ISOTOPES: production and some applications

Lev Inzhechik

KURCHATOV INSTITUTE
inzhechik@imp.kiae.ru

XIV-th International Baksan School
«Particles and Cosmology»
April 16 - 21, 2007

ISOTOPES: production and some applications

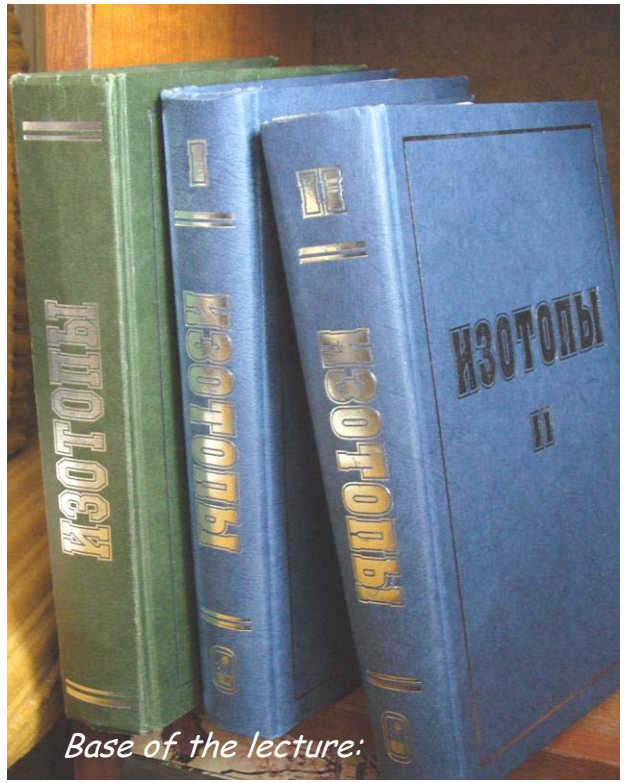
Lev Inzhechik

KURCHATOV INSTITUTE
inzhechik@imp.kiae.ru

XIV-th International Baksan School
«Particles and Cosmology»
April 16 - 21, 2007

Outline

- *Isotopes: discovery, definition, denotations.*
- *Isotope stability, "island of stability" of super-heavy elements.*
- *Creation in the USSR of the gas-kinetic technologies of enrichment of U -235 and production of Pu-239 by means of nuclear reactor for the Soviet A-bomb in the middle of the XX-th century.*
- *Modern industry for isotopes production in Russia and in the world.*
- *New isotope selection methods being now under development.*
- *Prospects for production of isotope quantities of scale of kg and ton for different elements.*
- *Some applications of some isotopes for physics, for nuclear technic, etc.*



Base of the lecture:

V. Baranov scientific editor

"ISOTOPES: PROPERTIES, PRODUCTION, APPLICATION"

Collective Monograph (in Russian)

1-st edition, 703 pages, IzdAT, Moscow, 2000

2-nd edition, 2 volumes, 1325 pages, Fizmatlit, Moscow, 2005

Milestones of history of isotopes

1896 — *A.A. Becquerel* *(1852 – 1908. Nobel price of 1903).* ***Discovery of radioactivity, start of nuclear physics — base for the isotope physics.***

1910 — *F. Soddy* *(1877 – 1956. Nobel price of 1921. Foreign Correspondent Member of RAS from 1924).* ***Term "ISOTOPE" . Investigation of the isotopes properties and origin.***

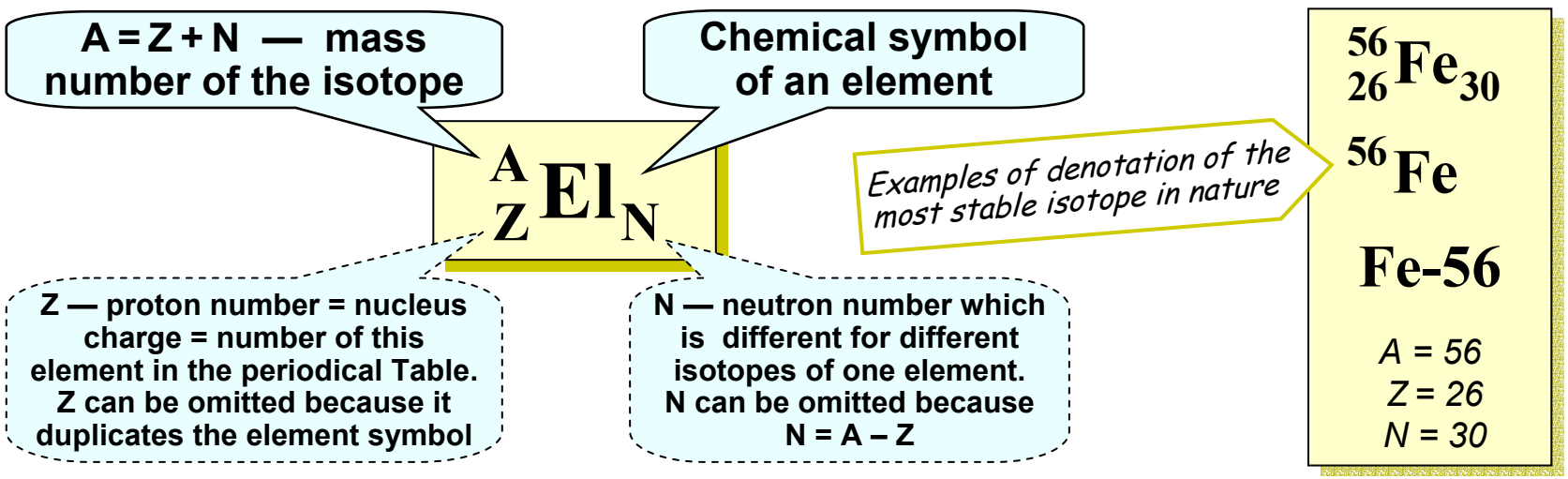
1911 — *J.J. Thomson* *(1856 – 1940. Nobel price of 1906. Foreign Correspondent Member of RAS from 1913. Foreign Advisory Member of RAS from 1925).* ***The first direct observation of the isotopes in experiments with the "cathode rays".***

1919 — *F.W. Aston* *(1877 – 1945. Nobel price of 1922. Foreign Correspondent Member of RAS from 1924).* ***Research for isotope phenomenon. The first mass-spectrometer. Curve of the nuclear "packing factors".***

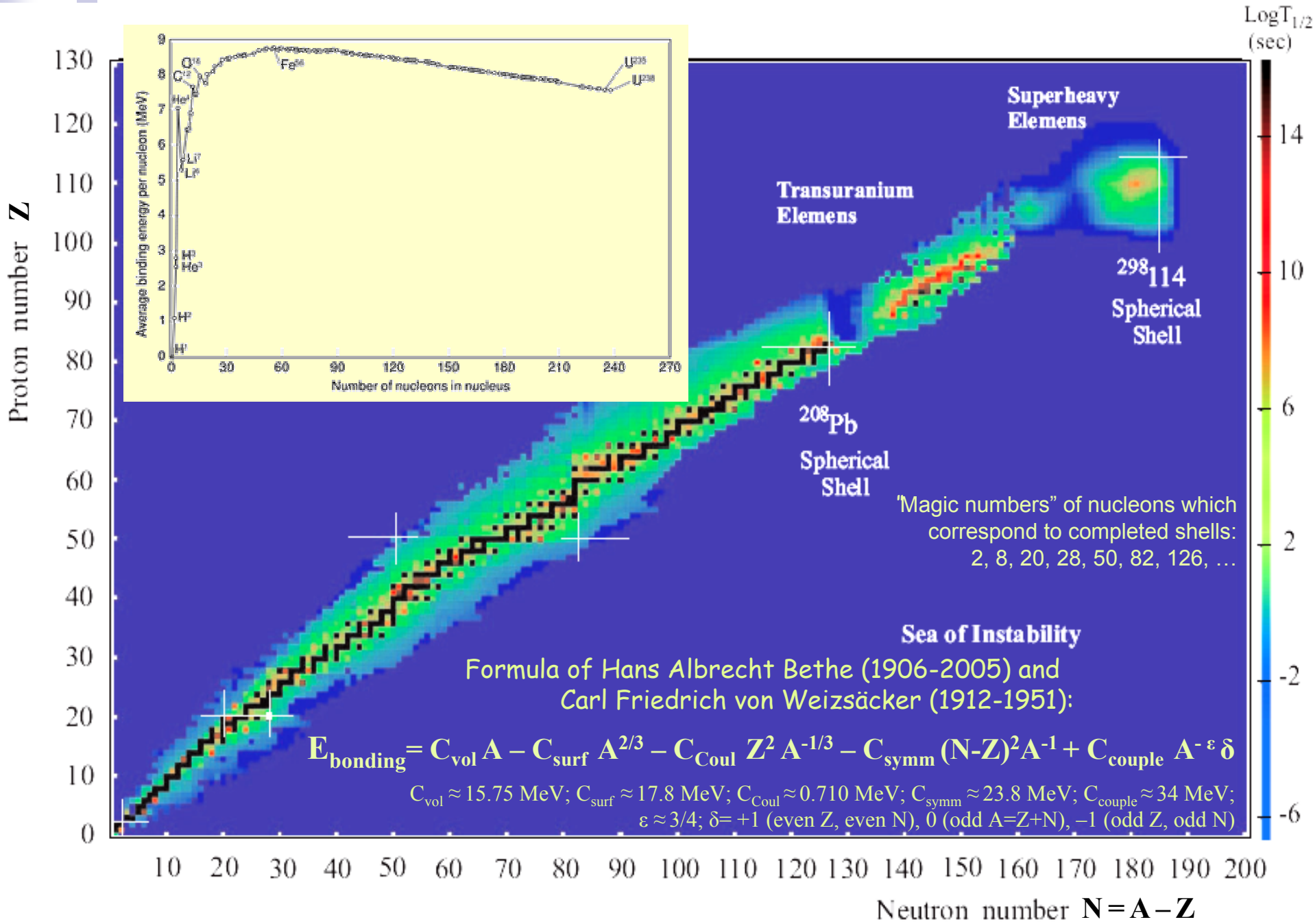
Definition. *Isotopes are any of the several different forms of an element each having different atomic mass.*

Isos (equal, Latin) + **τοποσ** (place, location, Greek) = **ISOTOPE**

Denotations. *All isotopes of an element with **atomic number Z** have nuclei with the same positive **charge Z** determined by a **number of protons Z** in the nuclei. The isotopes of one element have different **numbers of neutrons N** and, accordingly, different **mass number A** which is a sum A = Z + N.*



Properties. *Chemical and non-nuclear physical properties of isotopes of one element are the same or differ slightly because electron configuration determined mainly by the nuclear charge Z. Nuclear physics considers the isotopes as qualitatively different objects.*


Log$T_{1/2}$ (sec)
14
10
6
2
-2
-6
Proton number Z
Neutron number N = A – Z
Superheavy Elemens
Transuranium Elemens
^{298}114
Spherical Shell
^{208}Pb
Spherical Shell
Sea of Instability
'Magic numbers" of nucleons which correspond to completed shells:
2, 8, 20, 28, 50, 82, 126, …
Formula of Hans Albrecht Bethe (1906-2005) and Carl Friedrich von Weizsäcker (1912-1951):
$E_{bonding} = C_{vol} A - C_{surf} A^{2/3} - C_{Coul} Z^2 A^{-1/3} - C_{symm} (N-Z)^2 A^{-1} + C_{couple} A^{-\varepsilon} \delta$
$C_{vol} \approx 15.75$ MeV; $C_{surf} \approx 17.8$ MeV; $C_{Coul} \approx 0.710$ MeV; $C_{symm} \approx 23.8$ MeV; $C_{couple} \approx 34$ MeV;
$\varepsilon \approx 3/4$; $\delta = +1$ (even Z, even N), 0 (odd A=Z+N), –1 (odd Z, odd N)
Average binding energy per nucleon (MeV)
Number of nucleons in nucleus

Island of stability

According to a theory there are super-heavy nuclei which are expected and have appeared actually ore stable then heavy actinides!

