Principles of ISOL-type radioactive ion beam production

Simon Stegemann

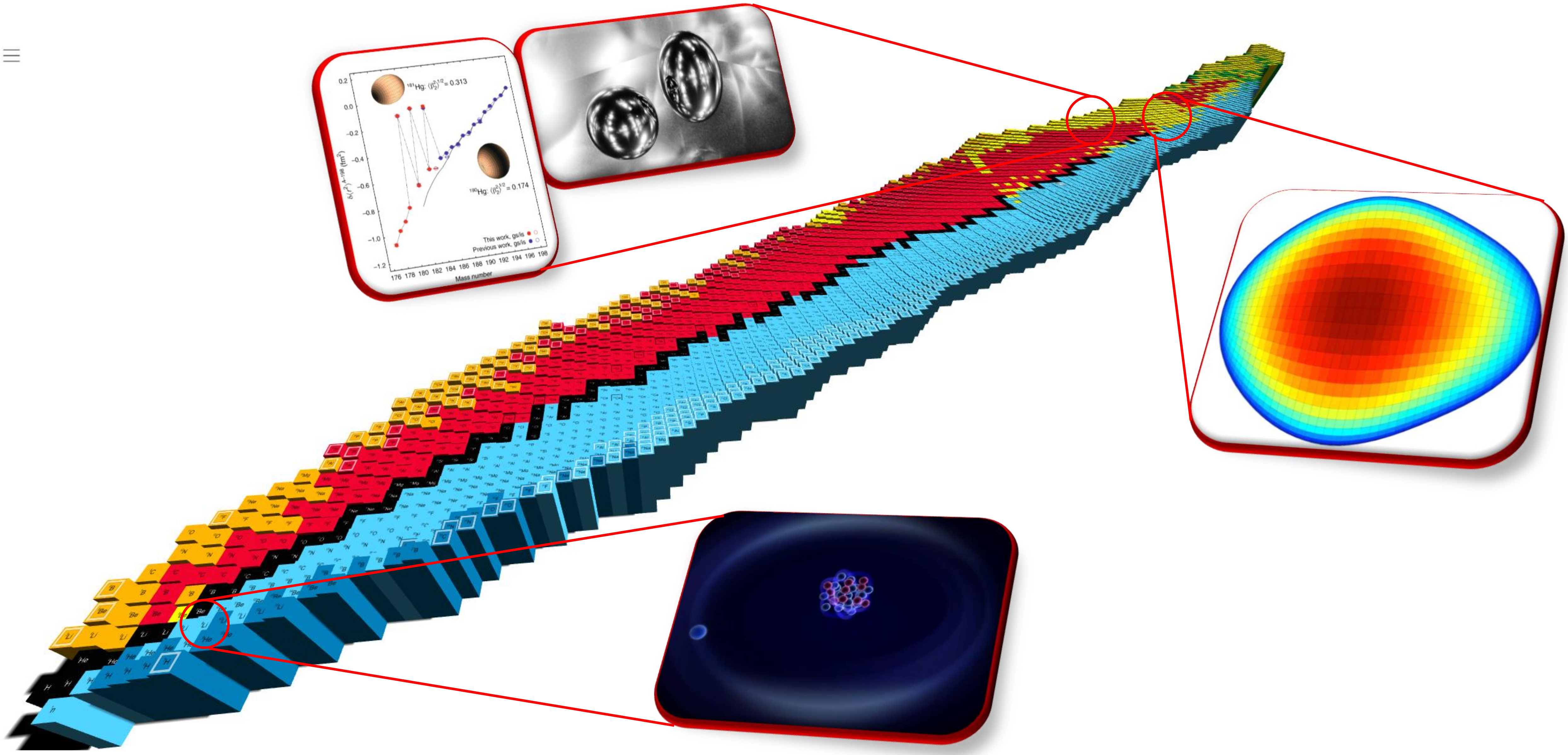
CERN-ISOLDE

SY-STI-RBS

20/03/2023 ISOL-France workshop V, Bordeaux

Content

1. Why ISOL beams?, ISOL history
2. ISOL challenges
3. ISOL stages
4. Use cases around the world



L.P. Gaffney, et al. Nature 497. 10.1038/nature12073
B.A. Marsh, et al. Nature Physics 14 (2018). 10.1038/s41567-018-0292-8
E.C. Simpson, M. Shelley. Phys. Edu. 52 (2017).
https://scitechdaily.com/physicists-reveal-neutron-halo-around-neutron-rich-magnesium-nuclei/
https://frontline.thehindu.com/science-and-technology/article25175946.ece

Why radioactive ion beams?

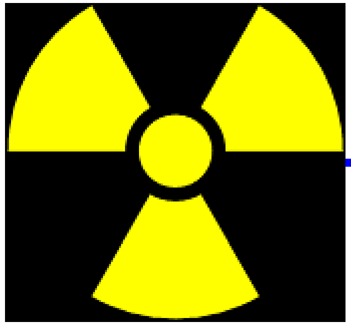
Production:

high radiation environment

primary

beam

target



Detection:

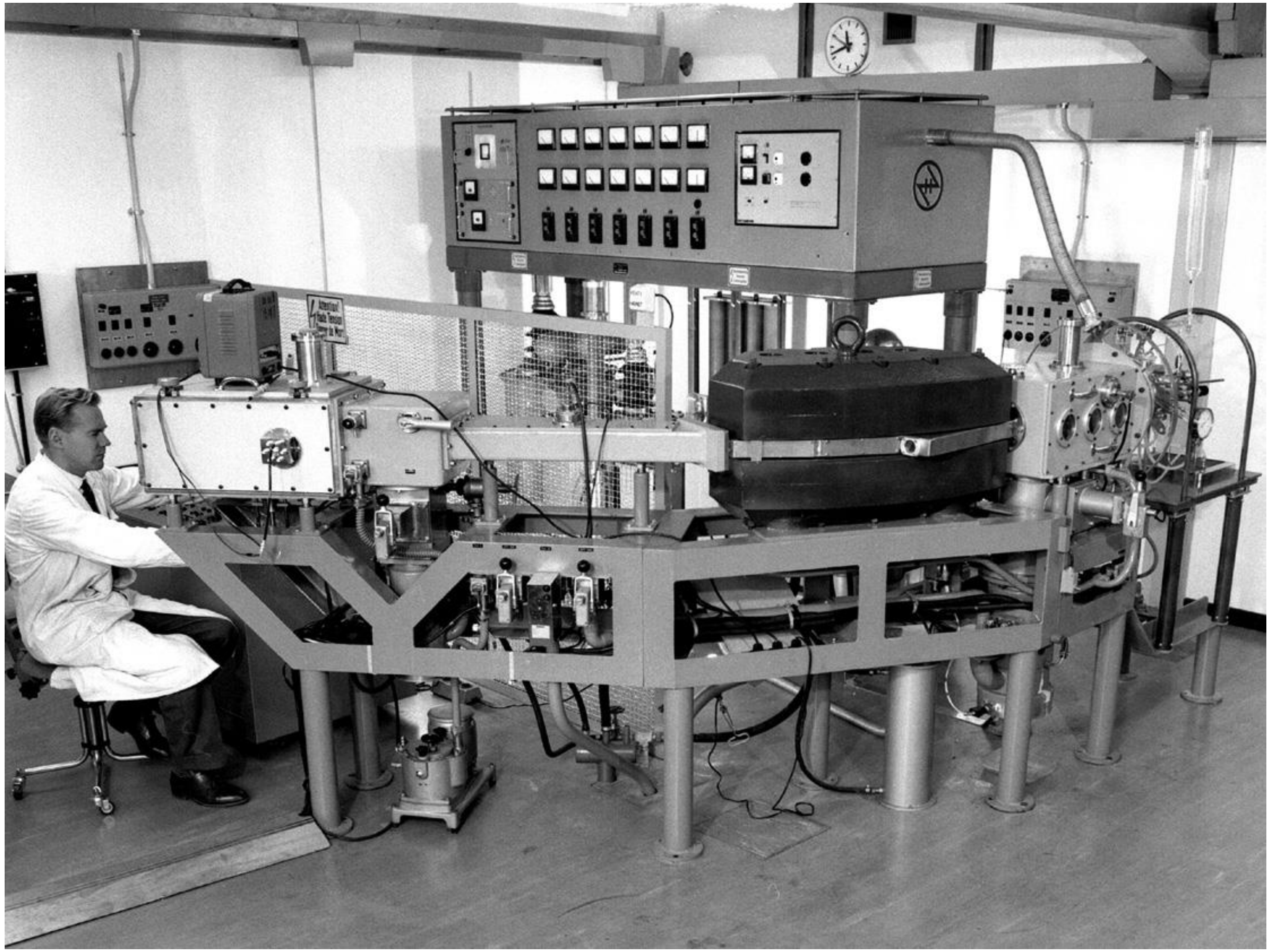
low radiation background

Transport methods:

	Speed (approx.)
• carry (“SRAFAP”)	10 m/s
• drive (*G.T. Seaborg and W.D. Loveland, The Elements beyond Uranium, John Wiley & Sons, 1990*)	50 m/s
• transport shuttle with pressurized air	100 m/s
• transport in gas-jet	1’000 m/s
• pump through vacuum system	
• **send as ion beam**	**1’000’000 m/s**

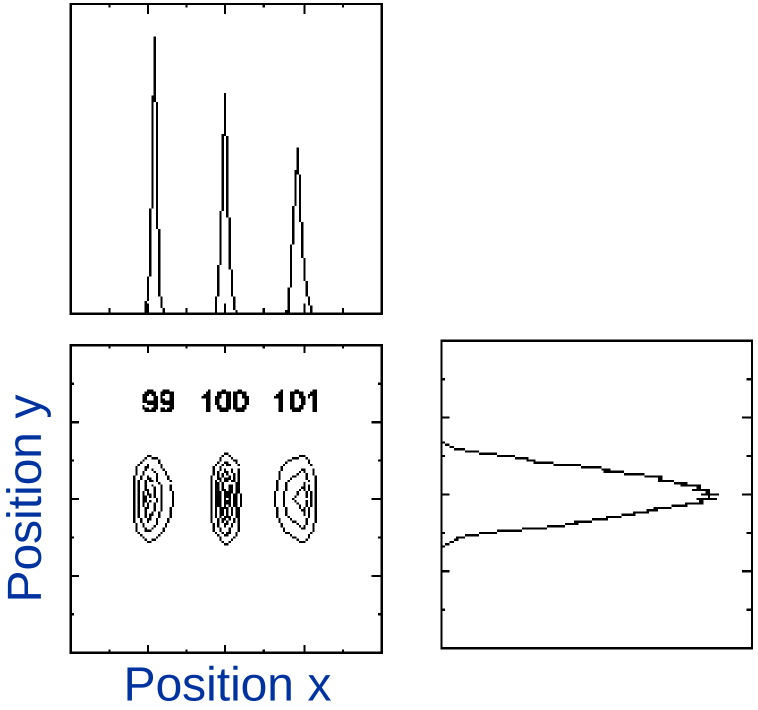
ISOL-history: irradiation of targets

ISOL-history: off-line mass separation



- Ionization to typ. q = 1+
- Acceleration to e.g. 60 keV
- Mass selection by magnetic deflection (Lorentz force)

$$(B\rho = p/q \propto \sqrt{A})$$



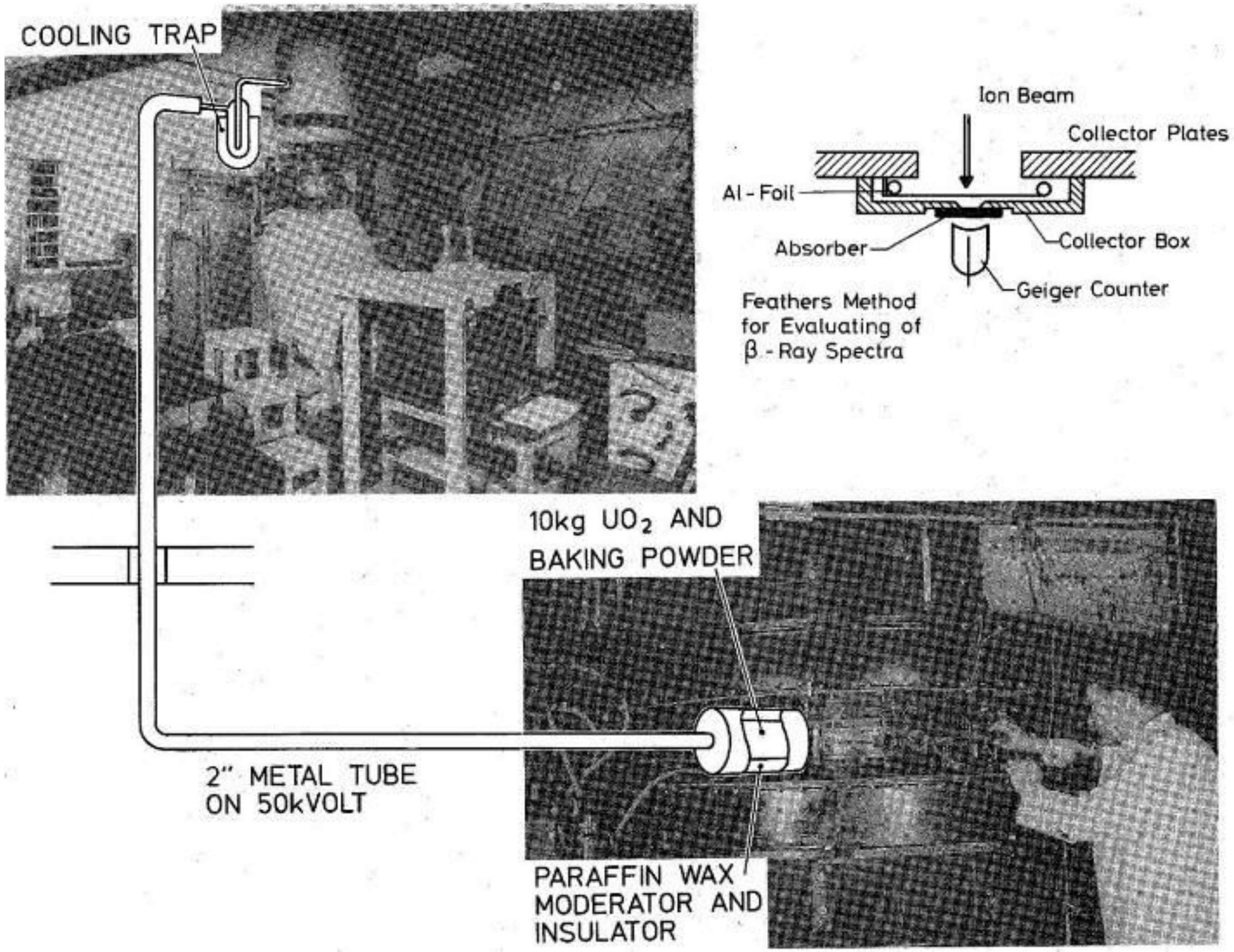
ISOL-history: first ISOL experiment at Niels Bohr Institute

Short-Lived Krypton Isotopes and Their Daughter Substances

O. Kofoed-Hansen and K. O. Nielsen
Institute for Theoretical Physics, University of Copenhagen, Copenhagen, Denmark

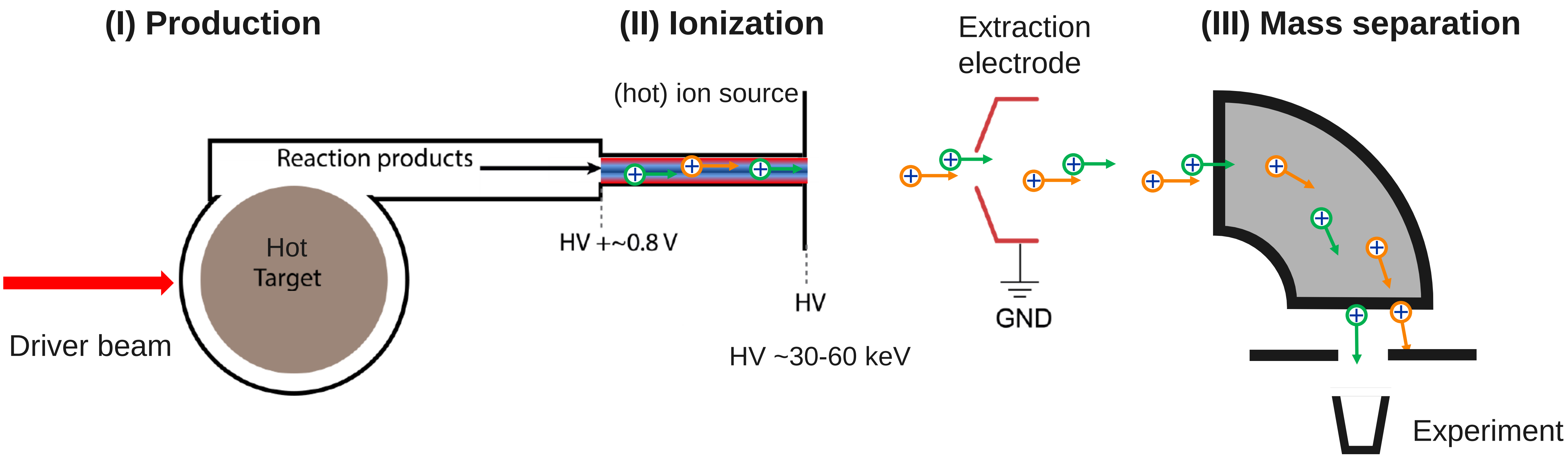
(Received February 9, 1951)

THE isotopes Kr^{89}, Kr^{90}, Kr^{91}, and their daughter substances have been investigated. Krypton formed in fission of uranium was pumped through a 10-m long tube directly from the cyclotron into the ion source of the isotope separator. The cyclotron and the isotope separator were operated simultaneously, and the counting could begin immediately after the interruption of the separation. The rubidium and strontium daughter substances were separated chemically; strontium was precipitated as carbonate. Half-lives were measured and an absorption analysis of the radiations was carried out. The results are given in Table I.



ISOL beams of $^{89-93}$Kr

The isotope separation on-line (ISOL) method



Content

1. Why ISOL beams?, ISOL history

2. ISOL challenges

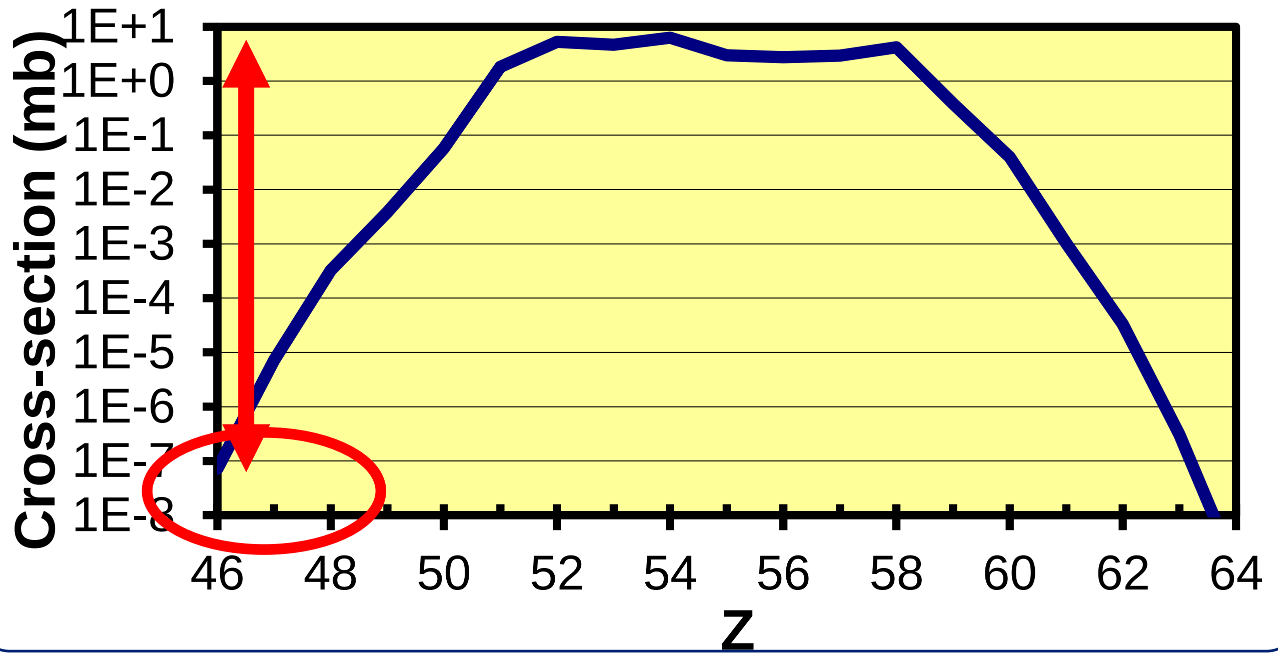
- **Challenges**
- **RIB optimization**

3. ISOL stages

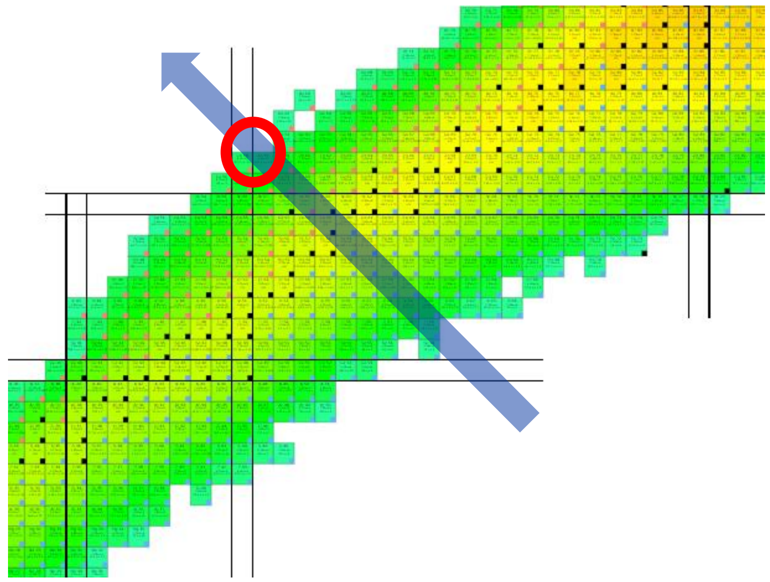
4. Use cases around the world

ISOL challenges

Isotope production



Isotope selection



1. low cross-sections ⇒ optimize **efficiency**
2. enormous production of isobars ⇒ optimize **selectivity**
3. short half-lives ⇒ optimize **rapidity**

ISOL: RIB optimization

Optimize event rate R of an experiment

In-target production — Efficiency

$$R = \Phi \cdot \sigma \cdot N_t \cdot \varepsilon$$

$$\varepsilon = \varepsilon_{rel} \cdot \varepsilon_{ion} \cdot \varepsilon_{sep} \cdot \varepsilon_{trans}$$

$$\varepsilon_{rel} = \varepsilon_{diff} \cdot (\varepsilon_f) \cdot \varepsilon_{eff}$$

To maximize event rate at experiment:

- Optimize in-target production
- Maximize efficiency cascade

Do for each beam!

