Joint Institute for Nuclear Research

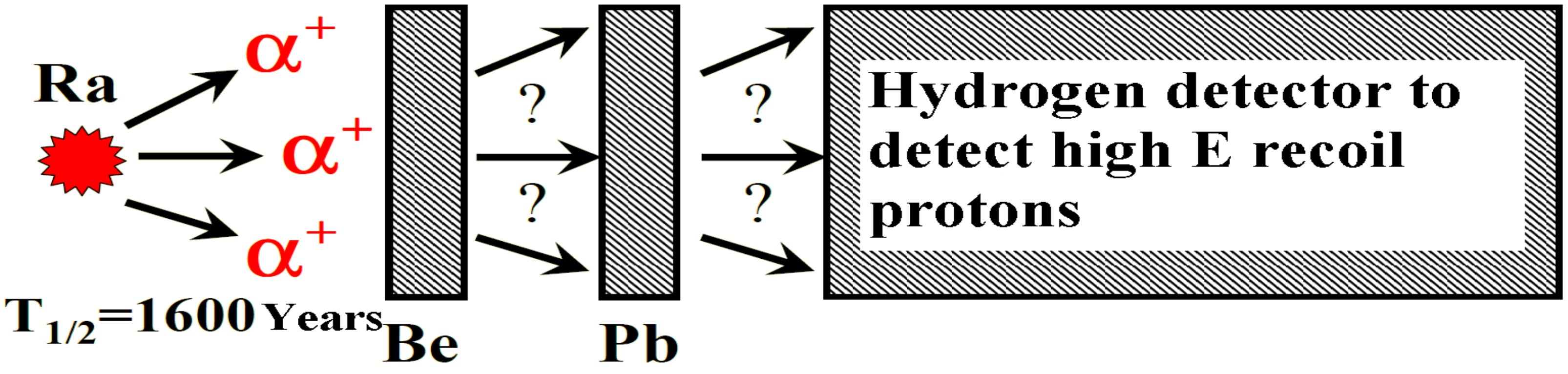
NEUTRON SOURCES AND PERIODIC PULSED REACTORS

Ahmed Hassan

ISINN-29

Dubna- Russia
2023

Discovery of the neutron by Chadwick (1932)



James Chadwick
(1891-1974)

- Were known: Atom, e-, p+, α+, ɣ. But they don't penetrate Pb.
- Chadwick suggested the existence of a neutral particle (neutron - n) in the atomic nucleus together with protons: "no charge with a mass close to the proton.".
- Neutron first named by the American chemist W. D. Harikins in 1921.
- The name derives from the Latin root for neutralis (neuter) and the Greek suffix –on (subatomic particles).

Properties of neutrons

Type of radiation	Electron (e)	Proton (p)	Neutron (n)	α – particle $^4_2He = 2p + 2n$	Gamma quanta
Mass, a.u.	1/1840	1.007276	1.008664	4	0
Charge, /e	-1	+1	0	+2	0
$T_{1/2}$, sec	∞	∞	611	∞	∞

Within the nucleus, neutrons can decay to protons, or vice versa. This process is called beta decay, and, for the neutron, it requires the emission of an electron and an anti-neutrino:

$$n \rightarrow p + {}^{-}e + \tilde{\nu}_e$$

Even though the neutron is a neutral particle, the magnetic moment of a neutron is not zero.

Important practical results from the discovery of the neutron

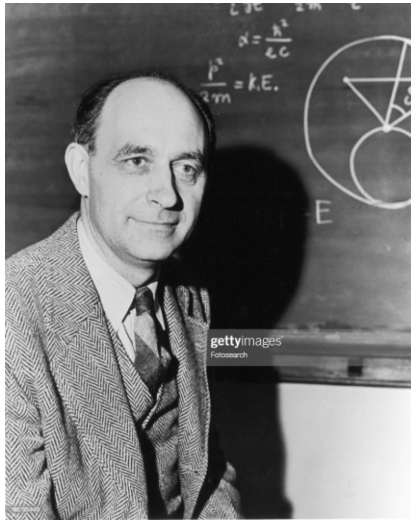
- The use of neutrons makes it possible to study nuclei more efficiently, since they have no charge (i.e. no Coulomb repulsion) and a comparatively large mass;
- Neutrons can interact with all nuclei, where α-particles of even high energy (3-5 MeV) can only bombard nuclei with a small charge, i.e. light elements;
- Discovery of most of the currently known nuclear transformations and artificially radioactive elements;
- In 1939, neutrons led to the discovery of the fission chain process;
- Neutron sources appeared;

History of neutron sources

The urgent need for neutron sources emerged after the discovery of new radioactive elements and the discovery of the chain fission reaction.

