



# STUDY OF PHOTONUCLEAR REACTIONS WITH THE CHARGED PARTICLES EMISSION FOR THE ZIRCONIUM-89 PRODUCTION

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# Positron emission tomography

allows to detect pathologies at the stage of metabolic violations, long before the morphological changes

Monoclonal antibodies are an attractive vector for tracing due to their specificity for antigens of diseases

- Biological half-life ~ 2-6 days
- Optimal signal-to-noise ratio can be obtained at 2-4 day

Hence only  $^{124}\text{I}$  and  $^{89}\text{Zr}$  with half-lives of 100,2 h and 78,4 h suit





## I-124

## Zr-89

Half-life

100,2 h

78,4 h

Positron yield

22,7 %

22,7 %

Positron energy

820 keV

395 keV

Resolution

2,3 mm

1 mm

Gamma yield

603\* keV (63 %)

909 keV (99 %)

\* close to 511 keV, poor contrast

Bad residual in cells due to dehalogenization



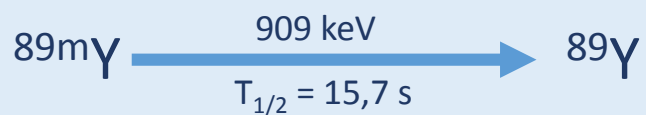
# Zr-89

$T_{1/2} = 78,4 \text{ h}$

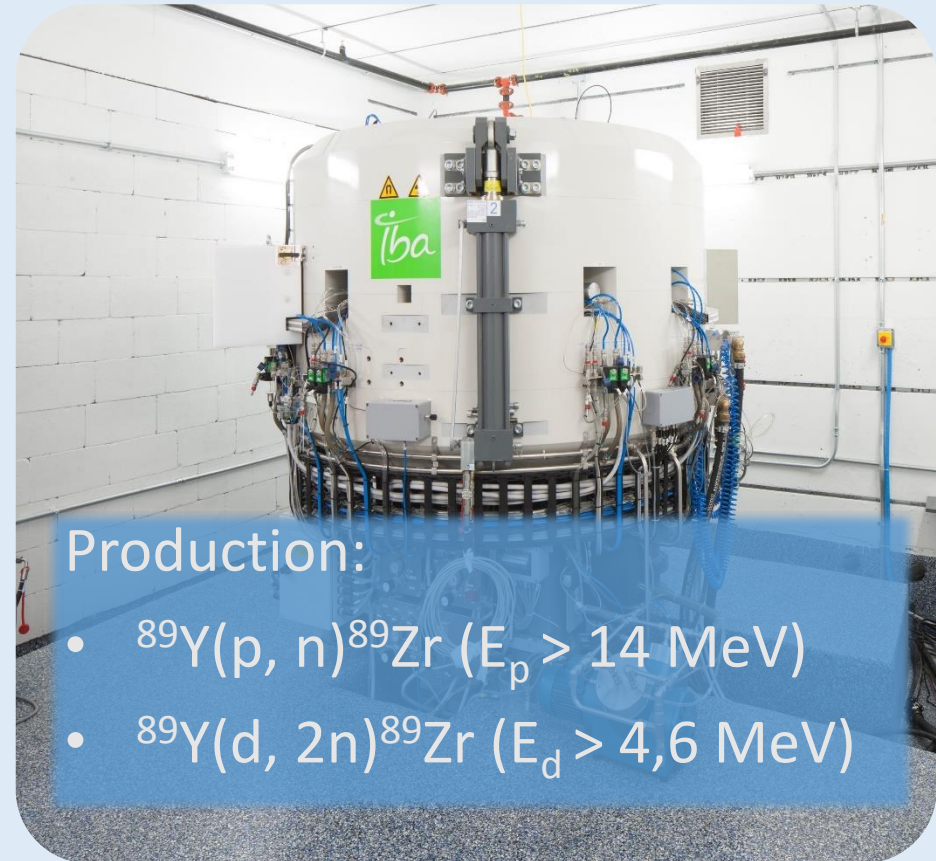
Decay channels:

- positron emission (22,3 %)
- electron capture (76,6 %)

