PHOTOACTIVATION YIELDS OF INDIUM AND TIN LONG-LIVED ISOMER STATES

T.Krasta[1], D.Riekstina[1], A.Chekhovska[2], I.Truten[2], D.Chvatil[3], I.Krausova[3]

[1]Institute of Solid State Physics of the University of Latvia

[2]NSC "Kharkiv Institute of Physics and Technology", Kharkiv, Ukraine

[3]Department of Accelerators, Nuclear Physics Institute, Prague, Czech Republik

Abstract No. RAD 14-90

Motivation

▪ Photonuclear reactions are an essential part of cosmic nucleosynthesis processes taking place, for example, in stars, novae, and interstellar gas media. The role of photoactivation is especially important for formation of isotopes heavier than iron when isomer states serve as β-decay waiting points [1].

▪The isotopes of indium (In, Z=49) and tin (Sn, Z=50) span a wide range of nuclei with shapes varying from near-spherical to deformed. Vicinity to the proton shell closure at Z=50 determines existence of a large number of In and Sn isomer states with different half-lives. The data about photoactivation reactions of indium and tin nuclei are important for modeling abundances of several A~100 region p-nuclei ^{112}Sn, ^{113}In, ^{114}Sn, ^{115}Sn.

▪Knowledge about photoactivation yields of indium and tin long-lived isomer states is necessary for their application in environments subjected to high γ-ray fluences.

Experiment

Experimental photoactivation measurements were performed at the microtron MT-25 of the Nuclear Physics Institute of the Czech Academy of Sciences (Prague). Several targets made of natural indium (1.8 g; 2.1 g; 2.1 g) and natural tin (0.4986 g and 0.6477 g) metal foils were irradiated for t_{irr}=20 min with bremsstrahlung photons produced with 14 MeV and 18 MeV electron energies E_{max} via tungsten converter (Fig.1).

Each test sample was irradiated together with a ~0.45 g metal copper (Cu) foil to monitor the photon flux at the target site. The measured yield of ^{63}Cu(γ,n)^{62}Cu reaction has been corrected for the ^{65}Cu(γ,n)^{64}Cu reaction admixture (assessed to be less than 0.1% for t_{cool} < 1 h cooling times) as well as for the difference between monitor and studied reaction threshold energies.

Decay γ-spectra were measured after different cooling times with a HPGe detector (efficiency 78%, and energy resolution FWHM 1.8 keV for 1332 keV γ-line of ^{60}Co) in the low-background room.

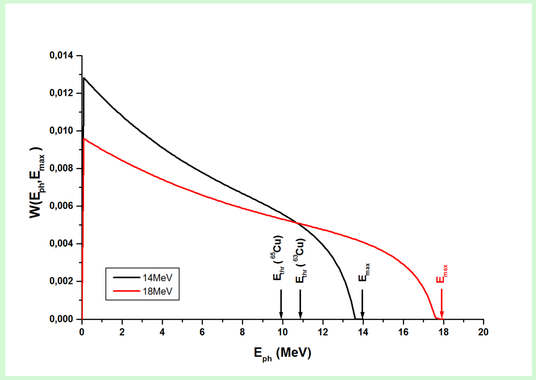

Figure 1. Spectral distribution of bremsstrahlung photons from tungsten converter irradiated with the electron beam at E_{max}=14 and 18 MeV energy. The total photon fluences are normalized to unity.

