Gamma Rays from Inelastic Scattering of ~14-MeV Neutrons by Titanium

Ivan N. Ruskov for TANGRA collaboration

Abstract

Within the framework of the international TANGRA project (TAgged Neutron & Gamma RAys), we measured the yield, energy and angular distribution of gamma rays from inelastic scattering of neutrons with an energy of ~ 14 MeV on the nuclei of a bulk sample of natural titanium powder (^{nat}Ti).

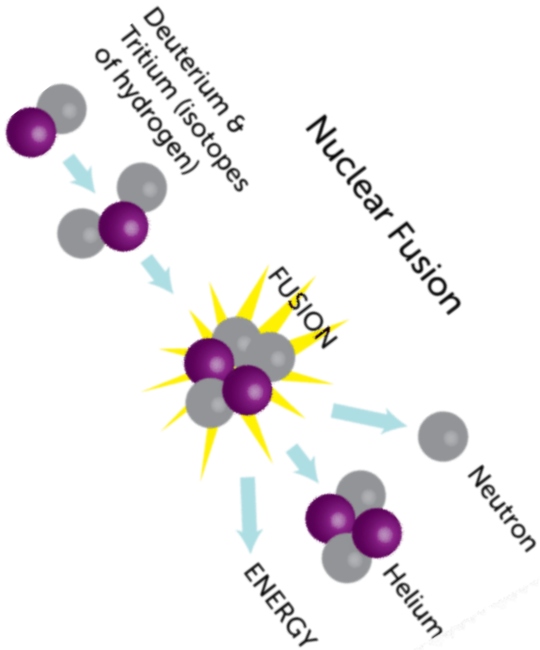
In the experiments, we used the TANGRA setup, which consisted of: VNIIA ING-27 (generator of a continuous beam of “tagged” neutrons with energies of ~14 MeV) and a gamma-spectrometric system "Romasha" (18 BGO and one HPGe, in ring geometry).

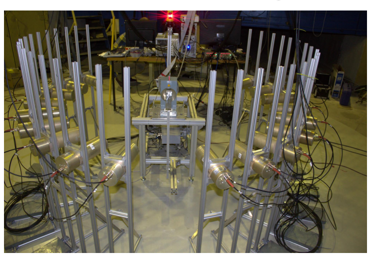
We were able to measure the cross section of gamma production for XX transitions in stable ^{nat}Ti isotopes, which can be used to determine the partial level and total INS cross sections.

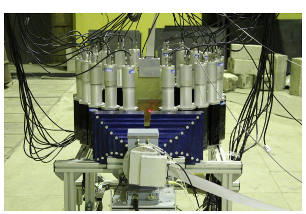
Here we report our preliminary experimental results on distribution of gamma-rays from the inelastic scattering of ~14-MeV “tagged” neutrons with ^{48}Ti(n, n′$\gamma_{983.5}$).

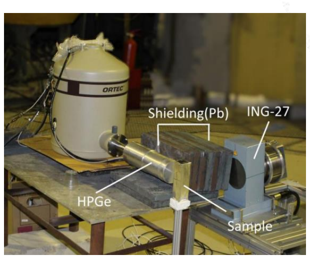
Gamma-rays from INS

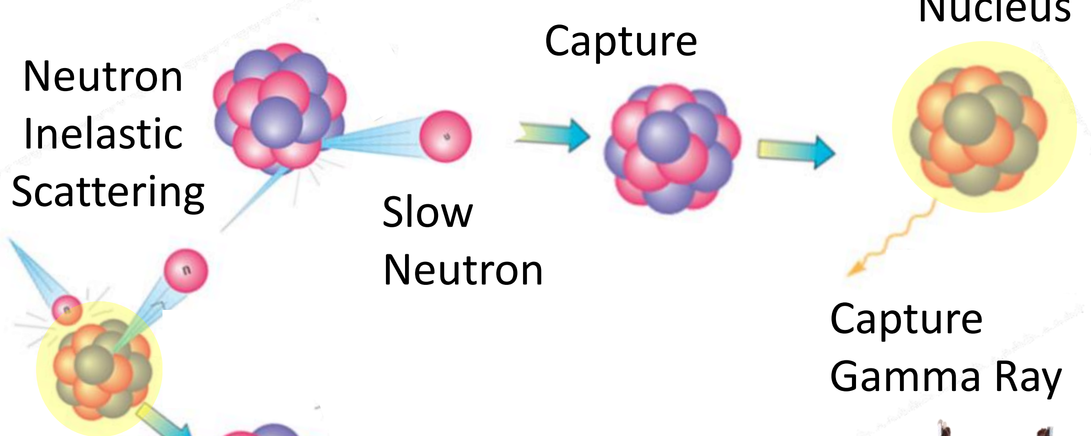
^{nat}Ti (n, n′γ)

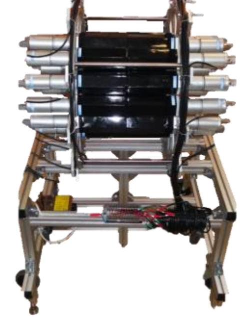






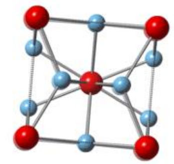






Motivation: Titanium Applications

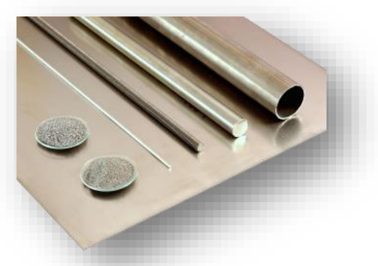
Titanium is as strong as steel but much less dense. It is therefore **important** as an alloying agent with many metals including Aluminium, Molybdenum and Iron.



Titanium powder (sponge) is an intermediate product in its purest form and material for [titanium alloy]

Titanium Sponge for Aerospace & Defense Market to go past 1.94 billion-dollar mark by 2024

These alloys are mainly used in aerospace industry: **aircraft, spacecraft and missiles**, because of their low density and ability to withstand extremes of temperature.



Titanium's mechanical and chemical properties make it an ideal metal for [power plant] condenser pipes

Bilobrov, I. and V. Trachevsky, NASU (2011), "Approach to modify the properties of titanium alloys for use in the nuclear industry", Journal of Nuclear Materials, 415, pp. 222-225. http://dx.doi.org/10.1016/j.jnucmat.2011.05.056.

https://energyeducation.ca/encyclopedia/Titanium#cite_note-nuclear-7

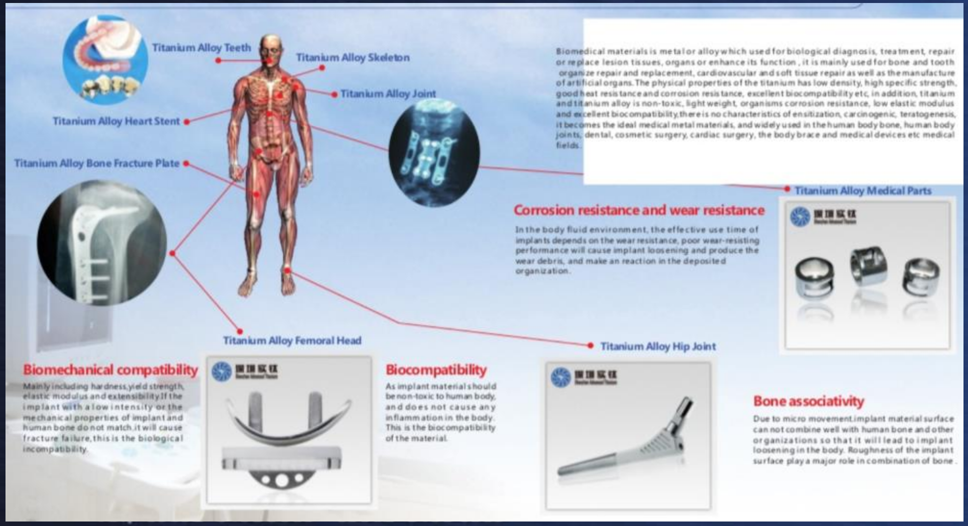
https://www.lucintel.com/aerospace-titanium-market.aspx

http://www.periodicvideos.com/

Titanium Infused Quartz Crystal

Motivation: Titanium Applications

SHENZHEN ADVANCED
深圳市实钛科技有限公司



The presence of ^{nat}Ti in nuclear reactors

Titanium (Ti, Z=22) is one of the important structural materials and the criticality safety study has paid attention to its neutron reaction data.

The isotopic abundance of each stable isotope of ^{nat}Ti and the corresponding areal density [*].






Isotopes	^{46}Ti	^{47}Ti	^{48}Ti	^{49}Ti	^{50}Ti
Isotopic composition (%)	8.25(3)	7.44(2)	73.72(3)	5.41(2)	5.18(2)
Areal density (g/cm^2)	0.176(1)	0.159(1)	1.576(1)	0.115(1)	0.110(1)

[*] National Institute of Standards and Technology, http://www.nist.gov. J. Meija et al., Pure Appl. Chem. 88, 293 (2016).

TABLE III. The threshold energies for the $(n,2n\gamma)$ reactions of interest with the excitation energy of the first level included.

Reaction	$^{47}\mathrm{Ti}(n,2n\gamma)^{46}\mathrm{Ti}$	$^{48}\mathrm{Ti}(n,2n\gamma)^{47}\mathrm{Ti}$	$^{49}\mathrm{Ti}(n,2n\gamma)^{48}\mathrm{Ti}$	$^{50}\mathrm{Ti}(n,2n\gamma)^{49}\mathrm{Ti}$
Q value (MeV)	9.0710(5)	11.8710(5)	9.313(5)	11.1600(5)

Motivation: Standard Reference Cross Sections

^{nat}Ti (^{nat}Cr, ^{nat}Fe) are structural materials for the Gen-IV neutron reactors. Data on scattering of fast neutrons are important for calculating future reactor's characteristics.

The first transition in ^{48}Ti with $E\gamma$=983.5 keV is a candidate for a reference cross section: constant large cross section over a broad neutron energy range.

Low price of the isotope and also the simple preparation of the sample.

The angular anisotropy and the contribution from the $^{48}Ti(n, p)^{48}Sc$ at En > 5 MeV,

This reaction creates ^{48}Sc which through $\beta-$ decay emits γ rays with $E\gamma$ = 983.5 keV, 1037.5 keV, 1212.9 keV and 1312.1 keV.

Small number of experimental results, some of them discrepant

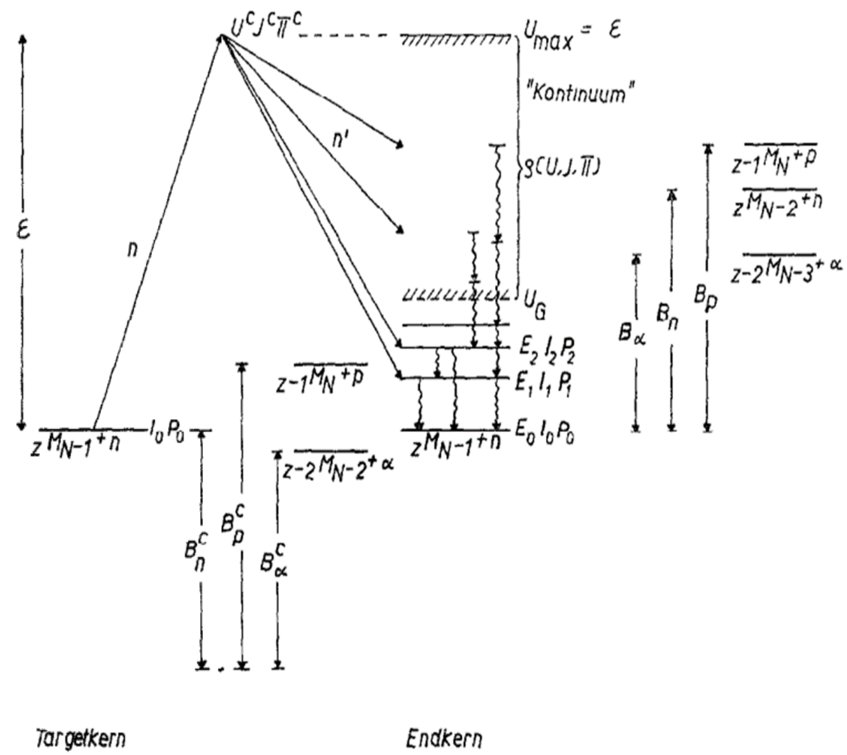
A.D. Carlson, V.G. Pronyaev, F.-J. Hambsch, W. Mannhart, A.Mengoni, R.O. Nelson, P. Talou, S. Tagesen, and H. Vonach, J. Korean Phys. Soc. 59,1390 (2011).

S.P. Simakov, V.G. Pronyaev, R. Capote, and R.O. Nelson, Proceeding of the 13th International Conference on Nuclear Reaction Mechanisms, edited by F. Cerutti, M. Chadwick, A.Ferrari, T. Kawano, S. Bottoni, and L. Pellegri (Villa Monastero,Varenna, Italy, 2012) CERN-Proceedings-2012-002, p. 321.

Motivation: Nuclear Data for Sci & Tech

From (n, xn′γ) cross sections and angular distribution of γ-rays (and neutrons) we can obtain important information about the *nuclear structure*, *exited levels* and *reaction mechanisms*: (Direct, Pre-equilibrium → CN-decay).

Measured $\sigma(n, xn'\gamma)$	
Nuclear structure information	Nuclear Model constrained by $\sigma(n, xn'\gamma)$
Deduced exp. $\sigma(n, xn')$	Calculated $\sigma(n, xn')$



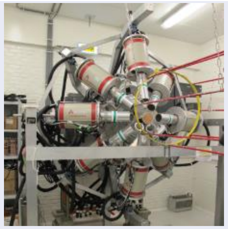
ıb. 1. Zum Reaktionsablauf.

D. Dashdorj, T. Kawano, P. E. Garrett et al., Effect of pre-equilibrium spin distribution on 48Ti + n cross sections, Phys. Rev. C75, 054612 (2007), https://doi.org/10.1103/PhysRevC.75.054612.

Kerveno, M., Dupuis, M., Borcea, C., Boromiza, M., Capote, R., Dessagne, P., Henning, G., Hilaire, S., Kawano, T., Negret, A., Nyman, M., Olacel, A., Party, E., Plompen, A., Romain, P. and Sin, M., What can we learn from (n, xnγ) cross sections about reaction mechanism and nuclear structure, In: ND2019, EPJ Web of Conferences, 2020, ISSN 2100 014X, 239, p. 01023, JRC117648. https://doi.org/10.1051/epjconf/202023901023.

Maëlle Kerveno, Greg Henning, Catalin Borcea, Philippe Dessagne, Marc Dupuis, et al., How toproduce accurate inelastic cross sections from an indirect measurement method?, EPJ N – Nuclear Sciences & Technologies, EDP Sciences, 2018, 4, pp.23, hal-02109918h, https://doi.org/10.1051/epjn/2018020.

Inelastic Neutron Scattering (INS) Cross Section Measurements on Titanium

Who	What	Where	How
M. V. Pasechnik *et al.*, Vol.14, Issue.11, 1874 (**1969**).	σ(984-keV) by 2.9 MeV	Van de Graaff	ToF, n-det by Organic Scintillator
W. Breunlich, and G. Stengel, Nuclear Physics A, Vol.184, 253 (**1971**).	σ^{nat}Ti(n,n'γ) for En=14.4 MeV and in the mass range A=46-88.	pulsed Cockroft-Walton	coaxial Ge(Li) detector.
E. S. Konobeevskij *et al.*, Vol.37, Issue.8, 1764 (1973).	$\sigma^{met.nat}$Ti(n,n'γ)	Van de Graaf	Ge(Li) detectors
W. E. Kinney, and F. G. Perey, Oak Ridge National Lab. Reports No.4810 (**1973**).	σ^{48}Ti(n,n'γ) for En=4.07-8.56 MeV	ORNL Van de Graaff	Time-of-Flight
I. A. Korzh *et al.*, Ukrainskii Fizichnii Zhurnal, Vol.22, 87 (**1975**).	σ^{48}Ti(n,n'γ)		
A. I. Lashuk *et al.*, Vol.1994, Issue.1, 26 (**1994**).	σ^{48}Ti(n,n'γ)	Van de Graaf	Ge(Li)
D. Dashdorj *et al.*, Nuclear Science and Engineering, Vol.157, 65 (**2007**).	σ^{48}Ti(n,n'γ) for En=1-200 meV 99.8%,	LANSCE WNR	GEANIE, 235, 238U fission-chamber
- A. Olacel et al., Report EUR 27621 EN (**2015**), https://doi.org/10.2787/08607 - A. Olacel et al., Neutron inelastic scattering measurements on the stable isotopes of titanium. Phys. Rev. C, **2017**, 96 (1), pp .014621. https://doi.org/10.1103/PhysRevC.96.014621	σ^{nat} Ti (n, n'γ)	GELINA, Geel-2, JRC, Belgium	GAINS, 235, 238 U Fission chamber 

Motivation: Standard Reference Cross Sections

S.P. Simakov, V.G. Pronyaev, R. Capote and R.O. Nelson, ^{48}Ti(n,n′γ) gamma production cross section as a candidate for a reference cross section, https://cds.cern.ch/record/1536999/files/p321.pdf

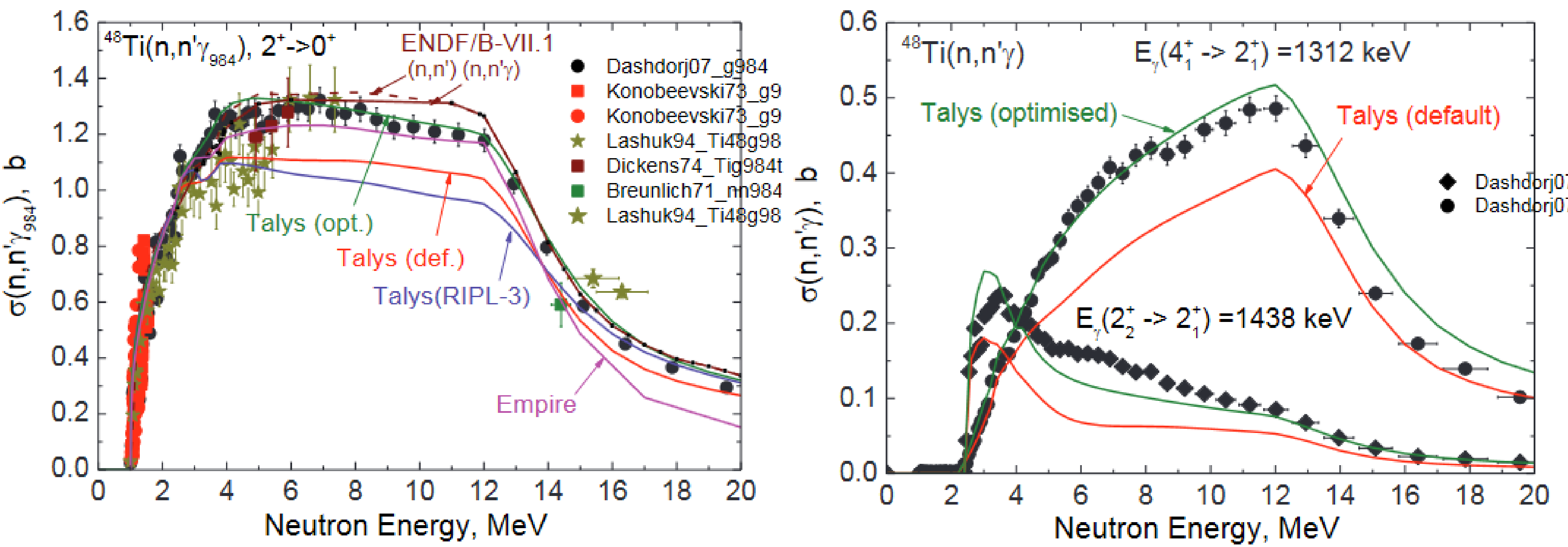


Fig. 2: ^{48}Ti(n,n′γ_{984}) (left) and ^{48}Ti(n, n′γ_{1312} γ_{1438}) (right) cross sections up to 20 MeV: symbols – experimental data; curves – TALYS & EMPIRE calculations and ENDF/B-VII.1 evaluation [16].

