Standard scientist's questions

How? When? Why? Who? What? Where?

Investigation of Rhenium by Neutrons

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Investigation of Rhenium by Neutrons

TANGRA SETUPS

JINR FLNP

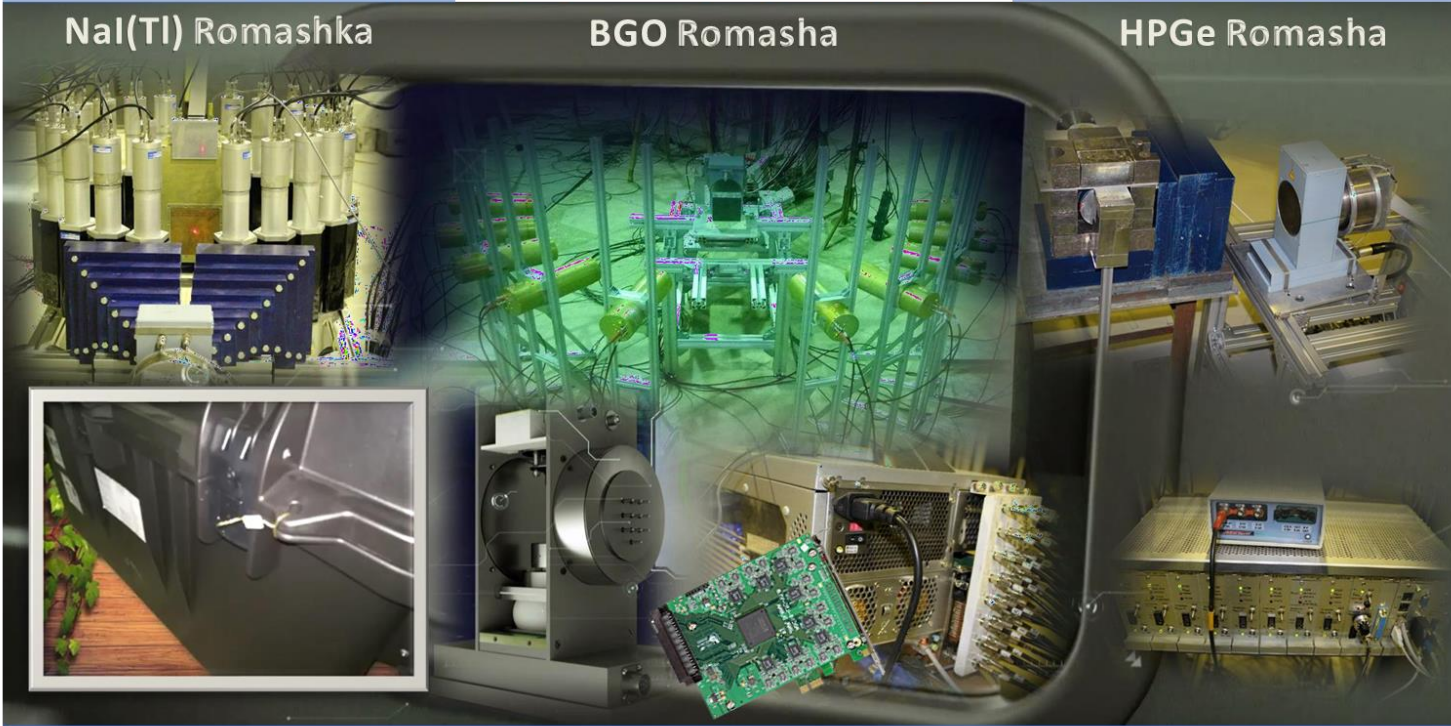http://flnph.jinr.ru/en/facilities/tangra-project

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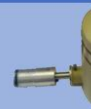
Number of NaI(Tl) detectors: 22
Size of NaI(Tl) crystals: hexagonal prism 78 x 90 x 200 mm
PMT type: Hamamatsu R1306
Gamma-ray Energy-resolution ~ 7.2 % @ 0.662 MeV
Gamma-ray Energy-resolution ~ 3.6 % @ 4.437 MeV
Gamma-ray Time-resolution ~ 3.8 ns @ 4.437 MeV

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

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FRANK LABORATORY OF NEUTRON PHYSICS, JINR, RUSSIA

强脉冲辐射环境模拟与效应
国家重点实验室
THE STATE KEY LABORATORY OF INTENSE PULSED RADIATION SIMULATION AND EFFECT, NINT, CHINA
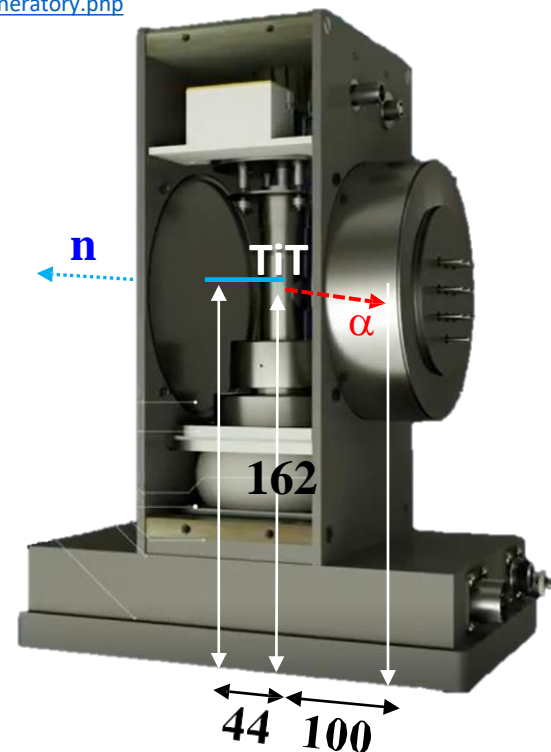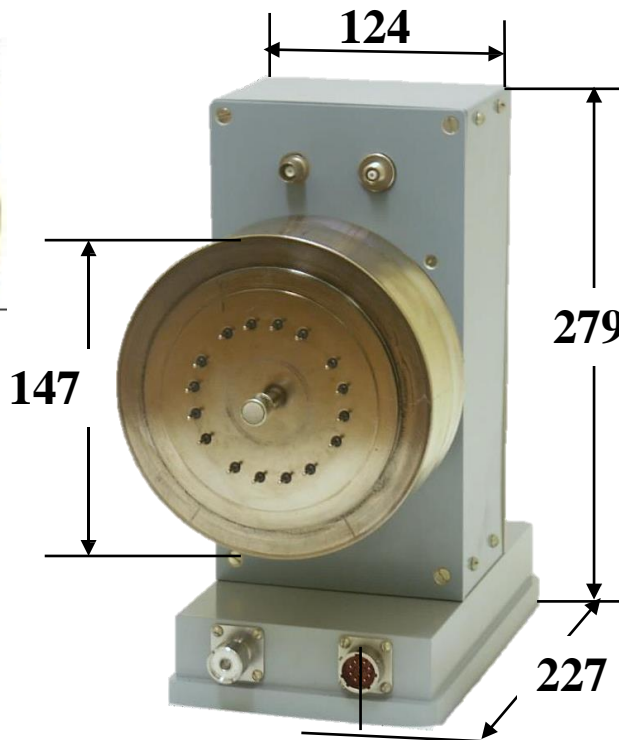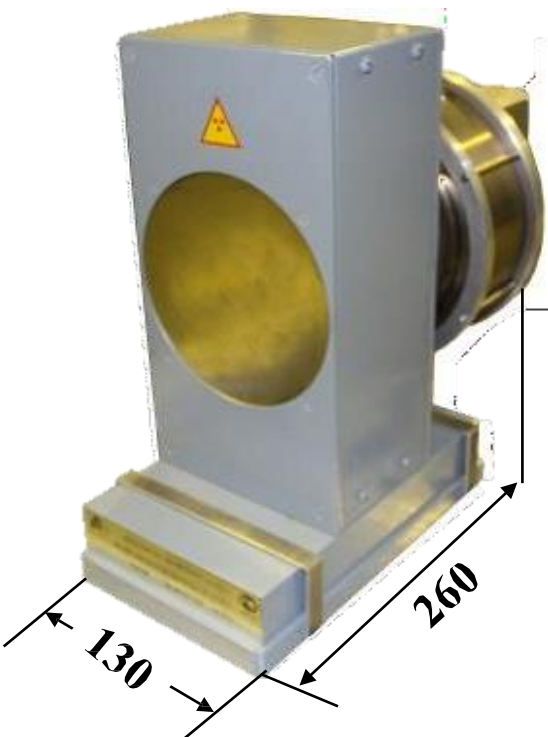
兰州大学 1909 LANZHOU UNIVERSITY

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

124

279

147

260

130

227

n → **TiT** → **α**

162

44 **100**

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: $> 5.0 \times 10^7$ n/s/4π

Final Intensity: $> 2.5 \times 10^7$ 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: $< 8\mu$A

n-tube life-time: > 800 h

$<$ ING Duty time $>$: 18 months

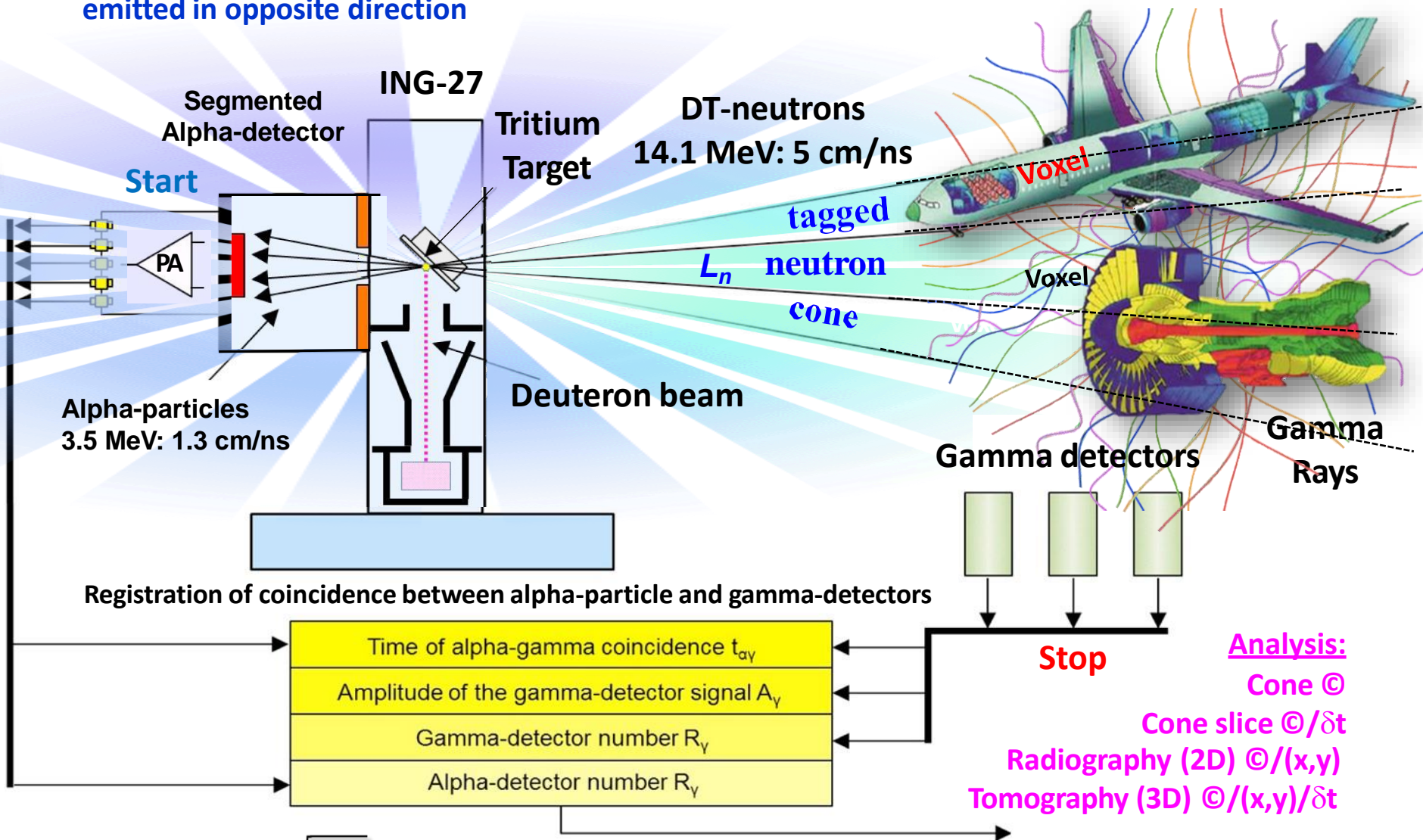Weight: ING-27: 7.5 ± 0.5 kg ; Power Supply and Operation Unit: 2.7 ± 0.3 kg

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

Segmented
Alpha-detector

ING-27

DT-neutrons
14.1 MeV: 5 cm/ns

Tritium
Target

Start

PA

tagged

L_n neutron

cone

Voxel

Alpha-particles
3.5 MeV: 1.3 cm/ns

Deuteron beam

Gamma detectors

Carbonoglass with
the honeycomb core

Carbon

Fiber reinforcered
composite material

Steel alloys

Titanium
alloys

Alluminum or
aluminum-lithium alloys

Carbon with
the honeycomb core

Nickel alloys

Registration of coincidence between alpha-particle and gamma-detectors

| Time of alpha-gamma coincidence $t_{\alpha\gamma}$ |
| Amplitude of the gamma-detector signal A_γ |
| Gamma-detector number R_γ |
| Alpha-detector number R_γ |

Stop

γ

n

n'

Before
collision

Momentarily,
both masses
are united.

After collision,
excess energy is
emitted as electro-
magnetic radiation.

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

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

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

ING-27

Segmented Alpha-detector
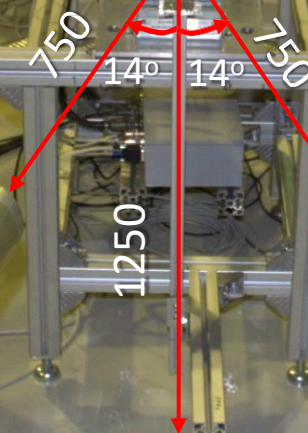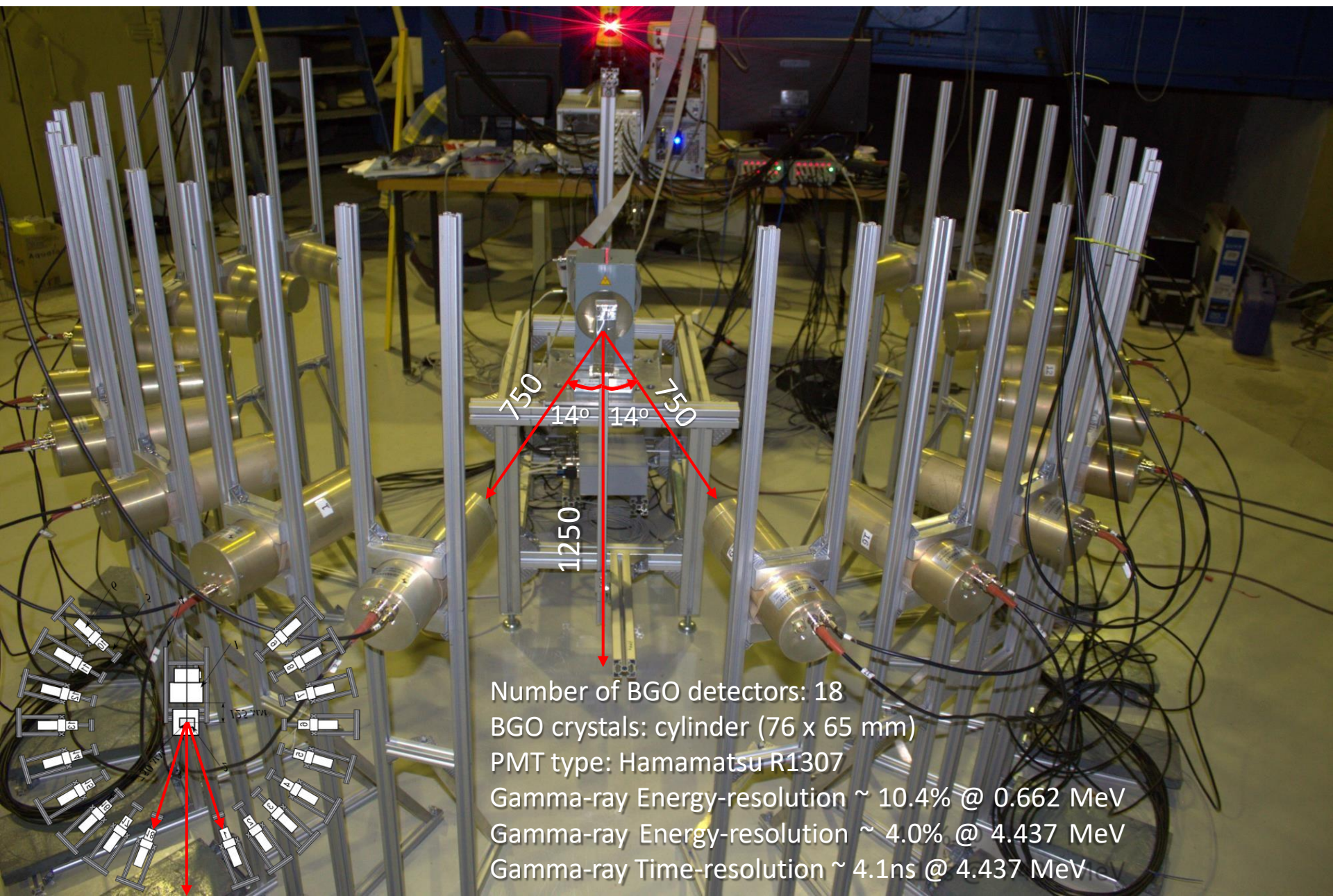
Start

PA

Tritium Target

DT-neutrons 14.1 MeV: 5 cm/ns

Voxel

tagged

L_n neutron

cone

Voxel

Deuteron beam

Alpha-particles 3.5 MeV: 1.3 cm/ns

Gamma detectors

Gamma Rays

Registration of coincidence between alpha-particle and gamma-detectors

| Time of alpha-gamma coincidence $t_{\alpha\gamma}$ |
| Amplitude of the gamma-detector signal A_γ |
| Gamma-detector number R_γ |
| Alpha-detector number R_γ |

Stop

Analysis:
Cone ©
Cone slice ©/δt
Radiography (2D) ©/(x,y)
Tomography (3D) ©/(x,y)/δt

