Electromagnetic separators (2)

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Outline

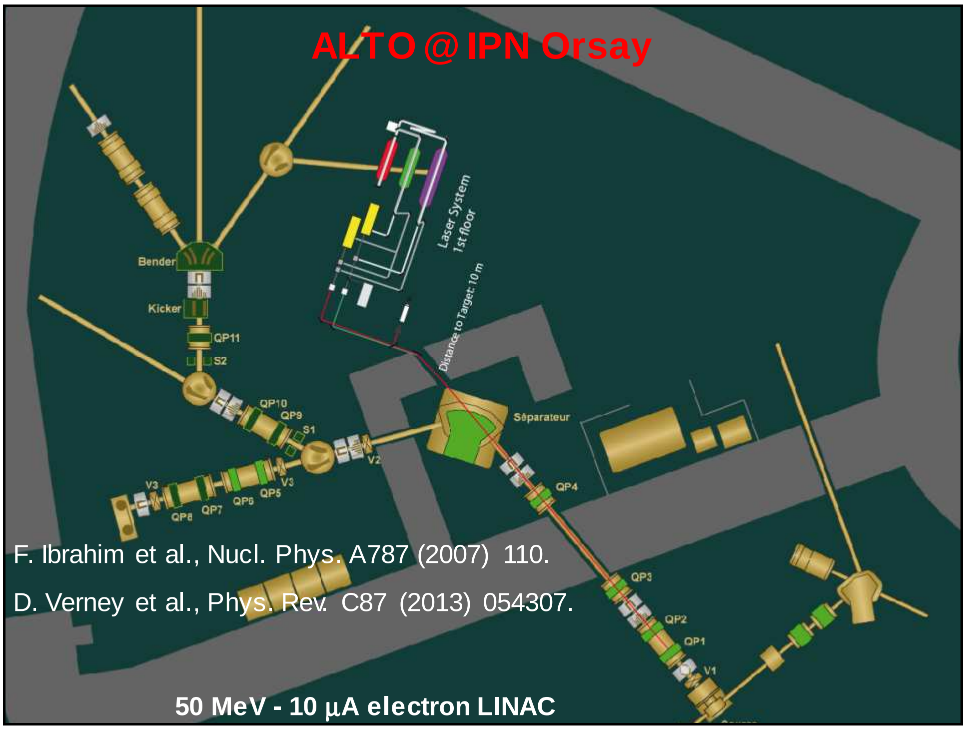
1. **Definitions and history**
2. **Basics of ion optics and dispersive elements**
3. **Static fields**
   a) deflection spectrometer
   b) retardation spectrometer
4. **Dynamic fields/separation**
   a) Time-of-Flight spectrometer
   b) Radiofrequency spectrometer
   c) Traps
5. **Technical realization (ion sources, etc.)**
6. **“Real examples” for nuclear physics applications**
   a) ISOL
   b) Recoil separators
   c) Fragment separators
   d) Spectrometer

Radioactive ion beam facilities for fission products

Previous, presently operating and future RIB facilities using fission:

^{252}Cf(sf)	CARIBU
^{235}U(n_{th},f)	OSTIS, OSIRIS, LOHENGRIN, TRIGA-SPEC, CARR-ISOL, PIAFE, MAFF, PIK-ISOL
^{238}U(p,f)	ISOLDE, IRIS, LISOL, JYFL, HRIBF, TRIAC, ISAC-II, SPES, ISOL@MYRRHA, EURISOL
W(p,xn..) > ^{238}U(n,f)	ISOLDE, IRIS, ISAC-II, EURISOL
^{12}C(d,n) > ^{238}U(n,f)	PARRNe, SPIRAL-II
^{2}H(d,n) > ^{238}U(n,f)	SPIRAL-II
^{9}Be(d,n) > ^{238}U(n,f)	PARRNe
^{7}Li(d,n) > ^{238}U(n,f)	FRIB
W(e^-,γ) > ^{238}U(γ,f)	ALTO, DRIBS, ARIEL
^{1}H, ^{9}Be..^{208}Pb(^{238}U,f)	GSI-FRS, RIKEN, FRIB, FAIR

ALTO @ IPN Orsay



F. Ibrahim et al., Nucl. Phys. A787 (2007) 110.

D. Verney et al., Phys. Rev. C87 (2013) 054307.

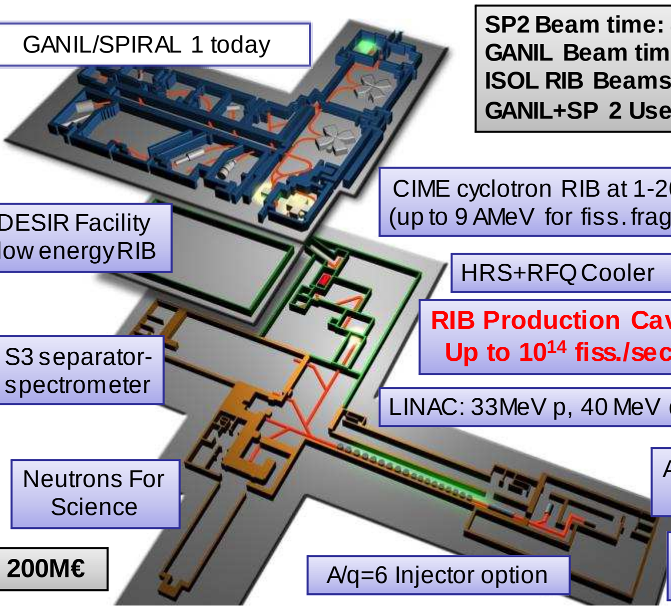
50 MeV - 10 µA electron LINAC

ISAC @ TRIUMF: ARIEL photo-fission upgrade

- 50 MeV, 10 mA electron LINAC
- <100 kW till 2015, 500 kW till 2020
- aim 4.6E13 fissions/s with
  liquid Hg converter
- but also 500 MeV protons with
  maximum 10 μA on UC_x

SPIRAL2 facility at GANIL

SP2 Beam time: 44 weeks/y
GANIL Beam time: 35 weeks/y
ISOL RIB Beams: 28-33 weeks/y
GANIL+SP 2 Users: 700-800/y



GANIL/SPIRAL 1 today

CIME cyclotron RIB at 1-20 AMeV
(up to 9 AMeV for fiss. fragments)

DESIR Facility
low energy RIB

HRS+RFQ Cooler

RIB Production Cave
Up to 10^{14} fiss./sec.

S3 separator-
spectrometer

LINAC: 33MeV p, 40 MeV d, 14.5 A MeV HI

Neutrons For
Science

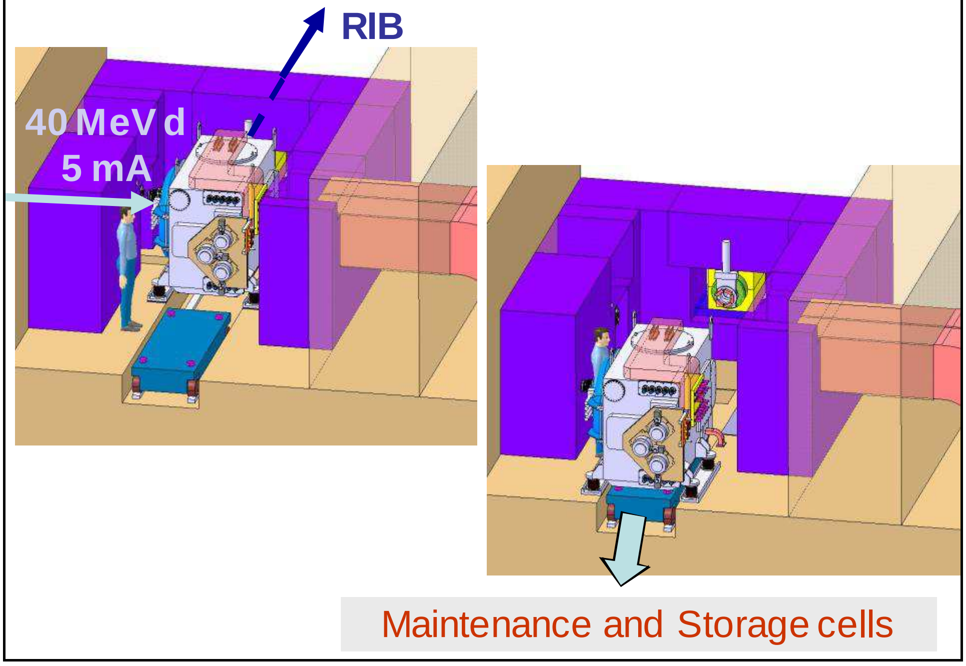
A/q=3 HI source
Up to 1mA

Cost: 200M€

A/q=6 Injector option

A/q=2 source
p, d, ^{3,4}He 5mA

SPIRAL2 RIB production module



EURISOL

1-2.2 GeV, multi-MW proton driver

Several **direct target** stations (ca. **100 kW**)

One **Hg spallation + fission** target station (**>1 MW, i.e. 1E15 fissions/s**)

Multiple user operation in parallel

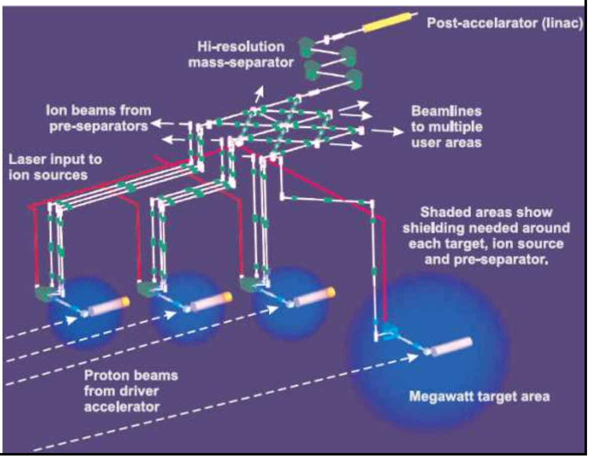
Low-energy beam area

Post-acceleration with
LINAC up to ca. 10 A.MeV

Post-acceleration to
ca. 100 A.MeV
with LINAC or cyclotron

Fragmentation of
post-accelerated RIBs

Commissioning: > 2020?



IGISOL method

$X^{n+} + He^0 \rightarrow X^{(n-1)+} + He^+$ or

$X^{n+} + Ar^0 \rightarrow X^{(n-1)+} + Ar^+$

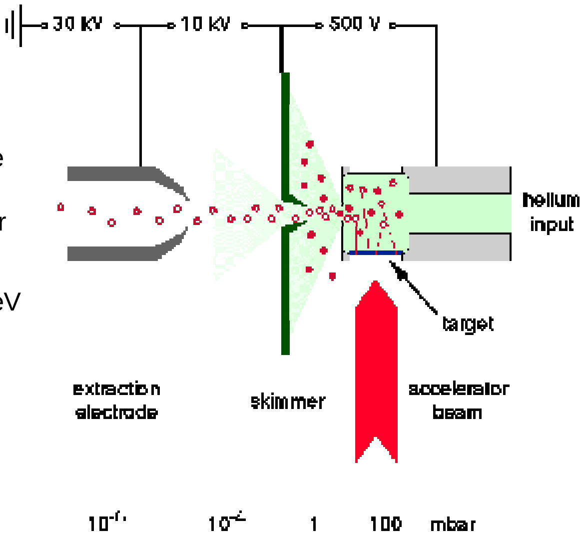
rapid reduction of ionic charge state to 2+ or 1+ by charge exchange reactions with buffer gas

IP(He)=24.6 eV, IP(Ar)=15.8 eV

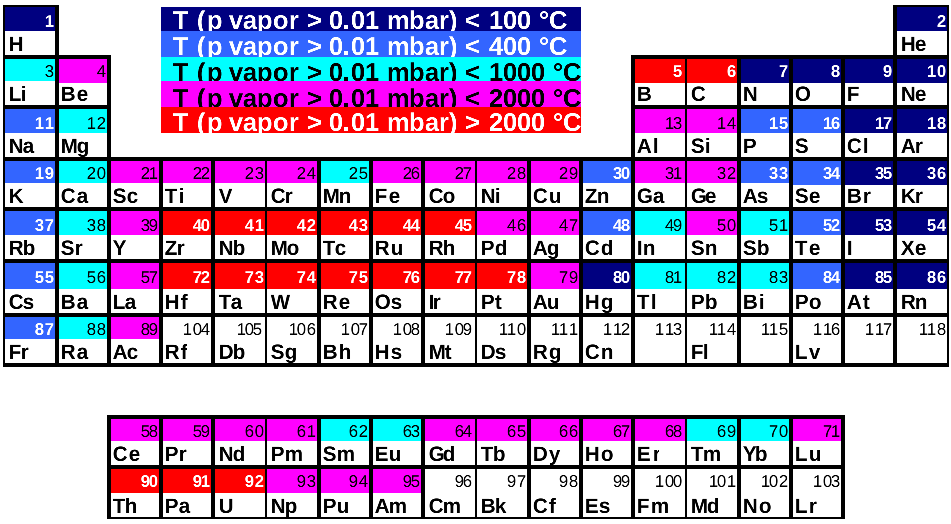
~~$X^+ + He^0 \rightarrow X^0 + He^+$~~ or

~~$X^+ + Ar^0 \rightarrow X^0 + Ar^+$~~

remains in 1+ or 2+ charge state until charge exchange reaction with impurity molecule (O_2, N_2,...) occurs



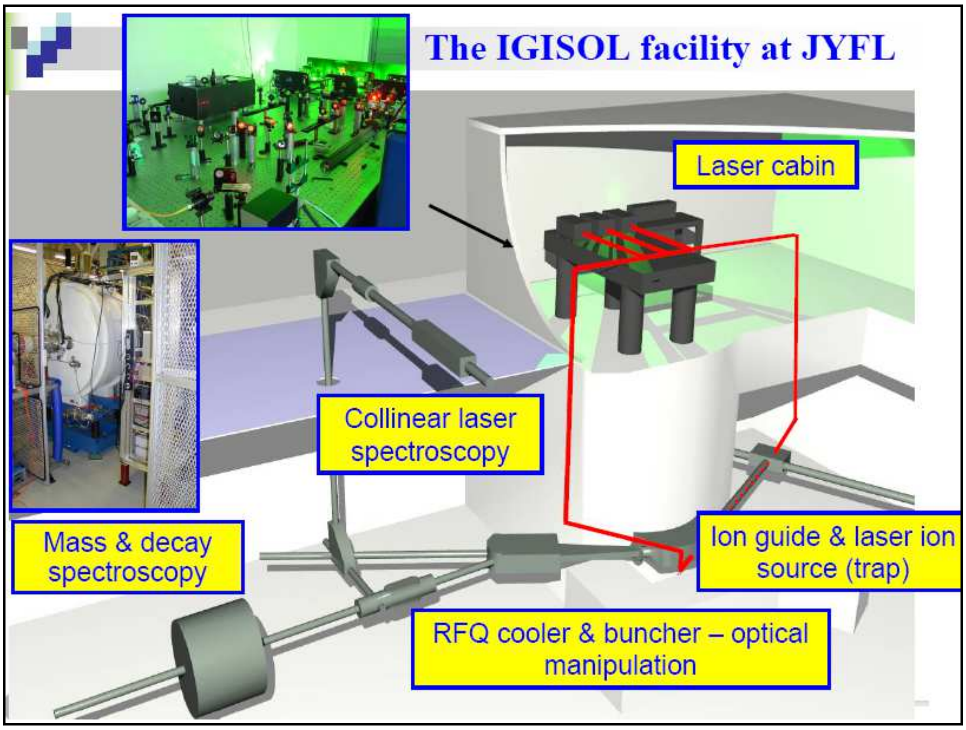
Volatility of the elements



T (p vapor > 0.01 mbar) < 100 °C
T (p vapor > 0.01 mbar) < 400 °C
T (p vapor > 0.01 mbar) < 1000 °C
T (p vapor > 0.01 mbar) < 2000 °C
T (p vapor > 0.01 mbar) > 2000 °C

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
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
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
55 Cs	56 Ba	57 La	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
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113	114 Fl	115	116 Lv	117	118

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
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



The IGISOL facility at JYFL

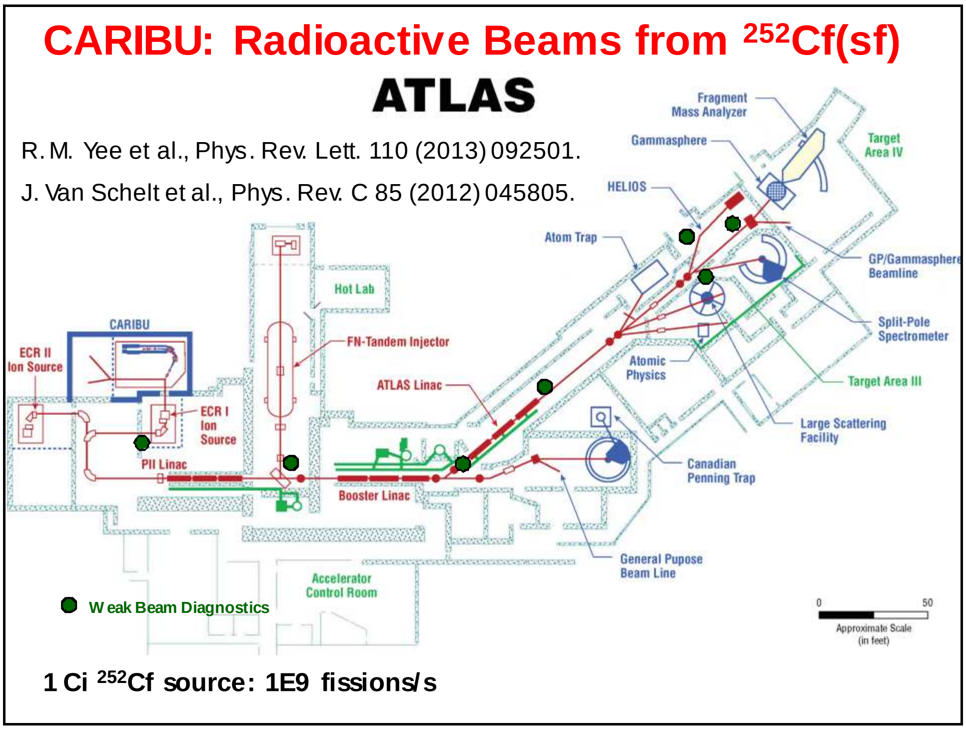
Laser cabin

Collinear laser spectroscopy

Mass & decay spectroscopy

Ion guide & laser ion source (trap)

RFQ cooler & buncher – optical manipulation



CARIBU: Radioactive Beams from ^{252}Cf(sf)

ATLAS

R. M. Yee et al., Phys. Rev. Lett. 110 (2013) 092501.

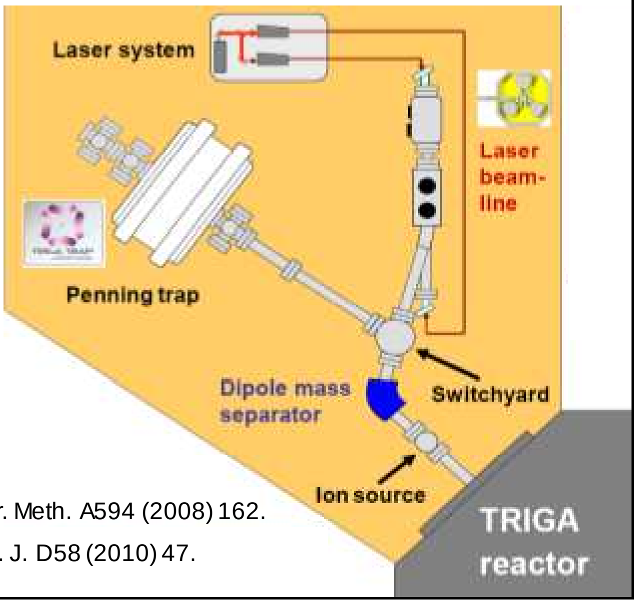
J. Van Schelt et al., Phys. Rev. C 85 (2012) 045805.