J. Nucl. Radiochem. Sci.,Vol. 3, No. 1, pp. 5–8, 2002
Synthesis and Properties of Even-even Isotopes with Z = 110–116 in ^{48}Ca Induced Reactions
Yu. Ts. Oganessian (JINR, Dubna)

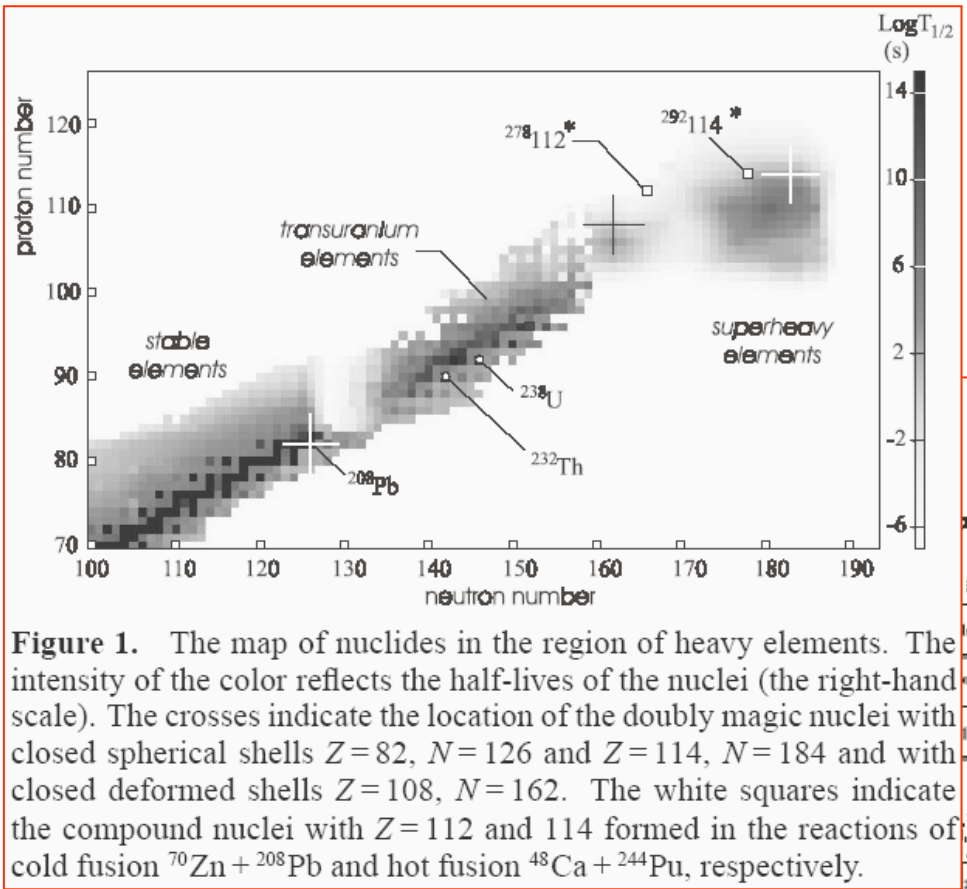
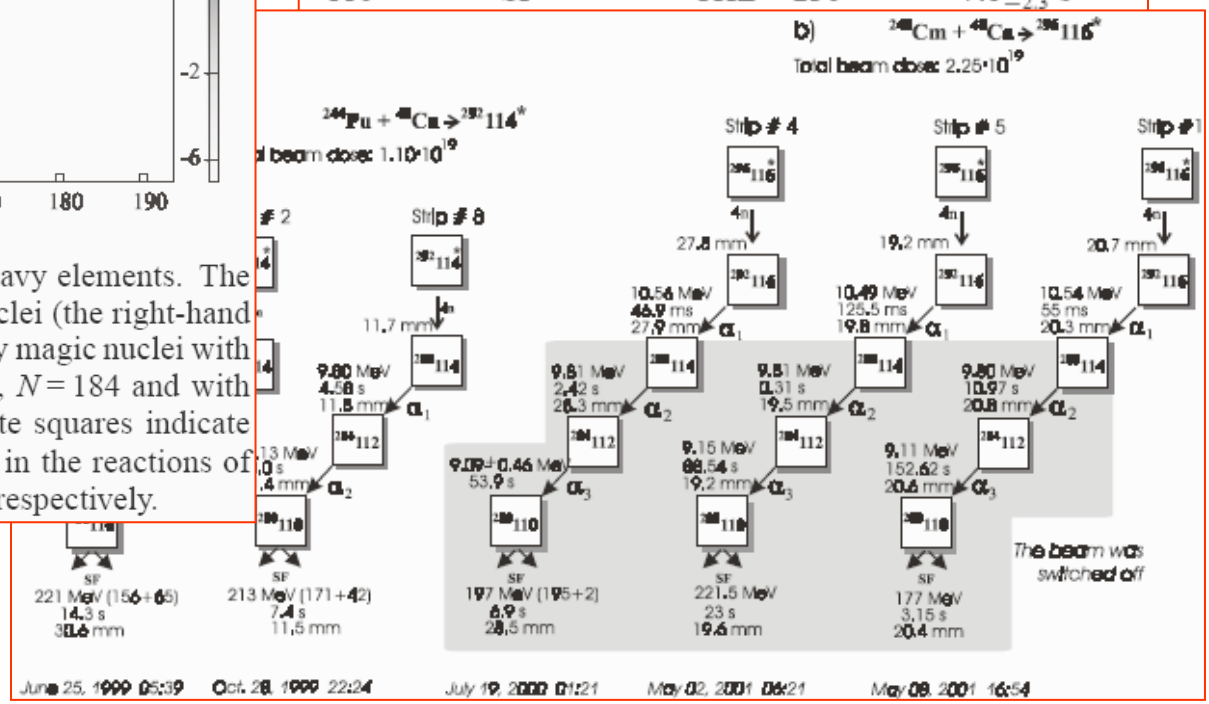


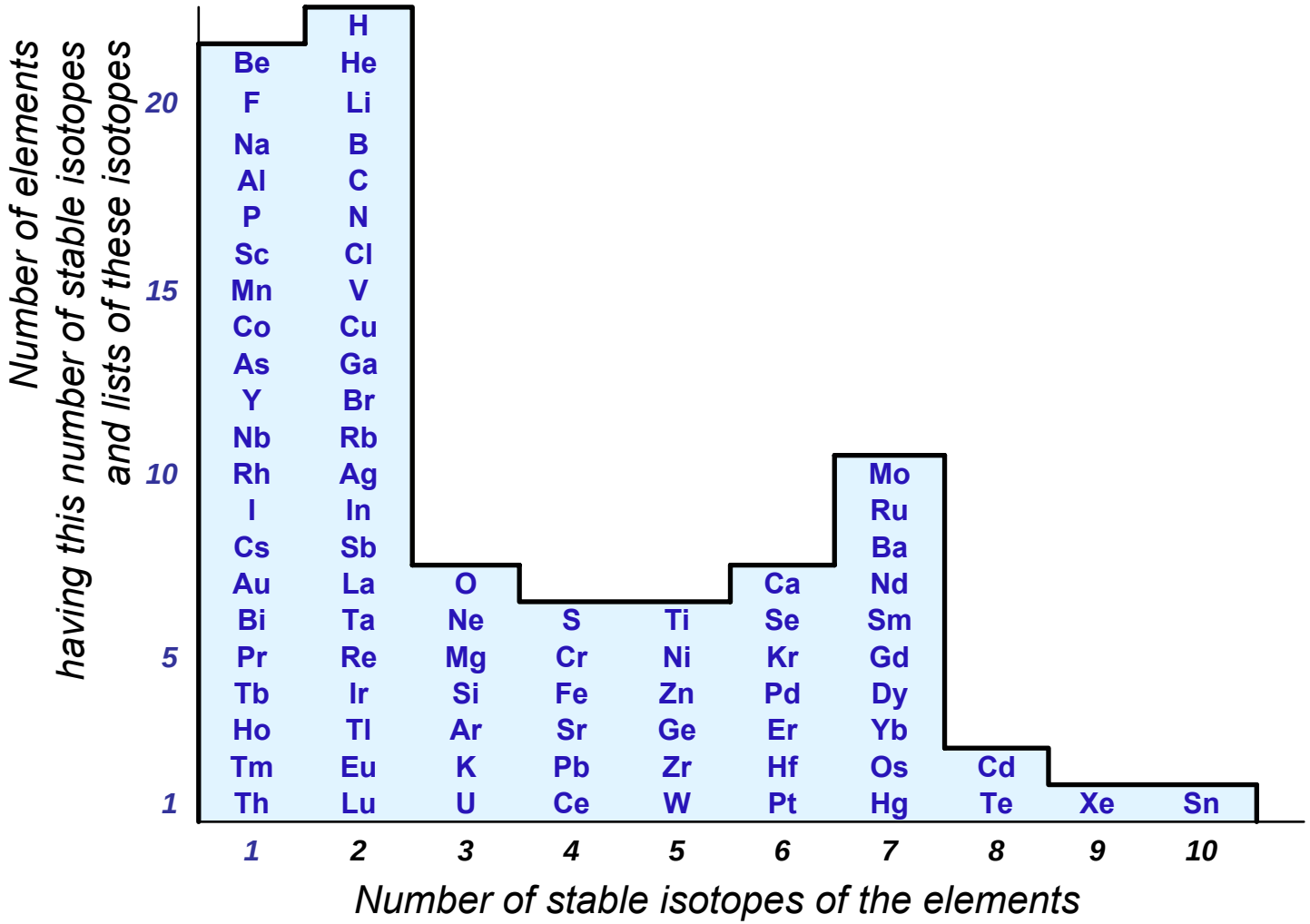
Figure 1. The map of nuclides in the region of heavy elements. The intensity of the color reflects the half-lives of the nuclei (the right-hand scale). The crosses indicate the location of the doubly magic nuclei with closed spherical shells $Z = 82$, $N = 126$ and $Z = 114$, $N = 184$ and with closed deformed shells $Z = 108$, $N = 162$. The white squares indicate the compound nuclei with $Z = 112$ and 114 formed in the reactions of cold fusion ^{70}Zn + ^{208}Pb and hot fusion ^{48}Ca + ^{244}Pu, respectively.

TABLE 1: Radioactive properties of even-even isotopes of the superheavy elements with $Z = 110$, 112, 114, and 116.

Z	Decay mode	Q_α / MeV	T_α
116	α	10.68 ± 0.06	53^{+62}_{-19} ms
114	α	9.96 ± 0.06	$2.6^{+2.0}_{-0.8}$ s
112	α	9.28 ± 0.06	$0.75^{+0.57}_{-0.23}$ min
110	SF	TKE ~ 230	$7.6^{+5.8}_{-2.3}$ s



Abundance of stable isotopes of elements



Nuclear explosive for A-bomb

Isotope technologies developed in the frame of the Atomic Projects

^{235}U *Principal possibility for creation of A-bomb on the base of 235 -th isotope of uranium was showed:* **in April of 1939** *by physicists of Grate Brittan, Germany, and France;*

in April of 1939 *in the USSR;*

in Autumn of 1939 *in the USA.*

In 1940 *R. Peierls[1] and O. Frisch[2] in the GB and independently Ya. Zel'dovich[3] and Yu. Khariton[4] in the USSR had estimated the "critical mass" of ^{235}U needed for A-bomb. They calculated that the explosive chain reaction of the neutron induced fission is possible for monolithic piece of ^{235}U of mass of the order of 1 kg.*

Isotopic content of native uranium is following:

^{234}U — 0,0055%; $T_{1/2} = 2.45 \times 10^5$ y

^{235}U — 0,7200%; $T_{1/2} = 7.038 \times 10^8$ y

^{238}U — 99,2745%; $T_{1/2} = 4.468 \times 10^9$ y

^{239}Pu **($T_{1/2} = 24.119 \times 10^3$ y)** *^{239}Pu for nuclear explosive can be produced by means of uranium nuclear rector by reaction of* $^{238}U + n \rightarrow {}^{239}U \xrightarrow{-\beta} {}^{239}Np \xrightarrow{-\beta} {}^{239}Pu$.

---

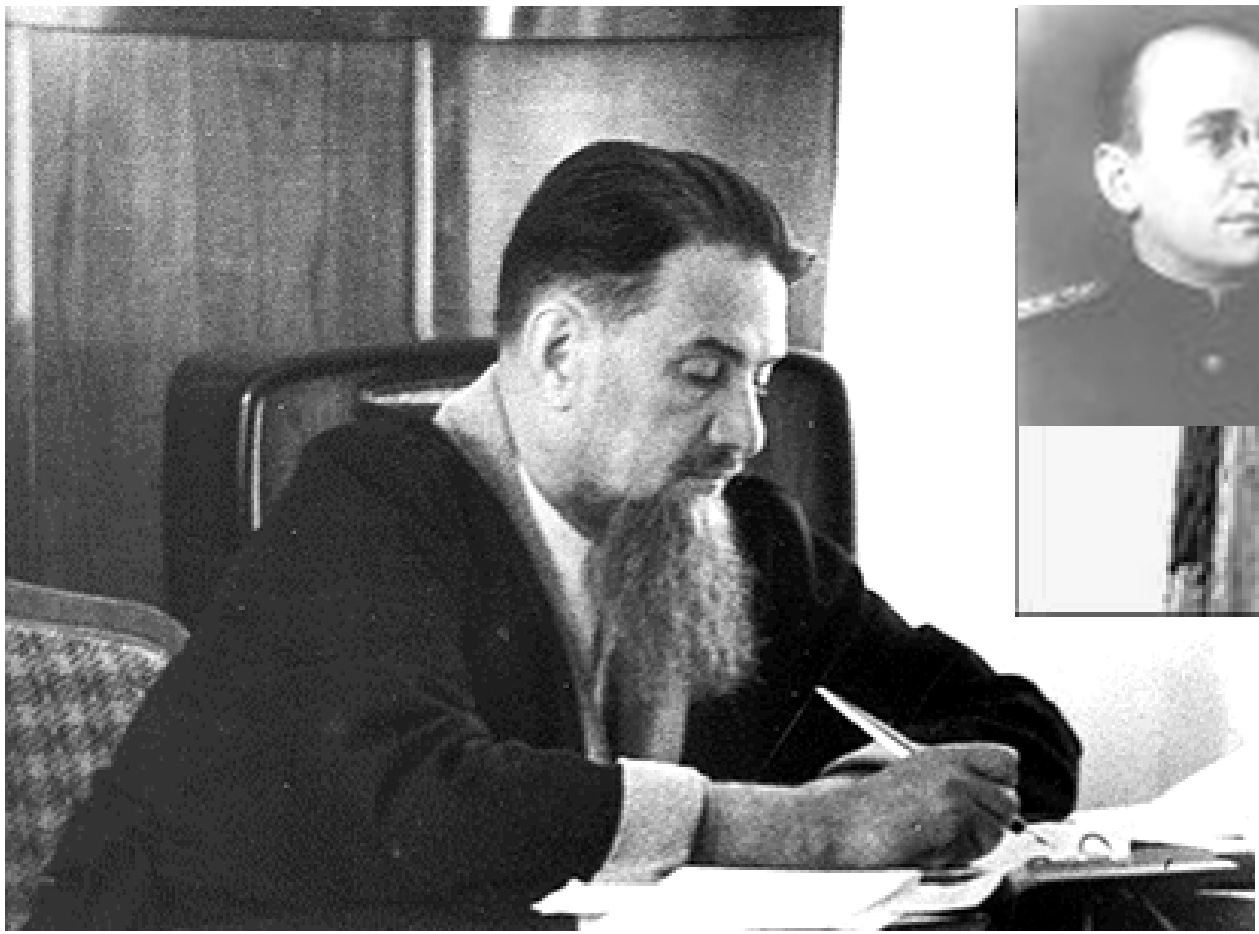
1) **Sir Rudolf Ernst Peierls (June 5, 1907, Berlin – September 19, 1995 Oxford) was a German-born British physicist.**

2) **Otto Robert Frisch (October 1, 1904 – September 22, 1979) Australian-Brotish physicist.**

3) **Yakov Borisovich Zel'dovich (March 08, 1914, Minsk – December 02, 1987 Moscow), Russian physicist, academician of RAS.**

4) **Yuly Borisovich Khariton (February 14/27, 1904 – December 19, 1996), Russian physicist, academician of RAS.**

1944. Igor Kurchatov is writing a letter to Lavrenty Beria about, in particularly, necessity to produce in the USSR enriched uranium-235.



