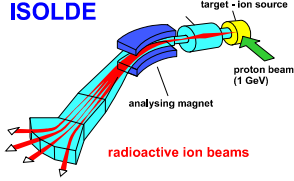


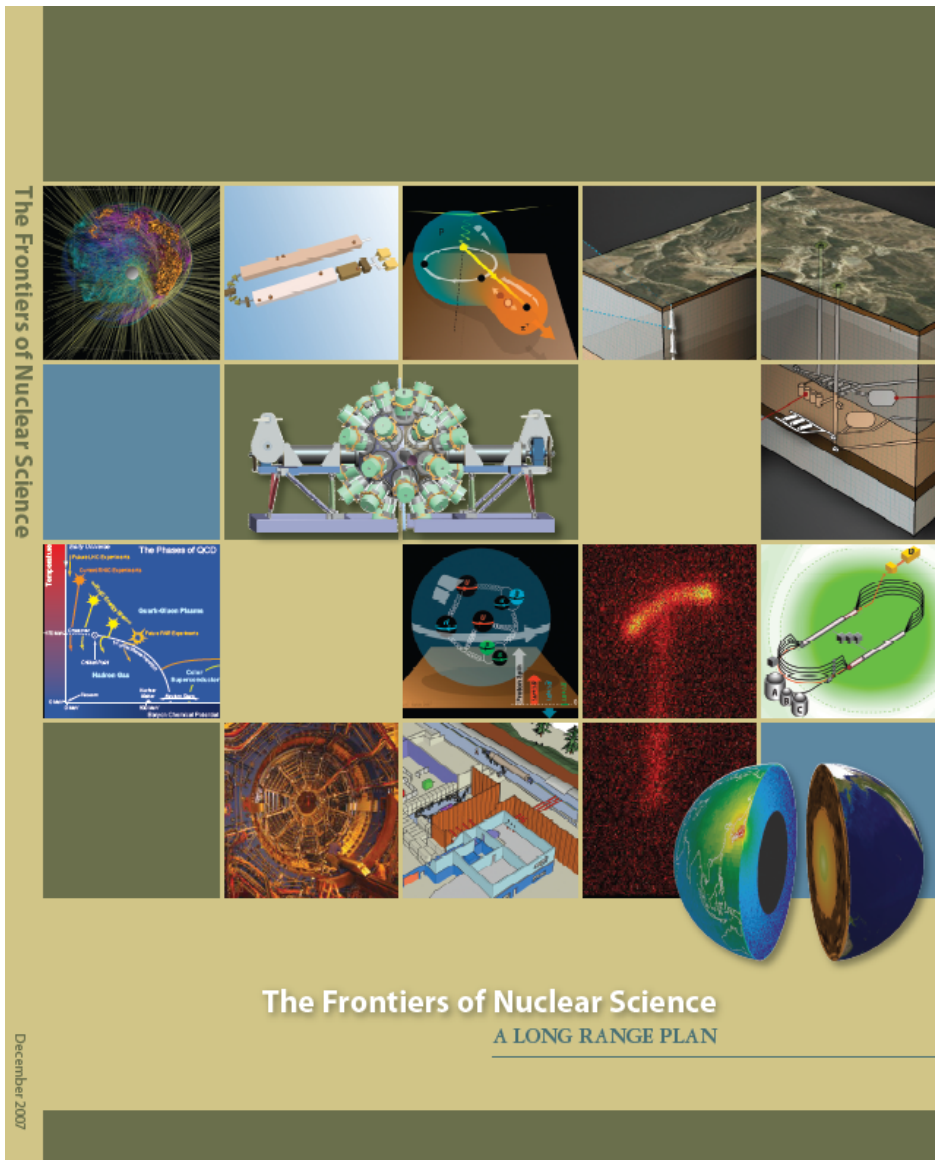
Surveying the n_TOF and ISOLDE facilities: a rich revenue from the use of radioactive beams and rare/radioactive targets

Mark Huyse

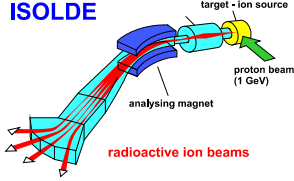
INTC, chair (2006-2009)

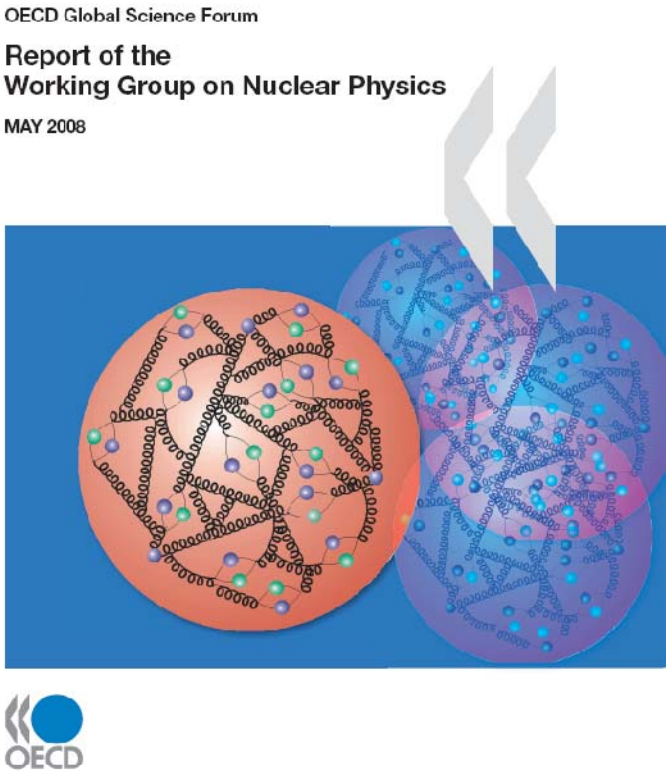
IKS, K.U.Leuven, Belgium

NuPECC & NSAC Long Range Plans



Overarching questions in nuclear physics





There is an international consensus on five key questions that motivate future research in nuclear physics:

(1) Is quantum chromodynamics (QCD) the complete theory of the strong interaction?

(2) What are the phases of nuclear matter?

