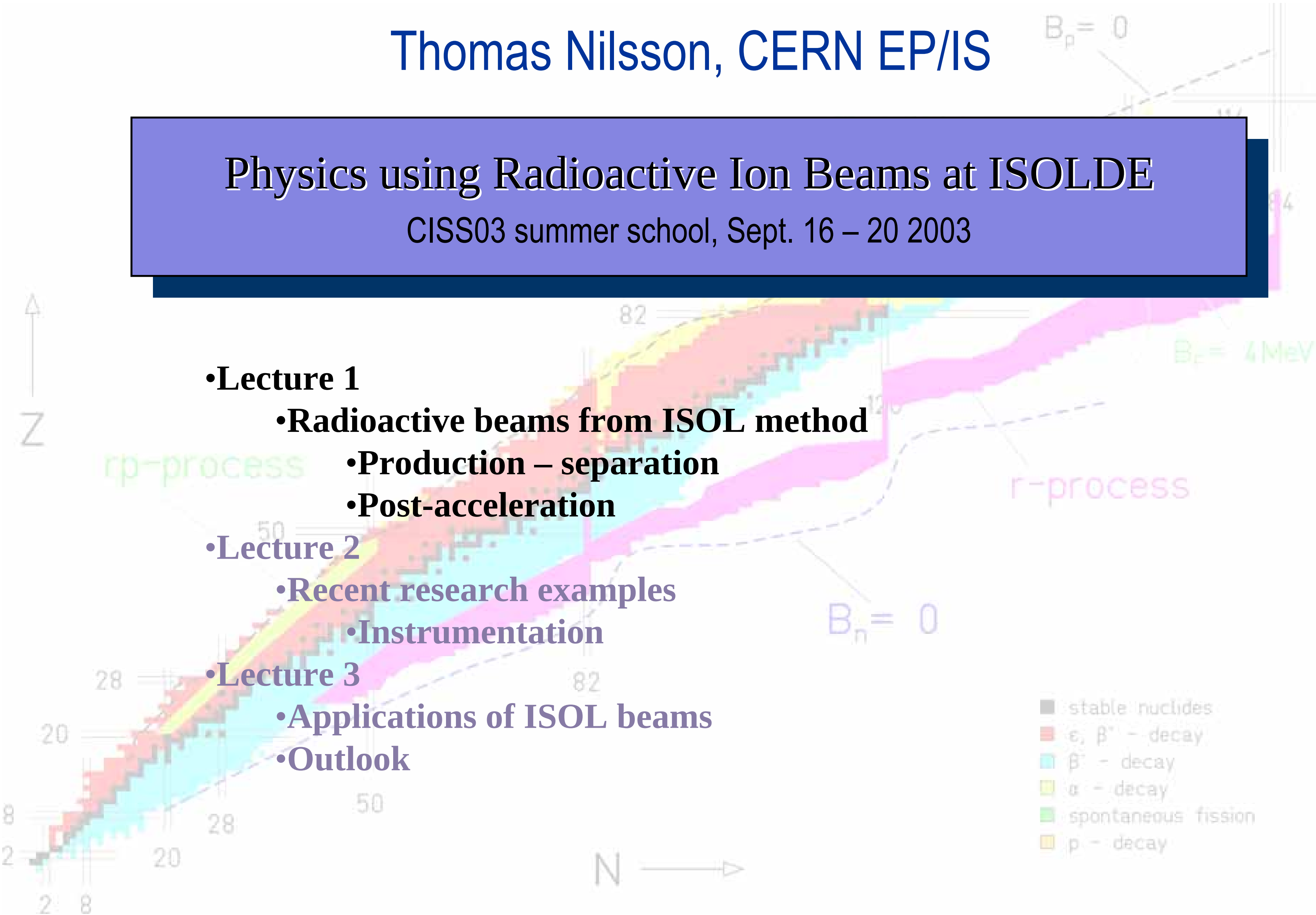
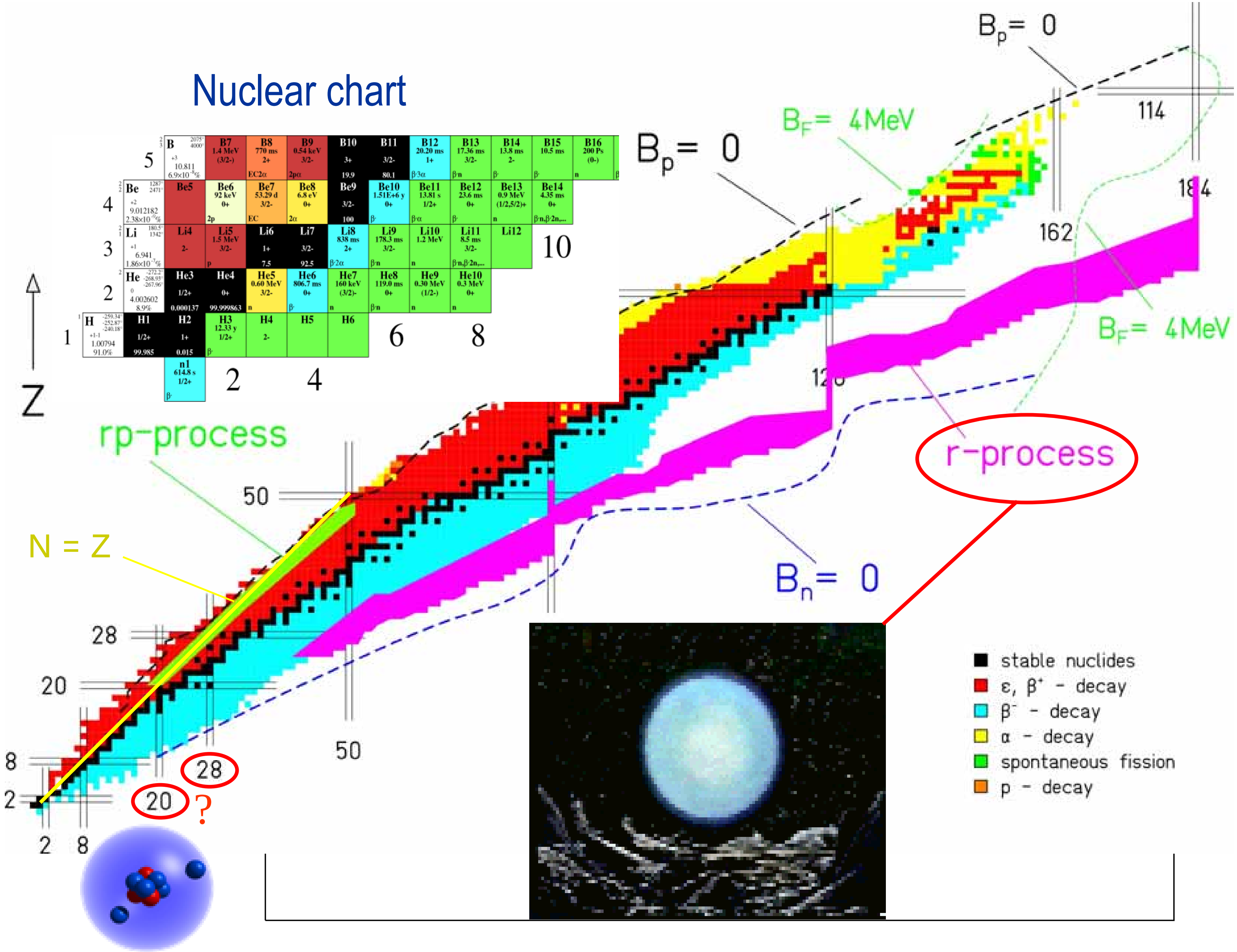
Thomas Nilsson, CERN EP/IS

Physics using Radioactive Ion Beams at ISOLDE

CISS03 summer school, Sept. 16 – 20 2003

- **Lecture 1**
  - **Radioactive beams from ISOL method**
    - **Production – separation**
    - **Post-acceleration**
- **Lecture 2**
  - **Recent research examples**
    - **Instrumentation**
- **Lecture 3**
  - **Applications of ISOL beams**
  - **Outlook**

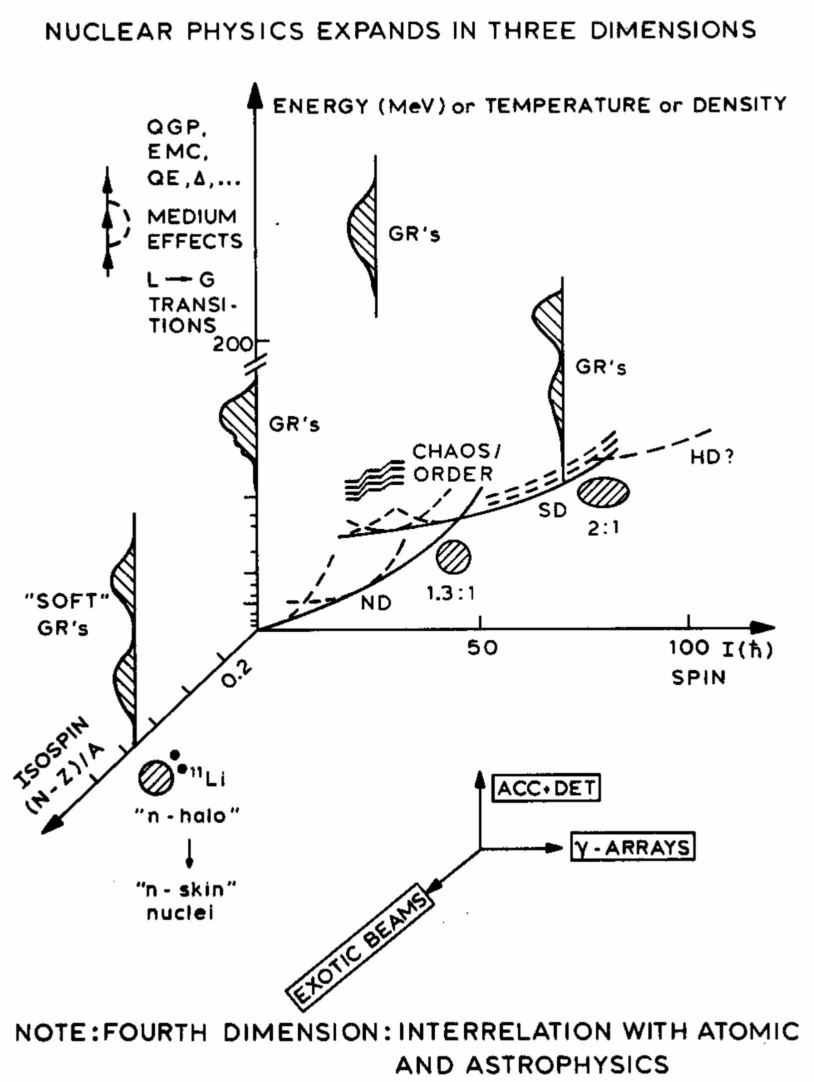




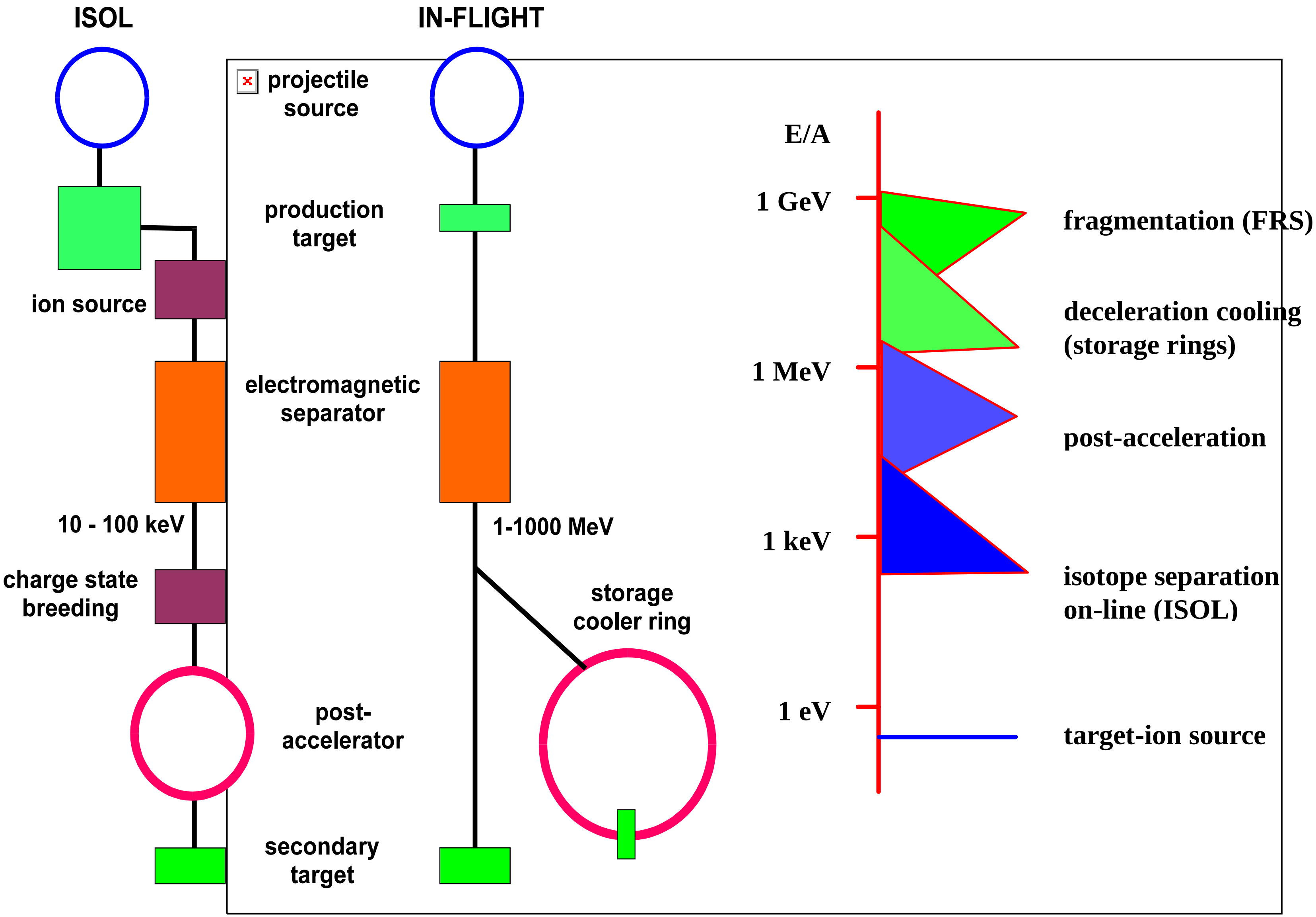
Nuclear chart
Z
rp-process
N = Z
r-process
$B_p = 0$
$B_p = 0$
$B_F = 4MeV$
$B_F = 4MeV$
$B_n = 0$
114
184
162
126
50
50
28
20
8
2
2
8
20
28
?
stable nuclides
ε, β+ - decay
β- - decay
α - decay
spontaneous fission
p - decay

Why Radioactive Ion Beams (RIB)?

- Nuclear structure
  - Additional isospin degree of freedom extreme N/Z ratios
  - Weakening of shell structure
  - Exotic features – clustering, halo
- Decays
  - Structure information from decay
  - Weak interaction probe
  - Tailored probes in applications
- Astrophysics
  - r-, rp-process
  - Solar processes

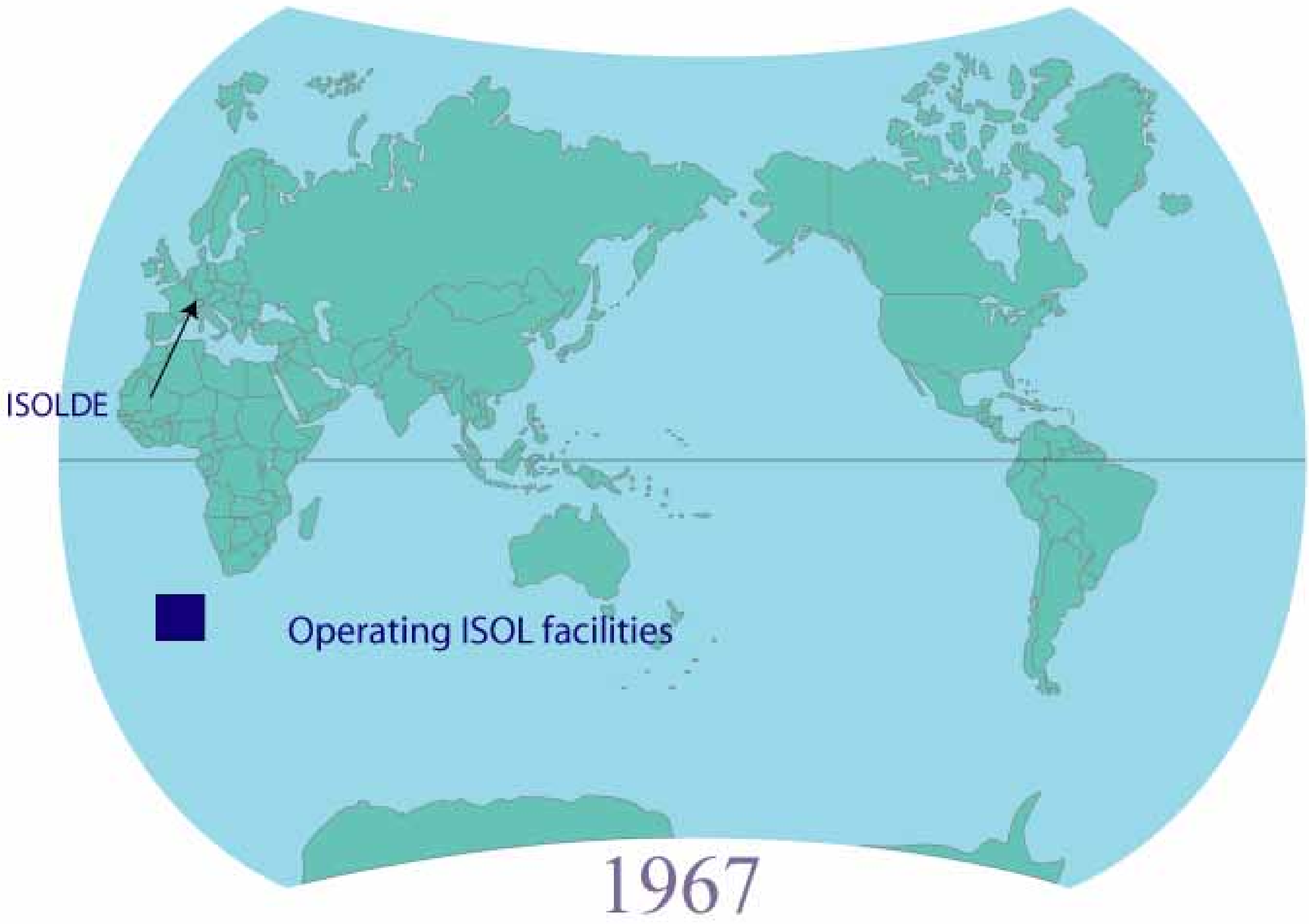


Radioactive beams – production and separation

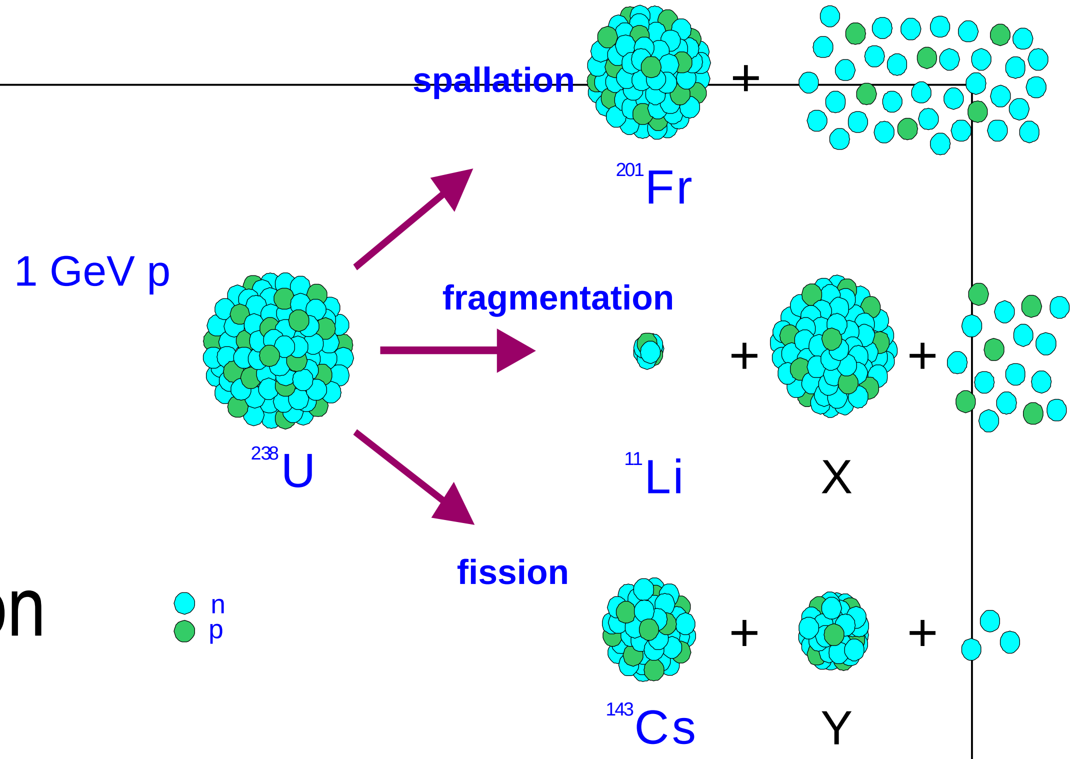


World Wide Radioactive Beam Facilities

2003

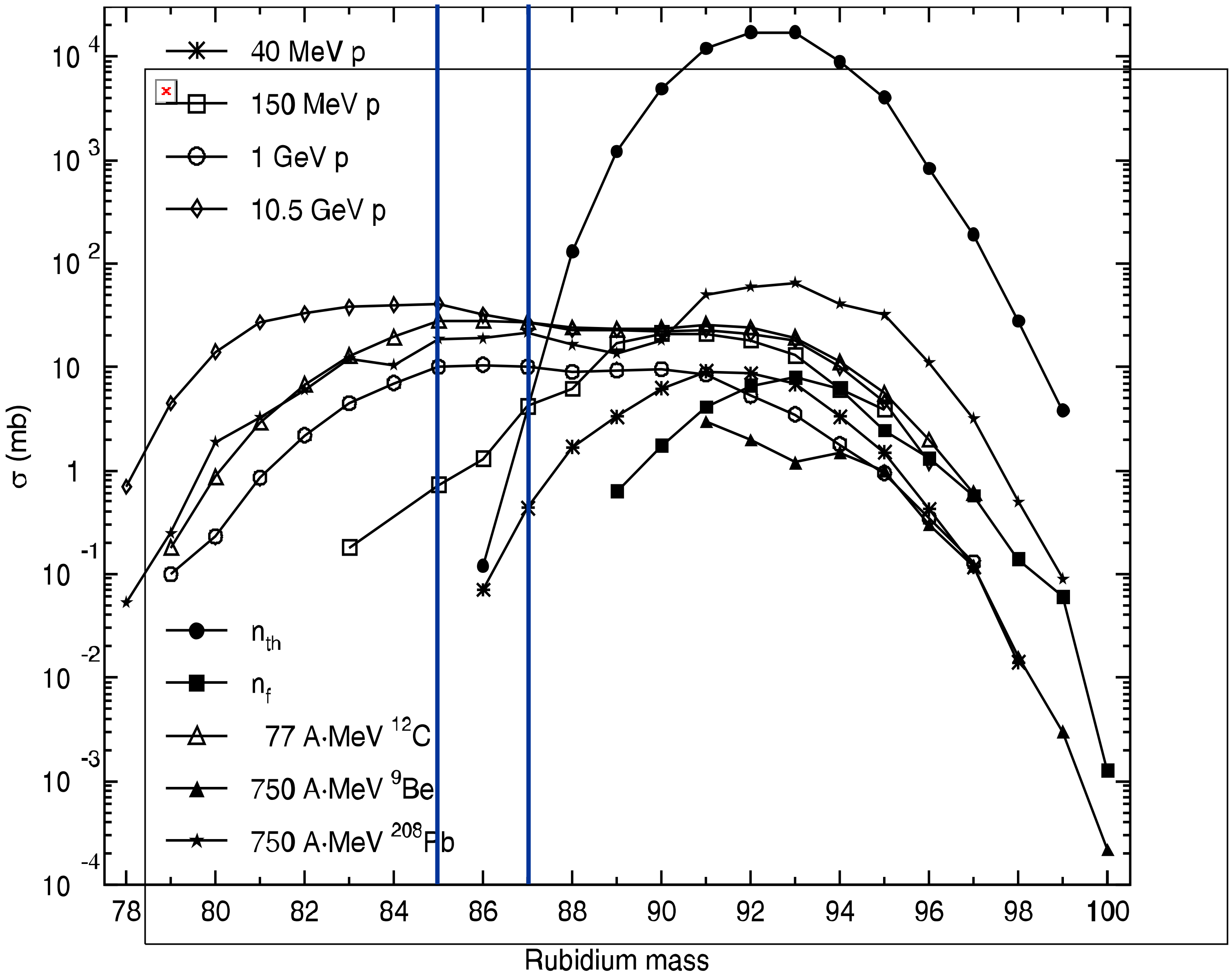

ISOLDE
Operating ISOL facilities
1967

RIB - Production reactions

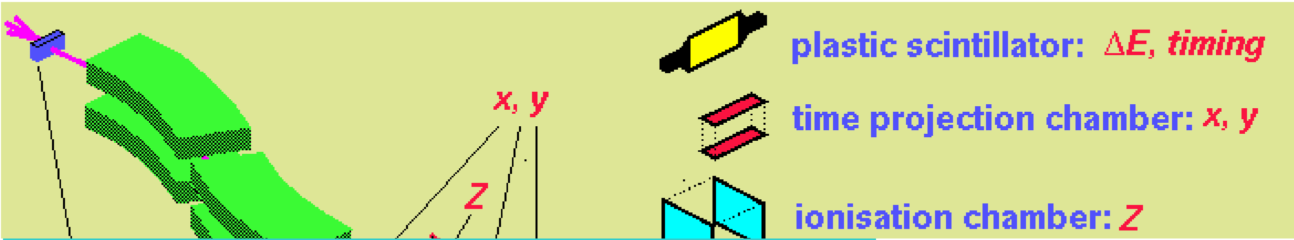


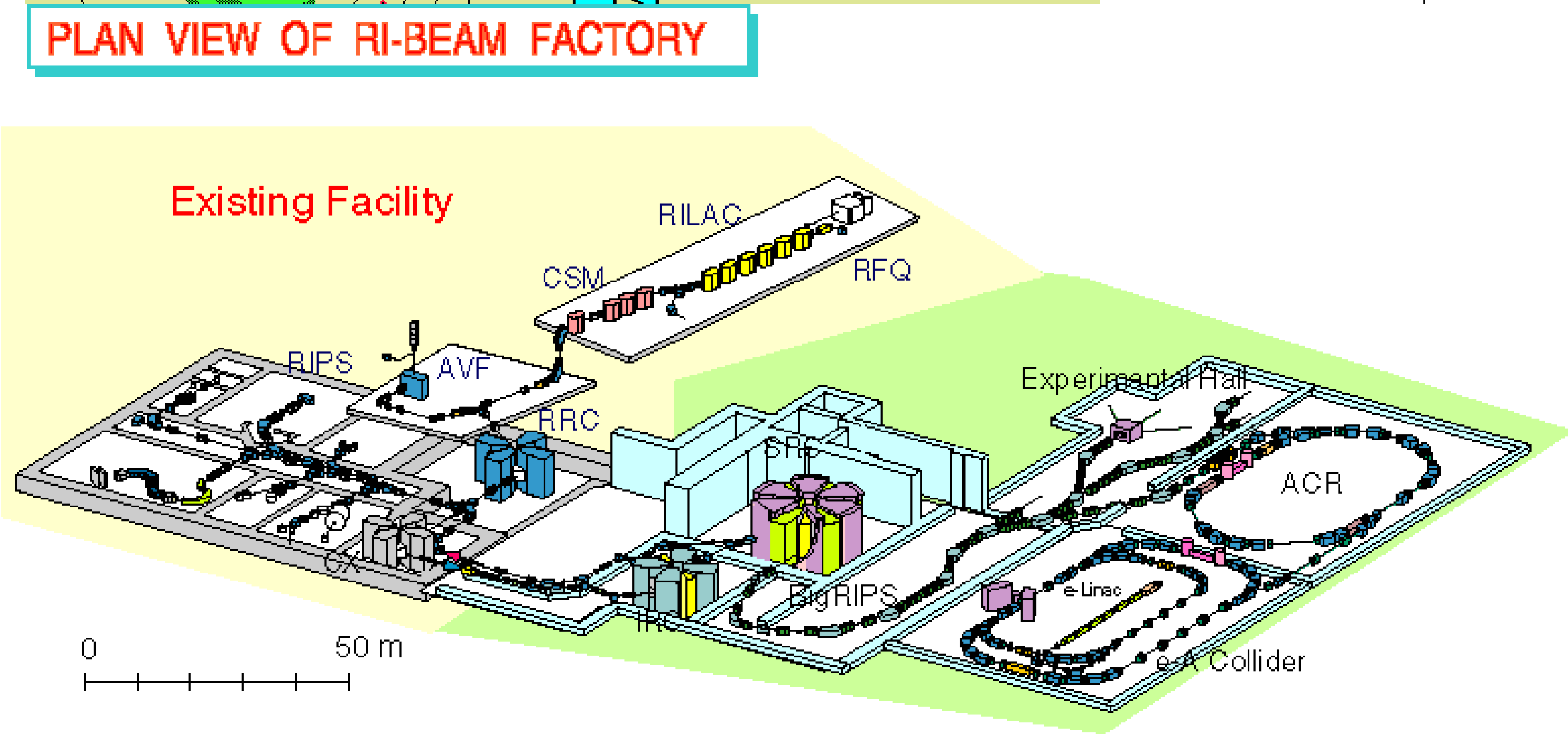
- Spallation
- Fragmentation
- Fission
  - n- (thermal or energetic), p-induced
  - Photofission (e-beam)