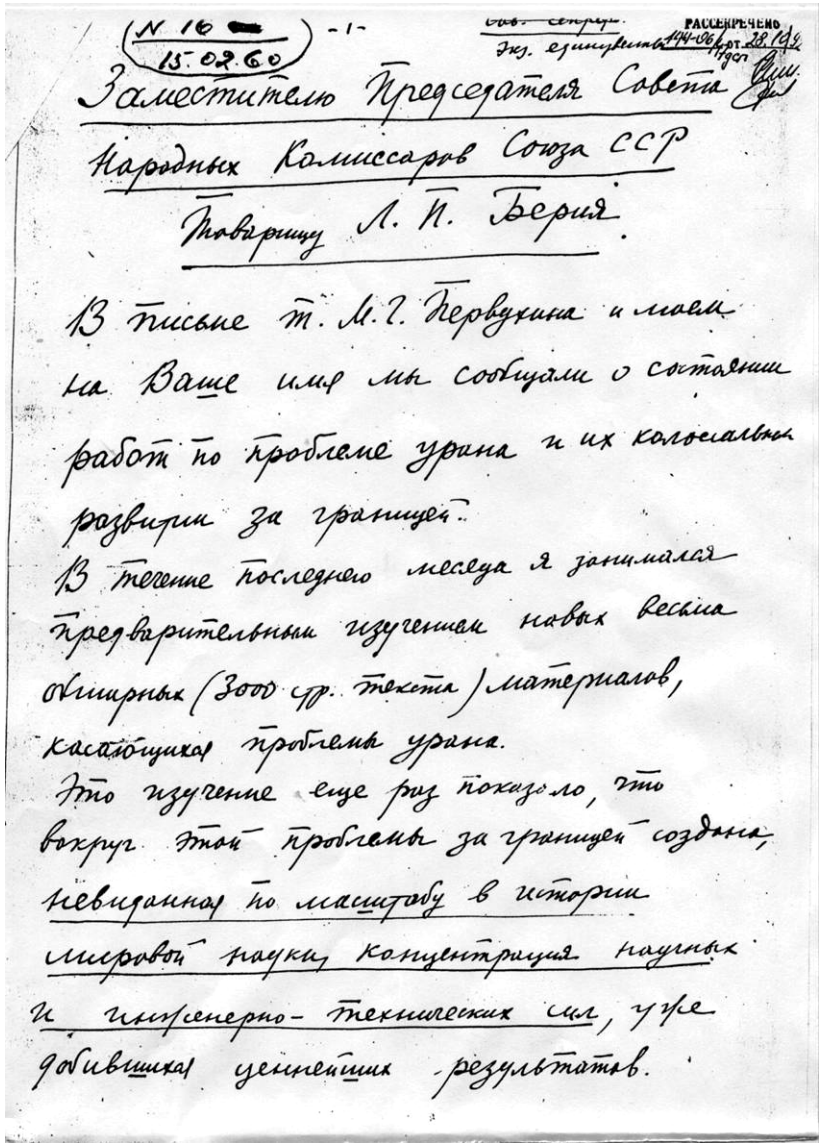
Igor Vasil'evich Kurchatov *(January 12, 1903, Ufa region – February 07, Moscow, 1960), academician of AS USSR, scientific leader of the Soviet Atomic Project*

Lavrenty Pavlovich Beria

(March 29, 1889, Merkheuli – December 12, 1953, Moscow)
Vice Chairman of the government of the USSR, minister of internal affairs (chief of "KGB"), administrative head of the Soviet Atomic Project

The letter of I. Kurchatov to L. Beria of September 29, 1944

Phrase about selection of isotopes (of uranium — L.I.) is marked



(N 10 — 15.02.60) -1-

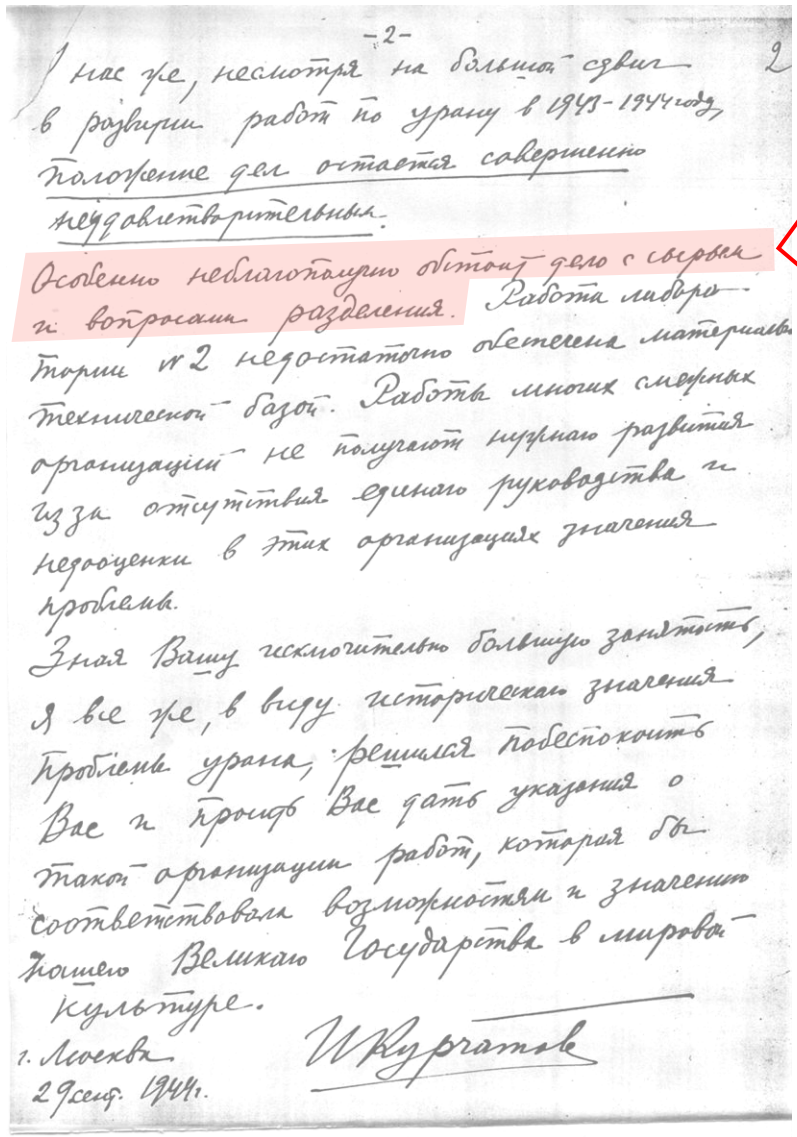
РАССЕКРЕЧЕНО

Заместителю Председателя Совета
Народных Комиссаров Союза ССР
Товарищу Л. П. Берия.

В письме т. М. Г. Первухина на имя Ваше мы сообщали о состоянии работ по проблеме урана и их колоссальных развитии за границей.

В течение последнего месяца я занимался предварительным изучением новых весьма обширных (3000 стр. текста) материалов, касающихся проблемы урана.

Это изучение еще раз показало, что вокруг этой проблемы за границей создана, невиданная по масштабу в истории мировой науки, концентрация научных и инженерно-технических сил, уже добившихся ценнейших результатов.



-2-

У нас же, несмотря на большой сдвиг в развитии работ по урану в 1943-1944 году, положение дел остается совершенно неудовлетворительным.

Особенно неблагополучно обстоит дело с сырьем и вопросами разделения. Работа лаборатории №2 недостаточно обеспечена материально-технической базой. Работа многих смежных организаций не получает нужного развития из-за отсутствия единого руководства и недооценки в этих организациях значения проблемы.

Зная Вашу исключительно большую занятость, я все же, в виду исторического значения проблемы урана, решил побеспокоить Вас и просить Вас дать указания о такой организации работ, которая бы соответствовала возможностям и значению нашего Великого Государства в мировой культуре.

г. Москва
29 сент. 1944 г.

И. Курчатов

KIKOIN Isaak Konstantinovich (Kushelevich)

Born 28.03.1908, Zhagory. Dead 28.12.1984, Moscow
Corresponding member of RAS since 29.09.1943 –
Division of Physical-Mathematical Sciences
Academician of RAS since 23.10.1953 –
Division of Physical-Mathematical Sciences

Director of the "Department of Devices of Thermal Control" of the "Laboratory No 2" founded 15.01.1944
Now — Institute of Molecular Physics in structure of the Russian Research Center "Kurchatov Institute"

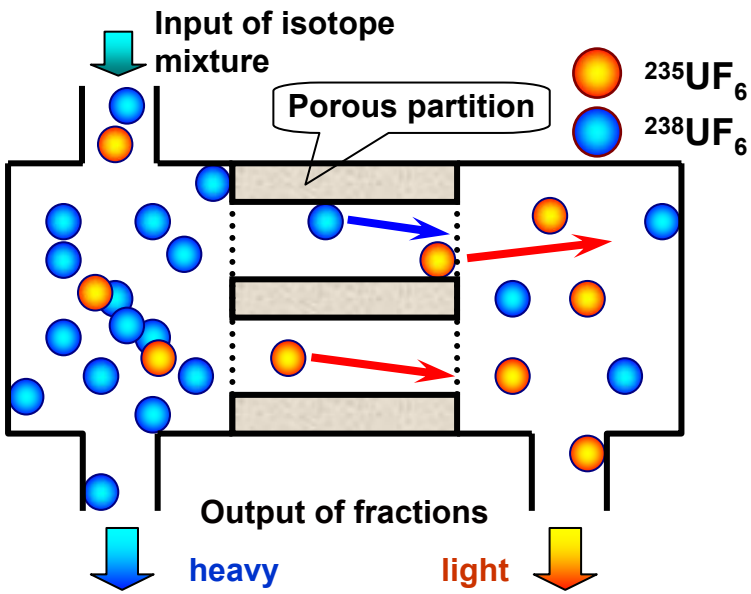
By a comission of I. Kurchatov Kikoin was a scientific head and administrative leader of R&D activity for creation of gas-kinetic technology for enrichment of ^{235}U needed for U A-bomb.

Firstly, the gas diffuse method was developed and tested in the lab scale under his direct leadership.

Then, he was a scientific director of the project of creation of the U enrichment industry.

Next stage of his activity was a leadership af development and introduction in the industry of the centrifuge technology of the isotope selection.

Physical principle of gas-diffusion selection of isotopes



Thermal velocity of a molecules of mass M at temperature T in Knudsen mode is proportional to $\sqrt{T/M}$

Working gas is uranium hexafluoride UF_6

Triple point — 64,05° C

Vapor pressure — 80 mm Hg at 20° C
800 mm Hg at 60° C

Advantage — fluoride has the only stable isotope ^{19}F

Theoretical limit of selection factor of a unit selector:

$$\alpha = \sqrt{M(^{238}UF_6)/M(^{235}UF_6)} \approx 1{,}004289$$

Disadvantages of the diffuse technology — high energy consumption, low selection factor of unit device. *To enrich ^{235}U from 0.7% up to 80% (minimal explosion condition) cascades of a lot of separators are to be used. Effective cascade should be assembled of separators of different standard sizes (of different UF_6 flux for different phases of the separation process) equipped by corresponding compressors.*

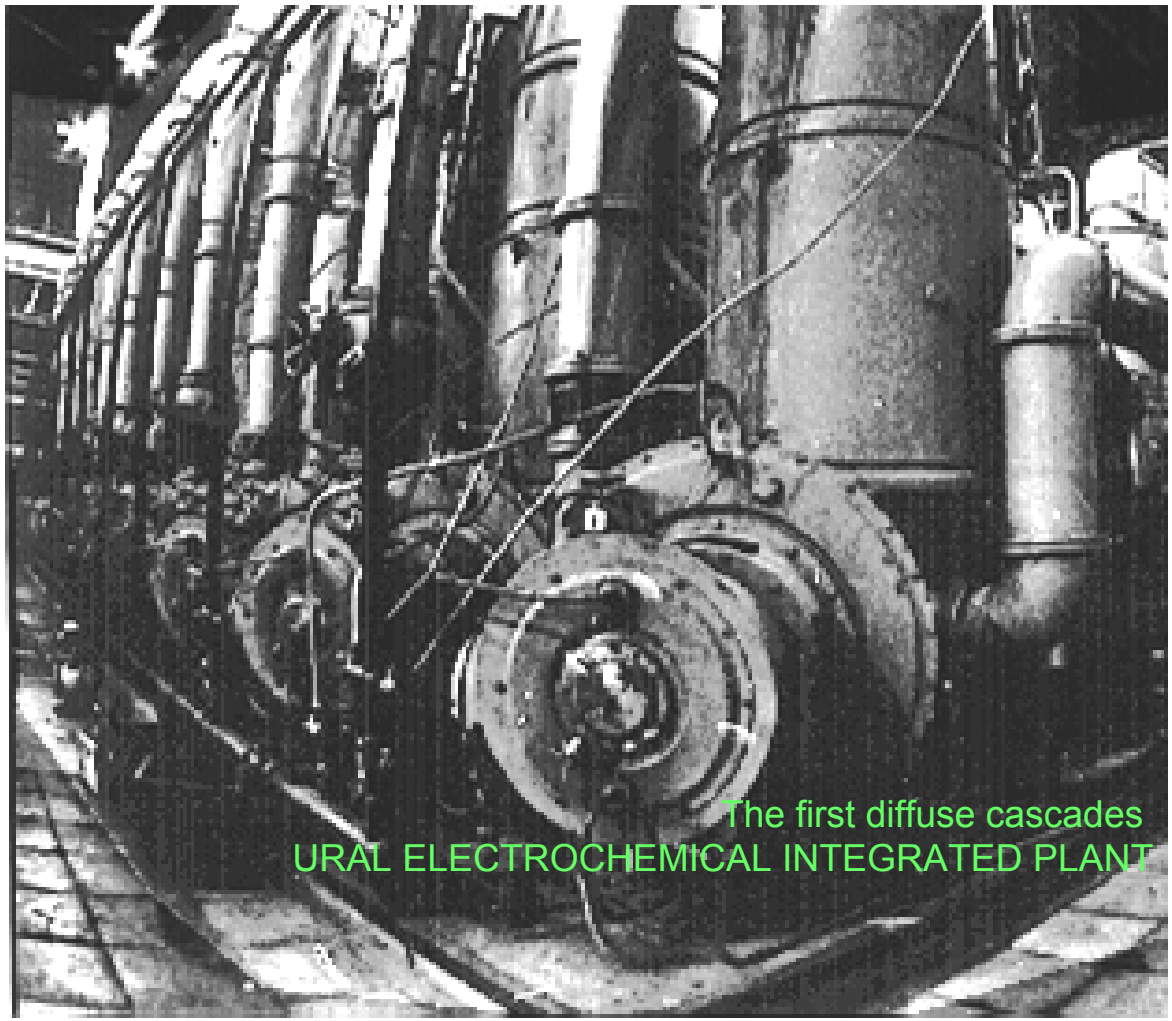
1951. *Theory of the diffusion selecting machine and of cascade of separators* — ***S. Sobolev, Ya. Smorodinsky***

