«Measurements of the γ ray emission yeilds in Fe$(n, x\gamma)$–type reactions»

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I. Ruskov, V. Skoy, S. Dabylova, C. Hramco and TANGRA collaboration

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The «TANGRA» (TAgged Neutrons and Gamma RAys) project

The project ”TANGRA” (TAgged Neutrons & Gamma-RAys), aimed at experimental investigations of the nuclear reactions induced by fast neutrons important for science and engineering, is realized at the Frank Laboratory of Neutron Physics in JINR. The main purposes of the collaboration are:

- Creation of the Tagged Neutrons Method (TNM)-based approach for fast elemental analysis
- Measurements of the γ-quanta cross-sections and angular distributions[1] to create database for the (TNM)-based elemental analysis and test theoretical models[2]
- $(n, n'\gamma)$ correlations measurements and $(n, 2n)$ reactions investigation.
- Design of algorythms and programs for the experimental data processing

[1] Dabylova S. *et al.*, oral report 17.10.2020, section 2
[2] Dashkov I. *et al.*, poster report, section 2

Participants of the TANGRA collaboration

- JINR (FLNP, VBLHEP, DLNP, LRB), Dubna, Russia
- VNIIA (Moscow, Russia)
- Diamant LLC, Dubna, Russia
- SINP-MSU (Moscow, Russia)
- INRNE-BAS (Sofia, Bulgaria)
- IC-ASM (Chisinau, Moldova)
- IGGP-ANAS (Baku, Azerbaijan)
- DP-Banaras Hindu University (Varanasi, India)
- SEPE, Xi'an Jiaotong University (China)
- Alexandria University (Egypt)
- University of Novi Sad (Serbia)
- Ruđer Bošković Institute (Zagreb, Croatia)

Why iron?

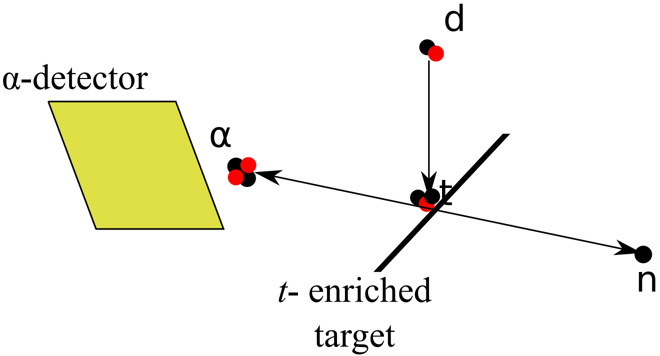
- **Iron-based alloys are important construction materials which are widely used in science and industry**
- There is a huge discrepancy between different measurements
- There is a range of the γ-transitions with unknown yeild in iron isotopes

Table 1: Measured cross-section of the 846.86 keV γ -line emission, mb

$^{nat}\mathrm{Fe}(n, n' + 2n)$	$^{56}\mathrm{Fe}(n, n')^{56}\mathrm{Fe}$	Reference
785(48)	621(29)	[1](Compilation)
333(60)	-	[1,2]
521(45)	-	[1,3]
663(70)	-	[4]
1280(270)	-	[1,5]

1: S. Simakov et al., INDC(CPP)-0413
2: F. Voss et. al. Proc. Int. Conf., Knoxville, 1971, p. 218, cited from[1]
3: I. Murata et. al. Int. Conf. on Nucl. Data for Sci. and Tech. (Mito,1988), p. 275, cited from[1]
4: R.O. Nelson et al., Report No.02-7167 (LA-UR-02-7167)
5: D. O. Nellis et.al. Phys. Rev., 1970, v. 1, p. 8, cited from[1]

