Activation bremsstrahlung yields of the ^{112}Sn(γ,n)^{111}Sn and ^{112}Sn(γ,p)^{111m,g}In reactions and the following ^{111}Sn decay γ–ray branching coefficients

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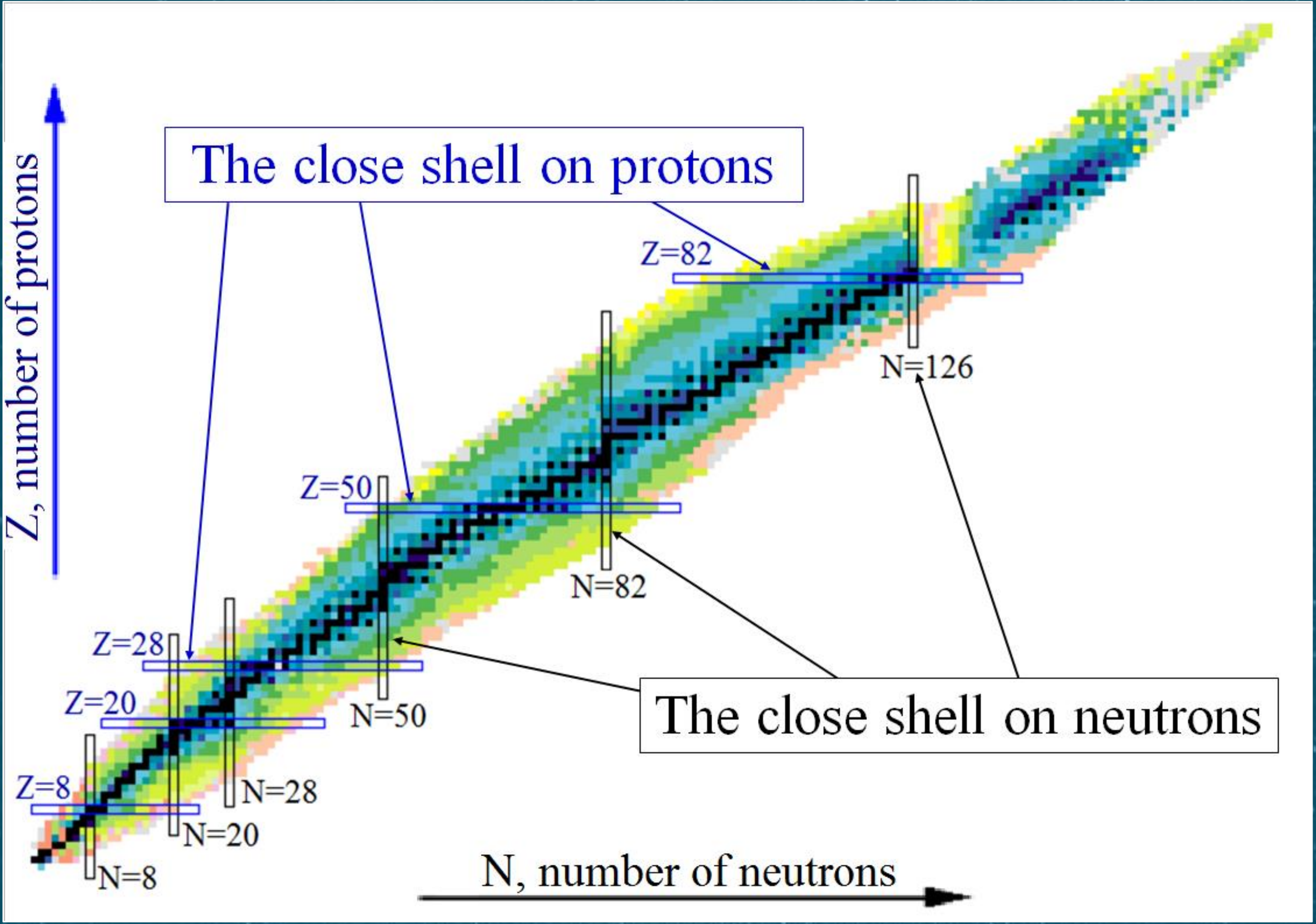
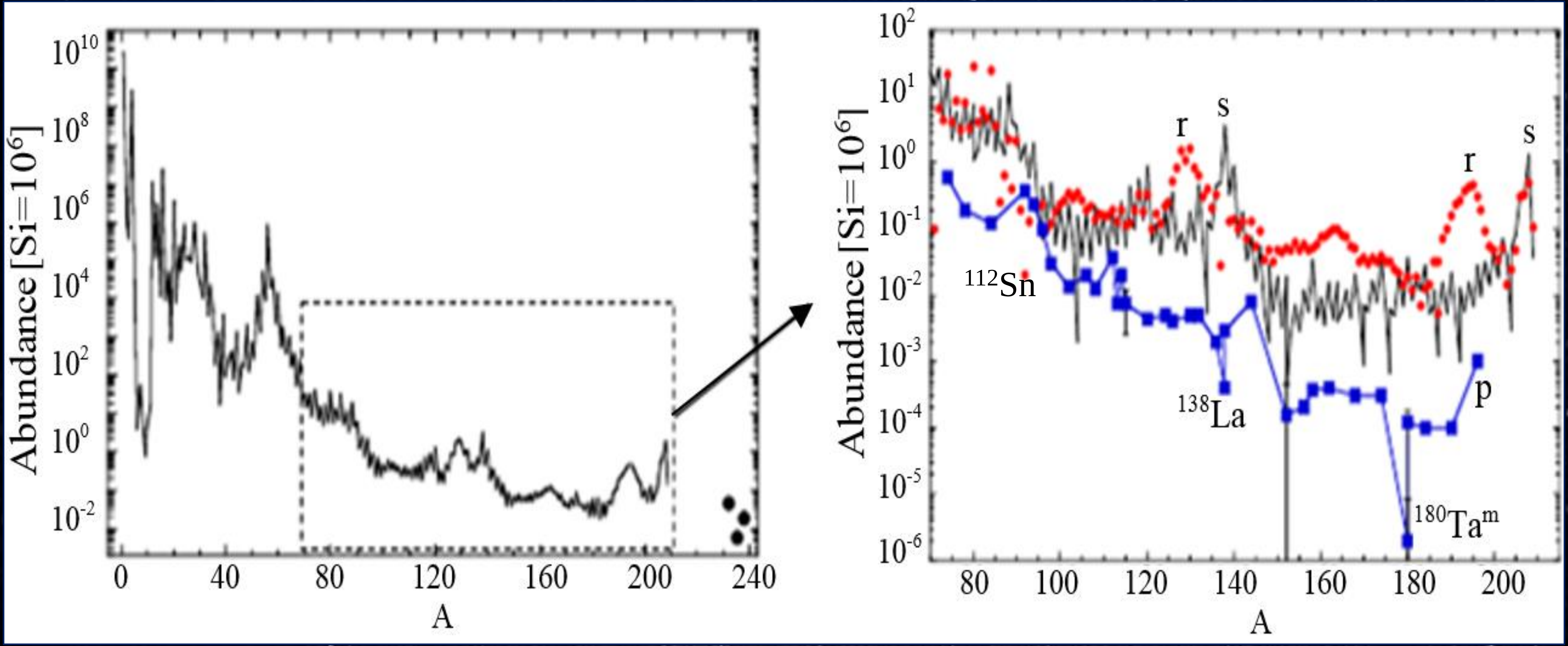
Joint ICTP-IAEA Workshop on Nuclear Structure and Decay Data:
Theory, Experiment and Evaluation