1950-52. *Theory of process of selection of gaseous mixtures inside porous mediums* — ***Yu. Kagan***

Diffuse separators are united in cascades up to 1600 stages in each

For pumping of UF_6 super-sound compressors were created * of productivity from 8 g/s up to 25 kg/s and up to 60 m3/s (axial)*

* Sound velocity of UF_6 is ≈ 85 m/s



The first diffuse cascades
URAL ELECTROCHEMICAL INTEGRATED PLANT

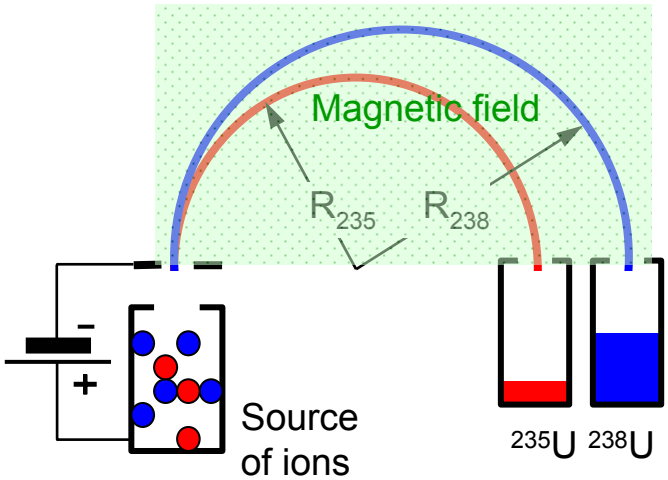
Assembly of pipe filters (UrE-CC)

Thickness	– 0,01 mm
Radius of pours	– 0,01 μ
Pressure	– up to 300 mm Hg
Square	– 400 m^2
Resource without regeneration	– 10 y

Grope of gas-diffuse separators

URAL ELECTROCHEMICAL INTEGRATED PLANT

Physical principle of electromagnetic (mass-spectrometric) separation of isotopes



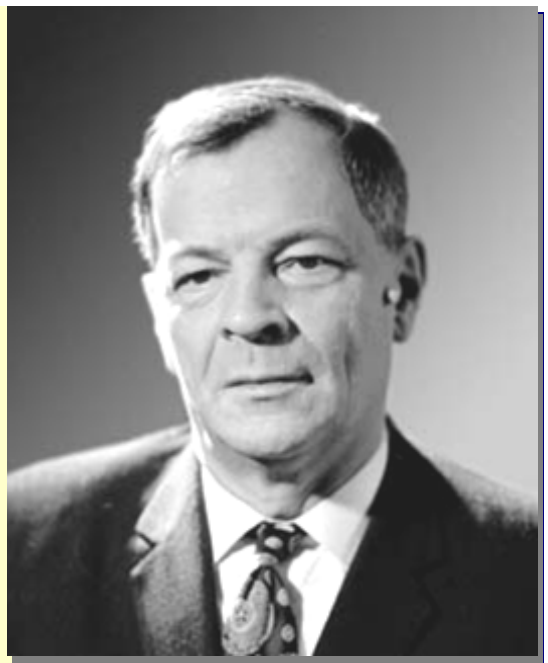
Radius R *of trajectory of a ion of mass* M *and of energy* E *in magnetic field* H *is:*

$$R = \frac{c}{H}\sqrt{\frac{2ME}{e}}$$

Accessible ion current which is limited by defocusing effect owing to volume charge of the ion beam, is of ***tens of mA.***

^{235}U *productivity of a single machine if natural isotope mixture of uranium separated —* ***tens of mg per day***

Artsimovich Lev Andreevich



Born 25.02.1909, Moscow
Dead 01.03.1973, Moscow
Corresponding member of RAS since 04.12.1946 – Division of Physical-Mathematical Sciences
Academician of RAS since 23.10.1953 - Division of Physical-Mathematical Sciences

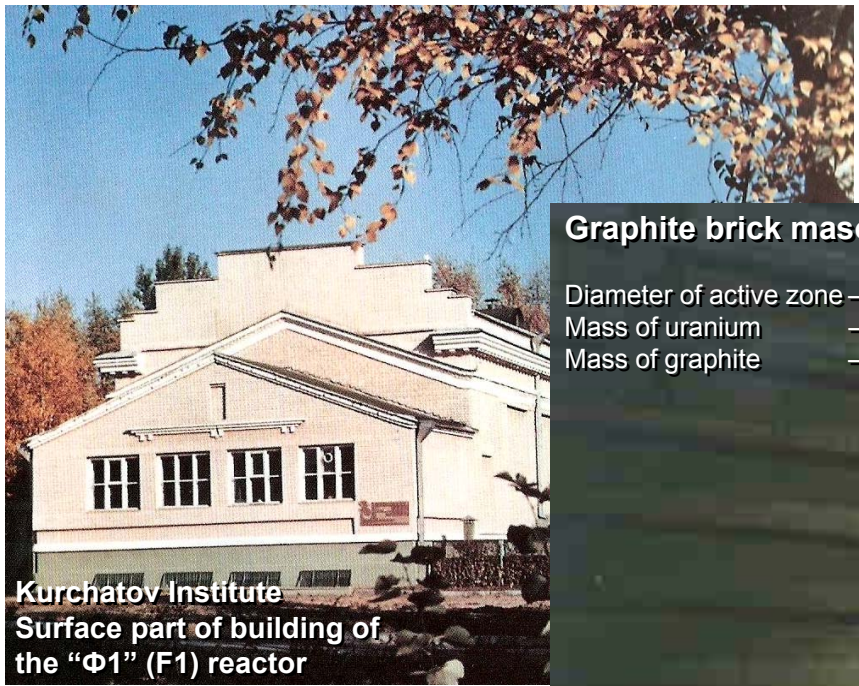
Scientific head of R&D of electromagnetic method of the isotope selection.

The first Soviet and European nuclear reactor for controllable chain reaction of fission of ^{235}U

Aim — to product ^{239}Pu by neutron irradiation of ^{238}U:

$$^{238}U + n \rightarrow {}^{239}U \xrightarrow{\beta} {}^{239}Np \xrightarrow{\beta} {}^{239}Pu$$

Only a nuclear reactor can supply neutron fluxes needed for kg scale production of ^{239}Pu.



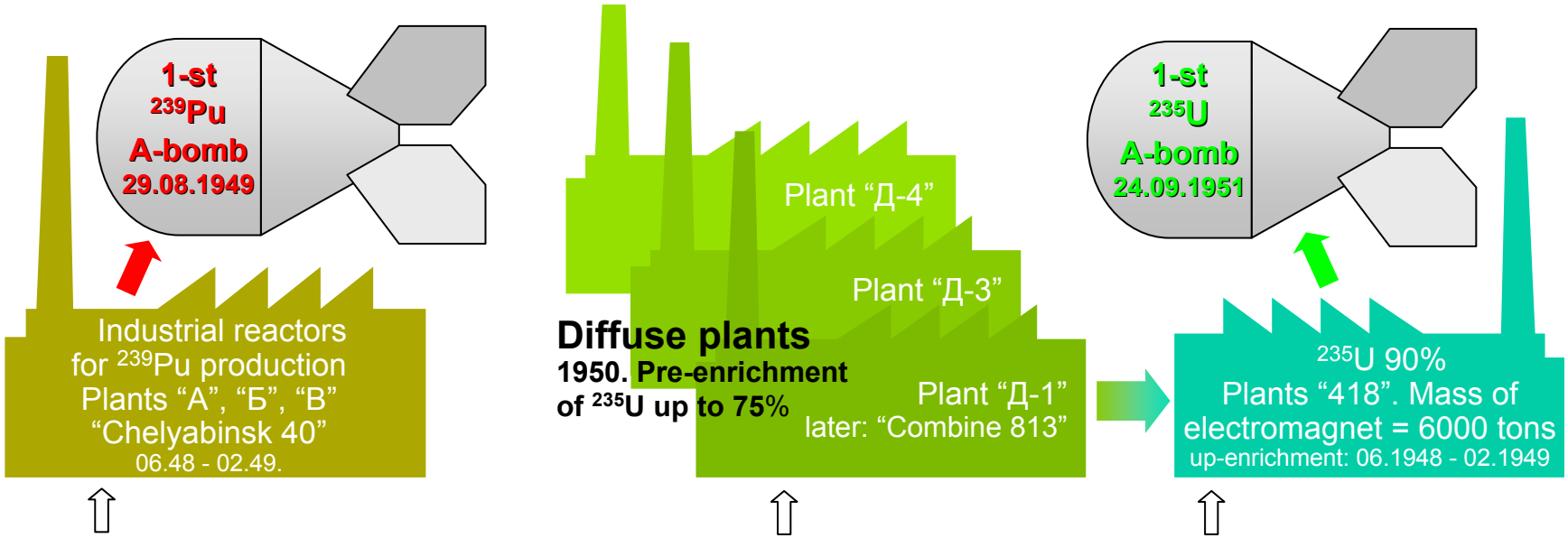
Kurchatov Institute
Surface part of building of the "Φ1" (F1) reactor

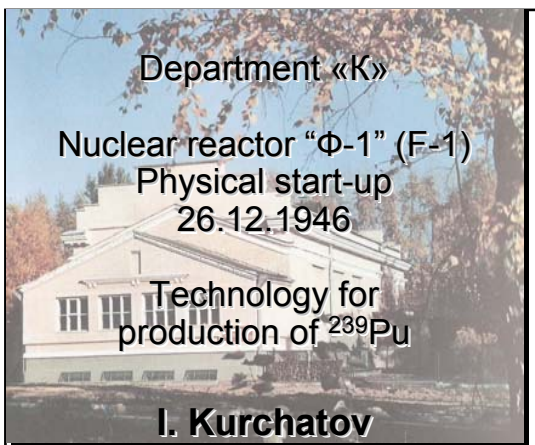
Graphite brick masonry of the reactor "Φ1" (F1)

Diameter of active zone — 6 m
Mass of uranium — 50 тон
Mass of graphite — 500 тон

25.12.46
I. Kurchatov
had actuated
the reactor "Φ1"

Nuclear explosive for the first soviet A-bombs





Lab-scale diffuse cascade 02.1947

Diffuse filters for Plant "D1" (Ni, d=0.7 mm)

20.08.1945
Department «Д»
Technology for
diffuse selection of
^{235}U
I Kikoin,
S. Sobolev

Lab model of electromagnetic separator 1947

1943
Department «А»
Technology for
electromagnetic
selection of ^{235}U

L. Artsimovich

R&D activity — "Laboratory No 2" 04.1943 *It is Kurchatov Institute now* ⇒

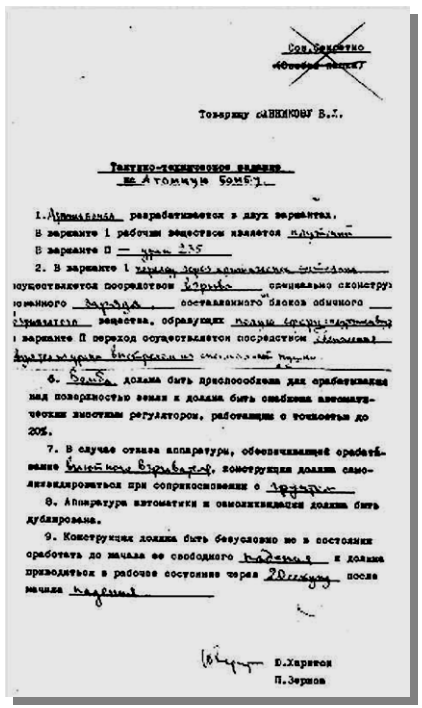
Khariton Julii Borisovich

27.02.1904, St. Peterburg — 18.12.1996, Arzamas
Corresponding member of RAS since 04.12.1946 –
Division of Physical-Mathematical Sciences
Academician of RAS since 23.10.1953 –
Division of Physical-Mathematical Sciences

Scientific head of
Federal Nuclear Center “Arzamas-16”

Chief-designer of nuclear weapon

J. Khariton and the museum model
of the 1-st soviet A-bomb «РДС-1»



Technical requirements
for A-bomb «РДС-1»
signed by J. Khariton

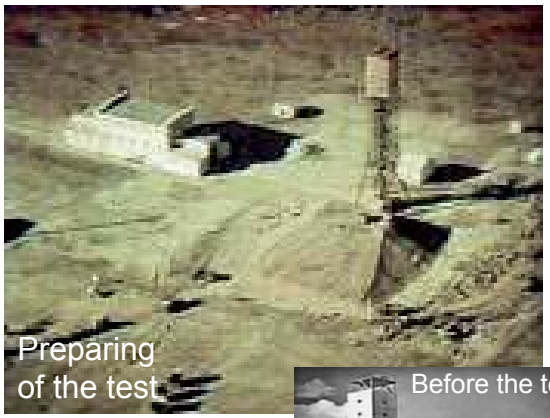
1-st soviet ^{239}Pu A-bomb “РДС-1”, museum model, “Arzamas-16”

Tower used for the test explosion, 37.5 m
Semipalatinsk Nuclear Test Site

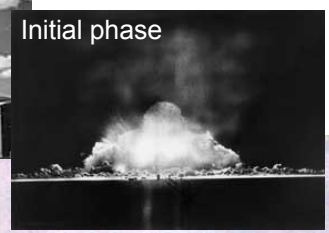
Photo of nuclear explosion made during the 1-st in the USSR test of A-bomb.
August 29, 1949, 07-00. Explosion power - 22 kton of trotyl equivalent.

