Stable Isotope Enrichment

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May 2025

01 Introduction

Introduction: Isotopes

The isotopes of one element is an atom with the same number of protons but a different number of neutrons

Number of protons and neutrons

Chemical symbol of element

$$^{A}_{Z}X_{N}$$

Number of protons
Same number for an element

Number of neutrons
Different number for each isotops of an element

Example of isotope of natural He:

$^{3}_{1}He_{2}$ 0,000137%

$^{4}_{2}He_{2}$ 99,999863%

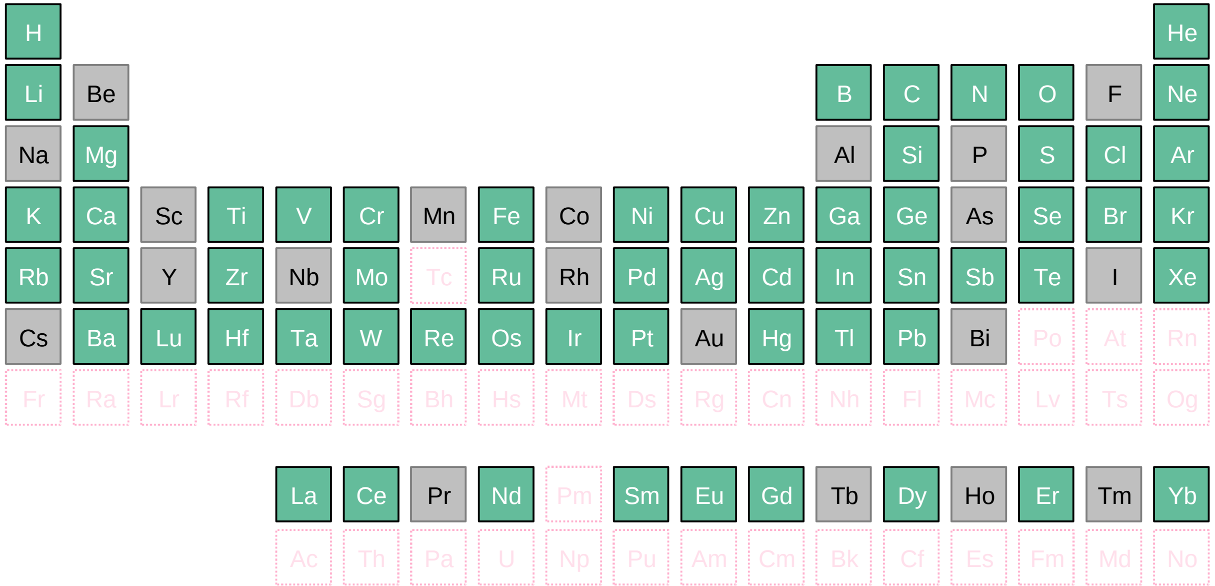
Nuclear properties very different

Chemical properties close

01

Introduction: Stable Isotopes

In this presentation, ‘Stable Isotopes’ means isotopes without spontaneously undergo radioactive decay or quasi-stable isotopes (e.g. isotopes with a very long decay like 136Xe with a half-life of 2.36×10^{21}yr)



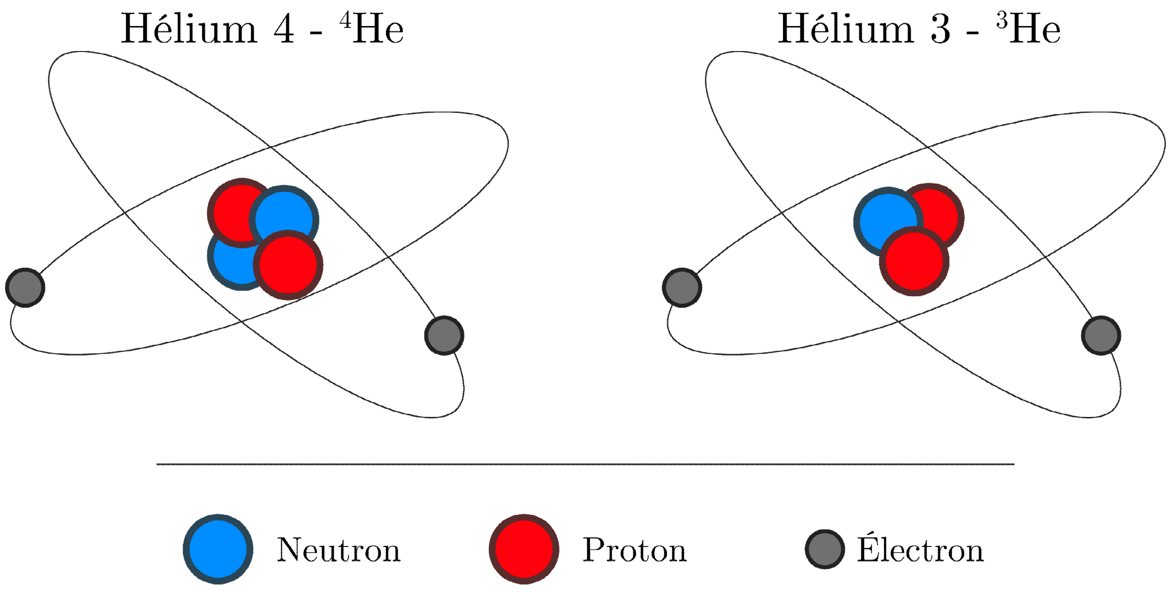
XX 61 stables elements (including quasi-stable elements) with several isotopes in the natural element

