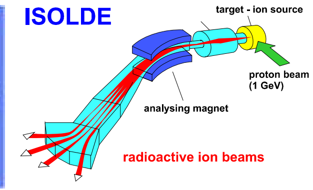


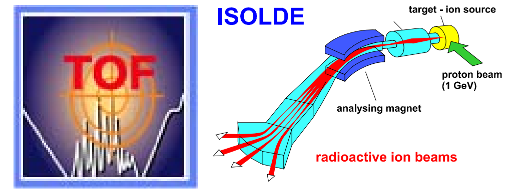
A rich revenue from the use of radioactive beams and radioactive targets: recent highlights from the n_TOF and ISOLDE facilities

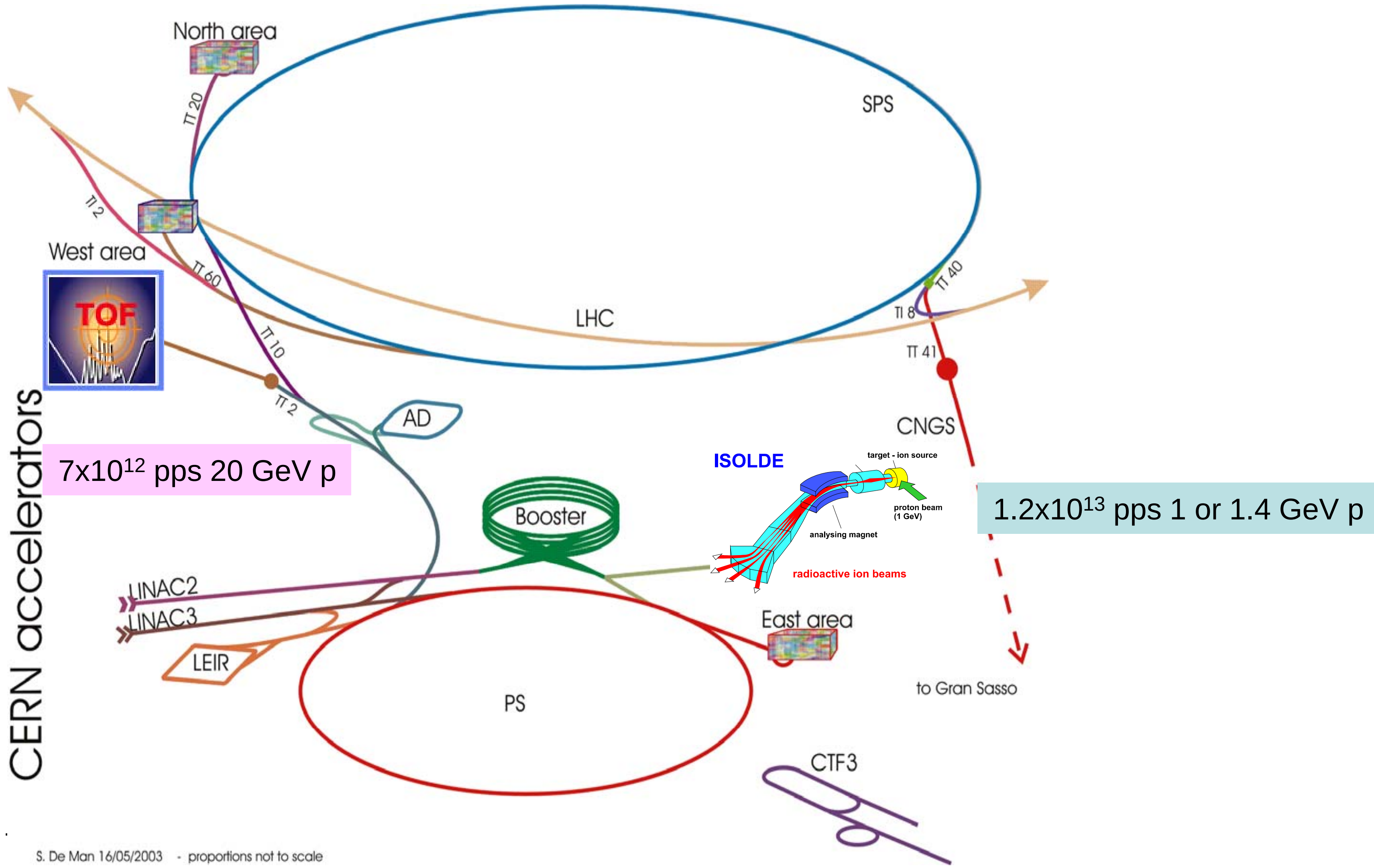
Mark Huyse

INTC, chair

IKS, K.U.Leuven, Belgium

CERN accelerator complex





Neutron reactions on rare or radioactive isotopes

- Measurements 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)

- Cross sections relevant for Nuclear Astrophysics
  - s-process: branchings
  - s-process: presolar grains

- Neutrons as probes for fundamental Nuclear Physics
  - Nuclear level density & n-nucleus interaction

n_TOF

41 research groups

120 users

Transparancies on nTOF: courtesy Alberto Mengoni

Transuranic elements produced by a 1000 MW_e Light Water Reactor

^{244}Cm
1.5 Kg/yr

^{241}Am: 11.6 Kg/yr
^{243}Am: 4.8 Kg/yr

^{239}Pu: 125 Kg/yr

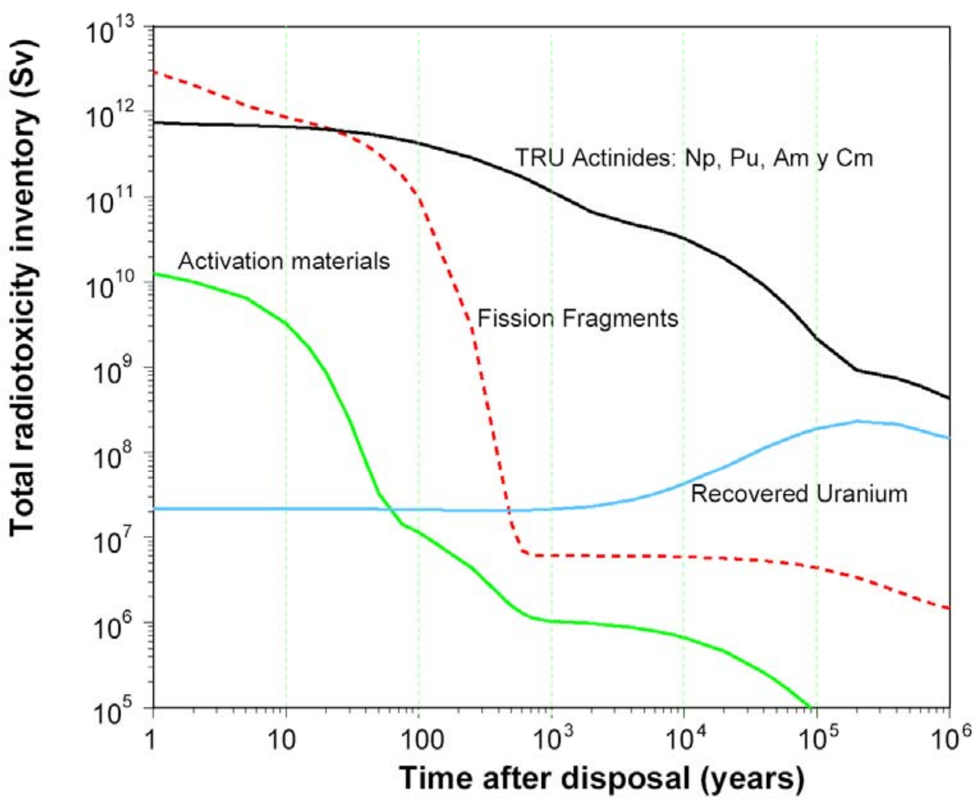
^{237}Np: 16 Kg/yr

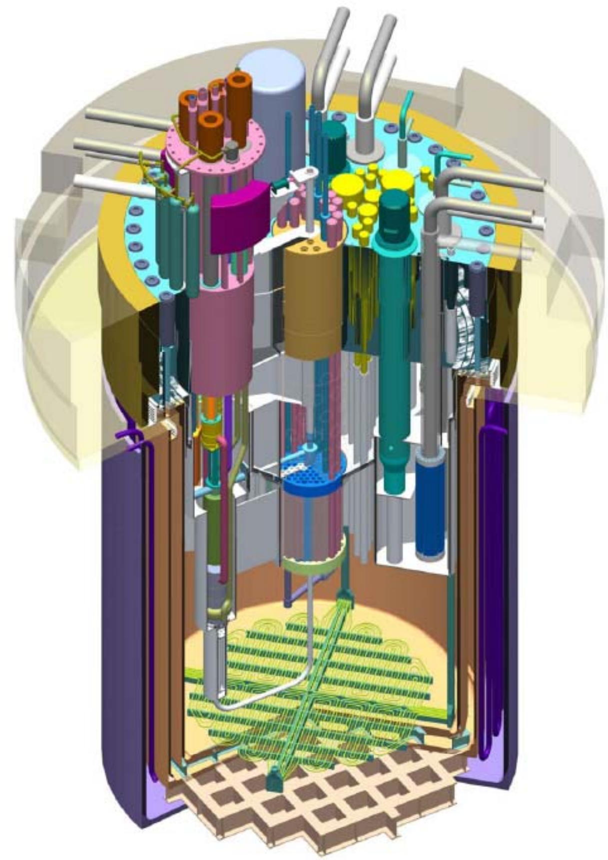
LLFP
76.2 Kg/yr

source: Actinide and Fission Product Partitioning and Transmutation – NEA (1999)

Accelerator Driven System

An ADS (Accelerator Driven System) - sometimes also called a nuclear amplifier - is an alternative concept to the critical nuclear reactor. The idea was first proposed by Nobel prize laureate E.O. Lawrence in the 1950's and was revived by another Nobel prize laureate C. Rubbia in 1993 after recent major advances in accelerator technology.





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

Fast neutron cross-sections needed!

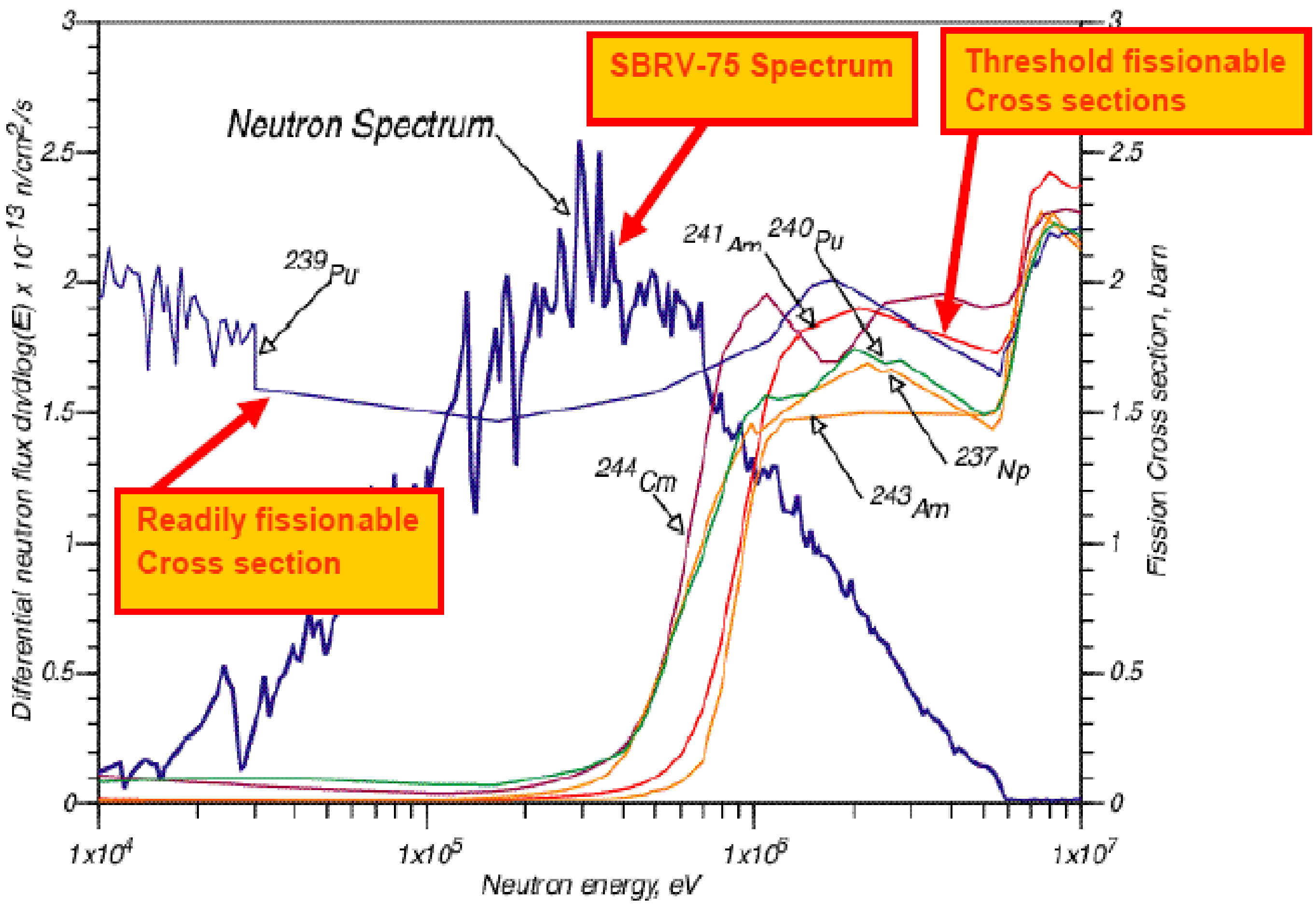
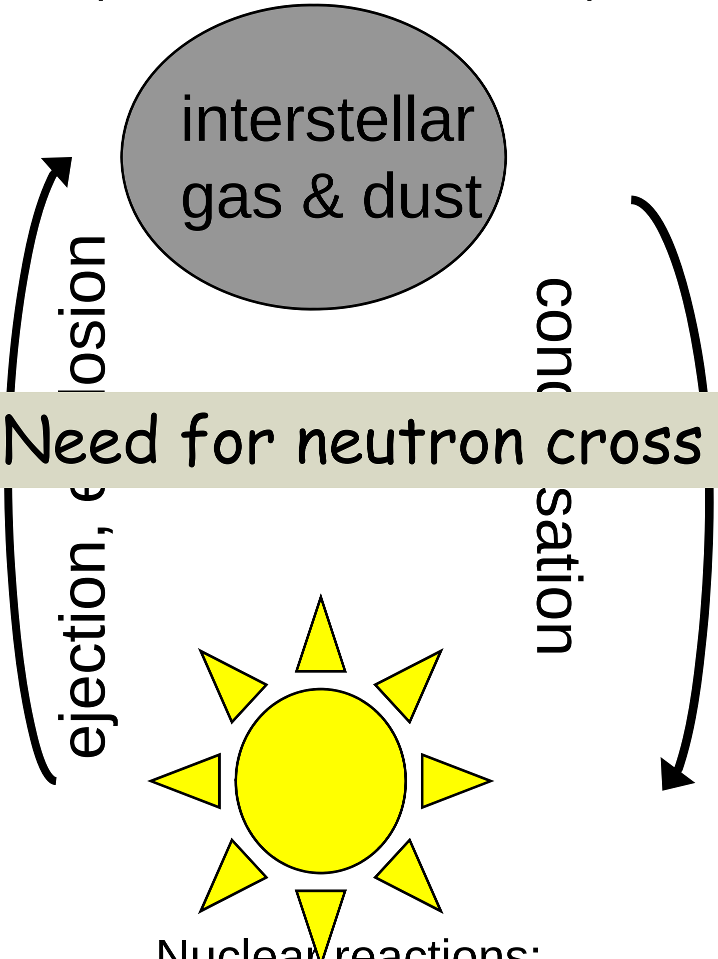


Figure 1: Simulation of the neutron spectrum in the SBRV-75 reactor [2], loaded with the Spiro MA fuel mixture (1/2 of ^{241}Am, 1/4 of ^{243}Am and 1/4 of equal amount of ^{244}Cm and ^{237}Np). The fission cross sections of several MA in consideration here are shown. The fission cross section of ^{239}Pu is also shown for a direct comparison with a non-threshold fission case.

source: C Rubbia

Nucleosynthesis

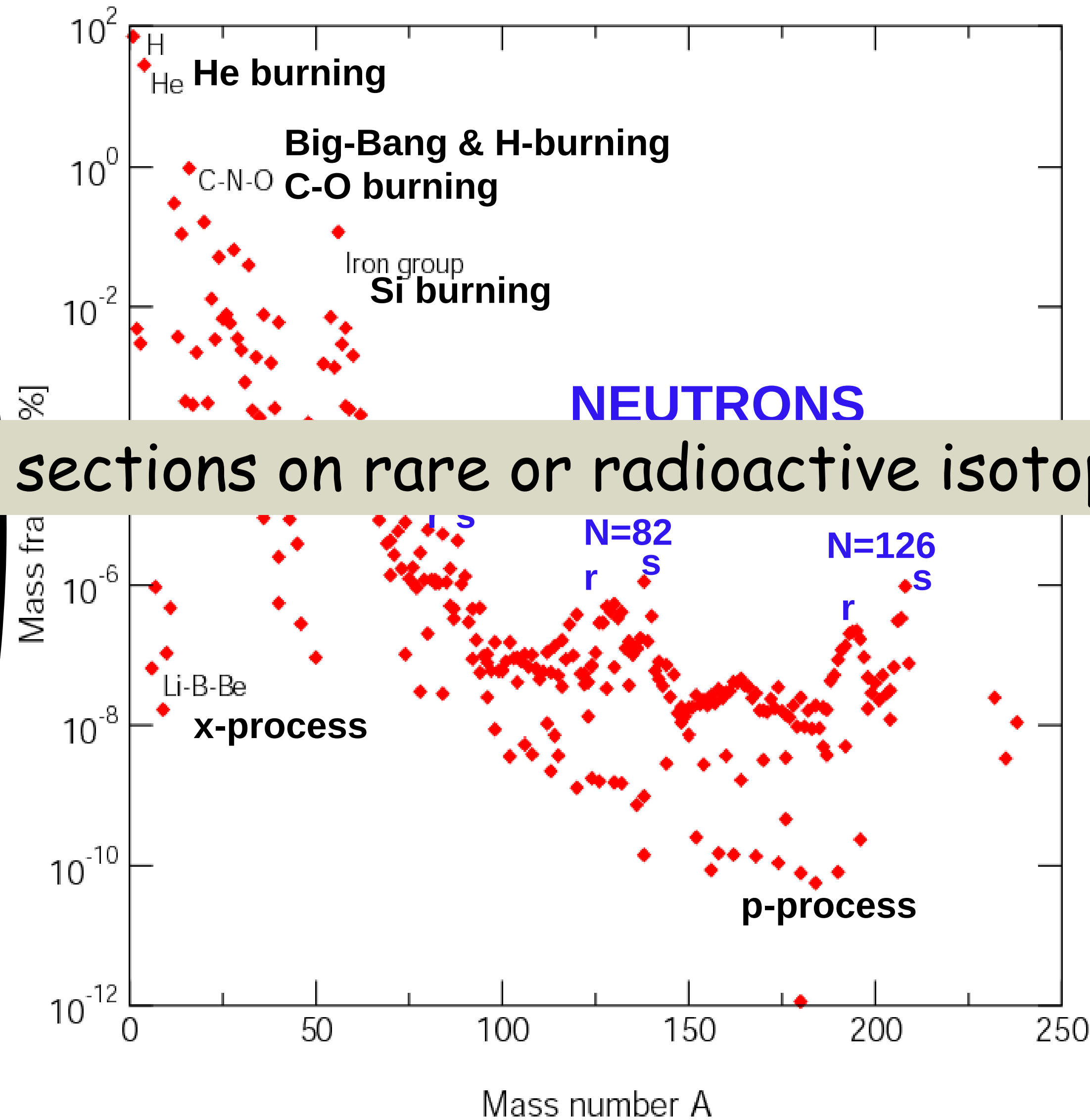
Mixing
(abundance distribution)



Nuclear reactions:

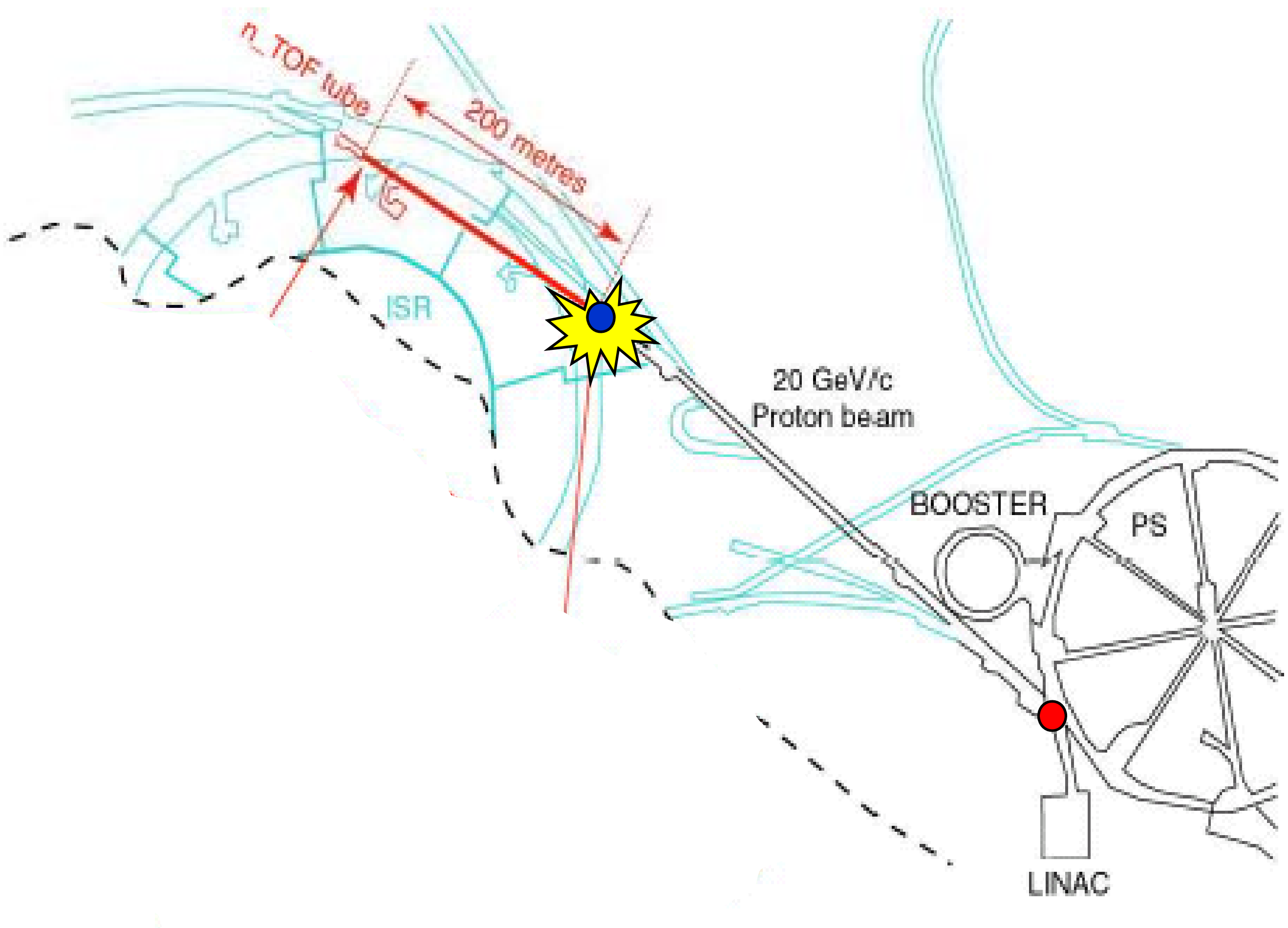
- energy generation
- nucleosynthesis

Abundances in the solar system



Need for neutron cross sections on rare or radioactive isotopes

The n_TOF facility at CERN



n_TOF basic parameters

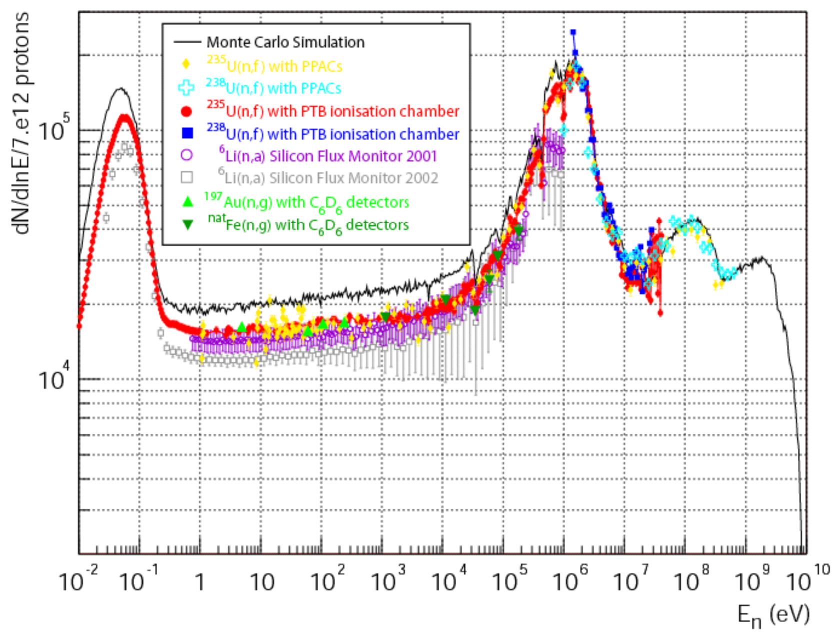
proton beam momentum	20 GeV/c
intensity (dedicated mode)	7×10^{12} protons/pulse
repetition frequency	1 pulse/2.4s
pulse width	6 ns (rms)
n/p	300
lead target dimensions	80x80x60 cm^3
cooling & moderation material	H_2O
moderator thickness in the exit face	5 cm
neutron beam dimension in EAR-1 (capture mode)	2 cm (FWHM)

CAARI 2002

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 x-section measurements on:

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



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

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

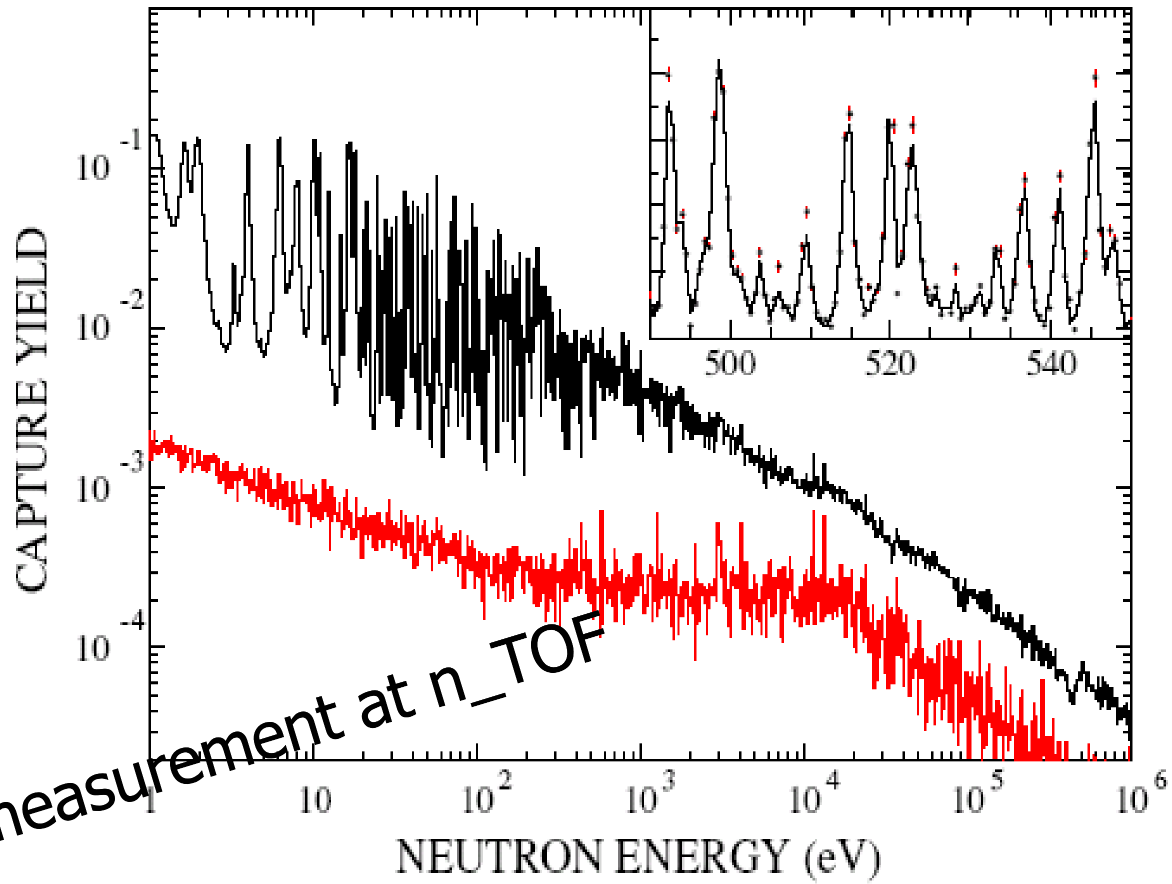
^{232}Th

^{209}Bi

^{237}Np

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

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



the 1st measurement at n_TOF

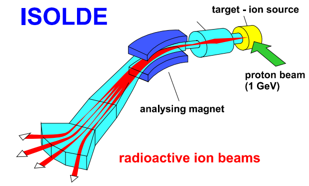
At a thermal energy of kT=30 keV the Maxwellian averaged cross section of this unstable isotope ($t_{1/2}$=93 yr) was determined to be 3100±160 mb, significantly larger than theoretical predictions

23 publications: see http://pceet075.cern.ch/

A new experimental campaign starts this year

- A new target will be 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

The many lives of ISOLDE

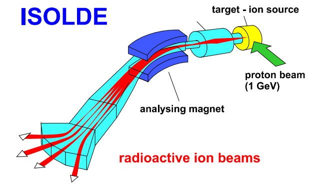


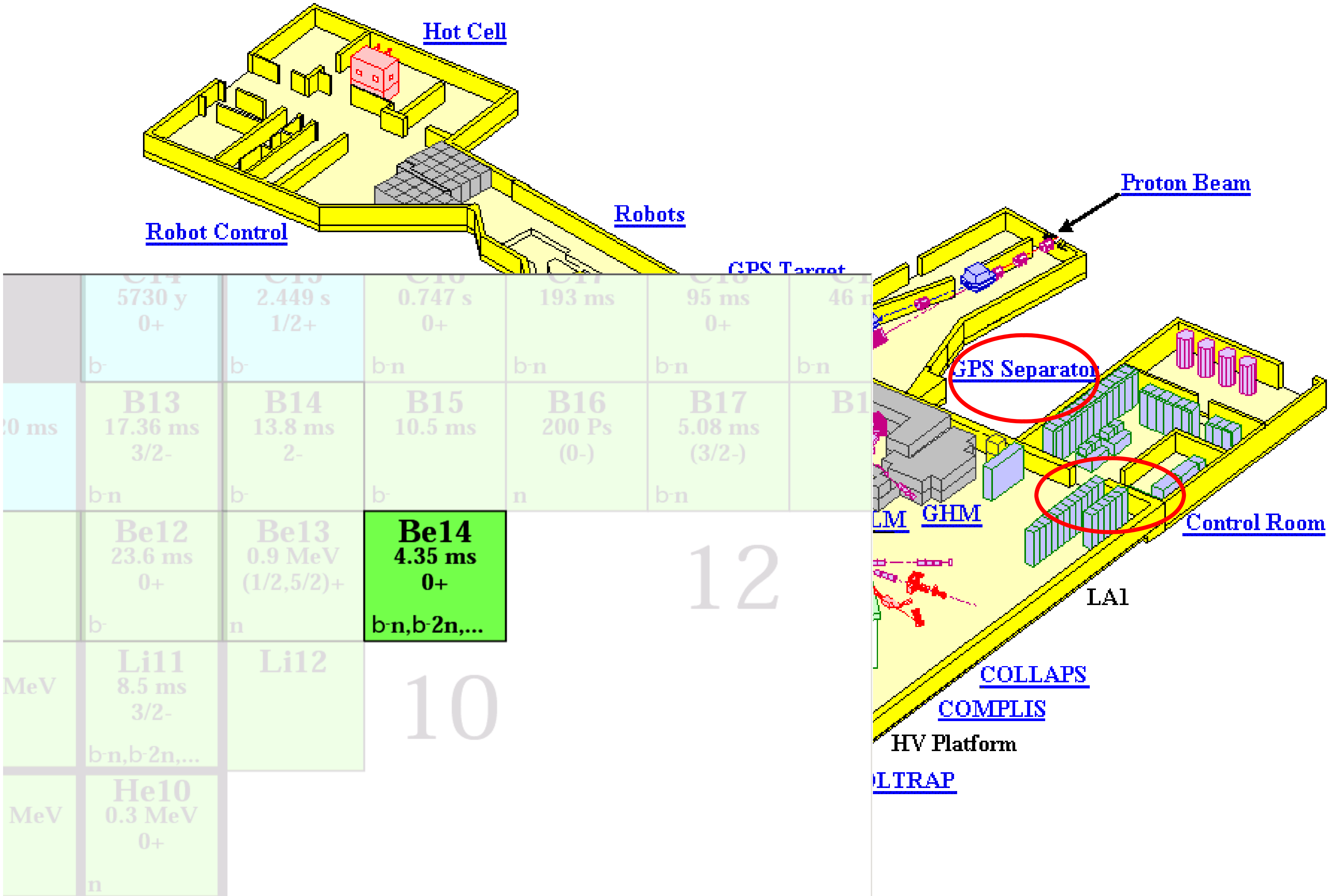
The first 40 years of physics at ISOLDE

ISOLDE PHYSICS WORKSHOP
AND
USERS MEETING
December 17 - 19, 2007

Prof. Bjorn JONSON (Chalmers University of Technology)

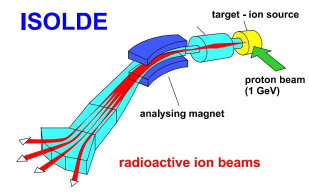
ISOLDE@CERN

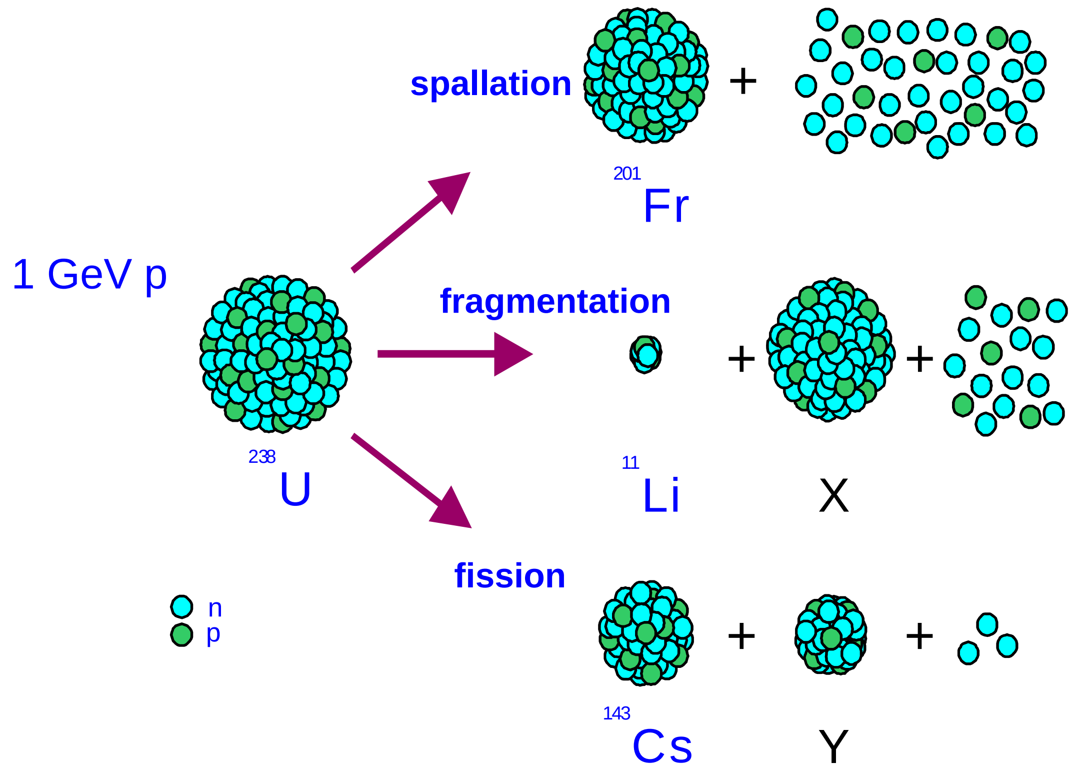




Courtesy of K. Riisager, P. Butler, A. Herlert, …

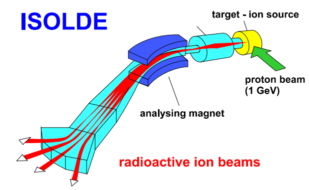
RIB - Production reactions

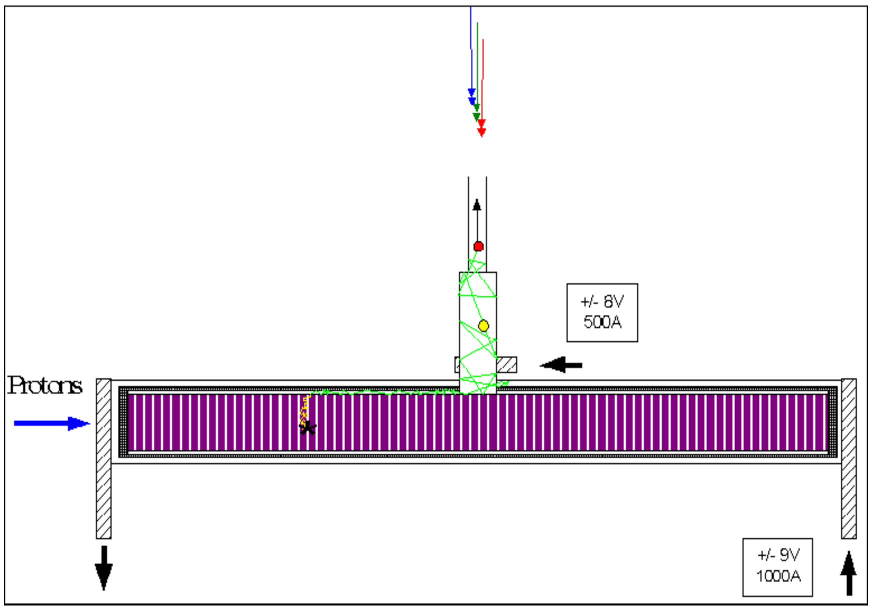




- Spallation
- Fragmentation
- Fission
  - n- (thermal or energetic), p-induced
  - Photofission (e-beam)
- Fusion

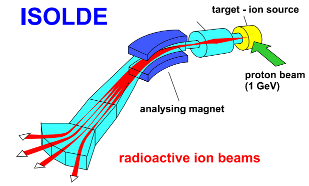
Target - Ion-source matrix

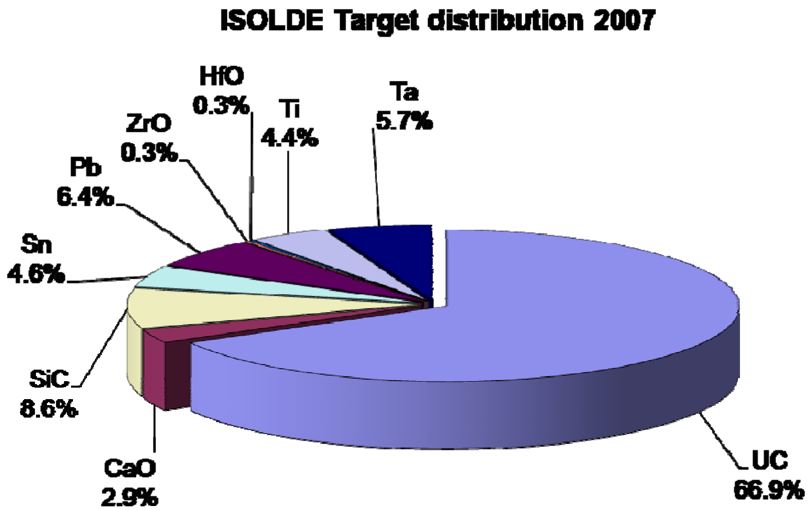


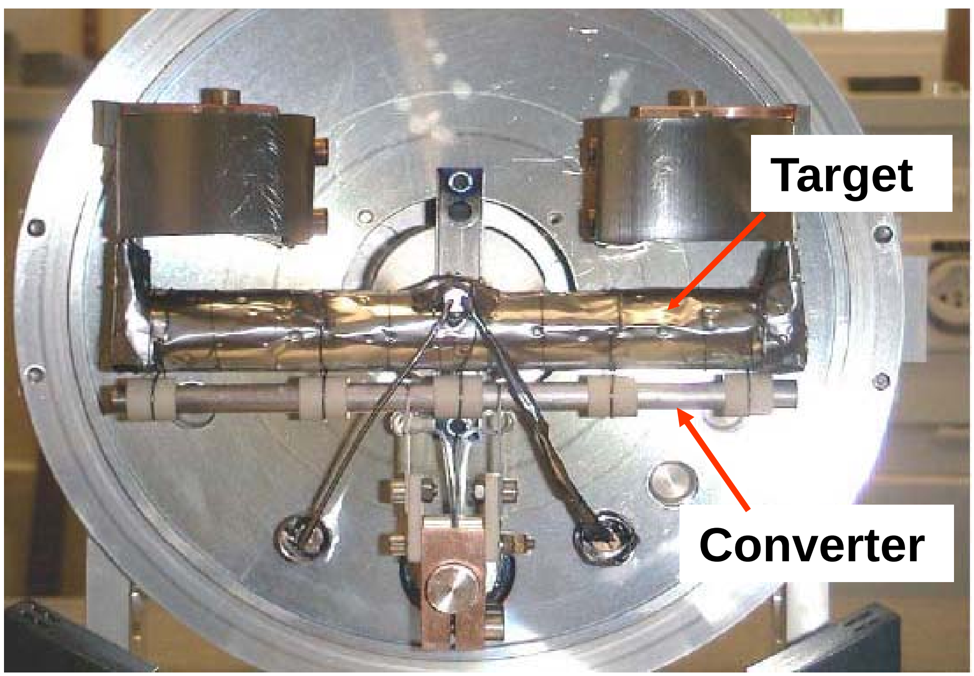


- Container: 20 x 2 cm cylinder of Ta
- Material:
  - Liquid La, Pb, Sn
  - Metal foil/powder Nb, Ti, Ta..
  - Oxides CaO, MgO
  - Carbides SiC, UC, ThC
- Ion-source
  - Surface
  - Plasma
  - Laser
- Fluorination CF4 or SF6