Production cross sections

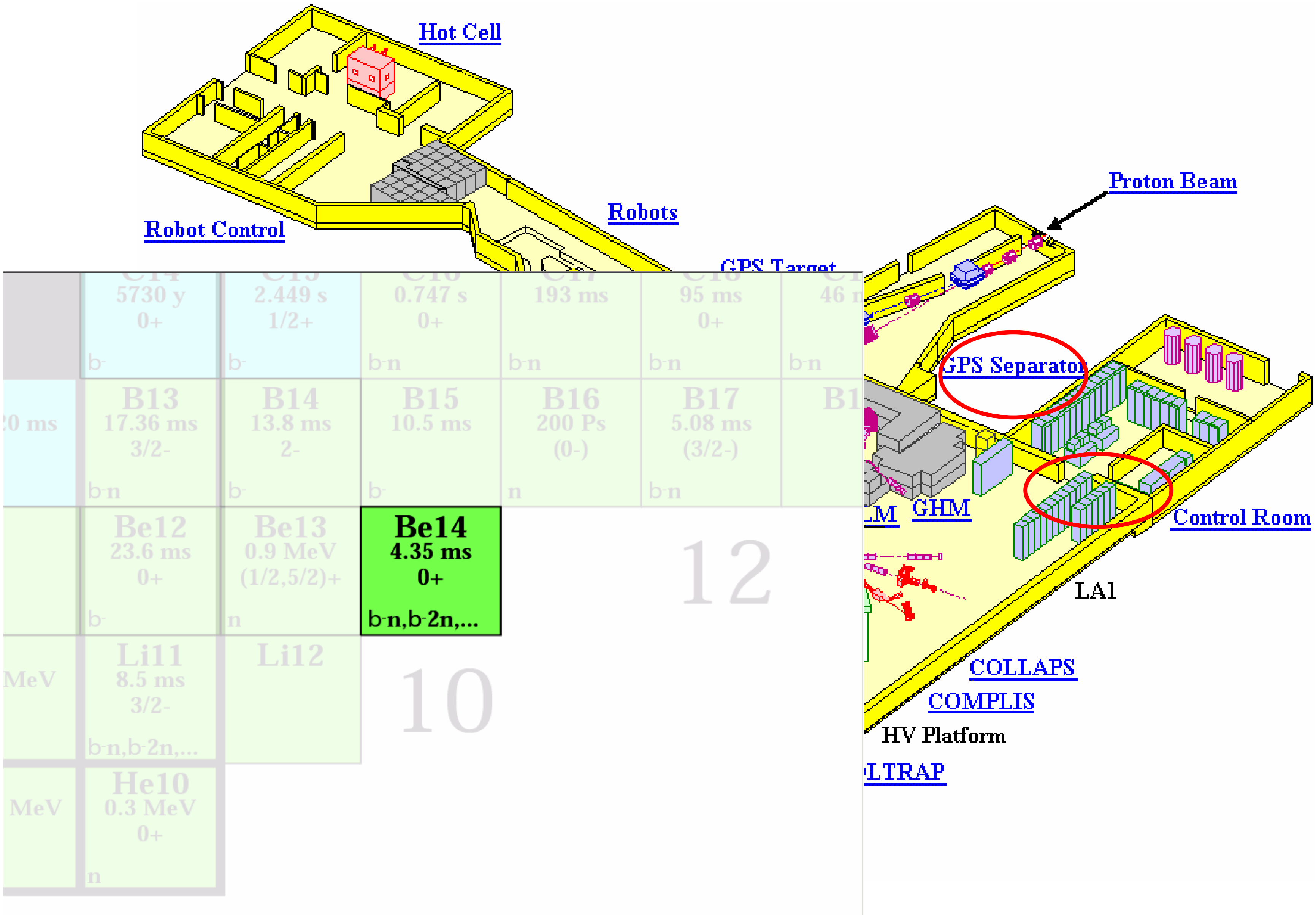


In-flight production (e.g. FRS@GSI)

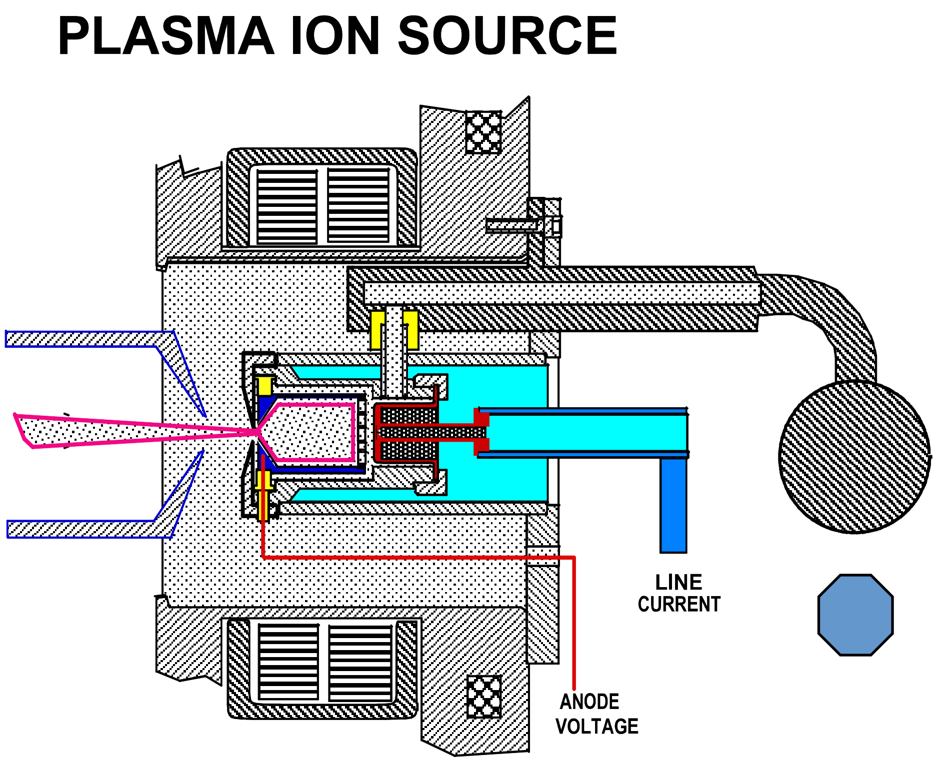


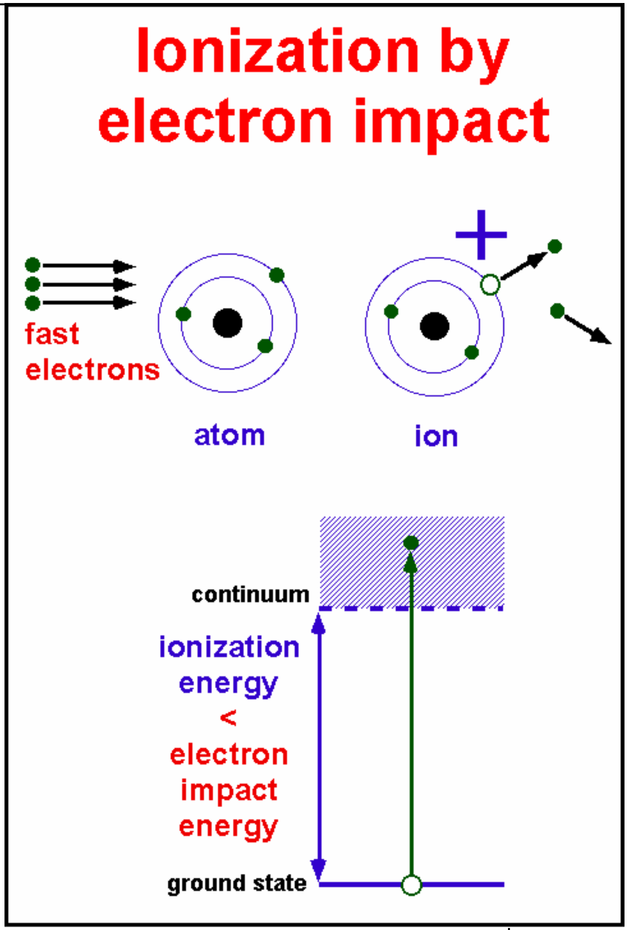


ISOL (e.g. ISOLDE@CERN)

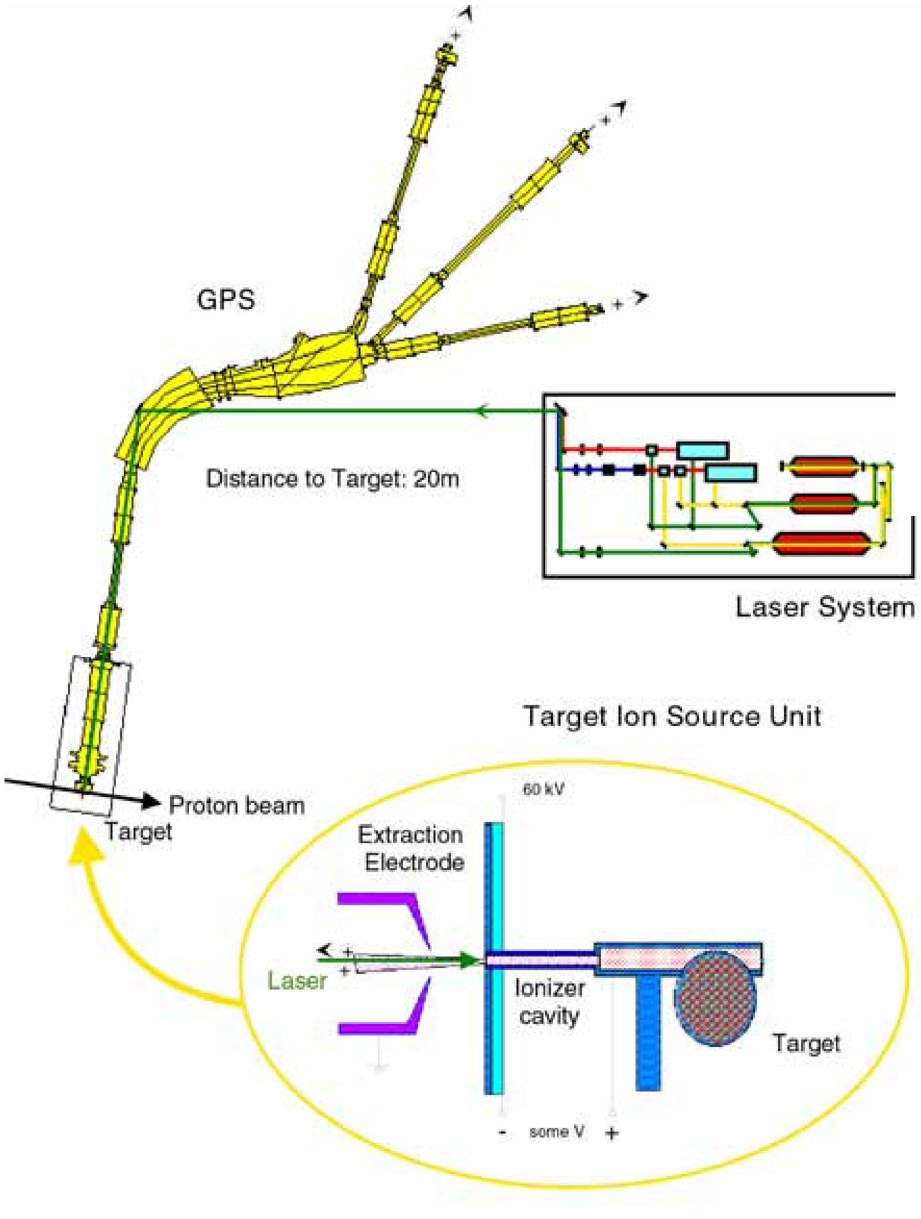


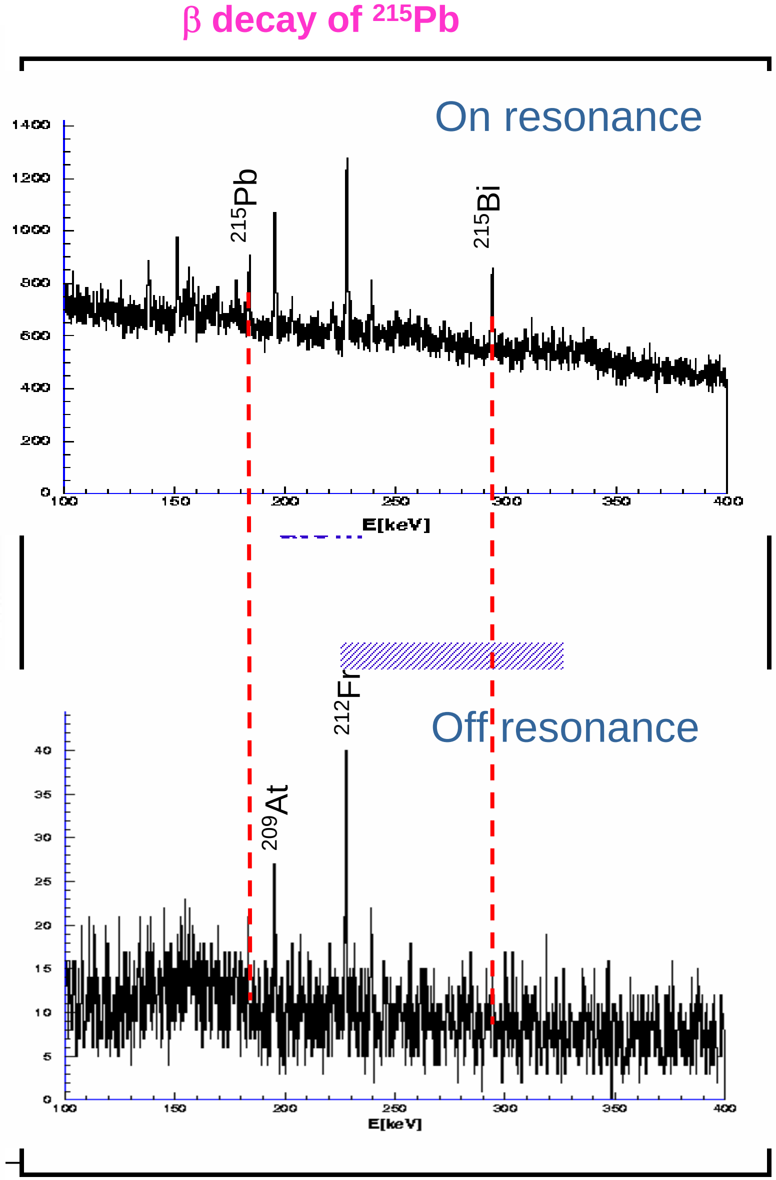
ISOL target


PLASMA ION SOURCE
LINE
CURRENT
ANODE
VOLTAGE

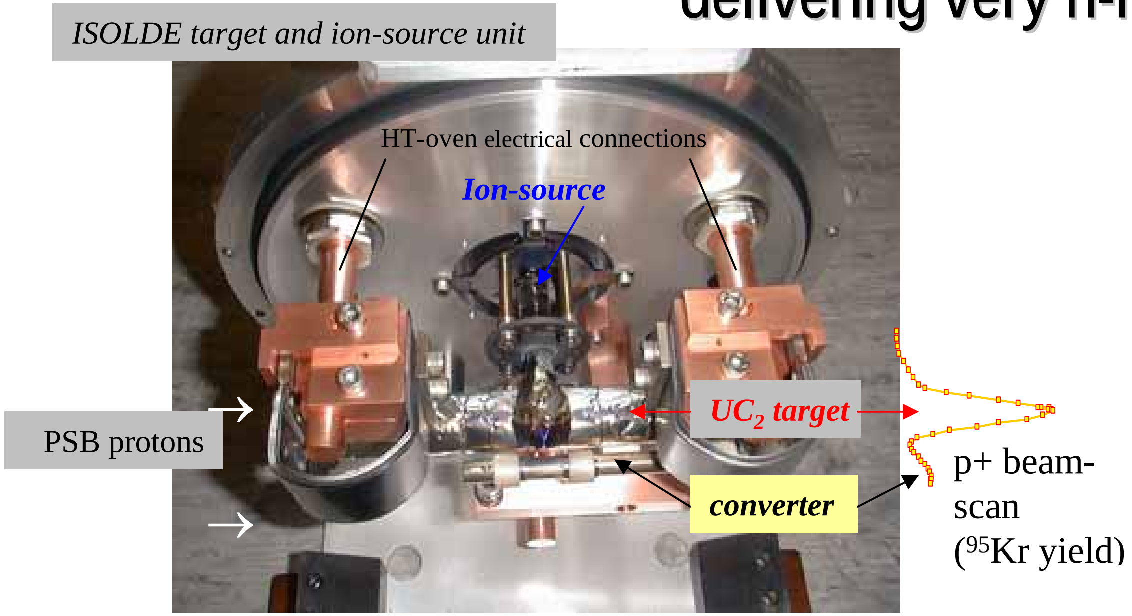

Ionization by
electron impact
fast
electrons
atom
ion
continuum
ionization
energy
<
electron
impact
energy
ground state

Resonant LASER Ion Source





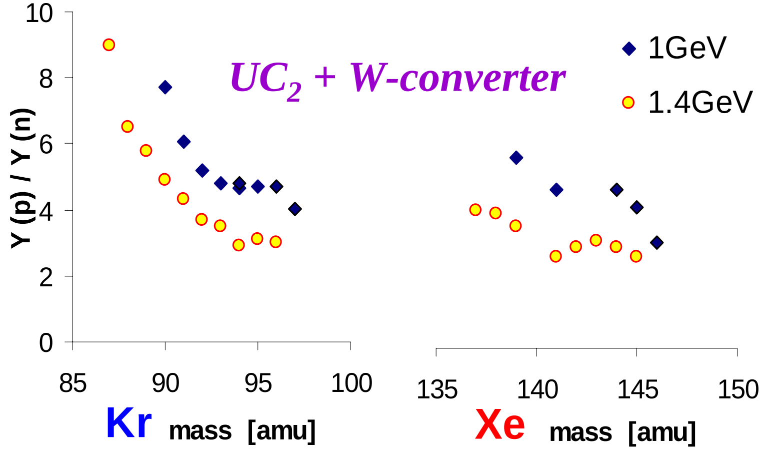
Towards pulsed high power U &Th targets delivering very n-rich fission products



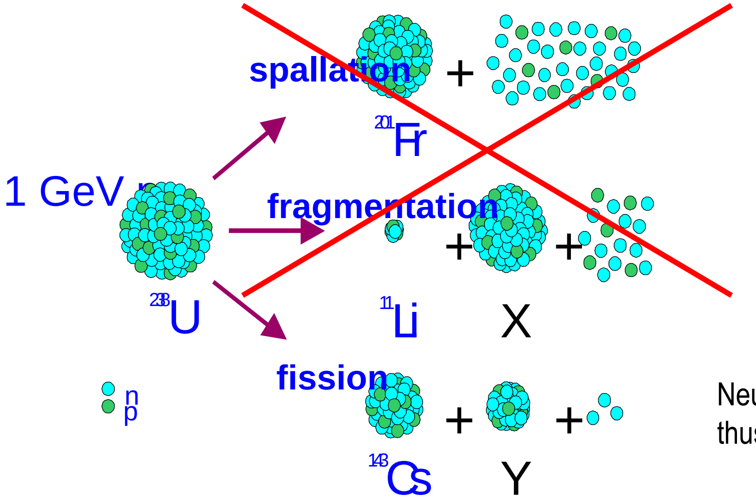
High energy protons (~1GeV) impacting on Ta- & W-rods (converters) generate an intense neutron flux.

The yields of very n-rich isotopes obtained via neutron induced fission of Th or U are close to those of high energy protons.

Further developments:
Geometrical optimum and n-reflectors

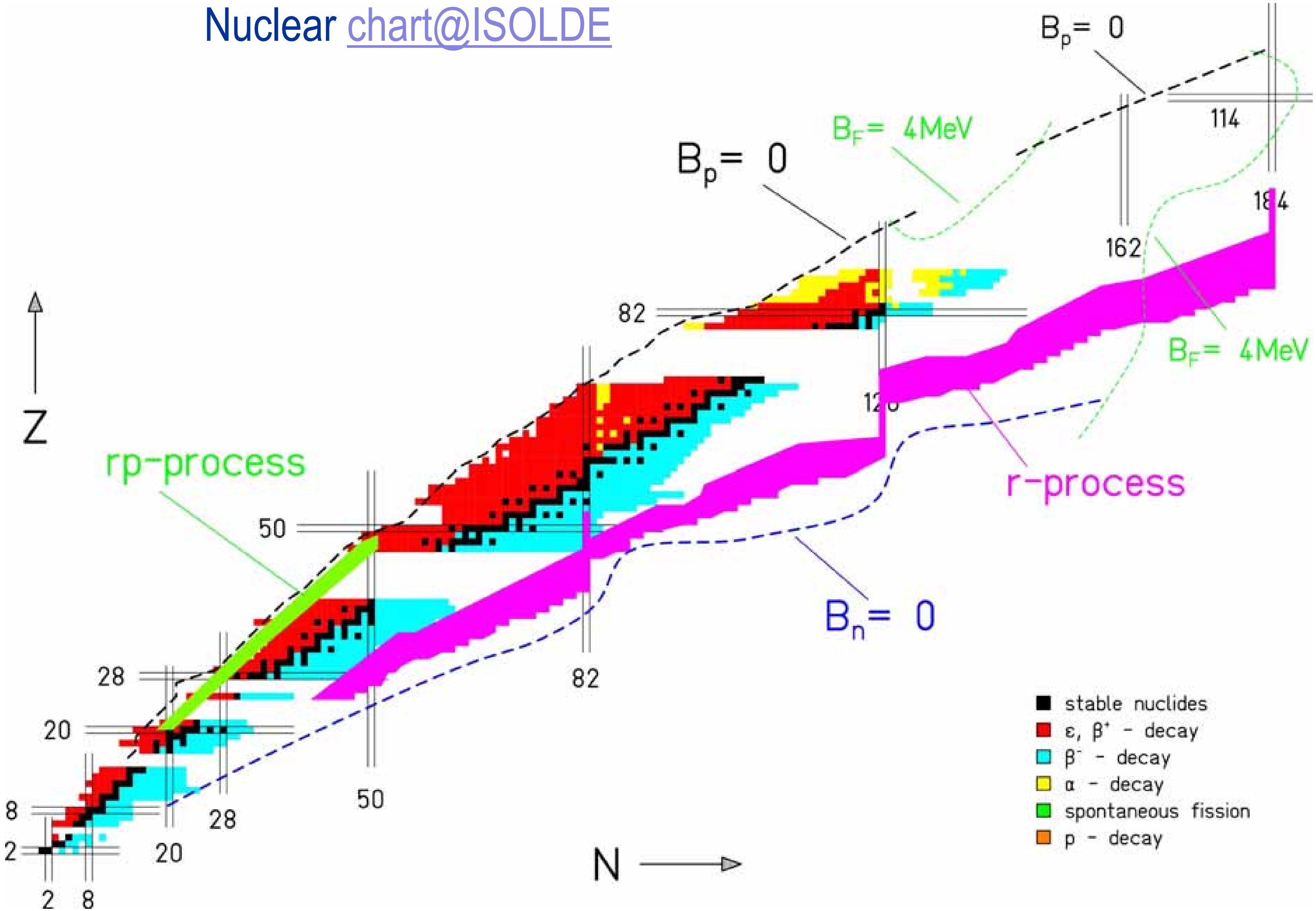


The thermal shock of the proton's dE/dx is transferred to the "cold" converter.



