New Direction in Nuclear Physics Originated from the

Neutron Activation Technique Application

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THE OUTLINE

- **Historical information**
- **Project for (n,x) reaction cross-section measurements**
- **Cross section data for 14 - MeV neutron induced reactions**
- **Cross section data for lower energy neutron induced reactions**
- **New findings based on the neutron activation technique application**
- **Conclusions**

Historical information

- Department of Nuclear Physics (DNP) was established on September 1, 1945 by the prominent nuclear physicist Alexander Leipunsky
- When moved to IPPE, Obninsk, RF, A. Leipunsky came to be known as the "Father" of the Soviet program for fast neutron reactors development
- International Nuclear Safety Center of Ukraine (INSCU) was established in March 2003 under International Nuclear Safety Program sponsored by the US Department of Energy

Historical information

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:

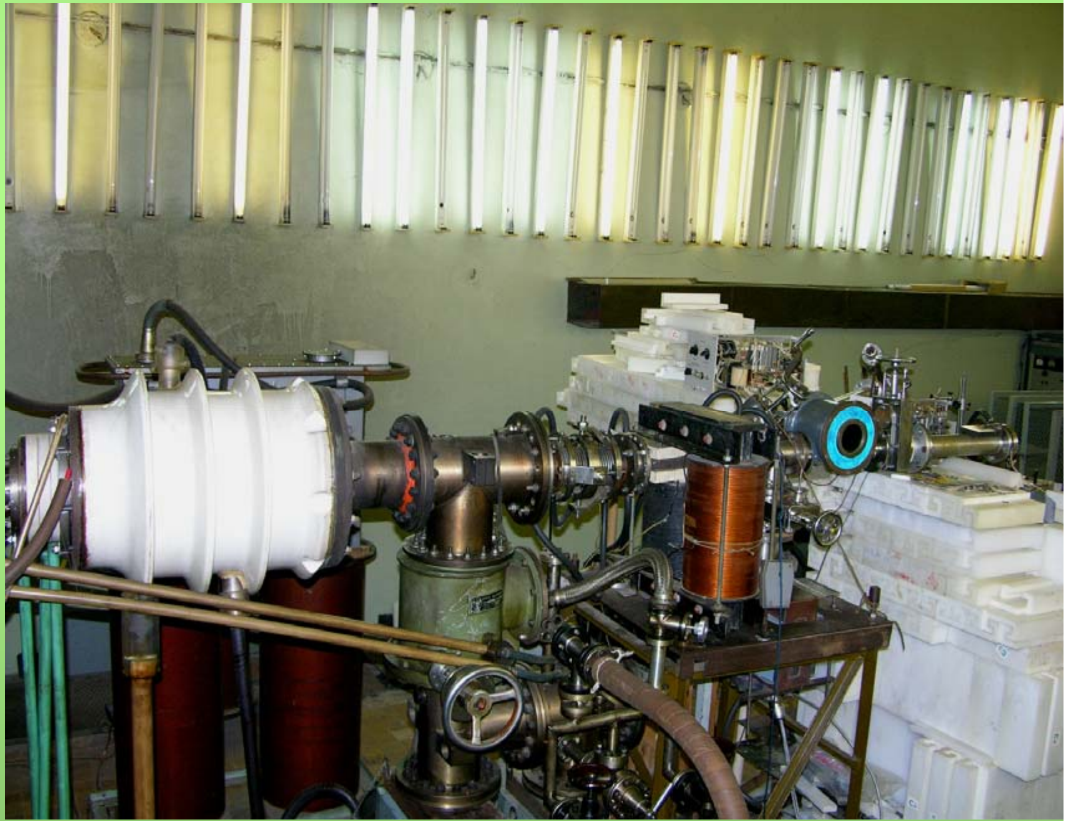
$$ {}_1H^3 + {}_1H^2 \rightarrow {}_2He^4 + {}_0n^1, $$

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)

Project for (n,x) reactions study: prerequisites

- **In-home designed and developed neutron generator**
- **Utilization of (D,T) reaction with fixed tritium target**
- **Up to 8 mA current**
- **Up to 10^{11} n/s output**
- **Neutron flux monitor**
- **Selection of rare earth elements as deformed nuclei**
- **Availability of smart PhD students**



Project for (n,x) reactions study:14 MeV energy

TABLE II. Measured cross sections for Lu isotopes.