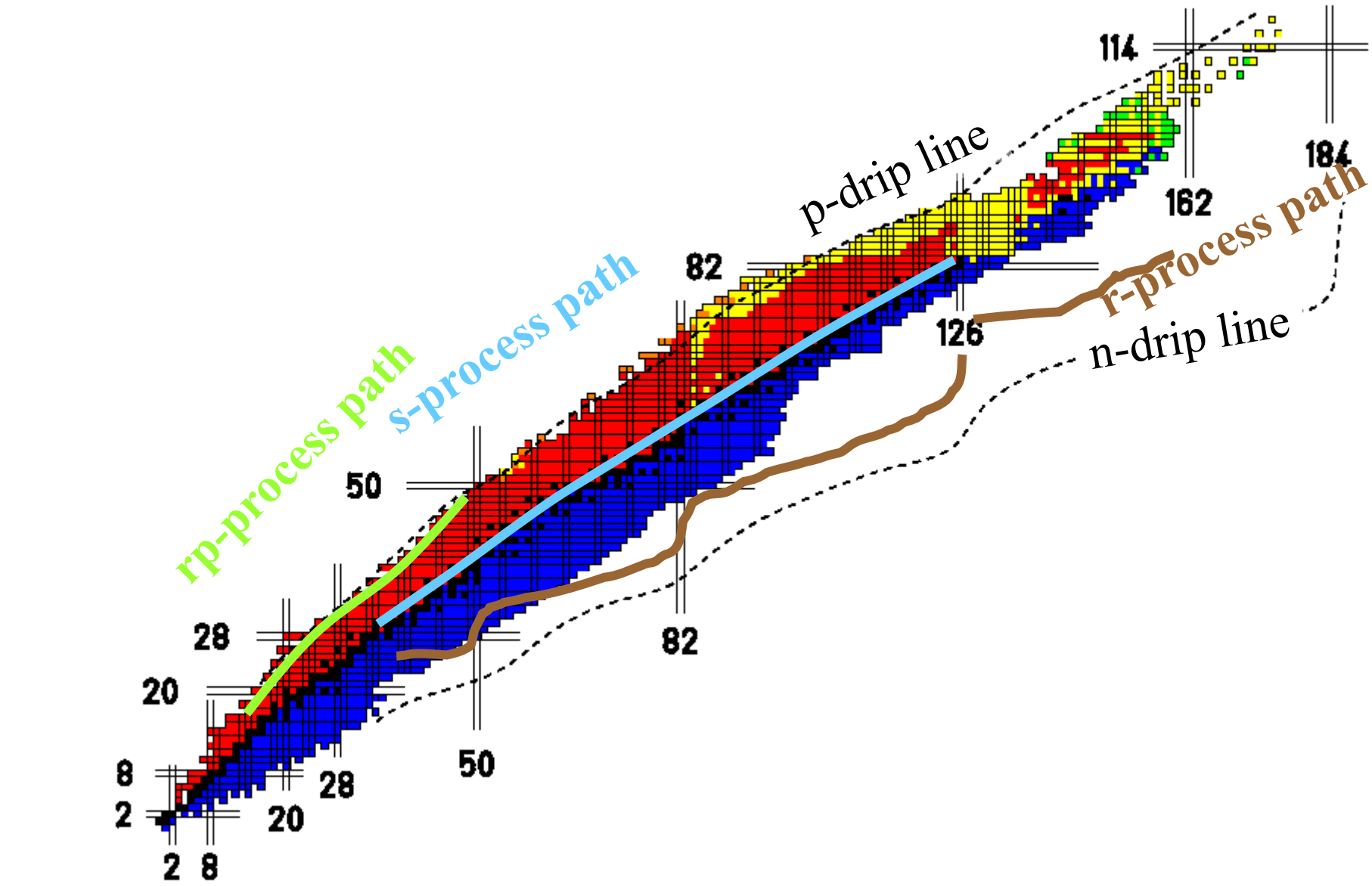
(3) What is the structure of nuclear matter?

(4) What is the role of nuclei in the evolution of the universe?

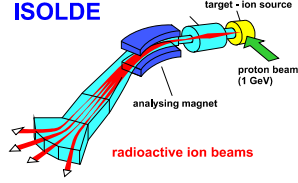
(5) What physics is there beyond the Standard Model?

Relevance of Nuclear Physics to other fields and to Society

The major strategy: the vigorous exploration of the nuclear chart



n_TOF: rare or radioactive nuclei for neutron-induced reactions



actinides

p-drip line

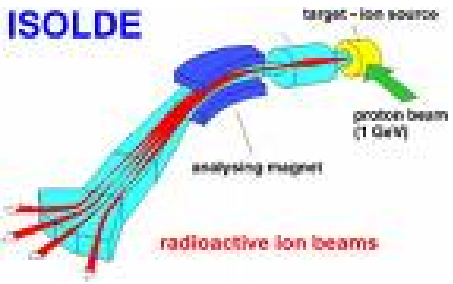
s-process path

n-drip line

114
184
162
82
126
50
82
28
20
50
8
2
28
20
2
8

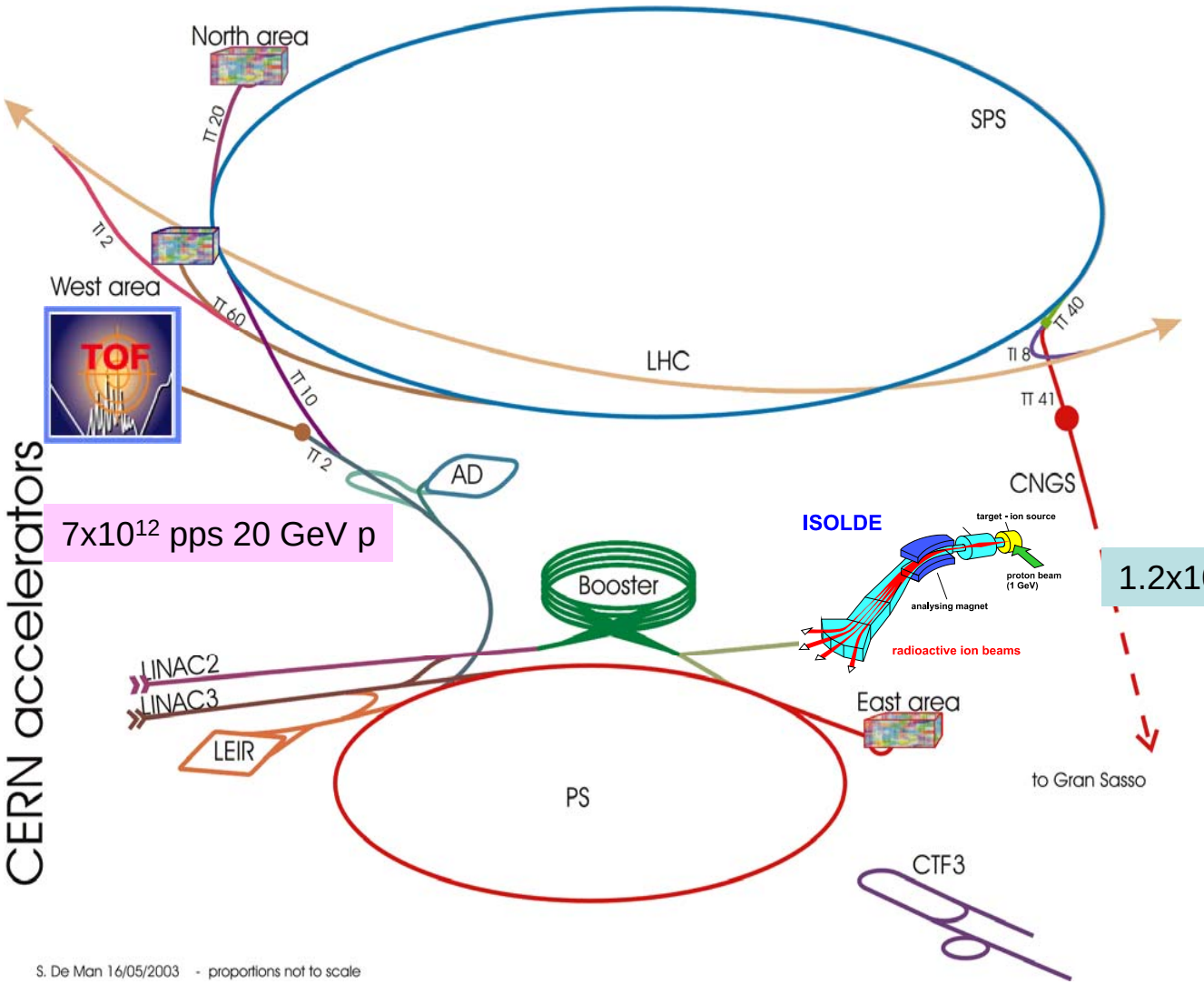
s-process isotopes
fission products
structure materials