Discovery of new radioactive elements thanks to neutrons

In 1934 - Enrico Fermi irradiated all the elements known at that time in order, and it was expected to obtain gamma rays and the next element.

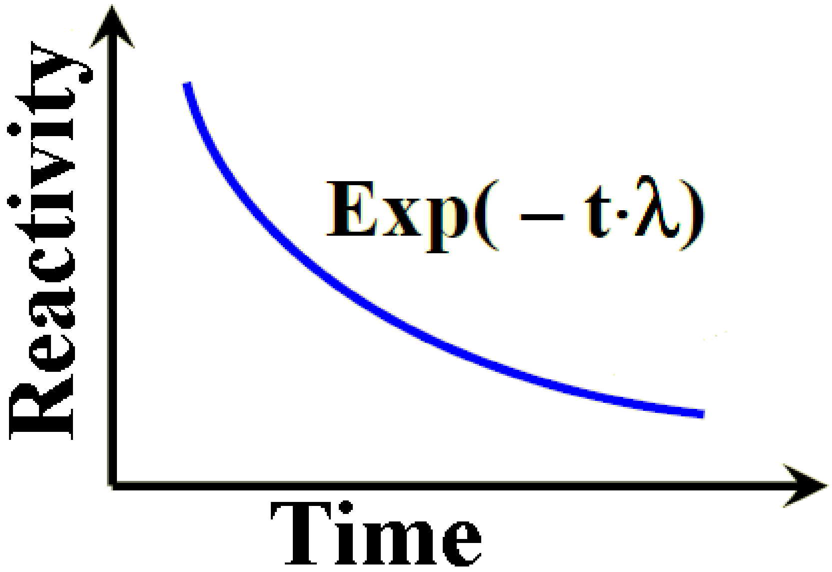


Enrico Fermi
(1901-1954)

$$ {}^{A}_{Z}B\,({}^{1}_{0}n,\,{}^{0}_{0}\gamma)\,{}^{A+1}_{Z}B \xrightarrow{\beta^{-}(e^{-})} {}^{A+1}_{Z+1}X $$

Usually radioactive — Usually stable

Investigated the activity decay: 1 exponent or overlap of 2 exponents, if X is also radioactive.



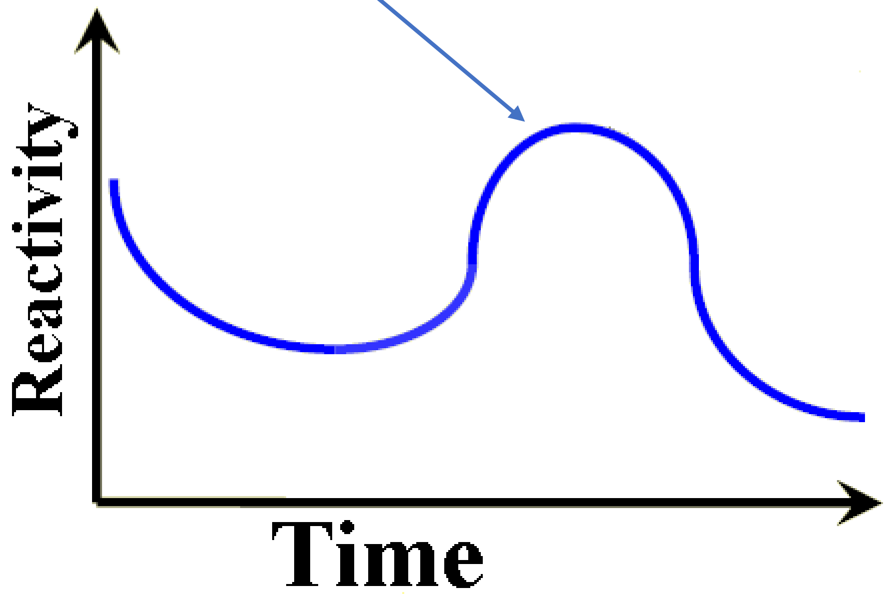
Discovery of new radioactive elements thanks to neutrons