XX 19 stables elements (including quasi-stable elements) with only one isotope in the natural element

XX Other elements

Introduction: Difference between isotopes of an element

There are two main differences: the mass and the repartition



Difference of mass

- Difference of frequency
- Difference of velocity
- Difference of abondance due to acceleration
- Difference of trajectory in a magnetic field
- ….

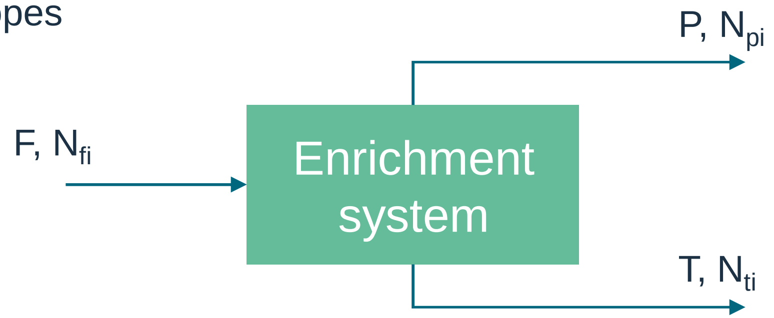
Difference of repartition

- Nuclear spin:
  - Cinetic moment
  - Magnetic moment

Introduction: Enrichment

The enrichment is characterized by the enrichment and depletion coefficients and the cut

Element with i isotopes



$F = P + T$

$F.N_{fi} = P.N_{pi} + T.N_{ti}$

Molecular abondance $R_{xi0} = \frac{N_{xi}}{N_{x0}} \ /0 \in [1;i] \ /x \in \{f,p,t\}$

Enrichment coefficient $\alpha_{0i} = \frac{R_{pi0}}{R_{fi0}} \ /0 \in [1;i]$

Depletion coefficient $\beta_{0i} = \frac{R_{ti0}}{R_{fi0}} \ /0 \in [1;i]$

Cut $\theta = \frac{P}{F}$

For an element with two isotopes:

$F = P + T$

$F.N_f = P.N_p + T.N_t$

$R_x = \frac{N_x}{1-N_x} \ /x \in \{f,p,t\}$

$\alpha = \frac{R_p}{R_f}$

$\beta = \frac{R_t}{R_f}$

$\theta = \frac{P}{F}$

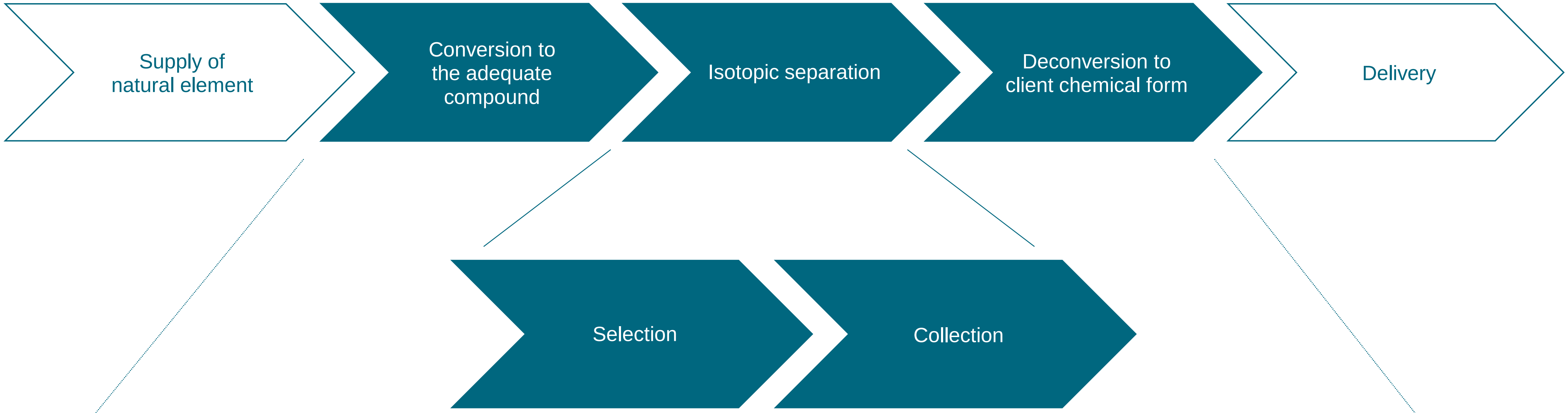
$\Delta U = P.V(N_p) + T.V(N_T) - F.V(N_F)$