σ: Cross section
Φ: Pr. Particle flux
N_t: Exposed target nuclei
ε: Efficiency

ISOL: RIB optimization

Optimize event rate R of an experiment

In-target production, Efficiency

$$R = \int_{E_f}^{E_i} dE\, \Phi \cdot \frac{\sigma(E)}{S(E)} \cdot N_t \cdot \varepsilon$$

$$\varepsilon = \varepsilon_{rel} \cdot \varepsilon_{ion} \cdot \varepsilon_{sep} \cdot \varepsilon_{trans}$$

$$\varepsilon_{rel} = \varepsilon_{diff} \cdot (\varepsilon_f) \cdot \varepsilon_{eff}$$

To maximize event rate at experiment:

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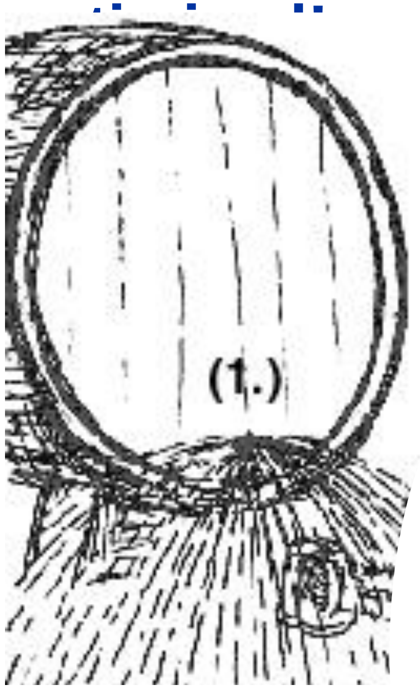
ISOL: RIB optimization

All steps of the production-separation chain need to be



$$R = \boxed{\Phi} \cdot \sigma \cdot N_t \cdot \varepsilon_{rel} \cdot \varepsilon_{ion} \cdot \varepsilon_{sep} \cdot \varepsilon_{trans} \cdot \varepsilon_{det}$$

powerful accelerator

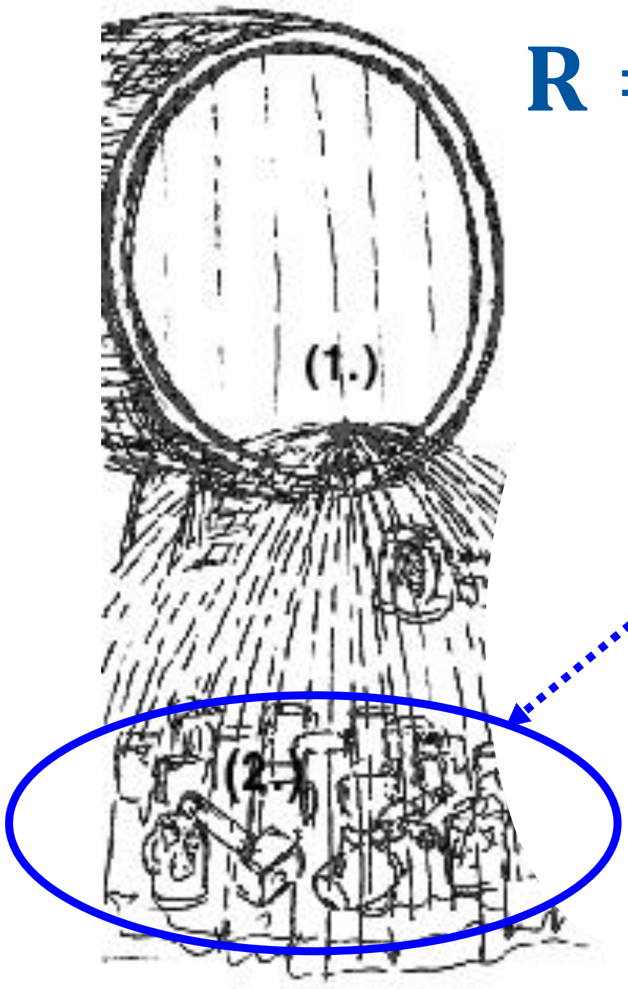
$\Rightarrow$ **accelerator technology**

σ: Cross section
Φ: Pr. Particle flux
N_t: Exposed target nuclei
ε: Efficiency

ISOL: RIB optimization

All steps of the production-separation chain need to be optimized!

$$R = \Phi \cdot \boxed{\sigma} \cdot N_t \cdot \varepsilon_{rel} \cdot \varepsilon_{ion} \cdot \varepsilon_{sep} \cdot \varepsilon_{trans} \cdot \varepsilon_{det}$$



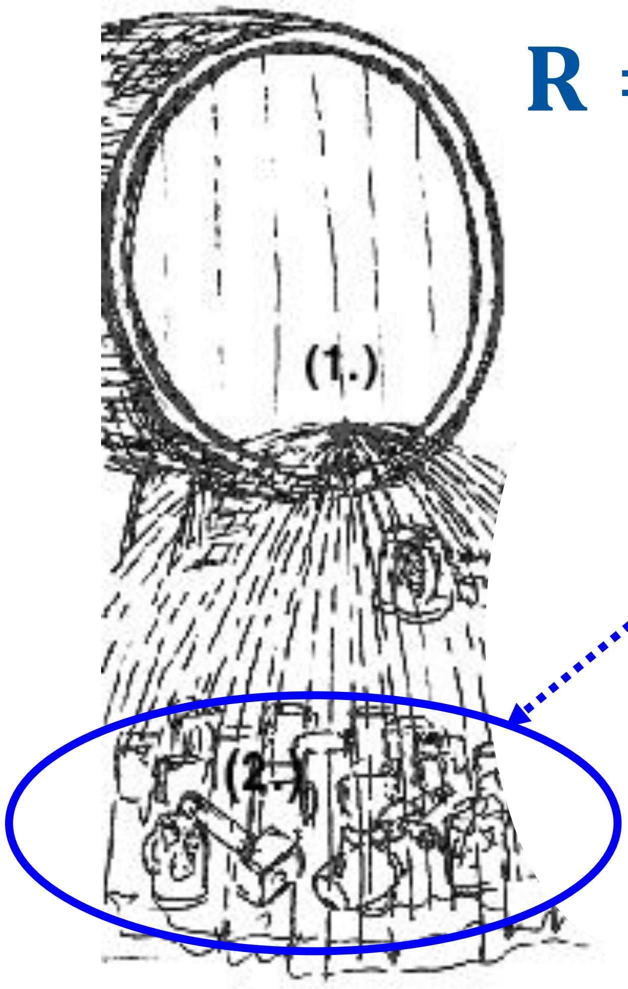
high production cross-sections

$\Rightarrow$ **nuclear physics**

σ: Cross section
Φ: Pr. Particle flux
N_t: Exposed target nuclei
ε: Efficiency

ISOL: RIB optimization

All steps of the production-separation chain need to be optimized!



$$R = \Phi \cdot \sigma \cdot N_t \cdot \varepsilon_{rel} \cdot \varepsilon_{ion} \cdot \varepsilon_{sep} \cdot \varepsilon_{trans} \cdot \varepsilon_{det}$$

reliable “thick” targets

⇒ material science

σ: Cross section
Φ: Pr. Particle flux
N_t: Exposed target nuclei
ε: Efficiency

ISOL: RIB optimization

All steps of the production-separation chain need to be optimized!

$$R = \Phi \cdot \sigma \cdot N_t \cdot \boxed{\varepsilon_{rel}} \cdot \varepsilon_{ion} \cdot \varepsilon_{sep} \cdot \varepsilon_{trans} \cdot \varepsilon_{det}$$

Extraction efficiency from target determined by:

- **diffusion**

⇒ **solid state physics**

- **surface desorption**

⇒ **surface chemistry**

- **effusion**

⇒ **gas phase chemistry**

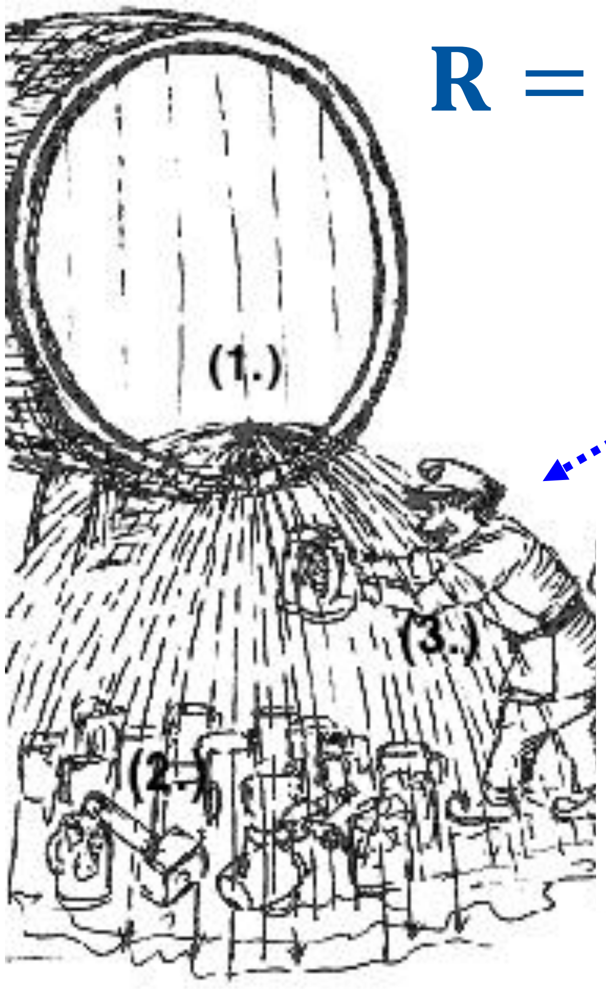
strongly element dependent!

σ: Cross section
Φ: Pr. Particle flux
N_t: Exposed target nuclei
ε: Efficiency

[UK01,UK6-mod]

ISOL: RIB optimization

All steps of the production-separation chain need to be optimized!



$$R = \Phi \cdot \sigma \cdot N_t \cdot \varepsilon_{rel} \cdot \boxed{\varepsilon_{ion}} \cdot \varepsilon_{sep} \cdot \varepsilon_{trans} \cdot \varepsilon_{det}$$

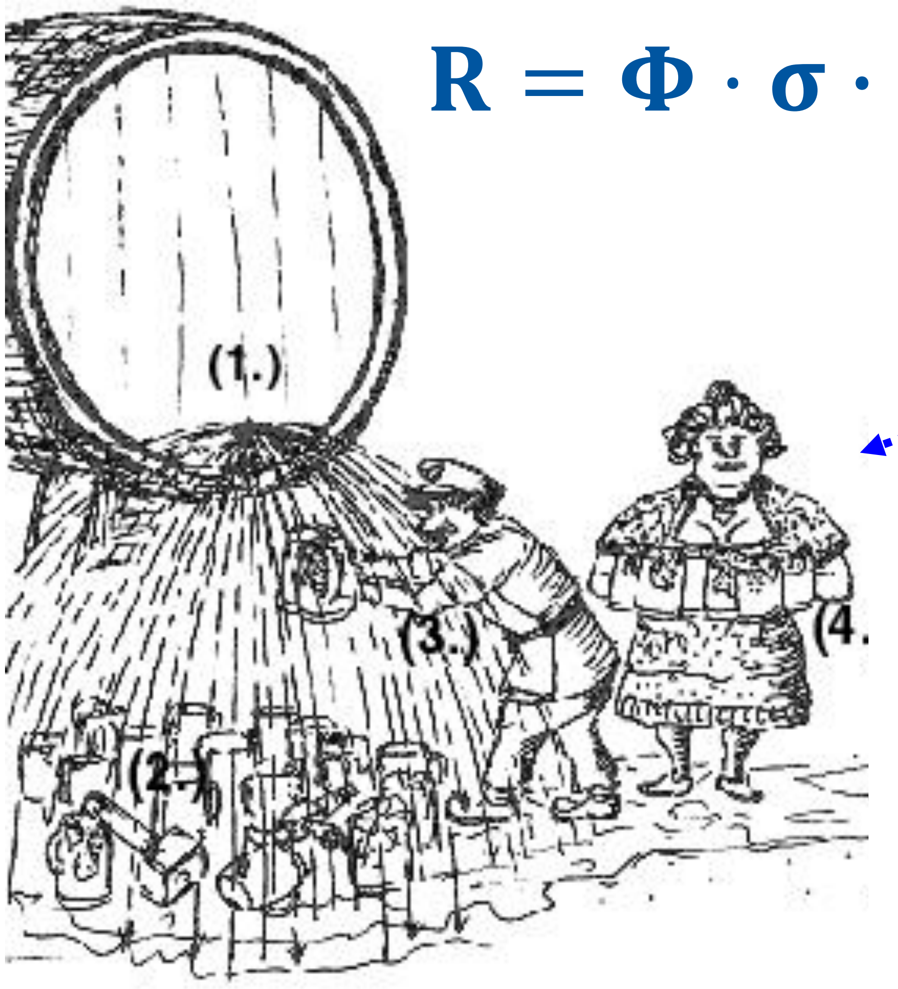
high ionization and extraction efficiency

$\Rightarrow$ **ion source technology**

ISOL: RIB optimization

All steps of the production-separation chain need to be optimized!

$$\mathbf{R} = \mathbf{\Phi} \cdot \boldsymbol{\sigma} \cdot \mathbf{N_t} \cdot \boldsymbol{\varepsilon}_{\mathbf{rel}} \cdot \boldsymbol{\varepsilon}_{\mathbf{ion}} \cdot \boxed{\boldsymbol{\varepsilon}_{\mathbf{sep}} \cdot \boldsymbol{\varepsilon}_{\mathbf{trans}}} \cdot \boldsymbol{\varepsilon}_{\mathbf{det}}$$



efficient separation and transport of RIB

⇒ ion optics

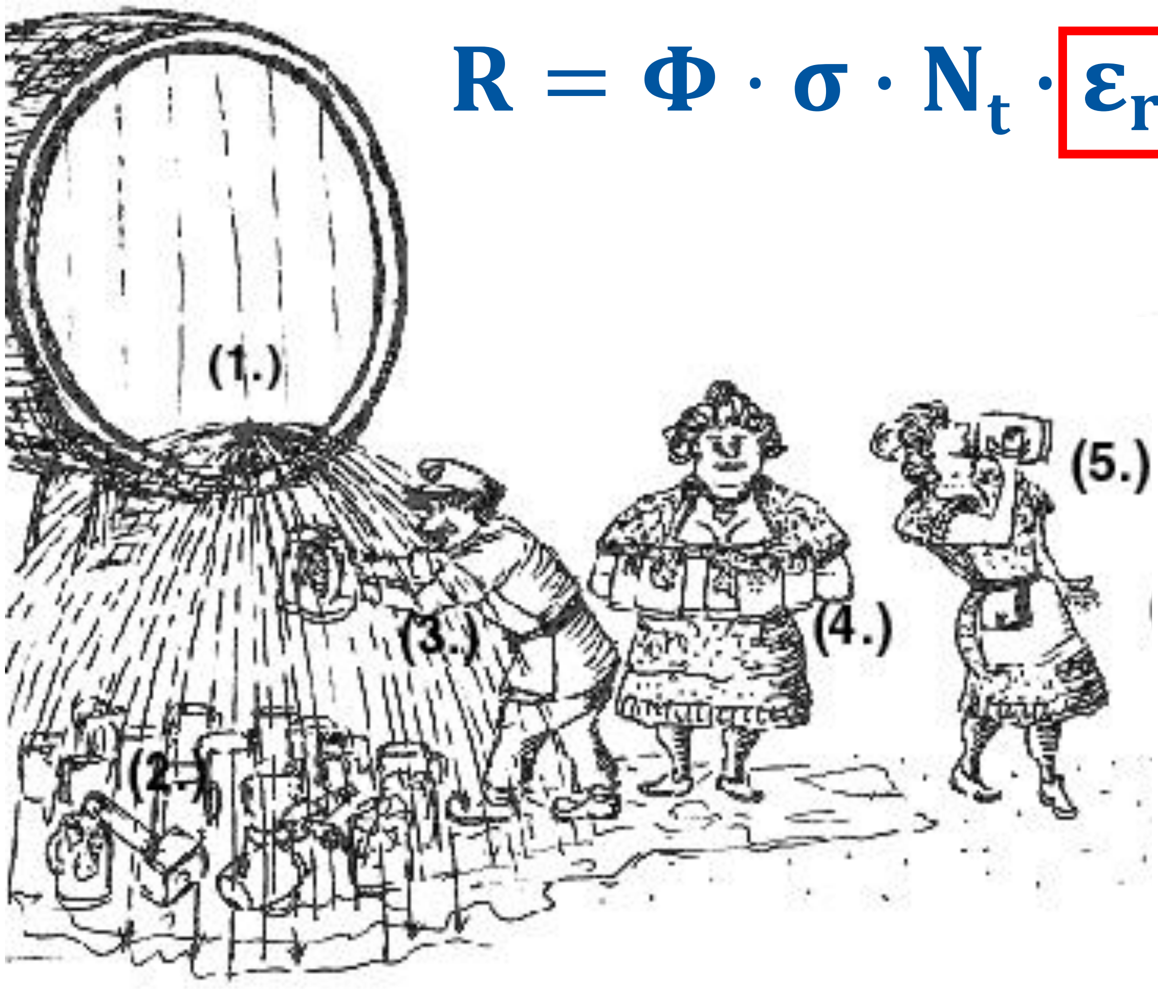
σ: Cross section
Φ: Pr. Particle flux
N_t: Exposed target nuclei
ε: Efficiency

[UK01,UK6-mod]

ISOL: RIB optimization

All steps of the production-separation chain need to be optimized!

$$R = \Phi \cdot \sigma \cdot N_t \cdot \boxed{\varepsilon_{rel} \cdot \varepsilon_{ion} \cdot \varepsilon_{sep} \cdot \varepsilon_{trans}} \cdot \varepsilon_{det}$$



Mind the decay losses during delays

⇒ efficiency strongly half-life dependent

⇒ rapid extraction required!

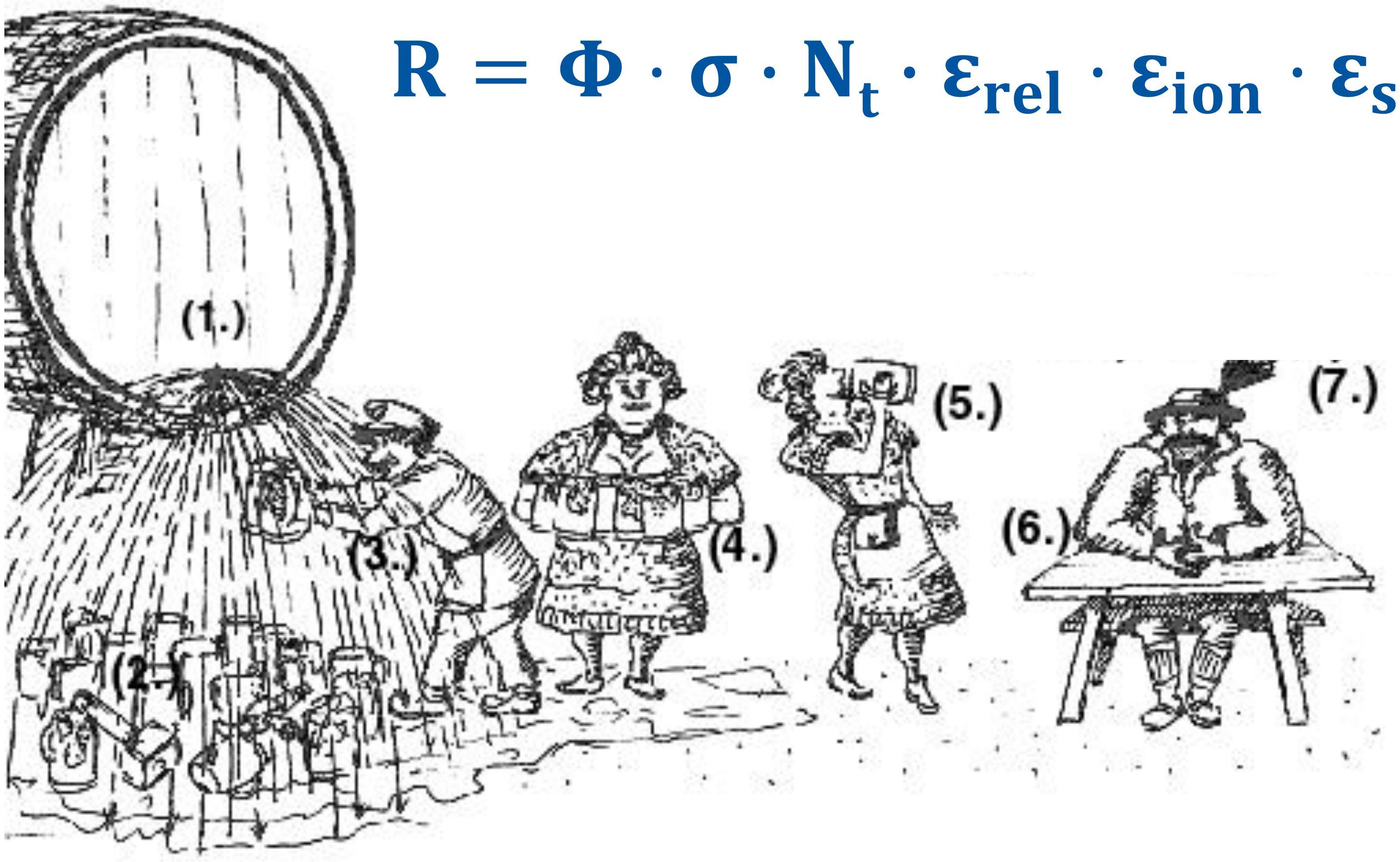
σ: Cross section
Φ: Pr. Particle flux
N_t: Exposed target nuclei
ε: Efficiency

ISOL: RIB optimization

All steps of the production-separation chain need to be optimized!

$$R = \Phi \cdot \sigma \cdot N_t \cdot \varepsilon_{rel} \cdot \varepsilon_{ion} \cdot \varepsilon_{sep} \cdot \varepsilon_{trans} \cdot \varepsilon_{det}$$

Detection efficiency



σ: Cross section
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- **Ionization**
- **Mass separation**

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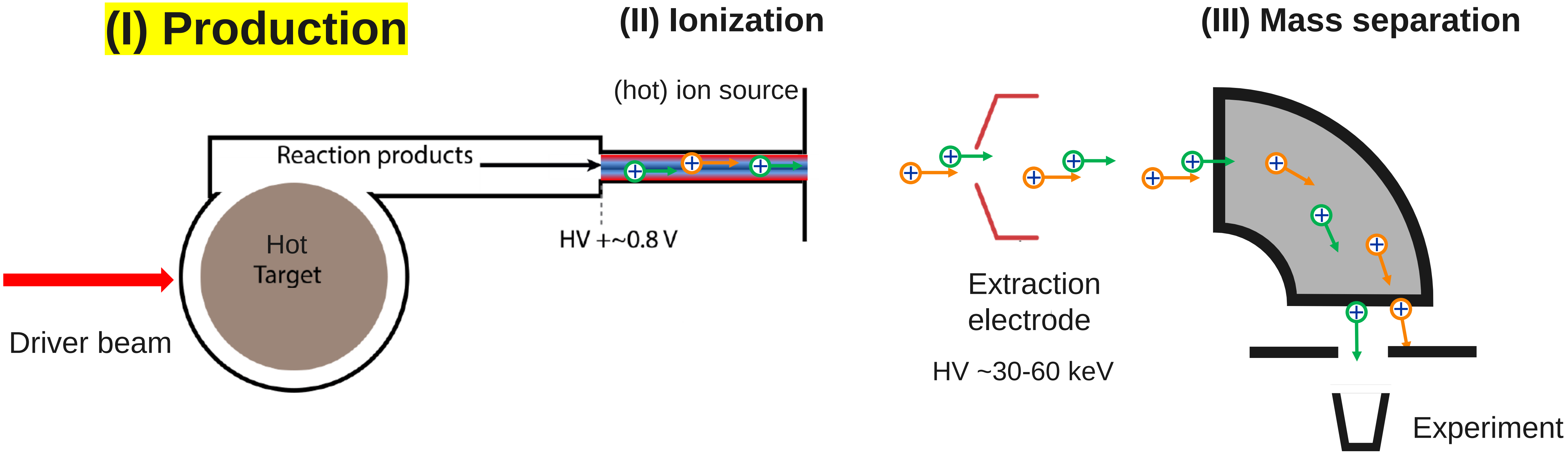
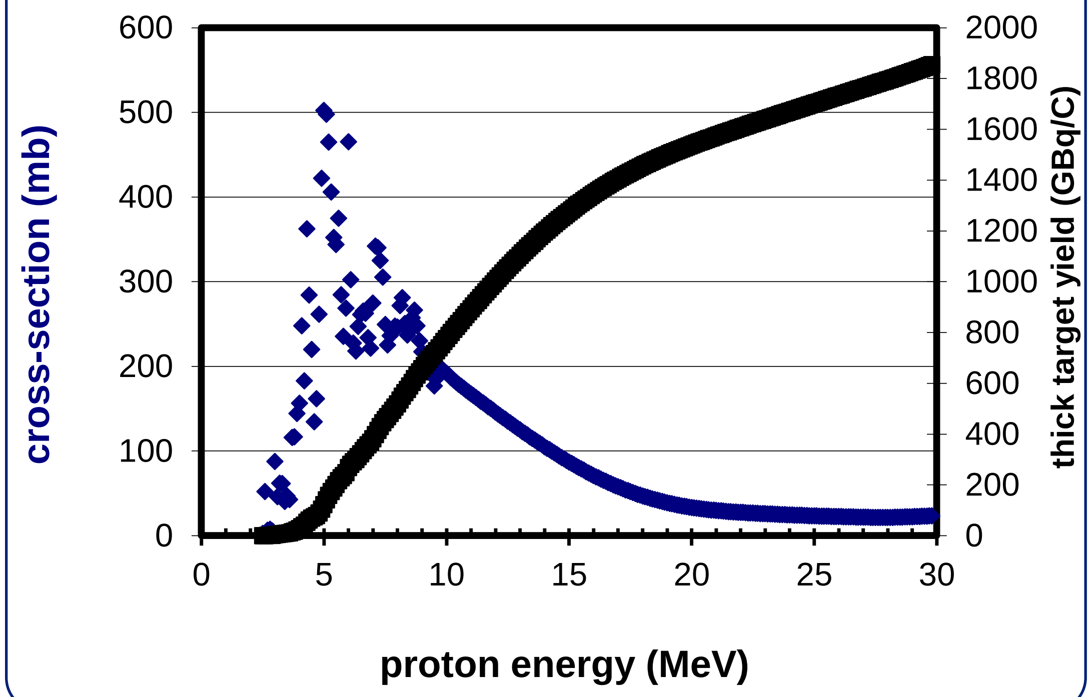
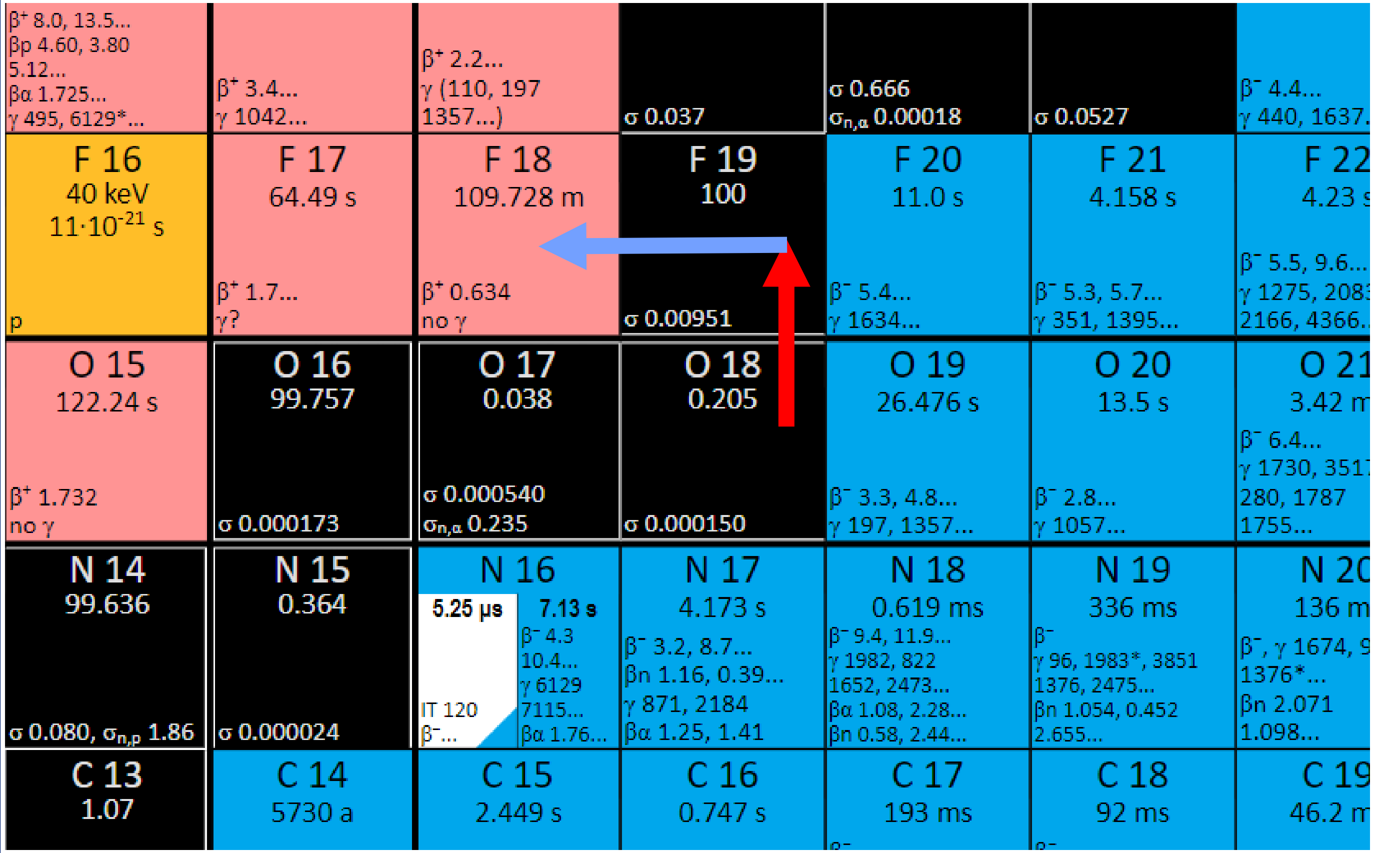
ISOL: stages