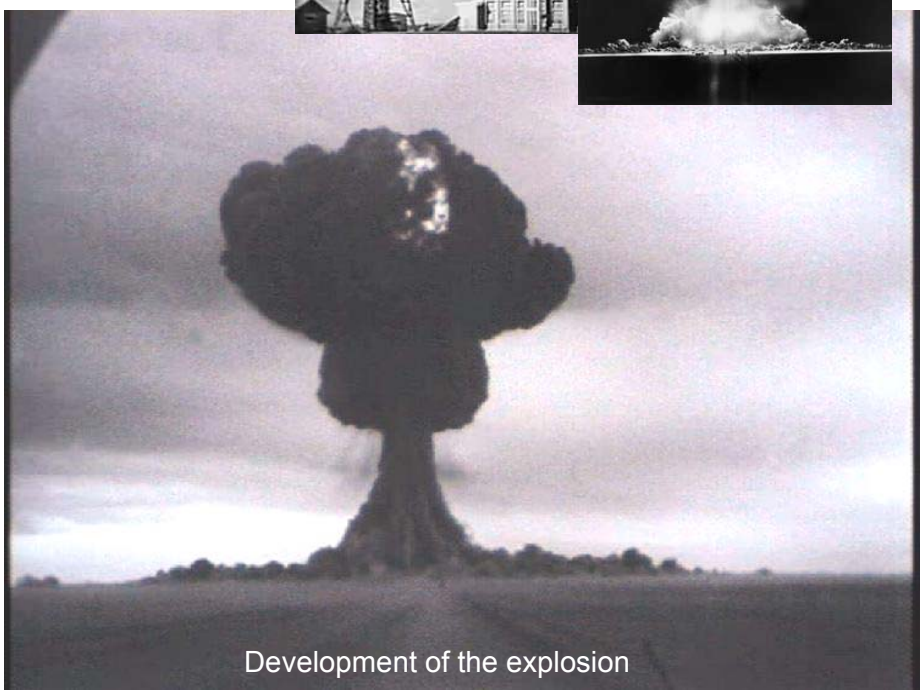
Firsts Soviet Nuclear Tests

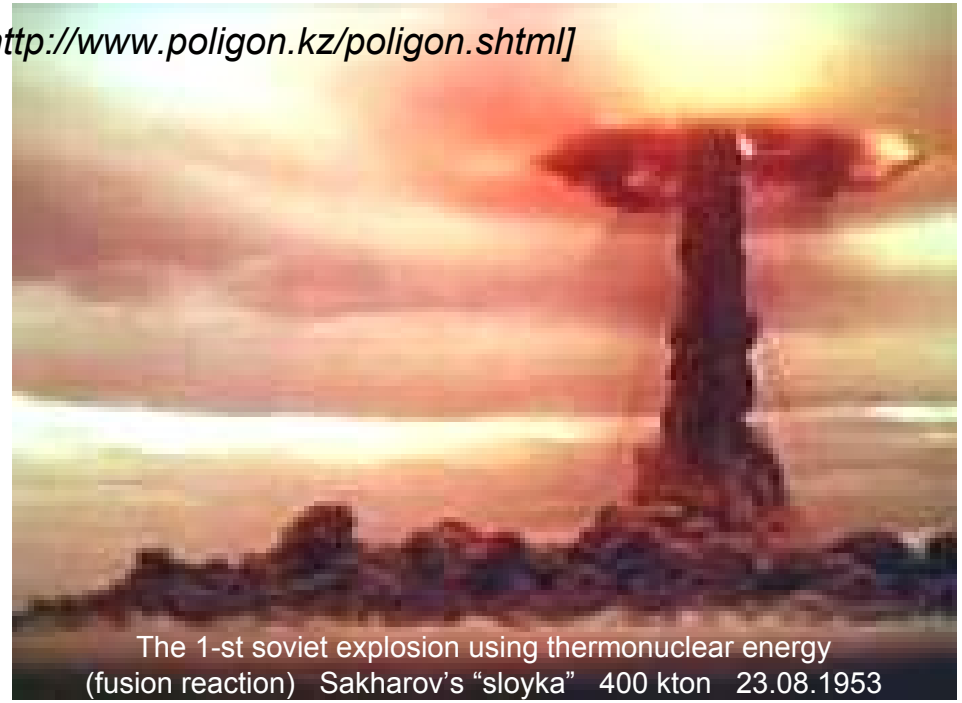
[http://www.poligon.kz/poligon.shtml]



1-st A-bomb
29. 08.1949
^{239}Pu fission
22 kton







Semipalatinsk Site for Nuclear Tests

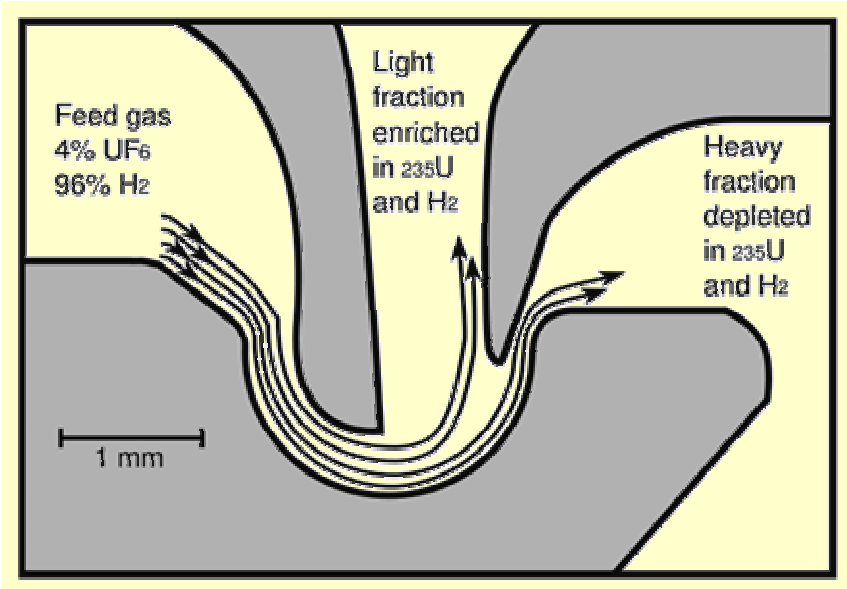
Was founded on August 21, 1947

http://www.poligon.kz/poligon.shtml

Used for nuclear tests till August 29 1992

Air-dynamic selection of isotopes

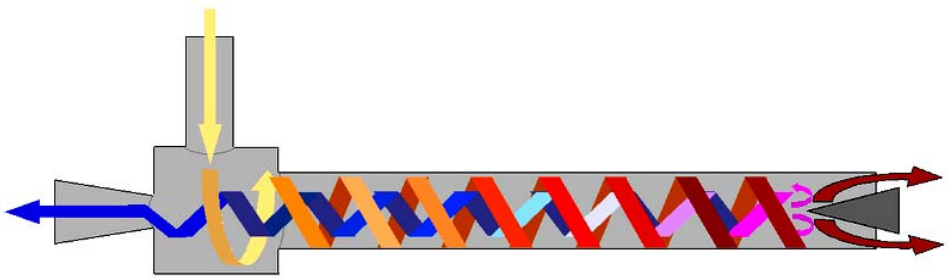
Scheme of air-dynamic separator using **E.W. Becker's jet nozzle** for selection of gases



For pure UF_6 the maximal speed of flow is less than 100 m/s. To increase the speed the UF_6 is diluted by H_2 or He.

Optimal parameters:

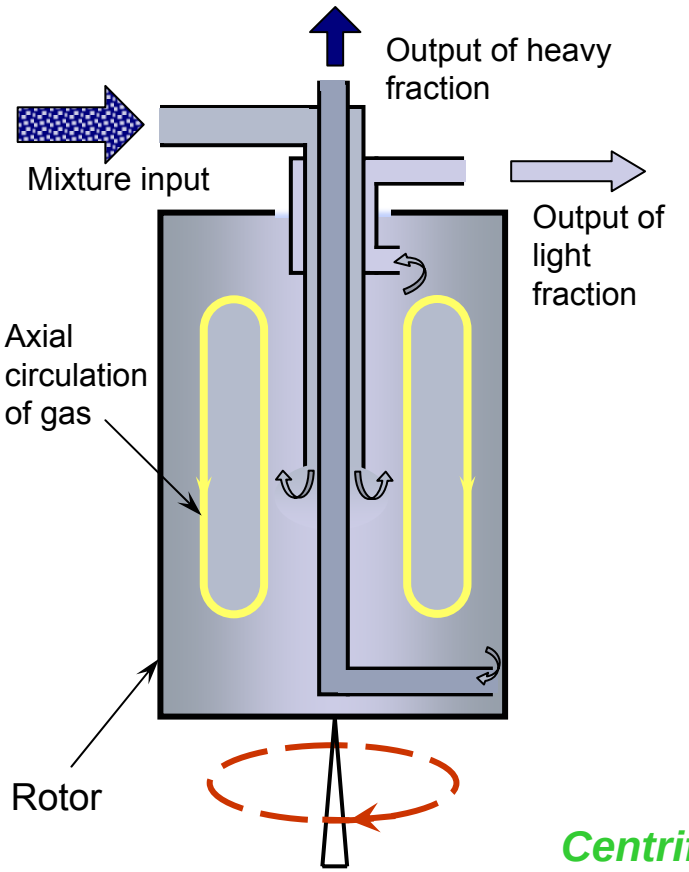
Gas mixture:	*UF_6 (4%) + H_2*
Input pressure	*0,26 bar (26 кПа)*
Factor of expansion	*2,1*
Factor of flow separation	*0,25*
Isotope selection factor	*1,48 10^{-2}*



Ranque-Hilsch vortex tube separates a compressed gas into hot and cold streams

Like the diffusion technology the air-dynamic separators are to be combined into the cascades and to be equipped by the compressors. The processes are not used industrially.

Gas centrifuge for selection of isotopes



Centrifugal acceleration is up to ***500 000 g.***

According to Boltzmann on periphery of a cavity of a rotor gas is enriched with a heavy faction ($^{238}UF_6$), is closer to an axis - easy ($^{235}UF_6$). Factor of separation α_0 *and limit of separation power* δU *of counter-flow centrifuge (by theory of P. Dirac and by the formula of K. Cohen, 1951) are:*

$$\alpha_0 = \exp\left(\frac{\sqrt{2}\,\Delta M v^2}{2RT}\frac{Z}{d}\right), \qquad \delta U = D\rho\left(\frac{\Delta M}{2RT}\right)^2 v^4 Z$$

Z, d — length, diameter of rotor,
v — linear speed of rotor,
D — diffusion quotient of gas,
ρ, T — gas density and temperature

Centrifuge is the most effective gas-dynamic separator:

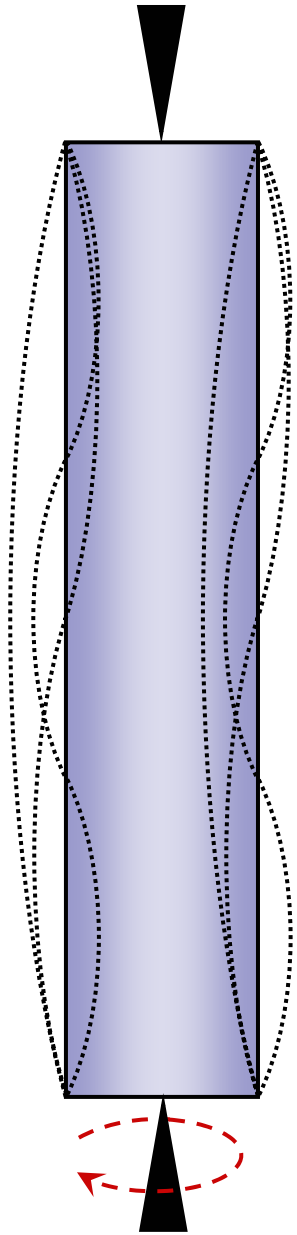
- *Cascade of the centrifuges does not need in compressors. The Pitot pipes for the fractions outputs give an extra-pressure which is enough to transport the gas to the next centrifuges.*
- *The selection effect of the centrifuge depend the* ***absolute*** *molecular mass difference. Thus, it is effective for any heavy elements.*
- *The longer centrifuge, the higher its productivity* ***but ...***

Problem of “critical frequency” of spinning of the centrifuge rotor

*At spinning up of the long rotor of the centrifuge there is a problem of trouble-free passing of resonances, which can take place, if the rotating frequency coincides with a frequency of the own bend oscillations of the rotor. This resonance frequency is called "**critical**".*

"Sub-critical" or "before-critical" centrifuges work at a frequency of rotor spinning being less than the first bending resonance. The rotor length and rotating speed of such a centrifuge have to be limited to avoid the problem.

