Possible LENR observation due to dineutron formation

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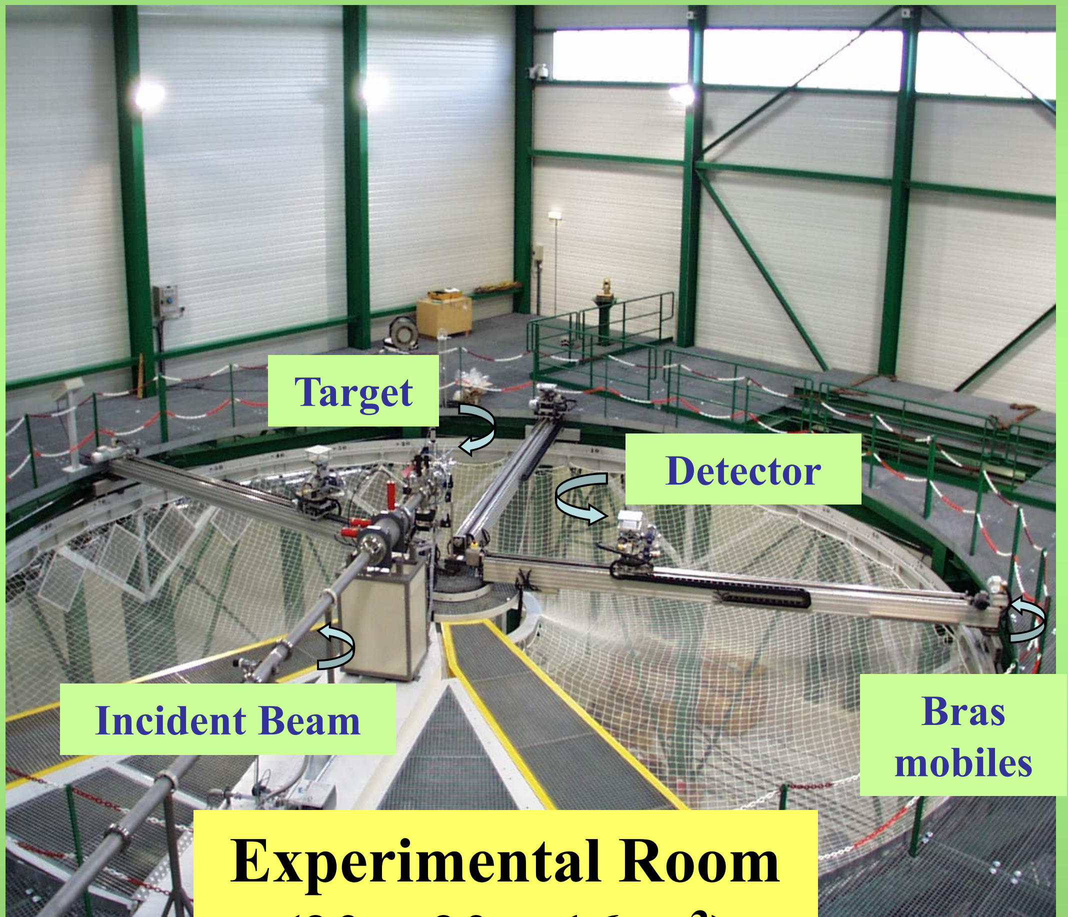
Outline

- **Irradiation of Tb-sample at IRSN Cadarache, France**
- **Experimental results**
- **Hypothesis on a bound dineutron existence**
- **Theoretical prerequisites**
- **Au- irradiation: in cooperation with Atomki, Hungary**
- **Measurements of Tb -sample (n,γ) induced activity**
- **Hypothesis and justification of LENR observation**
- **Conclusions**

Irradiation of Tb-sample at IRSN Cadarache, France



Experimental Room
(20 x 20 x 16 m^3)

- **AMANDE – neutron generation facility for neutron irradiation: Cadarache, IRSN, France**
- **Outstanding conditions for (n,γ) cross-section measurements**
- **Utilization of (D,D) reaction with fixed target to irradiate Tb samples with 3 - 7 MeV neutrons**

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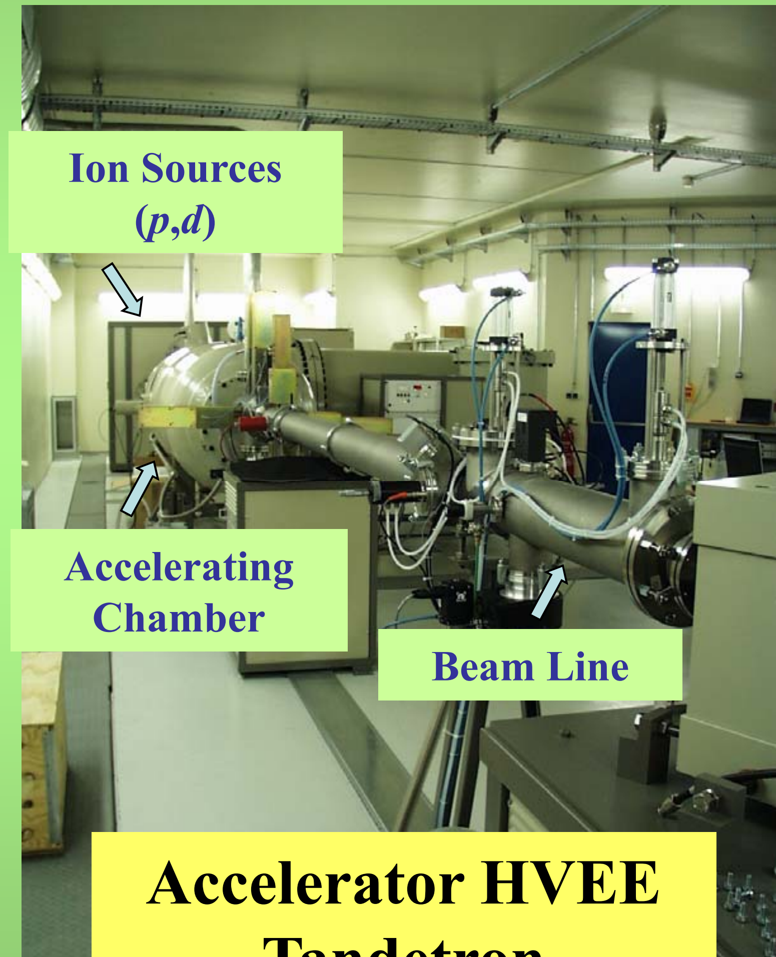
Irradiation of Tb-sample at IRSN Cadarache, France

- **All measurements related to the same Tb sample of 28.89 g mass**
- **It was used to determine the $^{159}Tb(n,\gamma)^{160}Tb$ nuclear reaction cross section for 6.85 MeV neutron energy**
- **Irradiation for this neutron energy at IRSN neutron facility AMANDE, Cadarache was completed on 06.12.2013**



Accelerator HVEE Tandetron

Irradiation of Tb-sample at IRSN Cadarache, France

Fig. 1. Photo of the experimental setup showing the end of AMANDE beamline in the low scattering experimental hall (left panel) and the terbium sample (30 mm diameter disk) placed in front of the target (right panel, an arrow directed).

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Irradiation of Tb-sample at IRSN Cadarache, France

Table 3
Measured and calculated cross sections for the $^{159}Tb(n,\gamma)^{160}Tb$.

Neutron energy (Δ) (MeV)	Cross section (Δ) (mb)	TALYS	Prior data (mb), the energy of incident neutron is in parenthesis
3.6700 (0.0008)	30.8 (2.2)	29.54	49.2 ± 7.0 (3 MeV) [19]
4.2800 (0.0010)	21.78 (1.80)	22.38	31.3 ± 3.2 (3.5 MeV) [18]
5.3900 (0.0015)	6.13 (0.55)	8.20	23.5 ± 2.6 (4.0 MeV) [18]
6.850 (0.002)	2.14 (0.83)	2.2	

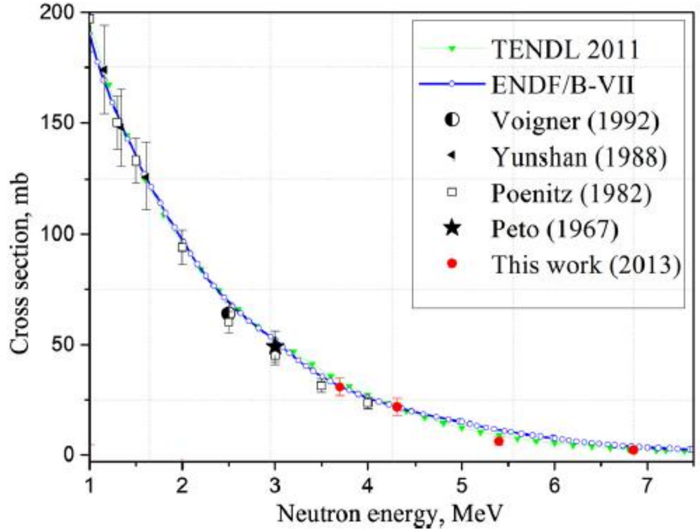
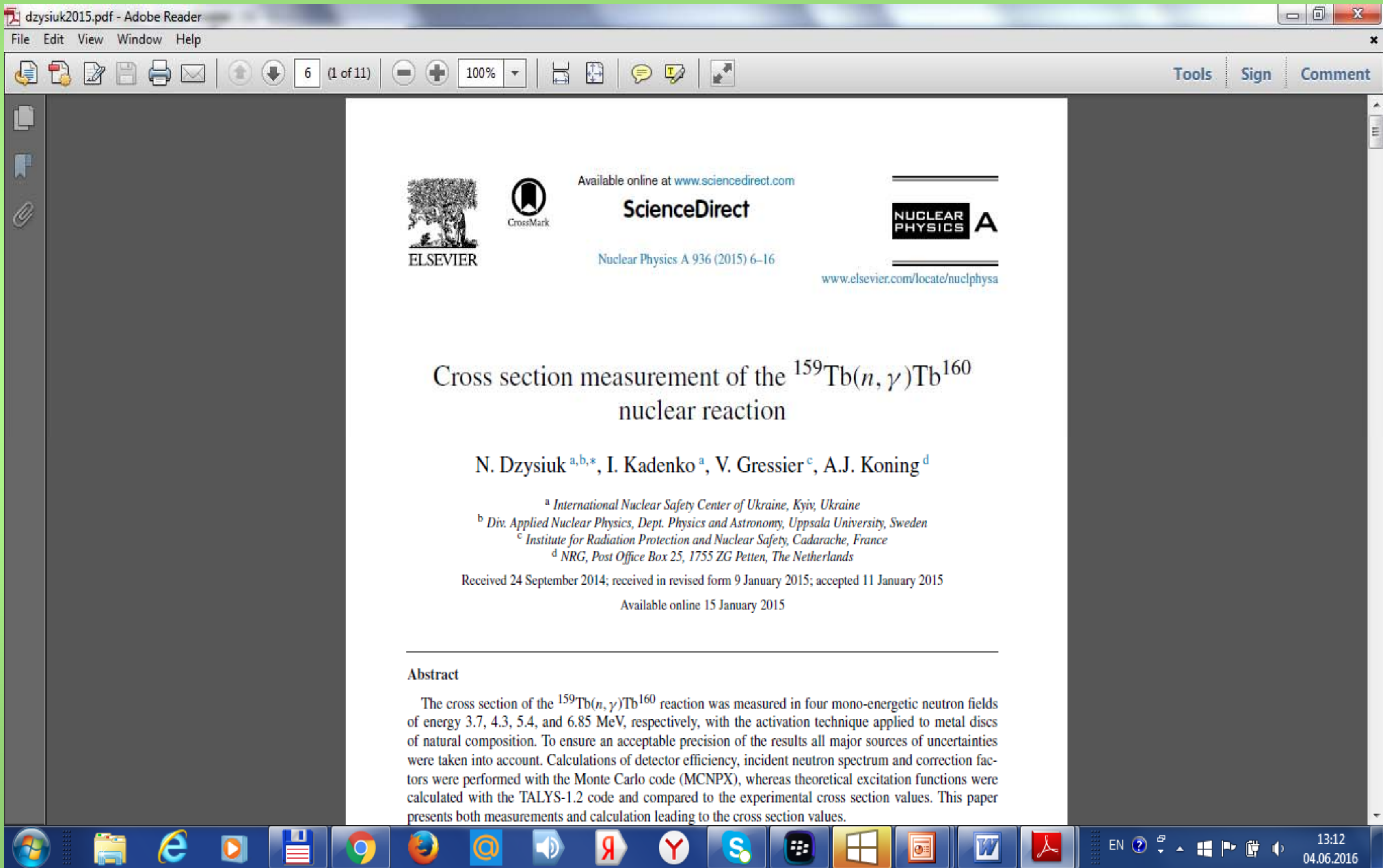