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

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

750

14° 14°

750

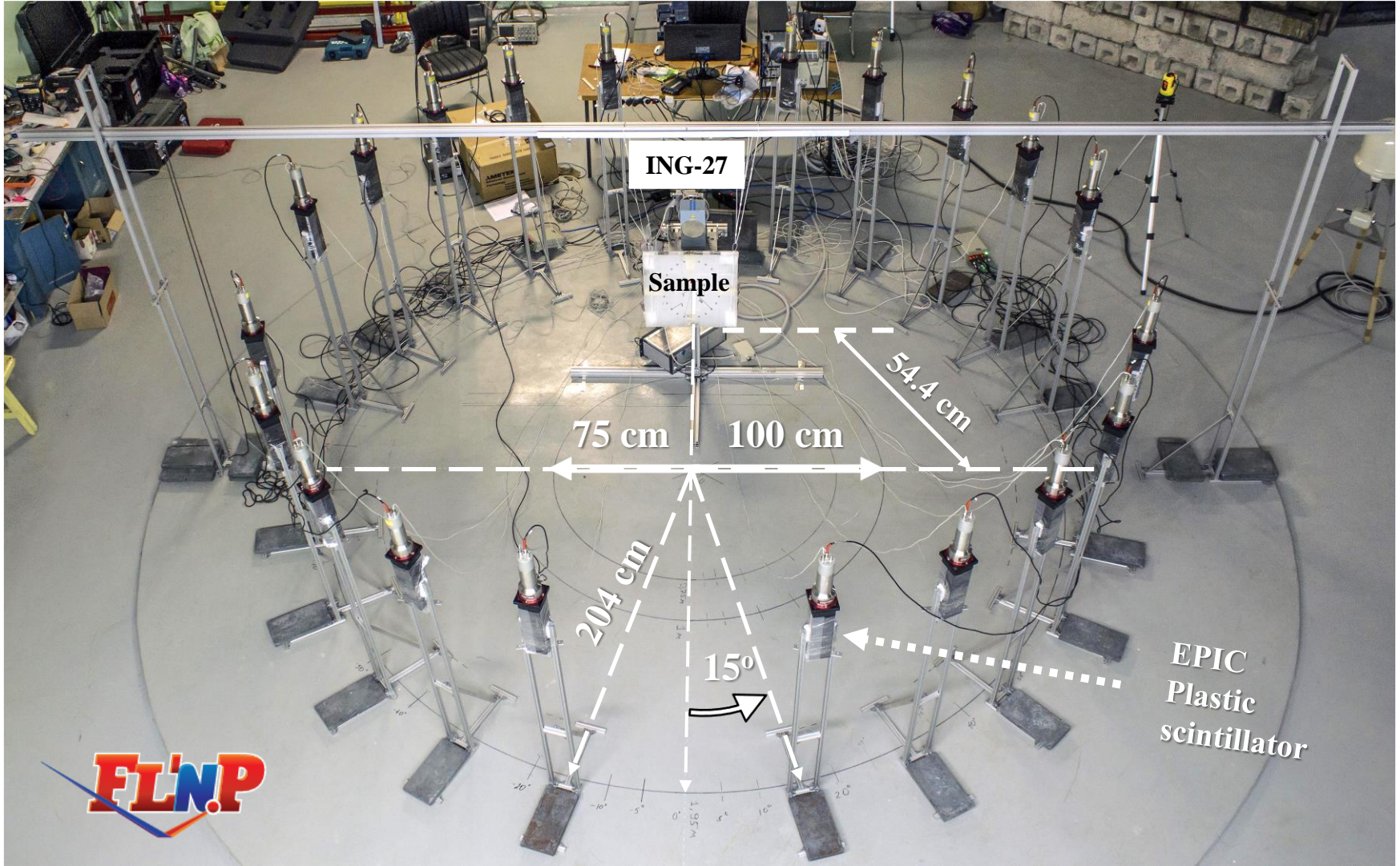1250

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
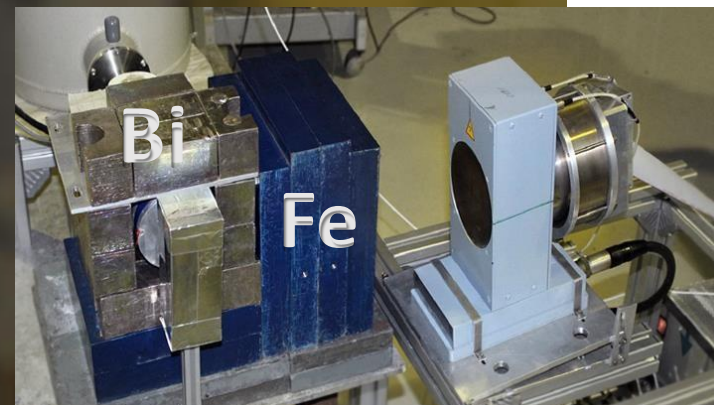Gamma-ray Time-resolution ~ 4.1ns @ 4.437 MeV
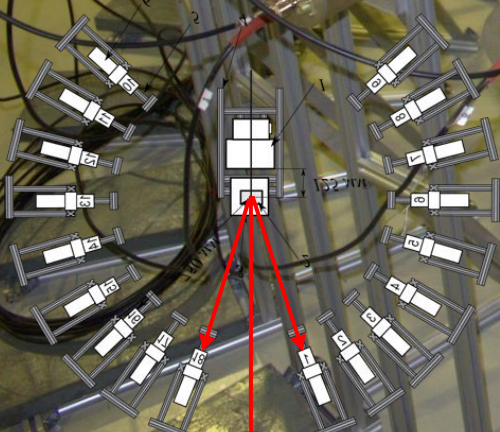
HPGe detector:
Type: Ortec®GMX 30-83-PL-S, ϕ 57.5 x 66.6 mm
Gamma-ray Energy-resolution ~ 3.4% @ 0.662 MeV
Gamma-ray Energy-resolution ~ 0.3% @ 4.437 MeV
Gamma-ray Time-resolution ~ 6.1 ns @ 4.4437MeV
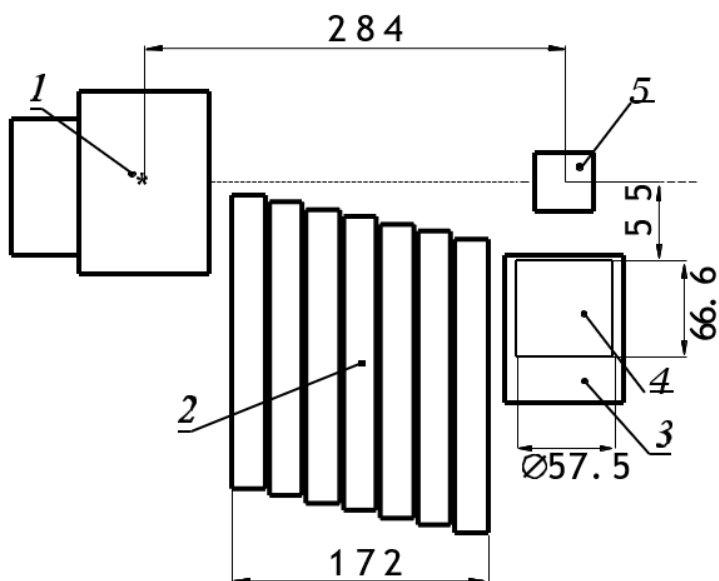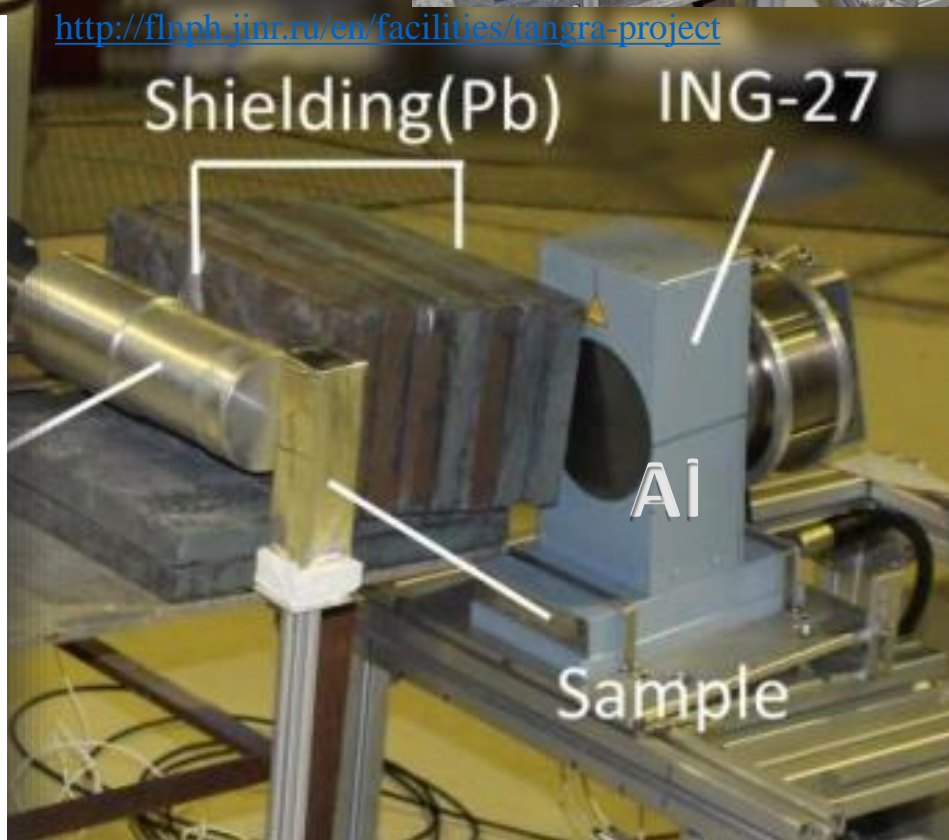
http://flnph.jinr.ru/en/facilities/tangra-project

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.

Elements important for Nuclear Science

Periodic Table 1-172

Legend:
- Green — NaI/BGO/HpGe
- Pink — NaI/HpGe
- Purple — BGO/HpGe
- Blue — HpGe
- Yellow — To be measured
- Red outline — Published

A promising neutron source based on the EG-5 accelerator at FLNP JINR

Doroshkevich Aleksandr at el.

E-mail: doroh@jinr.ru

Beam parameters of EG-5 accelerator

GasTarget

$D(d,n)^3He$

Neutron beam parameters

- Neutrons flow – $5 \cdot 10^7$ pat/s sm^2
- Max. neutrons energy - 5,5±0,1 MeV (Deutron current – 2mkA, deutron energy – 2,5MeV);

Ion beam parameters

Range of ion beam currents - 0,01 - 3 мкА (100 – 250mkA*);
- Real ion beam energy range - 800 keV – 2,5MeV (4,1 MeV*);
- Energy resolution (H$^+$, He^{2+}) - not worse than 15keV;
- Charged particles flow (H$^+$, He^{2+}) – $10^{12}-10^{13}$ part /s sm^{-2}

Nuclear physics

Nuclear reactions with fast quasimonoenergetic neutrons, including:
- research of fast neutron induced fission: measurements of the **prompt fission neutron (PFN) spectra and total kinetic energies (TKE) in reactions** $^{235}U(n,f)$, $^{238}U(n,f)$, $^{237}Np(n,f)$, $^{239}Pu(n,f)$ for neutron energy region of 1-5 MeV;
- **the study of the multiplicity of PFNs in these fast neutron reactions** in geometry with high efficiency of **PFN** registration;
- measurement of the **spectra of charged particles from reactions (n, α), (n, p)** depending on the neutron energy in the energies region up to 5 MeV and higher;
- measuring the **integral and differential cross sections of these reactions** as a function of neutron energy;
- investigation of the **spectrum and angular distributions of charged particles** at a neutron energy of ~ 20 MeV in order to study non-statistical effects;
- the study of reactions (α, n) and (p, n) in combination, respectively, with reactions (n, α) and (n,p);
- investigation of **elastic and inelastic scattering of fast neutrons** by atomic nuclei;
- Using the **TOF technique** in a pulsed mode (f~ 1 MHz, dt~1-10 ns).

The EG-5 accelerator complex

Building 42
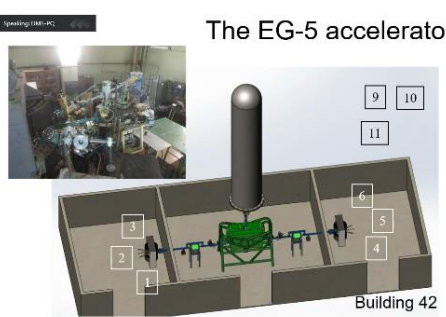
1 - Installation for the study of helium porosity;
2 – Ion irradiation chamber;
3 – Ion Beam Spectrometer Chamber;
4 – Installation of NAA (lithium target);
5 – Installation for the study of reactions with the departure of charged particles;
6 – Installation for channeling research;
7 – Besides IBT : Chemical Laboratory;
8 – Engineering Laboratory;

Nuclear Data High Priority Request List

ID	View	Target	Reaction	Quantity	Energy range	Sec.E/Angle	Accuracy	Cov Field	Date
2H		8-O-16	(n,a),(n,abs)	SIG	2 MeV-20 MeV	See details		Y Fission	12-SEP-08
3H		94-PU-239	(n,f)	prompt g	Thermal-Fast	Eg=0-10MeV	7.5	Y Fission	12-MAY-06
4H		92-U-235	(n,f)	prompt g	Thermal-Fast	Eg=0-10MeV	7.5	Y Fission	12-MAY-06
8H		1-H-2	(n,el)	DA/DE	0.1 MeV-1 MeV	0-180 Deg	5	Y Fission	16-APR-07
15H		95-AM-241	(n,g),(n,tot)	SIG	Thermal-Fast		See details	Fission	10-SEP-08
18H		92-U-238	(n,inl)	SIG	65 keV-20 MeV	Emis spec. See details		Y Fission	11-SEP-08
19H		94-PU-238	(n,f)	SIG	9 keV-6 MeV		See details	Y Fission	11-SEP-08
21H		95-AM-241	(n,f)	SIG	100 keV-20 MeV		See details	Y Fission	11-SEP-08
22H		95-AM-242M	(n,f)	SIG	0.5 keV-6 MeV		See details	Y Fission	11-SEP-08
25H		96-CM-244	(n,f)	SIG	65 keV-6 MeV		See details	Y Fission	12-SEP-08
27H		96-CM-245	(n,f)	SIG	0.5 keV-6 MeV		See details	Y Fission	12-SEP-08
29H		11-NA-23	(n,inl)	SIG	0.5 MeV-1.3 MeV	Emis spec. See details		Y Fission	12-SEP-08
32H		94-PU-239	(n,g)	SIG	0.1 eV-1.35 MeV		See details	Y Fission	12-SEP-08
33H		94-PU-241	(n,g)	SIG	0.1 eV-1.35 MeV		See details	Y Fission	12-SEP-08
34H		26-FE-56	(n,inl)	SIG	0.5 MeV-20 MeV	Emis spec. See details		Y Fission	12-SEP-08
35H		94-PU-241	(n,f)	SIG	0.5 eV-1.35 MeV		See details	Y Fission	12-SEP-08
37H		94-PU-240	(n,f)	SIG	0.5 keV-5 MeV		See details	Y Fission	15-SEP-08
38H		94-PU-240	(n,f)	nubar	200 keV-2 MeV		See details	Y Fission	15-SEP-08
39H		94-PU-242	(n,f)	SIG	200 keV-20 MeV		See details	Y Fission	15-SEP-08
41H		82-PB-206	(n,inl)	SIG	0.5 MeV-6 MeV		See details	Y Fission	15-SEP-08
42H		82-PB-207	(n,inl)	SIG	0.5 MeV-6 MeV		See details	Y Fission	15-SEP-08
45H		19-K-39	(n,p),(n,np)	SIG	10 MeV-20 MeV		10	Y Fusion	11-JUL-17
97H		24-CR-50	(n,g)	SIG	1 keV-100 keV		8-10	Y Fission	05-FEB-18
98H		24-CR-53	(n,g)	SIG	1 keV-100 keV		8-10	Y Fission	05-FEB-18
99H		94-PU-239	(n,f)	nubar	Thermal-5 eV		1	Y Fission	12-APR-18
102H		64-GD-155	(n,g),(n,tot)	SIG	Thermal-100 eV		4	Y Fission	09-MAY-18
103H		64-GD-157	(n,g),(n,tot)	SIG	Thermal-100 eV		4	Y Fission	09-MAY-18
114H		83-BI-209	(n,g)Bi-210g,m	BR	500 eV-300 keV		10	Y ADS,Fission	09-NOV-18
115H		94-PU-239	(n,tot)	SIG	Thermal-5 eV		1	Y Fission	08-APR-19

Most of the required neutron energies are in the range, which can be achieved in our accelerator. These tasks are difficult and expensive to solve at other types of neutron facilities.
[2] https://www.oecd-nea.org/dbdata/hprl/search.pl?vhp=on
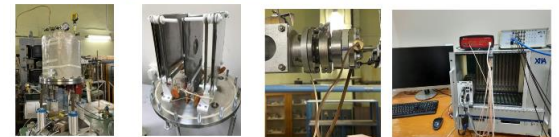
Experimental Hall EG-5, FLNP, JINR

Group of Yu.M. Gledenov

Unique results have been obtained

The recent results have been obtained at EG-5, FLNP, JINR, the technique has been developed at FLNP and tested at EG-5:

Cross sections of (n,α) reaction with fast neutrons have been measured

A charged particles - spectrometer   Neutron generator   Data Acquisition System

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兰州大学
LANZHOU UNIVERSITY

https://blog.uclm.es/fernandocarrillo/files/2015/03/TABLAUSOS.jpg

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ИЯИЯЕ INRNE

Rhenium - A METAL WITHOUT WHICH THERE WOULDN'T BE GASOLINE!

Abstract. Modern and advanced technologies require the synthesis and use of new materials with improved and well-known properties and characteristics. In recent years, due to the unique properties of rhenium (Re) as one of the other refractory elements (Ta, Mo, W, Ti, Zr, Tc), its use worldwide has increased significantly. Rhenium is used, for example, in the aerospace industry (high-temperature W- and Mo-alloys for jet and rocket engines), the chemical industry, coating and welding, electronics, photography, nuclear medicine, etc. Rhenium is among the rarest metals on Earth and it does not occur uncombined or as a compound in a mineable mineral species. However, it is spread throughout the Earth's crust to the extent of ~0.001ppm. Production of rhenium is by extraction from the flue dusts of molybdenum smelters or by phytoextraction from soils and waters. The EXFOR experimental nuclear data library for the cross sections of (n, γ), (n, n'), (n, 2n), (n, 3n), (n, p), (n, α) reactions (activation, differential, total), the energy and angular distributions of the reaction products contain not many data. Some of the included datasets significantly differ from each other, others have relatively large experimental error-bars. It is proposed to start a comprehensive study of the nuclear properties of rhenium isotopes using neutrons of various energies at the Frank Laboratory of Neutron Physics (FLNP) of the Joint Institute for Nuclear Research (JINR) in Dubna (Russia). The experimental results obtained can be used to better understand the mechanism of neutron-induced nuclear reactions, as well as for the needs of nuclear, life and environmental sciences.

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THE STATE KEY LABORATORY OF INTENSE PULSED RADIATION SIMULATION AND EFFECT, NINT, CHINA

兰州大学

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INRNE

Rhenium
Transition metal

Symbol	Neutrons
Re	**111**
Atomic number	Energy levels
75	**6**
Atomic weight (amu)	Shell structure
186.2	
Atomic radius (pm)	
188	
Proton/electrons	
75	

$[Xe]\ 4f^{14}\ 5d^5\ 6s^2$

Atomic orbitals

melting point	3,180 °C (5,756 °F)
boiling point	5,627 °C (10,161 °F)
specific gravity	20.5 at 20 °C (68 °F)

Rhenium (Re), chemical element, a very rare metal of Group 7 (VIIb) of the periodic table and one of the densest elements. Predicted by the Russian chemist Dmitry Ivanovich Mendeleyev (1869) as chemically related to manganese, rhenium was discovered (1925) by the German chemists Ida and Walter Noddack and Otto Carl Berg. The metal and its alloys have found limited application as turbine blades in fighter-jet engines, fountain pen points, high-temperature thermocouples (with platinum), catalysts, electrical contact points, and instrument-bearing points and in electrical components, such as in flashbulb filaments as an alloy with tungsten.

Rhenium does not occur free in nature or as a compound in any distinct mineral; instead it is widely distributed in small amounts in other minerals, usually in concentrations averaging about 0.001 parts per million. Chile is the world leader in rhenium recovery, followed by the United States, Poland, Uzbekistan, and Kazakhstan.

Aerospace

Chemical Processing

Furnace Components

Medical Equipment

Metallurgy

Research And Development

Semiconductor

REVIEW

Electronic and Optoelectronic Applications Based on ReS2

Yan Xiong, HuaWei Chen, David Wei Zhang, and Peng Zhou*
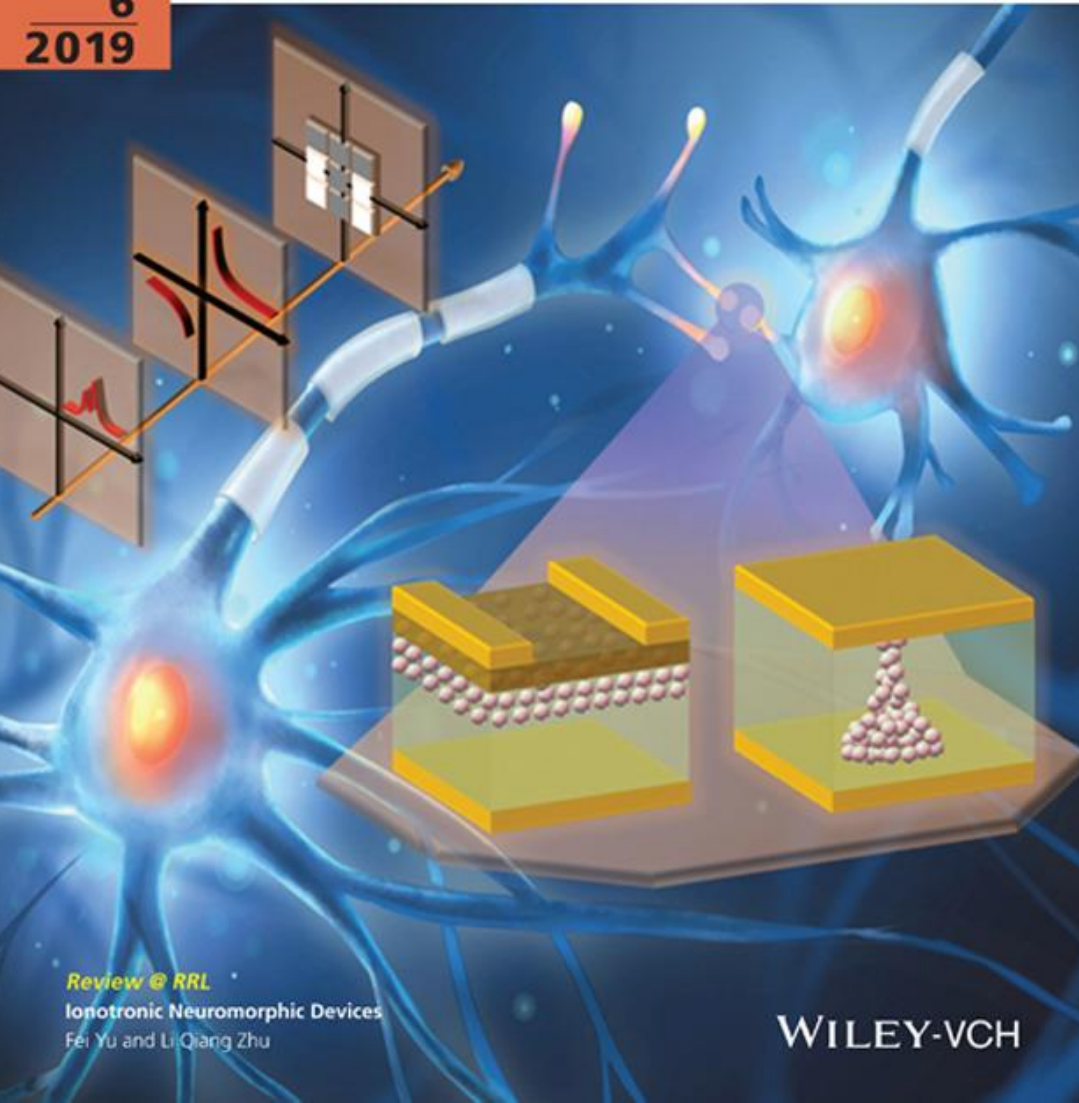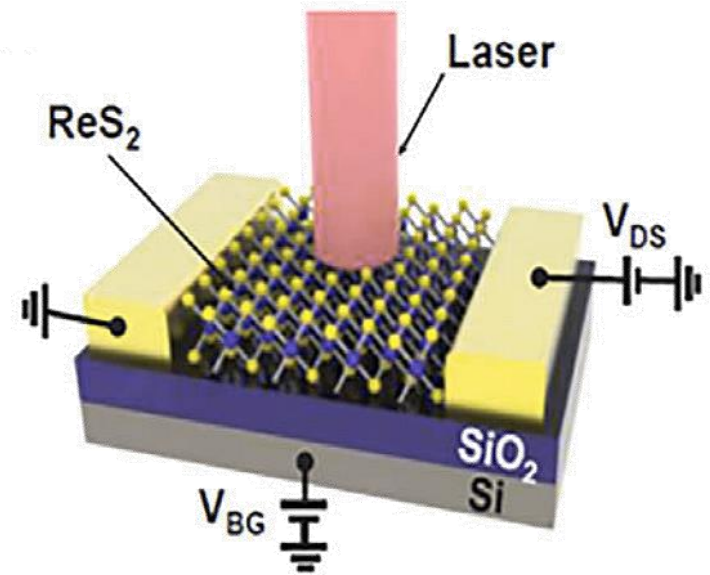
Schematic diagram of few-layer **Re**S2 based photodetector

Current state of production and consumption of rhenium abroad

Kaerbek Argimbaev[1,*], *Dmitry* Ligotsky[2], and *Egor* Loginov[3]

Pie chart legend:
- Salts used in industry and research
- Salts supplied to the production of metallic rhenium
- Stocks
- Salts
- Powder, fillets, rods, wire, etc..
- Heat treated alloys
- Thermocouples
- Chemical industry

Pie chart values: 2%, 2%, 6%, 2%, 2%, 9%, 5%, 72%
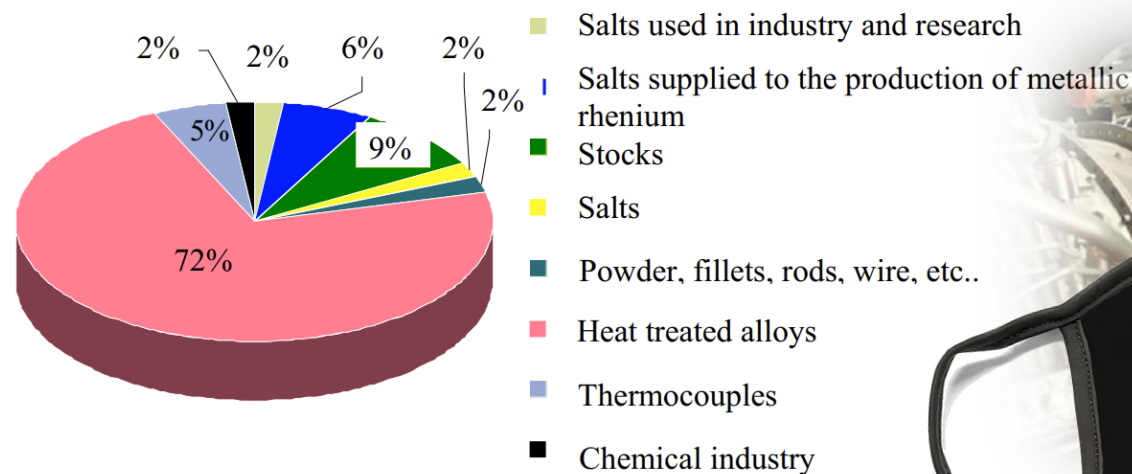
Fig. 4. Structure of consumption of rhenium products in the USA (2018).