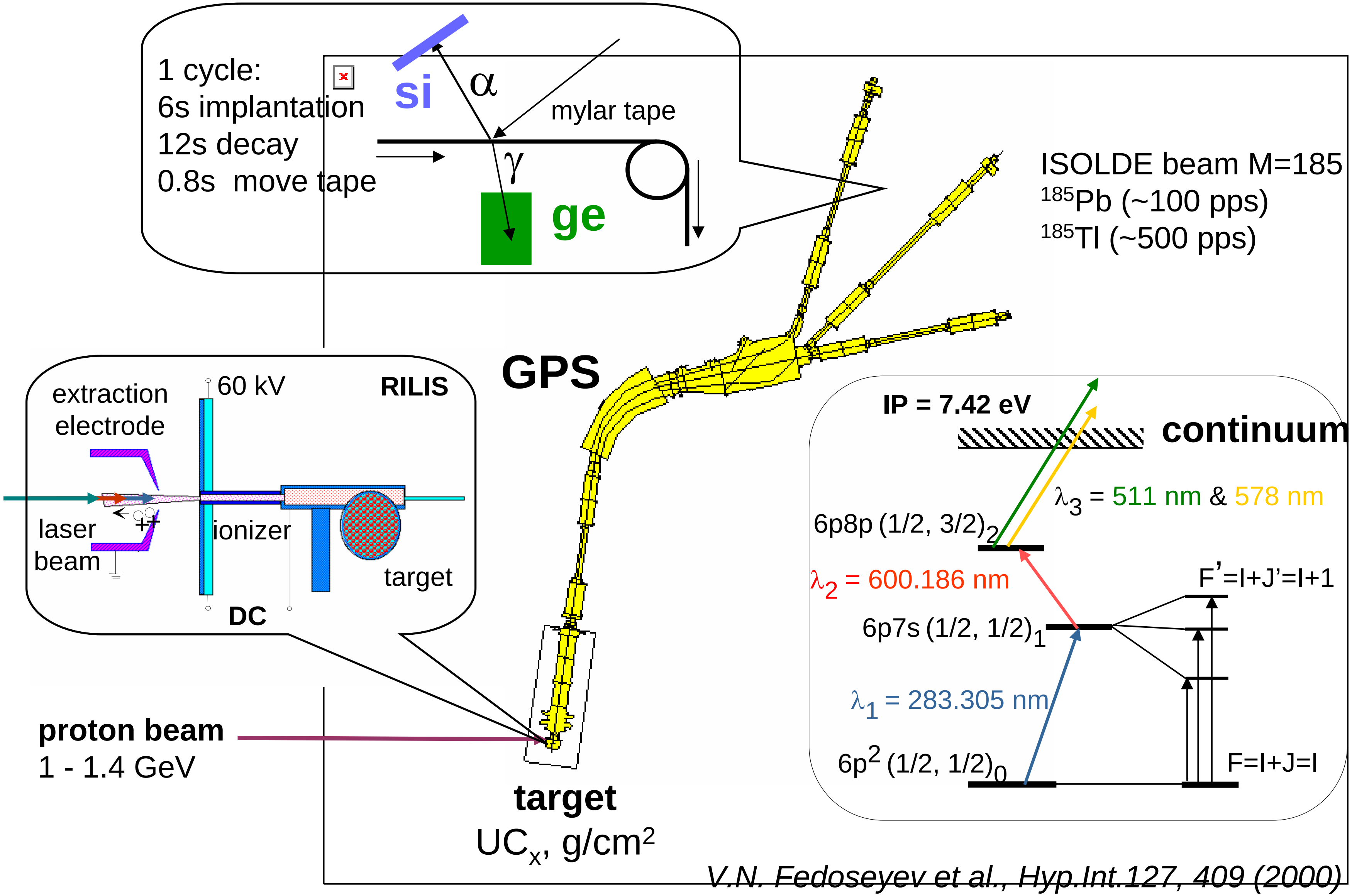
Neutron induced fission suppress the spallation and fragmentation processes thus reducing isobaric contamination by at least 2 orders of magnitude

Nuclear chart@ISOLDE



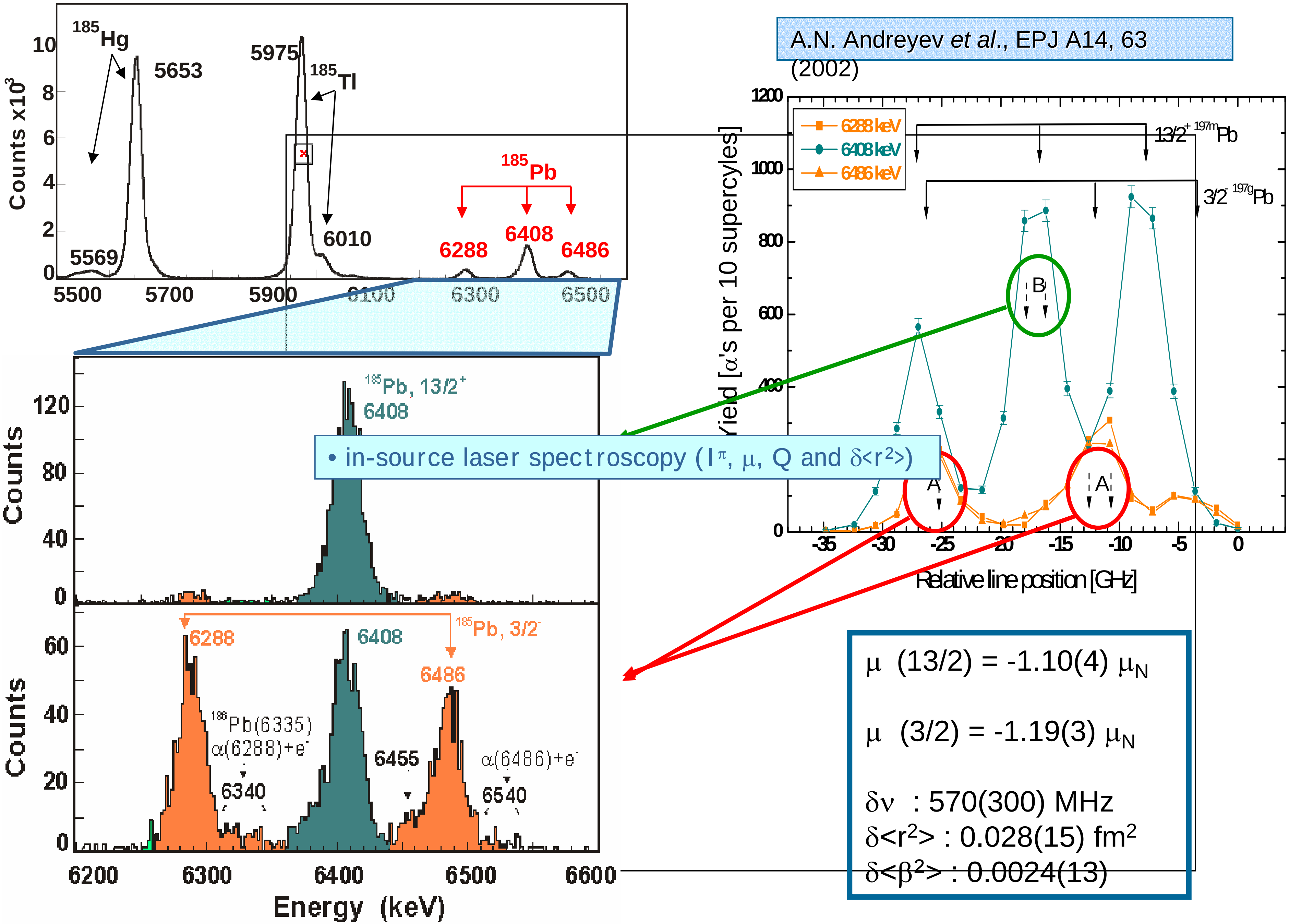
Experimental status: neutron-deficient isotopes around Z=82

- in-source laser spectroscopy: extreme selectivity!



V.N. Fedoseyev et al., Hyp.Int.127, 409 (2000)
http://isolde.cern.ch

Experimental status: neutron-deficient isotopes around Z=82



A.N. Andreyev *et al.*, EPJ A14, 63 (2002)

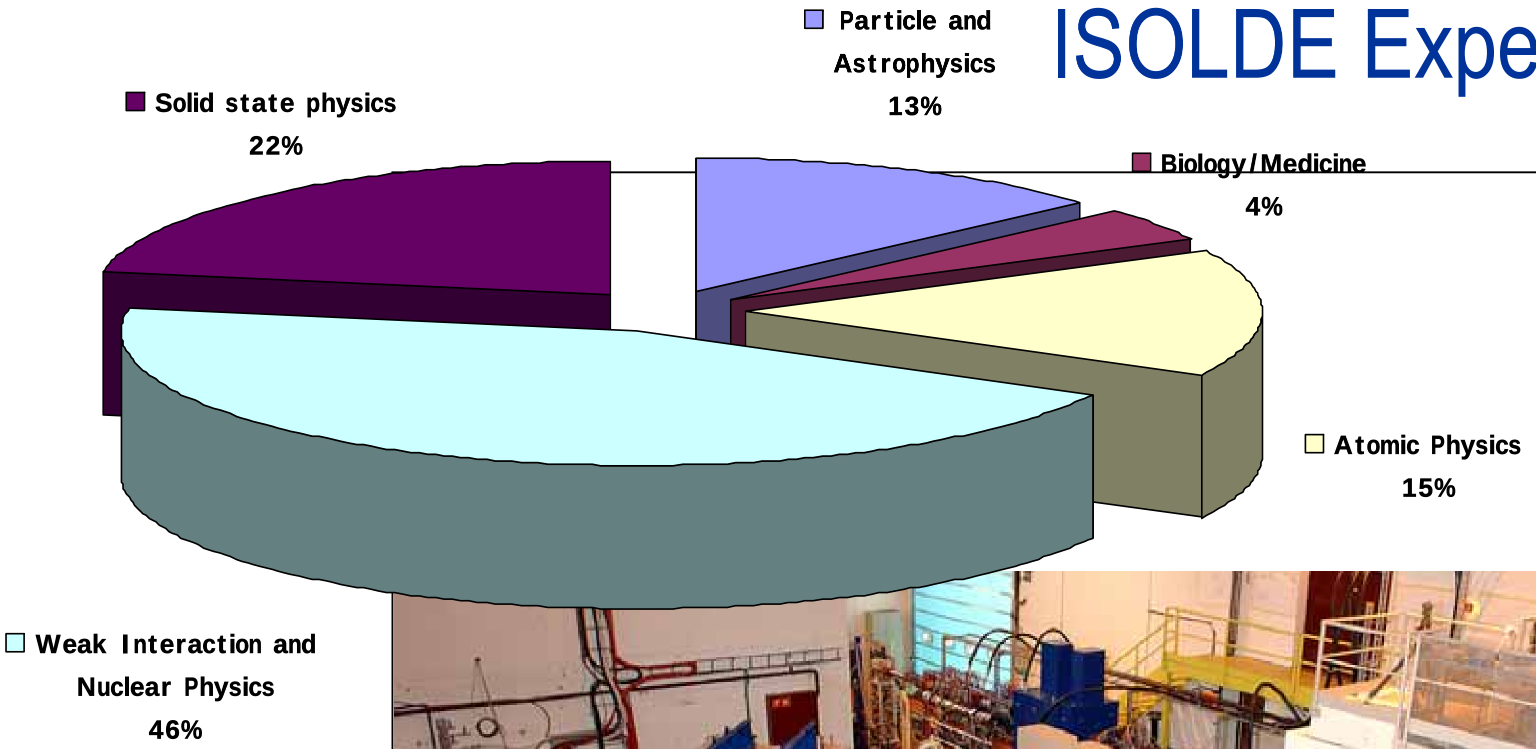
- in-source laser spectroscopy (I^{π}, μ, Q and $\delta\langle r^2\rangle$)

μ (13/2) = -1.10(4) μ_N

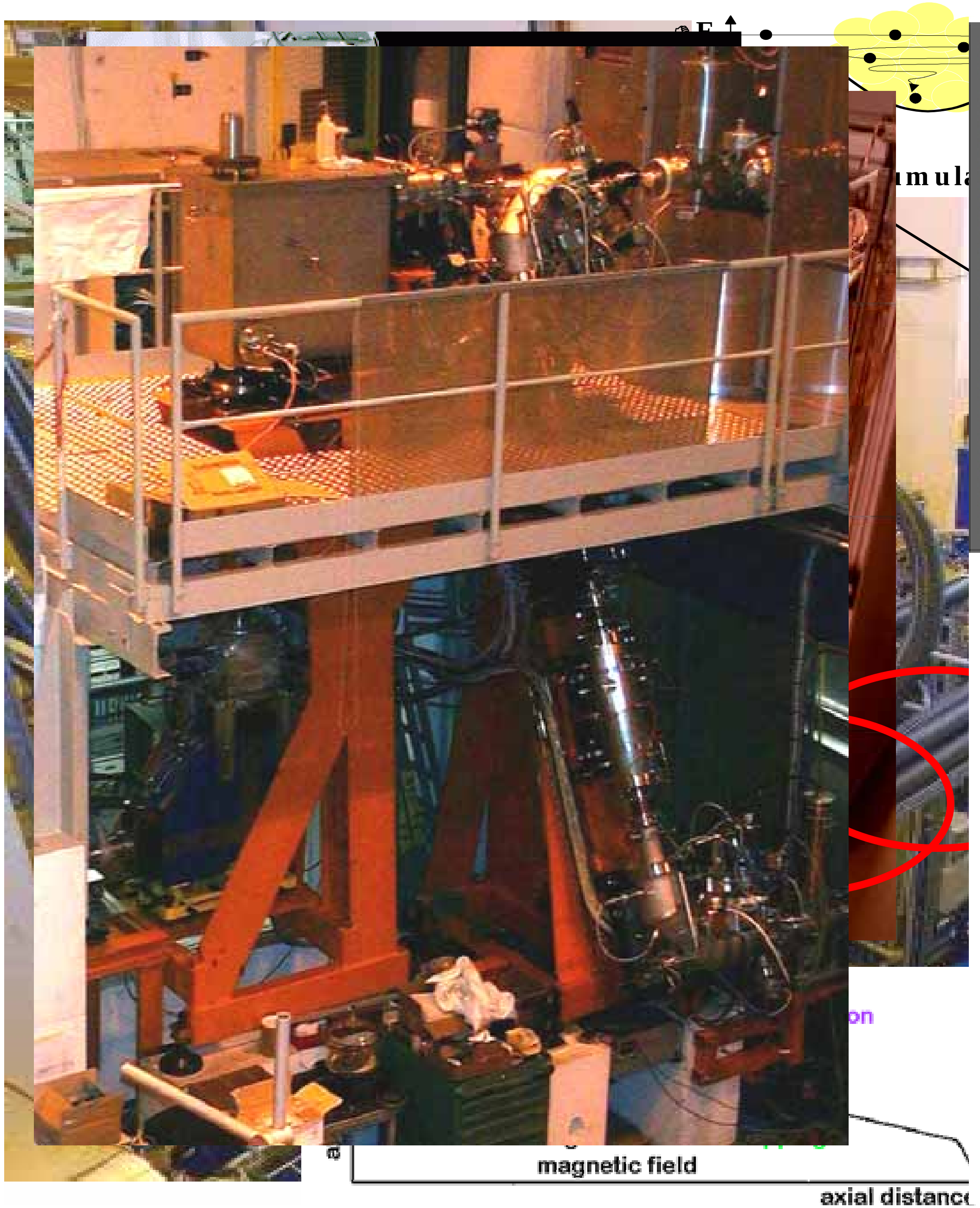
μ (3/2) = -1.19(3) μ_N

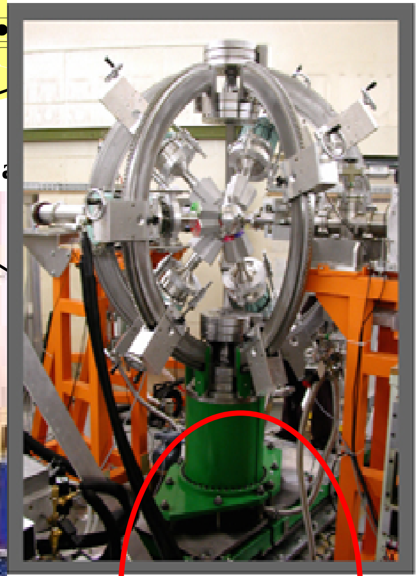
$\delta\nu$: 570(300) MHz
$\delta\langle r^2\rangle$: 0.028(15) fm^2
$\delta\langle\beta^2\rangle$: 0.0024(13)

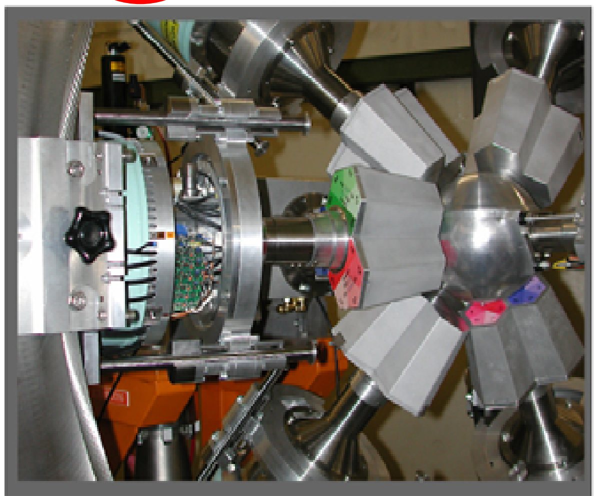
ISOLDE Experiments 2002



37 Experiments
300 Users
96 Institutes
22 Countries
375 RIB 8h-shifts

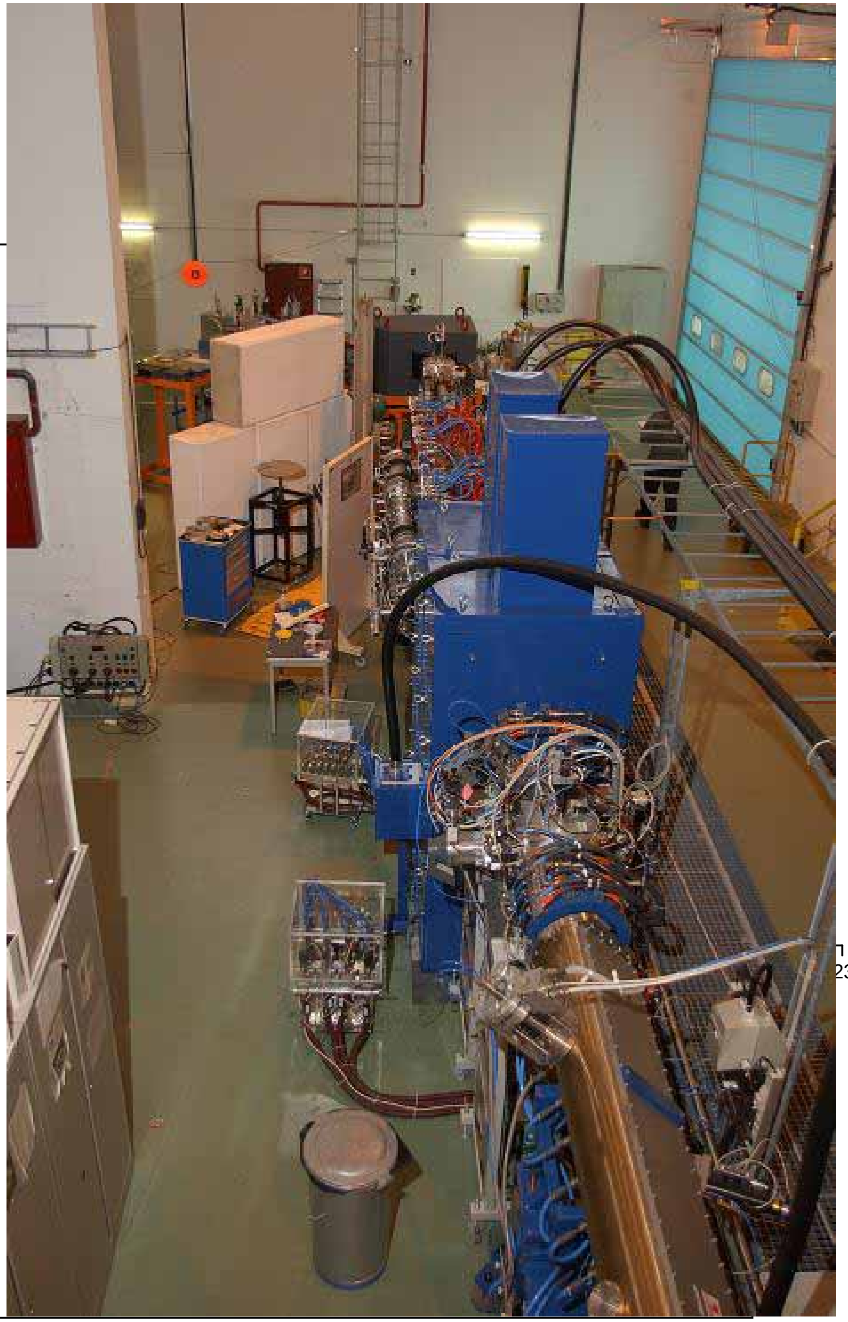

magnetic field





REX-ISOLDE facts

- Operating since 2001-10-30
- $0.3 < E < 2.3$ MeV/u
- $q/A > 1/4.5$
- $7 \leq A \leq 153$ cooled, charge-bred and accelerated
  - A = 208, 238 to be tested
- Works with all elements(?)
  - Molecular beams to be further tested
- $1 < \varepsilon < 5\%$ overall efficiency
- Single RIB facility with charge-breeder worldwide



REX-ISOLDE in 2002-2003

- Machine development
  - ^{133}Cs cooled and charge-bred
  - First tests with cooling of noble gases
- 4 REX+MINIBALL runs
  - n-rich Na
  - $^{30-31}Mg$
- ^{9}Li on d, ^{9}Be-targets
- Test deep implantation of ^{153}Sm for DLTS
- Second campaign starting next week

REX proposals

Proposals	Authors	Title
IS347 P68	D. Habs et al.	REX-ISOLDE Radioactive Beam Experiment at ISOLDE
IS367 P100	L. Axelsson et al.	Study of the unbound nuclei ^{10}Li and ^{7}He at REX-ISOLDE
IS371 P105	L. Axelsson et al.	Investigations of neutron-rich nuclei at the dripline through their analogue states: The cases of ^{10}Li-^{10}Be (T=2) and ^{17}C-^{17}N (T=5/2)
IS379 P114	H. Scheit et al.	Investigation of the single particle structure of the neutron-rich sodium isotopes $^{27-31}$Na
IS399 P134	M.V. Andres et al.	Exploring the dipole polarizability of ^{11}Li at REX-ISOLDE
IS405 P149	D.G. Jenkins et al.	Obtaining empirical validation of shape-coexistence in the mass 70 region : Coulomb excitation of a radioactive beam of ^{70}Se
IS409 P155	P. Reiter et al.	Fusion Reactions at the Coulomb Barrier with Neutron-rich Mg Isotopes
P156	D. Habs et al.	Coulomb Excitation of neutron-rich A~140 Nuclei
P158	P. Mayet et al.	Coulomb excitation of neutron-rich nuclei between the N=40 and N=50 shell gaps using REX-ISOLDE and the Ge MINIBALL array
IS410 P159	H. Scheit et al.	Evolution of single particle and collective properties in neutron-rich Mg isotopes

Halo nuclei

Weakening of magic numbers

Nuclear shapes

Fusion with n-rich beams

REX LoI

LOI	Authors	Title
I11	M. Wiescher et al.	A radioactive-ion beam experiment for the study of the astrophysical rp-process at CERN-ISOLDE
I12	G. Weyer et al.	Defects studies in high-energy ion implanted semiconductors
I13	D. Forkel-Wirth et al.	Energetic radioactive ion beam studies of hydrogen in semiconductors
I21	M.V. Andres et al.	Dipole Coulomb Polarizability in the scattering of halo nuclei
I20	L. Campajola et al.	Measurement of the ^{7}Be(p,γ)^{8}B absolute cross section in inverse kinematics
I41	O. Sorlin et al.	Determination of ^{44}Ar(n,γ) ^{45}Ar, and ^{46}Ar(n,γ)^{47}Ar reaction rates by (d,p) transfer reactions
I42	G. Pasold et al.	Postacceleration of rare earth isotope beams for radiotracer-DLTS on SiC.