● Weak Beam Diagnostics

1 Ci ^{252}Cf source: 1E9 fissions/s

TRIGA-SPEC at Mainz reactor

- 0.5 mg ^{235}U or 0.5 mg ^{239}Pu or 0.3 mg ^{249}Cf
- 1.8E11 n./cm^2/s
- 2E8 fissions/s



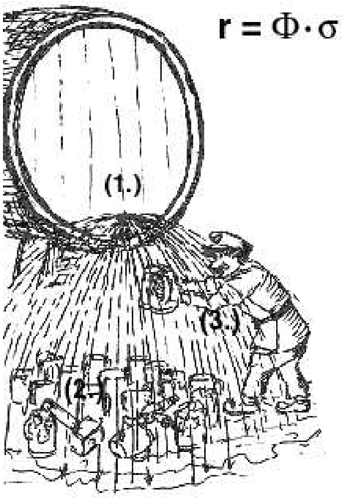
J. Ketelaer et al., Nucl. Instr. Meth. A594 (2008) 162.

J. Ketelaer et al., Eur. Phys. J. D58 (2010) 47.

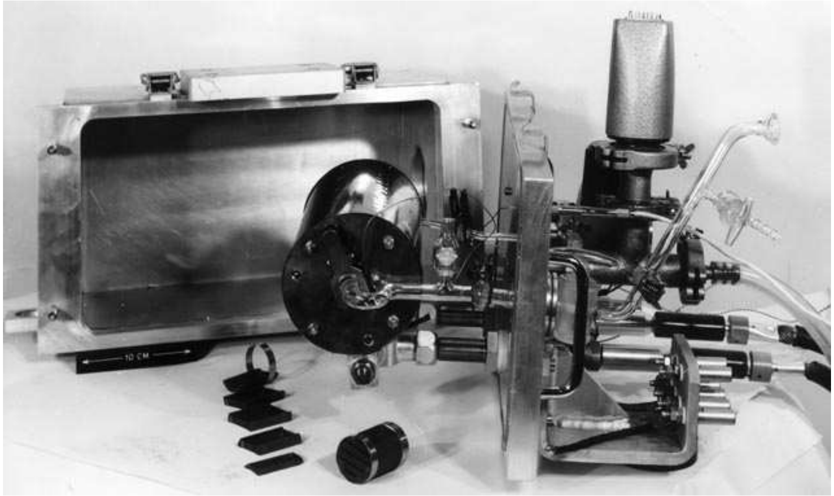
Optimize RIB intensity

All steps of the separation chain need to be optimized!

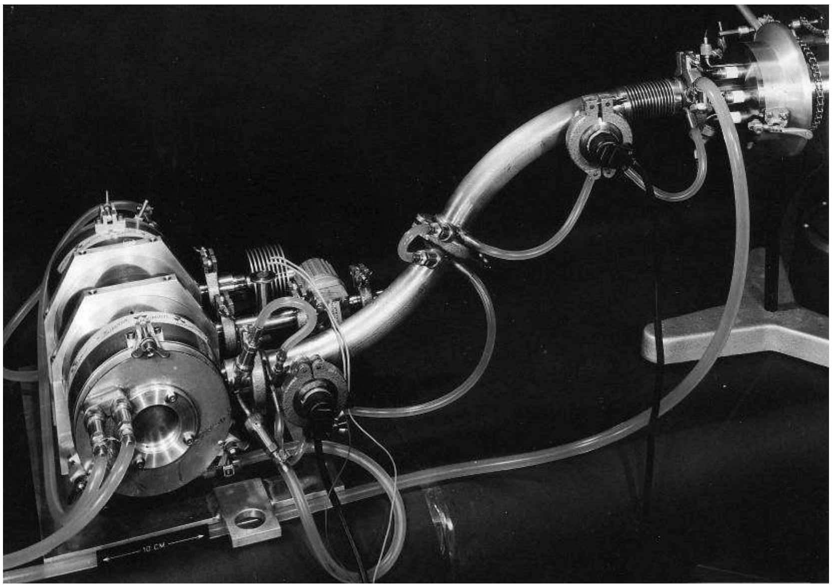
$$r = \Phi \cdot \sigma \cdot N \cdot \varepsilon_{target} \cdot \varepsilon_{source} \cdot \varepsilon_{transp} \cdot \varepsilon_{det}$$



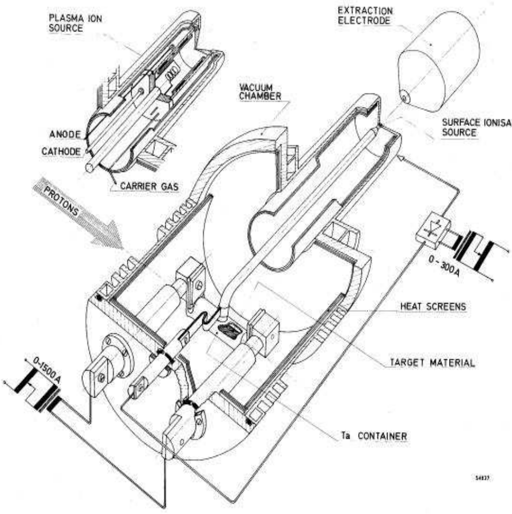
ISOLDE Target (1967)

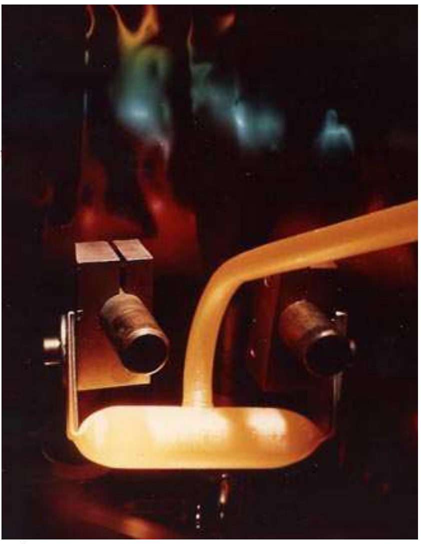


ISOLDE Target and ion source (1968)

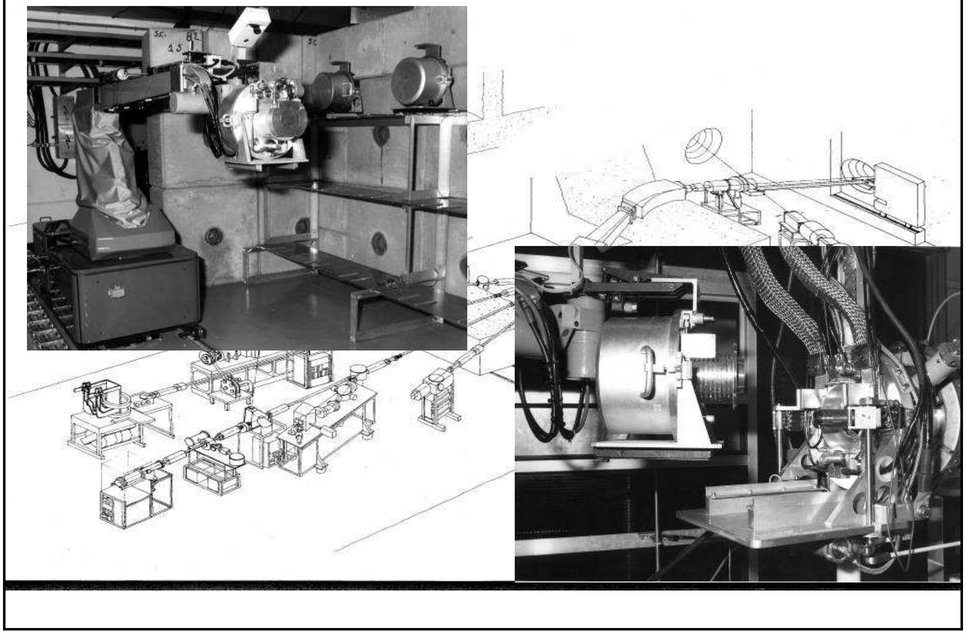


ISOLDE Compact target and ion source (1974)

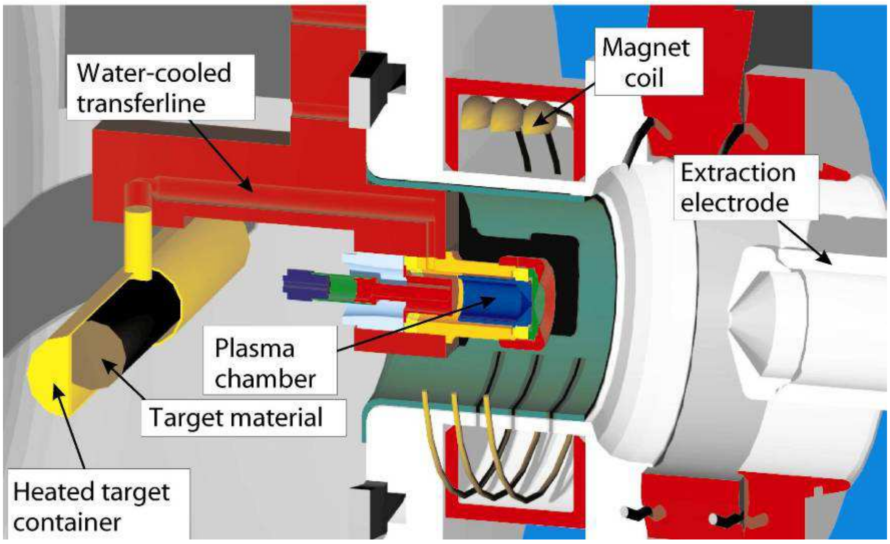




Robot handling



ISOLDE target and ion source unit



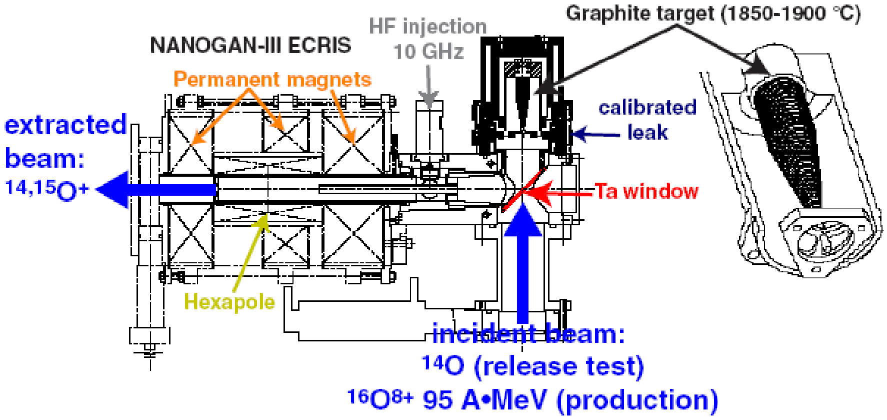
Historical development

Miniaturisation ⇒ faster release

Standardisation ⇒ easier mass-production

Remote handling ⇒ higher activities

SPIRAL target and ion source unit



NANOGAN-III ECRIS

HF injection
10 GHz

Graphite target (1850-1900 °C)

Permanent magnets

extracted
beam:
$^{14,15}O^{+}$

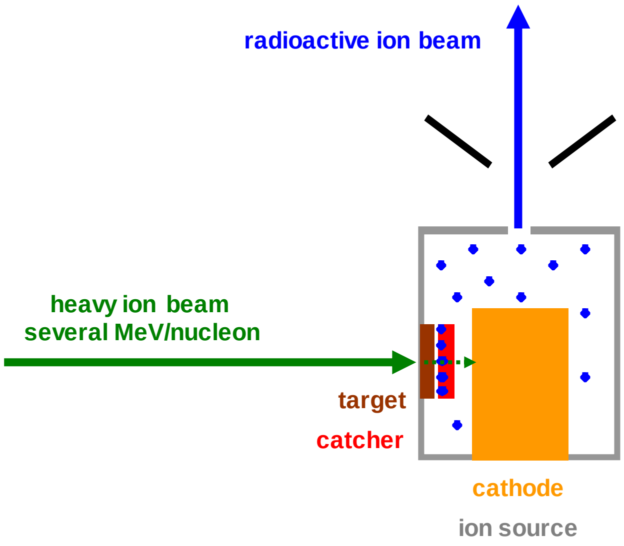
calibrated
leak

Ta window

Hexapole

incident beam:
^{14}O (release test)
$^{16}O^{8+}$ 95 A•MeV (production)

GSI-ISOL target and ion source unit



radioactive ion beam

heavy ion beam
several MeV/nucleon

target

catcher

cathode

ion source

Variants of ISOL facilities

1a protons on thick (heavy) target: fragmentation, spallation, fission
ISOLDE-CERN (1.4 GeV), IRIS-PNPI (1 GeV), ISAC-TRIUMF (0.5 GeV)

1b direct reactions in thick target
CRC Louvain-la-Neuve, HRIBF Oak Ridge, TRIAC Tokai

1c fission in thick target
OSIRIS (Studsvik), HRIBF Oak Ridge, TRIAC Tokai, SPIRAL2 (GANIL)

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, TRIμP KVI Groningen, 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), …

5 liquid helium catcher
JYFL Jyväskylä, KVI Groningen

ISOL targets

Target materials:

1. **molten metals:** Ge, Sn, La, Pb, Bi, U,…
2. **solid metals:** Ti, Zr, Nb, Mo, Ta, W, Th,…
3. **carbides:** Al_4C_3, SiC, VC, ZrC, LaC_x, ThC_x, UC_x,…
4. **oxides:** MgO, Al_2O_3, CaO, TiO_x, ZrO_2, CeO_x, ThO_2,…
5. **others:** graphite, borides, silicides, sulfides, zeolithes,…

Target dimensions:

target container: 20 cm long, 2 cm diameter

target thickness 2—200 g/cm^2, 10—100% of bulk density

micro-dimensions of foils, fibers or pressed powder: 1—30 μm

Radiochimica Acta 89 (2001) 749.

Diffusion characteristics

Bad diffusion hosts (narrow and/or stiff crystal lattice):

Re, diamond, SiC,...

Good diffusion hosts (wide crystal lattice):

Ti, Zr, Hf (fcc metals), Nb, Ta, graphite,
polycrystalline oxides (in particular fibers!)

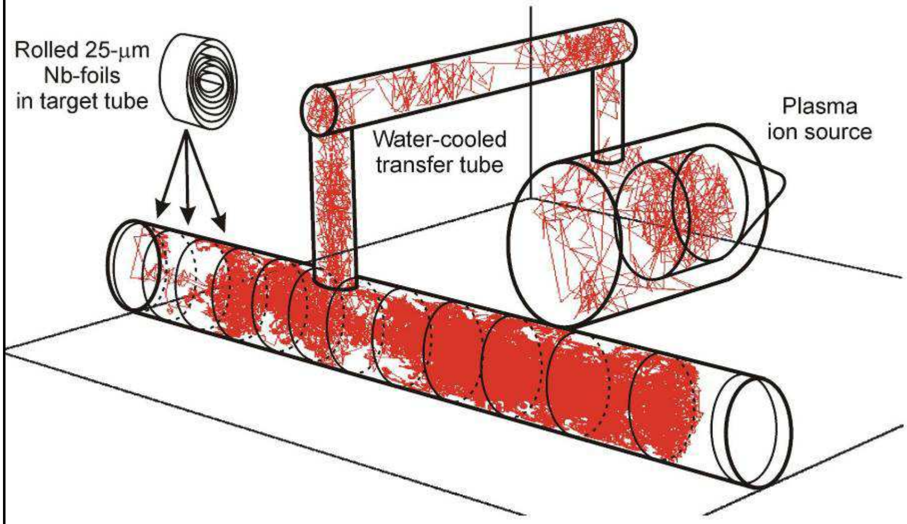
Characteristic diffusion length:

$d = (2\ n\ D\ t)^{1/2}$ n=1 (foil), n=2 (fiber), n=3 (sphere)

Maximize D and minimize diffusion path:

$\Rightarrow$ thin metal foils (2 μm ... 30 μm)
$\Rightarrow$ fine powders (μm)
$\Rightarrow$ thin fibers (some μm)

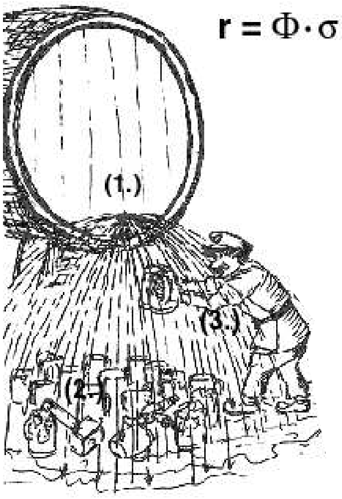
Effusion: random walk release



Optimize RIB intensity

All steps of the separation chain need to be optimized!

$$r = \Phi \cdot \sigma \cdot N \cdot \varepsilon_{target} \cdot \varepsilon_{source} \cdot \varepsilon_{transp} \cdot \varepsilon_{det}$$



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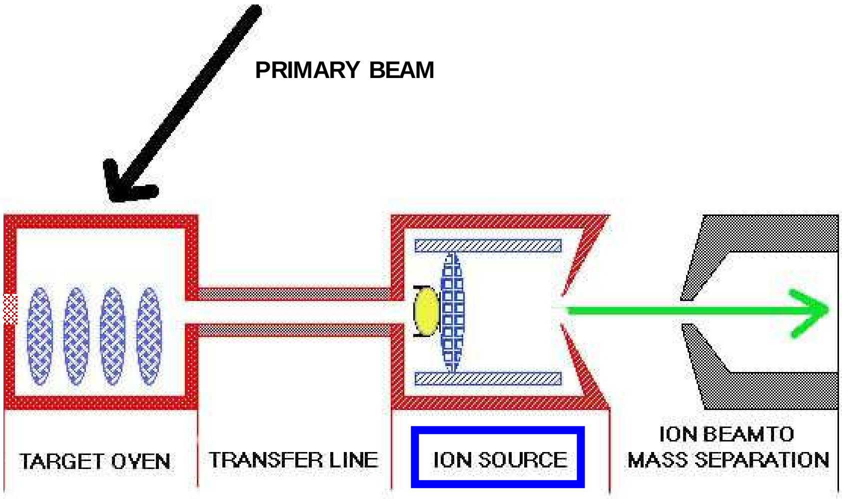
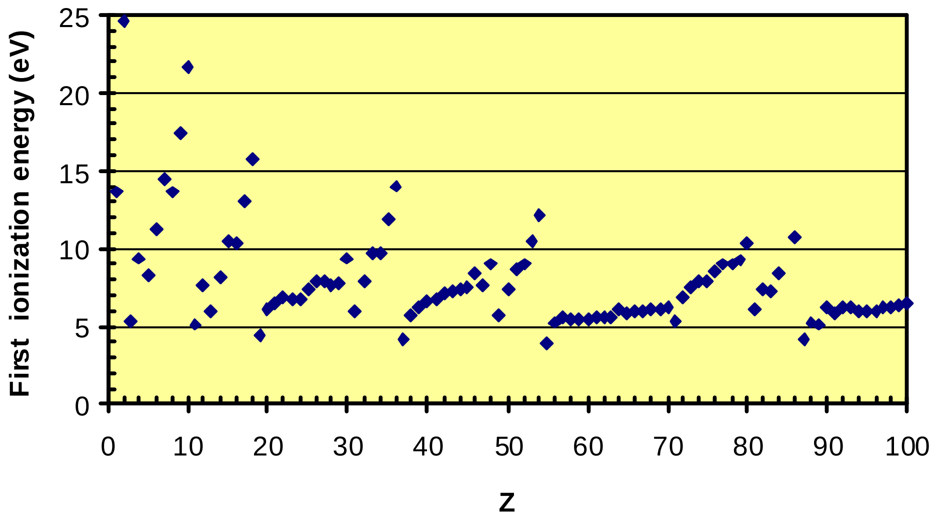
*I*sotope *S*eparation *O*n-*L*ine