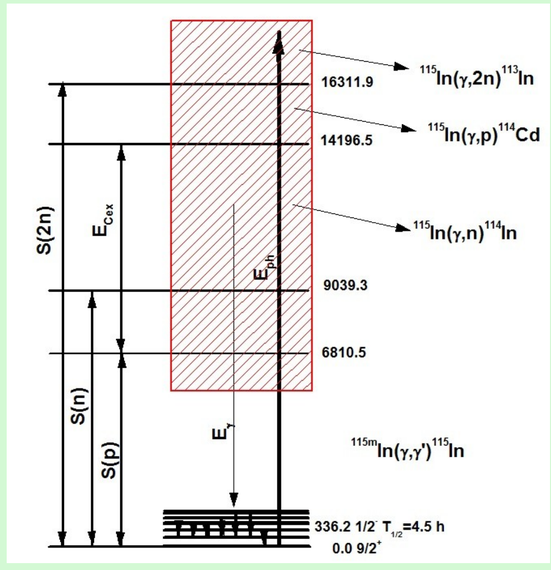

Figure 2. Schematic representation of concurrent processes taking place during irradiation of ^{115}In nuclei with photons. Photon energy E_{ph} and reaction cross-section $\sigma(E_{ph})$ determine probability of each specific outcome.

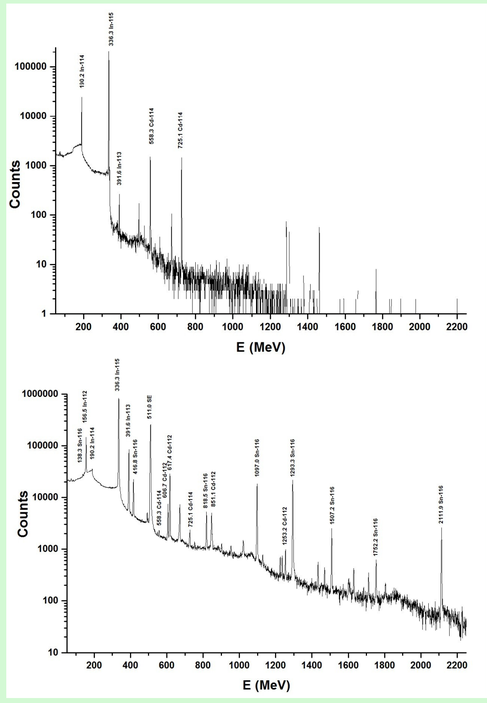

Figure 3. Decay spectra of ^{nat}In sample registered after t_{cool}=20 min and 17 h 10 min (the upper panel) following its irradiation with bremsstrahlung photons (E_{max}=14 MeV).

Photonuclear reactions caused by bremsstrahlung radiation are characterized by integral yields defined as follows (Eq.1):

$$Y(E_{max}) = N_R \int_{E_{thr}}^{E_{max}} \frac{\sigma(E_{ph})}{E_{ph}} \cdot W(E_{ph}, E_{max}) dE_{ph}$$

where $\sigma(E_{ph})$ is a photonuclear reaction cross-section and N_R is a normalization constant:

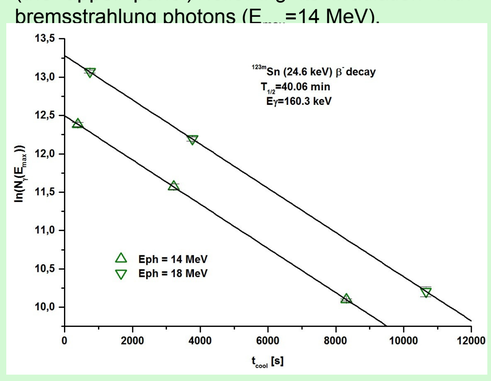

Figure 4. Measured area $N_\gamma(E_{max})$ of E_γ=160.3 keV spectral line in dependence on ^{nat}Sn sample cooling time

Results

In spectra measured after different cooling times, decay γ-lines of indium and tin long-lived isomer states ^{113m}In (391.7 keV; $T_{1/2}$=1.7 h), ^{114m}In (190.3 keV; $T_{1/2}$=49.5 days), ^{115m}In (336.2 keV; $T_{1/2}$=4.5 h), ^{116m}In (127.3 keV; $T_{1/2}$=54.3 min), ^{117m}In (315.3 keV; $T_{1/2}$=116.2 min), ^{117m}Sn (314.6 keV; $T_{1/2}$=13.9 days), ^{123m}Sn (24.6 keV, $T_{1/2}$=40.1 m, Fig. 4) have been identified (Figs. 5,6). The measured intensities allowed to determine experimental yields of photonuclear reactions ^{113}In(γ,γ')^{113m}In, ^{115}In(γ,γ')^{115m}In, ^{113}In(γ,n)^{112m}In, ^{115}In(γ,n)^{114m}In, ^{117}Sn(γ,γ')^{117m}Sn, ^{118}Sn(γ,n)^{117m}Sn, ^{124}Sn(γ,n)^{123m}Sb at bremsstrahlung end-point energy values 14 MeV and 18 MeV.