And when Fermi irradiated the heaviest known element, uranium, he got results that contradicted expectations.

$$^{238}_{92}U(n,\gamma)\,^{239}_{92}U \xrightarrow[23\,min]{\beta^-(e^-)} {}^{239}_{93}Np \xrightarrow[22\,days]{\beta^-(e^-)} {}^{239}_{94}Pu$$

E. Fermi did not know about the existence of: 235U, Np, Pu and got "Unexplained results"

The reason for the “Unexplained results” is the short-lived activity of fission products, i.e. imposition of a large number of decays.



Discovery of new radioactive elements and the fission chain reaction thanks to neutrons

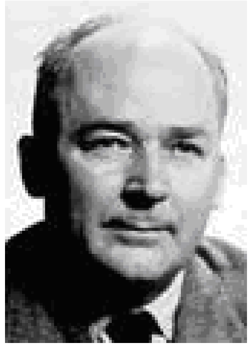
- German chemist Ida Noddack was the first to explain the unexpected results of Fermi irradiation of uranium and published her interpretation in the same year (1934).
- I. Noddak (chemist) suggested something that physicists did not even think about: the destruction of the U nucleus;
- Her arguments: in the U-nucleus there are 92 protons (a lot!), which repel each other, the U nucleus is not strong, a hit by a neutron can destroy the nucleus. Fermi called the article **stupid!**

Ida Noddack
(1896-1978)

Discovery of new radioactive elements and the fission chain reaction thanks to neutrons

- German chemists Otto Hahn and Fritz Strassmann irradiated U again with neutrons and carried out a chemical analysis of the products. Neutron sources were still very weak, therefore the concentration of fission products was very small.
- It took from the best chemists in the world about six months to separate the fission reaction products and detect the presence of Ba-137 and La-140 from the middle of periodic table. **How did they appear?**

Otto Hahn (1879-1968)

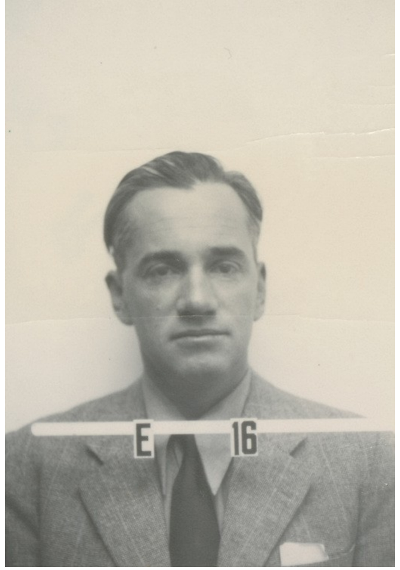


Fritz Strassmann (1902-1980)

- **O. Hahn: 1944 - Nobel Prize in Chemistry (!) for the discovery of fission of heavy nuclei (physics!)**
  - **Ida Noddack was forgotten In 1938,**

Discovery of new radioactive elements and the fission chain reaction thanks to neutrons

Lise Meitner
(1878-1968)



Otto Robert
Frisch
(1904 –1979)

- **In Jan. 1939 Otto Hahn published the results of the experiment, but could not explain them.**
- **A month later, Lise Meitner and her nephew Otto Robert Frisch published on 3 pages a physical explanation of the results of the experiment by "fission": "The fission process can give rise to a chain reaction, which can lead to large energy releases" (~200 MeV / fission).**

Noddack **predicted, and** ***Lise*** **explained the fission reaction, but did not receive the Nobel Prizes!**

How to release the energy of fission reaction?

Neutrons are needed, they produced in (α,n)-reactions on light nuclei, as Be:

$$ {}^{9}_{4}\mathrm{Be} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{12}_{6}\mathrm{C} + {}^{1}_{0}\mathrm{n} + 5.5\ \mathrm{MeV} $$

But this is a very weak source of neutrons. Where do we get such a dense source of neutrons?

Stable nuclides	${}^{8}_{16}O$	${}^{88}_{38}Sr$	${}^{139}_{57}La$	${}^{235}_{92}U$
$\frac{\text{№ of neutrons } (N)}{\text{№ of protons } (P)}$	1.0	1.32	1.44	1.55

After fission, fission fragments will be overloaded with neutrons, to sustain a fission chain reaction: $\nu_f > 1$

How to release the energy of fission reaction?