Astrophysics

Solid State Physics

Summary

- ISOL vs. in-flight:
  - Thicker targets -> higher production
  - Better RIB beam quality
  - Energy adapted for decay, traps and laser spect.
  - Decay losses
  - Isobaric contaminants
  - Chemistry of target/ion source
- Beam handling important for post-acc. etc.
- Protons most versatile driver, GeV regime optimal in x-section vs. intensity
- Production processes crucial parameters for the experiments

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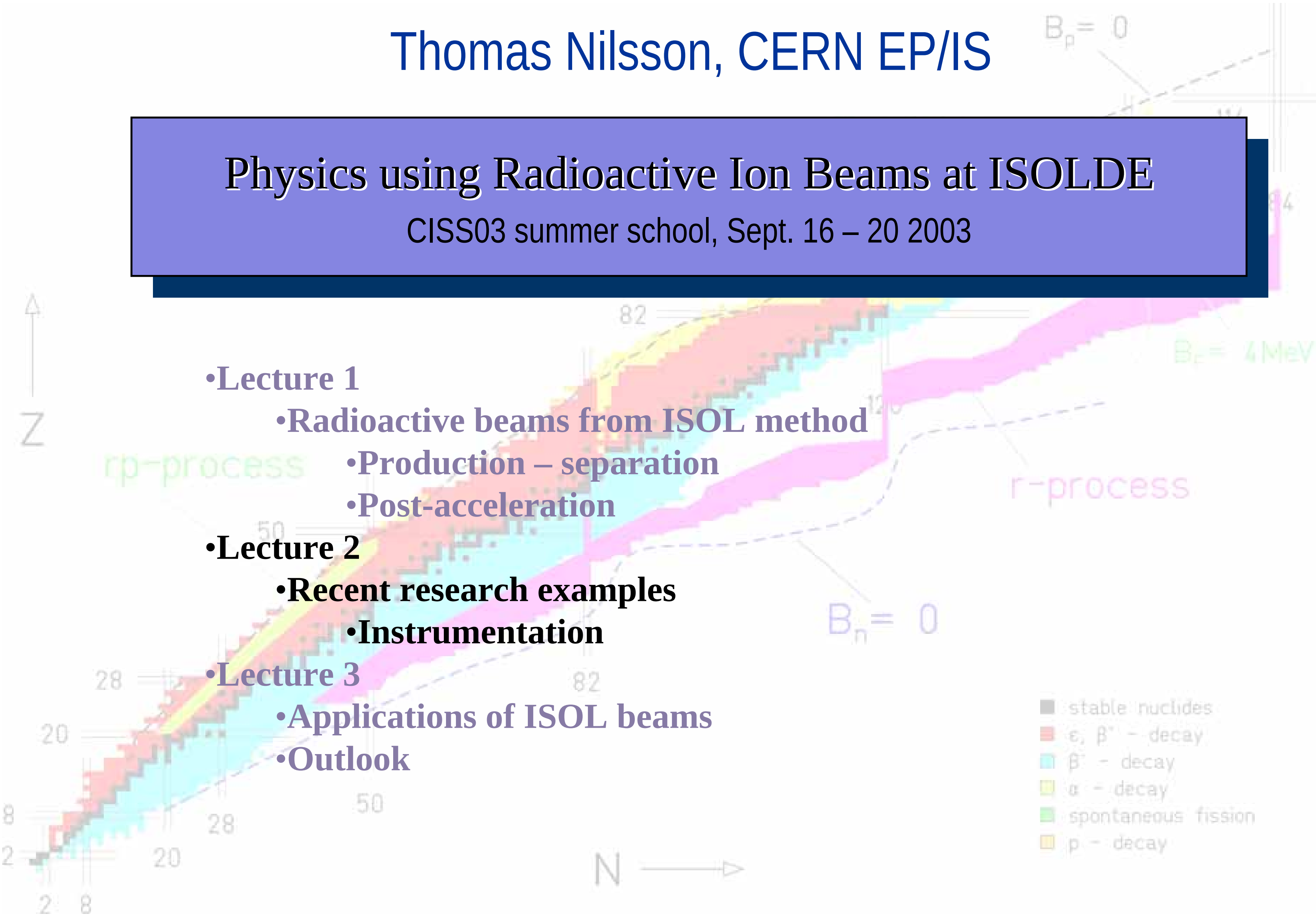
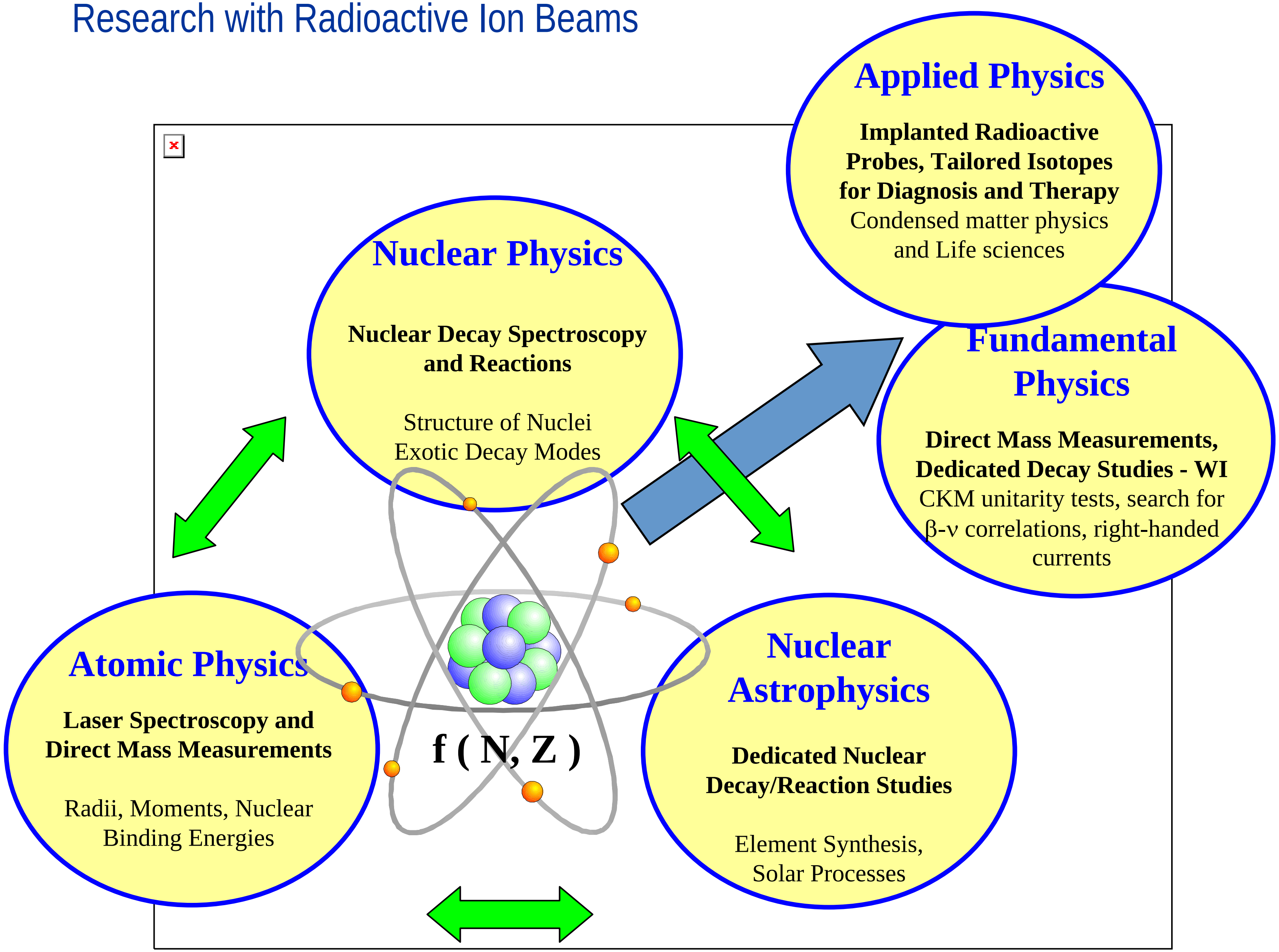
Physics using Radioactive Ion Beams at ISOLDE

CISS03 summer school, Sept. 16 – 20 2003

- Lecture 1
    - Radioactive beams from ISOL method
        - Production – separation
        - Post-acceleration
- **Lecture 2**
    - **Recent research examples**
        - **Instrumentation**
- Lecture 3
    - Applications of ISOL beams
    - Outlook

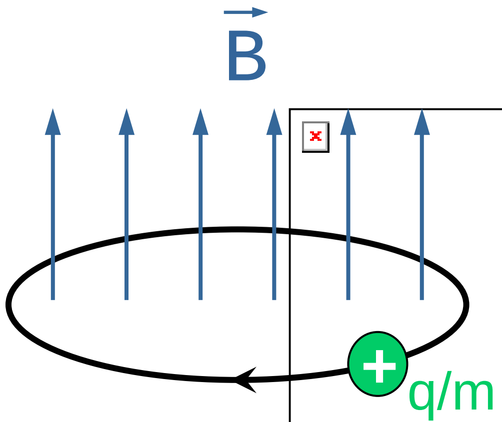


Research with Radioactive Ion Beams



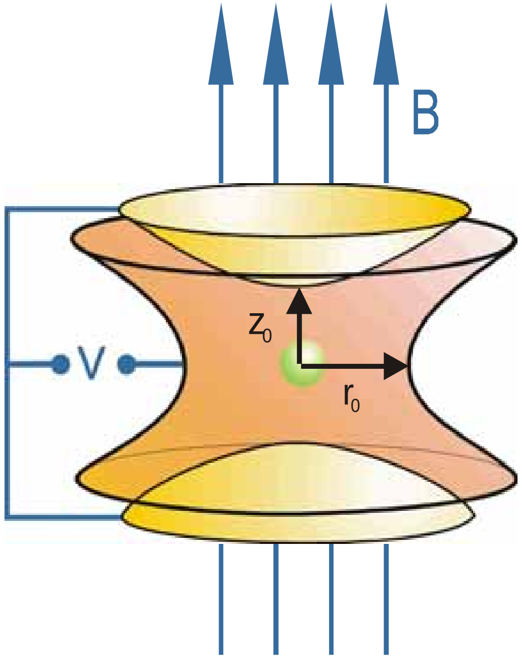
- Ground-state properties
  - Masses
  - Moments

Principle of a Penning trap



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

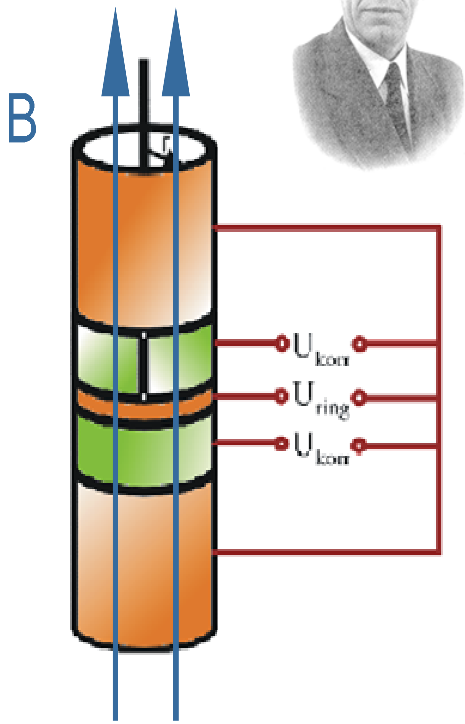
Frans Michel Penning



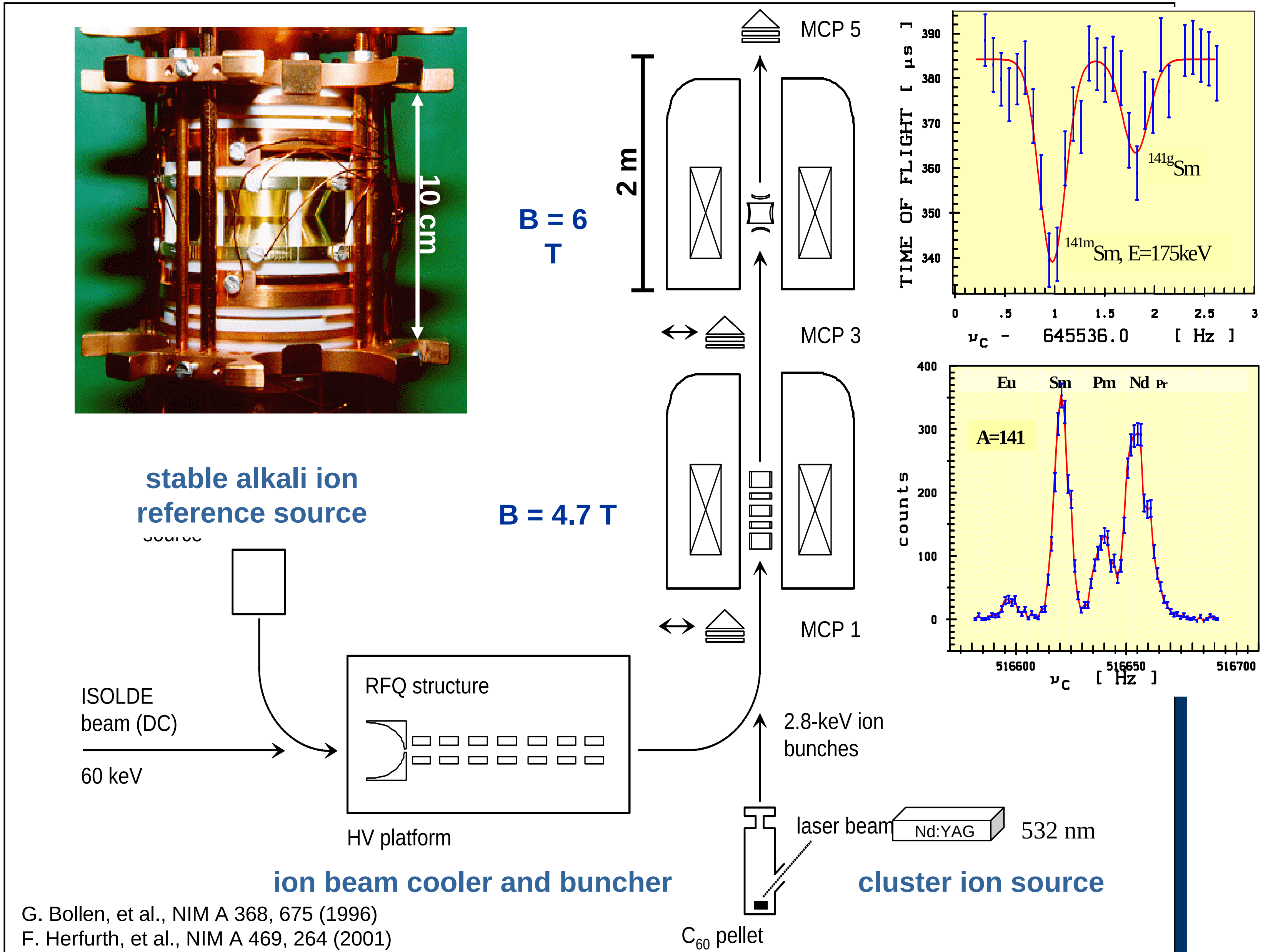
Superposition

- strong homogeneous magnetic field
- weak electrostatic quadrupole field

PENNING trap



The triple-trap mass spectrometer ISOLTRAP

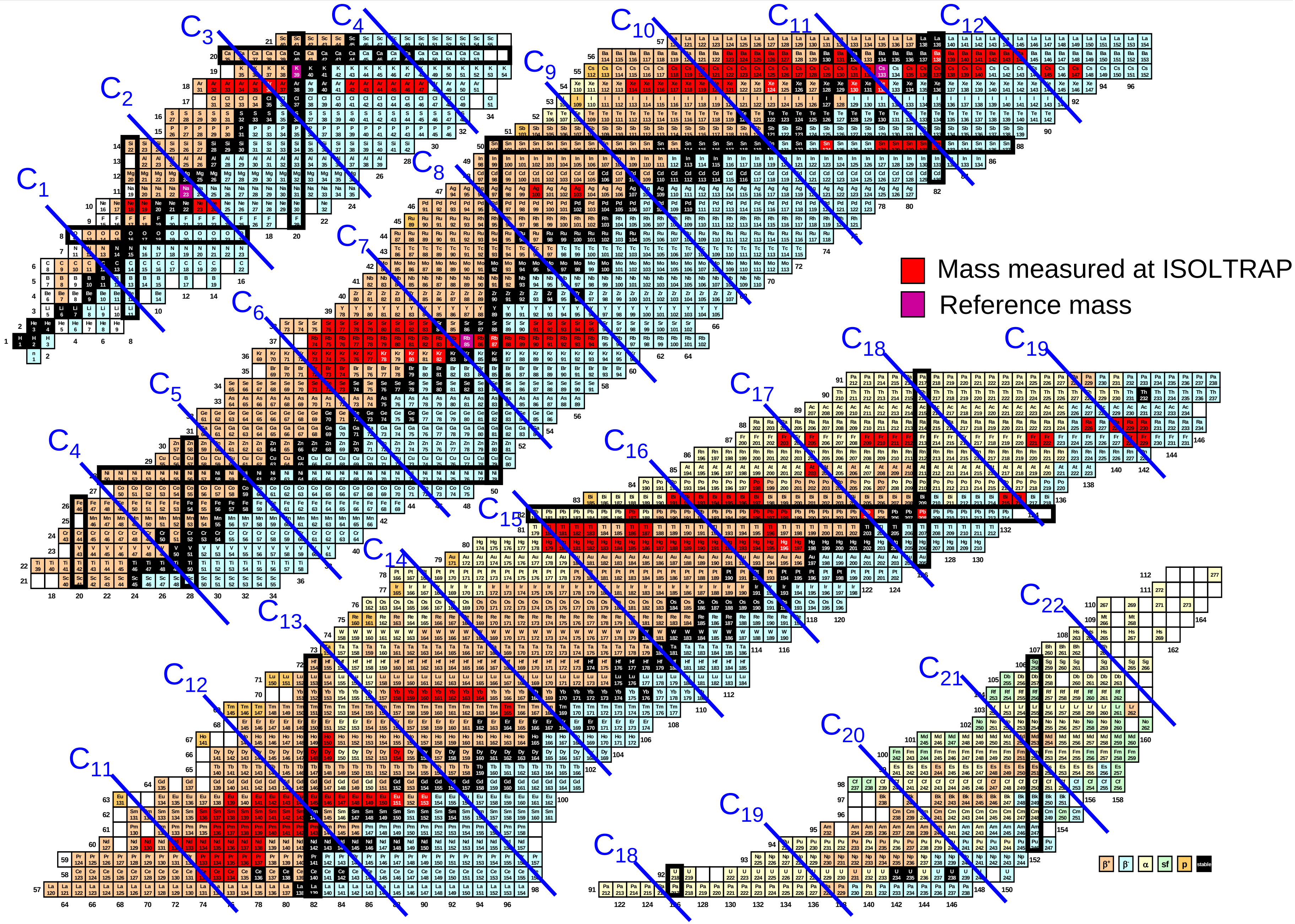


G. Bollen, et al., NIM A 368, 675 (1996)

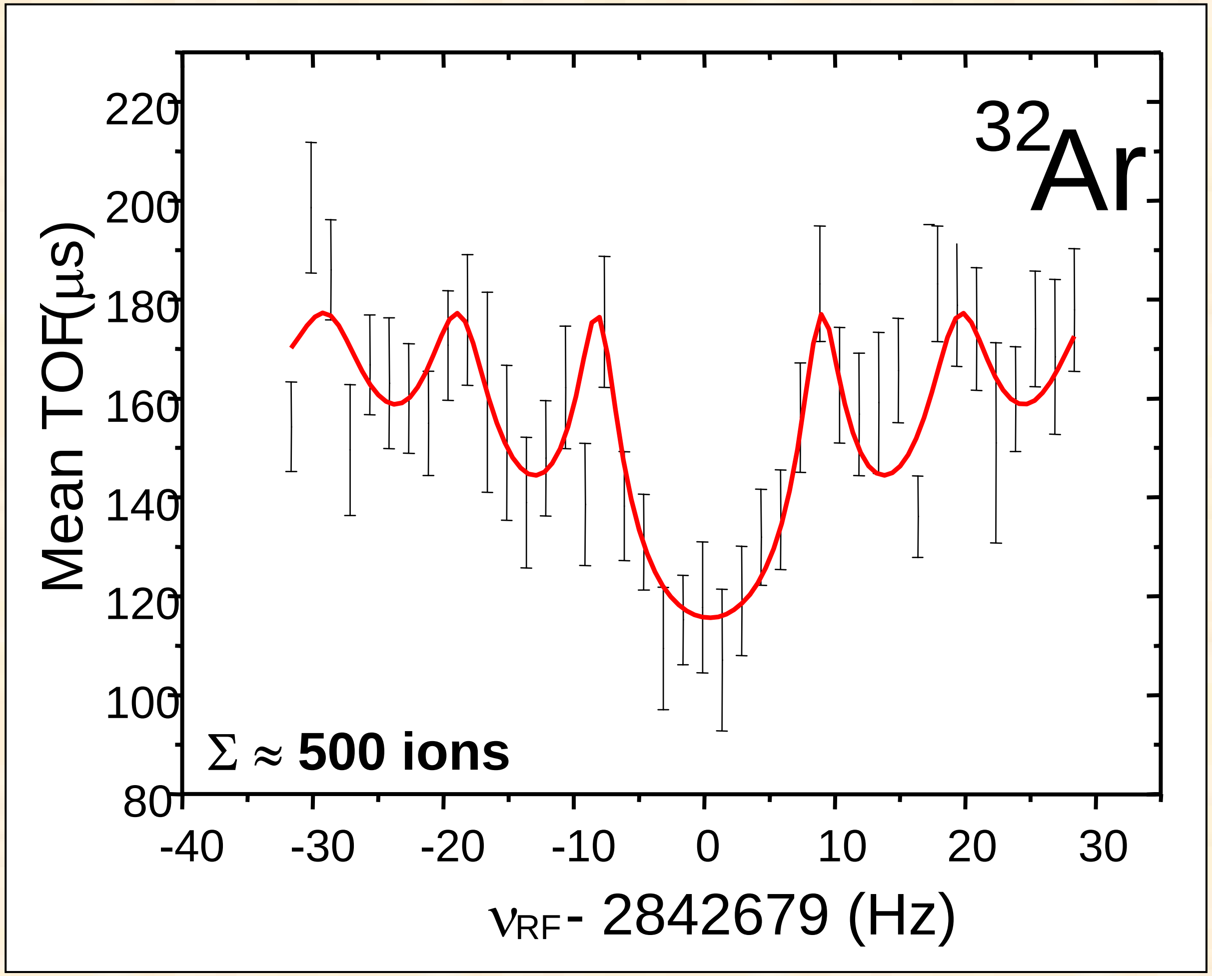
F. Herfurth, et al., NIM A 469, 264 (2001)

K. Blaum

Calibration: Carbon clusters



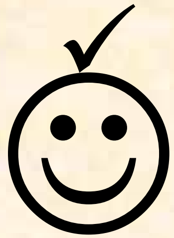
Recent results from ISOLTRAP on $^{32,33,34}Ar$



$T_{1/2}$ = 98 ms

Yield ~ 10^2/s

Mass uncertainty (prel.): $\delta m/m$ = $6\cdot10^{-8}$



K. Blaum *et al.*, PRL (in preparation)

For $^{33,34}Ar$: $\delta m/m \approx 1\cdot10^{-8}$

F. Herfurth *et al.*, Eur. Phys. J. A 15, 17 (2002)

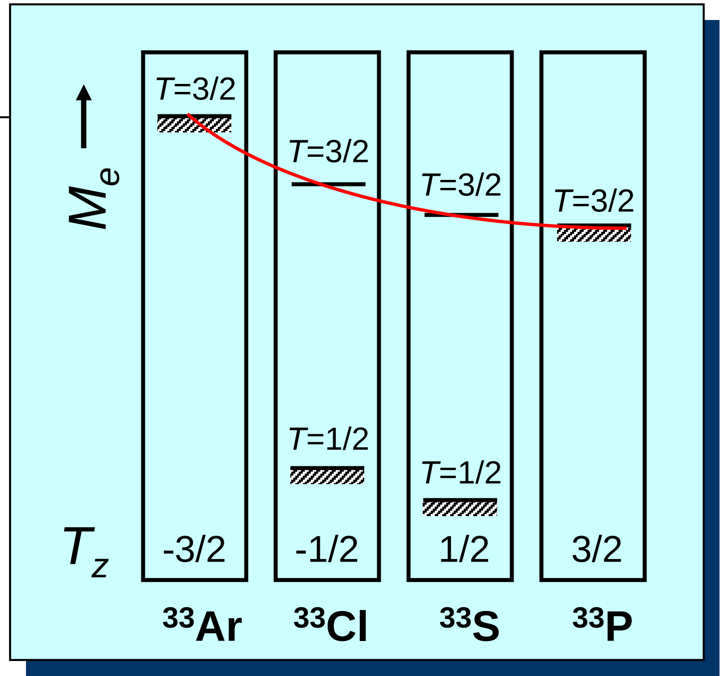
IMME test: T = 3/2 quartet @ A = 33

Isobaric Multiplet Mass Equation

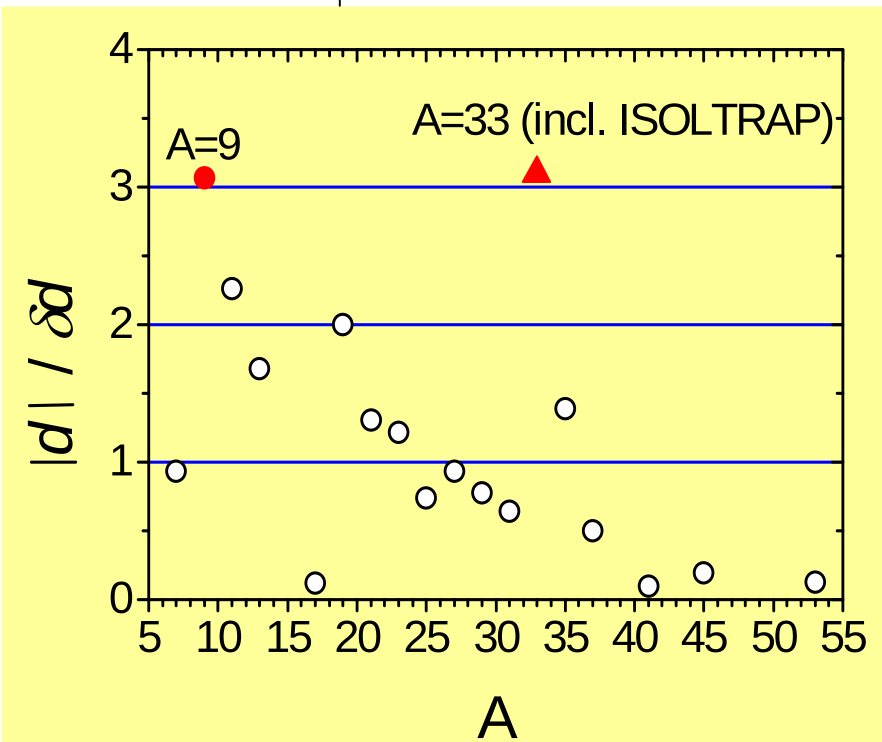
$$M = a + bT_z + cT_z^2 \quad + dT_z^3$$

Commonly used quadratic form

?



d coefficients for all 18 complete ground state quartets

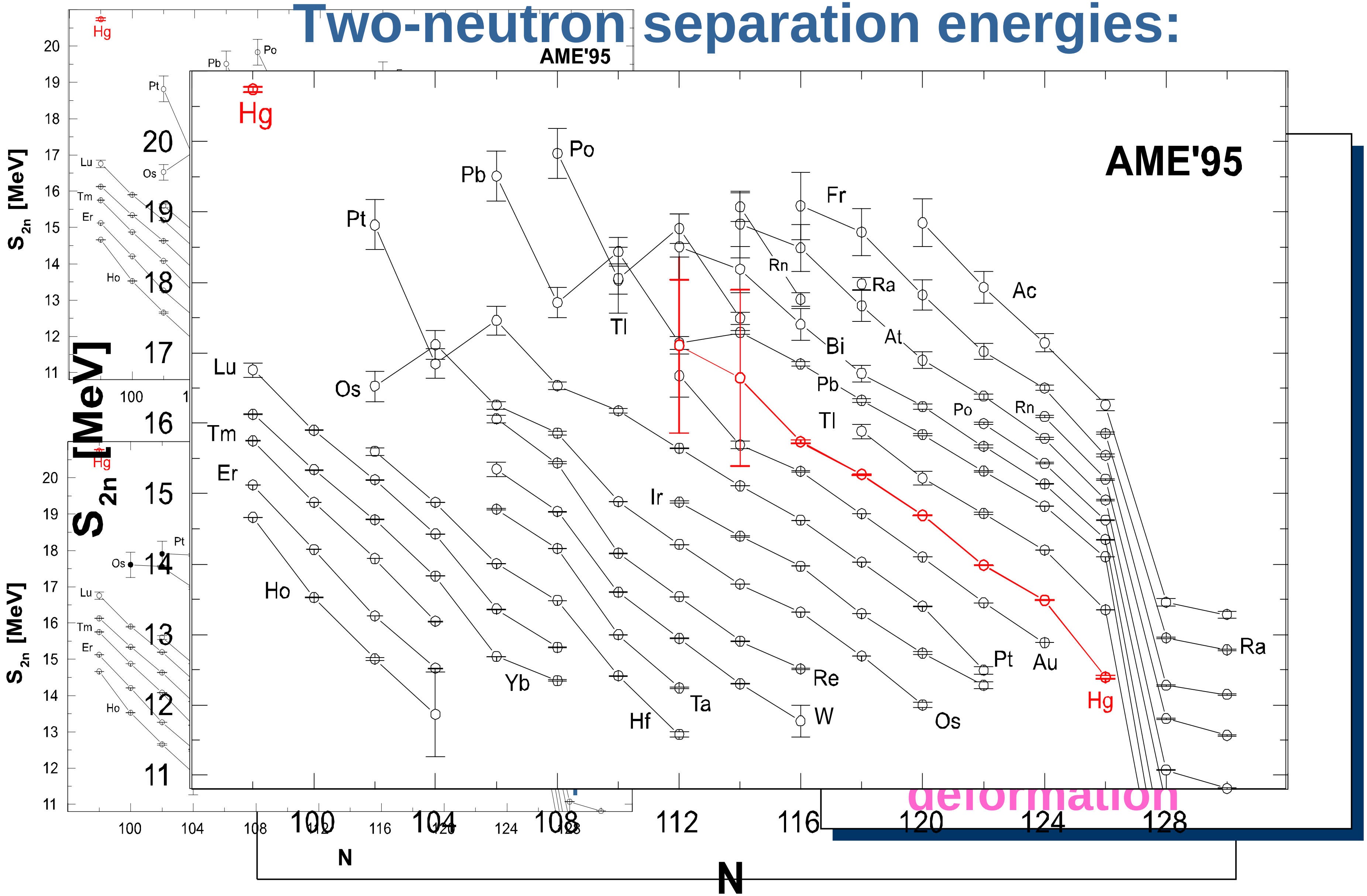


2001: Breakdown of IMME
F. Herfurth et al.
PRL 87 (2001) 142501

2002: Revalidation of IMME
T=3/2 state in ^{33}Cl wrong
M.C. Pyle et al.
PRL 88 (2002) 122501