The Abdus Salam
International Centre
for Theoretical Physics

☐ *The valley of stability*



❑ *Abundance of chemical elements in nature depending on mass number*

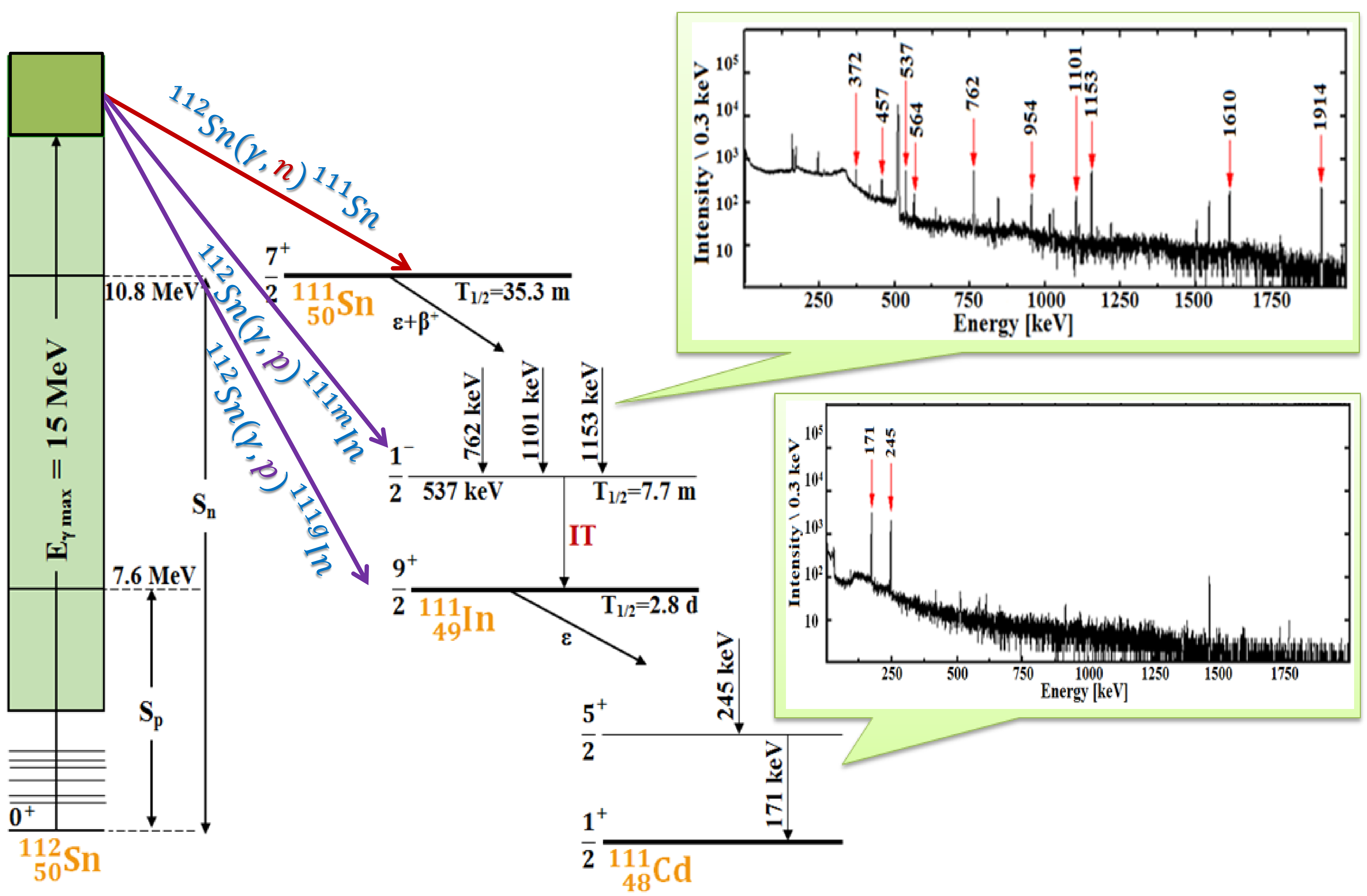


A ≤ 11 – primordial nucleosynthesis
A = 12-56 – fusion reactions
A > 56 – r- and s- process neutron radiation capture

List of p-nuclei

^{74}Se	^{78}Kr	^{84}Sr	^{92}Mo	^{94}Mo	^{96}Ru	^{98}Ru
^{102}Pd	^{106}Cd	^{108}Cd	^{113}In	^{112}Sn	^{114}Sn	^{115}Sn
^{120}Te	^{124}Xe	^{126}Xe	^{130}Ba	^{132}Ba	^{138}La	^{136}Ce
^{138}Ce	^{144}Sm	^{152}Gd	^{156}Dy	^{158}Dy	^{162}Er	^{164}Er
^{168}Yb	^{174}Hf	^{180m}Ta	^{180}W	^{184}Os	^{190}Pt	^{196}Hg

☐ *Gamma-activation method*



❑ The statistical theory of nuclear reactions

$$\sigma_{AB} = \pi\lambda_A^2 \frac{1}{(2I+1)(2i+1)} \sum_{J^\pi} (2J+1) \frac{T_A^{J^\pi} T_B^{J^\pi}}{\sum_{A'} T_{A'}^{J^\pi}}$$

Hauser-Feshbach model

I – the spin of the target nucleus;
i – the spin of the incident particle;
J – the spin of the compound nucleus;
T – coefficients of particle permeability;
ρ– density of the kernel levels.

$$T_A^{J^\pi} = \sum_{i=0}^{\omega} T_A^i(J^\pi) + \int_{\varepsilon_\omega}^{\varepsilon^{max}} \sum_{J',\pi'} T_A^i\left(\varepsilon^i, J'^{\pi'}\right) \rho\left(\varepsilon^i, J'^{\pi'}\right) d\varepsilon^i$$

$$\rho_F(E,J) = \rho_F(E)g(E,J) \approx \frac{\sqrt{\pi}}{12}\frac{\exp(2\sqrt{aE})}{a^{1/4}E^{5/4}}\frac{(2J+1)\exp\left[-\left(J+\frac{1}{2}\right)^2/2\sigma^2\right]}{2\sqrt{2\pi}\sigma^3}$$

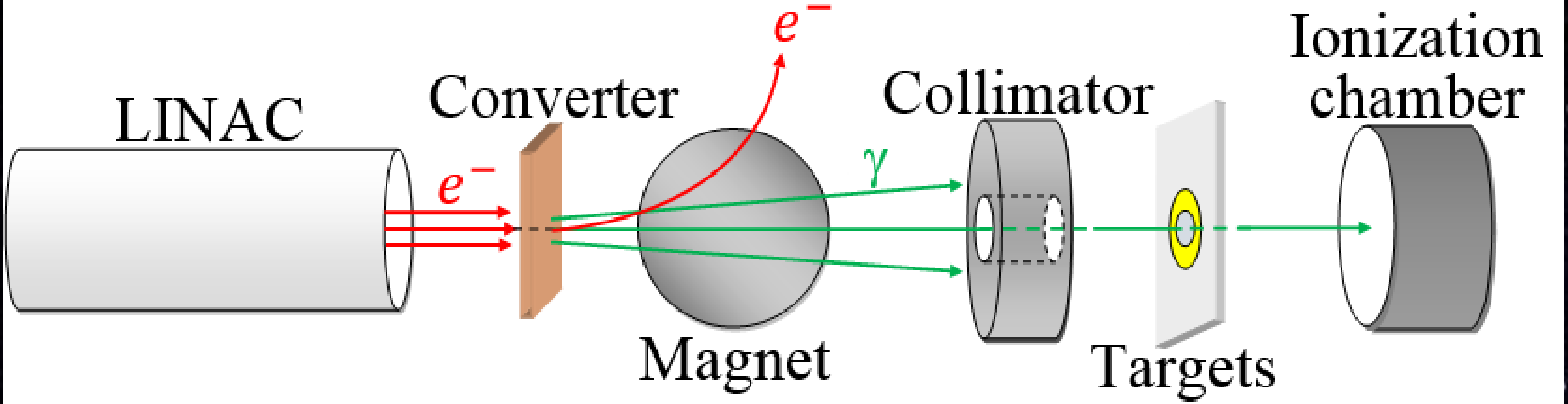
Fermi-gas model

E, J – the excitation and spin energies of the excited state of the nucleus, respectively;
a – the density parameter of the levels;
σ – the spin dependence parameter.

