STUDY of (γ, t)-REACTIONS ON ^{10}B

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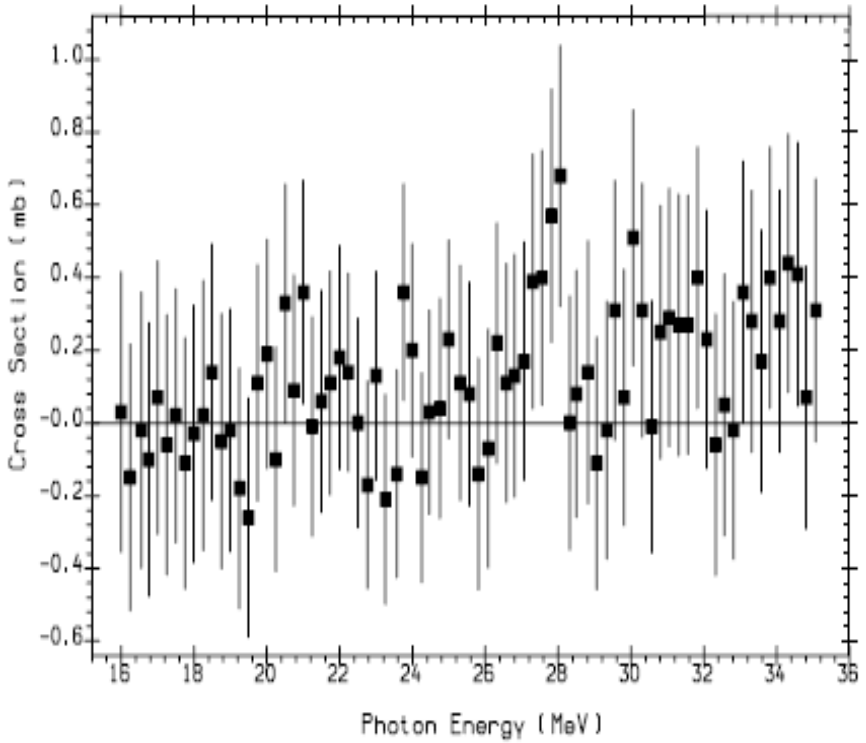
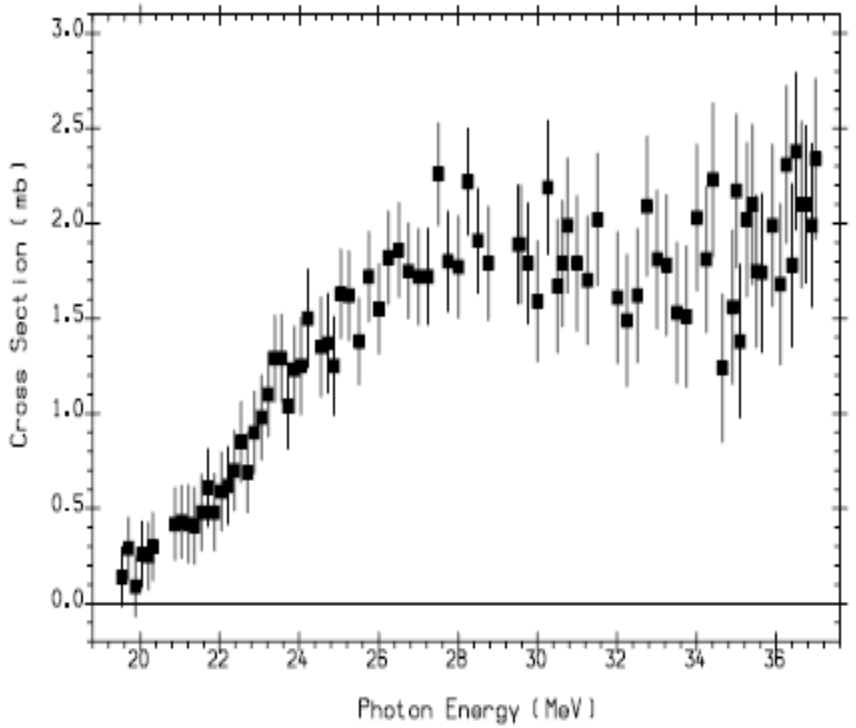
The cross-sections of ^{10}B and ^{9}Be (from EXFOR)



(5-B-10(G,2N)5-B-8)+(5-B-10(G,2N+P)4-BE-7)
QMPH,ARAD Positron annihilation in flight.
L0044003 J,NP/A,264,30,76 U.KNEISSL+