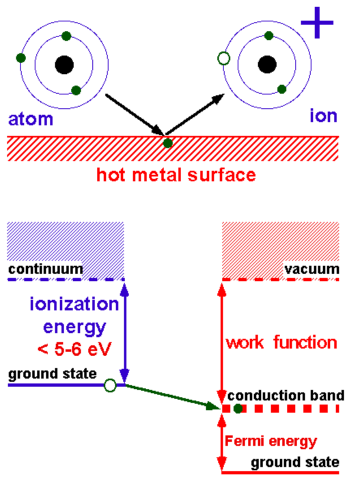


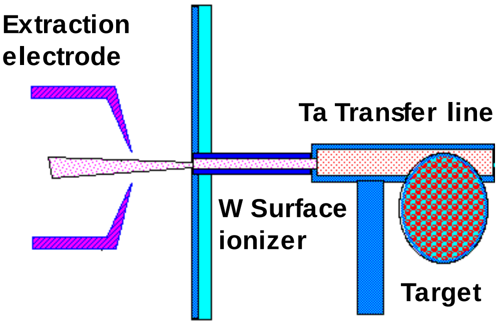
The first ionization energy of the elements



Positive surface ionization source

Surface Ionization





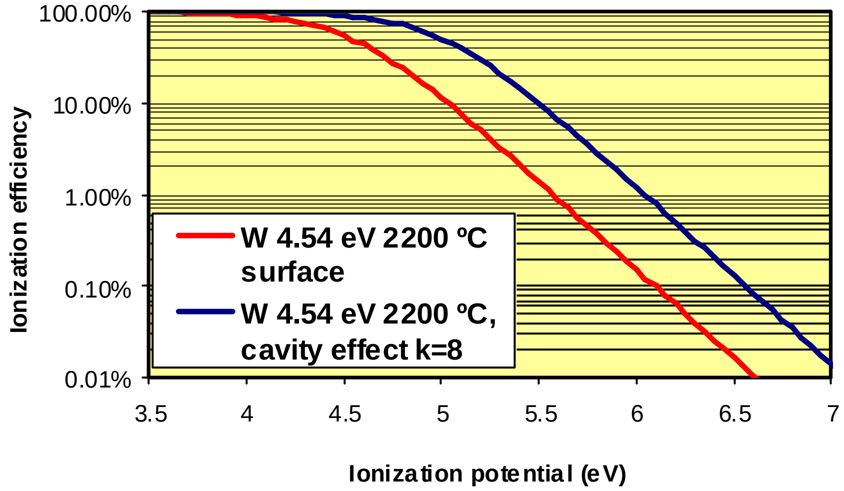
$$\boxed{\alpha_s = g_+/g_0 \exp(-(IP - \Phi)/kT)}$$

$$\varepsilon_s = \alpha_s / (1 + \alpha_s)$$

Saha-Langmuir equation

ε_s	surface ionization efficiency
Φ	work function of surface
IP	ionization potential of atom
$g=2J+1$	stat. factor ($g_0=2$, $g_+=1$ for alkalis)

Surface ionization versus thermal ionization

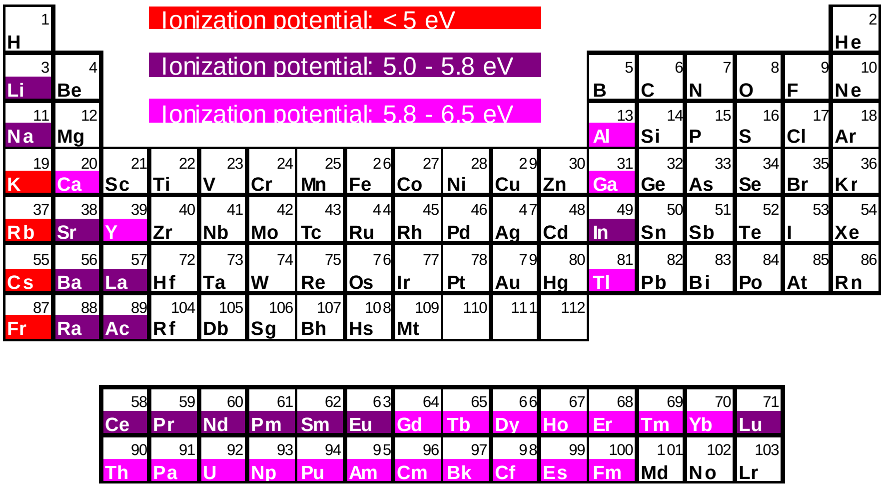


$$\boxed{\varepsilon_{th} = 1/(1 + g_0/g_+/k \exp((IP - \Phi)/kT))}$$

Thermal ionization efficiency in realistic ionizer cavity

R. Kirchner, Nucl. Instr. Meth. A292 (1987) 204.

Ionization potentials of the elements



🟥 Ionization potential: < 5 eV

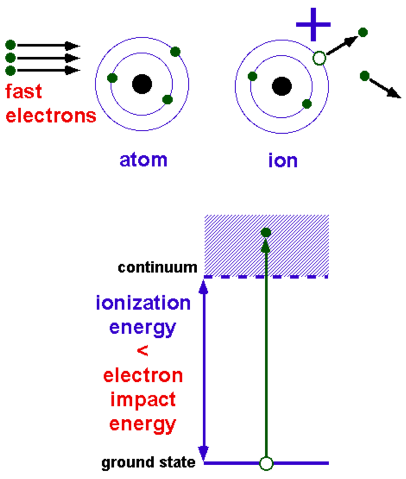
🟪 Ionization potential: 5.0 - 5.8 eV

▨ Ionization potential: 5.8 - 6.5 eV

1 H																	2 He
🟪 3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
🟪 11 Na	12 Mg											▨ 13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
🟥 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
🟥 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
🟥 55 Cs	🟪 56 Ba	🟪 57 La	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
🟥 87 Fr	🟪 88 Ra	🟪 89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110	111	112						
		🟪 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		
		▨ 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		

Ingredients of a plasma ion source

Ionization by electron impact



- Fast electrons:
  - A) Thermionic emission + accelerating field
  - B) RF heating
- Atom confinement: plasma chamber
- Electron "recycling": magnetic field
- Ion extraction system

$I[A] = A^* T[K]^2 \exp(-\Phi[eV]/kT[K])$

$A^* = 120\ A\ cm^{-2}\ K^{-2}$

$\nu_{cyc}[GHz] = 28\ B[T]$

$r[mm] = 0.35\ E_e[eV]^{1/2}/B[T]$

Ionization and neutralization

$X^0 + e^- \rightarrow X^+ + 2\ e^-,\ \ Q = -\ IP_1$

$X^0 + e^- \rightarrow X^{2+} + 3\ e^-,\ Q = -\ (IP_1 + IP_2)$

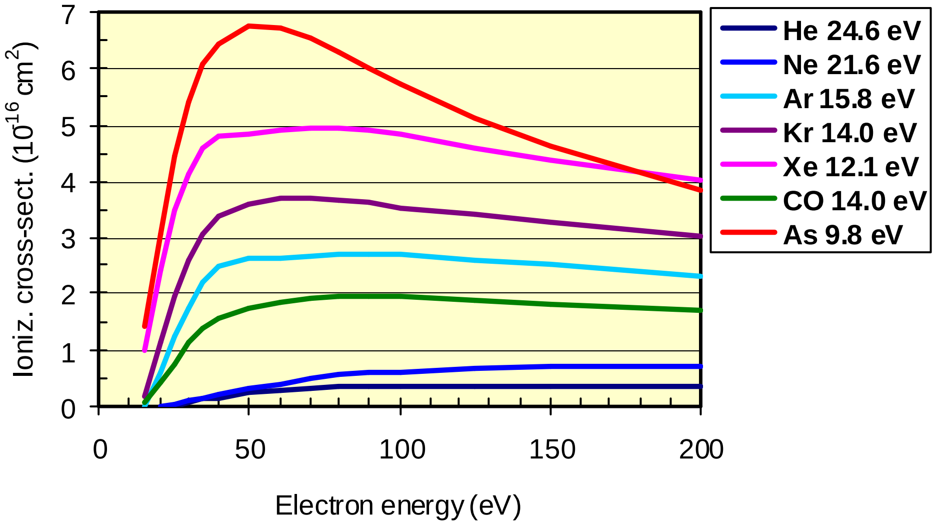
$X^0 + e^- \rightarrow X^{3+} + 4\ e^-,\ Q = -\ (IP_1 + IP_2 + IP_3)$

$X^+ + e^- \rightarrow X^{2+} + 2\ e^-,\ Q = -\ IP_2$

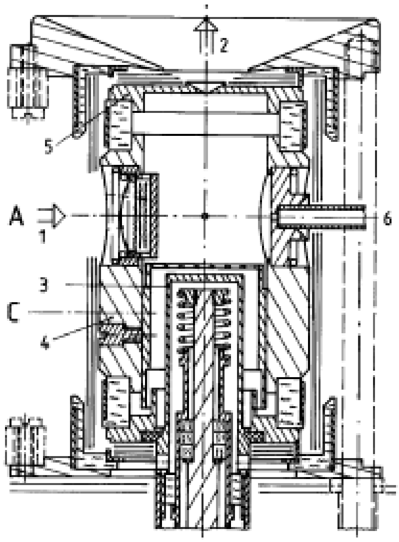
$X^+ + e^- \rightarrow X^0,\qquad Q = IP_1$ Neutralization

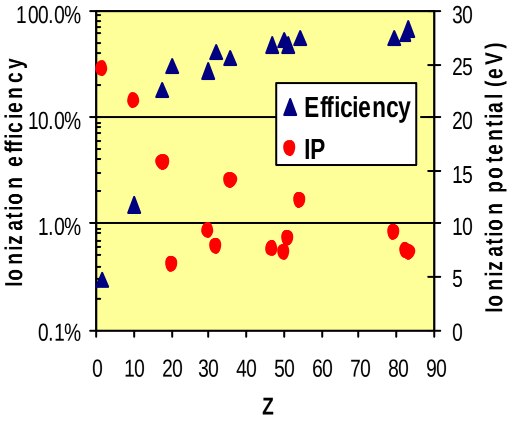
$X^0 + Y^+ \rightarrow X^+ + Y^0,\quad Q = IP_Y - IP_X$ Charge exchange

Electron impact ionization cross-sections



Forced Electron Beam Ion Arc Discharge (FEBIAD)

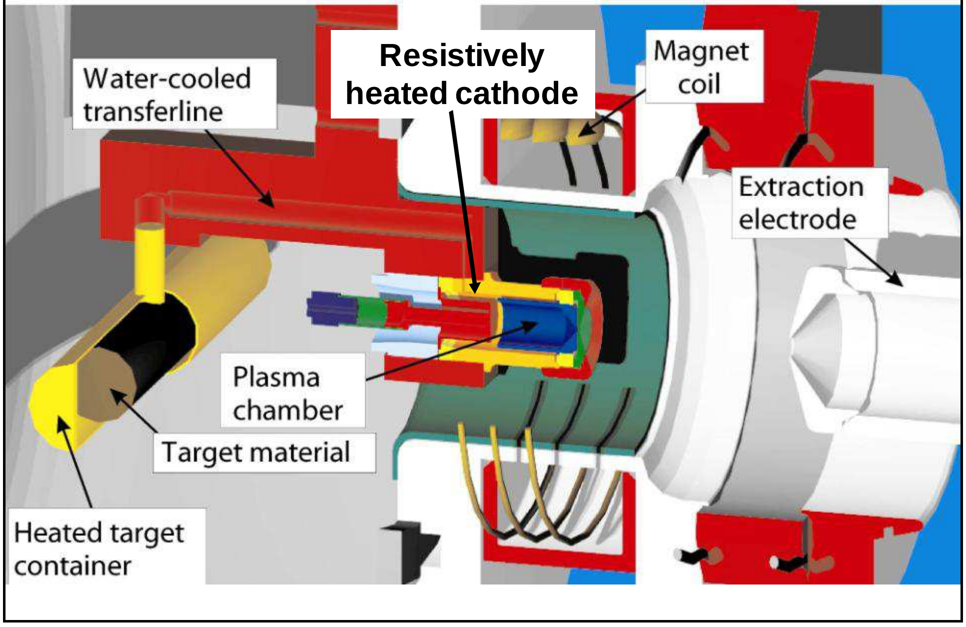




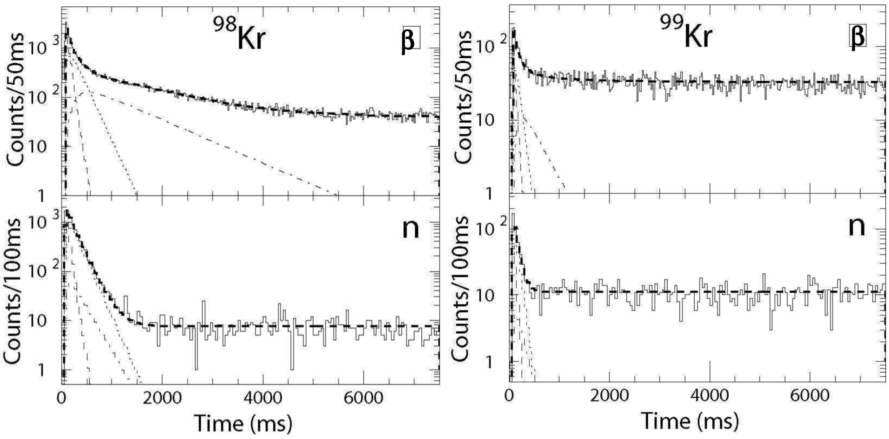
FEBIAD ion sources are excellent for heavier elements!

R. Kirchner, Rev. Sci. Instr. 67 (1996) 928.

ISOLDE “FEBIAD”

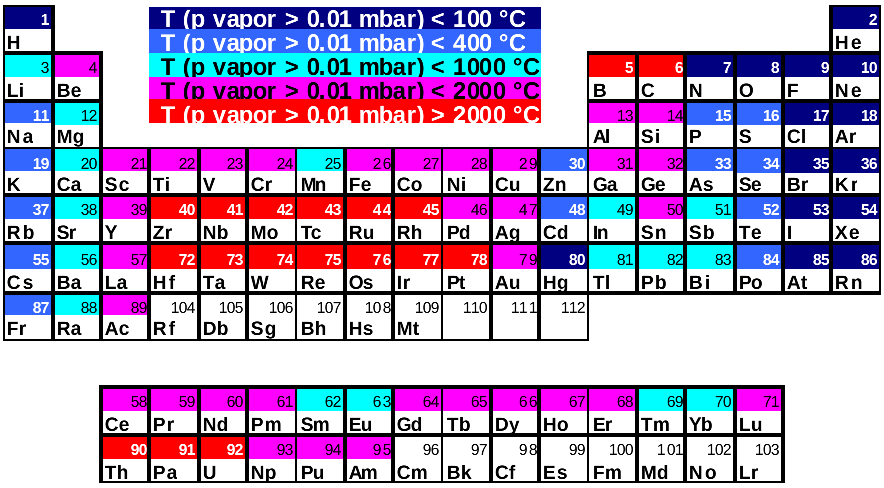


2001: $^{94-99}$Kr decay studied at ISOLDE



U.C. Bergmann et al., Nucl. Phys. A 714 (2003) 21.

Volatility of the elements



T (p vapor > 0.01 mbar) < 100 °C
T (p vapor > 0.01 mbar) < 400 °C
T (p vapor > 0.01 mbar) < 1000 °C
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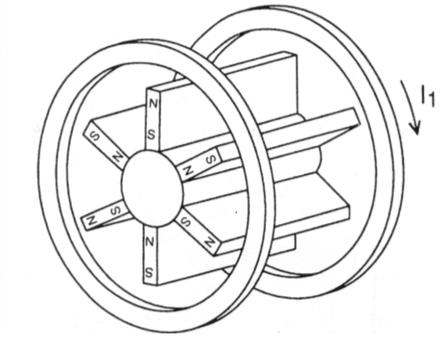
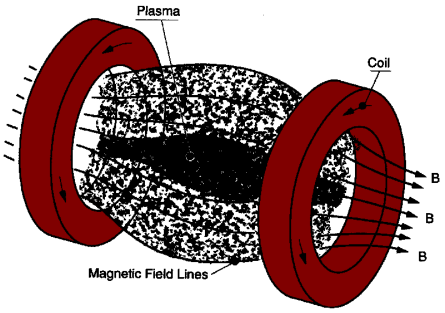
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110	111	112						

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
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

Electron Cyclotron Resonance Ion Source (ECRIS)





radial plasma confinement by magnetic multipole field

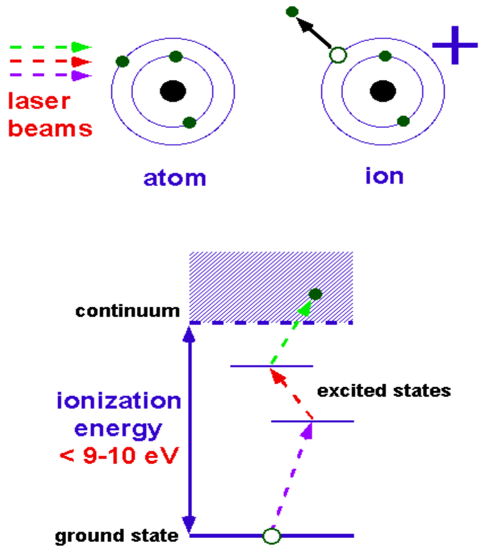
**longitudinal plasma confinement by magnetic bottle effect (1+ ECRIS)
or minimum B configuration (n+ ECRIS)**

plasma heating by RF (typically 2.45 – 30 GHz)

good efficiency for light elements (20% He$^+$, 50% C$^+$, O$^+$, Ar$^+$, 90% Xe$^+$)

R. Geller, Electron Cyclotron Resonance Ion Sources and ECR Plasmas, IOP, Bristol, 1996.

Laser Ionization



laser beams

atom

ion

+

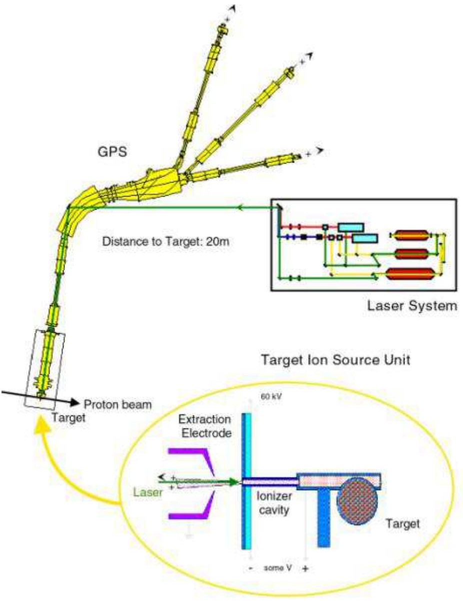
continuum

ionization energy < 9-10 eV

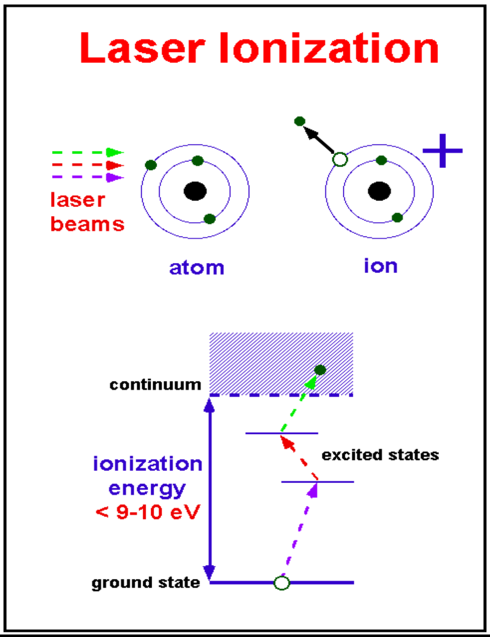
excited states

ground state

Resonance Ionization Laser Ion Source



Spectrochimica Acta B58 (2003) 1047.