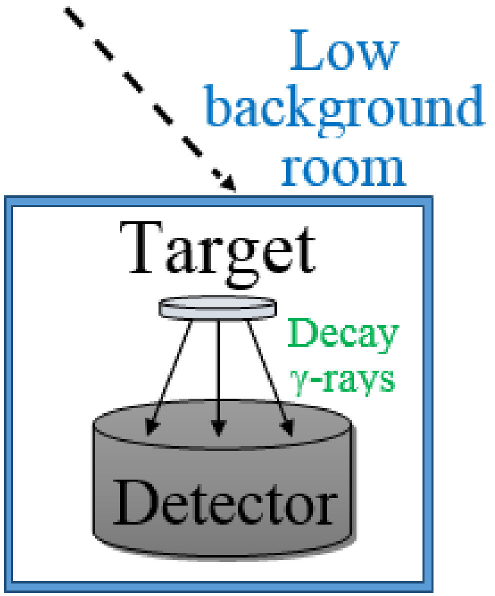
$$f_{E1}(\varepsilon_\gamma) = 8.68\cdot 10^{-8}(mb^{-1}MeV^{-2})\frac{\sigma_0\varepsilon_\gamma\Gamma^2}{\left(\varepsilon_\gamma^2 - E^2\right)^2 + \varepsilon_\gamma^2\Gamma^2}$$

Brink-Axel approximation

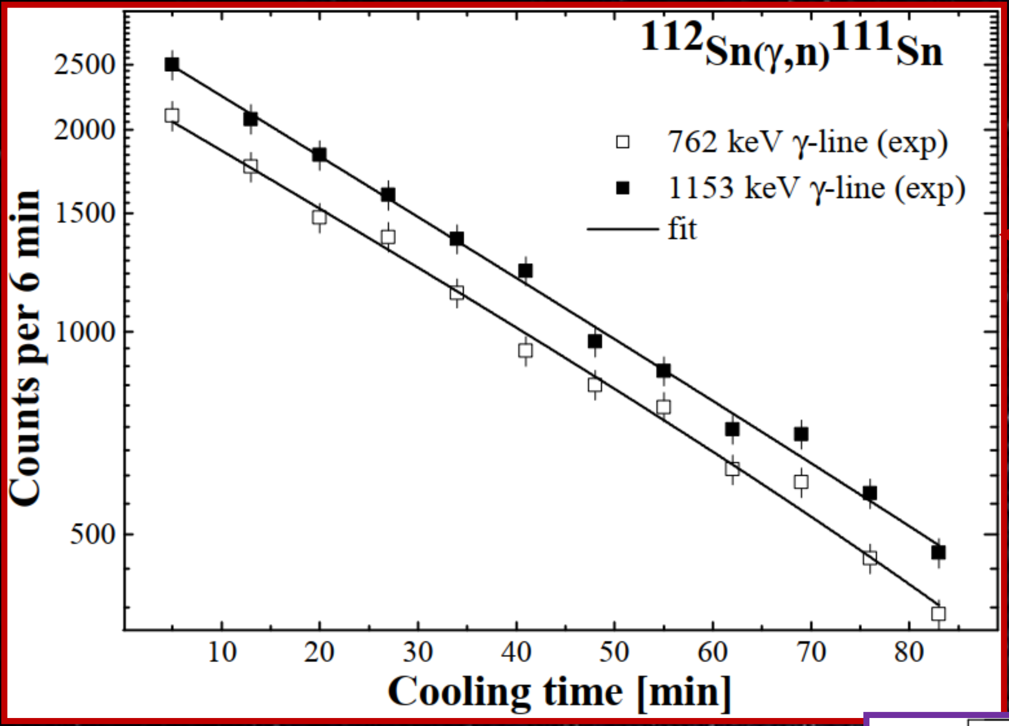
❑ *The scheme of the experiment on a beam of bremsstrahlung γ-quanta*



LINAC	linear electron accelerator up to 30 MeV
Converter	Tantalum 100 μm
Magnet	beam deflection magnet
Collimator	Lead 8 mm
Targets	Sn natural, ^{112}Sn enriched 80%, ^{197}Au
Ionization chamber	used as a monitor to registrate bremsstrahlung flux behind targets
Detector	HP(Ge) detector Canberra



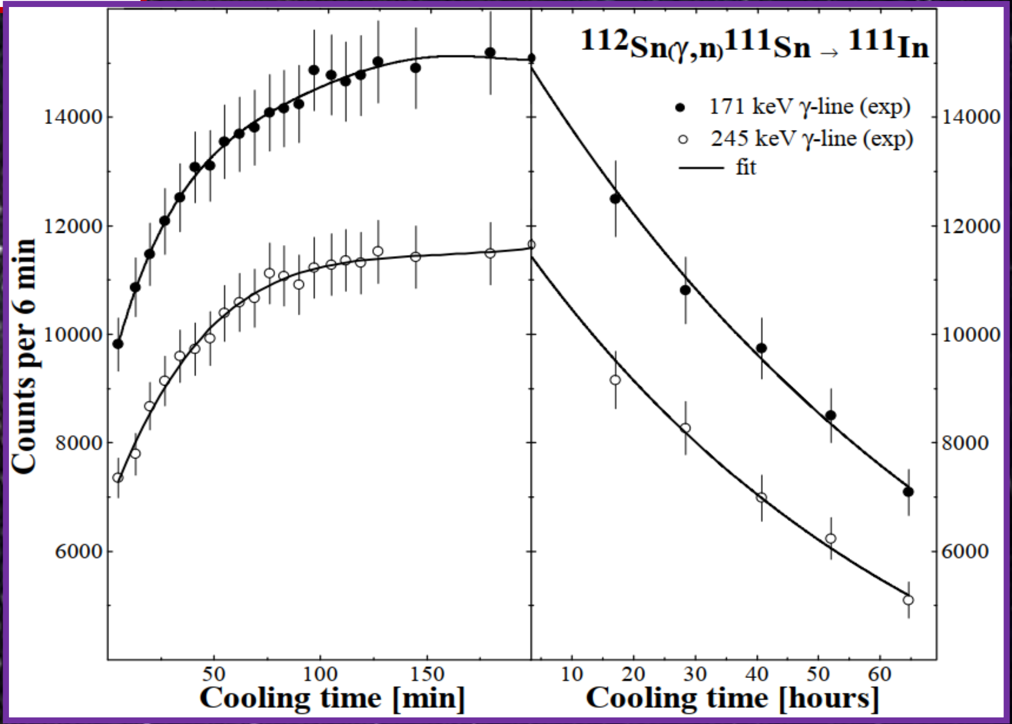
Decay curve of the ^{111}Sn isotope



$$T_{1/2}(^{111}Sn) = 35.3\ min$$

E_γ [keV]	I_γ [%]	Decay mode
762	1.48	e^+
1153	2.7	e^+

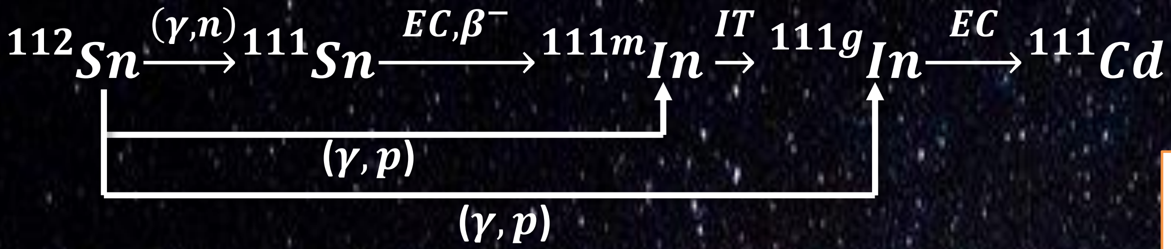
Accumulation and decay curves of the ^{111}In isotope



$$T_{1/2}(^{111}In) = 2.8\ d$$

E_γ [keV]	I_γ [%]	Decay mode
171	90	e^+
245	94	e^+

❑ Calculation of the integral yields



$$\begin{tikzcd}[column sep=large] {}^{112}Sn \arrow[r, "(\gamma{,}n)"] \arrow[rr, bend right, "(\gamma{,}p)"'] \arrow[rrr, bend right=50, "(\gamma{,}p)"'] & {}^{111}Sn \arrow[r, "EC{,}\beta^-"] & {}^{111m}In \arrow[r, "IT"] & {}^{111g}In \arrow[r, "EC"] & {}^{111}Cd \end{tikzcd}$$

N – number of events
ε – efficiency
B – branching
n – number of nuclei
ϕ – incident particles flux
Y – yield
λ – decay constant

The simple activation equation:

$$N = \frac{\varepsilon \cdot B \cdot n \cdot \phi \cdot Y}{\lambda} \cdot (1 - e^{-\lambda \cdot t_1}) \cdot e^{-\lambda \cdot t_2} \cdot (1 - e^{-\lambda \cdot t_3})$$