Fig. 5. Excitation function for the $^{159}Tb(n,\gamma)Tb^{160}$ nuclear reaction. The data are given with the statistical error bars only.

Irradiation of Tb-sample at IRSN Cadarache, France



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NUCLEAR PHYSICS A

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Cross section measurement of the ^{159}Tb(n,γ)Tb^{160} nuclear reaction

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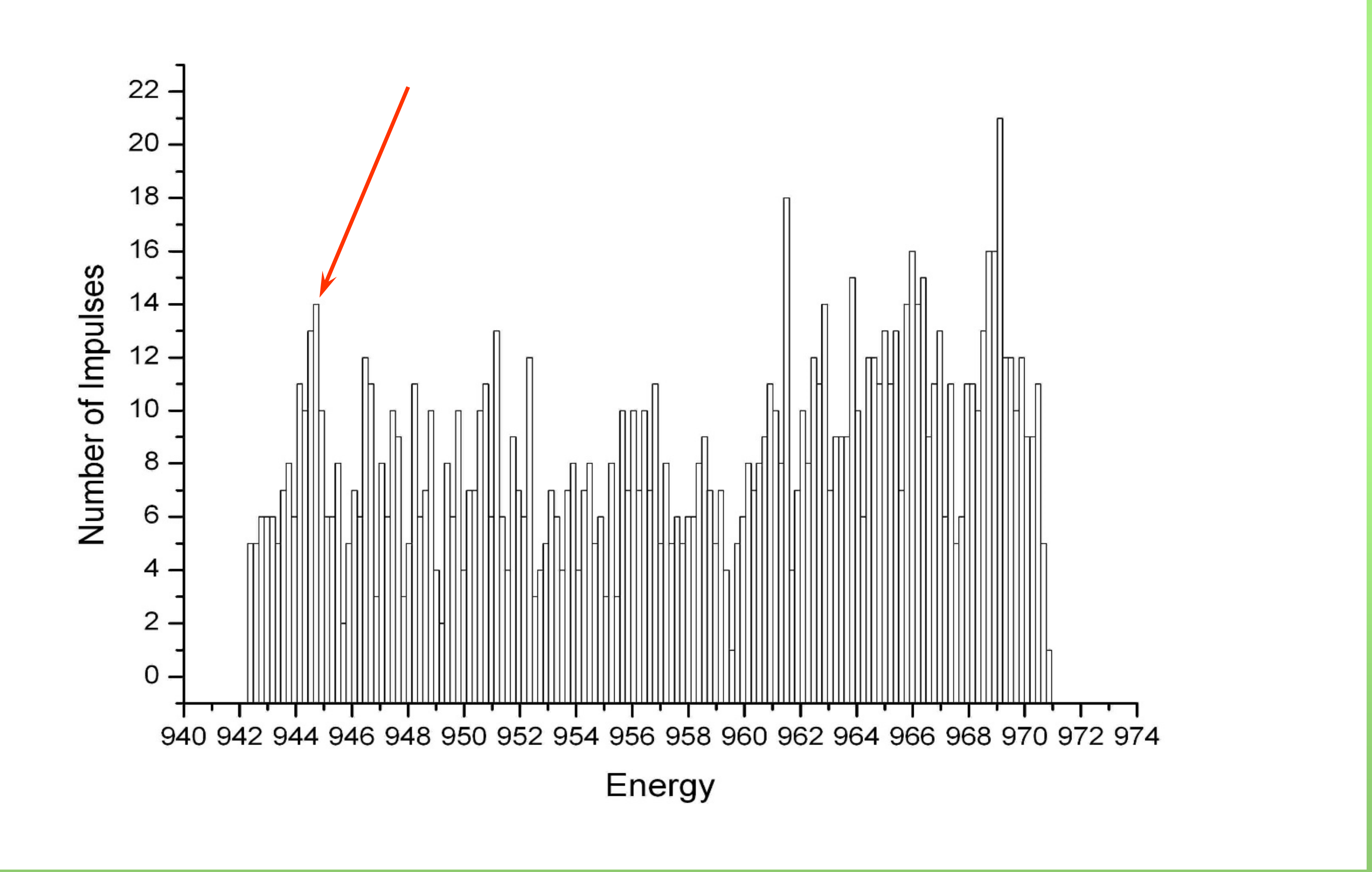
Abstract

The cross section of the ^{159}Tb(n,γ)Tb^{160} reaction was measured in four mono-energetic neutron fields of energy 3.7, 4.3, 5.4, and 6.85 MeV, respectively, with the activation technique applied to metal discs of natural composition. To ensure an acceptable precision of the results all major sources of uncertainties were taken into account. Calculations of detector efficiency, incident neutron spectrum and correction factors were performed with the Monte Carlo code (MCNPX), whereas theoretical excitation functions were calculated with the TALYS-1.2 code and compared to the experimental cross section values. This paper presents both measurements and calculation leading to the cross section values.

Experimental results

- **In one plus year after irradiation complete: counting of Tb big sample with HPGe spectrometer (GC 2019 detector)**



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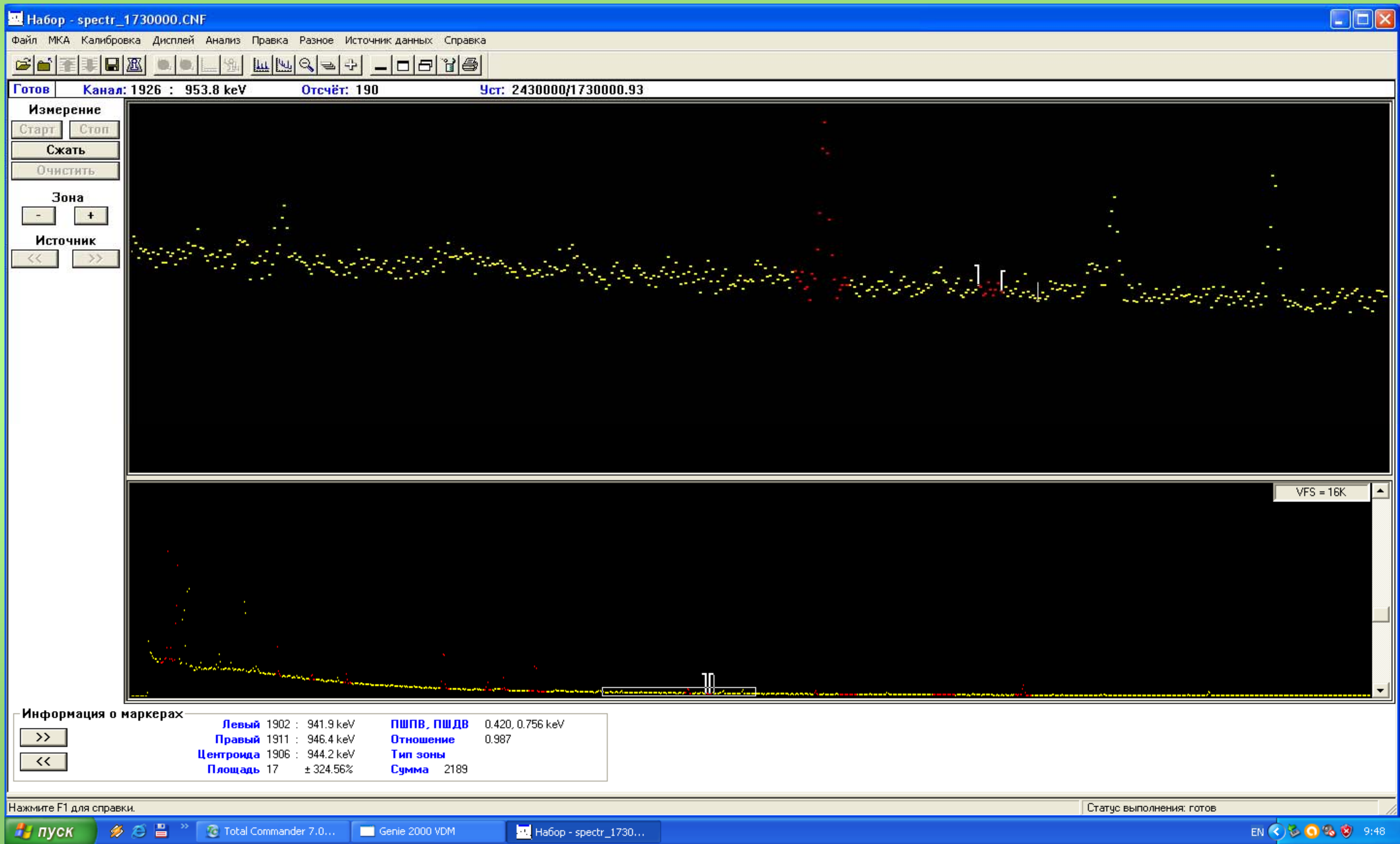
Experimental results – background