Laser Ionization

laser beams

atom

ion

+

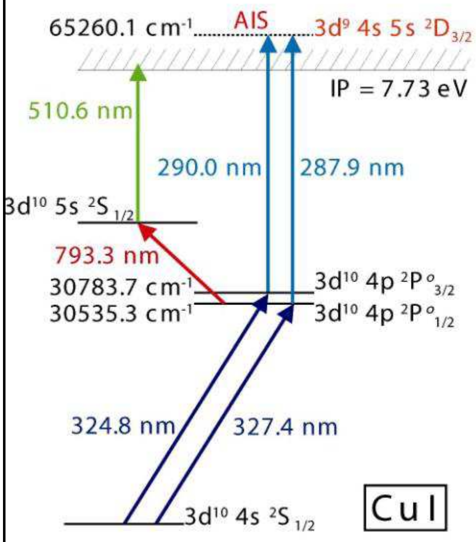
continuum

ionization energy < 9-10 eV

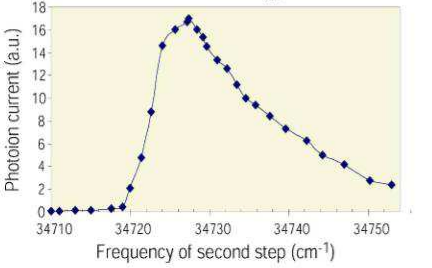
excited states

ground state

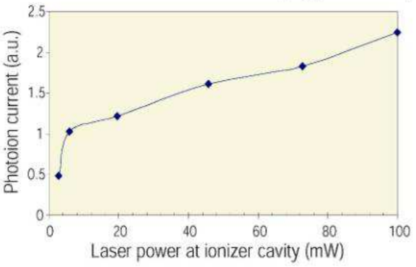
Ionization of Cu



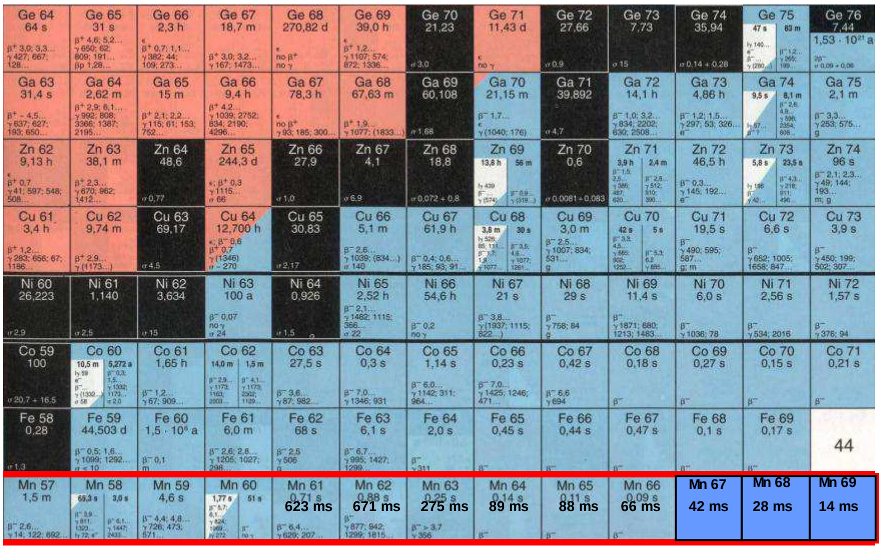
Structure of the $3d^9$ 4s 5s $^2D_{3/2}$ AIS at 65260.1 cm-1



Saturation curve of first step (l_1=327.4 nm)



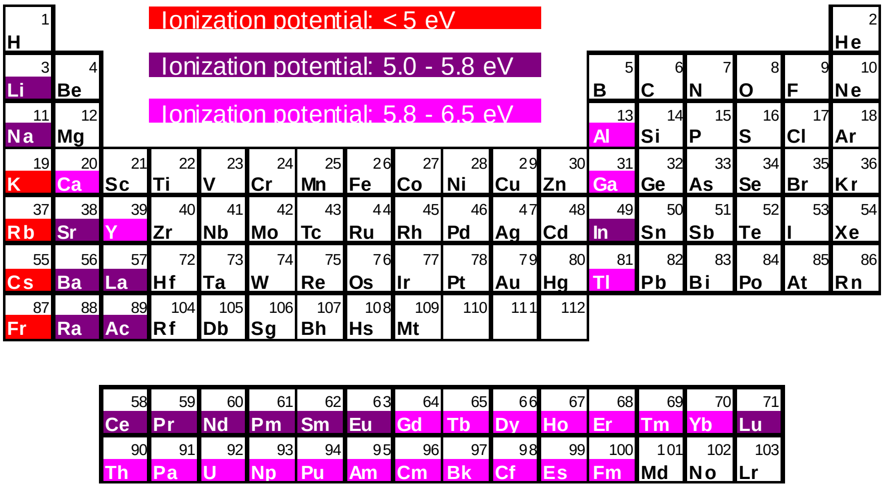
Neutron-rich Mn isotopes from UC_x/graphite target



Ge 64 64 s	Ge 65 31 s	Ge 66 2,3 h	Ge 67 18,7 m	Ge 68 270,82 d	Ge 69 39,0 h	Ge 70 21,23	Ge 71 11,43 d	Ge 72 27,66	Ge 73 7,73	Ge 74 35,94	Ge 75 47 s 83 m	Ge 76 7,44 1,53 · 10²¹ a
Ga 63 31,4 s	Ga 64 2,62 m	Ga 65 15 m	Ga 66 9,4 h	Ga 67 78,3 h	Ga 68 67,63 m	Ga 69 60,108	Ga 70 21,15 m	Ga 71 39,892	Ga 72 14,1 h	Ga 73 4,86 h	Ga 74 9,5 s 8,1 m	Ga 75 2,1 m
Zn 62 9,13 h	Zn 63 38,1 m	Zn 64 48,6	Zn 65 244,3 d	Zn 66 27,9	Zn 67 4,1	Zn 68 18,8	Zn 69 13,8 h 56 m	Zn 70 0,6	Zn 71 3,9 h 2,4 m	Zn 72 46,5 h	Zn 73 5,8 s 23,5 s	Zn 74 96 s
Cu 61 3,4 h	Cu 62 9,74 m	Cu 63 69,17	Cu 64 12,700 h	Cu 65 30,83	Cu 66 5,1 m	Cu 67 61,9 h	Cu 68 3,8 m 30 s	Cu 69 3,0 m	Cu 70 42 s 5 s	Cu 71 19,5 s	Cu 72 6,6 s	Cu 73 3,9 s
Ni 60 26,223	Ni 61 1,140	Ni 62 3,634	Ni 63 100 a	Ni 64 0,926	Ni 65 2,52 h	Ni 66 54,6 h	Ni 67 21 s	Ni 68 29 s	Ni 69 11,4 s	Ni 70 6,0 s	Ni 71 2,56 s	Ni 72 1,57 s
Co 59 100	Co 60 10,5 m 5,272 a	Co 61 1,65 h	Co 62 14,0 m 1,5 m	Co 63 27,5 s	Co 64 0,3 s	Co 65 1,14 s	Co 66 0,23 s	Co 67 0,42 s	Co 68 0,18 s	Co 69 0,27 s	Co 70 0,15 s	Co 71 0,21 s
Fe 58 0,28	Fe 59 44,503 d	Fe 60 1,5 · 10⁶ a	Fe 61 6,0 m	Fe 62 68 s	Fe 63 6,1 s	Fe 64 2,0 s	Fe 65 0,45 s	Fe 66 0,44 s	Fe 67 0,47 s	Fe 68 0,1 s	Fe 69 0,17 s	44
Mn 57 1,5 m	Mn 58 65,3 s 3,0 s	Mn 59 4,6 s	Mn 60 1,77 s 51 s	Mn 61 0,71 s 623 ms	Mn 62 0,88 s 671 ms	Mn 63 0,25 s 275 ms	Mn 64 0,14 s 89 ms	Mn 65 0,11 s 88 ms	Mn 66 0,09 s 66 ms	Mn 67 42 ms	Mn 68 28 ms	Mn 69 14 ms

M. Hannawald et al., Phys. Rev. Lett. 82 (1999) 1391.

Surface ionized background



Ionization potential: < 5 eV

Ionization potential: 5.0 - 5.8 eV

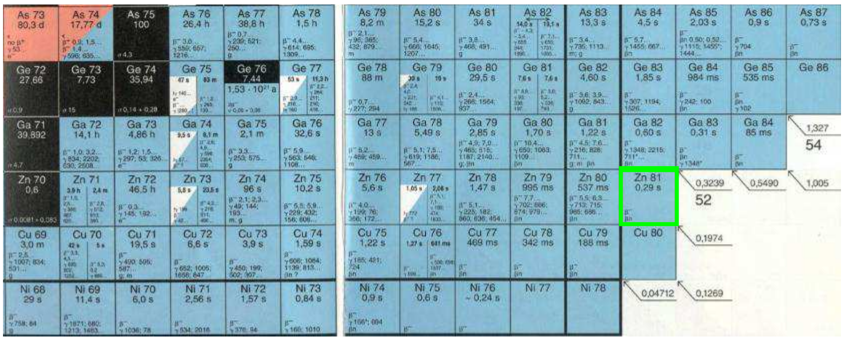
Ionization potential: 5.8 - 6.5 eV

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
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
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
55 Cs	56 Ba	57 La	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
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110	111	112						

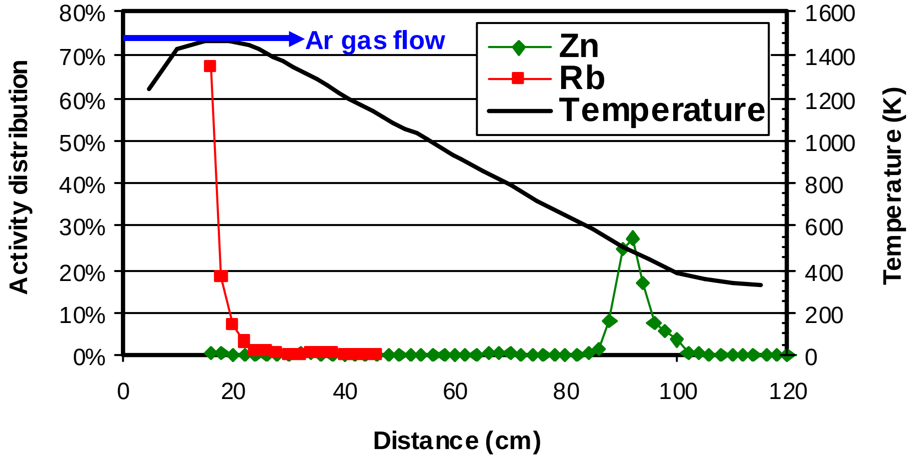
58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

ISOLDE beams around N=50

^{81}Rb background is 150000 times more abundant than ^{81}Zn!



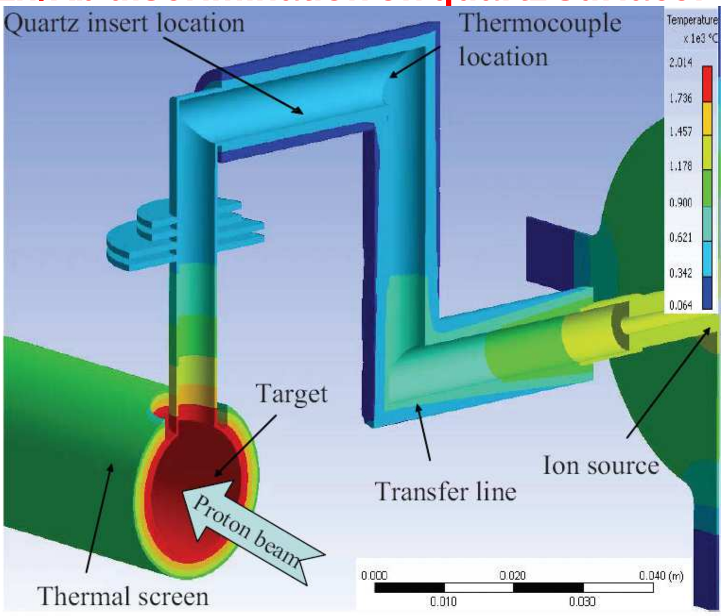
Zn/Rb discrimination on quartz surface!



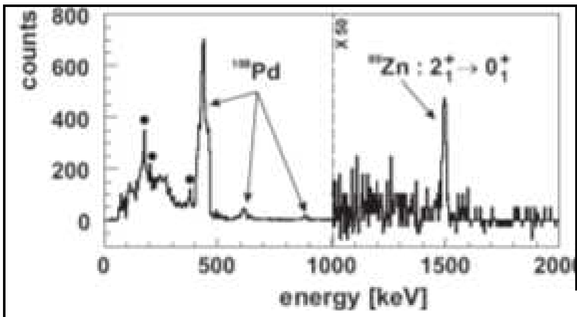
Combination of neutron converter and quartz transfer line provides ^{81}Zn/^{81}Rb selectivity gain of 100000!

Nucl. Instr. Meth. B266 (2008) 4229.

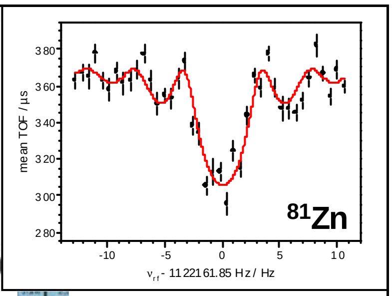
Zn/Rb discrimination on quartz surface!



E. Boucquerel et al., Nucl. Instr. Meth. B266 (2008) 4298.



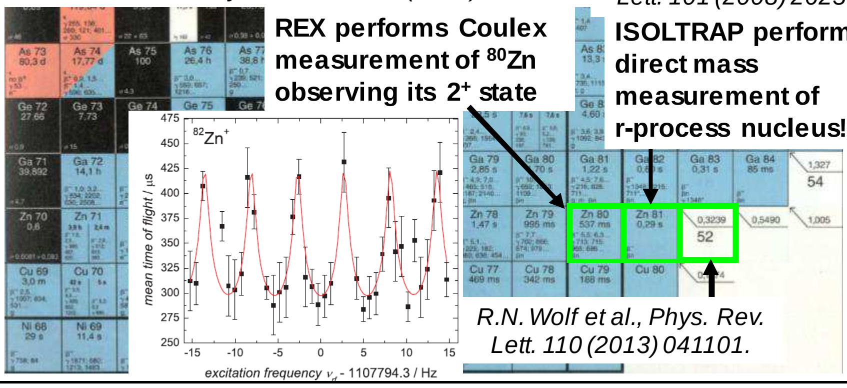
J. Van de Walle et al., Phys. Rev. Lett. 99 (2007) 142501.



S. Baruah et al., Phys. Rev. Lett. 101 (2008) 262501.

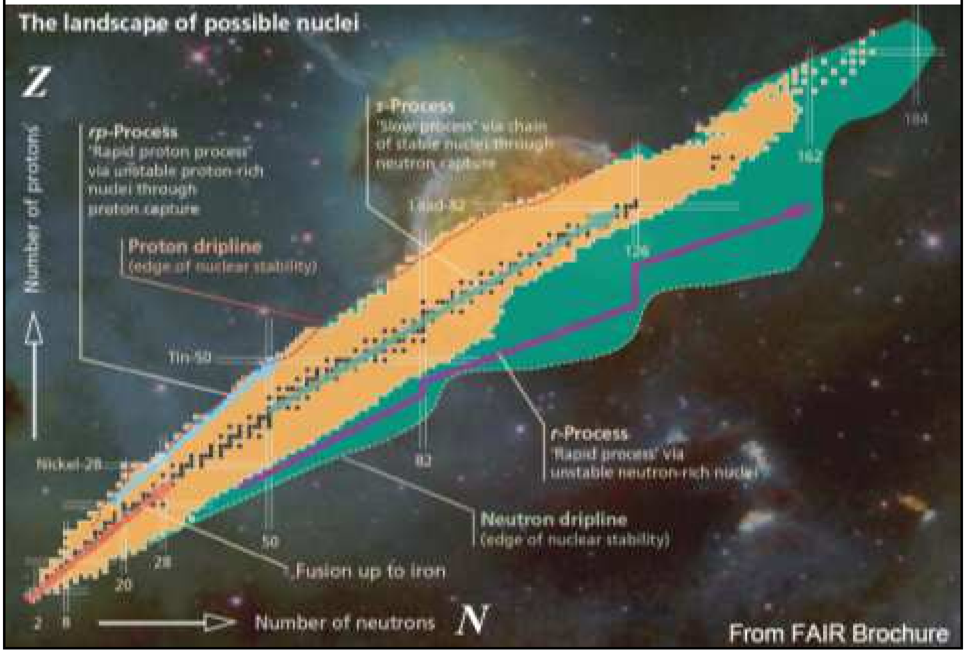
REX performs Coulex measurement of ^{80}Zn observing its 2^+ state

ISOLTRAP performs direct mass measurement of r-process nucleus!



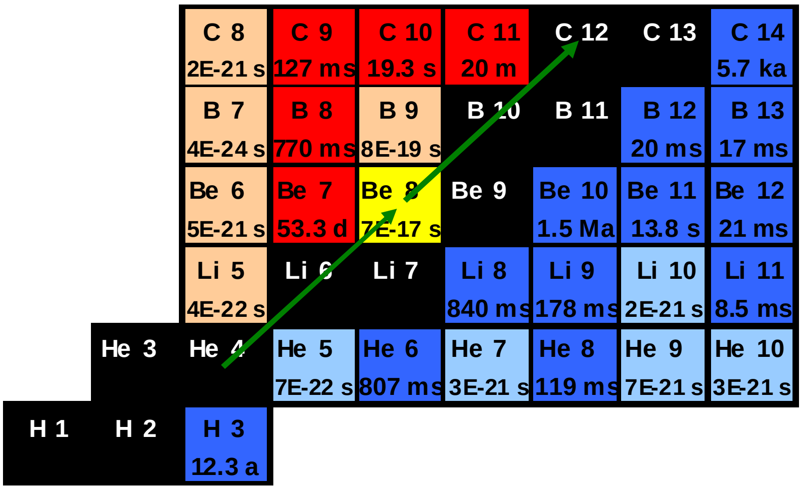
R.N. Wolf et al., Phys. Rev. Lett. 110 (2013) 041101.