Irene and her husband Frederic Joliot-Curie experimentally measured the value of ν_f for some heavy elements and showed that ***ν_f can be higher than 1***: $\nu_f > 1$

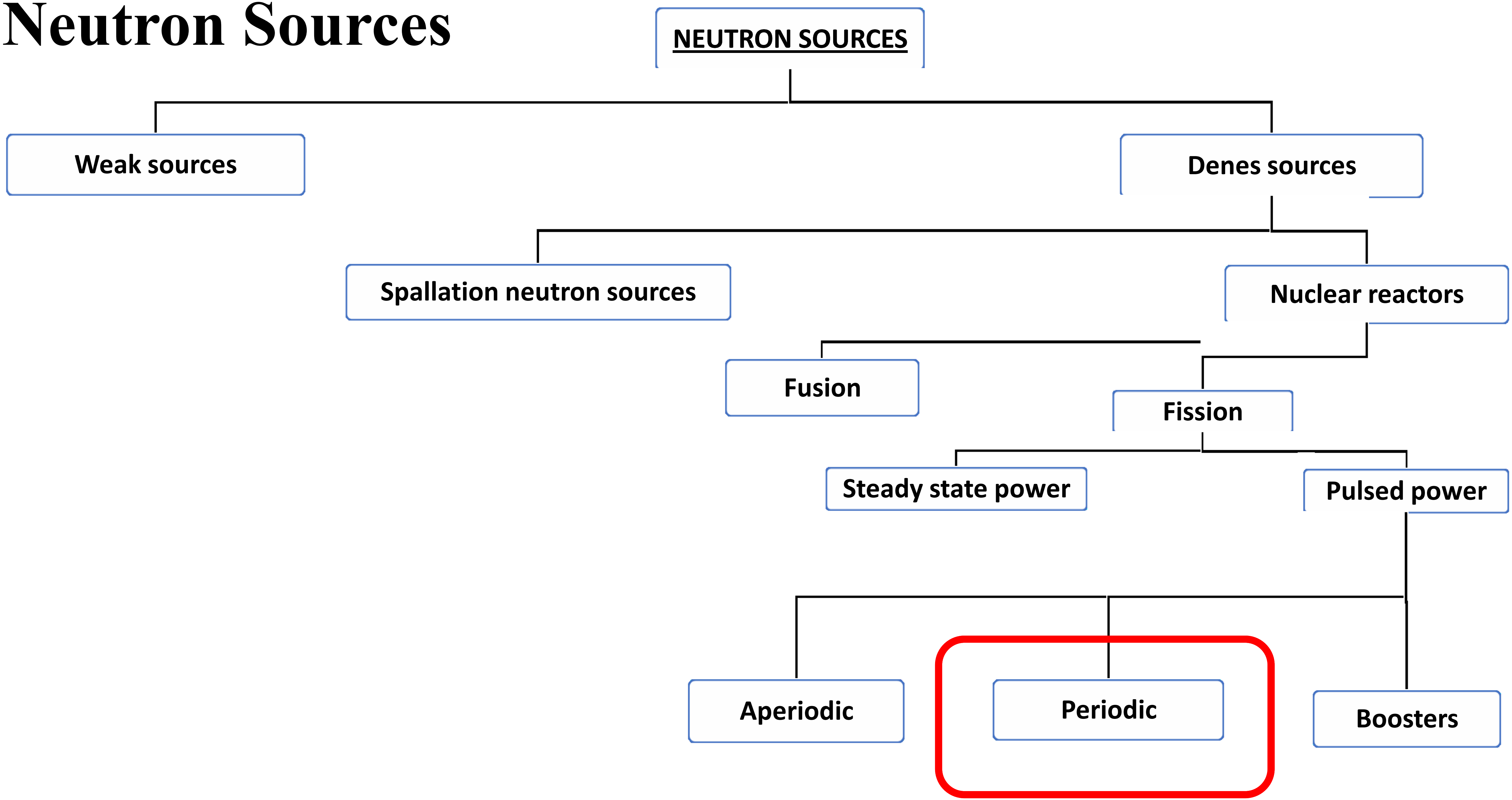
Nuclide	^{235}U	^{238}Pu	^{239}Pu	^{240}Pu	^{242}Pu	^{252}Cf
Fission type	Induced fission	Spontaneous fission	Induced fission	Spontaneous fission	Spontaneous fission	Spontaneous fission
P(0)	0.033	0.054	0.011	0.066	0.068	0.002
P(1)	0.174	0.205	0.101	0.232	0.230	0.026
P(2)	0.336	0.380	0.275	0.329	0.335	0.127
P(3)	0.303	0.225	0.323	0.251	0.247	0.273
P(4)	0.123	0.108	0.199	0.102	0.099	0.304
P(5)	0.028	0.028	0.083	0.018	0.018	0.185
P(6)	0.003	-	0.008	0.002	0.003	0.066
P(7)	-	-	-	-	-	0.015
P(8)	-	-	-	-	-	0.002
$\nu_f = ?$	2.406	2.212	2.879	2.156	2.145	3.757