^{48}Ti(n,n′γ) and ^{48}Ti(n,2nγ) were identified as the best candidates for γ-ray reference cross sections. However, the paucity of ^{48}Ti(n, n′γ) data requires more experimental and theoretical work to establish it as a viable reference cross section in the incident neutron energy range from about 4 to 12 MeV.

https://www-nds.iaea.org/nds-technical-meetings/TM-Std-Jul-2013/docs/Simakov_Ti-48.pdf

GELINA setups for INS measurements

European Commission

JRC TECHNICAL REPORT

JRC data for the Ti-48 standard

Summary report on the JRC contributions to the establishment of a new γ ray standard with the ^{48}Ti(n,n'γ) reaction

A. Olacel, F. Belloni, C. Borcea, A. Negret, M. Nyman, E. Pirovano, A.J.M. Plompen

2015

Report EUR 27621 EN

Joint Research Centre

https://doi.org/10.2787/08607

Markus Nyman, European Commission, Joint Research Centre, Geel, Belgium

Neutrons for the next decade and beyond, 4-6 February 2019, iThemba LABS, Cape Town, South Africa

GAINS (Gamma Array for Inelastic Neutron Scattering)

- 12 coaxial HPGe detectors (8 cm x 8 cm) at 110º, 125º, and 150º, four at each angle
- 3 Acquiris DC440 digitizers for the HPGe detectors, 12 bit amplitude resolution, 420 MS/s
- ^{235}U Fission chamber 2.1 m upstream from the sample position to monitor the neutron flux
  - 8 UF_4 deposits (Ø 70 mm) on 5 Al foils (20 mm)
- Located at flight path 3, 100 m

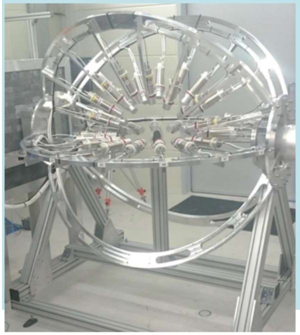
European Commission

High-precision measurement of the inelastic neutron scattering cross section of ^{19}F at GELINA

Markus Nyman, European Commission, Joint Research Centre, Geel, Belgium

Neutrons for the next decade and beyond, 4-6 February 2019, iThemba LABS, Cape Town, South Africa

Experimental setups at GELINA – ELISA



- For angular distribution and (in)elastic scattering cross section measurements
- 32 liquid organic scintillators
  - EJ301 (NE213) and EJ315 (C6D6)
  - Proton / deuterium based
- n/g separation by pulse-shape analysis
- elastic/inelastic separation by unfolding the pulse-height spectrum
- ^{235}U fission chamber and digital DAQ

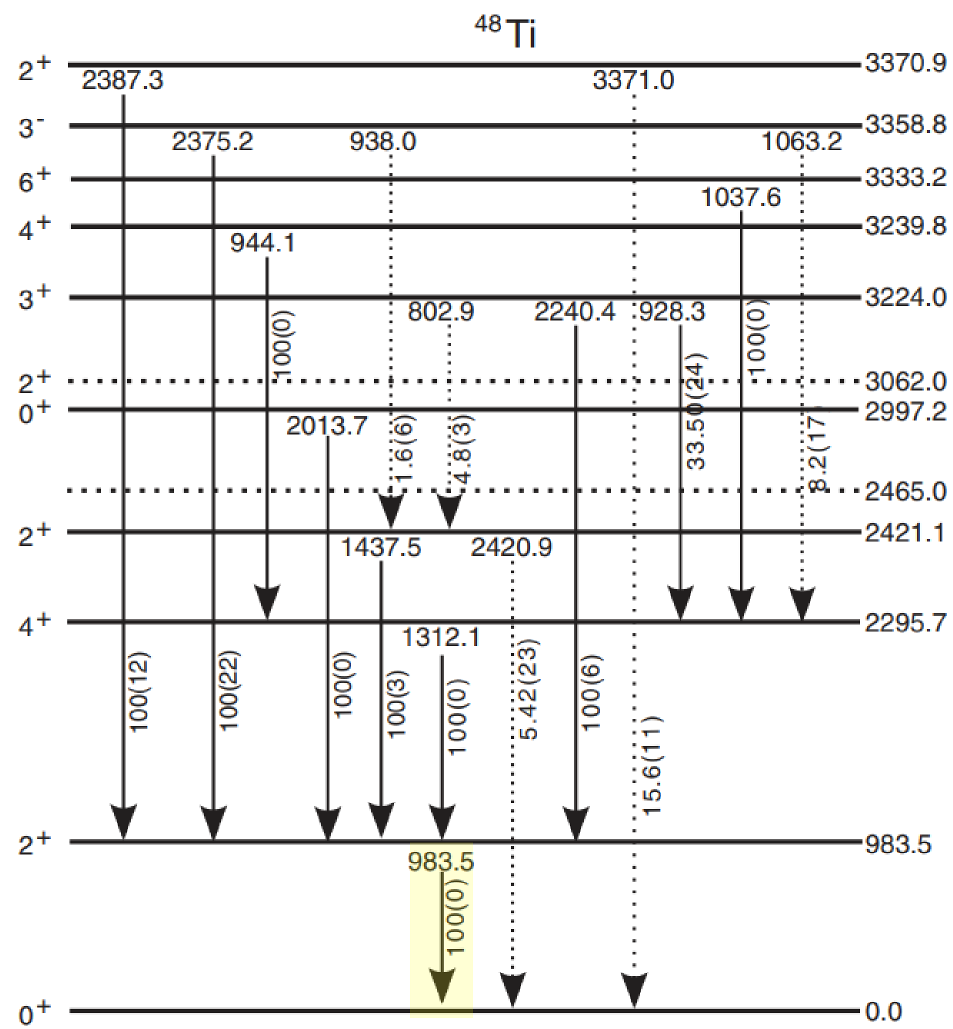
Four days ago: https://doi.org/10.1103/PhysRevC.99.024601

European Commission

High-precision measurement of the inelastic neutron scattering cross section of ^{19}F at GELINA

JRC data for ^{48}Ti(n, n′γ)-reaction

A.Olacel, F. Belloni, C. Borcea, M. Boromiza, P. Dessagne, et al., Neutron inelastic scattering measurements on the stable isotopes of titanium. Phys. Rev. C, 2017, 96 (1), pp. 014621. https://doi.org/10.1103/PhysRevC.96.014621



Simplified level scheme of the ^{48}Ti nucleus [39]. The observed transitions are displayed using solid lines. The dashed line is used to show known transitions that were not observed but were taken into account in the data analysis procedure or to display the levels with no or unknown γ -ray contribution.

[39] T. W. Burrows, Nucl. Data Sheets 107, 1747 (2006).

γ-production cross section ^{48}Ti(n, n′$\gamma_{983.5}$)

A. OLACEL et al., PHYSICAL REVIEW C 96, 014621 (2017), https://doi.org/10.1103/PhysRevC.96.014621

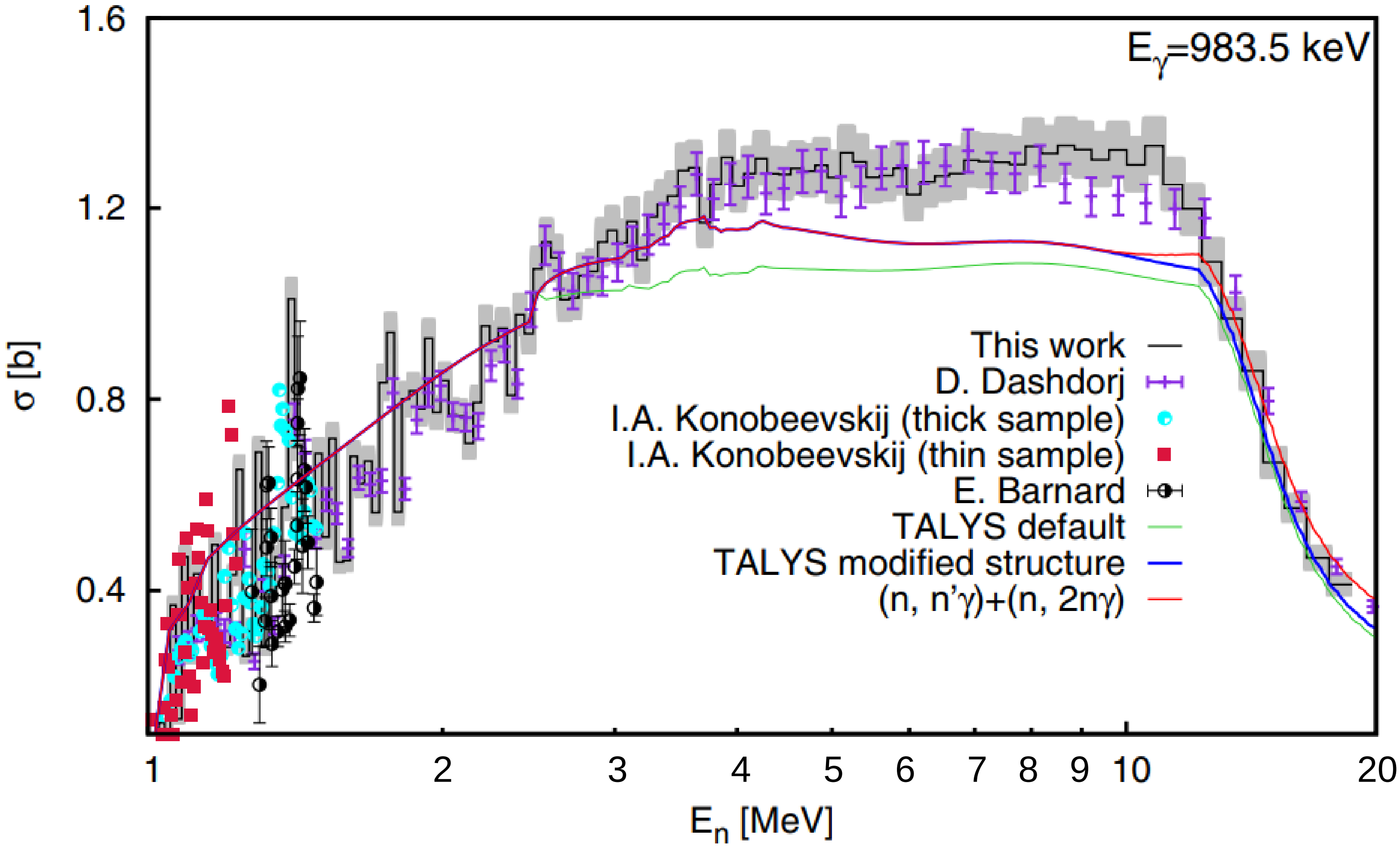
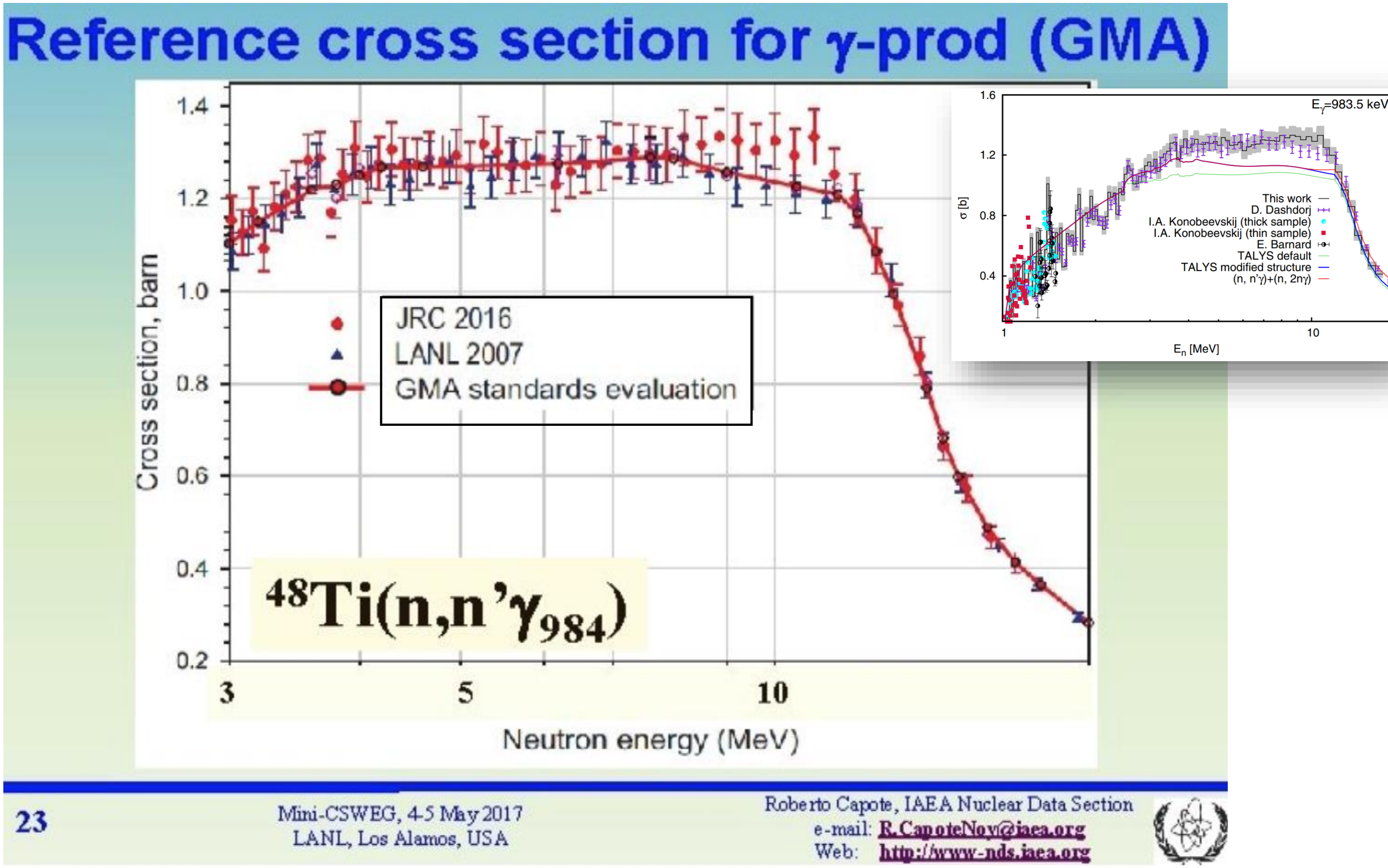


FIG. 2. The γ production cross section of the first transition in ^{48}Ti in comparison with previous experimental results and with TALYS 1.8 theoretical calculations. The gray band represents the total absolute uncertainties of our experimental values.



Reference cross section for prod (GMA) ^{48}Ti(n, n′γ_{984}) 3 5 10 23 Mini-CSWEG, 4 -5 May 2017 LANL, Los Alamos, USA Roberto Capote, IAEA Nuclear Data Section e-mail: R.Capote.Noy@iaea.org Web: http://www-nds.iaea.org,

https://slidetodoc.com/iaea-neutron-standards-2017-a-d-carlson-v/

TANGRA project

http://flnph.jinr.ru/en/facilities/tangra-project

Frank Laboratory of Neutron Physics
Joint Institute for Nuclear Research

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- IREN components
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CARS
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- Installation description
- Useful www-resources

TANGRA project

The project "TANGRA" (TAgged Neutrons and Gamma RAys) is devoted to study of neutron-nuclear interactions, using the tagged neutron method (TNM), also known as Associated Particle Imaging (API)

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)


JINR
TANGRA
COLLABORATION
FLNP
ING-27 power sup.
NaI(Tl) Romashka
PC ADCM 32 chan
Everything is possible
with a proper team

TANGRA SETUPS

JINR FLNP

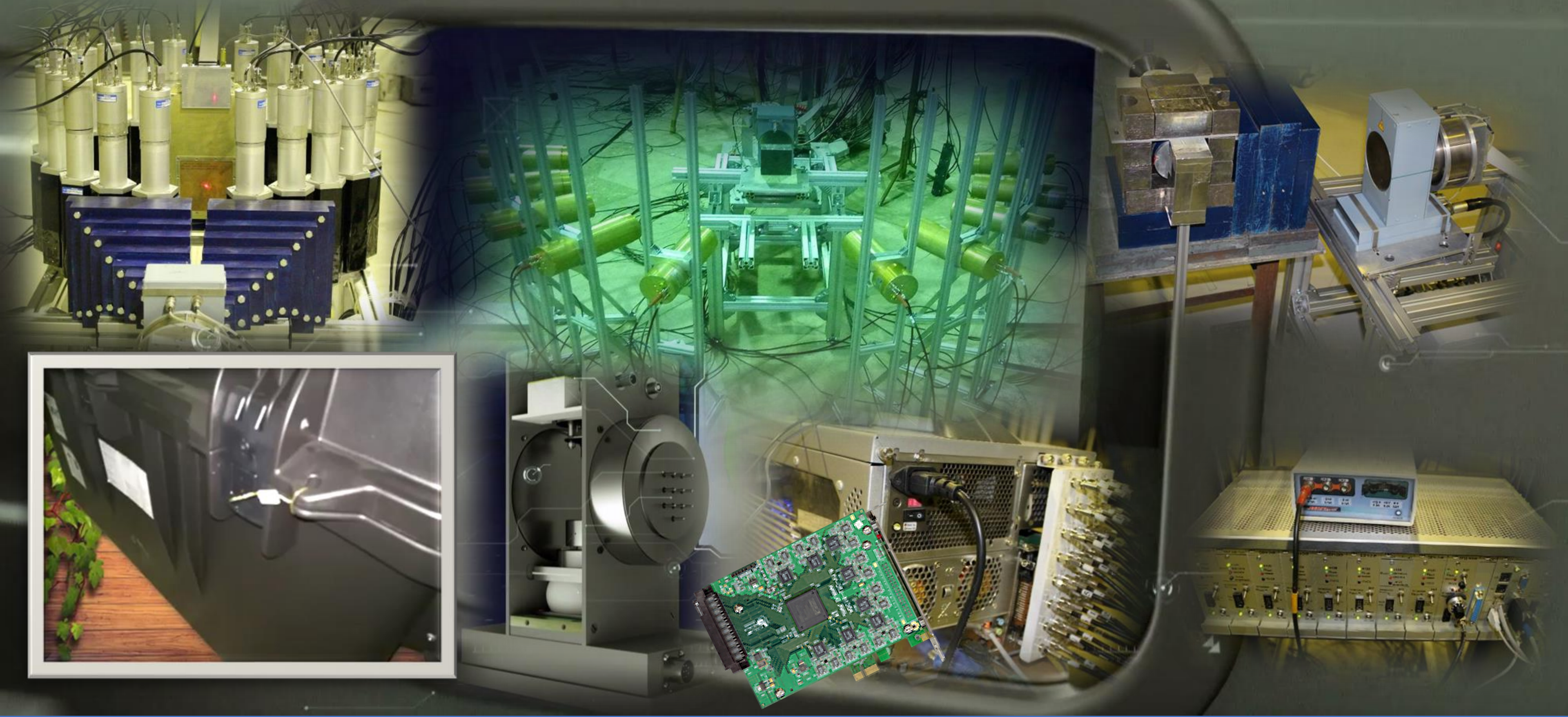
http://flnph.jinr.ru/en/facilities/tangra-project

Multidetector, multipurpose, multifunctional, mobile systems, to study the characteristics of the products from the nuclear reaction induced by 14 MeV tagged neutrons

NaI(Tl) Romashka

BGO Romasha

HPGe Romasha

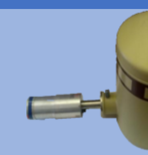


TANGRA Setups consist of a portable generator of “tagged” neutrons with an energy of 14.1 MeV, ING-27, with or without an iron shield-collimator, 2D fast neutron beam profilometer, arrays of neutron-gamma detectors in geometry of daisy-flower (Romashka, Romasha, HPGe), a computerized system for data acquisition and analysis (DAQ).

Number of NaI(Tl) detectors: 22
Size of NaI(Tl) crystals: hexagonal prism 78 x 90 x 200 mm
PMT type: Hamamatsu R1306
Gamma-ray Energy-resolution ~ 7.2 % @ 0.662 MeV
Gamma-ray Energy-resolution ~ 3.6 % @ 4.437 MeV
Gamma-ray Time-resolution ~ 3.8 ns @ 4.437 MeV

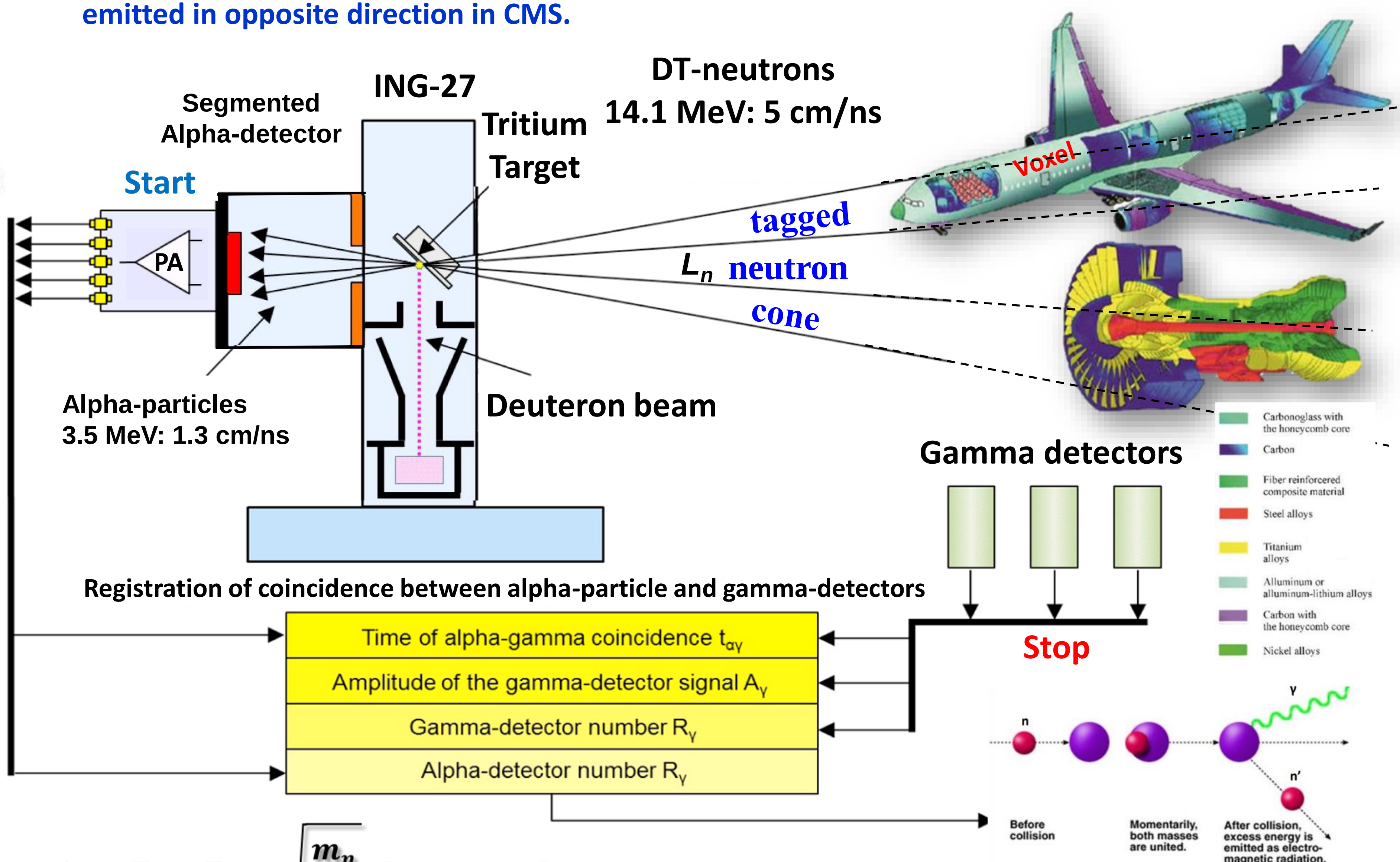
Number of BGO detectors: 18
Size of BGO crystals: cylinder ∅ 76 x 65 mm
PMT type: Hamamatsu R1307
Gamma-ray Energy-resolution ~ 10.4 % @ 0.662 MeV
Gamma-ray Energy-resolution ~ 4.0 % @ 4.437 MeV
Gamma-ray Time-resolution ~ 4.1 ns @ 4.437 MeV

Number of HPGe detectors: 1
Type: Ortec® GMX 30-83-PL-S, ϕ57.5 x 66.6 mm
Gamma-ray Energy-resolution ~ 3.4 % @ 0.662 MeV
Gamma-ray Energy-resolution ~ 0.3 % @ 4.437 MeV
Gamma-ray Time-resolution ~ 6.1 ns @ 4.4437MeV



TANGRA: Time-Correlated Associated Particle Method (TCAPM)

The 14-MeV neutron is tagged in time and direction by detecting the associated α-particle, emitted in opposite direction in CMS.