Rhenium is used in platinum-rhenium catalysts which in turn are primarily used in making lead-free, high-octane gasoline and in high-temperature superalloys that are used to make jet engine parts. Other uses:

* Widely used as filaments in mass spectrographs and in ion gauges.
* An additive to tungsten and molybdenum-based alloys to increase ductility in these alloys.
* An additive to tungsten in some x-ray sources.
* Rhenium catalysts are very resistant to chemical poisoning, and so are used in certain kinds of hydrogenation reactions.
* Electrical contact material due to its good wear resistance and ability to withstand arc corrosion.
* Thermocouples containing alloys of rhenium and tungsten are used to measure temperatures up to 2200 °C.
* Rhenium wire is used in photoflash lamps in photography.
* For use in booster rocket engine

https://www.refractorymetal.org/overview-of-the-refractory-metal-rhenium/

https://www.e3s-conferences.org/articles/e3sconf/pdf/2021/34/e3sconf_uesf2021_12012.pdf

Molybdenum Rhenium Alloy Foil   Rhenium Wire   Rhenium Pellet   Rhenium Rod

Isotope Applications:

Stable Rhenium Isotopes - Re Isotopes

Nominal Mass	Accurate Mass	% Natural Abundance	Chemical Form	Enrichment Available %
^{185}Re	184.952951 (3)	37.40 (2)	metal	94 - 97+
^{187}Re	186.955744 (3)	62.60 (2)	metal	95 - 99+

Re-185 Stable
184.95296
NA: 37.4%

• is used for research in nuclear physics;
• is used for Re-186 radionuclide production (can be used in life science for healthcare and medical applications and pharmaceuticals industries);

Re-187 Radioactive
186.95575
NA: 62.6%

• is used for Os-189m radionuclide production (can be used in life science for healthcare and medical applications and pharmaceuticals industries);

Re-185 and Re-187 isotopes are market available as metal foil and powder

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Nipponium as a new element (Z=75) separated by the Japanese chemist, **Masataka Ogawa and his son Eijiro Ogawa**: 1908.

Walter Noddack, Ida Tacke-Noddack, Otto Berg

First found **Rhenium** in *columbite* and *platinum* ores, 1925.

$$\rightarrow 2NH_4ReO_4 + 7H_2 \rightarrow 2Re + 8H_2O + 2NH_3$$

https://www.youtube.com/watch?v=VRccwkEmOYg&t=3s

IDA TACKE NODDACK 1896 – 1978
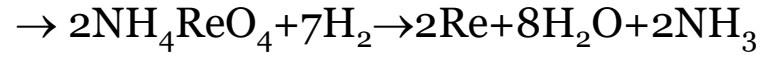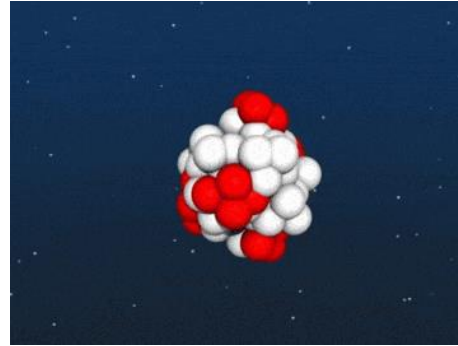
Ida Noddack Tacke (25 February 1896 in Wesel - 1978) was a German chemist and physicist. With her husband Walter Noddack she discovered element 75 Rhenium. She correctly criticized Enrico Fermi's chemical proofs in his 1934 neutron bombardment experiments, from which he postulated that transuranic elements might have been produced, and which was widely accepted for a few years. Her paper, "On Element 93" suggested a number of possibilities, centering around Fermi's failure to chemically eliminate *all* lighter than uranium elements in his proofs, rather than only down to lead. The paper is considered historically significant today not simply because she correctly pointed out the flaw in Fermi's chemical proof but because she suggested the possibility that **"*it is conceivable that the nucleus breaks up into several large fragments, which would of course be isotopes of known elements but would not be neighbors of the irradiated element.*"** In so doing she presaged what would become known a few years later as nuclear fission. However Noddack offered no theoretical basis for this possibility, which defied the understanding at the time, and her suggestion that the nucleus breaks into several large fragments is not what occurs in nuclear fission. The paper was generally ignored. Later experiments along a similar line to Fermi's, by Irene Joliot-Curie, and Pavel Savitch in 1938 raised what they called "interpretational difficulties" when the supposed transuranics exhibited the properties of rare earths rather than those of adjacent elements. Ultimately in 1939 Otto Hahn and Fritz Strassmann, working in consultation with long term colleague Lise Meitner (who had been forced to flee Germany) provided chemical proof that the previously presumed transuranic elements were isotopes of Barium. It remained for Meitner and her nephew Otto Frisch utilizing Fritz Kalckar and Neils Bohr's liquid drop hypothesis (first proposed by George Gamow in 1935) to provide a theoretical model and mathematical proof of what they dubbed nuclear fission (Frisch also experimentally verified the fission reaction by means of a cloud chamber, confirming the massive energy release)

Re
Rhenium

БЪЛГАРСКА
АКАДЕМИЯ
на НАУКИТЕ
1869

MoS₂ molybdenite

Ammonium
NH4
99% -
CAS Nr:

powder

NH₄ReO₄

No primary Sources of Rhenium are at hand, but it is extracted as a by-product from Mo-concentrates, which themselves are a by-product of mining Cu-ores.
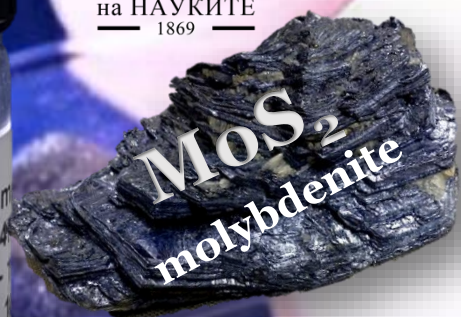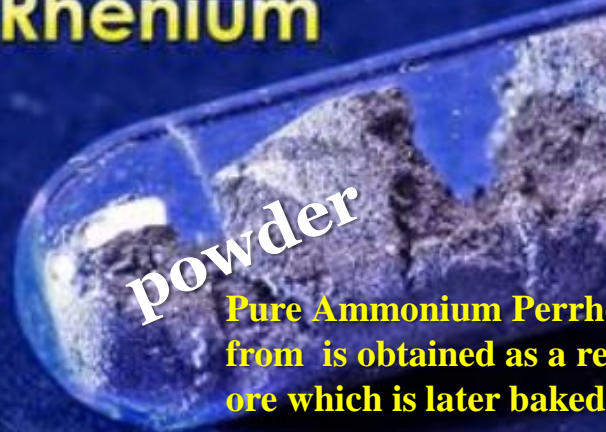
Pure Ammonium Perrhenate, that metallic rhenium is extracted from is obtained as a result of refining and concentration of the ore which is later baked or melted into small drops

$$2NH_4ReO_4(s) + 7H_2 = 2Re° + 2NH_3 + 8H_2O$$
$$(\Delta G°298K = -37.16 \text{ kcal})$$

1g

Pb   **Re**

Re
H₂   75
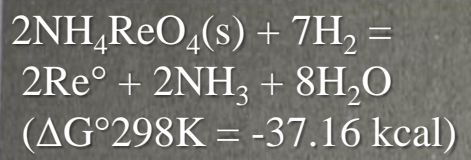
That is why such a small drop weight a whole gram and costs whopping 15 euros

NH4ReO4 is used for the direct production of rhenium-based catalysts used in petrochemical refining and as a precursor material for pure rhenium metal powder or pellets.

Rhenium has a melting point of 3186 °C, which is the 3rd-highest melting point among all elements after Carbon and Tungsten. Its boiling point is at top positions with 5627 °C.

1.00
g

(189) Dissolving a Super Rare Metal to make Ammonium Perrhenate - YouTube

2022
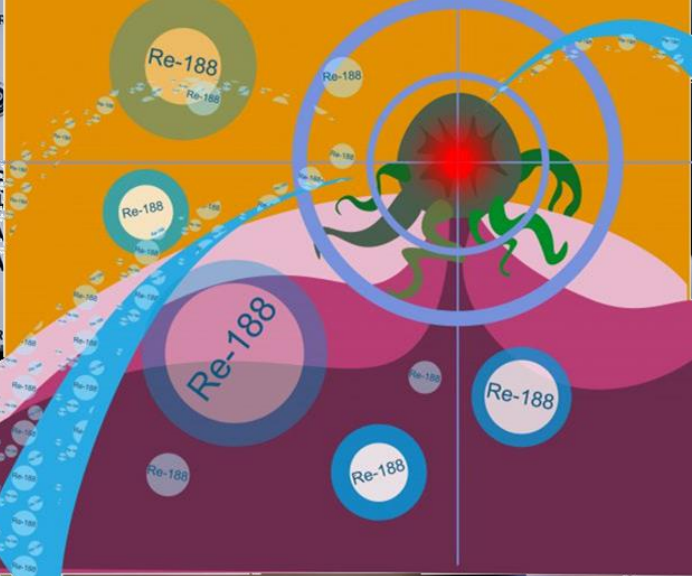
10 марта 2022 года стало знаковым событием не только для НМИЦ радиологии, но и всего отечественного здравоохранения. Именно в нашей стране был разработан, изготовлен и применён в процедуре радиосинвэктомии радиофармпрепарат на основе радионуклида Рений – 188 (Re).

В стенах филиала НМИЦ радиологии в г. Обнинск - МРНЦ им А.Ф. Цыба в рамках клинических исследований прошла процедура радиосиновэктомии - радионуклидного лечения хронического синовита коленного сустава. Заболевания суставов, в том числе синовиты, являются очень распространёнными и часто принимают хроническую форму. Сложность терапии заключается в том, что иногда заболевание становится резистентным к лекарственным препаратам.

ГЕНЕРАТОР РЕНИЯ-188-1

Re-188

ФОТО

ФГБУ «НАЦИОНАЛЬНЫЙ МЕДИЦИНСКИЙ ИССЛЕДОВАТЕЛЬСКИЙ ЦЕНТР РАДИОЛОГИИ»

Reactor SM-3 at NIIAR — generator of isotopes for nuclear medicine

Реактор СМ-3 в НИИАР — наработчик изотопов для ядерной медицины
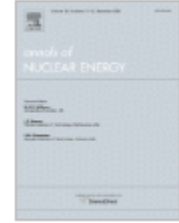
Prediction of the correct measured activity of ^{186}Re and ^{188}Re from reactor produced natural rhenium using an artificial neural network

B. Leila Moghaddam, Saeed Setayeshi,
Mohammad G. Maragheh, Reza Gholipour

Abstract. To optimize the cost effectiveness of ^{186}Re and ^{188}Re production, which have recently been used as **radio pharmaceuticals for therapeutic purposes**, we designed an artificial neural network (ANN) to evaluate the activity of combined ^{186}Re+ ^{188}Re. One of the production ways is the (n,γ) reaction of natural rhenium which leads to combined ^{186}Re + ^{188}Re. Using the counted activity of ^{186}Re + ^{188}Re mixtures by a well type isotope calibrator, the precise activity of ^{186}Re and ^{188}Re is obtained by the ANN. A back-propagation ANN was trained using 30 activities of mixed ^{186}Re + ^{188}Re. The performance of the ANN was tested by Early-Stopping validation method, and the ANN was optimized with respect to its architecture. **The response of the ANN shows significant precision that may be used for medical application of ^{186}Re + ^{188}Re mixtures.**

$$^{185}\text{Re} \xrightarrow{n,\gamma} {}^{186}\text{Re} \xrightarrow{\beta^-,\,89.25\text{ h}} {}^{186}\text{Os (stable)}$$

$$\gamma = 136 \text{ keV}(9\%), \quad \beta^-_{\max} = 1.08 \text{ MeV}$$

$$^{187}\text{Re} \xrightarrow{n,\gamma} {}^{188}\text{Re} \xrightarrow{\beta^-,\,16.9\text{ h}} {}^{188}\text{Os (stable)}$$

$$\gamma = 155 \text{ keV}(15\%), \quad \beta^-_{\max} = 2.12 \text{ MeV}$$

Decay schemes

^{188}Re

^{186}Re

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Pulsed transformer

Electron gun

1st accelerating section

2nd accelerating section

2nd klystron

1st modulator

2nd modulator

1st klystron

Magnetic spectrometer

Klystron 2

Beam line shutters

Target

REGATA-2
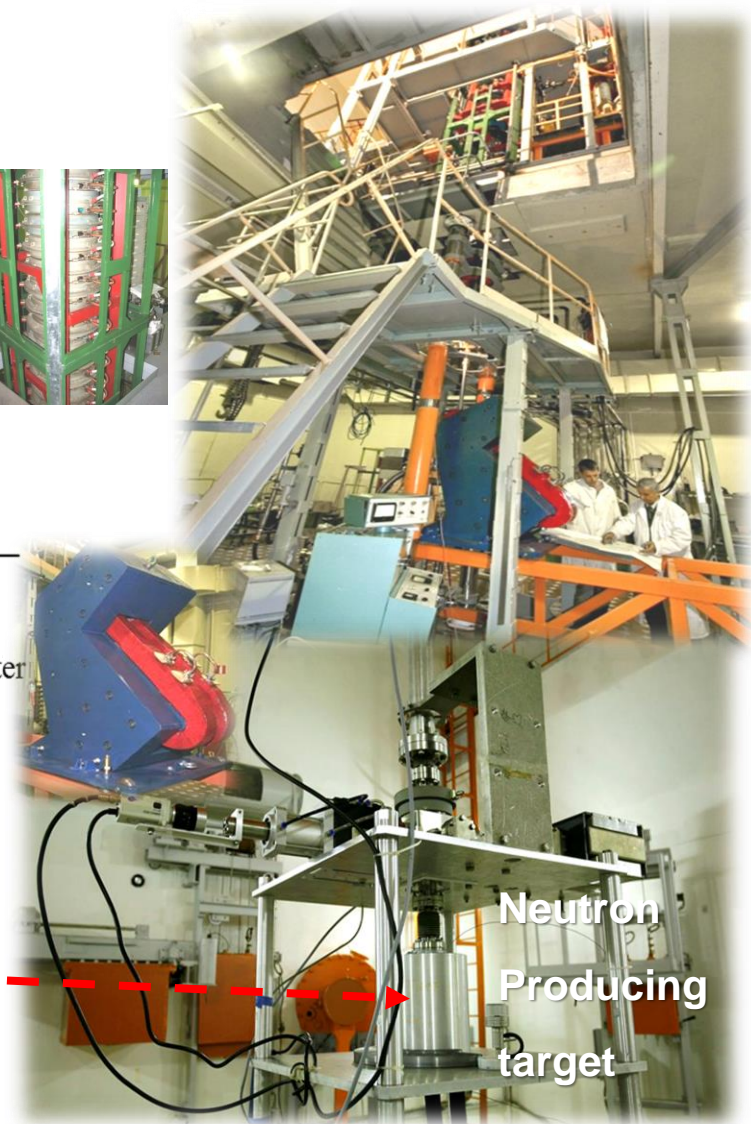
Neutron Producing target

http://flnp.jinr.ru/244/

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Investigation of Rhenium by Neutrons
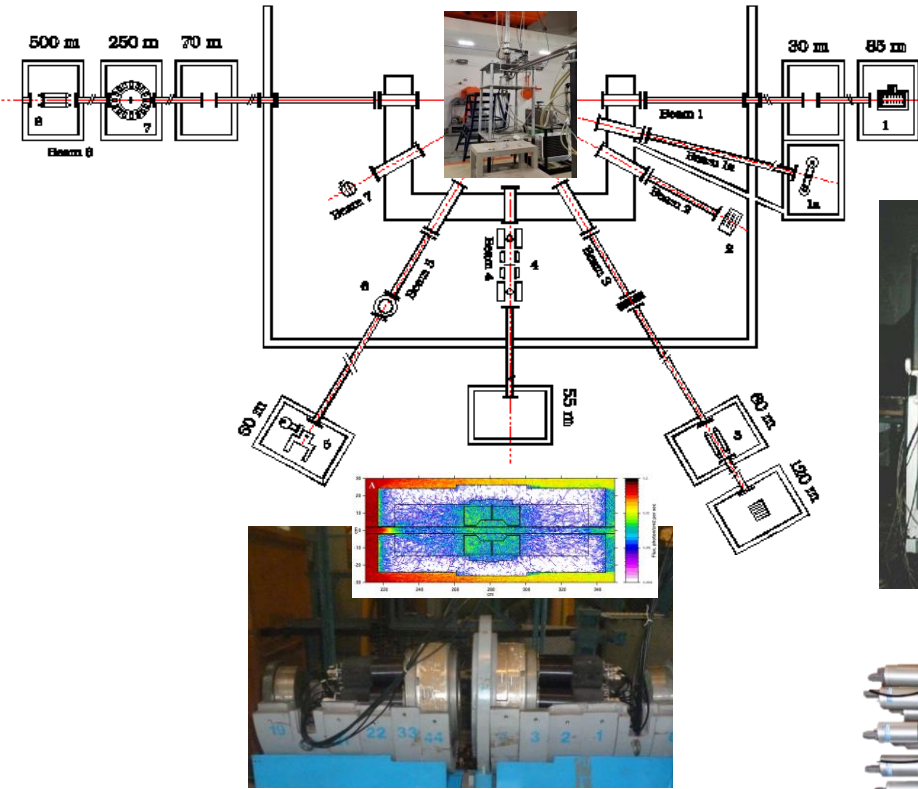
Table 3. IREN parameters.