Experimental Probabilities of Prompt Fission Neutrons [LANL, USA]

Irene Curie (1897-1956)

Frederic Curie (1900-1958)

Neutron Sources



Neutron sources

A) Weak sources:

1- Based on (α, n)-reactions;

$$^{4}He + ^{9}Be \rightarrow ^{13}C^{*} \rightarrow ^{12}C + n + 5{,}704\ МэВ.$$

2- Based on (γ, n)-reactions (photoneutron);

$$^{9}Be + \gamma \longrightarrow ^{9}Be^{*} \longrightarrow ^{8}Be + n$$
$$^{2}H + \gamma \longrightarrow ^{2}H^{*} \longrightarrow ^{1}H + n.$$

3- Based on (p, n)-reactions;

$$^{3}H + ^{1}H \rightarrow ^{3}He + n\ (E_{пор}=1.019\ МэВ)$$
$$^{7}Li + ^{1}H \rightarrow ^{7}Be + n\ (E_{пор}=1.88\ МэВ)$$

4- Based on fusion reactions

$$^{2}H + ^{2}H \rightarrow ^{3}He + n + 3.28\ МэВ$$
$$^{3}H + ^{2}H \rightarrow ^{4}He + n + 17.6\ МэВ$$

α-particle emitters: as Ro-210 (T1/2=138.4 days), Ra-226 (T1/2=1622), As-227 (T1/2=22 years), Pu-239 (T1/2=24360 years).

Reaction (α, n) can only take place if:

a) the kinetic energy of α-particle above the Coulomb barrier of the target and

b) excitation energy of a compound nucleus, resulting after the capture of α-particle core-target, more than the binding energy of a neutron in the compound nucleus.

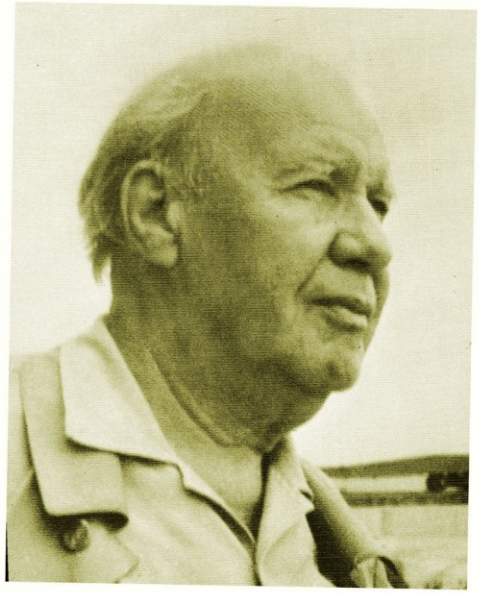
photoneutron reaction, may occur if energy-γ is higher than the binding energy of a neutron in the nucleus usually target binding energy of a neutron in the nucleus is 6-8 Mev and nuclides 9 Be and 2 (H) it is abnormally low (respectively 1.68 and 2.23 MEV).

(p, n)-reactions is a threshold reaction. Because of the need of penetration of a Proton with a relatively small energy through the Coulomb barrier set appropriate targets is limited to light nuclei.