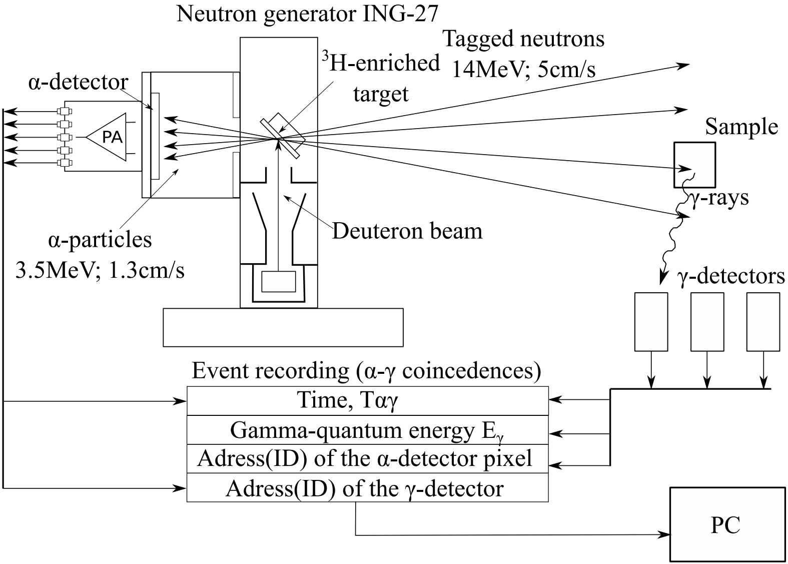
The tagged neutron method (TNM)



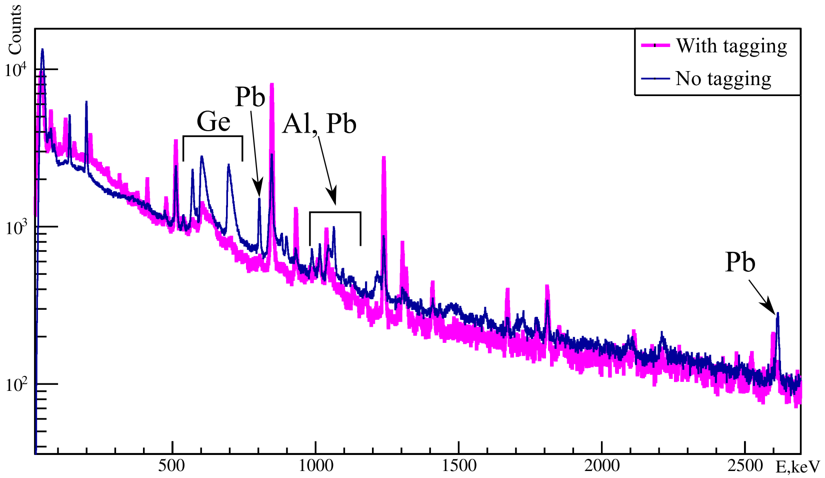
Registration of

α–particle in the (d, t) reaction allows one to determine direction and timestamp of the neutron emission

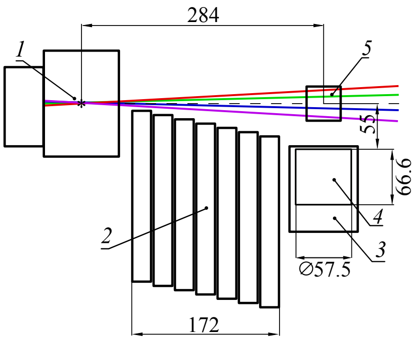
The tagged neutron method (TNM)



Advantages of the TNM



Experimental facility

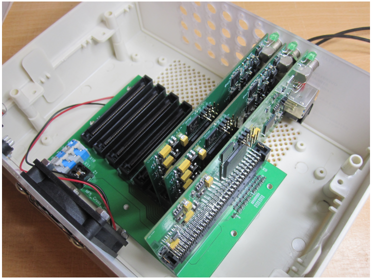


1. neutron generator ING-27
2. lead shielding
3. case of the HPGe detector
4. HPGe crystall
5. sample

Colored lines shows centroids of the tagged beams. The tritium target is marked by asterisk.