Nuclear reaction	$t_{1/2}$	$E\gamma$ (keV)	γ-ray emission probability (abs. units)	$K(\Delta)$ for $I\gamma$ (%)	$E_n(\Delta)$ (MeV)	Cross section(Δ) (mb)	Literature	TALYS
					13.5(2)	480(63)	–	774
$^{175}Lu(n,2n)^{174}Lu^m$	142 d	992.07	100.0(21)[8]	0.00546(18)	14.2(2)	382(59)	515(36)[15]	778
					14.6(3)	567(60)	627(52)[16]	770
					13.5(2)	1896(250)	–	2048
$^{175}Lu(n,2n)^{174}Lu$	3.31 yr	1241.8	100(2)[8]	0.0514(8)	14.2(2)	1473(219)	1670(159)[17]	2048
					14.6(3)	1860(190)	1984(115)[18]	2049
					13.5(2)	10.7(7)	–	5.65
		113.8	29.4(5)[8]					
		282.5	47.0(7)[8]	0.064(8)	14.2(2)	9.8(7)	–	7.03
$^{175}Lu(n,p)^{175}Yb$	4.19 d	396.32	100.0(15)[8]					18.5
					14.6(3)	13.2(9)	18.5(2.2)[19] 3.4(5)[20]	7.80
					13.5(2)	0.7(1)	–	0.78
		181.5	45.9(24)[8]					
$^{175}Lu(n,\alpha)^{172}Tm$	63.6 h	1093.6	100(5)[8]	0.060(5)	14.2(2)	1.00(3)	–	1.10
		1476.6	4.9(2)[8]					
					14.6(3)	1.5(2)	–	1.30
$^{176}Lu(n,\alpha)^{173}Tm$	8.24 h	461.4	7.8(3)[8]	0.879(9)	14.6(3)	1.6(3)	2.3(6)[19]	1.90

Published in: N. Dzysiuk, I. Kadenko, A. J. Koning, R. Yermolenko. Cross sections for fast-neutron interaction with Lu, Tb, and Ta isotopes. Phys. Rev. C 81, 014610 (2010)

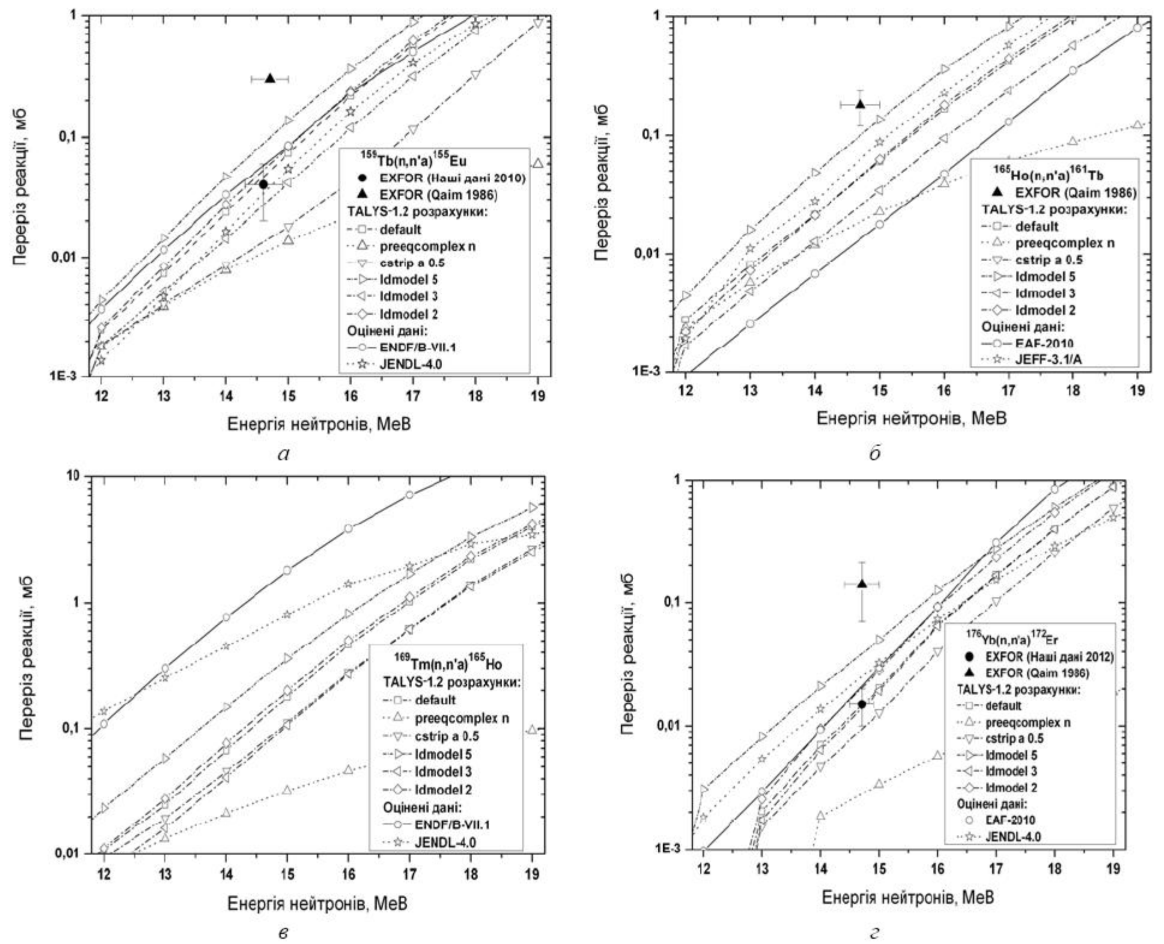
Project for (n,x) reactions study:14 MeV energy

TABLE III. Measured cross sections for Tb at (14.6 ± 0.2) MeV.