Experimental access to *r*-process nuclides



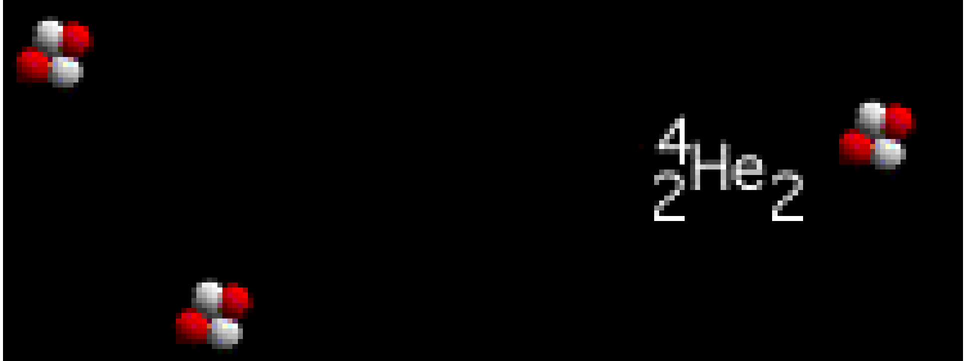
From FAIR Brochure

Production of ^{12}C in stars



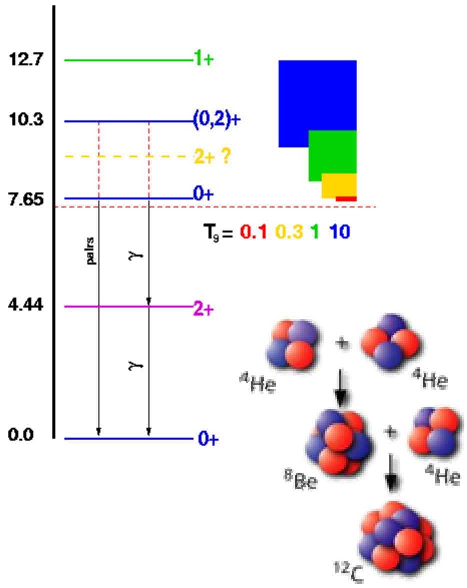
		C 8 2E-21 s	C 9 127 ms	C 10 19.3 s	C 11 20 m	C 12	C 13	C 14 5.7 ka
		B 7 4E-24 s	B 8 770 ms	B 9 8E-19 s	B 10	B 11	B 12 20 ms	B 13 17 ms
		Be 6 5E-21 s	Be 7 53.3 d	Be 8 7E-17 s	Be 9	Be 10 1.5 Ma	Be 11 13.8 s	Be 12 21 ms
		Li 5 4E-22 s	Li 6	Li 7	Li 8 840 ms	Li 9 178 ms	Li 10 2E-21 s	Li 11 8.5 ms
	He 3	He 4	He 5 7E-22 s	He 6 807 ms	He 7 3E-21 s	He 8 119 ms	He 9 7E-21 s	He 10 3E-21 s
H 1	H 2	H 3 12.3 a						

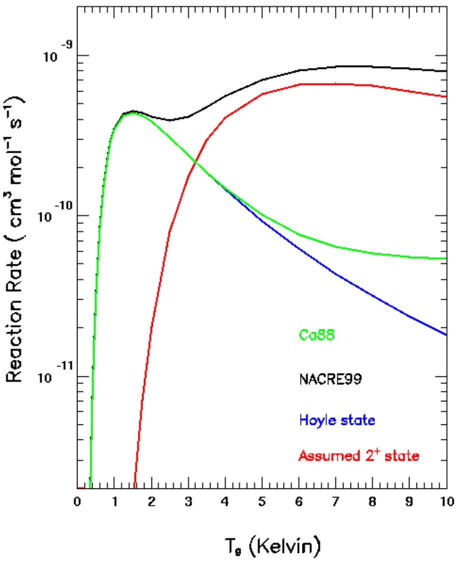
The triple-alpha process: rate



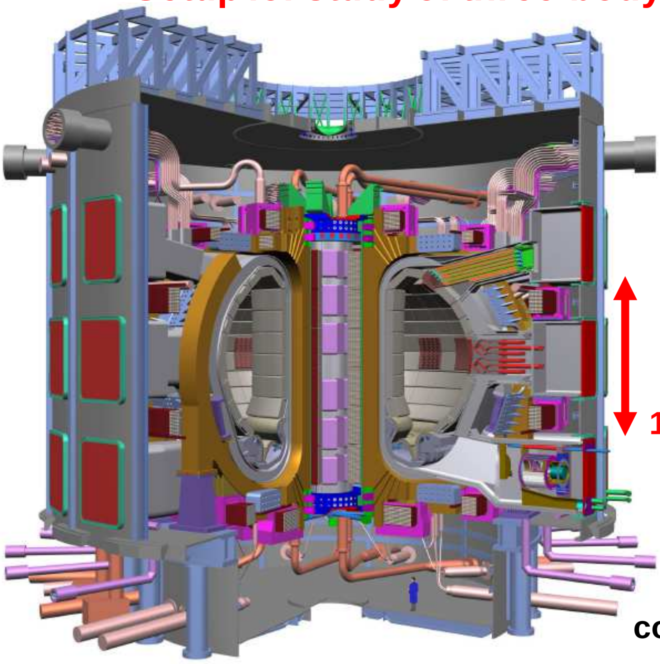
The triple-alpha process

$r_{3\alpha} \propto \Gamma_{rad}\, e^{-Q/kT}$





Setup for study of three-body-fusion?

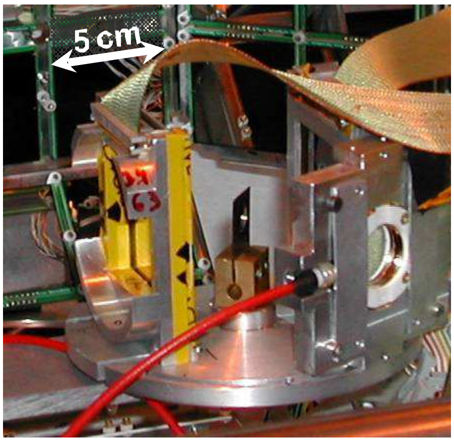


Exercise:

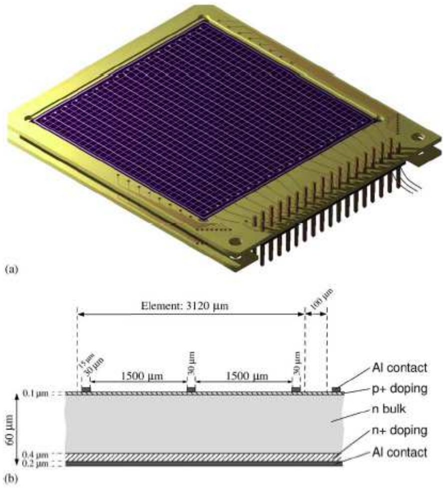
scale from two-body fusion d+t to three-body fusion ^{4}He+^{4}He+^{4}He!

cost ca. 10^{10} EUR

Setup for study of triple alpha reaction!

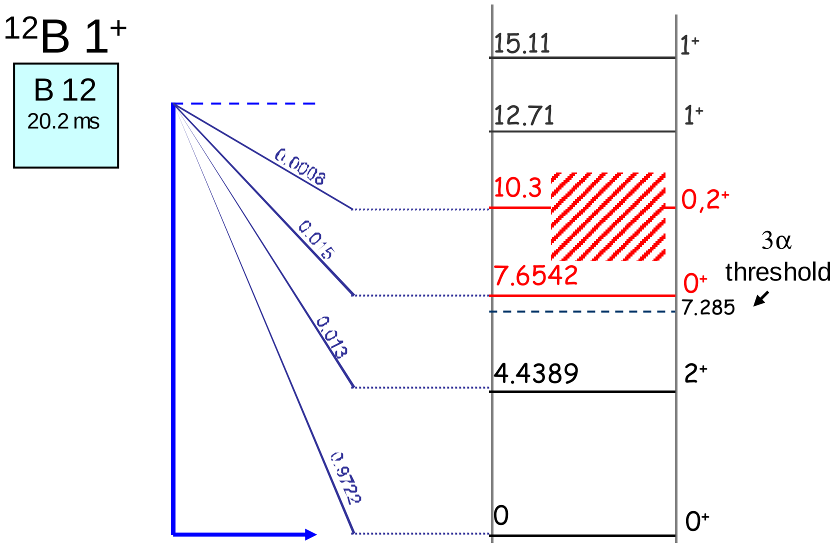


New detector design

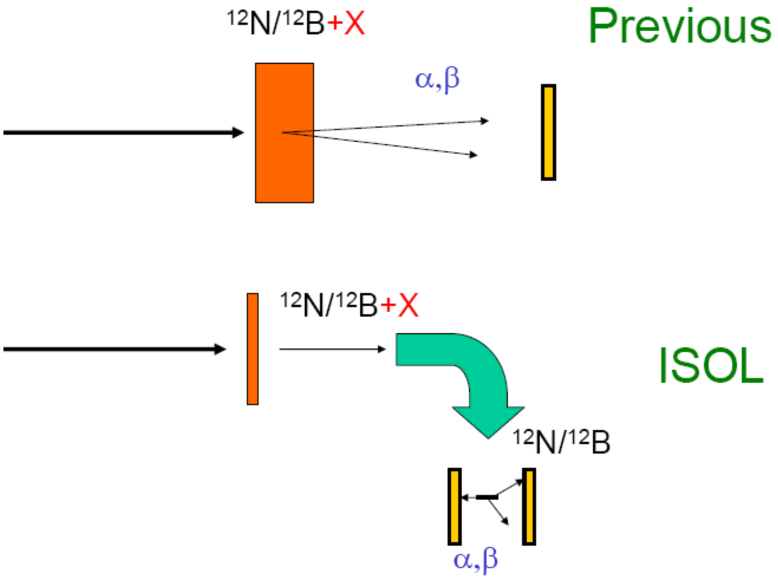


Reduced deadlayer

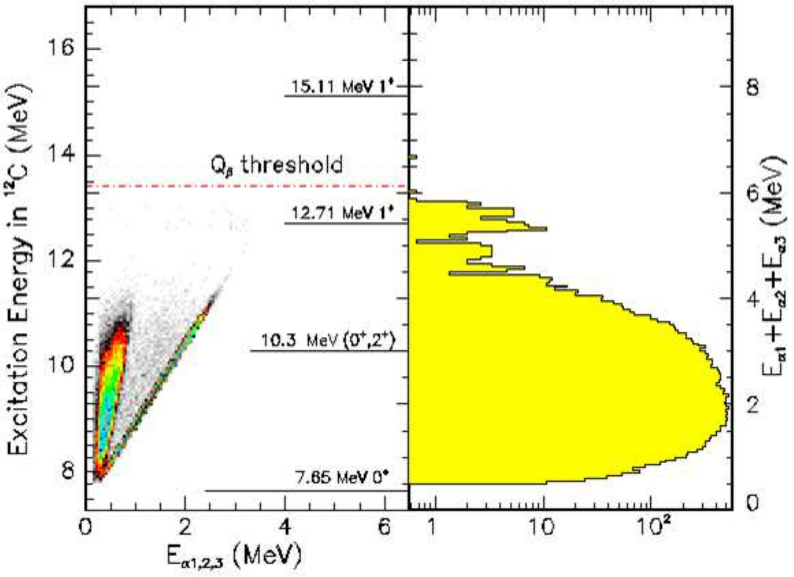
Inverse reaction: ^{12}B(β,3α) decay



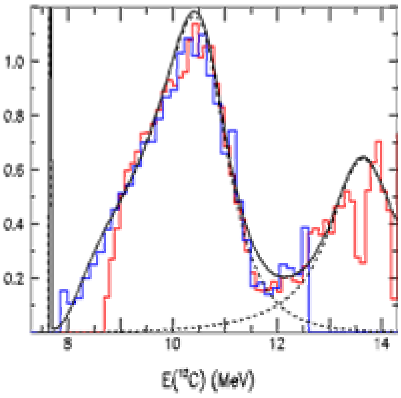
How to measure beta-delayed particle emission?



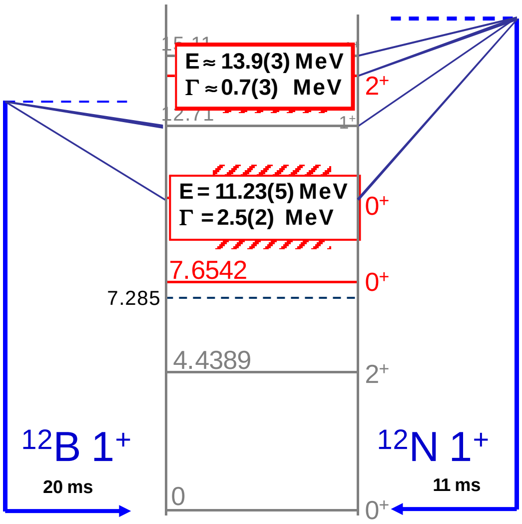
^{12}Be(β^-)^{12}B beta decay to ^{12}C* → 2α detected



The triple-alpha process: ^{12}B and ^{12}N decays

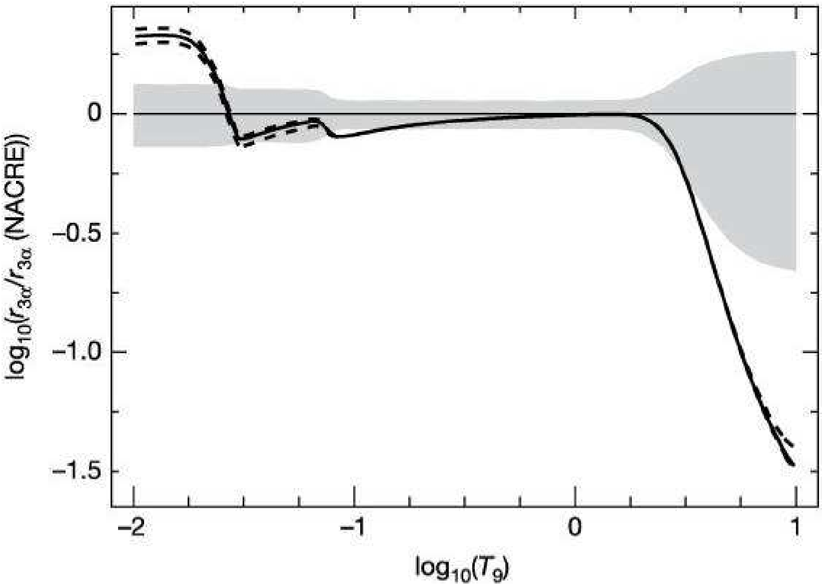


Combined R-matrix fit of
^{12}B and ^{12}N
ISOLDE - JYFL



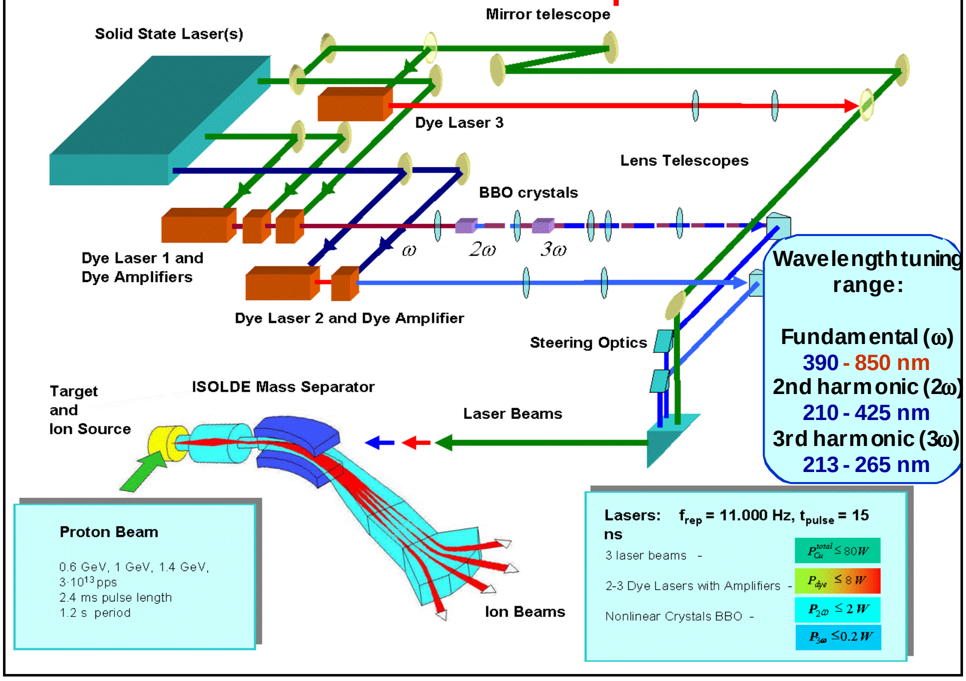
H.O.U. Fynbo et al., Nature 433 (2005) 136.

New rates for the triple-alpha process



H.O.U. Fynbo et al., Nature 433 (2005) 136.

RILIS laser setup



Wavelength tuning range:

Fundamental (ω)
390 - 850 nm
2nd harmonic (2ω)
210 - 425 nm
3rd harmonic (3ω)
213 - 265 nm

Proton Beam

0.6 GeV, 1 GeV, 1.4 GeV,
$3 \cdot 10^{13}$ pps
2.4 ms pulse length
1.2 s period

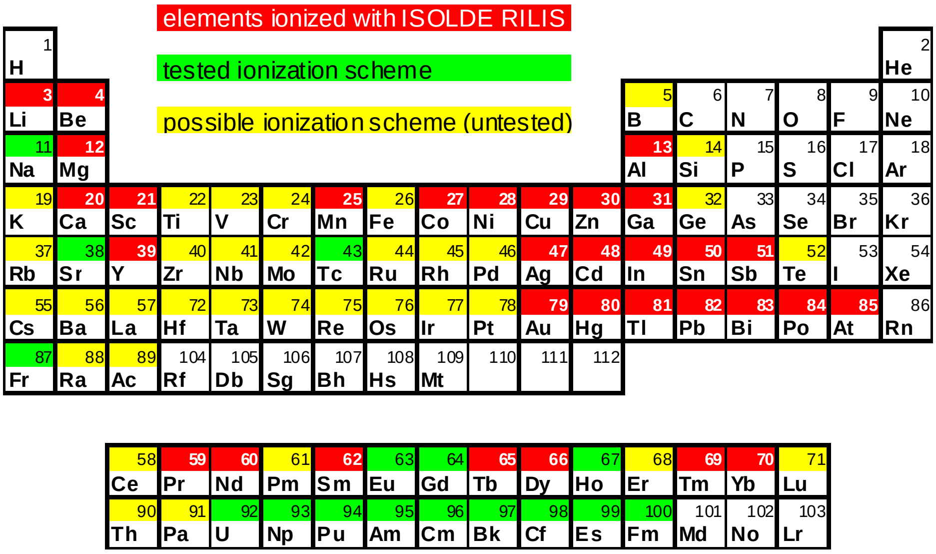
Lasers: f_{rep} = 11.000 Hz, t_{pulse} = 15 ns

3 laser beams - $P_{Cu}^{total} \leq 80 W$

2-3 Dye Lasers with Amplifiers - $P_{dye} \leq 8 W$

Nonlinear Crystals BBO - $P_{2\omega} \leq 2 W$, $P_{3\omega} \leq 0.2 W$

Elements ionizable with CVL or Nd-YAG pumped dye or Ti:Sa lasers



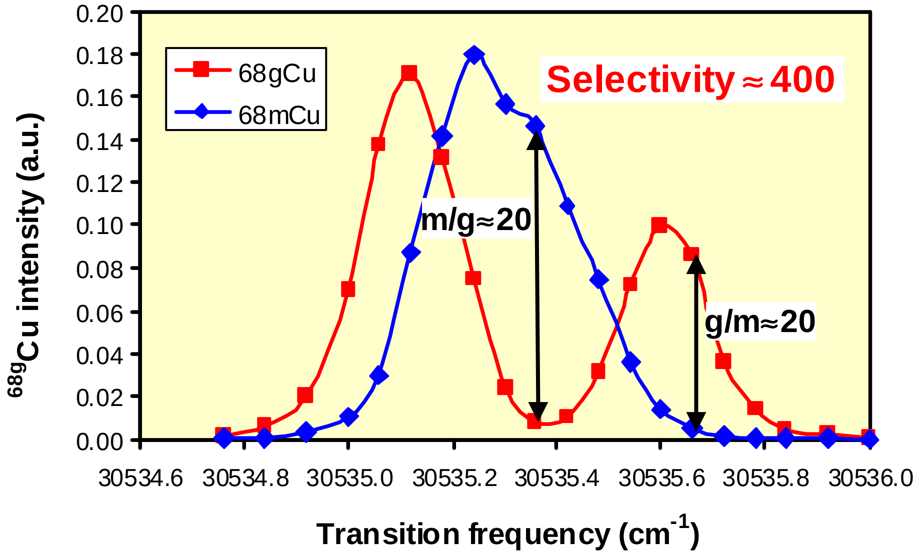
🟥 elements ionized with ISOLDE RILIS

🟩 tested ionization scheme

🟨 possible ionization scheme (untested)

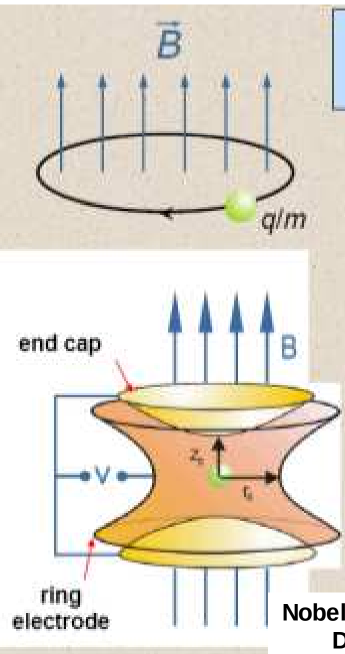
1 H																	2 He
🟥 3 Li	🟥 4 Be											🟨 5 B	6 C	7 N	8 O	9 F	10 Ne
🟩 11 Na	🟥 12 Mg											🟥 13 Al	🟨 14 Si	15 P	16 S	17 Cl	18 Ar
🟨 19 K	🟥 20 Ca	🟥 21 Sc	🟨 22 Ti	🟨 23 V	🟨 24 Cr	🟥 25 Mn	🟨 26 Fe	🟥 27 Co	🟥 28 Ni	🟥 29 Cu	🟥 30 Zn	🟥 31 Ga	🟨 32 Ge	33 As	34 Se	35 Br	36 Kr
🟨 37 Rb	🟩 38 Sr	🟥 39 Y	🟨 40 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
🟨 55 Cs	🟨 56 Ba	🟨 57 La	🟨 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
🟩 87 Fr	🟨 88 Ra	🟨 89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110	111	112						
		🟨 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		
		🟨 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		

Isomer separation



Hyperfine Interactions 127 (2000) 417.