The data acquisition system (DAQ)

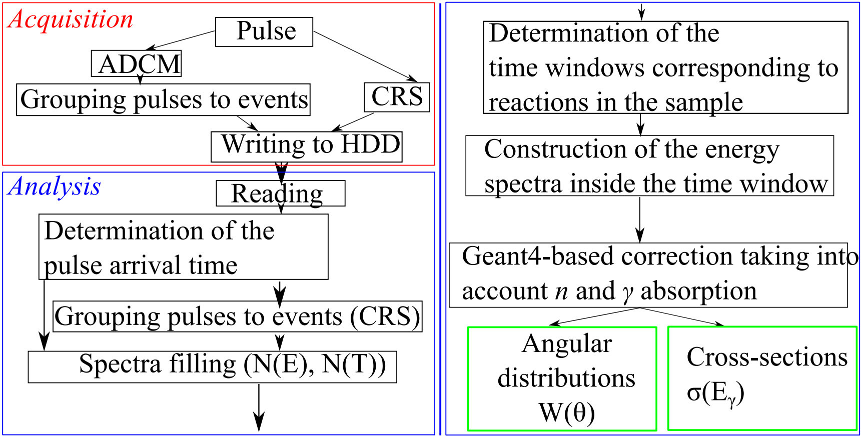
All signals from α-detector and HPGe γ getector are digitized by the CRS-6 system



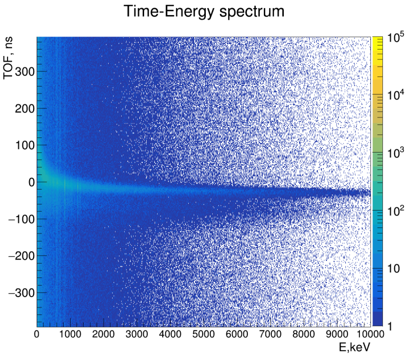
CRS-6

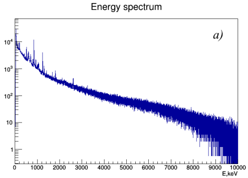
- Sampling frequency: 200MHz
- Max count rate: 10^5 ev/s
- ADC: 16 bit

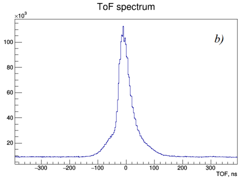
Data processing



Energy-amplitude spectra analysis

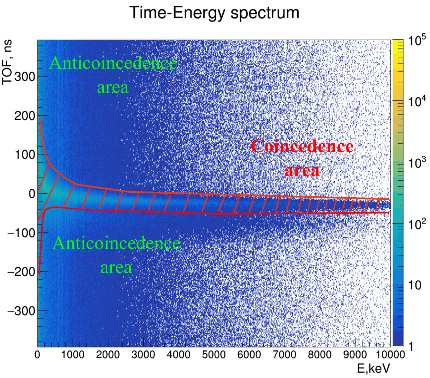


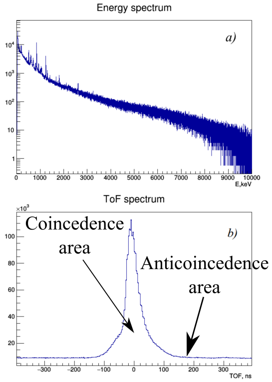




Good energy resolution of the HPGe allows one to investigate low-intensive γ-transitions *a)*; in the other hand, time resolution of the HPGe is low and single TOF spectrum is not enough for accurate background separation *b)*.