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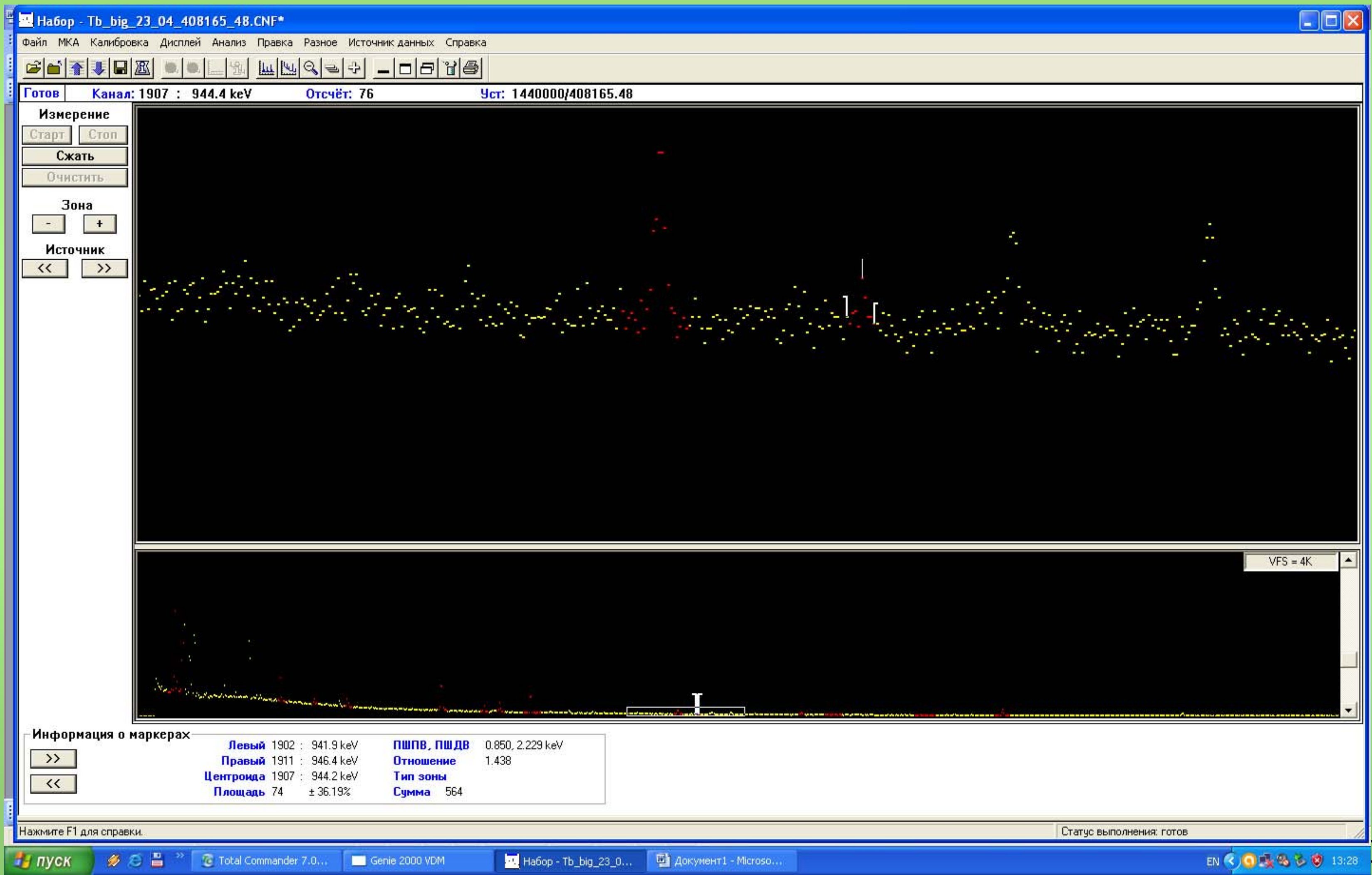
Experimental results – Tb sample measurements



Experimental results

- **Peak like structure is fixed for 944.2 keV energy of gamma-rays, possible candidates:**
  - **^{48}V: $T_{1/2}$ = 15.97 days, stronger line of 983.5 keV is missing;**
  - **^{156}Eu: $T_{1/2}$ = 15.19 days, stronger line of 811.8 keV is missing;**
  - **^{158g}Tb: $T_{1/2}$ = 180 years, reaction product from ^{158}Dy (*n*,*p*); ^{158}Dy isotope content is 0.1% in natural Dy abundance; experimental data in EXFOR are absent; TENDL-2017 evaluation ⇨ mass of Tb sample should be inadequate;**
  - **^{158g}Tb from the ^{159}Tb (*n*,2*n*) nuclear reaction**
- **Low cps in gamma peak - (1.4÷1.8)•10^{-4} 1/s:**
  - **background: 17 ± 324.56% for 1,730,000.93 seconds measurement;**
  - **peak area: 72 ± 36.19% for 408,165.48 seconds measurement**

Experimental results

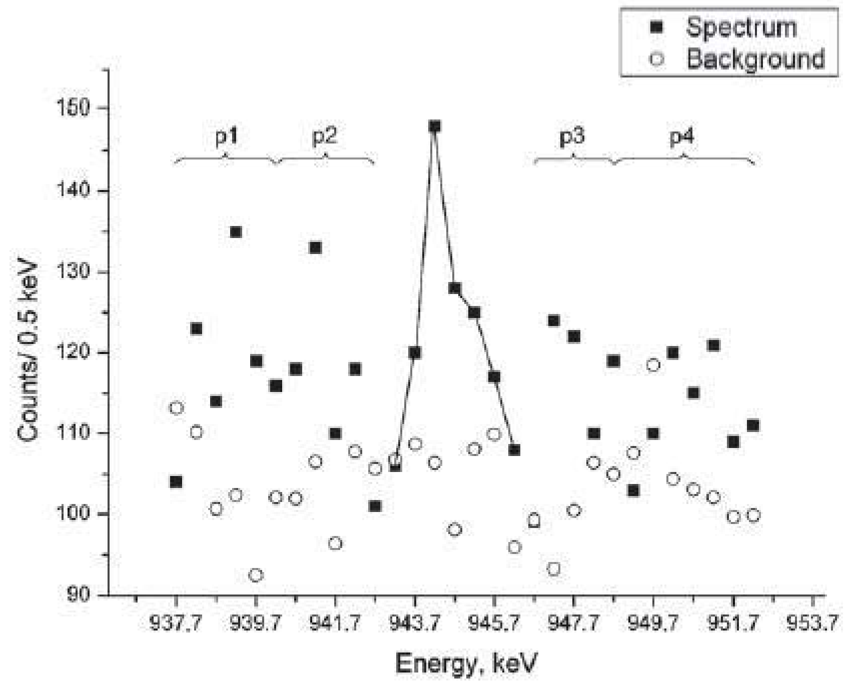


Fig. 2: ROI with 944.2 keV ($I\gamma$ = 0.439) peak of ^{158}Gd.

- **Experimental set up to execute the measurements**

Hypothesis on a bound dineutron existence

- **Dineutron escape was observed for 6.85 MeV incident neutrons: it is 1.3 MeV below the (n,2n) reaction threshold**

- **Analogously to the threshold of (*n*,*d*) reaction, which is 2.225 MeV lower of (*n*,*np*) reaction threshold due to the binding energy of the deuteron**

- **Interval estimate of the binding energy for the dineutron:**

$$1.3 \text{ MeV} < B_{dn} < 2.8 \text{ MeV}$$

Hypothesis on a bound dineutron existence

Possible observation of the dineutron in the ^{159}Tb $(n,{}^2n)$ ^{158g}Tb nuclear reaction

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PACS 21.10.-k - Properties of nuclei; nuclear energy levels
PACS 21.10.Dr - Binding energies and masses
PACS 27.10.+h - A ≤ 5

Abstract – Experimental observation of the ^{159}Tb$(n,{}^2n)$ reaction product was performed with application of the activation technique. Tb specimen of natural composition was irradiated with (d,d) neutrons of 5.39 and 7 MeV energies. Instrumental spectra of Tb specimen were measured with HPGe spectrometer. An unexpected 944.2 keV γ-ray peak was observed. Other γ-ray lines due to ^{158g}Tb decay were identified as well. A bonded dineutron emission with the binding energy (B_{dn}) within limitations 1.3 MeV $< B_{dn} <$ 2.8 MeV is evidenced by the energy of incident neutrons and by ^{158g}Tb presence in output channel. The specific nuclear properties of ^{158}Tb as deformed nucleus were discussed to explain a bonded dineutron formation based on theoretical assumptions and calculations, using standard parameters for this mass region.