Daughter nucleus –  $^{89\text{m}}\text{Y}$



Production of  $^{88}\text{Zr}$  ( $T_{1/2} = 83,4 \text{ d}$ ) and his daughter  $^{88}\text{Y}$  ( $T_{1/2} = 106,6 \text{ d}$ ) is a serious problem for both methods





# Experiments

Varian Trilogy Linac in 20 MeV bremsstrahlung regime  
20-40 min irradiation

Targets:

- Natural molybdenum 1,82 g (14,65 %  $^{92}\text{Mo}$ , 9,2 %  $^{94}\text{Mo}$ ...)
- Enriched molybdenum 1,27 g (88 %  $^{94}\text{Mo}$ )
- Niobium 2,1 g
- Zirconium 300 mg

Irradiated targets ( $Z = 40, 41, 42$ ) were measured on HPGe  $\gamma$ -spectrometers with energy resolution of 1,8 keV for 1332 keV ( $^{60}\text{Co}$ ).



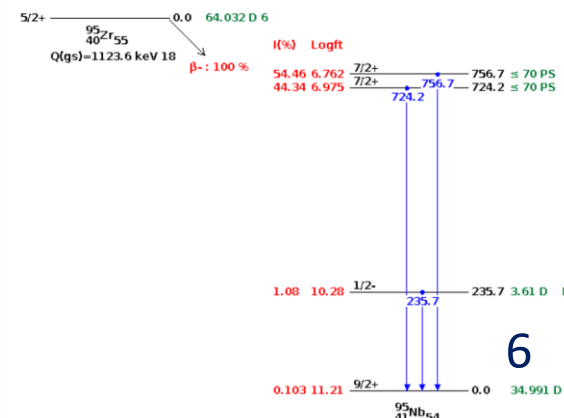
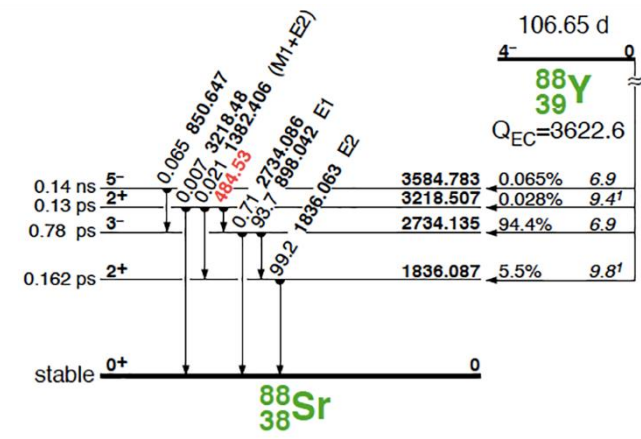
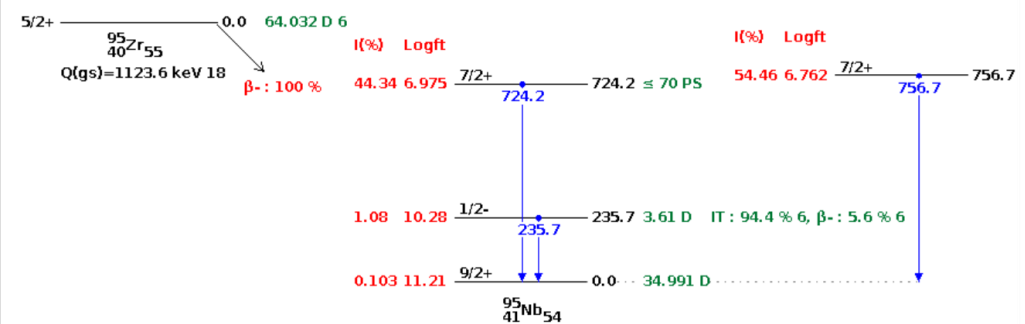
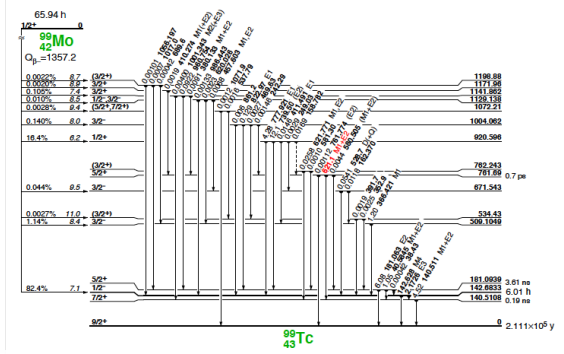
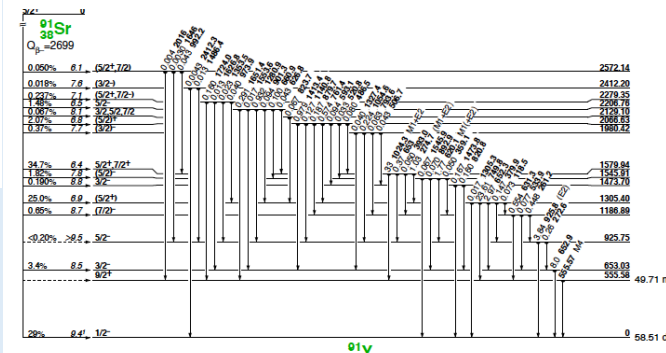
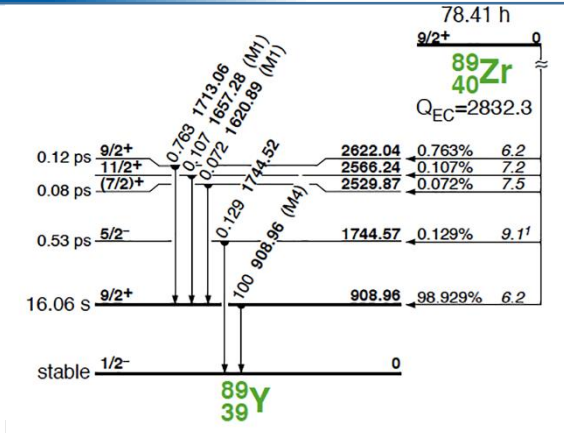
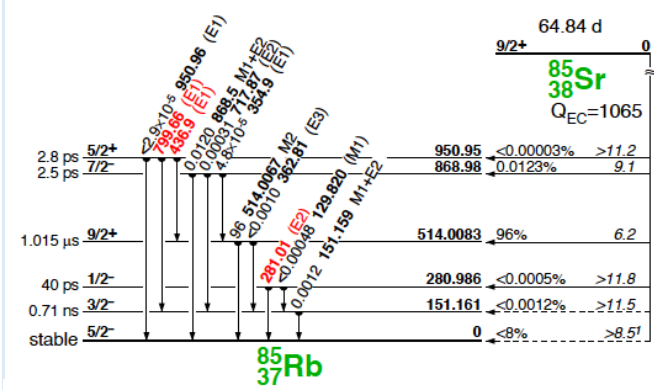
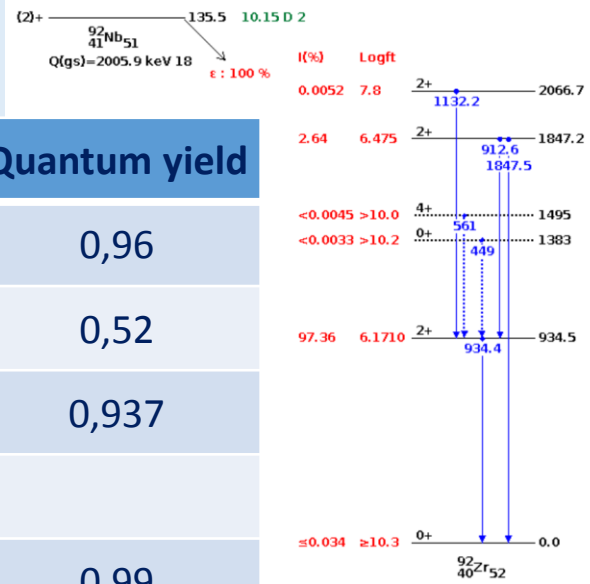