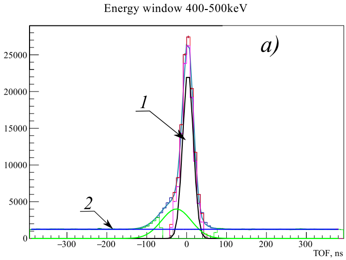
Energy-amplitude spectra analysis

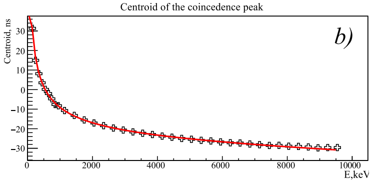


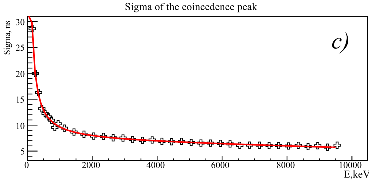


There is a way to remove a large part of the background: select events by TOF

Energy-amplitude spectra analysis



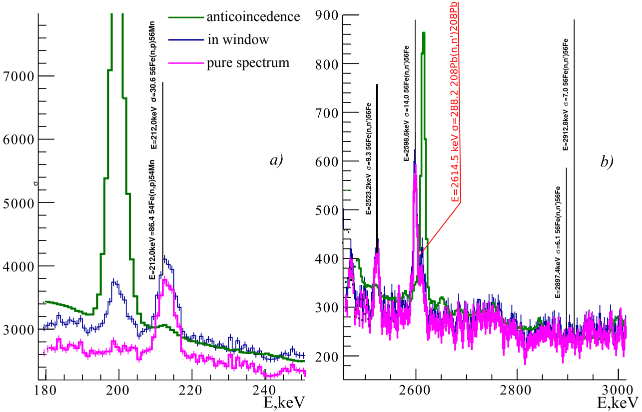




Due to features of the charge collection in HPGe the time resolution depends on the γ-quanta energy*, so to select proper time window for each energy the 2-dim spectrum was splitted to segments *a)* to determine centroid *b)* and sigma of the coincedence peak 1 *c)* in each window.

*F.C.L. Crespi, et al., Nucl. Instr. and Meth. A, 620 (2010) P. 299

Background substraction



We assume that random events background is non time-dependent. Substraction of the time-window width normalized anticoincedence spectrum from the gated coincedence spectrum often leads to removing of the background peaks *a)*, background events generated in the facility elements near the sample (i.e. in collimator) cannot be removed completely *b)*

Peak area determination

In HPGe data processing to determine area of the full energy absorption peak we use quite simple fit function. We use combination of gaussians and smooth substrate function for approximation. The full energy absorption peak area is proportional to the amount of emmitted γ-quanta. For point source relation between N_γ and number of emitted γ-quanta N_0 will be:

$$N_\gamma = N_0 \epsilon(E_\gamma) \tag{1}$$

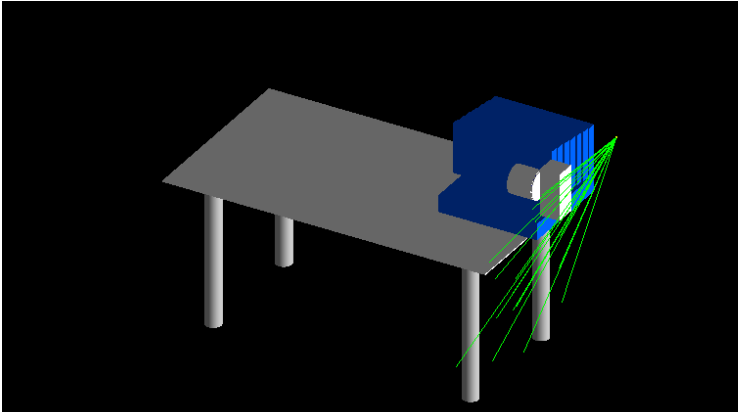
where N_0-number of emmited γ-quanta, $\epsilon(E_\gamma)$-efficiency of the γ-detector. In case of neutron irradiation the γ-rays are irradiated from relatively large area surrounded by dense substance so eq. 1 transforms into

$$N_\gamma = N_0 \varepsilon(E_\gamma) \tag{2}$$

where $\varepsilon(E_\gamma)$ includes impact of γ-ray and neutron beam absorption inside the sample and sizes of the γ-emission area:

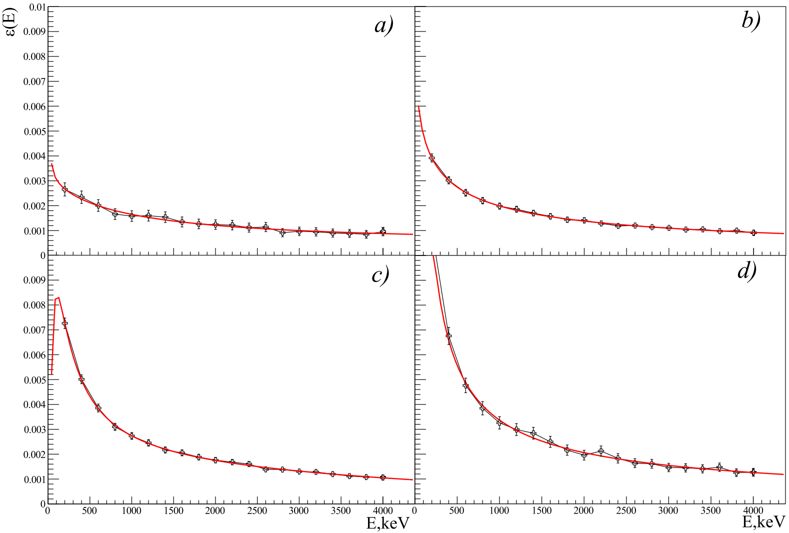
$$\varepsilon = \int_V \kappa(\overrightarrow{r}) \epsilon(\overrightarrow{r}) dV \tag{3}$$

