Taras Shevchenko National University of Kyiv

A new type nuclear reaction considering observation of a bound dineutron in the outgoing channel

Prof. I.M. Kadenko

Head, Department of Nuclear Physics

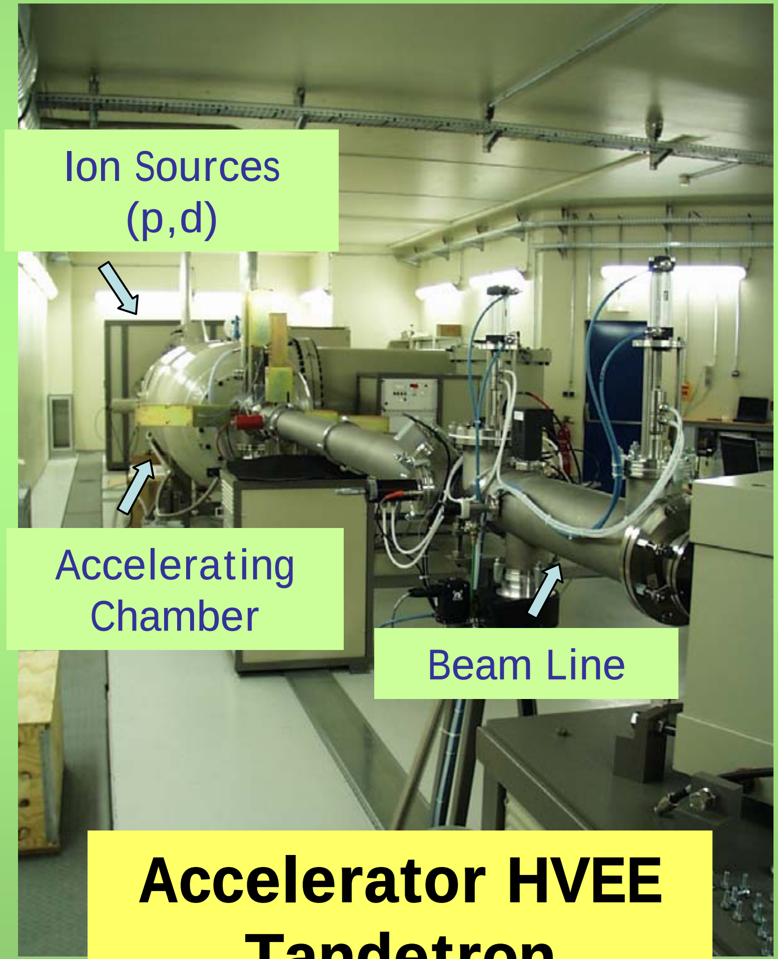
Faculty of Physics, Taras Shevchenko National University of Kyiv

French-Ukrainian Workshop, 26-28 September, LAL, France, 2018

Outline

- Ukraine-France cooperation: INSC of Ukraine - IRSN
- Experimental results
- Hypothesis on a bound dineutron existence
- Theoretical prerequisites
- Last years researches
- Latest results
- Conclusions

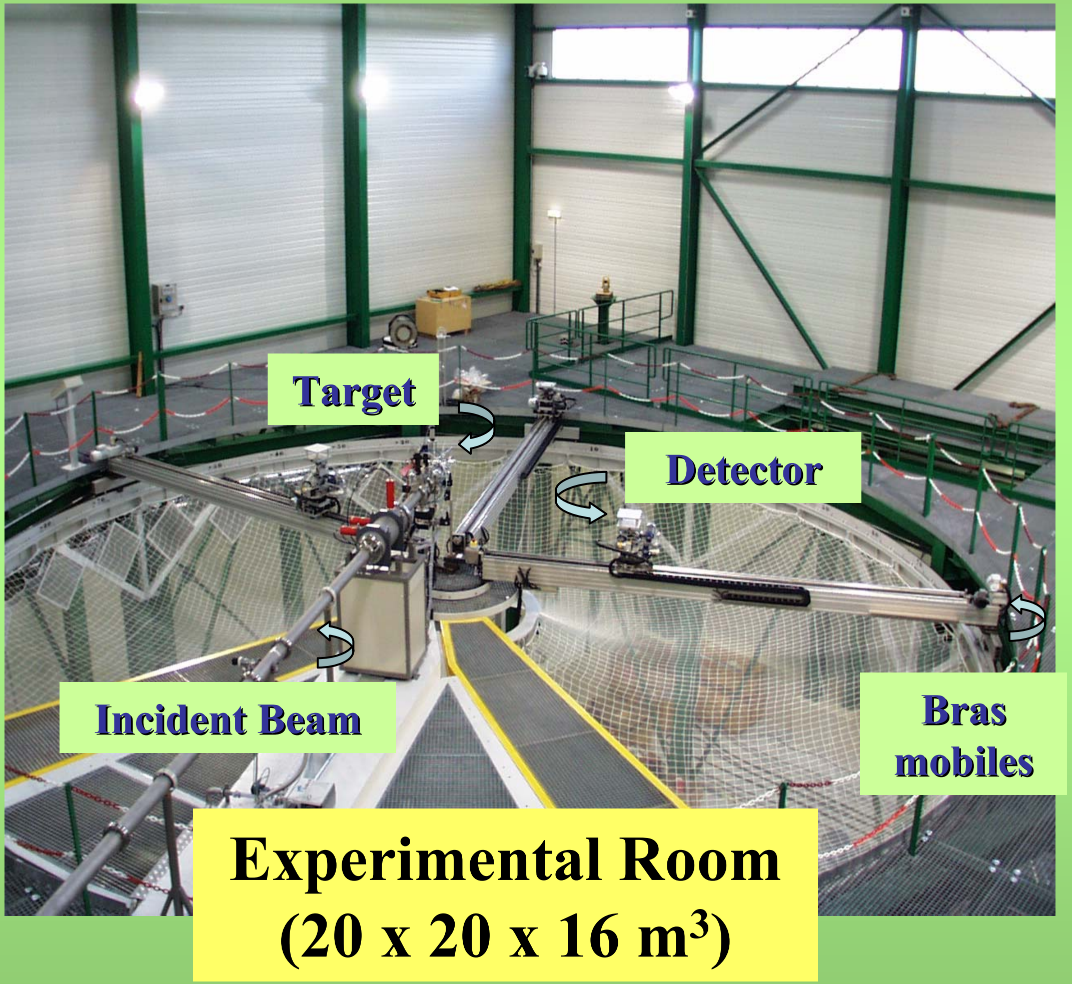
Ukraine-France cooperation: INSCU-IRSN



Accelerator HVEE Tandetron

- **Pattern source of mono energetic neutrons for energy range 2 keV - 20 MeV**

Ukraine-France cooperation: INSCU-IRSN



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

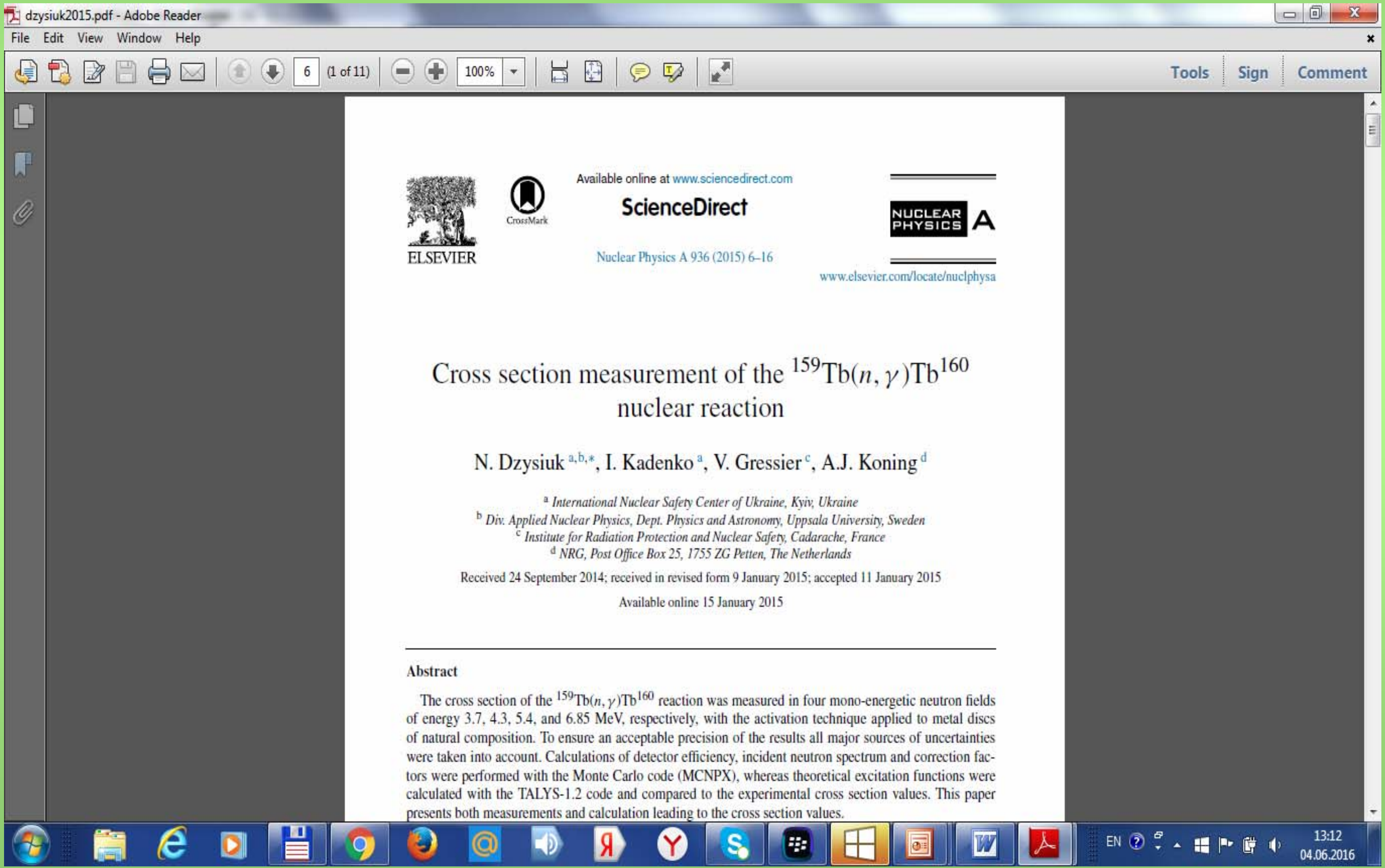
- **AMANDE – neutron generation facility for neutron irradiation: Cadarache, IRSN, France**
- **Outstanding conditions for (*n*,*γ*) cross-section measurements**
- **Utilization of (D,D) reaction with fixed target to irradiate Tb samples with 3 - 7 MeV neutrons**

Ukraine-France cooperation: INSCU-IRSN

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).