(4-BE-9(G,2N)4-BE-7)+(4-BE-9(G,2N+P)3-LI-6)
QMPH,ARAD Positron annihilation in flight.
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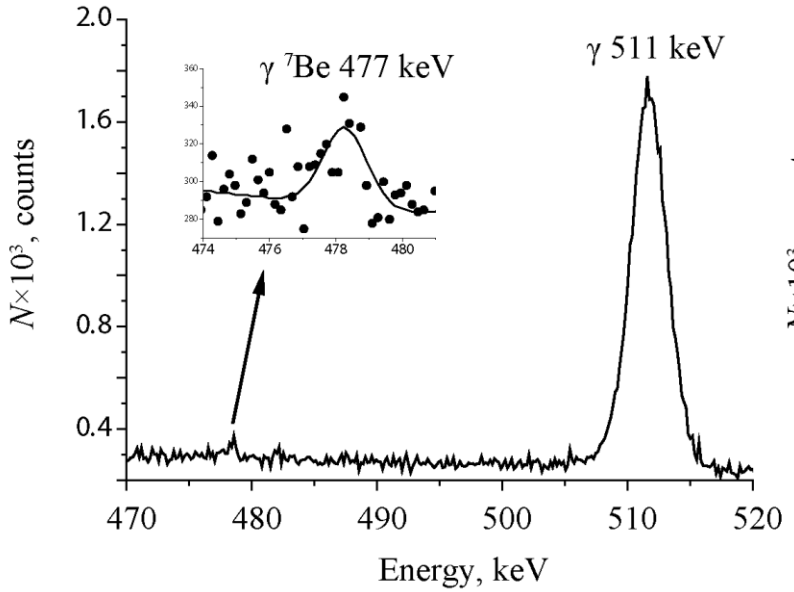
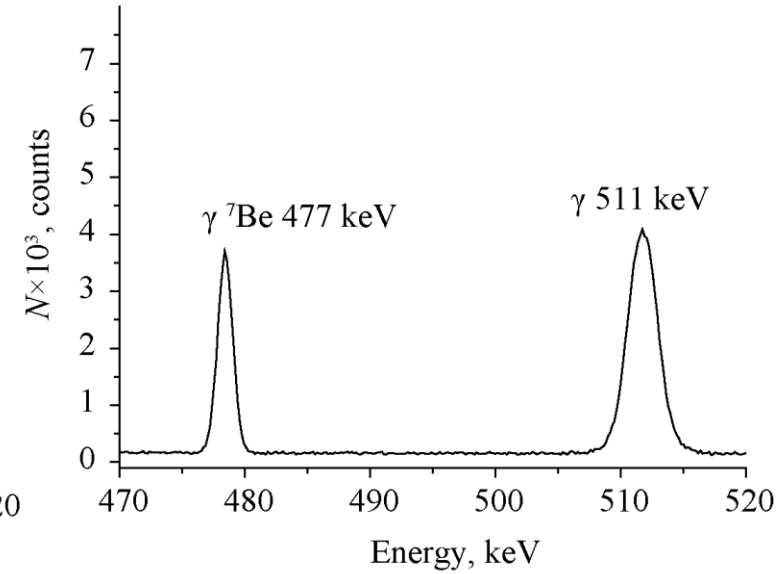
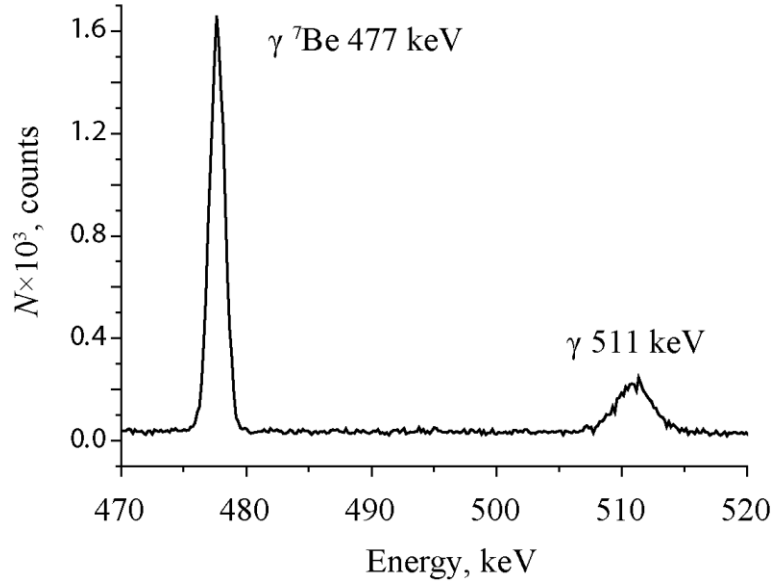
γ-spectra fragments of ^{nat}B irradiated targets by bremsstrahlung γ-quanta with E^{max} = 20, 40, 55 MeV





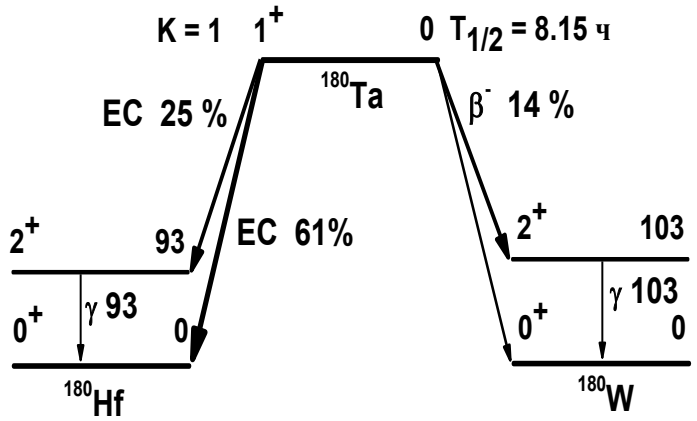


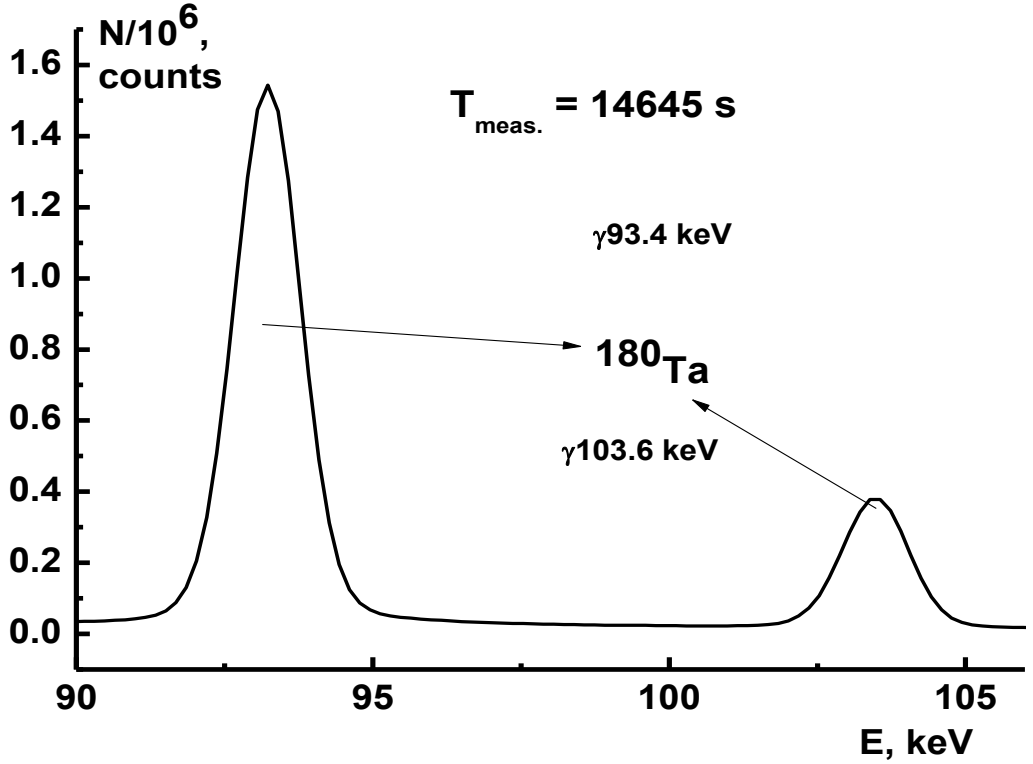
^{7}Be is formed by 20MeV irradiation only in the reaction (γ, t) at ^{10}B, and (γ,tn) at ^{11}B