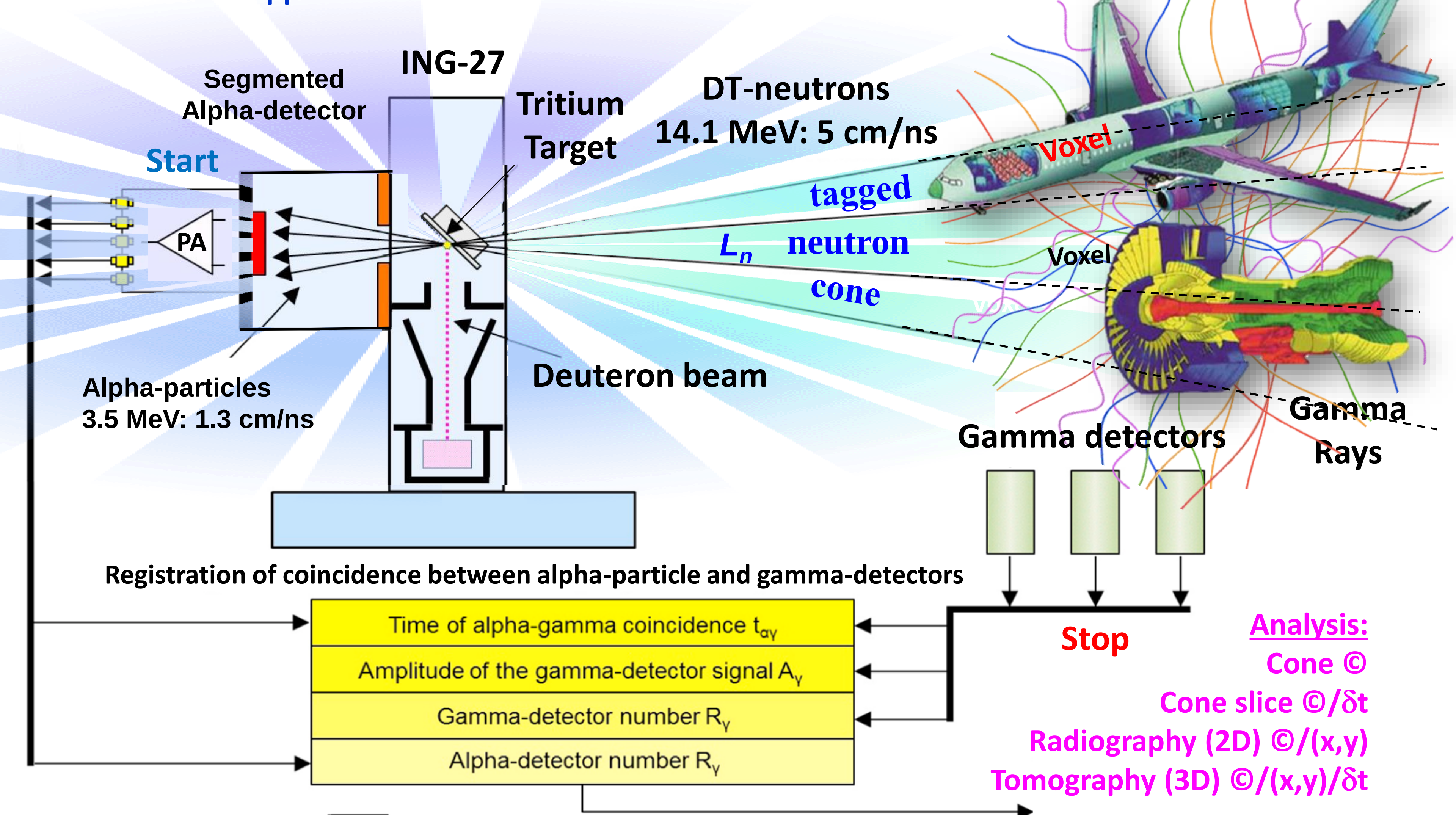


$$\Delta t = T_\gamma - T_\alpha = \sqrt{\frac{m_n}{2E_n}}.L = const.Ln$$

https://ars.els-cdn.com/content/image/1-s2.0-S0168900218316255-gr1_lrg.jpg

TANGRA: Time-Correlated Associated Particle Method, TCAPM

The 14-MeV neutron is tagged in time and direction by detecting the associated α-particle, emitted in opposite direction



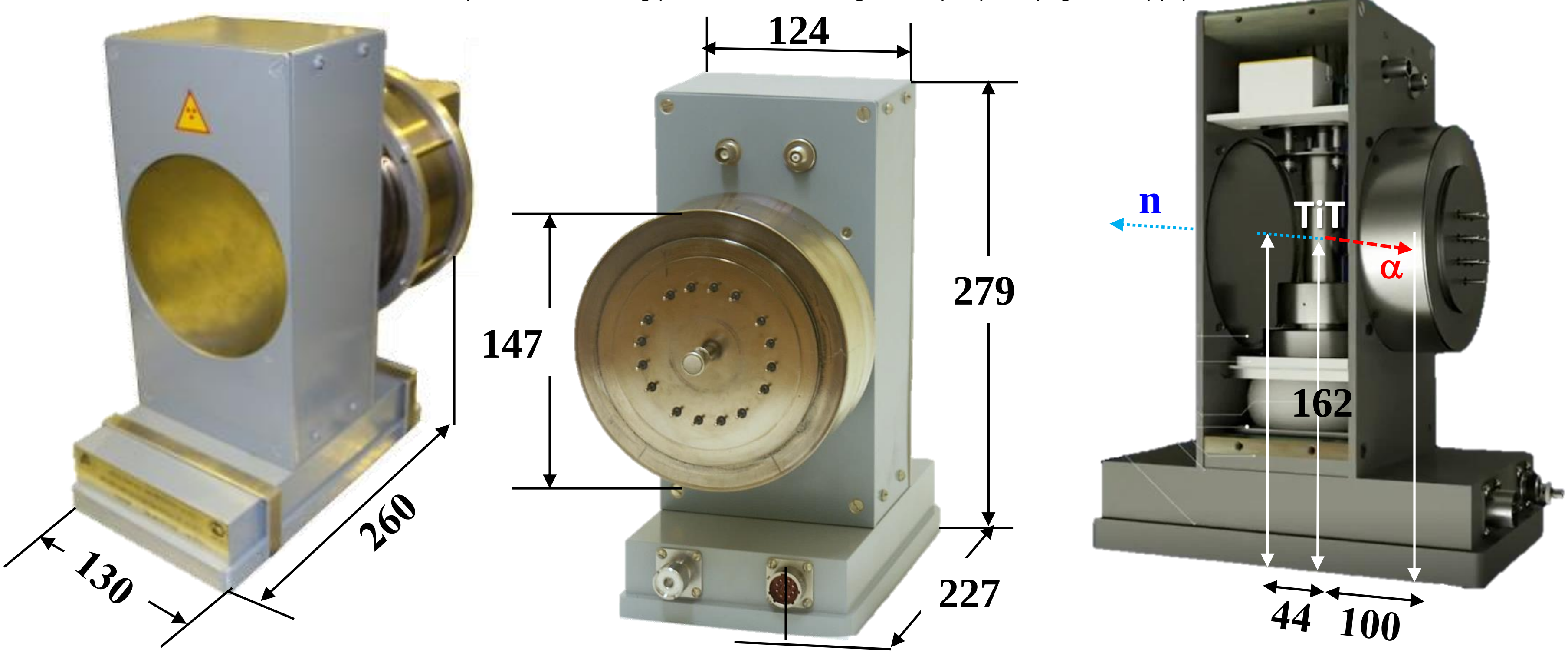
$$\Delta t = T_\gamma - T_\alpha = \sqrt{\frac{m_n}{2E_n}}.L = const.Ln$$

https://ars.els-cdn.com/content/image/1-s2.0-S0168900218316255-gr1_lrg.jpg

TANGRA: VNIIA ING-27 Neutron Generator

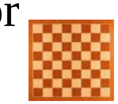
Based on a sealed DT-tube

http://www.vniia.ru/eng/production/neitronnie-generatory/neytronnye-generatory.php



TiT-to-front distance : 44.0 ± 1.4 mm
TiT-to-α–detector distance: 100 ± 2 mm
Power supply voltage: 200 ± 5 V
Max Power Supply Current: 300 ± 30 mV
Consumed Power: < 40 W
Continuous Mode: 14-MeV neutrons
Initial Intensity: > 5.0 x 10^7 n/s/4π
Final Intensity: > 2.5 x 10^7 n/s/4π

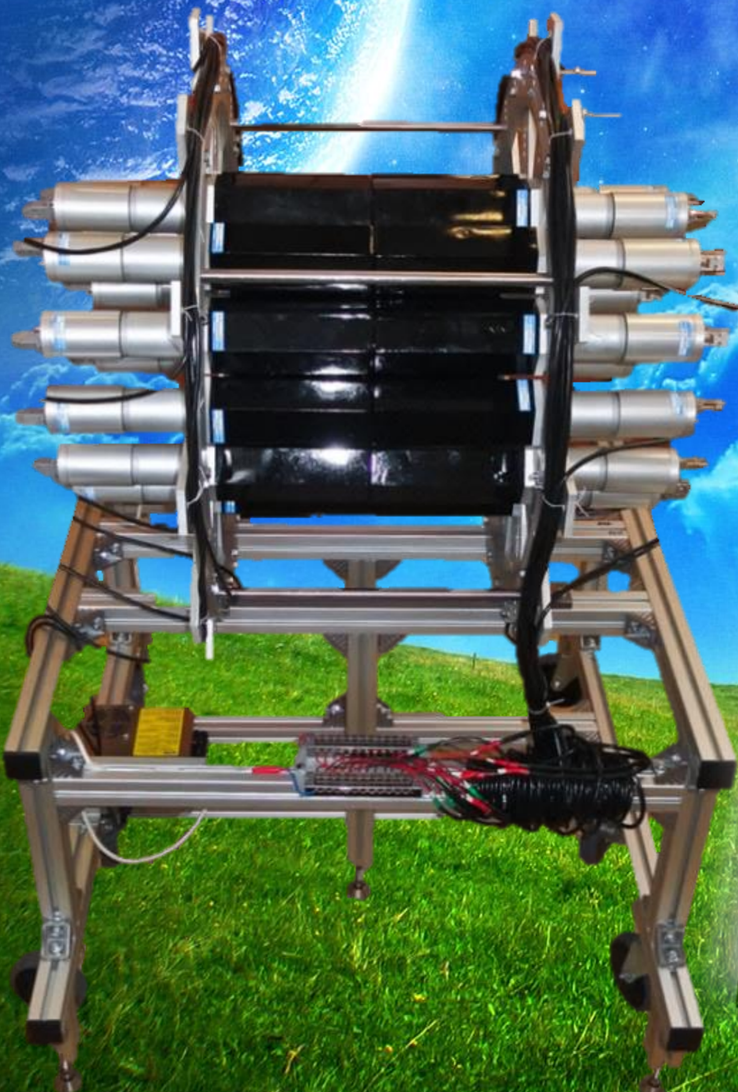
Double-side Si α-particles detector
Number of pixels: 64 (8x8 strips)
Pixel area: 6x6 mm^2
Distance between strips: 0.5 mm
Voltage bias: –250V DC
Dark current: < 8μA
n-tube life-time: > 800 h
< ING Duty time >: 18 months



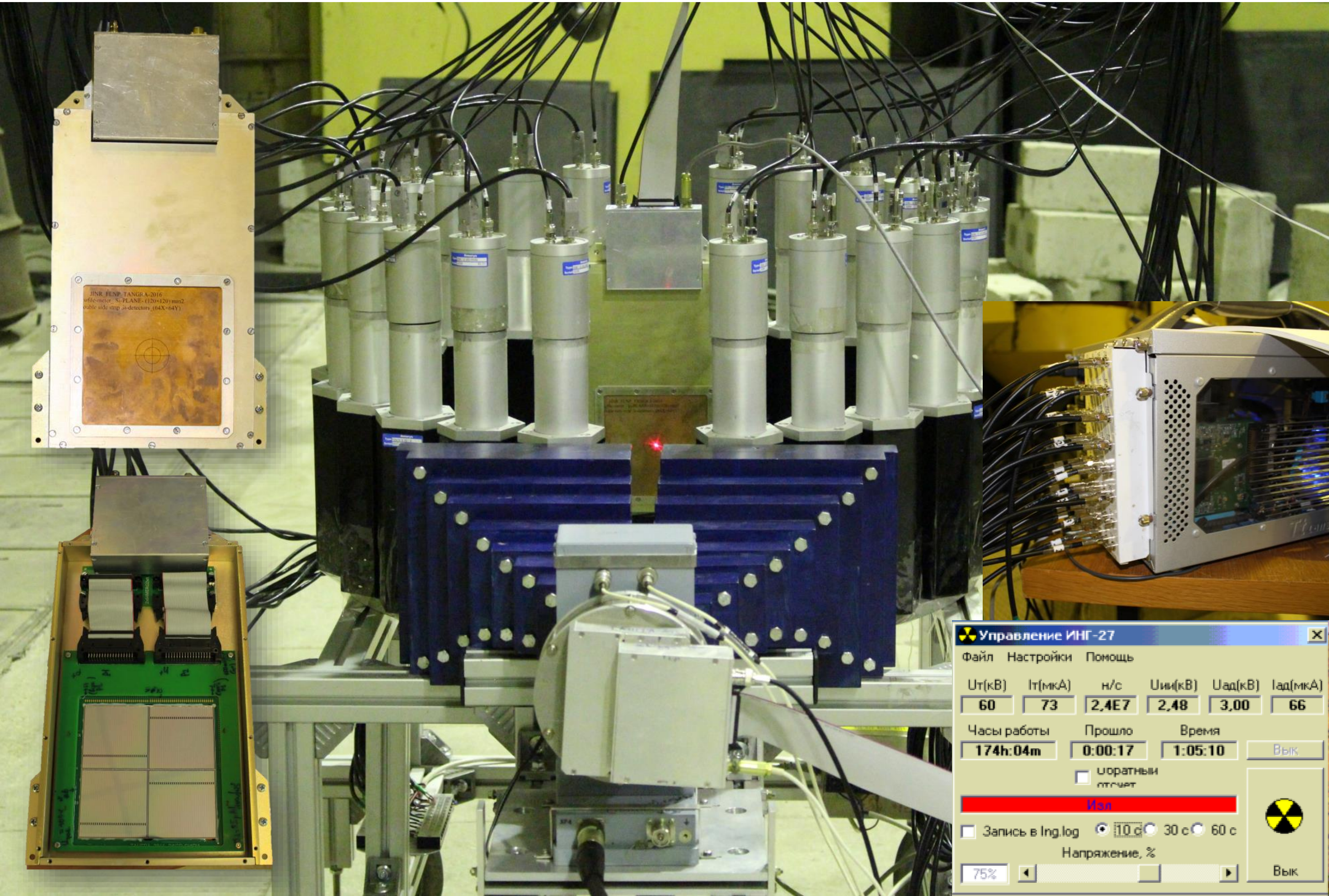
Weight: ING-27: 7.5 ± 0.5 kg ; Power Supply and Operation Unit: 2.7 ± 0.3 kg

FLNP

γ GAMMA-1,2



TANGRA-Setup: ING-27 + “Romashka” NaI(Tl)



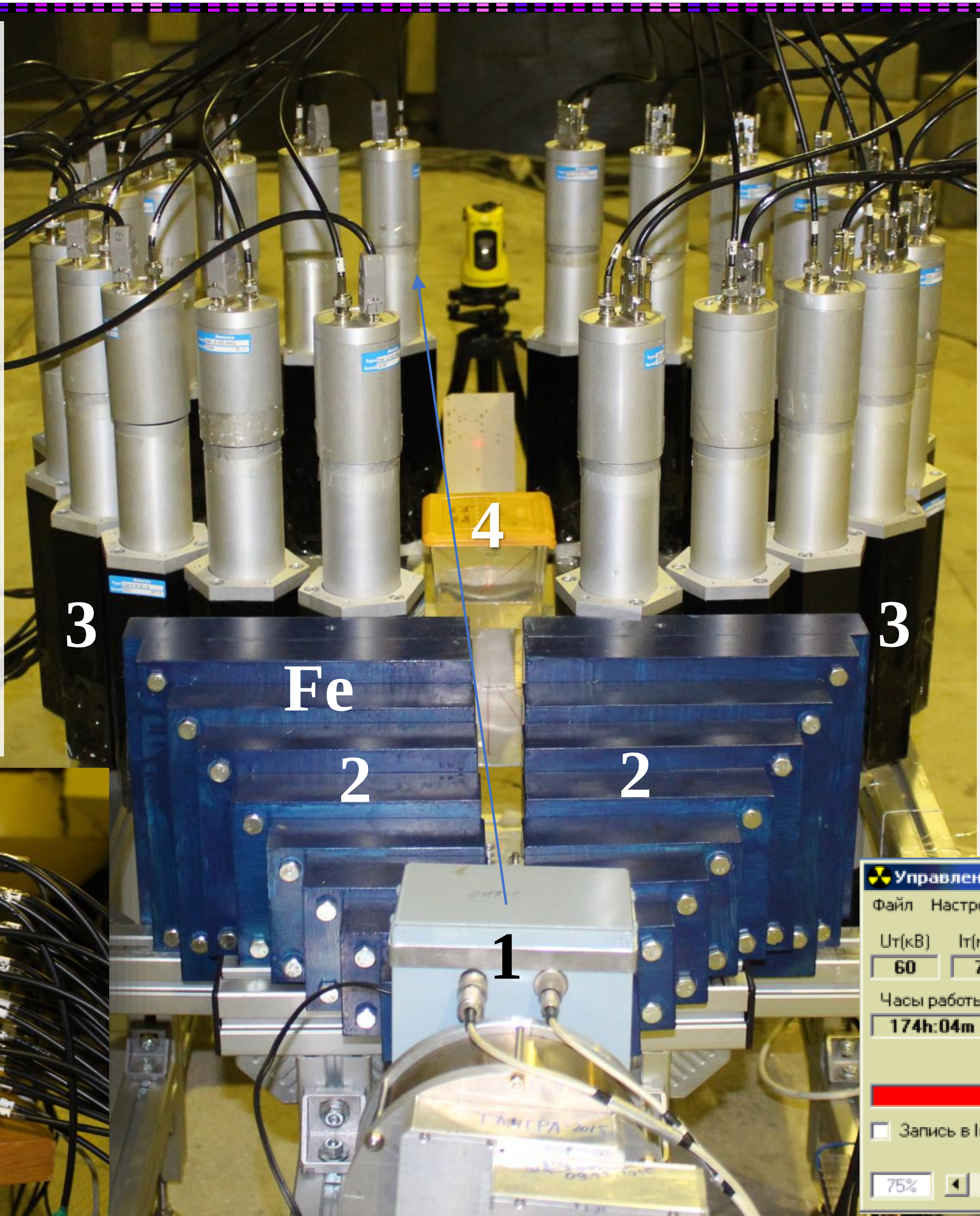
TANGRA-Setup: ING-27 + “Romashka” NaI(Tl)

32-channel digitizer, in the form of 2 PCI-E cards.

Sampling frequency: 100 MHz

The digitized signals are transmitted via the PCI-E bus in the computer's memory, where all the data processing and storage takes place.