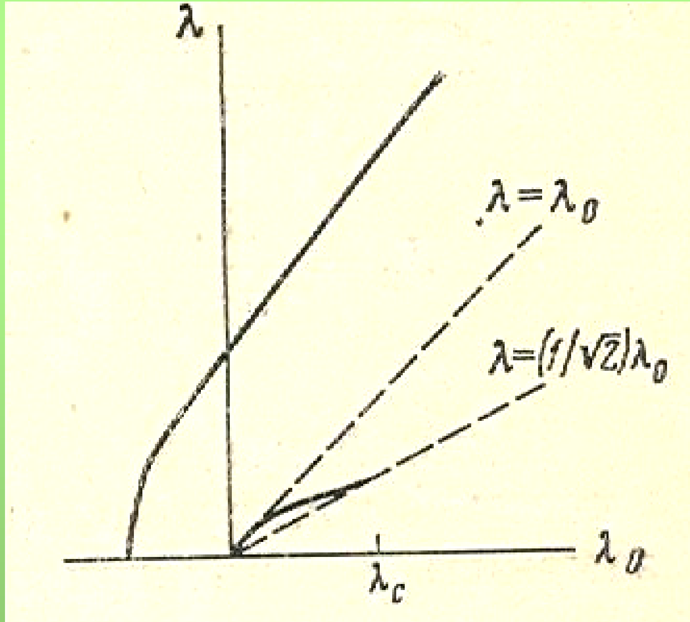
Introduction. The purpose of this Letter is to point out that the dineutron may exist as a bonded particle in the vicinity of the heavy nucleus in output channel of nuclear reaction. The field of nuclear physics knows long history of searching for dineutron bound states. Numerous attempts had been made to channels with expected low activities in output channel, the neutron activation technique is among the most suited ones. In order to understand the behaviour of new neutron induced reactions on Tb, the irradiations of specimen were made with incident neutrons at the AMANDE facility (the Institute for

Theoretical prerequisites

- **Paper of A.B. Migdal - "Two interacting particles in a potential well". Soviet Journal of Nuclear Physics, Vol.16, Iss.2, February 1973, pp. 238-241:**
  - **"It is shown that under certain circumstances there appears an additional bound state, which does not exist in perturbation theory. Possible applications to nuclear theory are discussed, in particular the possible existence of a dineutron near the surface of some nuclei."**
  - **"It is shown that in the case when the potential well is produced by a nucleus, there appears a state which has to be interpreted as a bound state of two neutrons near the nuclear surface."**

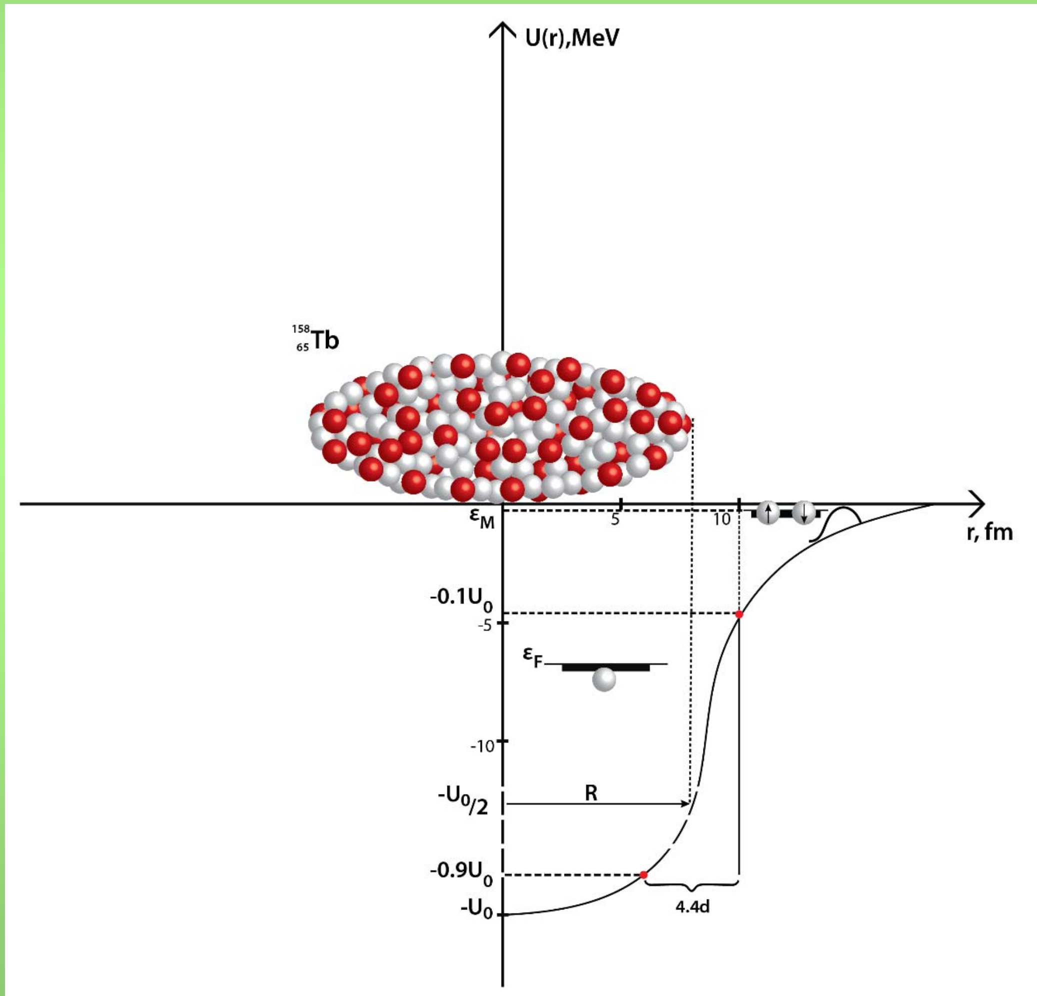
Theoretical prerequisites

- **"The physical nature of this additional level consists in the following. The particles form a bound state even in the case when their attraction is insufficient for the formation of a bound state outside the well..."**



- ***The dependence of the binding energy ε of two particles ($\varepsilon=\lambda^2$) on the binding energy ε_0 of the single-particle level in the well ($\varepsilon_0= \lambda_0^2/2$). For $\lambda_c>\lambda_0>0$ there are two branches for the two-particle energy***

Theoretical prerequisites



- **The dineutron is trapped in one of several level within (66÷400) keV energy range**
- **This level keeps the two neutrons in a bound state during some time as a single particle: the dineutron**

Experimental results

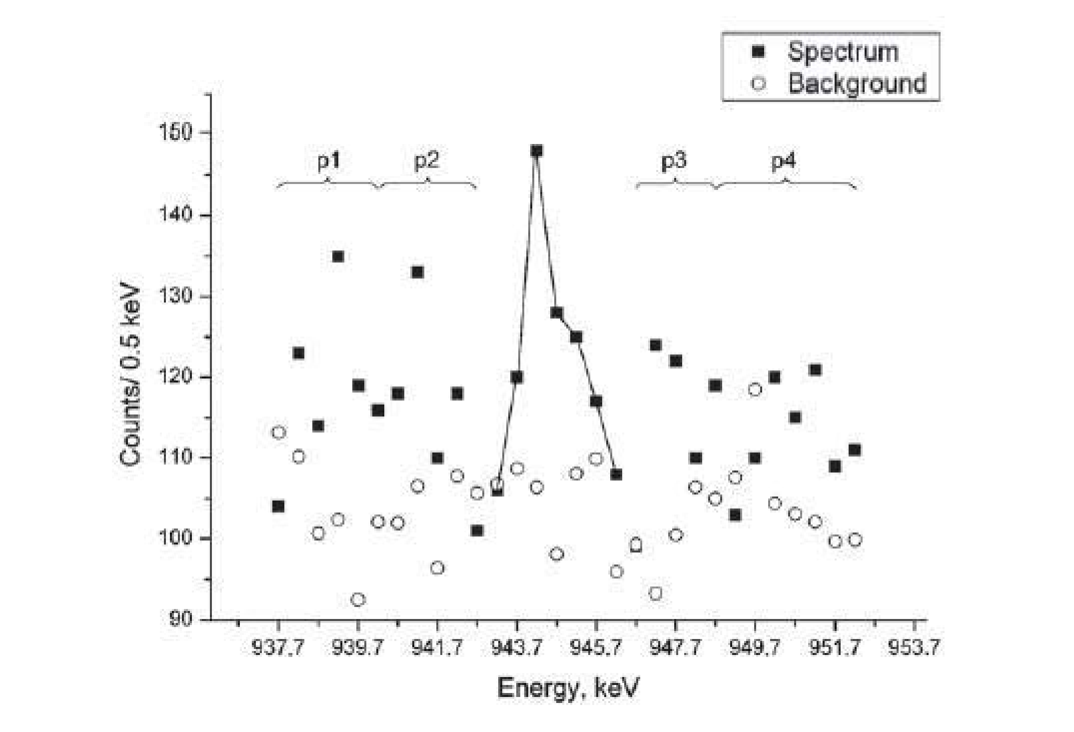


Fig. 2: ROI with 944.2 keV ($I\gamma = 0.439$) peak of ^{158}Gd.

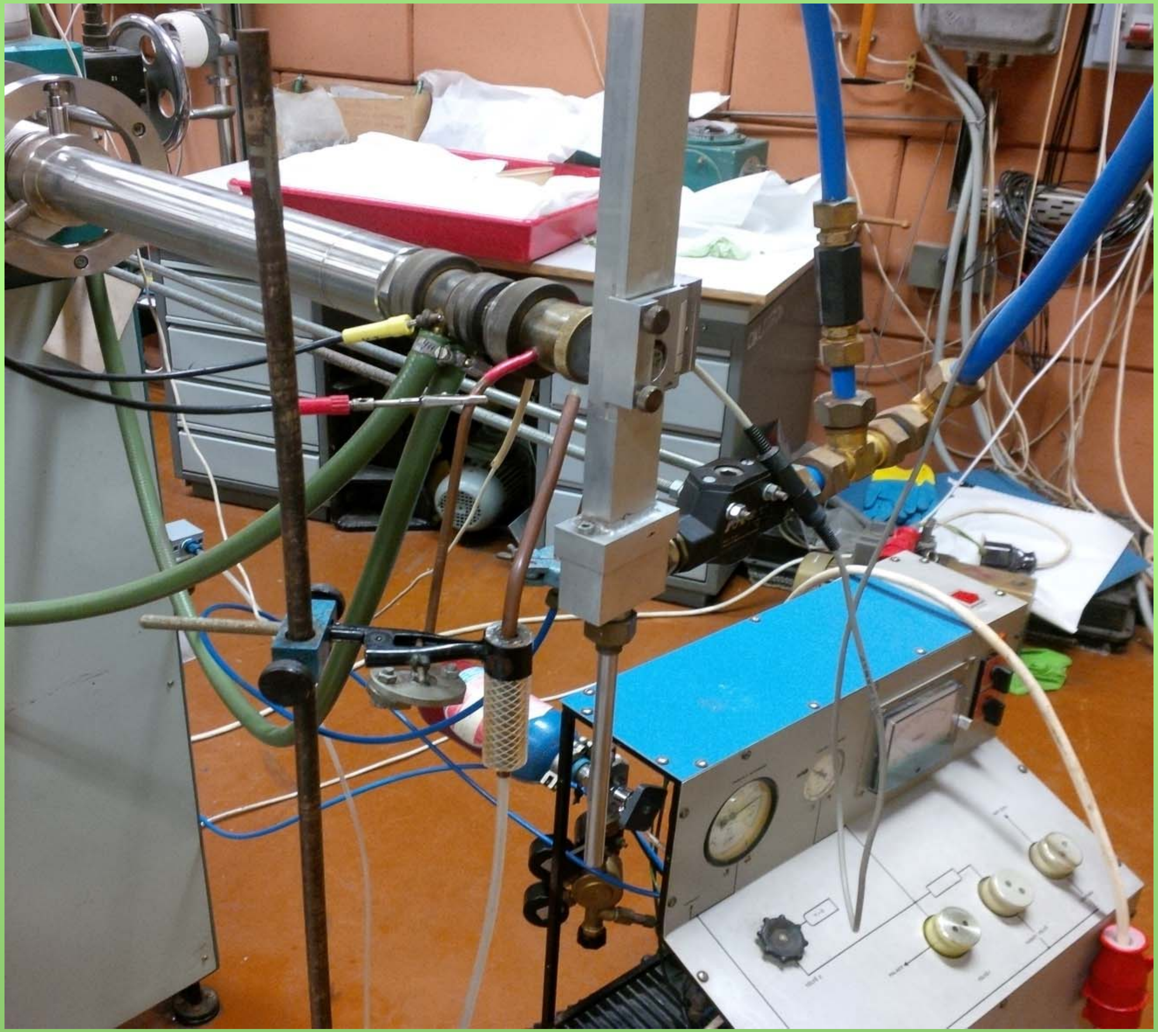
- **Experimental set up to execute the measurements**