Nuclear reaction	$t_{1/2}$	$E\gamma$ (keV)	γ-ray emission probability (abs. units)	$K(\Delta)$ for $I\gamma$ (%)	Cross section (Δ) (mb)	Literature	TALYS
^{159}Tb$(n,p)^{159}$ Gd	18.48 h	348.28	2.05(4)[8]	0.11(3)	4.8(5)	6.6(7)[21]	8.2
		363.54	100(5)[8]				
^{159}Tb$(n,\alpha)^{156}$Eu	15.19 d	723.47	55.86(25)[8]	0.097(8)	2.2(3)	2.2(5)[22]	2.5
		811.77	100(4)[8]				
		1153.67	70.0(6)[8]				
^{159}Tb$(n,n'\alpha)^{155}$Eu	4.71 yr	105.305	68.9(15)[8]	0.307(2)	0.04(2)	<0.30[23]	0.05
^{159}Tb$(n,2n)^{158}$Tb	180 yr	944.20	100(9)[8]	0.439(13)	1913(60)	1909(82)[24]	1922
		962.10	46.2(9)[8]				

Published in: N. Dzysiuk, I. Kadenko, A. J. Koning, R. Yermolenko. Cross sections for fast-neutron interaction with Lu, Tb, and Ta isotopes. Phys. Rev. C 81, 014610 (2010)

Project for (n,x) reactions study:14 MeV energy



Перерізи ядерних реакцій:
а - ^{159}Tb(n, n'α)^{155}Eu; *б* - ^{165}Ho(n, n'α)^{161}Tb; *в* - ^{169}Tm(n, n'α)^{165}Ho; *г* - ^{176}Yb(n, n'α)^{172}Er.

Published in:

A.O. Kadenko,
N.R. Dzysiuk,
I.M. Kadenko,
G.I. Primenko.

Cross sections of (n, n'α) nuclear reaction on rare earth elements at 14.7 MeV neutron energy. //

Nuclear Physics and Energy. – 2013. – T.14. – No.4. – p. 345-349

(in Ukrainian).

Project for (n,x) reactions study:14 MeV energy

TABLE II. Measured and calculated cross sections for Dy, Er, and Yb isotopes (14.7 MeV)[a].

Nuclear reaction	$T_{1/2}$	$E\gamma$ (keV)	γ-ray emission probability (abs. units)	$K(\Delta)$ for $I\gamma(\%)$	Cross section (mb)	TALYS (mb)	Prior measurements
^{156}Dy$(n,2n)^{155}$Dy	9.9 h	226.92	100	0.684	1736 (96)	1998	1852 (143) [17] 1982 (178) [18] 1943 (194) [19]
^{158}Dy$(n,2n)^{157(m+g)}$Dy	8.14 h	326.16	100	0.92	2044 (108)	1780	1990 (167) [17] 2115 (190) [18] 2047 (205) [19]
^{162,163}Dy$(n,x)^{162}$Tb	7.6 min	260.07	1870	0.043	3.9 (0.3)	6.616	0.67 (0.11) [20]
^{163,164}Dy$(n,x)^{163}$Tb	19.5 min	351.14	117	0.225	3.0 (0.2)	6.639	0.30 (0.07) [20]
^{156}Dy$(n,p)^{156}$Tb	5.35 d	199.19	132	0.31	17.3 (6.0)	16.22	Not available
^{162}Er$(n,p)^{162}$Ho$^{(m+g)}$	15 min	1319.3	100	0.038	10.5 (3.2)	16.22	Not available
^{170}Er$(n,p)^{170}$Ho^{g}	2.76 min	941.4	94	0.22	0.25 (0.05)	2.286	0.21 (0.02) [21]
^{174}Yb$(n,\alpha)^{171}$Er	7.516 h	295.9	289	0.100	1.16 (0.10)	0.37	2.0 (0.2) [22] 1.26 (0.20) [23] 1.22 (0.23) [24]
^{174}Yb$(n,p)^{174}$Tm	5.4 min	366.4	106	0.87	2.80 (0.27)	3.316	3.13 (0.20) [25] 4 (0.4) [26] 2.94 (0.21) [27]
^{176}Yb$(n,n'\alpha)^{172}$Er	49.3 h	407.34	100	0.421	0.015 (0.005)	0.013	0.14 (0.07) [28]
^{176}Yb$(n,\alpha)^{173}$Er	1.4 min	895.2	112	0.480	0.69 (0.10)	0.187	0.7 (0.2) [29] 0.52 (0.23) [30] 0.20 (0.05) [31]
^{176}Yb$(n,d+pn)^{175}$Tm$^{(m+g)}$	15.2 min	514.87	445	0.146	0.22 (0.03)	0.046	0.73 (0.2) [20]
^{168}Yb$(n,2n)^{167}$Yb	17.5 min	106.16	110	0.205	1875 (179)	1759	1912 (120) [26] 1913 (217) [17] 1948 (195) [32] 1873 (201) [18]