Maximum load of the system is ~ 10^5 events per second

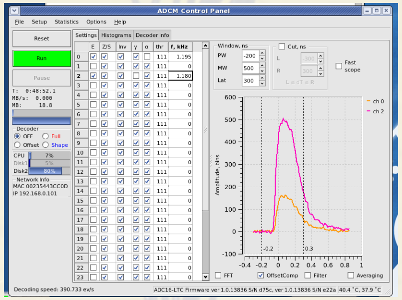


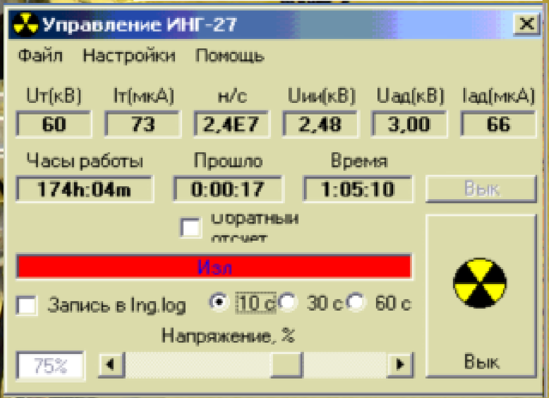
Number of NaI(Tl) detectors: 22

NaI(Tl) crystals: hexagonal prism (78 x 90 x 200 mm)

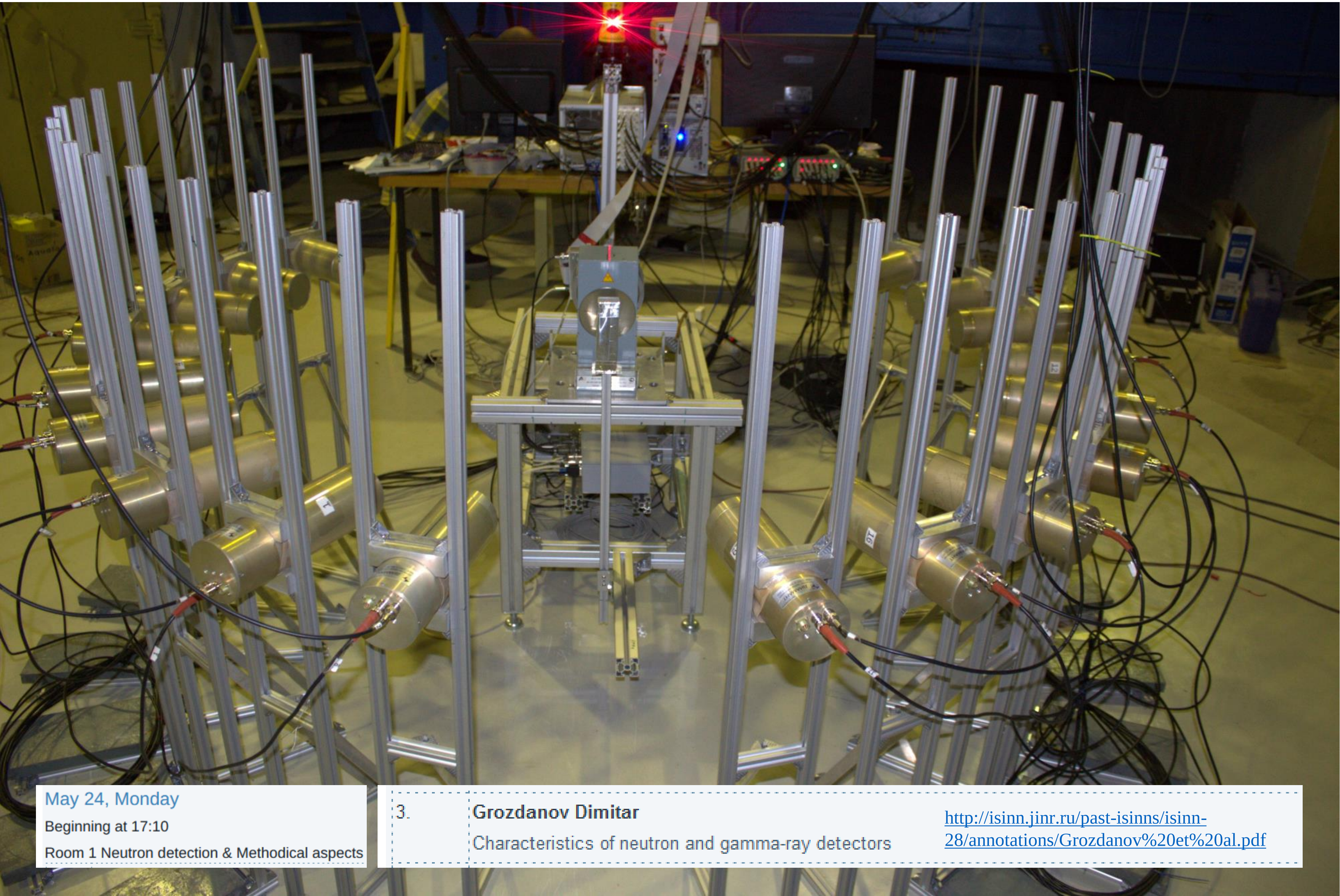
PMT type: Hamamatsu R1306

ΔE ~7.2% @ 0.662 MeV
ΔE ~3.6% @ 4.437 MeV
Δt ~3.8ns @ 4.437 MeV





TANGRA-Setup: ING-27 + “Romasha” BGO



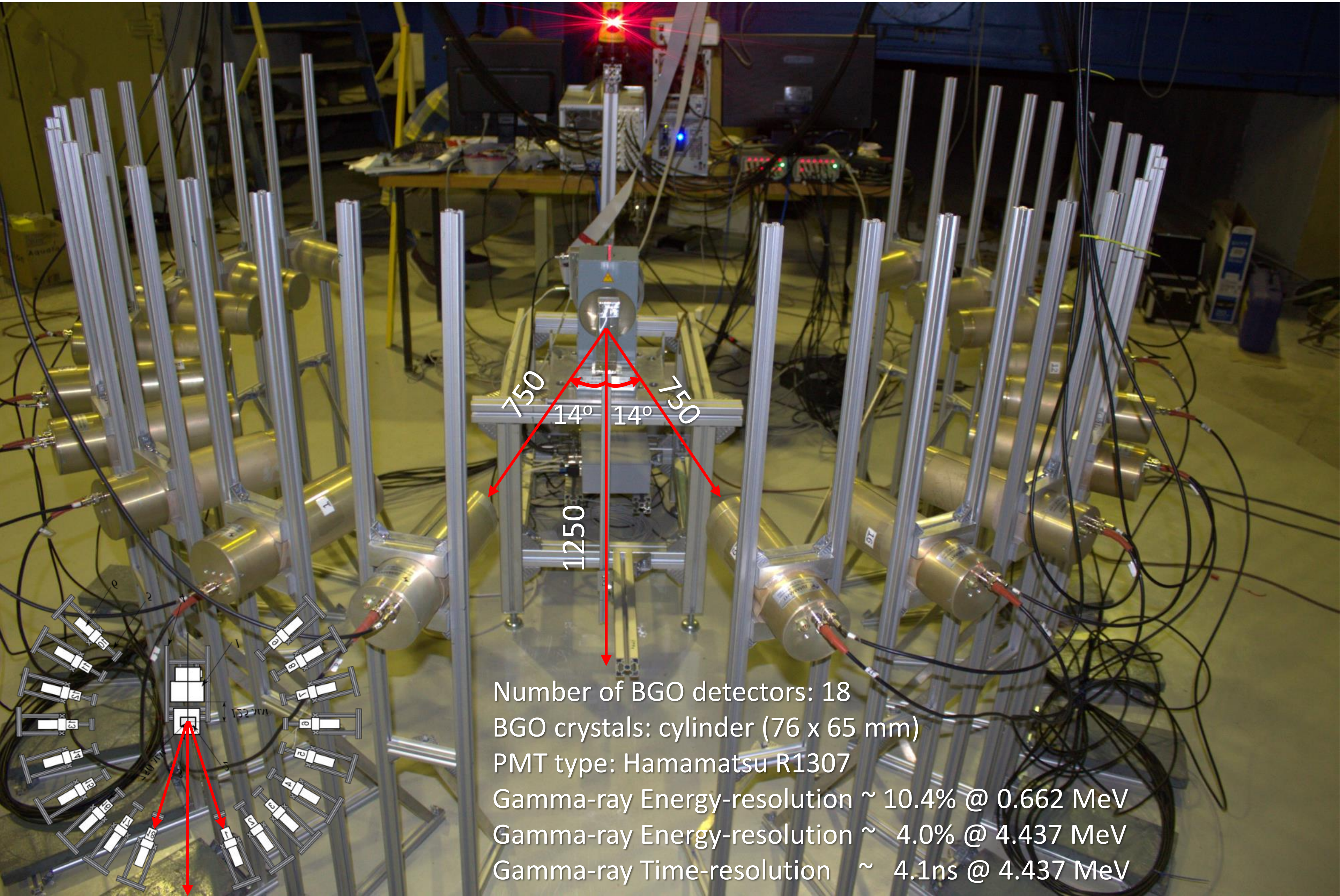
May 24, Monday

Beginning at 17:10

Room 1 Neutron detection & Methodical aspects

3.	**Grozdanov Dimitar** Characteristics of neutron and gamma-ray detectors	http://isinn.jinr.ru/past-isinns/isinn-28/annotations/Grozdanov%20et%20al.pdf

TANGRA-Setup: ING-27 + “Romasha” BGO

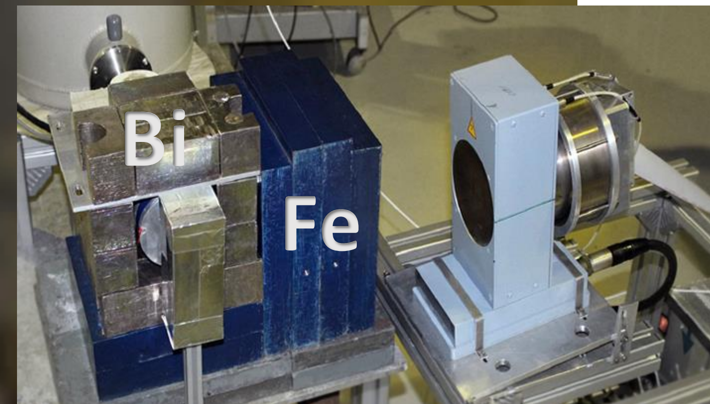


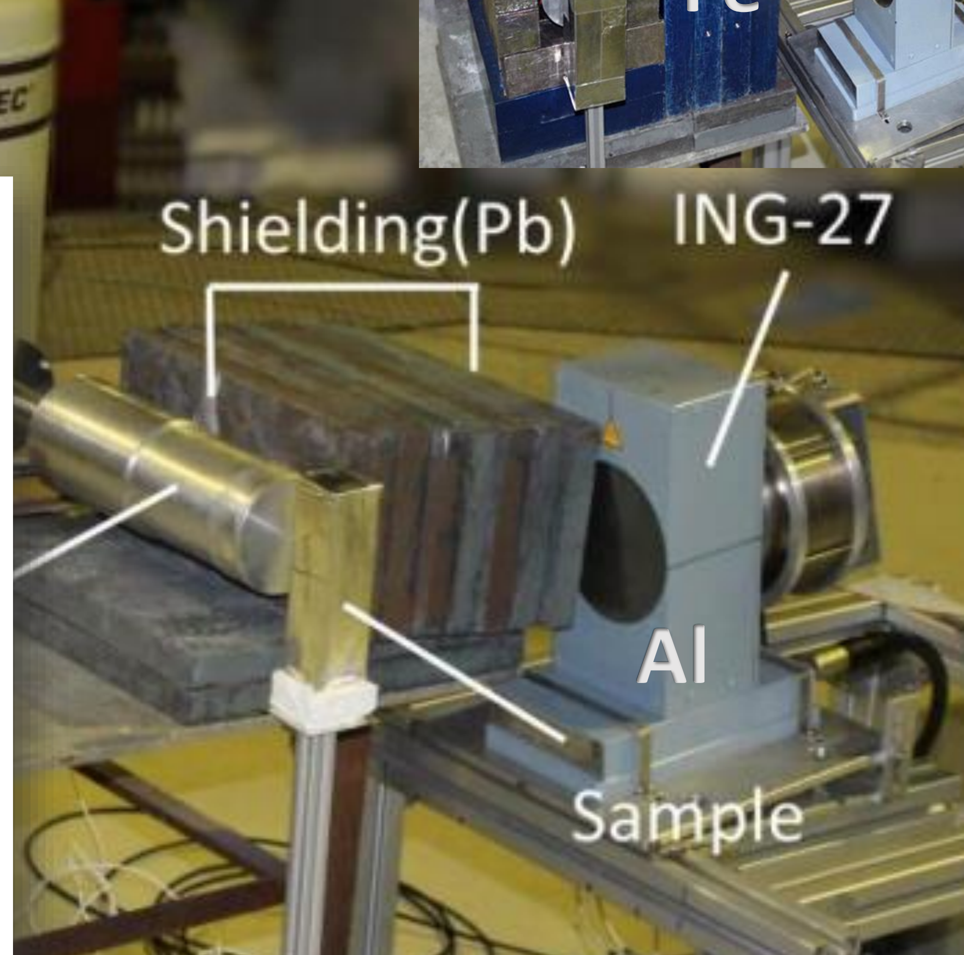
Number of BGO detectors: 18
BGO crystals: cylinder (76 x 65 mm)
PMT type: Hamamatsu R1307
Gamma-ray Energy-resolution ~ 10.4% @ 0.662 MeV
Gamma-ray Energy-resolution ~ 4.0% @ 4.437 MeV
Gamma-ray Time-resolution ~ 4.1ns @ 4.437 MeV

TANGRA-Setup: ING-27 + HPGe

http://flnph.jinr.ru/en/facilities/tangra-project

HPGe detector:
Type: Ortec®GMX 30-83-PL-S, ϕ 57.5 x 66.6 mm
Gamma-ray Energy-resolution ~ 3.4% @ 0.662 MeV
Gamma-ray Energy-resolution ~ 0.3% @ 4.437 MeV
Gamma-ray Time-resolution ~ 6.1 ns @ 4.4437MeV





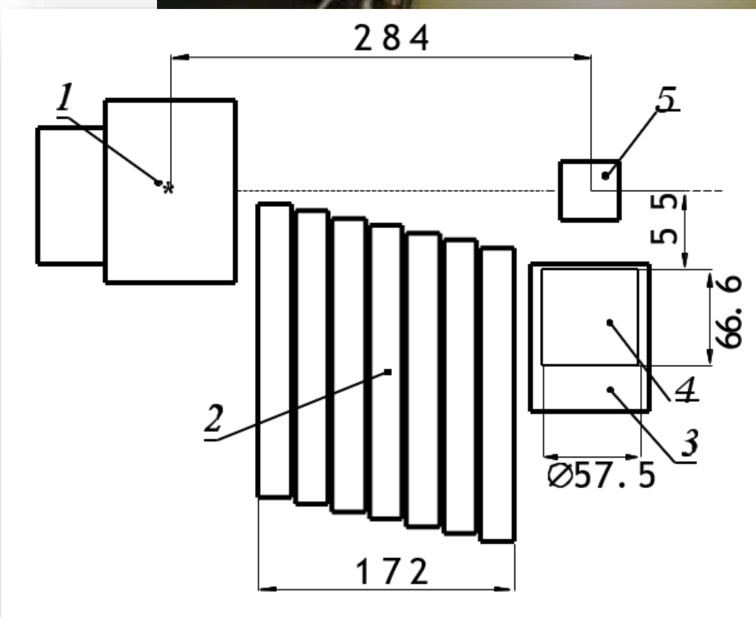


Fig. 2. Scheme of the TANGRA setup with the HPGe detector in the reaction plane: 1 – neutron generator ING-27, 2 – lead shielding, 3 – case of the HPGe detector, 4 – HPGe crystal, 5 – sample. Axis of the experimental setup is indicated by horizontal dashed line. Tritium-enriched target is marked as asterisk. All dimensions are in mm.

ADCM-16

May 25, Tuesday Neutron detection & Methodical aspects

28.	15:50 – 16:10	**Kopatch Yuri** Digitizers DSR (Digital Signal Recorder) and their application for nuclear physics research	20 min

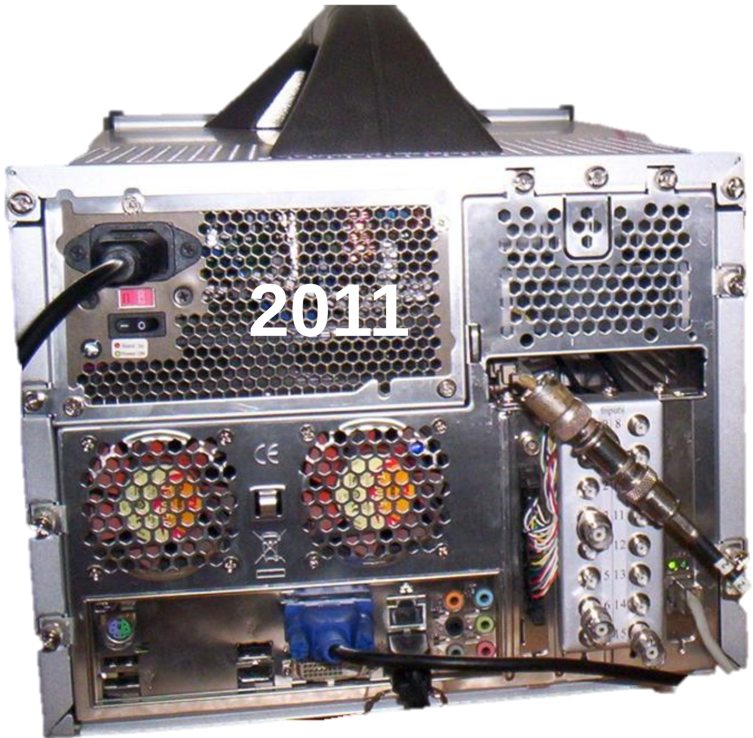
16/32/48-channel digitizers, in the form of one or several PCI-E cards.

Sampling frequency 100 MHz

The digitized signals are transmitted via the PCI-E bus in the computer's memory, where all the data processing and storage takes place.

Maximum load of the system is ~ 10^5 events per second

TANGRA: Multichannel DAQ Electronic Systems



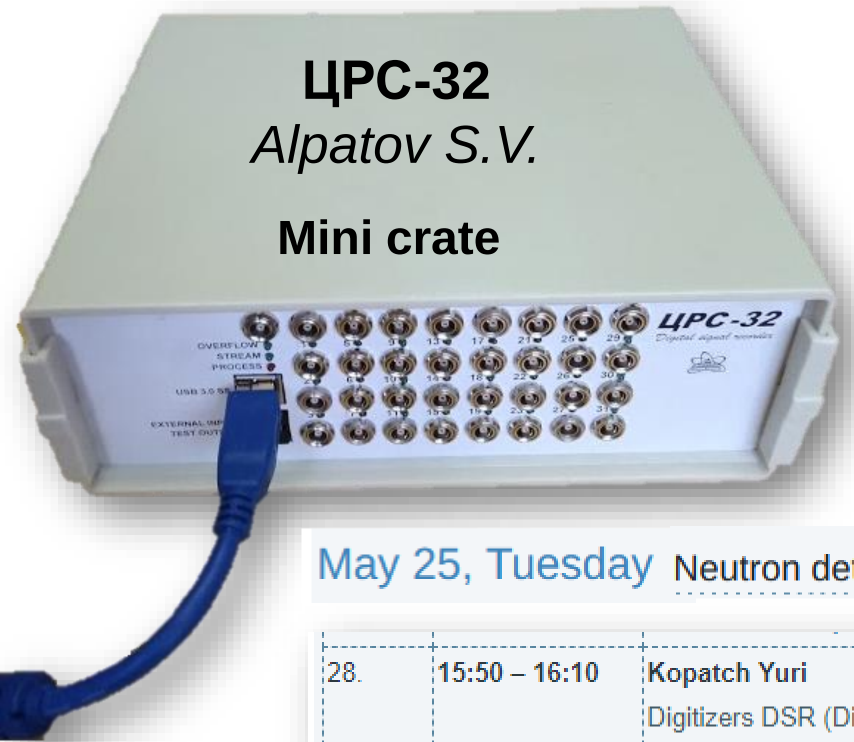
16/32/48/64-channel 14 bit digitizers,
in the form of one or several PCI-E cards.

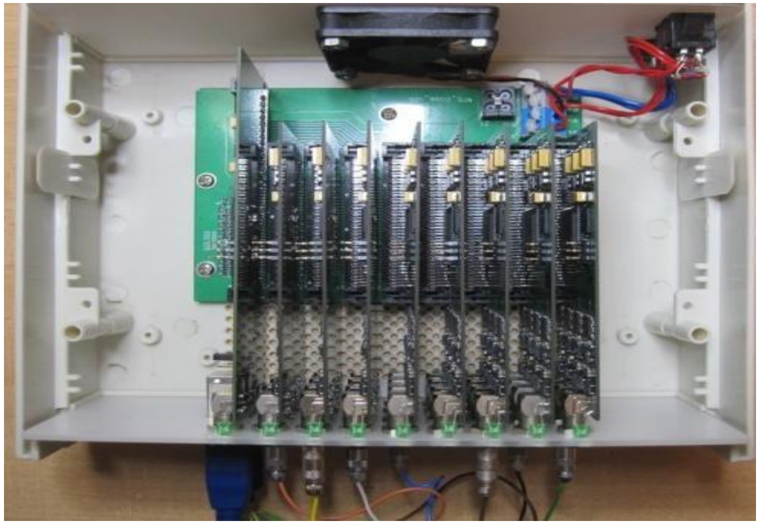
Sampling frequency 100 MHz

The digitized signals are transmitted via the PCI-E bus in the computer's memory, where all the data processing and storage takes place.