$with\ V(N_x) = (1 - 2.N_x).\ln(\frac{1-N_x}{N_x})$

Introduction: Enrichment means use of the difference to change the abondance of isotopes in an element

Difference of relative mass	Physical-chemical selection / Electrochemical process
Difference of trajectory in a magnetic field	Electromagnetic separation of ionized isotopes / Magnetic resonance method
Difference of frequency	Optical method of separation (transition frequency)
Difference of velocity	Gas diffusion method of separation
Difference of abondance due to acceleration	Centrifuge method of separation and other aerodynamic process

01 Introduction: 5 different phases of enrichment



Find a good compound:

- Good isotopic spectrum
- Good chemical et physical behaviour to allow enrichment

The easy part of isotopic separation

The difficult part of isotopic speration especially at industrial scale

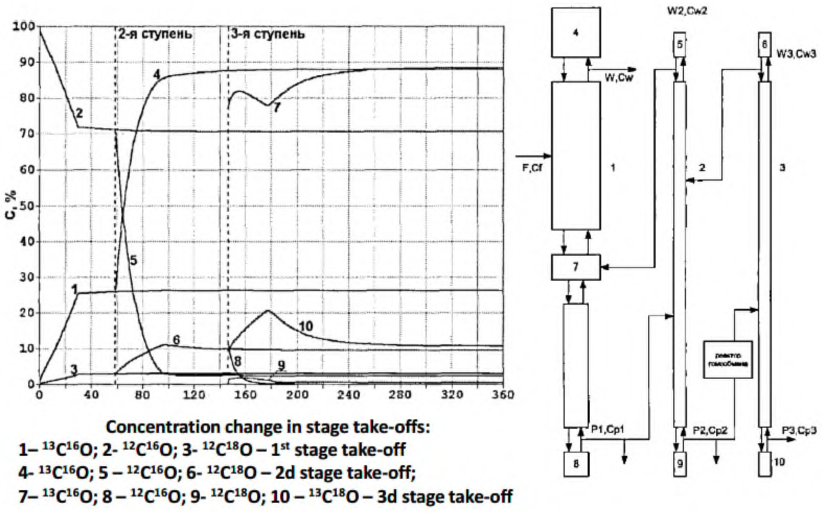
Do not decrease the isotopic purity (especially for very high assay)

02 Enrichment methods

Physical-chemical selection / Electrochemical process: Rectification

Rectification	
Process	Selection effect depend on the relative difference of molecular mass: it's effective for light mass elements like C, Na and O,
TRL	9 (working for light element)
Alpha	α < 1,05
Flow	High
Hold-up	High
Electrical consumption	Low
Equilibrium time	Long (months)

Cambridge Isotope laboratory



Example of the rectification column at Kurchatov institute

Physical-chemical selection / Electrochemical process: Other electrochemical processes – *slight difference between redox equilibrium constant*

COLEX	
Process	Electrochemical exchange between LiOH and Hg amalgam
TRL	9 (working for Li)
Alpha	α ~ 1,005
Flow	High
Hold-up	High
Electrical consumption	Low
Equilibrium time	Long (months)

CHEMEX	
Process	UIII in HCL and UIV in solvant
TRL	7
Alpha	α < 1,005
Flow	High
Hold-up	High
Electrical consumption	Low
Equilibrium time	Long (months)

Ion-exchange resin	
Process	Solid-liquid ion-exchange process on ion-exchange resin (eg ASAHI process)
TRL	9
Alpha	α << 1,005
Flow	High
Hold-up	High
Electrical consumption	Low
Equilibrium time	Long (months)

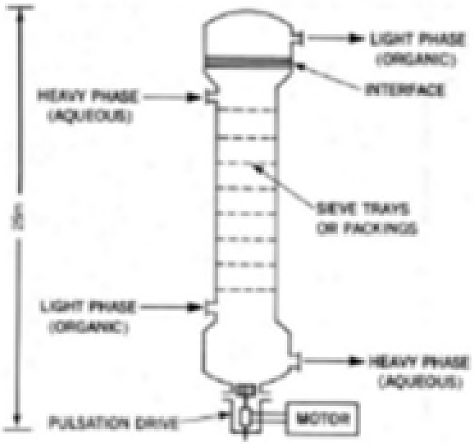


Figure 10. Chemical exchange process.