Published: N.Dzysiuk, I.Kadenko, V.Gressier, A.J.Koning. Cross section measurement of the ^{159}Tb(n,γ)^{160}Tb nuclear reaction. Nucl. Phys. A 936 (2015), pp. 6-16

Ukraine-France cooperation: INSCU-IRSN



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

N. Dzysiuk [a,b,*], I. Kadenko [a], V. Gressier [c], A.J. Koning [d]

[a] International Nuclear Safety Center of Ukraine, Kyiv, Ukraine
[b] Div. Applied Nuclear Physics, Dept. Physics and Astronomy, Uppsala University, Sweden
[c] Institute for Radiation Protection and Nuclear Safety, Cadarache, France
[d] NRG, Post Office Box 25, 1755 ZG Petten, The Netherlands

Received 24 September 2014; received in revised form 9 January 2015; accepted 11 January 2015

Abstract

The cross section of the $^{159}\text{Tb}(n,\gamma)\text{Tb}^{160}$ 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.

Ukraine-France cooperation: INSCU-IRSN

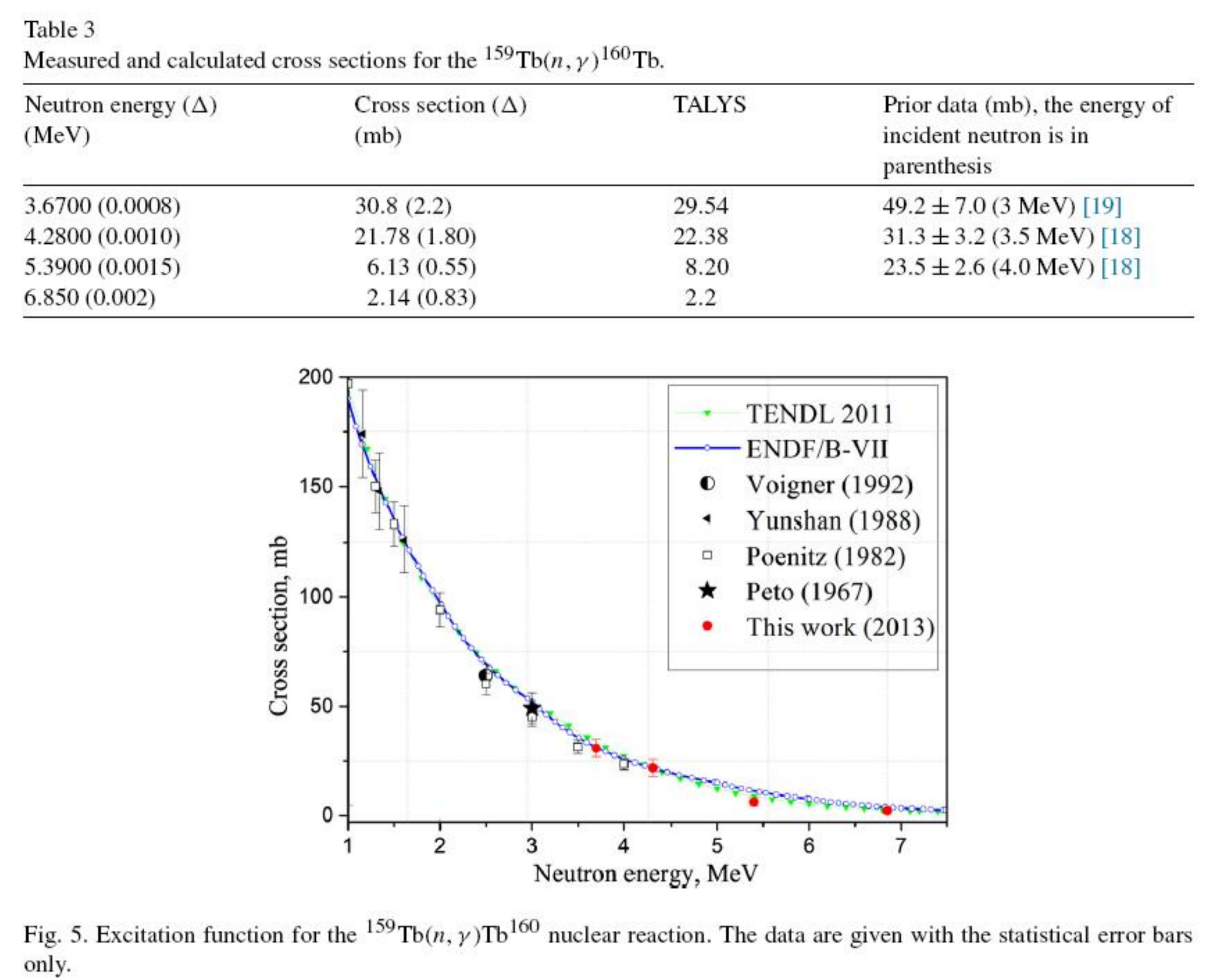


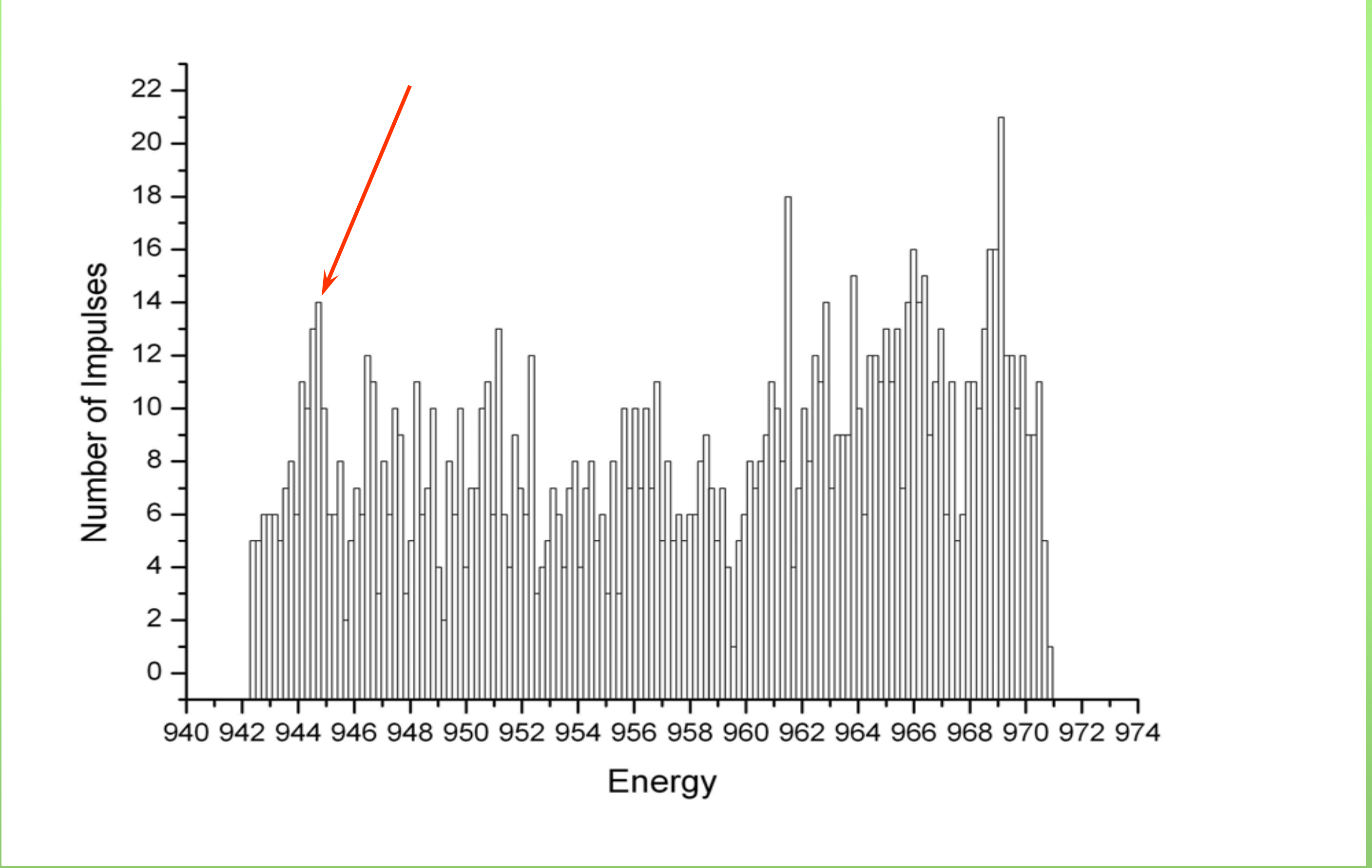
Table 3
Measured and calculated cross sections for the ^{159}Tb$(n, \gamma)^{160}$Tb.