Data correction



We use thick samples in our experiments to increase amount of events. It leads to significant γ-ray and neutron absorption inside the sample so these effects should be taken into account. We use Geant4-based program to calculate correction factor and apply it to experimental data.

Calculated efficiencies



Calculated ε values for 4 used α-strips, a)-the most distant from the HPGe α-srtip, c)-the closest one.

Results (Yeild>5%)

E_γ keV this work	ENDF	Reaction	Initial state $J_i^P(E_i, \text{keV})$	Final state $J_f^P(E_f, \text{keV})$	Y_γ, % this work	TALYS-1.9	[1]	[2]
123.5(4)* 126.0(4)*	123.5 126.0	^{56}Fe$(n,p)^{56}$Mn ^{56}Fe$(n,d)^{55}$Mn	5^+ (335.5) $\frac{7}{2}^-$ (125.9)	4^+ (212.0) $\frac{5}{2}^-$ (0)	6(1)	5.8		
211.9(2)	212.0 212.0	^{54}Fe$(n,p)^{54}$Mn ^{56}Fe$(n,p)^{56}$Mn	5^+ (368.2) 4^+ (212.2)	4^+(156.3) 0^+(0)	5.9(8)	4.81		
411.2(2)	411.9	^{56}Fe$(n,2n)^{55}$Fe	$\frac{1}{2}^-$ (411.4)	$\frac{3}{2}^-$ (0)	5.3(7)	7.05	6.8(8)	
846.86(2)	**846.8**	^{56}**Fe**$(n,n')^{56}$**Fe** ^{57}**Fe**$(n,2n)^{56}$**Fe**	**2^+ (846.8)**	**0^+ (0)**	**100**	**100**	**100**	**100**
931.4(1)	931.3	^{56}Fe$(n,2n)^{55}$Fe	$\frac{5}{2}^-$ (931.3)	$\frac{3}{2}^-$ (0)	12.0(8)	19.43	10.7(9)	15(5)
1038.1(2)	1037.8	^{56}Fe$(n,n')^{56}$Fe	4^+ (3123.0)	4^+ (2085.1)	8.2(8)	6.48	6.0(5)	10(2)
1238.53(4)*	1238.3	^{56}Fe$(n,n')^{56}$Fe ^{57}Fe$(n,2n)^{56}$Fe	4^+ (2085.1)	2^+(846.8)	43.8(1.1)	49.90	36(2)	46(5)
1304.0(1)*	1303.4	^{56}Fe$(n,n')^{56}$Fe ^{57}Fe$(n,2n)^{56}$Fe	6^+ (3388.6)	4^+ (2085.1)	9.2(6)	9.89	9.3(6)	10.1(1.5)
1316.0(2)	1316.4	^{56}Fe$(n,2n)^{55}$Fe	$\frac{7}{2}^-$ (1316.5)	$\frac{3}{2}^-$ (0)	5.6(5)	8.65	6.8(8)	7.4(1.2)
1810.7(2)	1810.8	^{56}Fe$(n,n')^{56}$Fe ^{57}Fe$(n,2n)^{56}$Fe	2^+ (2657.6)	2^+ (846.8)	6.7(5)	3.27	4.8(6)	7.7(1.2)

Table 2: Parameters of the γ-transitions. "*" marks unresolved γ-lines. Uncertainties in this work are statistical. Yeilds measured for the first time are marked with red. Values with difference > 30% from TALYS are marked with blue.