Au- irradiation: in cooperation with Atomki, Hungary

- **Last summer the following experiment was conducted:**
  - **Three foils made of 0.9999 Au were irradiated in a neutron field generated with MGC-20 cyclotron**
  - **Subject of the study: ^{197}Au (n,^{2}n)^{196}Au nuclear reaction**
  - **Reaction threshold: 8.114 MeV, neutron energy: about 2 MeV below the threshold**
  - **Expected results: presence of the following most intensive gamma peaks due to ^{196m,g}Au decay in the instrumental spectrum:**
    - E_γ=355.73 keV; k_γ=87%;
    - E_γ=333.03 keV; k_γ=22.9%;
    - E_γ=426.10 keV; k_γ=6.6%.

Au- irradiation: in cooperation with Atomki, Hungary

Au- irradiation: in cooperation with Atomki, Hungary



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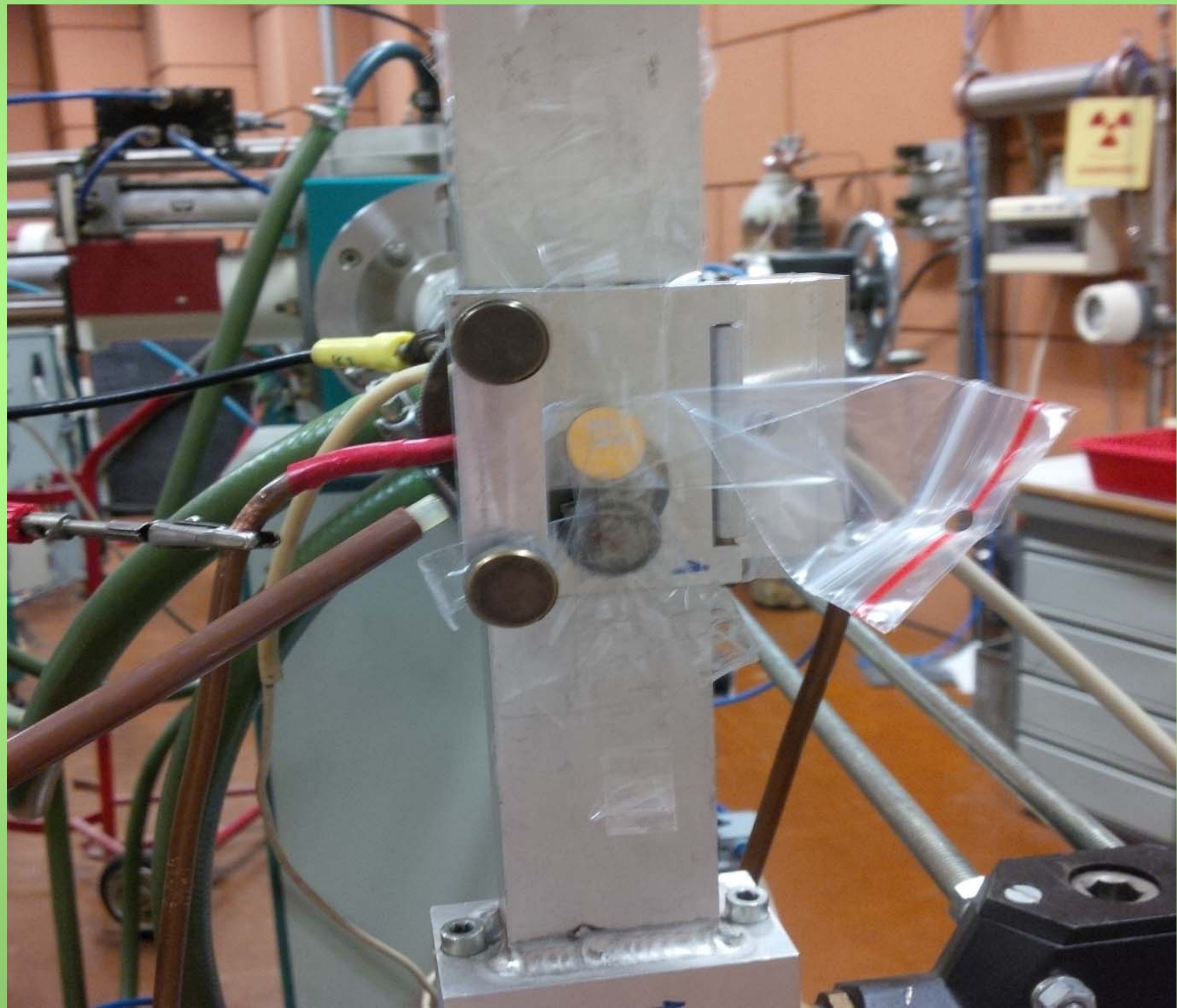
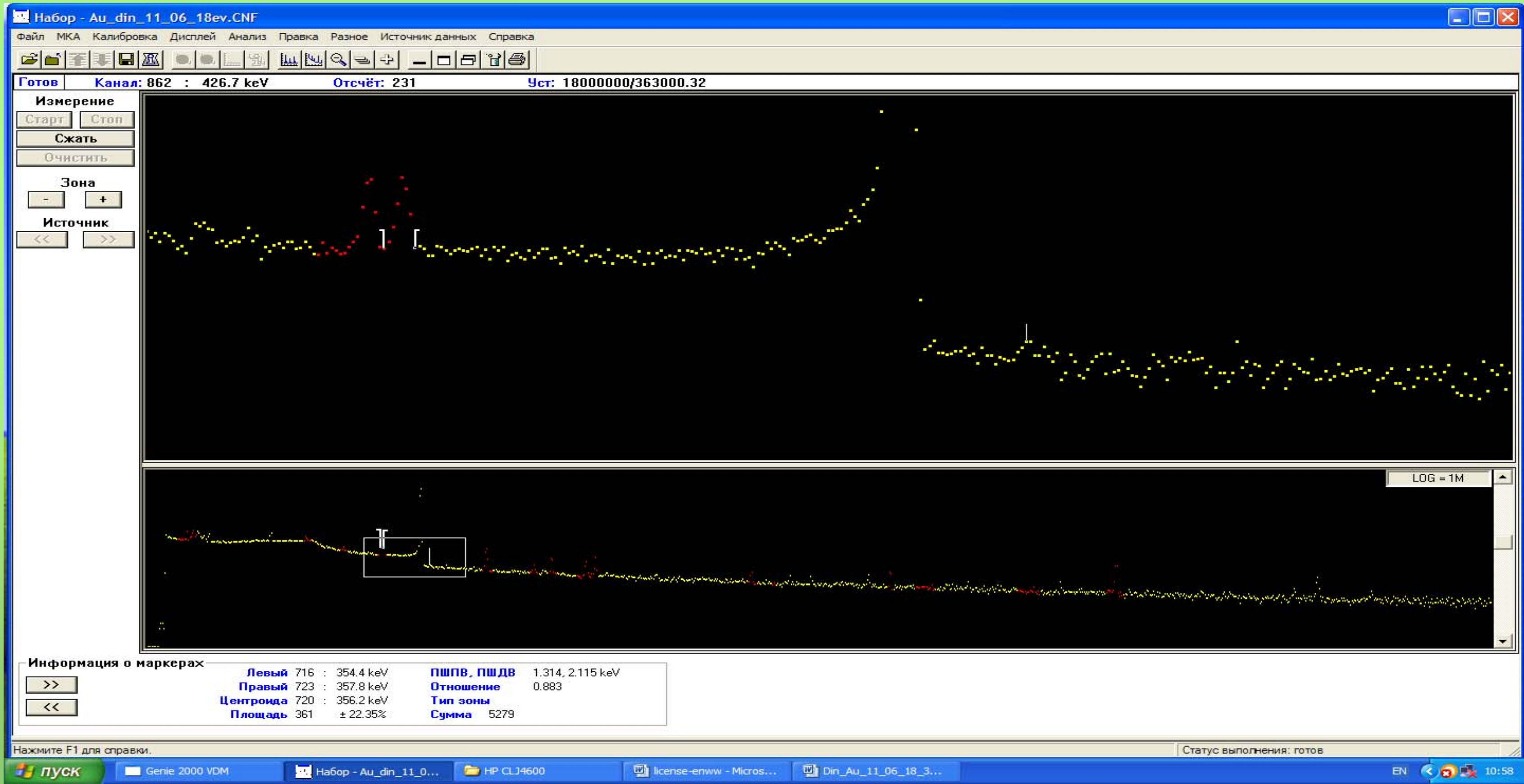