[a]Values in parentheses correspond to neutron energy in MeV. Data for quantum yield are taken from Ref. [33] and the cross-section data in bold are new; more details are in the Appendix to this paper.

Published in: N. Dzysiuk, A. Kadenko, I. Kadenko, G. Primenko. Measurement and systematic study of (n,x) cross sections for dysprosium (Dy), erbium (Er), and ytterbium (Yb) isotopes at 14.7 MeV neutron energy . Phys. Rev. C 86, 034609 (2012)

Project for (n,x) reactions study:14 MeV energy

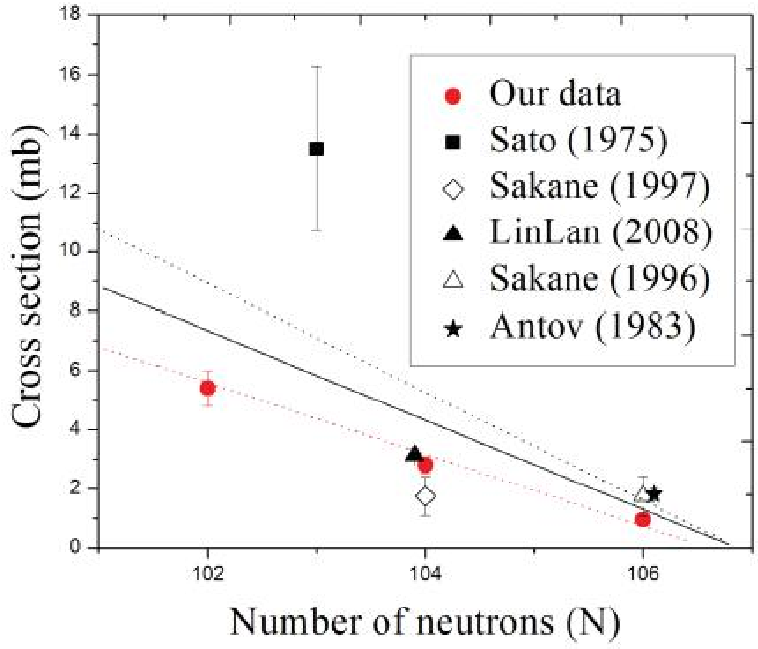


FIG. 7. (Color online) Systematic of the (*n,p*) reaction cross section for Yb isotopes at 14.7 MeV neutron energy. The experimental data are taken from Refs. [24,25,27,29,30].

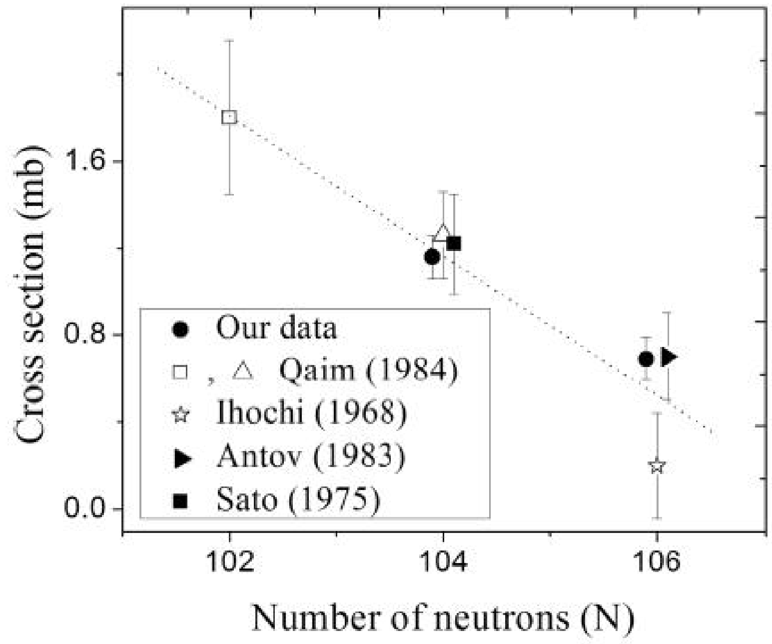


FIG. 10. Systematic of the (n,α) reaction cross section for Dy, Er, and Yb isotopes at 14.7 MeV neutron energy. The experimental data are taken from Refs. [23,24,29,31].