ISOLDE: the largest catalog of radioactive ion beams

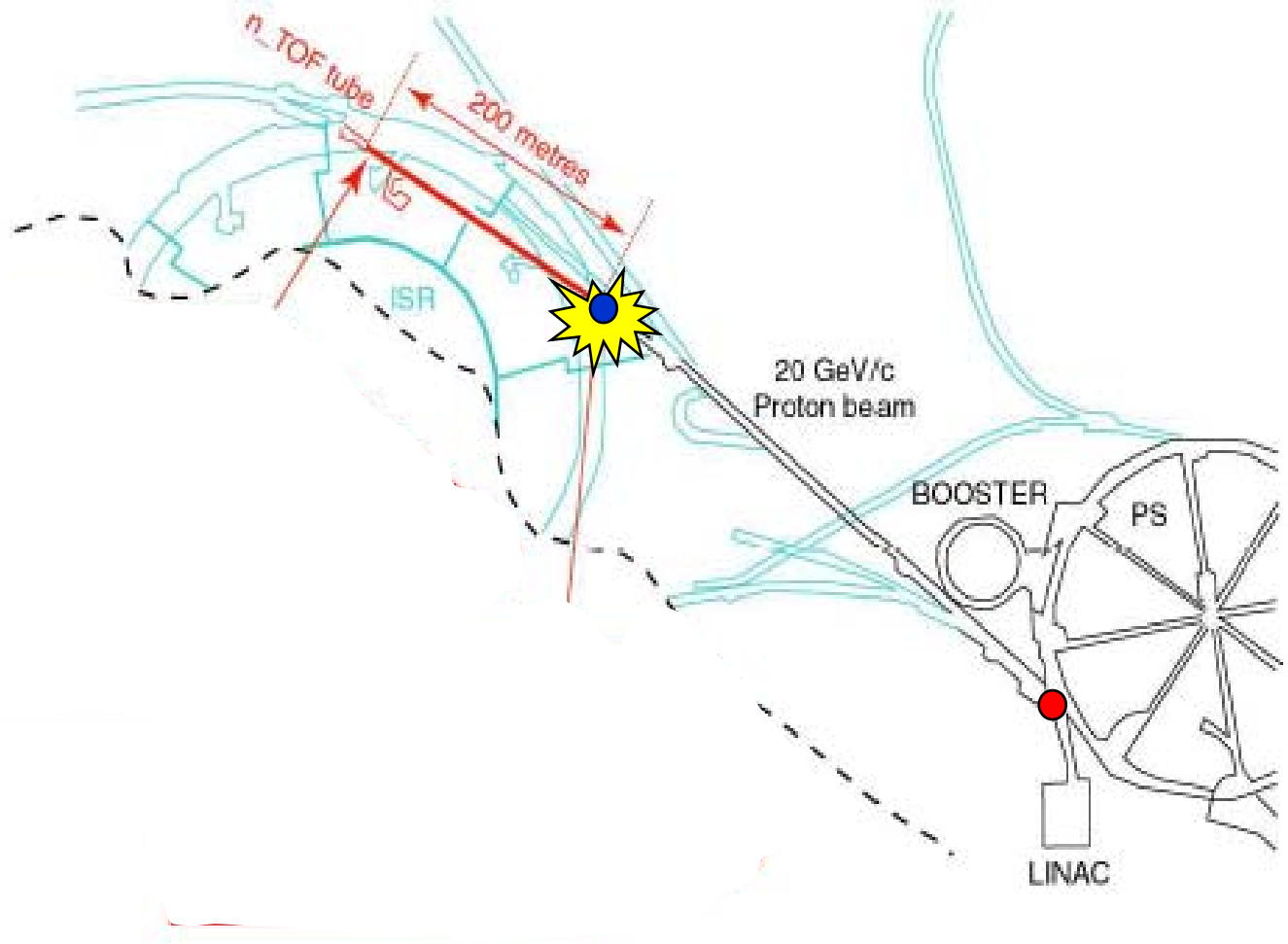


In principle everything below ^{238}U

CERN accelerator complex



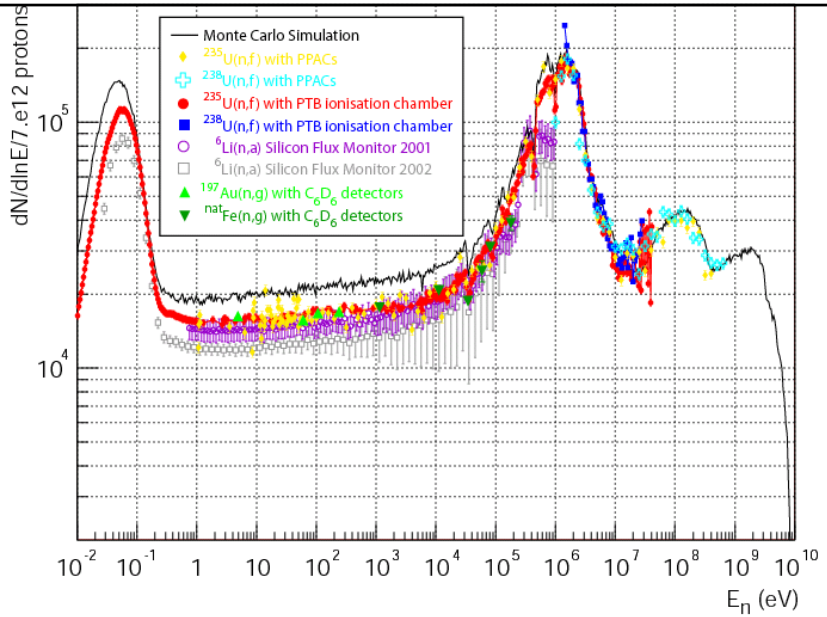
The n_TOF facility at CERN



Basic characteristics of experiments at n_TOF

The high instantaneous flux, the low duty cycle and the good energy resolution makes the n_TOF a unique facility for cross-section measurements on:

- radioactive samples
- rare isotopes
- isotopes with small cross sections
- in wide energy range (in particular at high energies)



Neutron reactions on rare or radioactive isotopes

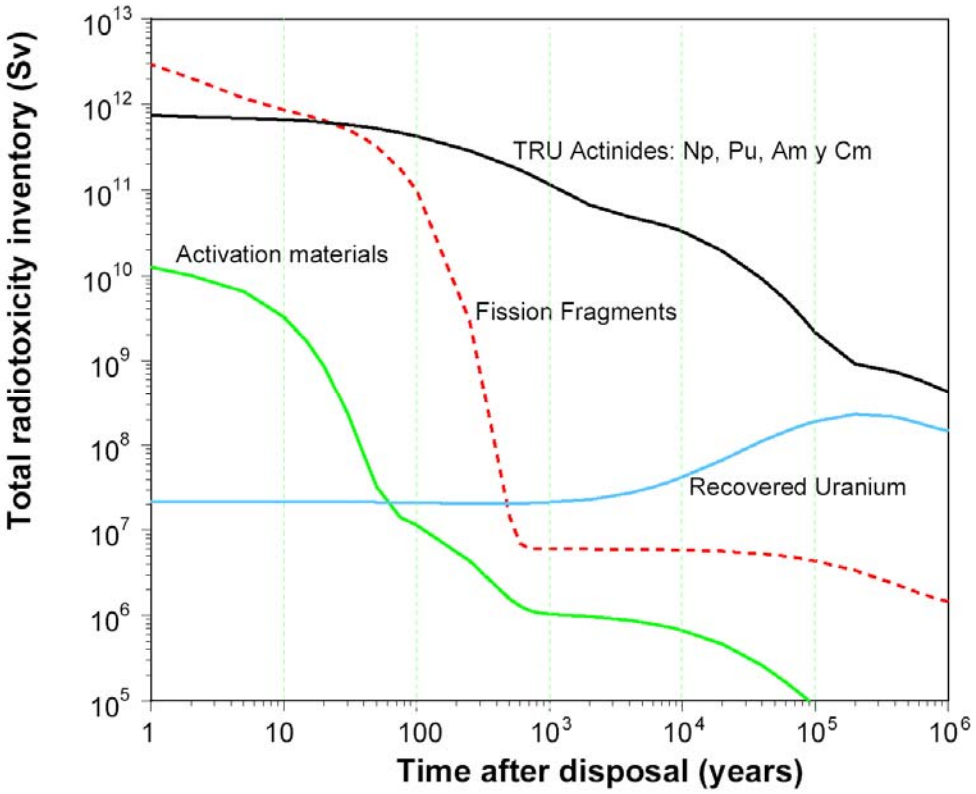
- **M**easurements of neutron cross sections relevant for Nuclear Waste Transmutation and related Nuclear Technologies
  - Th/U fuel cycle (capture & fission)
  - Transmutation of Minor Actinides (capture & fission)
  - Transmutation of Fission Products (capture)
- **C**ross sections relevant for Nuclear Astrophysics
  - s-process: branchings
  - s-process: presolar grains
- **N**eutrons as probes for fundamental Nuclear Physics
  - Nuclear level density & n-nucleus interaction