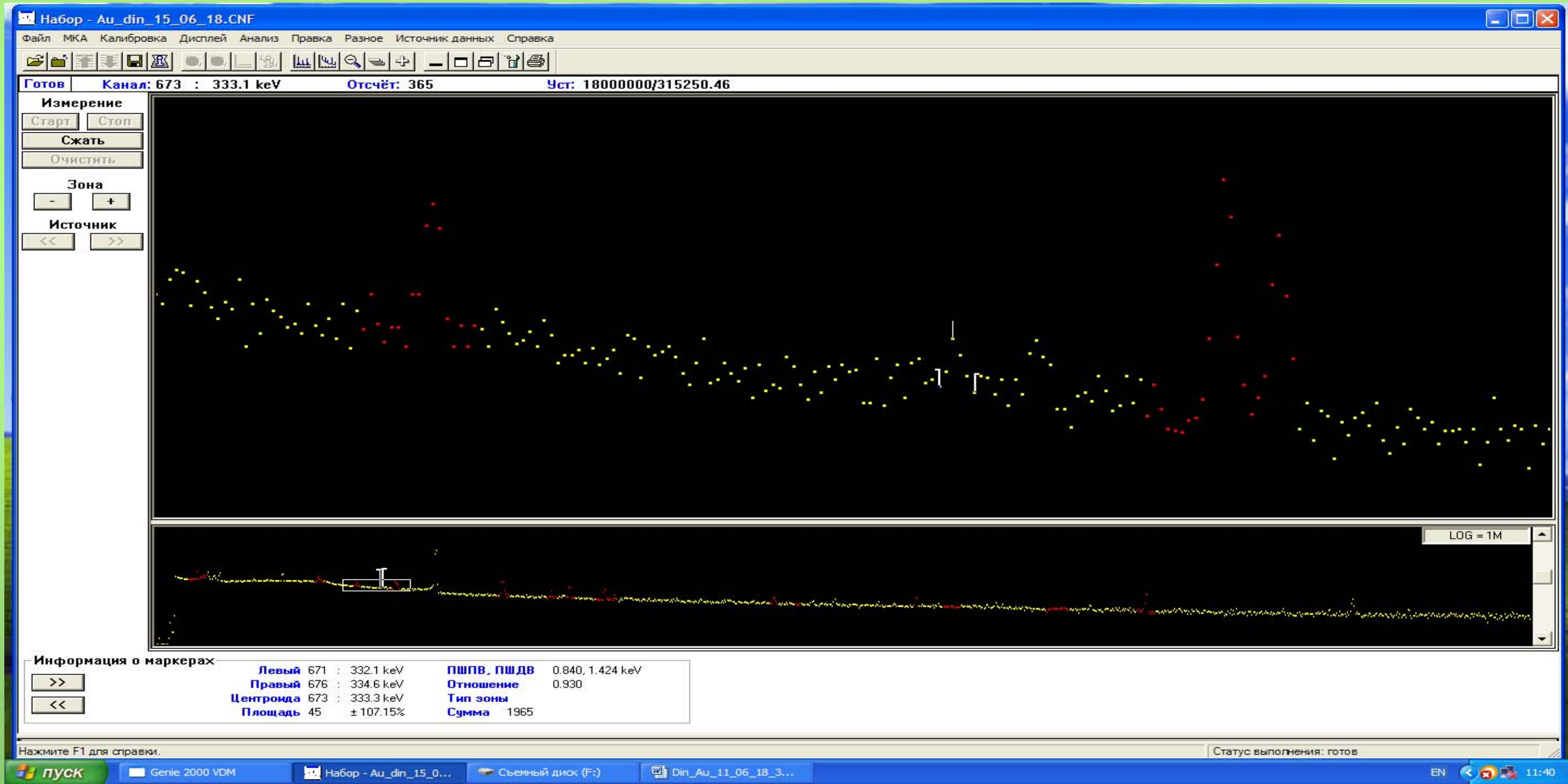
Au- irradiation: in cooperation with Atomki, Hungary

- E_γ=355.73 keV; k_γ=87%, statistical significance: 6.2 σ
- For neutron energy [6.175 ÷ 6.455] MeV: CS=0.037±0.008 mb



Au- irradiation: in cooperation with Atomki, Hungary

- E_{γ}=333.03 keV; k_{γ}=22.9%, statistical significance: 3.7 σ



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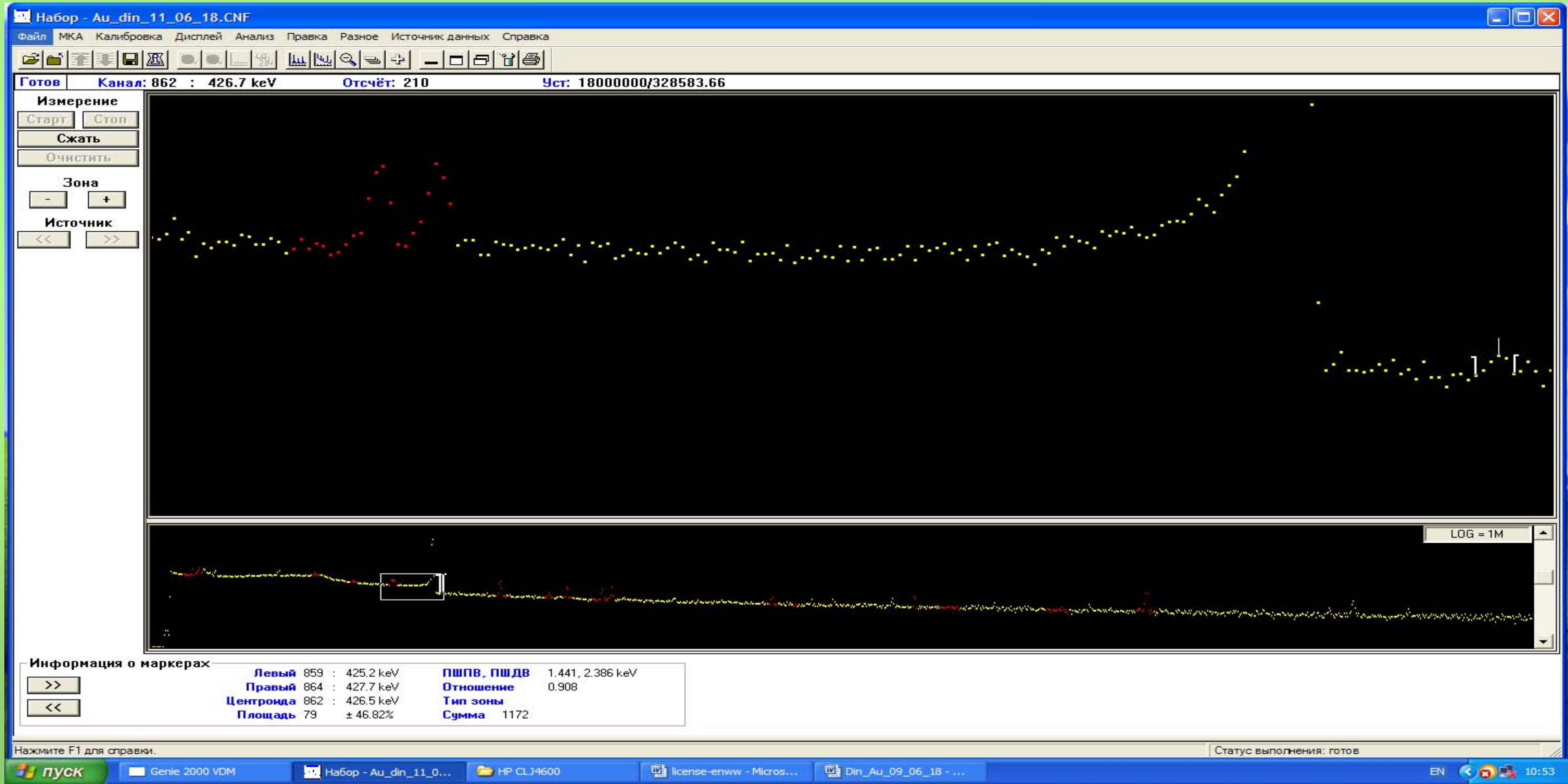
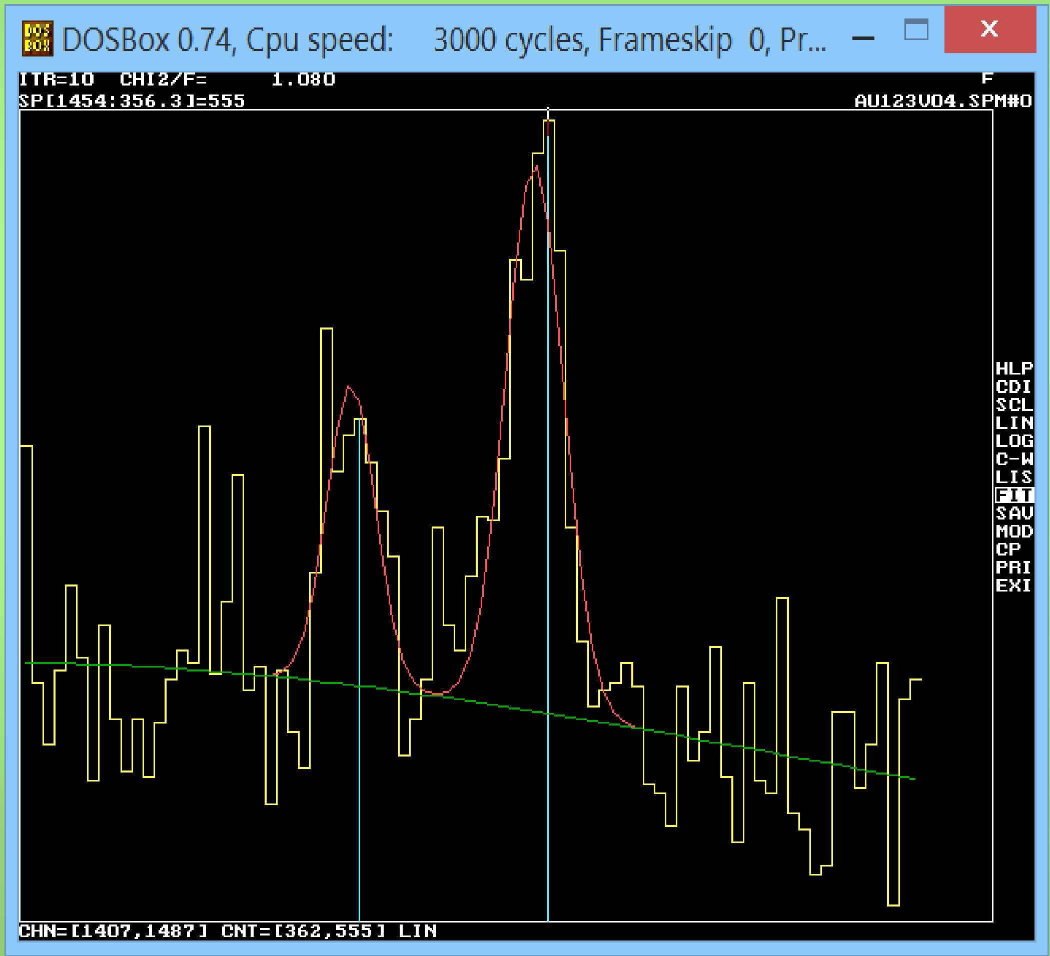
Au- irradiation: in cooperation with Atomki, Hungary