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	

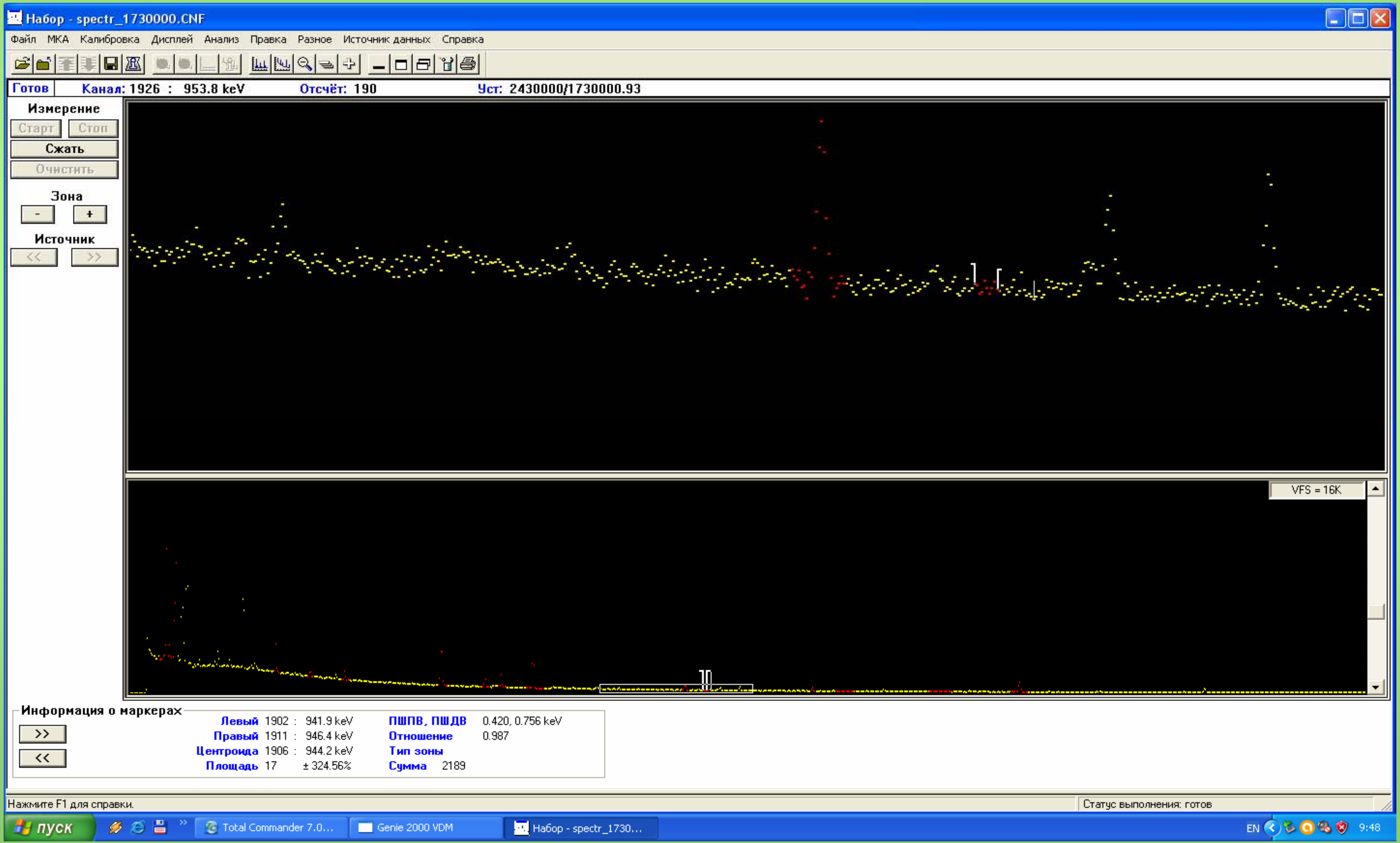
Fig. 5. Excitation function for the ^{159}Tb(n, γ)Tb^{160} nuclear reaction. The data are given with the statistical error bars only.

Experimental results

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



Experimental results – background



```
Готов   Канал: 1926 :   953.8 keV     Отсчёт: 190          Уст: 2430000/1730000.93
```

```
      Левый 1902 :  941.9 keV     ПШПВ, ПШДВ    0.420, 0.756 keV
     Правый 1911 :  946.4 keV     Отношение     0.987
  Центроида 1906 :  944.2 keV     Тип зоны
    Площадь 17     ± 324.56%      Сумма     2189
```

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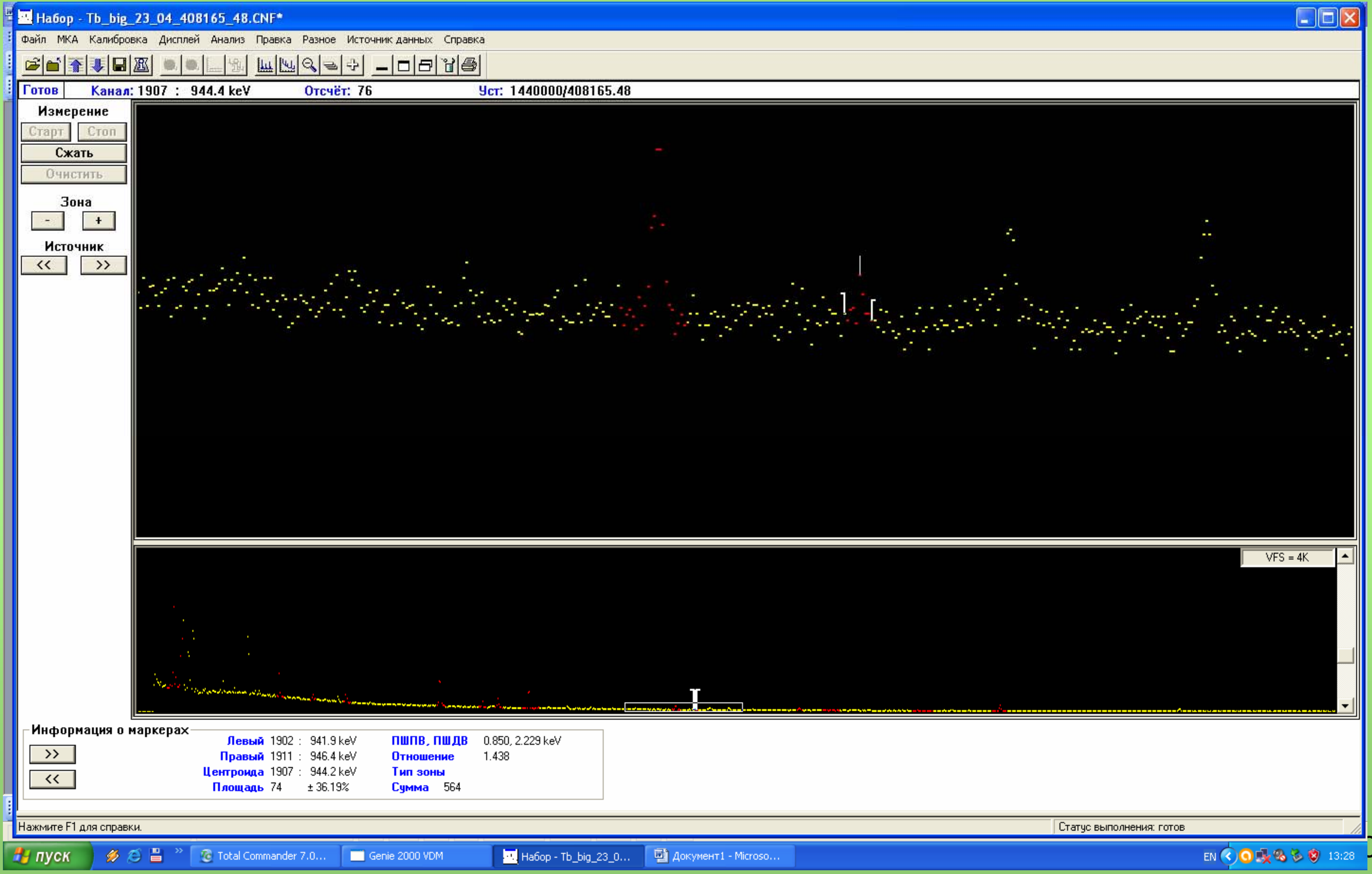
Experimental results – Tb sample measurements



Набор - Tb_big_23_04_408165_48.CNF*

Готов Канал: 1907 : 944.4 keV Отсчёт: 76 Уст: 1440000/408165.48

Информация о маркерах

Левый	1902 : 941.9 keV	**ПШПВ, ПШДВ**	0.850, 2.229 keV
Правый	1911 : 946.4 keV	**Отношение**	1.438
Центроида	1907 : 944.2 keV	**Тип зоны**	
Площадь	74 ± 36.19%	**Сумма**	564

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Статус выполнения: готов

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: 74 ± 36.19% for 408,165.48 seconds measurement.**

Experimental results

- **1.5 years of sample and background measurements;**
- **Very good results repeatability relating to the:**
  - **presence of 944.2 keV peak in instrumental gamma-spectra with the sample;**
  - **absence of 944.2 keV peak in background spectra.**
- **Appearance of peak-like structure with 944.2 keV energy for measurements from 400,000.00 s and up to 1,150,000.00 s.**
- **Value of neutron energy in Tb sample – 6.85 MeV.**
- **Gamma line with the biggest yield is fixed for decay of ^{158g}Tb.**
- **BUT: reaction threshold for ^{159}Tb(n,2n): 8.18 MeV or 1.3 MeV above the energy of neutrons in Tb sample!!!**

Experimental results

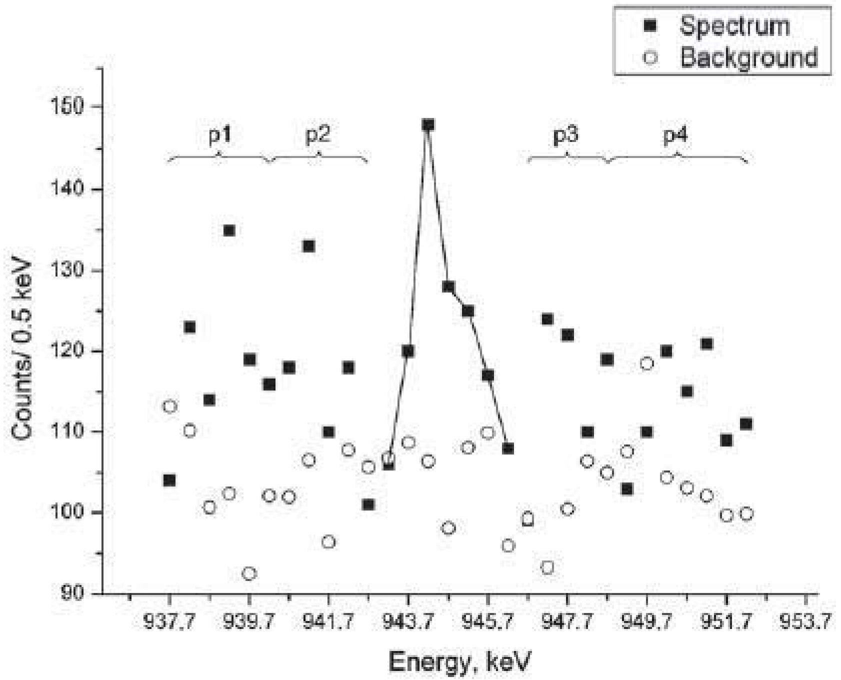


Fig. 2: ROI with 944.2 keV ($I\gamma = 0.439$) peak of ^{158}Gd.