Parameter	Project	I Stage	II Stage
Peak current (A)	1.5	1.5–2.5	1.5–2.5
Repetition rate (Hz)	150	25	50
Electron pulse duration (ns)	250	100	100
Electron energy (MeV)	212	32–42	45–65
Beam power (kW)	12	0.1–0.4	0.3–1.2
Neutron intensity (n/s)	2×10^{13}	3×10^{11}	6×10^{11}

https://doi.org/10.3390/qubs1010006
http://www.jinr.ru/posts/128935/

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Investigation of Rhenium by Neutrons

Rhenium resonance parameters from neutron capture and transmission measurements in the energy range 0.01 eV to 1 keV

B.E. Epping [a, c, *], G. Leinweber [a], D.P. Barry [a], M.J. Rapp [a], R.C. Block [a], T.J. Donovan [a], Y. Danon [b], S. Landsberger [c]

https://doi.org/10.1016/j.pnucene.2017.04.015

Abstract. **Rhenium** is a refractory metal with potential uses in nuclear reactor applications, particularly those at very high temperatures. Measurements have been made using natural samples. Natural rhenium consists of two isotopes: **^{185}Re (37.40%) and ^{187}Re (62.60%).** The electron linear accelerator (LINAC) at the Rensselaer Polytechnic Institute (RPI) Gaerttner LINAC Center was used to explore neutron interactions with rhenium in the energy region from 0.01 eV to 1 keV**. Neutron capture and transmission measurements were performed by the time-of-flight technique.** Two transmission measurements were performed at flight paths of 15 m and 25 m with ^{6}Li glass scintillation detectors. The neutron capture measurements were performed at a flight path of 25 m with a **16-segment sodium iodide multiplicity detector**. Resonance parameters were extracted from the data using the multilevel R-matrix Bayesian code SAMMY. A table of resonance parameters and their uncertainties is presented. The uncertainties in resonance parameters were propagated from a number of experimental quantities using a Bayesian analysis. Uncertainties were also estimated from fitting each Re sample measurement individually. **The measured neutron capture resonance integral for ^{185}Re is (4 ± 1)% larger than ENDF/B-VII.1. The capture resonance integral for ^{187}Re is (3 ± 1)% larger than ENDF/B-VII.1.** Other findings from these measurements include: **a decrease in the thermal capture cross section for ^{185}Re of (2 ± 2)% from ENDF/B-VII.1; a decrease in the thermal capture cross section for ^{187}Re of (3 ± 4)% from ENDF/B-VII.1; a decrease in the thermal total cross section for ^{185}Re of (2 ± 2)% from ENDF/B-VII.1; and a decrease in the thermal total cross section for ^{187}Re of (6 ± 5)% from ENDF/B-VII.1. Considering the uncertaint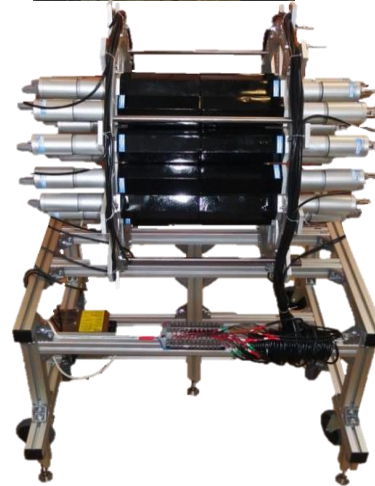ies, none of the indicated changes in thermal cross sections represents a statistically significant change from ENDF/B-VII.1.**

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2018

parent nucleus

^{187}Re

β -decay
half-life is 4.35×10^{10}y

daughter nucleus

^{187}Os

The ^{187}Re/^{187}Os abundance ratio changing with the ^{187}Re half-life can be a good chronometer for the r-process. However, slow neutron-capture process (s-process) through an isomer state of ^{186}Re ($T_{1/2}$ = 0.2 Myr) may contaminate the ^{187}Re/^{187}Os abundance ratio. It is necessary to evaluate a contribution from ^{186m}Re created from the ^{185}Re(n, γ) ^{186m}Re reaction.

Persistent Quest Research Activities 2005 (jaea.go.jp)
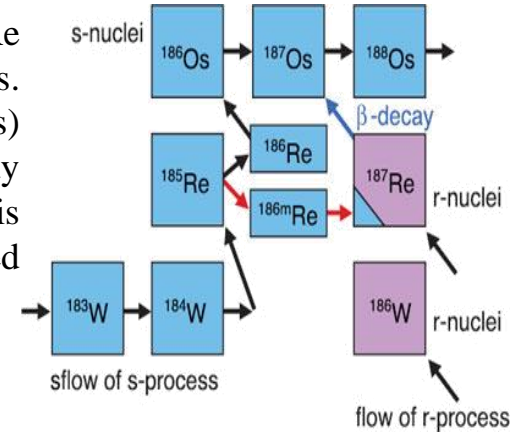
Neutron capture cross section of ^{185}Re leading to ground and isomer states of ^{186}Re in the keV-neutron energy region

https://doi.org/10.1051/epjconf/201817803005

T. Katabuchi[1,*], K. Takebe[1], S. Umezawa[1], R. Fujioka[1], T. Saito[1], and M. Igashira[1]

[1]Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo, 152-8550, Japan

Abstract. The neutron capture cross section of ^{185}Re was measured in the astrophysically important energy region. Measurements were made using a neutron beam from a ^{7}Li(p,n)^{7}Be neutron source with **energies ranging from 3 to 90 keV.** Two different experimental techniques, time-of-flight (TOF) and activation methods, were employed. **In the TOF experiments, the total neutron capture cross section of ^{185}Re was determined by the pulse-height weighting technique. In the activation method, the partial capture cross section leading to the ground state of ^{186}Re was measured by detecting decay γ-rays from neutron activated samples.** The present cross section values were compared with evaluated cross section data and previous measurements. **The difference between the TOF and activation results was smaller than experimental uncertainties. This suggests that the production cross section of isomer states of ^{186}Re is very small.**

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ROSATOM

Production of the ^{186m}Re isomer in nuclear reactor

Vladimir Koltsov

Khlopin Radium Institute Saint-Petersburg

E-mail: vladimir-koltsov@yandex.ru
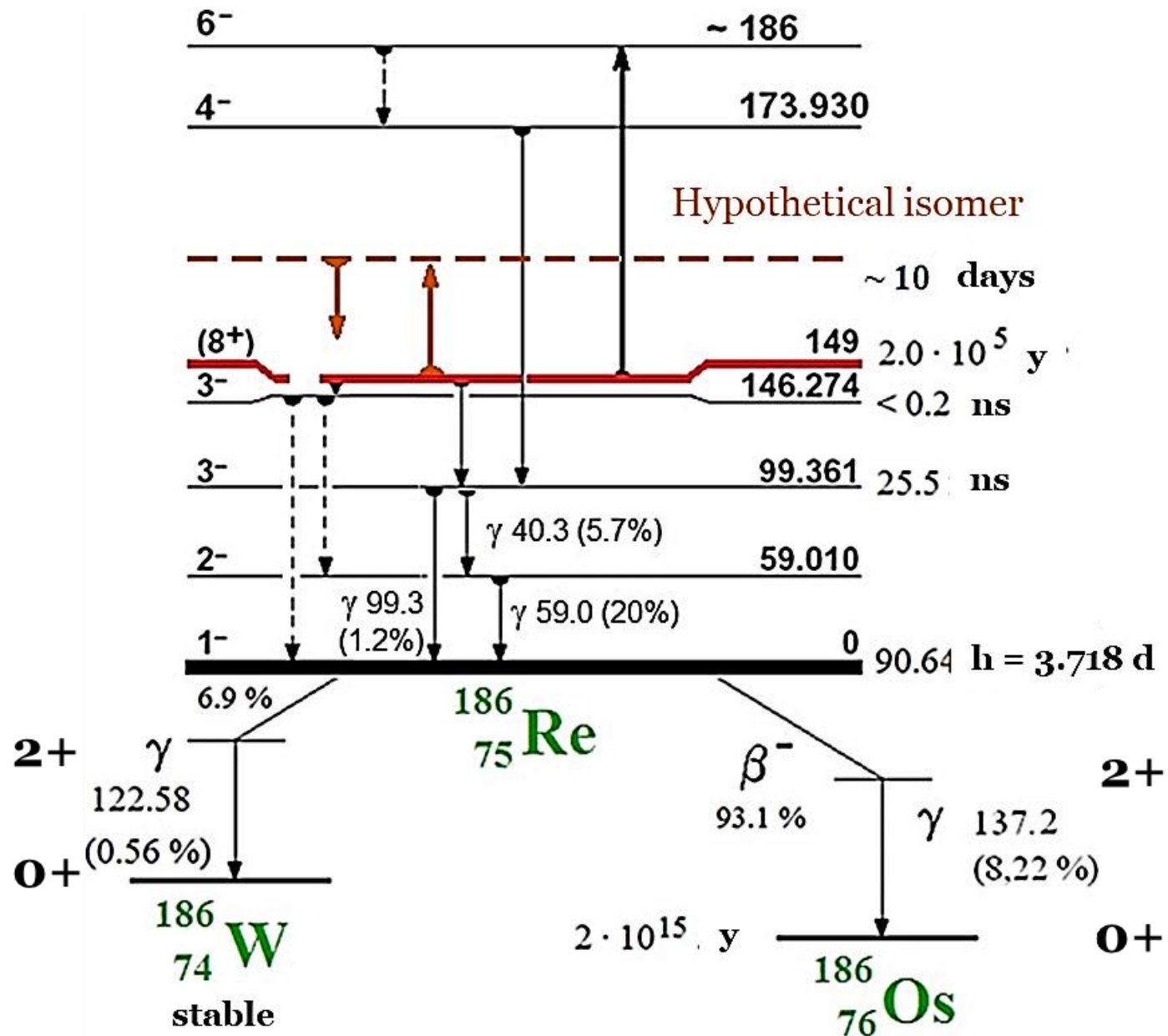
Possible reactions for the formation of the ^{186m}Re isomer

- $S_n = 7359$
- (n, γ)
- $(n, 2n')$ $E_n > 7359$ keV
- γ
- 8 + 149
- $2.0 \cdot 10^5$ y
- 5/2 + 0
- 1 − 0
- 5/2 + 0
- ^{185}Re stab. nat. 37.4 %
- ^{186}Re 90.64 h
- ^{187}Re $4.35 \cdot 10^{10}$ y nat. 62.6 %
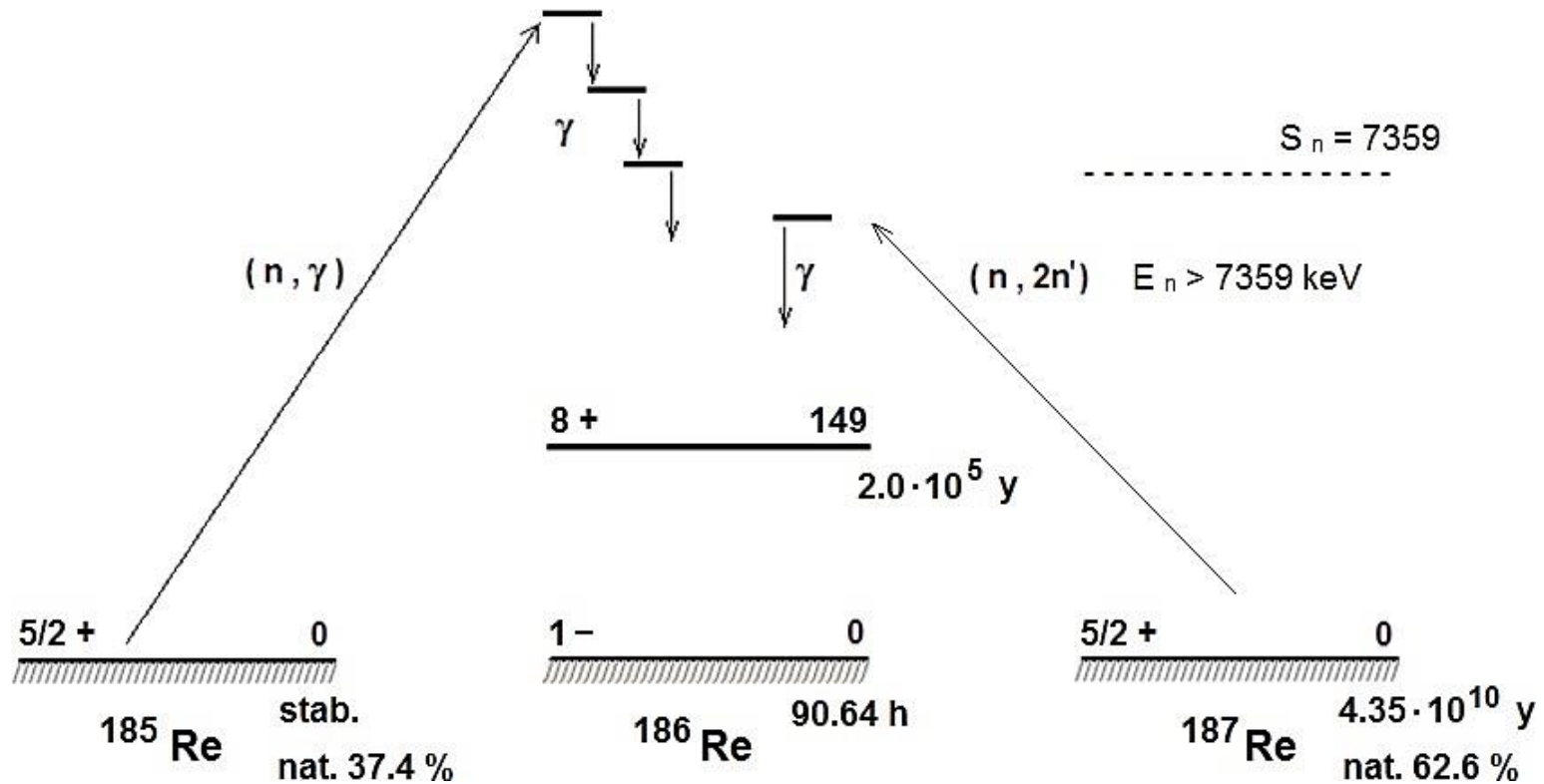
1. The integral cross section for the formation of the 186m isomer Re: $\sigma_{tot} \approx 300$ mbar.
1. Excitation of the isomer during inelastic scattering of neutrons by ^{186}Re nuclei is not significant (low concentration of ^{186}Re).
2. Restriction on the integral cross section of $\sigma(n,2n) < 10$ mbar.
3. Therefore, the main isomer formation reaction is (n, γ).

Formation of the ^{186m}Re isomer in the reaction (n, 2n)
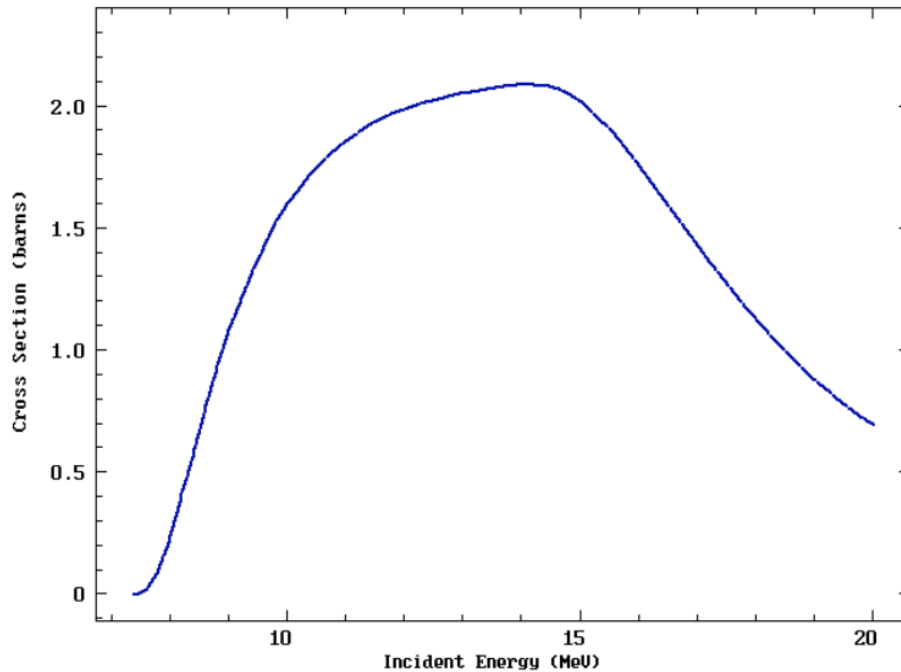
Total cross section for the ^{187}Re (n, 2n) reaction as a function of the neutron energy.

1. For the (n, 2n) reaction, neutrons with an energy of more than 8 MeV are required.
2. 2. Assuming the neutron fission spectrum in this energy range, it can be considered that approximately 0.5% of neutrons have energy more than 8 MeV.
3. Total cross section (n, 2n) of the reaction < 2000 mbar → integral cross section less than 100 mbar.
4. In a similar reaction (n, 2n) on ^{191}Ir, the isomer is formed with a probability of 3% of reactions.
5. It can be assumed that the integral cross section for the formation of the ^{186m} Re isomer is less than 10 mb.

Образование изомера ^{186m}Re в реакции (n , 2n)

Measurements of rhenium isotopic composition in low-abundance samples†

https://pubs.rsc.org/en/content/articlepdf/2020/ja/c9ja00288j

Mathieu Dellinger [iD] *[a], **Robert G. Hilton** [a] **and Geoffrey M. Nowell** [iD] [b]

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Abstract

Rhenium (Re) is a trace element whose redox chemistry makes it an ideal candidate to trace a range of geochemical processes. In particular, fractionation of its isotopes [187]Re (62.6% abundance) and [185]Re (37.4%) may be used to improve our understanding of redox reactions during weathering, both in the modern day and in geological archives. Published methods for measurement of Re isotopic composition are limited by the requirements of Re mass to reach a desirable precision, making the analysis of many geological materials unfeasible at present. Here we develop new methods which allow us to measure Re isotope ratios (reported as δ^{187}Re) with improved precision: ±0.10‰ (2σ) for a mass of Re of ~1 ng to ±0.03‰ (2σ) for a mass of Re of >10 ng. This is possible due to the combination of a modified column chemistry procedure and the use of 10^{13} Ω amplifiers for measurement *via* multicollector inductively coupled plasma mass spectrometry (MC-ICP-MS). For river water samples (with Re concentrations typically ~10^{-12} g g^{-1}) we design a field-based pre-concentration of Re that can be used with large volumes of filtered water (5–20 L) shortly after sample collection to provide abundant Re for isotope analysis. As a result of these developments we provide new measurements of δ^{187}Re in standards reference materials (δ^{187}Re values range from −0.06 ± 0.07‰ to +0.19 ± 0.05‰) and a seawater standard (δ^{187}Re = +0.10 ± 0.04‰), providing impetus for further exploration of the Re isotope system.

Rhenium is traditionally obtained as a by-product of roasting and hydrometallurgical treatment of molybdenum and copper concentrate

Phytomining: New Method for Rhenium

▶ Ognyan Bozhkov
Christina
Tzvetkova
*Institute of General
and Inorganic
Chemistry, Bulgarian
Academy of Sciences
Sofia, Bulgaria*

▶ Ludmila Borisova
*Russian Academy of
Sciences
Moscow, Russia*

▶ Boris Bryskin
*Bryskin Metallurgical
Consulting
Palm Coast, Fla.*

Application of Re phytomining is inexpensive and environmentally friendly and it leads to remediation of exhausted soils of copper mines and ore-dressing regions.

Rhenium (Re) is one of the rarest elements in the Earth's crust (7×10^{-8}%), and is one of the ten most expensive metals on the world market[1]. It has unique physicochemical properties that allow its use in preparation of high-temperature superalloys; rhenium improves the physicochemical properties of Ni-Re, W-Re, Pt-Re, and other superalloys. The main application of Re is Ni-Re alloy in preparing turbine blades for aircraft engines and gas turbines. The main world producers of Re are Chile, Kazakhstan, France, Germany, Russia, U.S., China, Great Britain, the Netherlands, and Poland[1].

The main consumers of Re world production are: Rolls Royce (28%), General Electric (28%), and Pratt & Whitney (12%) in the manufacture of superalloys used in aerospace industry and energetics. Re-Pt alloys account for 14% of Re use as catalysts for the production of lead-free gasoline. High-temperature thermocouples, x-ray sources, self-cleaning electrical contacts, and other products consume 18% Re. About 80% of Re is obtained as a by-product of the pyro- and hydrometallurgical treatment of molybdenum and copper ores and concentrates, and 20% is obtained from Re-containing wastes, such as alloys and catalysts.

The world production of Re in 2008 was 45 tons, while the annual demand of Re is about 60 tons[1]. Because world

production of Re cannot meet industry needs, there is a continual search for new Re sources and new, more effective technologies for its production. Current technologies for producing rhenium containing concentrates and extracting Re from them are not effective enough. During these processes, part of the rhenium is lost and dispersed as volatile Re_2O_7 in surrounding soils and as ReO_4^- ions in industrial waste solutions and water[2]. The scattered rhenium in the environment around copper and molybdenum mines and copper processing factories is a potential source for rhenium production.

How can this rhenium be collected & profitably?

The unique property of rhenium to accumulate and concentrate in the green parts of all kinds of vegetation can be used to this aim. The plant biosphere is a natural collector and concentrator of Re from the surface environment (soils and waters)[3]. The most mobile and bioavailable species of rhenium in the surface environment is ReO_4^- ions[4]. The vegetation in areas of copper mines and copper processing works is enriched in rhenium in amounts many times exceeding its natural occurrence[5]. It is known that rhenium occurs in copper and molybdenum sulfide ores as the water insoluble ReS_2[6].

There are sources of bioavailable ReO_4^- ions in these areas. This is the oxidation zone of ore deposits and dissolved oxygen in underground, hydrothermal, and surface waters. Some oxidation steps of the technology for producing copper and molybdenum concentrates by bacterial leaching with acidithiobacillus ferrooxidans in H_2SO_4 solution in presence of Fe^{3+} ions also generate ReO_4^- ions, which are dispersed in the surface environment of copper mine regions through waste waters and rain fall[7, 8]. Volatile Re_2O_7 is generated during roasting of the concentrate, which is dispersed as a gas emission in the environment and settles on the soils, where in contact with water, it easily transforms to ReO_4^- ions[2].

Asarel open pit copper mine, Bulgaria. Phytomining rhenium is an inexpensive, environmentally friendly green technology.

34 ADVANCED MATERIALS & PROCESSES • MAY 2012
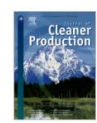
On the uptake of rhenium by plants: Accumulation and recovery from plant tissue

Christina Tzvetkova [a], Luís A.B. Novo [b], Stela Atanasova-Vladimirova [c],
Tsvetan Vassilev [c]

https://doi.org/10.1016/j.jclepro.2021.129534

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This study was the first to ever employ Scanning electron microscopy (SEM) imaging analysis and Infrared (IR) spectrometry to investigate the accumulation of Re in plants.