# Study of photonuclear reactions with the charged particles emission for the zirconium-89 production

LXXI International Conference  
NUCLEUS – 2021

Nuclide	Half-life	Line (keV)	Quantum yield
<sup>85</sup> Sr	68,85 d	514	0,96
<sup>91</sup> Sr	9,65 h	555	0,52
<sup>88</sup> Y	106,2 d	898	0,937
<sup>88</sup> Zr	83,4 d	from <sup>88</sup> Y	
<sup>89</sup> Zr	78,4 h	909	0,99
<sup>95</sup> Zr	64 d	757	0,534
<sup>92m</sup> Nb	10,15 d	912	0,018
<sup>99</sup> Mo	66 h	939	0,122





# Theory

Within the statistical model framework, reactions with  $\alpha$  or  $\alpha n$  emission are denied on 20 MeV bremsstrahlung:

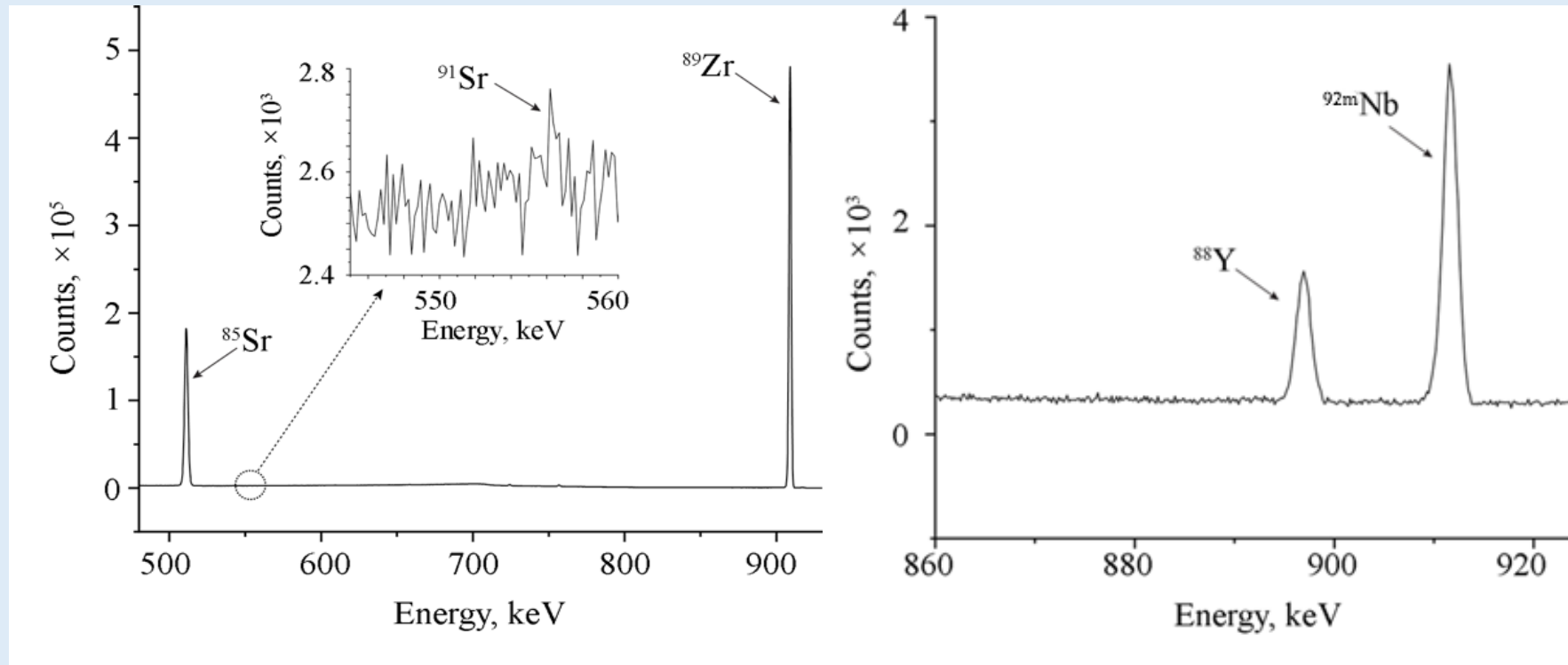
1. Reaction threshold  $\sim 13,5$  MeV and higher
2. Coulomb barrier  $\sim 13$  MeV ( $10^{-19}$  s formation)

Thus, such reactions can occur on photon energies only greater than 25 MeV.