The integral activation yields $Y(E_{max})$ at microtron energy E_{max} were determined from the measured relative intensities of strong γ-transitions using the simple activation equation (Eq.2)

$$Y(E_{max}) = \frac{N_\gamma(E_{max}) \cdot \lambda}{\varepsilon \cdot I_\gamma \cdot n \cdot \Phi(E_{max}) \cdot (1 - e^{-\lambda \cdot t_{irr}}) \cdot e^{-\lambda \cdot t_{cool}} \cdot (1 - e^{-\lambda \cdot t_{meas}})}$$

where $N_\gamma(E_{max})$ - the measured full peak count from which background and other possible admixtures are subtracted; λ – the radioactive decay constant, n - the number of target nuclei in the irradiated sample, ε - the full energy peak detection efficiency, I_γ - the absolute γ-ray intensity per one decay, $\Phi(E_{max})$ – photon flux, while t_{irr}, t_{cool}, and t_{meas} – the irradiation, cooling, and measuring times, correspondingly.The energies and absolute γ-ray intensities of decay γ-transitions were taken from Ref.[2]. Table 1 presents $Y(E_{max})$ values evaluated relative to Cu monitor reaction yield values determined from the measured intensity of the 511 keV annihilation peak. In order to compensate possible errors in photon flux determination due to presence of two stable copper isotopes: ^{63}Cu, and ^{65}Cu, as well as differences between studied and monitor reaction thresholds, statistical yield uncertainties of experimental yields were increased by 10%.

Table 1. Integral activation yields $Y(E_{max})$ of In and Sn long-lived isomer states registered in the decay spectra following the irradiation with 14 and 18 MeV bremsstrahlung photons. In the second column, the energy of the main decay γ-transition used for yield determination is given. Datails of corresponding decay processes are shown in Figs. 5,6. The decay intensities of several reactions activating ^{117m}Sn isomer at 314.6 keV cannot be separated in present ^{nat}Sn measurements. Experimental yield values are obtained from the yield ratios of studied and Cu monitor reactions as well as monitor yields evaluated using Eq.(1) and experimental ^{63}Cu(γ,n) reaction cross-sections of Sund et al. [3]. The last column shows yields evaluated with cross-section values from theoretical statistical model predictions TENDL-2023 [4].

Reaction	Isomer state	E_γ (keV); Nucl.	E_{max} (MeV)	$Y(E_{max})_{exp}$ (mb·MeV)	$Y(E_{max})_{ENDF}$ (mb·MeV)
^{113}In(γ,n)	^{112m}In	156.6; ^{112m}In	14	3.6(4)	9.4
			18	16.7(19)	20.2
^{113}In(γ,γ')	^{113m}In	391.7; ^{113m}In	14	1.15(19)	
			18	1.20(19)	
^{115}In(γ,n)	^{114m}In	190.3; ^{114m}In	14	6.5(14)	8.1
			18	25(5)	17.7
^{115}In(γ,n)	^{114m}In	725.2; ^{114}Cd	14	1.33(22)	
			18	1.32(21)	
^{115}In(γ,γ')	^{115m}In	336.2; ^{115m}In	14	1.33(22)	
			18	1.32(21)	
^{112}Sn(γ,n)	^{111g}Sn	1152.8; ^{111}In	18	43(7)	
^{117}Sn(γ,γ') + ^{118}Sn(γ,n)	^{117m}Sn	158.6; ^{117m}Sn	14	6.2(13)	
^{117}Sn(γ,γ') + ^{118}Sn(γ,n) + ^{119}Sn(γ,2n)			18	131(33)	
^{124}Sn(γ,n)	^{123m}Sn	160.3; ^{123}Sb	14	7.8(8)	
			18	40(6)	