ISINN-29
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2023
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国家重点实验室
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AND EFFECT, NINT, CHINA

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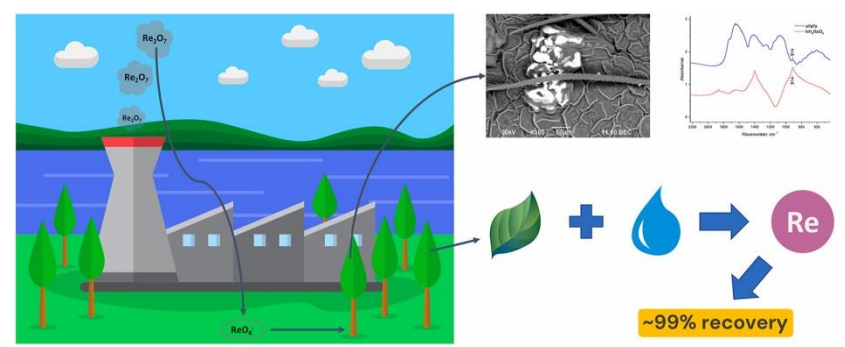
1- dry alfalfa
2- finely ground dried alfalfa
3- ammonium perrhenate powder

Extraction and determination of Re in alkaline and aqueous extracts spectrophotometrically or using TXRF technique

Highly selective and sensitive catalytic spectrophotometric determination of ng amounts of Re

The reaction is based on the catalytic action of Re (IV) on the reduction of organic reagent DMDTO with Sn (II) in an alkaline medium, yielding a blue colored product with A max at $\lambda=634$ nm. The calibration graph is linear in the range 2-15 ng Re/ml

Rapid spot semi-quantitative test

Reference scale

0   2   5   10   15 ng Re

Sample

Quantitative Spectrophotometric determination

Thermo Evolution 160 UV-vis spectrophotometer Thermo Scientific

Total X-ray Fluorescence Spectroscopy (TXRF)

An analytical technique for determining elemental content in liquids, solids and loose powders. The main principle is that atoms, when irradiated with X-rays, radiate secondary X-rays - the fluorescence radiation. Each element is associated with a 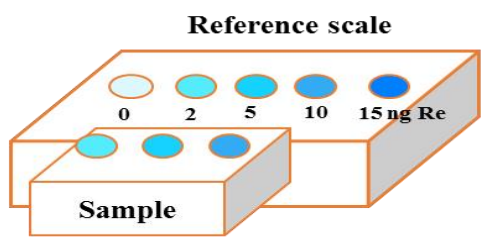specific wavelength and energy of the fluorescence radiation. The concentration is calculated using the fluorescence intensity. TXRF analysis is based on internal standardization: an element, which is not present in the sample, must be added for quantification purposes. In this case gallium (Ga).

Preparation steps for the TXRF analysis of the examined samples
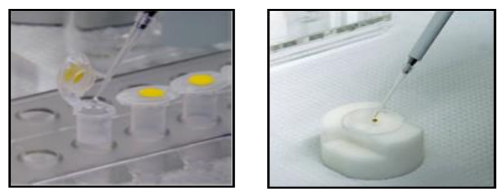
Schematic working principle of the S2 PICOFOX spectrometer

XFlash detector

X-ray tube (Mo anode)

Monochromator (Ni/C Multilayer)

Polished carrier disc with sample
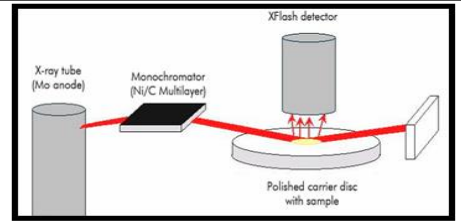
TXRF spectrum of aqueous extract from dried alfalfa
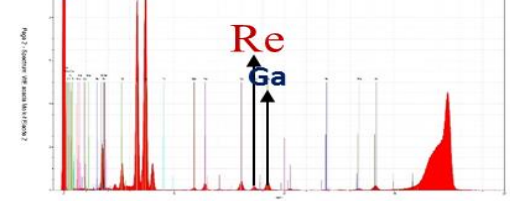
Re

Ga

ISINN-29 第29届中子与核相互作用国际研讨会 29th International Seminar on Interaction of Neutrons with Nuclei   2023   Online + Onsite (Dubna, Russia and Lanzhou, China)

Joint Institute for Nuclear Research   SCIENCE BRINGING NATIONS TOGETHER   FLNP 弗兰克中子物理实验室 FRANK LABORATORY OF NEUTRON PHYSICS, JINR, RUSSIA   强脉冲辐射环境模拟与效应国家重点实验室 THE STATE KEY LABORATORY OF INTENSE PULSED RADIATION SIMULATION AND EFFECT, NINT, CHINA   兰州大学 1909

Rhenium is traditionally obtained as a by-product of roasting and hydrometallurgical treatment of molybdenum and copper concentrate

microorganisms

MDPI

Article

Arthrospira platensis as Bioremediator of Rhenium Mono- and Polymetallic Synthetic Effluents

Inga Zinicovscaia [1,2,3,*], Liliana Cepoi [4], Ludmila Rudi [4], Tatiana Chiriac [4], Nikita Yushin [1] and Dmitrii Grozdov [1]

[1] Department of Nuclear Physics, Joint Institute for Nuclear Research, 6 Joliot-Curie Str., Dubna 1419890, Russia
[2] Department of Nuclear Physics, Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering, 30 Reactorului Str., P.O. Box MG-6, 077125 Bucharest, Romania
[3] Laboratory of Physical and Quantum Chemistry, Institute of Chemistry, 3, Academiei Str., MD-2028 Chisinau, Moldova
[4] Laboratory of Phycobiotechnology, Institute of Microbiology and Biotechnology, 1, Academiei Str., MD-2028 Chisinau, Moldova
* Correspondence: zinikovskaia@mail.ru; Tel.: +7-4962165609

Abstract: Rhenium is a scarce and highly important metal for industry and technology. In the present study, the cyanobacterium *Arthrospira platensis* (Spirulina) was used to remove rhenium and related elements (Mo and Cu) from mono- and polymetallic synthetic effluents. Metal ions in different concentrations were added to the culture medium on the first, third, and fifth days of biomass growth, and their uptake by the biomass was traced using ICP-AES technique. The accumulation of rhenium in the biomass was dependent on the chemical composition of the effluents, and the highest uptake of 161 mg/kg was achieved in the Re-Cu system. The presence of rhenium, copper, and molybdenum affected the productivity of Spirulina biomass and its biochemical composition (proteins, carbohydrates, lipids, phycobiliproteins, the content of chlorophyll α and β-carotene). With the growth of biomass in the presence of rhenium or rhenium and molybdenum, a pronounced increase in productivity and protein content was observed. The presence of copper in systems has a negative effect on biomass productivity and biochemical composition. *Arthrospira platensis* may be of interest as a bioremediator of rhenium-containing effluents of various chemical compositions.

Keywords: *Arthrospira platensis*; biochemical analysis; proteins; rhenium; molybdenum; copper; bioremediation

The presence of **rhenium**, copper, and molybdenum affected the productivity of **Spirulina** biomass and its biochemical composition (proteins, carbohydrates, lipids, phycobiliproteins, the content of chlorophyll &alpha: and &beta:-carotene).
With the growth of biomass in the presence of rhenium or rhenium and molybdenum, a pronounced increase in productivity and protein content was observed.

The content of Re, Cu, and Mo in Spirulina samples was determined using an inductively coupled plasma-optical emission spectrometer, PlasmaQuant 9000 Elite (Analytik Jena, Jena, Germany).

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LANZHOU UNIVERSITY

IBR-2 pulsed (epi)thermal neutron reactor

https://ibr-2.jinr.ru/

MINISTRY OF EDUCATION AND RESEARCH
INSTITUTE OF CHEMISTRY

inga_zinicovscaia_thesis.pdf (cnaa.md)

The title of manuscript:
U.D.S. 504.45.06(043.2) +579.22:546.3(043.2)

ZINICOVSCAIA INGA

IMPACT OF SOME METALS DETERMINED BY NEUTRON
ACTIVATION ANALYSIS ON THE QUALITY OF THE
ENVIRONMENT

145.01. ECOLOGICAL CHEMISTRY

Doctoral thesis in chemistry

Rhenium is a scarce and highly important metal for industry and technology.

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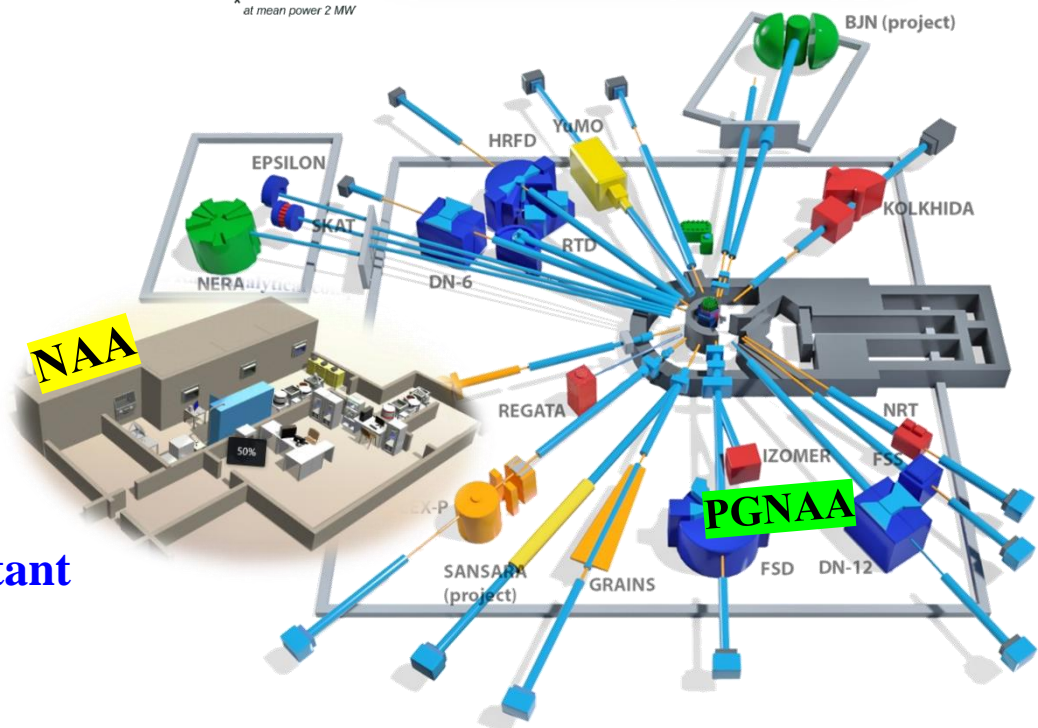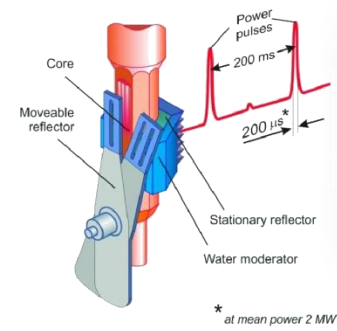
BR-1
The oldest active reactor in the world

Iv. Boyadjov, R. De Neve, J. Hoste, Determination of rhenium in molybdenites by neutron activation analysis, Analytica Chimica Acta, Volume 40, 1968, Pages 373-378, ISSN 0003-2670, https://doi.org/10.1016/S0003-2670(00)86750-1.

https://www.sckcen.be/en/infrastructure/br1-belgian-reactor-1

1 m
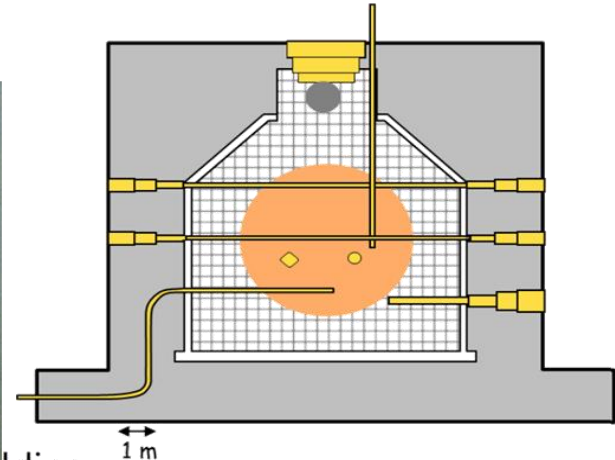
Cylindrical core:
Diameter = 4.7 m, Length = 4.9 m
25 ton natural metallic U in Al cladding

In-core experiments:
~70 irradiation experimental channels
Maximum thermal flux 4×10^{11} n/cm²s
Low neutron flux gradient
Possibility for online instrumentation
Pneumatic rabbit systems

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兰州大学

Interest in rhenium has increased in recent years because of its use in different branches of various new technologies. As the abundance of rhenium is generally low in rocks and minerals, sensitive methods for its determination are required. **Neutron activation analysis appears to be one of the most appropriate**. This technique has been used to determine rhenium in materials such as enzymes[1], marine organisms[2], rocks[3-5], ores[6], meteorites[7-9], tectites[10], granites[11], electrolytic zinc sulphate solutions[12] and molybdenites[13-15]. In all these determinations, separation techniques such as precipitation, distillation, ion exchange and liquid-liquid extraction have been applied ; most of the procedures involve rather complicated chemical separations, wit11 low chemical. yields and are time-consuming. The proposed method for the *determination of rhenium in molybdenites by thermal neutron activation analysis*, is based on a simple extraction with pyridine and $\gamma-$ or $\beta-$counting. It applies simple operations in a very short time, thus ensuring quantitative recovery.

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Elsevier Publishing Company, Amsterdam
Printed in The Netherlands

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DETERMINATION OF RHENIUM IN MOLYBDENITES BY NEUTRON ACTIVATION ANALYSIS

IV. BOYADJOV*, R. DE NEVE** AND J. HOSTE
Institute for Nuclear Sciences, Ghent University, Ghent (Belgium)
(Received September 15th, 1967)

Interest in rhenium has increased in recent years because of its use in different branches of various new technologies. As the abundance of rhenium is generally low in rocks and minerals, sensitive methods for its determination are required. Neutron activation analysis appears to be one of the most appropriate. This technique has been used to determine rhenium in materials such as enzymes[1], marine organisms[2], rocks[3-5], ores[6], meteorites[7-9], tectites[10], granites[11], electrolytic zinc sulphate solutions[12] and molybdenites[13-15]. In all these determinations, separation techniques such as precipitation, distillation, ion exchange and liquid–liquid extraction have been applied ; most of the procedures involve rather complicated chemical separations, with low chemical yields and are time-consuming.
The proposed method for the determination of rhenium in molybdenites by thermal neutron activation analysis, is based on a simple extraction with pyridine and γ- or β-counting. It applies simple operations in a very short time, thus ensuring quantitative recovery.

TABLE I

NUCLEAR DATA OF RHENIUM, MOLYBDENUM AND TECHNETIUM

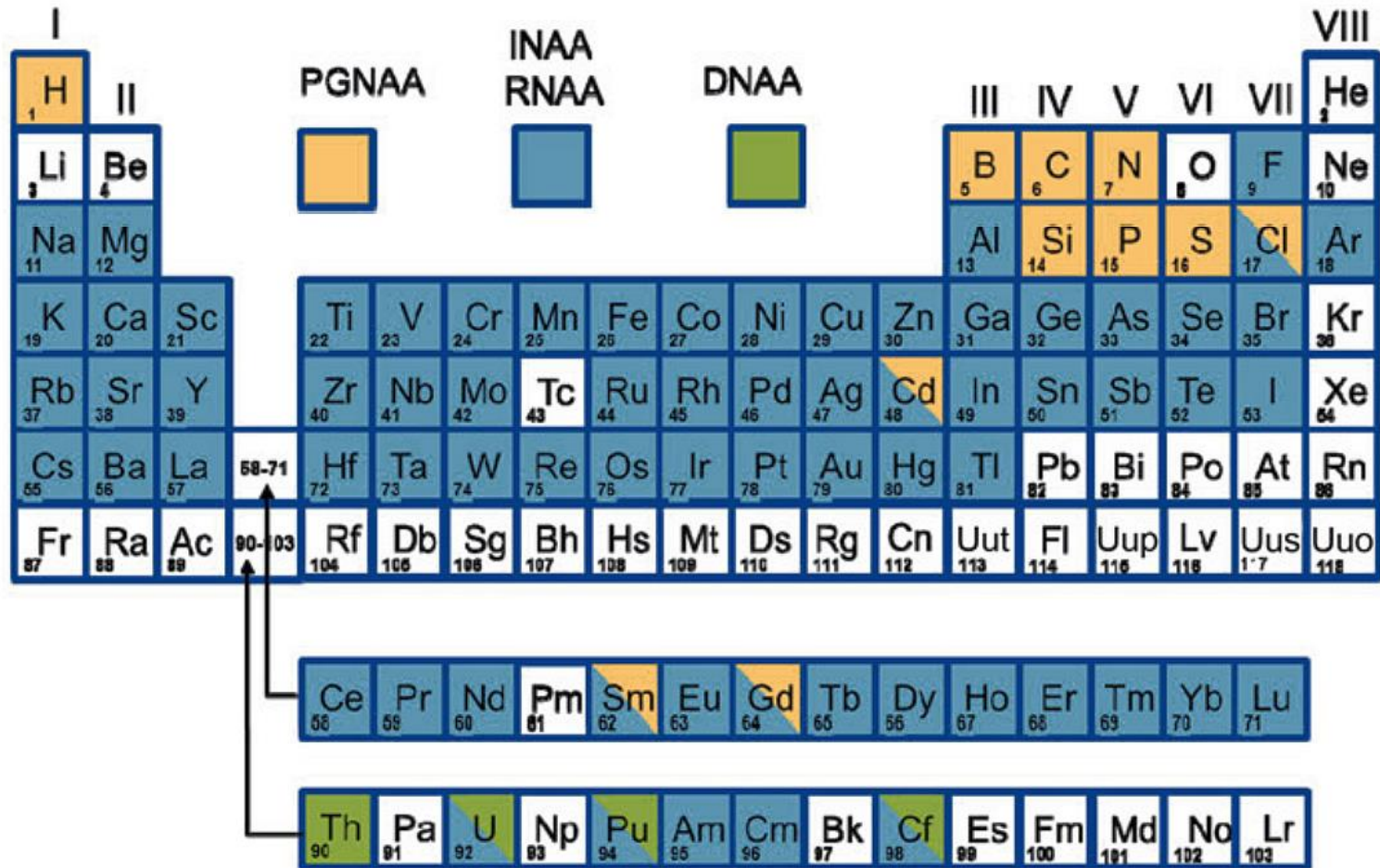| Natural isotope	Abundance (%)	Thermal cross-section (barn)	Isotope formed	Half-life	γ-Energy (MeV)	β-Energy E_{max} (keV)
^{185}Re	37.07	104	^{186}Re	89 h	0.063, 0.128, 0.137, 0.631, 0.769	1072(70 %) 934(22%) 307(0.11%)
^{187}Re	62.93	69	^{188m}Re	19 m	0.064, 0.092, 0.106	
			^{188}Re	17 h	0.063, 0.155, 0.477, 0.632	2116(80%) 1500
^{92}Mo	15.84	0.006	^{93m}Mo	6.9 h	0.684, 0.148	
^{98}Mo	23.78	0.51	^{99}Mo	67 h	0.181, 0.740	1420(2%) 1278(75%)
			^{99m}Tc	6 h	0.140	
			^{99}Tc	$2.12 \cdot 10^5$ y	——	310 (100%)
^{100}Mo	9.63	0.20	^{101}Mo	14.6 m	0.191, 0.510, 0.590, 1.02	
			^{101}Tc	14.0 m	0.130, 0.186, 0.307	

Fig. 3.10: Periodic Table of Elements indicating which neutron activation technique is commonly applied for the determination of a certain element.

Figure 3. Sensitivity of PGAA for the elements [9]. Shown are estimated limits for the detection of traces as given for the instrument PGAA at MLZ. These limits also depend on the matrix material.
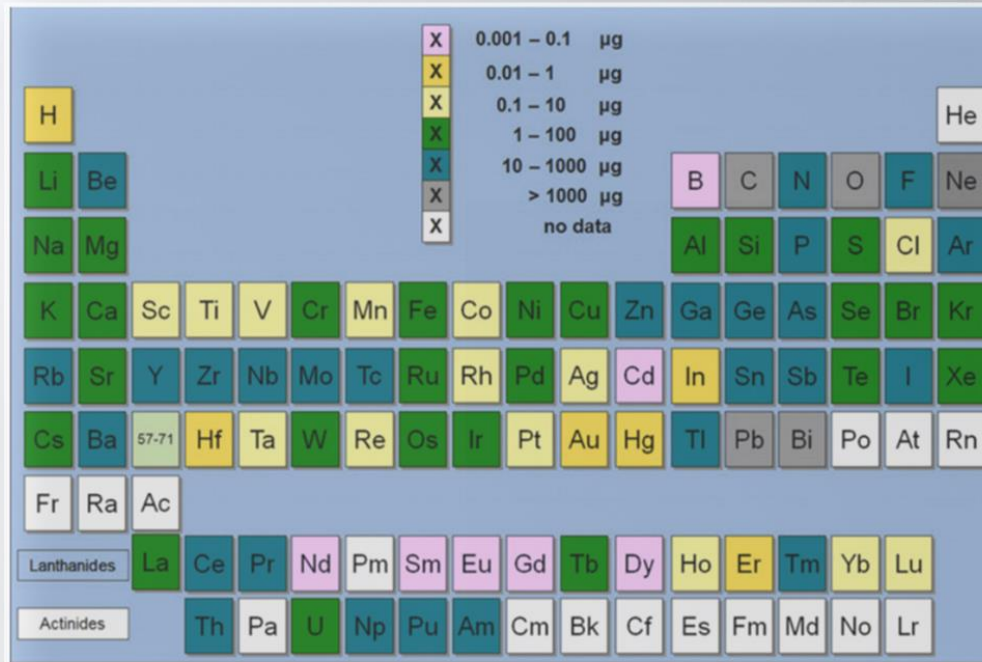
Prompt Activation Analysis http://www.mlz-garching.de/pgaa

Daqian Hei

Research progress on in situ on-line measurement technology of elemental composition of PGNAA.