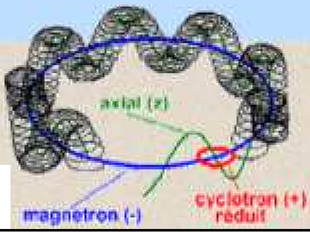
Mass measurements with Penning traps



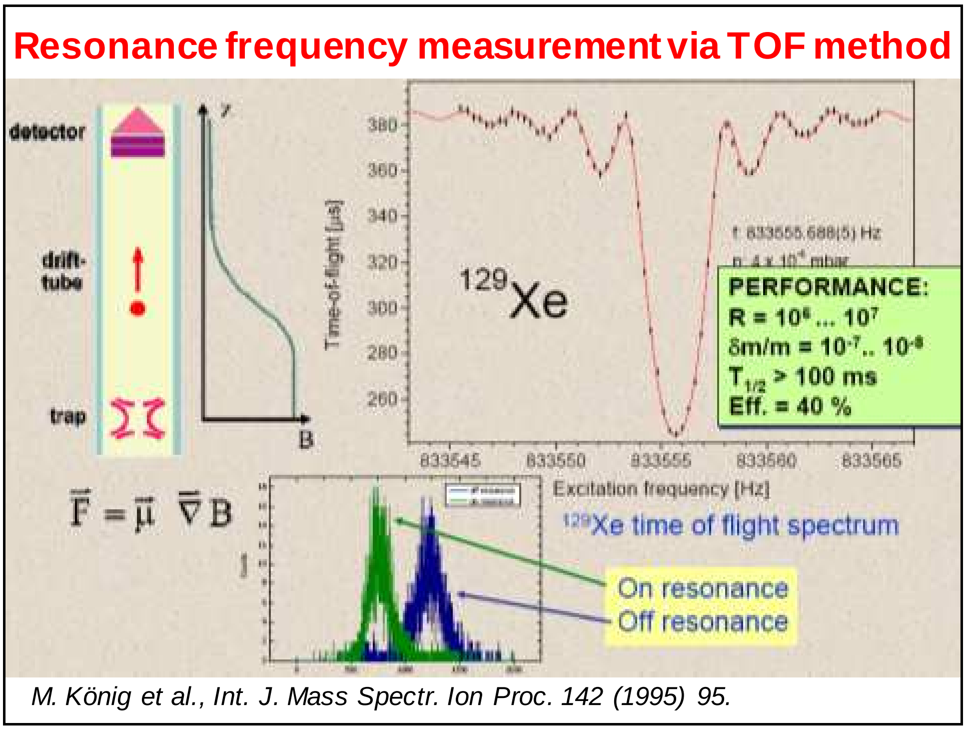
Cyclotron frequency: $f_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$

PENNING trap
- Strong homogeneous magnetic field
- Weak electric 3D quadrupole field

$$\omega_+ + \omega_- = \omega_c = \frac{q}{m} B$$



Nobel prize 1989: Dehmelt



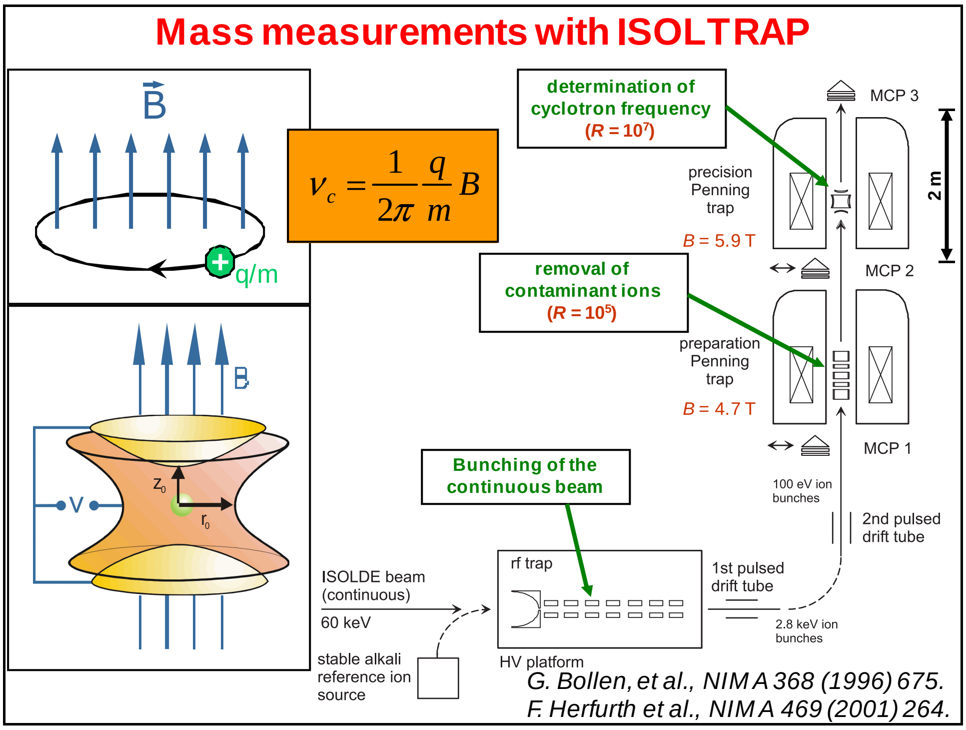
Resonance frequency measurement via TOF method

PERFORMANCE:
$R = 10^6 \dots 10^7$
$\delta m/m = 10^{-7} .. 10^{-8}$
$T_{1/2} > 100$ ms
Eff. = 40 %

^{129}Xe time of flight spectrum

On resonance
Off resonance

M. König et al., Int. J. Mass Spectr. Ion Proc. 142 (1995) 95.



Mass measurements with ISOLTRAP

$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$

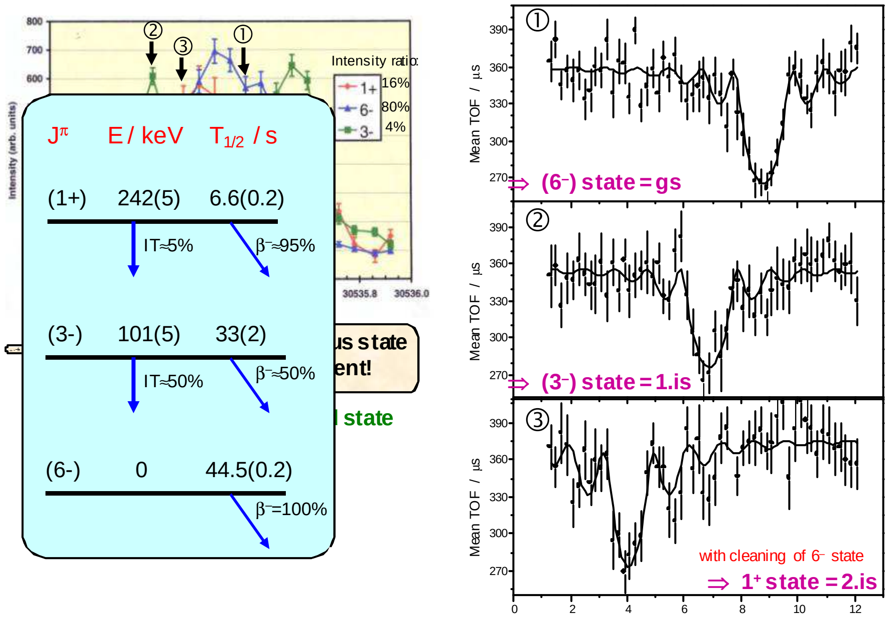
determination of cyclotron frequency ($R = 10^7$)

removal of contaminant ions ($R = 10^5$)

Bunching of the continuous beam

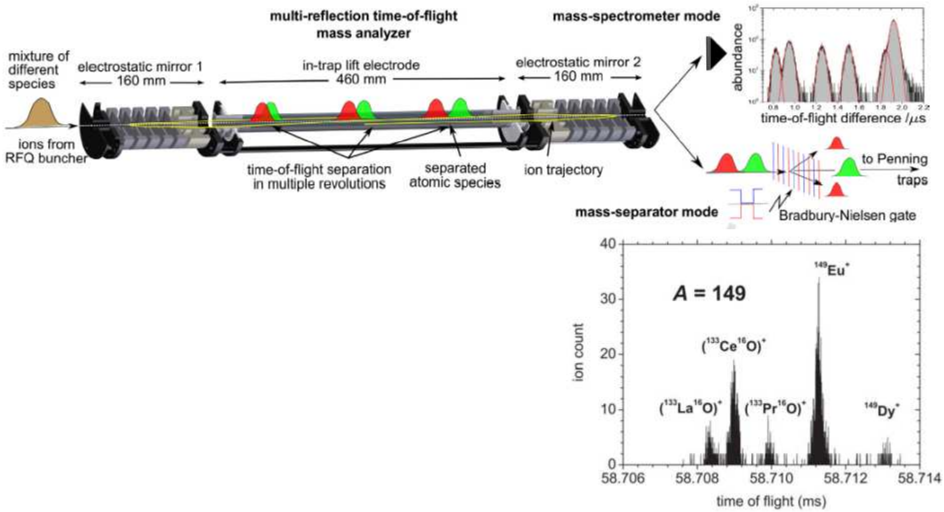
G. Bollen, et al., NIM A 368 (1996) 675.
F. Herfurth et al., NIM A 469 (2001) 264.

Solving the ^{70}Cu mass puzzle



J. Van Roosbroeck et al., Phys. Rev. Lett. 92 (2004) 112501.

Linear TOF spectrometer



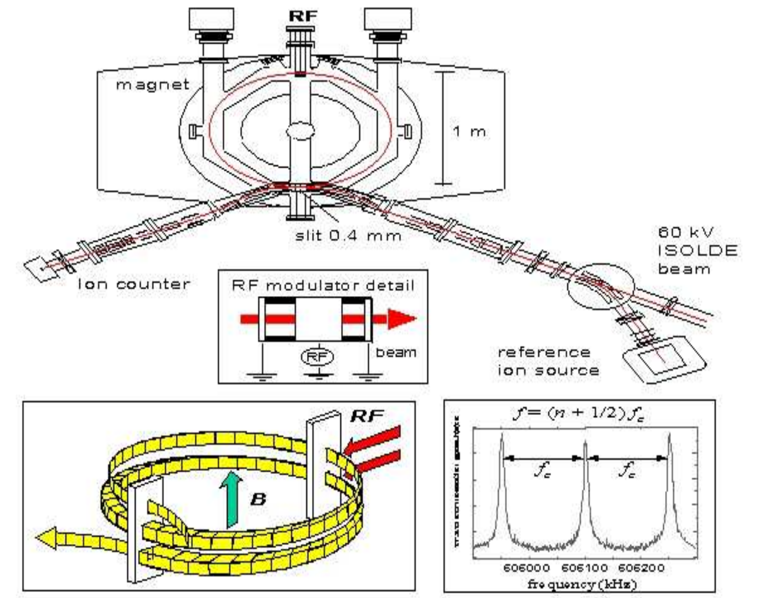
R.N. Wolf et al., Nucl. Instr. Meth. A686 (2012) 82.

R.N. Wolf et al., Int. J. Mass Spectrometry (2013) in press.

S. Kreim et al., Nucl. Instr. Meth. B, Proc. of EMIS-16, in press.

MISTRAL

MISTRAL - Mesures de masses à ISOLDE avec un spectromètre à Transmission et RAdiofréquence en-Ligne



M. de Saint Simon et al., Phys. Scr. T59 (1995) 406.

Mass measurement of ^{11}Li ($T_{1/2}$ = 9 ms)

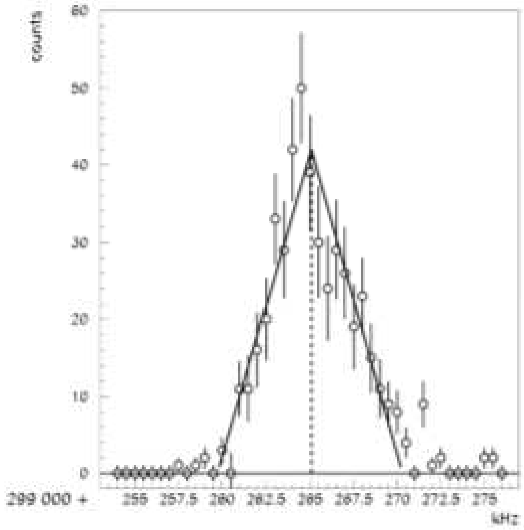
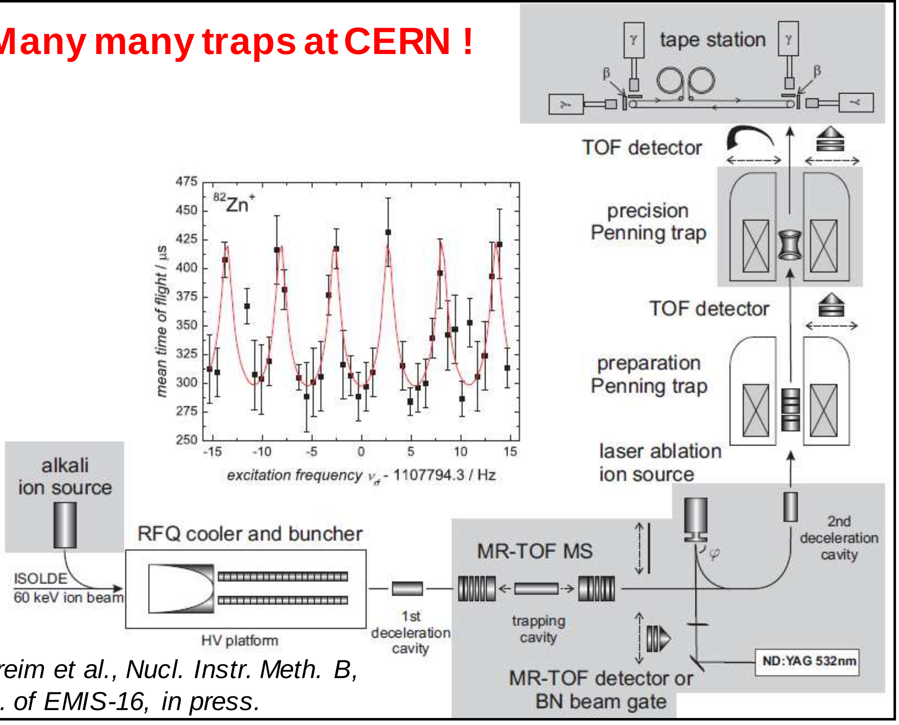


Fig. 2. Example of accumulated transmission peak for ^{11}Li. The center position (299 265 kHz) corresponds to the 917th harmonic of the cyclotron frequency. With a *RF* power of 100 W, a mass resolving power of $\frac{\Delta M}{M}$ ~ 57 000 was achieved.

C. Bachelet et al., Phys. Rev. Lett. 100 (2008) 182501.

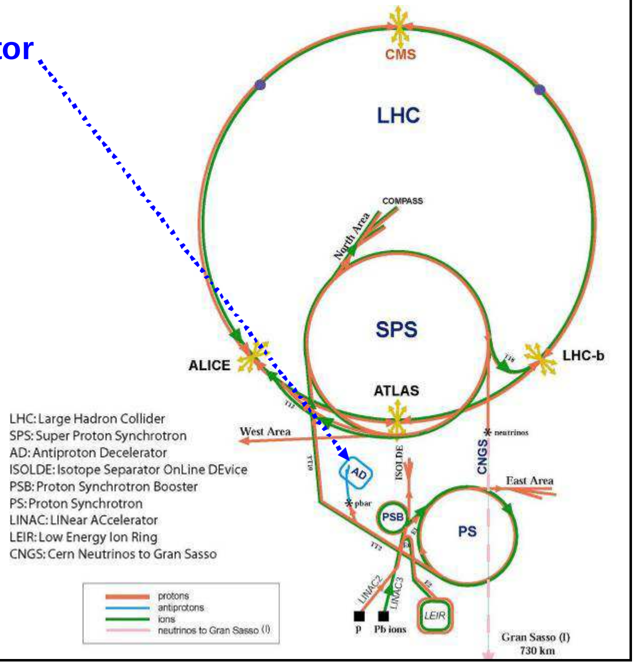
Many many traps at CERN !



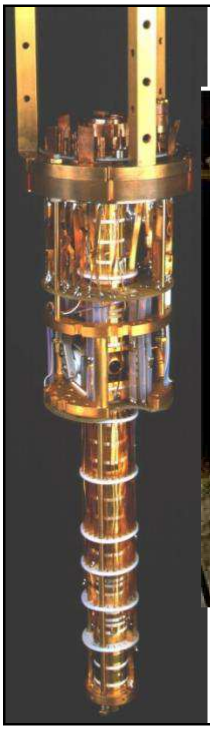
S. Kreim et al., Nucl. Instr. Meth. B,
Proc. of EMIS-16, in press.