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

Hypothesis on a bound dineutron existence

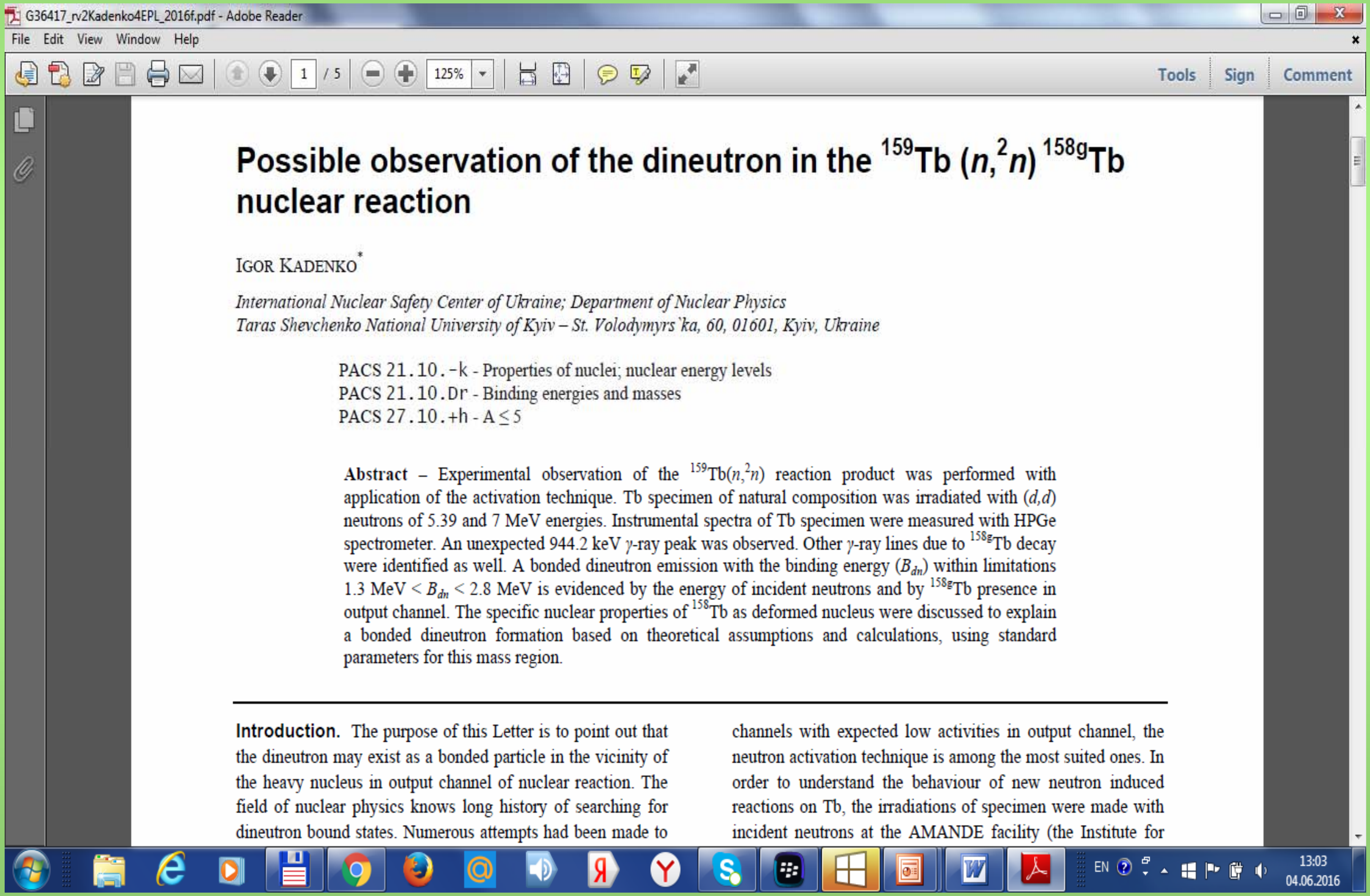
- Analogously to the threshold of (*n*,*d*) reaction, which is 2.225 MeV lower of (*n*,*np*) reaction threshold due to the binding energy of the deuteron

- Interval estimate of the binding energy for the dineutron:

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

- Published in: Igor Kadenko. Possible observation of the dineutron in the ^{159}Tb(n, ^{2}n)^{158g}Tb nuclear reaction. EPL, 114 (2016) 42001

Hypothesis on a bound dineutron existence



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

IGOR KADENKO*

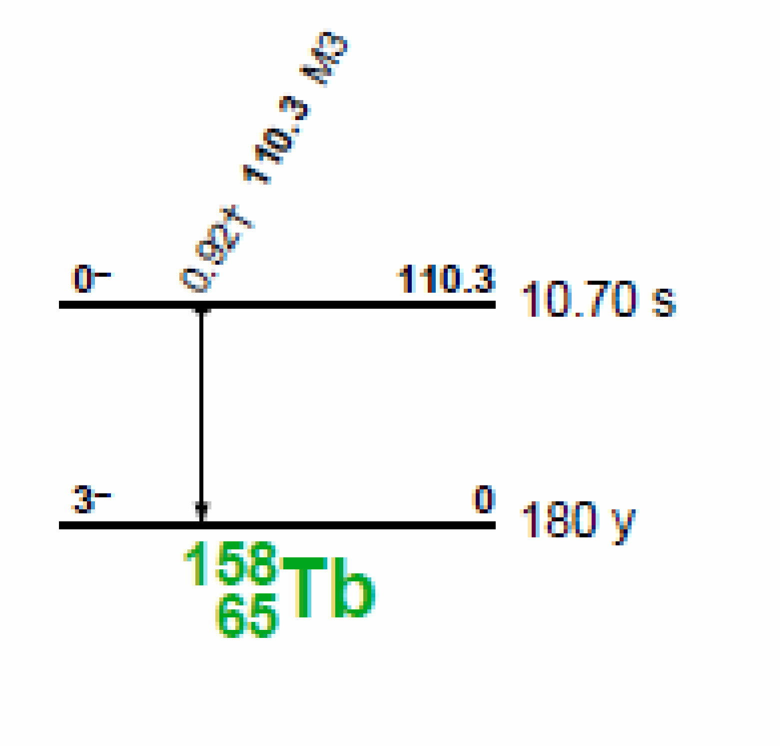
International Nuclear Safety Center of Ukraine; Department of Nuclear Physics
Taras Shevchenko National University of Kyiv – St. Volodymyrs`ka, 60, 01601, Kyiv, Ukraine

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

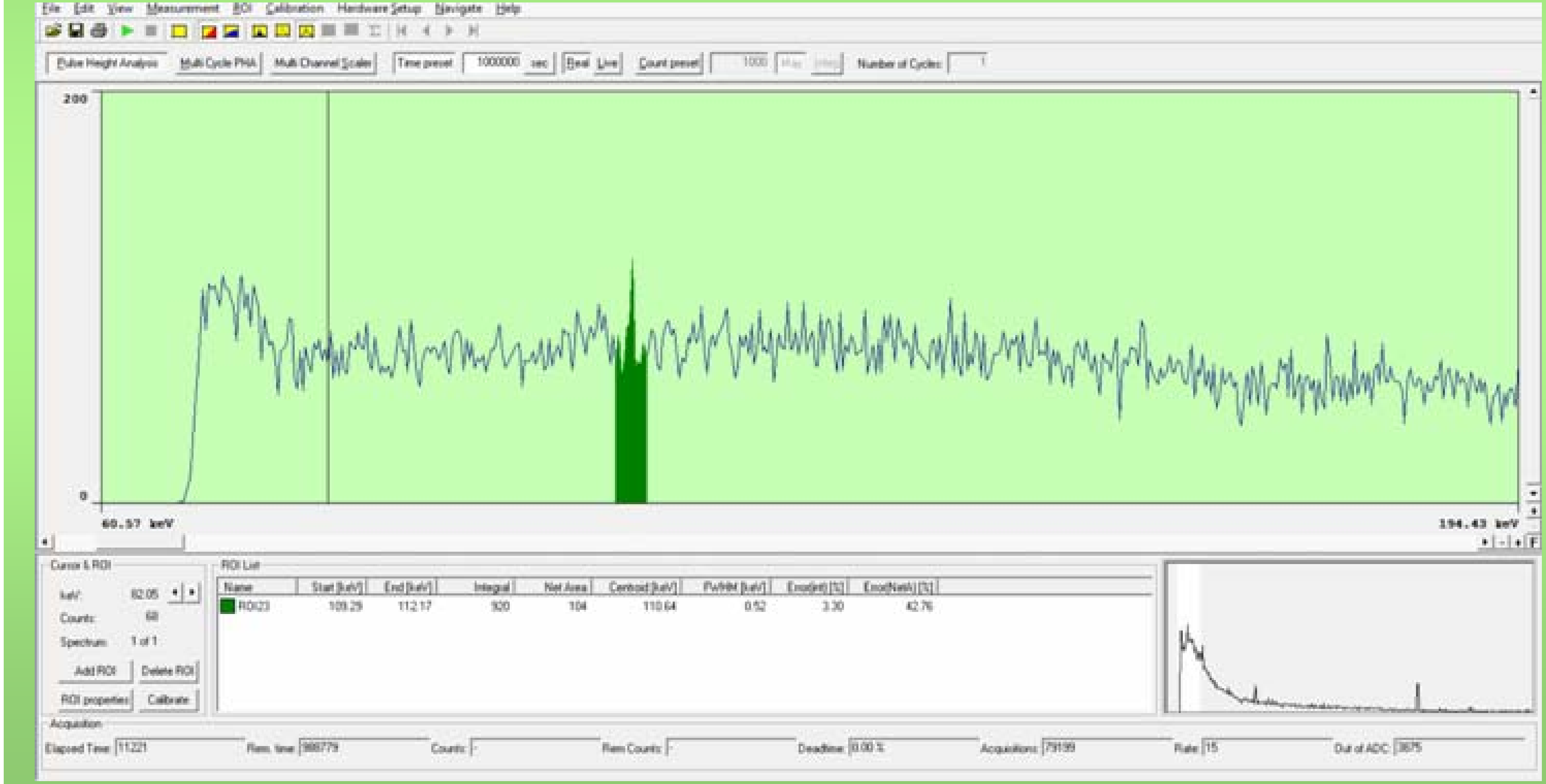
Abstract – Experimental observation of the ^{159}Tb$(n,^{2}n)$ reaction product was performed with application of the activation technique. Tb specimen of natural composition was irradiated with (d,d) neutrons of 5.39 and 7 MeV energies. Instrumental spectra of Tb specimen were measured with HPGe spectrometer. 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