"Super-critical" or "above-critical" centrifuges rotate with a frequency which is more than the resonance frequency of its oscillations of bend. The resonance problem is overcame by special design means. It is a key "know-how" for successful development of the long centrifuges.



Development of centrifugal technology for selection of isotopes

1895 German phys-chemist **G. Bredig**, (1868 – 1944, foreign correspondent of RAS from 1929) studied possibility selection of gases with different molecular masses by means of a centrifuge.

1919 **Liderman** and **Aston** proposed to use this idea for selection of isotopes. In 30-ths in USA professor **Bims** and his collaborators carried out successfully experiments with the gas centrifuge.

1940 Uranium Committee of the USSR supported a project of **Lange** (Khar'kov, Ukraine) on creation of the horizontal centrifuge for selection of uranium isotopes.

1941 German scientists **Martin** and **Kun** showed theoretically good perspectives for using of the counter-flow centrifuge.

1951 Formula of **Kohen** for the centrifuge.

1946-54 **Zippe, Steenbeck** (1904 – 1981, foreign correspondent member of RAS from 1966) , **Sinev, Artsimovich** (sci. leader), **Kamenev** had created the vertical centrifuge with short hard rotor (of sub-critical type).

Development of centrifugal technology for selection of isotopes

1958 ***Zippe***, ***Steenbeck***, *and* ***Shiffel*** *after their leaving from the USSR had patented (No 10715997 of 11.11.1957, USA, GB, FRG, Netherlands, …) a design of a gas centrifuge which is very similar to design that was developed in Russia with their participation. The USSR had not challenged the priority owing to privacy.*

From 1953 *the USSR developed (I. Kikoin — scientific head) industrial cascades of centrifuge for enrichment of the ^{235}U. Later the short sub-critical centrifuges replaced diffusion machines.*

1962-64 *In the USSR the first centrifugal plant for ^{235}U enrichment started to work.*

1970 *International consortium "URENCO" (**Ur**anium **En**richment **Co**mpany) was founded by GB, Netherlands, and FRG. The first cascades were equipped by short centrifuges of the type patented by Zippe and colleagues.*

Now *"URENCO" uses long overcritical centrifuges. Russia exploits short subcritical centrifuges which has been well advanced to be effective economically and extremely reliable — their recourse exceeds 20 years.*

Ural Electrochemical Integrated Plant

Panorama of a module of centrifugal manufacture for stable isotope selection


Centrifuge


cascades of URENCO


Jalanise centrifuges


Centrifuges of USA

World industry for production of low enriched uranium

Productivities of plants[1] in millions of Kilogram Separative Work Unit[2]

State	*Firm*	*Technology*	*2001[3]*	*2005*
USA	USEC	Diffusion	19.20	19.20
France	Consortium Eurodif	Diffusion	10.80	10.80
Grate Britain	Consortium Urenco	Centrifuge	2.00	2.10
Germany	Consortium Urenco	Centrifuge	1.30	1.80
Netherlands	Consortium Urenco	Centrifuge	1.50	1.50
Japan	Firm JNFL	Centrifuge	1.05	1.05
Brazil	Institute IPEN	Centrifuge	0.10	0.10
China	Corporation CNEIC	Diffusion	0.60	0.60
China	Corporation CNEIC	Centrifuge	1.00	1.50
Russia	Rosatom	Centrifuge	14.00	14.00
Plants of Argentine (0.02 millions of kg SW) and South African Republic (0.3 millions of kg SW) were stopped in 1994 and 1995 accordingly				
Total			**51.55[3]**	**52.65**

1) *Main produsers.*

2) *Kilogram Separative Work Unit measures the quantity of separative work (indicative of energy used in enrichment) when feed and product quantities are expressed in kilograms. SWUs, kg SW, or kg UTA (from the German Urantrennarbeit). Starting with 100 kilograms of natural uranium, it takes about 60 kg SW to produce 10 kilograms of uranium enriched in U-235 content to 4.5%.*

3) *In fact, total used capacity is ≈8 millions of kg SW.*

Physical-chemical selection of isotopes

The most usable processes are:

RECTIFICATION
ISOTOPE EXCHANGE

These methods for isotope production are researched and developed in the Mendeleyev University of Chemical Technology of Russia, Moscow, http://www.muctr.ru/

The technology is used for industrial production isotopes of light elements:

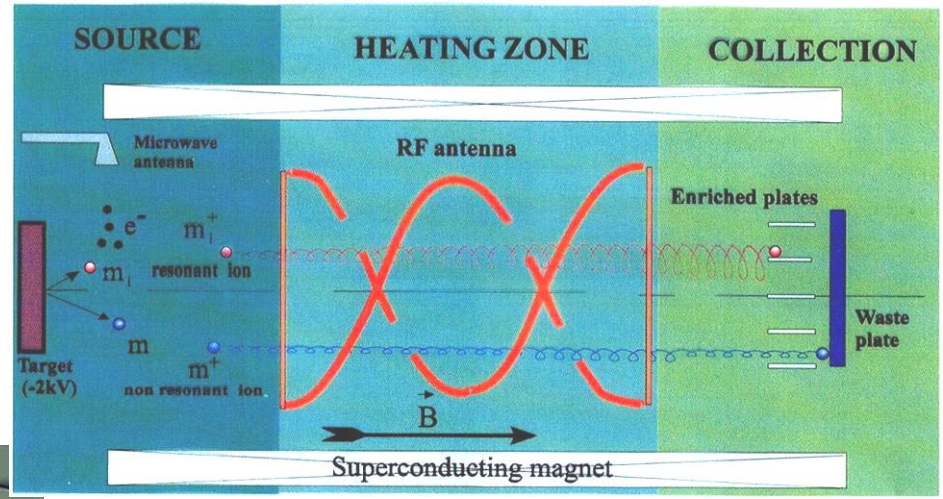
H, Li, B, C, N, O, ...

Tower with rectification columns for enrichment of ^{13}C

INSTITUTE OF MOLECULAR PHYSICS OF KURCHATOV INSTITUTE

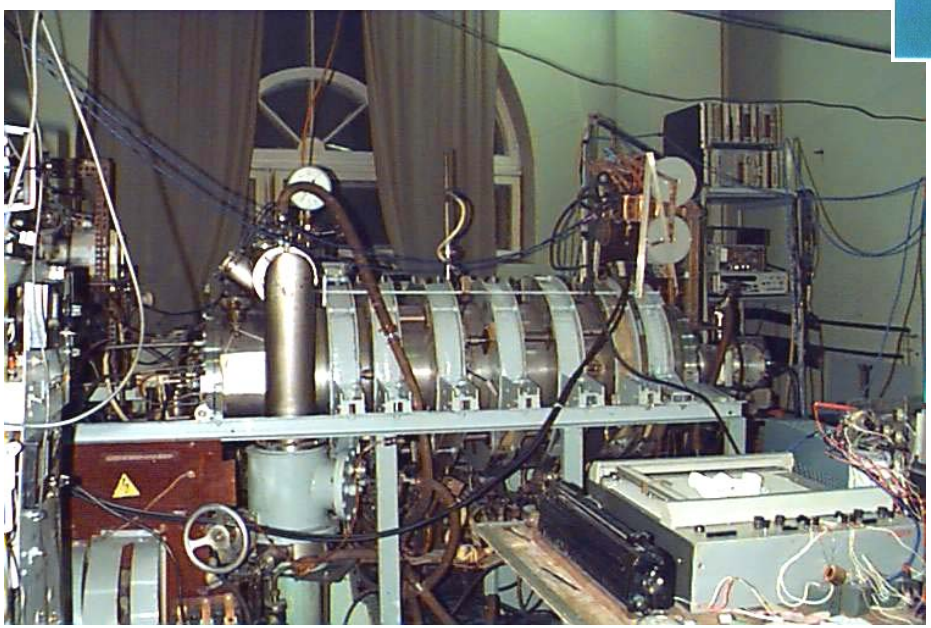
Ion cyclotron resonance (ICR) for selection of isotopes

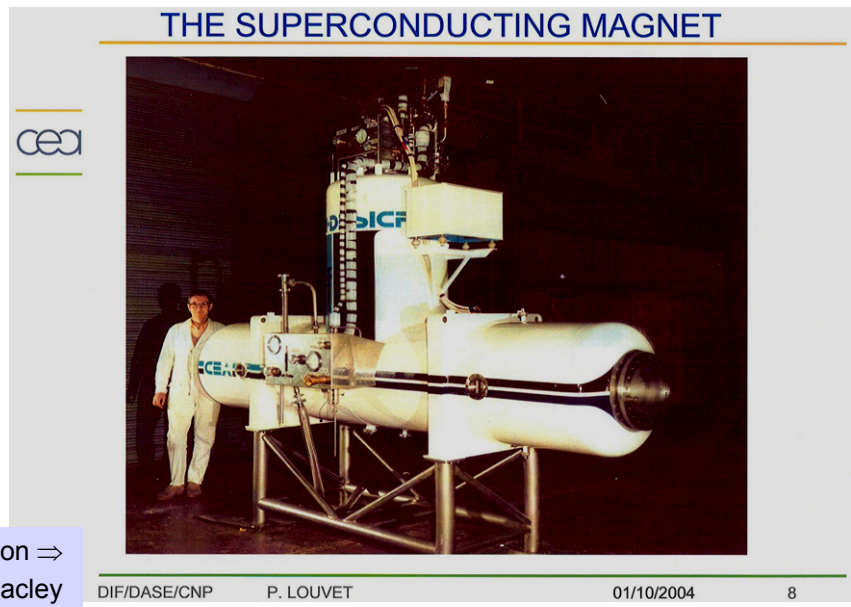
Scheme of the ICR separator ⇒



State, Institution	*Target isotopes of elements*
Russia, Kurchatov Institute (R&D)	***Gd, Nd, U, ...***
USA, Oak Ridge National Laboratory	***Pd, ...***
France, Centre d'Estudes de Sacley (R&D)	***U, Gd, Nd, ...***

"Sirena" ICR lab separator for selection of Li isotopes Institute of Molecular Physics, Kurchatov Institute ⇓

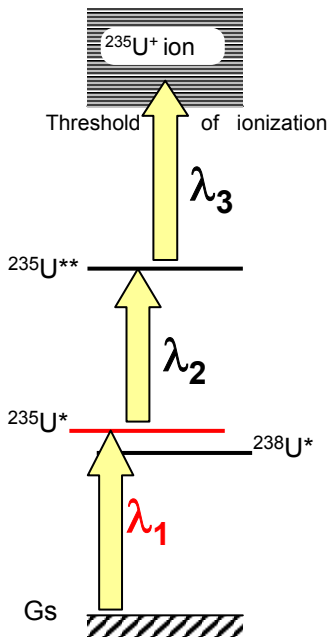




Part of ICR installation ⇒
Departement des Pocedes d'Enrichissement, Centre d'Etudes de Sacley

Laser (optical) methods for selection of isotopes

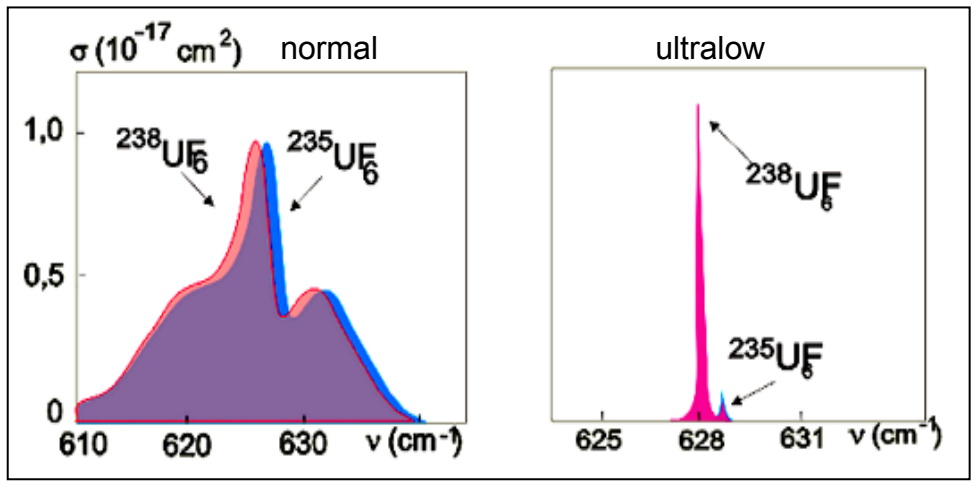
AVLIS *— **a**tom **v**apor **l**aser **i**sotope **s**election based on selective poly-photon ionization of atomic vapor*



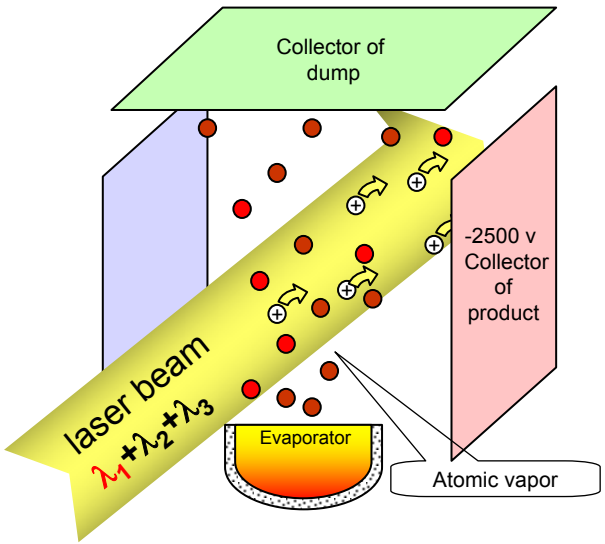
Energy scheme of a variant of selective photo-ionization of ^{235}U: 3 photons are used consistently for the ionization

MLIS *— **m**olecular **l**aser **i**sotope **s**election based on selective excitation of molecules by photons. The process is followed by essential difference of reactionary capability excited and not excited molecules.*