Maximum load ~ 10^5 events/second/channel

32-channel Digital Signal Recorder DSR-32





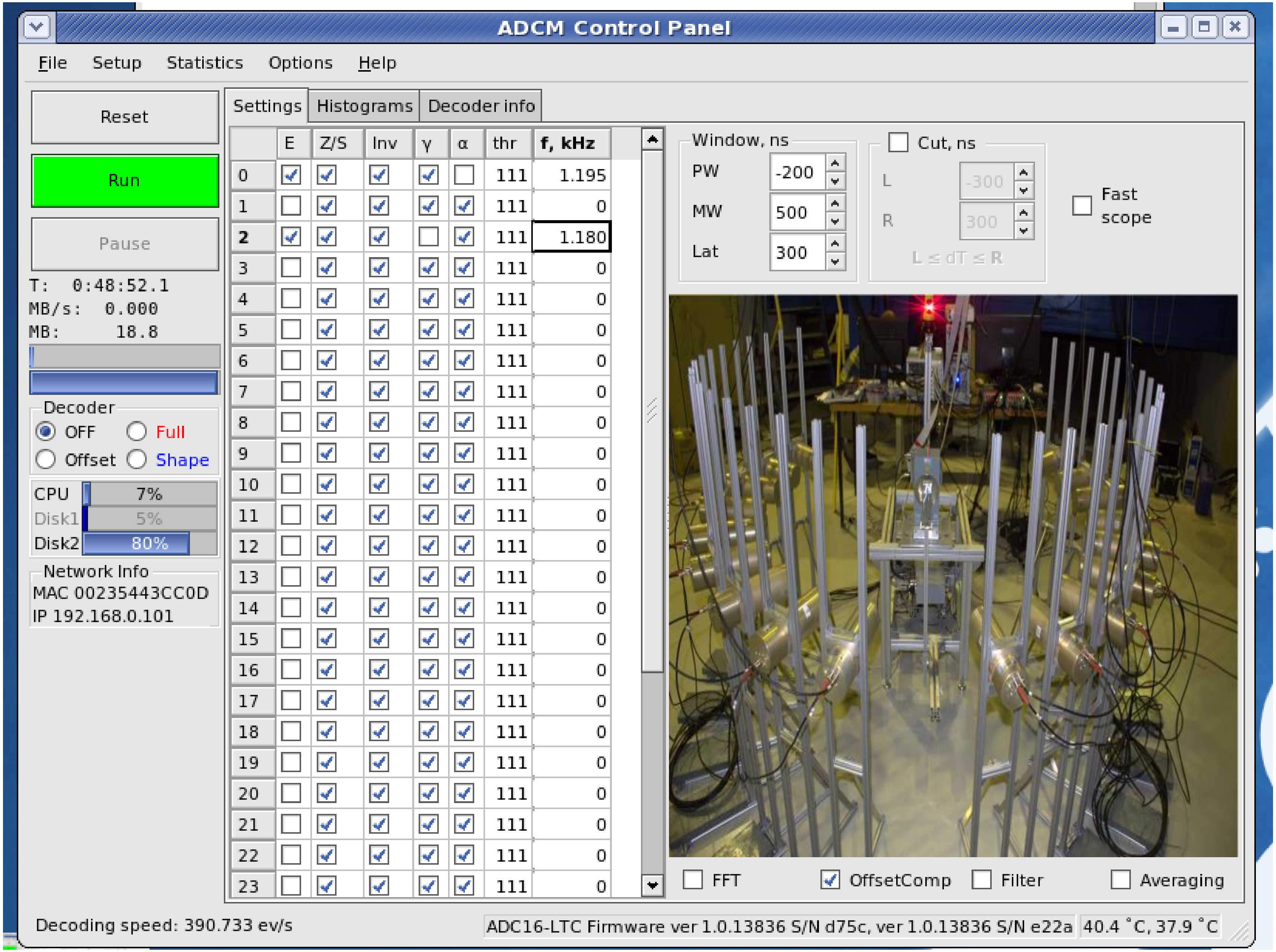
2020-2021

May 25, Tuesday Neutron detection & Methodical aspects

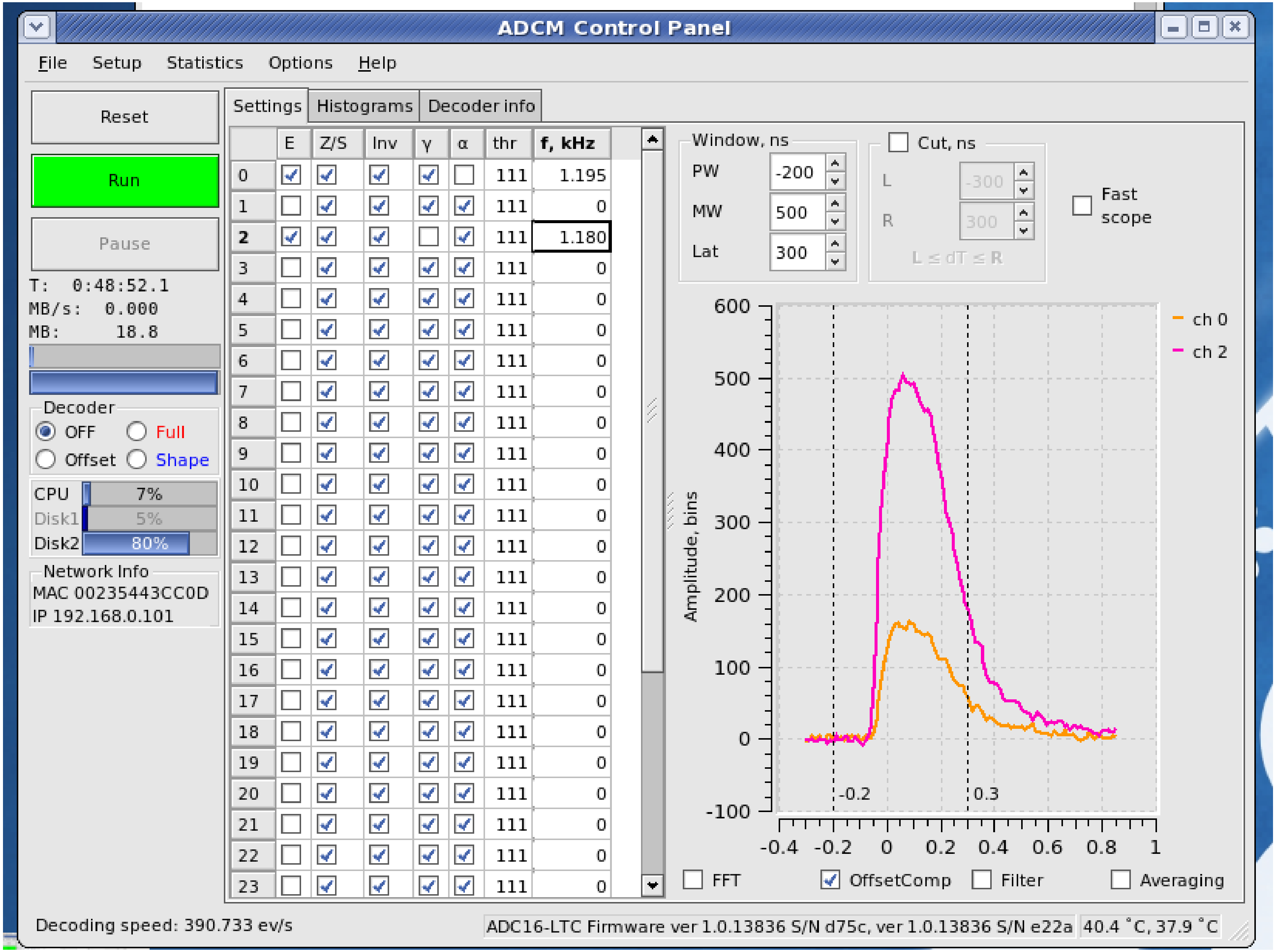
28.	15:50 – 16:10	Kopatch Yuri http://isinn.jinr.ru/past-isinns/isinn-28/annotations/kopatch.pdf Digitizers DSR (Digital Signal Recorder) and their application for nuclear physics research	20 min

- **200 MHz sampling, 11 bit**
- **USB-3 connection**
- **~10^5 event/sec for each input channel**
- **can work with HPGe detectors**

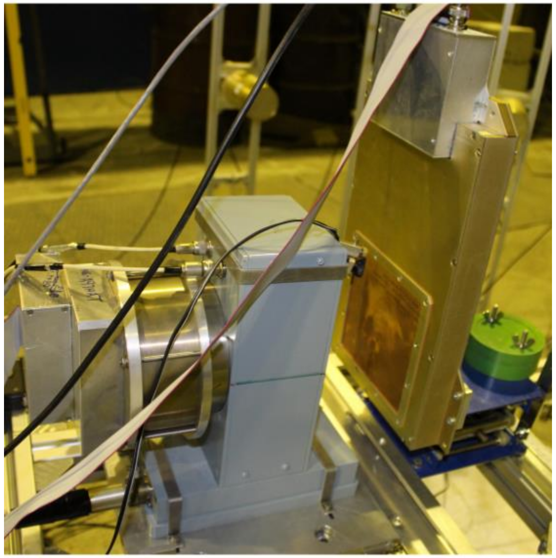
TANGRA: ADCM Operation Control Panel



TANGRA: ADCM Operation Control Panel

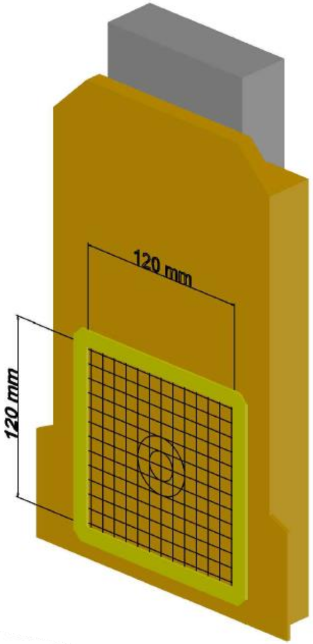


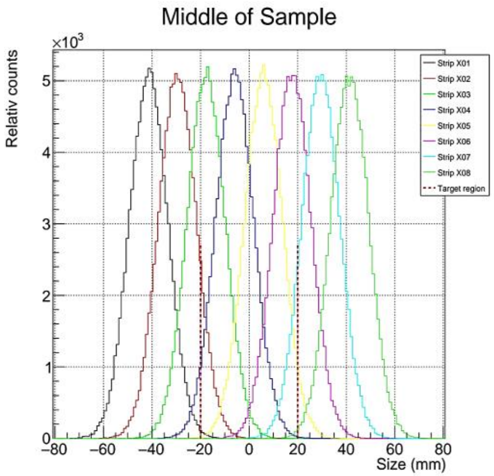
Construction of a silicon two-dimensional position-sensitive fast neutron detector for beam profile measurement

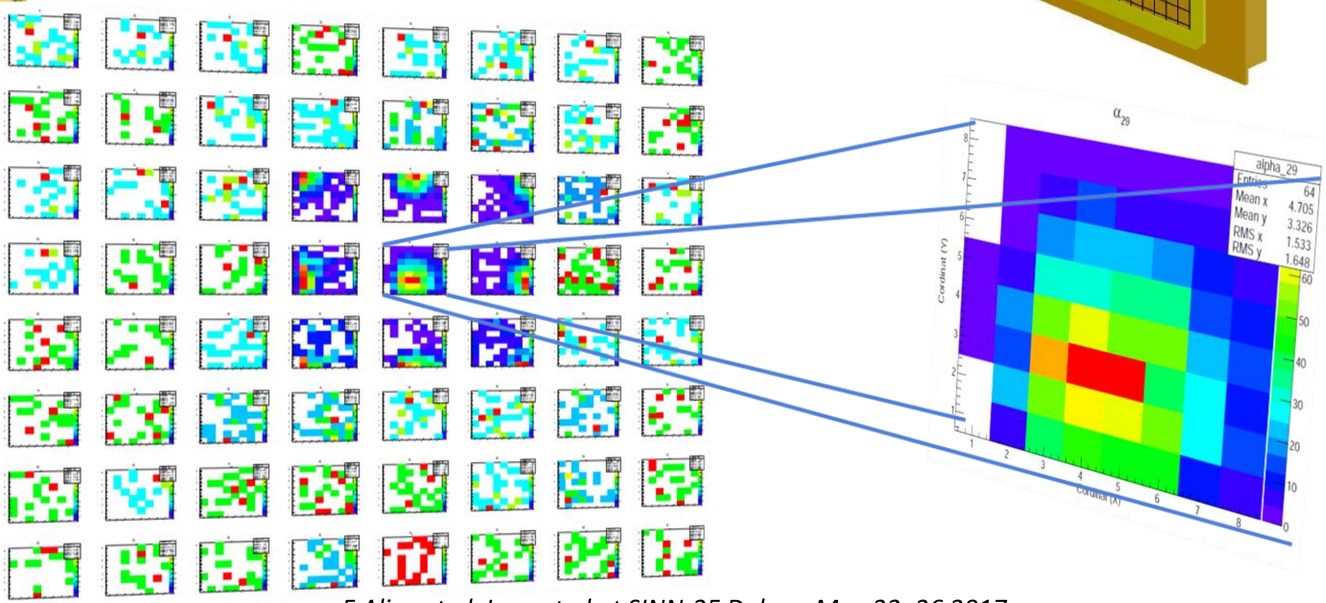


2D-detector, made of 4 double-sided stripped position-sensitive Si-detectors

Each Si detector consists of 32x32 strips ~1.8 mm thick
Size of one detector: 60x60mmm
Total size: 120x120 mm
Thickness: 300 mkm
Neutron detection efficiency: ~0.8%
At this stage each 8 strips are grouped together forming a matrix 8x8 with a pixel size of ~1.5x1.5 cm

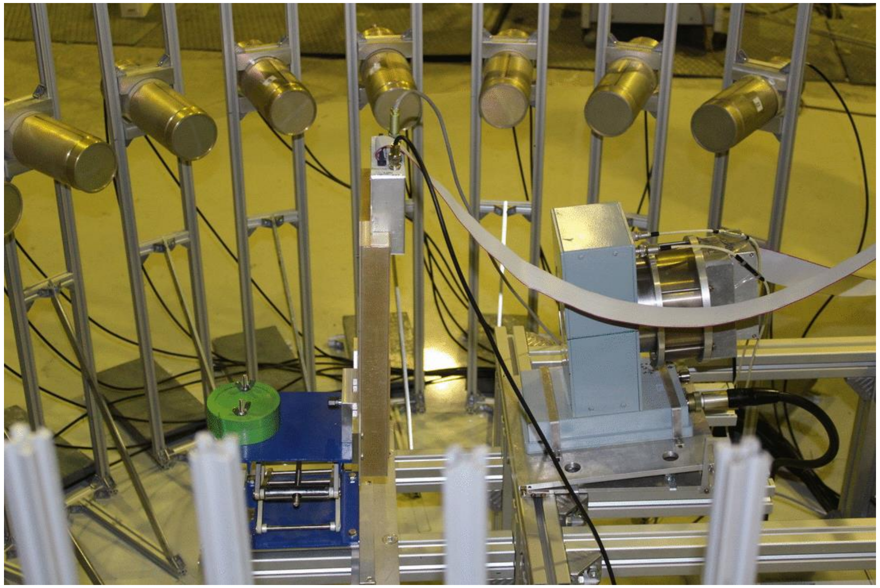


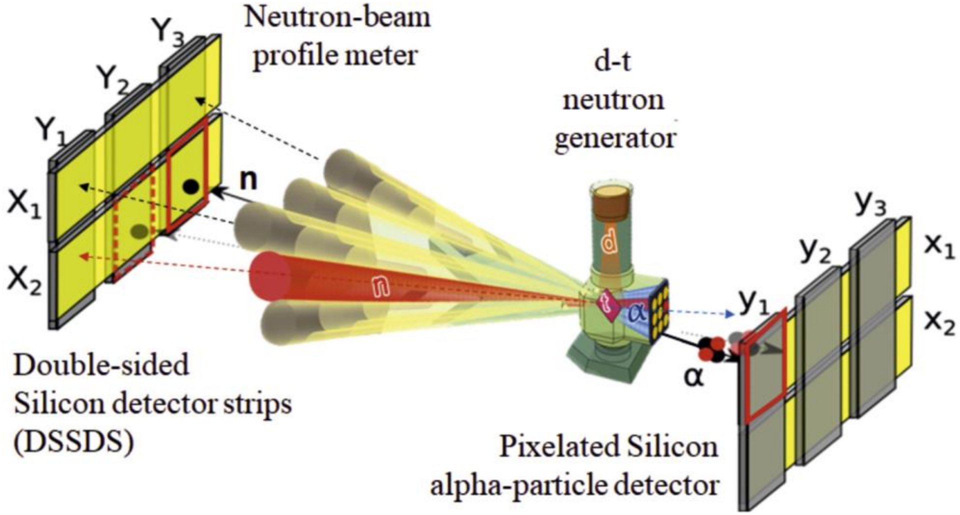


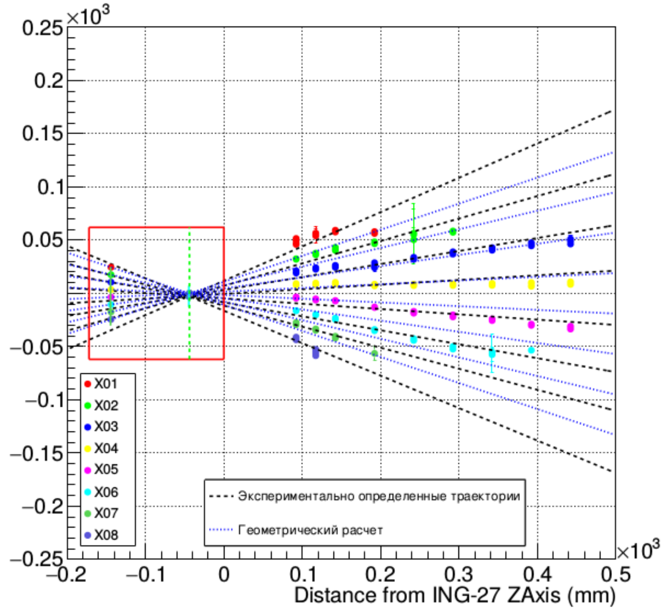


F.Aliev et al, Ireported at SINN-25 Dubna, May 22–26 2017

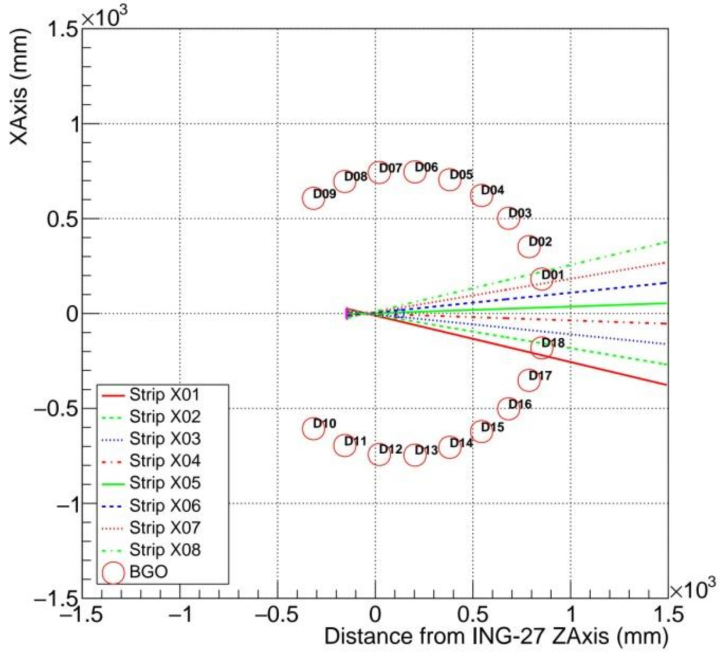
Measurements of tagged neutron beams profiles