^{7}Be is formed by 40 MeV irradiation in the reactions (γ, p2n) -, (γ, dn) -, (γ, t) at ^{10}B, and (γ,tn) at ^{11}B

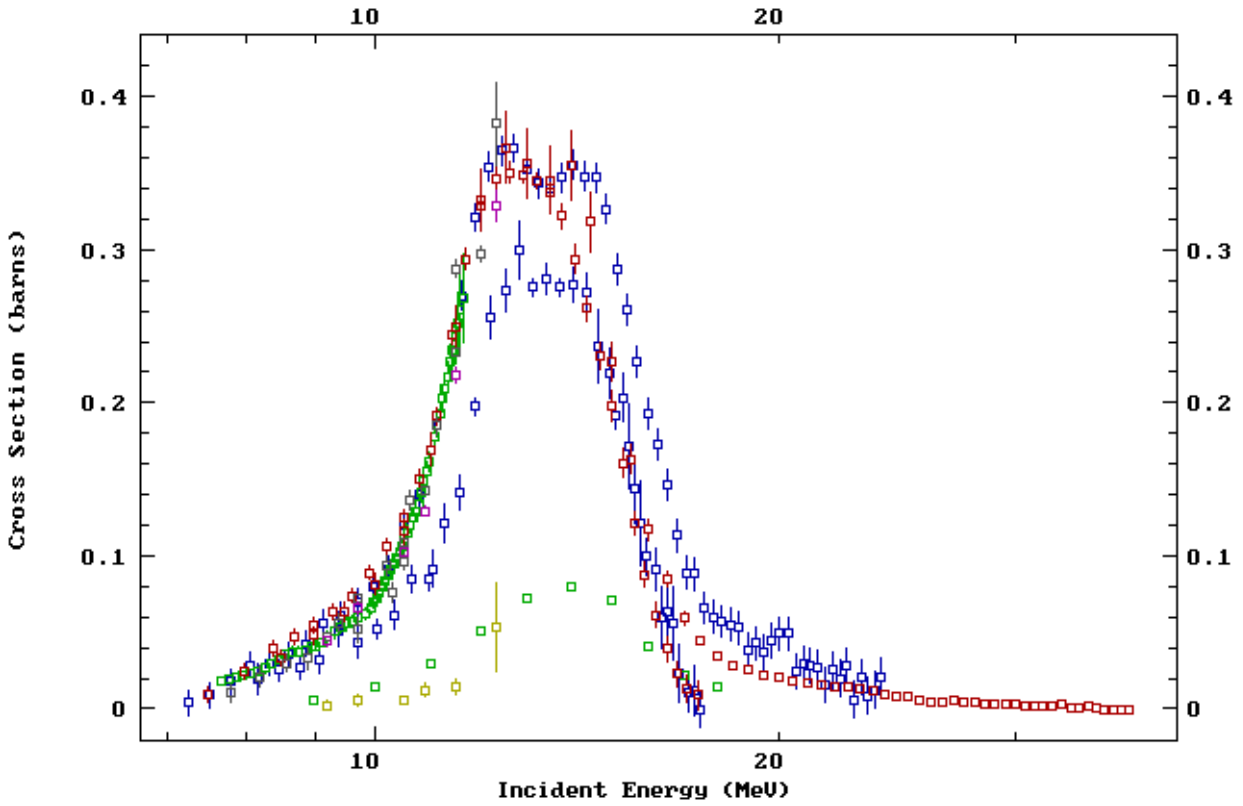
^{7}Be is formed by 55 MeV irradiation in the reactions (γ, p2n)-, (γ, dn)-, (γ,t) at ^{10}B, and (γ, p3n)-, (γ, d2n)-, (γ,tn) at ^{11}B