Fine structure of the mass surface

Two-neutron separation energies:



Laser spectroscopy and nuclear physics

With laser spectroscopy it is possible to study nuclear properties:

Hyperfine structure splitting in electronic transitions:

$$\Delta E_{HFS} = \frac{A}{2} * K + \frac{B}{4} * \frac{\frac{3}{2}K(K+1) - 2I(I+1)j(j+1)}{I(2I-1)j(2j-1)}$$

$$K = \frac{F(F+1) - j(j+1) - I(I+1)}{j(j+1)(2I+1)}$$

A $\Rightarrow$ magnetic dipole moment μ (I > 0)

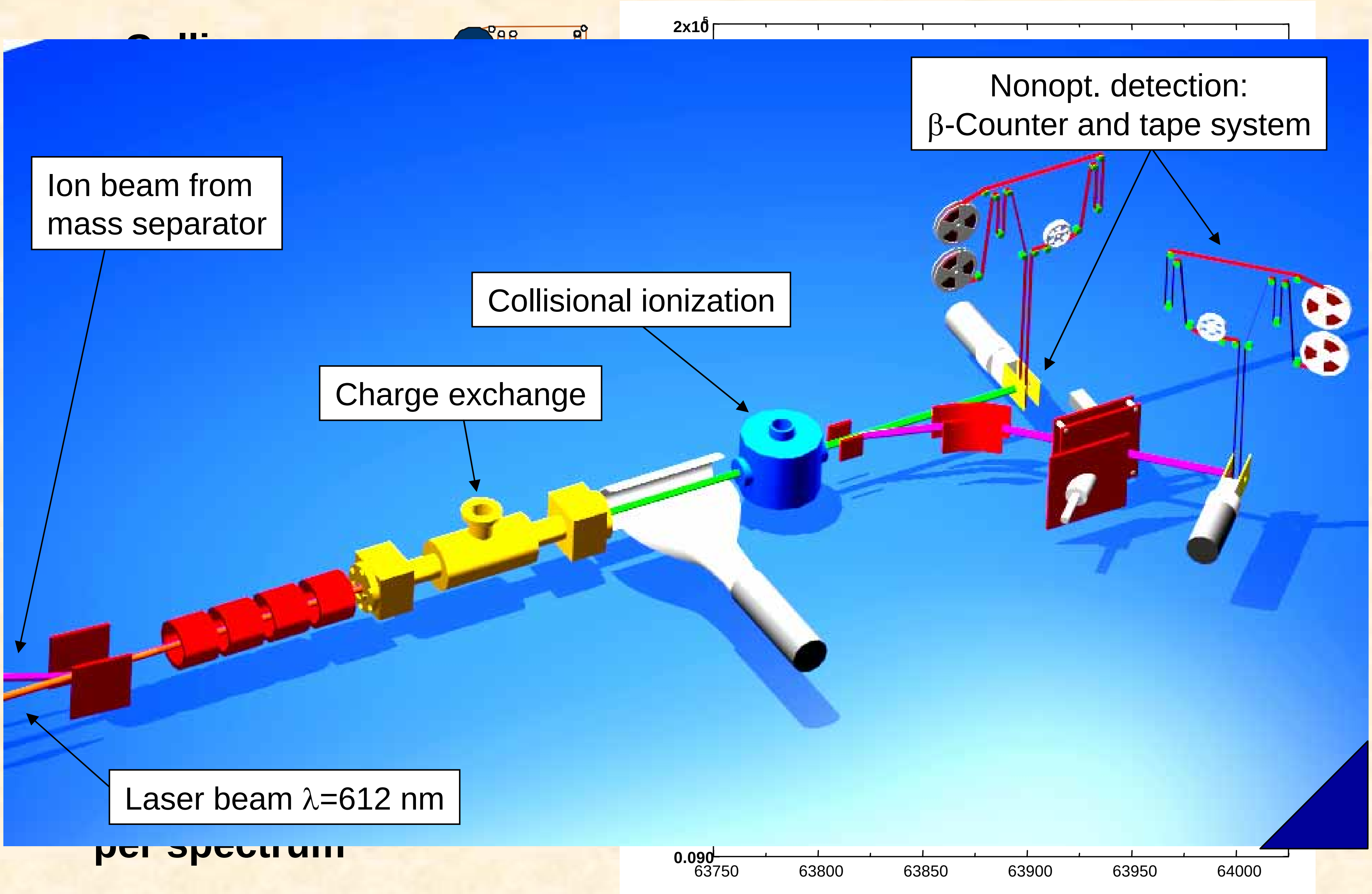
B $\Rightarrow$ electric quadrupole moment Q (I > 1/2)

Isotopic between two isotopes

$$\delta\nu_{IS}^{A,A'} = (K_{NMS} + K_{SMS}) * \frac{M_{A'} - M_A}{M_{A'}M_A} + F_{el.} * \delta\langle r^2\rangle^{A'A}$$

$\Rightarrow$ nuclear charge radii

HFS and IS measurements



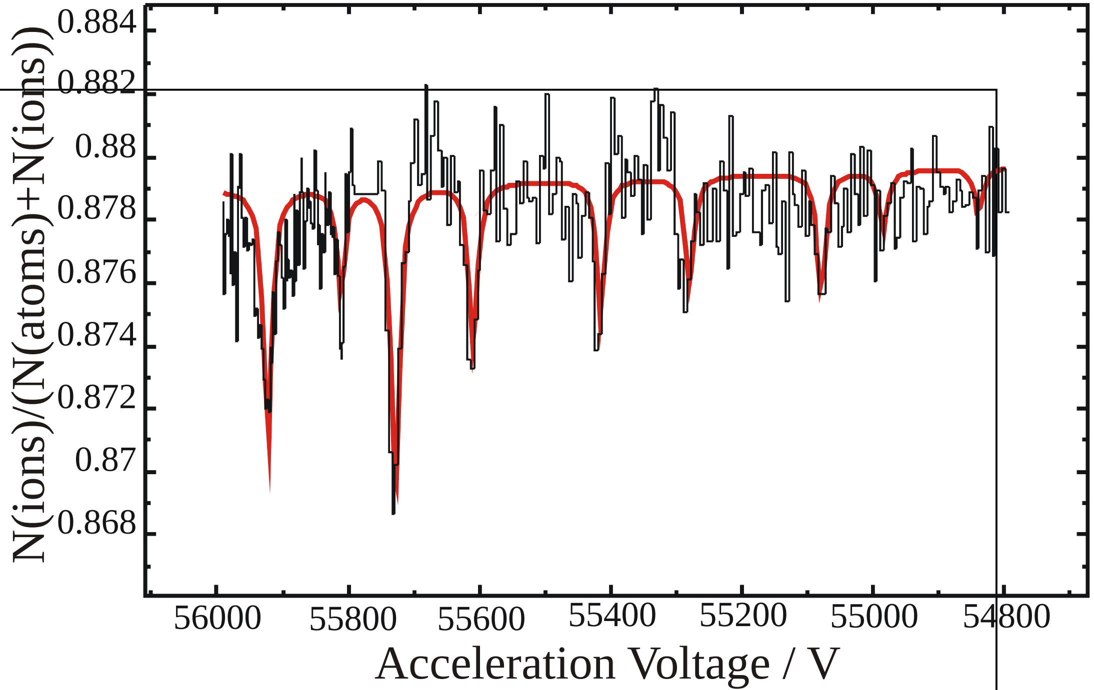
Recent Results on ^{73}Kr: nuclear moments & spin

Spin of ^{73}Kr long lasting open question:

- 5/2 ?? (spherical shell model, β-decay studies)

- 3/2 ?? (deformed shell model, β-decay studies)

- 7/2 ???



Laser-Spectroscopy:

- Spin-*measurement* from HFS:

  ⇒ I=3/2

- Nuclear moments from A-B-factors and reference to ^{83}Kr

Magnetic moment:

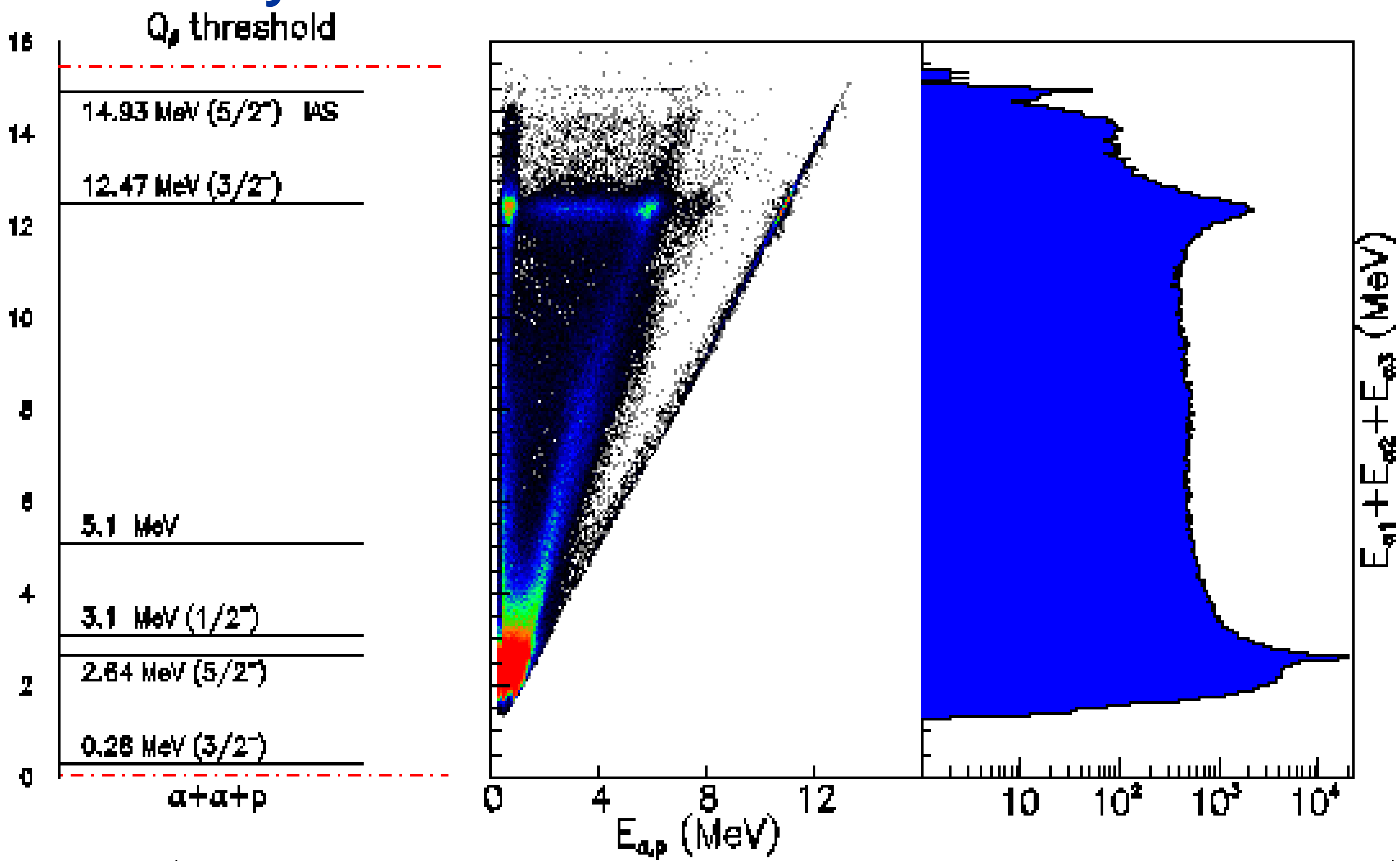
$$\mu(^{73}\mathrm{Kr}) = 0.912(3)\ \mu_N$$

Quadrupole moment:

$$Q_s(^{73}\mathrm{Kr}) = 0.63(2)\ \mathrm{b}$$

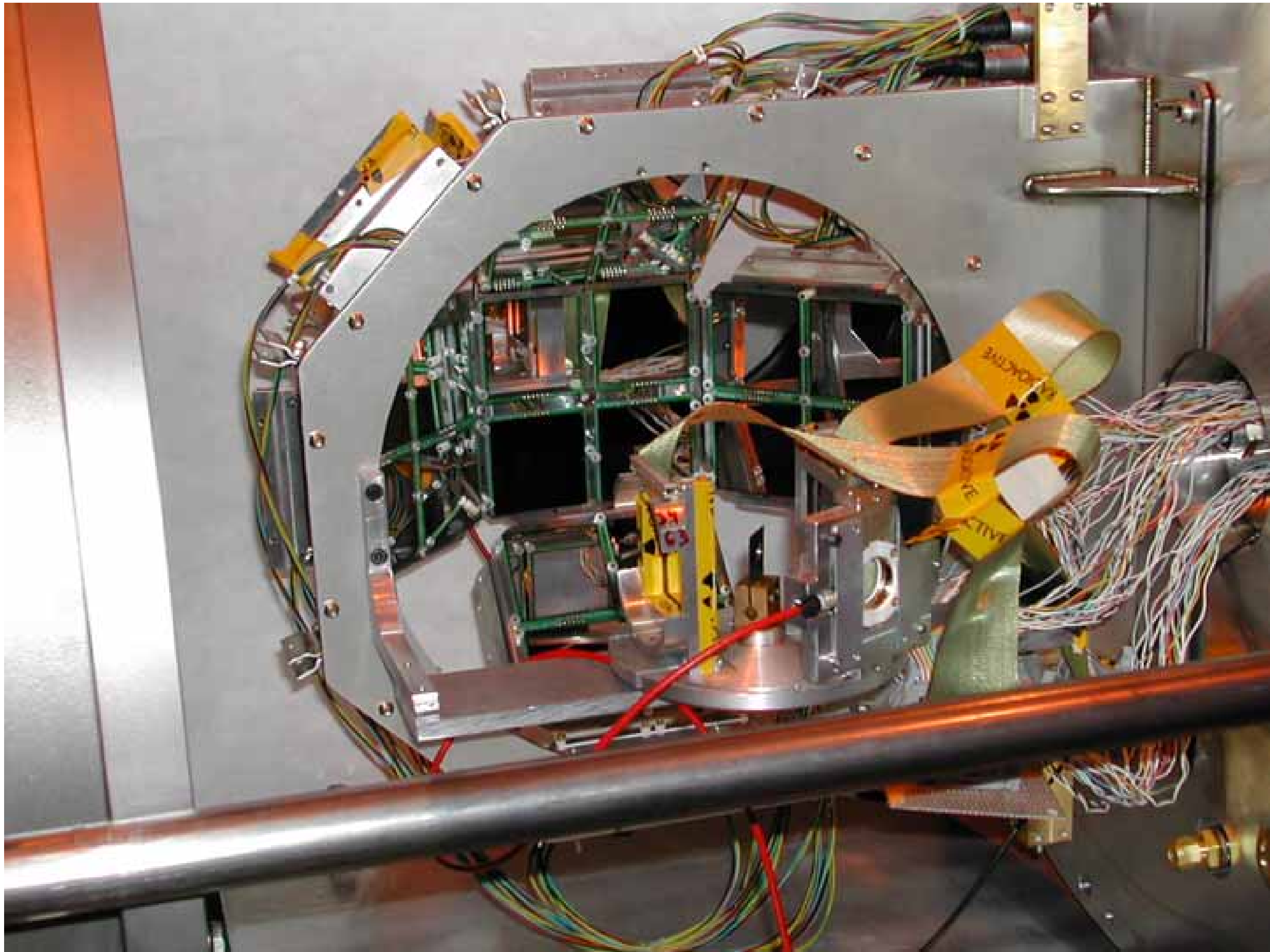
- Nuclear structure studies
  - Decay properties
  - Low-energy reactions

IS361: Unbound states in ^{9}B from ^{9}C β-decay



U.C.Bergmann et al. NPA692 (2001) 427

ISOLDE Si-ball (EP+EU project)



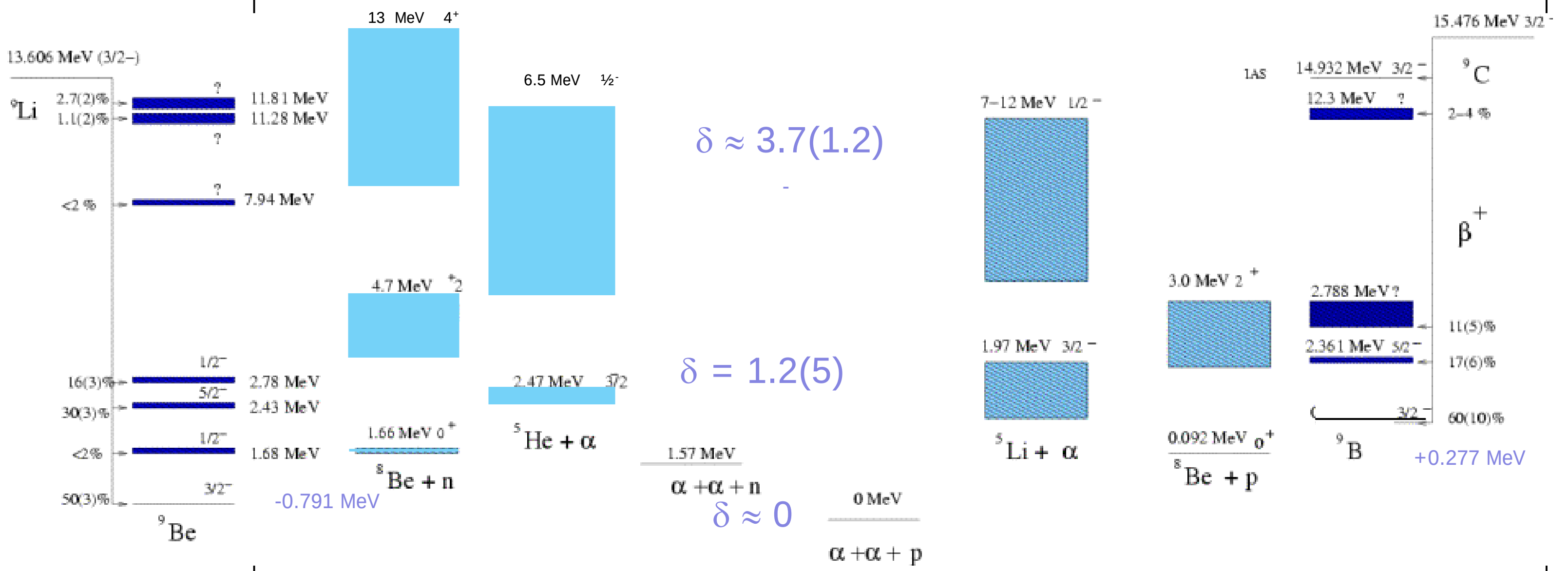
Mass 9 isobar

Large asymmetries

$$\delta = \frac{(ft)^+}{(ft)^-} - 1$$

Differences in radial w.f.