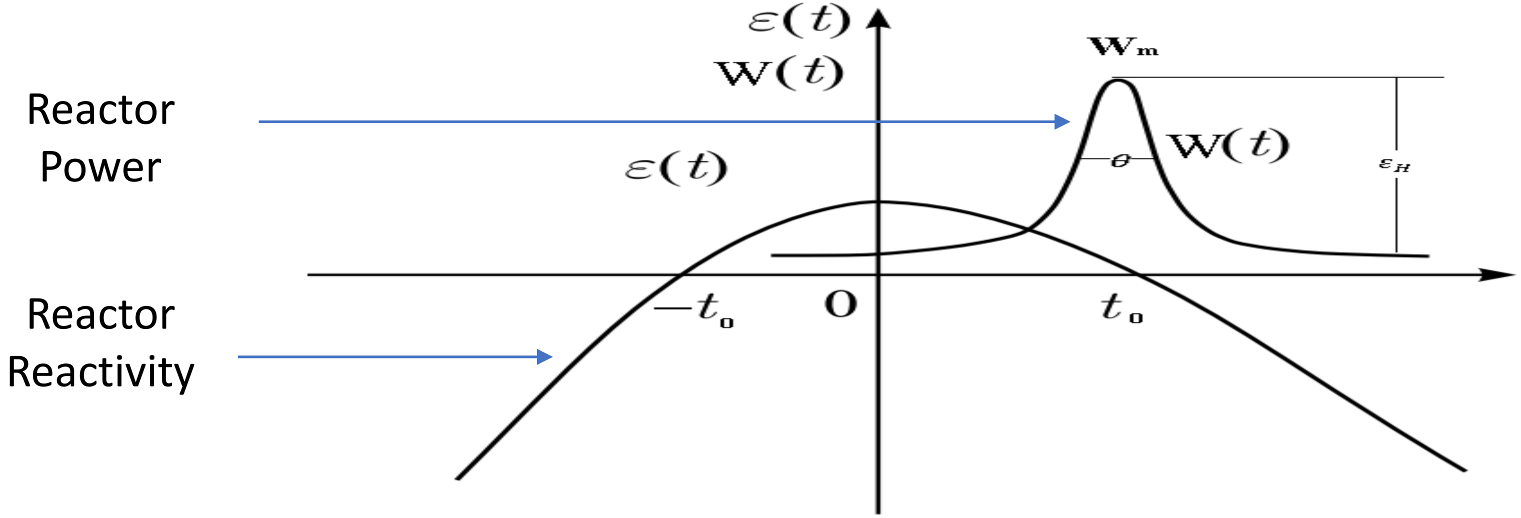
Neutron sources

B) Denes sources : 2- Periodic Pulsed power reactors:

- In 1955- in the Obninsk Pysical-Power institute (Russia), D. I. Blokhintsev suggested the idea of a periodic pulsed reactors with mechanically periodically reactivity modulation.
- To combines the best features of Aperiodic reactors (pulsed nature without any choppers – time of flight) and steady state power reactors (good enough fluence to neutron spectroscopy).
-



Dmitry Blokhintsev (1907-1979)



The course of reactivity and power of the reactor during the development of the power pulse

Neutron sources

B) **Denes sources** : **2- Periodic** Pulsed power reactors:

	IBR-1 1960 - 1968	IBR-30 19	IBR-2 с 1984 г	IBR-3 (NEPTUNE)
Thermal power	1- 3 кWт	20 кWт	2 MWт	12-15 MWт
Fissile material	Pu-239 metal	Pu-239 metal	PuO_2	Np-237, NpN
Reactivity modulator, frequency	U-235 5-50 Hz	U-235 0.1 - 10 Hz	Moveable reflector from Ni 5-25 Hz	TiH_2+and void, 10 Hz
The half width pulse	40 μs	70 μs	240 μs	~260-μs
Neutron flux at the surface of moderators, см²/ s,	$\sim 10^{10}$	10^{11}	10^{13}	10^{14}

Reactor NEPTUNE

1- MAIN FEATURES OF THE REACTOR NEPTUN:

1 - The generation time of fast neutrons (τ) in the neptunium core is 5-7 times shorter than that in the core with plutonium (**the task of having a short pulses of neutrons becomes easier**).

2 - The proposed source will have a peak neutron flux up to **$5\ 10^{16}$** $n.sec^{-1}.cm^{-2}$ and a time average flux density of up to **10^{14}** $n.sec^{-1}.cm^{-2}$(**in IBR – 2M: 0.7 10^{16} and 10^{13}**).