Absorption spectra of UF_6 at temperatures



AVLIS-setup for isotope separation of Kurchatov Institute



Principle of AVLIS selector

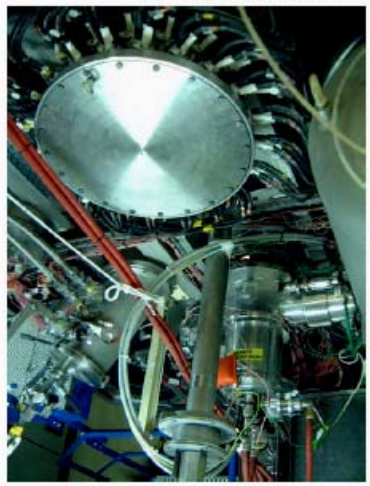
SILVA/AVLIS Project in France

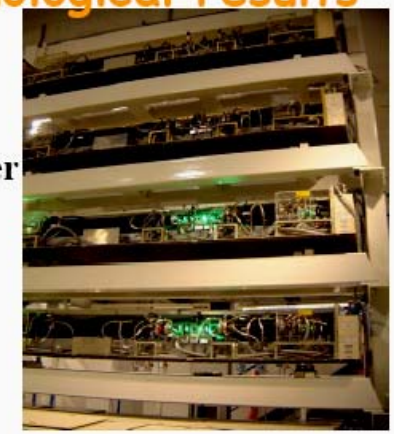
by presentation of
Serge JULLIAN
jullian@lal.in2p3.fr
for ILIAS Annual Meeting
Chambéry, February 27, 2007

Menphis experiment technological results

LASER :

- ≥ 600 hours for each CVL
- 170 hours for dye laser at full power

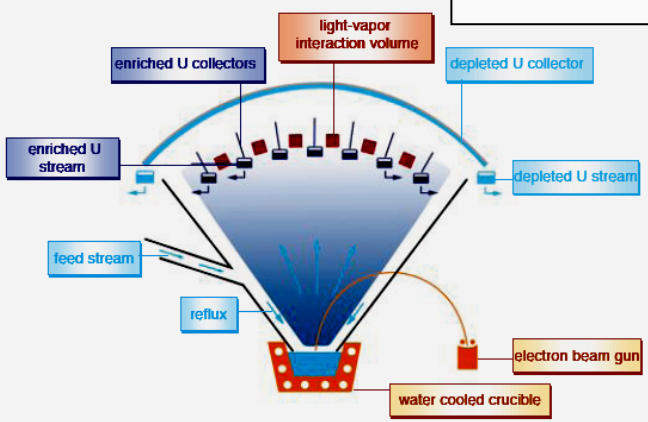




SEPARATOR :

- Several hundred hours at the operational temperature and extractor voltage without significant failures nor material damages
- Long time evaporation

Basics of the SILVA/AVLIS

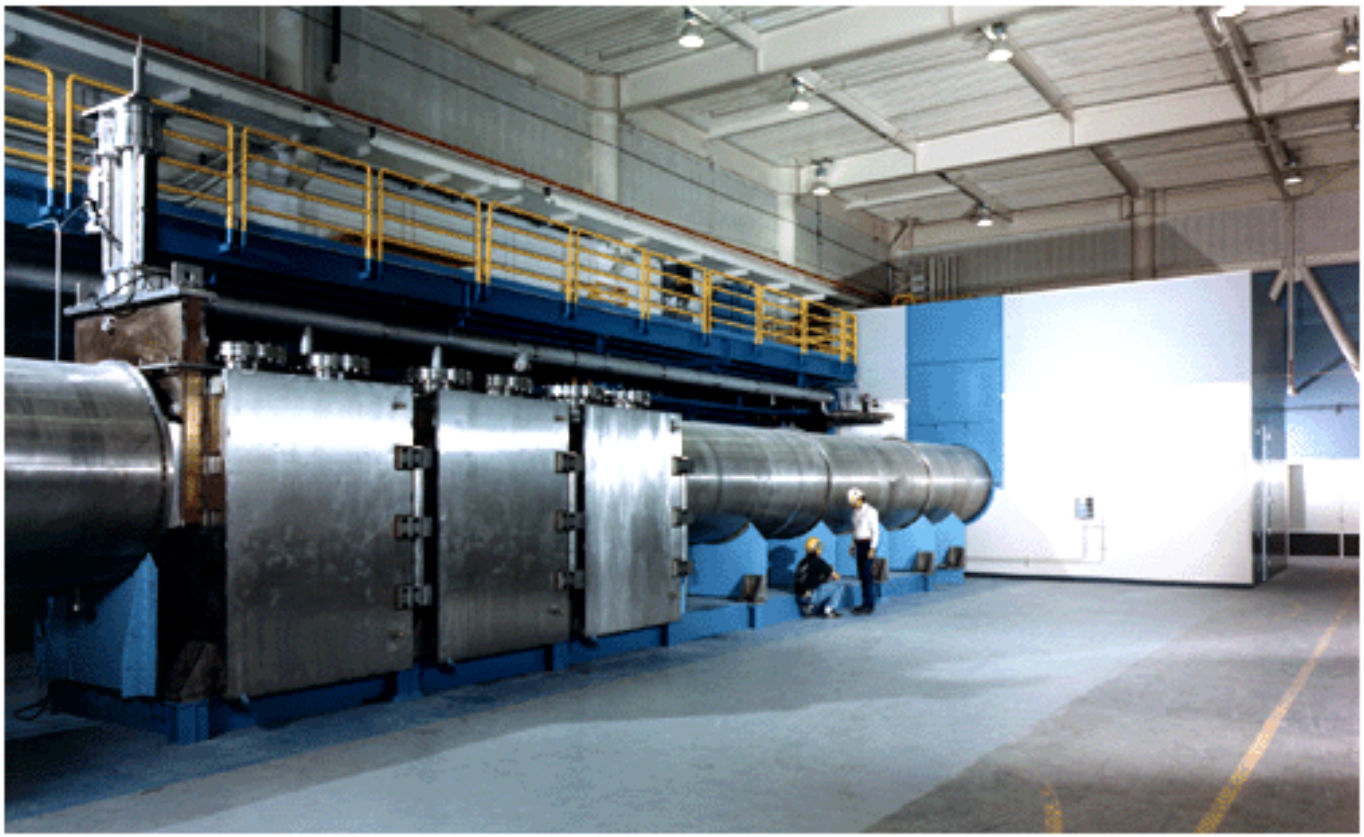


Future of MENPHIS ?

R&D to design the operation of the set-up to enrich Nd (Zr ? to be confirmed)

Large device which must be operated by a professional team

AVLIS equipment in LLNL



The separator demonstration facility at Lawrence Livermore's laser isotope separation (LIS) pilot plant tested full-scale equipment. One of three separator units shown for enriching uranium was operational for demonstrations. Also visible are beam tubes for transporting precisely tuned laser light to the separator units.

MLIS plant for selection of isotopes of carbon

KALININGRAD
Russia

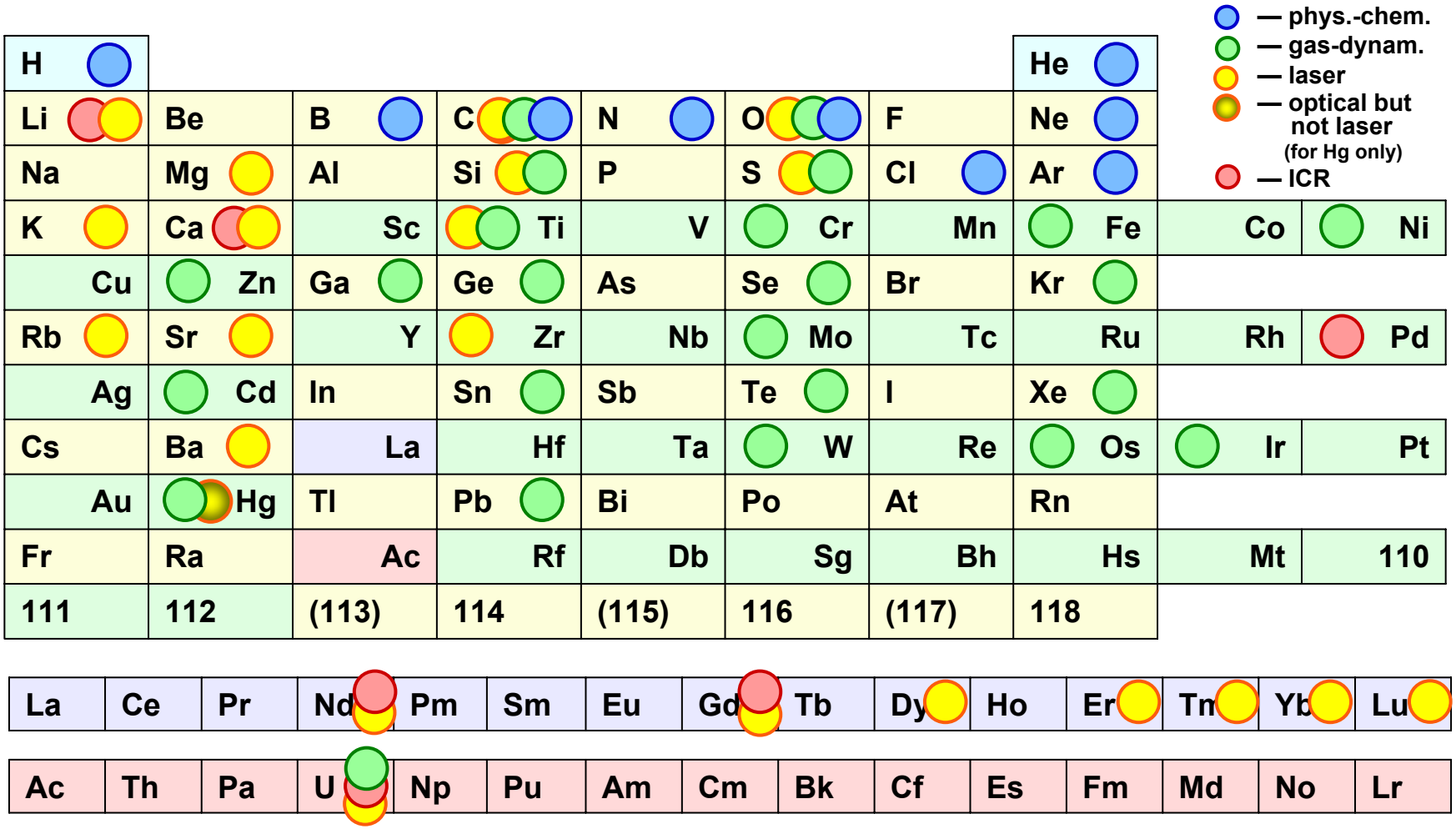
The equipment was developed by TRINITY
http://www.triniti.ru/
at a support of Gazprom

Productivity	**15 kg/y ^{13}C 30÷50%**
	150 kg/y ^{12}C 99,99%
CO_2 Lasers:	
Frequency	**600 Hz**
Pulse Energy	**3 J**
Pulse Duration	**~ 200 ns**
Wave Length	**9,4÷10,8 μm**
Gas mixture	**CO_2:N_2:He (1:1:4)**
Power supply	**20 kWt**

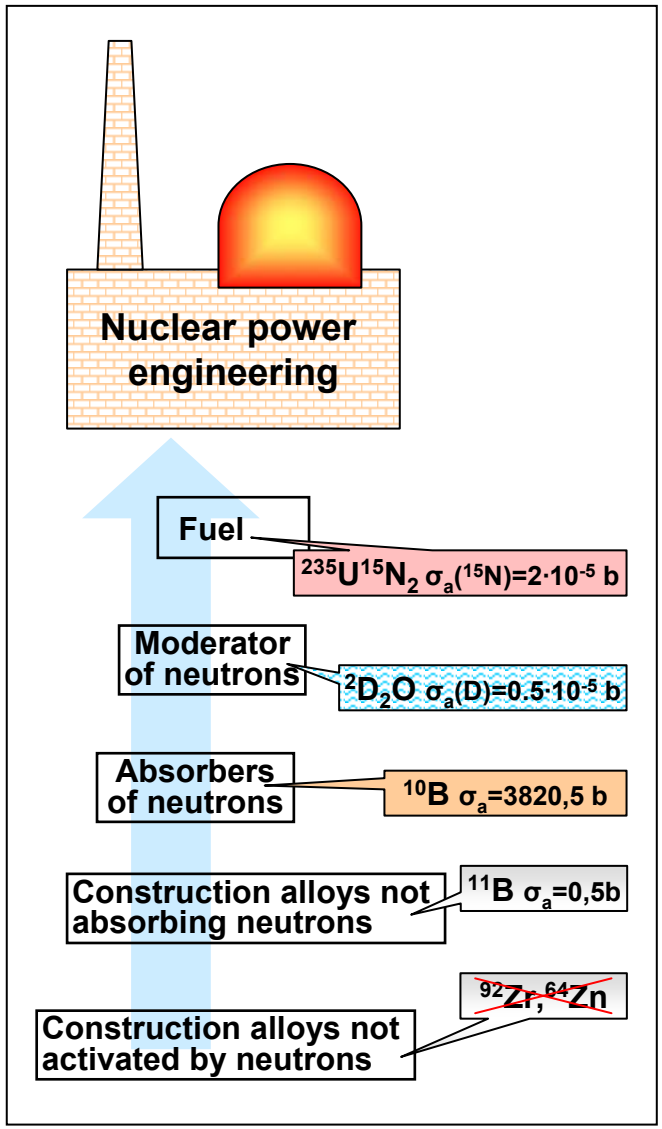
Comparison of methods for selection of stable isotopes