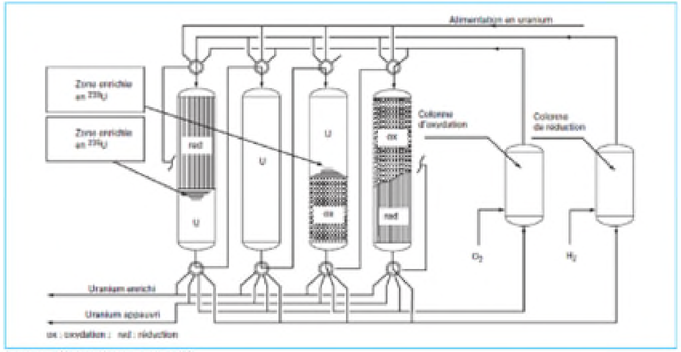
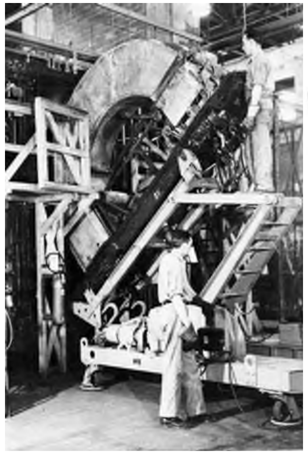


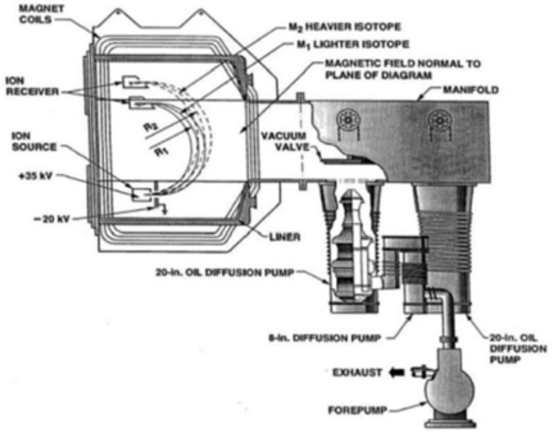
Figure 22 – Module d'échange d'ions [27]

Magnetic processes

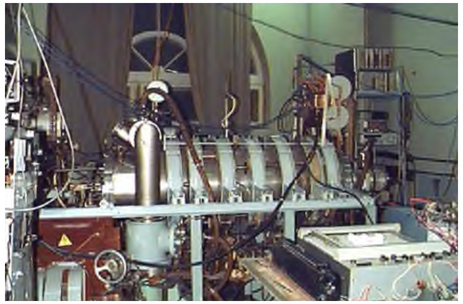
Calutron - EMIS	
Process	Ionization and deviation in a magnetic field
TRL	9 (working for many stable isotopes)
Alpha	α ~ 30
Flow	Very low
Hold-up	Very low
Electrical consumption	Very high
Equilibrium time	Very short

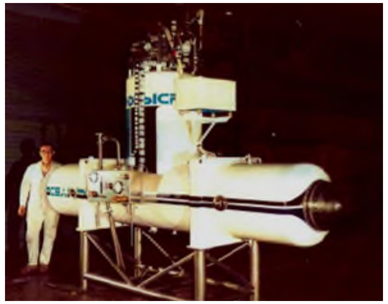
$$\Delta d \propto \frac{\Delta M}{M}$$

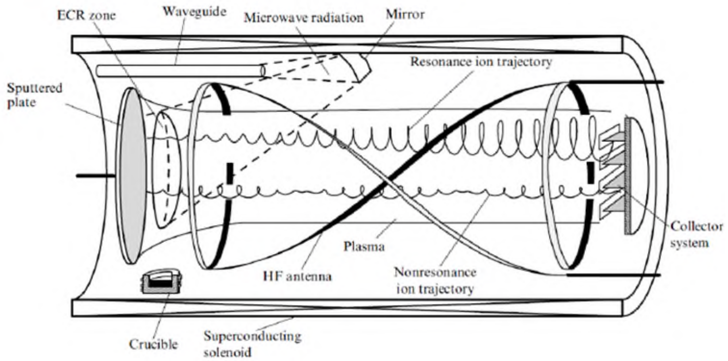




Ion Cyclotron resonance (ICR)	
Process	Ionization and deviation in an oscillating magnetic field
TRL	9
Alpha	α ~ 10
Flow	Very low
Hold-up	Very low
Electrical consumption	Low
Equilibrium time	Very short