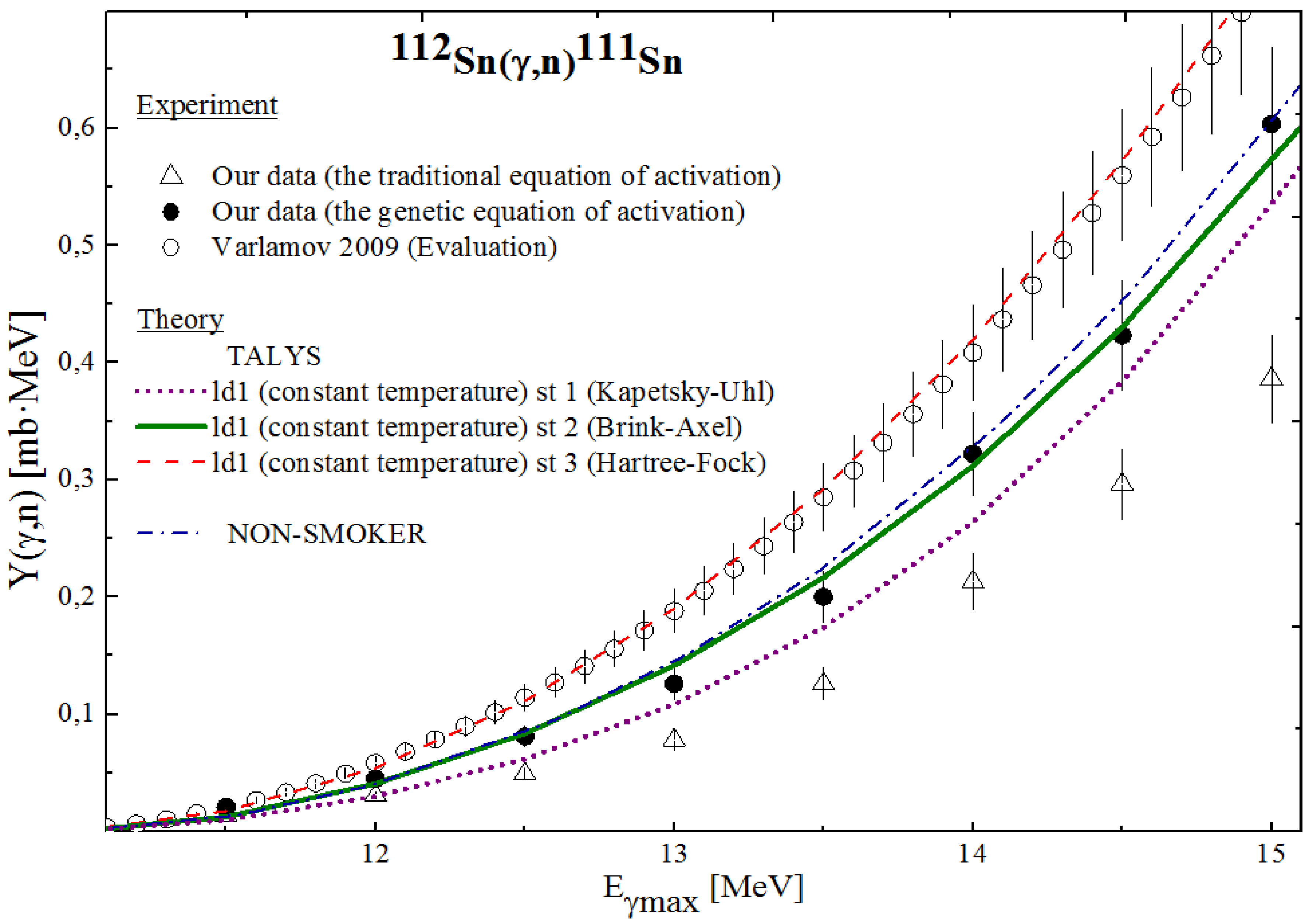
The activation equation for genetically coupled pair:

$$\frac{N_\gamma}{\varepsilon \cdot B \cdot n \cdot \phi} = Y_p \cdot \frac{\lambda_p \cdot \lambda_d}{\lambda_d - \lambda_p}\left[\frac{1-e^{-\lambda_p \cdot t_1}}{\lambda_p^2} \cdot e^{-\lambda_p \cdot t_2} \cdot (1-e^{-\lambda_p \cdot t_3}) - \frac{1-e^{-\lambda_d \cdot t_1}}{\lambda_d^2} \cdot e^{-\lambda_d \cdot t_2} \cdot (1-e^{-\lambda_d \cdot t_3})\right] +$$

$$+Y_d \cdot \frac{1-e^{-\lambda_d \cdot t_1}}{\lambda_d} \cdot e^{-\lambda_d \cdot t_2} \cdot (1-e^{-\lambda_d \cdot t_3})$$

Y_p – yield of the **p**arent nuclei; Y_d – yield of the **d**aughter nuclei
λ_p, λ_d – decay constants of the **p**arent and **d**aughter nuclei responsible;
t_1 – irradiation time; t_2 – cool time; t_3 – measure time.

❑Results


$^{112}Sn(\gamma,n)^{111}Sn$
Experiment
△ Our data (the traditional equation of activation)
● Our data (the genetic equation of activation)
○ Varlamov 2009 (Evaluation)
Theory
TALYS
ld1 (constant temperature) st 1 (Kapetsky-Uhl)
ld1 (constant temperature) st 2 (Brink-Axel)
ld1 (constant temperature) st 3 (Hartree-Fock)
NON-SMOKER
$Y(\gamma,n)$ [mb·MeV]
0,1
0,2
0,3
0,4
0,5
0,6
12
13
14
15
$E_{\gamma max}$ [MeV]

Calculation of Branching Coefficients

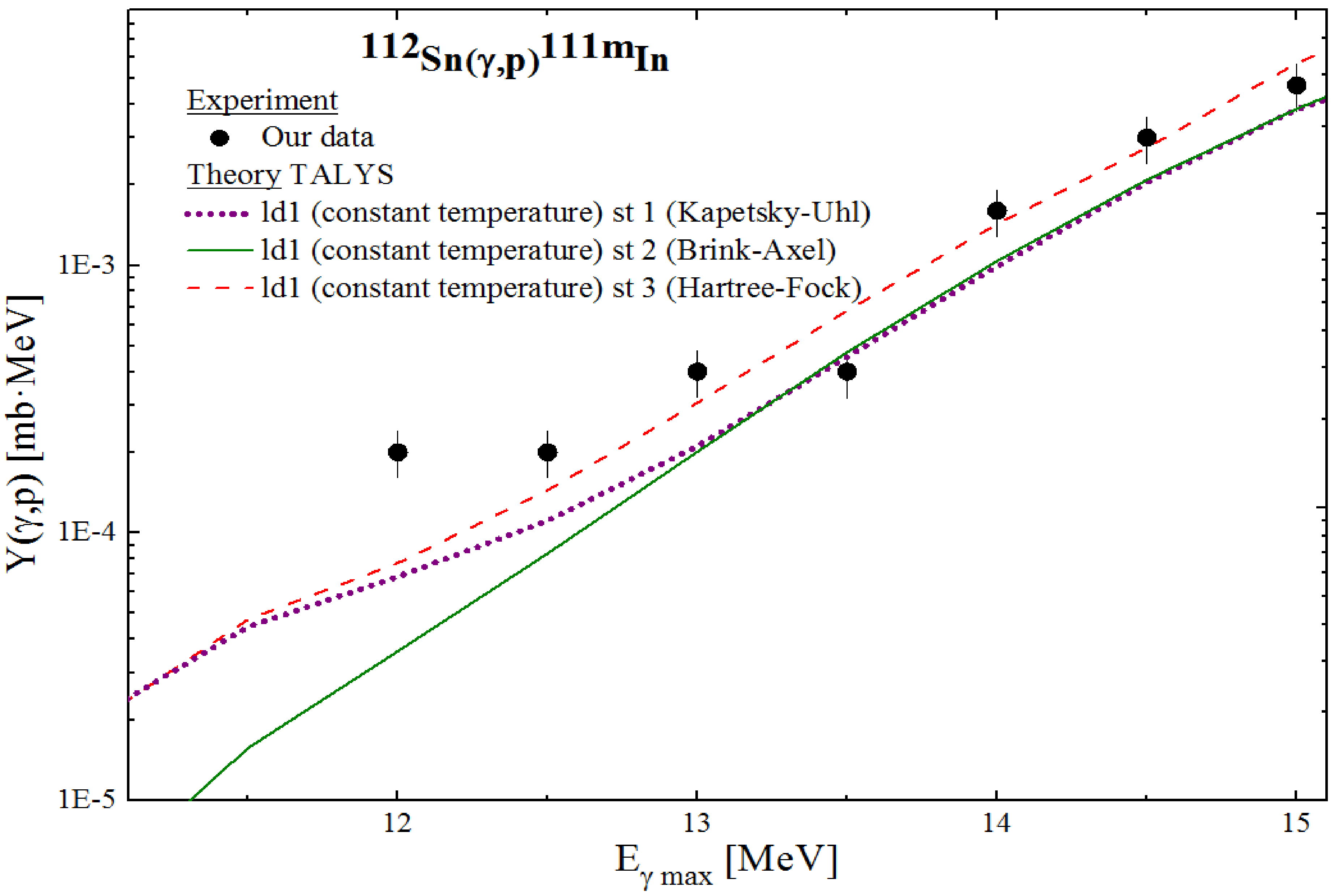
(for the decay of a nucleus ^{111}Sn)

