2}·s^{-1}	^{47}Ti; 10 g	up to 10	^{46}Sc	5·10^{-2}	[1]
^{46}Ca(n,γ)^{47}Ca→^{47}Sc	E_n=0.025 eV Φ_n=1·10^{13}, n·cm^{-2}·s^{-1}	^{46}Ca; 10 g	up to 1·10^2	^{46}Sc	<5·10^{-3}	[1]
^{48}Ti(p,2p)^{47}Sc	E_p=35 MeV I_p=50 μA	^{nat}Ti; 17.4 mm	2.5	^{44m}Sc ^{46}Sc ^{48}Sc	90 5 4	[14]
^{48}Ca(p,2n)^{47}Sc	E_p=24…17 MeV I_p=1 μA	^{nat}CaCO$_3$; 0.35, g·cm^{-2}	3.5·10^{-3}	^{46}Sc ^{48}Sc	0.2 14.7	[15]
^{48}Ti(γ,p)^{47}Sc	E_e=40 MeV I_e=300 μA	^{nat}Ti; 7 g	18	^{46}Sc ^{48}Sc	0.87 9.2	-

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ОЦЕНКА ФОТОЯДЕРНОГО ВЫХОДА ^{47}Sc В ТЕХНОЛОГИЧЕСКОЙ МИШЕНИ

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^{47}Sc считается перспективным бета-эмиттером в иммунотерапии рака. Для производства изотопа без носителя может быть использована реакция ^{48}Ti(γ,p)^{47}Sc в поле тормозного излучения ускорителя электронов. На основе разработанной аналитической модели и метода совместной активации двух фольг установлены основные характеристики фотоядерного производства изотопов и оптимальные размеры технологической мишени. Полученные экспериментальные данные по выходу ^{47}Sc и основных примесных изотопов скандия в тонких фольгах из природного титана в диапазоне значений энергии электронов 35…95 МэВ позволяют уточнить имеющиеся данные по сечению реакции ^{48}Ti(γ,p)^{47}Sc. На основе этих результатов методом моделирования рассчитаны общая и удельная активность ^{47}Sc в цилиндрических мишенях из титана оптимальных размеров. Проведено сравнение производительности фотоядерной технологии производства ^{47}Sc с другими методами.

ОЦІНКА ФОТОЯДЕРНОГО ВИХОДУ ^{47}Sc У ТЕХНОЛОГІЧНІЙ МІШЕНІ

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^{47}Sc вважається перспективним бета-емітером в імунотерапії раку. Для виробництва ізотопу без носія може бути використана реакція ^{48}Ti(γ,p)^{47}Sc у полі гальмівного випромінення прискорювача електронів. На основі розробленої аналітичної моделі і методу сумісної активації двох фольг встановлені основні характеристики фотоядерного виробництва ізотопів та оптимальні розміри технологічної мішені. Одержані експериментальні дані щодо виходу ^{47}Sc і основних домішкових ізотопів скандію в тонких фольгах з природного титану в діапазоні значень енергії електронів 35…95 МеВ дозволяють уточнити наявні дані щодо перетину реакції ^{48}Ti(γ,p)^{47}Sc. На основі цих результатів методом моделювання розраховані загальна і питома активність ^{47}Sc у циліндричних мішенях з титану оптимального розміру. Проведено порівняння продуктивності фотоядерної технології виробництва ^{47}Sc з іншими методами.