Targets



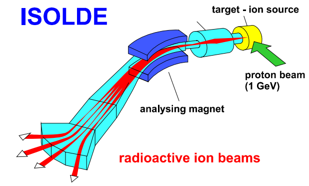


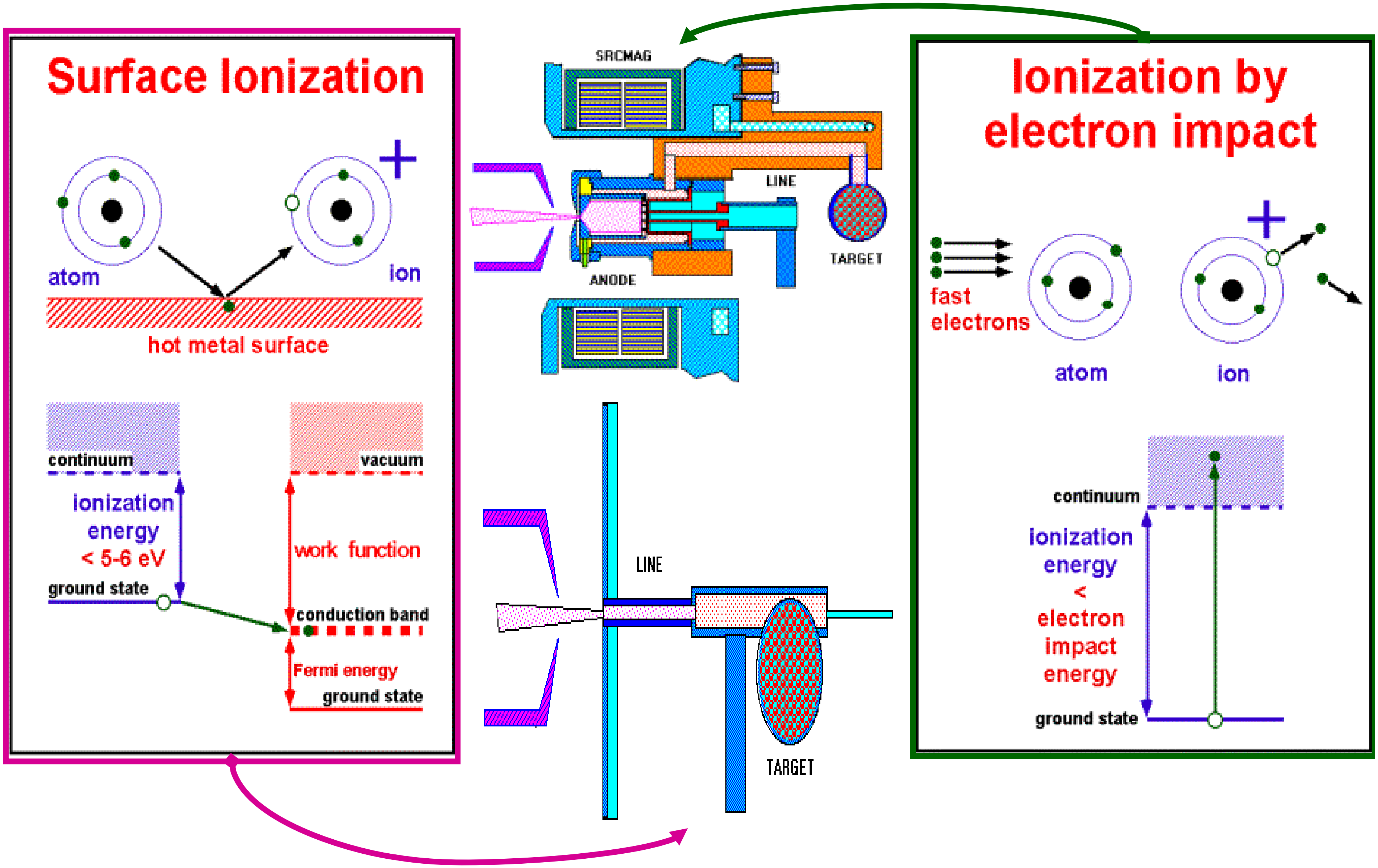


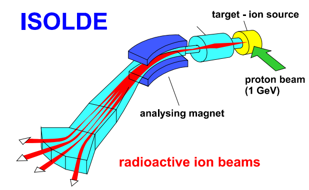
Converter Target

Standard

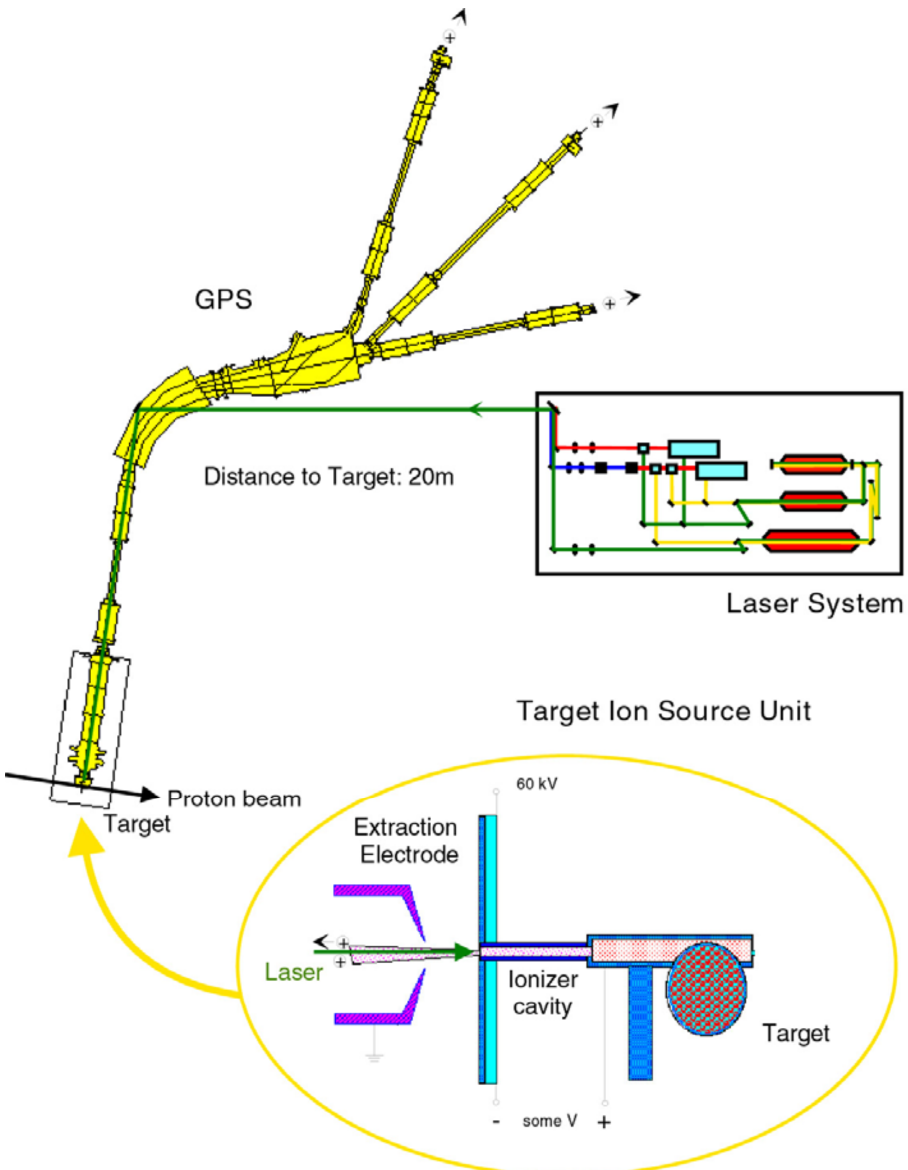
Surface & plasma ionization

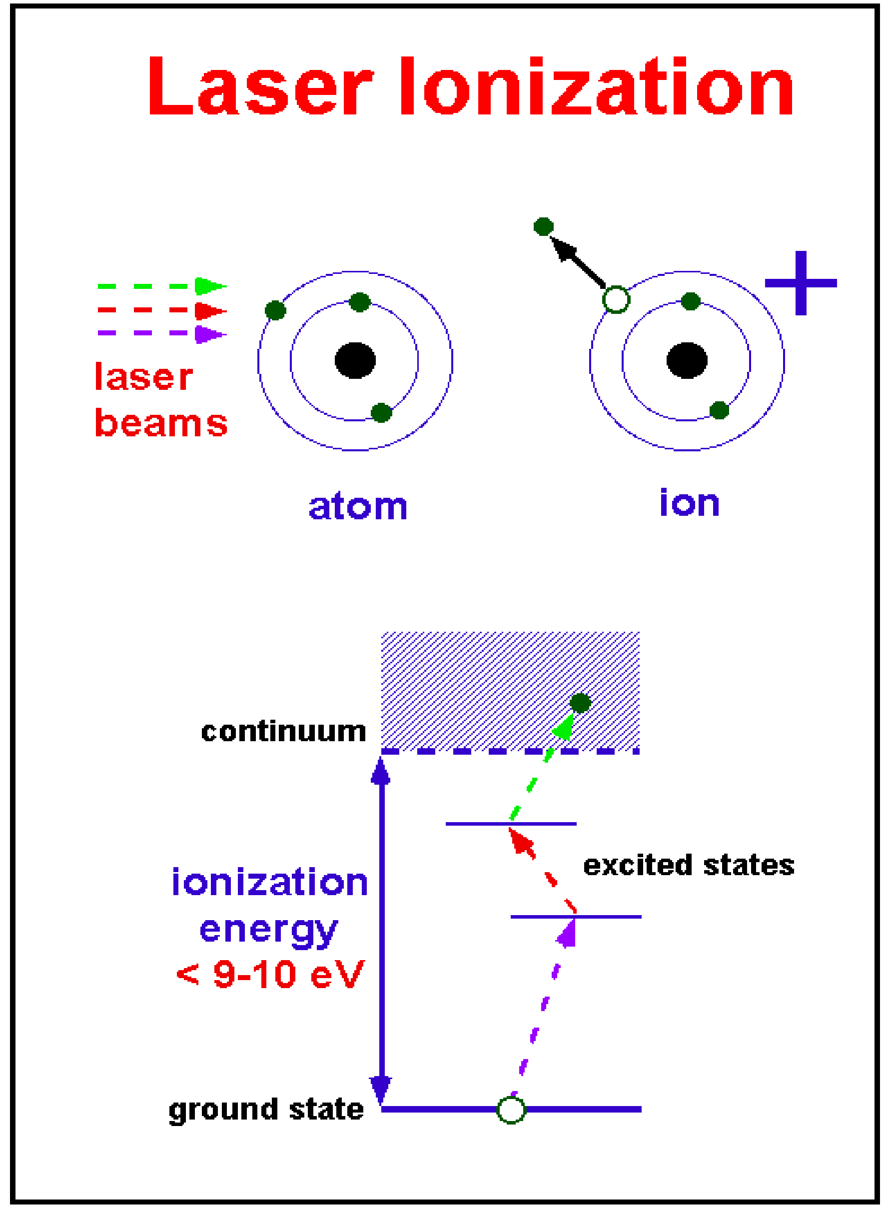




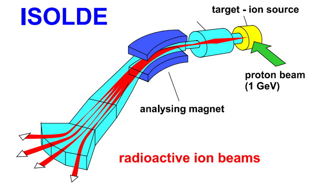


Laser ionization





ISOLDE Table of elements



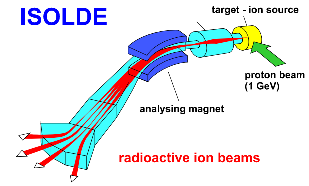
ION SOURCE:

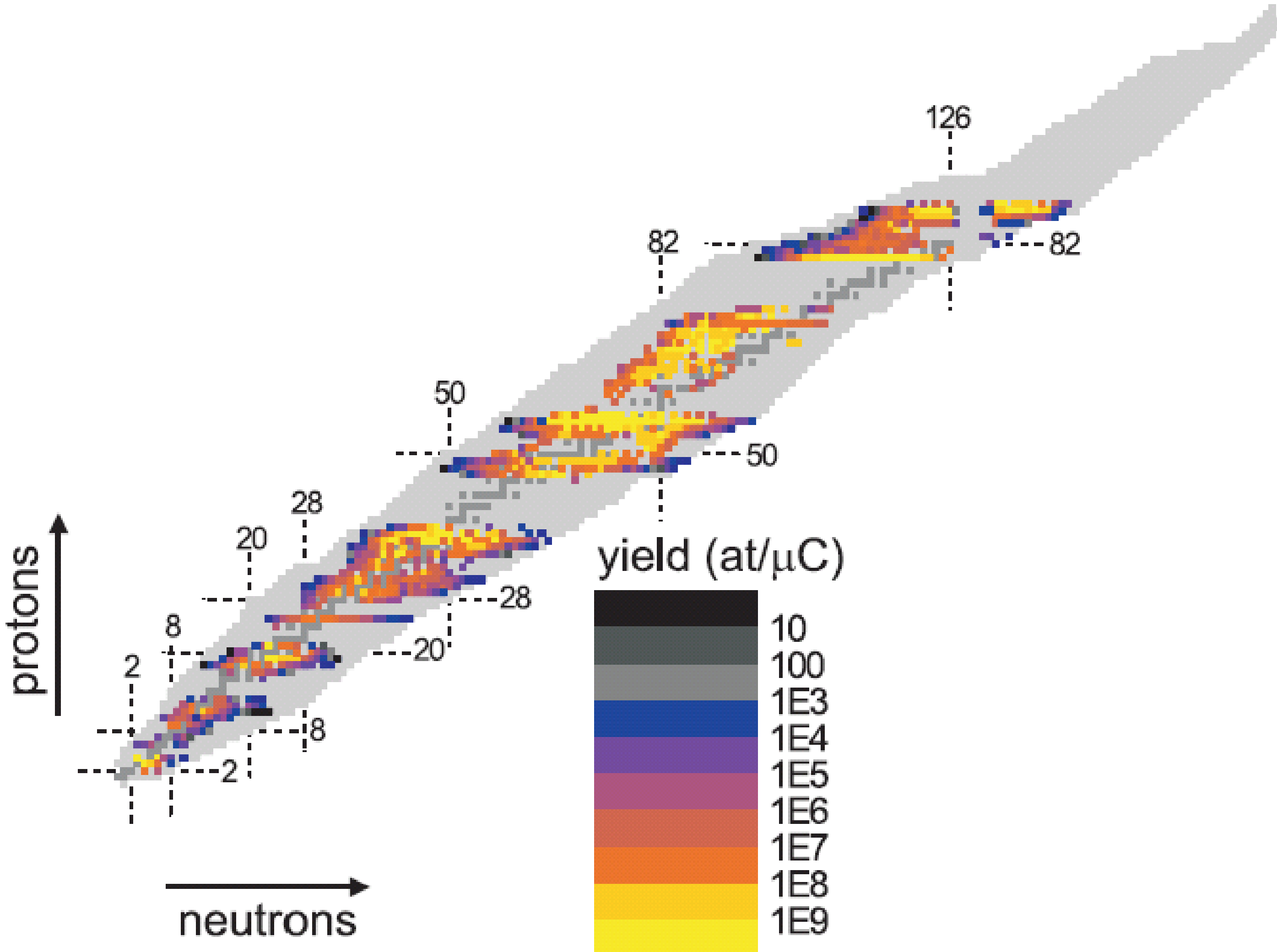
+	SURFACE	–
hot	PLASMA	cooled
	LASER	

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



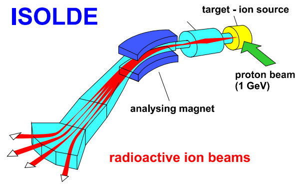


So far >600 radioactive isotopes of >60 elements @ 60 keV

ISOLDE target group: M. Turrion

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

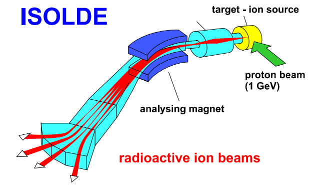
October 2001: a new dimension



Post acceleration by REX-ISOLDE

up to 3 MeV/u

REX-ISOLDE OVERVIEW

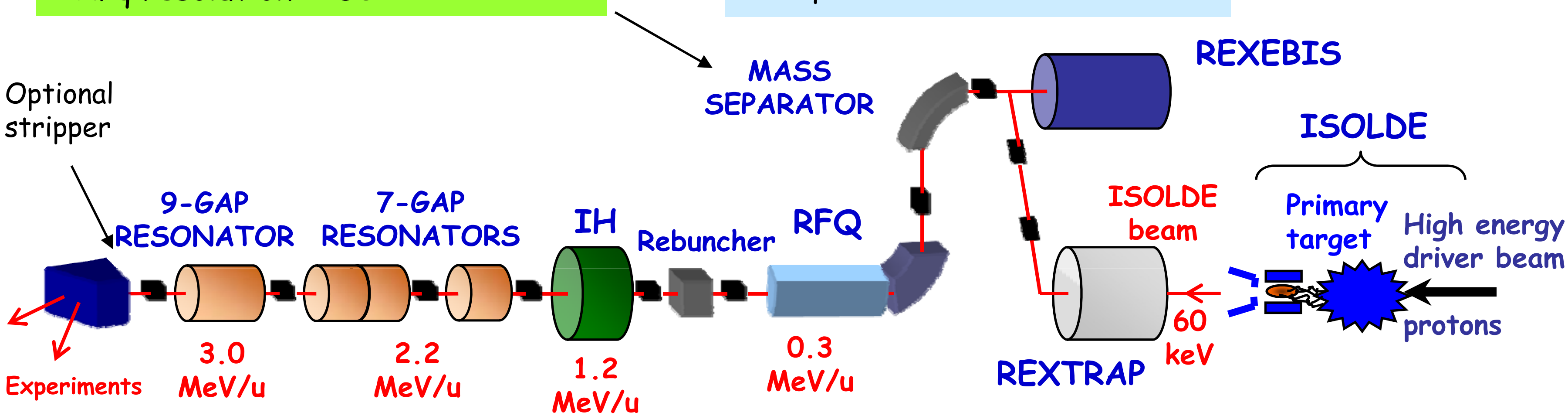


EBIS

- Super conducting solenoid, 2 T
- Electron beam < 0.4A 3-6 keV
- Breeding time 3 to >200 ms
- Total capacity $6 \cdot 10^{10}$ charges
- A/q < 4.5

Nier-spectrometer

- Select the correct A/q and separate the radioactive ions from the residual gases.
- A/q resolution ~150



Linac

Length	11 m
Freq.	101MHz (202MHz for the 9GP)
Duty cycle	1ms 100Hz (10%)
Energy	300keV/u, 1.2-3MeV/u
A/q max.	4.5 (2.2MeV/u), 3.5 (3MeV/u)

REX-trap

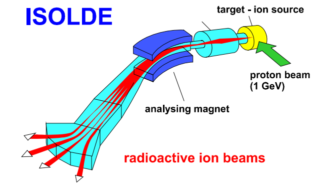
- Cooling (10-20 ms)
  Buffer gas + RF
- (He), Li,...,U
- 10^8 ions/pulse

(Space charge effects >10^5)

Thanks to Didier Voulot

Total efficiency : 1 -10 %

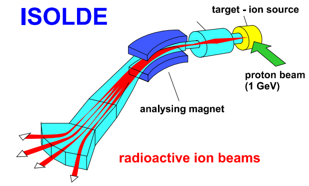
World ISOL accelerated beams

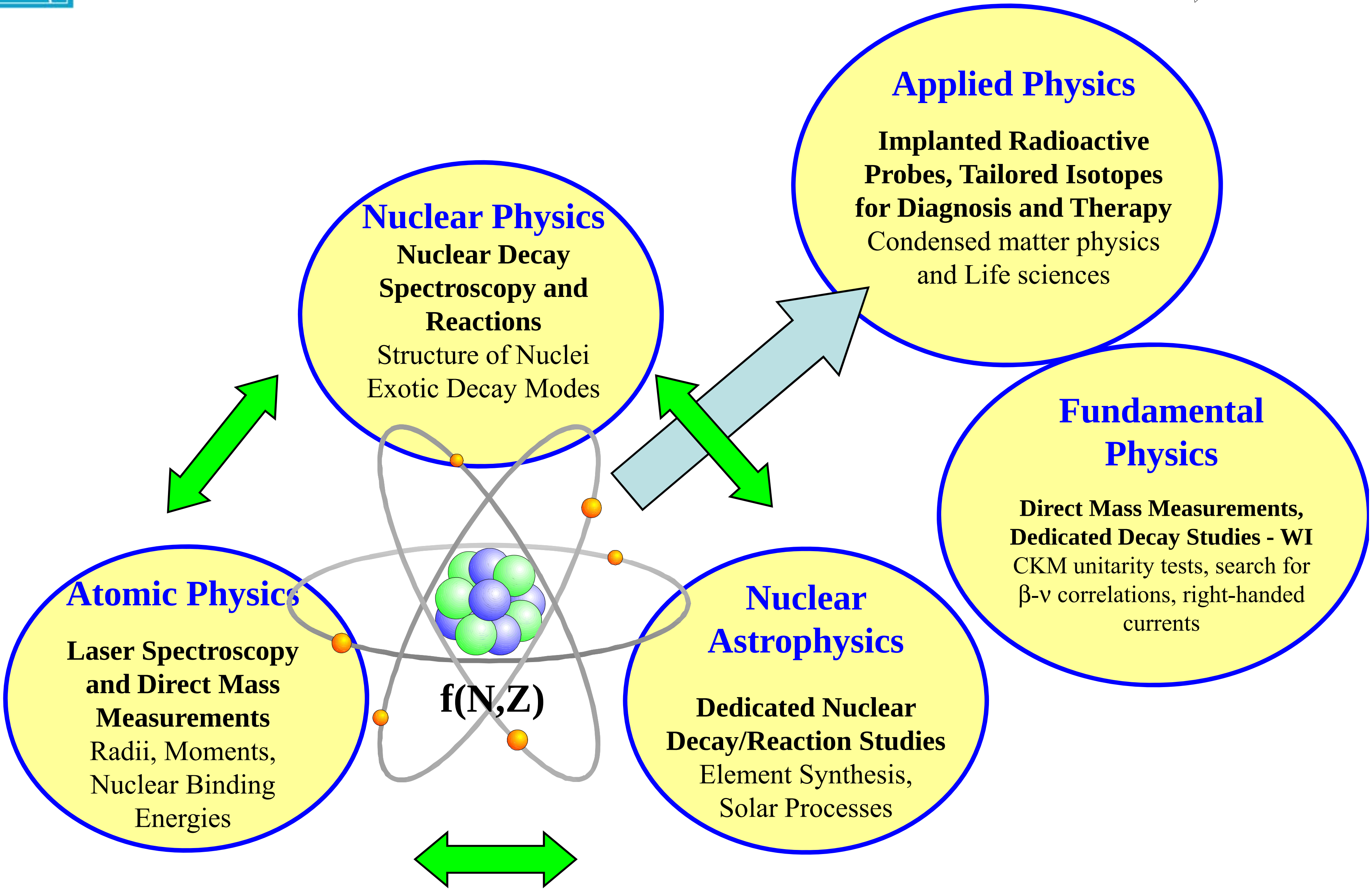


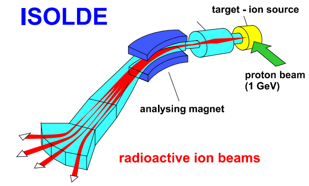
FACILITY	DRIVER	POWER	USER BEAMS ACCELERATED	ENERGY	PHYSICS REACH
LOUVAINE-LA-NEUVE (BELGIUM) 1989	30 MeV protons	6 kW	^{6}He, ^{7}Be, ^{10,11}C, ^{13}N, ^{15}O, ^{18}F, ^{18,19}Ne, ^{35}Ar	10 MeV/u cyclotron	Astrophysics, Nuclear structure
HRIBF Oak Ridge (USA) 1997	100 MeV p, d, α *(-ve ion source)*	1 kW	^{7}Be, ^{17,18}F, ^{69}As, ^{67,83}Ga, $^{75-79}$Cu, $^{80-87}$Ge, ^{84}Se, ^{92}Sr, ^{118,120,122,124}Ag, ^{129}Sb, $^{130-134}$Sn, ^{132,134,136}Te	2 - 10 MeV/u tandem	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}Li, $^{10-12}$Be, ^{17}F, $^{24-29}$Na, $^{28-32}$Mg, ^{68}Ni, $^{67-73}$Cu, ^{74,76,78,80}Zn, ^{70}Se, ^{88,92}Kr, ^{108}In, ^{106,108,110}Sn, ^{122,124,126}Cd^{138,140,142,144}Xe, ^{148}Pm, ^{153}Sm, ^{156}Eu, ^{184,186,188}Hg	0.3 - 3 MeV/u linac	Nuclear structure, Condensed matter, Astrophysics