Hypothesis on a bound dineutron existence



Hypothesis on a bound dineutron existence (in cooperation with ATOMKI, Hungary: Dr. A.Fenyvesi, Mr.B.Biró)



Time preset: 1000000 sec

Count preset: 1000

Number of Cycles: 1

keV: 82.05

Counts: 68

Spectrum: 1 of 1

Name	Start [keV]	End [keV]	Integral	Net Area	Centroid [keV]	FWHM [keV]	Error(Int) [%]	Error(NetA) [%]
🟩 ROI23	109.29	112.17	920	104	110.64	0.52	3.30	42.76

Elapsed Time: 11221

Rem. time: 988779

Counts: -

Rem Counts: -

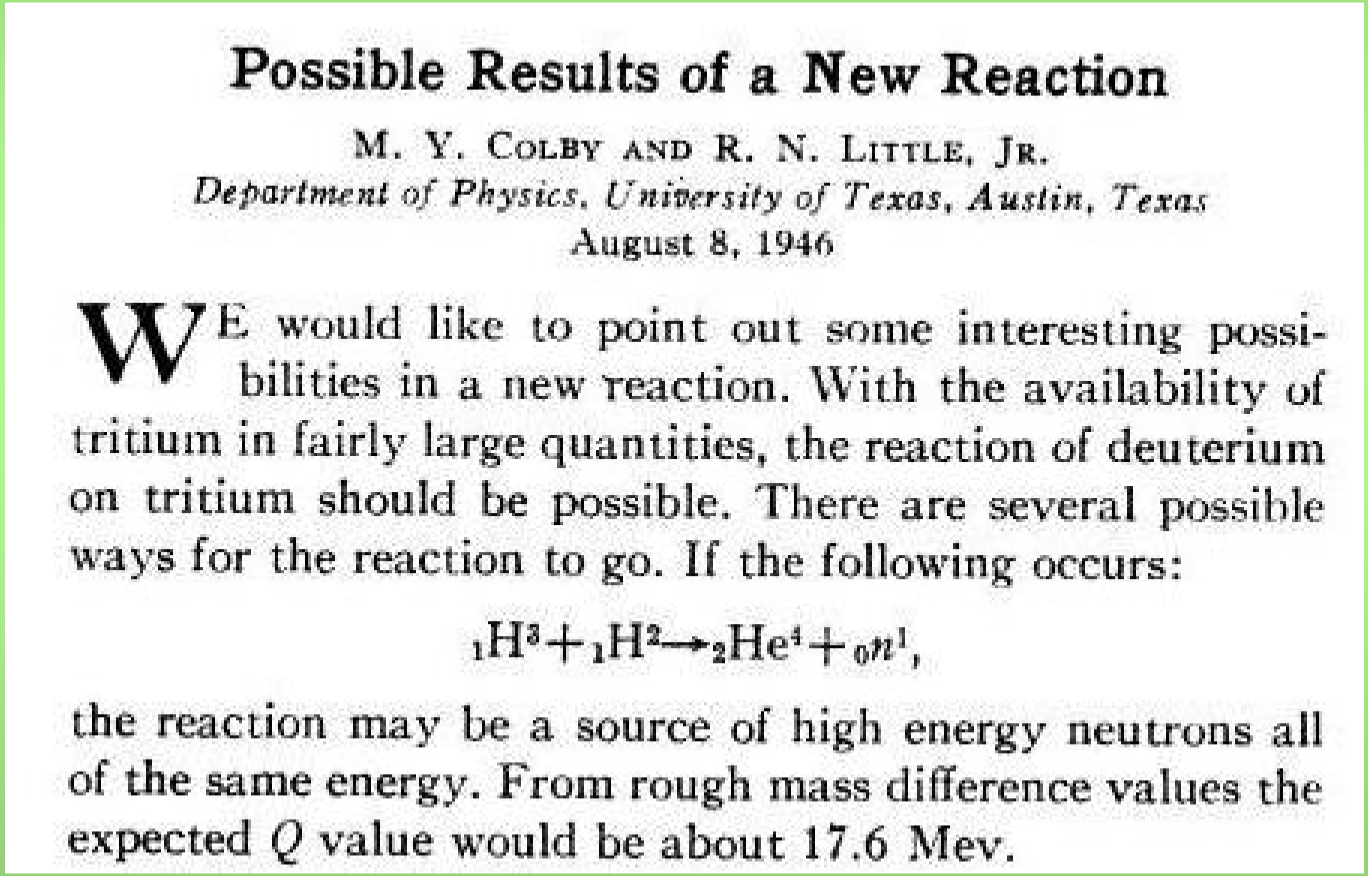
Deadtime: 0.00 %

Acquisitions: 79199

Rate: 15

Out of ADC: 3875

Hypothesis on a bound dineutron existence



Possible Results of a New Reaction

M. Y. Colby and R. N. Little, Jr.
Department of Physics, University of Texas, Austin, Texas
August 8, 1946

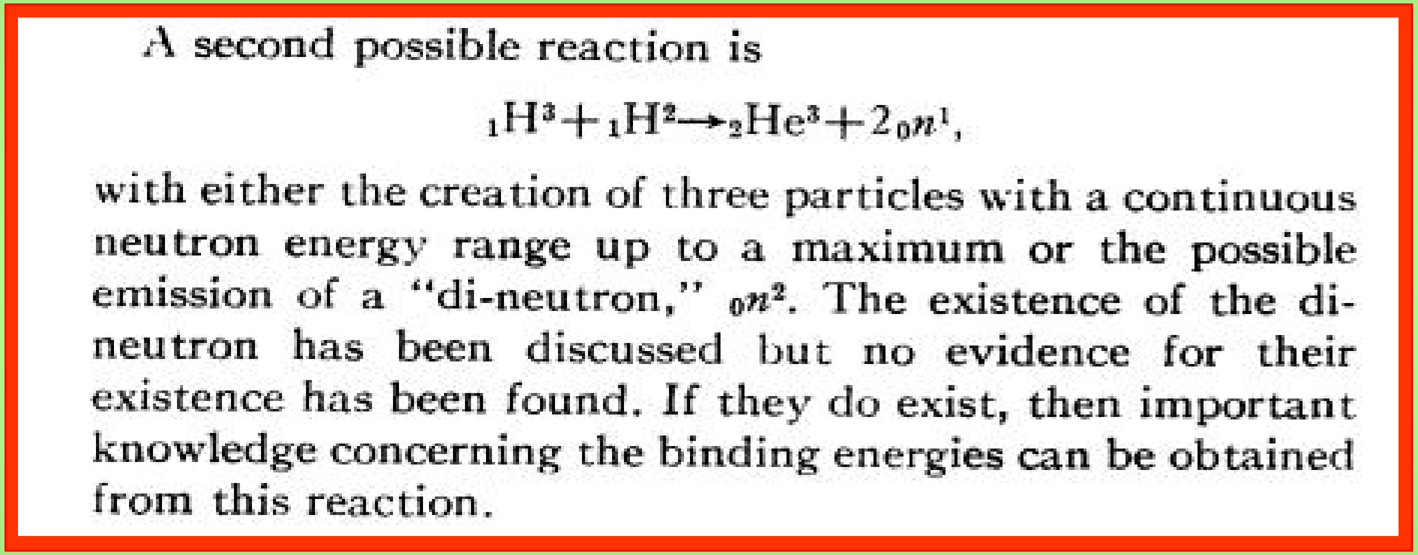
We would like to point out some interesting possibilities in a new reaction. With the availability of tritium in fairly large quantities, the reaction of deuterium on tritium should be possible. There are several possible ways for the reaction to go. If the following occurs:

$$ {}_1H^3+{}_1H^2\rightarrow{}_2He^4+{}_0n^1, $$

the reaction may be a source of high energy neutrons all of the same energy. From rough mass difference values the expected Q value would be about 17.6 Mev.

Published in: M. Y. Colby and R. N. Little. Phys. Rev. 70, 437 (1946)

Hypothesis on a bound dineutron existence



A second possible reaction is

$$ {}_1H^3+{}_1H^2\rightarrow{}_2He^3+2\,{}_0n^1, $$

with either the creation of three particles with a continuous neutron energy range up to a maximum or the possible emission of a "di-neutron," ${}_0n^2$. The existence of the di-neutron has been discussed but no evidence for their existence has been found. If they do exist, then important knowledge concerning the binding energies can be obtained from this reaction.