3 - A low value of the delayed neutrons fraction (β-eff) determines a low background power in the intervals between pulses (**3-4 times less**).

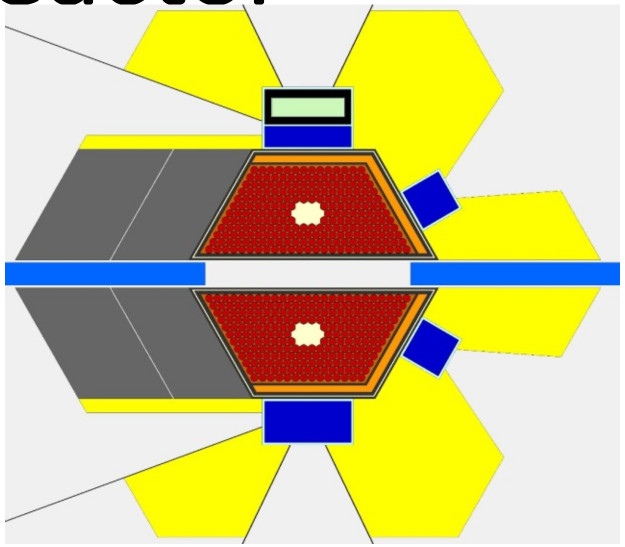
4 - Possibility of using neutron moderating materials as a Reactivity Modulator (RM) (like high-temperature resistance - hydride's metal **TiH_2, YH_2**).

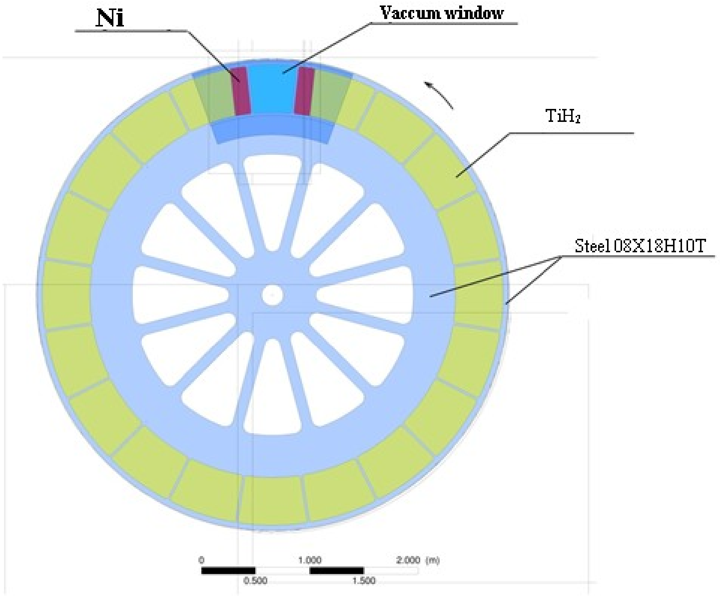
5 – There is no reactivity effect from the fuel burnup (it is possible to work without additional fuel loading during the entire reactor cycle):

Np237 (n absorption) → Np238 (β-decay, (2.117 days) → Pu238 (Fissionable material)