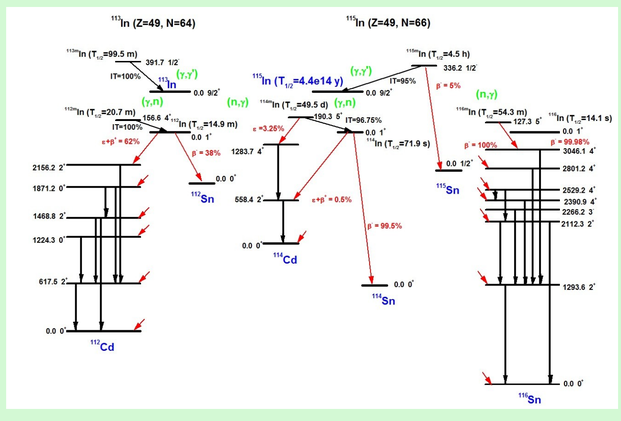

Figure 5. The decay schemes of long-lived isomers observed in present photoactivation experiment with natural indium targets

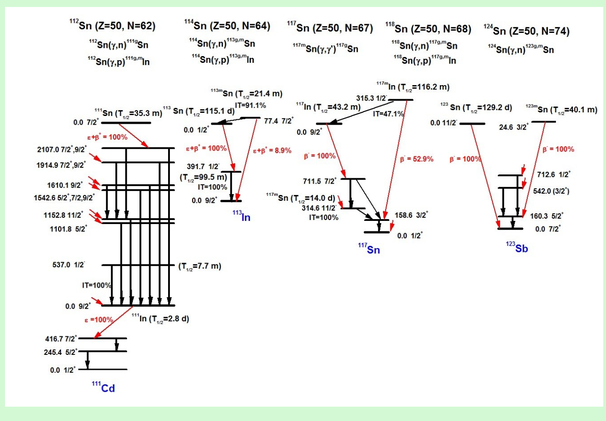

Figure 6. The decay schemes of long-lived isomers observed in present photoactivation experiment with natural tin targets

References

1. E.M.Burbidge et al., Rev.Mod.Phys. 29 (1957) 547-650.
2. Evaluated Nuclear Structure Data File (ENSDF), https://www-nds.iaea.org
3. R.E.Sund et al., Phys.Rev. 176 (1968) 1366.
4. A.J.Koning et al. NDS, 155 (2019) 1-55; https://www-nds.iaea.org
5. I.Semisalov, A.Chekhovska, Y.Skakun, S.Karpus, V.Kasilov. Applied Radiation and Isotopes 176 (2021) 109843
6. M.Versteegen et al., Phys.Rev. C94 (2016) 044325.

Conclusions.

1.The integral activation yields of several indium and tin isomer states have been obtained at bremsstrahlung photon end-point energies 14 MeV and 18 MeV. Measured values show satisfactory agreement with theoretical predictions of statistical model.

2. The activation yields of ^{111m}Sn, ^{112m}Sn, ^{113m}Sn isomers should be evaluated using equations for genetically linked nuclides (see, e.g., [5]).

3. Prominent activation of ^{nat}In samples with the products of photoneutron capture reactions ^{115}In(n,γ)^{116g,m}In has been registered. It is explained by the large neutron capture cross sections inherent to indium isotopes and is in agreement with the results of Ref.[6].

4. Present photoactivation measurements of indium and tin long-lived isomers should be continued at other E_{max} values provisioning measurements also after longer cooling times in order to improve results for longer living isomers (^{114m}In, ^{117m}In). Since correct choice of the photon flux monitor reaction is crucial for precision of obtained results it is desirable to include the use of Au monitor reactions for photon and photoneutron flux determination..

5. More detailed theoretical statistical model calculations are necessary in order to improve understanding of indium and tin photoactivation reactions and their impact on cosmic nucleosynthesis processes.