Published in : M. Y. Colby and R. N. Little. Phys. Rev. 70, 437 (1946)

Theoretical prerequisites

- **Hundreds of publications:**
  - **The dineutron was the subject to search since 1946 including reactions with light nuclei of Borromean type (^{6}He, ^{8}He, ^{7}Li, ^{11}Li, ^{11}Be, ^{14}Be, ^{17}B, ^{19}B, ^{22}C) as well in reactions on and in fission of heavy nuclei (A≥209)**
  - **Up-to-date research direction: dineutron correlations: "The di-neutron correlation is a spatial correlation with which two valence neutrons are located at similar position inside a nucleus"**
  - **Different estimates of dineutron binding energies: from dozens keV up to 3 MeV**

Theoretical prerequisites

- **Interpretation of dineutron states in light nuclei: including reference to 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**

▼

- ***"In a related development, Migdal (1972) has proved that a potential containing two interacting unbound particles allows many bound states if the particles are sufficiently close to the threshold. When this principle is applied to two neutrons loosely bound to a nucleus, the resulting states <u>can be interpreted as dineutrons at the nuclear surface</u>"*** **(A.S. Jensen et. al., REVIEWS OF MODERN PHYSICS, Vol. 76, January 2004)**

Theoretical prerequisites

- **Actually in this paper of A.B. Migdal:**
  - **“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 <u>the possible existence of a dineutron near the surface of some nuclei.</u>”**
  - **“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 energy range of additional states to bind the two neutrons in the dineutron according to Migdal:**

  [0÷0.4] MeV

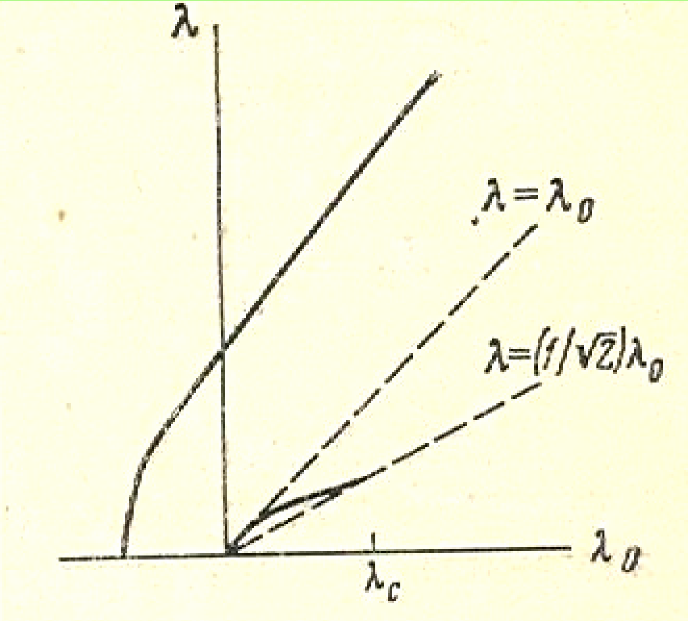
- **The mass range:**

  "The problem, solved in the present paper is a special case of the three-body problem, when one of the three particles has a considerably larger mass than the other two, so that the action of the heavier particle on the lighter ones can be considered as an external field."

- **Is this condition met for ^{6}He, ^{8}He, ^{7}Li… ???**

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 one-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***

Last years research

- **Paper of G.F.Steyn *et al, Nucl. Instrum. Methods Phys. Res., Sect. B*, 319 (2014), pp. 128-140:**
  - **The well-known stack-foil technique was employed for measurements of the ^{159}Tb (p,3n) ^{157}Dy reaction cross-sections within 14 - 66 MeV with 66 MeV initial energy of proton beam**
  - **Cross-section: σ_1=1.17±0,11 mb for Ep_1=15.47±1.78 MeB while the reaction threshold is: 17.14 MeV (only 0.11 MeV overlapping)**

Last years research

- **Paper of F.Tárkányi, A.Hermanne, F.Ditrói, S.Takács, A.V.Ignatyuk, *Appl. Radiat. Isot.*, 127 (2017), pp.7-15:**
  - **The same stack-foil technique, reaction: ^{159}Tb (p,3n) ^{157}Dy, the proton energy range: 5.5 - 34 MeV for incident proton beam energy 34 MeV**
  - **Cross-section: σ_2=90±10 μb for Ep_2=14.86±0.85 MeV (without any overlapping!!!).**
  - **The most likely explanation: a new nuclear reaction type and channel:**

    ^{159}Tb (p, ^{2}n+n) ^{157}Dy

Last years research

- **Paper of F.Tárkányi, A.Hermanne, F.Ditrói, S.Takács, A.V.Ignatyuk, *Appl. Radiat. Isot.*, 127 (2017), pp.7-15:**
    - **Statistical significance of a dineutron detection: the condition $S_p=S_b+5\Delta S_p$ is met for number of counts 153 and more in a gamma-peak due to ^{157}Dy decay ($T_{1/2}$=8.14 hours; E_γ=326.33 keV; k_γ=93%)**
    - **Dineutron decay: $^2n \to d + e^- + \tilde{\nu}_e$, this transition is superallowed**
    - **New interval limits for the binding energy of the dineutron: 2.2 MeV < B_{dn}< 2.8 MeV**

Last years research

- **Interval assessment of a dineutron radius:**
- **From these energy limits and a very well known theoretical expression**

$$r_{dn}^2 = \hbar^2 / \left(m_n \cdot B_{dn} \right)$$

where m_n is a neutron mass, an interval estimate of a dineutron radius r_{dn} may be obtained

Last years research

- For upper value of the binding energy (B_{dn}= 2.8 MeV) this gives the lower estimate of a dineutron radius $r_{dn,l}$= 3.85 fm, while for lower value of the binding energy (B_{dn}= 2.2 MeV) the upper estimate of a dineutron radius $r_{dn,u}$ equals 4.34 fm.

- Then 3.85 fm < r_{dn}< 4.34 fm and the dineutron by spatial structure is similar to a "friable" deuteron with it's r_d = 4.3 fm.

Last years research

$$\lg f_{dn} = 4.0 \cdot \lg E_{max-dn} + 0.78 + 0.02 A_d - 0.005\left(A_d - 1\right) \cdot \lg E_{max-dn}$$

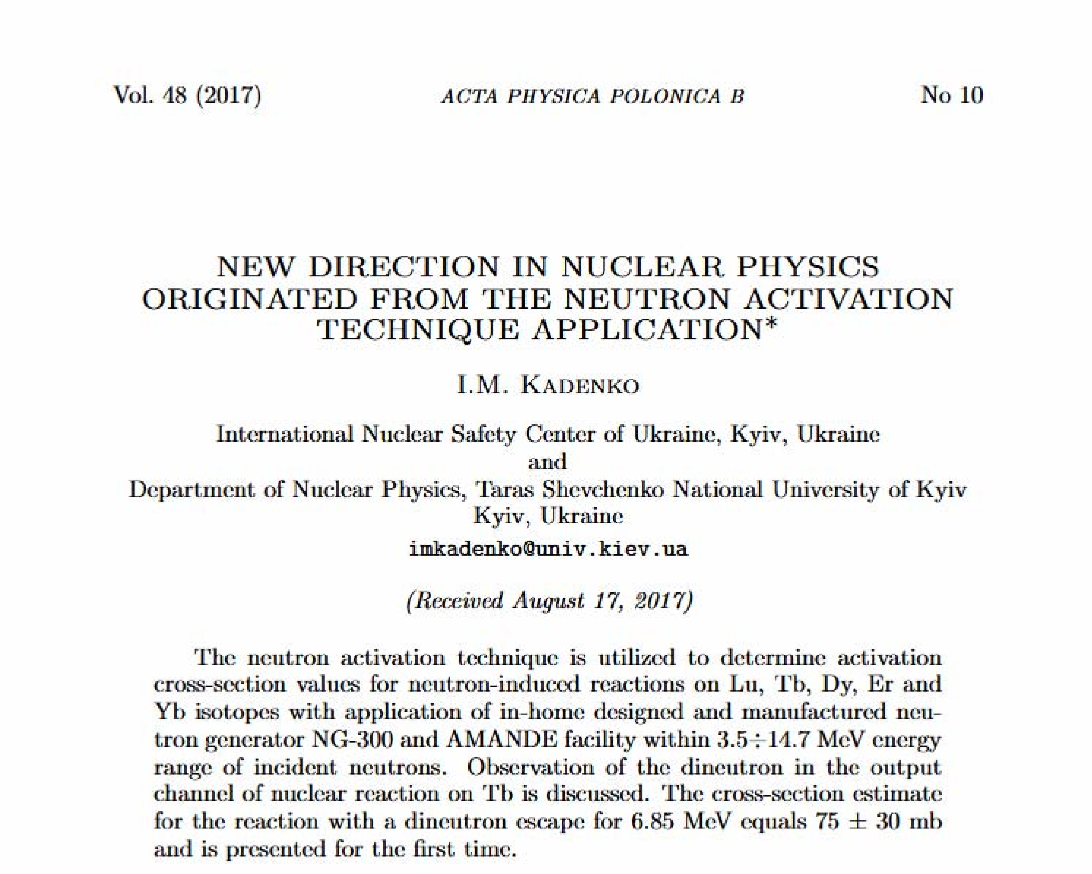
$E_{max\text{-}dn}$, MeV lg ($f_{dn} \bullet t_{1/2\ dn}$)	2.2	2.8
3.0	6.5 s	2.5 s
3.5	20.5 s	7.8 s

- **Interval estimate of a dineutron half-life:**

  $$\underline{2.5\ \text{s} < t_{1/2\ dn} < 20.5\ \text{s}}$$

- $f_{dn} \bullet t_{1/2\ dn}$ – **comparative half-life; Sargent’s rule**

Last years research



Vol. 48 (2017) *ACTA PHYSICA POLONICA B* No 10

NEW DIRECTION IN NUCLEAR PHYSICS ORIGINATED FROM THE NEUTRON ACTIVATION TECHNIQUE APPLICATION*

I.M. Kadenko

International Nuclear Safety Center of Ukraine, Kyiv, Ukraine
and
Department of Nuclear Physics, Taras Shevchenko National University of Kyiv
Kyiv, Ukraine
imkadenko@univ.kiev.ua

(Received August 17, 2017)

The neutron activation technique is utilized to determine activation cross-section values for neutron-induced reactions on Lu, Tb, Dy, Er and Yb isotopes with application of in-home designed and manufactured neutron generator NG-300 and AMANDE facility within 3.5÷14.7 MeV energy range of incident neutrons. Observation of the dineutron in the output channel of nuclear reaction on Tb is discussed. The cross-section estimate for the reaction with a dineutron escape for 6.85 MeV equals 75 ± 30 mb and is presented for the first time.