The γ-ray beam was monitored by the ^{181}Ta (γ, *n*)-reaction





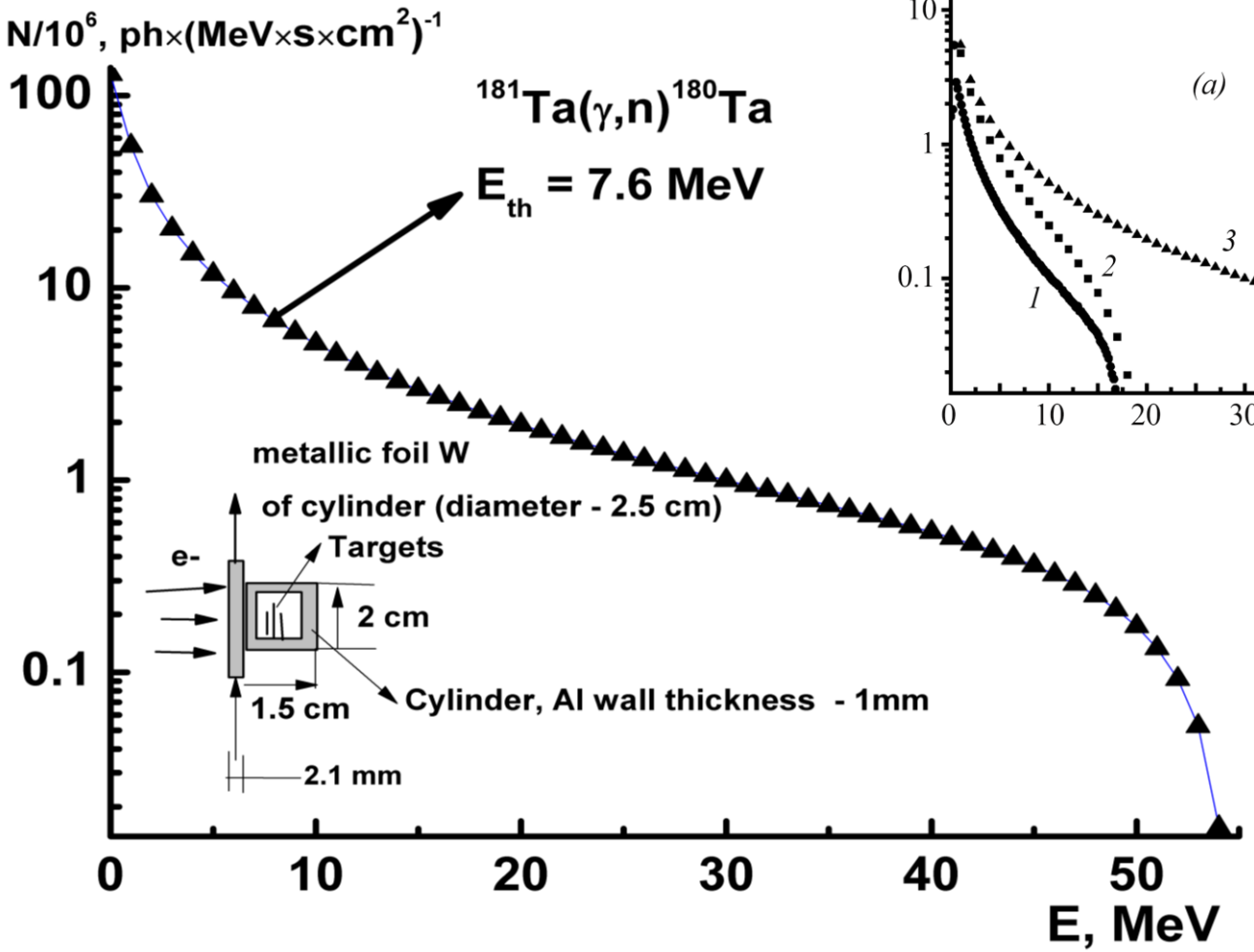
Estimation of the flux of bremsstrahlung γ-quanta

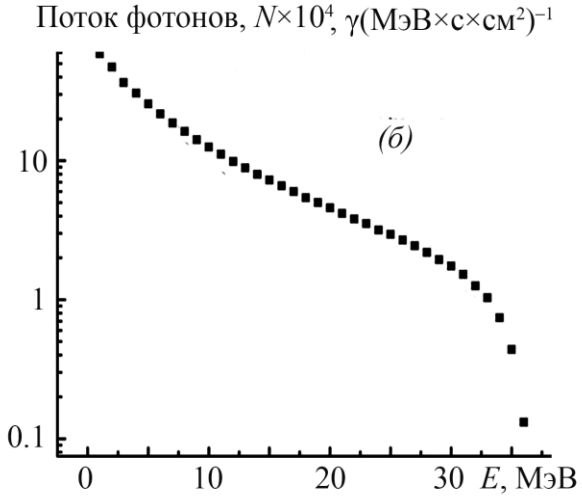


$$Y = \frac{\sum_{i=1}^{N} \sigma_i \varphi_i}{\sum_{i=1}^{N} \varphi_i}$$

σ_i are tabular values of the ^{181}Ta(γ, n)^{180}Ta reaction cross-sections for monochromatic γ-quanta (Varlamov et al., 2013); φ_i are the relative values of the bremsstrahlung γ-quanta flux spectra, modeled in Geant4 and reduced to the threshold value of the E^{th} reaction for a different number of events.

The spectrum of accelerator bremsstrahlung γ-quanta modeled using Geant4





Estimation of the flux of bremsstrahlung γ-quanta

- The bremsstrahlung γ-quanta fluxes were calculated using the formula (n_γ × cm^{-2} × s^{-1} × MeV^{-1}):

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

S is the area of photopeaks corresponding to the ^{180}Ta decay; η is the quantum yield of the ^{180}Ta γ-quanta decay; ξ is the detection efficiency of γ-quanta accompanying the decay of ^{181}Ta(γ, *n*)^{180}Ta reaction; t_{irr}, t_c, t_m are times of irradiation, cooling, and measurement, respectively (in seconds); *k* is the self-absorption coefficient of γ-quanta of the decay; *p* is the ^{181}Ta absolute content in the natural mixture; N_A = 6.02 × 10^{23} is the Avogadro's number (in nuclei number × g^{-1} × mol^{-1}); *Y* is the yield of the ^{181}Ta(γ, n)^{180}Ta reaction calculated according to (1) (in bn); *m* is the mass of tantalum targets per area (in g × cm^{-2}); *A* = 181 is the mass number of tantalum atoms (in a.m.); λ is the ^{180}Ta decay constant (in s^{-1}). The λ, η, *A*, *p* values are taken from (Briesmeister, 1997); *S* is taken from experimental γ-spectra, and ξ is taken from calibration curves, additionally verified by simulation using the Geant4 program code.

Experimental and theoretical yields of the ^{7}Be population reaction at different boundary energies of bremsstrahlung γ-quanta

E, MeV	20	40	55
Y, μbn	11(2)	390(40)	920(90)
Nuclear Reactions / Energy thresholds, MeV	^{10}B(γ,t)/18.7	^{11}B((γ,tn)/30.1 ^{10}B((γ,dn)/24.9 ^{10}B((γ,p2n)/27.2	^{11}B((γ,tn)/30.1 ^{10}B((γ,dn)/24.9 ^{10}B((γ,p2n)/27.2 ^{11}B((γ,d2n)/36.4 ^{11}B((γ,p3n)/38.6
Talys1-9	0.09	556	491