Published in: N. Dzysiuk, A. Kadenko, I. Kadenko, G. Primenko. Measurement and systematic study of (n,x) cross sections for dysprosium (Dy), erbium (Er), and ytterbium (Yb) isotopes at 14.7 MeV neutron energy. Phys. Rev. C 86, 034609 (2012)

Project for (n,x) reactions study: lower energies

TABLE IV. Measured cross sections for ^{181}Ta$(n,\gamma)^{182}$Ta^{m2} ($t_{1/2}$ = 950 s) reaction.

Neutron energy (keV)	Δ Neutron energy (keV)	Cross section (Δ) (mb)	ADL-3 [25]	JEFF-2.2 [26]	TALYS
1.9	1.5	3.7(3)	3.21	3.25	1.84
58.7	2.7	0.8(2)	1.33	0.28	0.77
144.5	16.8	0.7(1)	1.43	0.20	1.09
2850	120	0.50(14)	0.51	0.14	1.4
14340	460	0.100(28)	0.09	0.09	0.2

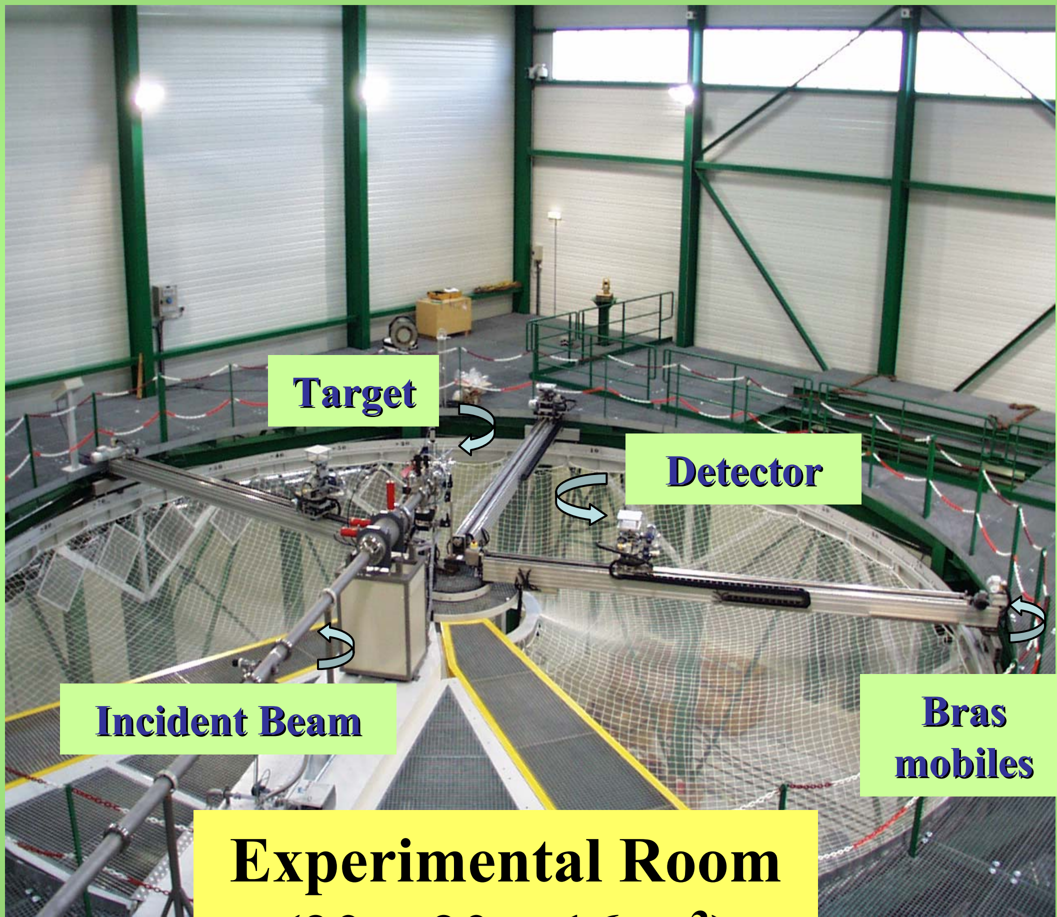
Published in: N. Dzysiuk, I. Kadenko, A. J. Koning, R. Yermolenko. Cross sections for fast-neutron interaction with Lu, Tb, and Ta isotopes. Phys. Rev. C 81, 014610 (2010)