PGNAA technique — Challenges

Lanzhou university

With the development of other analytical methods and instruments, such as ICP-MS, AMS and LIF, PGNAA and NAA was greatly challenged.

Analysis Method	Detection Limit
PGNAA	1E-6
ICP-MS	1E-12
NAA	1E-14
AMS	1E-16
SXRF	1E-17
LIMS	1E-18
LIF	1E-22

8 ORDERS to Laser Introduced Fluorescen

Fast Neutron Activation Analysis
Prompt Gamma Activation Analysis
Thermal Neutron Activation Analysis
Not done by NAA
*Numbers represent ppm

Analytical capabilities and detection limits for elements by NAA and PGNAA.

HPGe detector array for high resolution gamma spectroscopy

Progress of Neutron Reaction Data Measurement at CIAE

Xichao Ruan

China Nuclear Data Center, Key Laboratory of Nuclear Data
China Institute of Atomic Energy (CIAE)

http://isinn.jinr.ru/past-isinns/isinn-26/0529PM/T8.pdf

The 26th International Seminar on Interactions of Neutrons with Nuclei
May 28th – June 1st , 2018, Xian, China

CNDC
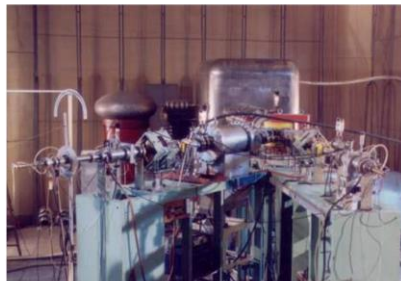CHINA NUCLEAR DATA CENTER

- 6 Clover and 6 HPGe detectors
- Mainly used for (n, 2nγ) and (n, n'γ) measurement

35

600 kV Cockcroft-Walton neutron generator

- Provide 14 and 2.5 MeV neutrons for ND measurement, detector calibration and other applications
- Provide 6.13 MeV gammas for detector calibration

- > 1000 hours beam time every year for different users

Ions	p and d		
Current	Maximum 1 mA (DC) ~30 μA (pulsed)		
Pulse width	~2 ns		
Neutron yield	10^{11} n/s for DC	14 MeV	
	10^9 n/s for pulsed		
	10^9 n/s for DC	2.5 MeV	
	10^8 n/s for pulsed		

9

^{89}Zr(n,2n)^{88}Zr	^{96}Zr(n,2n)^{95}Zr	^{92}Mo(n,p)^{92}Nb	^{98}Mo(n,r)^{99}Mo
^{109}Ag(n,2n)^{108m}Ag	^{113}In(n,2n)^{112m}In	^{113}In(n,n')^{113m}In	^{115}In(n,2n)^{114m}In
^{115}In(n,p)^{115}Cd	^{115}In(n,a)^{112}Ag	^{127}I(n,2n)^{126}I	^{124}Xe(n,2n)^{123}Xe
^{134}Ba(n,2n)$^{133m+g}$Ba	^{134}Ba(n,p)$^{134m+g}$Cs	^{134}Ba(n,a)^{131m}Xe	^{137}Ba(n,p)^{137}Cs
^{136}Ce(n,2n)^{135}Ce	^{138}Ce(n,2n)^{137m}Ce	^{140}Ce(n,2n)^{139}Ce	^{140}Ce(n,p)^{140}La
^{151}Eu(n,r)^{152m}Eu	^{151}Eu(n,r)^{152g}Eu	^{153}Eu(n,2n)^{152g}Eu	^{153}Eu(n,r)^{154}Eu
^{165}Ho(n,r)^{166m}Ho	^{169}Tm(n,2n)^{168m}Tm	^{169}Tm(n,3n)^{167}Tm	^{169}Tm(n,r)^{170}Tm
^{180}Hf(n,r)^{181}Hf	^{179}Hf(n,2n)^{178m2}Hf	^{180}Hf(n,2n)^{179m2}Hf	^{181}Ta(n,2n)^{180m}Ta
^{185}Re(n,2n)^{184m}Re	^{185}Re(n,2n)$^{184m+g}$Re	^{187}Re(n,2n)^{186g}Re	^{187}Re(n,2n)^{186m}Re
^{198}Pt(n,2n)^{197}Pt	^{197}Au(n.2n)^{196}Au	^{197}Au(n,3n)^{195}Au	^{204}Pb(n,2n)^{203}Pb

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兰州大学
LANZHOU UNIVERSITY

2016

The neutron cross-section functions for the reactions ^{187}Re(n, α)^{184}Ta, ^{187}Re(n, 2n)^{186}Re and ^{185}Re(n, 2n)^{184}Re in the energy range 13.08–19.5 MeV

THE EUROPEAN PHYSICAL JOURNAL A

N. Jovančević[1,2], L. Daraban[1], H. Stroh[1], S. Oberstedt[1,a], M. Hult[1], C. Bonaldi[1], W. Geerts[1], F.-J. Hambsch[1], G. Lutter[1], G. Marissens[1], and M. Vidali[1]

2019

Activation cross-sections for the ^{185}Re(n, 2n) reaction and the isomeric cross-section ratio of ^{184m,g}Re in the neutron energy range of 13–15 MeV

Junhua Luo[1,2,a] and Li Jiang[3]

THE EUROPEAN PHYSICAL JOURNAL A

2020

Namrata Singh, A Gandhi, Aman Sharma, Mahesh Choudhary & A Kumar
Excitation functions of (n,p) and (n,2n) reactions of tantalum, rhenium, and iridium in the neutron energy range up to 20 MeV

2021

Fengqun Zhou (周丰群), Yueli Song (宋月丽), Xinyi Chang (畅心怡) *et al.* Cross section measurements for (n,2n), (n,α), and (n,p) reactions on rhenium isotopes around 14 MeV neutrons and their theoretical calculations of excitation functions

2022

Yong Li (李勇), Fengqun Zhou (周丰群), Yajuan Hao (郝亚娟) *et al.* New cross section measurements on tungsten isotopes around 14 MeV neutrons and their excitation functions

2019

Tsugio Yokoyama and Masaki Ozawa,
Production of Low Activity Rhenium by Transmuting Tungsten Metal in Fast Reactors with Moderator

2016

Regular Article

The neutron cross-section functions for the reactions ^{187}Re(n, α)^{184}Ta, ^{187}Re(n, 2n)^{186}Re and ^{185}Re(n, 2n)^{184}Re in the energy range 13.08–19.5 MeV

N. Jovančević[1,2], L. Daraban[1], H. Stroh[1], S. Oberstedt[1,a], M. Hult[1], C. Bonaldi[1], W. Geerts[1], F.-J. Hambsch[1], G. Lutter[1], G. Marissens[1], and M. Vidali[1]

Abstract. In the present work, measurements of the cross-section functions for the ^{187}Re(n, α)^{184}Ta, ^{187}Re(n, 2n)^{186}Re and ^{185}Re(n, 2n)^{184}Re reactions were performed in the energy range 13.08–19.5 MeV. We applied the neutron activation technique using several wide-energy neutron beams (NAXSUN), recently developed at the JRC-IRMM. This method involves measuring the activity of the radionuclides produced in a target by the in energy overlapping neutron beams and a subsequent unfolding procedure. The present results are the first experimental data on these cross-sections for incident neutron energies between 15 and 19.5 MeV and may contribute to improving evaluations and nuclear models.
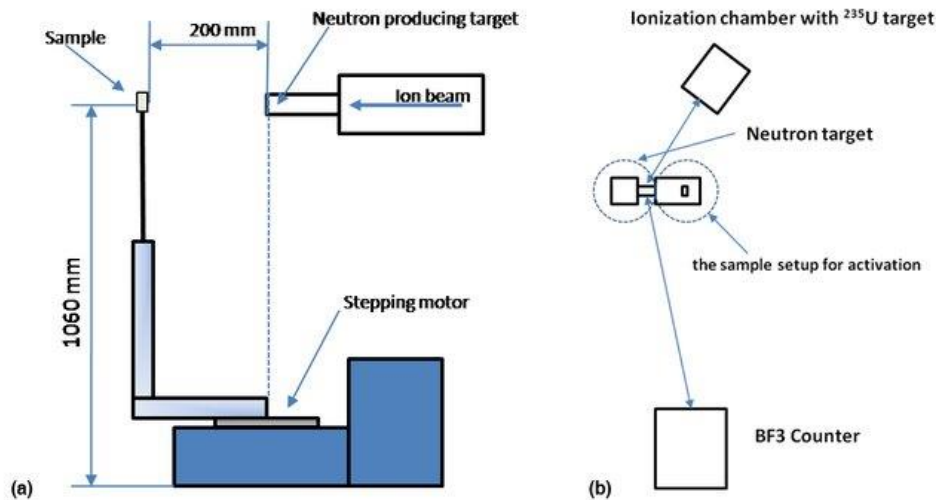
Fig. 1. (a) Schematic drawing of the sample setup for activation (not to scale). (b) Schematic drawing of the neutron fluence rate monitoring setup during an activation run (not to scale).

Table 2. Neutron irradiation data. E_i: ion energy (with uncertainty), E_n: neutron energy at $0°$ relative to the incident ion beam (with uncertainty) and t: irradiation time (with uncertainty).

Disk No.	E_i (MeV)	E_n (MeV)	t (s)
1	3.300(11)	19.78(20)	86921(10)
2	2.500(11)	18.71(20)	248402(10)
3	2.000(11)	18.10(28)	157632(10)
4	2.000(11)	18.10(28)	166564(10)
5	1.500(11)	17.16(30)	231958(10)
6	1.000(11)	15.97(82)	243608(10)
7	0.800(11)	15.26(131)	144831(10)

The neutron cross-section functions for the reactions
^{187}Re(n, α)^{184}Ta, ^{187}Re(n, 2n)^{186}Re and ^{185}Re(n, 2n)^{184}Re
in the energy range 13.08–19.5 MeV

Regular Article – Experimental Physics

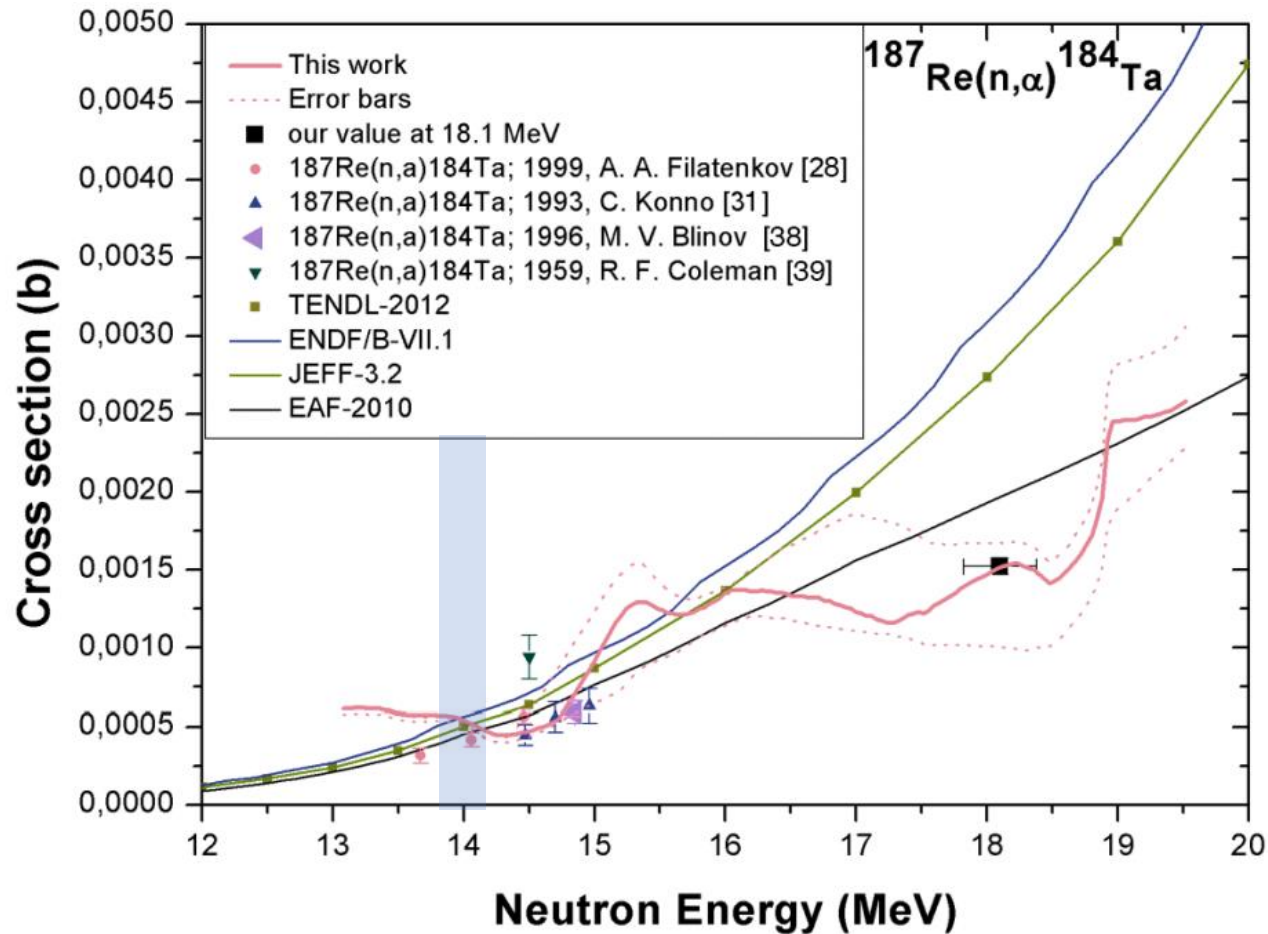**Fig. 16.** Comparison of the obtained results in this work with ENDF and EXFOR data for the ^{187}Re(n, α)^{184}Ta reaction [28, 31, 38, 39].
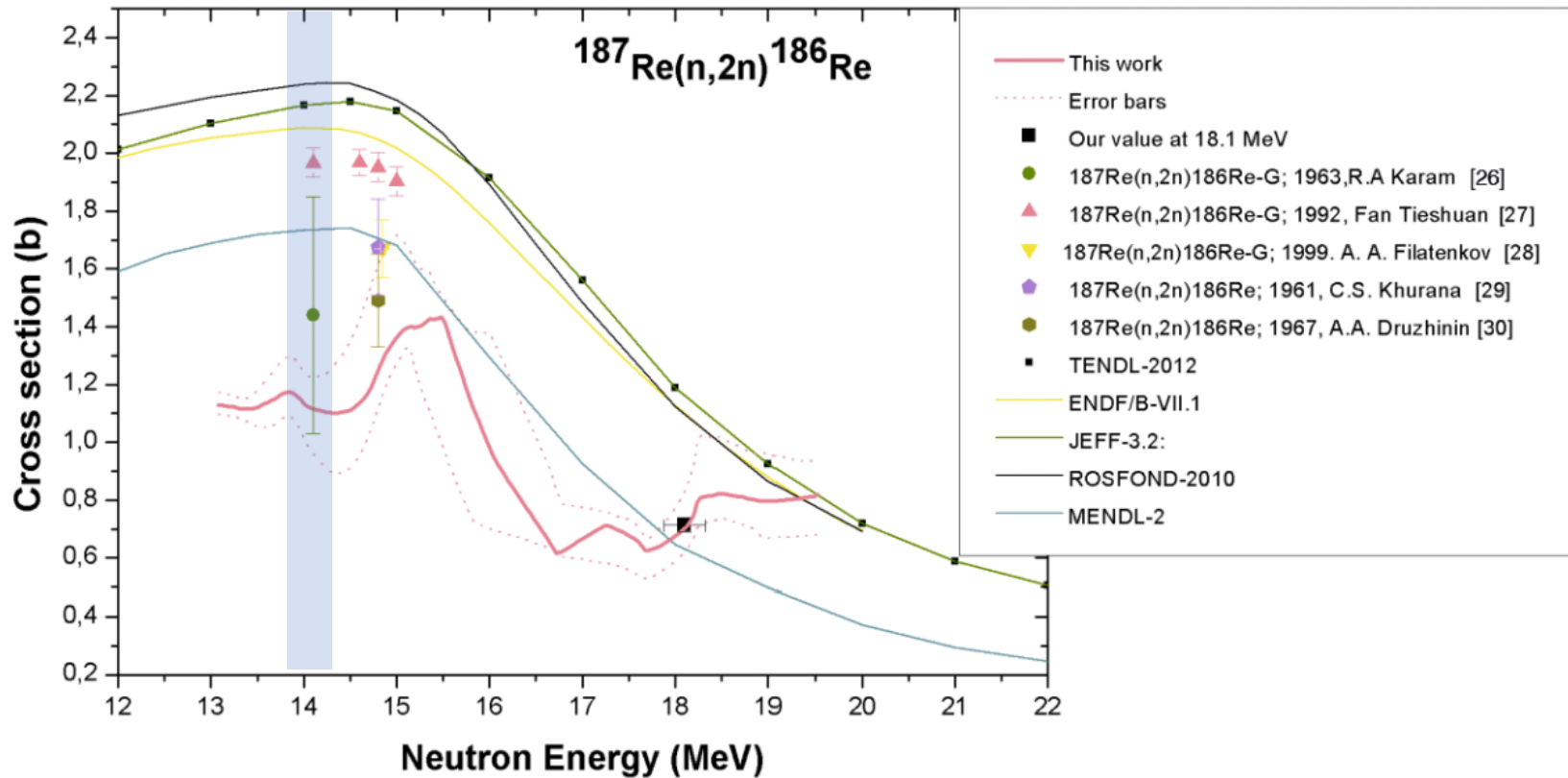
The neutron cross-section functions for the reactions
^{187}Re(n, α)^{184}Ta, ^{187}Re(n, 2n)^{186}Re and ^{185}Re(n, 2n)^{184}Re
in the energy range 13.08–19.5 MeV

Regular Article – Experimental Physics

Fig. 14. Comparison of the obtained results in this work with ENDF and EXFOR data for the ^{187}Re(n, 2n)^{186}Re reaction [26–30].

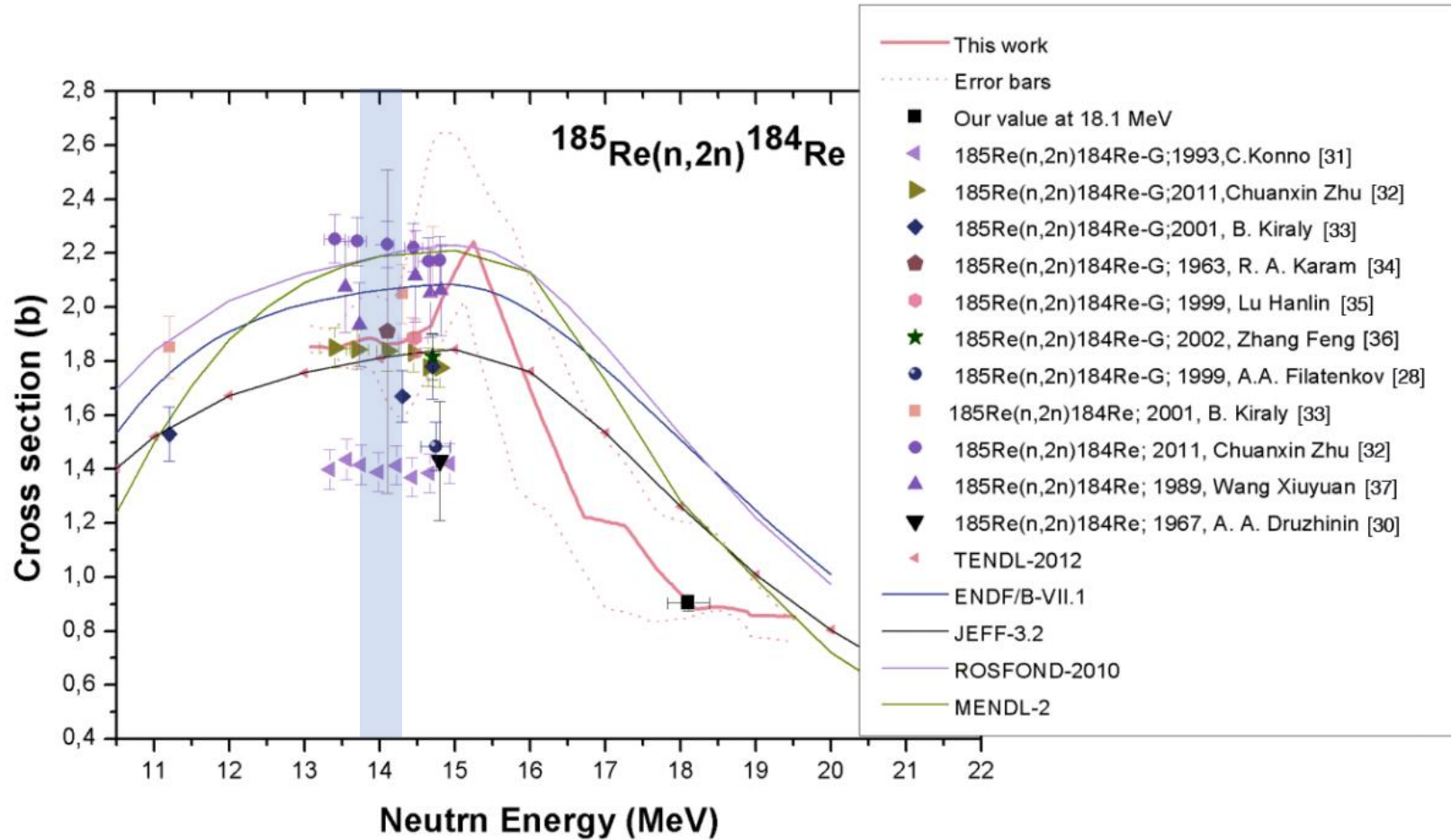**The neutron cross-section functions for the reactions**
^{187}Re(n, α)^{184}Ta, ^{187}Re(n, 2n)^{186}Re and ^{185}Re(n, 2n)^{184}Re
in the energy range 13.08–19.5 MeV

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Fig. 15. Comparison of the obtained results in this work with ENDF and EXFOR data for the ^{185}Re(n, 2n)^{184}Re reaction [28, 30–37].