Radioecological monitoring at Nuclear Power Plant

Solid waste sorting place at nuclear power plant

Capacity of liquid radioactive waste at nuclear power plant

Activated non-gamma emitters in structural materials of the reactor core

- ^{14}C $T_{1/2}$= 5730 years

Reactions: $^{13}C(n,\gamma)^{14}C$, $^{14}N(n,p)^{14}C$

- ^{59}Ni $T_{1/2}=7.6\times10^4$ years

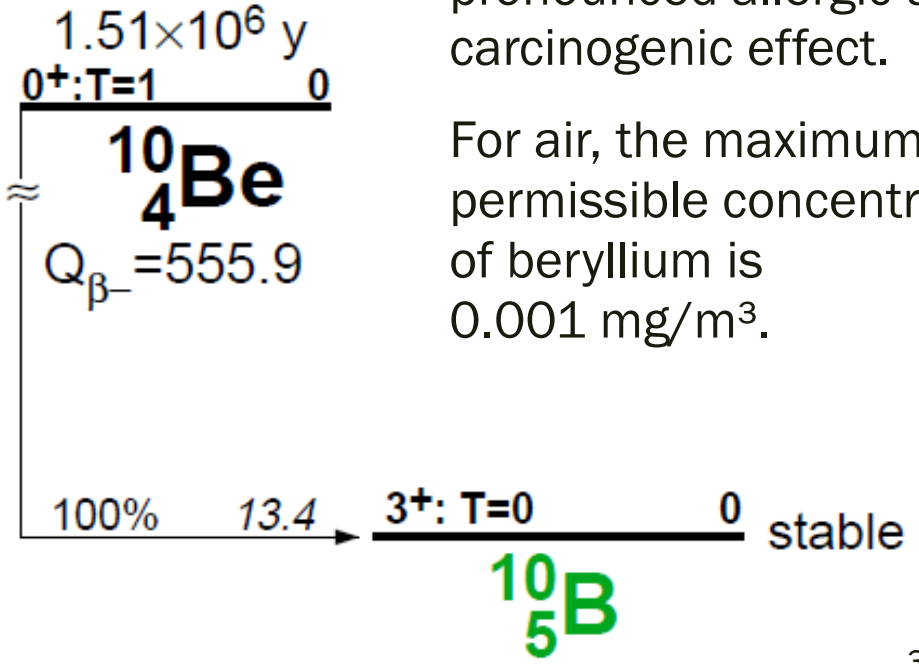
Reaction: $^{58}Ni\ (n,\gamma)\ ^{59}Ni$

- ^{10}Be $T_{1/2}= 1.51\times10^6$ years

Reactions: $^{9}Be(n,\gamma)^{10}Be$ σ= 7,6 ±0,4 mb,

$^{10}B(n,p)^{10}Be$ σ= 6,4 ±0,5 mb

$\bar{\sigma}$ (^{10}B, ^{9}Be) = 7 mb



Beryllium has a pronounced allergic and carcinogenic effect.

For air, the maximum permissible concentration of beryllium is 0.001 mg/m³.

Description of the proposed method

^{9}Be (n,γ) ^{10}Be

Ideally, for the studied RW sample, it is known:

^{9}Be content (%) in the sample volume

φ is the thermal neutron fluence

σ is a cross-section of ^{9}Be neutron capture

Then the number of ^{10}Be atoms in the RW sample:

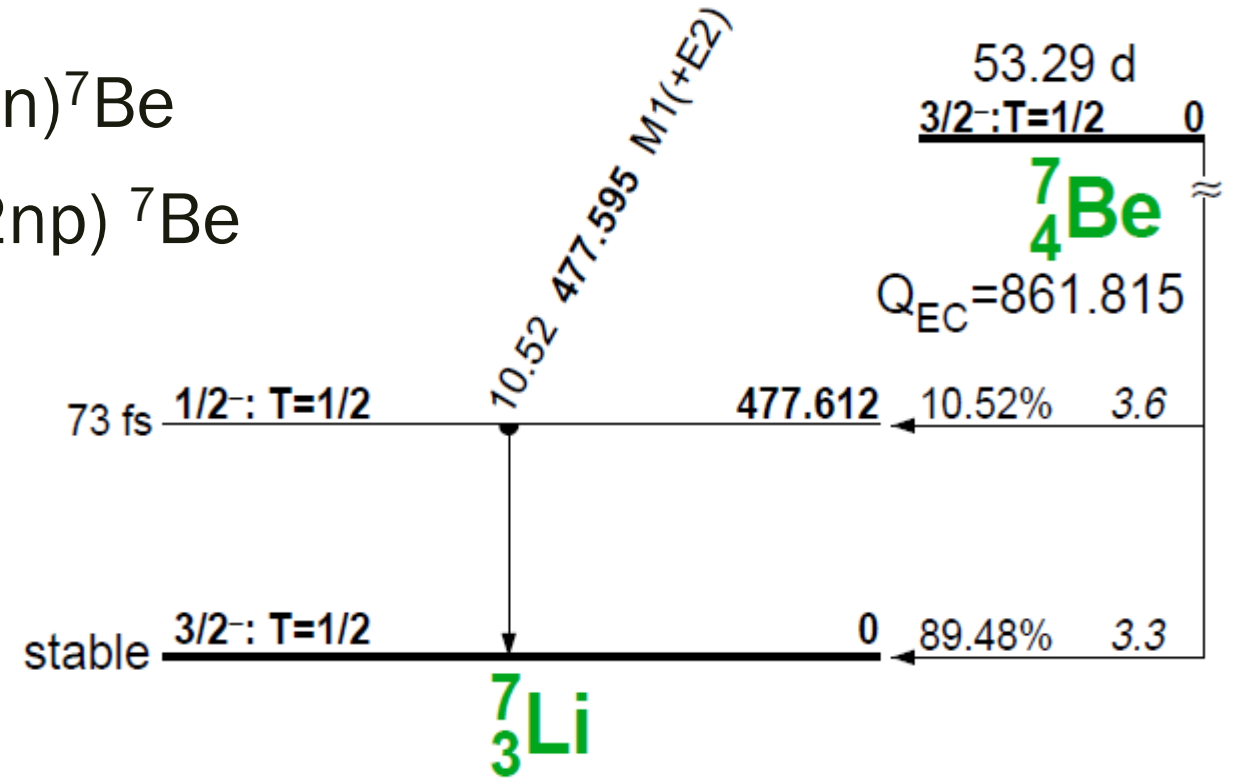
$$A(^{10}\mathrm{Be}) = N\,\varphi\,\sigma\,(1 - e^{-\lambda t_{irr}}),$$

where *N* is the number of ^{9}Be atoms in the sample, t_{irr} is the time of reactor operating

Description of the proposed method

$^{9}Be(\gamma, 2n)^{7}Be$

$^{10}B\ (\gamma, 2np)\ ^{7}Be$



Description of the proposed method

$$A(^{7}\mathrm{Be}) = N(Be)(1 - e^{-\lambda(Be)t_{irr}}) \int_{E_{threshold}}^{E_{\gamma}^{max}} \sigma(E) \cdot \Phi(E) \cdot dE$$

where N is the number of ^{9}Be atoms in the irradiated sample,

$\sigma\ (E)$ is the reaction cross section,

$\Phi\ (E)$ is the flux density of quanta,

$\lambda\ (\mathrm{Be})$ is the ^{7}Be radioactive decay constant,

t_{irr} is the target irradiation time.