So far 53 radioactive isotopes of 20 elements

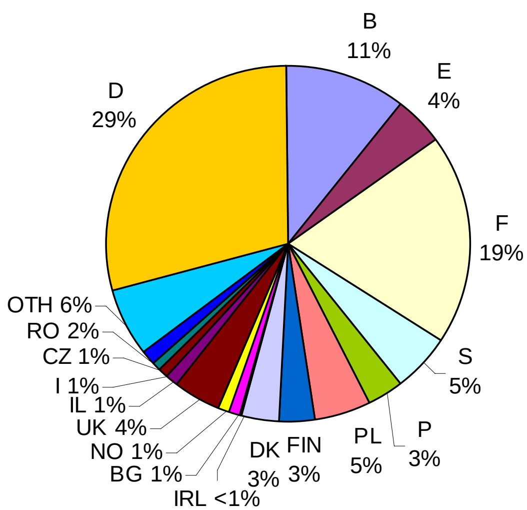
Research with Radioactive Ion Beams

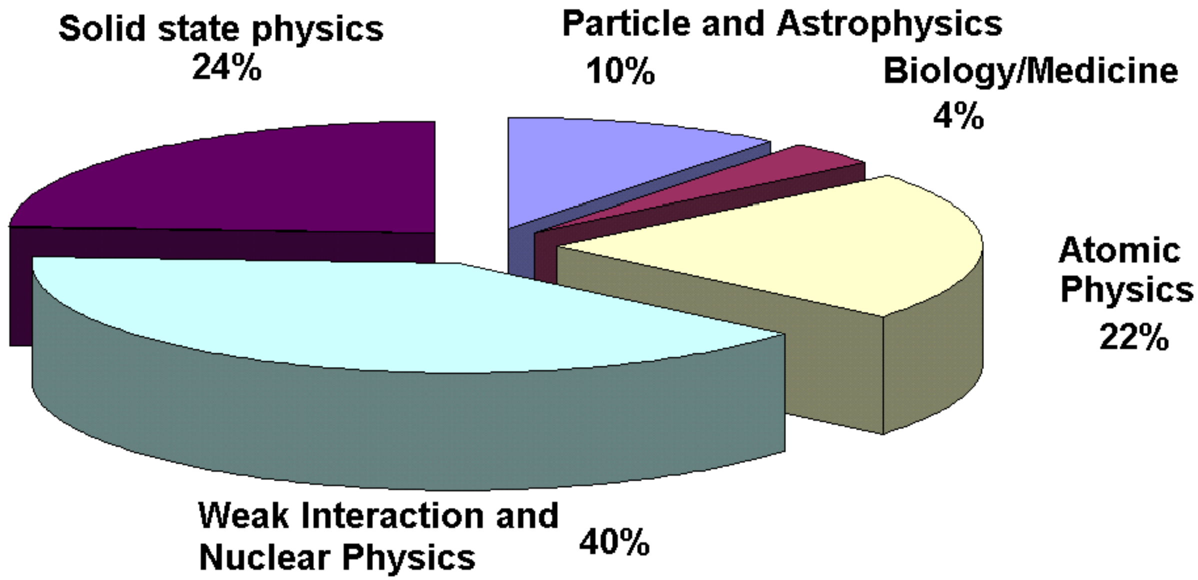






Users & Science



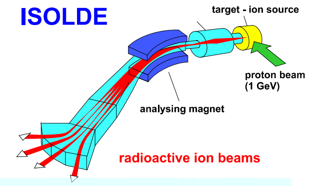


450 users

25 countries; 100 institutions

175 projects (4 years)

The nuclear chart: a rich physics potential



The end of Mendeleev's table: superheavies

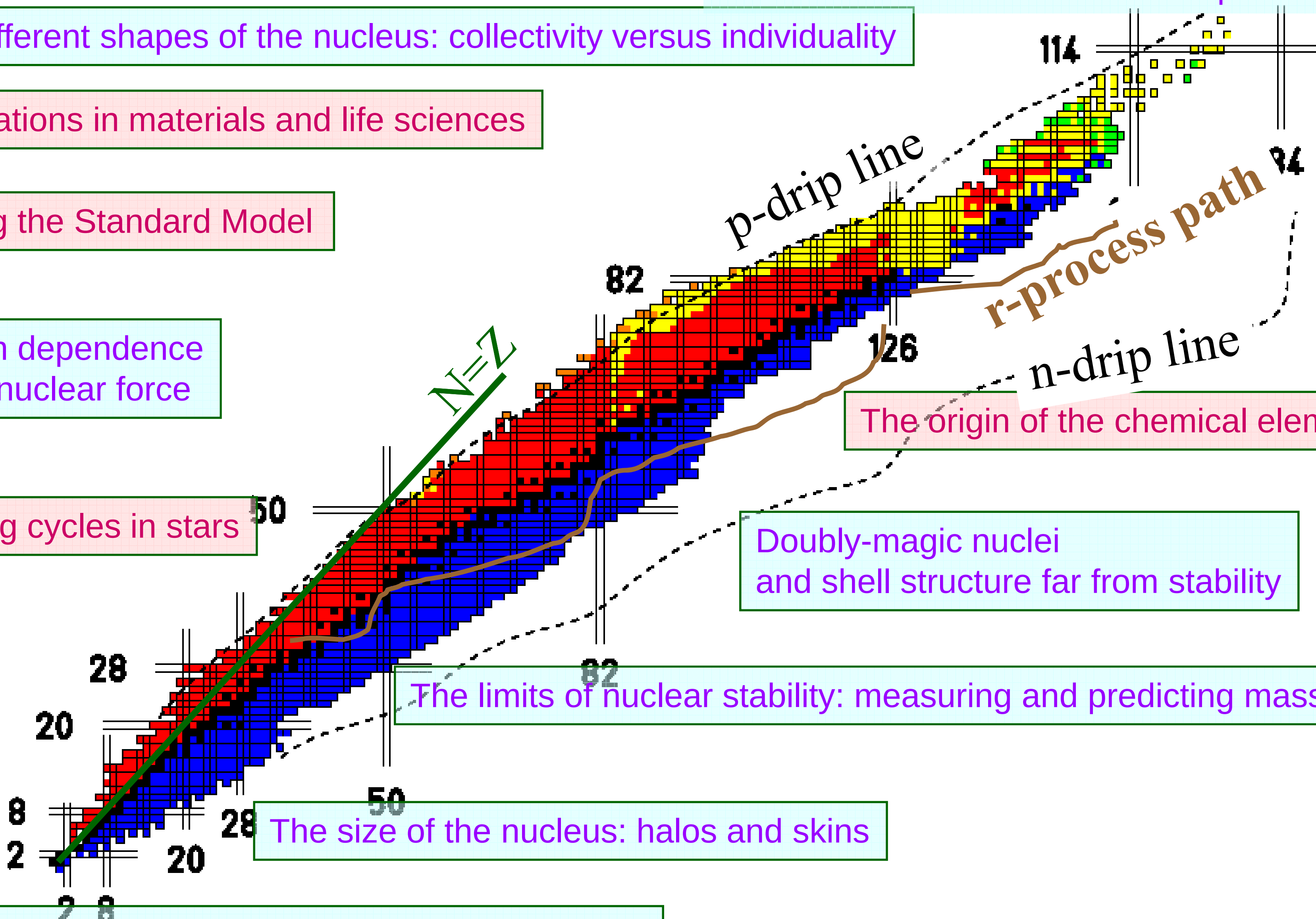
The different shapes of the nucleus: collectivity versus individuality

Applications in materials and life sciences

Testing the Standard Model

Isospin dependence
of the nuclear force

Burning cycles in stars



The origin of the chemical elements

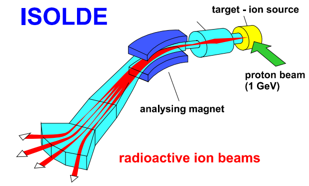
Doubly-magic nuclei
and shell structure far from stability

The limits of nuclear stability: measuring and predicting masses

The size of the nucleus: halos and skins

Explaining complex nuclei from basic constituents

Shell structures far from stability



PHYSICAL REVIEW C VOLUME 12, NUMBER 2 AUGUST 1975

Direct measurement of the masses of ^{11}Li and $^{26-32}$Na with an on-line mass spectrometer

C. Thibault, R. Klapisch, C. Rigaud, A. M. Poskanzer,* R. Prieels,† L. Lessard,‡ and W. Reisdorf§
Laboratoire René Bernas du Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, 91406 Orsay, France
(Received 17 March 1975)

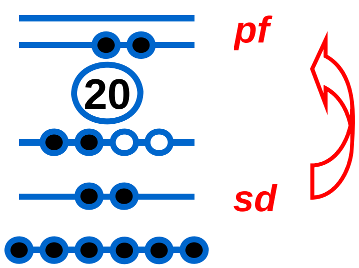
The use of an on-line mass spectrometer to make direct mass measurements of short-lived isotopes far from the stability line has been improved to yield more accurate mass measurements for $^{27-30}$Na, new mass measurements for ^{11}Li, ^{31,32}Na, and to remove a discrepancy between existing mass measurements of ^{26}Na. The mass

PHYSICAL REVIEW C VOLUME 19, NUMBER 1 JANUARY 1979

Beta decay of $^{27-32}$Na and their descendants

C. Détraz, D. Guillemaud, G. Huber, R. Klapisch, M. Langevin, F. Naulin, C. Thibault, L.C. Carraz,* and F. Touchard
Laboratoire René Bernas, Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, 91406 Orsay, France and Institut de Physique Nucléaire, 91406 Orsay, France
(Received 10 July 1978)

The γ activities from the β decay of Na isotopes up to ^{32}Na, which are formed in high-energy fragmentation and analyzed through mass spectrometry techniques, are observed, as well as those from their Mg or Al descendants. Their intensities are measured, in most cases, in absolute value. The radioactive half-lives of ^{29}Mg, ^{30}Mg, and ^{31}Mg are determined. Delayed-neutron branching ratios P_n are measured for ^{29}Na, ^{30}Na, and ^{32}Na. In some cases, partial branching ratios to excited states of the daughter nucleus are also measured. The most prominent γ ray in the β decay of even Na isotopes is assigned to $2^+ \to 0^+$ transition in the daughter Mg isotopes. The position of the first excited 2^+ level is therefore deduced for ^{30}Mg and ^{32}Mg. For ^{32}Mg, the excitation energy drops markedly. It is taken as an indication of a stronger deformation for that isotope.



PHYSICAL REVIEW C VOLUME 41, NUMBER 3 MARCH 1990

Mass systematics for $A=29-44$ nuclei: The deformed $A\sim32$ region

E. K. WARBURTON, J. A. BECKER, AND B. A. BROWN

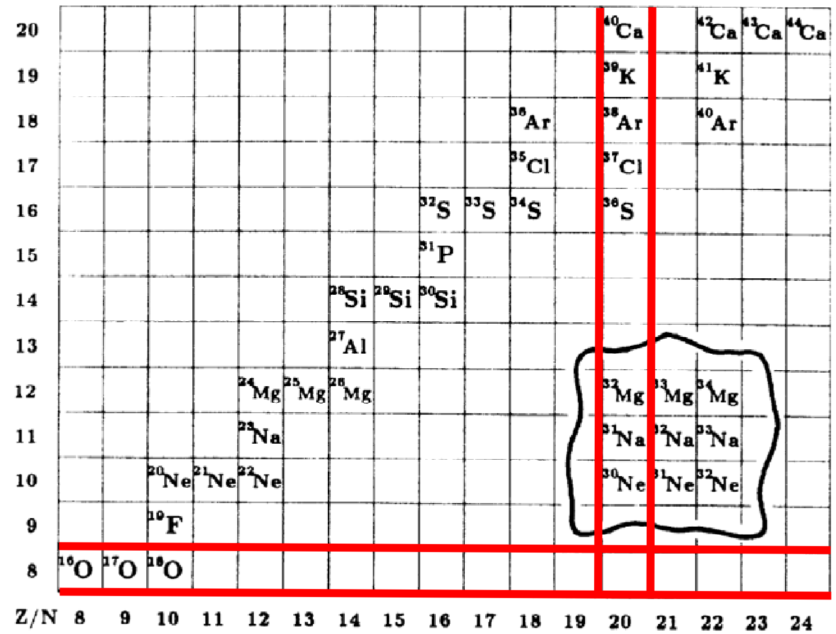


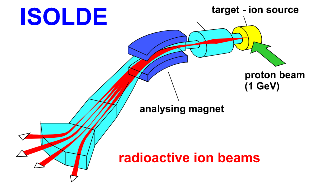
FIG. 1. Partial periodic table highlighting the "island of inversion" centered at ^{32}Na. The extent of the "island" is an important aspect of the study. The magic numbers $Z=8$ and $N=20$ are emphasized with double lines. Apart from the "island," only stable nuclei are shown.

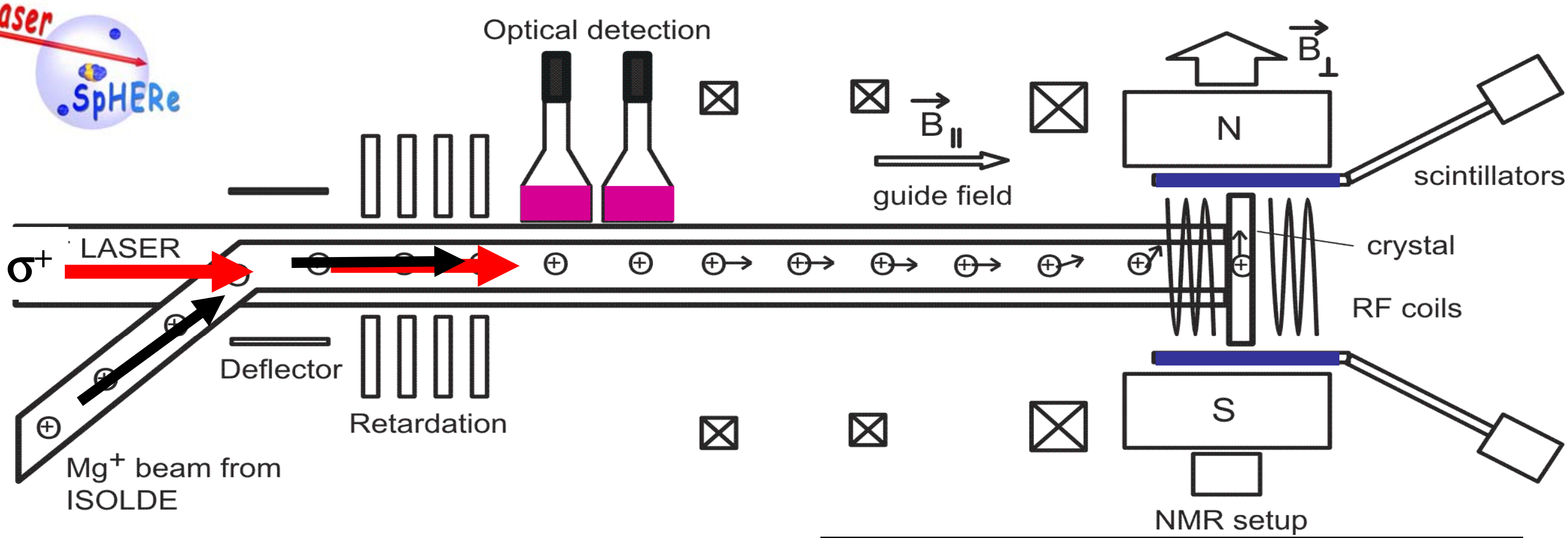
J. Phys. G: Nucl. Part. Phys. 17 (1991) 135–143. Printed in the UK

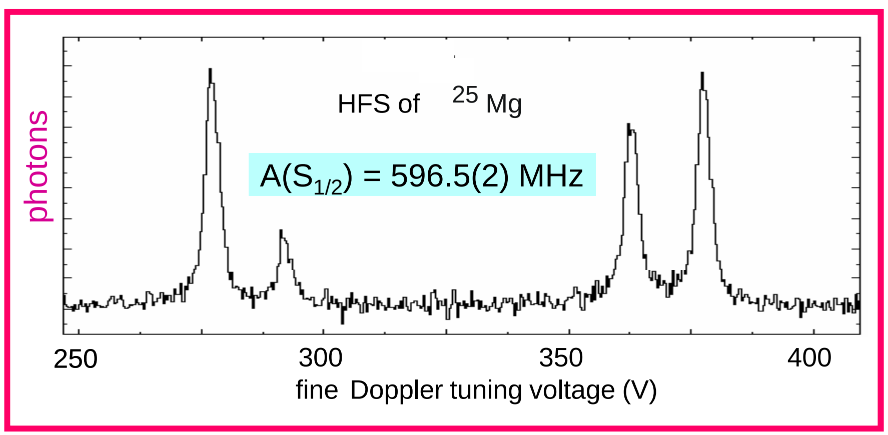
Intruder states and shape coexistence in the region $N\sim20$, $Z\sim12$*

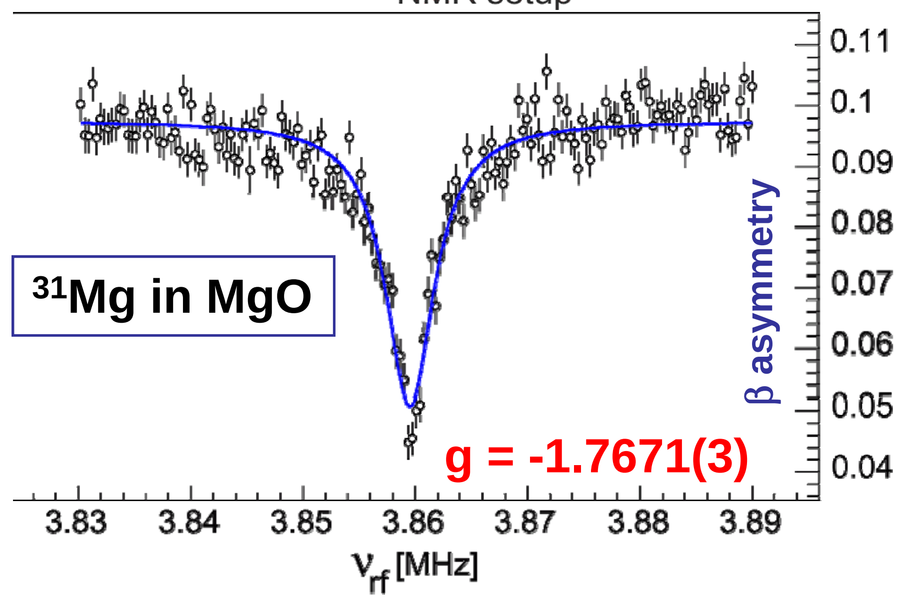
K Heyde† and J L Wood‡

Fundamental properties: spins, moments radii

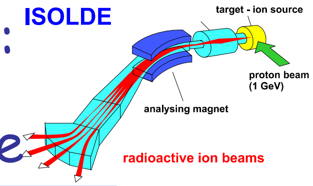




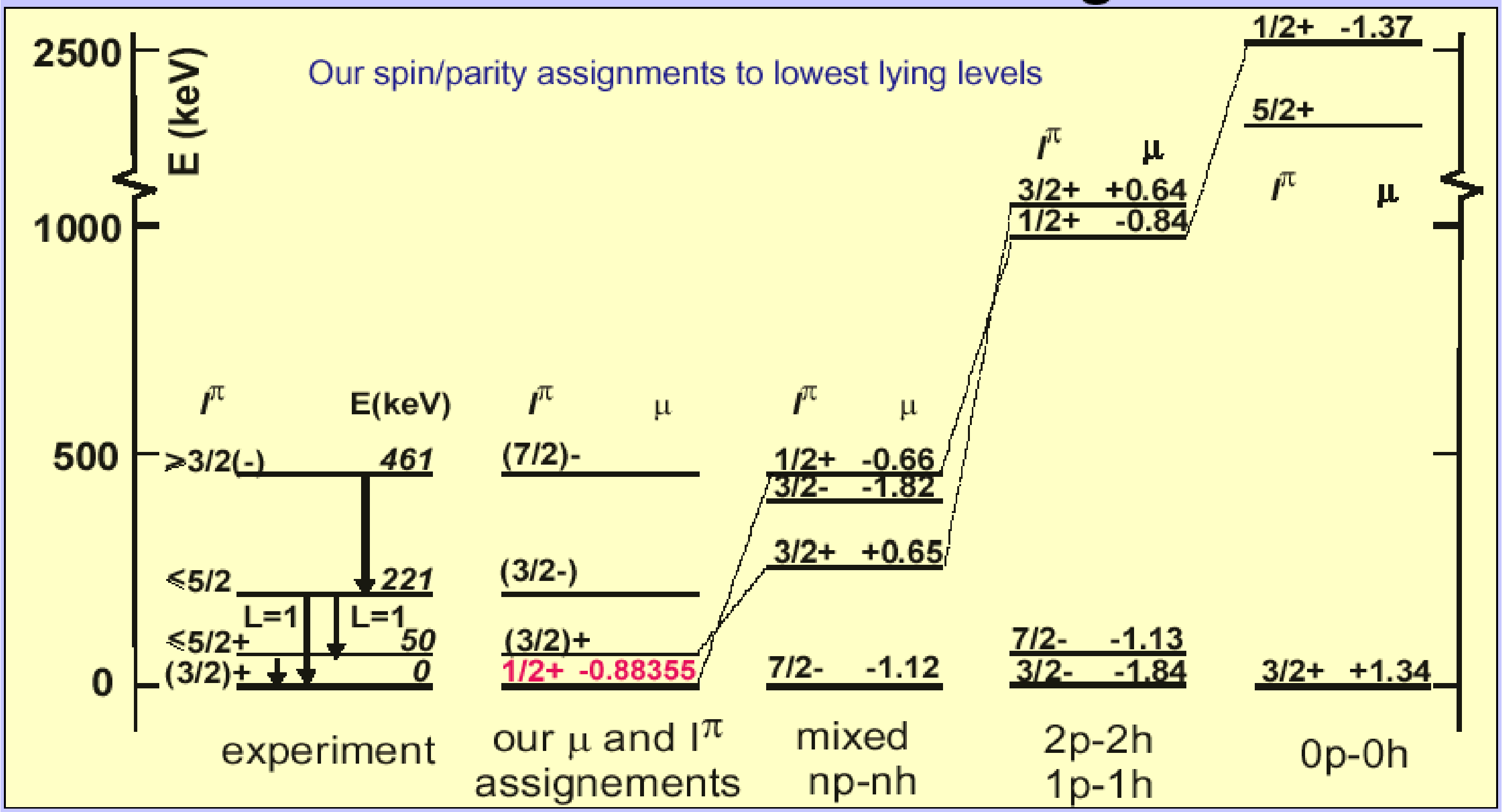




Measurement of the Spin and Magnetic Moment of 31Mg: Evidence for a Strongly Deformed Intruder Ground State