Cross-sections at a level of  $10^{-4}$ - $10^{-5}$  mb begin to appear only for the upper 20 MeV energy gamma-quanta under analysis with the TALYS program code.



# Fragments of the obtained spectra



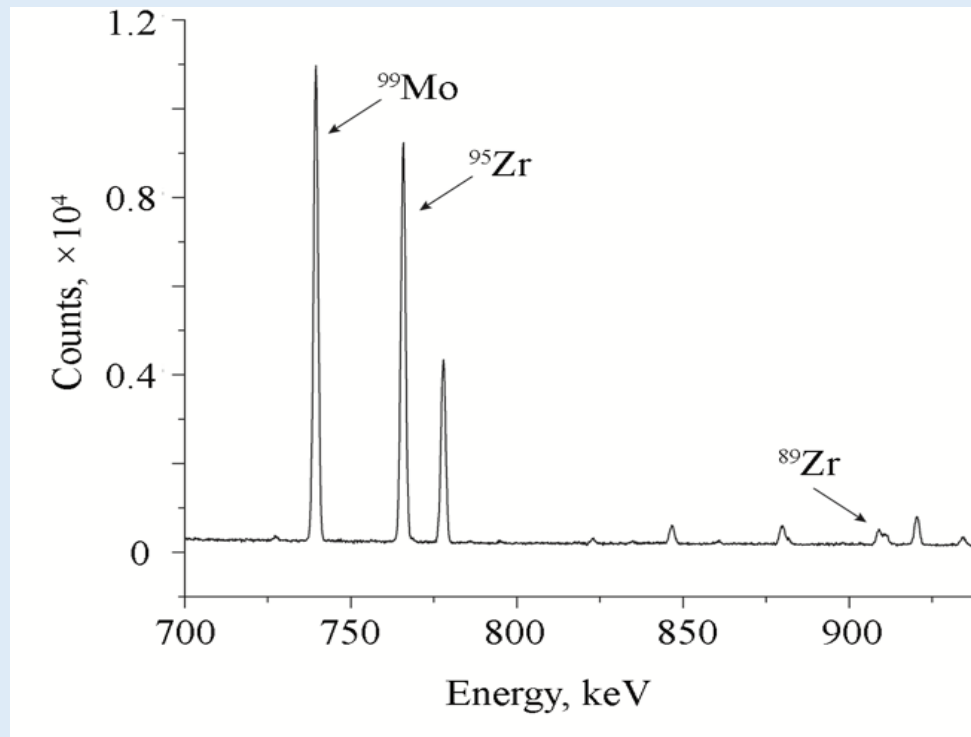
Zirconium spectrum

Niobium spectrum

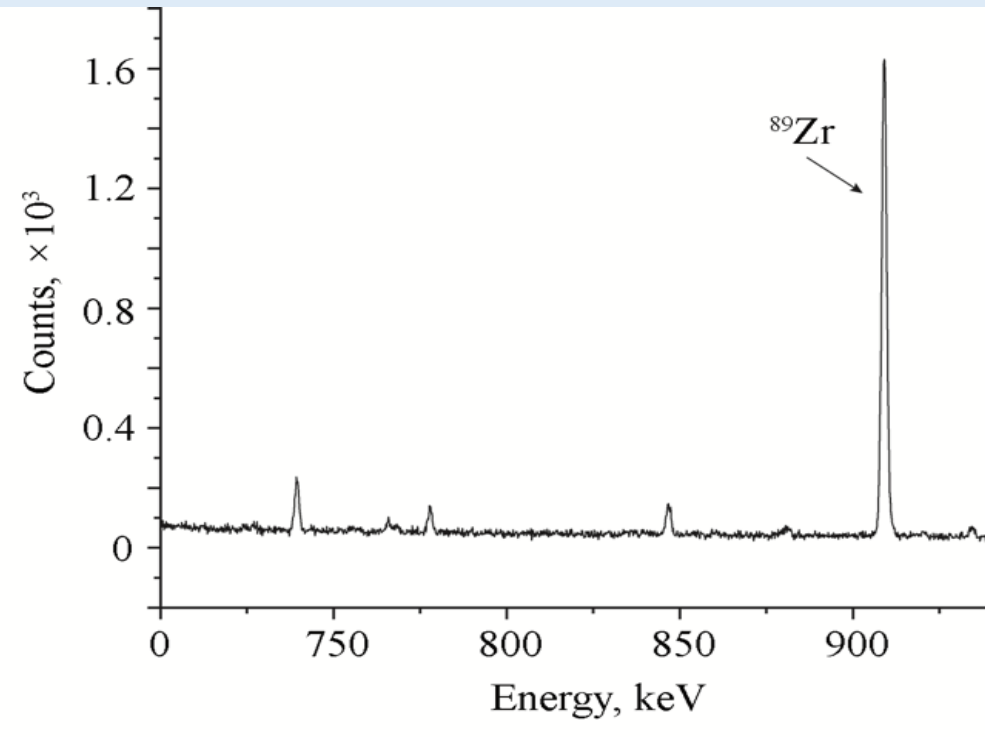




# Fragments of the obtained spectra



Nat. molybdenum spectrum



Enr. (88 %) molybdenum spectrum