CERN accelerator structure

Antiproton decelerator



LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso



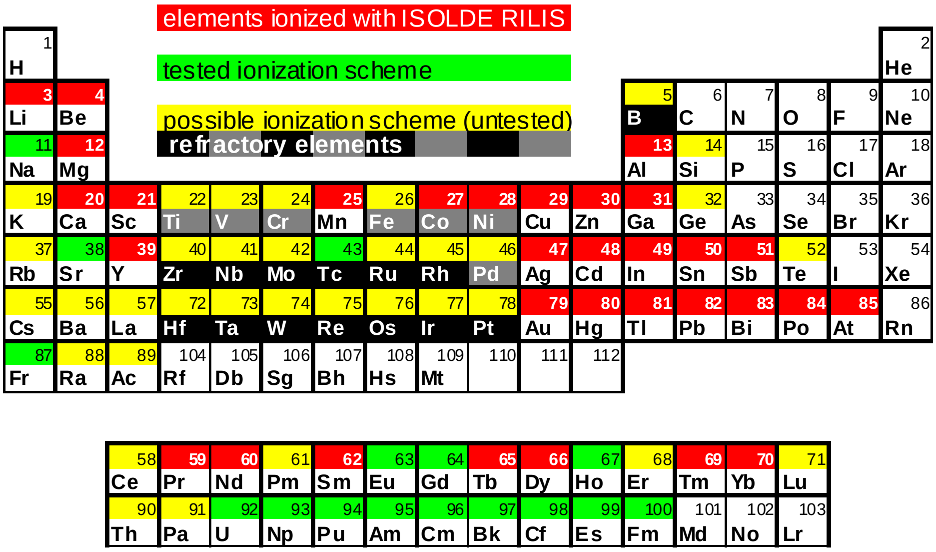
Antiproton traps at CERN

G. Gabrielse et al., Phys. Rev. Lett. 100 (2008) 113001.

M. Amoretti et al., Phys. Lett. B 583 (2004) 59.

D. Brown, R. Howard et al., “Angels and Demons” (2009).

Elements ionizable with CVL or Nd-YAG pumped dye or Ti:Sa lasers



🟥 elements ionized with ISOLDE RILIS

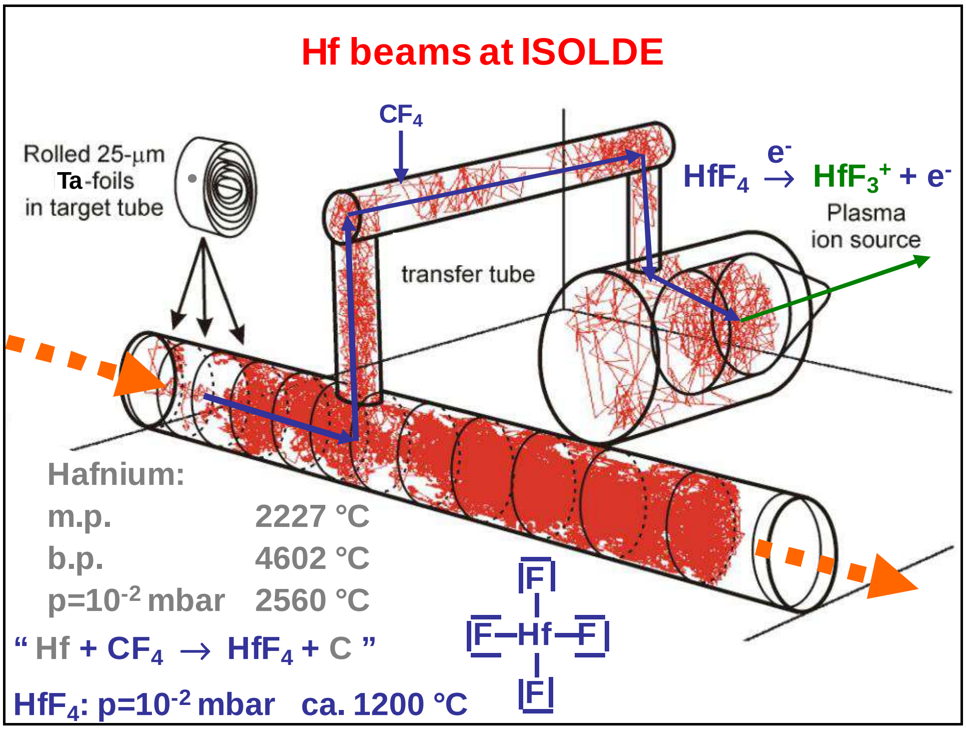
🟩 tested ionization scheme

🟨 possible ionization scheme (untested)

⬛▨ refractory elements

1 H																	2 He
🟥 3 Li	🟥 4 Be											🟨 5 ⬛ B	6 C	7 N	8 O	9 F	10 Ne
🟩 11 Na	🟥 12 Mg											🟥 13 Al	🟨 14 Si	15 P	16 S	17 Cl	18 Ar
🟨 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
🟨 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
🟨 55 Cs	🟨 56 Ba	🟨 57 La	🟨 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
🟩 87 Fr	🟨 88 Ra	🟨 89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110	111	112						

🟨 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
🟨 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



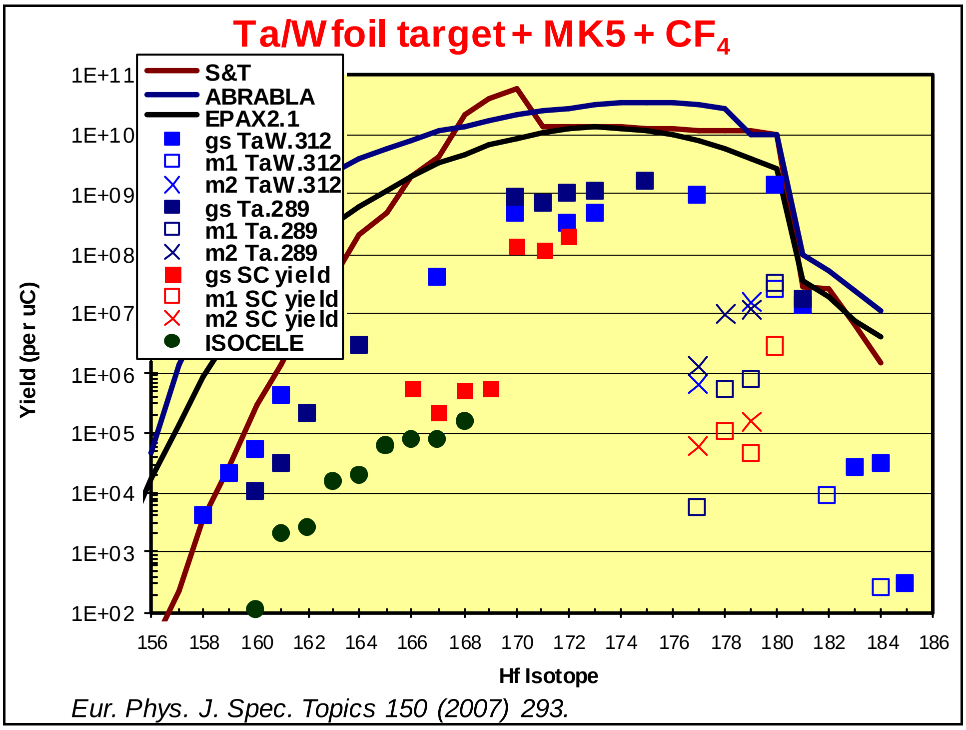
Hf beams at ISOLDE

Hafnium:

m.p.	2227 °C
b.p.	4602 °C
p=10^{-2} mbar	2560 °C

“ Hf + CF$_4$ → HfF$_4$ + C ”

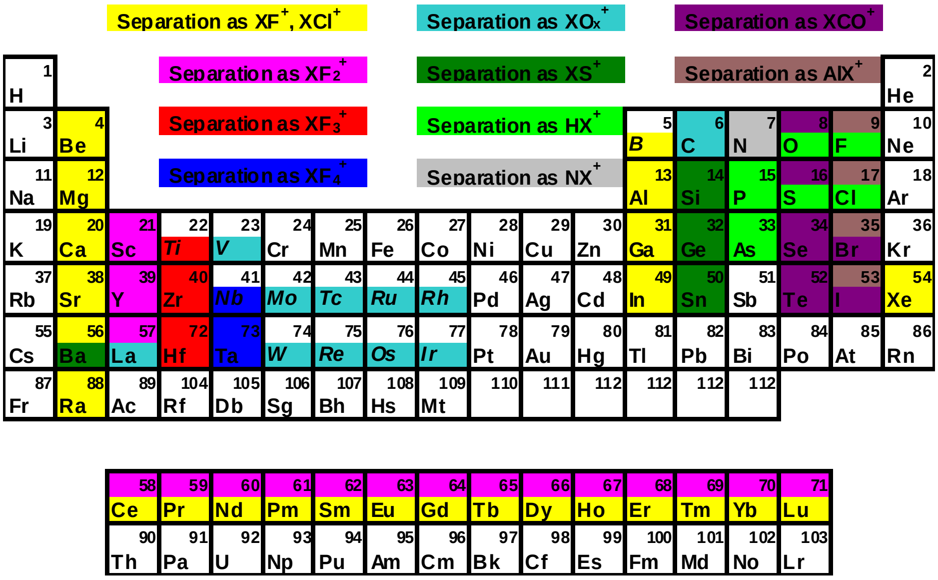
HfF$_4$: p=10^{-2} mbar ca. 1200 °C



Ta/W foil target + MK5 + CF$_4$

Eur. Phys. J. Spec. Topics 150 (2007) 293.

Overview of molecular ISOL beams



1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
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
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
55 Cs	56 Ba	57 La	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
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110	111	112	112	112	112			

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
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

Nucl. Instr. Meth. B266 (2008) 4229.

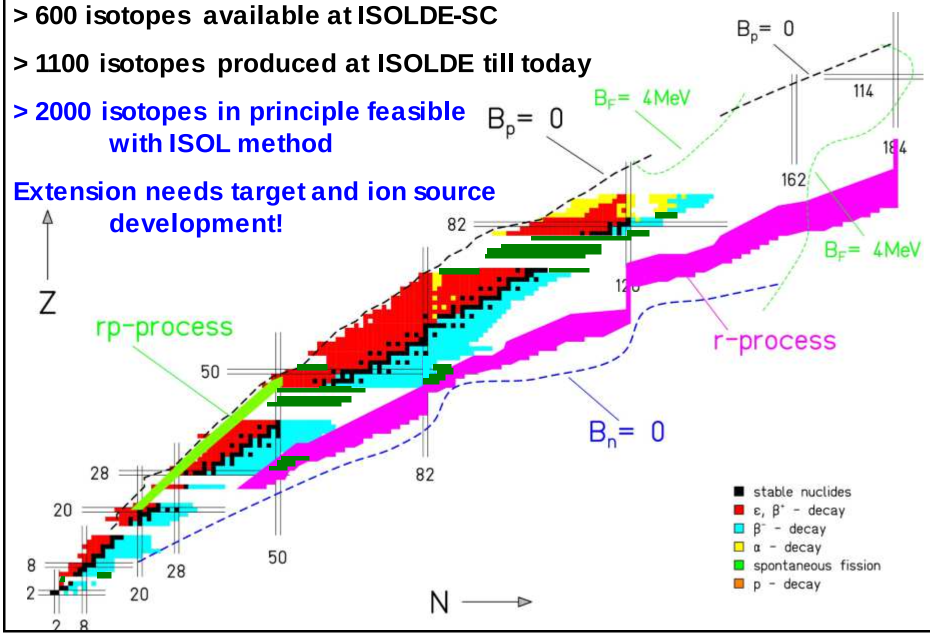
Nuclear chart at ISOLDE

> 600 isotopes available at ISOLDE-SC

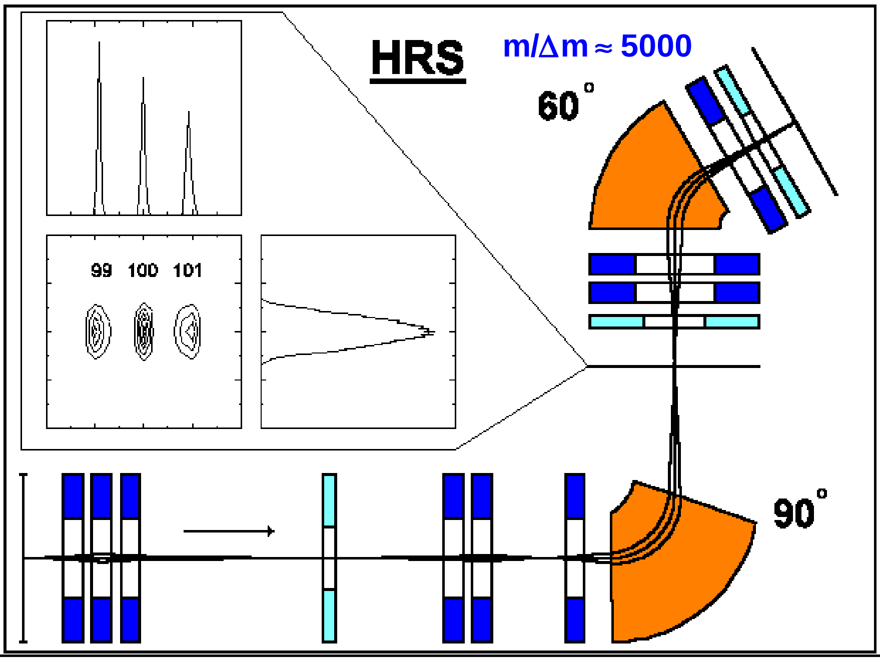
> 1100 isotopes produced at ISOLDE till today

> 2000 isotopes in principle feasible with ISOL method

Extension needs target and ion source development!



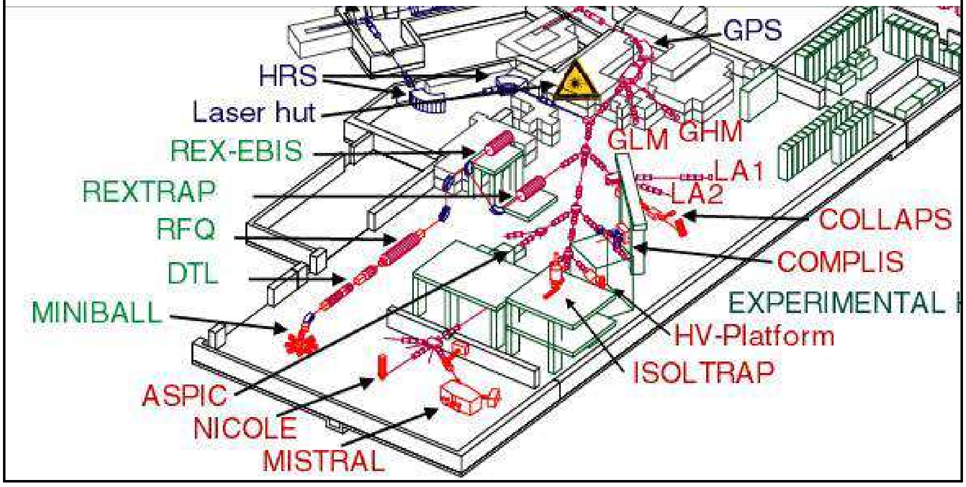
High Resolution Separator (HRS)

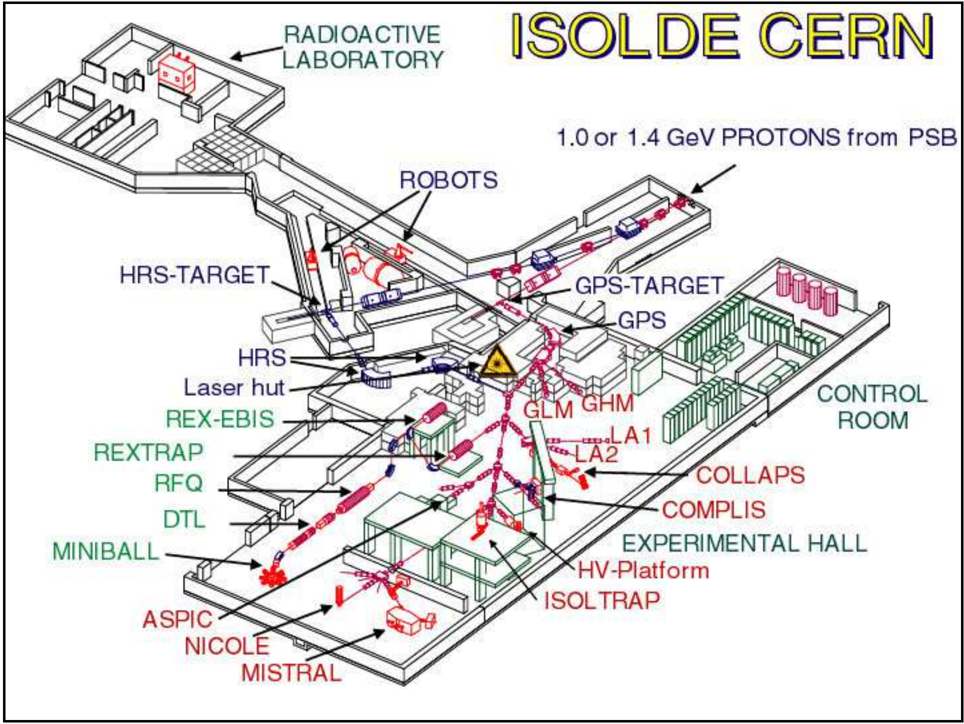


Beam transport

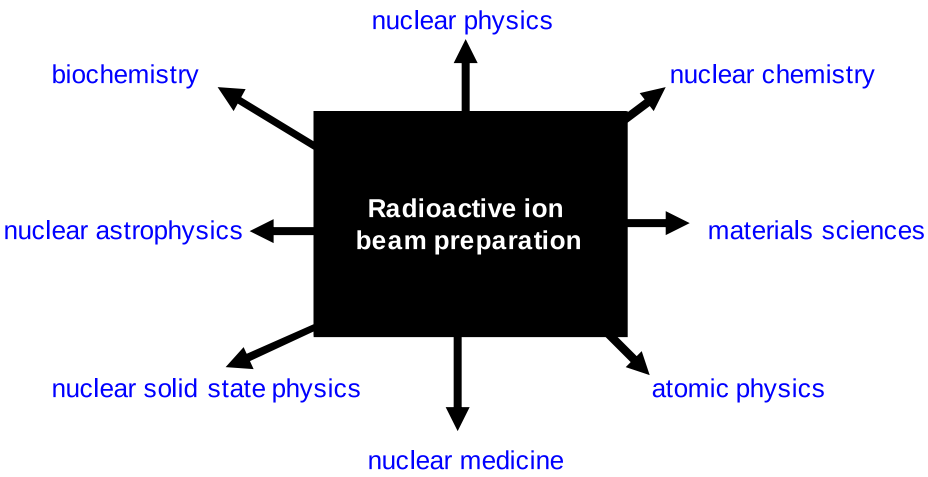
electrostatic beam transport is mass-independent (E=60 keV), but has space charge limit for high beam intensities (>10 μA)