Level scheme of ^{31}Mg



Klotz et al., PRC 47, 2502 (1993)

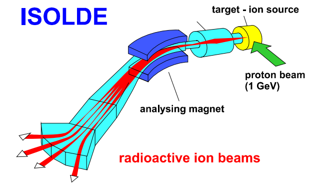
MCSM, sd, $p_{3/2}f_{7/2}$
Utsuno et al., PRC 64, 011301 (2001)

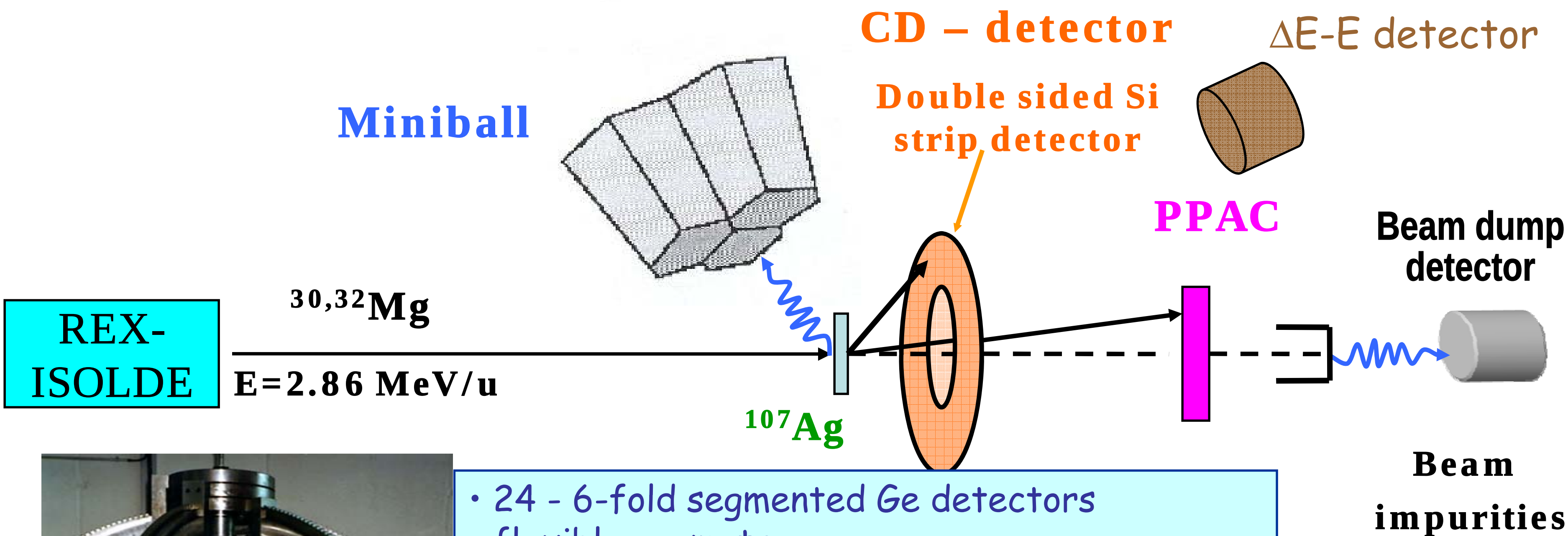
SM,full sd-pf space
Nummela et al., PRC 63, 044316 (2001)

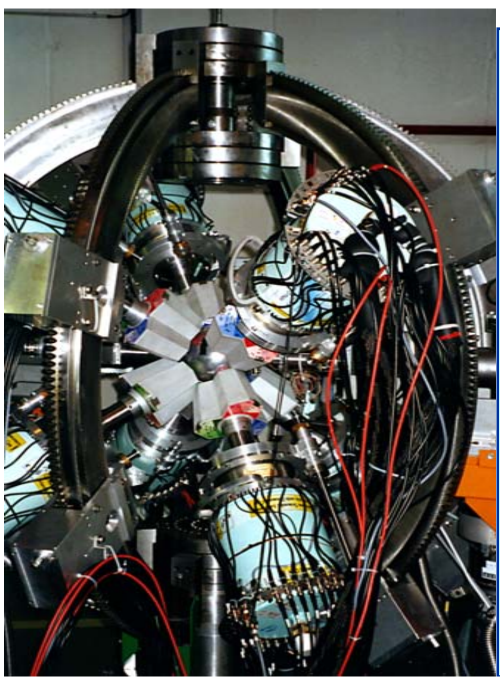
USD, sd-shell only
Wildenthal et al., PRC 28, 1343 (1983)

G Neyens et al, PRL 94, 022501 (2005)

Collective properties studied by Coulomb excitation

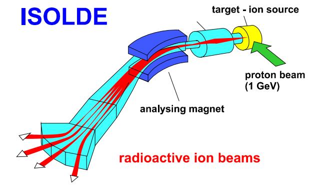


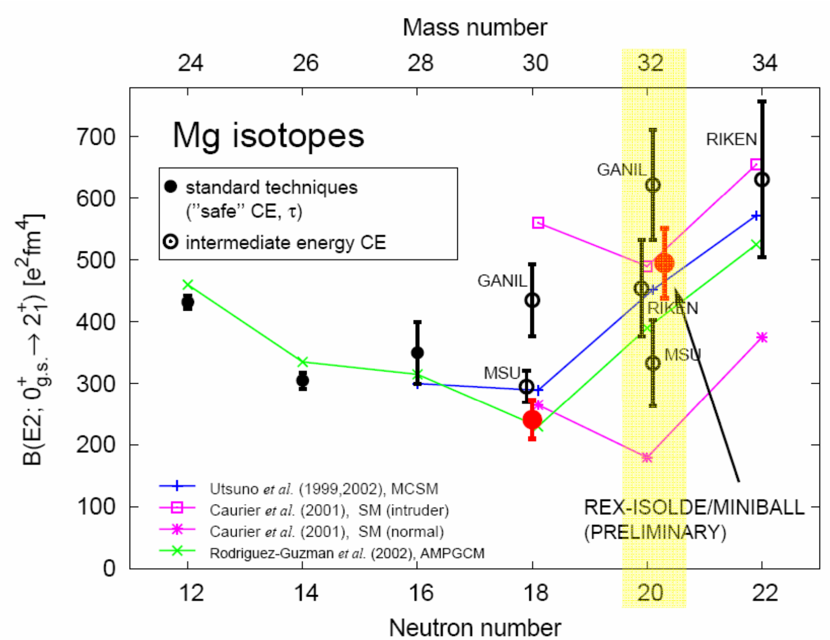




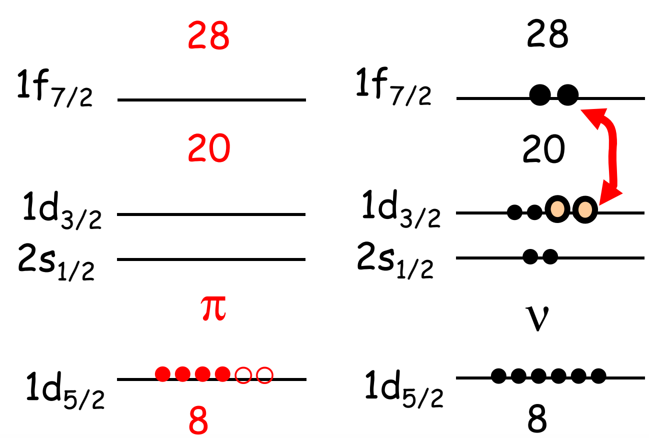
- 24 - 6-fold segmented Ge detectors
- flexible geometry
- $\varepsilon_{full\ energy}$(@ 1.33 MeV) ≈ 7 %
- fully digital electronics + pulse shape analysis (PSA)
- electronic segmentation and PSA: 50-100 fold increase in granularity
  - r from central core
  - ϕ from induced charge in neighboring segments
- low-multiplicity γ-ray experiments with weak exotic beams

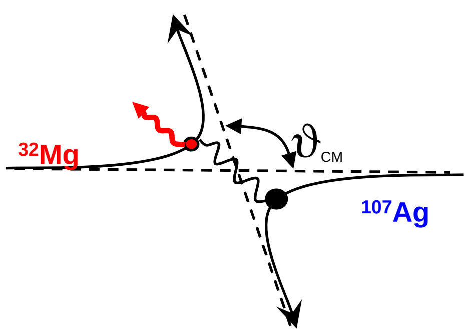
Coulomb excitation of $^{30,32}Mg$

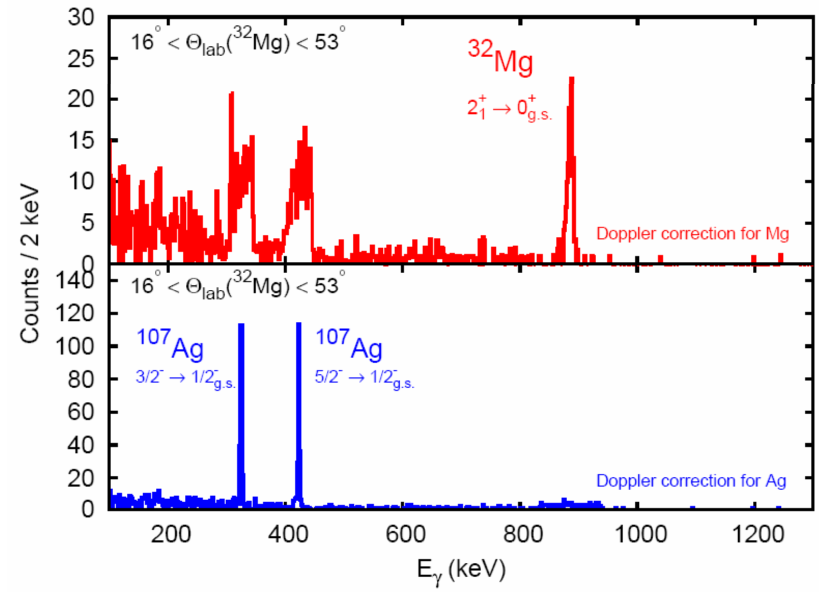




$^{32}Mg = 12\ \pi + 20\ \nu$

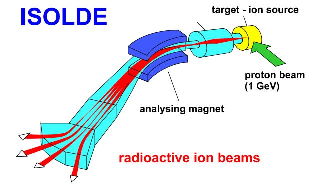




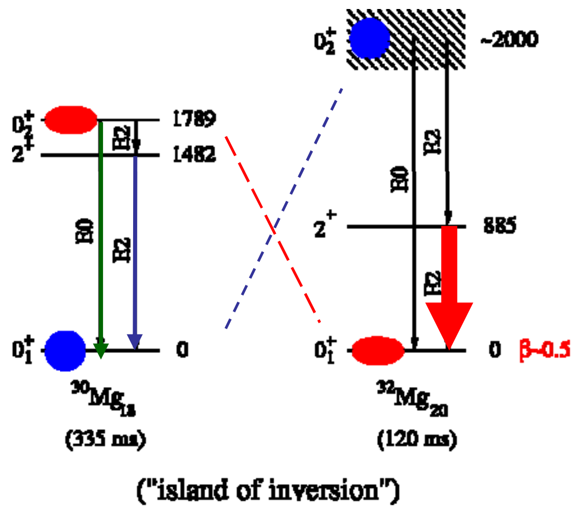


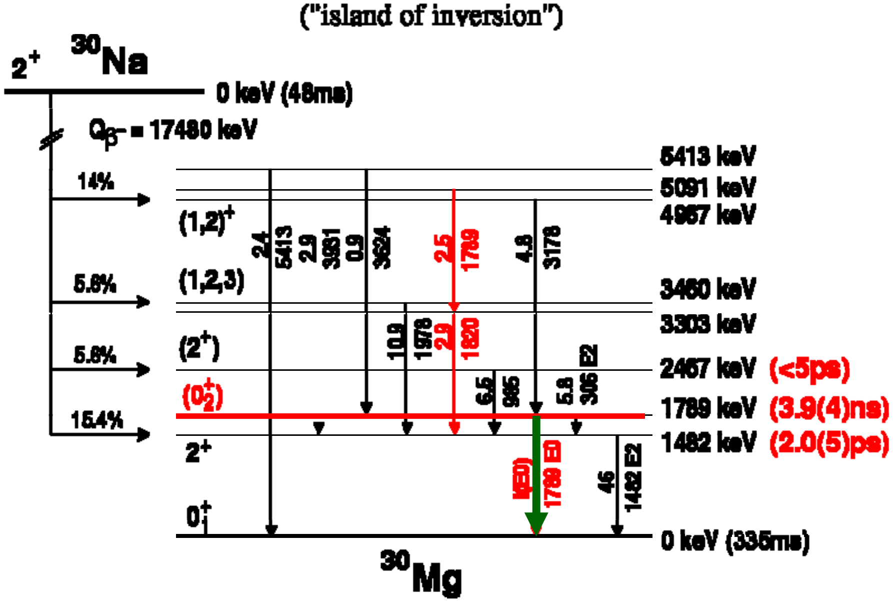
Heiko Scheit, Oliver Niedermaier, PRL 94 172501 (2005) + ISOLDE Workshop 2005-2006

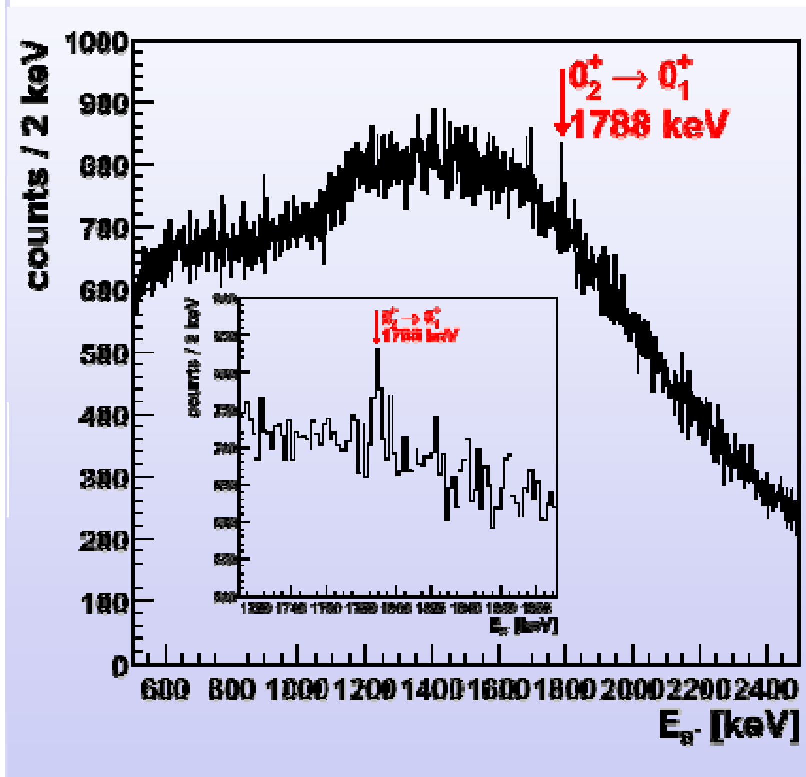
Decay studies @ ISOLDE



335 (62) E0 counts measured
in 143 h of beamtime (7 days)





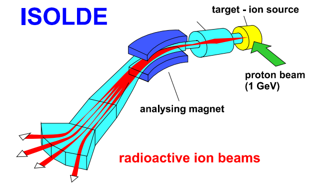


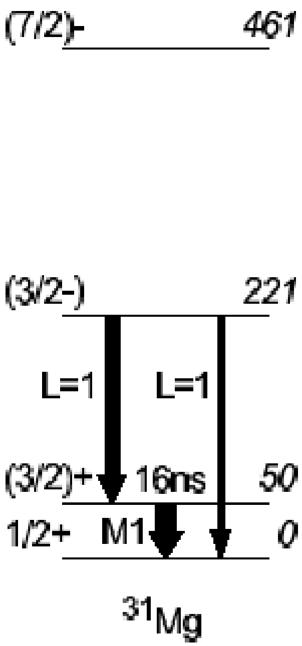
→ $\rho^2(E0) = 5.7(1.2) * 10^{-3}$
→ indicates weak mixing

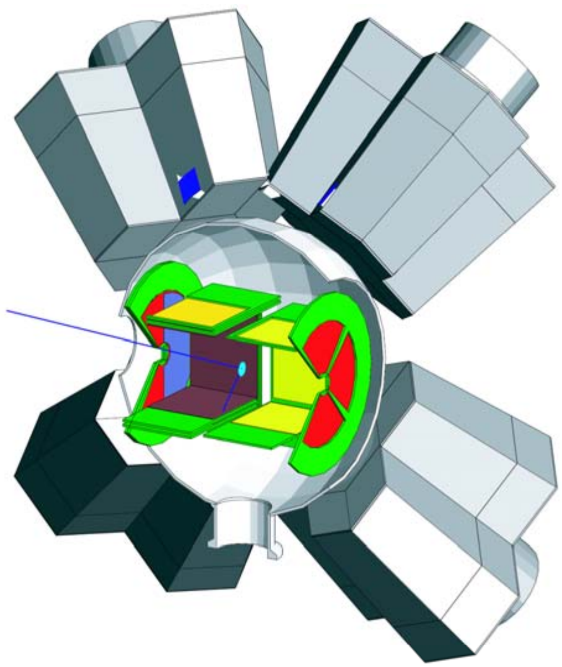
Wolfgang Schwerdtfeger, LMU Munich

previous IS414 results: H. Mach et al.