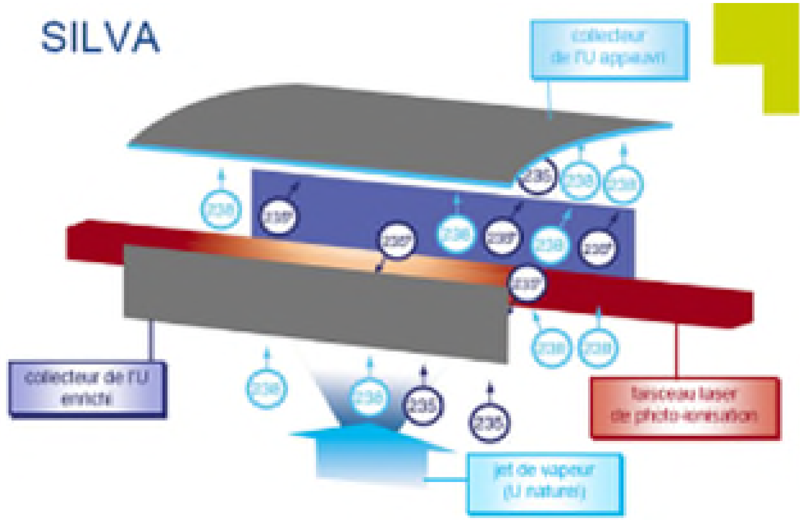


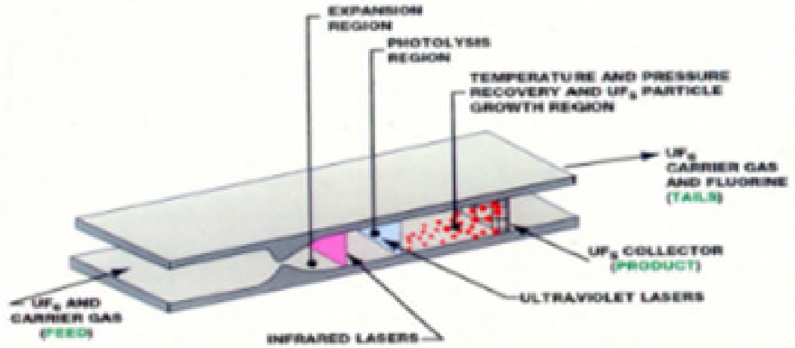
Optical method of separation (transition frequency) [1/2]

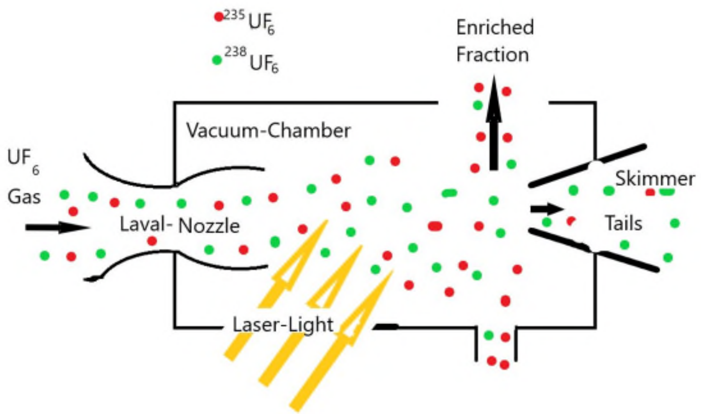
Atomic vapor laser isotope separation (AVLIS)	
Process	Selective ionization and collection on electrically charged plates
TRL	7-8
Alpha	α ~ 5
Flow	High
Hold-up	Low
Electrical consumption	Low
Equilibrium time	Short (hours)

Molecular Laser Isotope Separation (MLIS)	
Process	Selective dissociation of a gaseous compound
TRL	?
Alpha	α ~ 5
Flow	High
Hold-up	Low
Electrical consumption	Low
Equilibrium time	Short (hours)

Separation of Isotopes by Laser Excitation (SILEX)	
Process	Selective excitation to delay dimer formation or to dissociate dimer
TRL	6 ?
Alpha	α ~ 10
Flow	High
Hold-up	Low
Electrical consumption	Low
Equilibrium time	Short (hours)