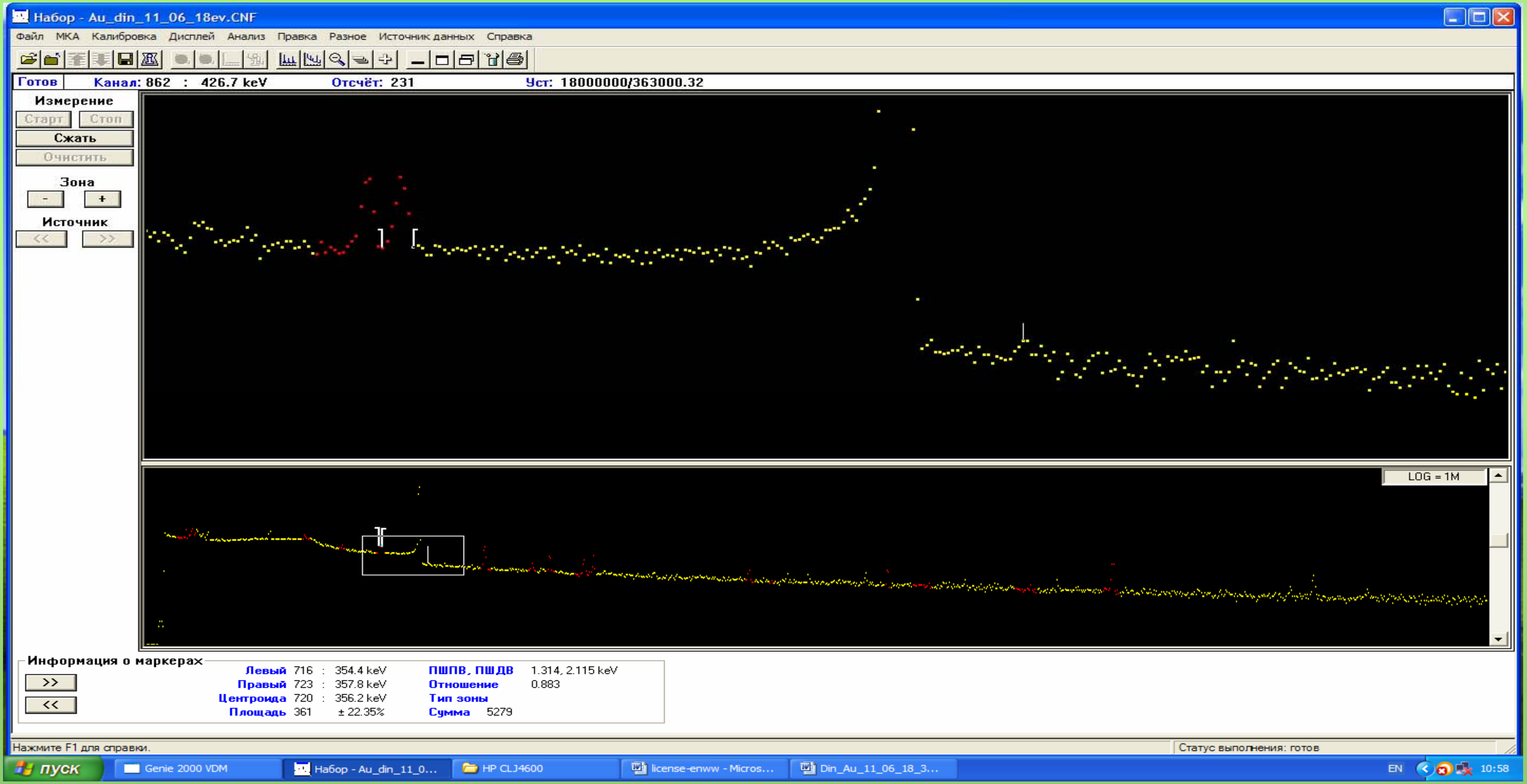
- **For development of idea to measure cross-section values in the outgoing channel:**
- **σ_3=75 ± 30 mb for nuclear reaction ^{159}Tb *(n,^{2}n)* ^{158g}Tb and neutron energy 6.850±0.002 MeV**

Last years research – in cooperation with ATOMKI, Hungary

- This 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: 2 MeV below the threshold
  - Expected results: availability 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%

Last years research – in cooperation with ATOMKI, Hungary

- E_γ=355.73 keV; k_γ=87%, statistical significance: 6.2 σ



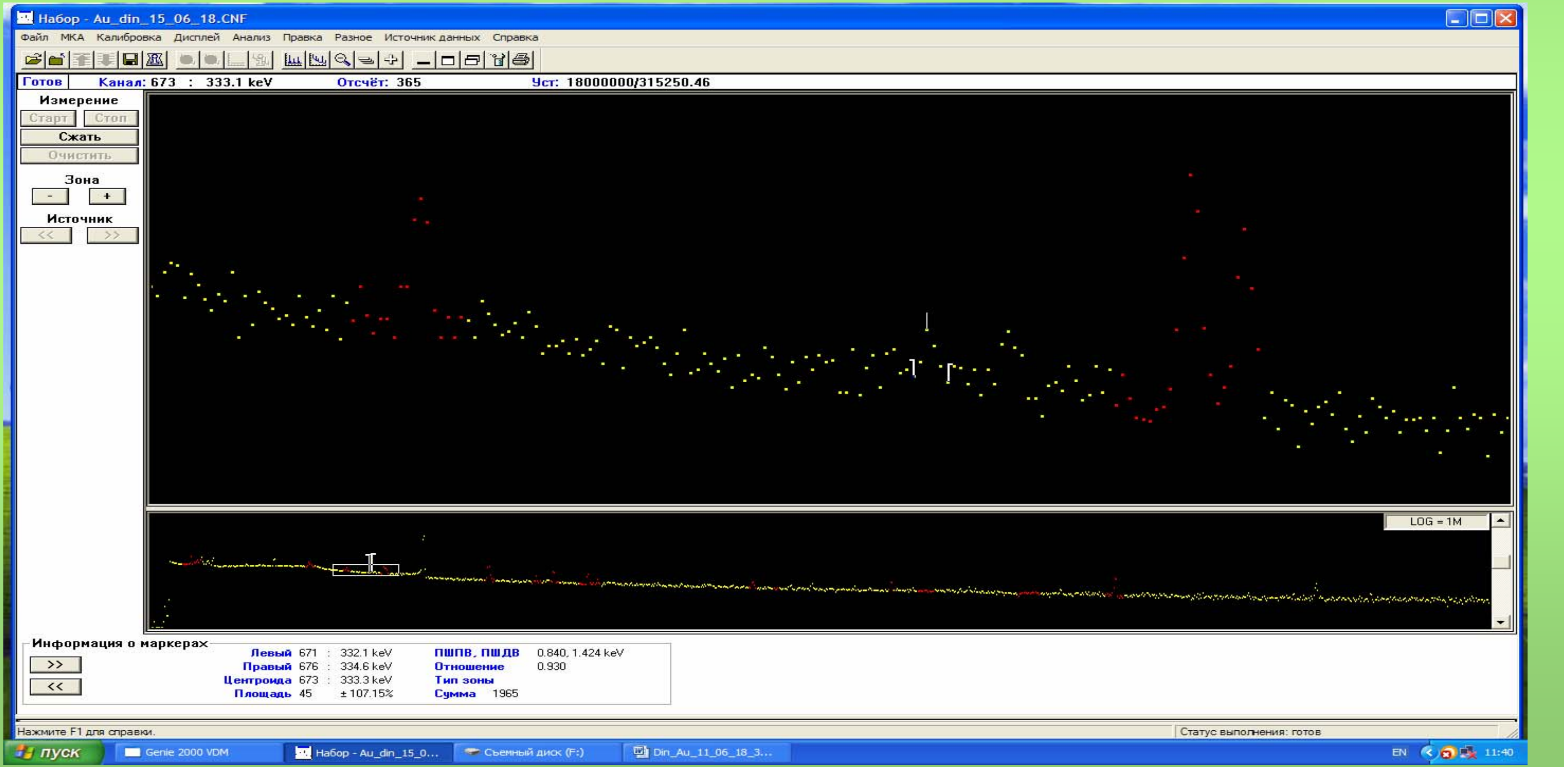
Готов Канал: 862 : 426.7 keV Отсчёт: 231 Уст: 18000000/363000.32

Левый 716 : 354.4 keV
Правый 723 : 357.8 keV
Центроида 720 : 356.2 keV
Площадь 361 ± 22.35%

ПШПВ, ПШДВ 1.314, 2.115 keV
Отношение 0.883
Тип зоны
Сумма 5279

Last years research – in cooperation with ATOMKI, Hungary

- **E_{γ}=333.03 keV; k_{γ}=22.9%, statistical significance: 4.7 σ**



Набор - Au_din_15_06_18.CNF

Готов **Канал:** 673 : 333.1 keV **Отсчёт:** 365 **Уст:** 18000000/315250.46

Информация о маркерах

Левый 671 : 332.1 keV
Правый 676 : 334.6 keV
Центроида 673 : 333.3 keV
Площадь 45 ± 107.15%

ПШПВ, ПШДВ 0.840, 1.424 keV
Отношение 0.930
Тип зоны
Сумма 1965

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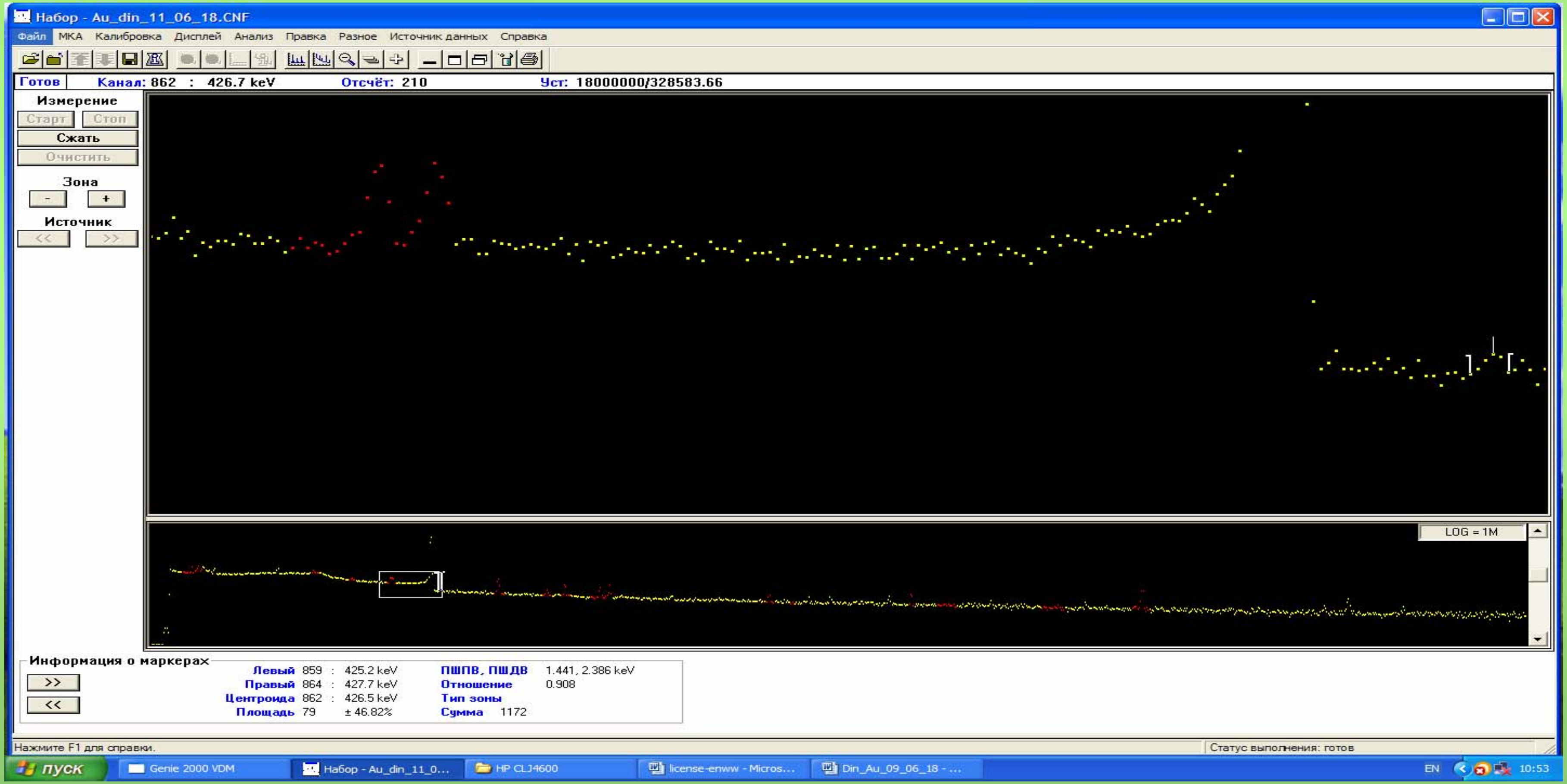
Статус выполнения: готов