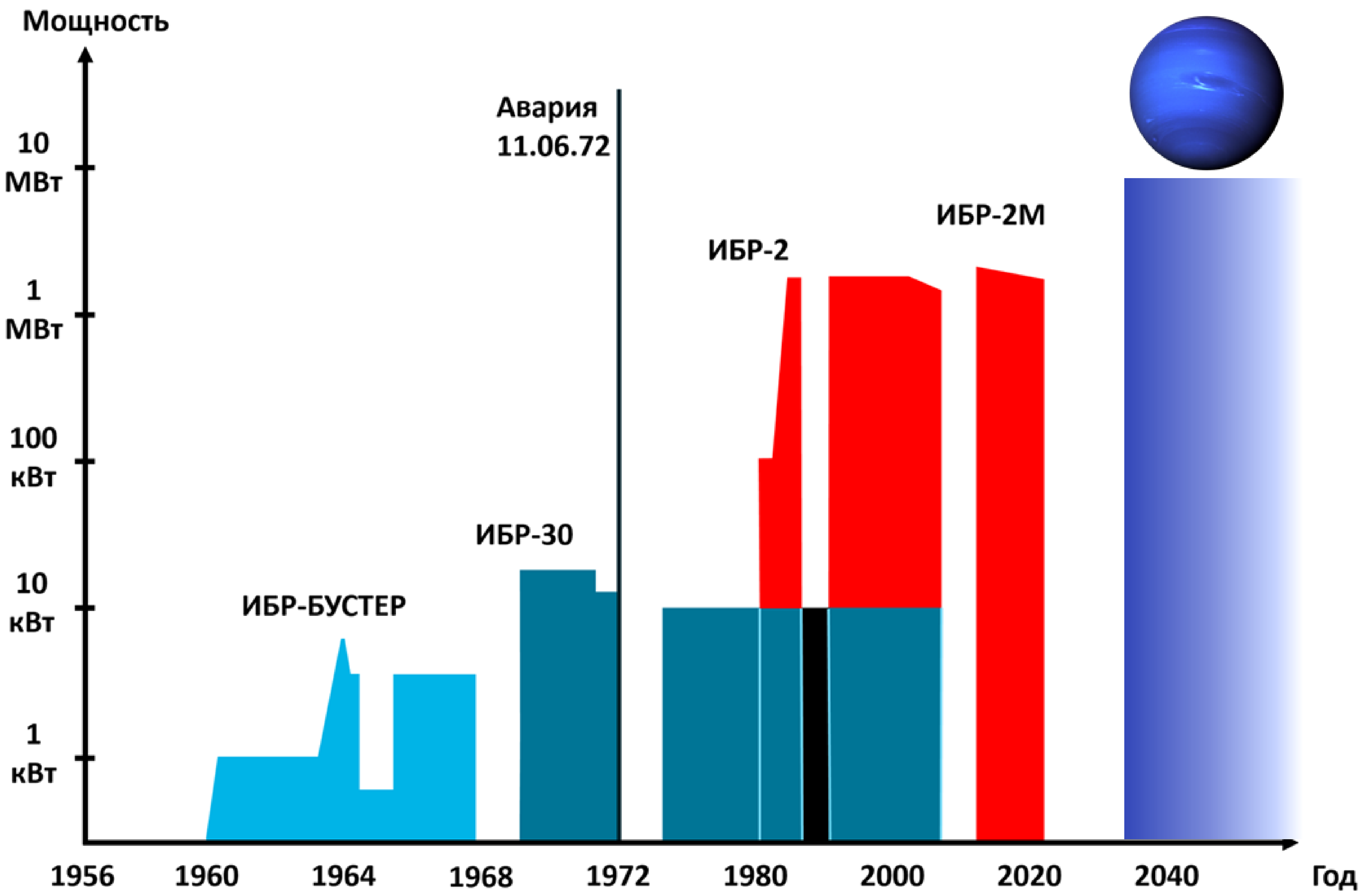
The main parameters of the reactor

Параметр	Значение
AVERAGE THERMAL POWER , MW	12 - 15
OPERATING MODE	pulsed
PULSE FREQUENCY, Hz	10
FUEL	NpN
CLADDING MATERIAL OF FUEL RODS	S.Steel ЧС-68
COOLER	Na
REFLECTOR	NICKEL ALLOY + BERYLLIUM
MODERATOR, PREMODERATOR	Hydrides, water, beryllium
COOLANT TEMPERATURE AT THE INLET TO THE CORE AND AT THE OUTLET, ^{0}C	290-390
PRESSURE DROP THROUGH THE CORE, Pa	$0,33 \cdot 10^{5}$
FLUENCE ON THE REACTOR SURROUNDING'S FOR 20,000 h, n / CM^{2}	$4,1 \cdot 10^{22}$
AVERAGE NEUTRON THERMAL FLUX AT THE SURFACE OF WATER MODERATOR, 2π- equivalent 10^{13} cm^{-2}·sec^{-1}	12
EFFECTIVE FRACTION OF DELAYED NEUTRONS	0,00131
GENERATION TIME OF THE SPONTANEOUS NEUTRONS , n,sec	30





Thank you for your attention.
Any questions??



Мощность
10 МВт
1 МВт
100 кВт
10 кВт
1 кВт
Авария 11.06.72
ИБР-БУСТЕР
ИБР-30
ИБР-2
ИБР-2М
1956
1960
1964
1968
1972
1980
2000
2020
2040
Год