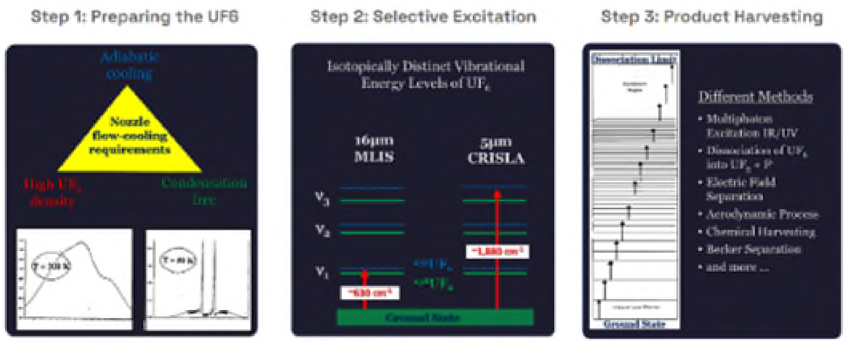






Optical method of separation (transition frequency) [2/2]

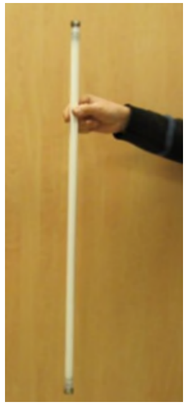
Condensation Repression Isotope Selective Laser Activation (CRISLA)	
Process	Selective excitation to delay dimer formation or to dissociate dimer
TRL	?
Alpha	α > 5
Flow	High
Hold-up	Low
Electrical consumption	Low
Equilibrium time	Short (hours)

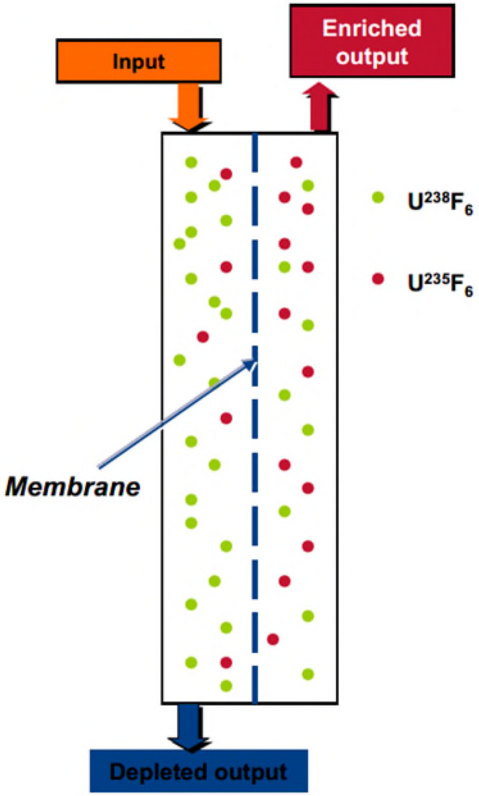


Gas diffusion method of separation

Gas diffusion	
Process	Difference of velocity
TRL	9 (no more working)
Alpha	α ~1,004
Flow	High
Hold-up	High
Electrical consumption	High
Equilibrium time	Long (months)