- **All cross section data was obtained with application of the Neutron Activation Technique.**
- **Follow up: small statistics and lower energies might be of some interest!**

Project for (n,x) reactions study: lower energies

- Development of cooperation with IRSN, France
- Rare-earth elements available for further study
- Access to IRSN facilities

Project for (n,x) reactions study: lower energies



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

- **AMANDE neutron irradiation facility at Cadarache, France**
- **Excellent experimental conditions for neutron capture reaction cross section measurements**
- **Utilization of (D,D) reaction with the fixed deuterium target**

Project for (n,x) reactions study: lower energies

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

Project for (n,x) reactions study: lower energies

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	

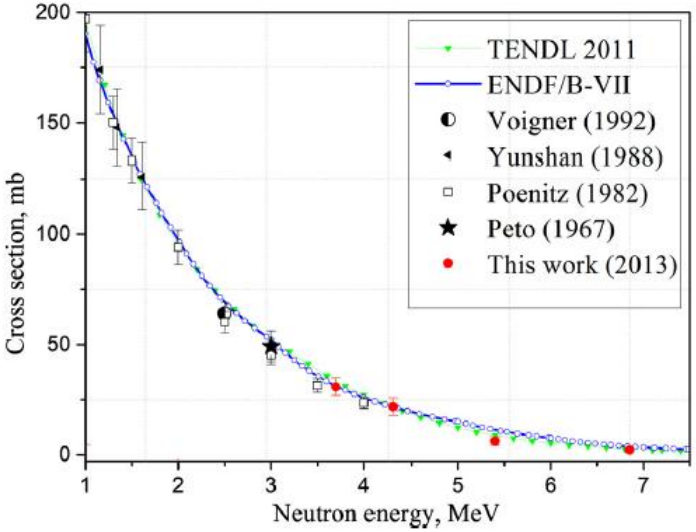


Fig. 5. Excitation function for the $^{159}Tb(n,\gamma)Tb^{160}$ nuclear reaction. The data are given with the statistical error bars only.

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

New findings

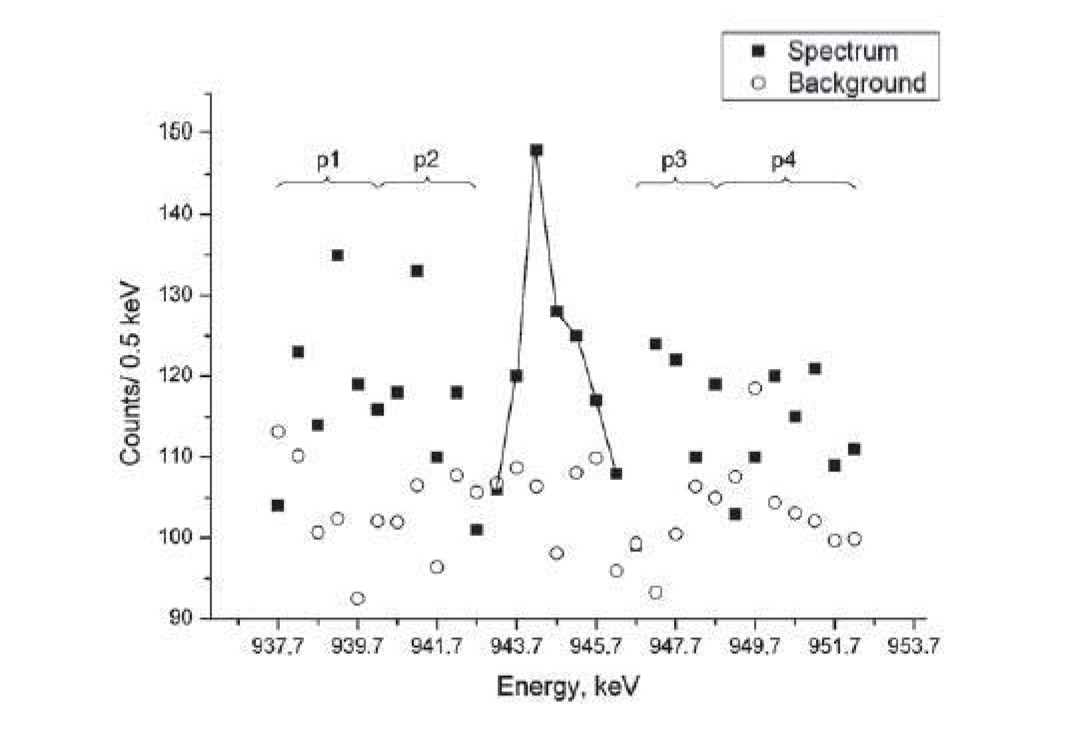


Fig. 2: ROI with 944.2 keV ($I\gamma = 0.439$) peak of ^{158}Gd.