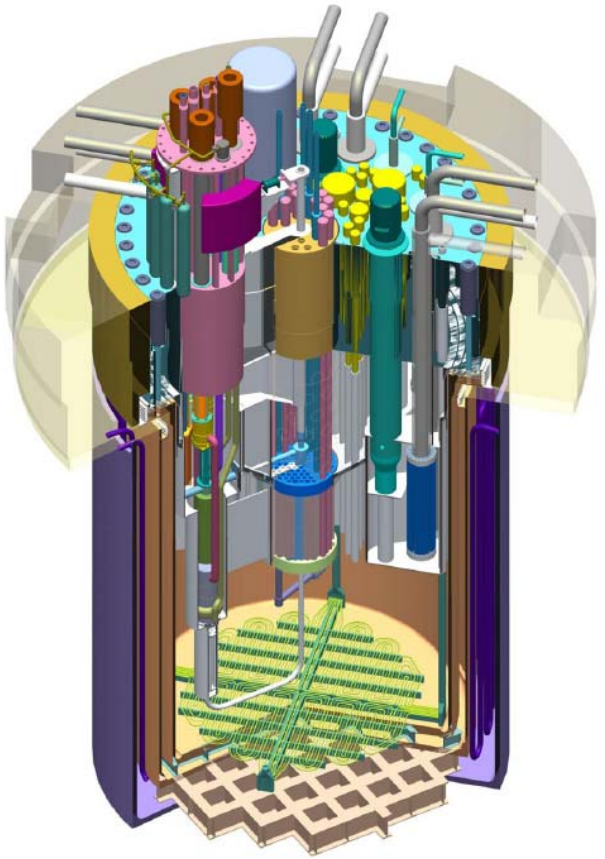
n_TOF

Phase I
41 institutes
120 users

Phase II
27 institutes
77 users

Accelerator Driven System

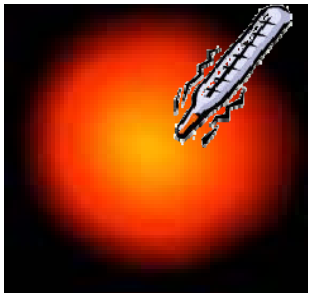




http://www.sckcen.be/myrrha/

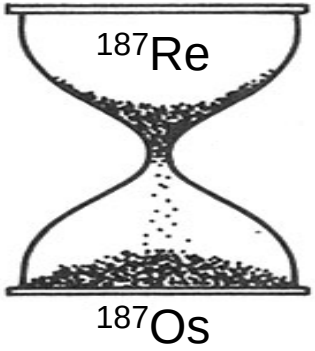
Fast neutron cross-sections needed!

Astrophysics: what can we learn from (n,γ) experiments?



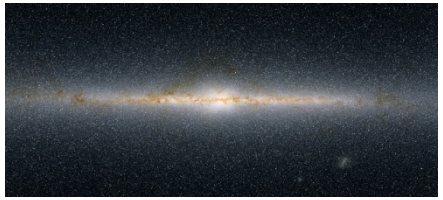
• How hot is the stellar environment where s-process nucleosynthesis takes place?

^{151}Sm(n,γ)



• How old is the Universe?

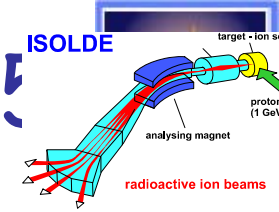
^{186,187}Os(n,γ)



• Where were the heaviest stable isotopes, Lead and Bismuth, produced?

^{204,206,207}Pb(n,γ) ^{209}Bi(n,γ)

n_TOF experiments: 2002-2005



Capture

^{151}Sm

$^{204,206\text{-}208}$Pb, ^{209}Bi

^{232}Th

^{24,25,26}Mg

^{90,91,92,94,96}Zr, ^{93}Zr

^{139}La

^{186,187,188}Os

^{233,234}U

^{237}Np,^{240}Pu,^{243}Am

Fission

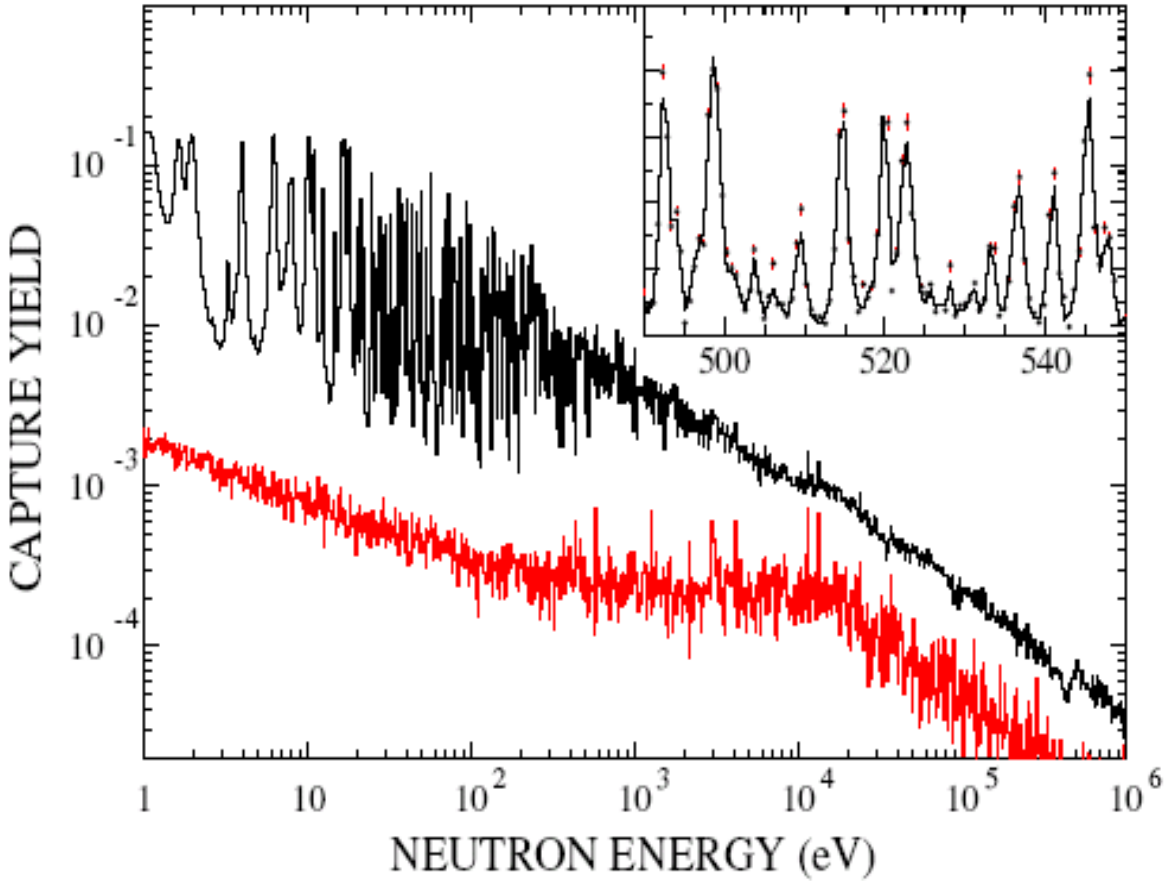
^{233,234,235,236,238}U

^{232}Th

^{209}Bi

^{237}Np

^{241,243}Am, ^{245}Cm



U Abbondanno et al. Phys. Rev. Lett. **93** (2004), 161103

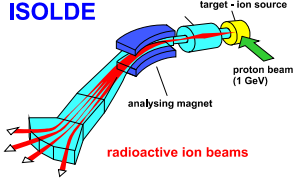
At a thermal energy of kT=30 keV the Maxwellian averaged cross section of this unstable isotope ($t_{1/2}$=93 yr) was determined to be 3100±160 mb, significantly larger than theoretical predictions