$\alpha \propto \sqrt{M1/M2}$

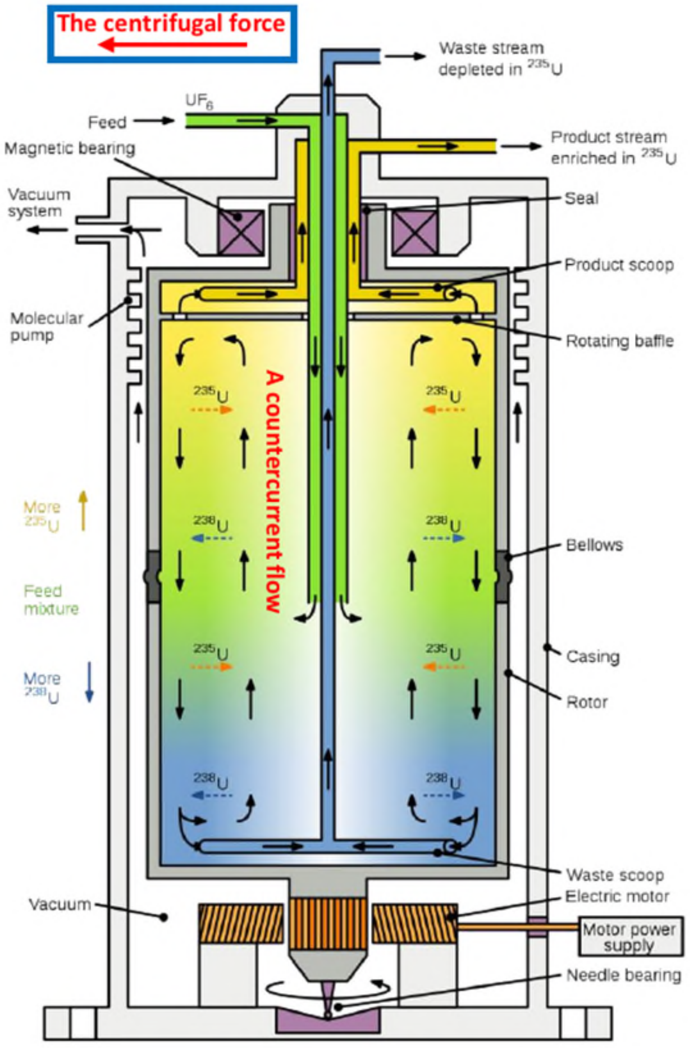


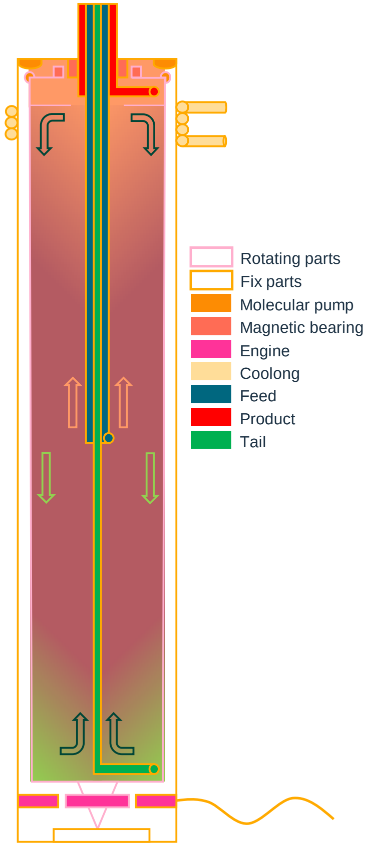


Centrifuge process

Centrifuge	
Process	Centrifugation
TRL	9 (working for many stable isotopes)
Alpha	α ~1,3
Flow	High
Hold-up	Low
Electrical consumption	Low
Equilibrium time	Short (hours)

$$\Delta U \propto \Delta M^2 . \omega^4 . L$$

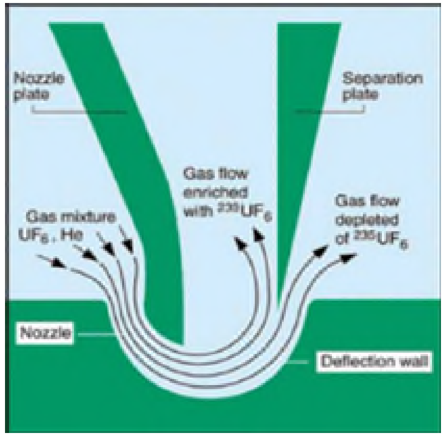




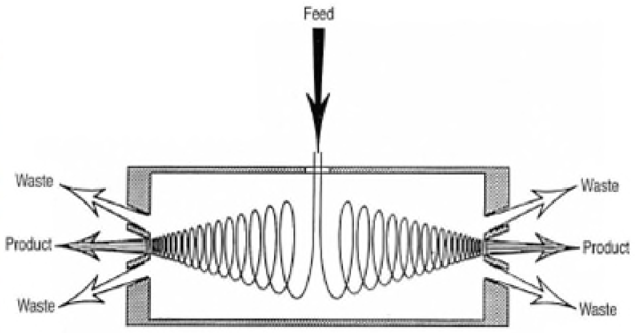
Other aerodynamic process

Becker's Vortex	
Process	High-velocity gas flow in a fix semi-circular hole
TRL	8-9
Alpha	α <1,05
Flow	High
Hold-up	Low to medium
Electrical consumption	High
Equilibrium time	Short (days)

Vortex Tube	
Process	Fixed wall centrifugation
TRL	9
Alpha	α ~ 1,03
Flow	High
Hold-up	Low to medium
Electrical consumption	High
Equilibrium time	Short (days)



The **ASP separation device** separates gas species and isotopes in a volatile state.