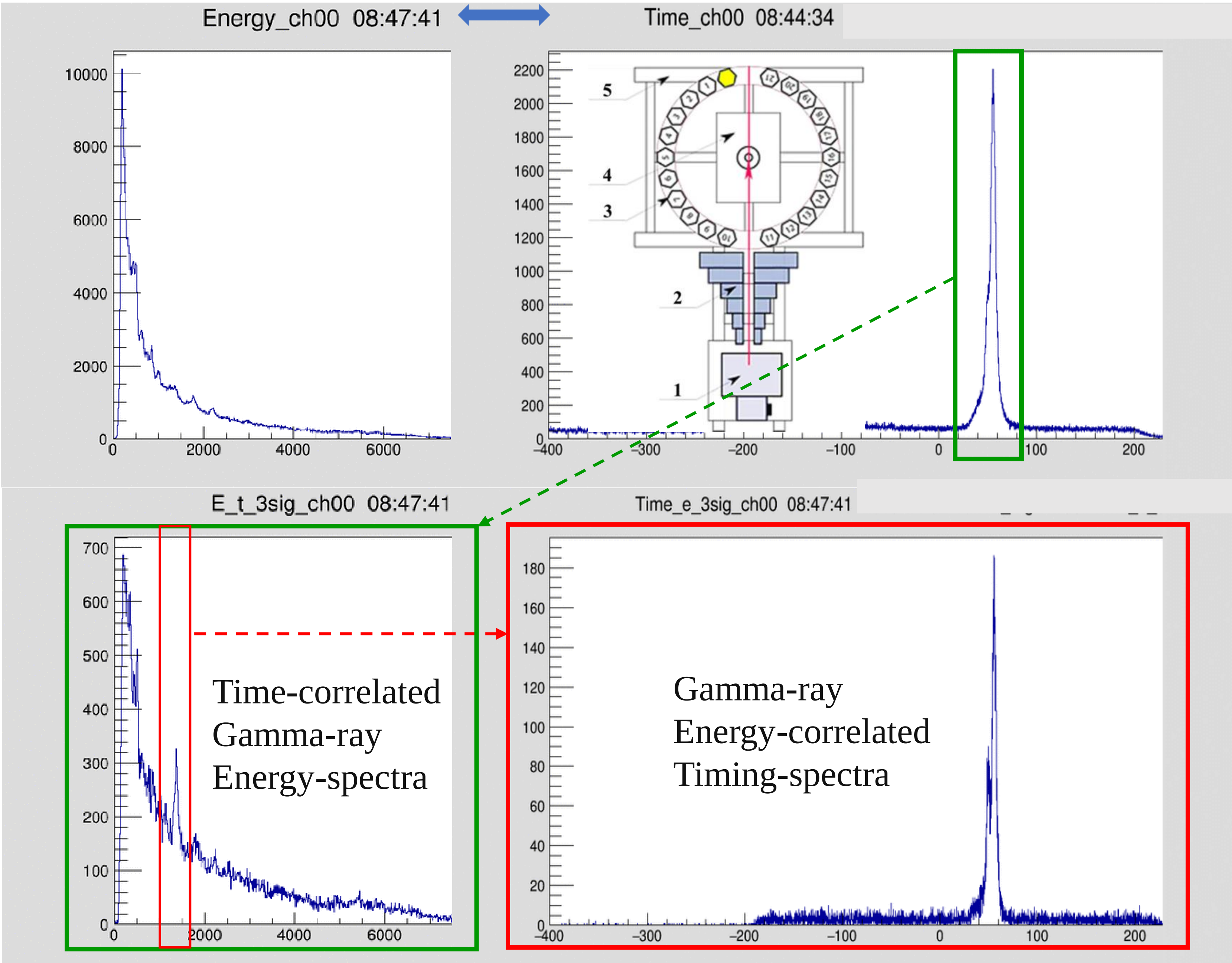




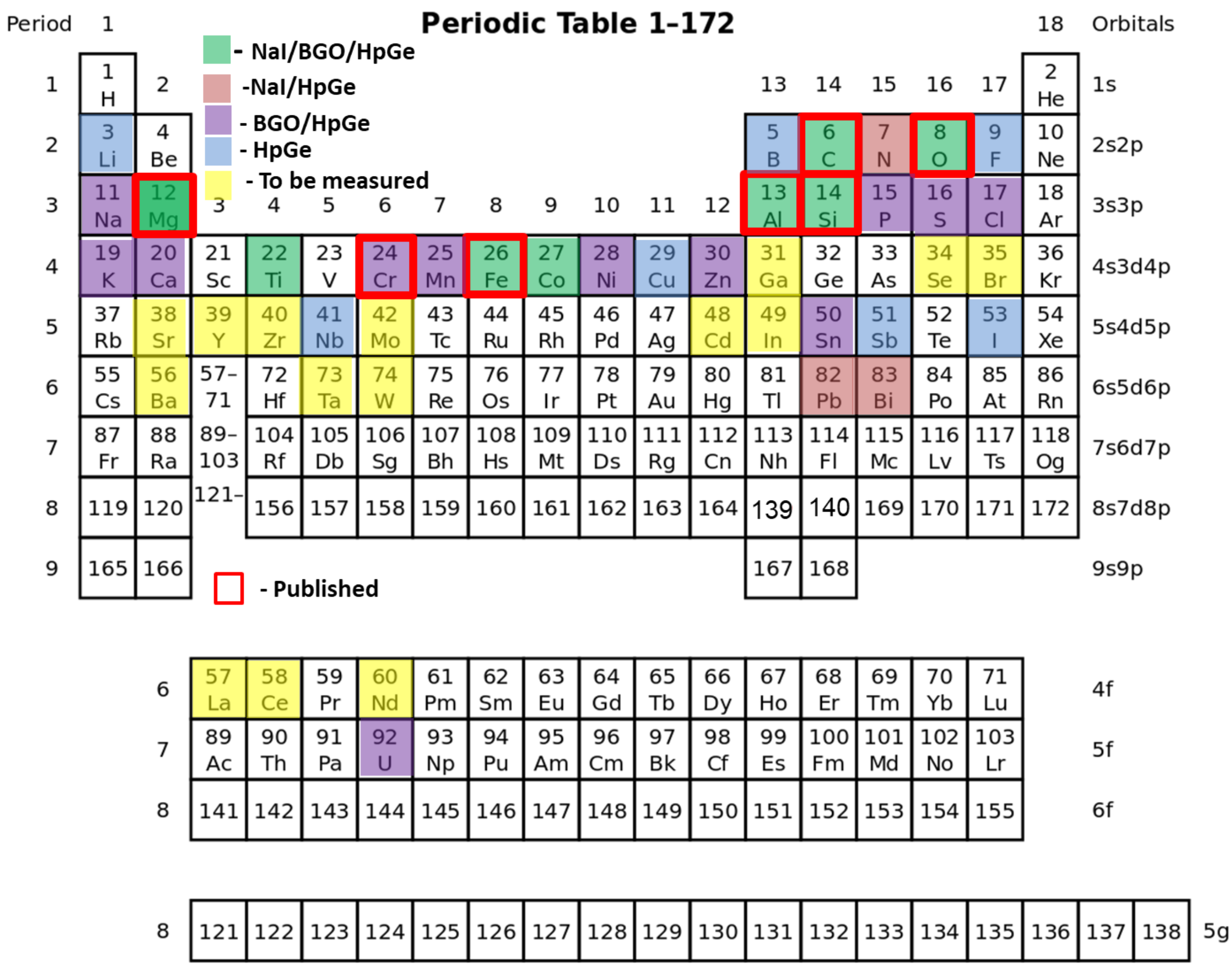
Top view



TANGRA: Analysis of the Experimental Data



Elements important for Nuclear Science



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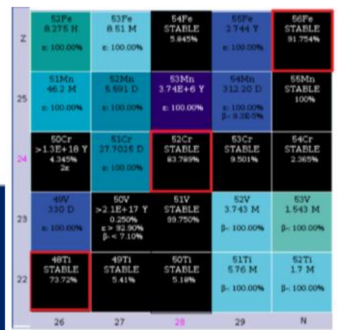
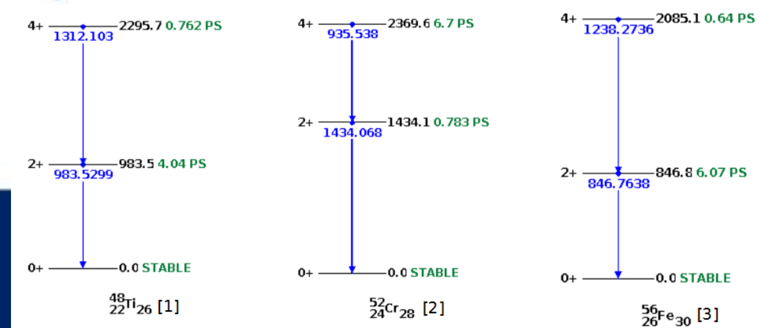
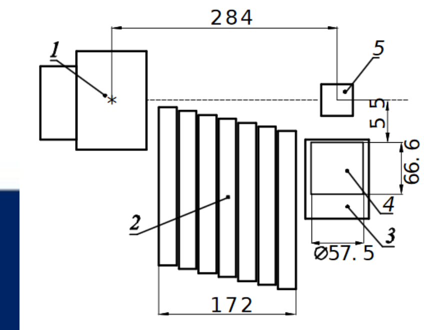
For a model description of the TANGRA experimental data, the sensitivity of the TALYS 1.9 calculations to model variations and their correspondence with the estimates from the nuclear database were checked.

Simulation of 14 MeV neutron scattering on titanium, chromium and iron nuclei







I.D. Dashkov on behalf of TANGRA collaboration

https://indico.cern.ch/event/839985/contributions/3985226/

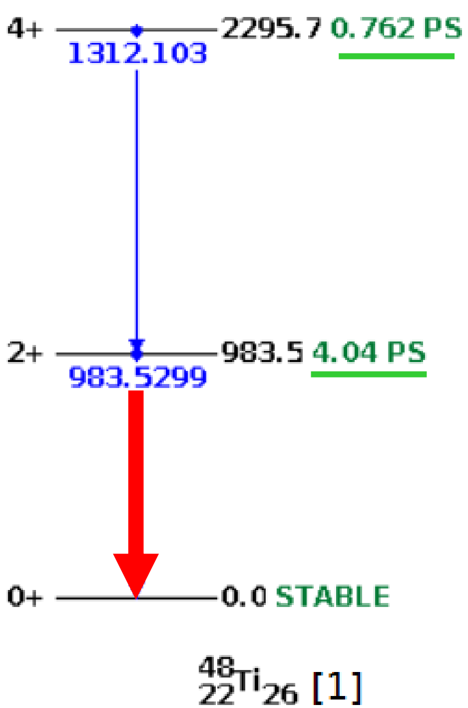
https://indico.cern.ch/event/839985/contributions/3985226/attachments/2120422/3573801/Dashkov_poster.pdf

15.10.2020

Leading candidates to establish a recognized γ-ray reference cross sections for neutron-induced reactions

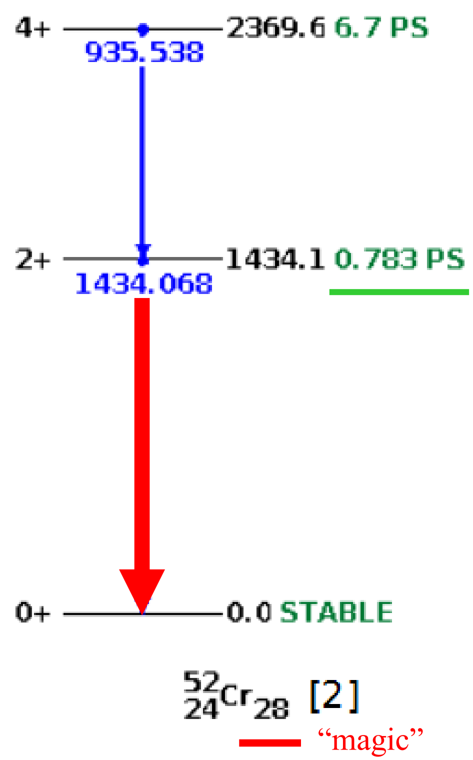
^{48}Ti(n, n′γ)

J$^{\pi}$ Eγ (keV) E* (keV) τ



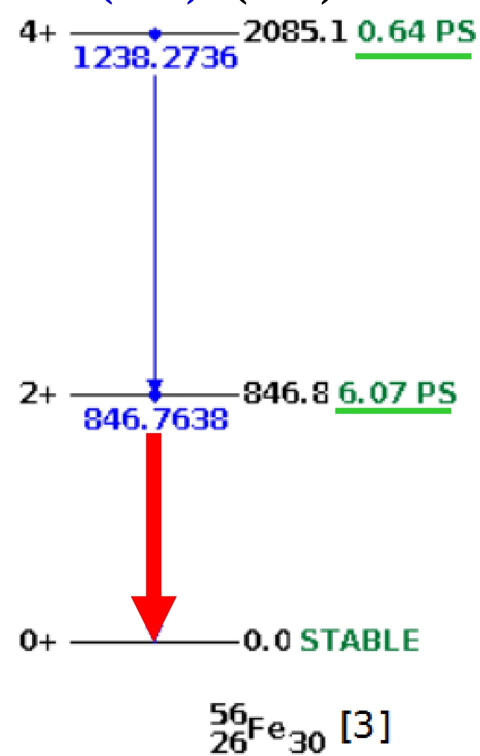
^{52}Cr(n, n′γ)

J$^{\pi}$ Eγ (keV) E* (keV) τ



^{56}Fe(n, n′γ)

J$^{\pi}$ Eγ (keV) E* (keV) τ



1. T. W. Burrows, Nucl. Data Sheets 107, 1747 (2006).

2. Yang Dong, Huo Junde Nucl. Data Sheets 128, 185 (2015).

3. Huo Junde, Huo Su, Yang Dong Citation: Nucl. Data Sheets 112, 1513 (2011).

Conclusions

- New experimental results for γ-yields on ^{48}Ti, ^{52}Cr ^{56}Fe were obtained on the TANGRA facility with the TNM for 14.1 MeV neutron induced reactions. The results were in good agreement with other experimental data, except ones for several γ-lines.
- Nuclear reaction code TALYS 1.9 was used for checking up the calculation sensitivity to changes in model approach. Calculations for DWBA model, CC model in rotational and vibrational approaches were performed for same deformation and optical model parameters.
- DWBA model was considered the most appropriate for ^{48}Ti ^{52}Cr, CC with vibrational level excitation was chosen for ^{56}Fe.
- TALYS 1.9 calculated γ-yields were in good agreement with our experimental data. Calculation results for considered approaches showed no signifiant difference for γ-yields, but varied for integral and differential cross sections.

DWBA-distorted wave Born approximation; CC – Coupled-Channel

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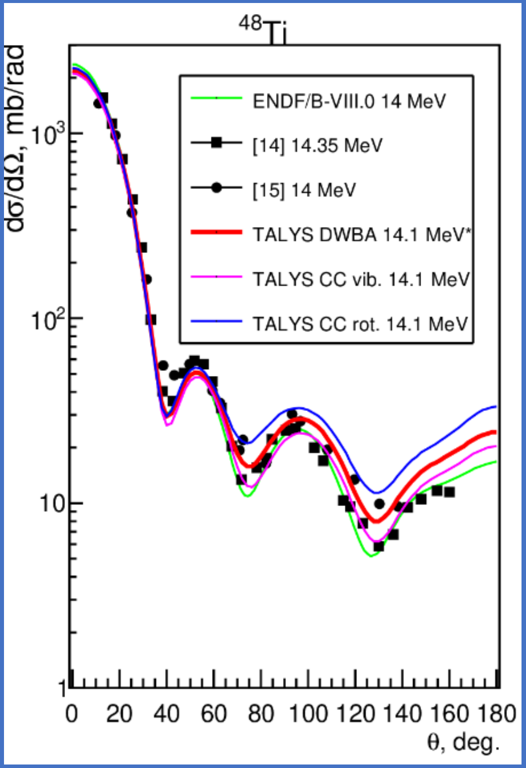
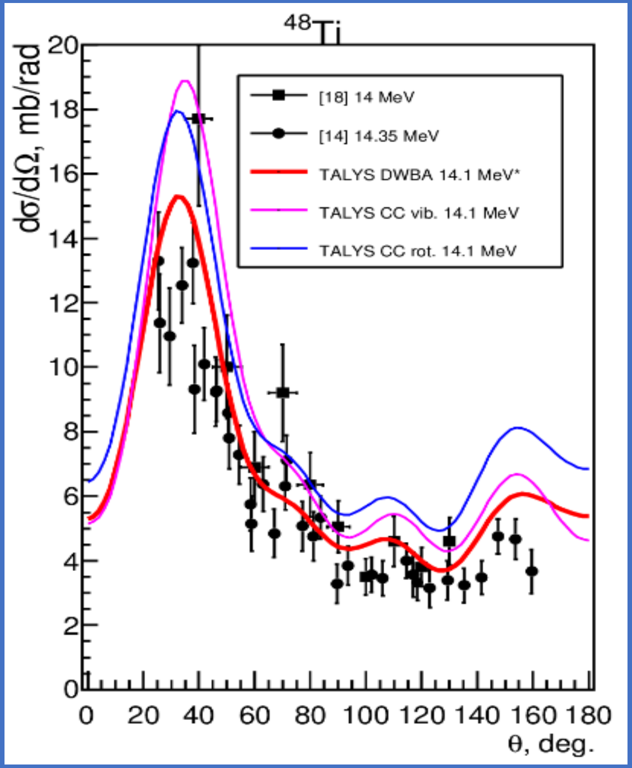
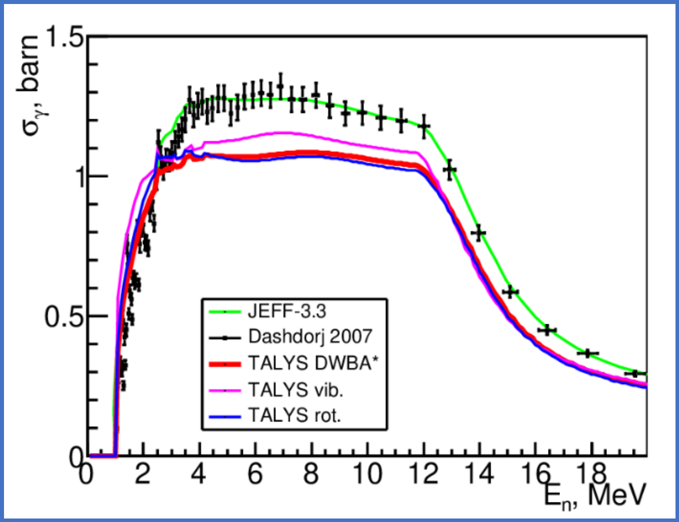
Angular distribution of elastically scattered neutrons



Angular distribution of inelastically scattered neutrons (to the 2^+_1 state)



$2^+_1 \rightarrow 0^+_{g.s.}$ γ-transition cross-section as function of E_n



Dashdorj, et al. Nuclear Science and Engineering 157, 65 (2007)
14. Schmidt D., et al. CM-P00061940, report PTB-N-50 (2006)
15. Pierre C. S., et al. Phy. Rev. 115, Issue. 4., p.999 (1959).
18. Leshchenko B.E., et al. Yadernaya Fizika, Vol.15, Issue.1, p.10 (1972).

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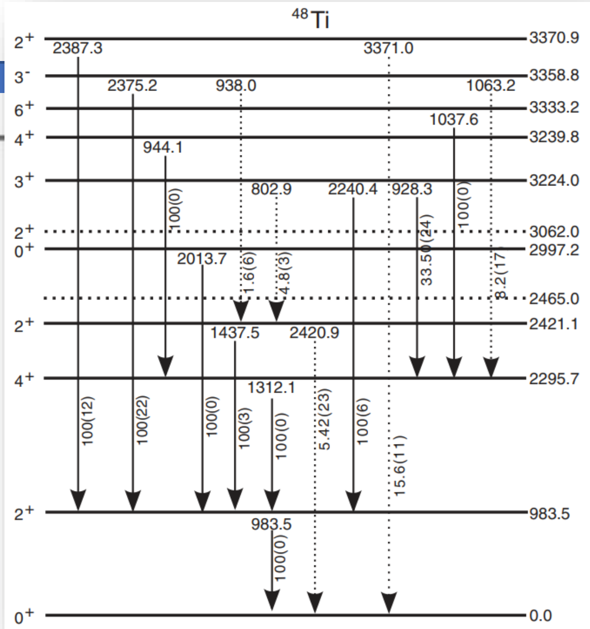
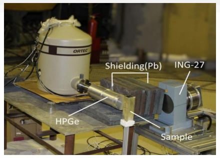


γ-transition yields in (n,n') reaction on ^{48}Ti

Eγ, keV	$J^P_i \rightarrow J^P_f$	TANGRA			[21]			[12]			TALYS 1.9 14.1 MeV
		14.1 MeV			14.5 MeV			13.96 MeV			DWBA*
423.6	$4_1^- \rightarrow 3_1^-$	4.9	±	0.4				4.1	±	0.2	1.8
944.1	$4_2^+ \rightarrow 4_1^+$	7.5	±	0.2	7.1	±	0.9	7.6	±	0.3	4.6
983.5	$2_1^+ \rightarrow 0_{g.s.}^+$	100.0	±	0.5	100.0	±	9.2	100.0	±	3.4	100.0
1037.5	$6_1^+ \rightarrow 4_1^+$	10.8	±	0.3				0.9	±	0.1	9.6
1312.1	$4_1^+ \rightarrow 2_1^+$	40.0	±	0.4	35.7	±	4.1	42.6	±	1.5	41.0
1437.5	$2_2^+ \rightarrow 2_1^+$	7.5	±	0.2	7.4	±	1.1	6.0	±	0.2	4.8
1750.3	$5_1^- \rightarrow 4_1^+$	3.2	±	0.2	3.5	±	2.0	4.0	±	0.2	2.3
2240.4	$3_1^+ \rightarrow 2_1^+$	2.9	±	0.4	4.8	±	0.8	2.8	±	0.2	2.7
2387.3	$2_4^+ \rightarrow 2_1^+$	2.0	±	0.2				2.2	±	0.1	1.1



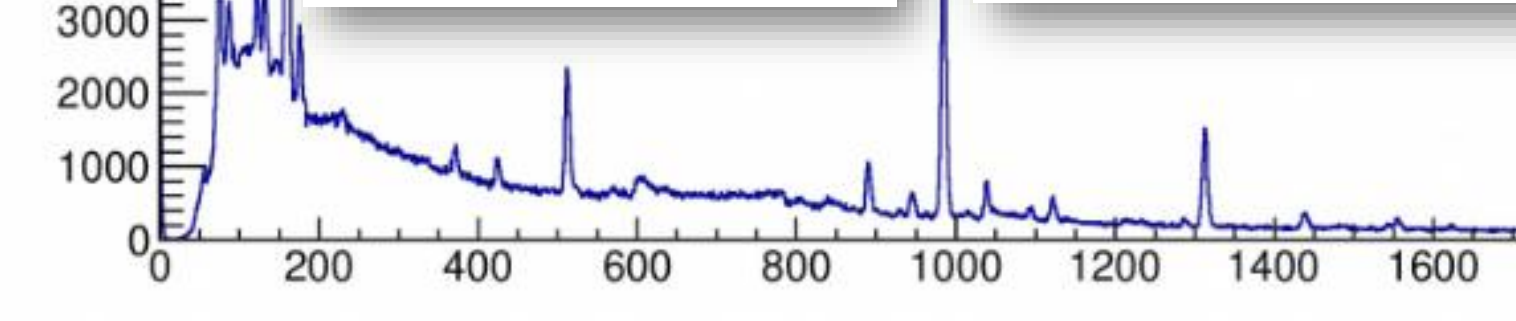


Fig. 5. Gamma-spectrum obtained by irradiating a Ti sample with 14.1 MeV neutrons.