37MeV and 55 MeV irradiation:

^{10}B: σ (37MeV) = 220 **μ**b

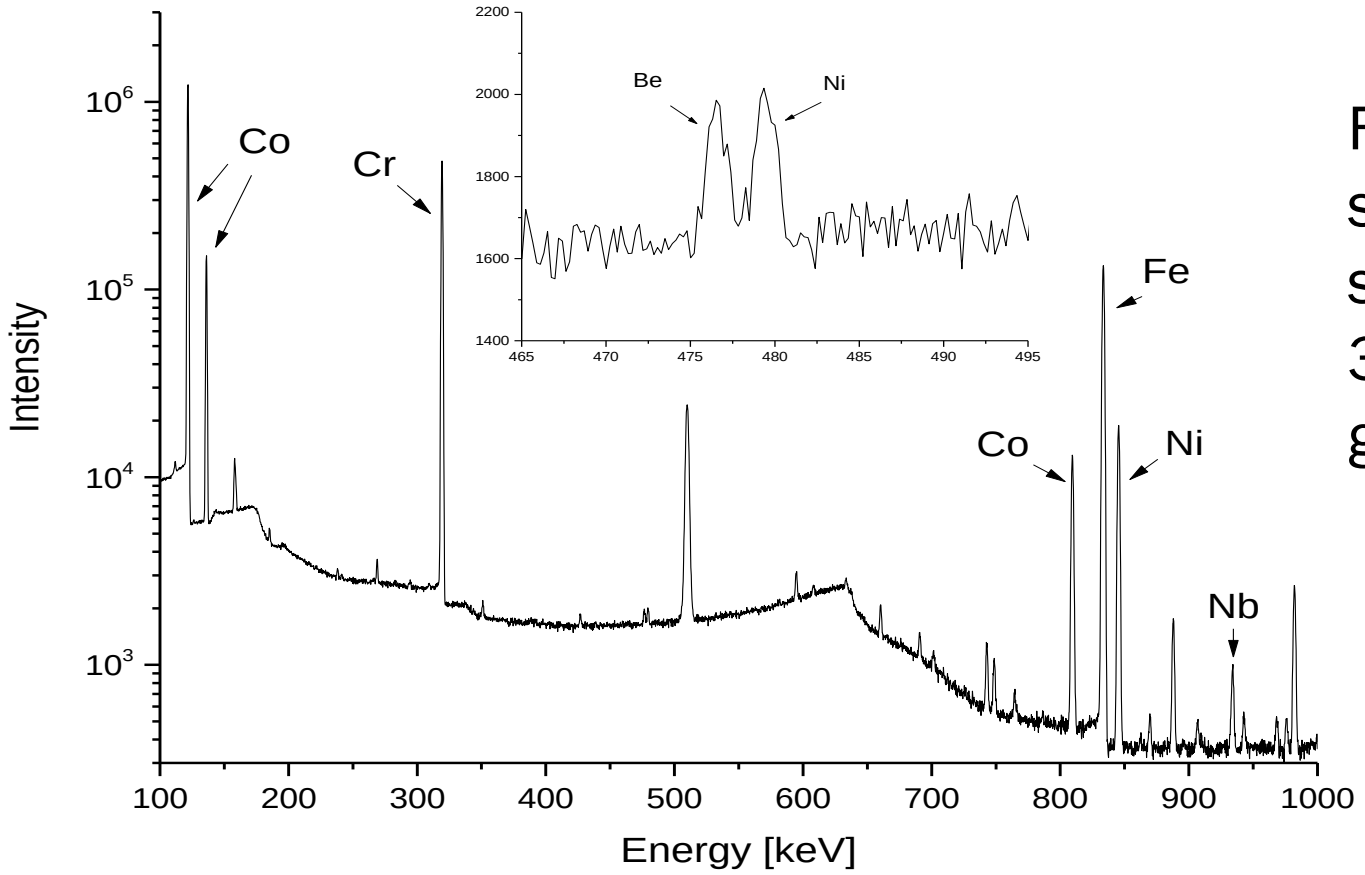
σ (55 MeV) = 101 **μ**b

^{9}Be: σ (37MeV) = 180 **μ**b

σ (55 MeV) = 44 **μ**b

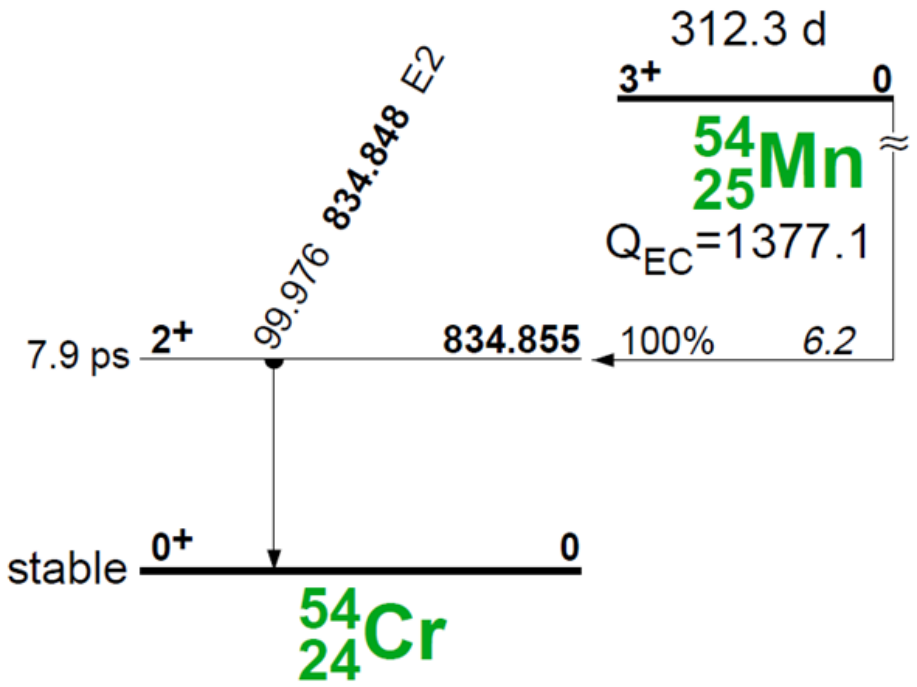
37 MeV: $\bar{\sigma}$ (^{10}B, ^{9}Be) = 200 **μ**b