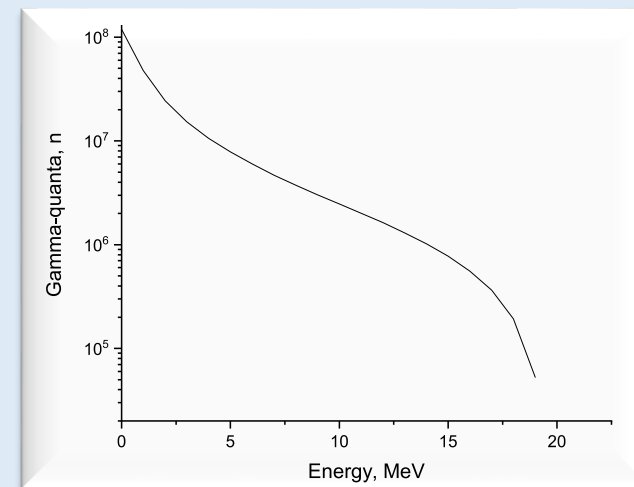
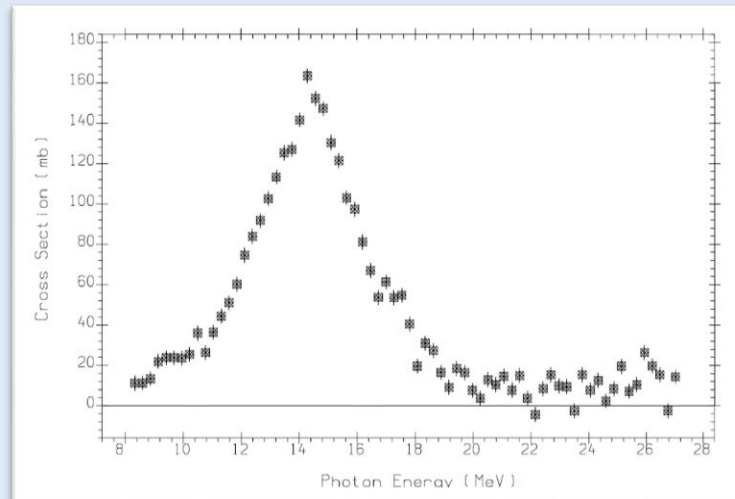
# Flux determination

$$F = \frac{S \lambda A}{(1 - e^{-\lambda t_{irr}}) e^{-\lambda t_c} (1 - e^{-\lambda t_m}) \xi k \eta Y N_A m p}$$

$$Y = \frac{\sum_{i=1}^N \sigma_i \phi_i}{\sum_{i=1}^N \phi_i}$$

$\sigma_i$  -  $^{100}\text{Mo}(\gamma, n)^{99}\text{Mo}$  tabular cross-sections for monochromatic  $\gamma$ -quanta;  $\phi_i$  – relative flux value modeled with Geant4