A new tool: transfer reactions



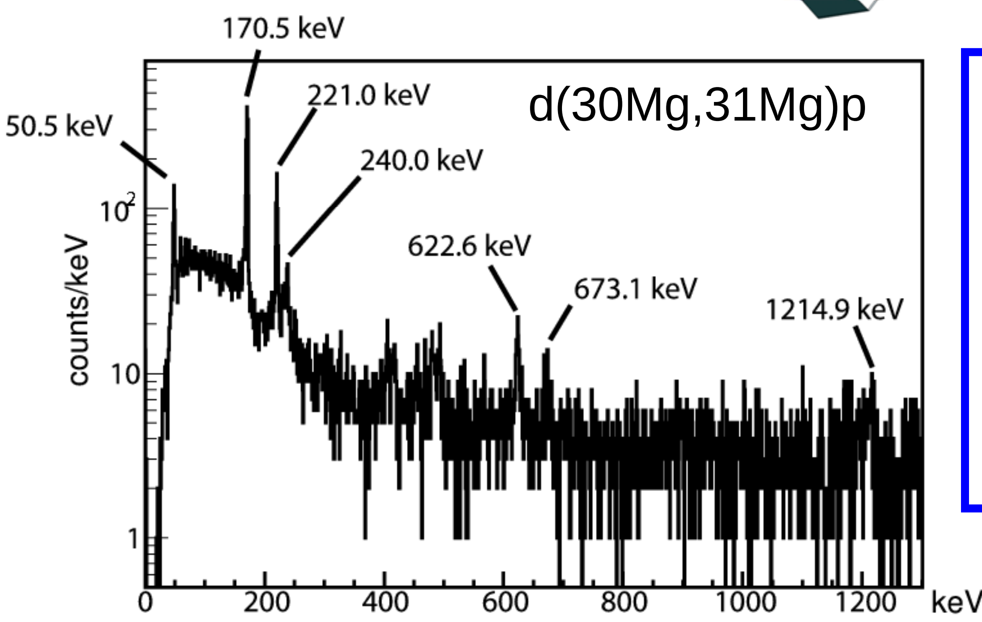




Also applied in the light mass region
See e.g.
$^{9}Li+^{2}H \rightarrow t+^{8}Li^{*}$

H.B.Jeppesen *et al*. Nucl. phys. **A748** (2005) 374

H.B.Jeppesen *et al*. Phys. Lett. **B635** (2006) 17

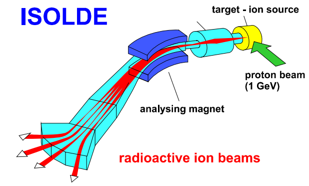


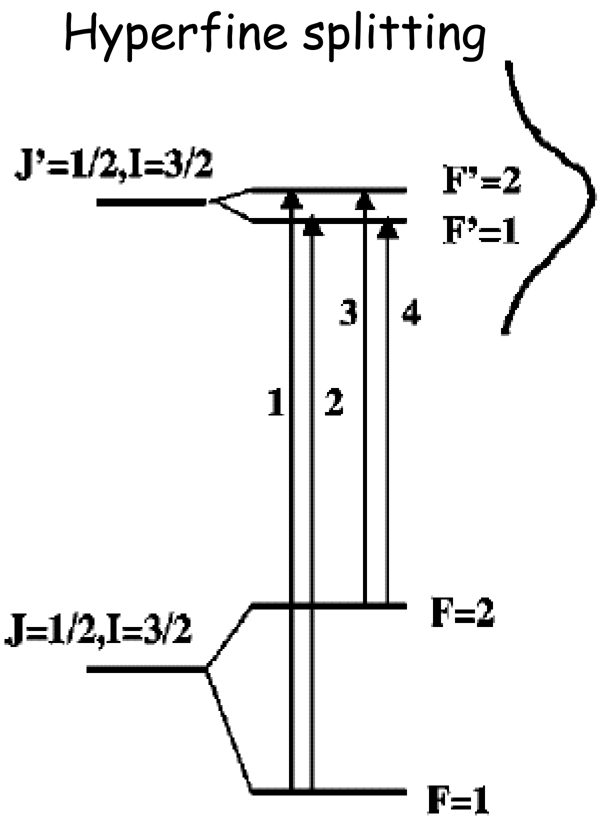
New proposal:

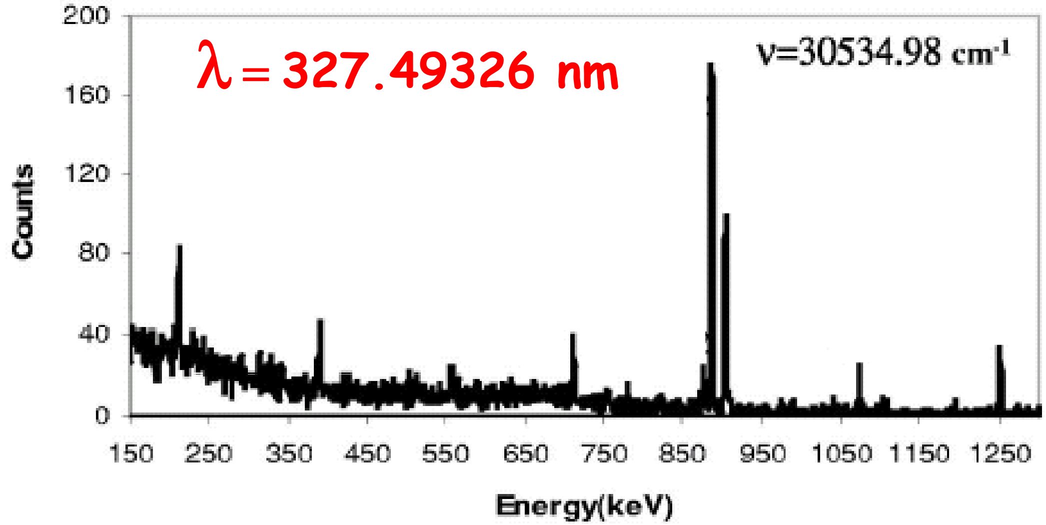
two-neutron transfer
^{3}H (^{30}Mg, ^{32}Mg) ^{1}H @ 2 MeV/u
Tritium loaded Titanium foil
48 mg/cm2 3H / 450 mg/cm2 Ti
activity: 10 GBq

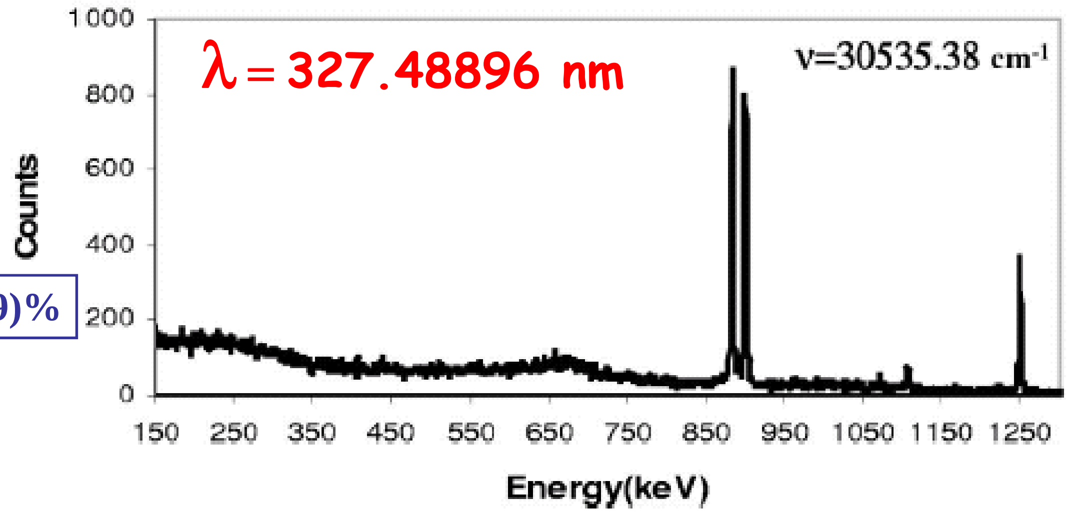
Courtesy Vinzenz Bildstein

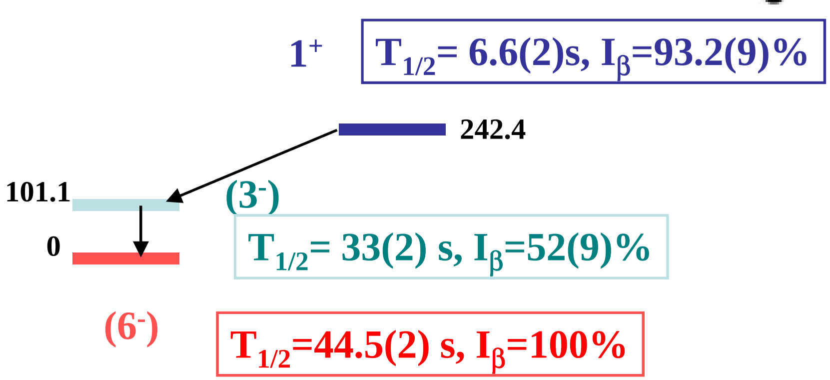
The n-rich Ni region: Isomeric beams





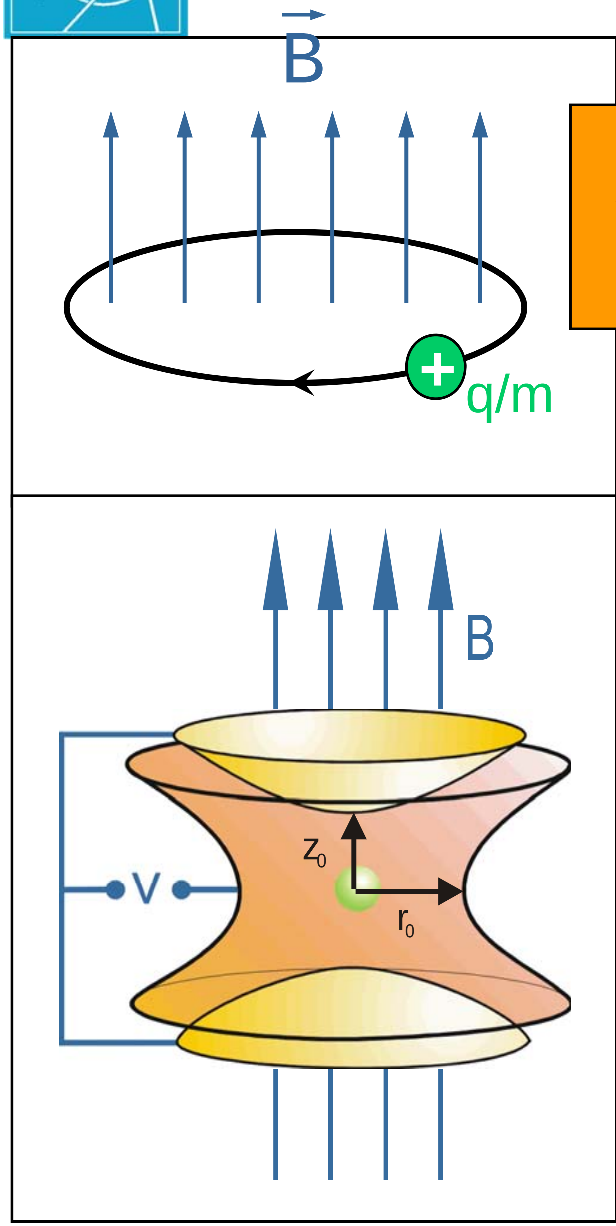






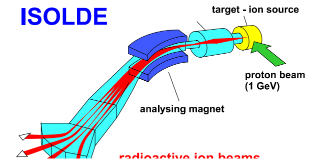
Three β-decaying states in ^{70}Cu

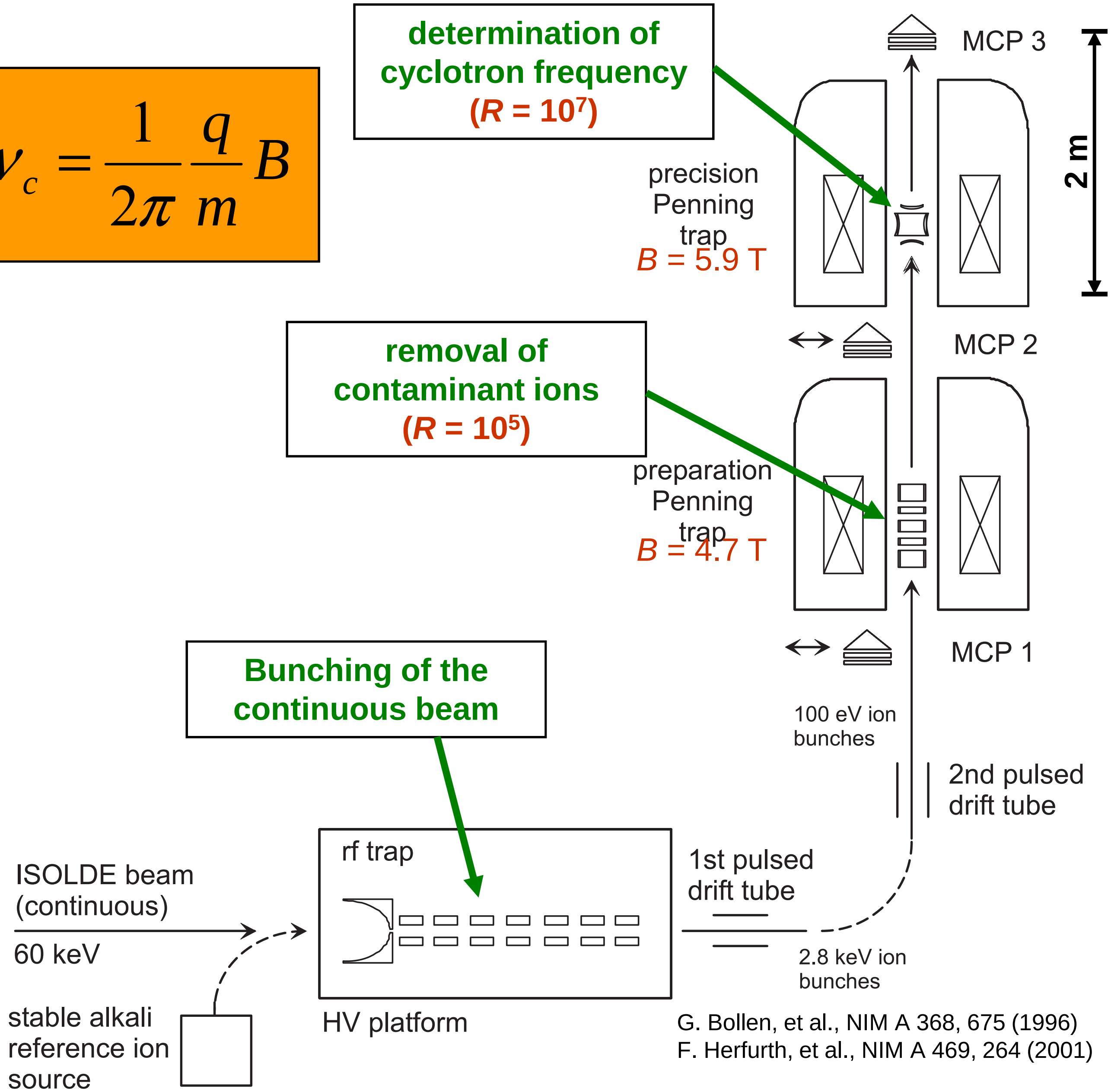
ISOLTRAP



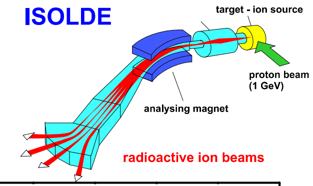
A. Herlert

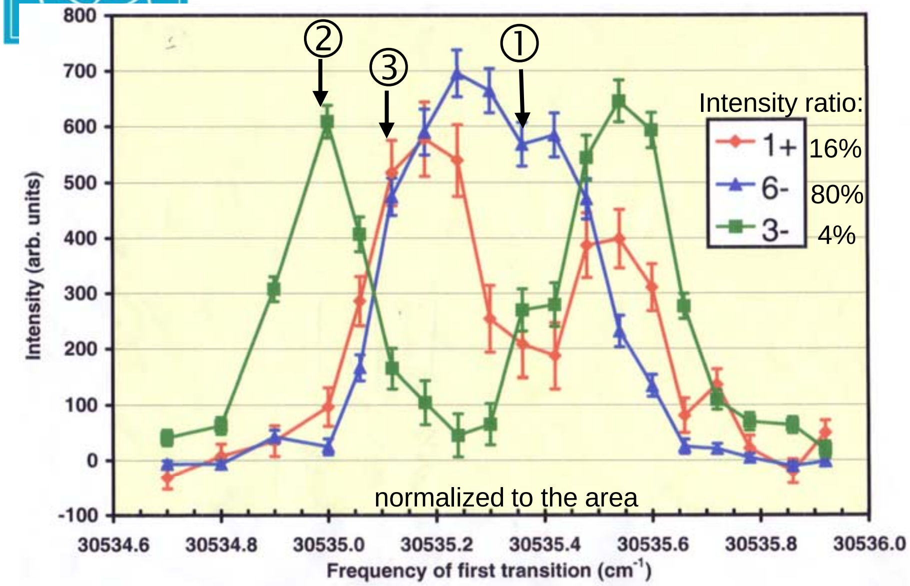
$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$

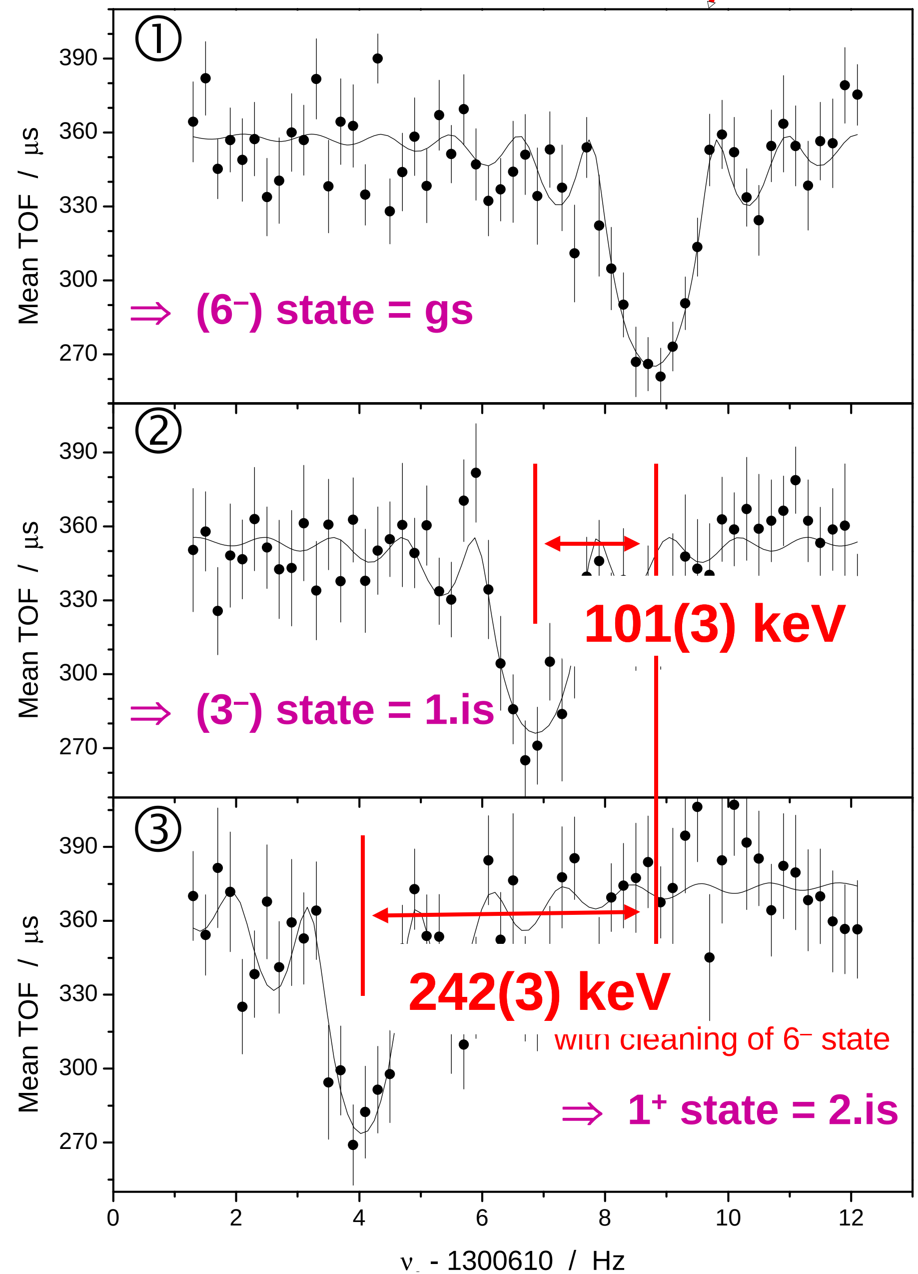




Combination of β–γ spectroscopy, laser ionization and mass measurements







$$\omega_c = \frac{q}{m} \cdot B$$

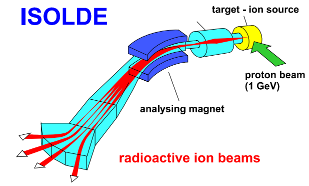
Unambiguous state assignment!

ME of ground state is 240 keV higher than literature value!

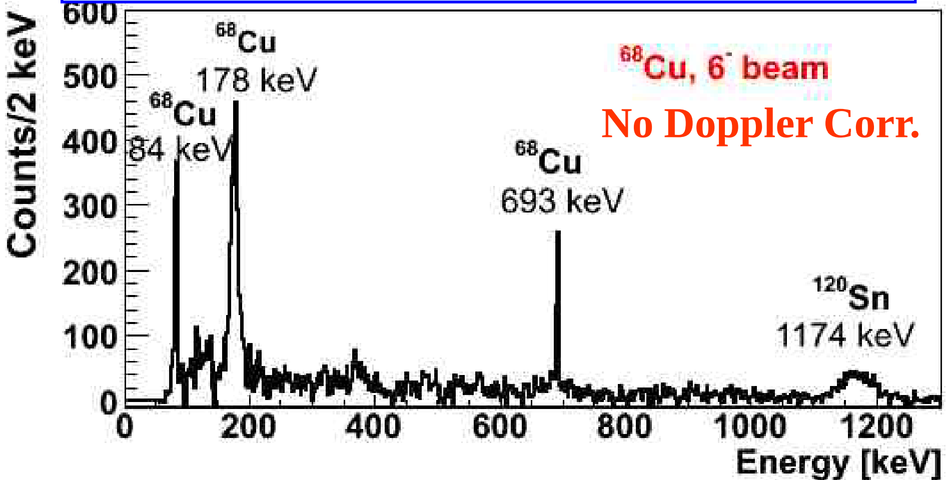
Excellent agreement with decay studies.