$$B_x = \frac{N_\gamma \cdot \lambda}{\varepsilon \cdot n \cdot \phi \cdot Y \cdot (1 - e^{-\lambda \cdot t_1}) \cdot e^{-\lambda \cdot t_2} \cdot (1 - e^{-\lambda \cdot t_3})}$$

X=1.64

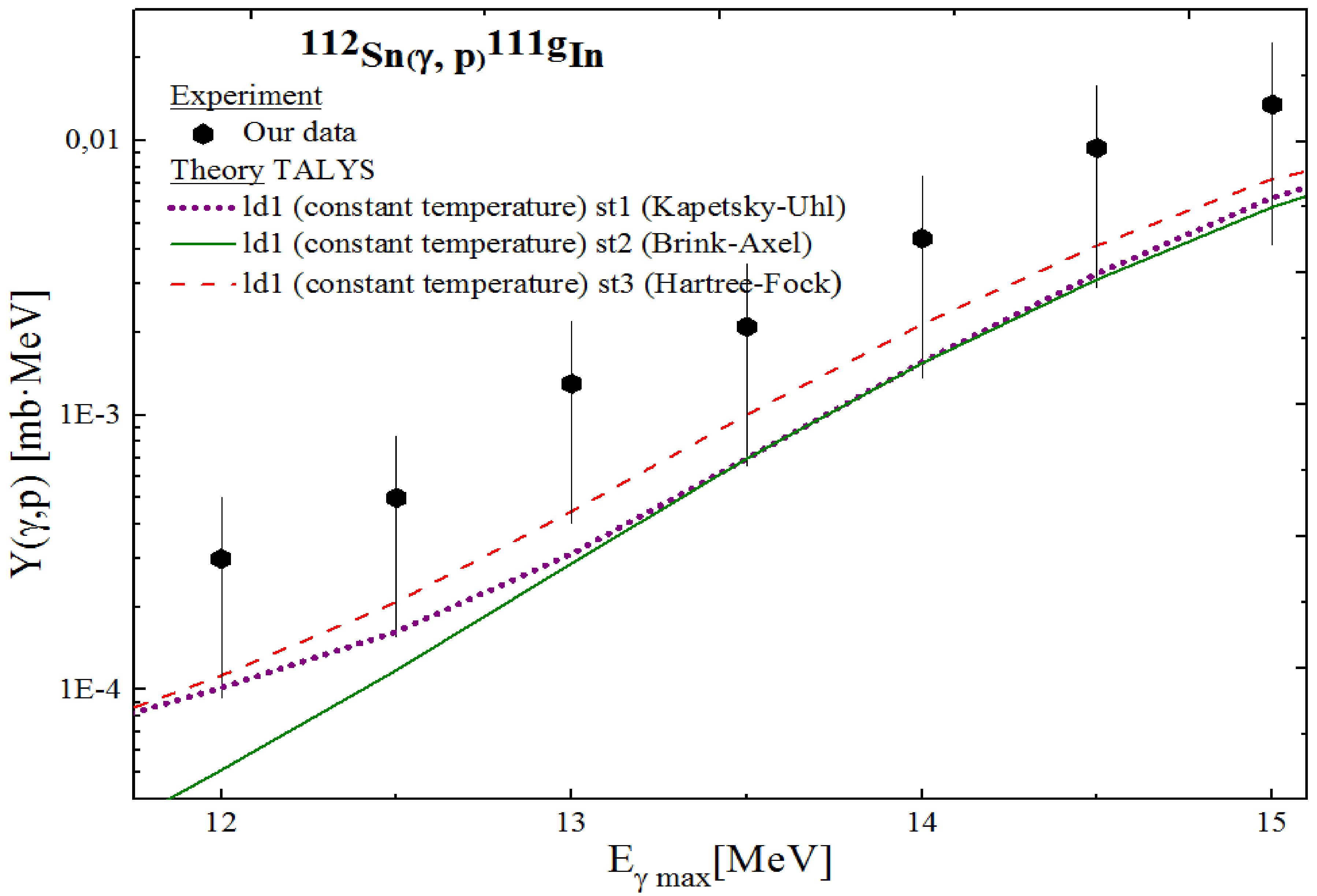
Eγ [keV]	Branching coefficient [%]		
	NUDAT	LBLN	Our data
372.3	0.42 ± 0.08	0.42 ± 0.02	0.26 ± 0.05
457.1	0.38 ± 0.08	0.38 ± 0.02	0.23 ± 0.04
564.3	0.30 ± 0.08	0.30 ± 0.02	0.19 ± 0.03
761.9	1.47 ± 0.01	1.48 ± 0.05	0.90 ± 0.08
954.1	0.50 ± 0.08	0.50 ± 0.02	0.31 ± 0.03
1101.1	0.63 ± 0.02	0.64 ± 0.05	0.39 ± 0.04
1152.9	2.7	2.7	1.65 ± 0.11
1610.0	1.31 ± 0.01	1.31 ± 0.05	0.80 ± 0.07
1914.7	1.98 ± 0.03	1.99 ± 0.08	1.21 ± 0.08

☐ *Results*



$^{112}Sn(\gamma,p)^{111m}In$
Experiment
● Our data
Theory TALYS
ld1 (constant temperature) st 1 (Kapetsky-Uhl)
ld1 (constant temperature) st 2 (Brink-Axel)
ld1 (constant temperature) st 3 (Hartree-Fock)
Y(γ,p) [mb·MeV]
1E-3
1E-4
1E-5
12
13
14
15
$E_{\gamma\ max}$ [MeV]

☐ *Results*


^{112}Sn(γ, p)^{111g}In
Experiment
Our data
Theory TALYS
ld1 (constant temperature) st1 (Kapetsky-Uhl)
ld1 (constant temperature) st2 (Brink-Axel)
ld1 (constant temperature) st3 (Hartree-Fock)
0,01
1E-3
1E-4
Y(γ,p) [mb·MeV]
12
13
14
15
E$_{\gamma\ max}$[MeV]

❑ Conclusions

- ✓ $^{112}Sn\,(\gamma,n)^{111}Sn$ The Fermi gas model for the density of nuclear levels.
  The Brink-Axel model for radiation strength function.

- ✓ $^{112}Sn\,(\gamma,p)^{111m}In$ The Fermi gas model for the density of nuclear levels.
  The Hartree-Fock model for radiation strength function.