Description of the proposed method



Fragment of the gamma spectrum of a liquid RW sample irradiated with the 37 MeV bremsstrahlung gamma quanta

Description of the proposed method



$^{56}Fe\ (\gamma, pn)\ ^{54}Mn$

Description of the proposed method

The mass ratio of B, Be and ^{56}Fe will be:

$$\frac{m(\mathrm{Be,B})}{m(\mathrm{Fe})} = \frac{N_\gamma(\mathrm{Be+B})(1-e^{-\lambda_{\mathrm{Mn}}t_{irr}})(1-e^{-\lambda_{\mathrm{Mn}}t_m})e^{-\lambda_{\mathrm{Mn}}t_c} \cdot Y_{\mathrm{Mn}}\lambda_{\mathrm{Be}}}{N_\gamma(\mathrm{Fe})(1-e^{-\lambda_{\mathrm{Be}}t_{irr}})(1-e^{-\lambda_{\mathrm{Be}}t_m})e^{-\lambda_{\mathrm{Be}}t_c} \cdot Y_{\mathrm{Be,B}}\lambda_{\mathrm{Mn}}}$$

where N (Be) is the number of ^{9}Be atoms, N (Fe) is the number of ^{56}Fe atoms, t_{irr} is the time of target irradiation with the linear accelerator, t_p is the exposure time of the irradiated target before the start of measurements, t_m is the time of measurement of the irradiated target on the spectrometer, λ (Mn) is the constant of ^{54}Mn radioactive decay, λ (Be) is the constant of ^{7}Be radioactive decay.

Description of the proposed method

$$\frac{m(\mathrm{Be,B})}{m(\mathrm{Fe})} = 1.7\,\frac{N_\gamma(477)\cdot\xi(834)\cdot e^{-\lambda_{\mathrm{Mn}}t_c}}{N_\gamma(834)\cdot\xi(477)\cdot e^{-\lambda_{\mathrm{Be}}t_c}}$$

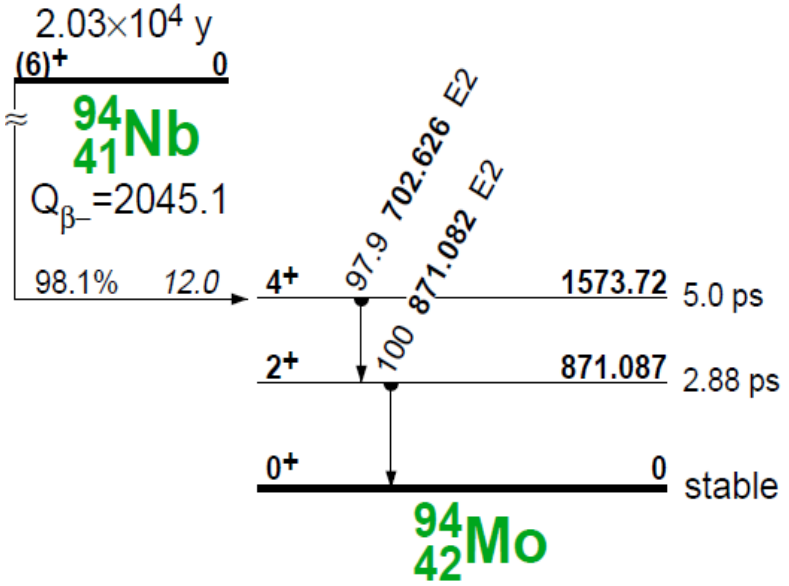
- $N\gamma(834)$ is the number of counts in the 834 keV gamma peak, $N\gamma(477)$ is the number of counts in the 477 keV peak, t_c is the exposure time of the irradiated target before the start of their measurements, λ_{Mn} is the ^{54}Mn decay constant, λ_{Be} is the ^{7}Be decay constant, ξ (834) is the relative detection efficiency of the 834 keV gamma line, ξ (477) is the relative detection efficiency of the 477 keV gamma line.

Thermal neutron flux estimation

For further recalculations of the ^{10}Be content in RW samples, it is necessary to determine the number of ^{9}Be and ^{10}B atoms. We require data about the thermal neutron flux.