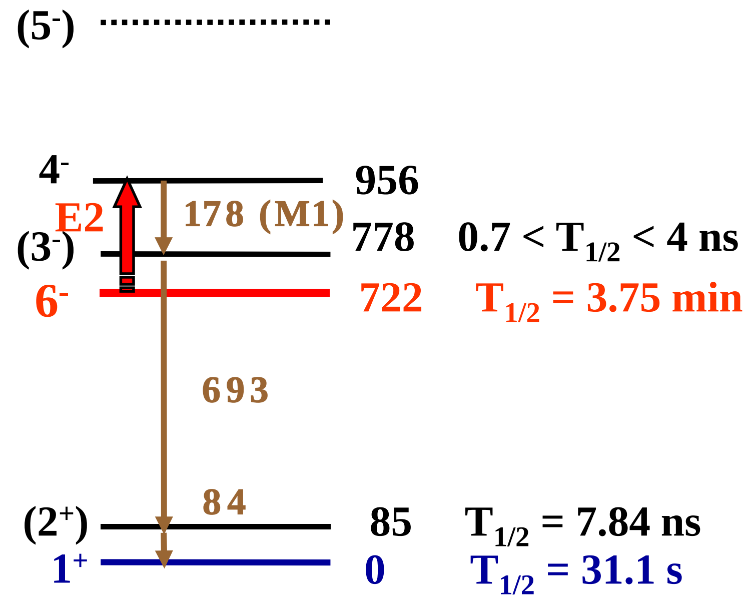
$R \approx 1 \cdot 10^{-7}$

Post-accelerated isomeric beams
Coulomb excitation of $^{68,70}Cu$

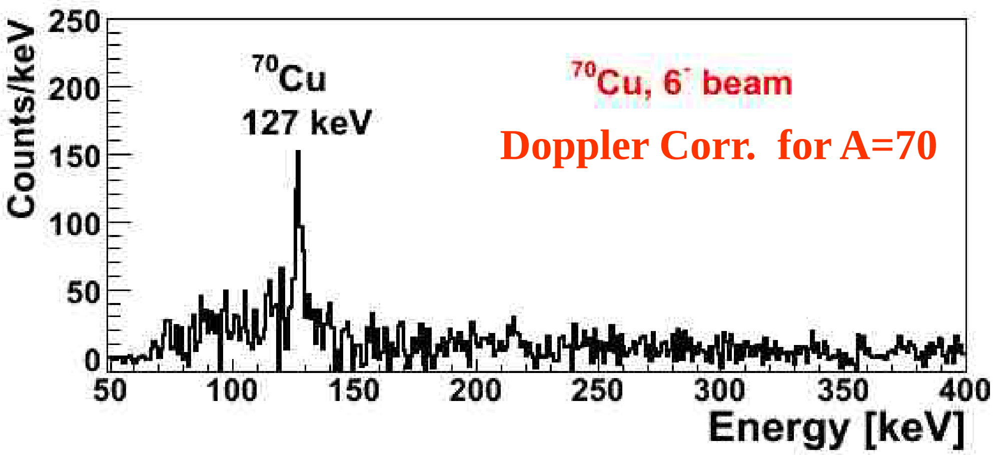


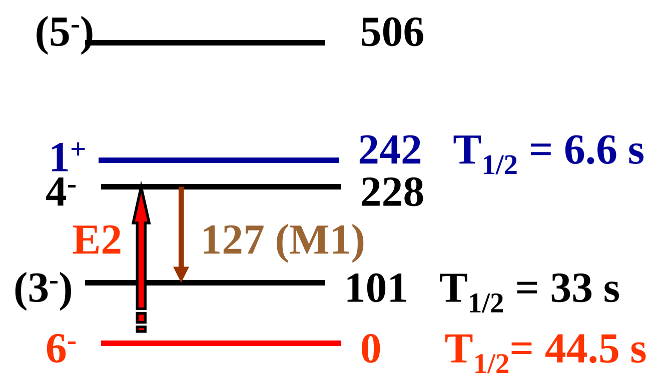
➤ $^{68,m}Cu$ (2.83 MeV/u) @ ^{120}Sn (2.3 mg/cm^2)





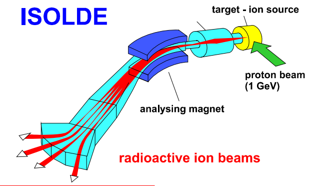
➤ ^{70}Cu (2.83 MeV/u) @ ^{120}Sn (2.3 mg/cm^2)



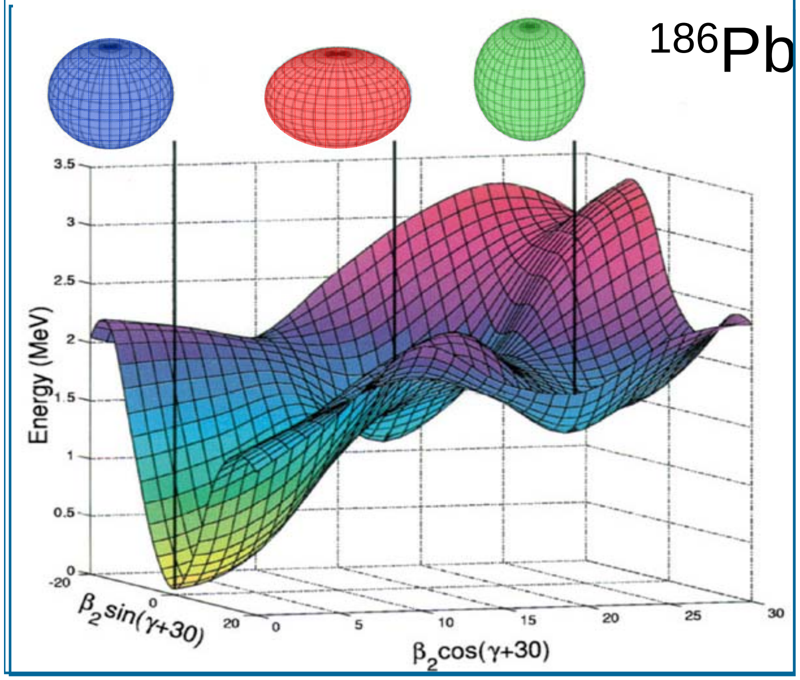


I Stefanescu et al, PRL 98 (2007) 122701

Shape coexistence in the Pb region

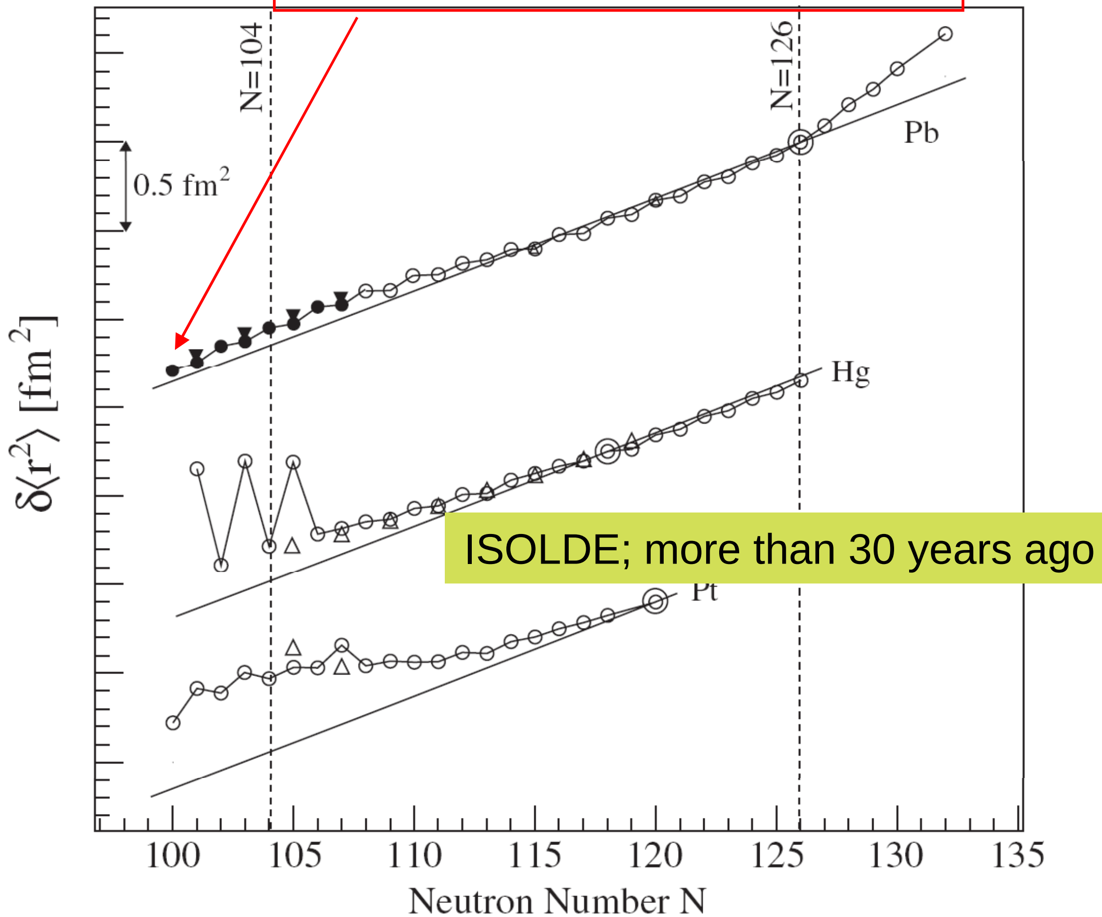


A.Andreyev et al. Nature, 405, 430 (2000)

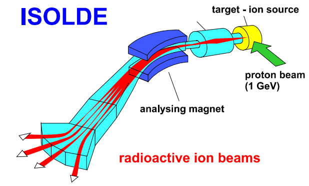


Nilsson-Strutinsky

^{182}Pb: $T_{1/2}$ 55 ms 1 count/min

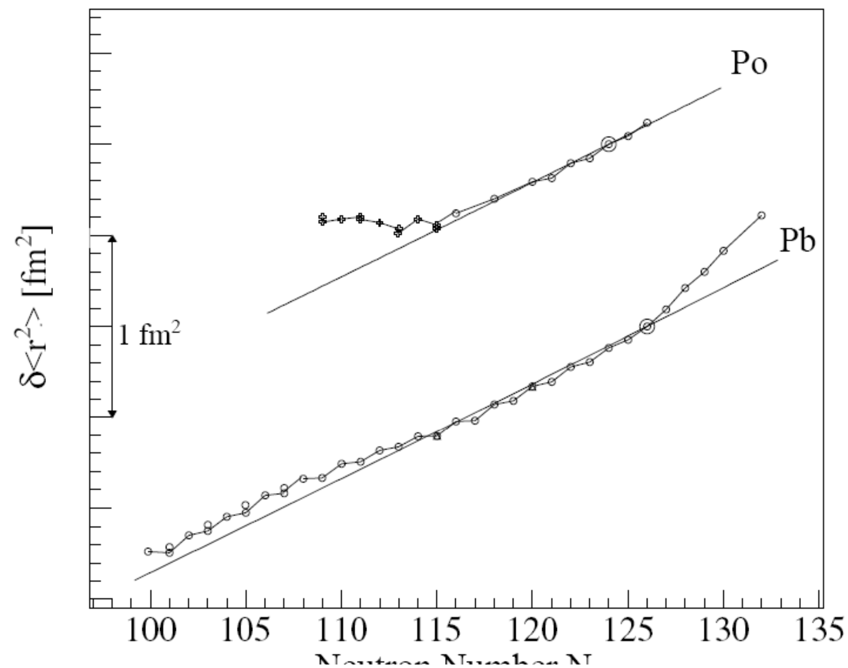


Resonant Laser Ionization
H. De Witte et al. PRL **98,** 112502 (2007)

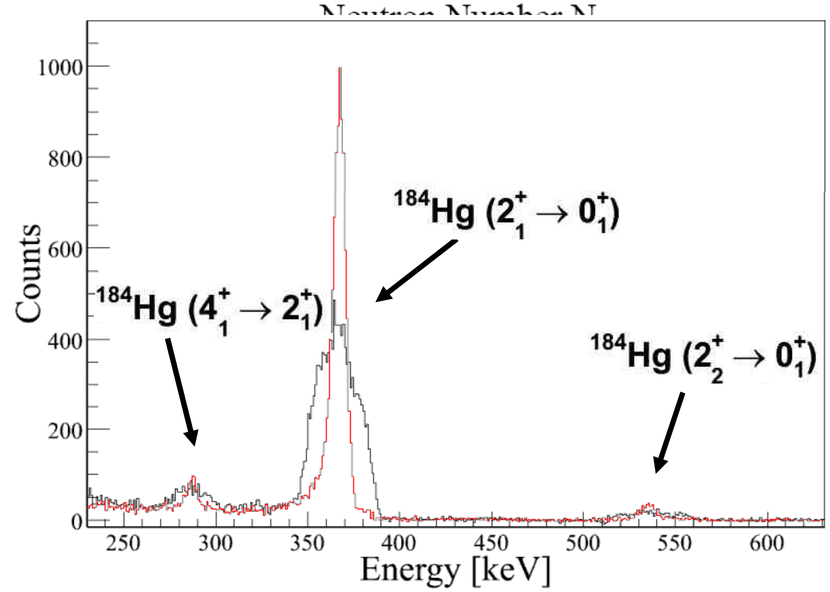


More evidence

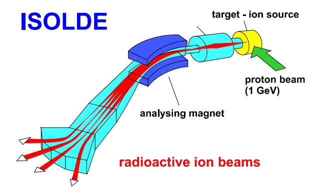
Resonant Laser Ionization of Po isotopes
T. Cociolis et al., preliminary results



Coulomb excitation of ^{184,186,188}Hg isotopes
N. Bree, A.Petts et al., preliminary results



Solid-state physics



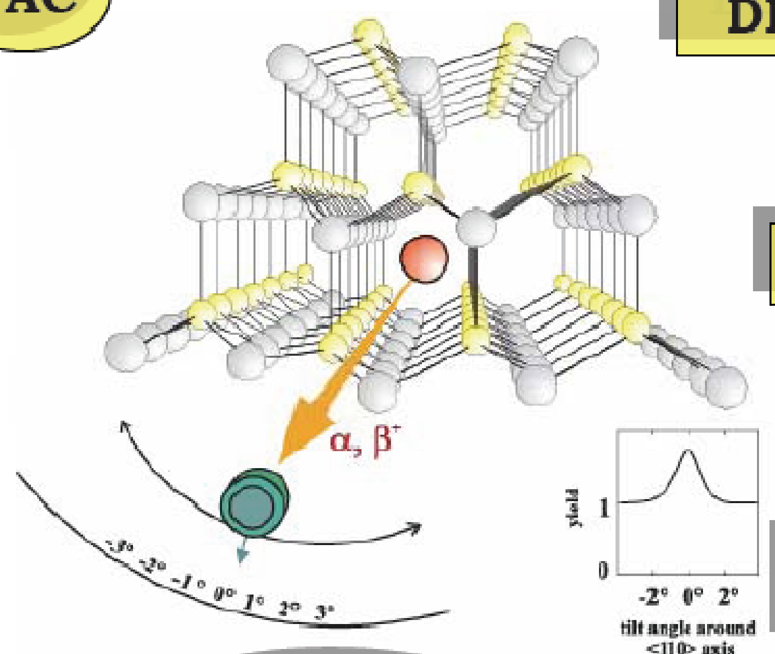
Channeling
Blocking

PAC

DLTS

NO

Diffusion



PL

ESR

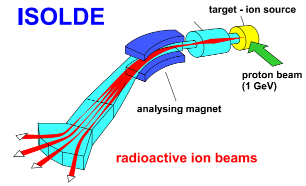
Mössbauer

SOLID STATE PHYSICS at ISOLDE

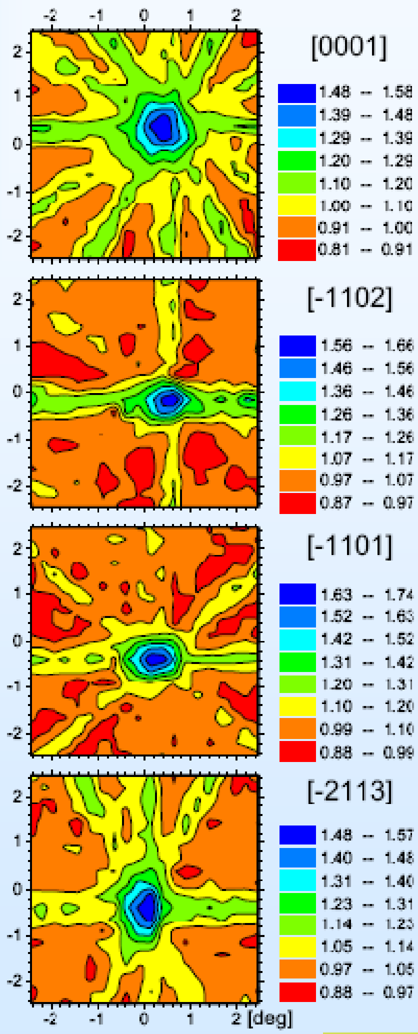
- Semiconductor
- Surface
- Bio, Molecular
- Magnetic materials
- Metals
- Superconductors

Doris Forkel-Wirth,
Rep. Prod. Phys. 62 (99) 527

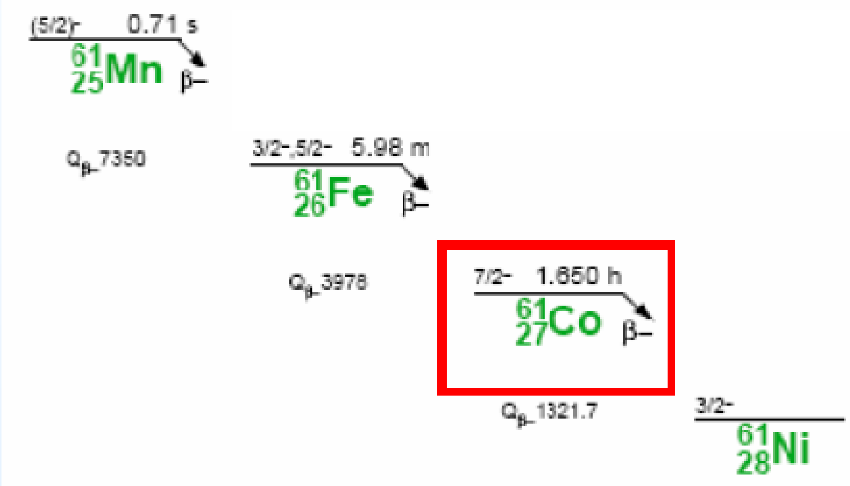
First results from electron emission channeling on-line experiments



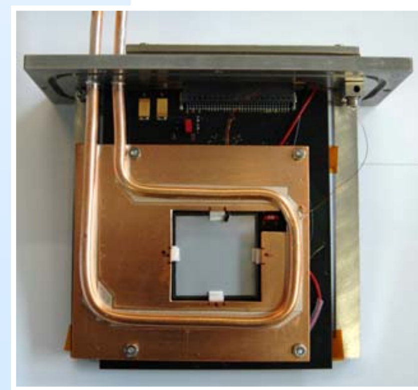
β⁻ emission channeling patterns from ^{61}Co in ZnO



T_A=800°C

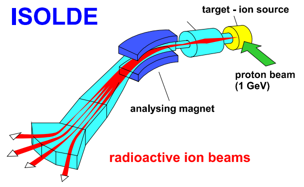


- ^{61}Mn implanted
- wait 25 min
- emission channeling patterns measured from ^{61}Co β⁻ particles
- qualitative result: ^{61}Co on substitutional Zn sites

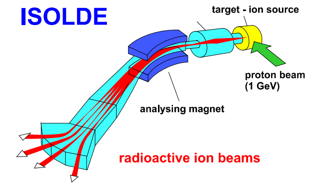


U. Wahl at the ISOLDE Workshop December 2007

A rich basket

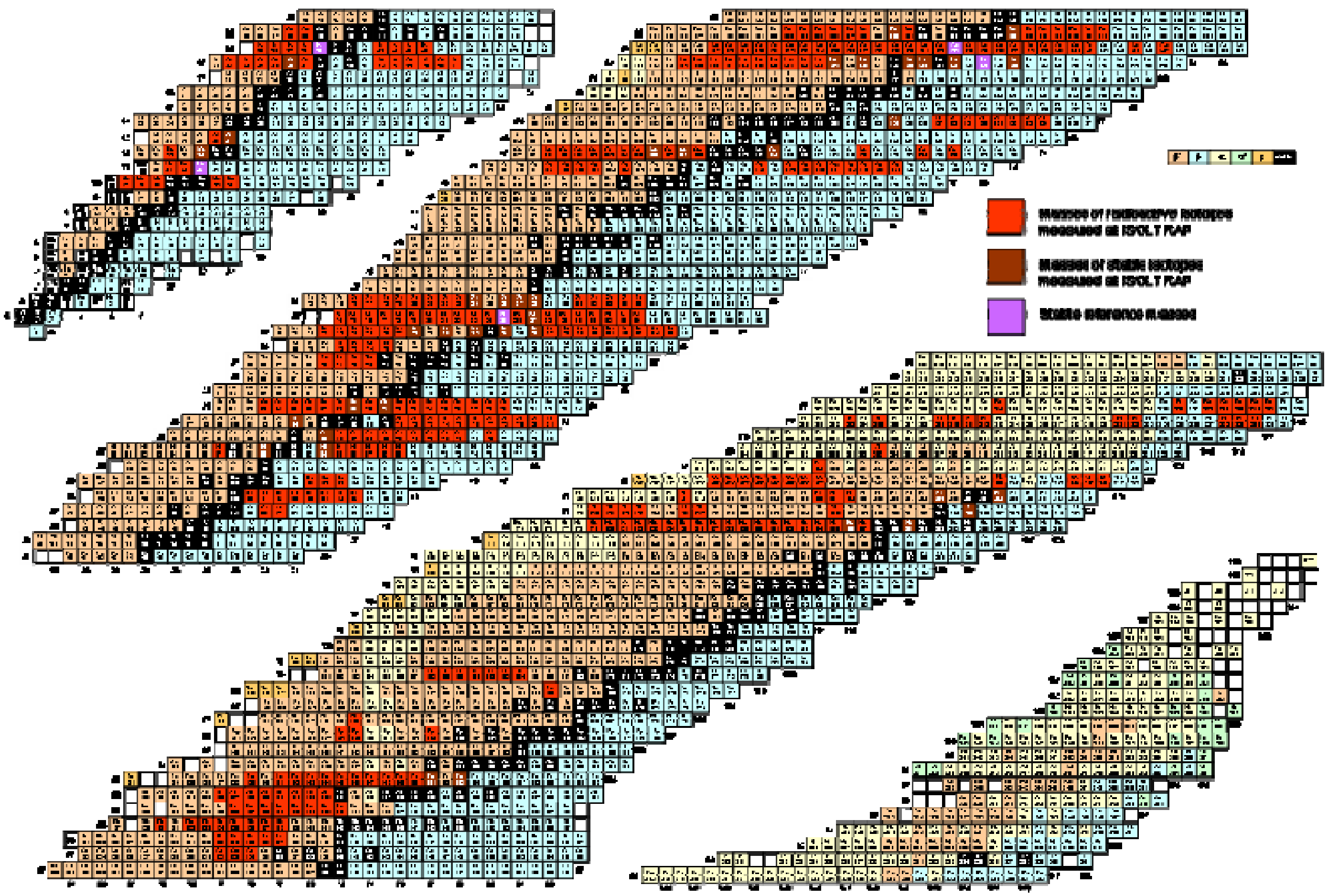


- Mass measurements
- Moments and radii
- Decay studies
- Solid-state studies
- Coulomb excitation
- Elastic scattering
- Transfer reactions



20 years of ISOLTRAP

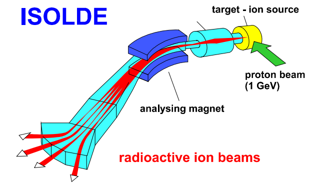
The Masses of Over 300 Isotopes Were Measured by ISOLTRAP with an Uncertainty of 10^{-7} or Better