03 Summary

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The technology used for enrichment dépend of the element and the enrichment target

	TRL	Constrain	Alpha	Beta	Hold-up	Equilibrium time	Flow	Energy consuption	Difficulty to collect
Rectification and isotope exchange	High	High deltaM/M	Very low <1,05	Very low	Very high	Months	Very high (up to tons/yrs)	Very low	Very easy
EMIS / ICR	High	No constrain	Very high	Low	Very low	Very short	Very low (up to tens of g/yrs)	Very high (EMIS) to very low (ICR)	Medium
SILVA/SILEX/CRISLA/MLIS	Medium to low	Way to select or to collect different for each element	High	High (SILVA) to low (SILEX)	Very low	Days	High (up to tens of kg/yrs)	Very low	Very difficult
Gazeous diffusion	High	Gazeous compound	Very low <1,05	Very low	Very high	~ Month	Very high (up to tons/yrs)	Very high	Very easy
Centrifuges / Vortex	High	Gazeous compound	Low	Low	Low	Short	High	Very low (centrifuge) to high (other technologies)	Medium to easy

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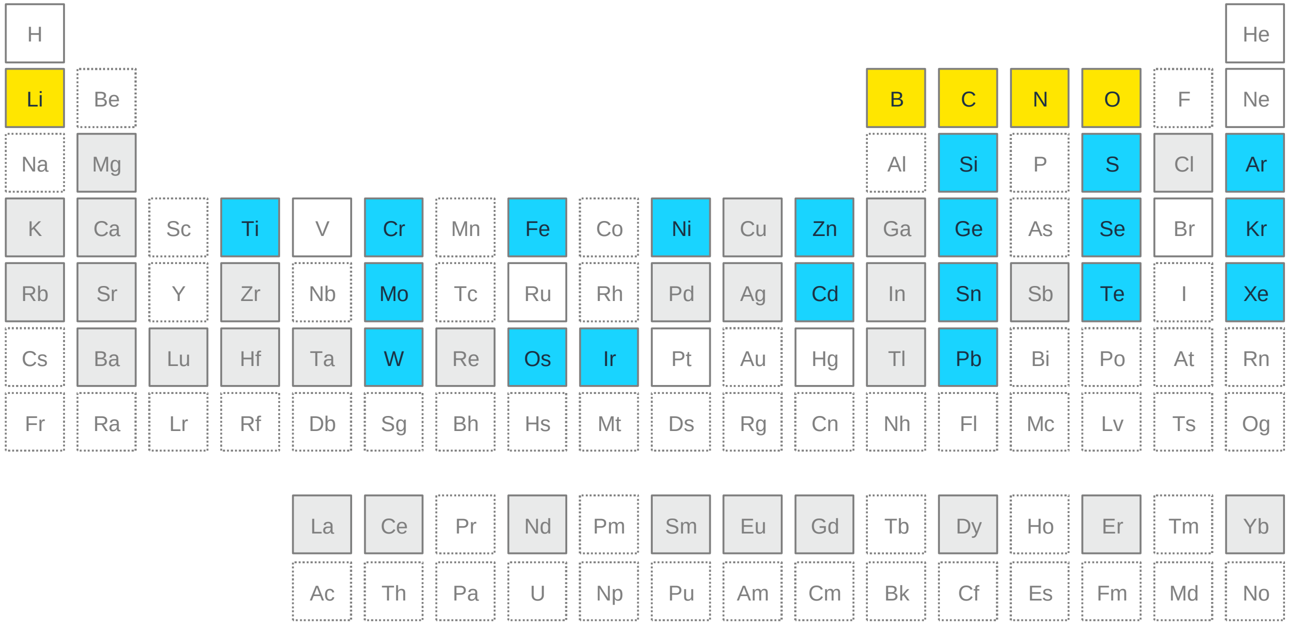
Today, only three principal type of processes are used to enrich stable isotopes



Element currently separated by centrifuges

Element currently separated by physical-chemical selection / electrochemical process

Other stable isotopes

Element currently separated by EMIS

Other elements

Today, only three principal types of process are used to enrich stable isotopes

Production at industrial level

Process	Producers	Market share
Light	Cambridge Isotope Laboratories, Inc. (CIL) – Enriching Scientific Discovery; TAIYO NIPPON SANSO; ROTEM; MARSHALL ISOTOPES; Jiangsu Zhengneng Isotope Co., Ltd.	3/4 of the market
Centrifugation	ROSATOM; urenco; orano; 中核集团 CNNC (only Ge)	1/8 of the market
EMIS	ROSATOM	1/8 of the market (mainly Yb-176)

Light isotopes : CIL

Light isotopes : Taiyo

Centrifuge :
Top ECP Rosatom
Bottom Urenco

Centrifuge :
Orano

EMIS :
EKP Rosatom