^{93}Nb(n,γ) ^{94}Nb

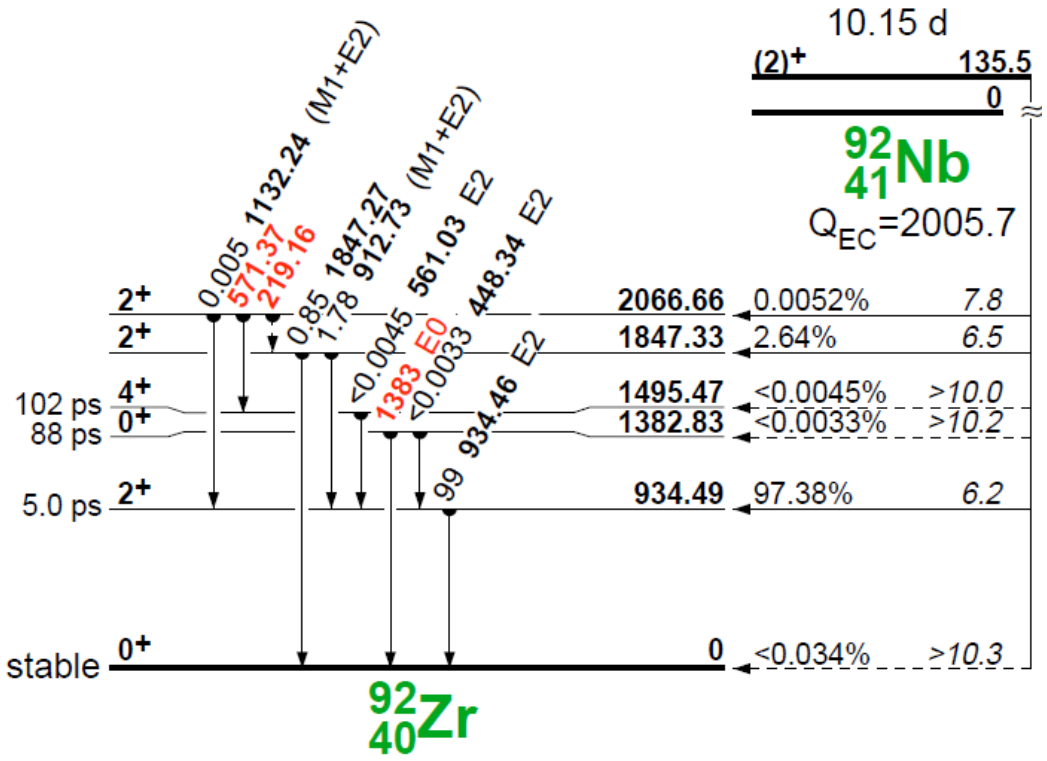
$T_{1/2}$= 2×10^{4} year



Thermal neutron flux estimation

$^{93}Nb(\gamma, n)^{92m}Nb$,

$T_{1/2}$ = 10 days.

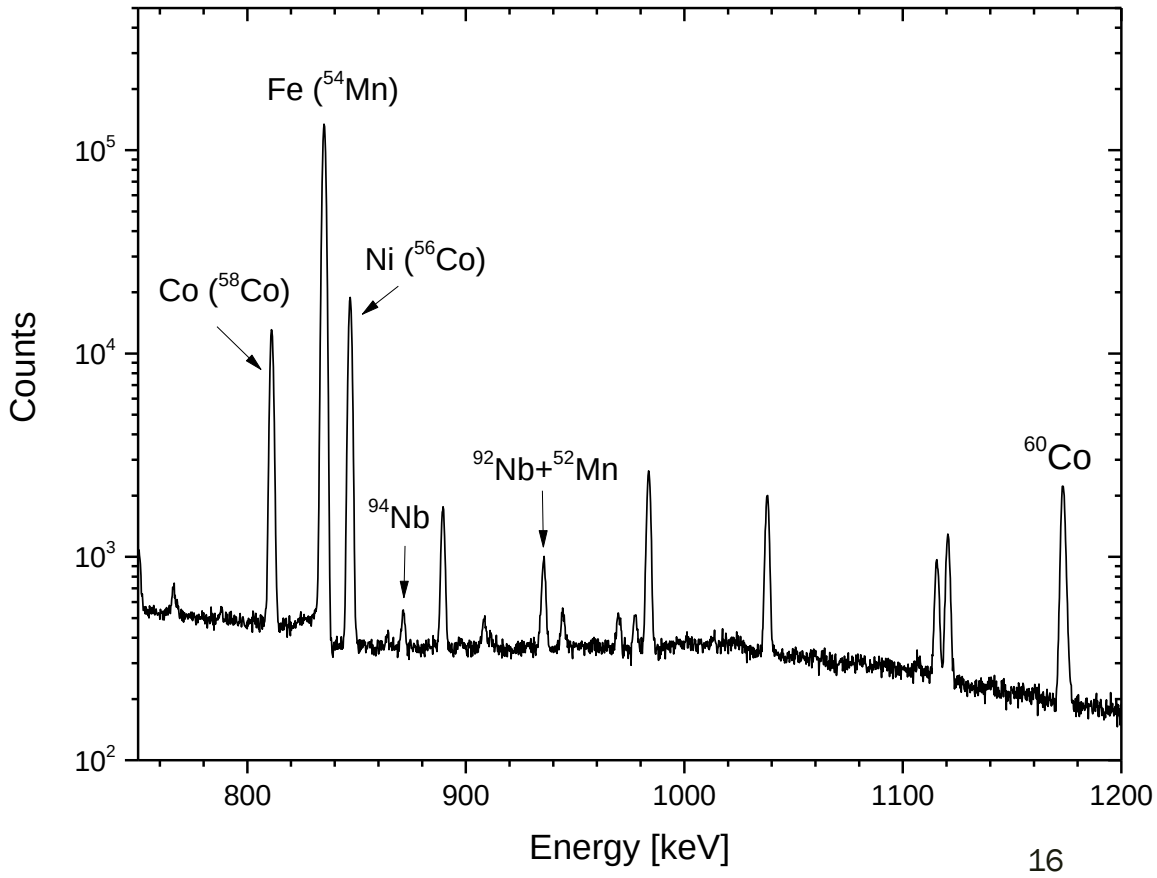


Thermal neutron flux estimation

From the measured data, it was found that the ^{93}Nb impurity is 2.7×10^{-7}.

The activity of ^{94}Nb was determined from the 871 keV gamma line and was found to be 2.5 Bq/g.

Using these data, it was obtained that the thermal neutron fluence is 7.5×10^{20}.



^{10}Be activity (Bq/g)

Sample of reactor core construction materials	Solid RW sample 1	Solid RW sample 2	Solid RW sample 3
0,6	<0.1	0.8	1.8

In accordance with TLV the activity level for RW samples is ~10^6 (Bq/g)

Masses of our samples were 50 mg, thus their activities were in 1-2 Bq/g range

Conclusion

- The activation method for the ^{10}Be determination can simplify the procedures for the identification, control, and certification of this isotope in reactor core constructional materials and various types of radioactive waste.
- The proposed method is unique and efficient as compared with traditional radiochemical methods especially because of the huge volume of radioactive waste generated at nuclear power plants. The calculated error of the method is about 20%, the sensitivity of the method is 10^{-2} Bq/g.