Binding energies effects



Nyman et al., NPA510 (1990)189

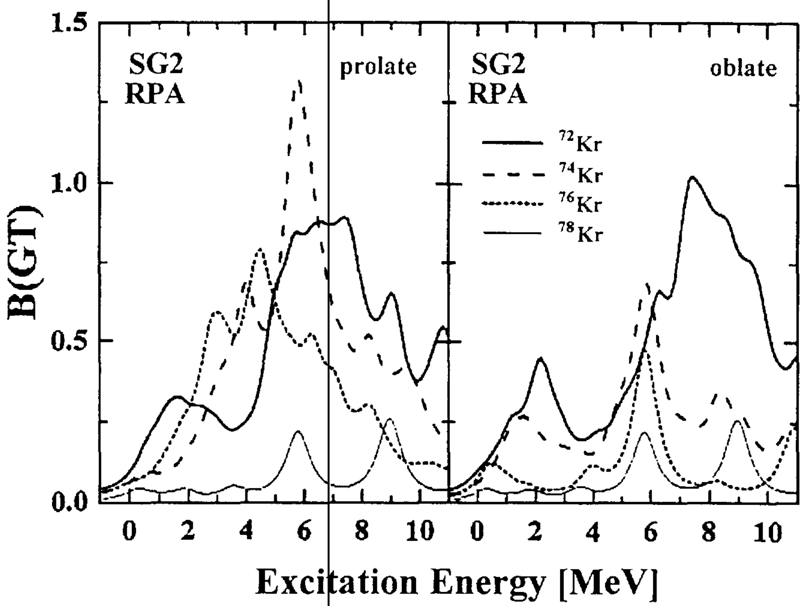
Bergmann et al. NPA692 (2001) 427

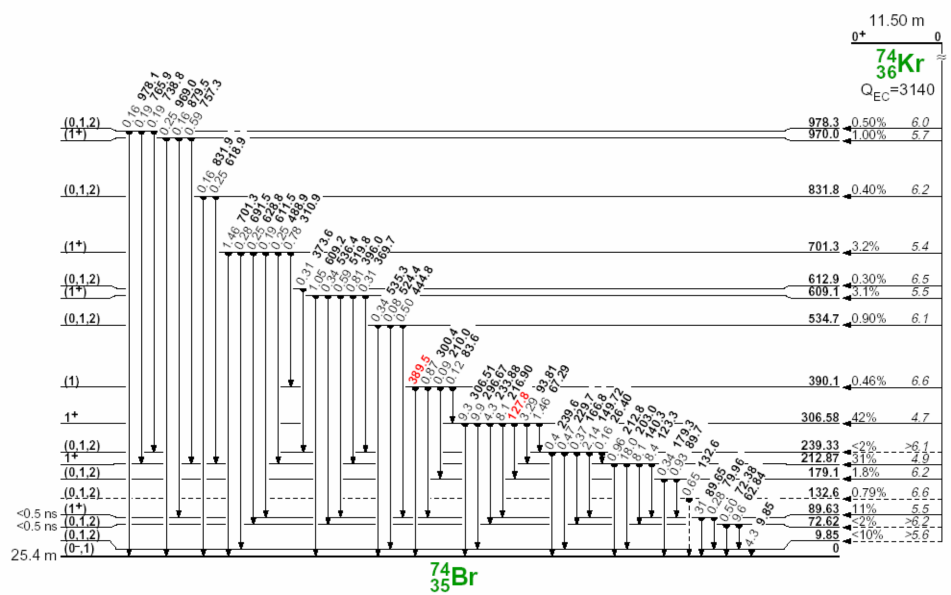
IS210

F. Ajzenberg-Selove NPA490 (1988) 1

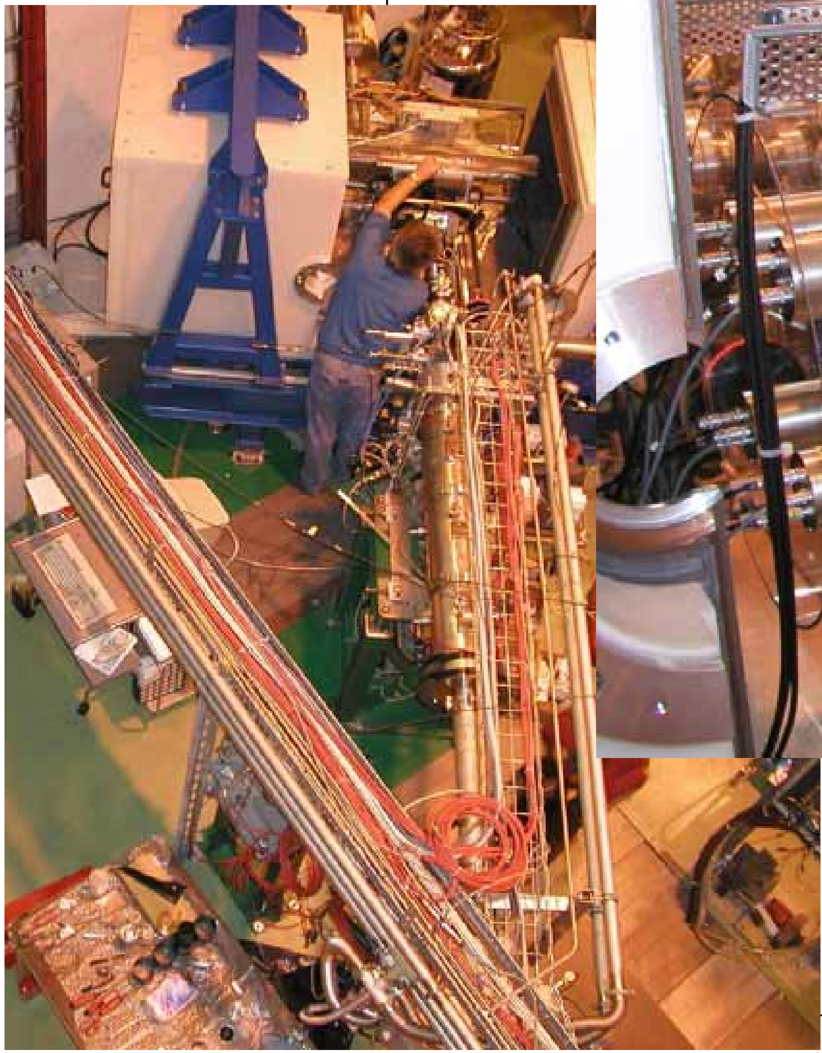
IS361

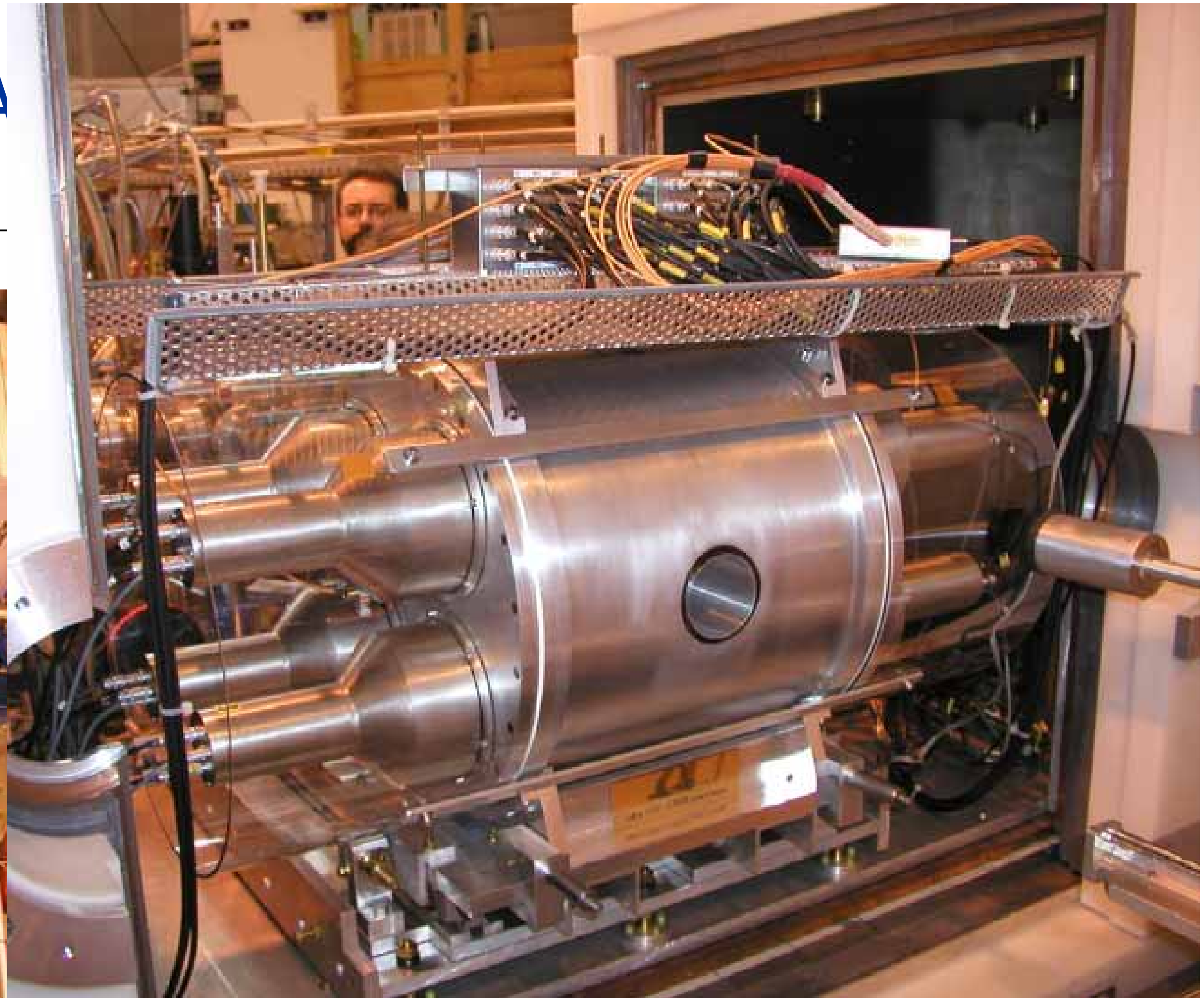
B(GT) along the N~Z line



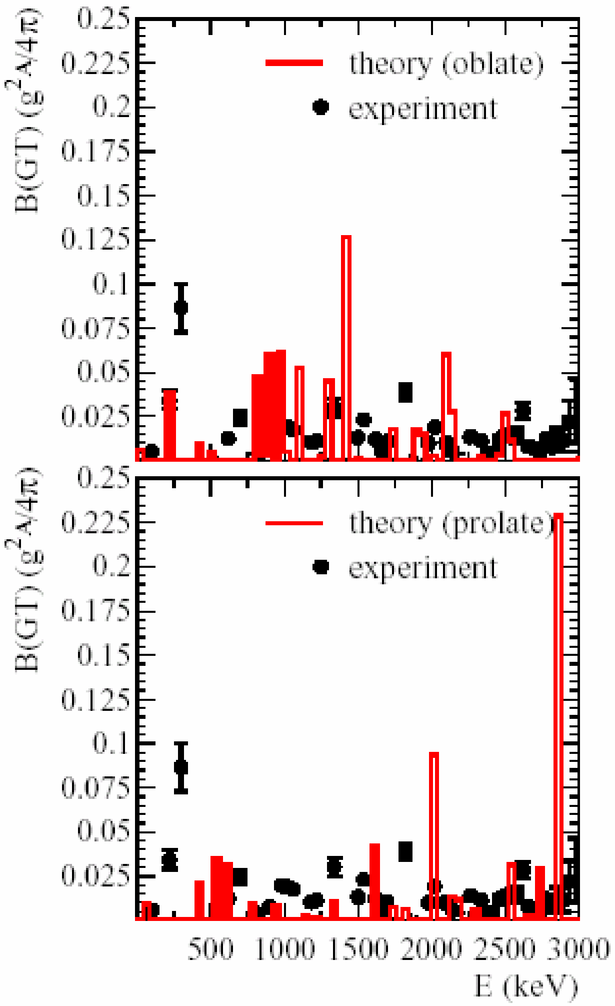


IS370 TA





The ^{74}Kr ground state



TAgS measurements (IS370 experiment)

- $\Sigma B(GT) = 0.67 \pm 0.03$ (0–3 MeV)

Theoretical calculations P.Sarriguren *et al.* NPA **691** (2001) 631

- $\Sigma B(GT) = 0.65$ (0–3 MeV) oblate shape
- $\Sigma B(GT) = 0.60$ (0–3 MeV) prolate shape

HF+BCS+QRPA
SG2 interaction

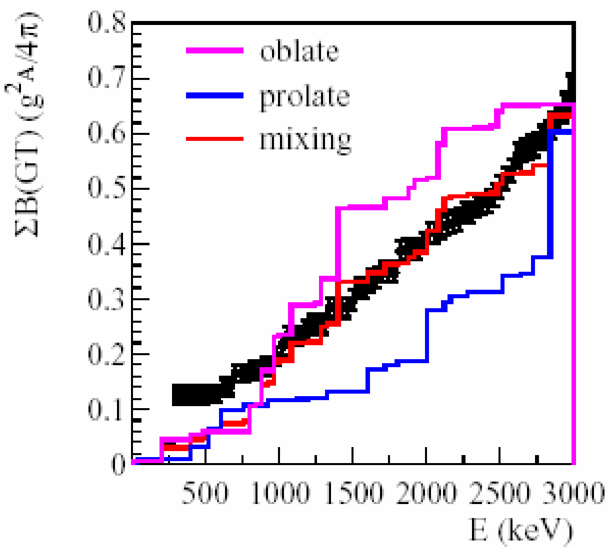
Neither oblate and prolate solutions reproduce exp. B(GT)

Description of the ground state as a mixing

$$|0^+> = \sqrt{\alpha}|0^+_{ob}> + \sqrt{(1-\alpha)}|0^+_{pr}>$$

mixing parameter $\alpha = 0.60$

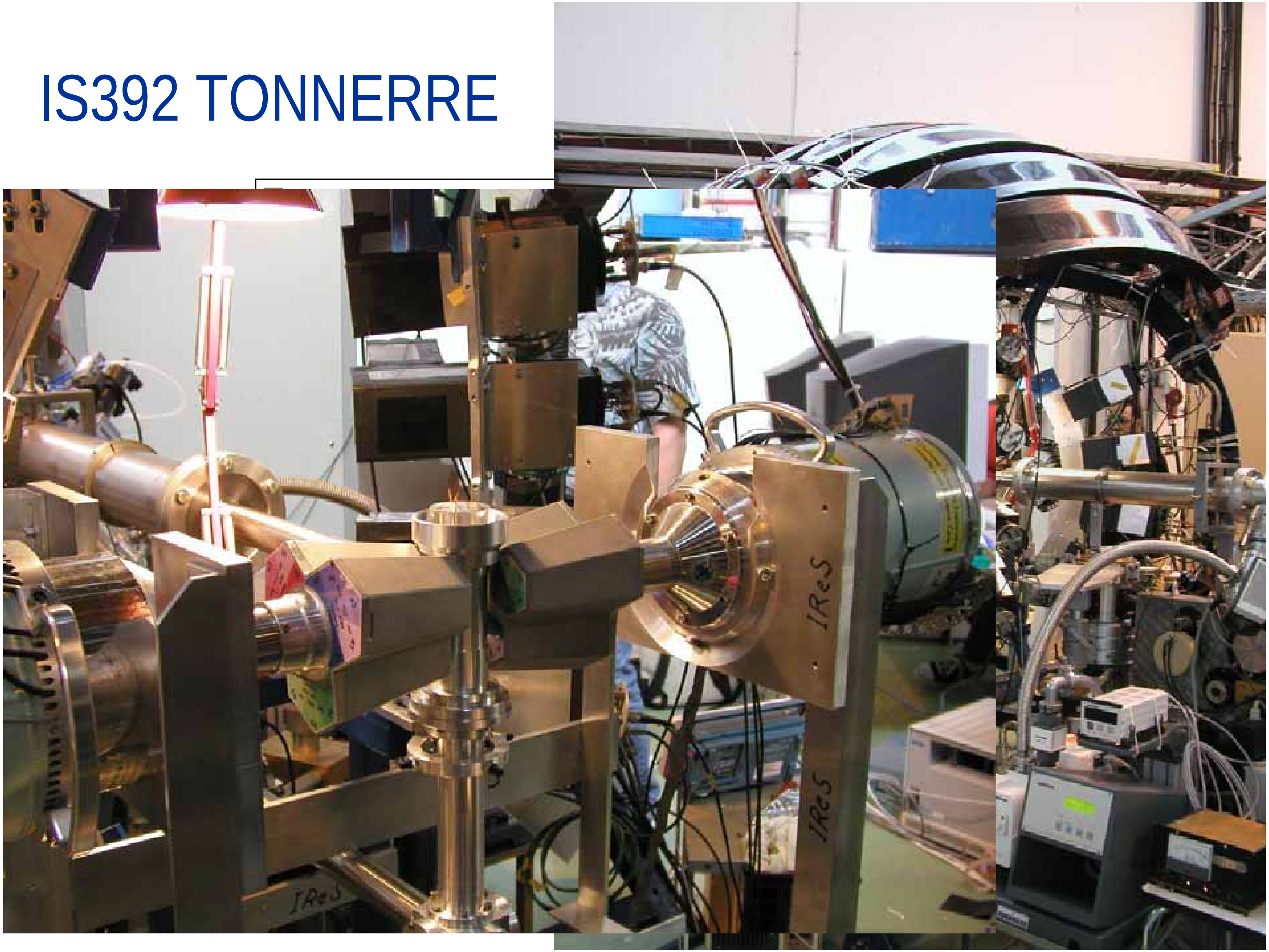
i. e. g. s. shape coexistence

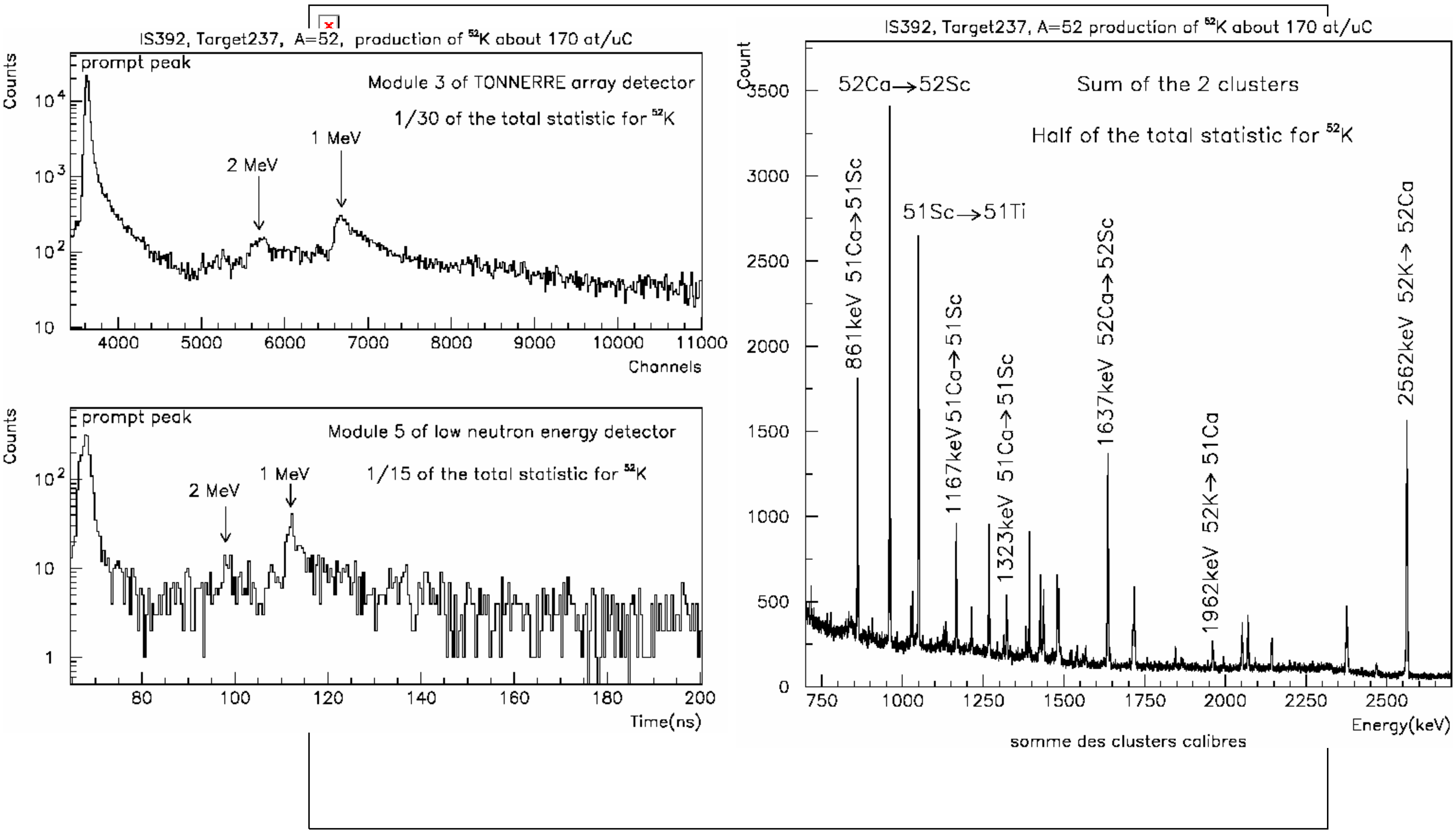


Agreement with in–beam results $\alpha = 0.52$

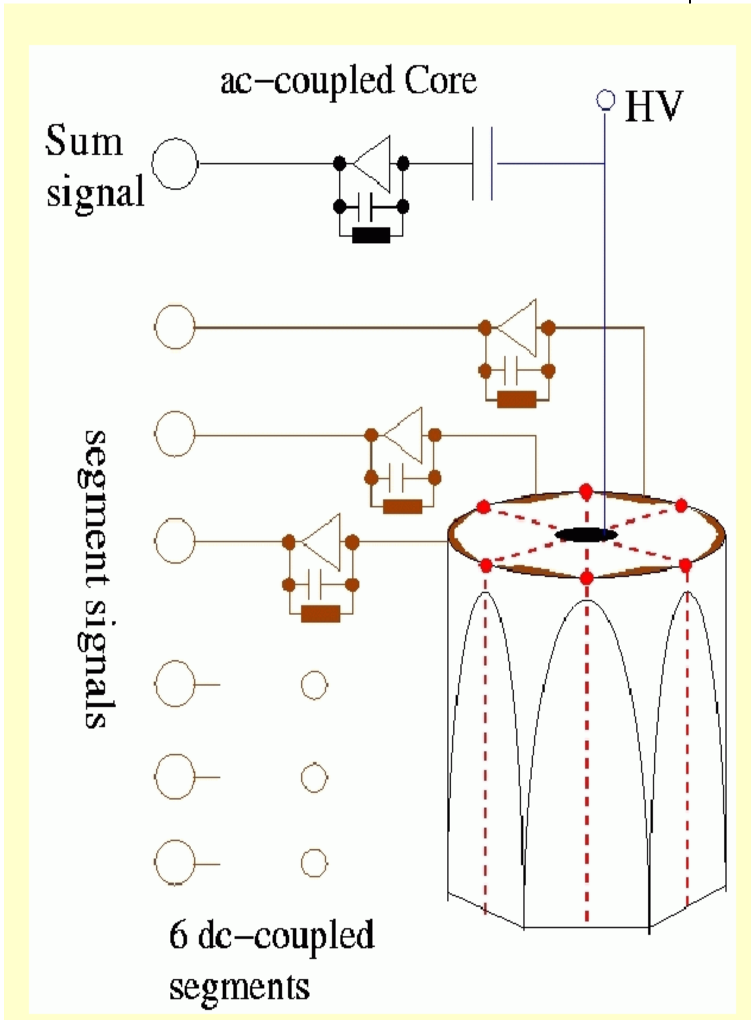
E. Poirier PhD. Thesis ULP Strasbourg (2002)

IS392 TONNERRE




IS392, Target237, A=52, production of 52K about 170 at/uC
prompt peak
Module 3 of TONNERRE array detector
1/30 of the total statistic for 52K
1 MeV
2 MeV
Counts
Channels
prompt peak
Module 5 of low neutron energy detector
1/15 of the total statistic for 52K
1 MeV
2 MeV
Counts
Time(ns)
IS392, Target237, A=52 production of 52K about 170 at/uC
Count
52Ca→52Sc
Sum of the 2 clusters
Half of the total statistic for 52K
51Sc→51Ti
861keV 51Ca→51Sc
1167keV 51Ca→51Sc
1323keV 51Ca→51Sc
1637keV 52Ca→52Sc
1962keV 52K→51Ca
2562keV 52K→52Ca
Energy(keV)
somme des clusters calibres

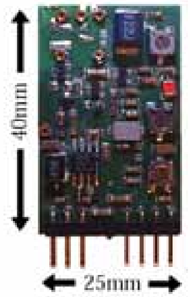
MINIBALL segmented Ge-detectors



ε=9.5% (1.3MeV) with
8*3 detectors,
2.3-2.6 keV res.

Digital electronics

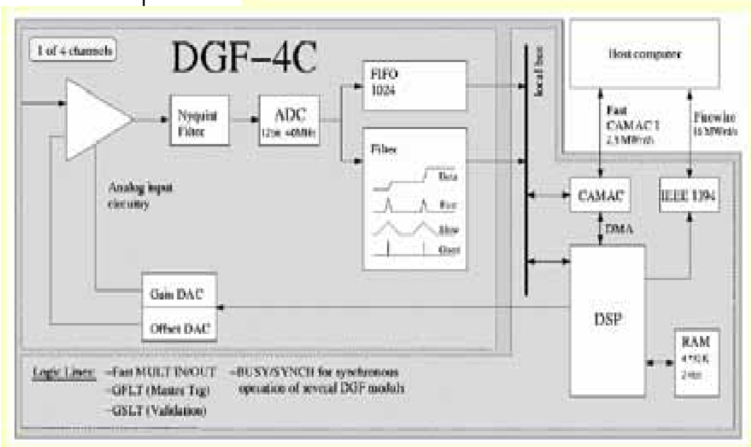
HEKO SMD Preamplifier

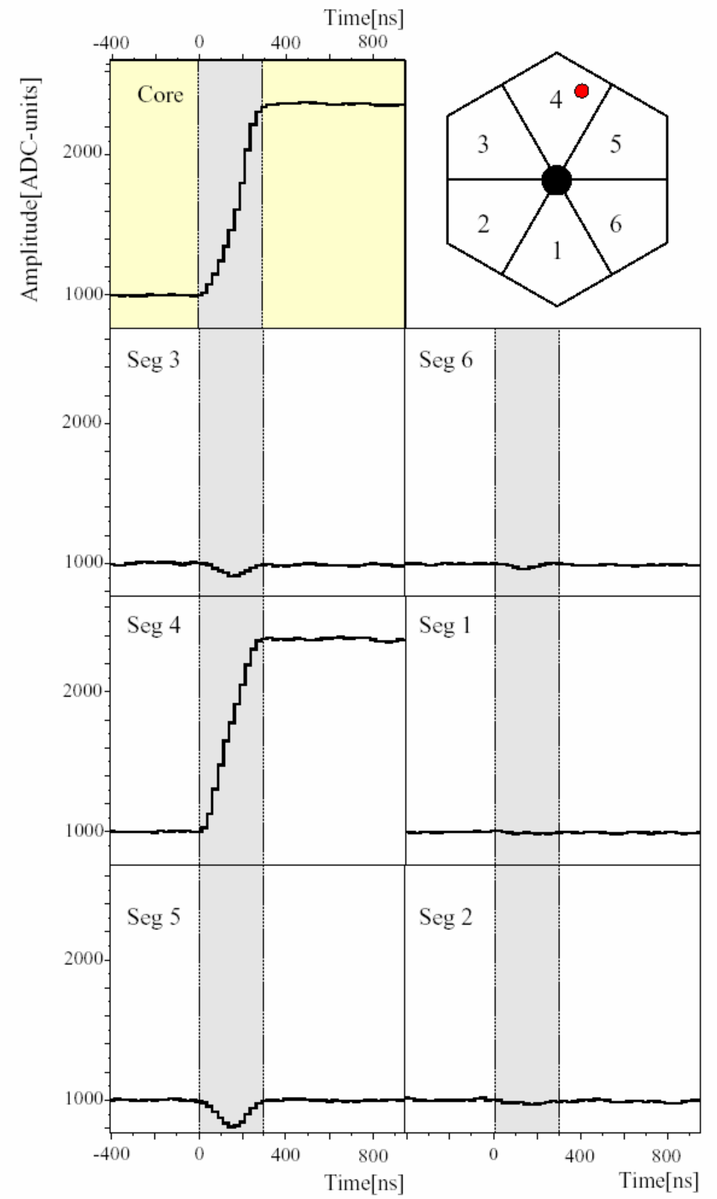


Gain: 175mV/MeV
Noise: 0.6keV at 0pF
Slope: 17eV/pF

Rise Time: 15ns at 0pF
Slope:0.3ns/pF

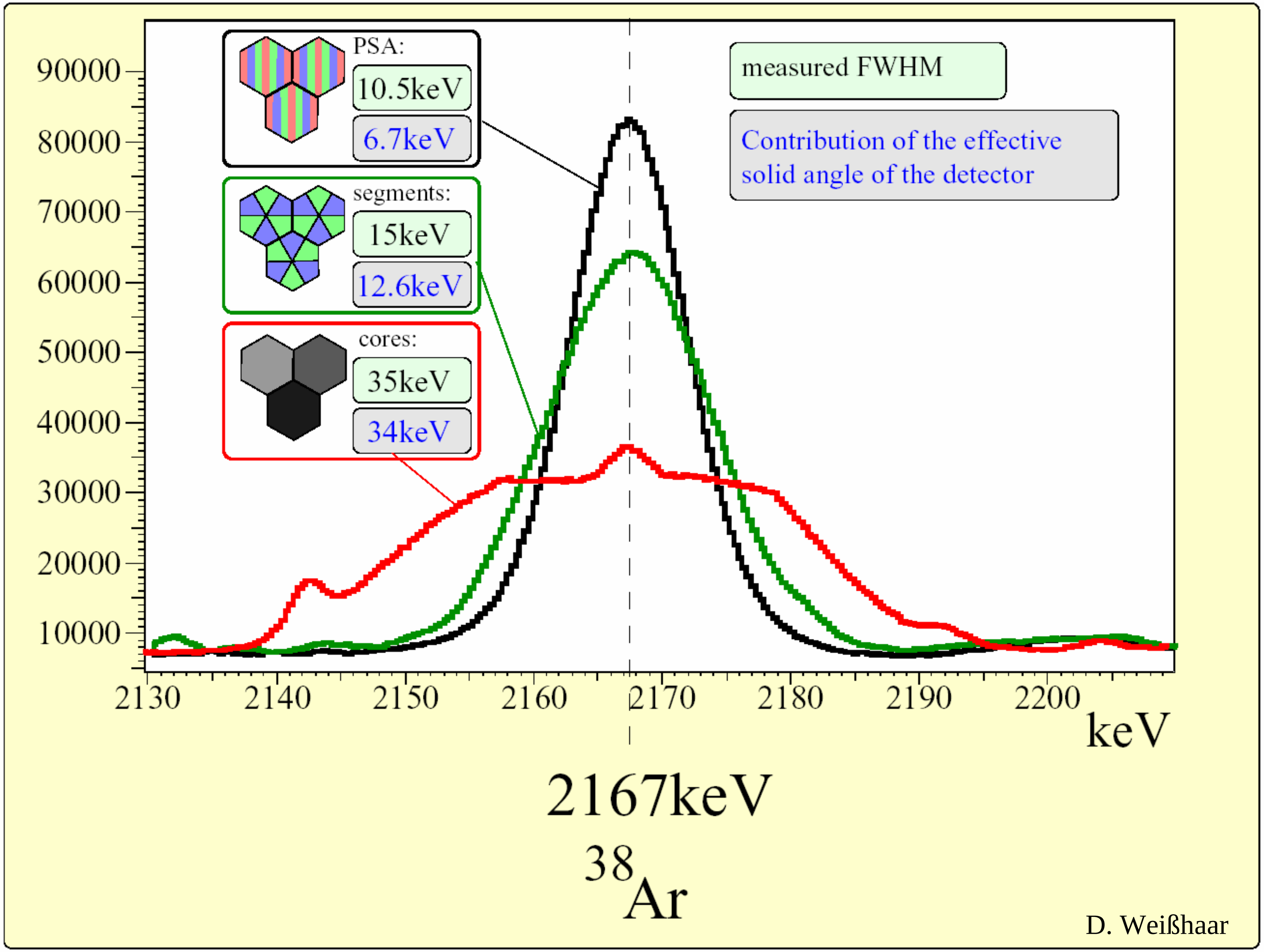
PPADC spectroscopy module XIA DGF-4C (CAMAC)





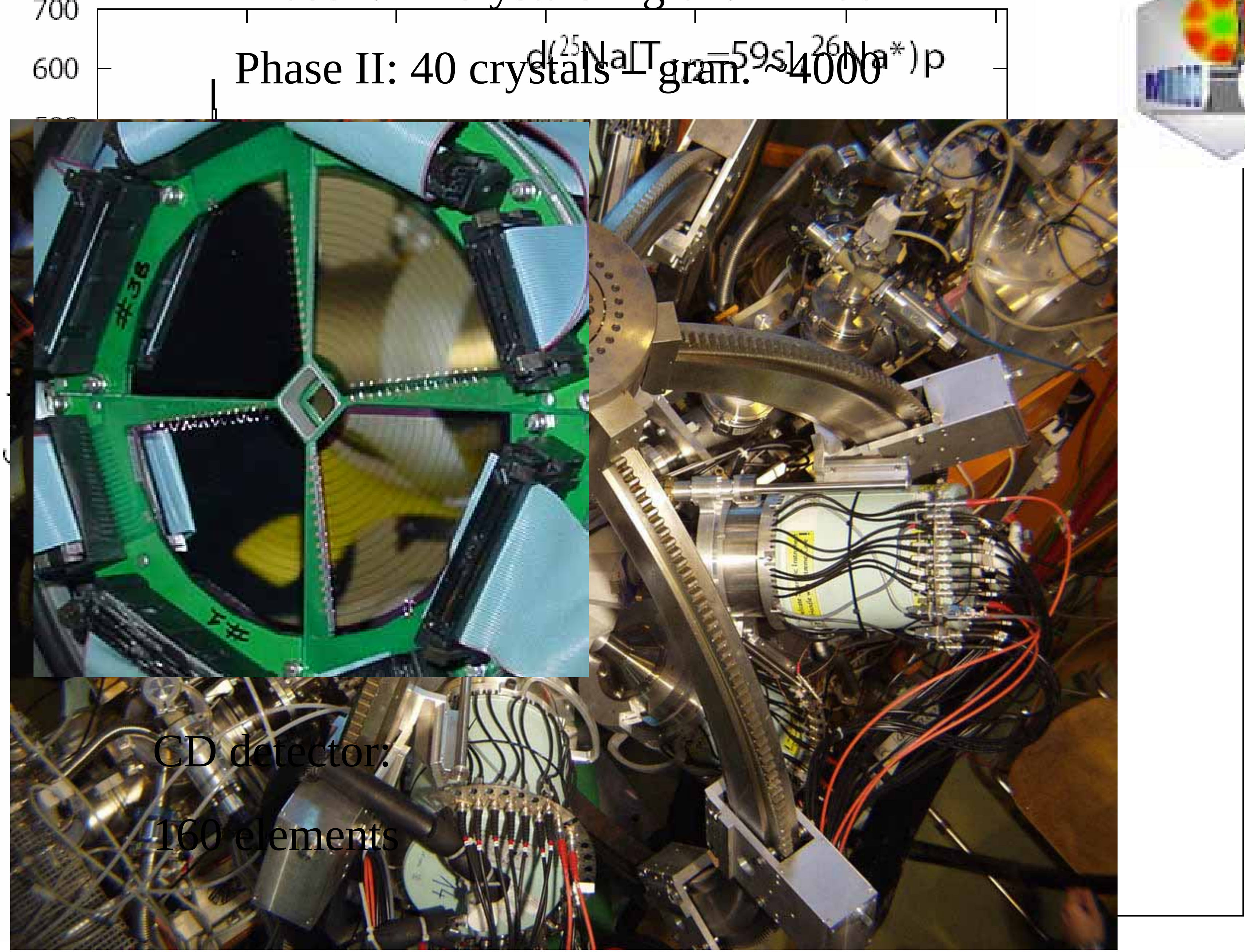
~16 * granularity

Position sensitivity in an in−beam experiment to reduce the Doppler−broadening (v/c=5.6%)