Gamma-ray energy spectra from $^{nat}Ti(n, n'\gamma)$

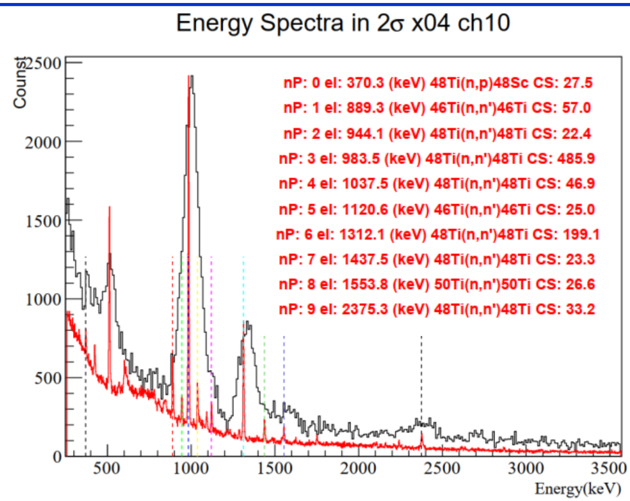
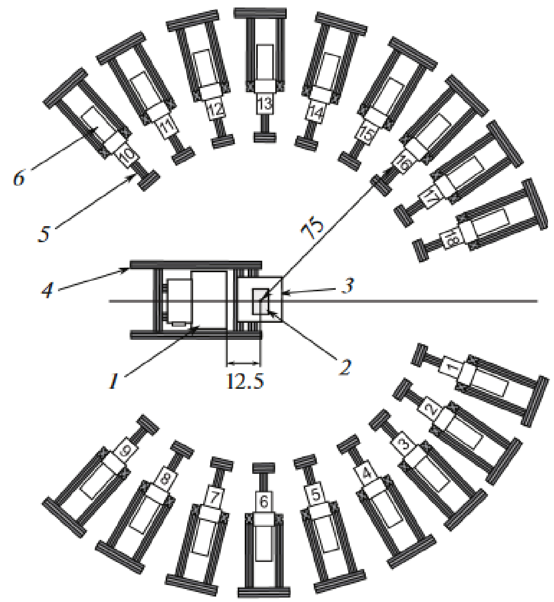


Fig. 1



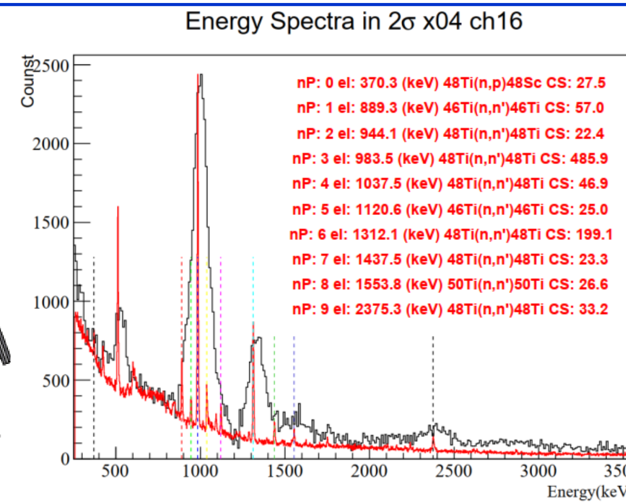
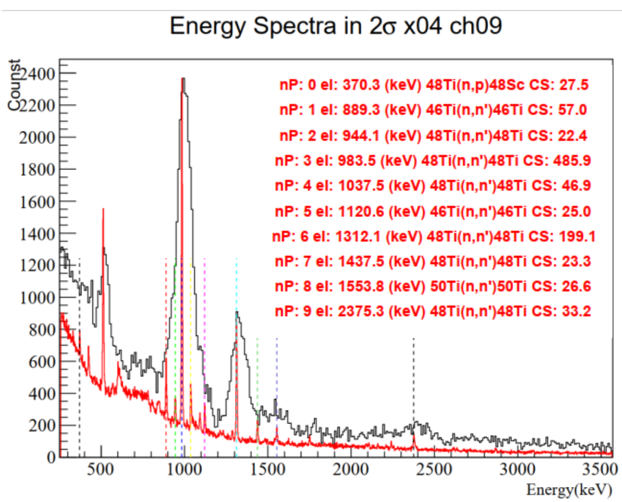


Fig. 1. Layout of the Romasha spectrometer: (*1*) ING-27 neutron generator, (*2*) target, (*3*) target bearer, (*4*) aluminum frame of the setup, (*5*) support for gamma detectors, and (*6*) gamma detectors numbered from 1 to 18. The distances are measured in centimeters.

Fig. 2. Layout of the experimental setup involving a detector of the HPGe type: (*1*) ING-27 neutron generator, (*2*) lead shield, (*3*) HPGe gamma detector, and (*4*) sample. The distances are measured in centimeters.



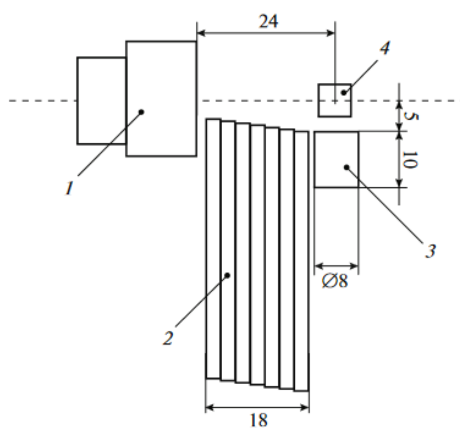
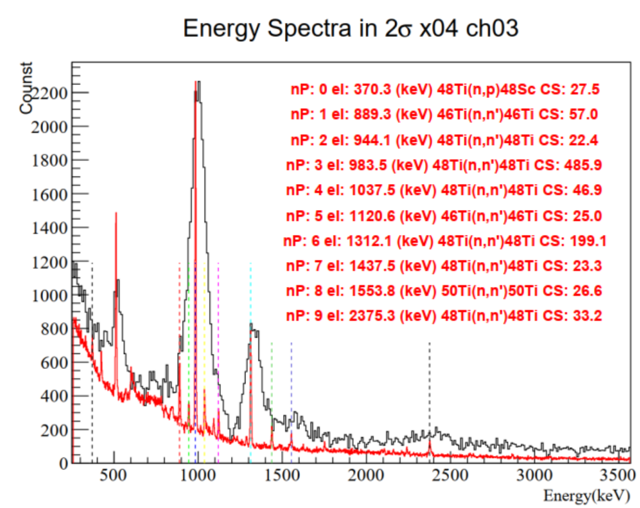


Fig. 2



n-induced reaction gamma-ray yield

E_γ, кэВ	Reaction	$J^P{}_i \to J^P{}_f$	Y_γ, %			
			TANGRA	[27]	[17]	TALYS 1.9 (DWBA)
			14.1 МэВ	14.5 МэВ	14.0±0.5 МэВ	14.1 МэВ
121.4	^{48}Ti(n,p)^{48}Sc	$4_1^+ \to 6_1^+$	4.5±0.2		5.8±0.3	11.9
130.9	^{48}Ti(n,p)^{48}Sc	$5_1^+ \to 6_1^+$	5.8±0.2		7±0.3	14.0
159.4	^{48}Ti(n,2n)^{47}Ti	$7/2_1^- \to 5/2_1^-$	37.8±0.2	62.7±6.7	22.5±1.1	31.0
174.3	^{48}Ti(n,α)^{45}Ca	$5/2_1^- \to 7/2_1^-$	6.5±0.2		1.6±0.1	1.2
175.4	^{48}Ti(n,n')^{48}Ti	$6_2^+ \to 6_1^+$			3.6±0.2	3.6
227.8	^{46}Ti(n,p)^{46}Sc	$3_1^+ \to 4_1^+$	2±0.3			1.1
370.3	^{48}Ti(n,p)^{48}Sc	$3_1^+ \to 4_1^+$	4.5±0.4			5.7
423.6	^{48}Ti(n, n')^{48}Ti	$4_1^- \to 3_1^-$	4.8±0.4		4.1±0.2	1.8
889.3	^{46}Ti(n, n')^{46}Ti	$2_1^+ \to 0_{g.s.}^+$	15.8±0.3	1.9±0.2		11.7
944.1	^{48}Ti(n, n')^{48}Ti	$4_2^+ \to 4_1^+$	7.6±0.2	7.1±0.9	7.6±0.4	4.6
983.5	^{48}Ti(n, n')^{48}Ti	$2_1^+ \to 0_{g.s.}^+$	100	100	100	100
1037.5	^{48}Ti(n, n')^{48}Ti	$6_1^+ \to 4_1^+$	11.6±0.3		0.9±0.1	9.6
1048.6	^{46}Ti(n, n')^{46}Ti	$3_1^- \to 4_1^+$	2.2±0.2			0.2
1091.3	^{48}Ti(n,2n)^{47}Ti	$3/2_1^- \to 7/2_1^-$	4.1±0.2			1.4
1092.7	^{48}Ti(n,2n)^{47}Ti	$9/2_1^- \to 7/2_1^-$			4.4±0.2	2.8
1120.6	^{46}Ti(n, n')^{46}Ti	$4_1^+ \to 2_1^+$	8.8±0.2			5.2
1121.1	^{50}Ti(n, n')^{50}Ti	$4_1^+ \to 2_1^+$				2.7
1284.9	^{48}Ti(n,2n)^{47}Ti	$11/2_1^- \to 7/2_1^-$	2.8±0.2		1.3±0.1	1.6
1312.1	^{48}Ti(n, n')^{48}Ti	$4_1^+ \to 2_1^+$	39.8±0.4	35.7±4.1	42.6±2.1	41.0
1437.5	^{48}Ti(n, n')^{48}Ti	$2_2^+ \to 2_1^+$	7.5±0.2	7.4±1.1	6.0±0.3	4.8
1542.2	^{49}Ti(n, n')^{49}Ti	$11/2_1^- \to 7/2_1^-$	2.5±0.2			2.1
1553.8	^{50}Ti(n, n')^{50}Ti	$2_1^+ \to 0_{g.s.}^+$	5.5±0.2	0.3±0.0		5.5
1750.3	^{48}Ti(n, n')^{48}Ti	$5_1^- \to 4_1^+$	3.3±0.2	3.5±2.0	4.0±0.2	2.3
2240.4	^{48}Ti(n,n')^{48}Ti	$3_1^+ \to 2_1^+$	3.4±0.4	4.8±0.8	2.8±0.2	2.7
2387.3	^{48}Ti(n,n')^{48}Ti	$2_4^+ \to 2_1^+$	1.8±0.2		2.2±0.2	1.1

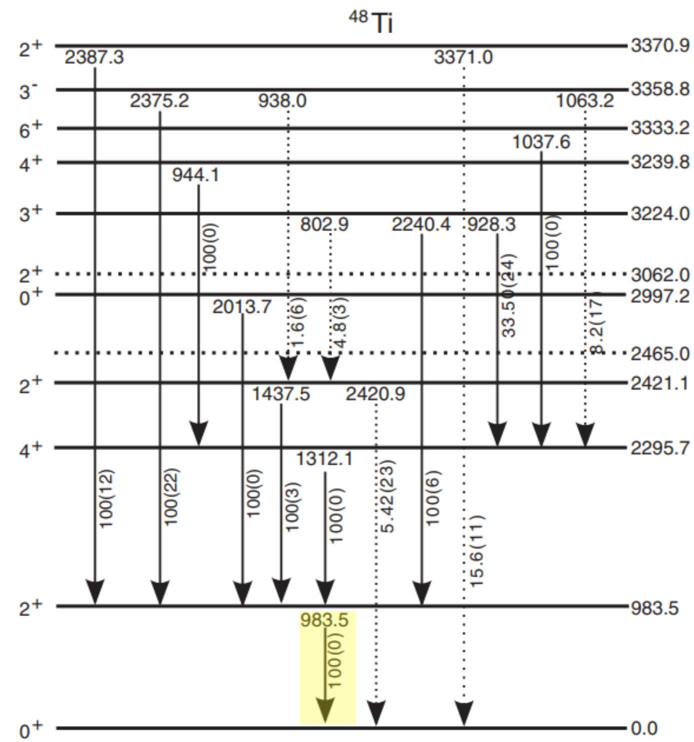


FIG. 1. Simplified level scheme of the ^{48}Ti nucleus [39]. The observed transitions are displayed using solid lines. The dashed line is used to show known transitions that were not observed but were taken into account in the data analysis procedure or to display the levels with no or unknown γ-ray contribution.

^{48}Ti (983.5 keV)	σ_γ, mb
TANGRA exp	524 ± 3
TALYS 1.9	659 ± 1
Ref. [27]	666 ± 6
Ref. [17]	797 ± 3

[17] Dashdorj D., Mitchell G.E., Becker J.A. et al., Nucl. Sci. and Engin. 2007. V.157. P. 65.

[27] Simakov S.P., Pavlik A. , Vonach H., Hlavac S., Status of experimental and evaluated discrete γ-ray production at En=14.5 MeV. № INDC (CCP)-413. IAEA NUCLEAR DATA SECTION, Vienna. 1998.

Gamma-ray Angular Distribution

K.A. Connell, A.J. Cox, The use of a small accelerator to study the gamma rays associated with the inelastic scattering of I4-MeV Neutrons in ^{28}Si, ^{32}S and ^{48}Ti, The International Journal of Applied Radiation and Isotopes, Volume 26, Issue 2, **1975**, Pages 71-78, ISSN 0020-708X, https://doi.org/10.1016/0020-708X(75)90105-2.

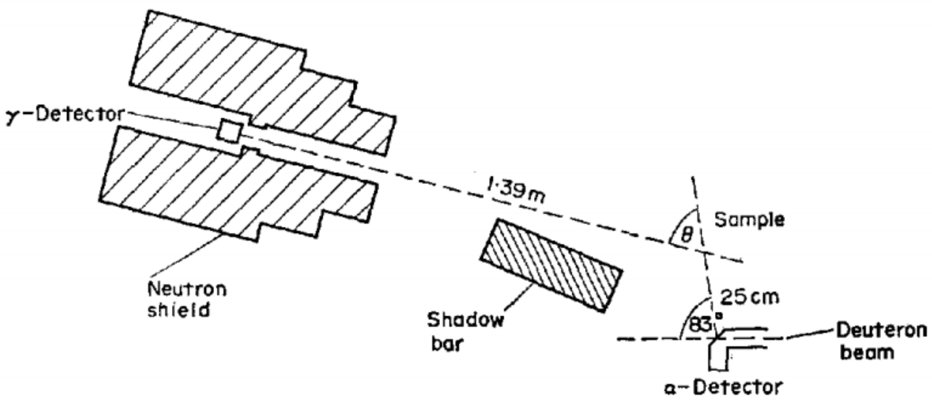


FIG. 1. Experimental arrangement.

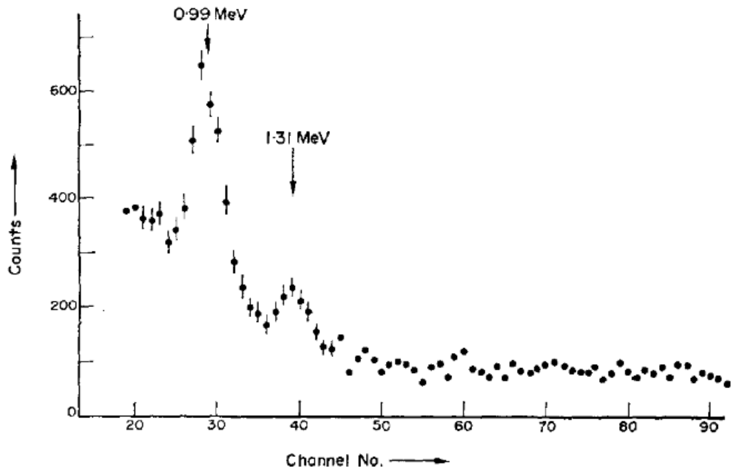


FIG. 6(a). ^{48}Ti spectrum.

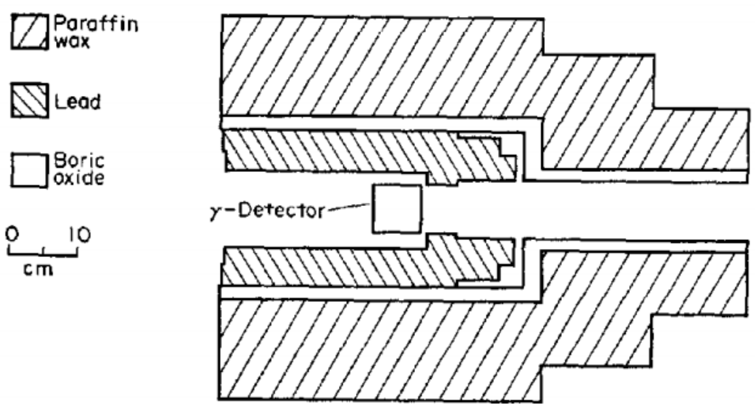


FIG. 2. γ-ray detector and shield.

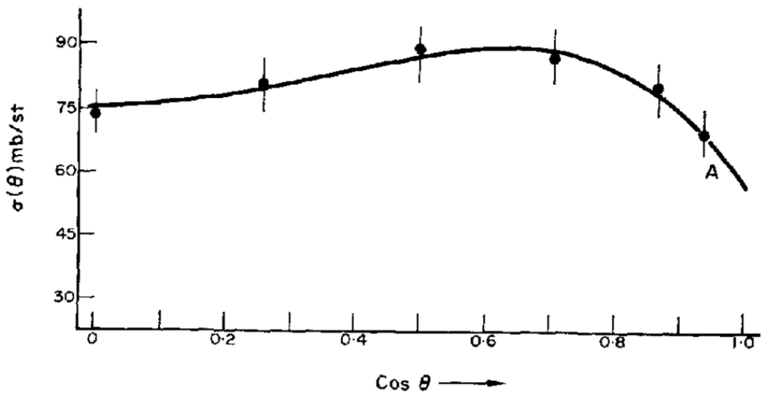
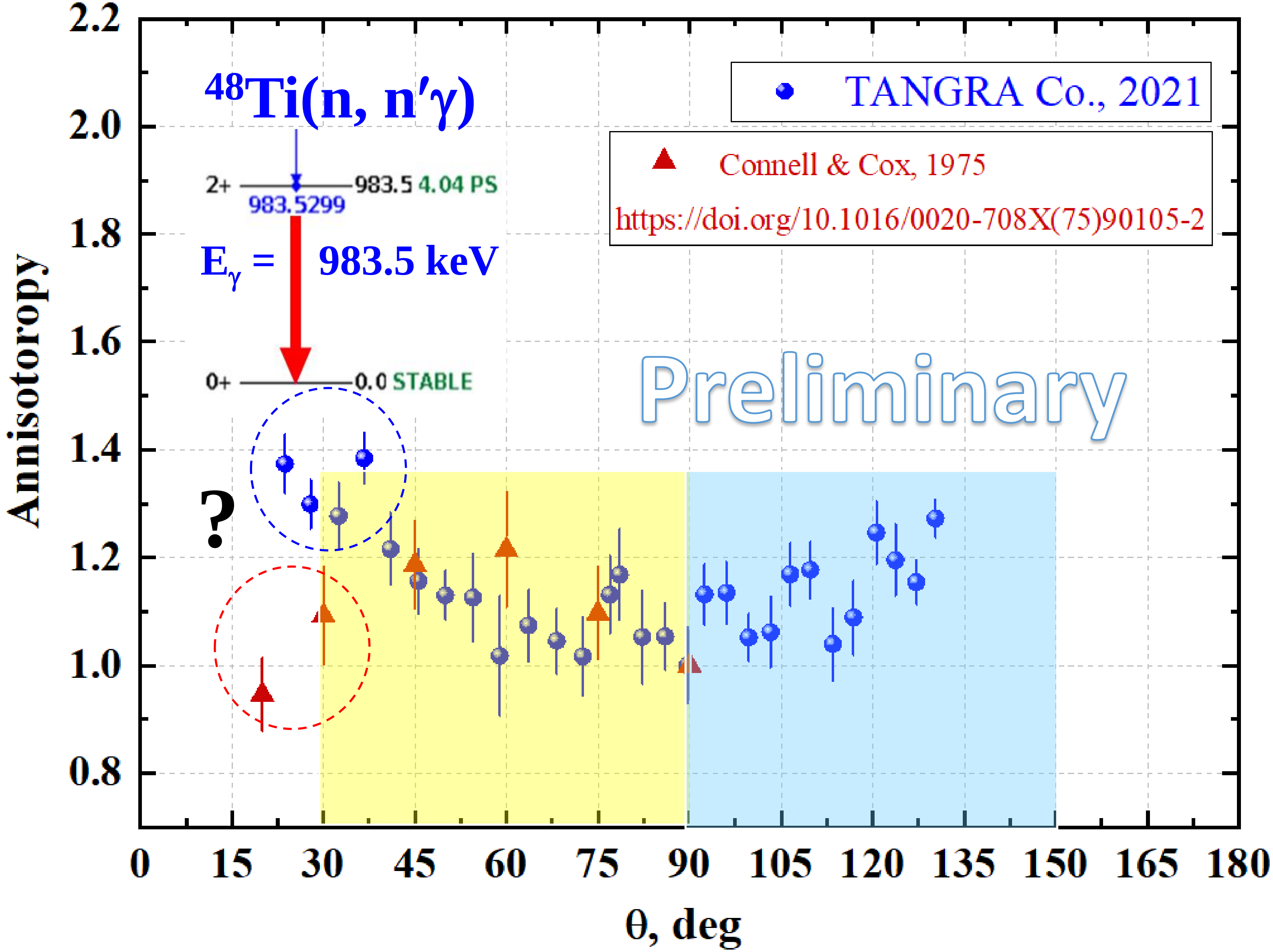


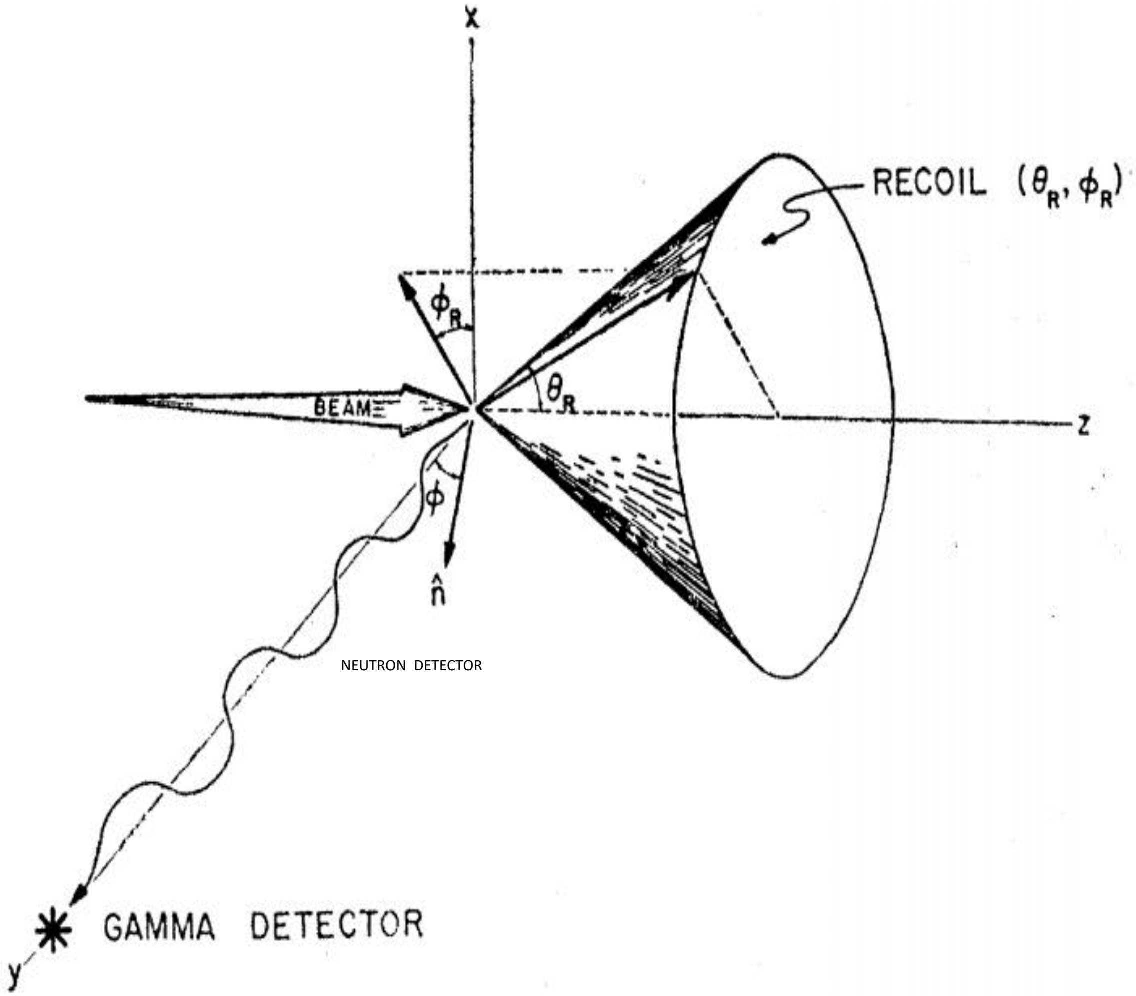
FIG. 6(b). 0·99-MeV γ-ray angular distribution: (a) Present work.