- E_{γ}=426.10 keV; k_{γ}=6.6%, statistical significance: 3.8 σ



Au- irradiation: in cooperation with Atomki, Hungary



- **Neutron energy range: [6.09 - 6.39] MeV**
- **Second set of Au foils**
- **Statistical significance:**
- ***E_γ*=355.73 - <u>9.3 *σ*</u>;**
- ***E_γ*=333.03 keV - <u>3.3 *σ*</u>**

- **Cross section estimate:**

  0.18 ± 0.06 mb

- **Results presented at ND2019: May 22, Beijing** iNSC of Ukraine

Measurements of Tb -sample (n,γ) induced activity

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Cross section measurement of the $^{159}Tb(n,\gamma)Tb^{160}$ nuclear reaction

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Abstract

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Measurements of Tb -sample (n,γ) induced activity

- **In the instrumental gamma spectrum due to ^{160}Tb decay, three the most powerful gamma lines are expected to be present:**
  - **298.58 keV (26.1%);**
  - **879.38 keV (30.1%);**
  - **966.17 keV (25.1%).**
- **879.38 keV peak was selected for our consideration:**
  - **its very good "purity";**
  - **absence of any unexpected contributions like from the background (300.1 keV of ^{212}Pb, ^{231}Pa and ^{227}Th might distort a peak area of 298.58 keV line);**
  - **absence of overlapping peak structures (962.3 keV (9.81%) of ^{160}Tb as well as 964.77 keV (4.99%) and 968.71 keV (15.8%) of ^{228}Ac may also contribute to 966.17 keV full absorption peak).**
- **Two other peaks were double-checked in the instrumental gamma-ray spectra for their presence: to be sure ^{160}Tb was reliably identified in a current spectrum.**

Measurements of Tb -sample (n,γ) induced activity

- **Three spectrometers were utilized for this study:**
  - **GC1212 with HPGe detectors at IRSN, Cadarache;**
  - **GX4019 at Kyiv Institute for Nuclear Research of National Academy of Sciences of Ukraine (KINR)**
  - **GC2020 at Department of Nuclear Physics, Taras Shevchenko National University of Kyiv, Ukraine (NUK).**
- **First instrumental spectrum was acquired within first 6 hours after the end of Tb sample neutron irradiation, last one – about 2.5 years later.**
- **In the background measurement during 420,043.12 s with GC2020 spectrometer in April 2016, zero counts of peak area were detected within 875÷885 keV region of interest.**

Measurements of Tb -sample (n,γ) induced activity

No. of count.	HPGe spectrometer / location	$T_{cool.}$, days	Start date of measurement	$T_{count.}$, s live/real	S_p, counts	ΔS_p, %
1.	GC1212/IRSN	0.097384	06 Dec 2013	11,136.39 / 11,146.54	486	4.75
2.	GX4019/KINR	12.375	18 Dec 2013	23,223.14 / 23,230.55	3,248	2.8
3.	GX4019/KINR	434.09	13 Feb 2015	602,386.59 / 602,516.90	2,151	3.7
4.	GC2020/NUK	532.2688	22 May 2015	946,320.82 / 946,523.93	973	6.2
5.	GC2020/NUK	575.0037	04 Jul 2015	2,003,882.66 / 2,004,379.4	1,235	5.5
6.	GC2020/NUK	624.00	22 Aug 2015	1,056,547.79 / 1,056,816.89	447	12.3
7.	GC2020/NUK	864.3324	18 Apr 2016	408,165.48 / 408,241.57	72	39.2

- $T_{cool.}$ corresponds to cooling time before measurements;
- $T_{count.}$ - to live/real counting times of Tb sample;
- S_p stays for 879.38 keV gamma-line peak area detected in a current spectrum;
- ΔS_p – gamma-line peak area uncertainty, in %.

Measurements of Tb -sample (n,γ) induced activity

- **With computed efficiency values we calculated activity *A*(*t*) of Tb – irradiated sample for ^{160}Tb isotope**
- **It was assigned to the moment of the end of corresponding spectrum counting**
- **The reference values of ^{160}Tb activity $A^r(t)$ was calculated:**

$$A^r(t) = A_0 \cdot \exp\left[-\frac{\ln 2}{T_{1/2}} \cdot t\right]$$

where $T_{1/2}$ is half-life of ^{160}Tb decay

Measurements of Tb -sample (n,γ) induced activity

- A_0 was estimated as averaged value of A_0* and A_{ver}
- A_0* was derived from the very first counting at IRSN Cadarache and equals 20.1 ± 1.9 Bq
- A_{ver} was calculated from irradiation by:

$$A_{ver} = \frac{\ln 2}{T_{1/2}} \cdot \sigma \cdot \varphi \cdot \frac{m_{Tb}}{\mu} \cdot N_A$$

where cross section σ, neutron flux density φ and m_{Tb} (mass of Tb - irradiated sample) were taken as per 6.85 MeV neutron energy for (n, γ) reaction; μ - is Tb molar mass and N_A is the Avogadro number.

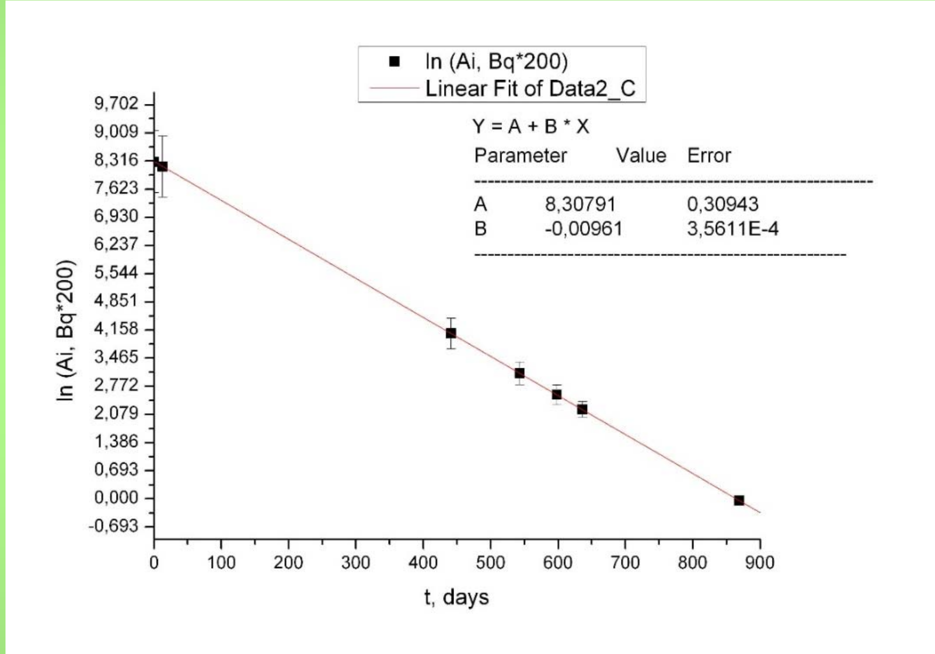
- Our calculation gave the following estimate: A_{ver} = 19.7 ± 7.7 Bq.

Measurements of Tb -sample (n,γ) induced activity

No. of counting	$A_i(t)$, Bq i=1,…,7	$\Delta A_i(t)$, Bq	A_i^r, Bq	ΔA_i^r, Bq	$R_i=A_i(t)/A_i^r$	ΔR_i
1.	20.1	1.1	20.1	1.8	1.00	0.11
2.	17.8	0.6	17.8	1.6	1.00	0.10
3.	0.45	0.02	0.29	0.03	1.55	0.16
4.	0.27	0.02	0.11	0.01	2.48	0.30
5.	0.16	0.01	0.065	0.006	2.52	0.29
6.	0.22	0.02	0.045	0.004	4.94	0.69
7.	0.047	0.019	0.0048	0.0004	9.76	3.93

Measurements of Tb -sample (n,γ) induced activity

Fitting of reference data activity calculations A_i^r

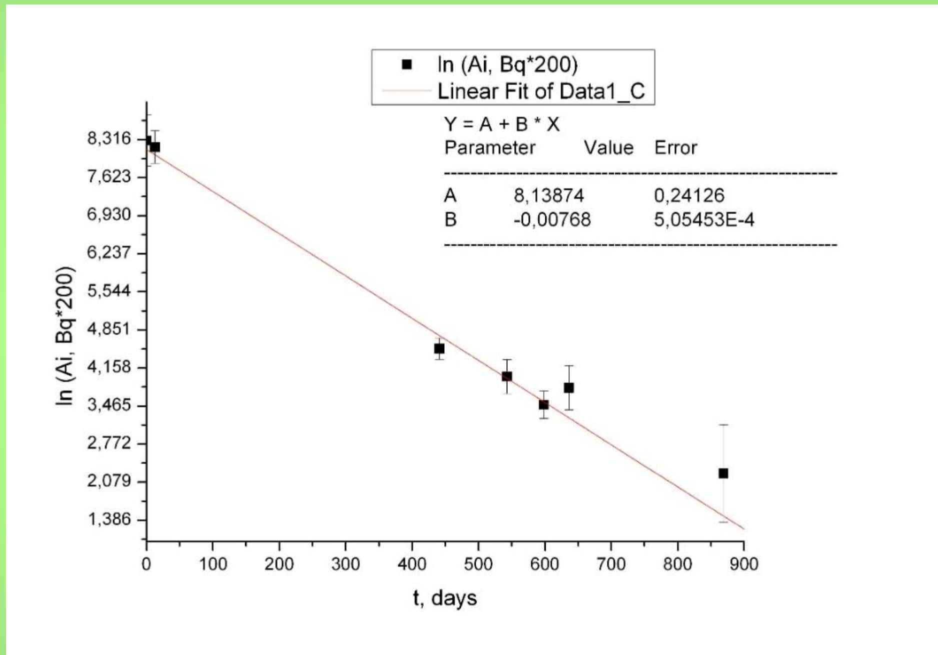


- **For verification we can easily derive an estimate of ^{160}Tb half-life from the following equation:**

$$T_{1/2} = \frac{\ln 2}{0.00961} = 72.18^{+3.72}_{-1.63} \text{ days}$$

Measurements of Tb -sample (n,γ) induced activity

- **Fitting of measured data A(t) activity results**



- **Got the following estimate of new "modified" ^{160}Tb half-life which is certainly different from expected value of ^{160}Tb half-life above:**

$$T^{m}{}_{1/2} = \frac{\ln 2}{0.00768} = 90.25^{+6.36}_{-5.57}\,\text{days}$$

Measurements of Tb -sample (n,γ) induced activity

- **Then calculated activity of ^{160}Tb A_{fus} due to the reaction between ^{158}Tb and $_0{}^2n$ or ^{158}Gd and d:**

A_{fus} (t = 869.0574 days) = $A(t) - A_r(t)$ = 0.047 – 0.0048 = = 0.0422 ± 0.017 Bq.