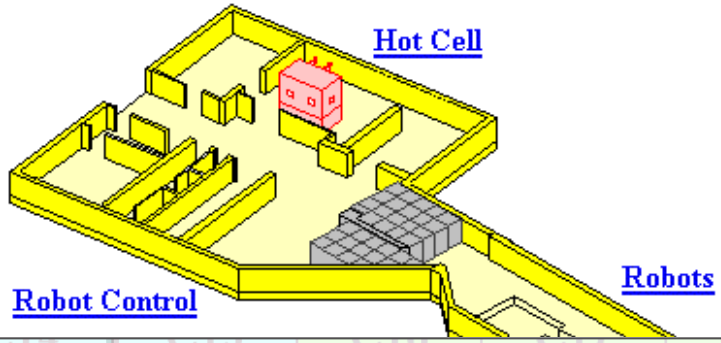
23 publications: see http://www.cern.ch/ntof

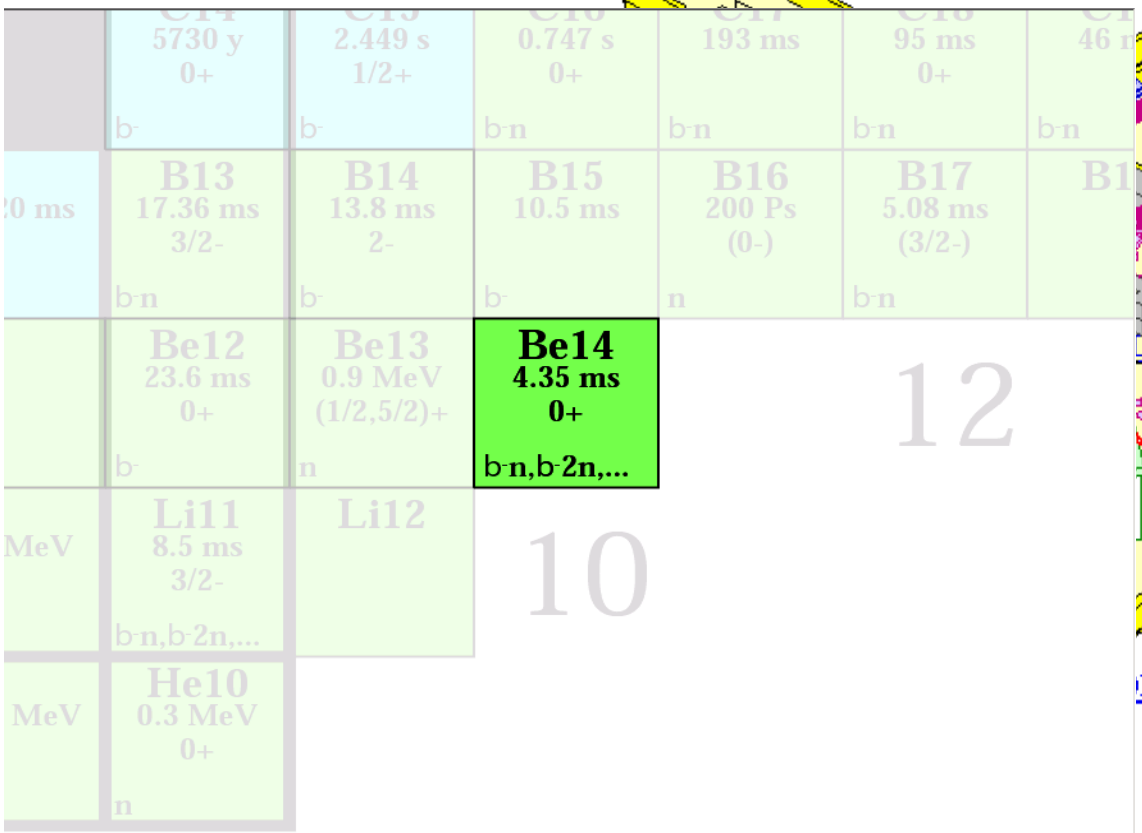
A new experimental campaign starts this year

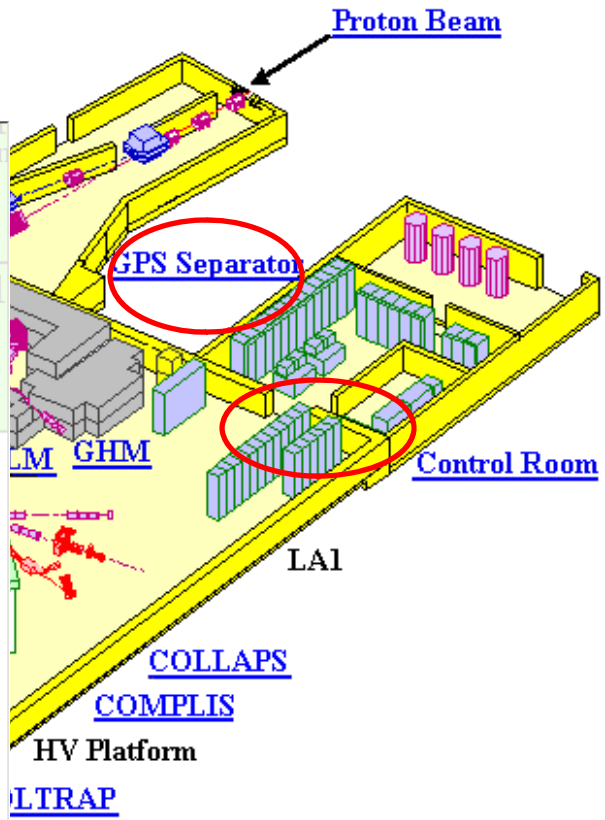
- A new target is installed: keep the performance without compromising safety
- New experiments
  - The role of Fe and Ni for *s*-process nucleosynthesis in the early Universe and for innovative nuclear technologies
  - Proposed study of the neutron-neutron interaction at the CERN n_TOF facility
  - Angular distributions in the neutron-induced fission of actinides

ISOLDE@CERN

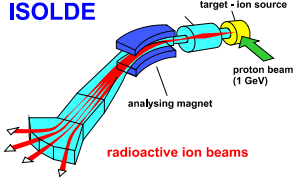

ISOLDE
target - ion source
proton beam
(1 GeV)
analysing magnet
radioactive ion beams