- **In one year: spectra measurements of Tb specimen.**

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

New findings

- **Absence of 944.2 keV gamma peak in the background spectra**
- **Detection of ^{158g}Tb ($T_{½}$= 180 y) in the output channel of nuclear reaction**
- **The only possible reaction channel: ^{159}Tb (n,2n)**
- **The threshold for ^{159}Tb (n,2n) reaction: 8.18 MeV**
- **Irradiation energy of Tb specimen: 6.85 MeV!**
- **Two neutrons as (one bonded nucleus?) separate particles are in output channel but prohibited from escaping!**

New findings

- **Returning to the ideas and publications of M.Y. Colby & R.N. Little, and N. Feather, and book of V.I. Strizhak et al.**

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);

-N. Feather. Nature 162, 213 (1948);

-Strizhak V. I., Gurtovoy M. E., Leshchenko B. E., Prokopets G. A. and Sitko S. P., Physics of Fast Neutrons (Atomizdat, Moscow) 1977, pp. 208–213 (in Russian)

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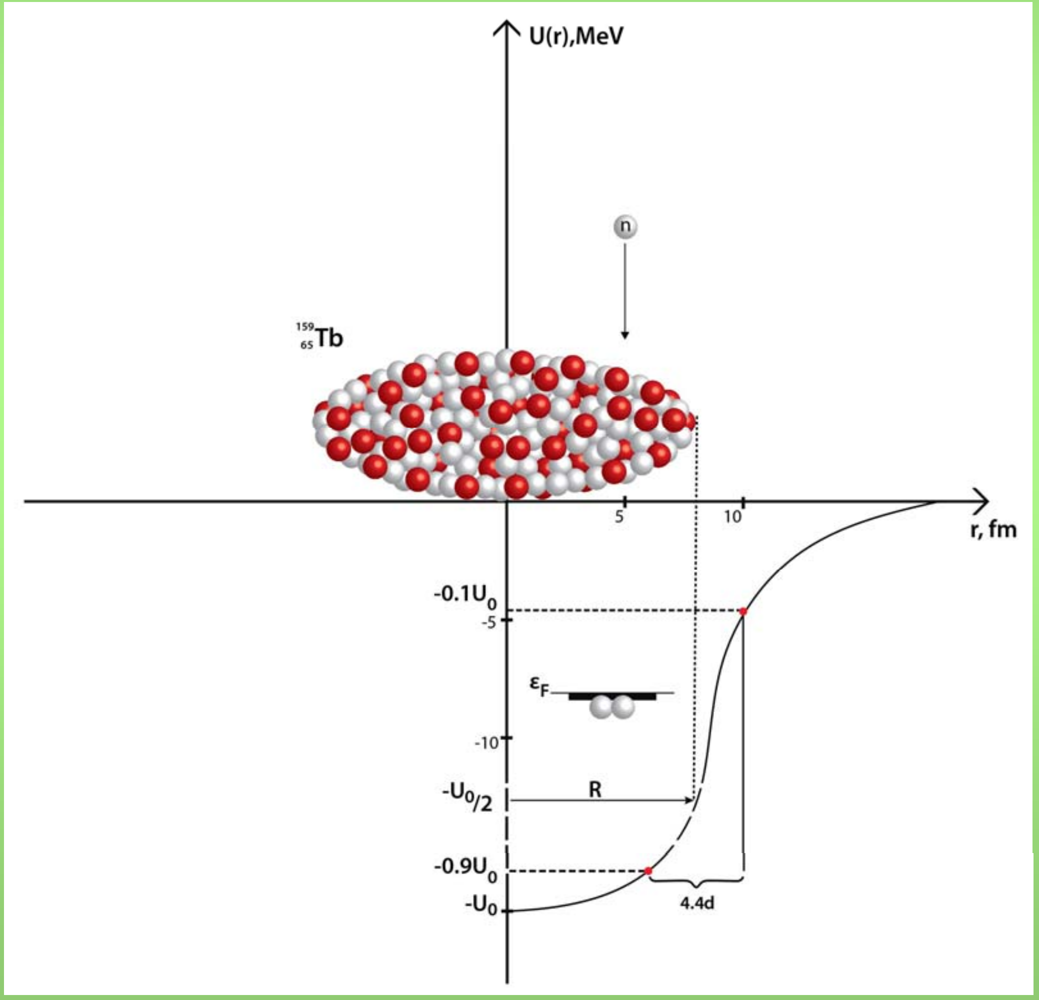
New findings