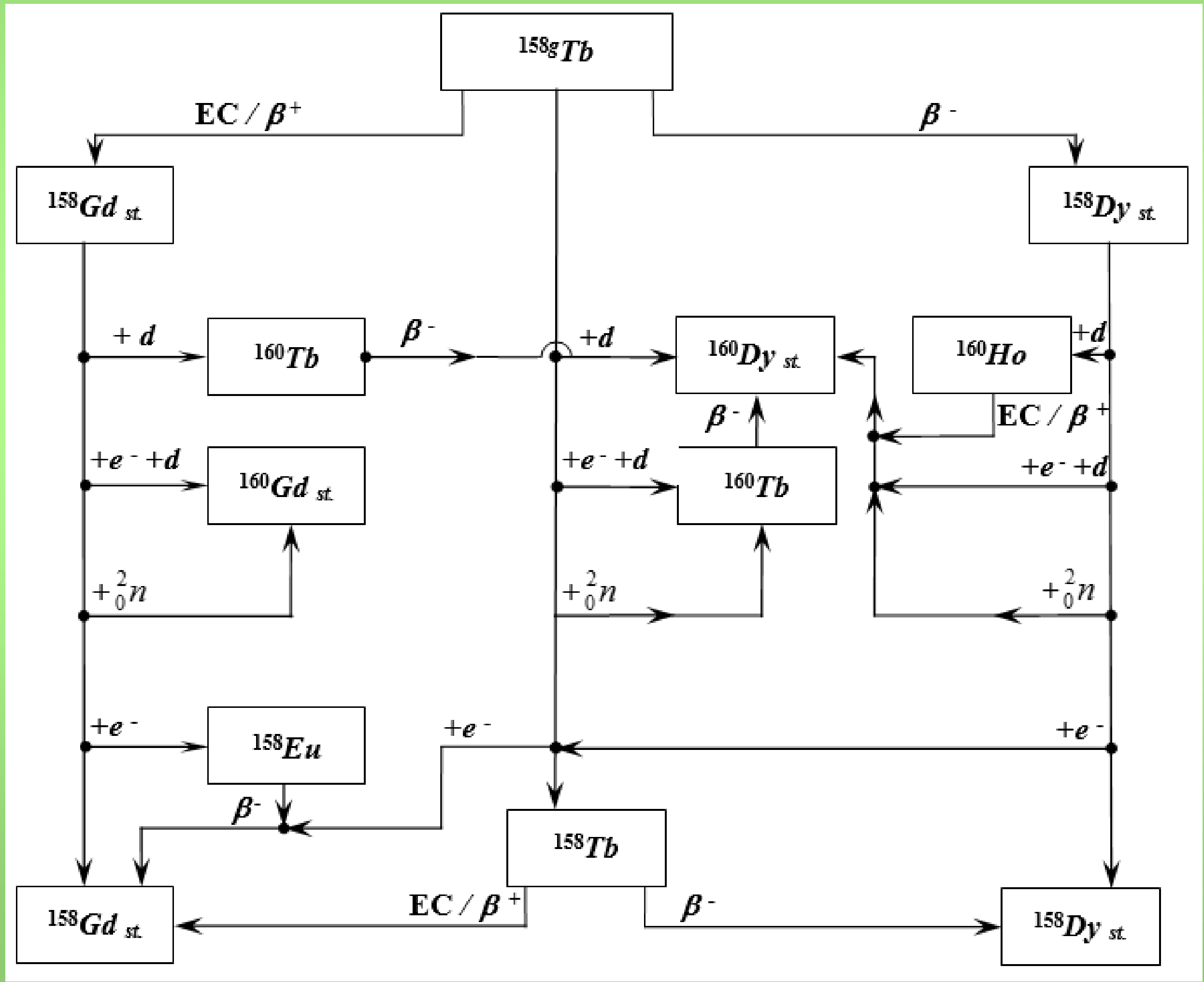
- **The current balance of ^{160}Tb nuclei in our sample for a permanent accumulation with a constant fusion reaction rate r:**

$$A(t) = A_0 \cdot \exp\left[-\frac{\ln 2}{T_{1/2}} \cdot t\right] + A_{fus}(t),$$

where

$$A_{fus}(t) = r_1 \cdot \left[1 - \exp\left(-\frac{\ln 2}{T_{1/2}} \cdot t\right)\right] + r_2 \approx r_1 + r_2, \quad \left(t >> T_{1/2}\right).$$

Hypothesis and justification of LENR observation



Hypothesis and justification of LENR observation

- ^{158g}Tb as a nuclear reaction ^{159}Tb (n,^2n) product is EC and β^+-decaying in 83%, β^-- in 17% of total decays
- Dineutron decay: $^{2}n \to d + e^{-} + \tilde{\nu}_e$
- Possible reaction: ^{158g}Tb + e^- → ^{158} Gd (stable):

$$\begin{cases} \dfrac{dN_{dn}(t)}{dt} = -\lambda_{dn} \cdot N_{dn}(t) \\ \dfrac{dN_{Tb}(t)}{dt} = -\lambda_{Tb} \cdot N_{Tb}(t) - \lambda_{dn} \cdot P \cdot N_{dn}(t) \end{cases},$$

$$N_{dn}(t) = N_0 e^{-\lambda_{dn} t} \qquad N_{Tb}(t) = \frac{P\lambda_{dn}}{\lambda_{dn} - \lambda_{Tb}} N_{dn}(t) + N_0 \frac{\lambda_{dn}(1-P) - \lambda_{Tb}}{\lambda_{dn} - \lambda_{Tb}} e^{-\lambda_{Tb} t}$$

- For a dineutron half-life it is possible, that during first ~100 s: $N_{Tb}(t) \approx N_{dn}(t)$ ⇨ <u>$A_{Tb}(t) = \lambda_{Tb} N_0 \exp(-\lambda_{dn} t)$.</u>
- <u>I.Kadenko, APPB Vol.50 (2019) , No.1, pp. 55-64</u>

Hypothesis and justification of LENR observation

- **Get the following value of reaction rate (1/s) in our Tb sample from previous equation: *r* = 0.037 1/s.**

- **Assume, that the projectile (*d*) and target nuclei (^{158}Gd) are in thermal equilibrium and follow a Maxwell-Boltzmann relative velocity distribution:**

$$\Phi(\nu) = 4\pi \cdot \left(\frac{\mu_{Gd-d}}{2\pi \cdot k \cdot T_R} \right)^{3/2} \cdot \nu^2 \cdot \exp\left(-\frac{\mu \cdot \nu^2}{2k \cdot T_R} \right)$$

where $m_{Gd\text{-}d}$ is the reduced mass: $\mu_{Gd-d} = (m_d \cdot M_{Gd})/(m_d + M_{Gd})$

k is the Boltzmann constant and T_R is a room temperature.

Hypothesis and justification of LENR observation

- **A reaction rate for fusion is:**

$$r = N_{Gd} \cdot N_d / V \cdot \int_0^{\infty} \Phi(v) \cdot \sigma_{fus}(v) dv = N_{Gd} \cdot N_d \cdot \sigma_{fus} \cdot v_{th} / V$$

where $N_{Gd} = N_d$ are numbers of Gd and *d* - nuclei in our sample and these values can be calculated from:

$$N_{Gd} = \frac{P \cdot \lambda_{dn}}{\lambda_{dn} - \lambda_{Tb}} \cdot N_0 \cdot (1 - \exp[-\lambda_{dn} \cdot t]) + k_2 \cdot \frac{\lambda_{dn}(1-P) - \lambda_{Tb}}{\lambda_{dn} - \lambda_{Tb}} \cdot N_0 \cdot (1 - \exp[-\lambda_{Tb} \cdot t])$$

σ_{fus} (v) - fusion cross section; V - volume of Tb sample; σ_{fus} and v_{th} – averaged fusion cross section and thermal velocity, accordingly.

Hypothesis and justification of LENR observation

- **Can evaluate averaged relative thermal velocity with the following parameters: T_R = 293.6 ° K; $m_{Gd\text{-}d}$=3.3·10^-27^kg.**
- **We have:** $$\langle v_{th} \rangle = \sqrt{\frac{2k \cdot T_R}{\mu_{Gd-d}}} = 1{,}567 \text{ m/s} = 1.567 \cdot 10^5 \text{ cm/s}$$

where $N_{Gd} = N_d$ are numbers of Gd and *d* - nuclei in our sample and these values can be calculated from:

- **Knowing *r*, N_{Gd} and N_d, N_{Tb} and N_d, can calculate the resulting reaction rate $< s_{fus}, n_{th} > = rV/(N_{Gd})^2$.**
- **The estimates of averaged fusion cross-section for dineutron half-life within 1-10^6 s, depending on different *P*.**

Hypothesis and justification of LENR observation

- **Nuclei accumulation vs probability *P* and fusion cross sections**

N_0	P	t, days	N_{Dy}	$N_{Tb}=N_{dn}$	$N_{Gd}=N_d$	Sig_{fus}, b
2.70E+08	0.0	869.0574	4,09E+05	2.68E+08	2.04E+06	200.5
2.70E+08	0.2	869.0574	3.27E+05	2.14E+08	5.56E+07	269.5
2.70E+08	0.3	869.0574	2.86E+05	1.87E+08	8.24E+07	122.8
2.70E+08	0.5	869.0574	2.04E+05	1,34E+08	1.36E+08	45.1
2.70E+08	0.7	869.0574	1.23E+05	8,02E+07	1.89E+08	23.2
2.70E+08	0.9	869.0574	4.08E+04	2,67E+07	2.43E+08	14.1
2.70E+08	1.0	869.0574	0	0	2.70E+08	11.4

- **Cross-section estimate for ^{158}Tb + *d* → ^{160}Dy : 11.6 b**

Conclusions

- **Experimentally proved the possibility of dineutron existence in a bound state as a particle-satellite of the nucleus in the outgoing channel of nuclear reactions on ^{159}Tb with neutrons in the input channel**
- **Independently and statistics significantly observed the dineutron in the outgoing channel of the ^{197}Au (n,^{2}n) ^{196}Au nuclear reaction**
- **Assumption is made and proved about a possible interaction of dineutron decay products with the heavy nucleus in the outgoing channel to consume ^{158}Tb nuclei and convert them into ^{160}Tb/ ^{160}Dy**
- **This process represents LENR – being observed at room temperature conditions with possible high enough cross sections**

Many thanks for your time, attention and questions!