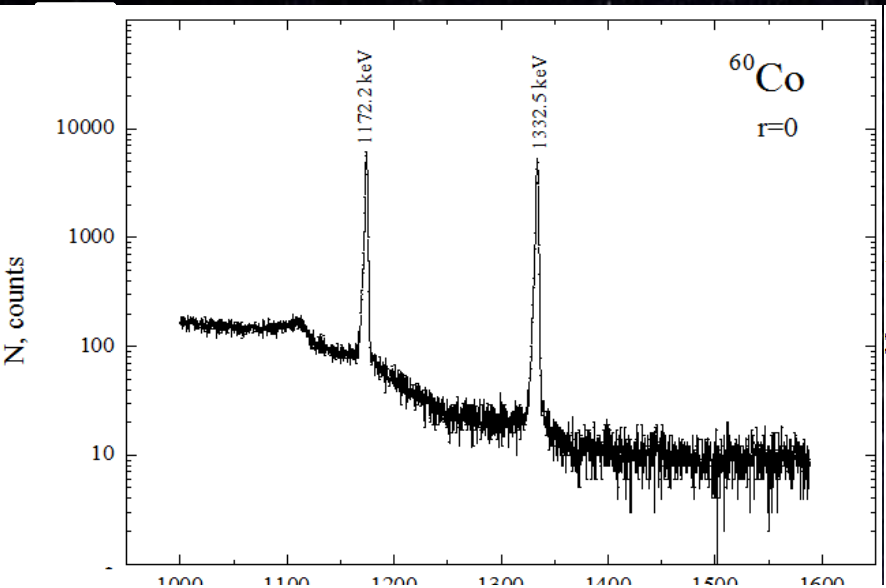
- ✓ $^{112}Sn\,(\gamma,p)^{111g}In$ The Fermi gas model for the density of nuclear levels.
  The Hartree-Fock model for radiation strength function.

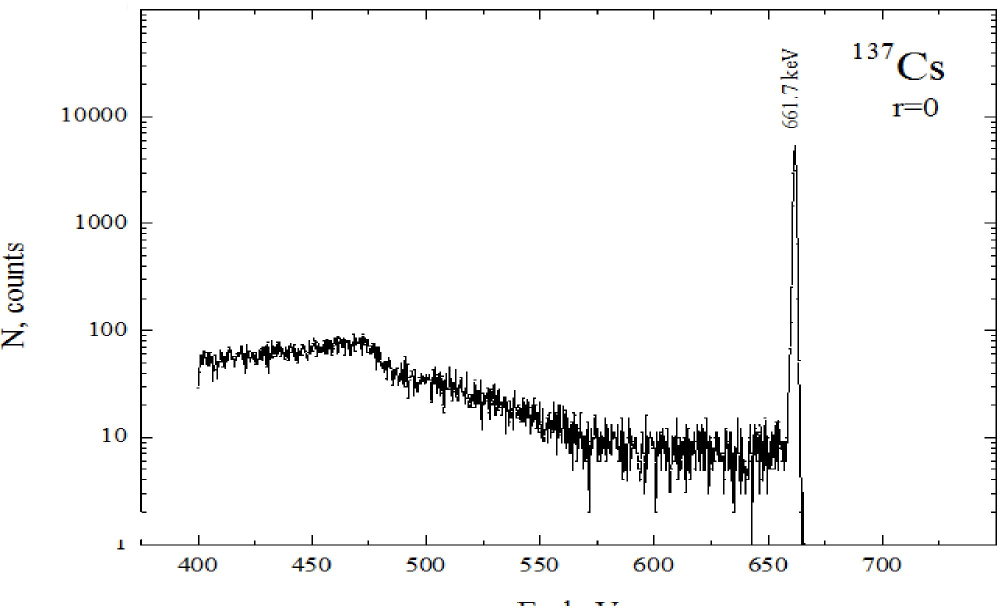
- ✓ The new values of the branching coefficients of the γ-transitions following the decay of the ^{111}Sn nucleus are determined, which differ from the base values by a weighted average coefficient of ***1.64.***

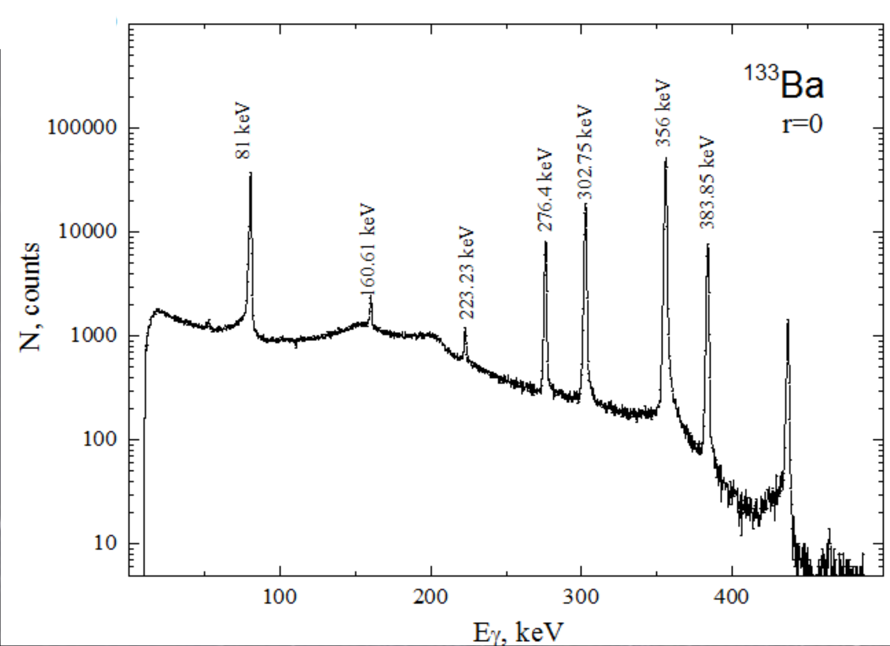
Thank you for your attention!

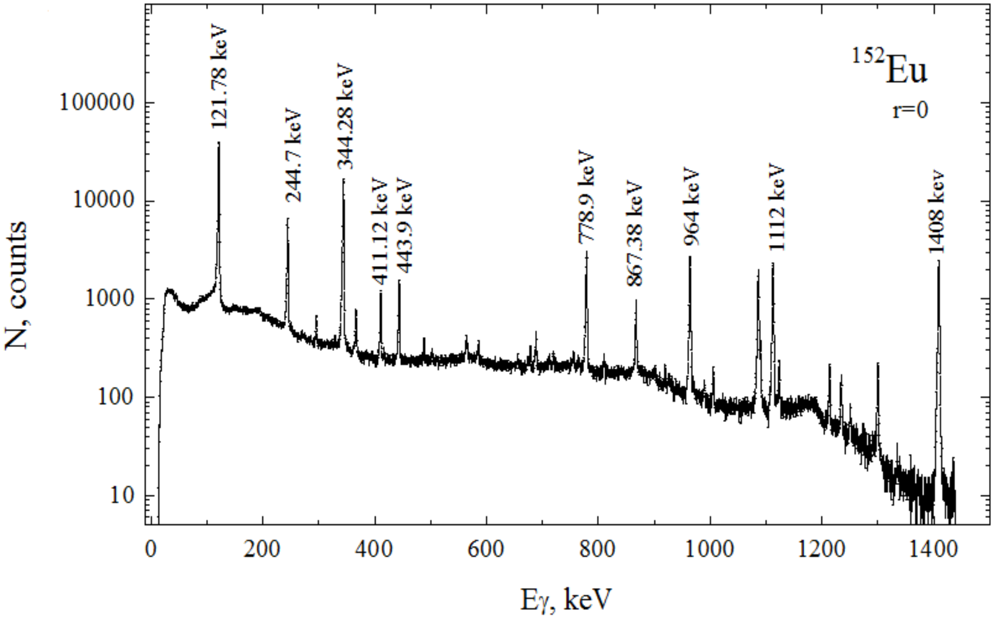
❑ *Efficiency calculation (HPGe – detector)*