(I) Production
(II) Ionization
(III) Mass separation
(hot) ion source
Reaction products
Hot
Target
HV +~0.8 V
Driver beam
Extraction
electrode
HV ~30-60 keV
Experiment

(I) Isotope production: Direct reactions

$^{18}O(p,n)^{18}F$





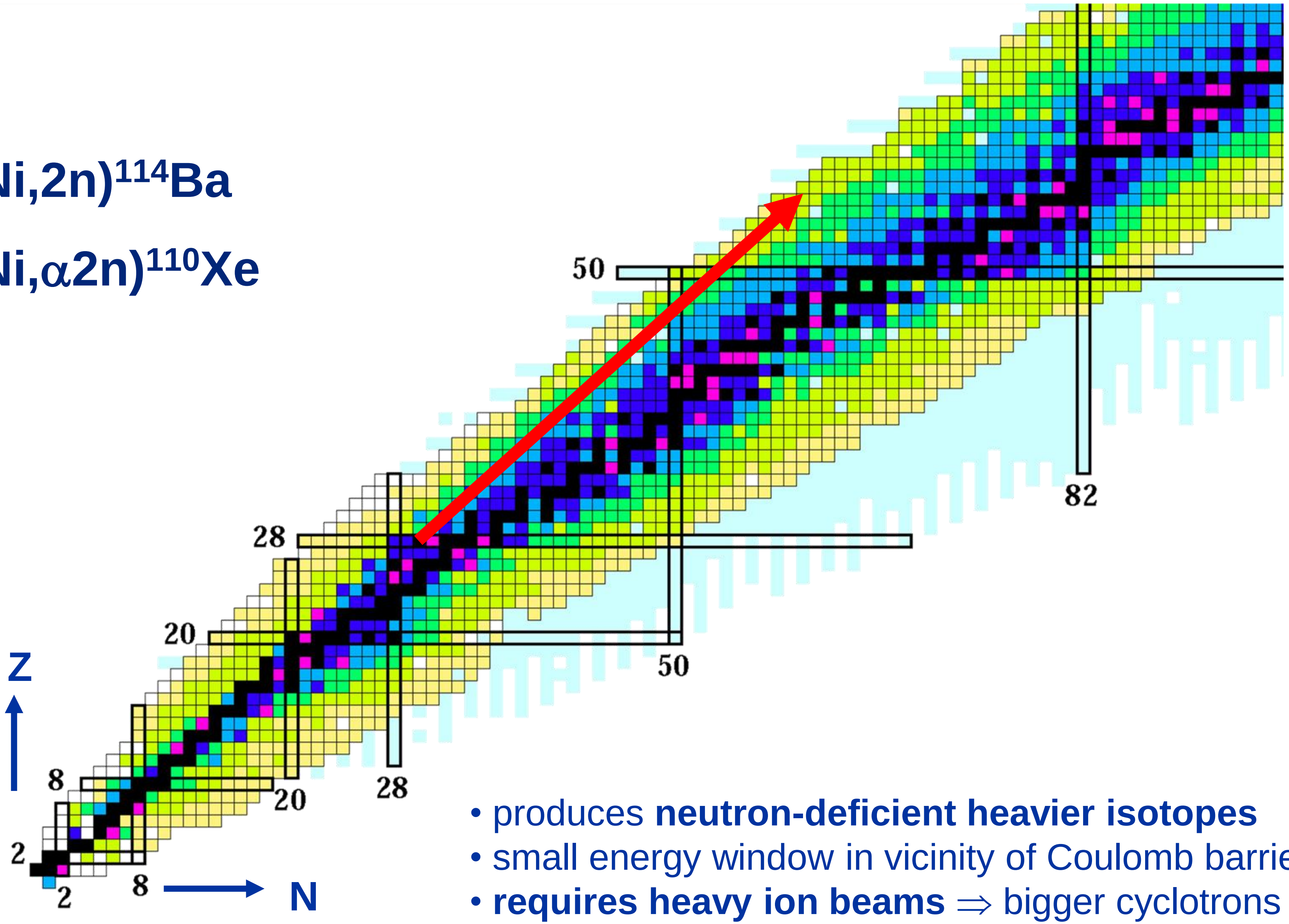
(p,n), $(^{3}He,n)$, (α,n), (n,α), …

- high cross-sections, **products relatively close to stability**
- driver beams from (low-cost) cyclotrons

(I) Isotope production: Fusion-evaporation

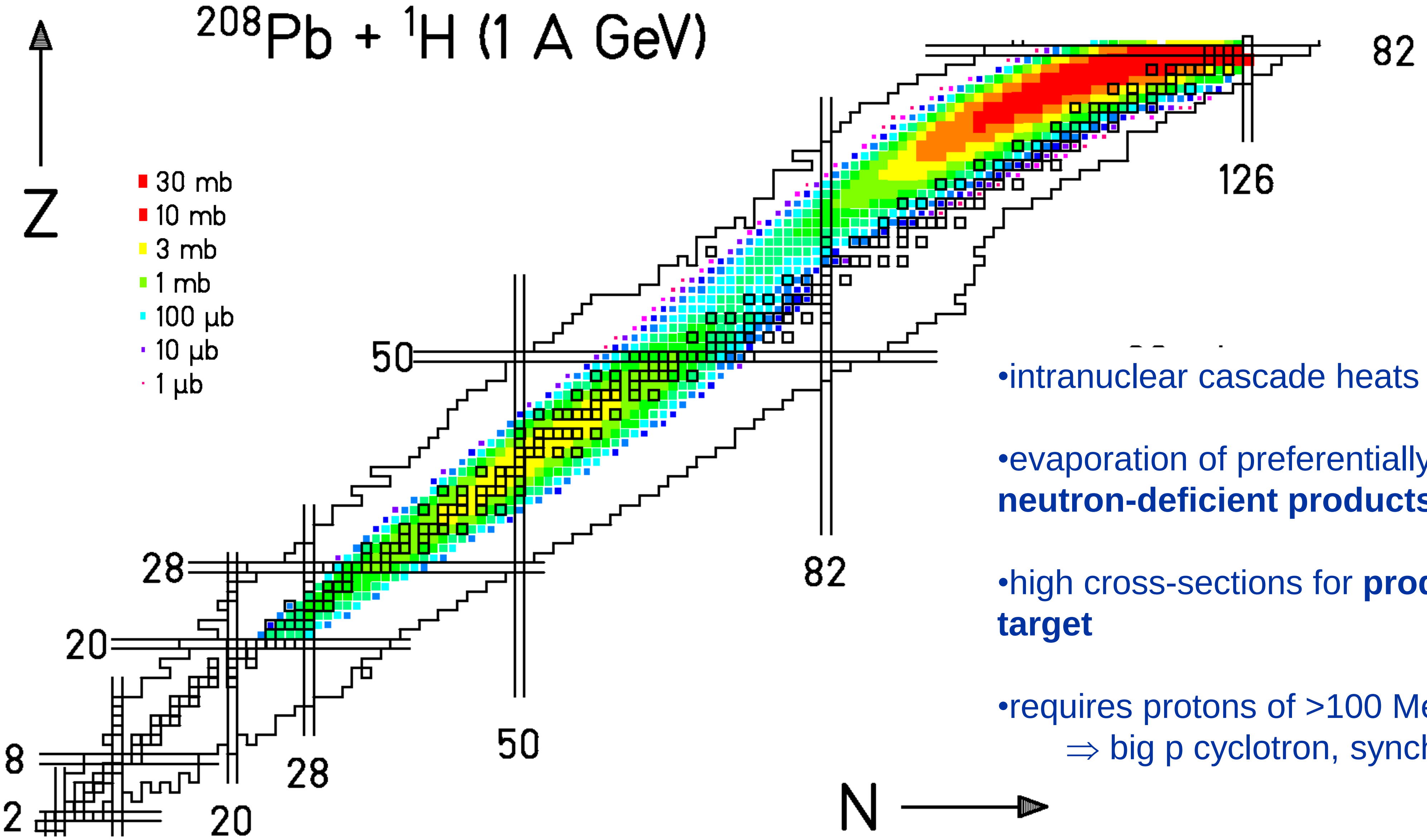
$^{58}Ni(^{58}Ni,2n)^{114}Ba$

$^{58}Ni(^{58}Ni,\alpha 2n)^{110}Xe$



- produces **neutron-deficient heavier isotopes**
- small energy window in vicinity of Coulomb barrier (some MeV/nucleon)
- **requires heavy ion beams** ⇒ bigger cyclotrons or LINACs

(I) Isotope production: Spallation



•intranuclear cascade heats nucleus

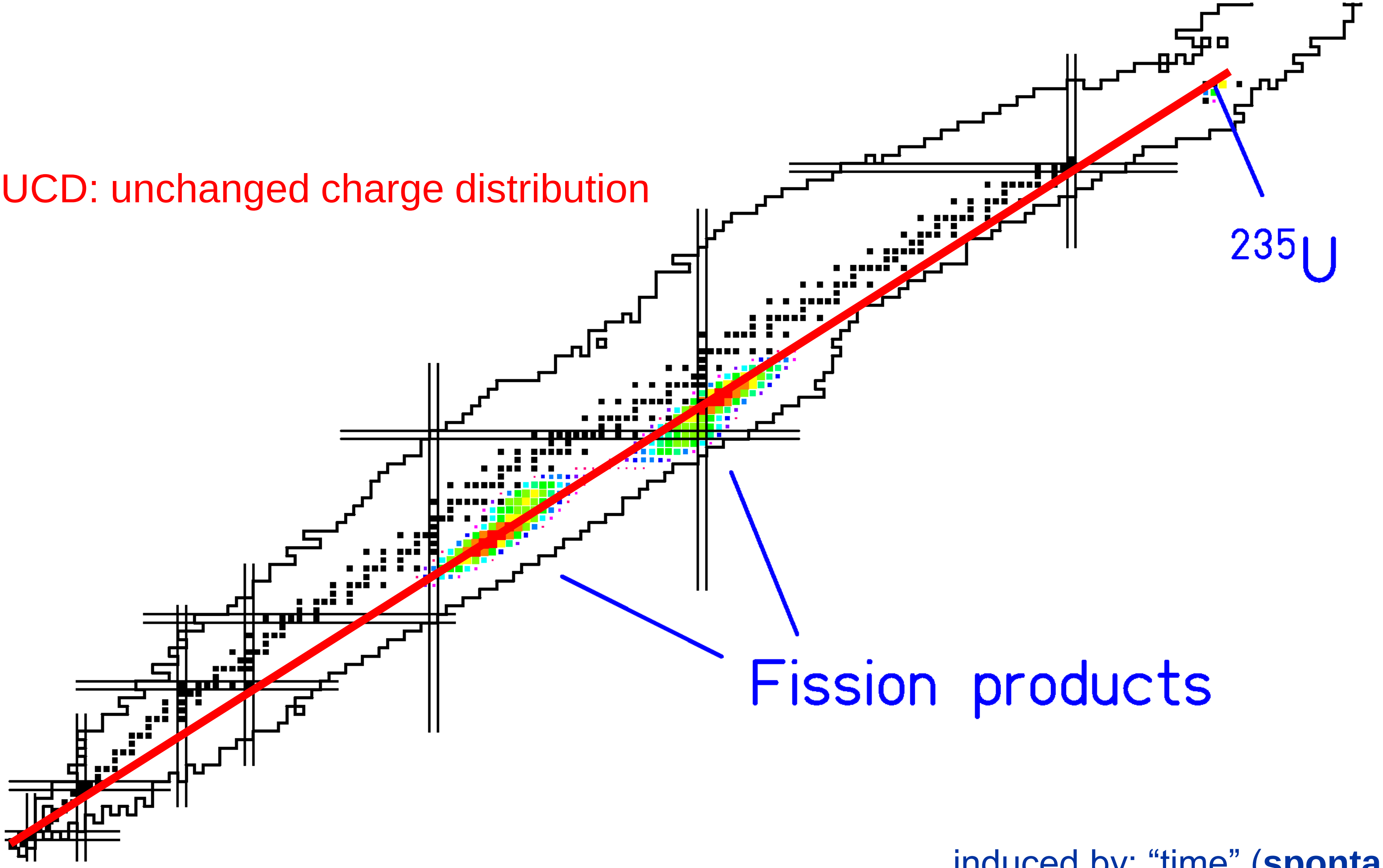
•evaporation of preferentially neutrons ⇒ **neutron-deficient products**

•high cross-sections for **products close to target**

•requires protons of >100 MeV
⇒ big p cyclotron, synchrotron or LINAC

T. Enqvist et al., Nucl. Phys. A686 (2001). 10.1016/S0375-9474(00)00563-7
K.-H. Schmidt, et al. Phys. Rev. ST Accel. Beams 10 (2007). 10.1103/PhysRevSTAB.10.014701

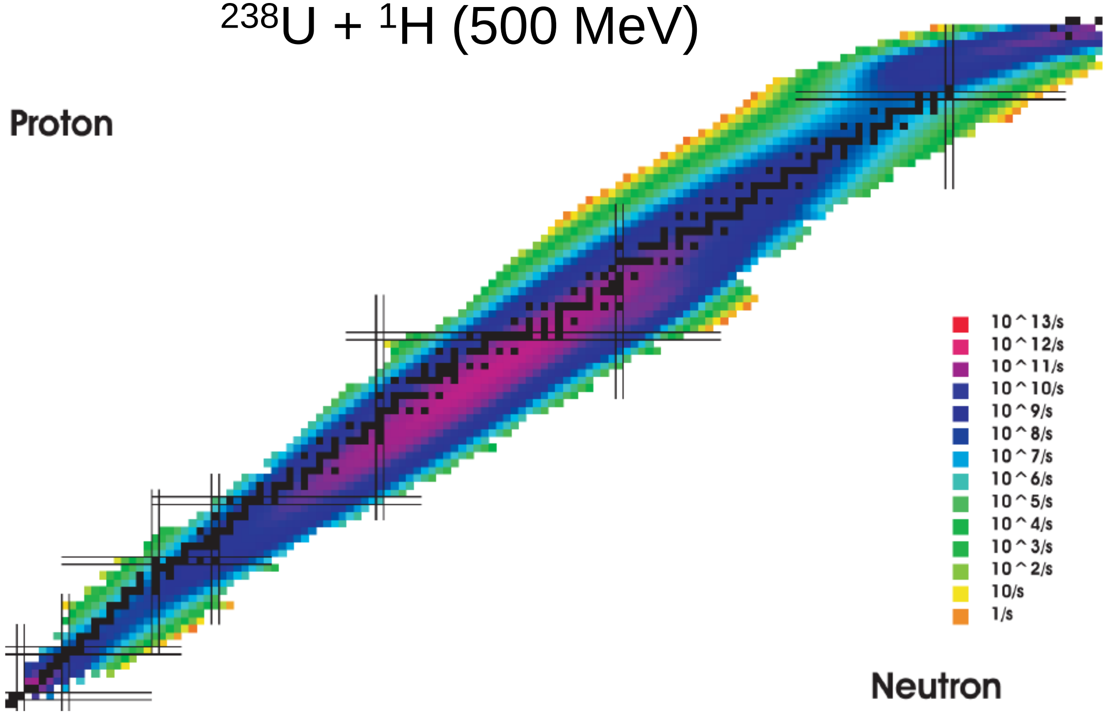
(I) Isotope production: Low energy fission



induced by: “time” (**spontaneous**)

(I) Isotope production: High energy fission

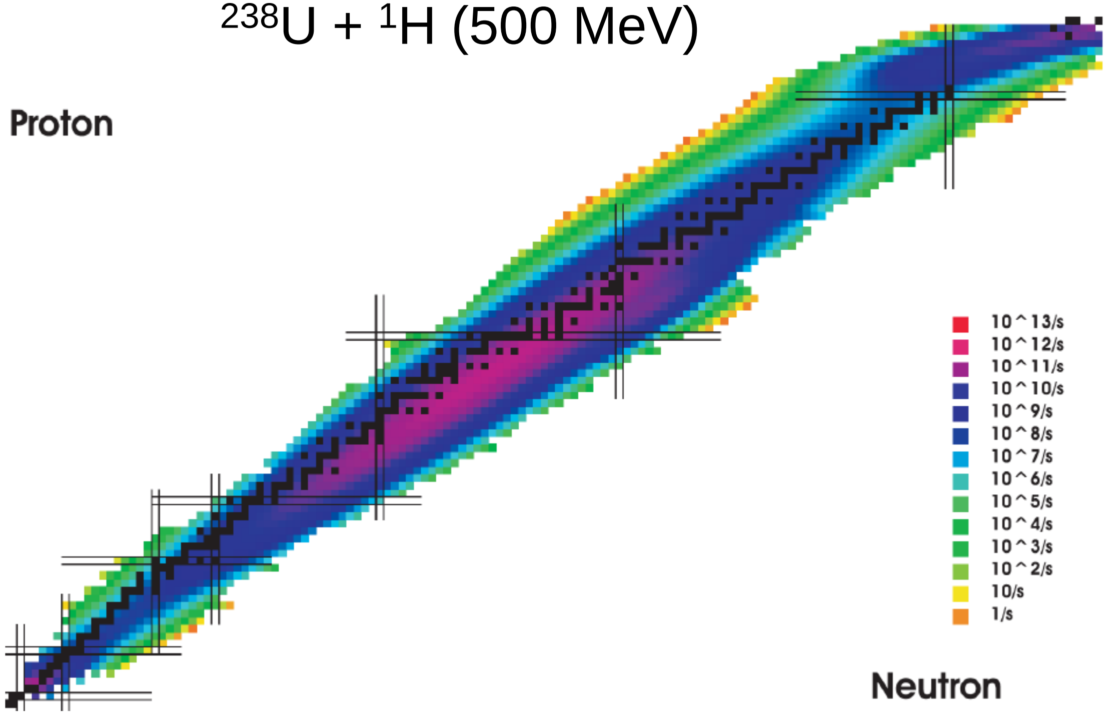
$^{238}U + ^{1}H$ (500 MeV)



- induced by: **neutrons**, photons, **protons**, heavy ions, antiprotons, pions, post fusion-evaporation, beta-decay/EC
- with increasing excitation energy **symmetric and far asymmetric fission is favored**, but the products get in average less neutron-rich!
- driver accelerators: reactors, medium-energy (some MeV to tens MeV) deuterons from cyclotron or LINAC, microtron or LINAC for electron beams,…

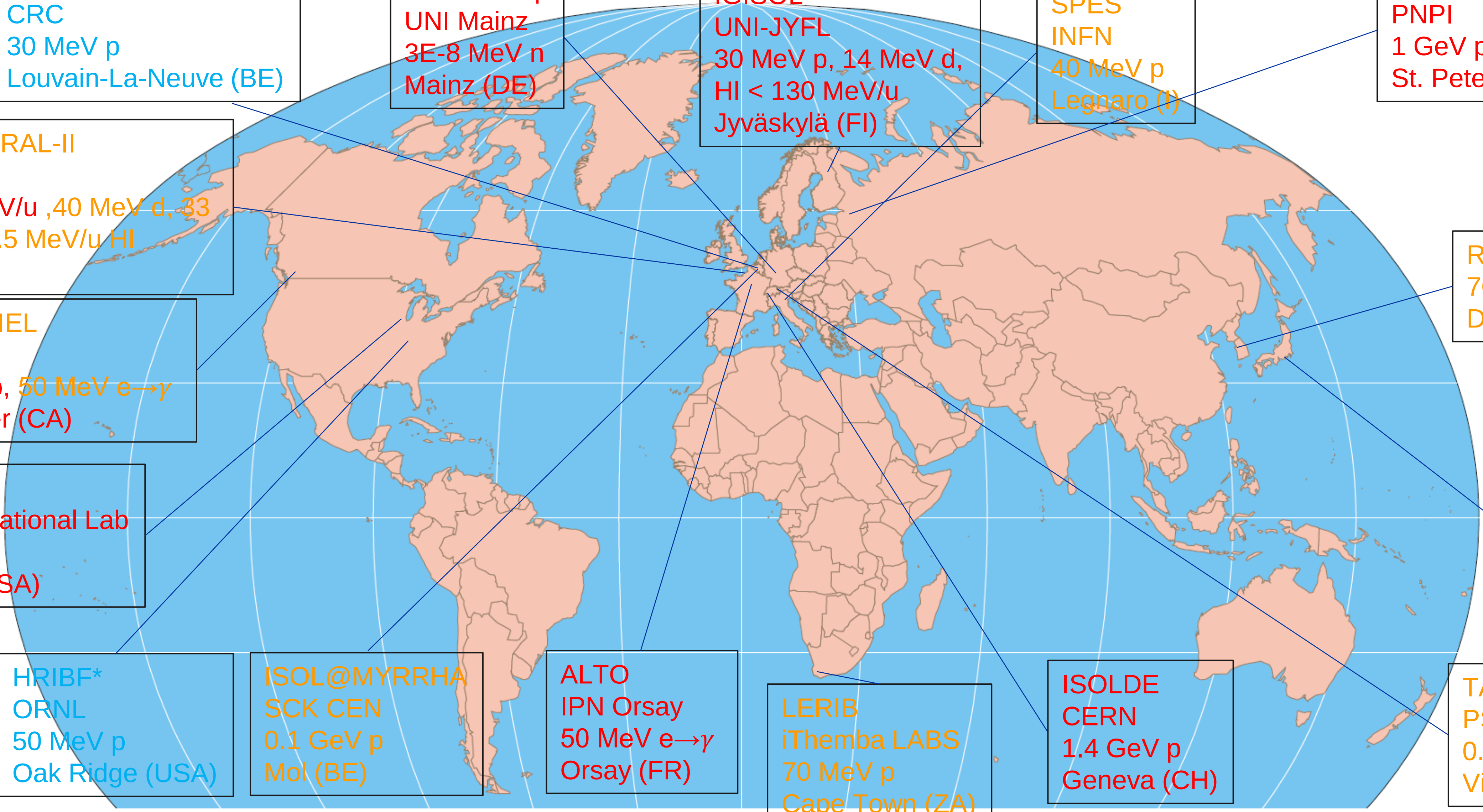
(I) Isotope production: Fragmentation

$^{238}U + {}^{1}H$ (500 MeV)



- target fragmentation needs high energy protons
- Projectile fragmentation needs high energy heavy ions
- Lower-Z fragments $Z\sim \leq 23$ (U)
- Needs, big cyclotrons, synchrotron or LINAC

Variants of ISOL facilities (past and present, future, non exhaustive)



Variants of ISOL facilities (past and present, future non exhaustive)

1a **protons on thick (heavy) target**: **fragmentation, spallation, fission**
ISOLDE-CERN (1.4 GeV), IRIS-PNPI (1 GeV), ISAC-TRIUMF (0.5 GeV), TATTOOS (0.6 GeV), ISOL@MYRRHA (0.1(6) GeV) (SCK CEN), SPES (INFN), SPIRAL2 (GANIL), LERIB (iThemba LABS), RAON

1b **direct reactions** in thick target
CRC Louvain-la-Neuve, HRIBF Oak Ridge, TRIAC Tokai, SPES (INFN), LERIB (iThemba LABS)

1c (photo) **fission** in thick target
OSIRIS (Studsvik), HRIBF Oak Ridge, TRIAC Tokai, SPIRAL2 (GANIL), ARIEL (TRIUMF), ALTO

2 **projectile fragmentation** in **thick (carbon) target**
SPIRAL (GANIL), DRIBS (Dubna), EXCYT (LNS Catania)

3 **fusion-evap**. or multinucleon transfer in **thin target** plus **solid catcher**
GSI-ISOL, UNIRIB (ORNL), DOLIS (Daresbury), LISOL (Leuven), IMP Lanzhou, MASHA (Dubna), SPIRAL2 (GANIL)

4 **fusion-evap**., **direct reaction** or **fission** in **thin target** plus **gas catcher** (Ion Guide ISOL =IGISOL)
IGISOL (Jyväskylä), LISOL (Leuven), …

(I) Isotope production: target material

Material requirements

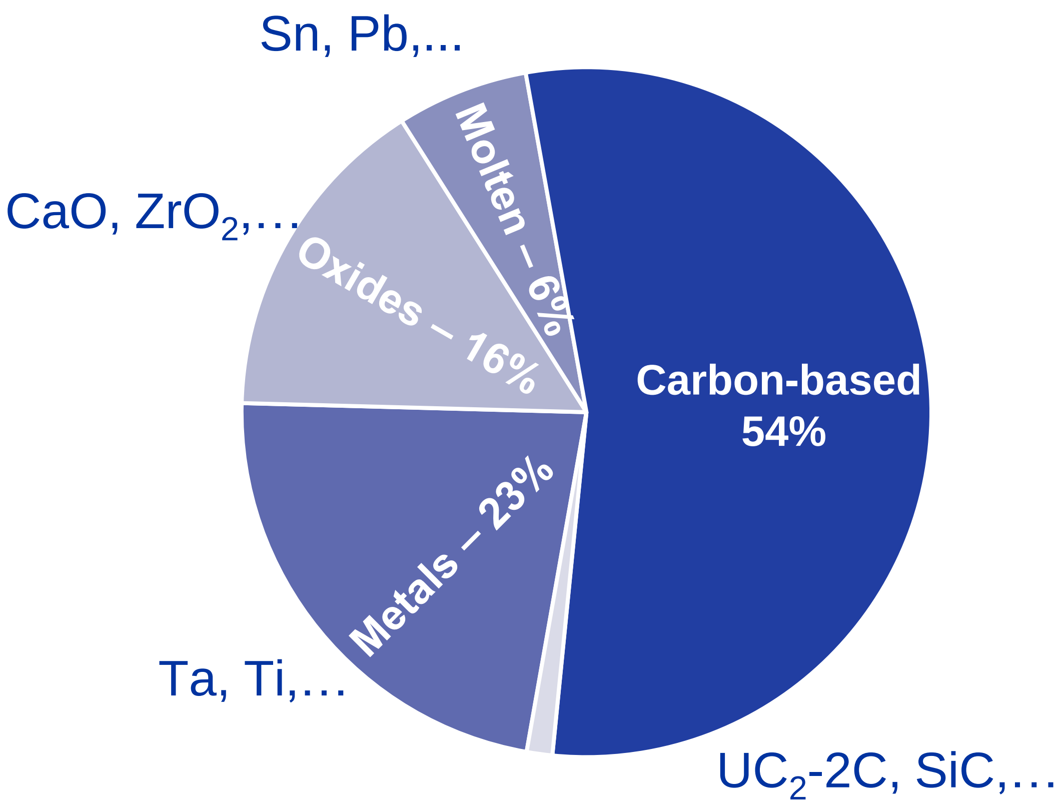
- High **production cross section** of the isotope(s) of interest
- Stability at **high temperatures**
- Chemically **stable and inert**
- Resistance to radiation damage
- Rapid **diffusion** and **effusion** rates of the element(s) of interest