Gamma-ray Angular Distribution



Outlook: INS n-γ correlations

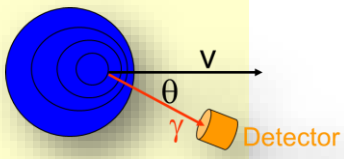
Angular Correlation Between Gamma Rays and 14-MeV Neutrons Scattered Inelastically by Nuclei

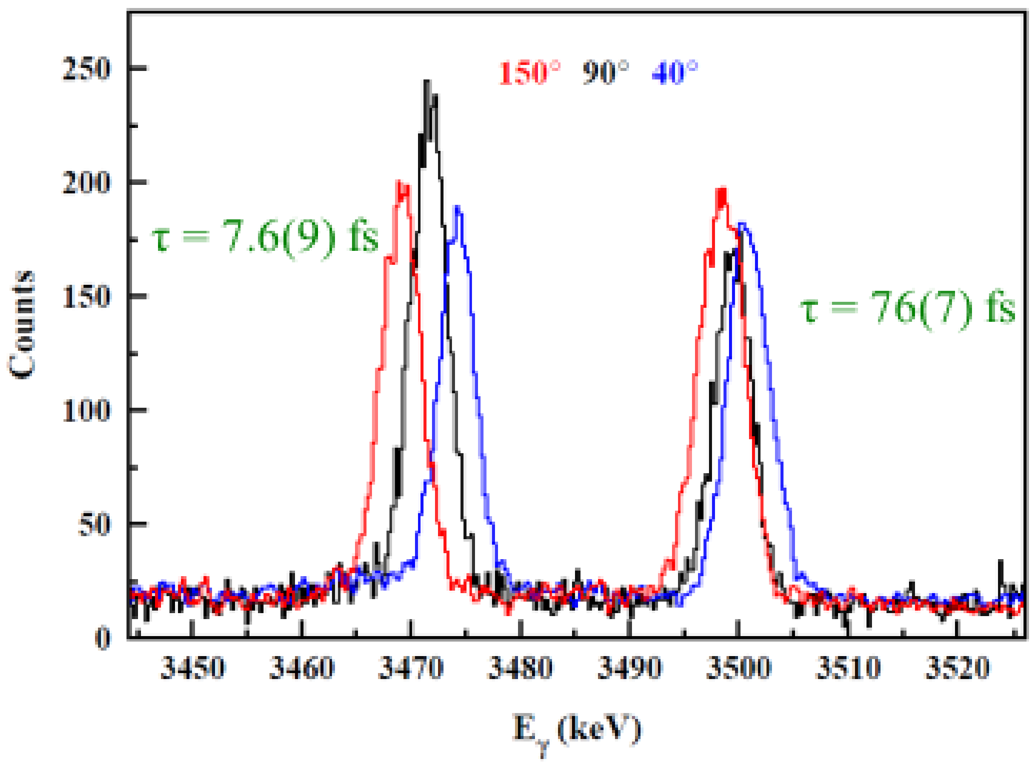


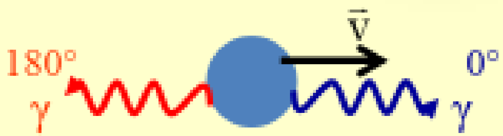
Outlook: Lifetime by DSAM

Level Lifetimes: Doppler-Shift Attenuation Method (DSAM)

https://slidetodoc.com/research-at-ukal-lessons-learned-and-new-adventures/







Scattered neutron causes the nucleus to recoil.

Emitted γ rays experience a Doppler shift.

Level lifetimes in the femtosecond region can be determined.

T. Belgya, G. Molnár, and S.W. Yates, Nucl. Phys. A607, 43 (1996).
E.E. Peters *et al.*, Phys. Rev. C 88, 024317 (2013).

Outlook: Lifetime by DSAM

The energy of emission ($E\gamma$) is deter mined according to the following expression with taking into account for the Doppler shift:

$$E_{\gamma} = E_{\gamma}^{0}\left[1 + \beta_0 F(t)\cos\theta\right],$$

E_{γ}^{0} is the emission energy of a nucleus at rest;

$\beta_0 = v(0)/c$ is the velocity of a recoil nucleus at the initial moment, in units of the speed of light;

θ is the emission angle of γ quanta relative to the velocity of the recoil nucleus;

$F = \beta_t / \beta_0$ is the attenuating factor of velocity over time t.

After measuring energies of emission E1 and E2 at angles $\theta 1$ and $\theta 2$, experimental value F_{exp} was calculated according to the following equation:

$$F_{\exp}(\langle t_n \rangle) = \frac{\Delta E_{\exp}}{E_{\gamma}^{0}\beta_0(\cos\theta_1 - \cos\theta_2)},$$

$< t_n >$is the average lifetime of a level, and

ΔE_{exp} = E1– E2 is the shift in the position of center of gravity of the γ line.

The theoretical factor of attenuation Fth, in dependence on the lifetime of level τ for a homogeneous slow ing down medium, is given by the following expression:

$$F(\tau) = \frac{1}{\tau\beta_0}\int_0^{\infty}\beta(t)e^{-\frac{t}{\tau}}\langle\cos\Phi\rangle dt,$$

Φ is the scattering angle of a recoil nucleus relative to the direction of the beam.

$\beta(t)$ can be calculated using Lindhard– Sharff–Schiott theory [1]

<cos Φ> can be determined according to the procedure in [2].

Weakening factors Fth(τ) (3) can be calculated as in [3].

The lifetimes of the levels can be determined from the theoretical curves at the value $F = F_{exp}$.

[1] Lindhard, J., Scharff, M., and Schiott, H.E., Mat. Phys. Dan. Vid. Selsk., 1963, vol. 33, p. 3.

[2] Blaugrund, A.E., Nucl. Phys., 1966, vol. 88, p. 501.

[3] Kaipov, D.K., Kosyak, Yu.G., Lysikov, Yu.A., and Sere brennikov, A.I., Izv. Akad. Nauk Kaz. SSR, 1977, no. 4, p. 1.

Outlook: Lifetime by DSAM

Adymov, Z.I., Burtebayev, N. & Sakuta, S.B. Lifetimes of ^{48}Ti, ^{52}Cr and ^{80}Se excited states. Bull. Russ. Acad. Sci. Phys. 75, 914 (2011). https://doi.org/10.3103/S1062873811070033.

Republic of Kazakhstan's WWRK IYaF research reactor.

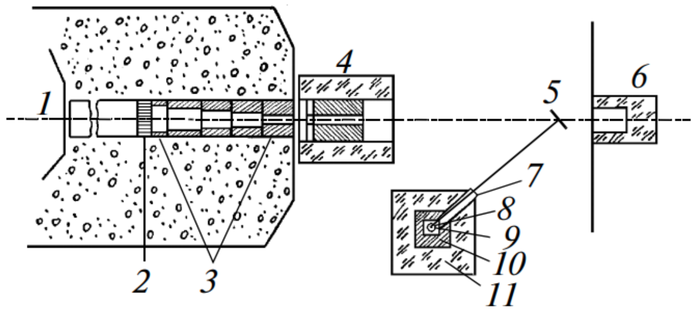


Fig. 1. Scheme of the experimental setup: (*1*) active zone of reactor, (*2*) filter, (*3*) collimator, (*4*) paraffin shielding with collimator made of boron carbide and an additional boron carbide filter, (*5*) target, (*6*) neutron trap, (*7*) collimator with LiH filter, (*8*) Ge detector, (*9*) ring of NaI(Tl) crystal, (*10*) lead shielding, and (*11*) paraffin.

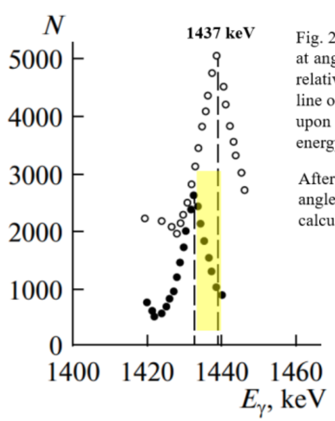


Fig. 2. Fragment of γ spectrum of ^{48}Ti **(n, n′γ)** ^{48}Ti at angles of **51°** (white dots) and **140°** (black dots) relative to the incident beam of neutrons for the γ line of **1437 keV**, upon discharge of the **2+** state with excitation energy $\mathbf{E_x}$ **= 2421 keV** of ^{48}**Ti.**

After measuring energies of emission E1 and E2 at angles θ1 and θ2, experimental value F_{exp} was calculated according to the following equation:

$$F_{\rm exp}(\langle t_n \rangle) = \frac{\Delta E_{\rm exp}}{E_\gamma^0 \beta_0 (\cos\theta_1 - \cos\theta_2)},$$

ΔE_{exp} = 6.4 keV

Republic of Kazakhstan's WWRK IYaF research reactor.

[3] Georgieva M. K., Elenkov D. V., Lefterov D. P., Toumbev G. H. Two-target DSAM for mean lifetime measurements of nuclear states excited in the (n, n'γ) reaction with reactor fast neutrons, Fiz. Elem. Chastits At. Yadra, 1989, vol. 20, p. 930. http://www1.jinr.ru/Archive/Pepan/1989-v20/v-20-4/4.htm http://www1.jinr.ru/Archive/Pepan/1989-v20/v-20-4/pdf_obzory/v20p4-4.pdf

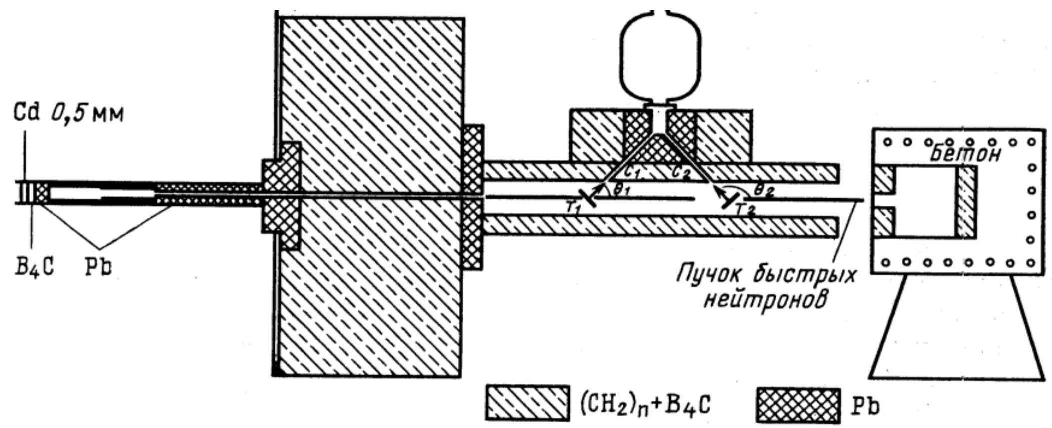


Рис. 9. Экспериментальная установка для измерения времени жизни ядерных уровней в реакции $(n, n'\gamma)$ по методу ОДС с двумя мишенями одновременно

Lifetimes of the excited states of ^{48}Ti, ^{52}Cr, and ^{80}Se nuclei

^{48}Ti				^{52}Cr				^{80}Se			
E_x, keV	E_g, keV	τ, fs (n, n'g)	τ, fs [10]	E_x, keV	E_g, keV	τ, ps (n, n'g)	τ, ps [11]	E_x, keV	E_g, keV	τ, ps (n, n'g)	τ, ps [12]
2421	1437	20(4)	27.1(27)	1434	1434	>0.7	0.793(2)	1701.5	1035.1	1.1(9)	0.66(2)
2998	2014	300(50)	78(9)	2964	1530	0.6(3)	0.42(8)	1960.2	1292.2	0.50(21)	0.38(17)
3223	928	42(25)	29(6)	3162	1728	0.05(1)	0.066(14)	2311.5	1645.0	0.22(3)	0.152(20)
3240	944	72(15)	46(7)	3472	2037	>0.7	7.2(8)	2344.1	894.8	0.50(20)	0.35(13)
3333	1038	>10 ps		3616	1246	0.15(10)	2.6(12)	2495.0	793.0	1.60(10)	1.1(7)
3359	1063	260(80)	184(21)	3771	2336	0.013(4)	0.0109(13)	2513.2	1847.2	0.07(1)	0.048(7)
3371	2387	42(8)	11.0(8)	3947	1578	0.02(1)	0.033(6)	2716.6	2050.6	0.55(20)	0.38(14)
3699	2716	20(4)		4752	1637	0.11(14)	0.64(18)	2826.6	1124.2	0.26(6)	0.18(4)
4381	1142	40(20)	24(10)					2947.3	1498.1	0.40(30)	0.18(8)
4387	1165	80(60)	35(14)					3025.5	2358.2	0.07(2)	0.049(14)
4580	1221	90(30)	28(14)					3038.7	1078.6	0.45(40)	0.13(7)
4719	1478	95(25)	66(14)					3125.5	2459.3	0.055(10)	0.028(14)
								3224.4	1522.8	0.10(4)	0.070(28)

Note: *The ranges of experimental error are given in parentheses, in units of the last significant digit.

Outlook: Lifetime by DSAM

Adymov, Z.I., Burtebayev, N. & Sakuta, S.B. Lifetimes of ^{48}Ti, ^{52}Cr and ^{80}Se excited states. Bull. Russ. Acad. Sci. Phys. 75, 914 (2011). https://doi.org/10.3103/S1062873811070033.

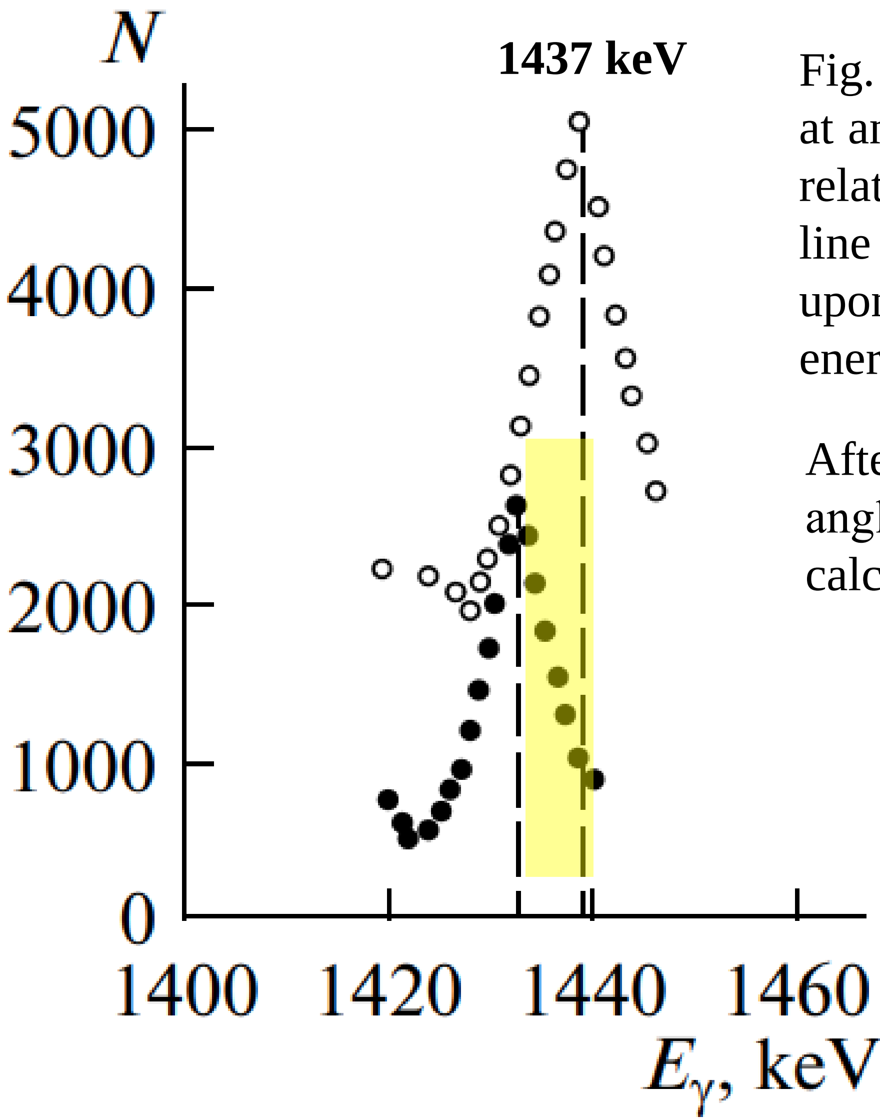


Fig. 2. Fragment of γ spectrum of **^{48}Ti (n, n′γ) ^{48}Ti** at angles of **51°** (white dots) and **140°** (black dots) relative to the incident beam of neutrons for the γ line of **1437 keV,**
upon discharge of the **2+** state with excitation energy **E_x = 2421 keV** of **^{48}Ti.**

After measuring energies of emission E1 and E2 at angles θ1 and θ2, experimental value F_{exp} was calculated according to the following equation:

$$F_{\mathrm{exp}}(\langle t_n \rangle) = \frac{\Delta E_{\mathrm{exp}}}{E_\gamma^0 \beta_0 (\cos\theta_1 - \cos\theta_2)},$$

$$\Delta E_{exp} = 6.4 \text{ keV}$$

Republic of Kazakhstan's WWRK IYaF research reactor.

Outlook: Lifetime by DSAM

Lifetimes of the excited states of ^{48}Ti,

^{48}Ti			
E_x, keV	E_g, keV	τ, fs	
		(n, n'g)	[10]
2421	1437	20(4)	27.1(27)
2998	2014	300(50)	78(9)
3223	928	42(25)	29(6)
3240	944	72(15)	46(7)
3333	1038	>10 ps	
3359	1063	260(80)	184(21)
3371	2387	42(8)	11.0(8)
3699	2716	20(4)	
4381	1142	40(20)	24(10)
4387	1165	80(60)	35(14)
4580	1221	90(30)	28(14)
4719	1478	95(25)	66(14)

[10] Singh, B., Nucl. Data Sheets, 2005, vol. 105, p. 223.

[3] Georgieva M. K., Elenkov D. V., Lefterov D. P., Toumbev G. H. Two-target DSAM for mean lifetime measurements of nuclear states excited in the (n, n'γ) reaction with reactor fast neutrons, Fiz. Elem. Chastits At. Yadra, 1989, vol. 20, p. 930. http://www1.jinr.ru/Archive/Pepan/1989-v20/v-20-4/4.htm

Георгиева М. К., Еленков Д. В., Лефтеров Д. П., Тумбев Г. Х. Измерение времени жизни возбужденных состояний ядер методом ОДС в реакции (n, n'γ) с двумя мишенями. http://www1.jinr.ru/Archive/Pepan/1989-v20/v-20-4/pdf_obzory/v20p4-4.pdf

Of the lifetimes given in the table, those for four levels of ^{48}Ti (E_x = 2421, 2998, 3371, and 3699 keV) and two levels of ^{52}Cr (Ex = 2964 and 3947 keV) were also measured earlier by DSAM in the (n,n'γ) reaction [3]. Our results generally correspond to the data from [3], with the exception of levels E_x = 2998 and 3371 keV (^{48}Ti) and E_x = 2964 keV (^{52}Cr).

Errors in determining the lifetimes of nuclear levels in reactor experiments are due mainly to the precision in measuring the positions of the centers of gravity of the γ lines under study, which in turn depends on the energy resolution of the detector system and the initial energy of the output nucleus.

DSAM is therefore most efficient for relatively light nuclei with A < 90.


Everything can be done with a proper team
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Thank You for Your Attention

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collaboration

FLNP