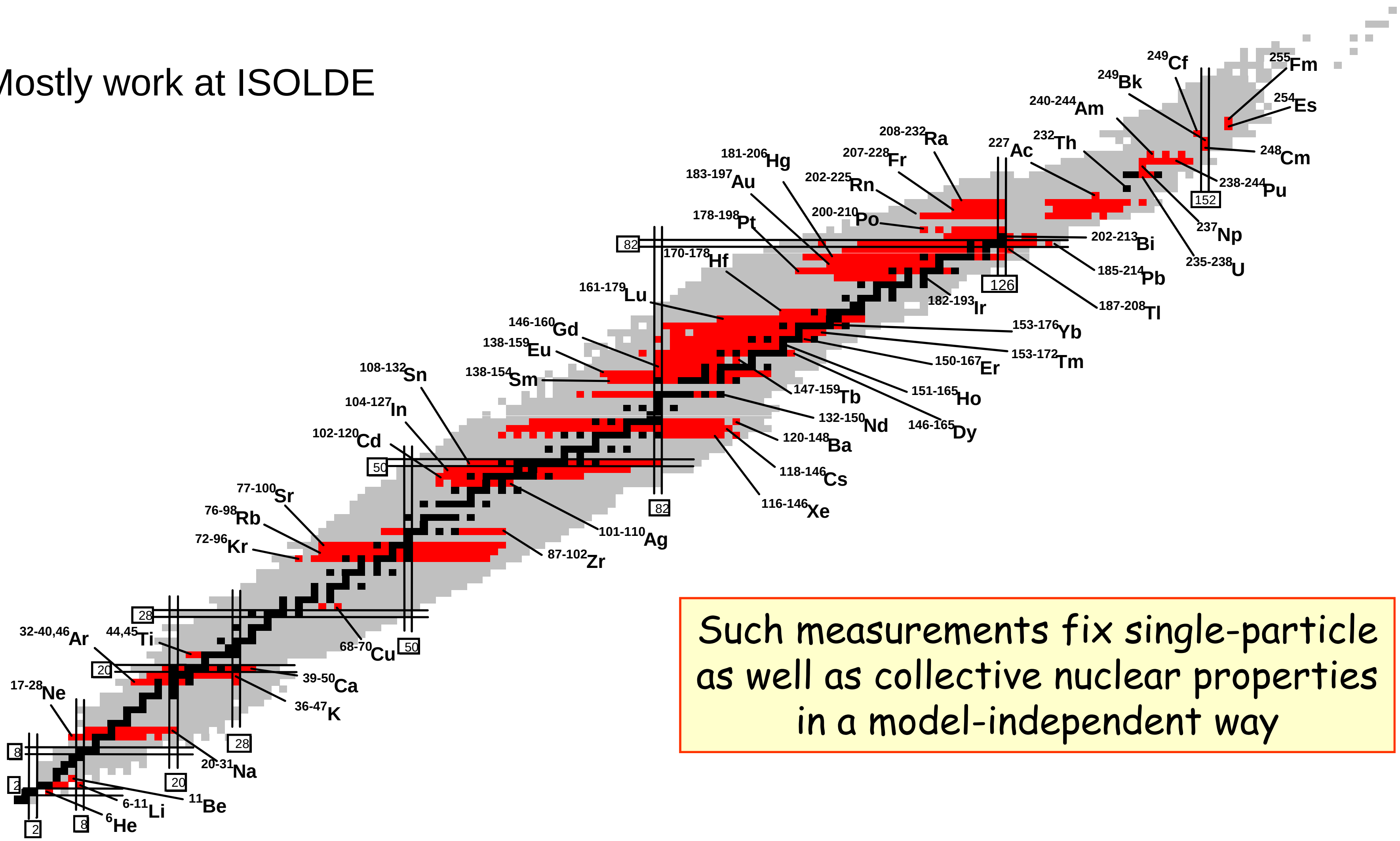
H. Jurgen Kluge at the ISOLDE workshop December 2007

http://isoltrap.web.cern.ch/isoltrap/presentation.html

Laser Spectroscopy in Long Isotopic Chains



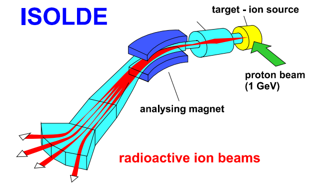
Mostly work at ISOLDE

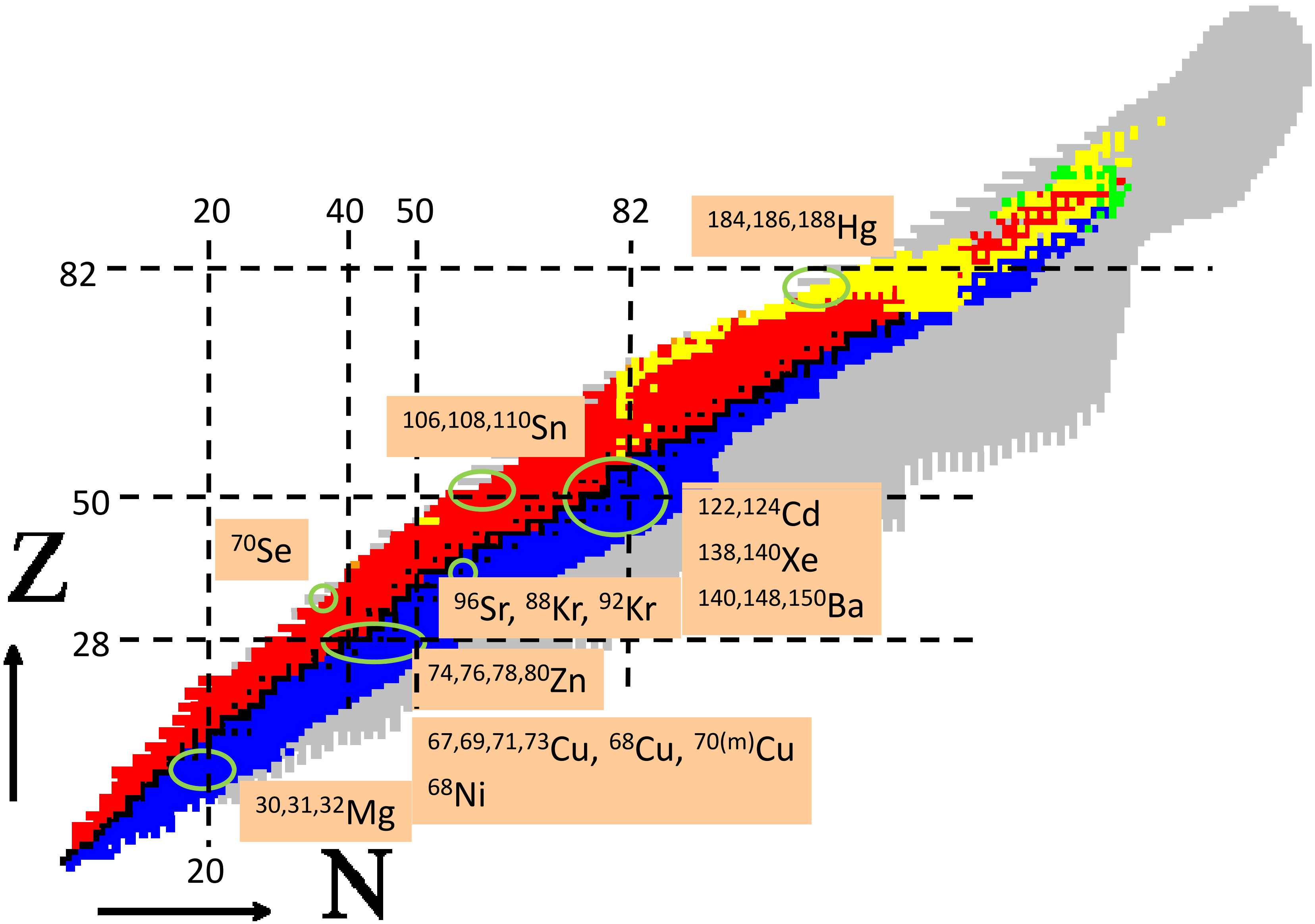


Such measurements fix single-particle as well as collective nuclear properties in a model-independent way

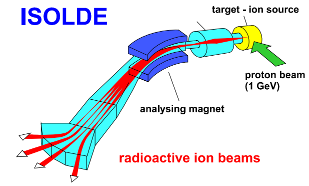
H.-J. Kluge. W. Nörtershäuser, Spectrochimica Acta 2003

The Coulex program



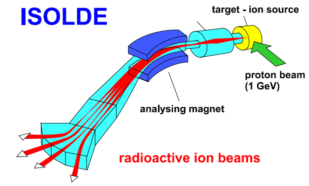


The many lives of ISOLDE



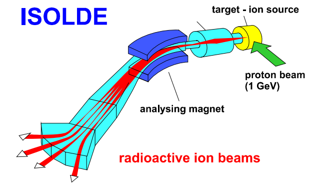
Thanks to

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

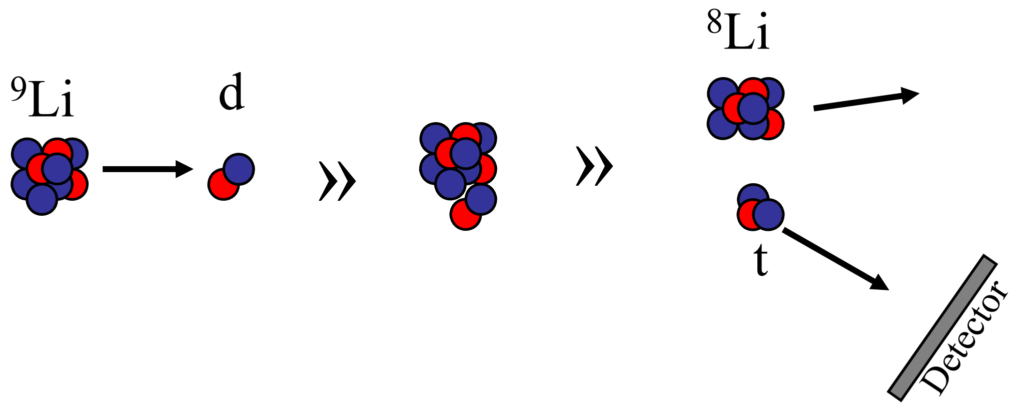


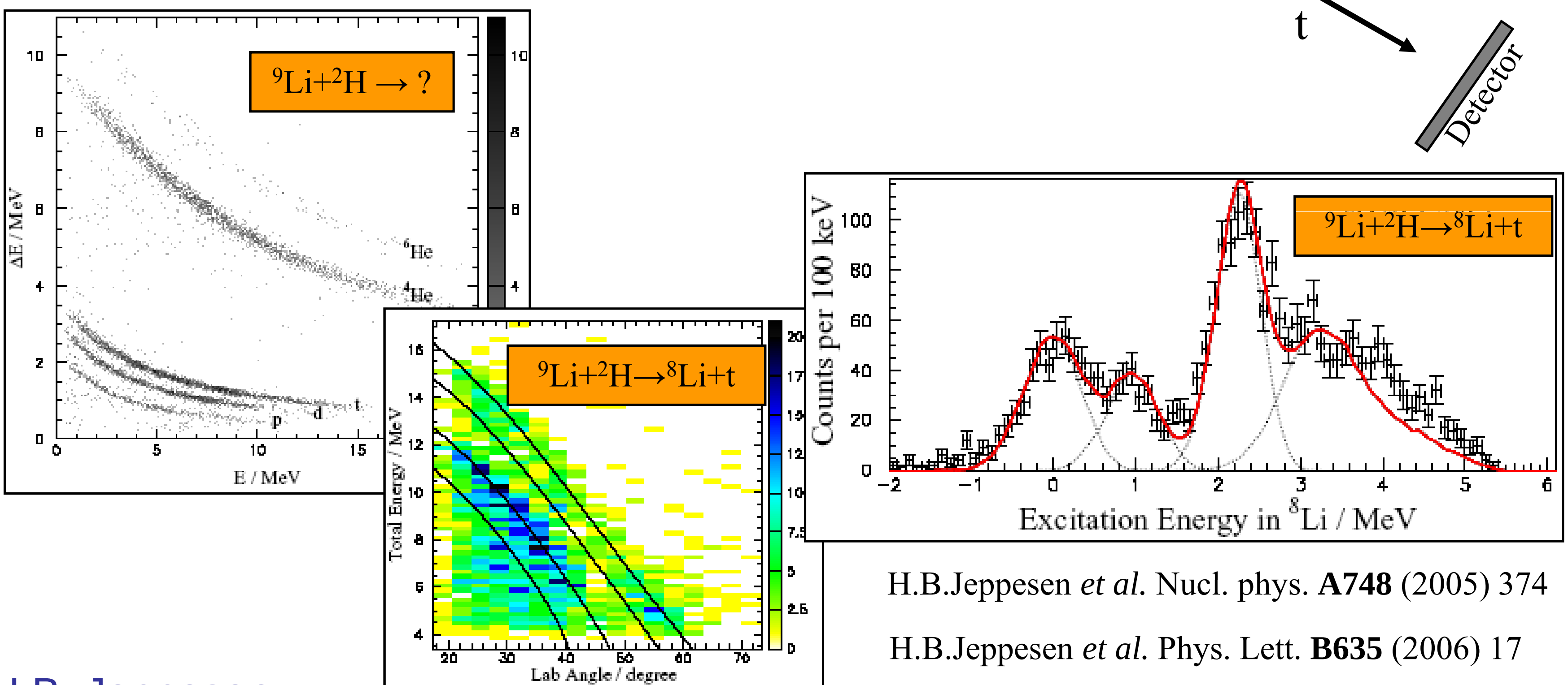
And yet more to come

$^{9}Li+^{2}H \rightarrow t+^{8}Li^{*}$



Example of neutron transfer from ^{9}Li to a deuteron – forming a triton



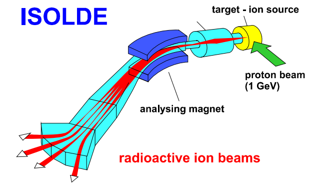


H.B.Jeppesen *et al.* Nucl. phys. **A748** (2005) 374

H.B.Jeppesen *et al.* Phys. Lett. **B635** (2006) 17

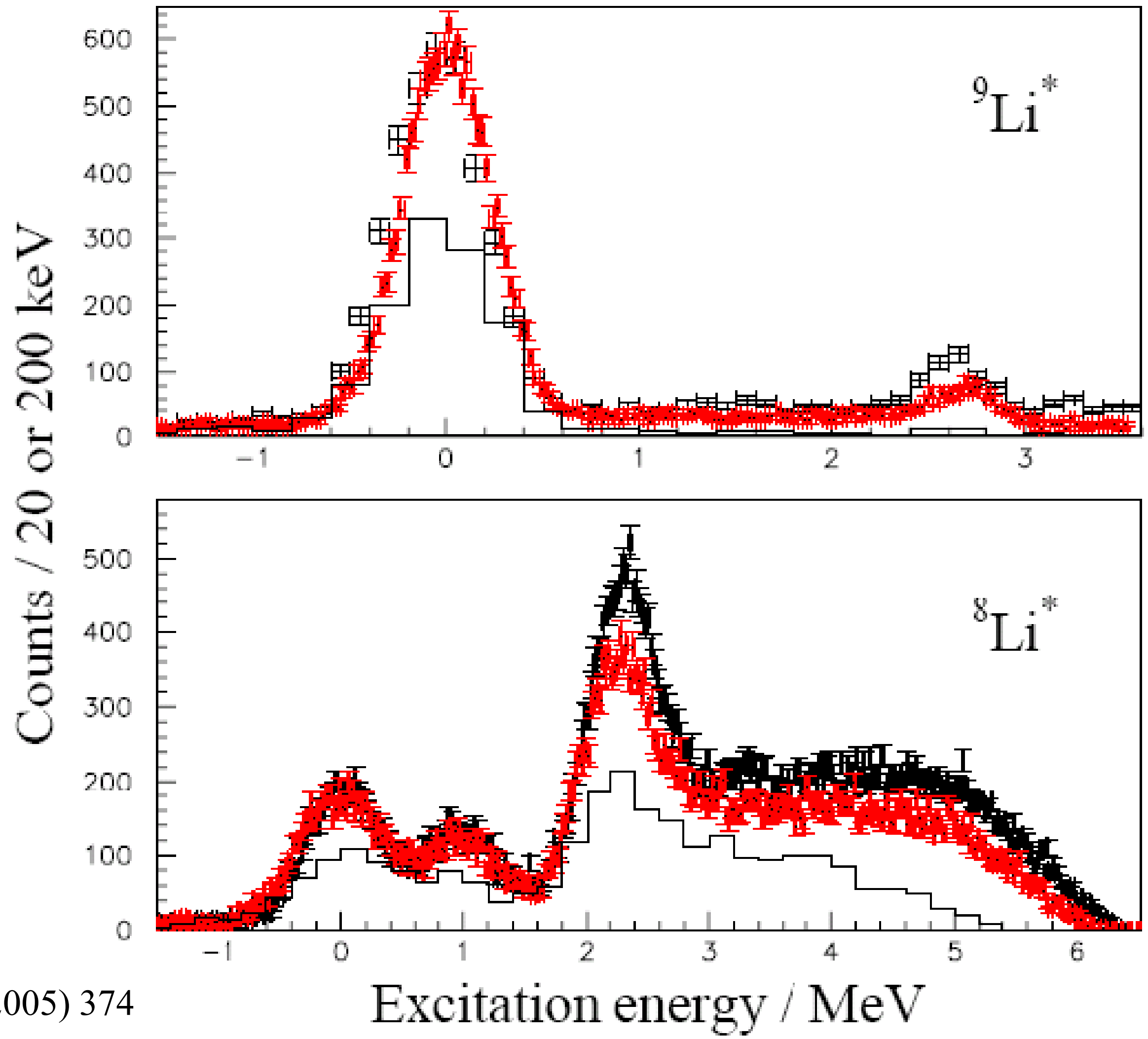
H.B. Jeppesen

$^9Li + ^2H \rightarrow t + ^8Li^*$



First run:
2.2 MeV/u
(histogram)

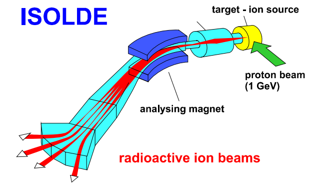
Second run:
2.8 MeV/u
(data points)

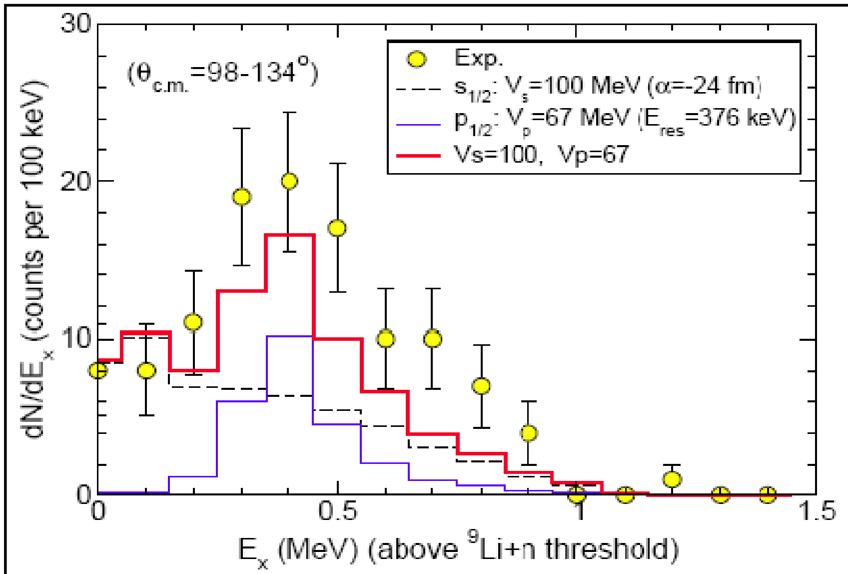


H.B.Jeppesen *et al.* Nucl. phys. **A748** (2005) 374

H.B.Jeppesen *et al.* Phys. Lett. **B635** (2006) 17

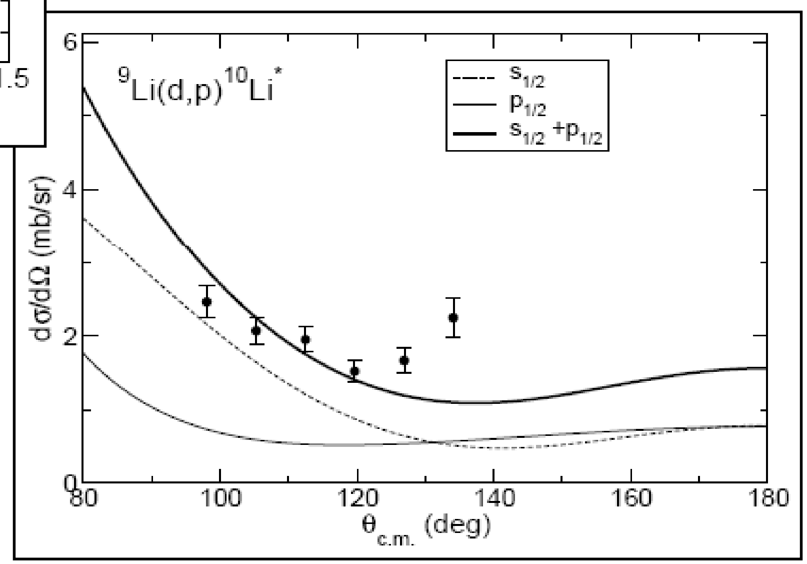
^{10}Li, comparison to theory





CCBA calculations

- Performed by A.M. Moro
- Only potential-depth varied (2 free parameters)



Conclusion:

Need *s*- and *p*-wave component to describe energy spectrum

H.B.Jeppesen *et al.*, Phys. Lett. **B642** (2006) 449

World scene for tof measurements

facility		driver and energy	repetition rate	n source	n energy range	flight path length
FZK TIT ...	Karlsruhe Tokyo ...	varii in the MeV range	MHz	$^{7}Li(p,n)$ & others	few keV up to 1 MeV monoE above	10s cm
GELINA	EC-JRC Geel	electron linac 150 MeV	800 Hz	photo-n photo-f	10 meV – 20 MeV	10m to 400m
LANSCE	Los Alamos National Laboratory	proton linac 800 MeV	20 Hz	spallation	< 500 keV (DANCE)	20m
n_TOF	CERN	PS 20 GeV	0.4 Hz (average)	spallation	10 meV – 250 MeV (or wider)	200m