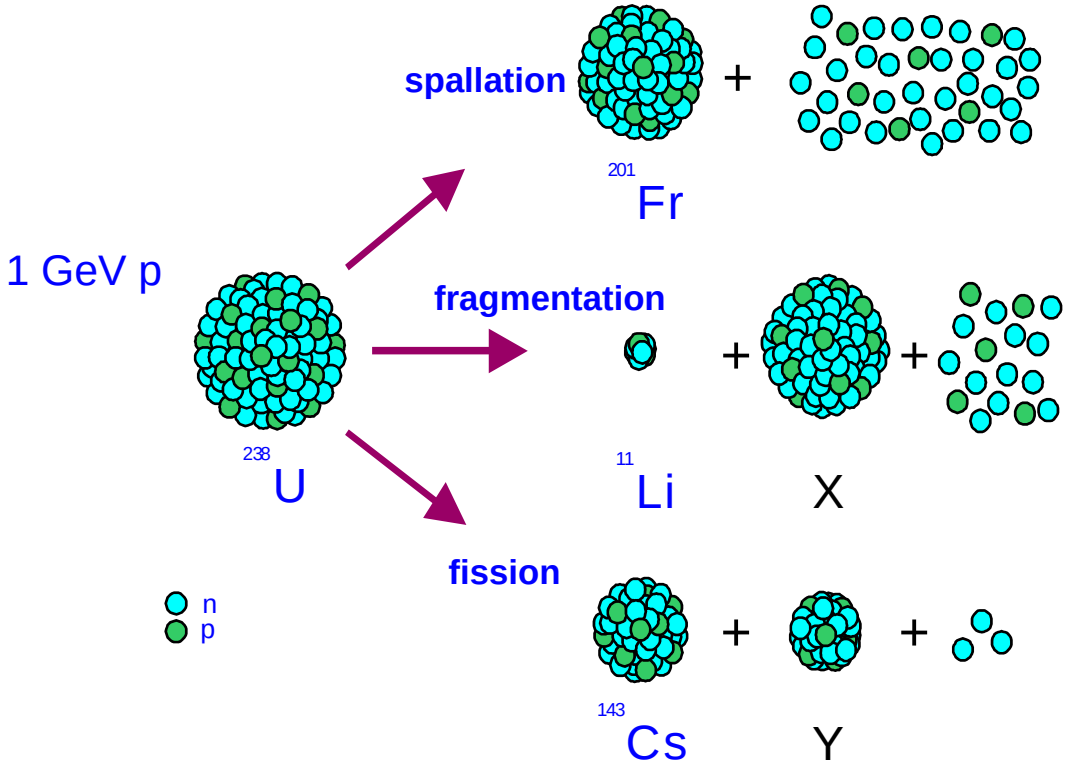

Hot Cell
Robots
Robot Control


5730 y
0+
b-
2.449 s
1/2+
b-
0.747 s
0+
b-n
193 ms
b-n
95 ms
0+
b-n
B13
17.36 ms
3/2-
b-n
B14
13.8 ms
2-
b-
B15
10.5 ms
b-
B16
200 Ps
(0-)
n
B17
5.08 ms
(3/2-)
b-n
Be12
23.6 ms
0+
b-
Be13
0.9 MeV
(1/2,5/2)+
n
Be14
4.35 ms
0+
b-n,b-2n,...
12
Li11
8.5 ms
3/2-
b-n,b-2n,...
Li12
10
He10
0.3 MeV
0+
n


Proton Beam
GPS Separator
GHM
Control Room
LA1
COLLAPS
COMPLIS
HV Platform
LTRAP

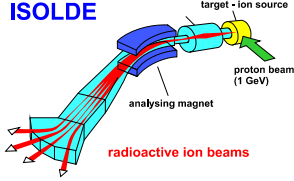
RIB - Production reactions

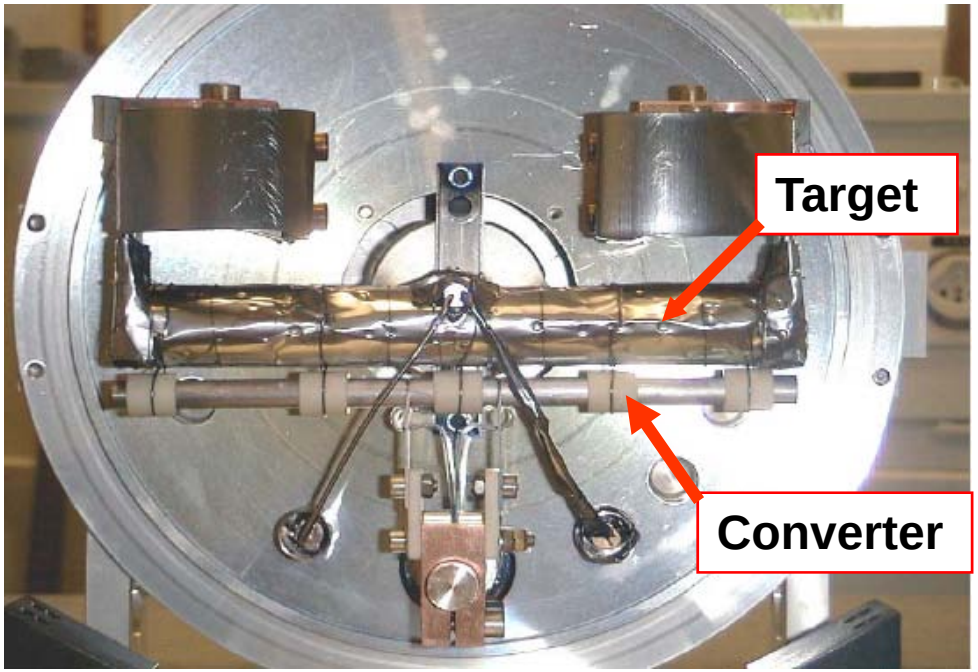


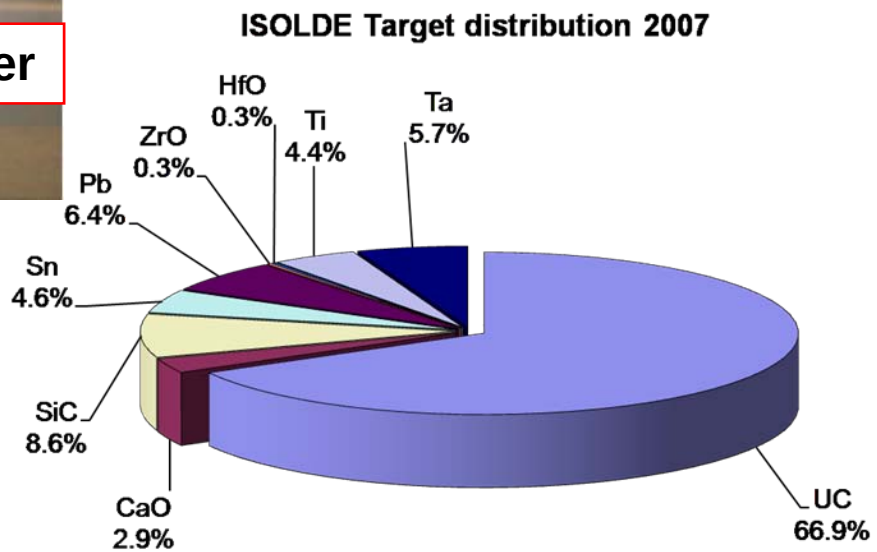


- Spallation
- Fragmentation
- Fission (p or n-induced)

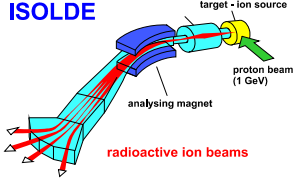
Target - Ion-source matrix







ISOLDE Table of elements



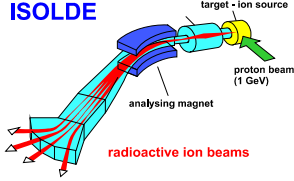
ION SOURCE:

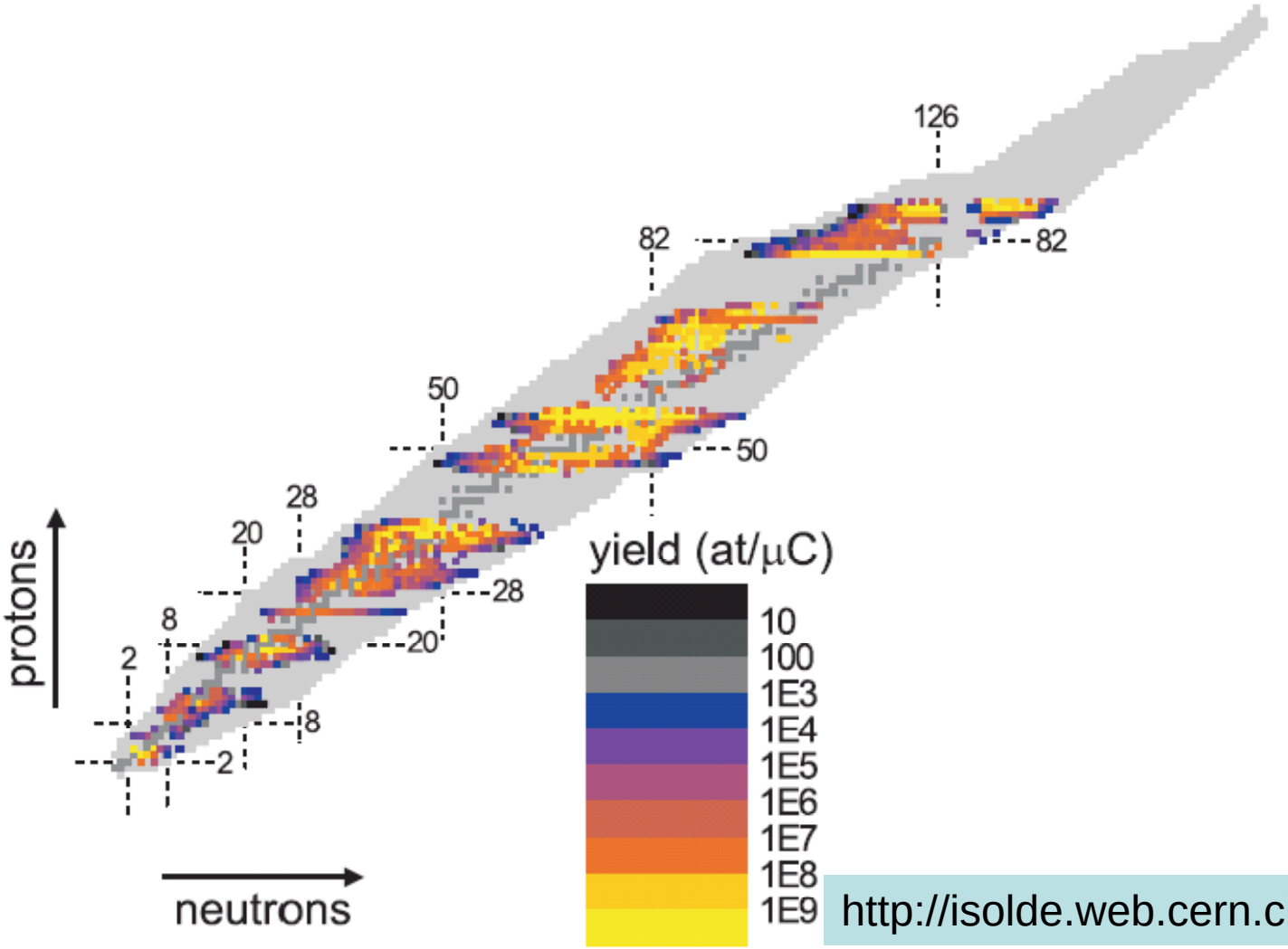
+	SURFACE –
hot	PLASMA cooled
	LASER

H															He
Li	Be									B	C	N	O	F	Ne
Na	Mg									Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	112	113	114	115			

Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

ISOLDE yields, 2006

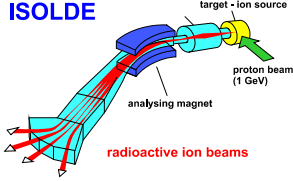




http://isolde.web.cern.ch/ISOLDE/

So far >600 radioactive isotopes of >60 elements @ 60 keV

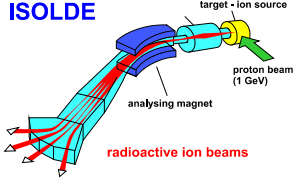
October 2001: a new dimension



Post acceleration by REX-ISOLDE

up to 3 MeV/u

REX-ISOLDE OVERVIEW

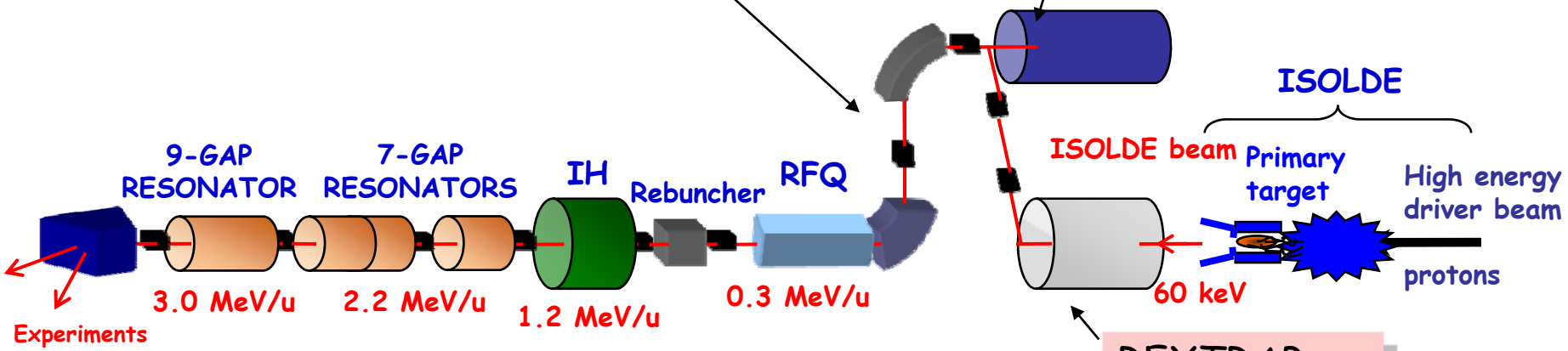


Mass separator

Select the correct A/q and separate the radioactive ions from the residual gases.

REXEBIS

- Charge-state breeding
- Breeding time 3 to >200 ms
- A/q < 4.5



Linac

Duty cycle	1ms 100Hz (10%)
Energy	300 keV/u, 1.2-3MeV/u
A/q max.	4.5 (2.2MeV/u), 3.5 (3MeV/u)

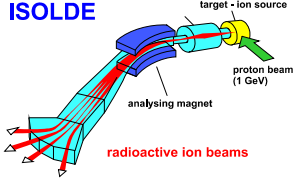
REXTRAP

- Cooling
- Bunching

Total efficiency : 1 -10 %

-Unique and universal charge-state breeding scheme for radioactive ion beams
-Originally aimed for isotopes with A<40 now up to the heaviest isotopes produced

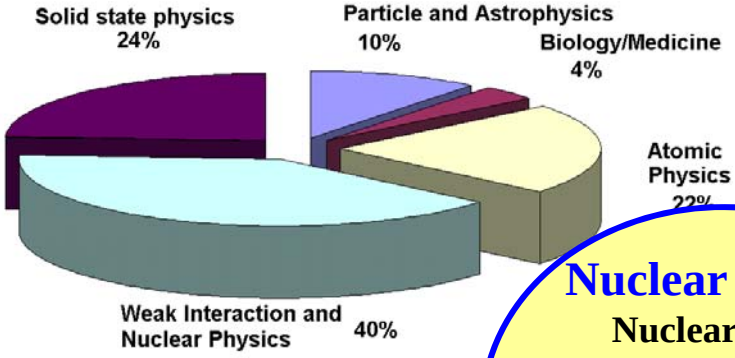
World ISOL accelerated beams

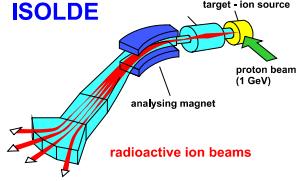


FACILITY	DRIVER	POWER	USER BEAMS ACCELERATED	ENERGY	PHYSICS REACH
LOUVAINE-LA-NEUVE (BELGIUM) 1989	30 MeV protons	6 kW	^{6}He, ^{7}Be, ^{10,11}C, ^{13}N, ^{15}O, ^{18}F, ^{18,19}Ne, ^{35}Ar	10 MeV/u cyclotron	Astrophysics, Nuclear structure
HRIBF Oak Ridge (USA) 1997	100 MeV p, d, α *(-ve ion source)*	1 kW	^{7}Be, ^{17,18}F, ^{69}As, $^{76-79}$Cu, $^{67,83-85}$Ga, $^{80, 82-86}$Ge, ^{69}As, $^{83-84}$Se, ^{92}Sr, ^{118,120,122,124}Ag, $^{128, 132-134}$Sn, ^{129}Sb, ^{129,132,134,136}Te	2 - 10 MeV/u Tandem *-ve ion source*	Nuclear Structure, Astrophysics
ISAC TRIUMF (CANADA) 2000	500 MeV protons	50 kW	^{8,9,11}Li, ^{11}Be, ^{18}F, $^{20-22, 24-29}$Na, ^{23}Mg, ^{26}Al	1.5 - 5 MeV/u linac	Astrophysics, Condensed matter, Nuclear Structure
SPIRAL GANIL (FRANCE) 2001	100 MeV/u heavy ions	6 kW	^{6,8}He, $^{14,15,19-21}$O, ^{18}F, $^{17-19,23-26}$Ne, $^{33-35, 44,46}$Ar, $^{74-77}$Kr	2 - 25 MeV/u cyclotron	Nuclear structure, Astrophysics
REX ISOLDE (CERN) 2001	1.4 GeV protons	3 kW	^{8,9,11}Li, $^{10-12}$Be, ^{10}C, ^{17}F, $^{24-29}$Na, $^{28-28,30-32}$Mg, $^{61-62}$Mn, $^{61-62}$Fe, ^{68}Ni, $^{67-73}$Cu, ^{74,76,78,80}Zn, ^{70}Se, ^{88,92}Kr, ^{96}Sr, ^{108}In, ^{106,108,110}Sn, ^{100,102,104,122,124,126}Cd, ^{138,140,142,144}Xe, ^{140,142,148}Ba ^{148}Pm, ^{153}Sm, ^{156}Eu, ^{182,184,186,188}Hg, ^{202,204}Rn	0.3 - 3 MeV/u linac	Nuclear structure, Condensed matter, Astrophysics