Operation temperature limitations:

- **Sintering** (preserve target microstructure)
- Limited reactivity with surrounding materials
- Reduced stable beam contaminants (chemical impurities)
- Moderate equilibrium vapor pressure compatible with ion source (~10^{-4} mBar)

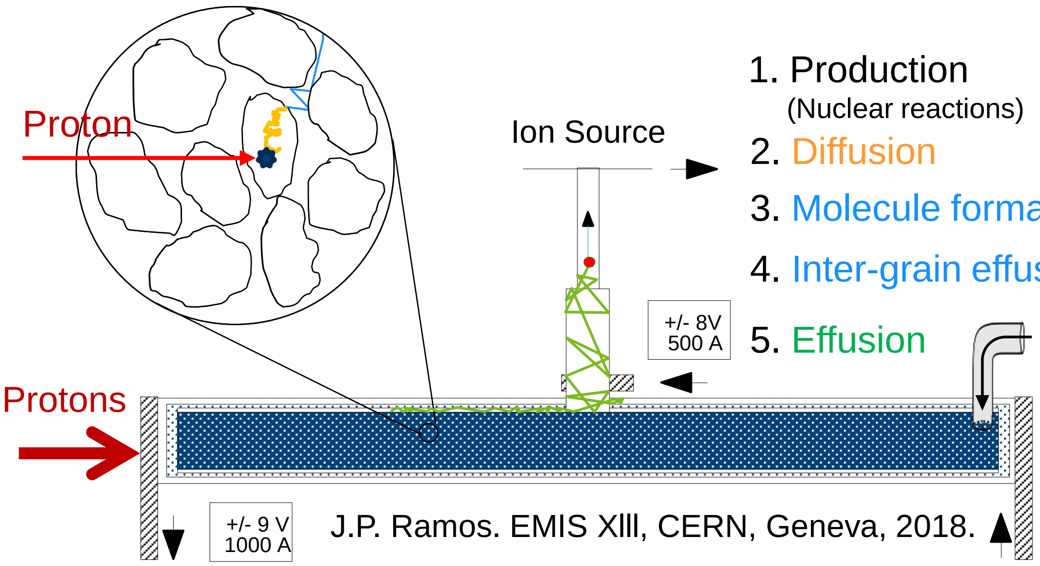
Example: ISOLDE

Target materials in the last 16 years



Powders, pellets or liquid form

(I) Isotope production: target material



1. Production
   (Nuclear reactions)
2. Diffusion
3. Molecule formation
4. Inter-grain effusion
5. Effusion

$$R = \Phi \cdot \sigma \cdot N_t \cdot \varepsilon_{rel} \cdot \varepsilon_{ion} \cdot \varepsilon_{sep} \cdot \varepsilon_{trans} \cdot \varepsilon_{det}$$

$$\varepsilon_{rel} = \varepsilon_{diff} \cdot (\varepsilon_f) \cdot \varepsilon_{eff}$$

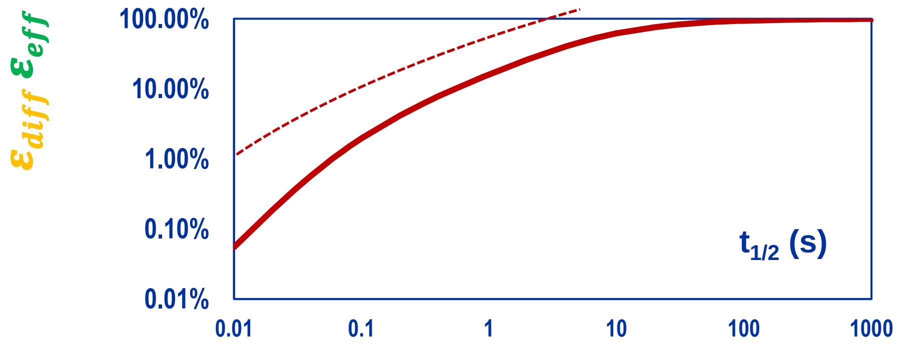
σ: ⟷ target-isotope chemistry, T-boundaries

N_t: High ρ → high production ⟷ low release

ε_{rel}: Optimize microstructure, stable at operation conditions

(I) Isotope production: target microstructure

In most cases $\varepsilon_{diff}\varepsilon_{eff}$ limit by far the yields.



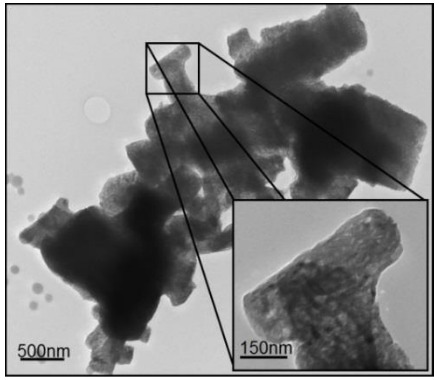
Diffusion limited release: $\lambda \leq 2\mu$

$$\varepsilon_{diff} = \frac{3}{\pi}\sqrt{\frac{\mu}{\lambda}}, \mu = \frac{\pi^2 D}{r^2} \Rightarrow r/10 \Rightarrow \varepsilon_{diff}\text{x}10$$

Same T!

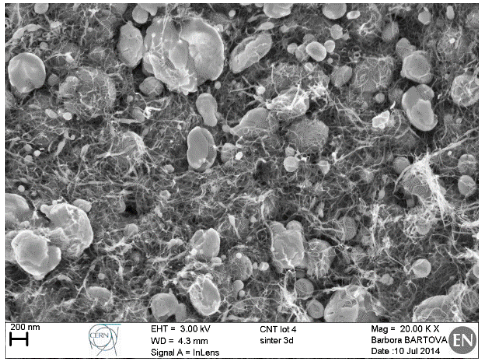
Operation T ⟷ Sintering - Grain size/Porosity

Specific surface area ⟷ Reactivity



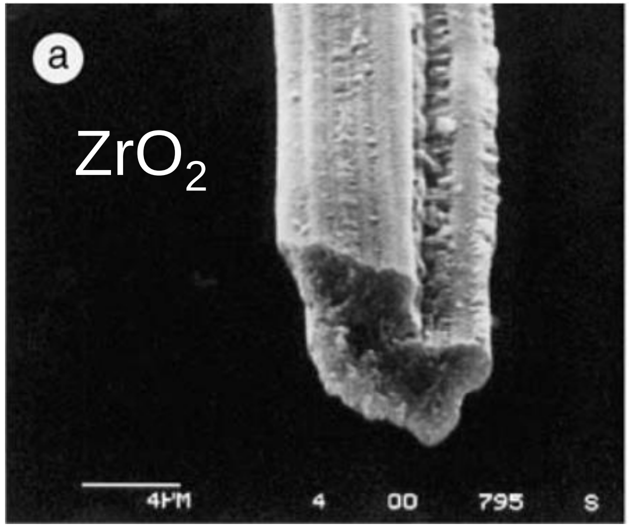
2011

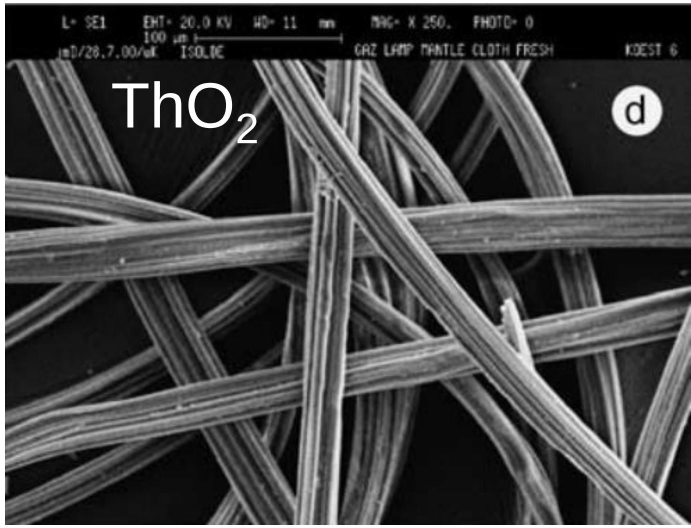
CaO – J.P. Ramos, et al.



Nov- 2014

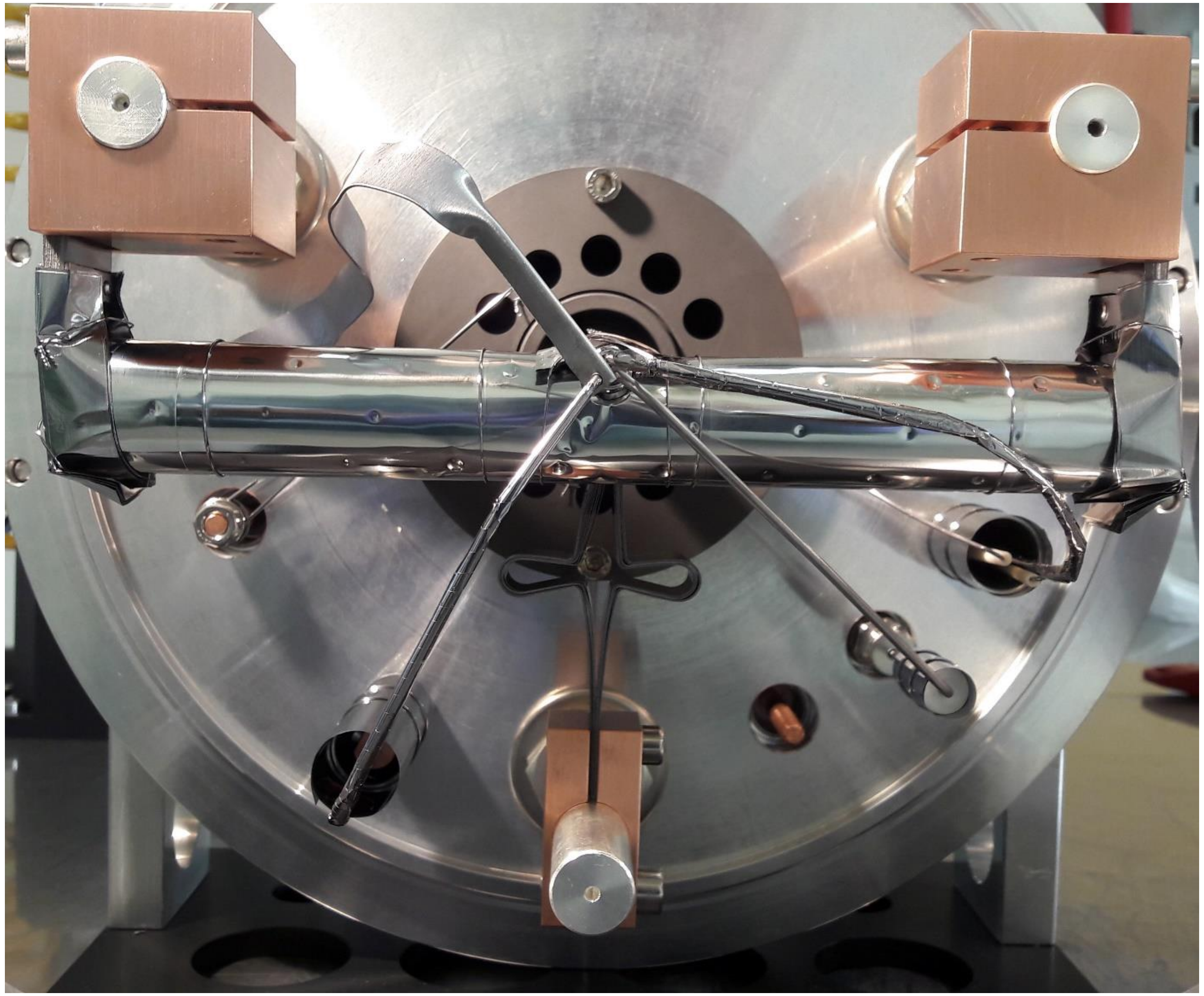
LaC_2 + 2C – J. Guillot, et al.

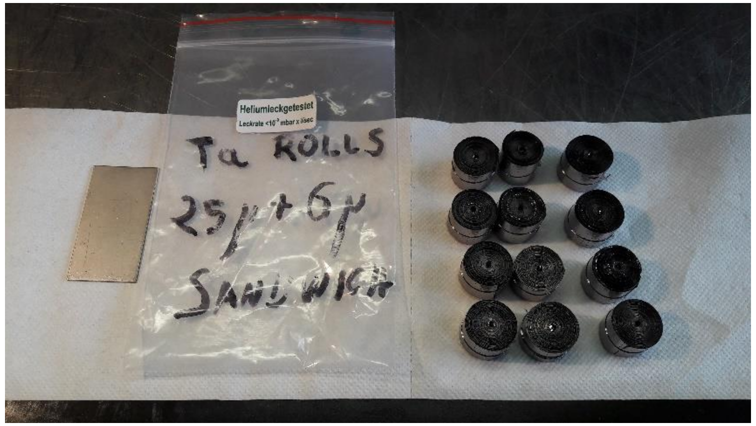


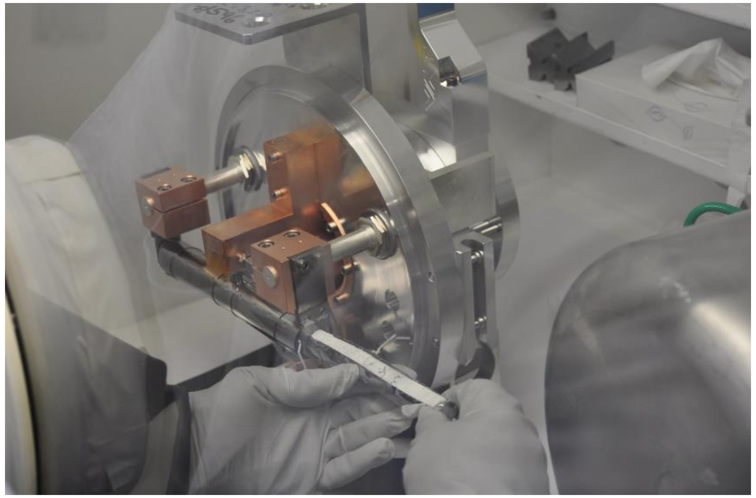


J.P. Ramos, et al. NIM B 320 (2014). 10.1016/j.nimb.2013.12.009
U. Köster, et al. NIM B 204 (2003). 1016/S0168-583X(03)00505-6
J. Guillot. PhD thesis. (2017)

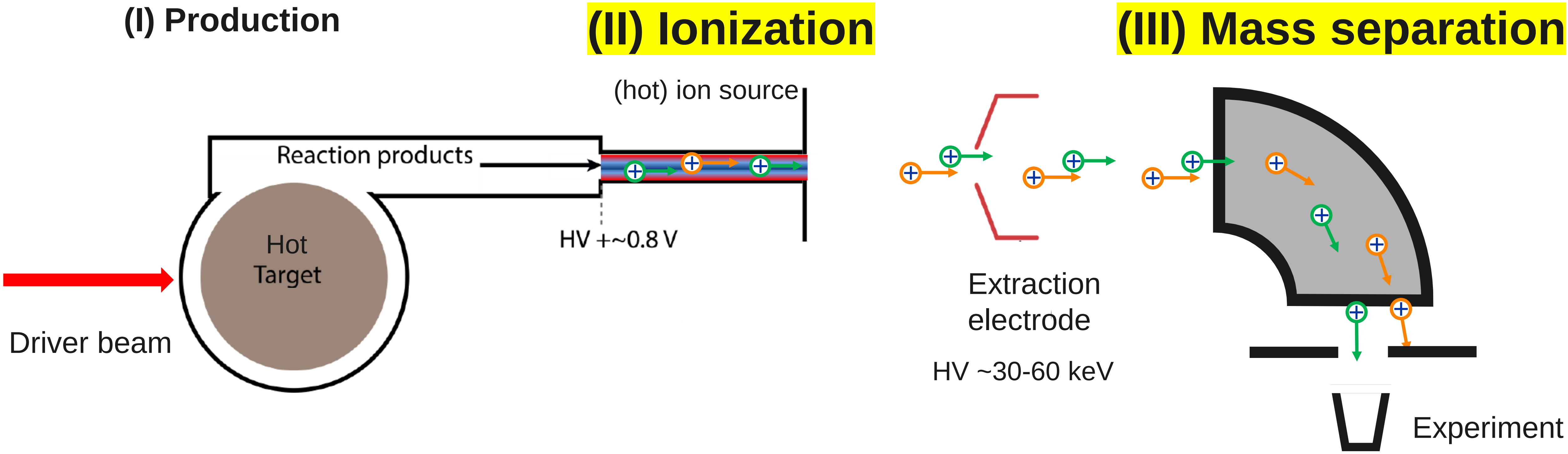
Example ISOLDE :Target and ion source unit



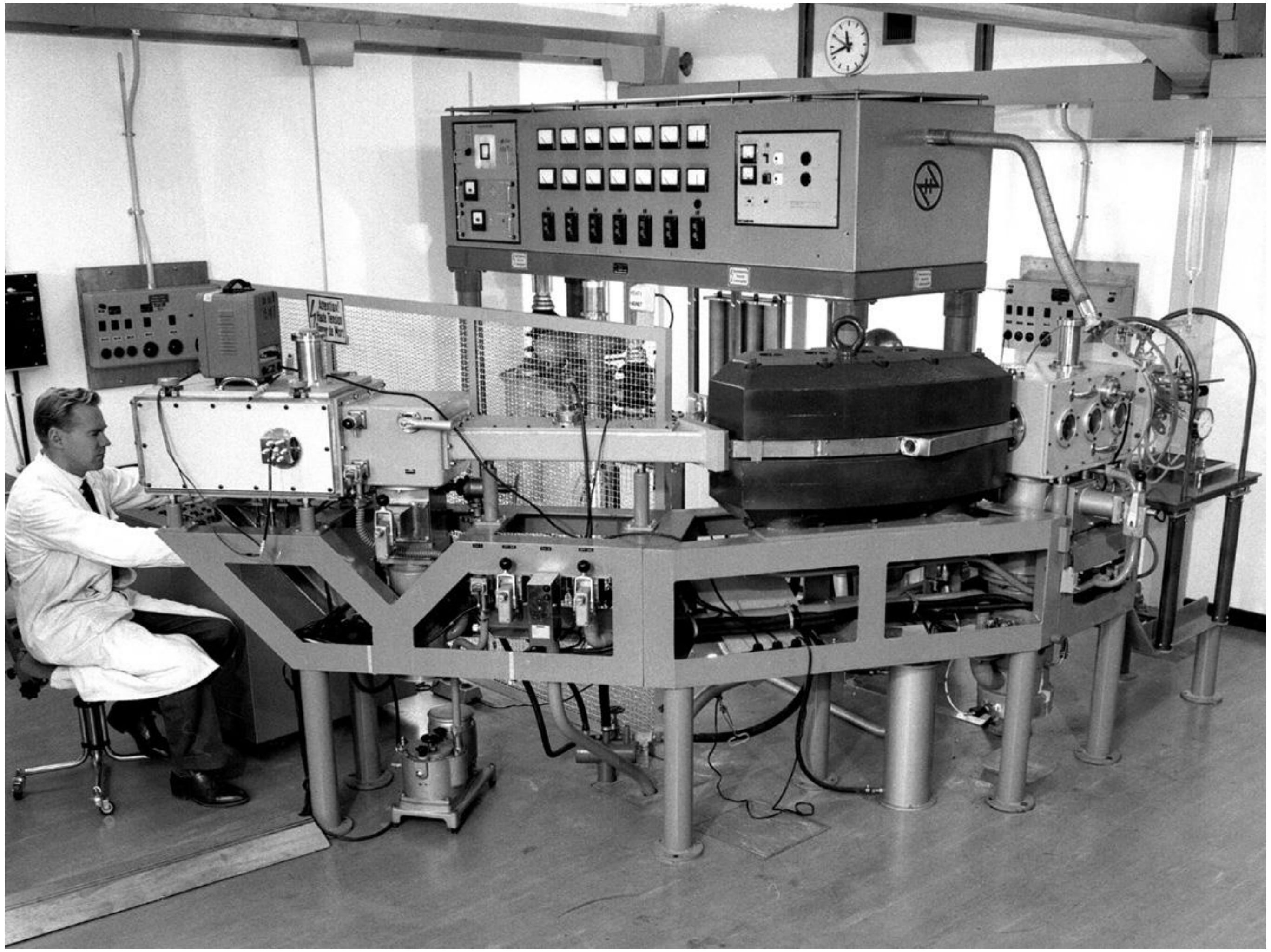




ISOL: stages

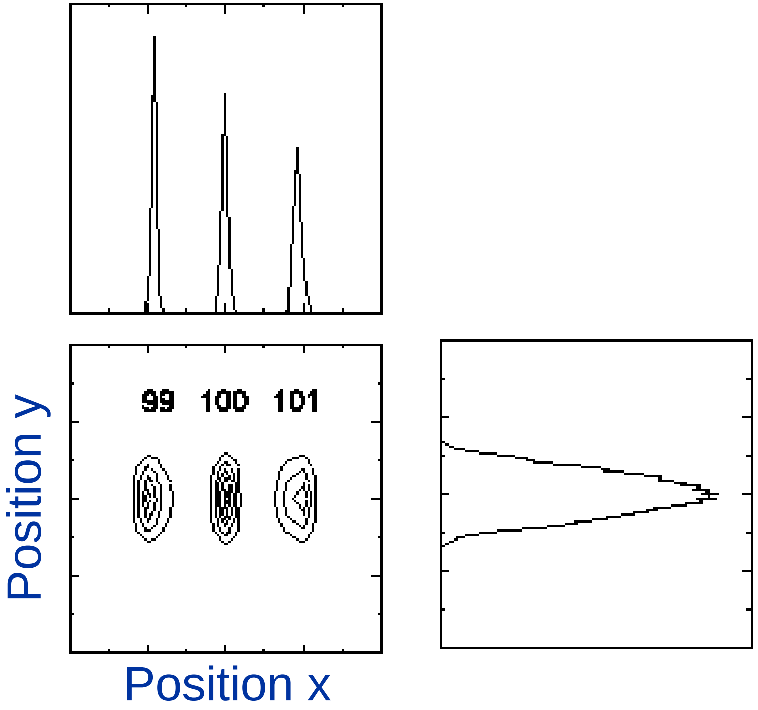

(I) Production
(II) Ionization
(III) Mass separation
(hot) ion source
Reaction products
Hot
Target
HV +~0.8 V
Driver beam
Extraction
electrode
HV ~30-60 keV
Experiment

(III) Mass separation



- Ionization to typ. q = 1+
- Acceleration to e.g. 60 keV
- Mass selection by magnetic deflectio (Lorentz force)

$$(B\rho = p/q \propto \sqrt{A})$$



(III) Mass separation

- onization to typ. q = 1+
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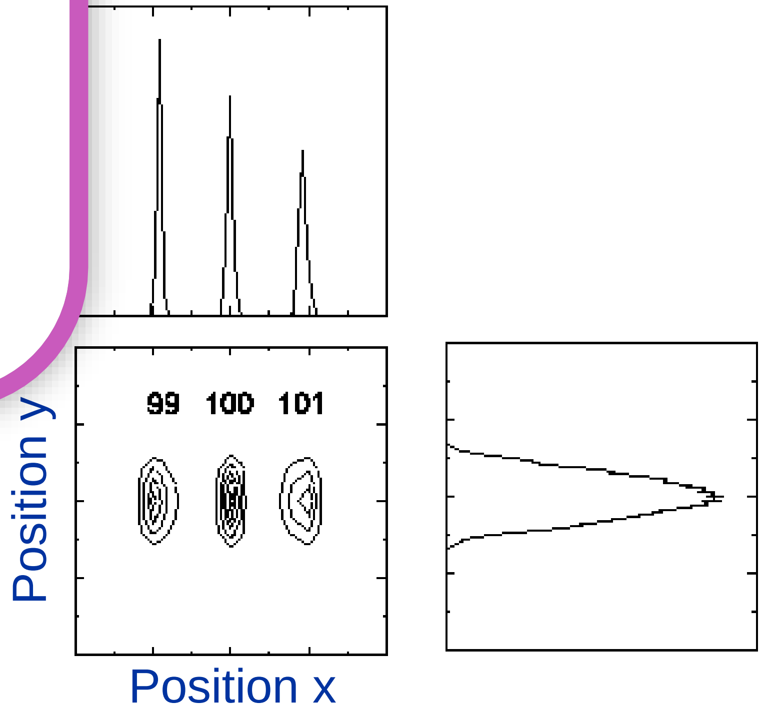
($B\rho = p/q \propto \sqrt{A}$)