$S$  is area of  $^{99}\text{Mo}$  photopeak in spectrum;  $\eta$  is quantum yield of  $^{99}\text{Mo}$  decay;  $\xi$  is registration efficiency for  $^{99}\text{Mo}$  quanta;  $t_{irr}$ ,  $t_m$ ,  $t_s$  are irradiation, measurement and cooling times (s);  $k$  is self-absorption coefficient;  $p$  is  $^{99}\text{Mo}$  content in natural compound;  $N_A = 6.02 \cdot 10^{23}$  is Avogadro constant ( $\text{mol}^{-1}$ );  $Y$  is weighted average yield of  $^{100}\text{Mo}(\gamma, n)^{99}\text{Mo}$  (b);  $m$  is molybdenum mass ( $\text{g} \cdot \text{cm}^{-2}$ );  $A$  is a mass number of molybdenum atoms;  $\lambda$  is decay constant,  $\text{s}^{-1}$





# Results and discussion

$^{94}\text{Mo}(\gamma, \alpha)^{89}\text{Zr}$	$1.04 \pm 0.09$ mb
$^{100}\text{Mo}(\gamma, \alpha)^{95}\text{Zr}$	$0.03 \pm 0.01$ mb
$^{92}\text{Mo}(\gamma, \alpha)^{88}\text{Zr}$	$0.081 \pm 0.009$ mb
$^{93}\text{Nb}(\gamma, \alpha)^{88}\text{Y}$	$1.16 \pm 0.12$ mb
$^{93}\text{Nb}(\gamma, \alpha)^{88}\text{Y}^*$	$0.97 \pm 0.10$ mb
$^{90}\text{Zr}(\gamma, \alpha)^{85}\text{Sr}$	$0.030 \pm 0.015$ mb
$^{96}\text{Zr}(\gamma, \alpha)^{91}\text{Sr}$	$0.15 \pm 0.05$ mb

1. *The mechanism of semi-direct nuclear reactions was revealed.*

$\alpha$ -particle escapes from the nucleus during  $t \sim 10^{-21}$  s, whereas the time for the Coulomb barrier formation is  $10^{-18}$ - $10^{-19}$  s.

After the escape of an alpha particle, the residual nucleus decays through ordinary statistical transitions.

\*  $^{93}\text{Nb}(\gamma, n)^{92\text{m}}\text{Nb}$  monitor reaction

2. *Magic numbers ( $N = 50$ ) and closeness affect cross sections*

Transitions in filled shell (magic nuclei) have a higher probability within nuclear shell framework. Such alpha-particles mostly have  $\sim 3$  MeV energy.

Alfa-particles of nuclei with unfilled shells have wider spread of possible energies due to interactions of the configurations and therefore less probability of emission.



# Results and discussion

Estimated  $(\gamma, \alpha n)$  reaction yield for average alpha-particle energy of 3 MeV and further decay of the residual nucleus through the statistical channel is about 1-2 mb (using the TALYS program code). It is in good agreement with the experimental results for the  $(\gamma, \alpha n)$  reaction on  $^{94}\text{Mo}$  and  $^{93}\text{Nb}$ .

Estimates of the reaction yields for higher energies of alpha particles show that if even energy particles increase by 1 MeV, the outputs decrease by ten times for 20 MeV bremsstrahlung gamma-quanta. It is in qualitative agreement with our data for reactions on nuclei with unfilled shells.



Contribution of  $^{88}\text{Zr}$  to the final product upon irradiation of molybdenum targets enriched in  $^{94}\text{Mo}$  does not exceed  $4 \times 10^{-4}$  of the  $^{89}\text{Zr}$  activity.

Such isotope impurity can increase the patient's dose by no more than 1%.

## Acknowledgements

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Thank you for your attention