So far 63 radioactive isotopes of 24 elements

Research with Radioactive Ion Beams





Nuclear Physics

Nuclear Decay Spectroscopy and Reactions

Structure of Nuclei
Exotic Decay Modes

Applied Physics

Implanted Radioactive Probes, Tailored Isotopes for Diagnosis and Therapy

Condensed matter physics and Life sciences

Fundamental Physics

Direct Mass Measurements, Dedicated Decay Studies - WI

CKM unitarity tests, search for β-ν correlations, right-handed currents

Atomic Methods

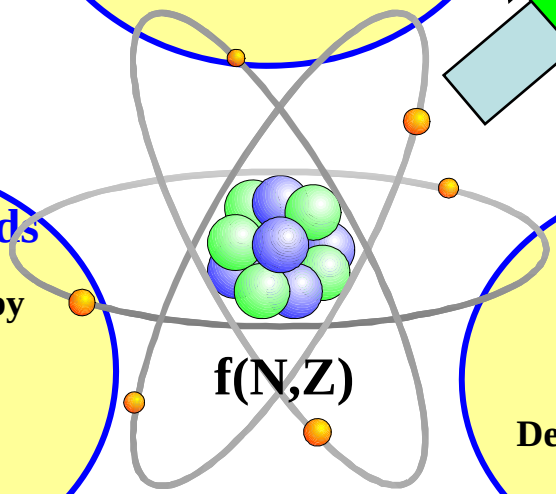
Laser Spectroscopy and Direct Mass Measurements

Radii, Moments, Nuclear Binding Energies

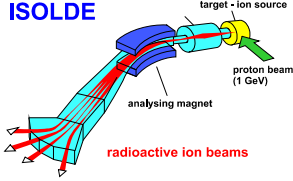
Nuclear Astrophysics

Dedicated Nuclear Decay/Reaction Studies

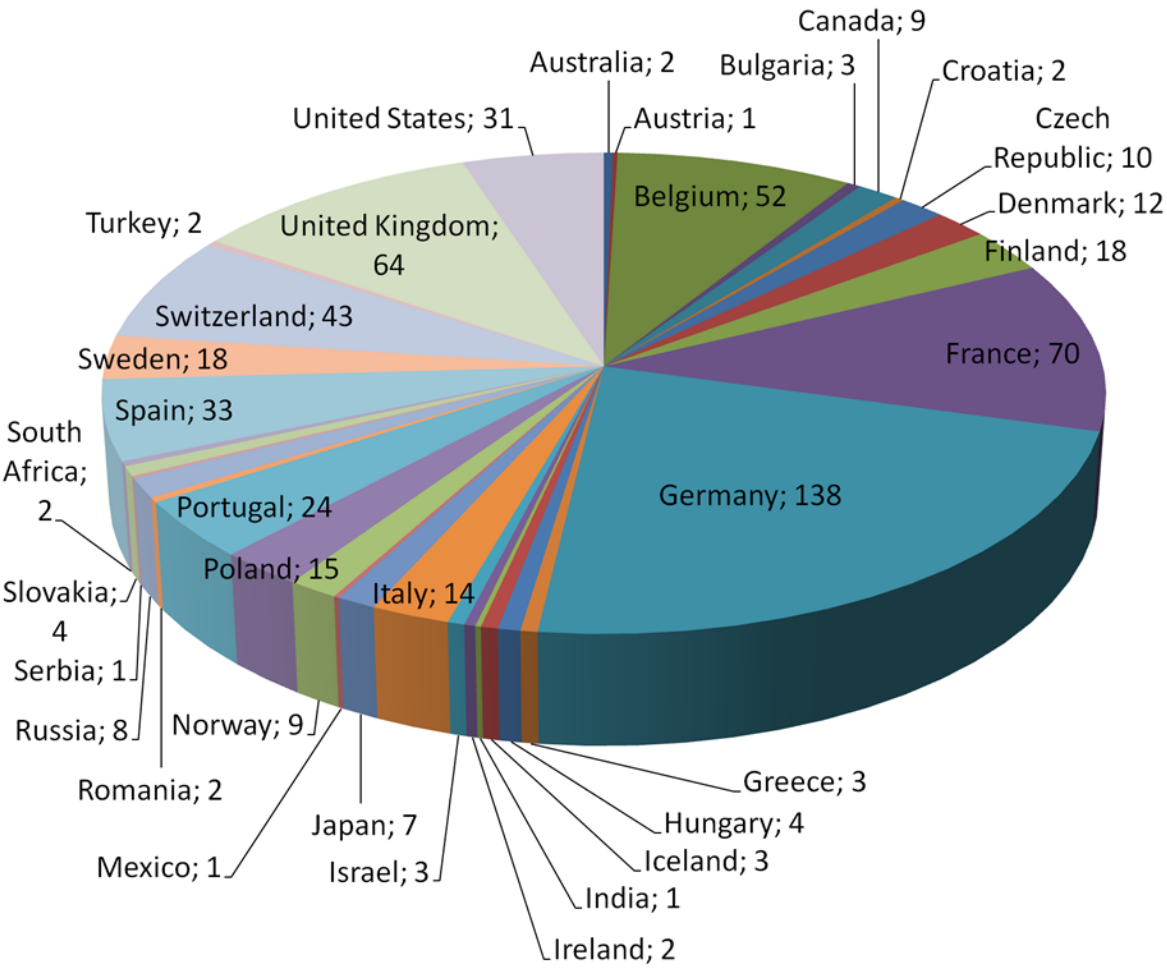
Element Synthesis, Solar Processes



ISOLDE users community



Number of scientists per country



2004 – 2008

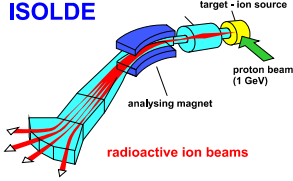
68 approved experiments
579 scientists
134 institutes
34 countries

236 publications in refereed journals

of which 42 in "Letters"

more than 20 PhD's

The science



The different shapes of the nucleus: collectivity versus individuality

Testing the Standard Model

Isospin dependence of the nuclear force

Doubly-magic nuclei
and shell structure far from stability

Burning cycles in stars

The origin of the chemical elements

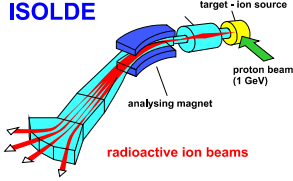
Applications in materials and life sciences

The limits of nuclear stability: measuring and predicting masses

The size of the nucleus: halos and skins

Explaining complex nuclei from basic constituents

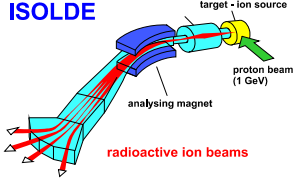
The uniqueness of ISOLDE



Thanks to

- The primary beams of CERN
  - Almost the whole nuclear chart is available when combined with e.g. ^{238}U target
- Continuous target-ion source developments
  - Laser ion source
- Innovative beam manipulation
  - Rex concept, ISCOOL
- Innovative experimental set-ups
  - Collaps, ISOLTRAP, MiniBall, Witch, …
- Strong users community with strong involvement in the technical developments

And yet more to come …



HIE-ISOLDE