(II) Ionization

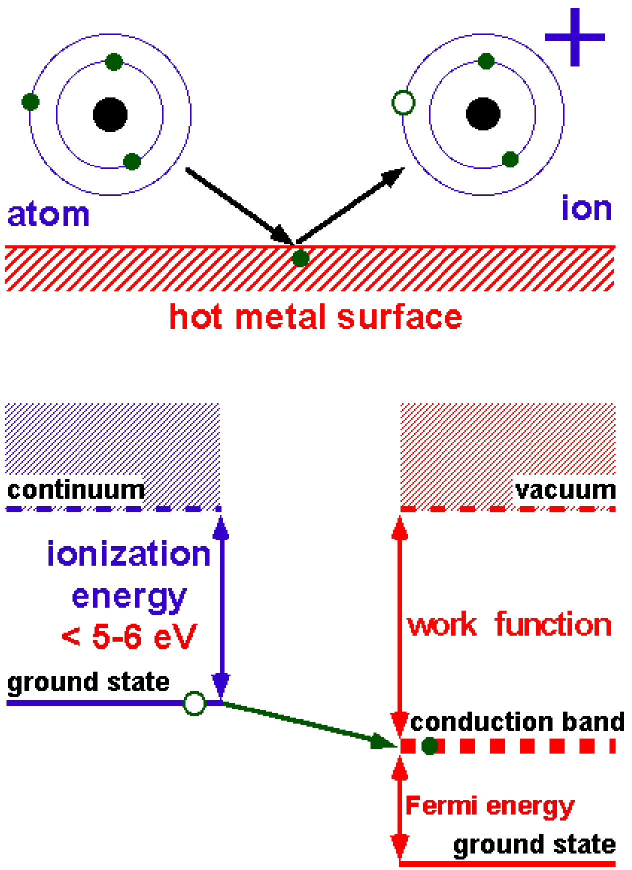
Surface Ionization

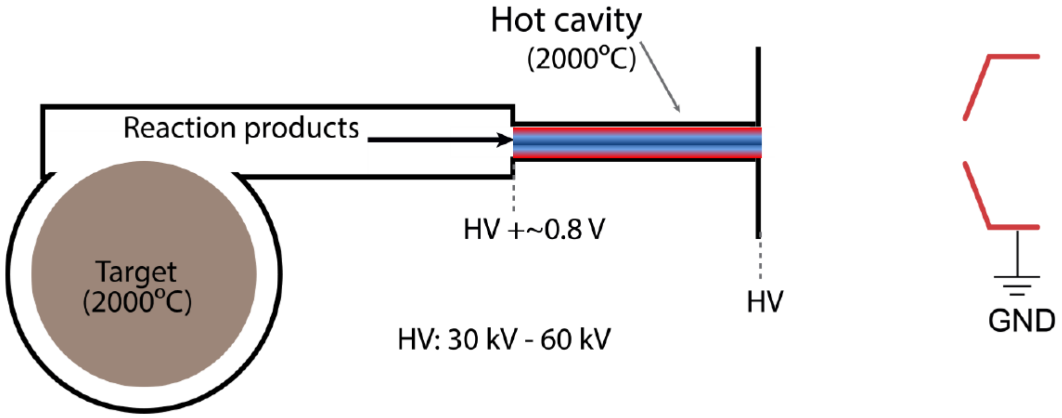
Laser Ionization

Ionization by electron impact

(II) Ionization

Surface Ionization





$$\alpha = N \cdot \varepsilon \cdot e^{\frac{\phi - IP}{k_B T}}$$

$$\varepsilon_{ion} \approx \frac{\alpha}{1+\alpha}$$

Increasing the work function increases the ionization efficiency if $N \cdot \varepsilon$ are preserved
→ Sufficient thermal electron emission must be maintained

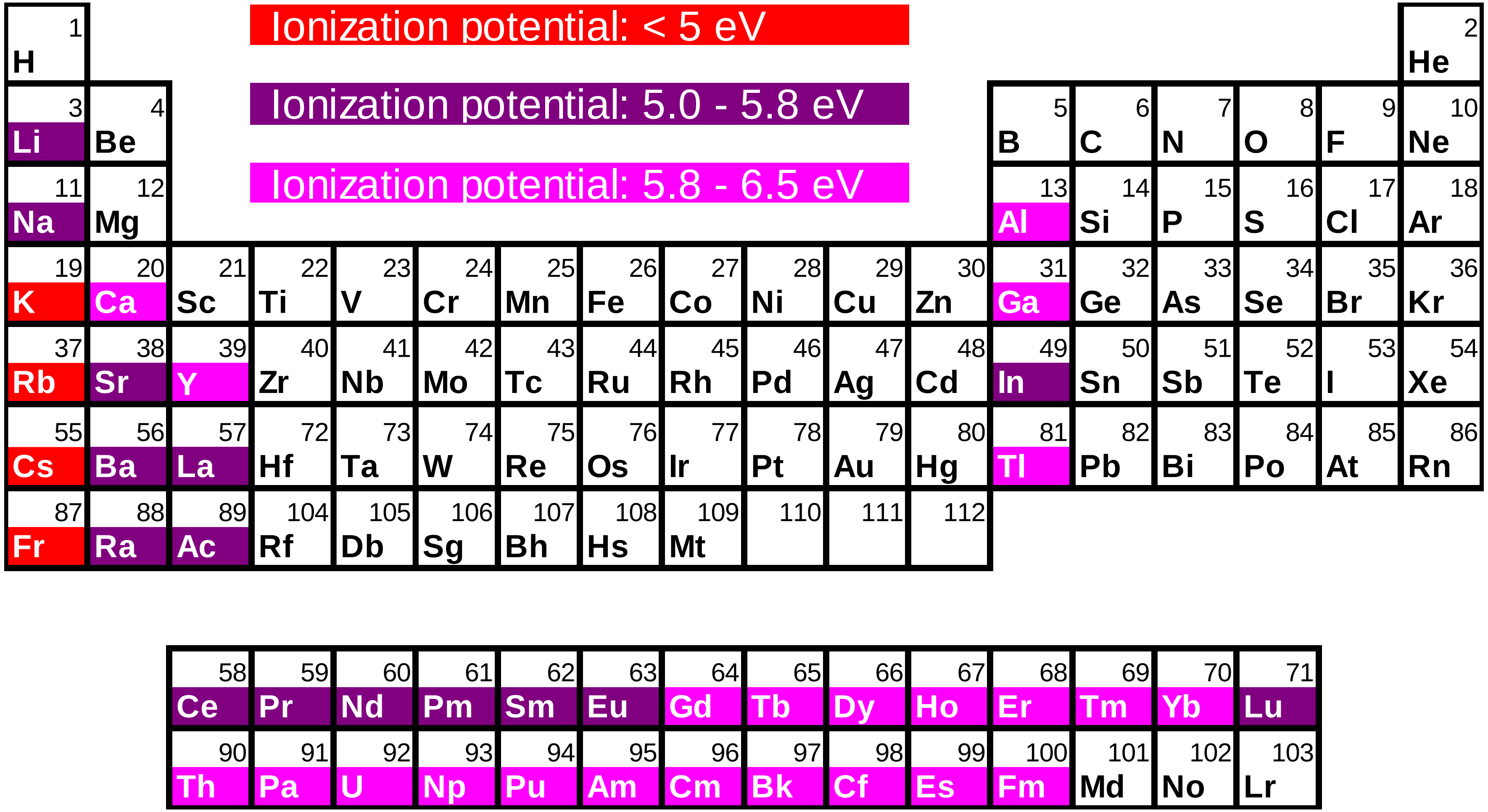
α: ionization degree
N: atom-wall collision
ε: ion survival probability

ϕ: *work function*
IP: ionization potential
$k_B T$: *Boltzmann constant and temperature*

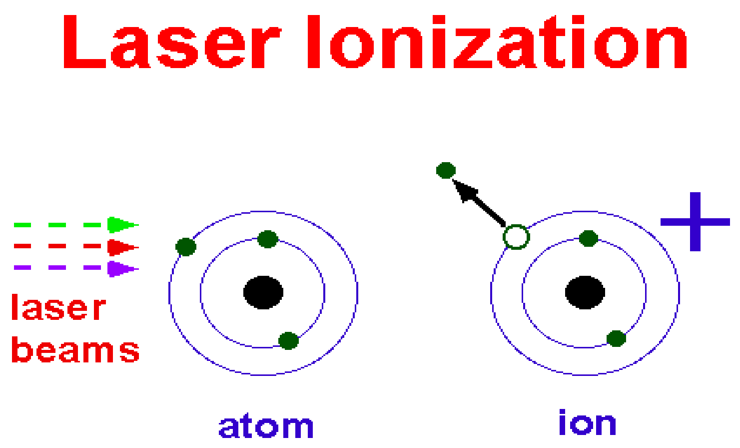
[UK06-mod, TDG17-mod]

R. Kirchner. NIM 198 (1981) 10.1016/0029-554X(81)90916-2
R. Kirchner. NIM A 292 (1990). 10.1016/0168-9002(90)90377-I
R. Kirchner. NIM B 204 (2003). 10.1016/S0168-583X(02)01900-6

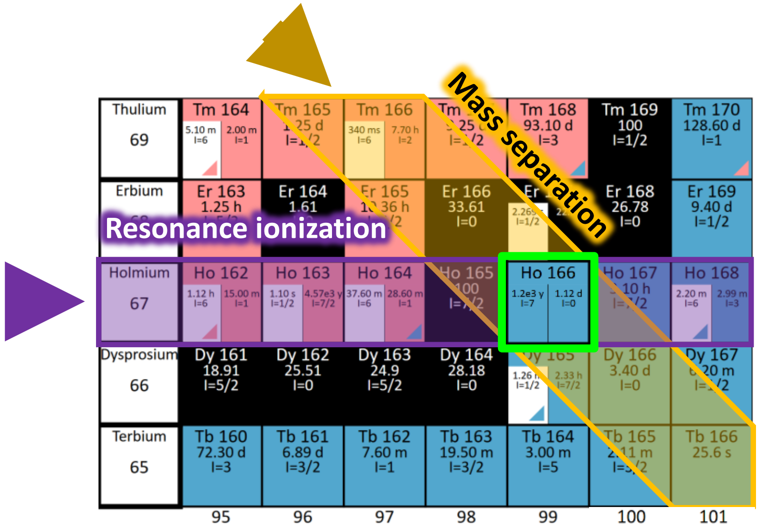
Ionization potentials of the elements



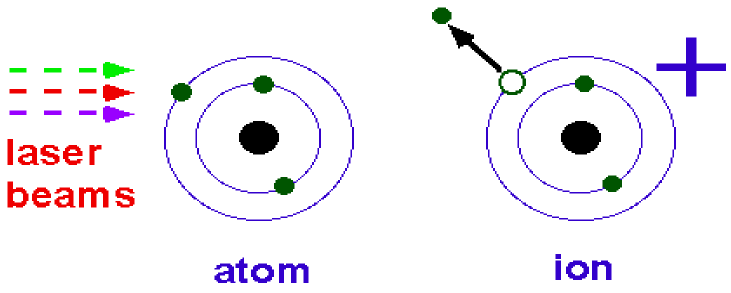
(II) Ionization



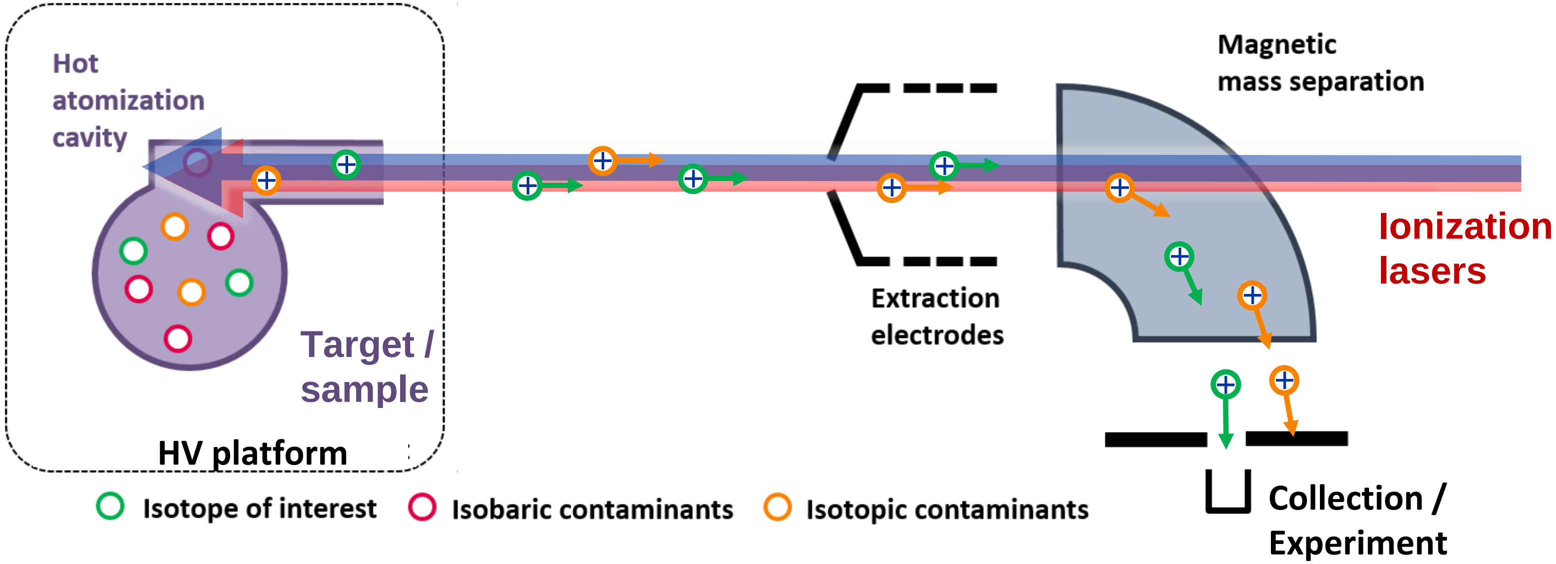
(II) Ionization

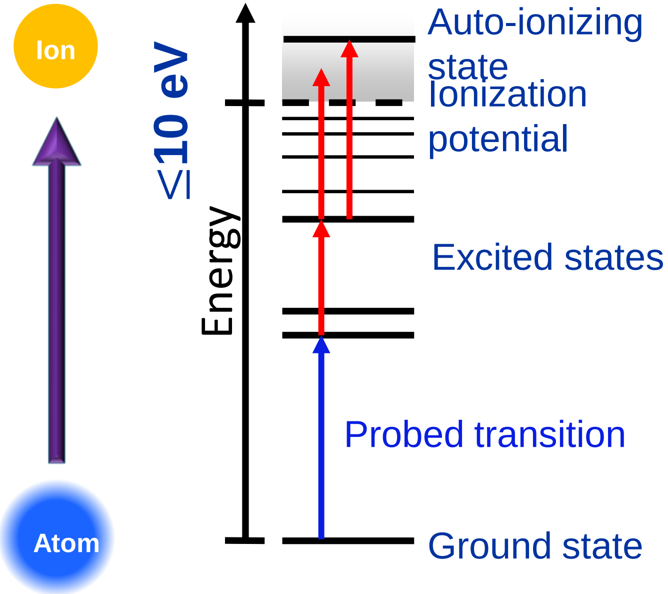


Laser Ionization

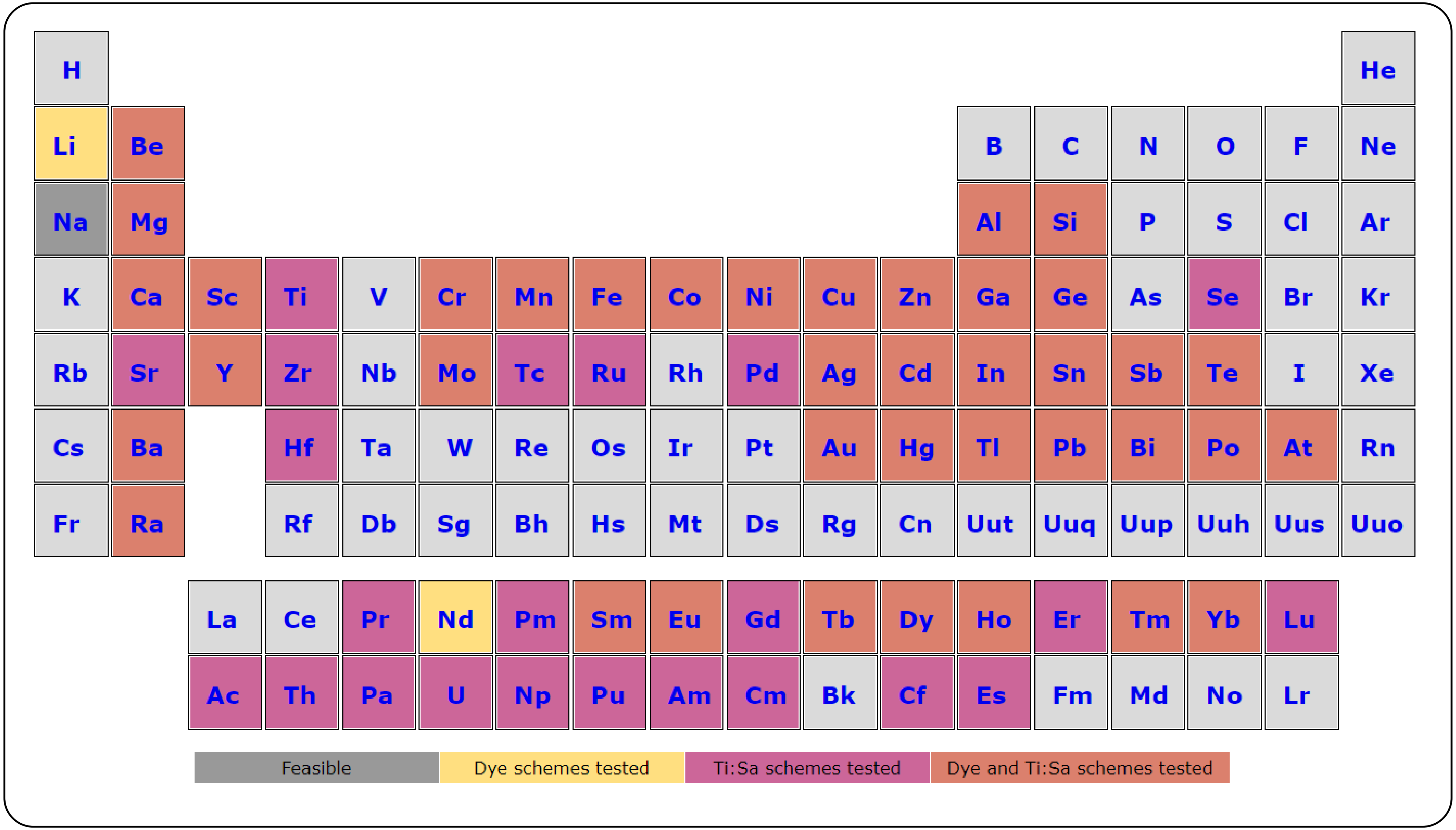


CERN-RILIS: Resonance Ionization Laser Ion source

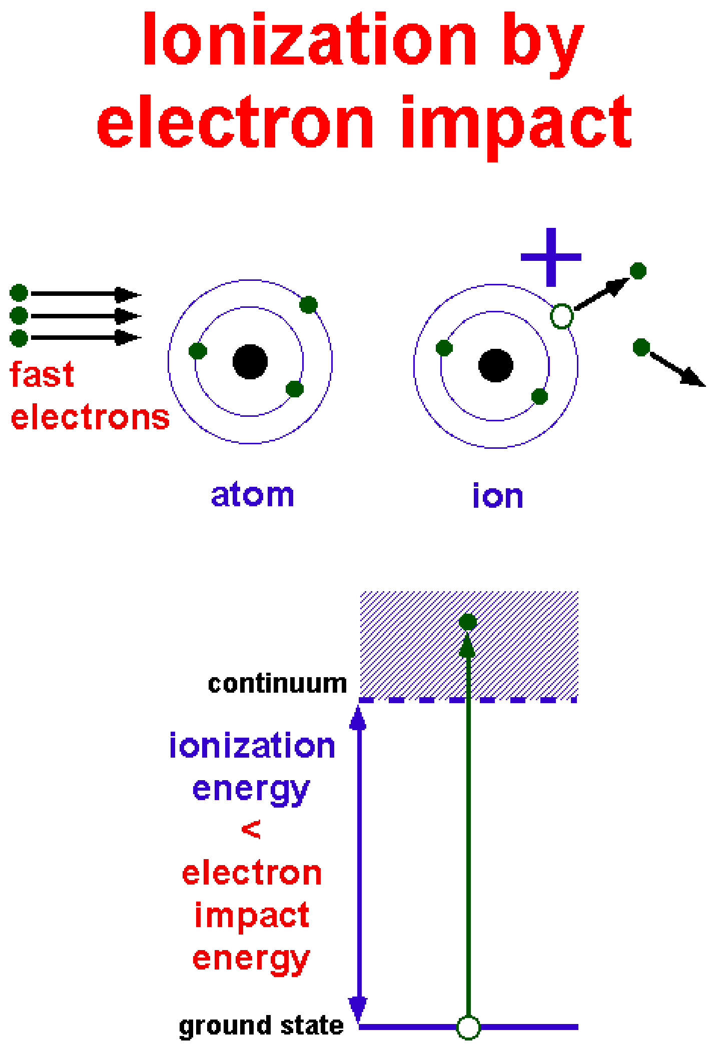




RILIS elements

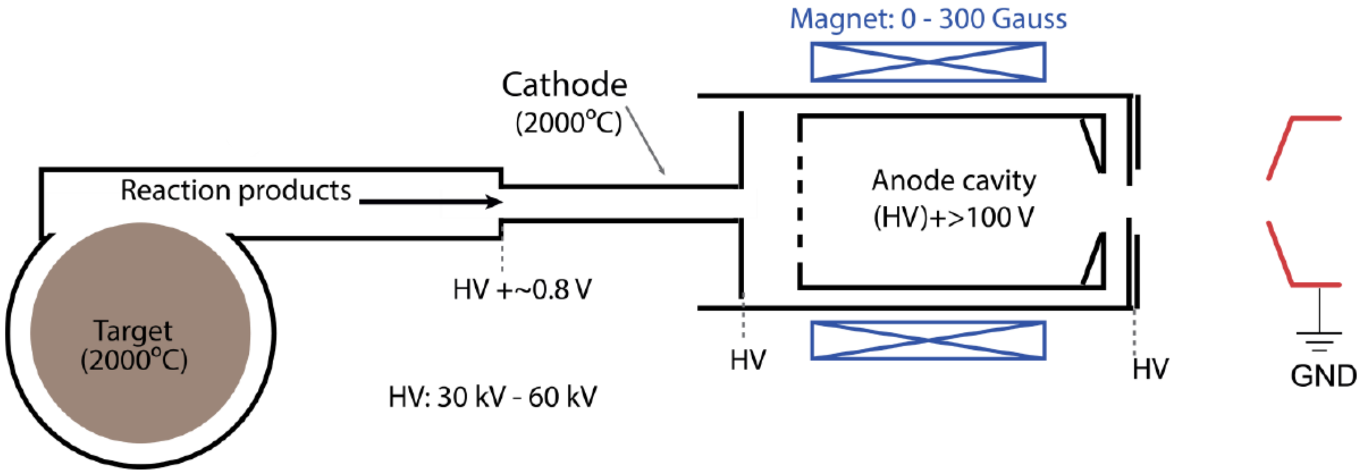


(II) Ionization

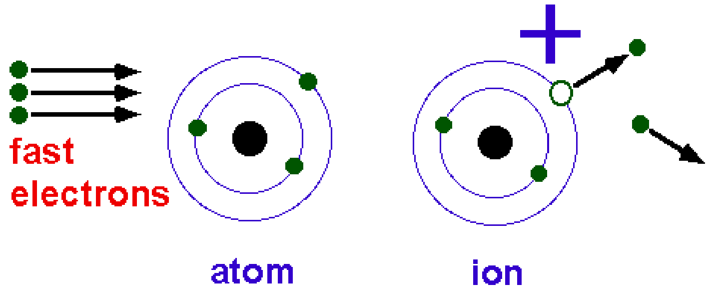


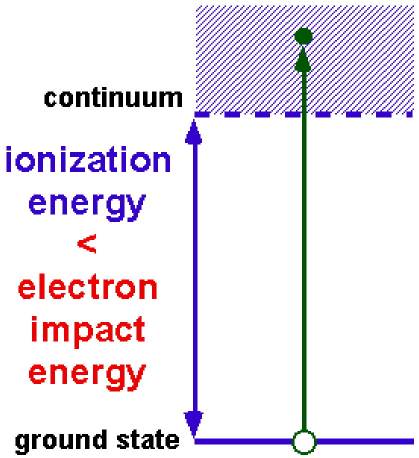
(II) Ionization:

Example: Forced Electron Beam Arc Discharge ion source



Ionization by electron impact





Properties

+ **universal ionization** (our “dirty” ion source)
+ **good efficiency for noble gasses and volatile species**
+ moderate emittance (<20 π mm mrad at 15 kV, 95%)
- Limited lifetime
+ stable operation with little support gas (Pressures 5E-4 to 3E-5 mbar)
+ low ion current density (1-20 μA/mm^2)
+ low energy spread (<2 eV)
+ volume as small as 1.3 cm^3 (6 ms intrinsic delay)

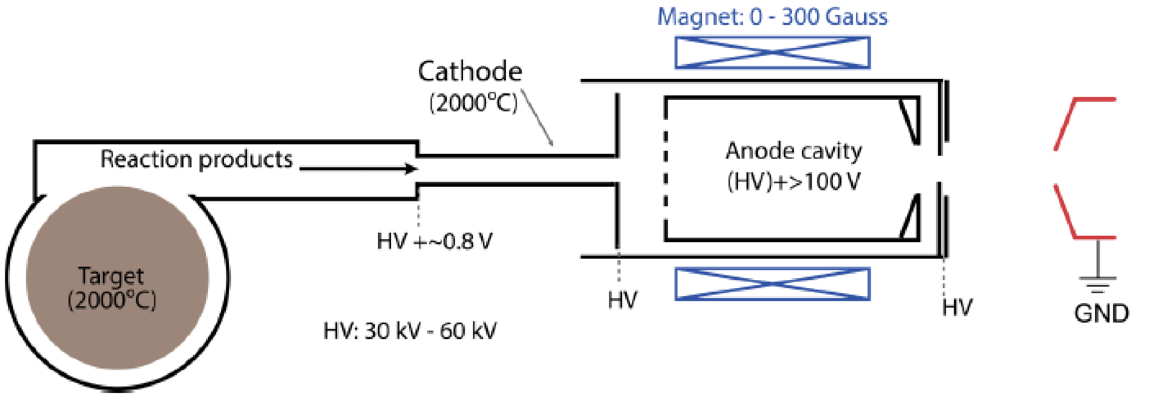
FEBIAD : Forced Electron Beam Arc Discharge ion source

1. Efficiency: ~universal typically 1-50 %
2. Extraction/ionization time: ~10-100 ms (neglecting sticking times)
3. Chemical selectivity: Introduced via transfer line development

Selective operation for:

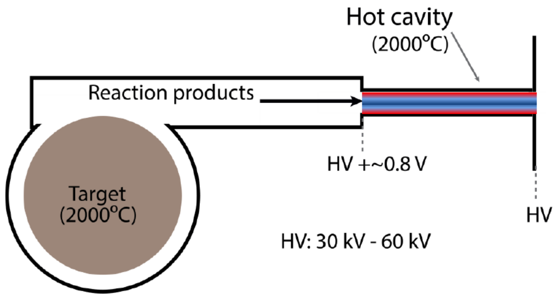
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	**2 He**
2	3 Li	4 Be											5 B	**6 C**	**7 N**	8 O	9 F	**10 Ne**
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	**18 Ar**
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	**36 Kr**
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	**48 Cd**	49 In	50 Sn	51 Sb	52 Te	53 I	**54 Xe**
6	55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	**80 Hg**	81 Tl	82 Pb	83 Bi	84 Po	85 At	**86 Rn**
7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo
Lanthanides				57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides				89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

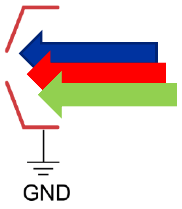
Dedicated arc discharge ion source for ISOL: operation over a range of pressures down to 10^{-5} mbar

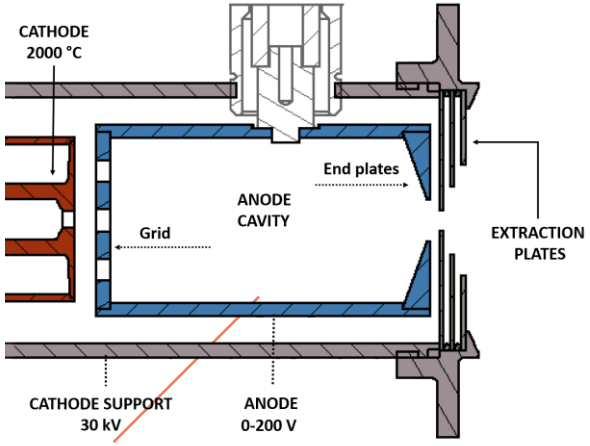


(II) Ionization: overview

ISOLDE







Hot cavity

Surface ionization | Laser ionization | FEBIAD – Plasma ion source

Efficiency

Universality

Selectivity

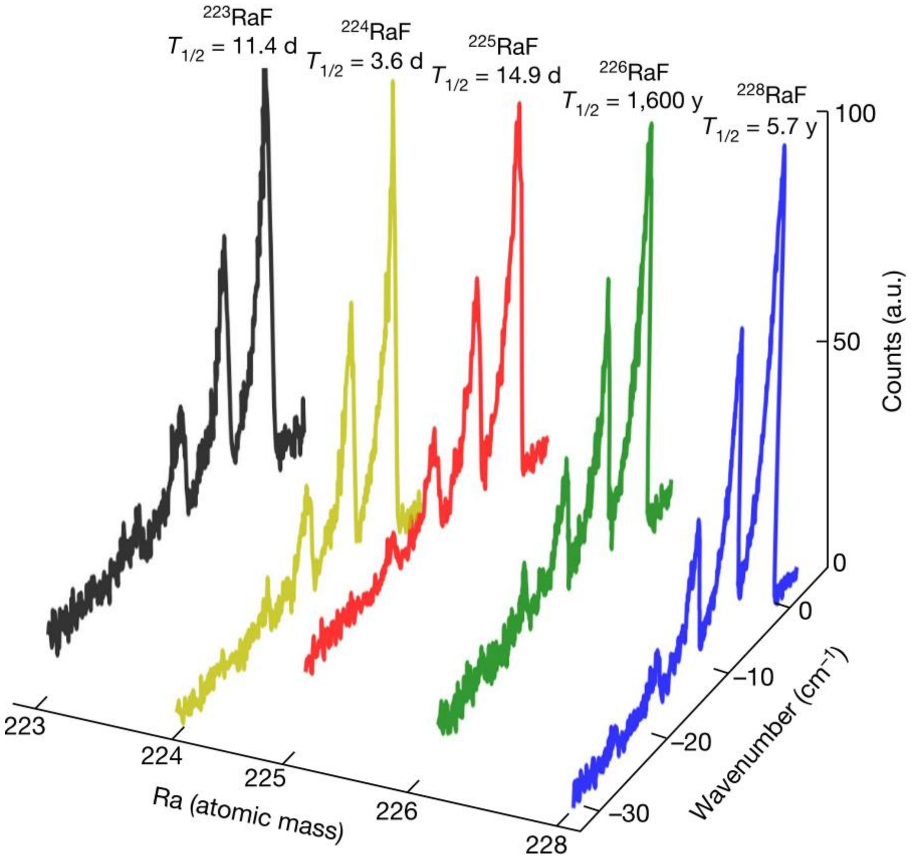
Simplicity

Reliability

[YM17-mod, SR22]

Content

Laser spectroscopy of radioactive molecules



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Article | Open Access | Published: 27 May 2020

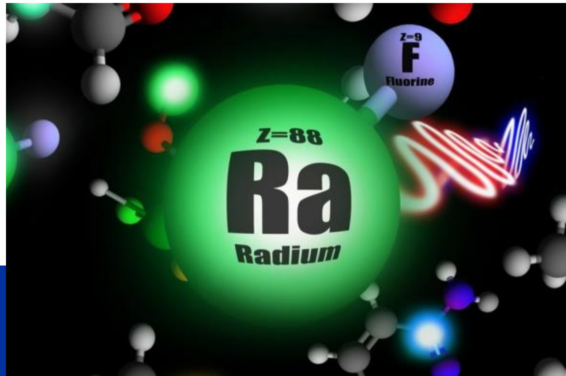
Spectroscopy of short-lived radioactive molecules

R. F. Garcia Ruiz, R. Berger, J. Billowes, C. L. Binnersley, M. L. Bissell, A. A. Breier, A. J. Brinson, K. Chrysalidis, T. E. Cocolios, B. S. Cooper, K. T. Flanagan, T. F. Giesen, R. P. de Groote, S. Franchoo, F. P. Gustafsson, T. A. Isaev, Á. Koszorús, G. Neyens, H. A. Perrett, C. M. Ricketts, S. Rothe, L. Schweikhard, A. R. Vernon, K. D. A. Wendt, F. Wienholtz, S. G. Wilkins & X. F. Yang — Show fewer authors

Nature **581**, 396–400 (2020) | Cite this article

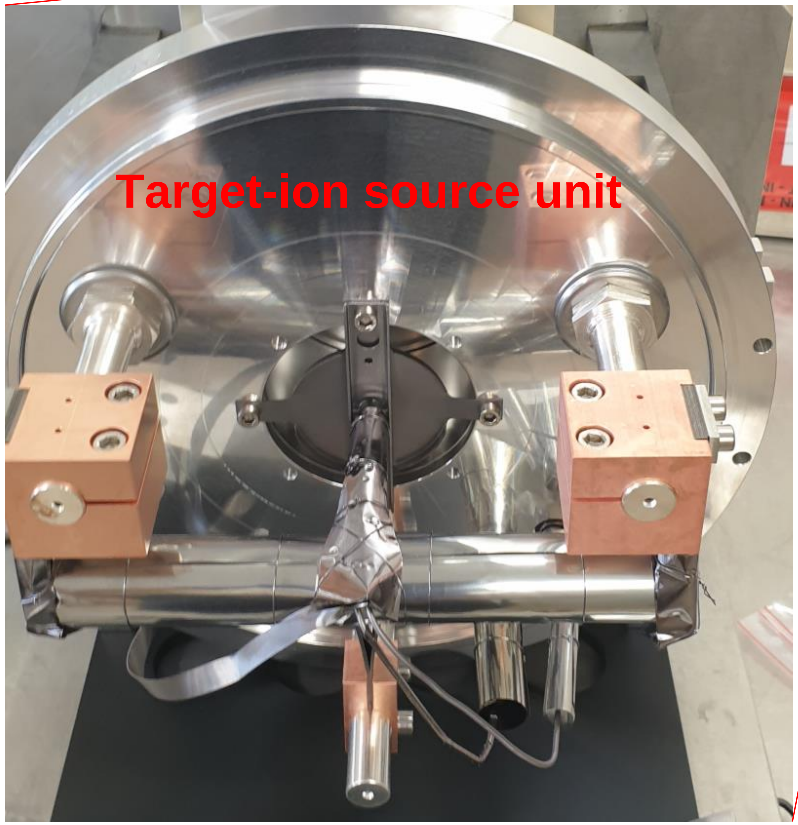
Abstract

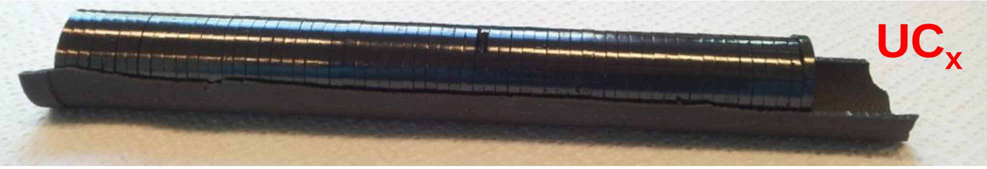
Molecular spectroscopy offers opportunities for the exploration of the fundamental laws of nature and the search for new particle physics beyond the standard model[1,2,3,4]. Radioactive molecules—in which one or more of the atoms possesses a radioactive nucleus—can contain heavy and deformed nuclei, offering high sensitivity for investigating parity- and time-reversal-violation effects[5,6]. Radium monofluoride, RaF, is of particular interest because it is predicted to have an electronic structure appropriate for laser cooling[6], thus paving the way

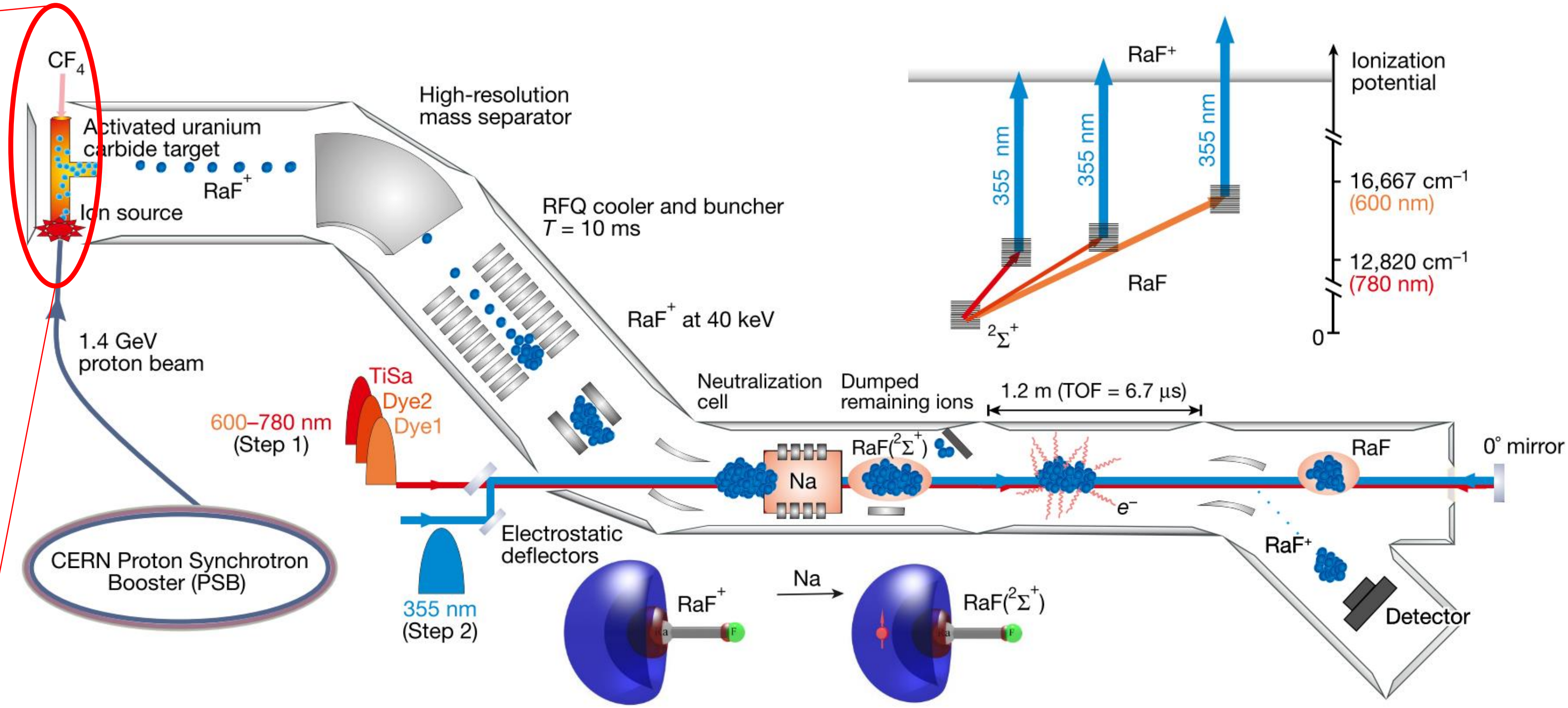


- 1st laser spectroscopy of short-lived radioactive molecules
- $^{223-226,228}$RaF
- ➢ Avenue for search of physics beyond the standard model

Laser spectroscopy of radioactive molecules

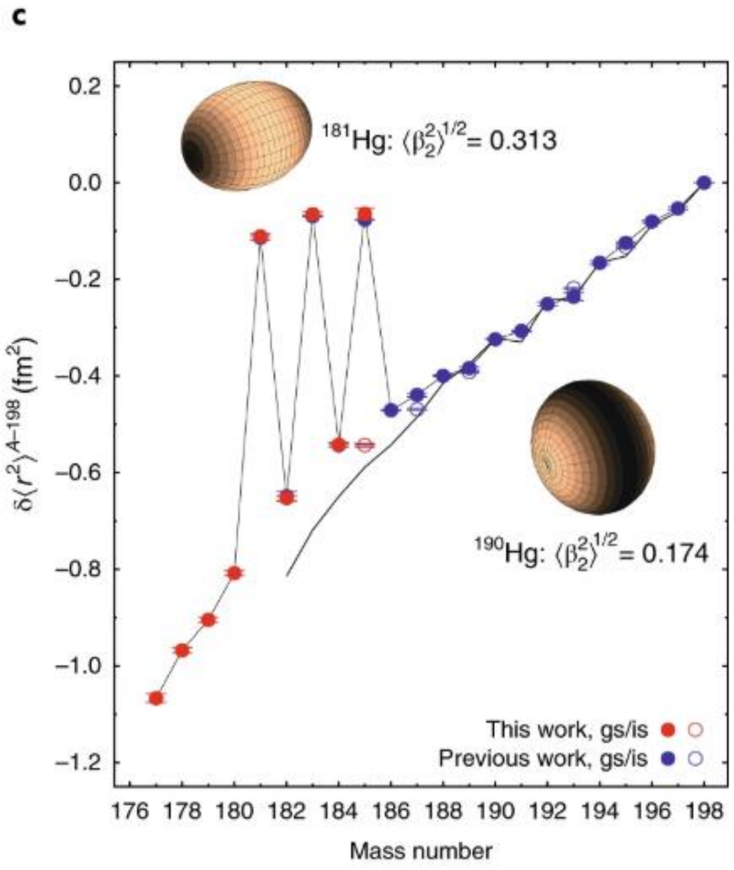






- ➢ UC_x target with W-surface ion source with CF_4 injection
- ➢ Collinear Resonance Ionization Spectroscopy (CRIS) setup

Shape staggering in Hg-isotopes



- Odd-even shape staggering for $^{181\text{-}185}$Hg isotopes
- Monopole and quadrupole interactions driving quantum phase transitions

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Letter | Published: 01 October 2018

Characterization of the shape-staggering effect in mercury nuclei

B. A. Marsh, T. Day Goodacre, S. Sels, Y. Tsunoda, B. Andel, A. N. Andreyev, N. A. Althubiti, D. Atanasov, A. E. Barzakh, J. Billowes, K. Blaum, T. E. Cocolios, J. G. Cubiss, J. Dobaczewski, G. J. Farooq-Smith, D. V. Fedorov, V. N. Fedosseev, K. T. Flanagan, L. P. Gaffney, L. Ghys, M. Huyse, S. Kreim, D. Lunney, K. M. Lynch, V. Manea, Y. Martinez Palenzuela, P. L. Molkanov, T. Otsuka, A. Pastore, M. Rosenbusch, R. E. Rossel, S. Rothe, L. Schweikhard, M. D. Seliverstov, P. Spagnoletti, C. Van Beveren, P. Van Duppen, M. Veinhard, E. Verstraelen, A. Welker, K. Wendt, F. Wienholtz, R. N. Wolf, A. Zadvornaya & K. Zuber

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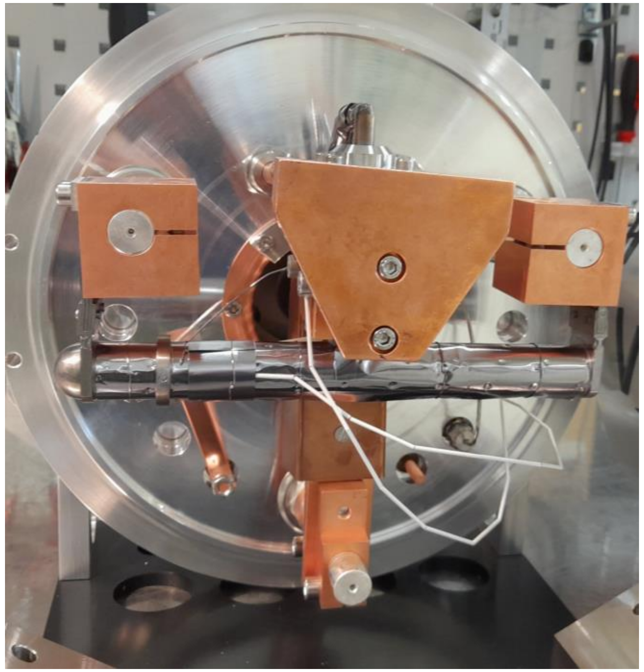
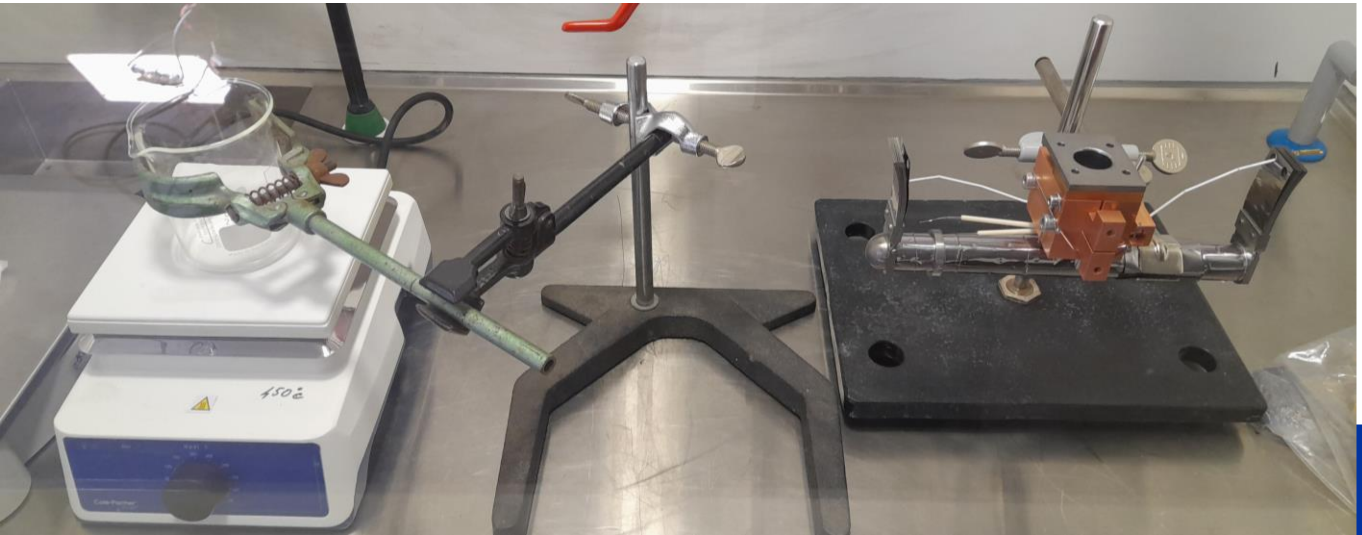
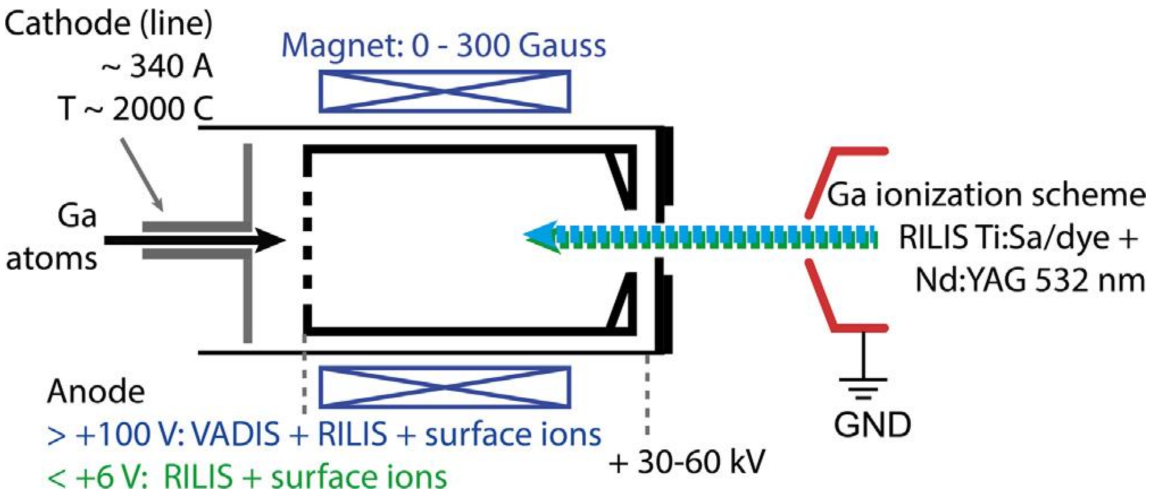
Nature Physics **14**, 1163–1167 (2018) | Cite this article

Shape staggering in Hg-isotopes



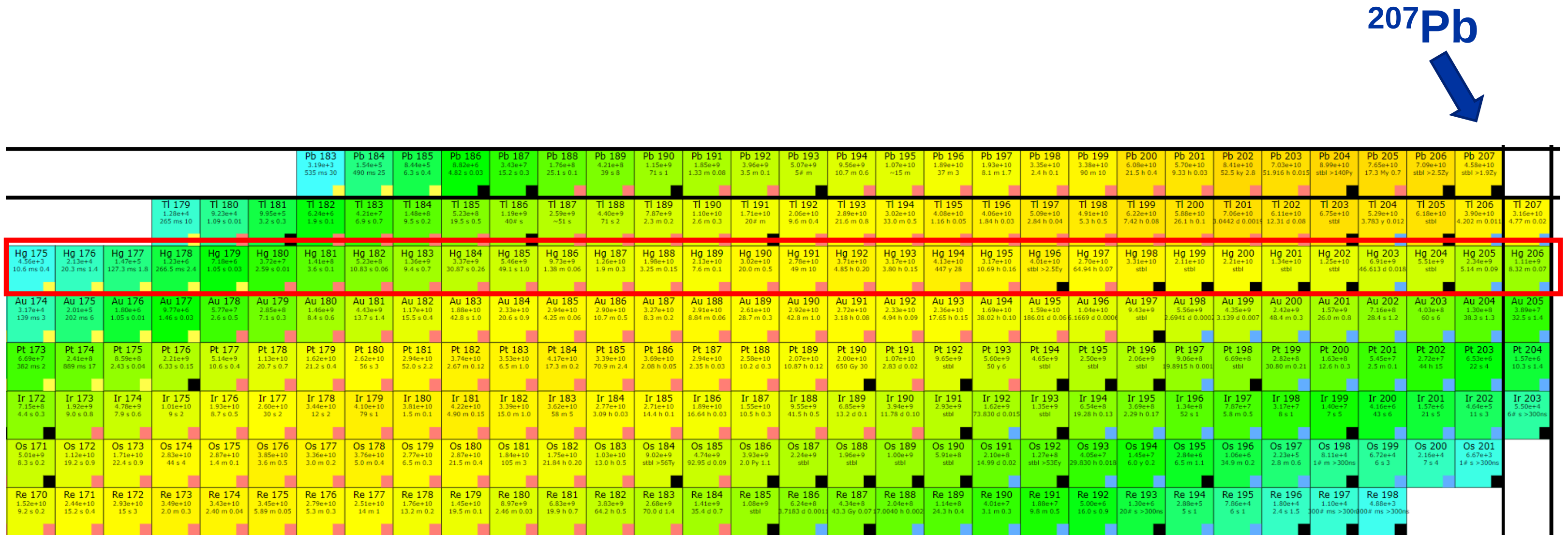
- Liquid Pb target
- Temperature-controlled chimney
  - Enable Hg-effusion
  - Suppress less volatile species (e.g. Pb)
- Special plasma-laser ion source ("VADLIS")