Last years research – in cooperation with ATOMKI, Hungary

- E_γ=426.10 keV; k_γ=6.6%, statistical significance: 3.8 σ



Готов   Канал: 862 : 426.7 keV   Отсчёт: 210   Уст: 18000000/328583.66

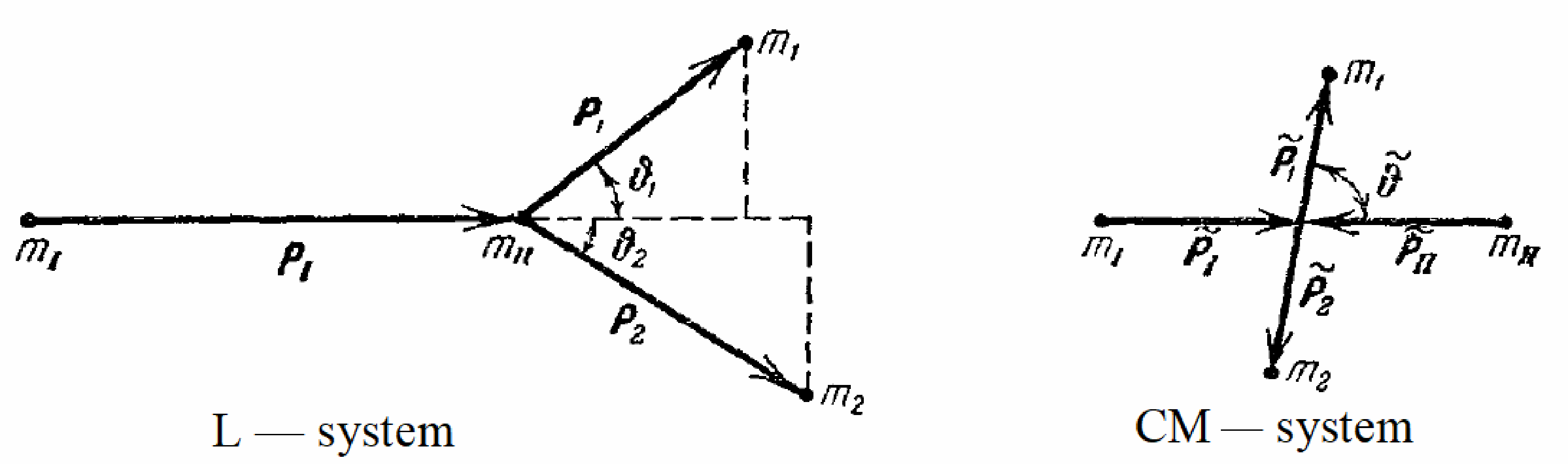
Левый 859 : 425.2 keV   ПШПВ, ПШДВ 1.441, 2.386 keV
Правый 864 : 427.7 keV   Отношение 0.908
Центроида 862 : 426.5 keV   Тип зоны
Площадь 79 ± 46.82%   Сумма 1172

Нажмите F1 для справки.

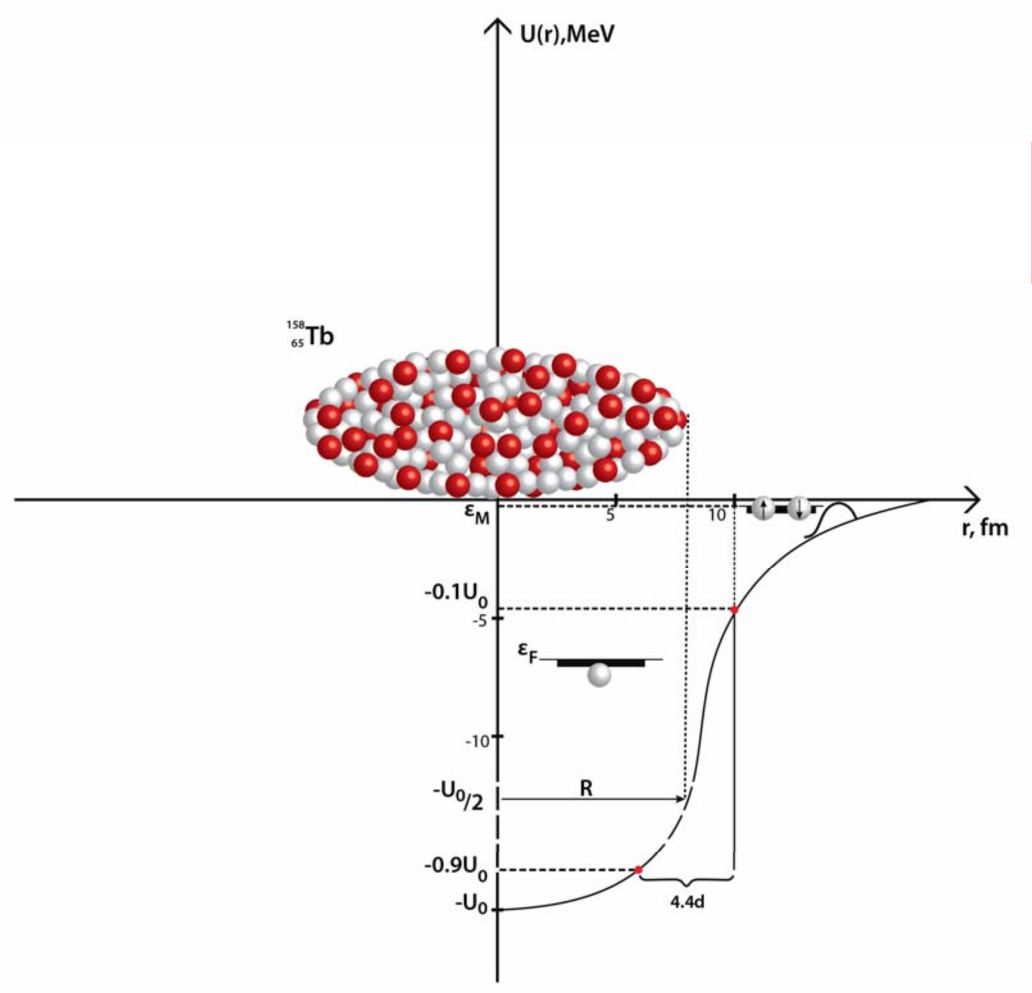
Статус выполнения: готов

Features of the outgoing channels in some nuclear reactions

- **Classical representation of nuclear reaction :**
    - **Hans Paetz gen. Schieck. Nuclear reactions: An introduction. Springer, 2014.**
    - **C.A. Bertulani, P. Danielewicz. Introduction to Nuclear Reactions. IoP, 2004.**



Features of the outgoing channels in some nuclear reactions



- **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**
- **The dineutron is allowed to beta minus decay with an electron and the deuteron escape**

Features of the outgoing channels in some nuclear reactions

- ^{158g}Tb as a nuclear reaction ^{159}Tb $(n,^2n)$ product is EC and β^+- decaying in 83%, β^-- in 17% of total decays
- Possible reaction: $^{158g}\mathrm{Tb} + e^- \rightarrow {}^{158}\mathrm{Gd}$ (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: $N_{Tb}(t) \approx N_{dn}(t) \Rightarrow \underline{A_{Tb}(t) = \lambda_{Tb} N_0 \exp(-\lambda_{dn} t)}$

Features of the outgoing channels in some nuclear reactions

- **Observation of ^{157}Dy as a product of the ^{159}Tb (p,3n) ^{157}Dy nuclear reaction for proton energies below the reaction threshold does not exclude the possibility for existence of the following reaction channel: ^{159}Tb (p,^3n) ^{157}Dy**
- **Search for the trineutron could be justified in the following energy range provided the binding energies for the dineutron and the trineutron are known:**

$$E_{th}^{3n} - B_{tn} < E < E_{th}^{3n} - B_{dn}$$

- **Some conclusive remarks from Migdal's paper: *"One might think that an analogous mechanism leads to bound states which are more complicated than the dineutron..."***

Conclusions

- **Experimentally proved the possibility of dineutron existence in a bound state as a particle-satellite of recoil nucleus in the outgoing channel of nuclear reactions on ^{159}Tb with protons and neutrons in the input channel**
- **Independently observed the dineutron in the outgoing channel of the ^{197}Au $(n,^{2}n)$ ^{196}Au nuclear reaction**
- **The interval estimates are obtained for the binding energy, half-life and radius of the dineutron as well as cross-sections for generation of the dineutron**
- **Assumption is made about a possible interaction of dineutron decay products with the heavy nucleus in the outgoing channel to fostering it's "faster decay"**

Many thanks for your attention and questions!