Junhua Luo[1,2,a] and Li Jiang[3]

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Activation cross-sections for the ^{185}Re(n, 2n) reaction and the isomeric cross-section ratio of ^{184m,g}Re in the neutron energy range of 13–15 MeV
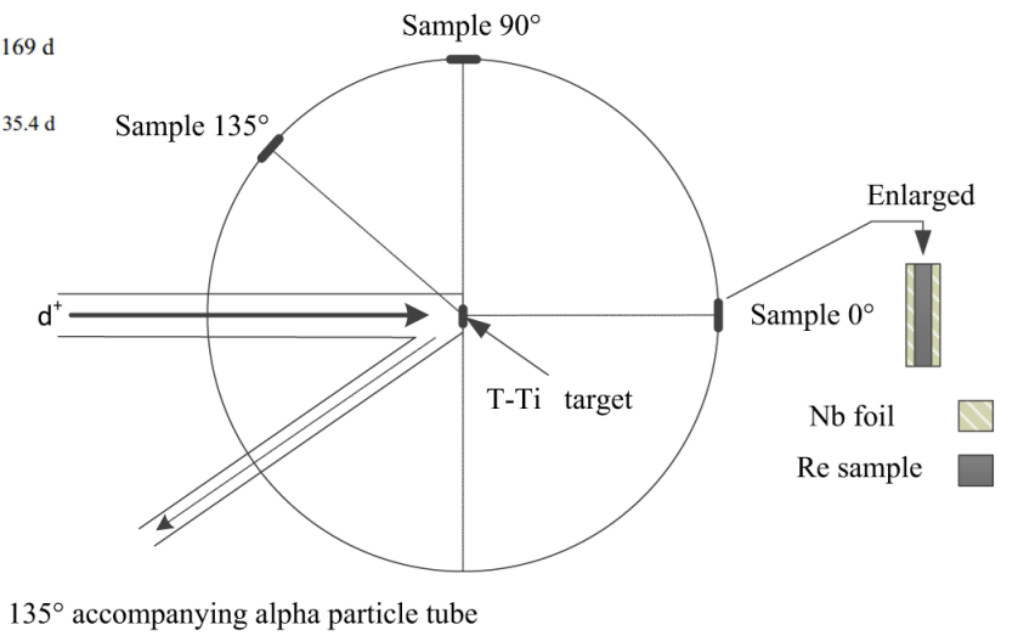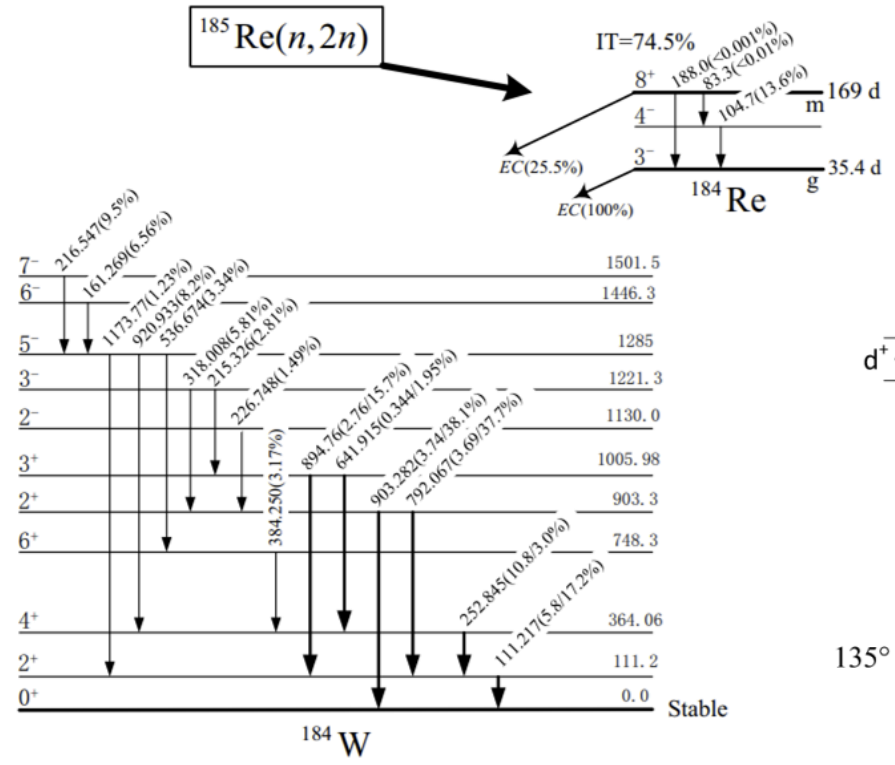

Fig. 1. Metastable and ground states in the ^{185}Re(n, 2n)^{184m,g}Re reactions [2]. All energies are in keV. Transition from both the excited and ground state is represented by the bold black line, with the intensity in brackets indicating rays originating from both states.

Fig. 2. Sketch of the experimental geometry.

https://rdcu.be/cPi1X

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Activation cross-sections for the ^{185}Re(n, 2n) reaction and the isomeric cross-section ratio of ^{184m,g}Re in the neutron energy range of 13–15 MeV *Junhua Luo & Li Jiang*

Table 2. Measured nuclear reactions on rhenium and decay data (taken from [2]). The boldface font is used in the calculation.

Reaction	Abundance of target isotope (%)	Half-life of product	E-threshold (MeV)	Mode of decay (%)	$E\gamma$ (keV)	$I\gamma$ (%)
^{185}Re(n, 2n)^{184m}Re	37.40_2	$169\ d_8$	7.900	IT(74.50)	**104.739**	**13.6$_4$**
				EC(25.50)	111.217	5.8$_4$
					161.269	**6.56$_{24}$**
					226.748	**1.49$_6$**
					252.845	10.8$_4$
					318.008	5.81$_{20}$
					384.250	3.17$_{11}$
					536.674	3.34$_{12}$
					641.915	0.344$_{16}$
					792.067	3.69$_{14}$
					894.760	2.76$_{13}$
					903.282	3.74$_{14}$
					920.933	8.2$_3$
^{185}Re(n, 2n)^{184g}Re	37.40_2	$35.4\ d_7$	7.711	EC(100)	111.217	17.2$_7$
					252.845	3.0$_3$
					641.915	1.95$_6$
					792.067	**37.7$_{11}$**
					894.760	15.7$_5$
					903.282	38.1$_{12}$
^{93}Nb(n, 2n)^{92m}Nb	100	$10.15\ d_2$	8.972	EC(100)	**934.44**	**99.15$_4$**

Fig. 3. (a) γ-ray spectrum of rhenium obtained after 246 days of cooling from the end of irradiation; acquisition time: about 30 hours. (b) γ-ray spectrum of rhenium obtained after 25.5 hours of cooling from the end of irradiation, acquisition time: about 16 hours; (c) Background spectrum.

Activation cross-sections for the ^{185}Re(n, 2n) reaction and the isomeric cross-section ratio of ^{184m,g}Re in the neutron energy range of 13–15 MeV   *Junhua Luo & Li Jiang*

Fig. 4. Excitation functions of the ^{185}Re(n, 2n)^{184m}Re reaction for measured and literature data.

Activation cross-sections for the ^{185}Re(n, 2n) reaction and the isomeric cross-section ratio of ^{184m,g}Re in the neutron energy range of 13–15 MeV

Junhua Luo & Li Jiang
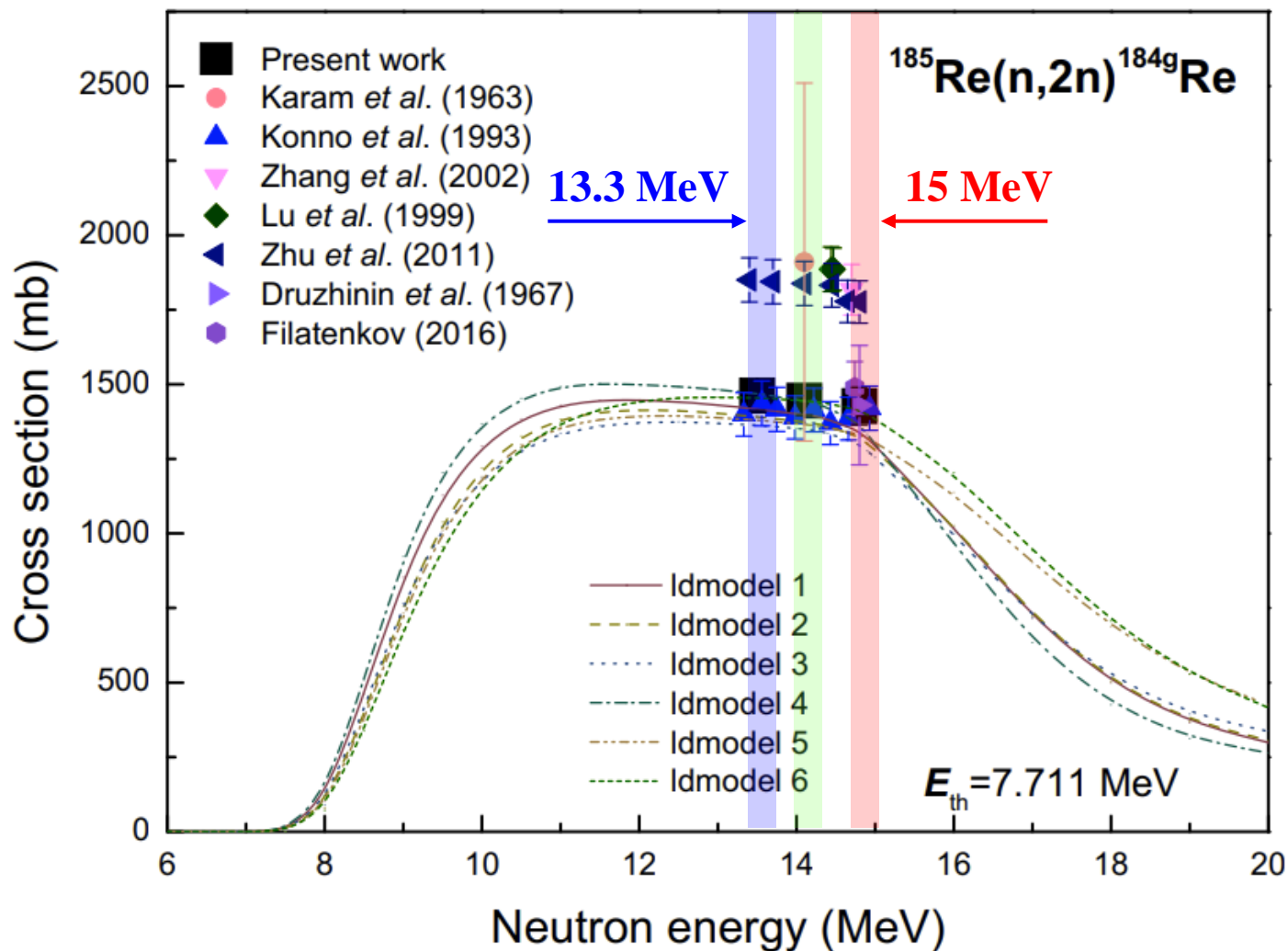
Fig. 5. Excitation function of the ^{185}Re(n, 2n)^{184g}Re reaction for measured and literature data.

Activation cross-sections for the ^{185}Re(n, 2n) reaction and the isomeric cross-section ratio of ^{184m,g}Re in the neutron energy range of 13–15 MeV
Junhua Luo & Li Jiang

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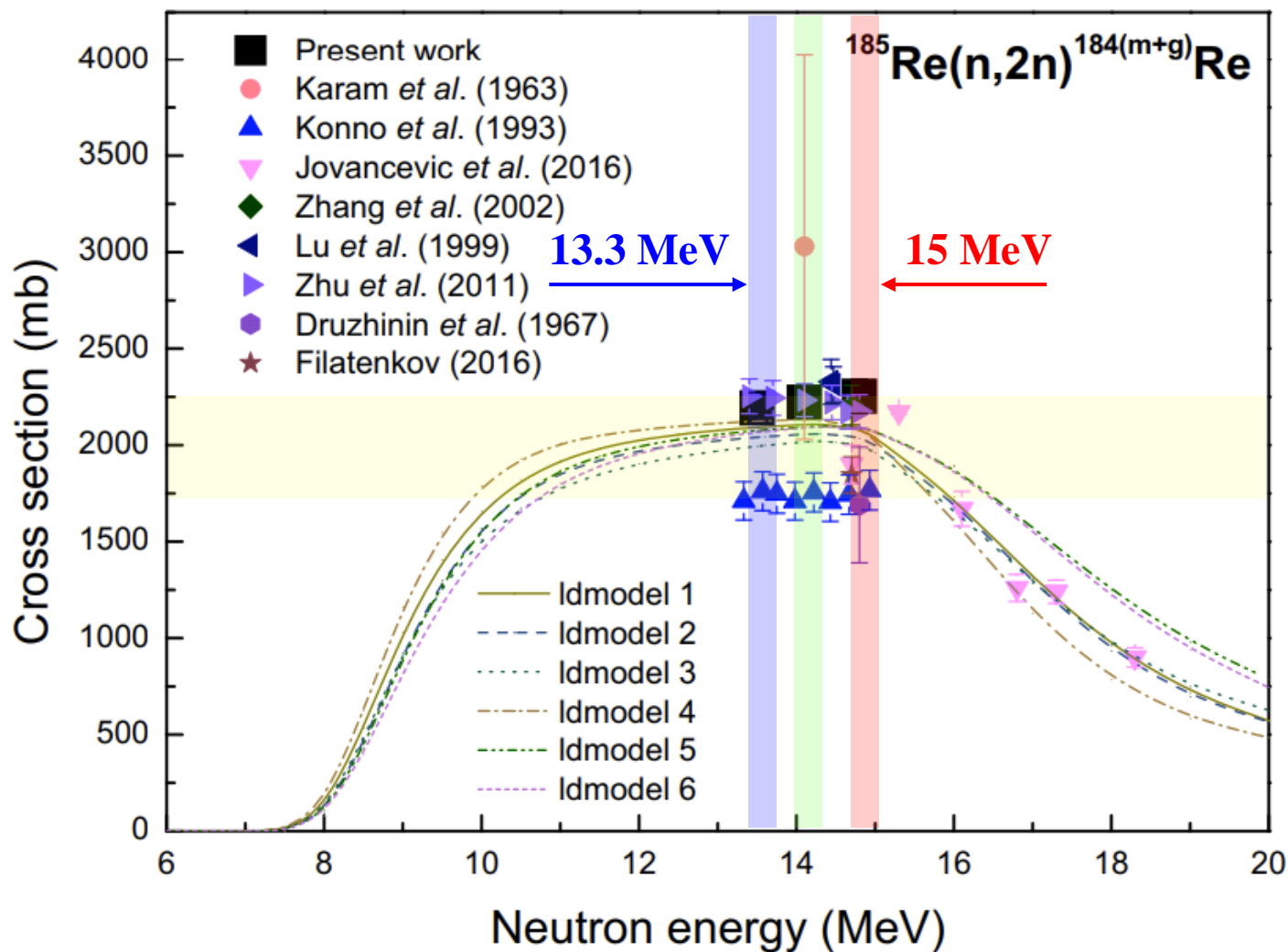
Fig. 6. Excitation function of the ^{185}Re(n, 2n)$^{184m+g}$Re reaction.

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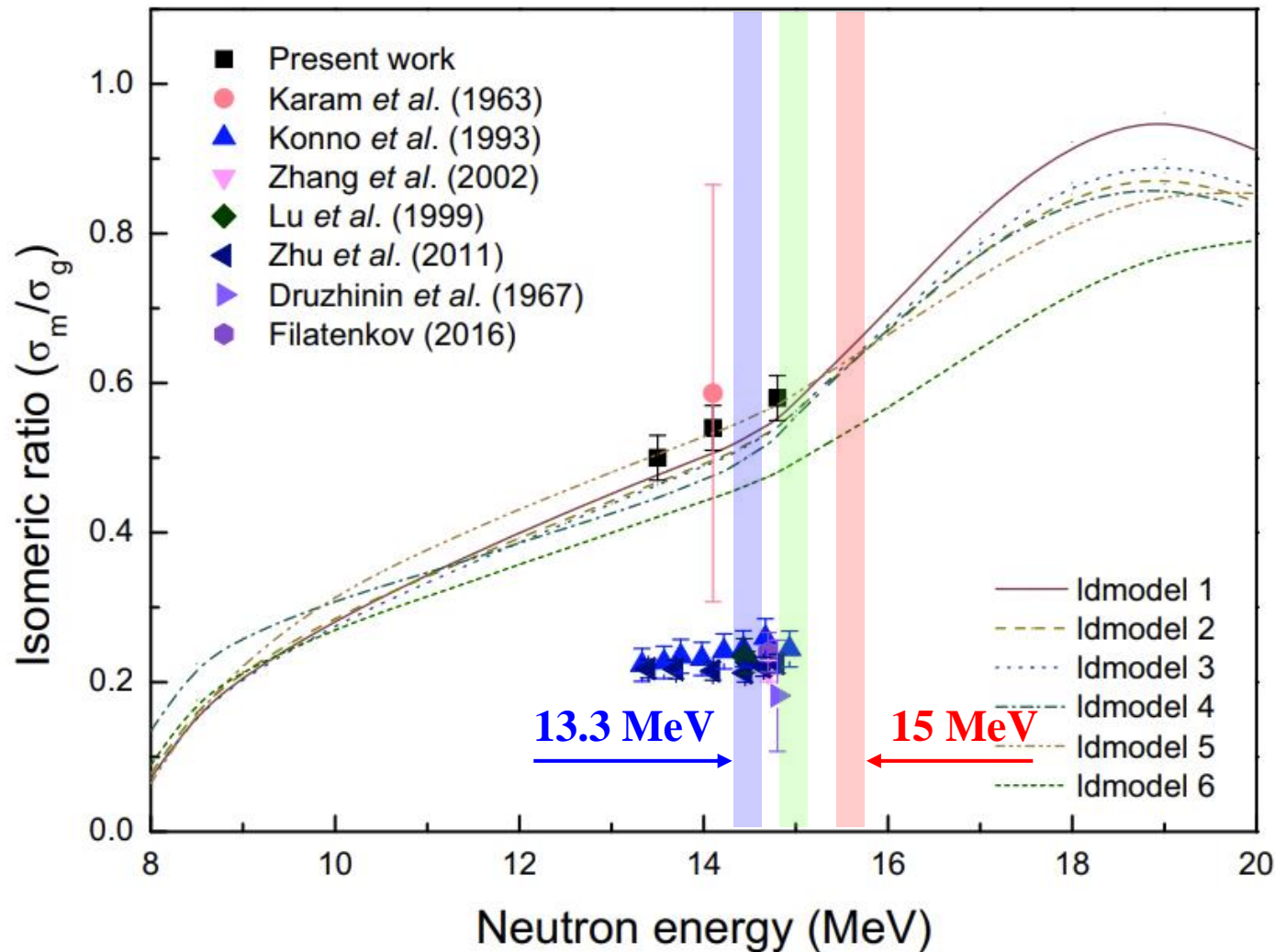
Fig. 7. Cross-section ratio of the ^{185}Re(n, 2n)^{184m}Re and ^{185}Re(n, 2n)^{184g}Re reactions as a function of the neutron energy.

Excitation functions of (n,p) and (n,2n) reactions of tantalum, rhenium, and iridium in the neutron energy range up to 20 MeV

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The excitation functions for (n,p) and (n,2n) reactions up to 20 MeV on Tantalum, Rhenium, and Iridium have been calculated using the TALYS-1.9 nuclear reaction model code. Different level density models have been used to get a good agreement between the calculated and measured data. In the present work, we have carried out the TALYS-1.9 calculations to quantitatively understand the experimental data by optimizing input p[...] $^{185}Re(n,p)^{185m}W$, $^{185}Re(n,2n)^{184}Re$, $^{191}Ir(n,p)^{191}Os$ and $^{191}Ir(n,2n)^{190}Ir$. The [...] experimental data (taken from the EXFOR database) up to 20 MeV. A[...] ENDF/B-VIII.0 and TENDL-2015 evaluated data.