⇒ high current beams need magnetic beam transport





Applications



nuclear physics

biochemistry

nuclear chemistry

Radioactive ion beam preparation

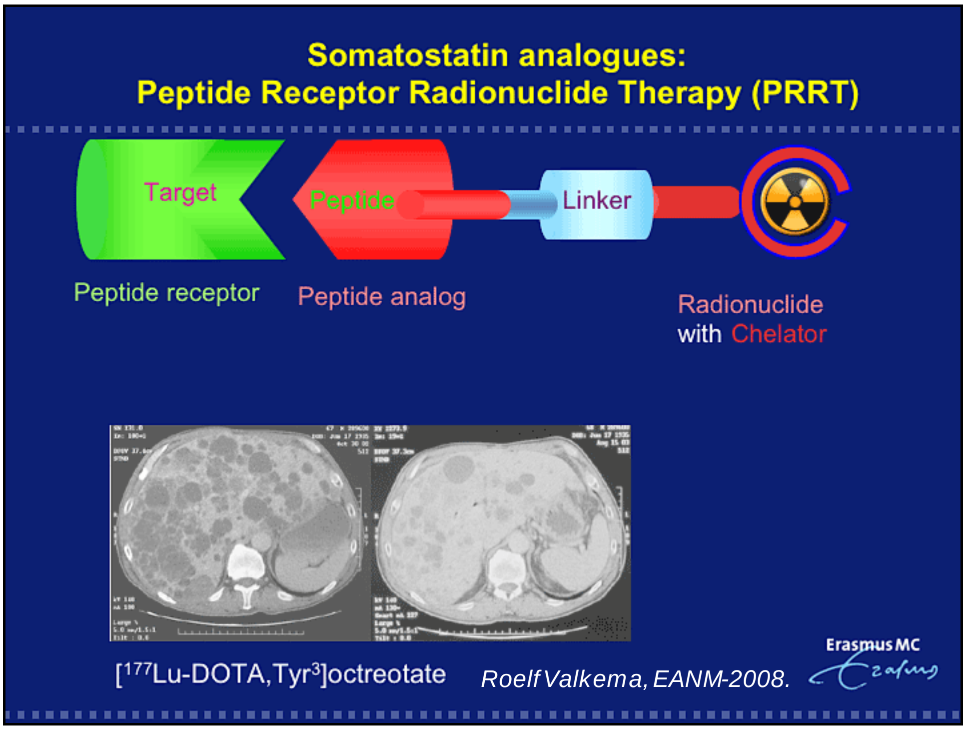
nuclear astrophysics

materials sciences

nuclear solid state physics

atomic physics

nuclear medicine



Somatostatin analogues: Peptide Receptor Radionuclide Therapy (PRRT)

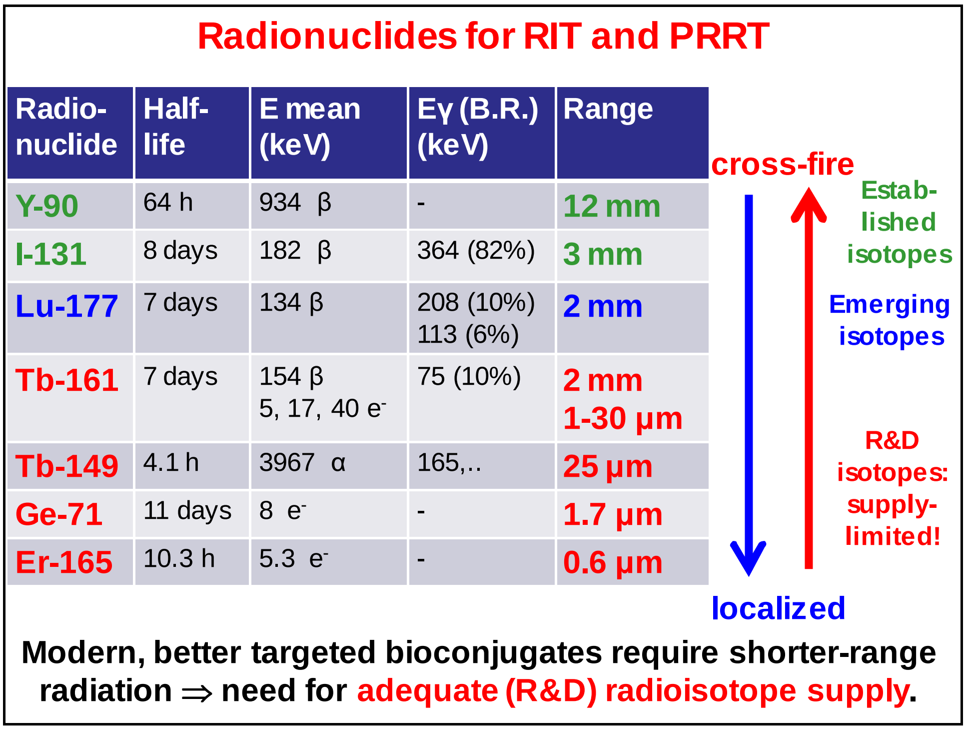
Peptide receptor

Peptide analog

Radionuclide
with Chelator

[^{177}Lu-DOTA,Tyr^{3}]octreotate

Roelf Valkema, EANM-2008.



Radionuclides for RIT and PRRT

Radio-nuclide	Half-life	E mean (keV)	Eγ (B.R.) (keV)	Range
Y-90	64 h	934 β	-	**12 mm**
I-131	8 days	182 β	364 (82%)	**3 mm**
Lu-177	7 days	134 β	208 (10%) 113 (6%)	**2 mm**
Tb-161	7 days	154 β 5, 17, 40 e$^-$	75 (10%)	**2 mm** **1-30 µm**
Tb-149	4.1 h	3967 α	165,..	**25 µm**
Ge-71	11 days	8 e$^-$	-	**1.7 µm**
Er-165	10.3 h	5.3 e$^-$	-	**0.6 µm**

cross-fire

Established isotopes

Emerging isotopes

R&D isotopes: supply-limited!

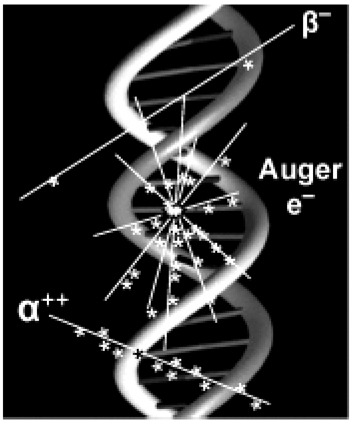
localized

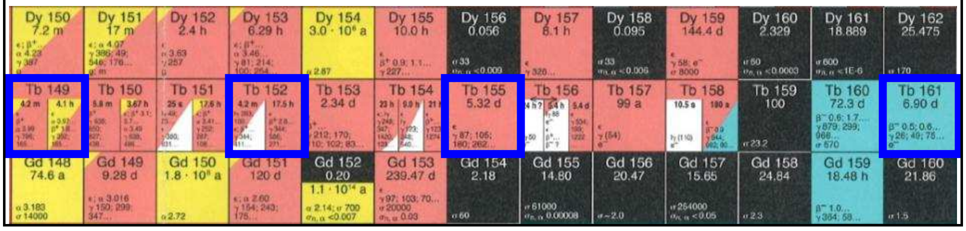
Modern, better targeted bioconjugates require shorter-range radiation ⇒ need for adequate (R&D) radioisotope supply.

Isotopes for targeted alpha therapy

^{149}Tb for targeted alpha therapy

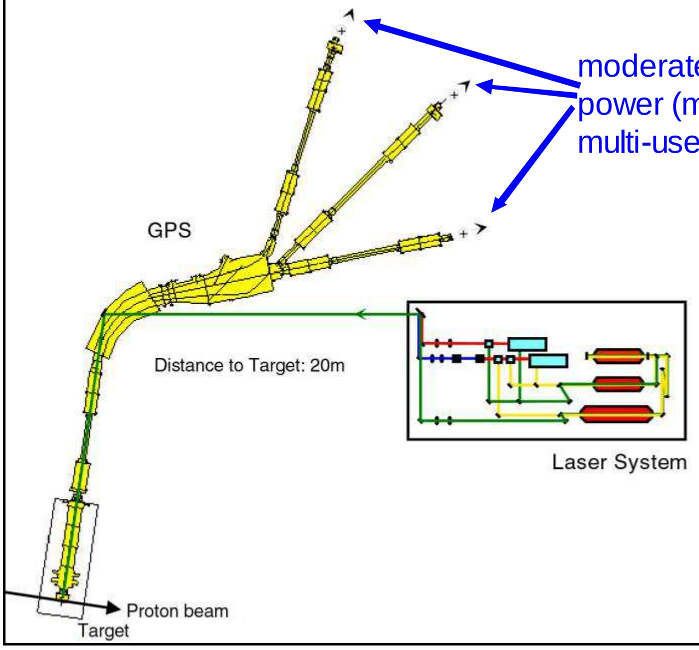
Terbium: a unique element for nuclear medicine





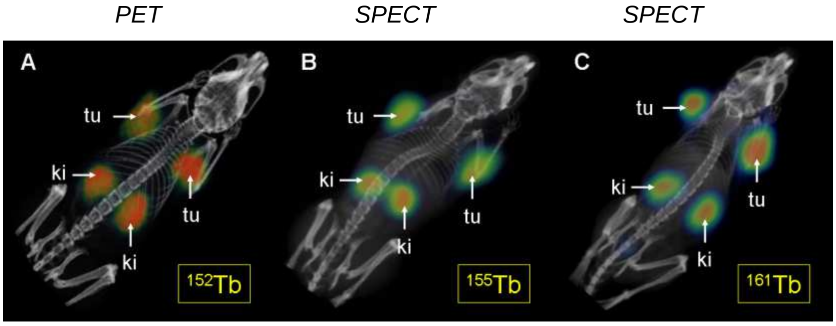
Dy 150 7.2 m	Dy 151 17 m	Dy 152 2.4 h	Dy 153 6.29 h	Dy 154 $3.0 \cdot 10^6$ a	Dy 155 10.0 h	Dy 156 0.056	Dy 157 8.1 h	Dy 158 0.095	Dy 159 144.4 d	Dy 160 2.329	Dy 161 18.889	Dy 162 25.475
Tb 149 4.2 m 4.1 h	Tb 150 5.8 m 3.67 h	Tb 151 25 s 17.6 h	Tb 152 4.2 m 17.5 h	Tb 153 2.34 d	Tb 154 23 h 9.0 h 21 h	Tb 155 5.32 d	Tb 156 24 h? 5.4 h 5.4 d	Tb 157 99 a	Tb 158 10.5 s 180 a	Tb 159 100	Tb 160 72.3 d	Tb 161 6.90 d
Gd 148 74.6 a	Gd 149 9.28 d	Gd 150 $1.8 \cdot 10^6$ a	Gd 151 120 d	Gd 152 0.20 $1.1 \cdot 10^{14}$ a	Gd 153 239.47 d	Gd 154 2.18	Gd 155 14.80	Gd 156 20.47	Gd 157 15.65	Gd 158 24.84	Gd 159 18.48 h	Gd 160 21.86

General Purpose Separator (GPS)



moderate mass resolving power (m/Δm ≈ 1000), but multi-user capability!

Theranostics with terbium isotopes



^{152}Tb-folate: 9 MBq
Scan Start: 24 h p.i.
Scan Time: 4 h

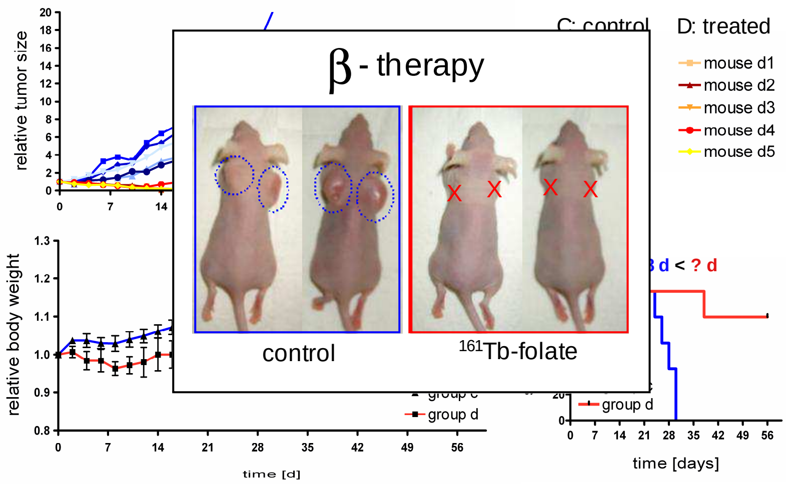
^{155}Tb-folate: 4 MBq
Scan Start: 24 h p.i.
Scan Time: 1 h

^{161}Tb-folate: 30 MBq
Scan Start: 24 h p.i.
Scan Time: 20 min

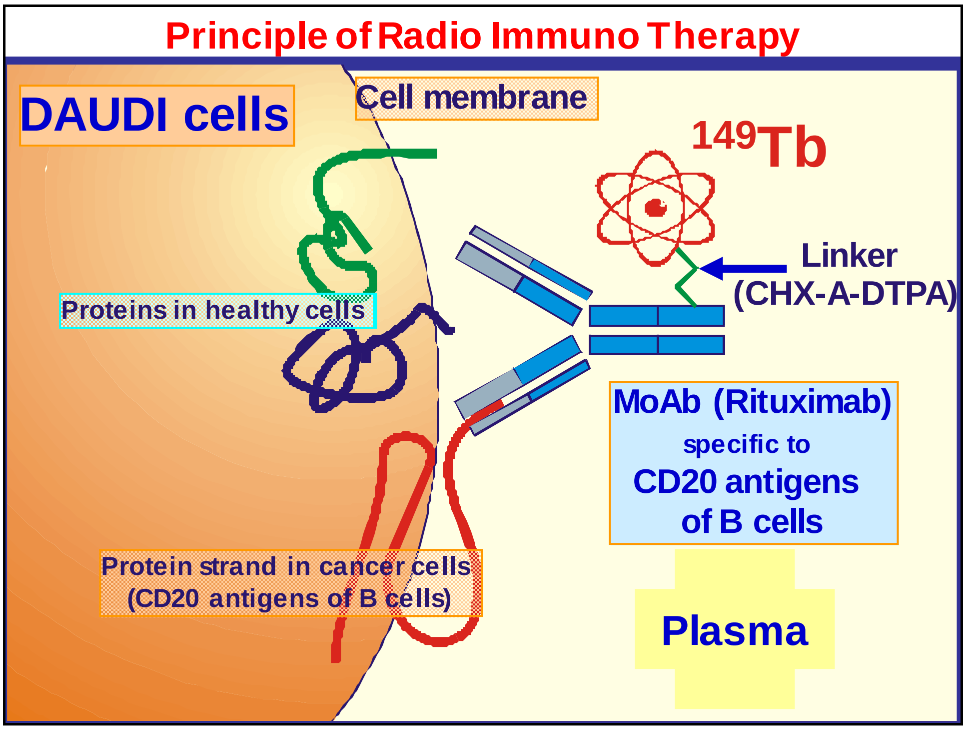
IS528 Collaboration: C. Müller et al., J. Nucl. Med. 53 (2012) 1951.

Targeted Beta Radionuclide Therapy

KB Tumor-Bearing Mice Treated with ^{161}Tb-Folate



IS528 Collaboration: C. Müller et al., J. Nucl. Med. 53 (2012) 1951.



Principle of Radio Immuno Therapy

DAUDI cells

Cell membrane

^{149}Tb

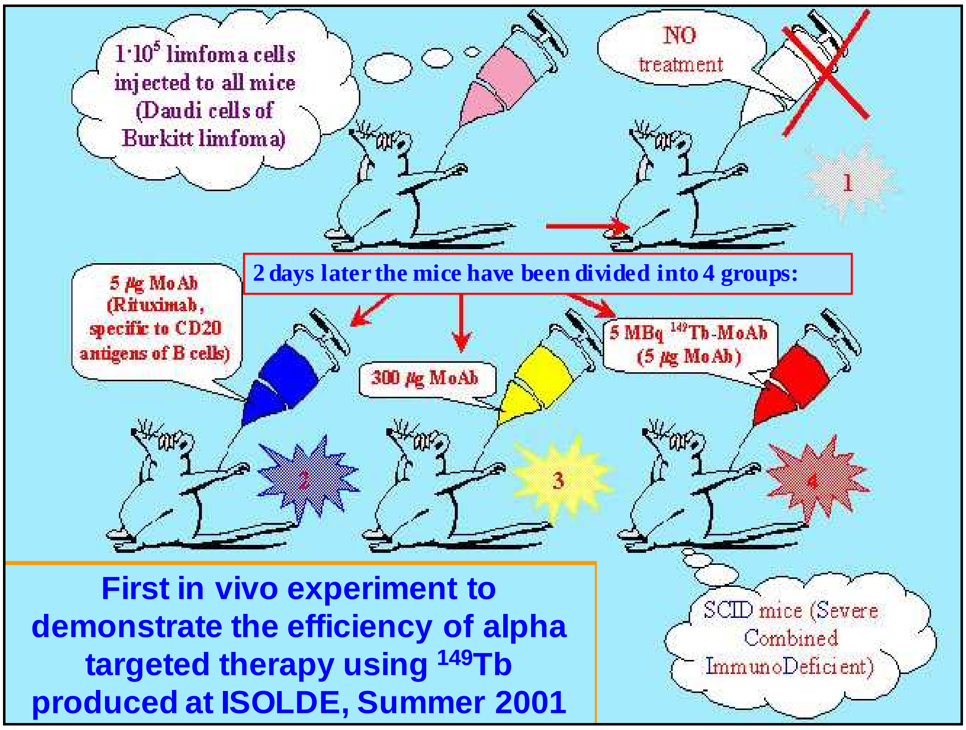
Linker
(CHX-A-DTPA)

Proteins in healthy cells

MoAb (Rituximab)
specific to
CD20 antigens
of B cells

Protein strand in cancer cells
(CD20 antigens of B cells)

Plasma



$1 \cdot 10^5$ limfoma cells injected to all mice (Daudi cells of Burkitt limfoma)

NO treatment

2 days later the mice have been divided into 4 groups:

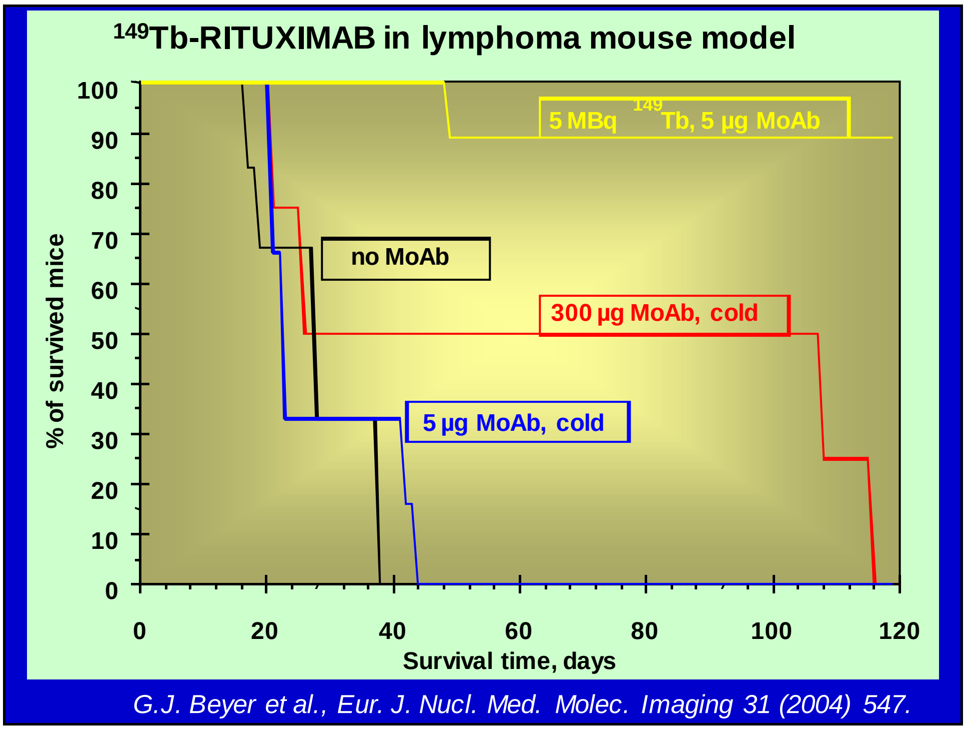
5 µg MoAb (Rituximab, specific to CD20 antigens of B cells)

300 µg MoAb

5 MBq ^{149}Tb-MoAb (5 µg MoAb)

SCID mice (Severe Combined ImmunoDeficient)

First in vivo experiment to demonstrate the efficiency of alpha targeted therapy using ^{149}Tb produced at ISOLDE, Summer 2001



^{149}Tb-RITUXIMAB in lymphoma mouse model

G.J. Beyer et al., Eur. J. Nucl. Med. Molec. Imaging 31 (2004) 547.