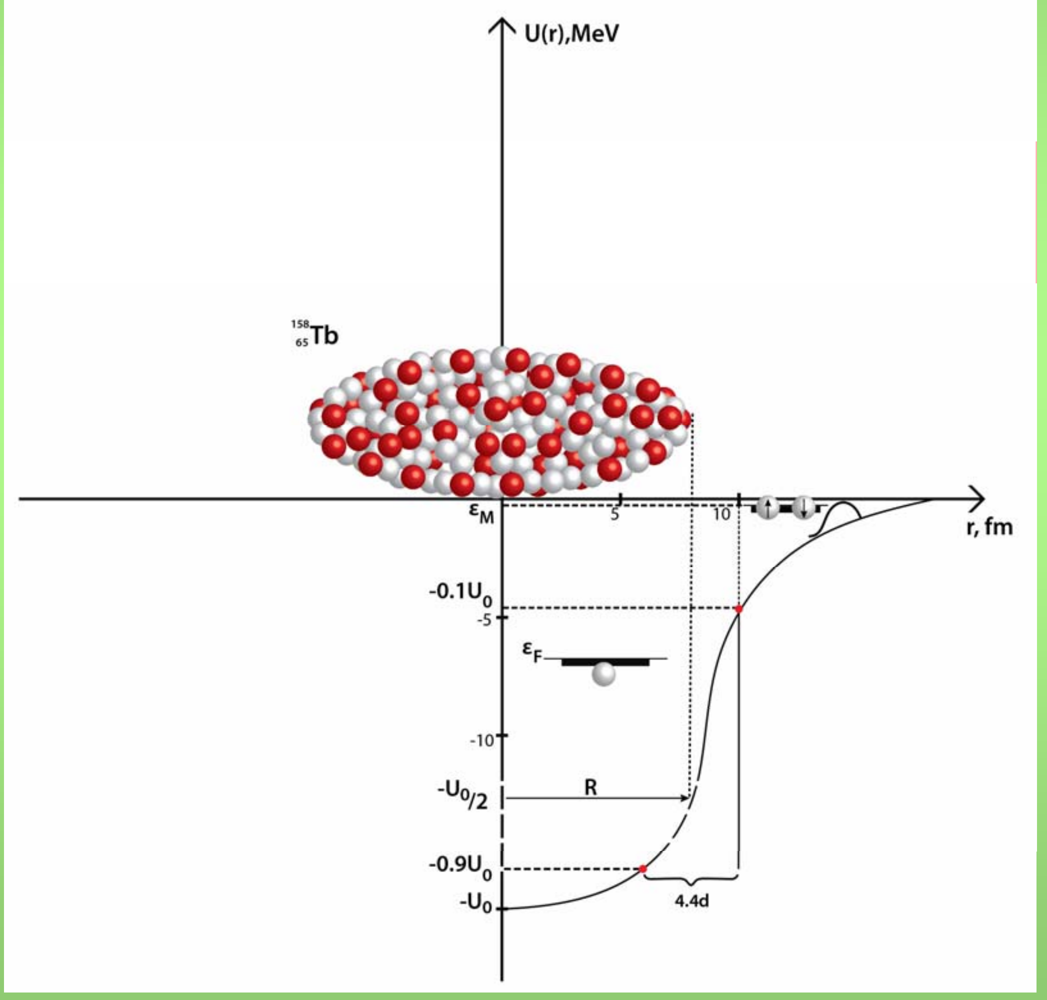
- **Binding energy: 1.6 MeV < B_{dn} < 2.8 MeV**
- **Half-life: 7.4 ms < T_{dn} < 185.7 ms**
  - **Published in: Igor Kadenko. Possible observation of the dineutron in the 159Tb(n, ^{2}n)158gTb nuclear reaction. EPL, 114 (2016) 42001**
- **Cross-section estimate:**
  - **(75 ± 30) mb for 6.85 MeV neutron energy**
- **Possibility for existence of the dineutron in a close proximity but outside of heavy neutron rich nucleus was predicted by A.B. Migdal in his paper:**
  - **Migdal A. B. Yad. Fiz., 16 (1972) 427 (Sov. J. Nucl.Phys., 16 (1973) 238)**

New findings



- **Interaction of the incident neutron with the two paired-up neutrons near Fermi level**
- **Movement of the two paired-up neutrons as a single particle from the nucleus in the direction of the z-axis**
- **The paired-up neutrons escape from the nucleus but not from the potential well!**

New findings



- **The dineutron is then captured at Migdal level within (100÷400) keV energy range**
- **This energy level provides the binding mechanism for the two neutrons to exist as a single particle - the dineutron**
- **Additional measurements proved the existence of the dineutron!**

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Conclusions

- The neutron activation technique is still a very powerful instrument both for practical applications and for new fundamental findings
- In 70 years since the theoretical foundation of the dineutron the evidence for a dineutron existence as a bonded particle was provided
- This event opens up the new direction in Nuclear Physics: Physics of the dineutron, or Dineutron Physics!

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Thank you for your attention!