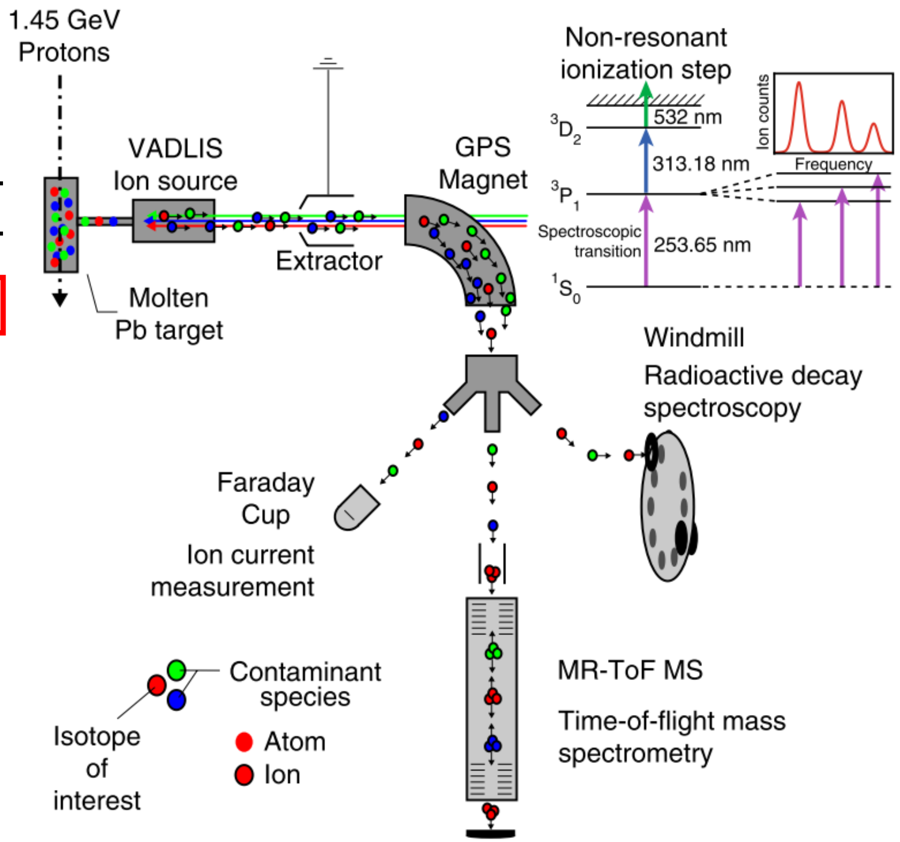




T. Day Goodacre, et al. NIM B 376 (2016). 10.1016/j.nimb.2016.03.005

Shape staggering in Hg-isotopes





- ^{x}Hg-isotopes from high-energy proton (1.4 GeV) induced spallation
- In-source laser spectroscopy to bridge to more n-deficient isotopes

B.A. Marsh, et al. Nature Physics 14 (2018). 10.1038/s41567-018-0292-8
J. Ballof, et al. NIM B 463 (2020). 10.1016/j.nimb.2019.05.044

Shape coexistence in ^{110,112}Cd

PHYSICAL REVIEW LETTERS 123, 142502 (2019)

Editors' Suggestion | Featured in Physics

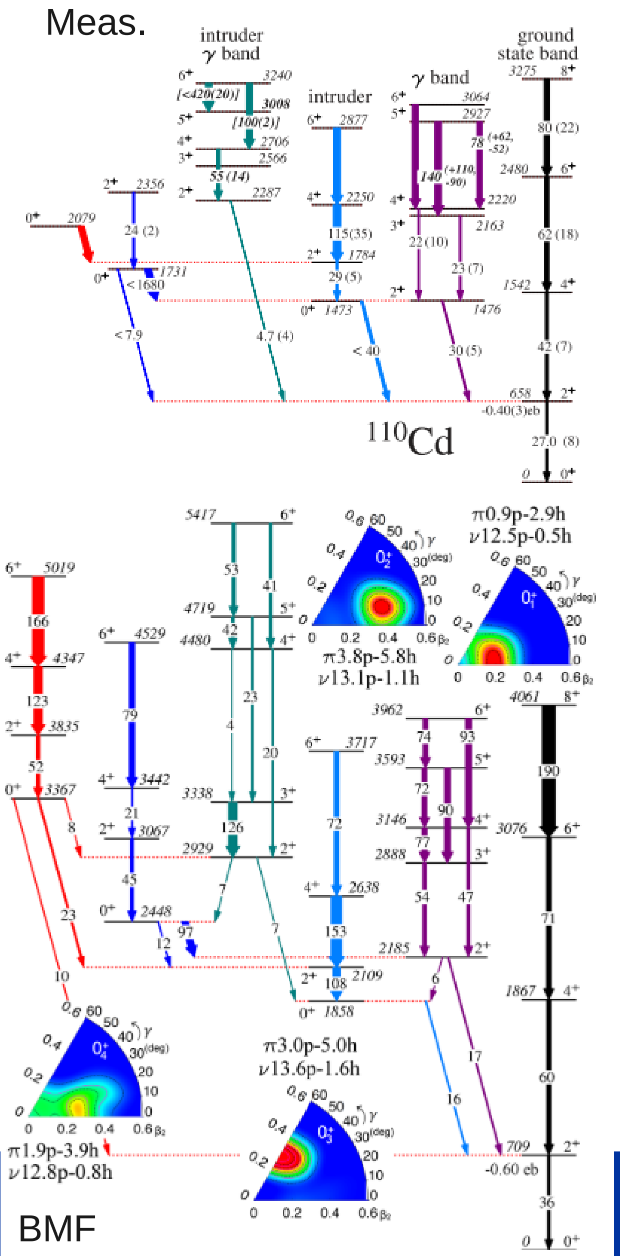
Multiple Shape Coexistence in ^{110,112}Cd

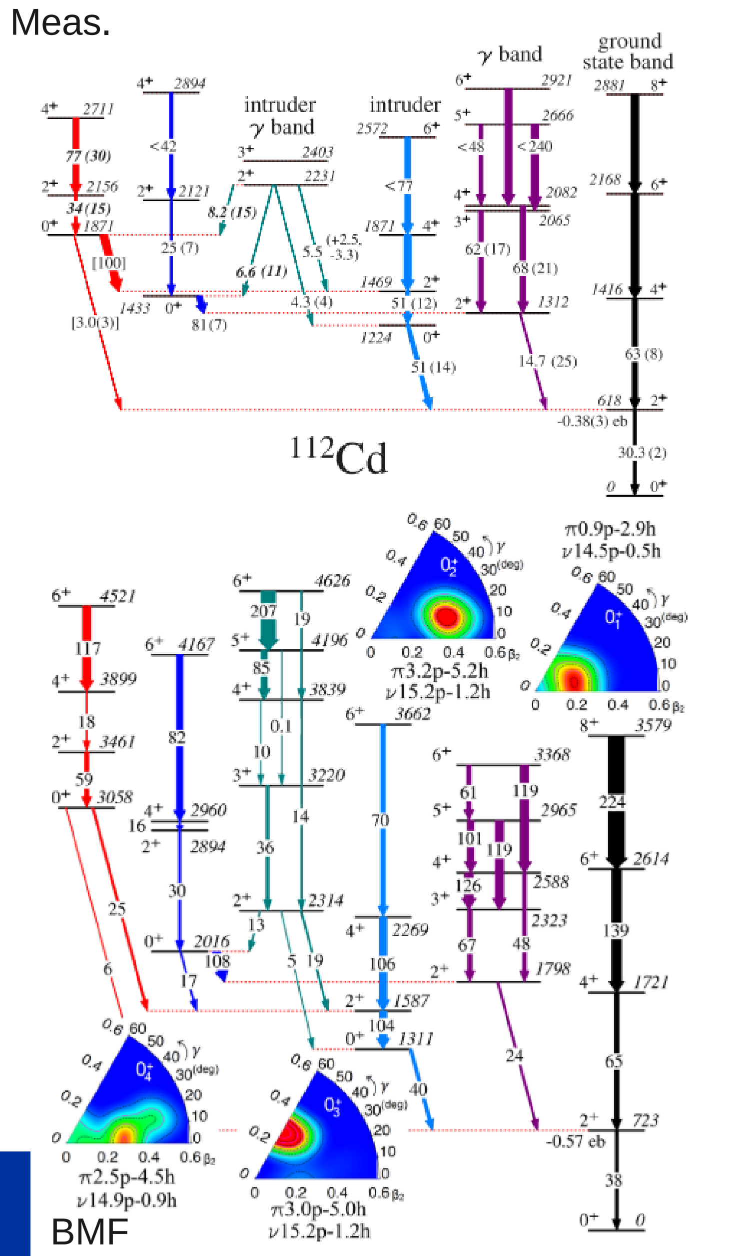
P. E. Garrett,[1,2] T. R. Rodríguez,[3] A. Diaz Varela,[1] K. L. Green,[1] J. Bangay,[1] A. Finlay,[1] R. A. E. Austin,[4] G. C. Ball,[5] D. S. Bandyopadhyay,[1] V. Bildstein,[1] S. Colosimo,[4] D. S. Cross,[6] G. A. Demand,[1] P. Finlay,[1] A. B. Garnsworthy,[5] G. F. Grinyer,[7] G. Hackman,[5] B. Jigmeddorj,[1] J. Jolie,[8] W. D. Kulp,[9] K. G. Leach,[1,*] A. C. Morton,[5,†] J. N. Orce,[2] C. J. Pearson,[5] A. A. Phillips,[1] A. J. Radich,[1] E. T. Rand,[1,‡] M. A. Schumaker,[1] C. E. Svensson,[1] C. Sumithrarachchi,[1,†] S. Triambak,[2] N. Warr,[8] J. Wong,[1] J. L. Wood,[10] and S. W. Yates[11]

[1]Department of Physics, University of Guelph, Guelph, Ontario N1G2W1, Canada
[2]Department of Physics and Astronomy, University of the Western Cape, P/B X17, Bellville ZA-7535, South Africa
[3]Departamento de Física Teórica and CIAFF, Universidad Autónoma de Madrid, E-28049 Madrid, Spain
[4]Department of Physics and Astronomy, St. Mary's University, Halifax, Nova Scotia B3H3C3, Canada
[5]TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T2A3, Canada
[6]Department of Chemistry, Simon Fraser University, Burnaby, British Columbia V5A1S6, Canada
[7]Department of Physics, University of Regina, Regina, Saskatchewan S4S0A2, Canada
[8]Institut für Kernphysik, Universität zu Köln, Zülpicherstrasse 77, D-50937 Köln, Germany
[9]Defense Threat Reduction Agency, 8725 John J Kingman Road, Fort Belvoir, Virginia 22060-6217, USA
[10]Department of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332, USA
[11]Departments of Chemistry and Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40506-0055, USA

(Received 31 August 2018; revised manuscript received 29 June 2019; published 3 October 2019)

- ^{110,112}Cd decay spectroscopy
- Suggests: multiple shape coexistence (SC) in low-lying states
- ➢ Endorses: SC not as rare as thought
- ➢ Suggests: SC may begin immediately, even at closed-shell

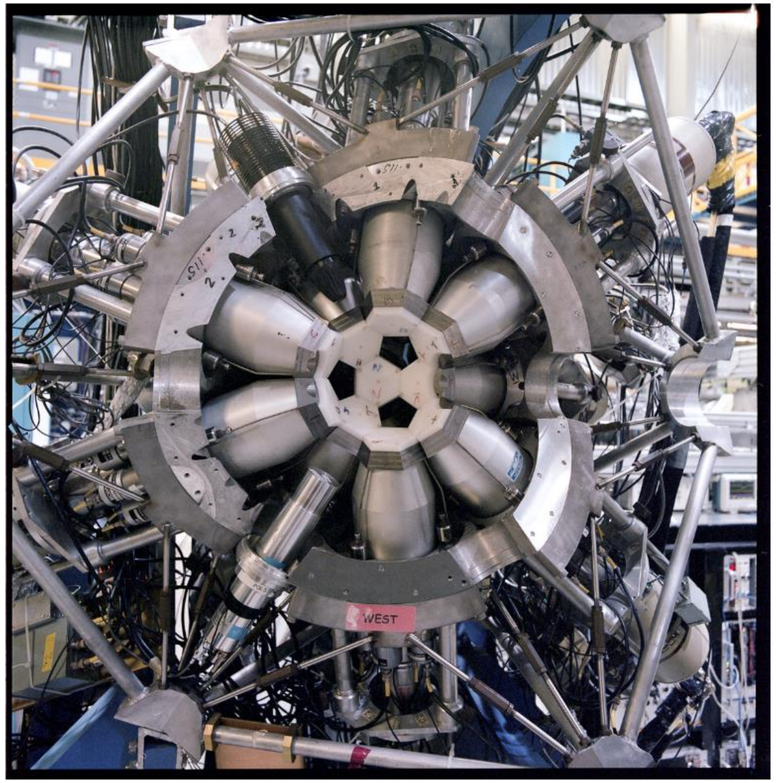


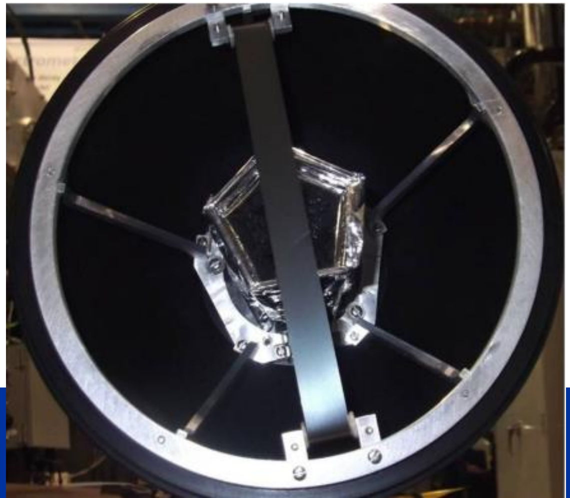


Shape coexistence in $^{110,112}Cd$

- TRIUMF-ISAC 0.5 GeV, 40-65 µA protons
- Tantal target, Re-surface and TRILIS
- Primary RIBs: $^{110g,m,112g,m}In$, ^{112}Ag; rates ~E6-E7 s^{-1}

- Implanted on Mylar tape
- Decay spectroscopy using 8π spectrometer
  - 20 HPGe-detector with BGO Compton-suppression





P.E. Garret, et al. PRL 123 (2019). 10.1103/PhysRevLett.123.142502
P.E. Garret, et al. J. of Phys.: Conf. Ser. (2015). 10.1088/1742-6596/639/1/012006

Atomic mass difference of ^{76}As-^{76}Se and ^{155}Tb-^{155}Gd

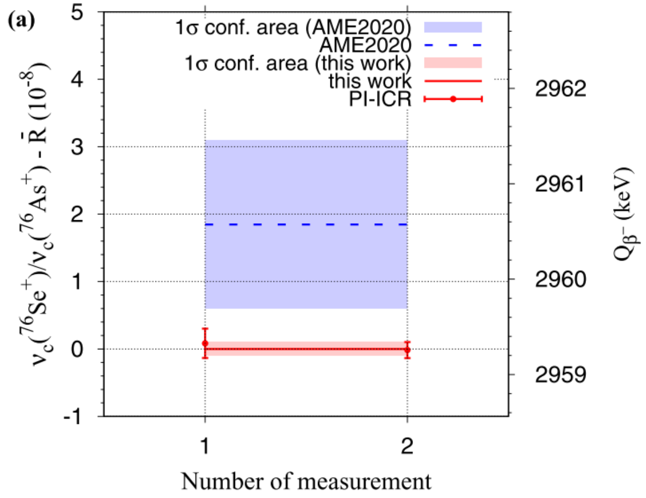
JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

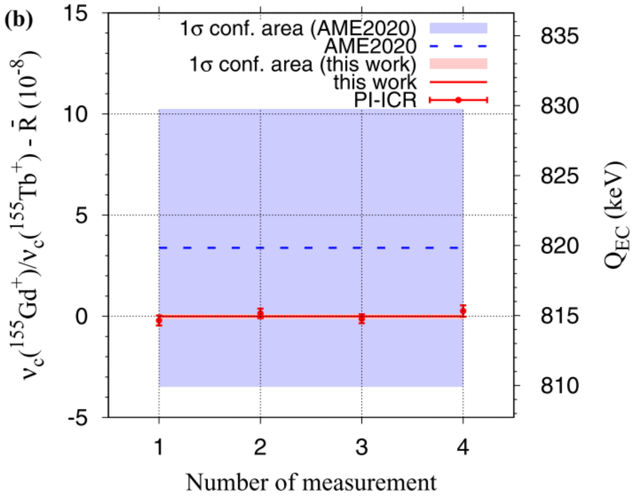
- Direct high-precision determination of Q_{β^-}, Q_{EC} using JYFLTRAP Penning-trap mass spectrometer
- Determined $Q^*_{\beta^-}$, Q^*_{EC} using tabulated energy-level data from γ-spectroscopy

➢ Energetically forbidden channels (negative)

➢ Unsuitable candidates for (anti)neutrino mass determination

Q_{β^-}: ^{76}As-^{76}Se

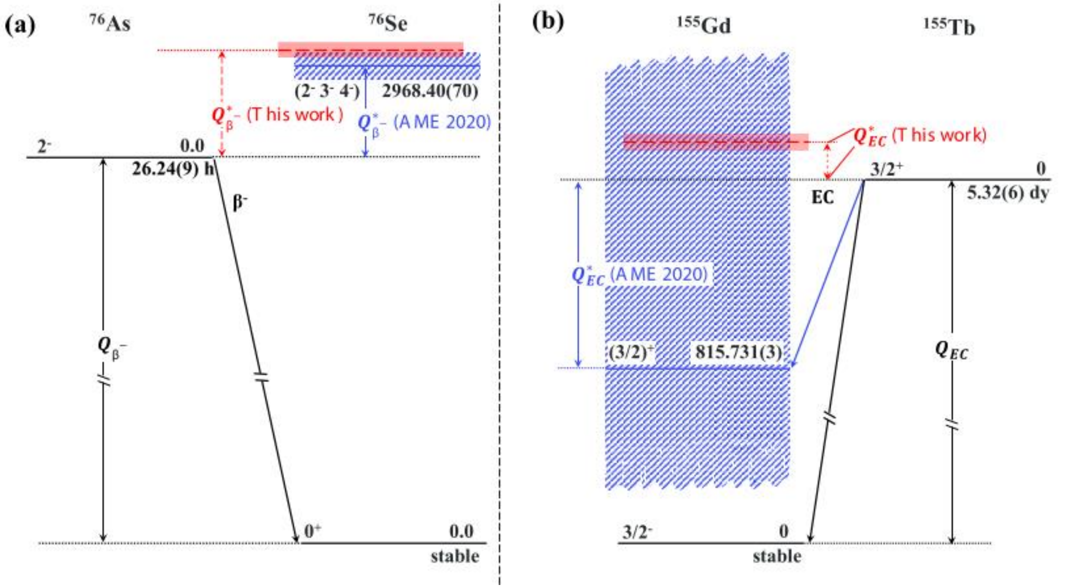




Q_{EC}: ^{155}Tb-^{155}Gd

$Q^*_{\beta^-}$: ^{76}As-^{76}Se*

Q^*_{EC}: ^{155}Tb-^{155}Gd*



PHYSICAL REVIEW C **106**, 015502 (2022)

Direct determination of the atomic mass difference of the pairs ^{76}As - ^{76}Se and ^{155}Tb - ^{155}Gd rules out ^{76}As and ^{155}Tb as possible candidates for electron (anti)neutrino mass measurements

Z. Ge,[1,*] T. Eronen,[1,†] A. de Roubin,[2] J. Kostensalo,[3] J. Suhonen,[1] D. A. Nesterenko,[1] O. Beliuskina,[1] R. de Groote,[1] C. Delafosse,[1] S. Geldhof,[1,‡] W. Gins,[1] M. Hukkanen,[1,2] A. Jokinen,[1] A. Kankainen,[1] J. Kotila,[1,4,5] Á. Koszorús,[6,§] I. D. Moore,[1] A. Raggio,[1] S. Rinta-Antila,[1] V. Virtanen,[1] A. P. Weaver,[7] and A. Zadvornaya[1,||]

[1]Department of Physics, University of Jyväskylä, P.O. Box 35, FI-40014 Jyväskylä, Finland
[2]Centre d'Etudes Nucléaires de Bordeaux Gradignan, UMR 5797 CNRS/IN2P3 - Université de Bordeaux, 19 Chemin du Solarium, CS 10120, F-33175 Gradignan Cedex, France
[3]Natural Resources Institute Finland, Yliopistokatu 6B, FI-80100 Joensuu, Finland
[4]Finnish Institute for Educational Research, University of Jyväskylä, P.O. Box 35, FI-40014 Jyväskylä, Finland
[5]Center for Theoretical Physics, Sloane Physics Laboratory Yale University, New Haven, Connecticut 06520-8120, USA
[6]Department of Physics, University of Liverpool, Liverpool L69 7ZE, United Kingdom
[7]School of Computing, Engineering and Mathematics, University of Brighton, Brighton BN2 4JG, United Kingdom

(Received 16 February 2022; accepted 21 June 2022; published 13 July 2022)

Atomic mass difference of ^{76}As-^{76}Se and ^{155}Tb-^{155}Gd

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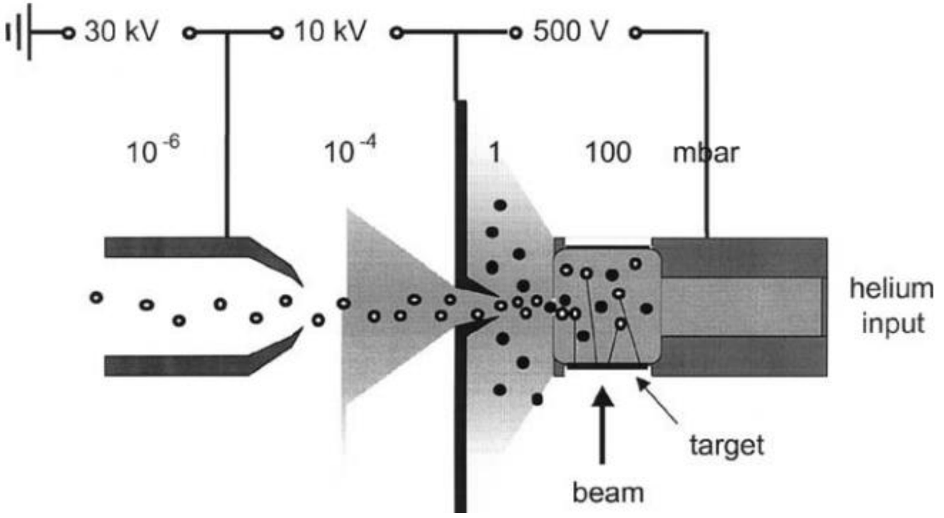
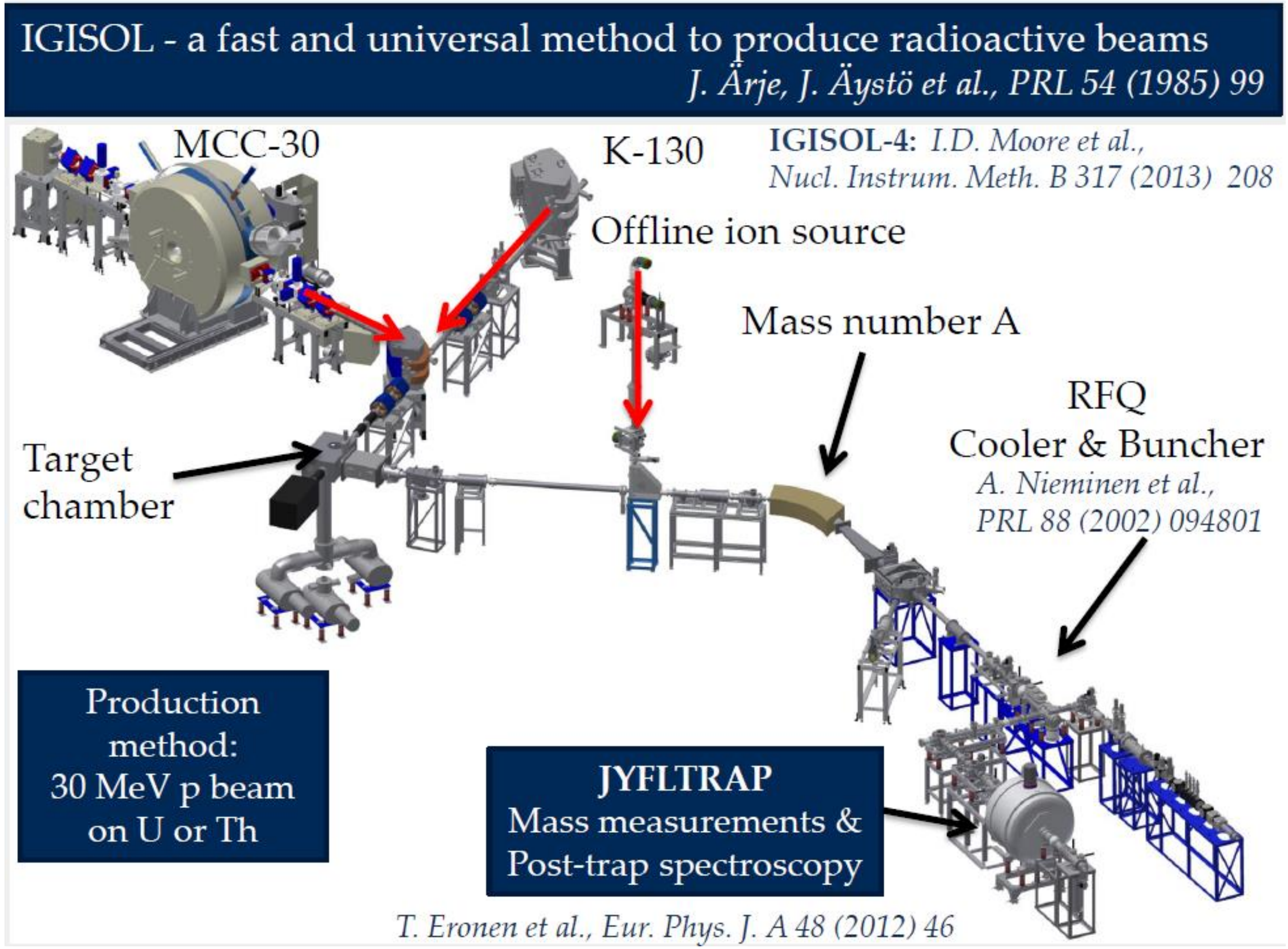
UNIVERSITY OF JYVÄSKYLÄ



- IGISOL
- 2 mg/cm2 Ge target - 9 MeV d ($^{76}As^{+}$,$^{76}Se^{+}$)
- 2 mg/cm2 Gd target - 60 MeV p ($^{155}Tb^{+}$, $^{155}Gd^{+}$)
- Mass separation, cooled and bunched (RFQ)
- JYFLTRAP double Penning trap
- Separation of isobaric contaminants (1st trap)
- ➢ Measured cyclotron frequency via phase-imaging ion-cyclotron-resonance (PI-ICR)



Nuclear structure of $^{253\text{-}255}$Es via laser spectroscopy

PHYSICAL REVIEW C **105**, L021302 (2022)

Letter

Nuclear structure investigations of $^{253-255}$Es by laser spectroscopy

S. Nothhelfer,[1,2,3] Th. E. Albrecht-Schönzart,[4] M. Block,[1,2,3] P. Chhetri,[2,3] Ch. E. Düllmann,[1,2,3] J. G. Ezold,[5] V. Gadelshin,[1,6] A. Gaiser,[4,*] F. Giacoppo,[2,3] R. Heinke,[1,†] T. Kieck,[1,2,3] N. Kneip,[1] M. Laatiaoui,[1,2,3] Ch. Mokry,[1,2] S. Raeder,[2,3] J. Runke,[1,3] F. Schneider,[1,2] J. M. Sperling,[4] D. Studer,[1] P. Thörle-Pospiech,[1,2] N. Trautmann,[1] F. Weber,[1] and K. Wendt[1]