Sources – ^{60}Co, ^{133}Ba, ^{137}Cs, ^{152}Eu

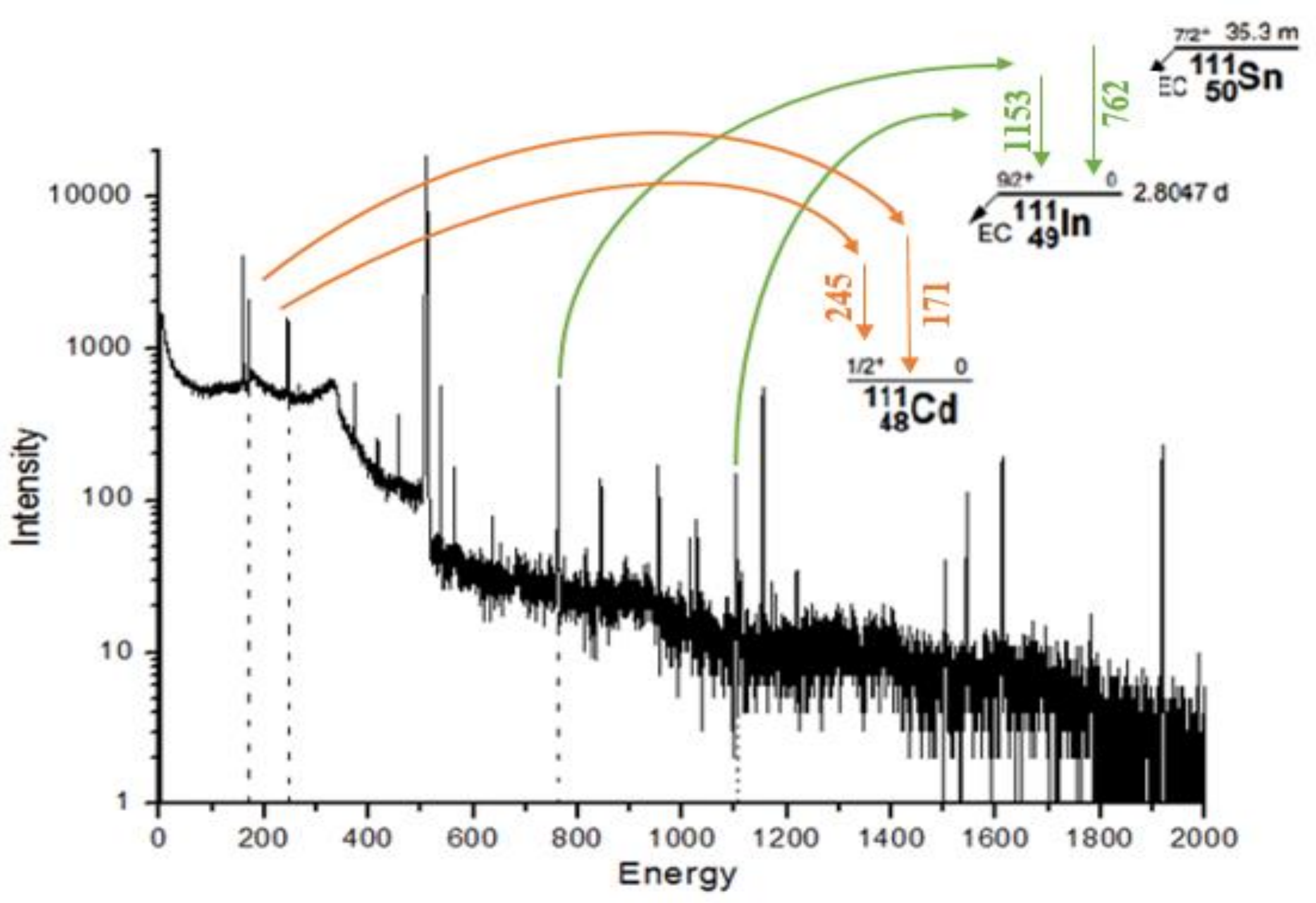








❑ *The decay spectrum of the ^{111}Sn nucleus*



❑ *Monitor reaction (standard reaction)*

(to determine the flux of incident photons)

Absolute integral yield of the studied reaction

Measured in our experiment, the ratio of the yields of reactions on the ^{112}Sn and ^{197}Au targets

$$Y_{abs}\left(^{112}Sn\right) = \frac{Y_{exp}\left(^{112}Sn\right)}{Y_{exp}\left(^{197}Au\right)} \cdot Y_{abs}\left(^{197}Au\right)$$

Absolute integral yield of the monitor reaction

$$Y_{abs}\left(^{197}Au\right) = \int_{S_n}^{E_{\gamma\,max}} \sigma\left(E_\gamma\right) \cdot \Phi\left(E_\gamma, E_{\gamma\,max}\right) dE_\gamma$$

The cross section of the reaction as a function of the energy of the γ-quantum

Energy spectrum of bremsstrahlung with finite energy $E_{\gamma\,max}$

☐ *Nucleosynthesis*

- A<56 => nucleus fusion
- A>56 => neutron capture processes – (n,γ)-reaction :
  - s-process (slow)
  - r-process (rapid)
- p-nuclei (35) forming in p-process ((p,γ)-reaction) or in (γ,n), (γ,p) and (γ,α) reactions.

λ (T) - the (γ,n)-reaction rate for a nucleus disposed in a thermal photon bath of a stellar medium having temperature T;

c – the speed of light ;

$\sigma_{(\gamma,n)}$(E) – the reaction cross section depending on photon energy E;

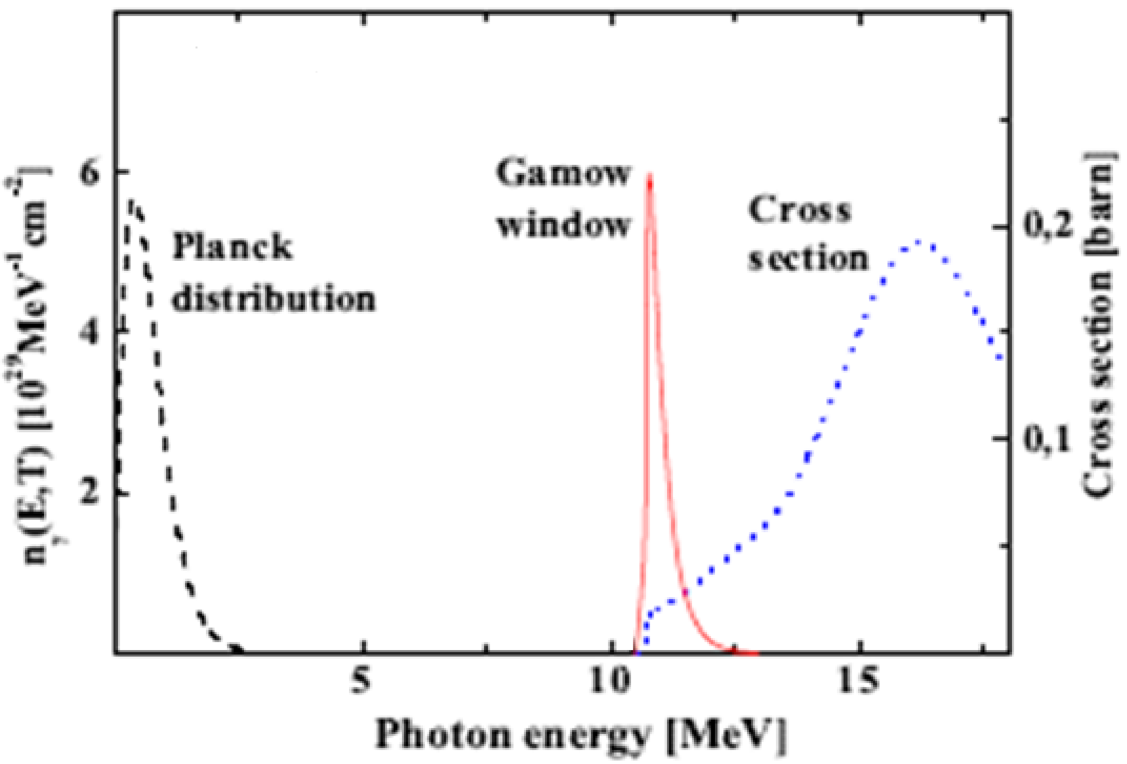
n(E,T) – the number of photons per unit energy and volume of a star interior.

$$\lambda(T) = \int_0^\infty c n_\gamma(T, E_\gamma) \sigma_{(\gamma,n)}(E_\gamma) d E_\gamma$$

The reaction cross-section obtained under laboratory conditions

$$n_\gamma(E_\gamma, T) = \left(\frac{1}{\pi}\right)^2 \left(\frac{1}{hc}\right)^3 \frac{E_\gamma^2}{\exp\left(\frac{E_\gamma}{kT}\right) - 1}$$