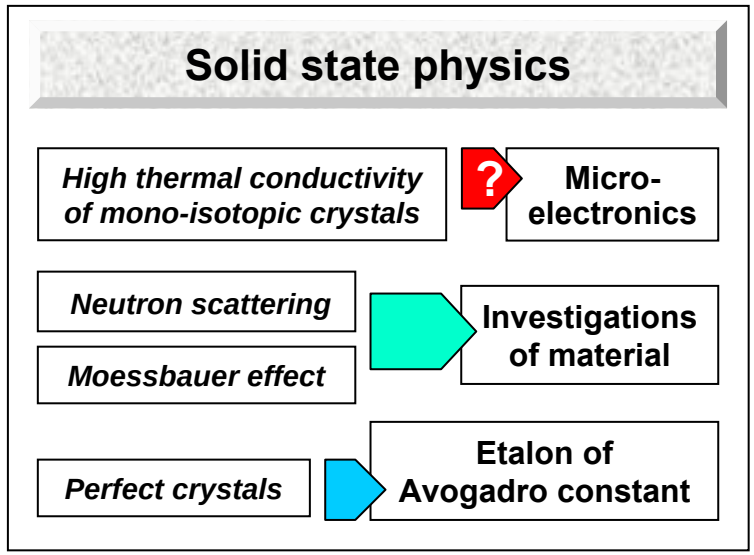
Method of selection	*Energy, eV/atom*	*Status*	*Productivity scale or capacity of prototype*	*Scale of price (approximately)*	*Special requirements*
Electromagnetic (mass-spectrometric)	$10^{6\div7}$	Commercial	Tens of g per year	10÷100 $/mg	—
Gas diffusion	$3\cdot10^{6}$	Industrial	> tons per year	200 $/kg (4.5% U)	Gas compound
Gas nozzle	10^{6}	Industrial	> tons per year	200 $/kg (4.5% U)	Gas compound
Gas centrifuge	$3\cdot10^{5}$	Industrial	> tons per year	200 $/kg (4.5% U)	Gas compound
Rectification	10^{3}	Industrial	> tons per year	100 $/kg	Light elements
Isotope exchange	10^{2}	Industrial	> tons per year	100 $/kg	Light elements
ICR	10^{3}	R&D	10 kg per year	?	—
AVLIS/SILVA, laser efficiency ≈10%	10^{2}	R&D	10 kg per year	?	—
MLIS, laser efficiency ≈10%	10^{2}	R&D	10 kg per year	?	—

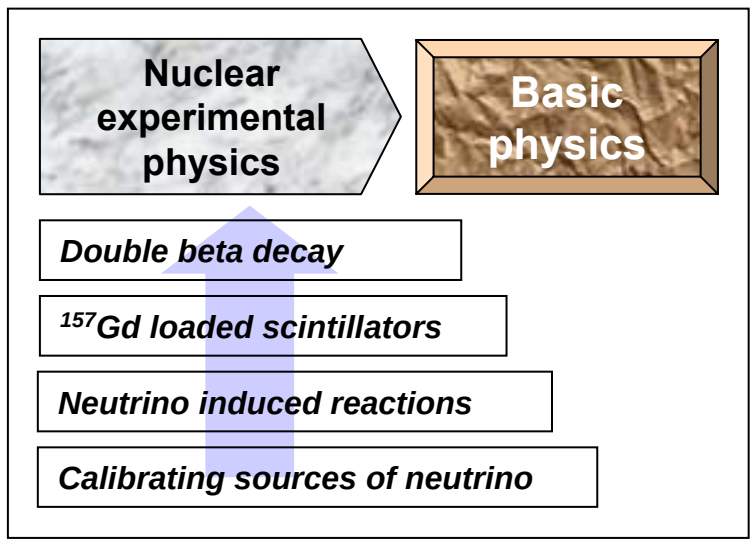
Methods for selection of stable isotope of elements



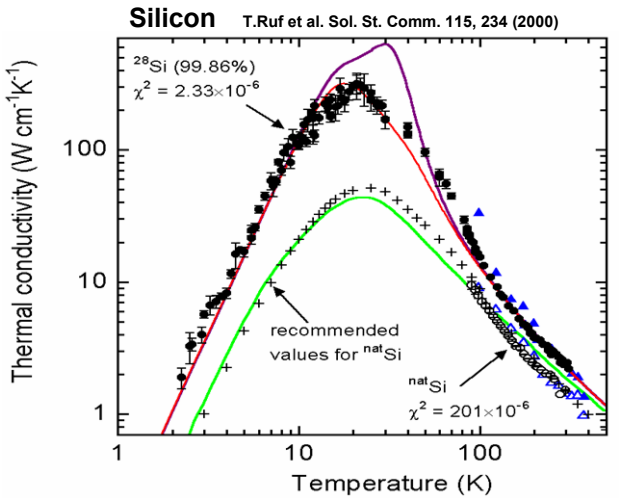
Some fields of applications of stable isotopes

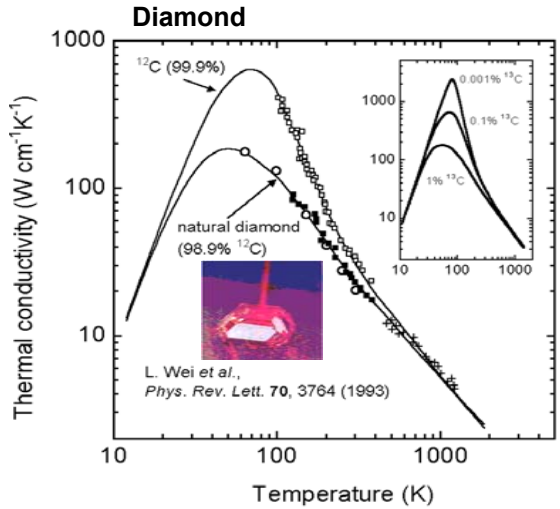


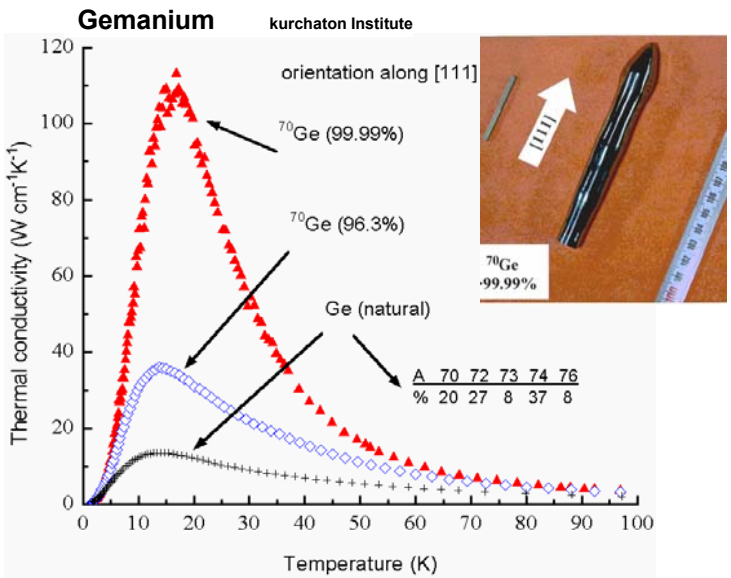


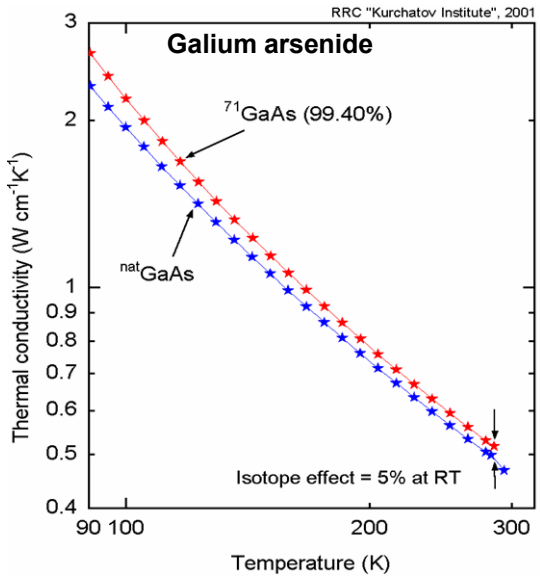


Temperature dependence of thermal conductivity of isotopically enriched crystals









International Avogadro constant project — measuring isotope ratios of silicon

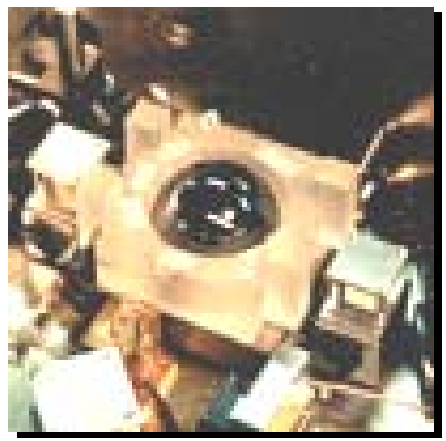
http://www.irmm.jrc.be/html/activities/international_Avogadro_constant_project/index.htm:

*"The kilogram is the only remaining base **Si** unit defined by a man-made artefact. For many years now research groups have been trying to find a way to define it in a more independent and easily reproducible manner, like the other units. An international cooperation is focussing on a solution based on determining the Avogadro constant.*

The Avogadro constant can be determined via the mass of a specified number of atoms. If the uncertainty on the Avogadro constant is sufficiently small, this definition can be inverted to define the mass - the unit kg - via a known number of particles.

The approach chosen involves measurements of the dimensions, lattice parameters, mass and isotopic composition of single crystals of silicon, one of the purest materials available.

IRMM can determine the isotopic composition of silicon with the accuracy and precision required, and is at the moment the only laboratory in the world able to conduct such measurements."



A silicon single crystal.

Becker, P., Bettin, H., Danzebrink, H., Gläser, M., Kuetgens, U., Nicolaus, A., Schiel, D., De Biévre, P., Valkiers, S., Taylor , P., Determination of the Avogadro constant via the silicon route, Metrologia **40** (2003)5 271-287

Fujii, K., Waseda, A., Kuramoto, N., Mizushima, S., Tanaka, M., Valkiers, S., Taylor, P., Kessel, R., De Bièvre, P., Evaluation of the molar volume of silicon crystals for a determination of the Avogadro constant, IEEE Transactions on Instrumentation and Measurement **52** (2003)2 646-651

Allowed $2\beta^-$ и $2\beta^+$ transitions of nuclei

Transition	Abundance, %	Q, keV	Transition	Abundance, %	Q, keV
$2\beta^-$			$^{142}Ce \rightarrow ^{142}Nd$	11,1	1414
$^{46}Ca \rightarrow ^{46}Ti$	0,0035	985	$^{146}Nd \rightarrow ^{146}Sm$	17,2	61
$^{48}Ca \rightarrow ^{48}Ti$	0,187	4272	$^{148}Nd \rightarrow ^{148}Sm$	5,7	1928
$^{70}Zn \rightarrow ^{70}Ge$	0,62	1001	$^{150}Nd \rightarrow ^{150}Sm$	5,6	3367
$^{76}Ge \rightarrow ^{76}Se$	7,8	2045	$^{154}Sm \rightarrow ^{154}Gd$	22,6	1250
$^{80}Se \rightarrow ^{80}Kr$	49,8	136	$^{160}Gd \rightarrow ^{160}Dy$	21,8	1731
$^{82}Se \rightarrow ^{82}Kr$	9,2	3005	$^{170}Er \rightarrow ^{170}Yb$	14,9	655
$^{86}Kr \rightarrow ^{86}Sr$	17,3	1249	$^{176}Yb \rightarrow ^{176}Hf$	12,6	1077
$^{94}Zr \rightarrow ^{94}Mo$	17,4	1148	$^{186}W \rightarrow ^{186}Os$	28,6	489
$^{96}Zr \rightarrow ^{96}Mo$	2,8	3350	$^{192}Os \rightarrow ^{192}Pt$	41,0	408
$^{98}Mo \rightarrow ^{98}Ru$	24,1	111	$^{198}Pt \rightarrow ^{198}Hg$	7,2	1043
$^{100}Mo \rightarrow ^{100}Ru$ *)	9,6	3033	$^{204}Hg \rightarrow ^{204}Pb$	6,9	414
$^{104}Ru \rightarrow ^{104}Pd$	18,7	1301	$^{232}Th \rightarrow ^{232}U$	100	850
$^{110}Pd \rightarrow ^{110}Cd$	11,8	2014	$^{238}U \rightarrow ^{238}Pu$	99,275	1146
$^{114}Cd \rightarrow ^{114}Sn$	28,7	540	$2\beta^+$		
$^{116}Cd \rightarrow ^{116}Sn$	7,5	2808			
$^{122}Sn \rightarrow ^{122}Te$	4,56	358	$^{78}Kr \rightarrow ^{78}Se$	0,356	838
$^{124}Sn \rightarrow ^{124}Te$	5,64	2278	$^{96}Ru \rightarrow ^{96}Mo$	5,5	676
$^{128}Te \rightarrow ^{128}Xe$	31,7	869	$^{106}Cd \rightarrow ^{106}Pd$	1,26	738
$^{130}Te \rightarrow ^{130}Xe$	34,5	2533	$^{124}Xe \rightarrow ^{124}Te$	0,096	1024
$^{134}Xe \rightarrow ^{134}Ba$	10,4	843	$^{130}Ba \rightarrow ^{130}Xe$	0,106	534
$^{136}Xe \rightarrow ^{136}Ba$	8,9	2481	$^{136}Ce \rightarrow ^{136}Ba$	0,190	362

*) The ν-induced 2β decay of ^{100}Mo was proposed to detect neutrino of energy >168 keV:

$$\nu_e + {}^{100}\mathrm{Mo} \rightarrow e^- + {}^{100}\mathrm{Tc} \xrightarrow{\beta^-\ 16\ c} {}^{100}\mathrm{Ru} + e^- + \bar{\nu}_e$$

L.V. Inzhechik, Yu.V. Gaponov, S.V. Semenov. Izv. RAN, ser. fiz. v. 64, p. 38, 2000
H. Ejiri et al. Phys. Rev Lett. v 85, p. 2917, 2000

Be successful, using isotopes in your experiments!