1: S. Simakov et al., INDC(CPP)-0413

Results (Yeild<5%)

E_γ keV this work	ENDF	Reaction	Initial state $J_i^P(E_i, \text{keV})$	Final state $J_f^P(E_f, \text{keV})$	Y_γ, % this work	TALYS-1.9	[1]	[2]
335.7(5)	335.5	$^{56}\text{Fe}(n,p)^{56}\text{Mn}$	3^+ (341.0)	2^+ (26.6)	2.2(8)	1.04		
477.4(5)	477.2	$^{56}\text{Fe}(n,2n)^{55}\text{Fe}$	$\frac{7}{2}^-$ (1408.5)	$\frac{5}{2}^-$ (931.3)	4.6(7)	3.97	6.4(9)	
1289.7(5)	1289.6	$^{56}\text{Fe}(n,\alpha)^{53}\text{Cr}$	$\frac{7}{2}^-$ (1289.5)	$\frac{3}{2}^-$ (0)	1.7(5)	1.68		
1408.3(3)*	1408.1 1408.5	$^{54}\text{Fe}(n,n')^{54}\text{Fe}$ $^{56}\text{Fe}(n,2n)^{55}\text{Fe}$	2^+ (1408.2) $\frac{7}{2}^-$ (1408.5)	0^+ (0) $\frac{3}{2}^-$ (0)	4.0(6)	6.50	3.0(6)	5.7(1.2)
1670.6(2)	1670.8	$^{56}\text{Fe}(n,n')^{56}\text{Fe}$	6^+ (3755.6)	4^+ (2085.1)	4.5(5)	5.1	6.9(7)	6.3(1.2)
2114.2(6)	2113.1	$^{56}\text{Fe}(n,n')^{56}\text{Fe}$	2^+ (2960.0)	2^+ (846.8)	2.5(7)	1.8	1.9(6)	4.5(1.2)
2524.2(8)	2523.1	$^{56}\text{Fe}(n,n')^{56}\text{Fe}$	2^+ (3370.0)	2^+ (846.8)	2.5(7)	1.37	2.7(6)	
2600.3(5)	2598.5	$^{56}\text{Fe}(n,n')^{56}\text{Fe}$	3^+ (3445.3)	2^+ (846.8)	3.4(5)	2.07	4.5(6)	

Table 3: Parameters of the γ-transitions. ”*” marks unresolved γ-lines. Uncertainties in this work are statistical. Yeilds measured for the first time are marked with red. Values with difference > 30% from TALYS are marked with blue.

1: S. Simakov et al., INDC(CPP)-0413

2: R.O. Nelson et al., Report No.02-7167 (LA-UR-02-7167)

Cross-section comparison

Table 4: Measured cross-section of the 846.86 keV γ -line emission, mb

^{nat}Fe$(n, n' + 2n)$	^{56}Fe$(n, n')^{56}$Fe	Reference
785(48)	621(29)	[1](Compilation)
333(60)	-	[1,2]
521(45)	-	[1,3]
535(10)	-	TANGRA(Very preliminary)
621.92	656.94	TALYS-1.9
663(70)	-	[4]
1280(270)	-	[1,5]

1: S. Simakov et al., INDC(CPP)-0413
2: F. Voss et. al. Proc. Int. Conf., Knoxville, 1971, p. 218, cited from[1]
3: I. Murata et. al. Int. Conf. on Nucl. Data for Sci. and Tech. (Mito,1988), p. 275, cited from[1]
4: R.O. Nelson et al., Report No.02-7167 (LA-UR-02-7167)
5: D. O. Nellis et.al. Phys. Rev., 1970, v. 1, p. 8, cited from[1]

Conclusion

- The obtained yeild values are generally consistent with the known literature data
- The comparison of the measured γ-yields with calculated one shows a large discrepancy for $(n, 2n)$ reactions
- Yeilds for 123.5, 126.0, 212.0, 123.5, 335.5, 1289.6 γ-transitions were measured for the first time
- A huge discrepancy was found between 846.86 keV γ-ray transition cross-sections values in literature. Preliminary cross-section measured in our experiment lies almost in the middle between minimal and maximal values from the databases but it is significantly lower than one obtained from TALYS 1.9 and compilation[1].

Thank you for your attention!