<u>**Planck distribution**</u>

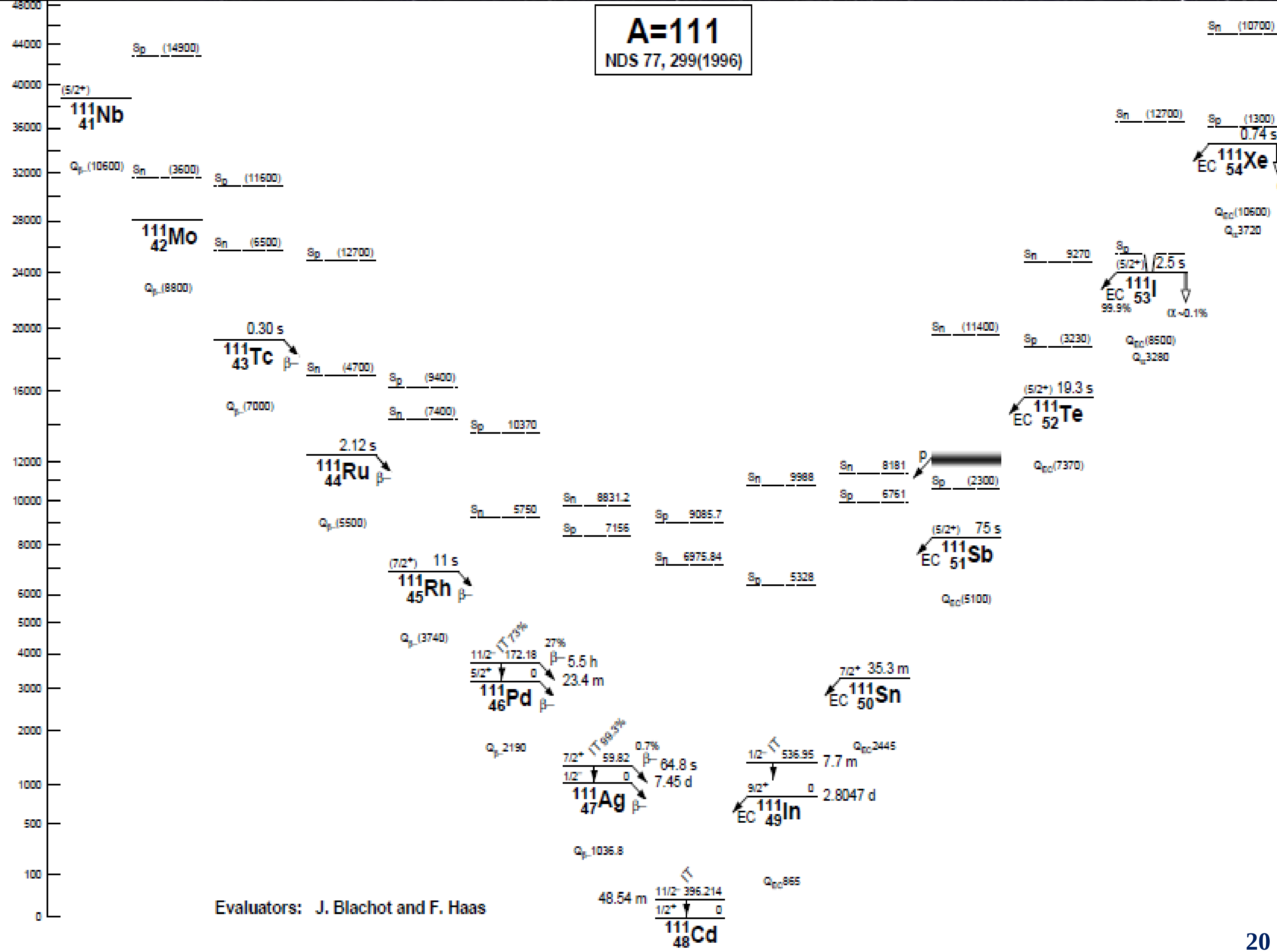


❑ The computational code TALYS uses

OPTICAL POTENTIAL MODEL	**DENSITY LEVEL MODEL**	**MODEL OF RADIATION STRENGTH FUNCTION**
1. Spherical OMP: Neutrons and protons; 2. Spherical dispersive OMP: Neutrons; 3. Spherical OMP: Complex particles; 4. Semi-microscopic optical model (JLM).	1. Constant temperature + Fermi gas model; 2. Back-shifted Fermi gas model; 3. Generalised superfluid model; 4. Microscopic level densities (Skyrme force) from Goriely's tables; 5. Microscopic level densities (Skyrme force) from Hilaire's combinatorial tables.	1. Kopecky-Uhl generalized Lorentzian; 2. Brink-Axel Lorentzian; 3. Hartree-Fock BCS tables; 4. Hartree-Fock-Bogolyubov tables; 5. Goriely's hybrid model.

A=111

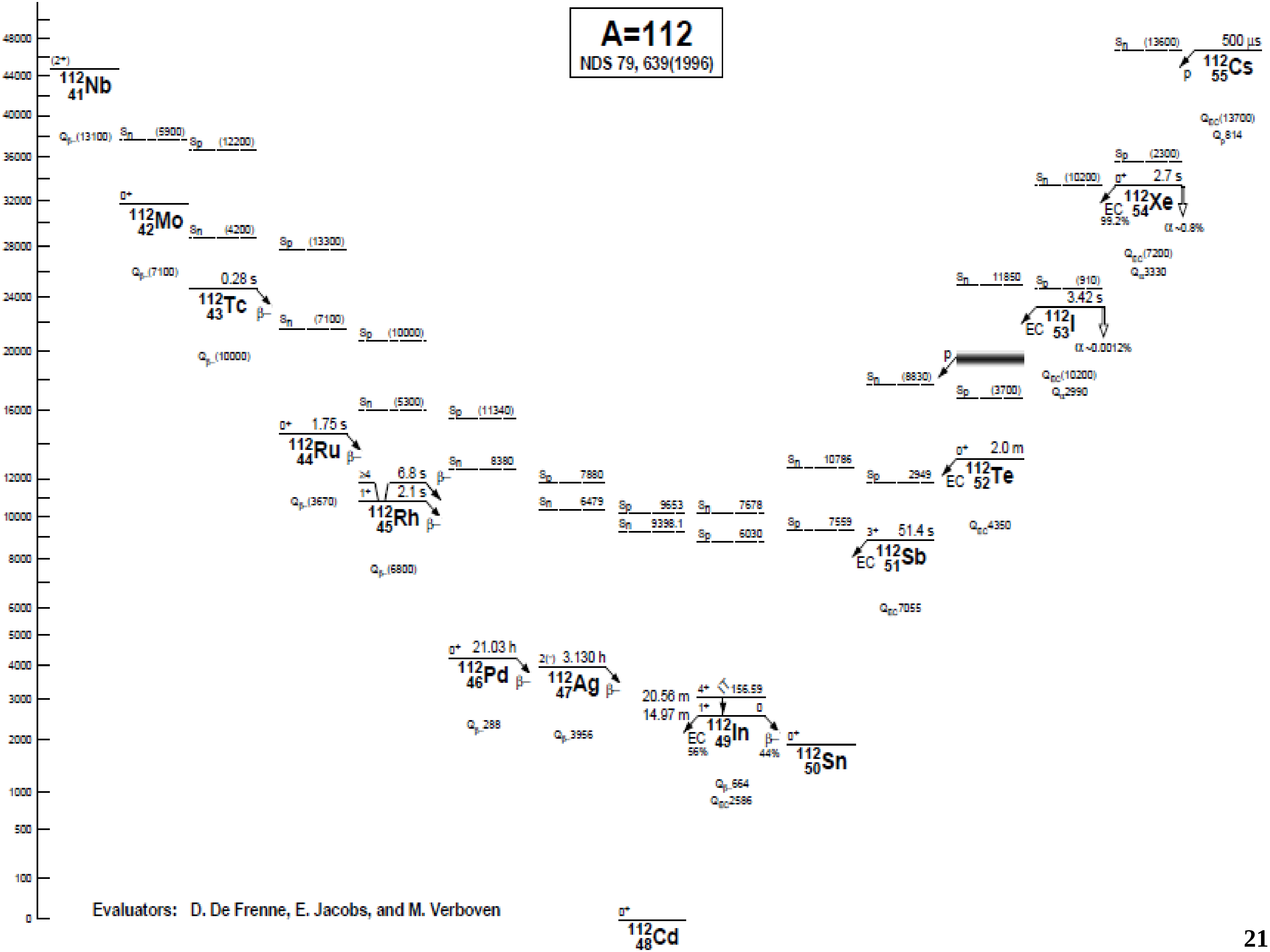
NDS 77, 299(1996)



Evaluators: J. Blachot and F. Haas

A=112

NDS 79, 639(1996)



Evaluators: D. De Frenne, E. Jacobs, and M. Verboven