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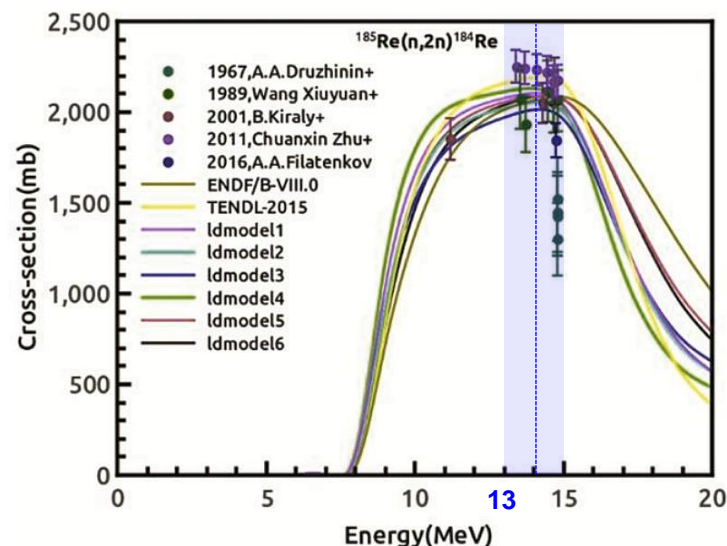
Cross section measurements for $(n,2n),(n,\alpha)$, and (n,p) reactions on rhenium isotopes around 14 MeV neutrons and their theoretical calculations[*]

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Abstract: Cross-section data of the $^{185}\text{Re}(n,2n)^{184m}\text{Re}$, $^{185}\text{Re}(n,2n)^{184g}\text{Re}$, $^{185}\text{Re}(n,\alpha)^{182m1+m2+g}\text{Ta}$, $^{187}\text{Re}(n,2n)^{186g,(m)}\text{Re}$, $^{187}\text{Re}(n,\alpha)^{184}\text{Ta}$, and $^{187}\text{Re}(n,p)^{187}\text{W}$ reactions were measured at four neutron energies, namely 13.5, 14.1, 14.4, and 14.8 MeV, by means of the activation technique, relative to the reference cross-section values of the $^{93}\text{Nb}(n,2n)^{92m}\text{Nb}$ reaction. The neutrons were generated from the $\text{T}(d,n)^{4}\text{He}$ reaction at the K-400 Neutron Generator at China Academy of Engineering Physics. The induced γ activities were measured using a high-resolution γ-ray spectrometer equipped with a coaxial high-purity germanium detector. The excitation functions of the six above-mentioned nuclear reactions at neutron energies from the threshold to 20 MeV were calculated by adopting the nuclear theoretical model program system Talys-1.9 with the relevant parameters properly adjusted. The measured cross sections were analyzed and compared with previous experiments conducted by other researchers, and with the evaluated data of BROND-3.1, ENDF/B-VIII.0, JEFF-3.3, and the theoretical values based on Talys-1.9. The new measured results agree with those of previous experiments and the theoretical excitation curve at the corresponding energies. The theoretical excitation curves based on Talys-1.9 generally match most of experimental data well.

Keywords: cross sections of $(n,2n)$, (n,α) and (n,p) reactions, rhenium isotopes, activation technique, off-line γ-ray spectrometry, theoretical calculations
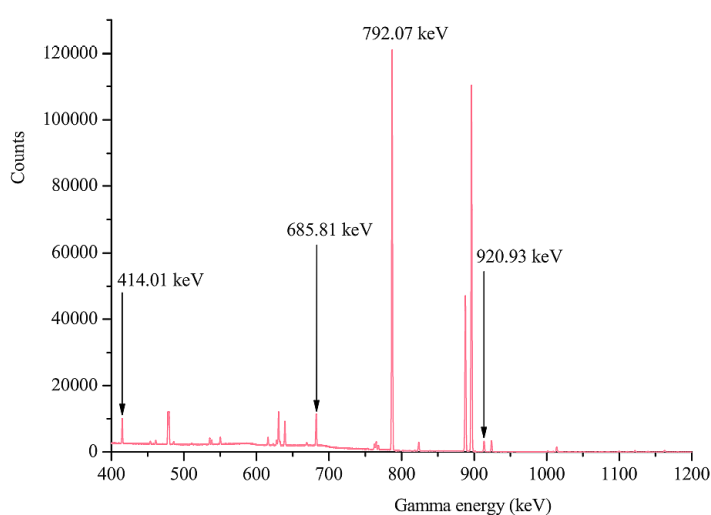
Fig. 1. (color online) Part of the γ-ray spectrum of rhenium obtained after 6.78 h of cooling following the end of irradiation; the measurement duration was approximately 3.82 h.
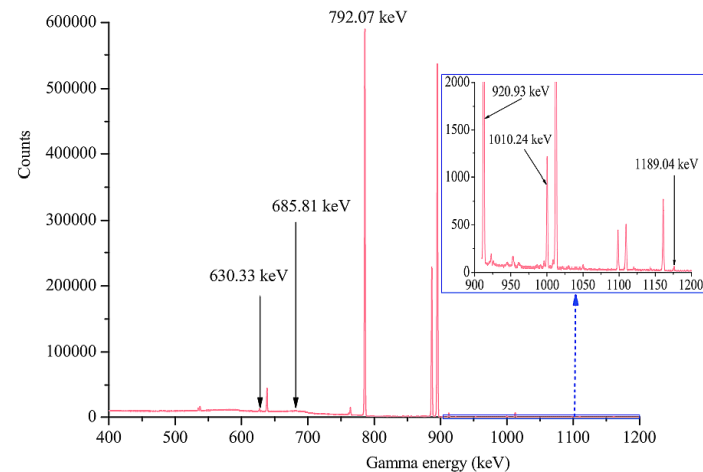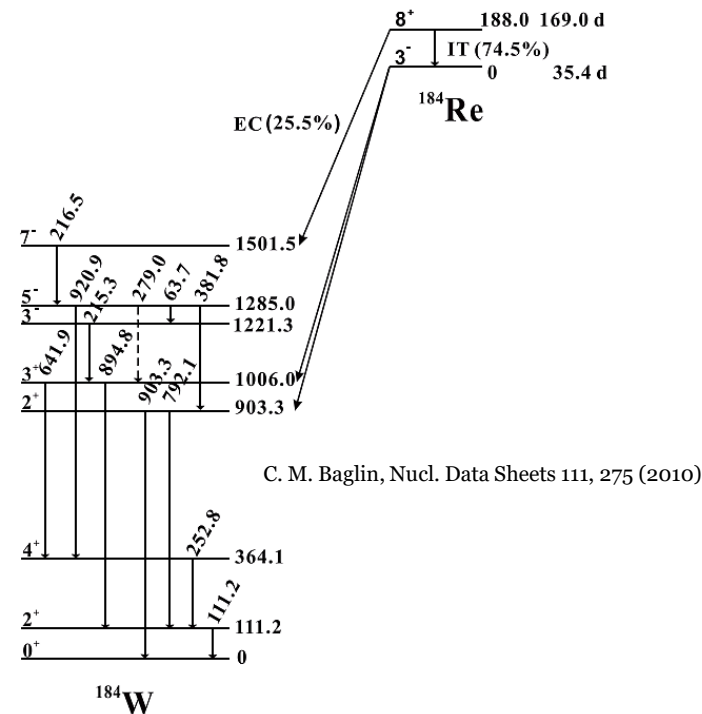

Fig. 2. (color online) Part of the γ-ray spectrum of rhenium obtained after 125.45 h of cooling following the end of irradiation; the measurement duration was approximately 20.78 h.

C. M. Baglin, Nucl. Data Sheets 111, 275 (2010)

Table 1. Reactions and associated decay data of activation products

Reaction	Abundance (%)	Activation products	$T_{1/2}$	E_γ/keV	I_γ(%)
^{185}Re(n,2n)	37.40	^{184m}Re	169 d	920.93	8.2
^{185}Re(n,2n)	37.40	^{184g}Re	35.4 d	792.07	37.7
				1010.24	0.092
^{185}Re(n,α)	37.40	$^{182m1+m2+g}$Ta	114.74 d	1189.04	16.49
^{187}Re(n,2n)	62.60	^{186g}Re	3.7183 d	630.33	0.0294
^{187}Re(n,α)	62.60	^{184}Ta	8.7 h	414.01	72
^{187}Re (n,p)	62.60	^{187}W	24.0 h	685.81	33.2
^{93}Nb(n,2n)	100	^{92m}Nb	10.15 d	934.44	99.15
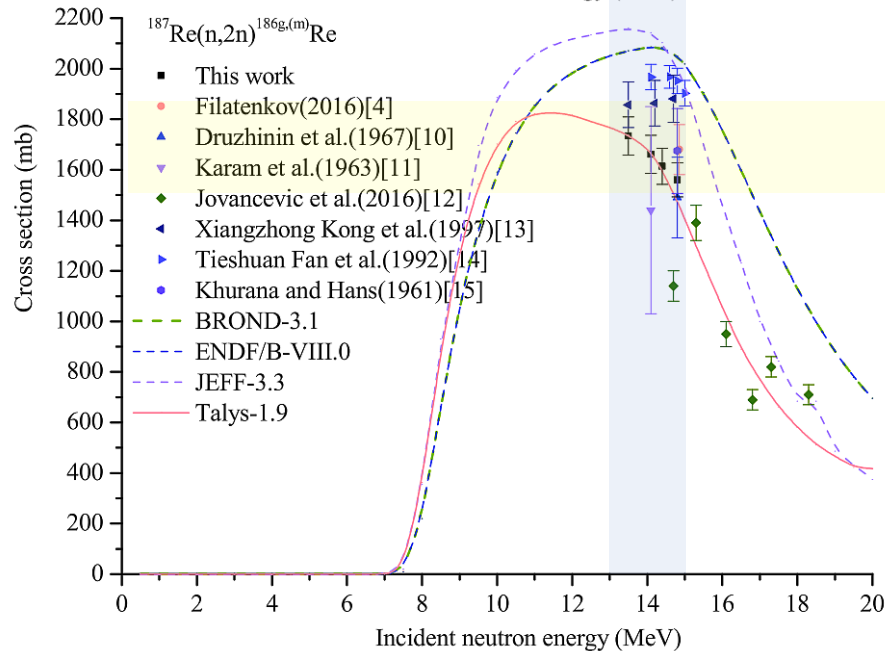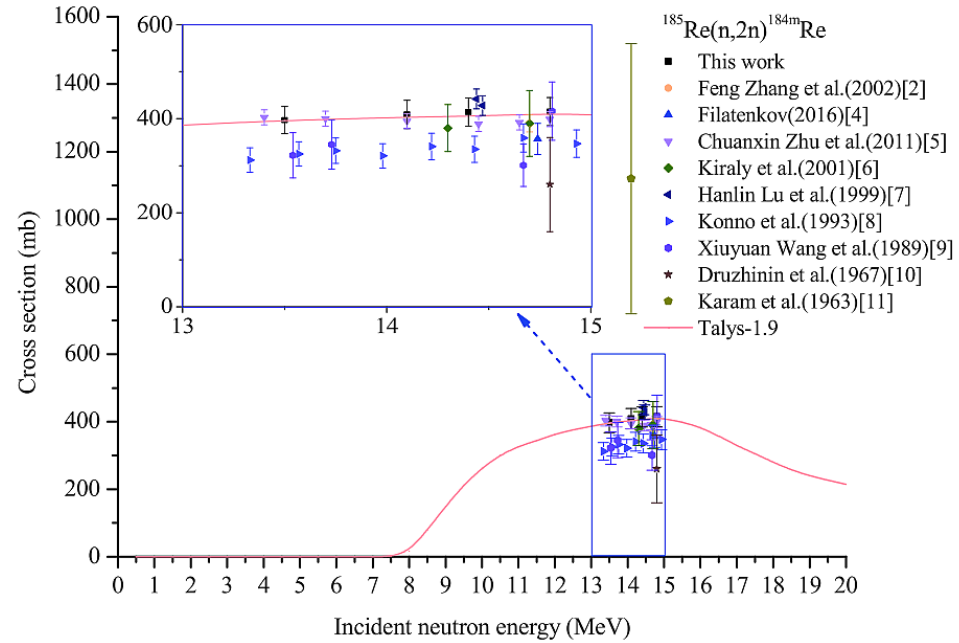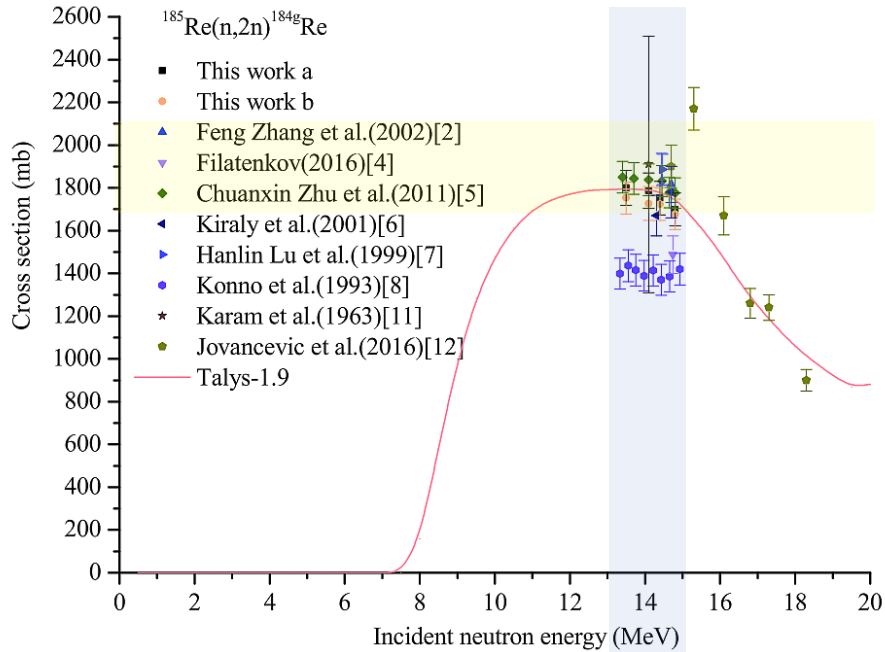
In general, our experimental cross-section values are consistent, within experimental error, with those of previous experiments and theoretical excitation curves at the corresponding energies.

Comparison with these evaluation curves shows that the theoretical excitation curves based on Talys-1.9 code agree well with the experimental results.

The new measured results in the present study would improve the quality of the neutron cross section database and are expected to assist with new evaluations of cross sections on rhenium isotopes in the incident neutron energy range from the threshold to 20 MeV.

In addition, the theoretical excitation curves are relevant for the design of fusion reactors and related applications.
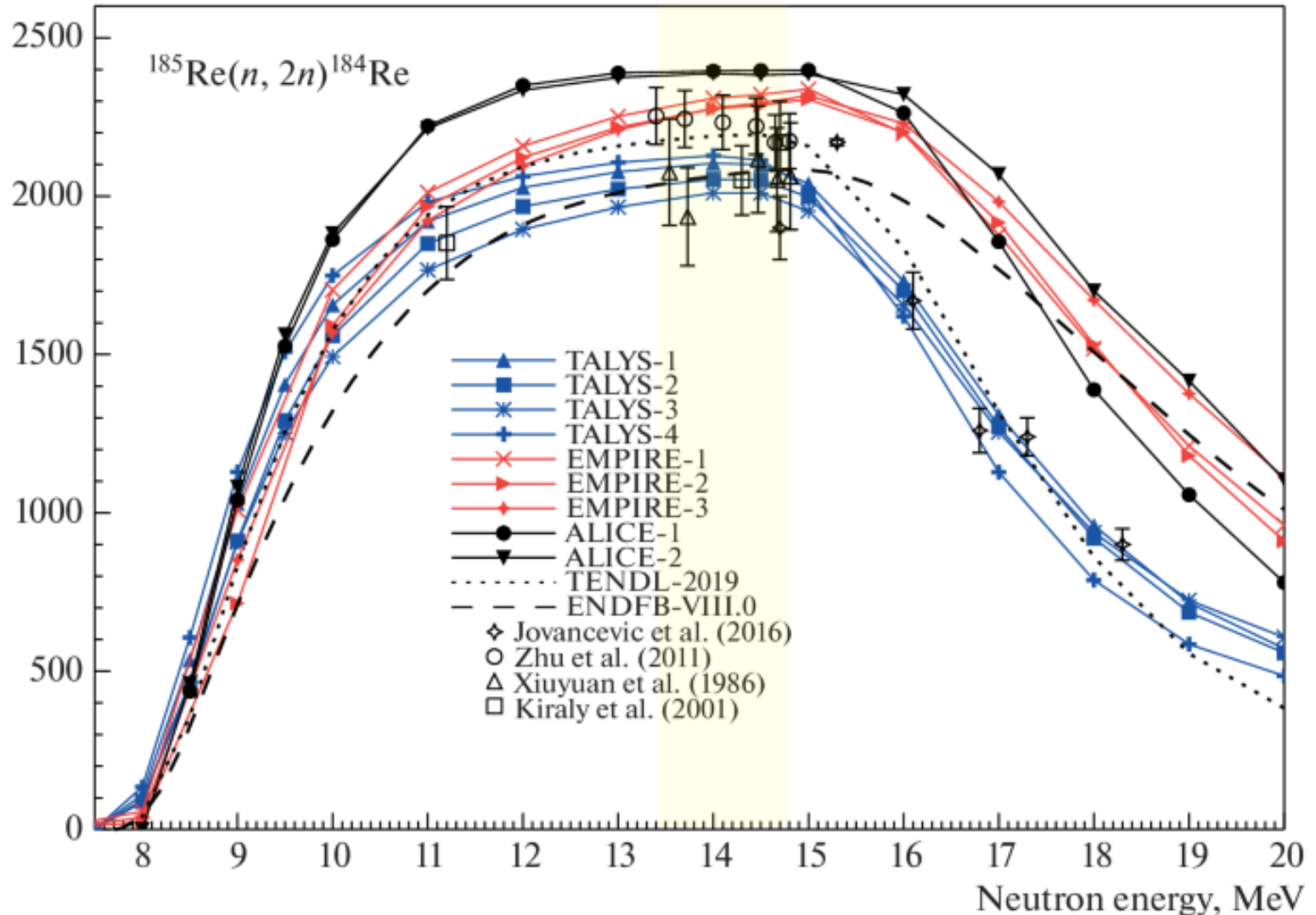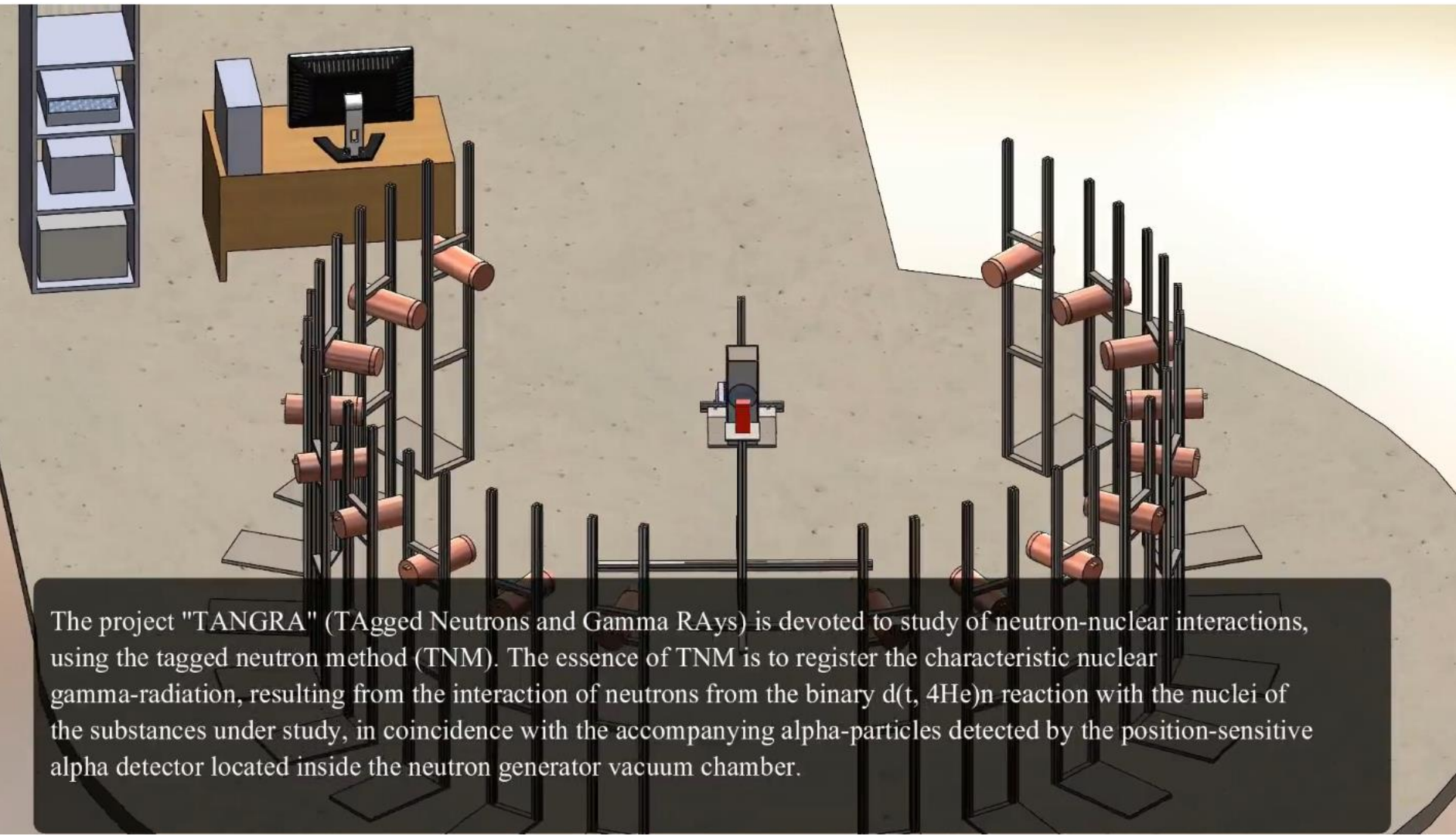
The project "TANGRA" (TAgged Neutrons and Gamma RAys) is devoted to study of neutron-nuclear interactions, using the tagged neutron method (TNM). The essence of TNM is to register the characteristic nuclear gamma-radiation, resulting from the interaction of neutrons from the binary $d(t, 4He)n$ reaction with the nuclei of the substances under study, in coincidence with the accompanying alpha-particles detected by the position-sensitive alpha detector located inside the neutron generator vacuum chamber.