[1] *Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany*
[2] *Helmholtz-Institut Mainz, 55099 Mainz, Germany*
[3] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany*
[4] *Florida State University, 32306 Tallahassee, Florida, USA*
[5] *Oak Ridge National Laboratory, Oak Ridge, 37831 Oak Ridge, Tennessee, USA*
[6] *Ural Federal University, 620002 Yekaterinburg, Russia*

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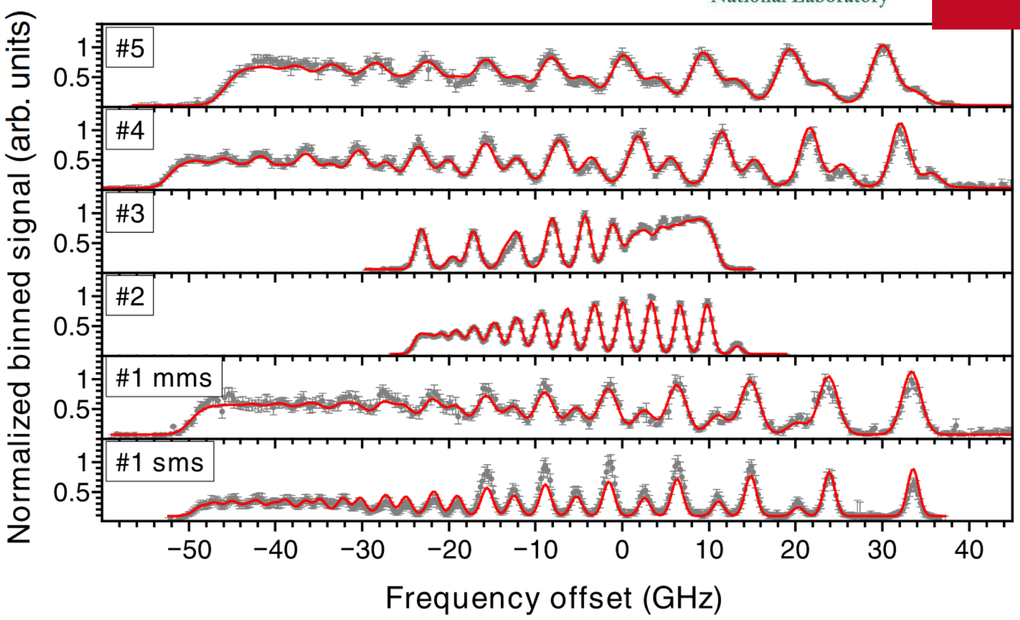
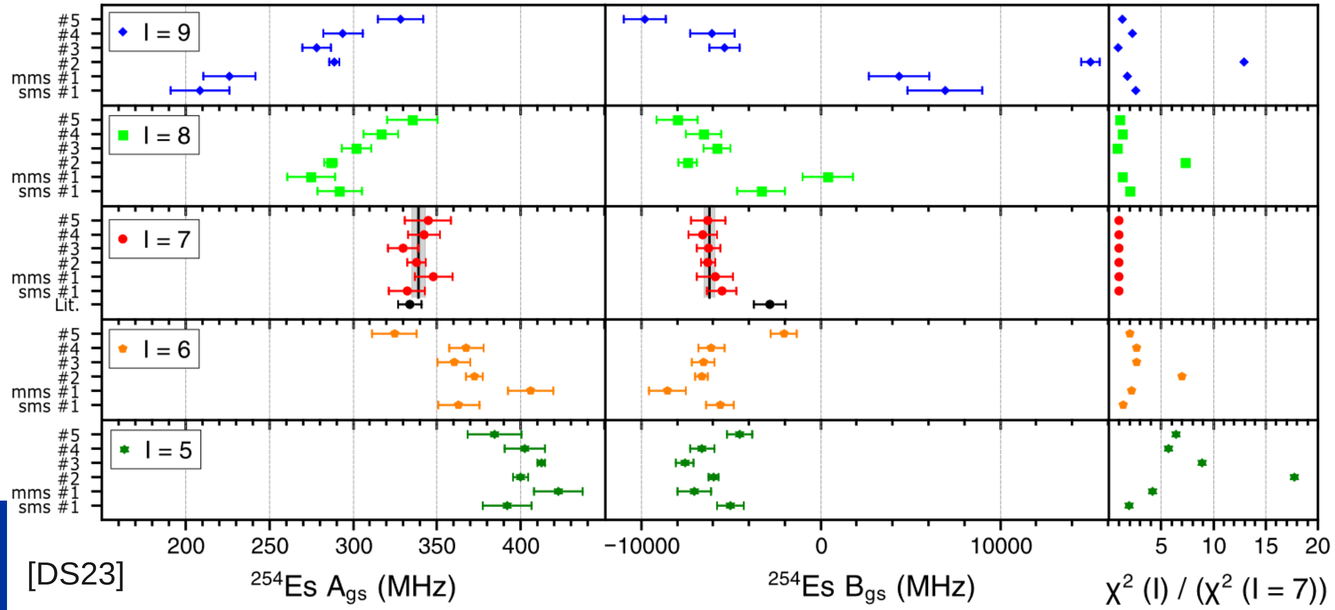


- Hyperfine structures measured for 5 ground-state transitions in ^{254}Es
- Accurate determination of spin and A_{gs}, B_{gs} coupling constants through large dataset
- x100 atomic transitions recorded; scheme dev.



[DS23]

The isotopes used in this research were supplied by the U.S. Department of Energy, Office of Science, by the Isotope Program in the Office of Nuclear Physics. The ^{253,254,255}Es and ^{255,257}Fm were provided to Florida State University and the University of Mainz via the Isotope Development and Production for Research and Applications Program through the Radiochemical Engineering and Development Center at Oak Ridge National Laboratory.

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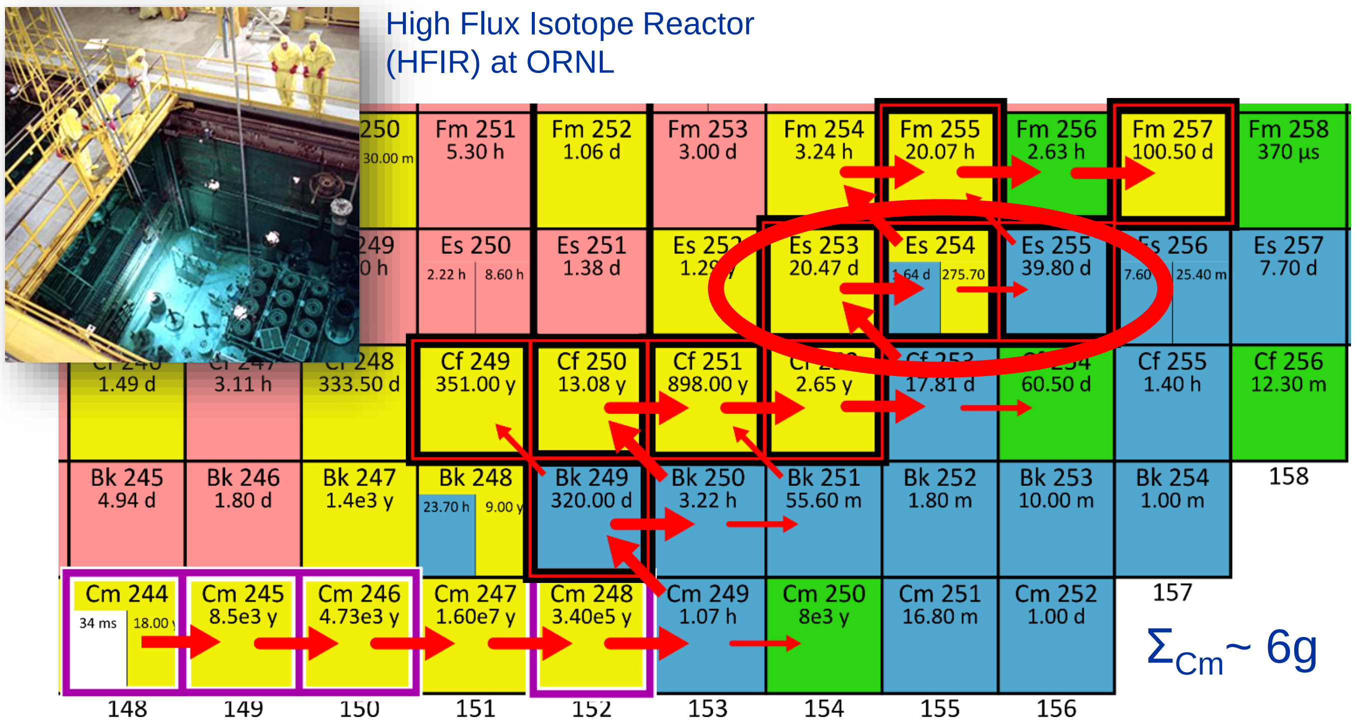
Nuclear structure of $^{253-255}$Es via laser spectroscopy



- Irradiation of 6g Cm at ORNL for ~5 months in 2018
- Chemical separation after ~4 months cooling
- Shipping of Es/Fm fraction to U. Mainz in Aug. 2019 (short-lived isotopes have decayed)

Specified sample contents Jan. 2019

^{257}Fm	~0.5 pg	~1e9 atoms
^{255}Es	~4 pg	~ 1e10 atoms
^{254}Es	~4 ng	~ 1e13 atoms
^{253}Es	~2 ng	~ 5e12 atoms
*Cf	n.d.	

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Summary

- What are the stages of ISOL-type RIB production?
- What are general and stage-specific ISOL challenges?
- What reactions are employed and where?
- ISOL is powerful for nuclear physics research

Acknowledgements & References

- **S. Rothe**
- **U. Köster**
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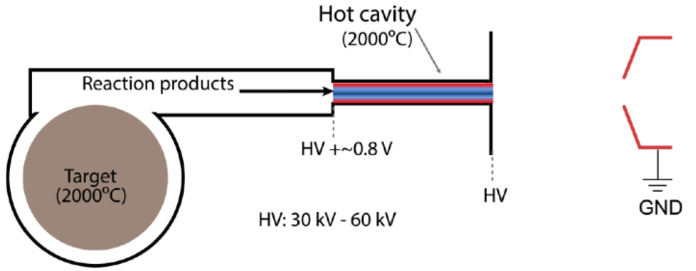
- **D. Studer**
- **J.P. Ramos**
- **F. Wenander**

[SR22] Sebastian Rothe, CERN Academic Training Lecture series I 2022
[UK06] Ulli Köster, Oleron School, 2006
[UK01] Ulli Köster, Prog. Part. Nucl. Phys. 46 (2001) 411.
[JPR18] J.P Ramos, Presentation at EMIS 2018
[JPR17b] J.P.Ramos, MEDICIS-Promed Specialized Training on Radioisotope production
[TDG17] Tom Day Goodacre, Presentation ICIS conference 2017
[RH22] Reinhard Heinke, Presentation material
[FW03] F.Wenander, Presentation: "Ion sources for radioactive beams - and the extra options",, XXXVIIIth RENCONTRE DE MORIOND, Les Arcs, 2003
[YM17] Y.Martinez Palenzuela, Presentation ICIS Conference 2017
[AK18] Anu Kankainen, Presentation FRIB and the GW170817 kilonova
[MAu22] M. Au Presentation, ISOLDE Workshop 2022, https://indico.cern.ch/event/1183259
[JB17] J.Ballof, Presentation, ISOLDE Workshop 2017, https://indico.cern.ch/event/660622/
[MIT20] MIT News Article, "Physicists measure a short-lived radioactive molecule for first time", https://news.mit.edu/2020/physicists-measure-short-lived-radioactive-molecule-0527
[LISA] LISA – Laser Ionization and Spectroscopy of Actinides, https://lisa-itn.web.cern.ch/ , (MSCA) Innovative Training Networks (ITN) under grant agreement no. 861198.
[NUC23] www.nucleonica.com
[RE23] RILIS Elements Website, https://riliselements.web.cern.ch

Thank you!

Questions, comments?

(positive) surface ionization source



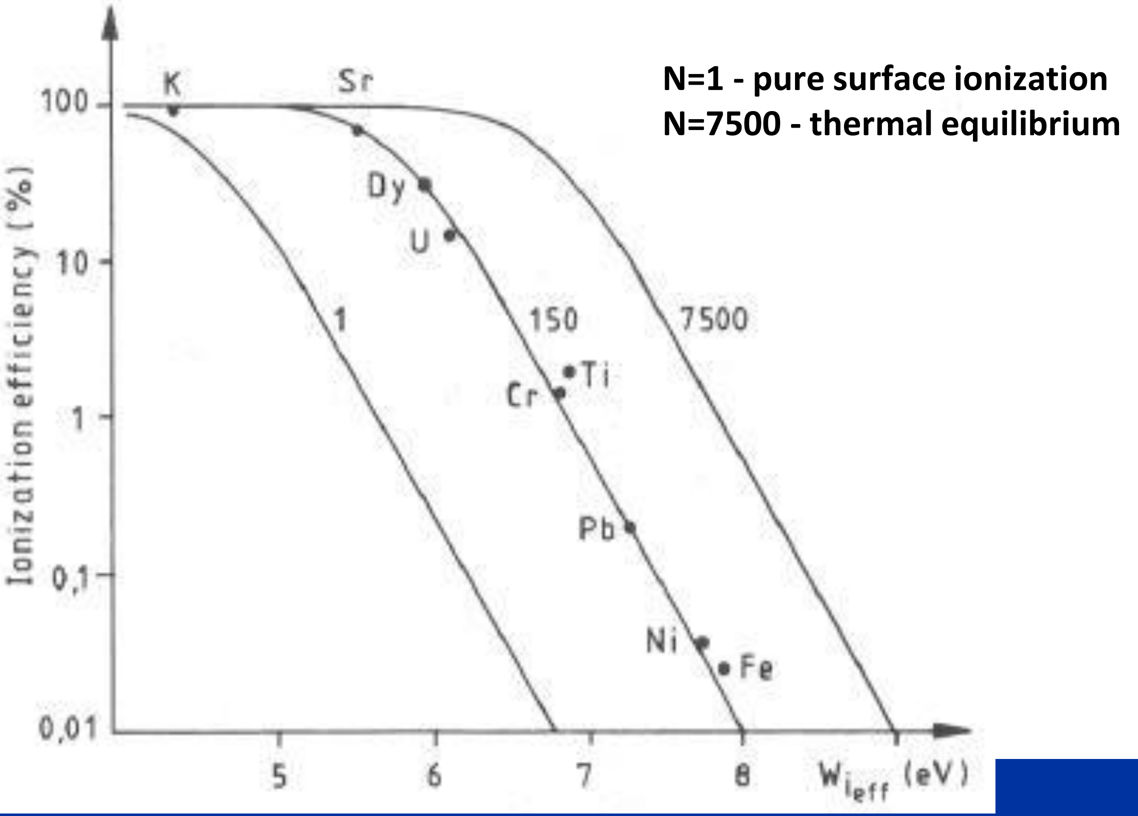
Properties

* **Ionisation efficiency 100% for Wi<5 eV,** few % for Wi=6.5 eV
* **Used for alkalines, alkaline earths**, rare earths, Ga, In and Tl
also **molecules as BaF and SrF**
* Emittance ~ 10 π mm mrad (60 kV, 95%)
* Energy spread <2 eV
* max current 1 μa/mm2
* Short delay time (half-lives as short as 10 ms)
small ionisation volume
operates at elevated temperatures
closely coupled to targets

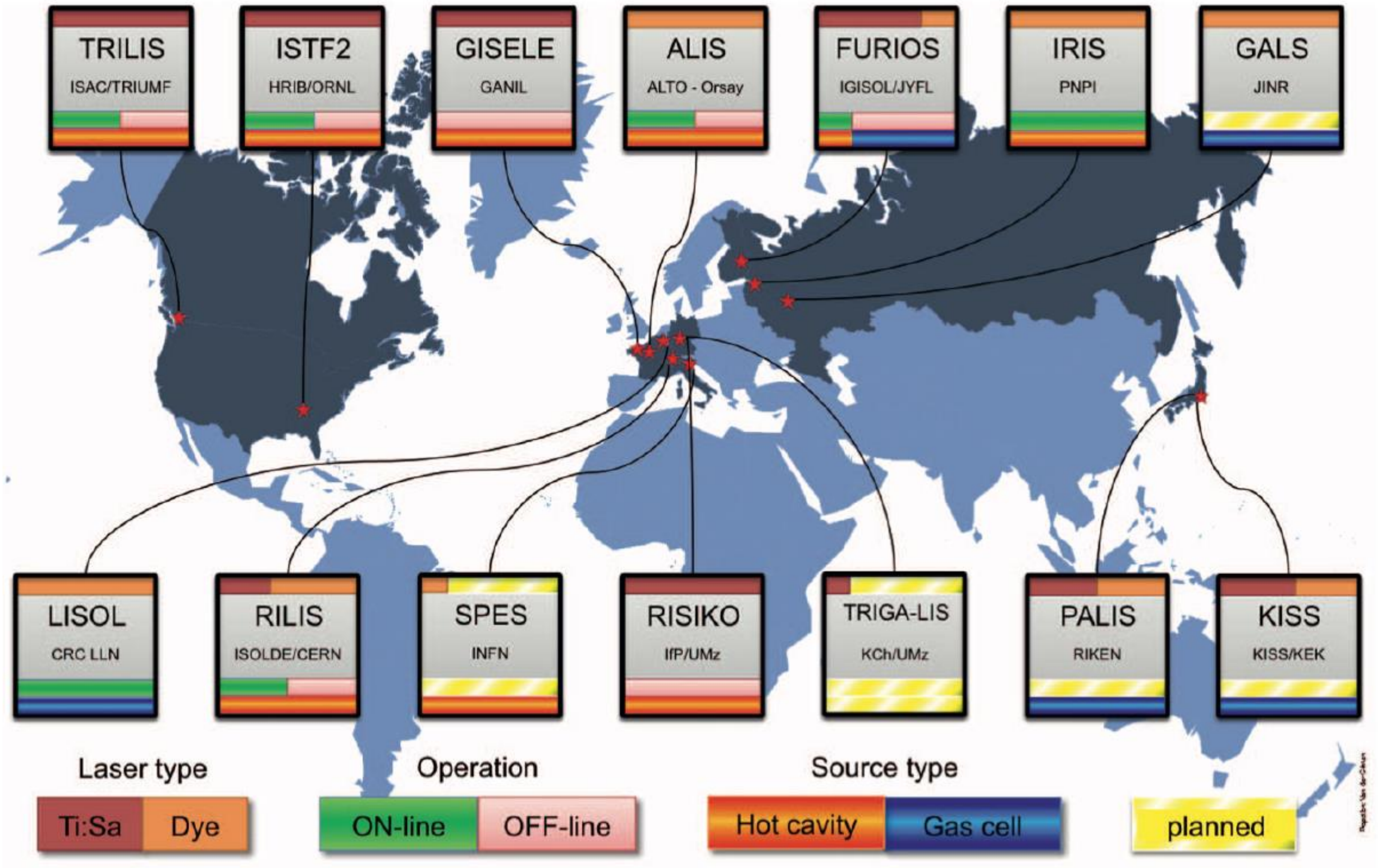
Ionizer material

* **Ta, W, Re**, Ir, Pt
* temperatures up to 2800 K
* e.g. tungsten with ϕ~4.5 eV at 2400 °C
* Work function depends on crystal orientation, temperature and cleanliness

Ionization efficiency vs (eff.) ionization potential



Laser ion sources worldwide



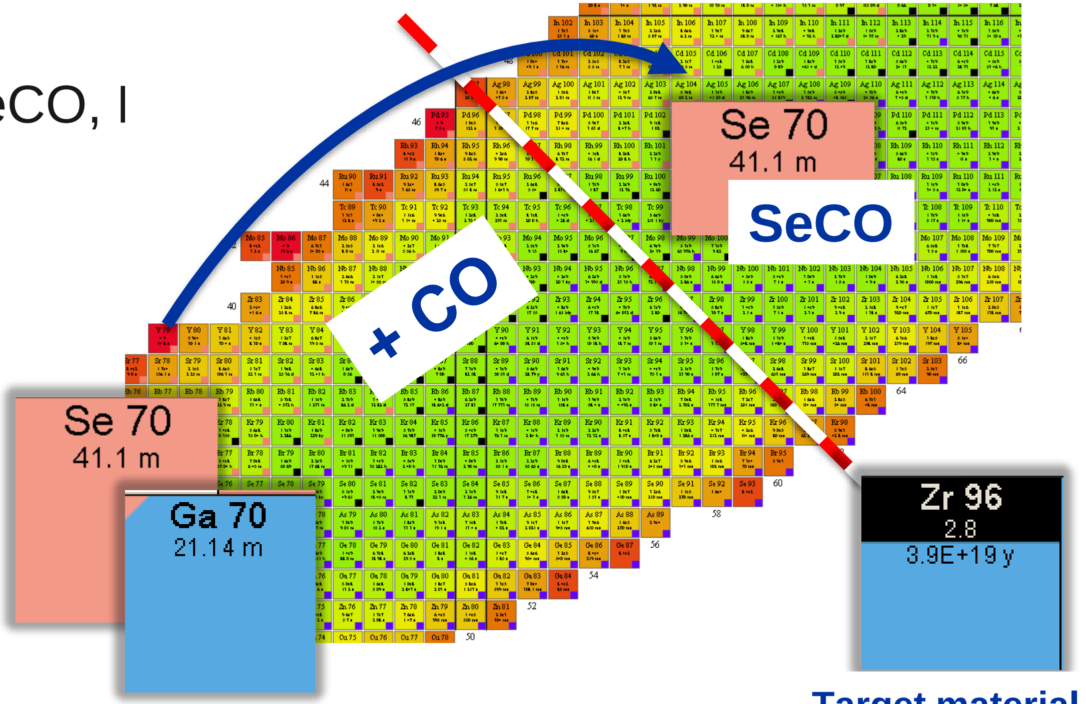
Molecular beams development

Beam purification

- Shift the mass region to a higher mass
- **avoid isobaric contaminants**. e.g. GeS, SnS, SeCO, I

Beam extraction by *In-situ* volatilization

- Elements with very low volatility are not released
- Reactive elements can be chemically trapped



Target material

Physics with radioactive molecules


Article

Spectroscopy of short-lived radioactive molecules

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LISA – Laser Ionization and Spectroscopy of Actinides
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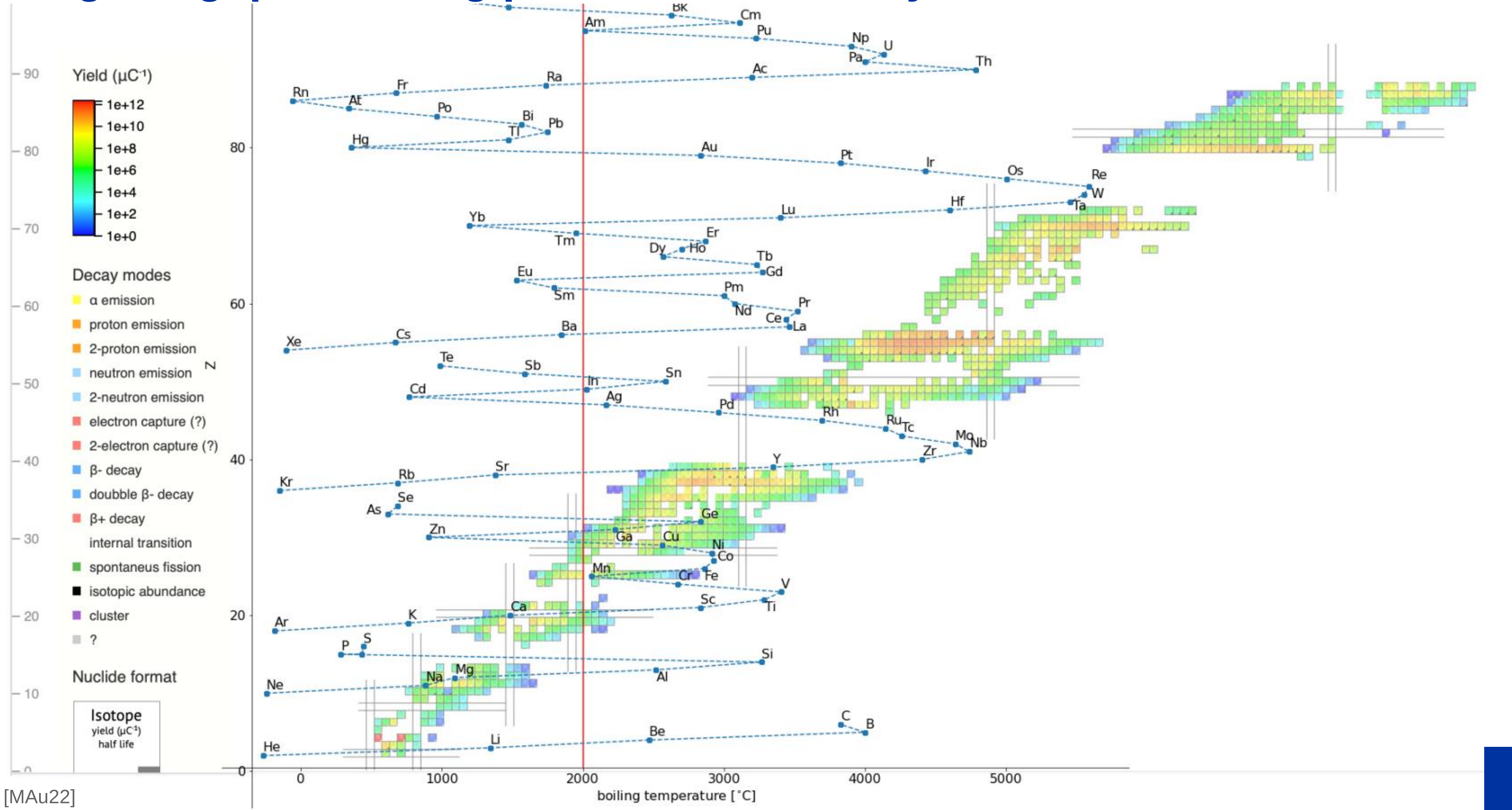
Filling the gaps - boiling points vs. ISOLDE yields



[MAu22]