Phase I: 24 crystals – gran. ~ 2400

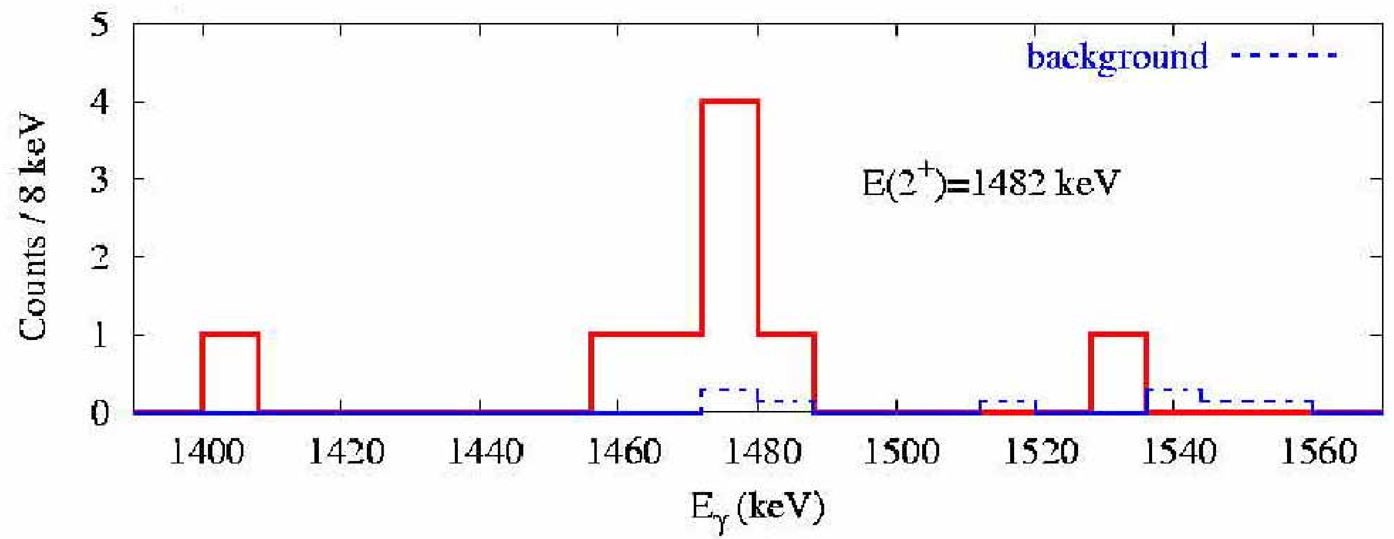
Phase II: 40 crystals – gran. ~4000



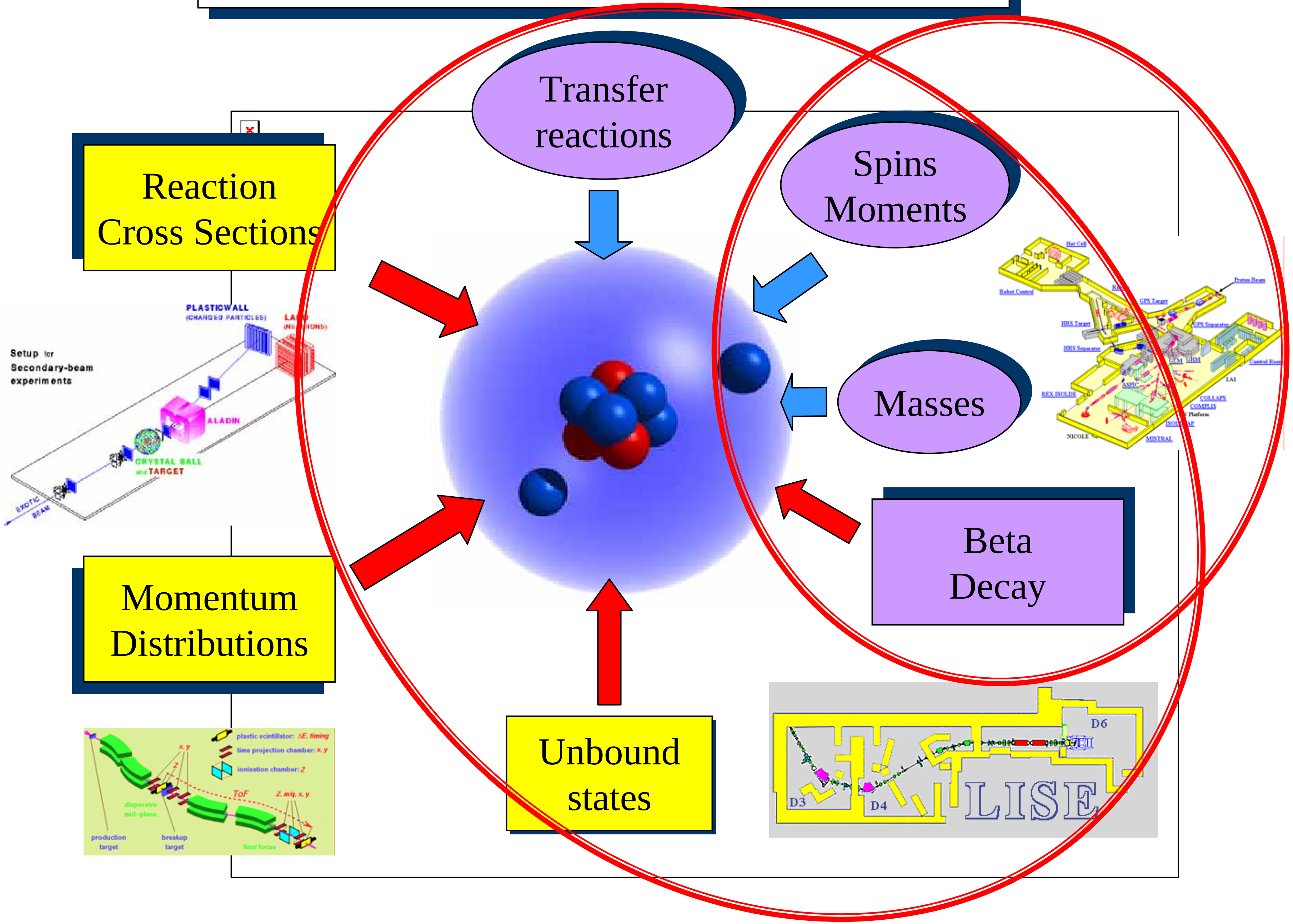
CD detector:

160 elements

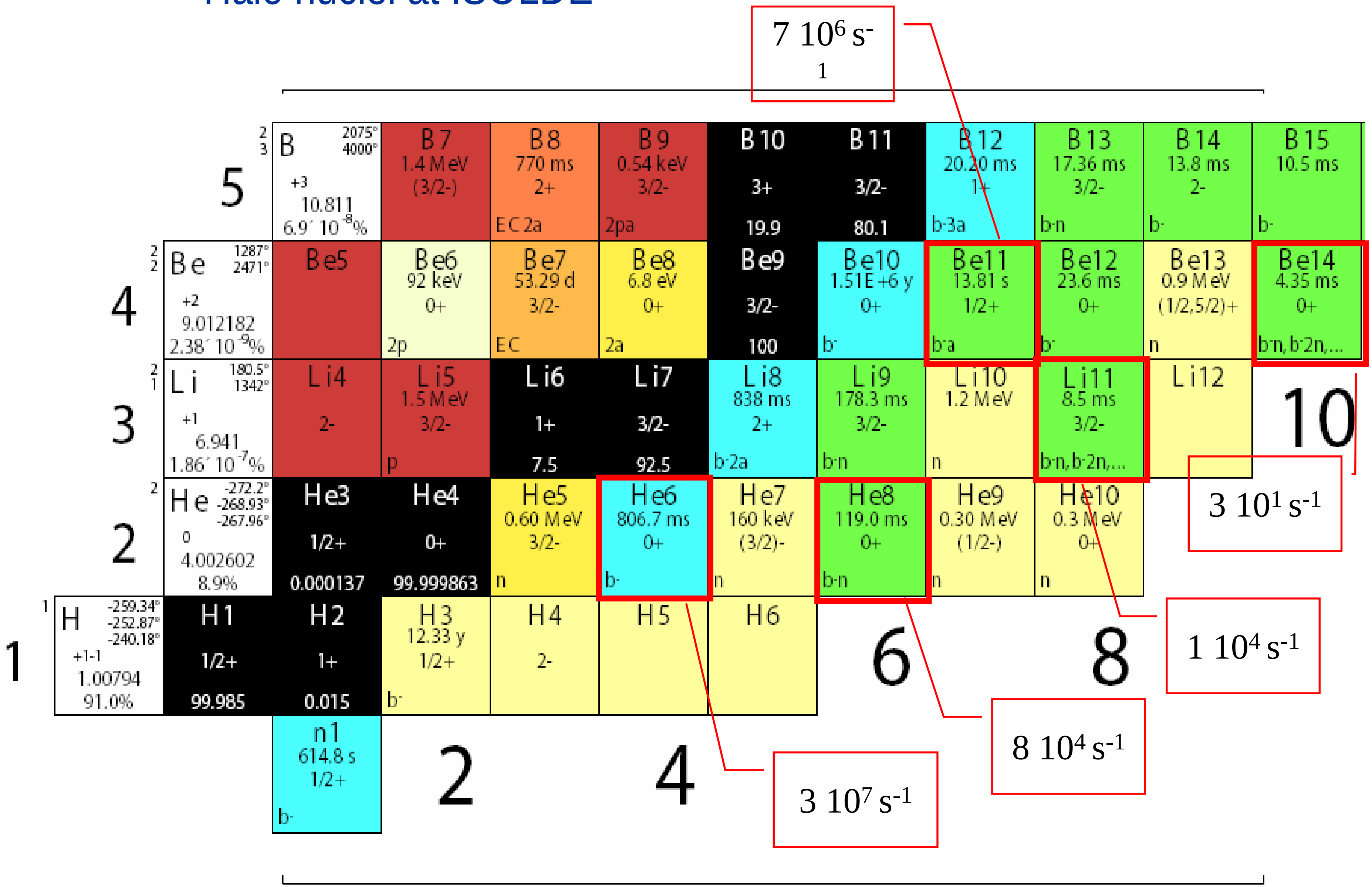
Coulomb excitation of ^{30}Mg



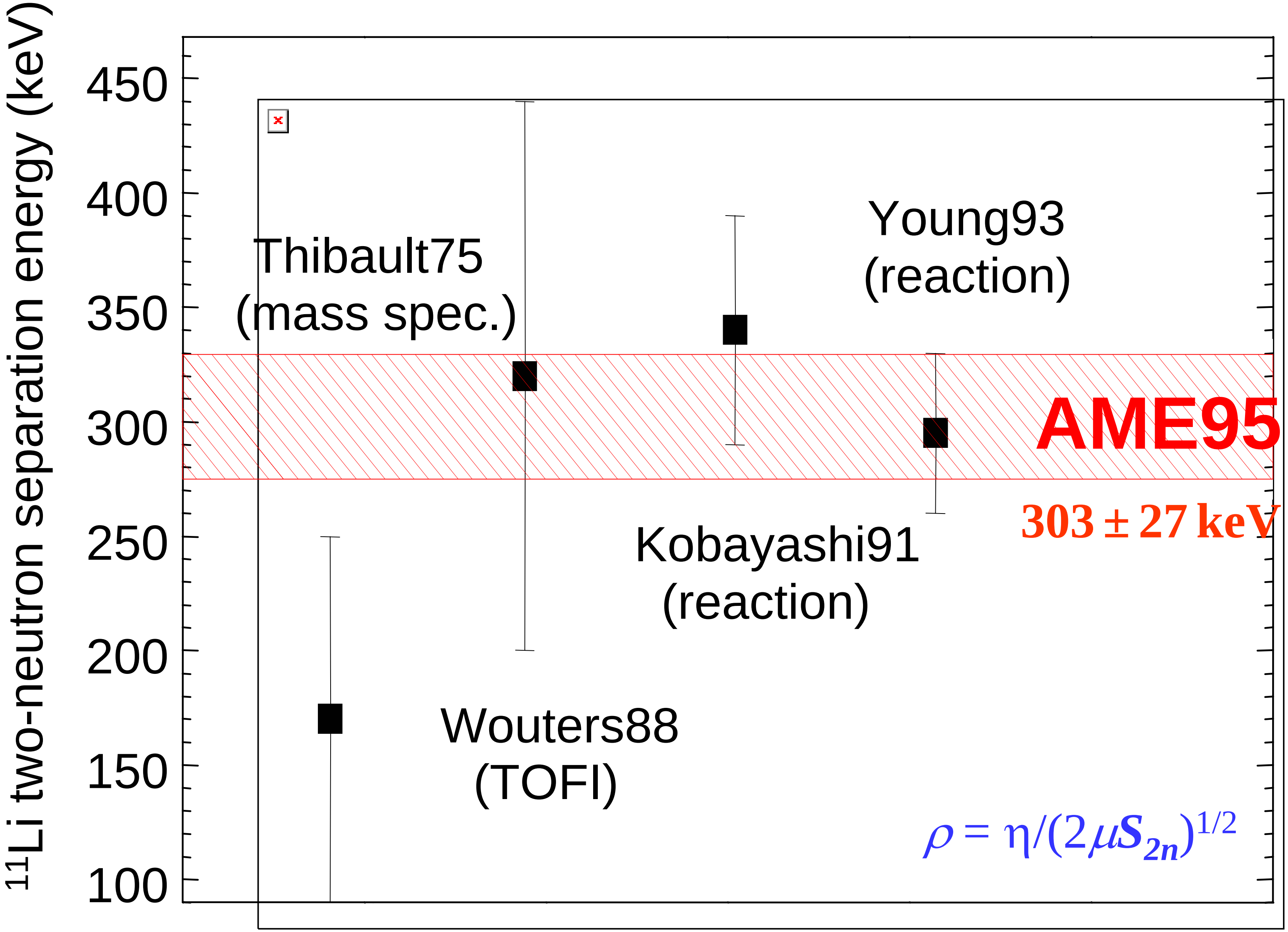
Halo Nuclei – a Dripline Phenomenon



Halo nuclei at ISOLDE

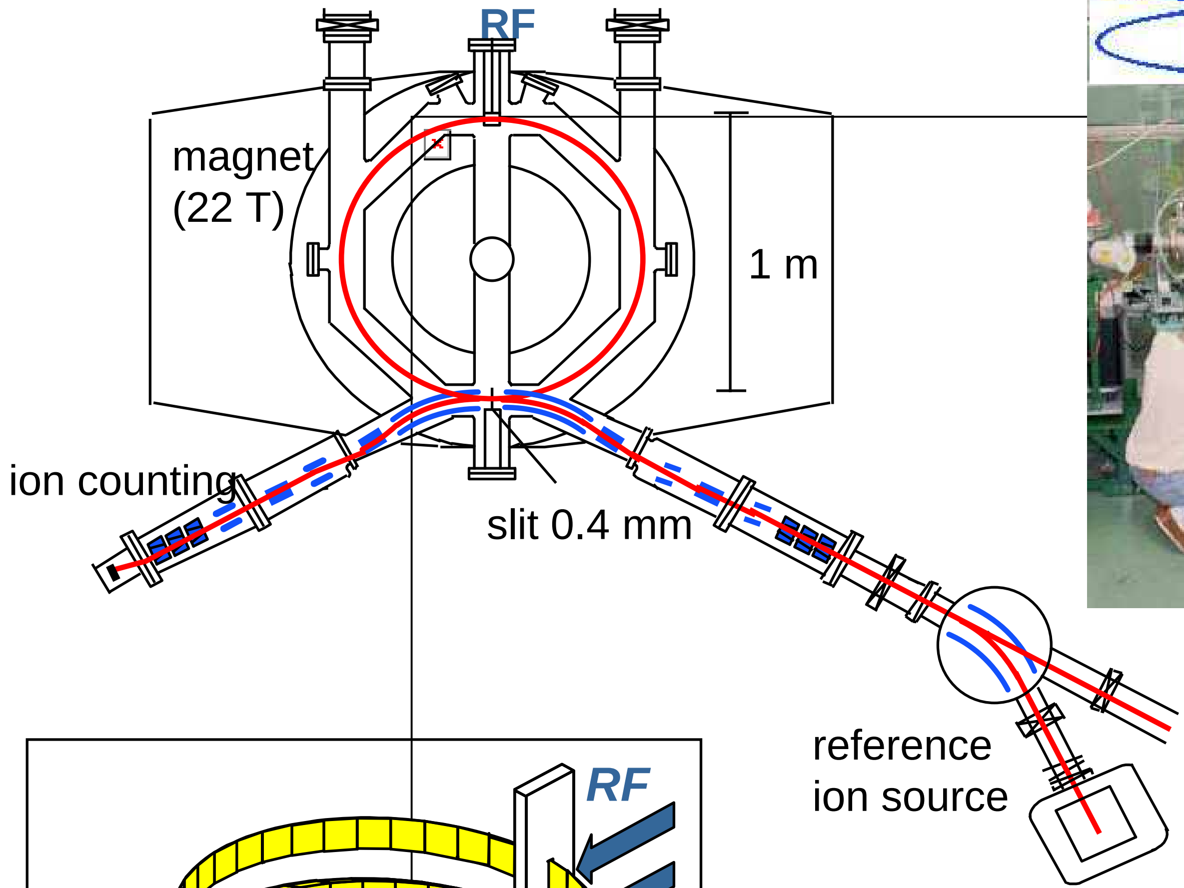


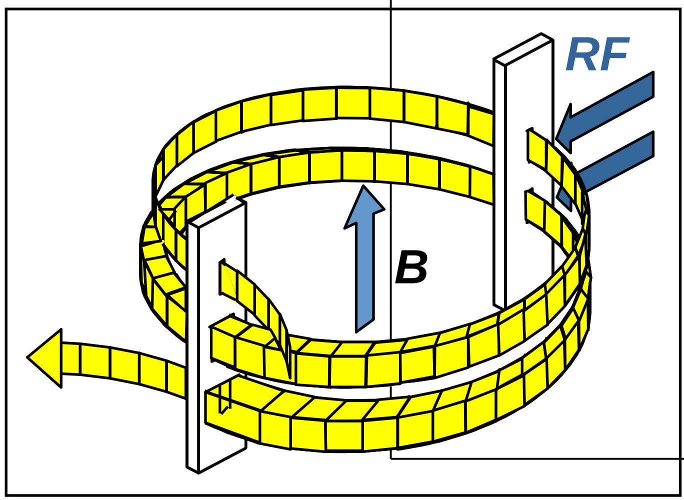
mass measurements of ^{11}Li

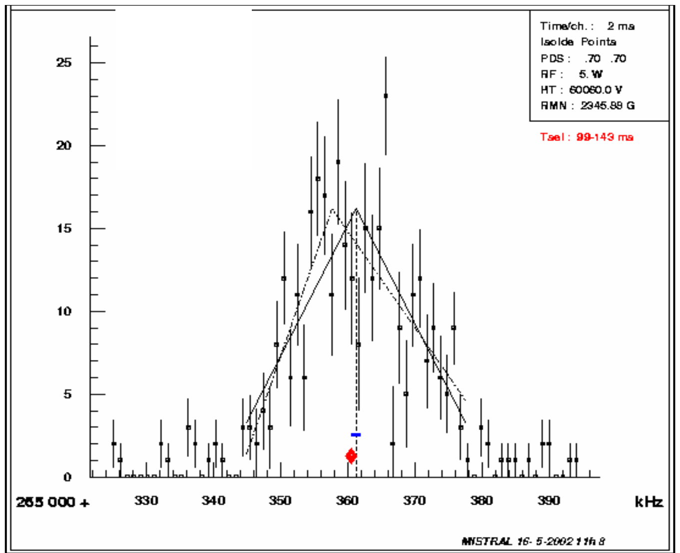


D. Lunney

Mass measurement of ^{11}Li at *ISOLDE* with *MISTRAL*





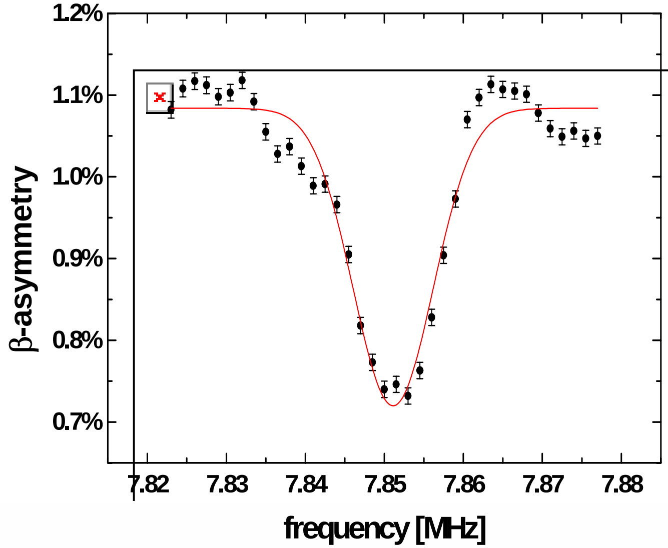


AME: S_{2n} = 303 ± 27 keV

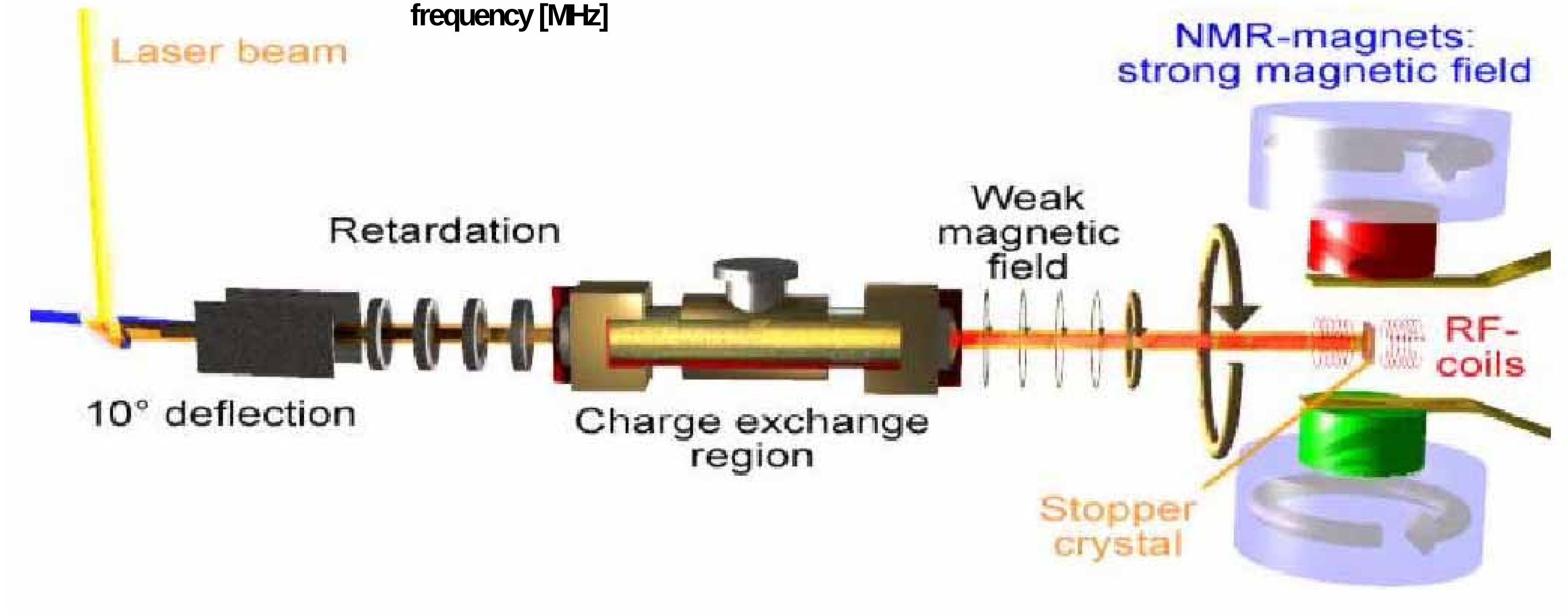
Mistral should achieve < 20 keV

D. Lunney

COLLAPS – polarized RIBs - β-NMR

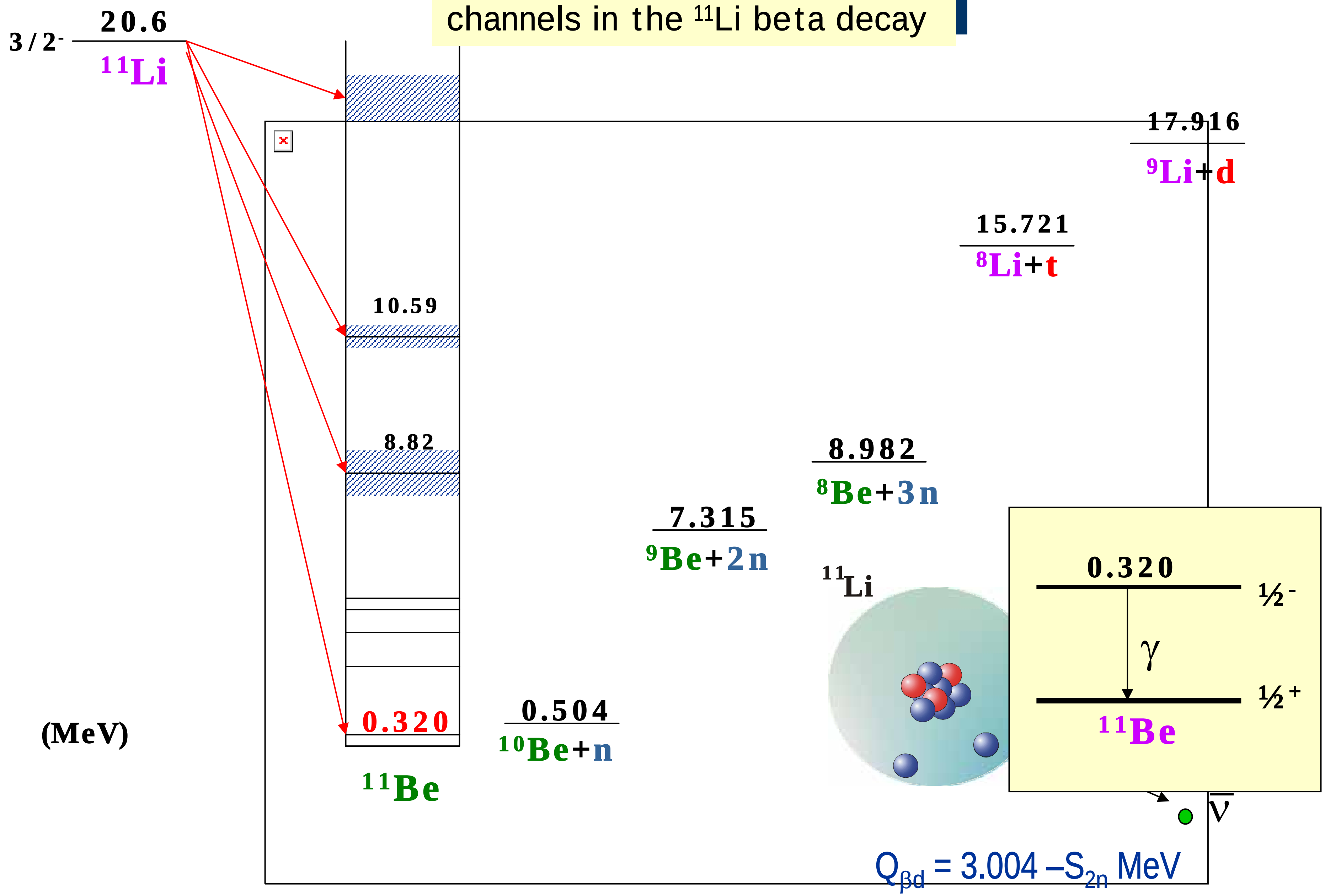


$\mu_I(^{11}Be) = -1.682(3)\ \mu_N$

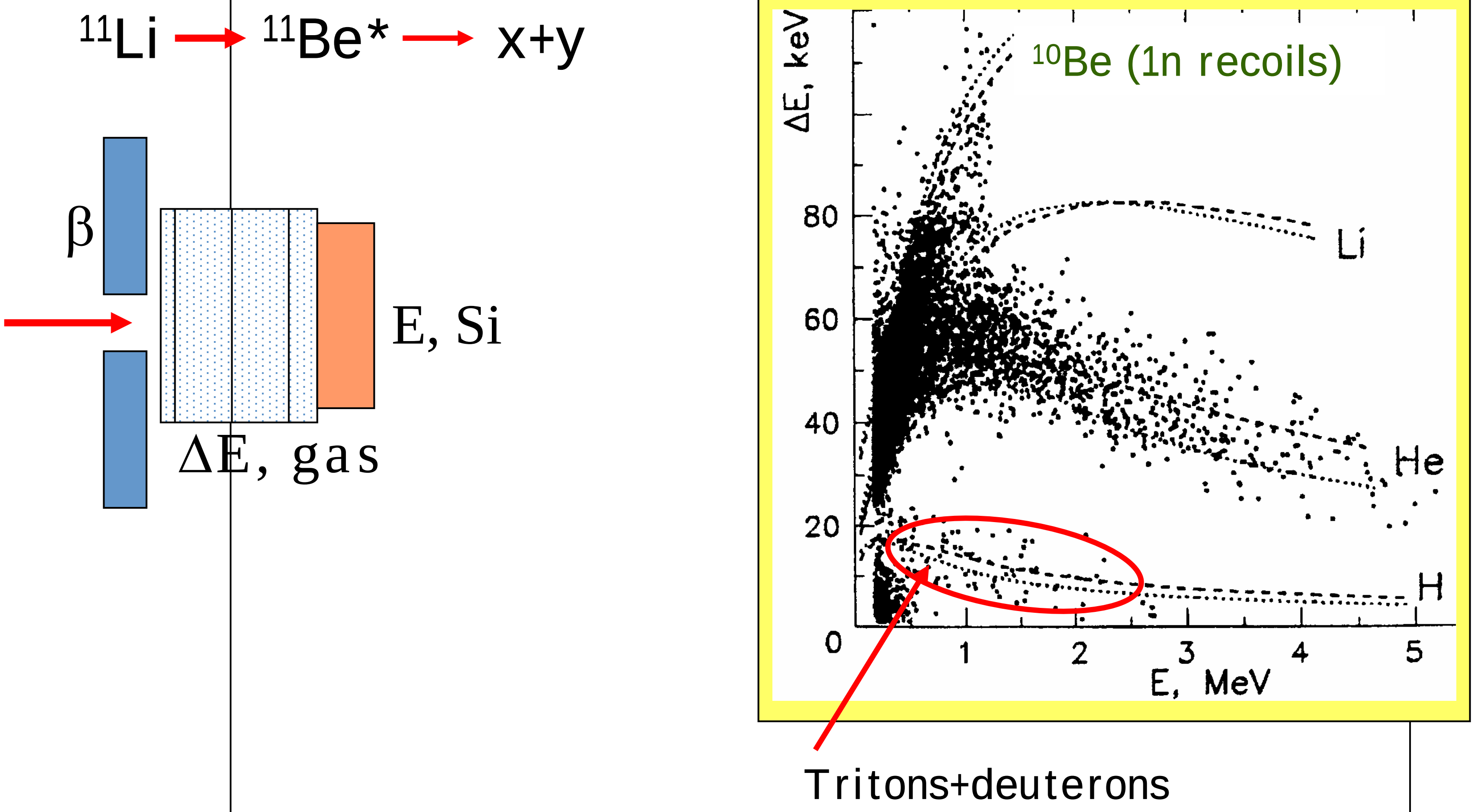


W. Geithner et al., PRL 83 (1999) 3793

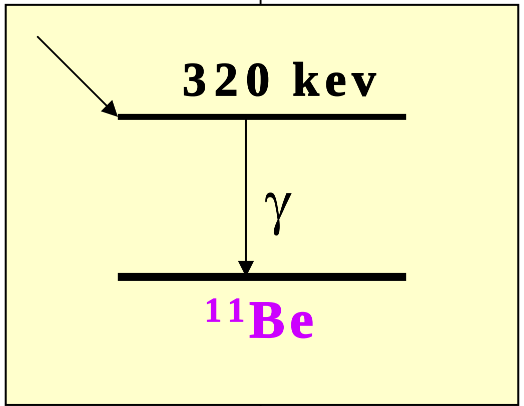
Open delayed-particle channels in the ^{11}Li beta decay

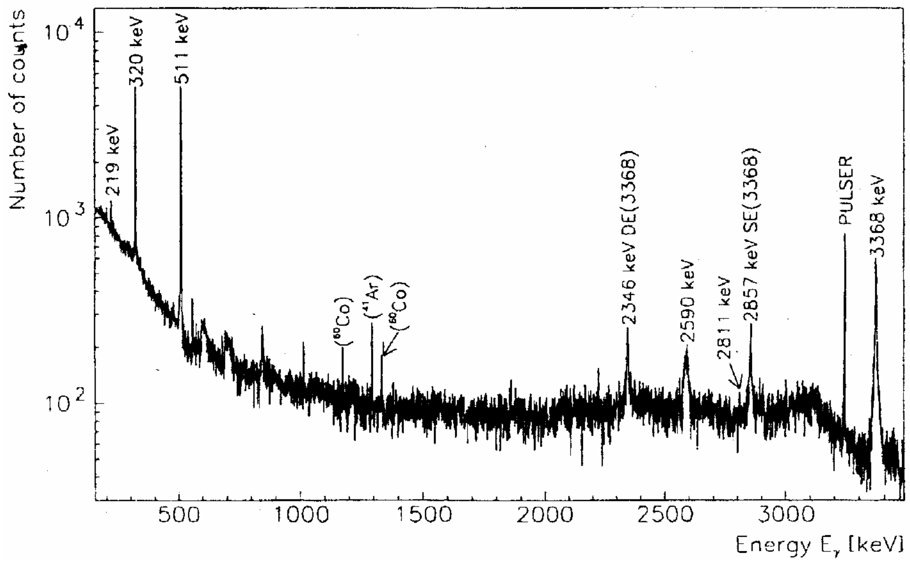


^{11}Li, charged particles



^{11}Li, gamma rays





M.J.G. Borge et al., PRC55 (97) R8

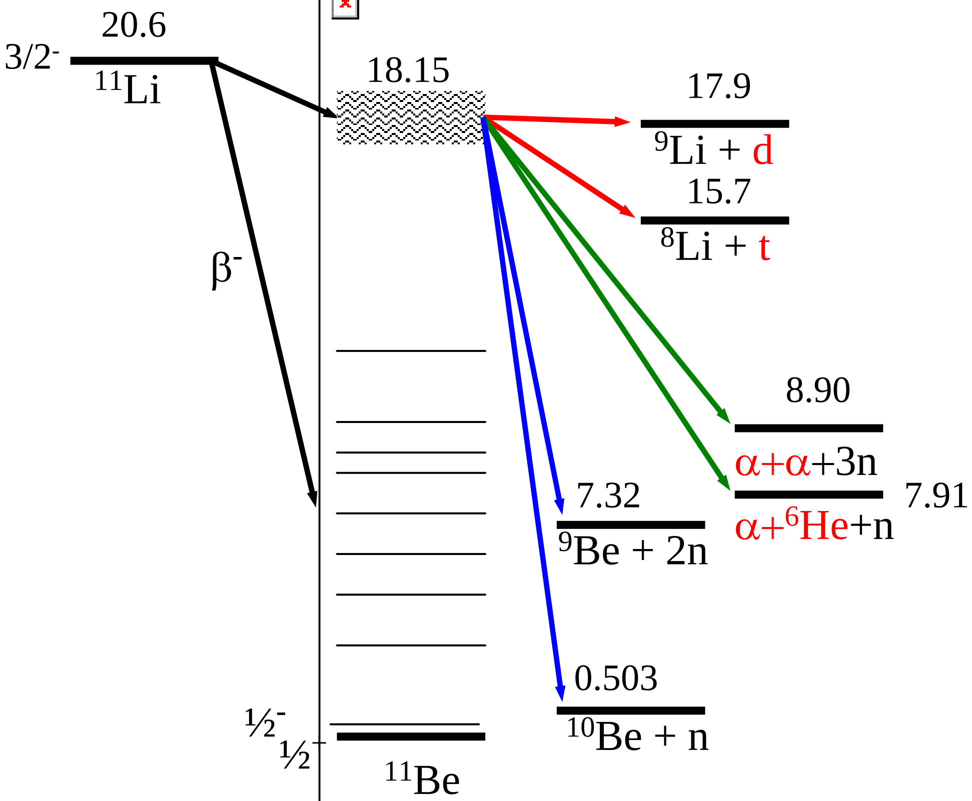
N. Aoi et al., NPA616 (97) 181c

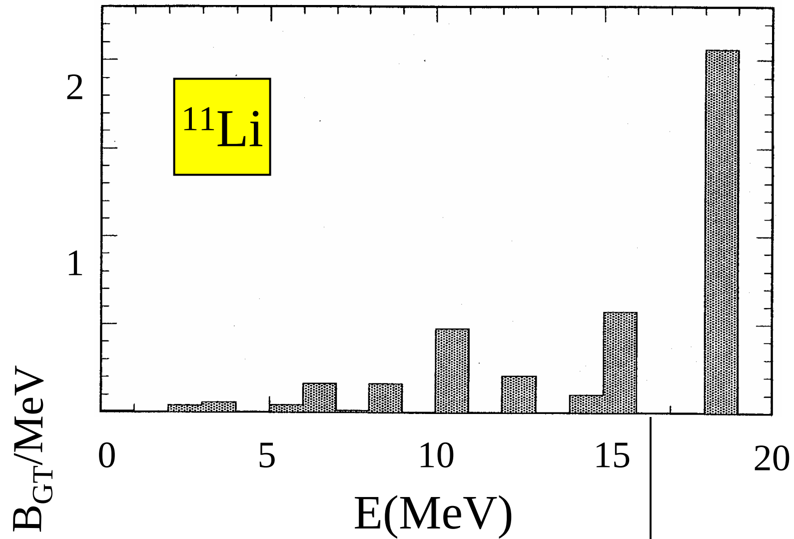
D. Morrisey et al., NPA627 (97) 222

Q = 20.62, $T_{1/2}$ = 8.2 ms
b(320) = 6.3(6) %
log *ft* = 5.73

$(1s_{1/2})^2/(0p_{1/2})^2 \sim 1$

Beta-strength function





M.J.G. Borge et al, PRC 55 (1997) R8

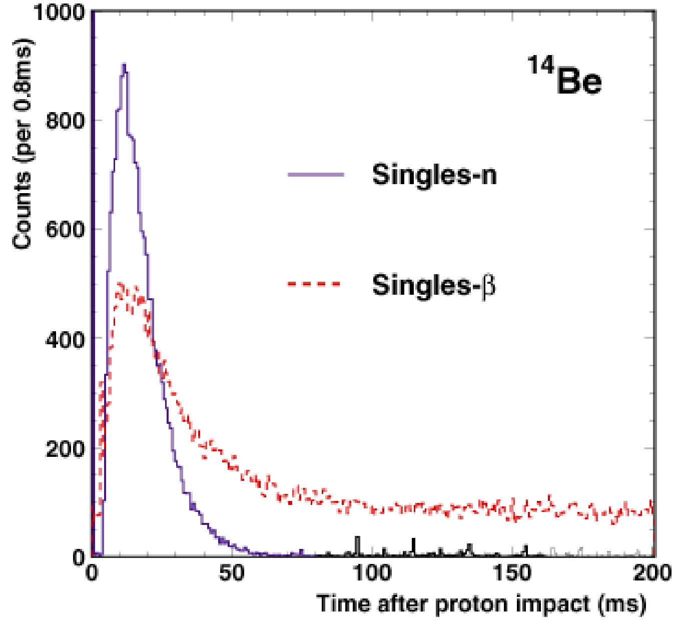
I.Mukha et al., PL B367 (1996) 65

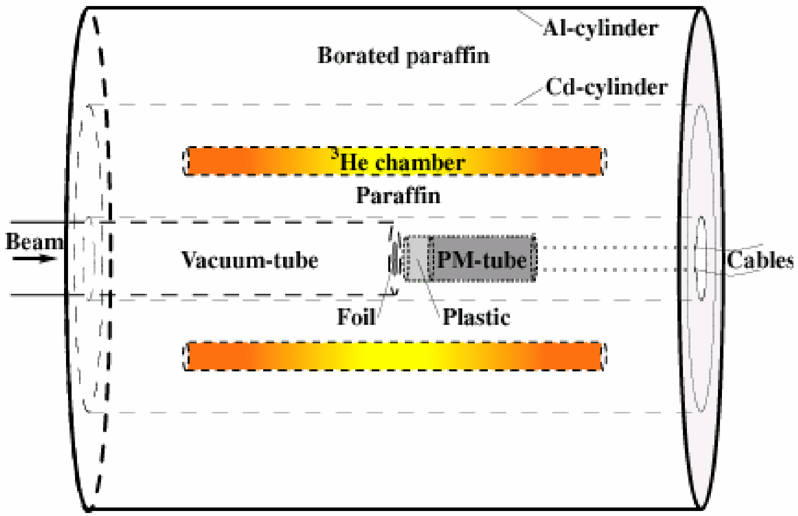
M.J.G. Borge et al.. Nucl. Phys. A613 (1997) 199

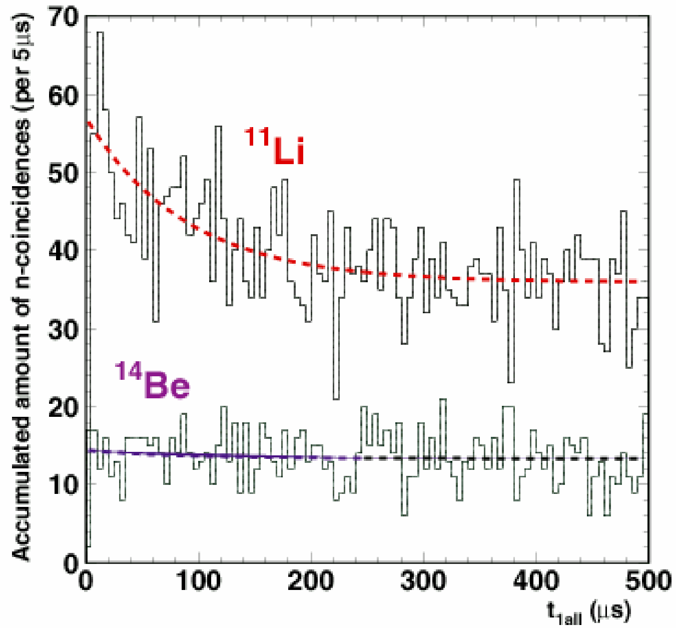
Beta-delayed neutrons from ^{14}Be

$$P_n = \Sigma\, i\, P_{in} = 101(4)\ \%$$

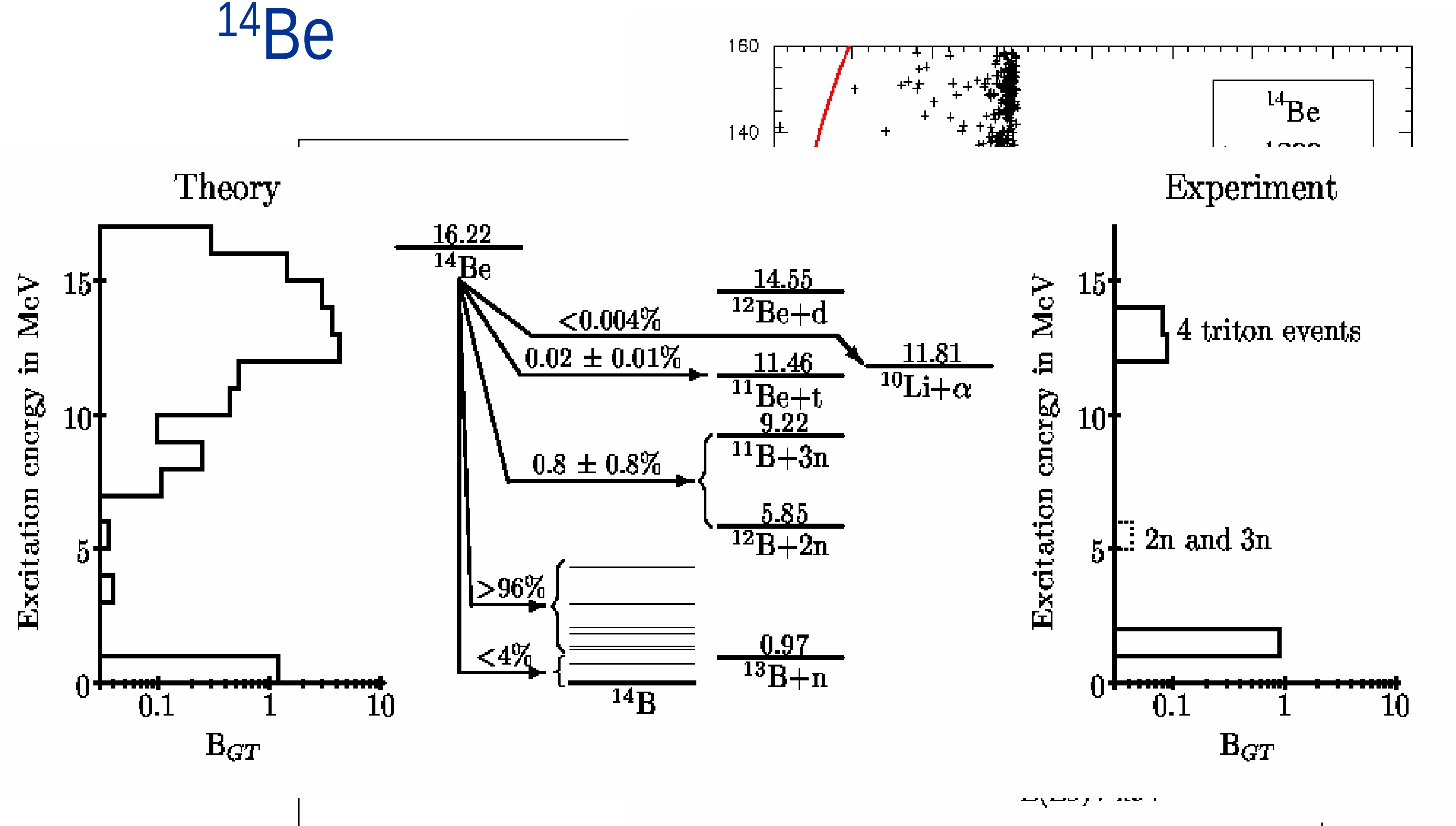
$$P_{2n} + 3P_{3n} = 0.8(8)\ \%$$







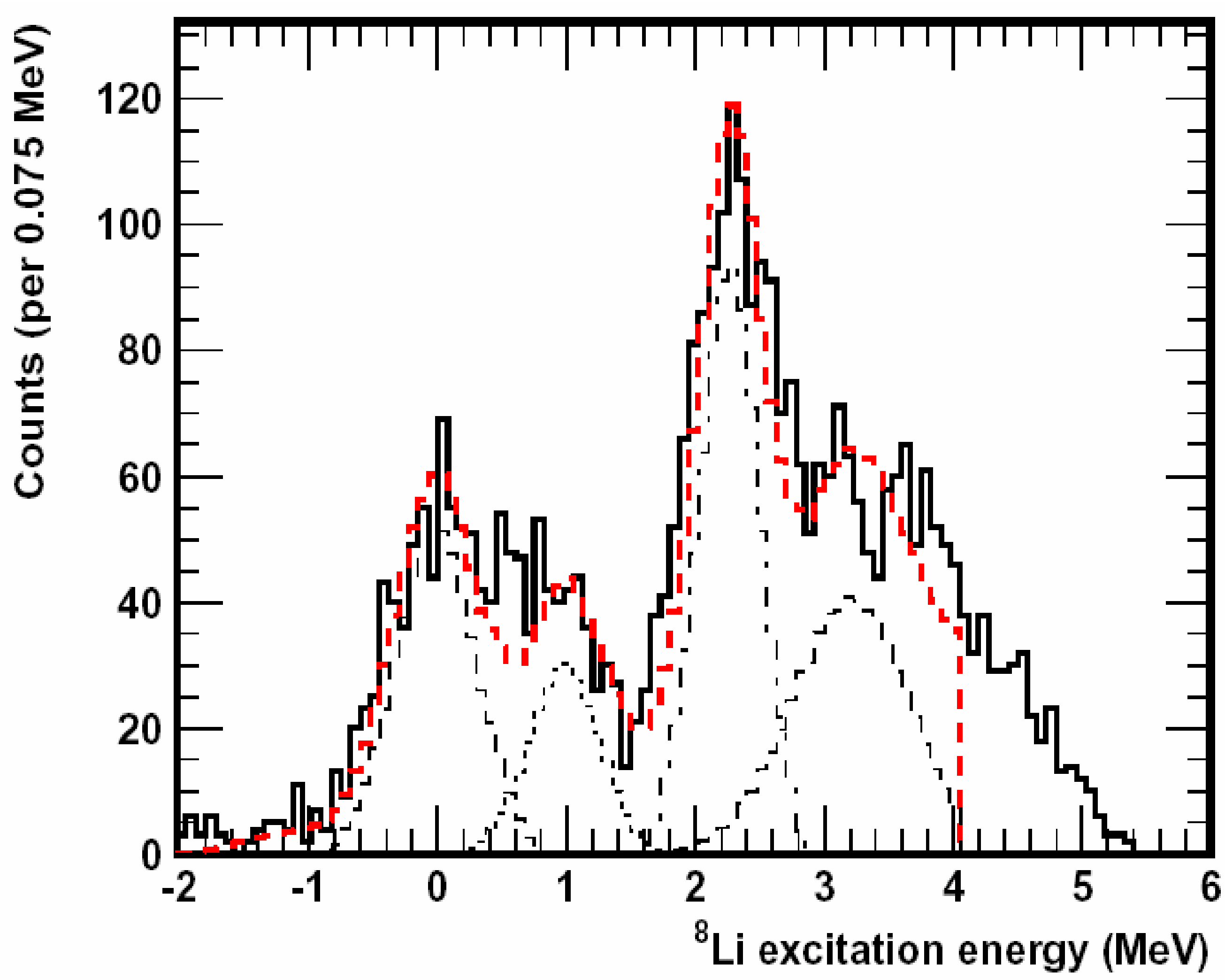
^{14}Be



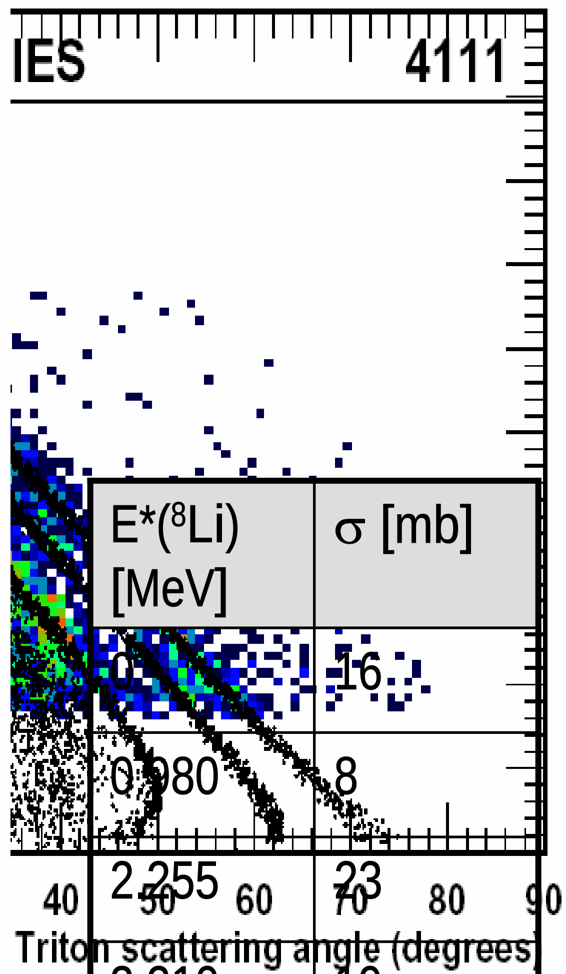
$$\mathcal{O}_\beta|\text{halo state}\rangle = \mathcal{O}_\beta\big(|\text{core}\rangle|\text{halo}\rangle\big) = \big(\mathcal{O}_\beta|\text{core}\rangle\big)|\text{halo}\rangle + |\text{core}\rangle\big(\mathcal{O}_\beta|\text{halo}\rangle\big)$$

T. Nilsson, G. Nyman, K. Riisager HFI 129(2000)67

^{9}Li on d, ^{9}Be-targets using REX-ISOLDE



Ex.: d(^{9}Li,$^{8}Li^{*}$)t



E*(^{8}Li) [MeV]	σ [mb]
0	16
0.980	8
2.255	23
3.210	19

- Fundamental interactions
  - CVC and CKM unitarity
  - Scalar currents

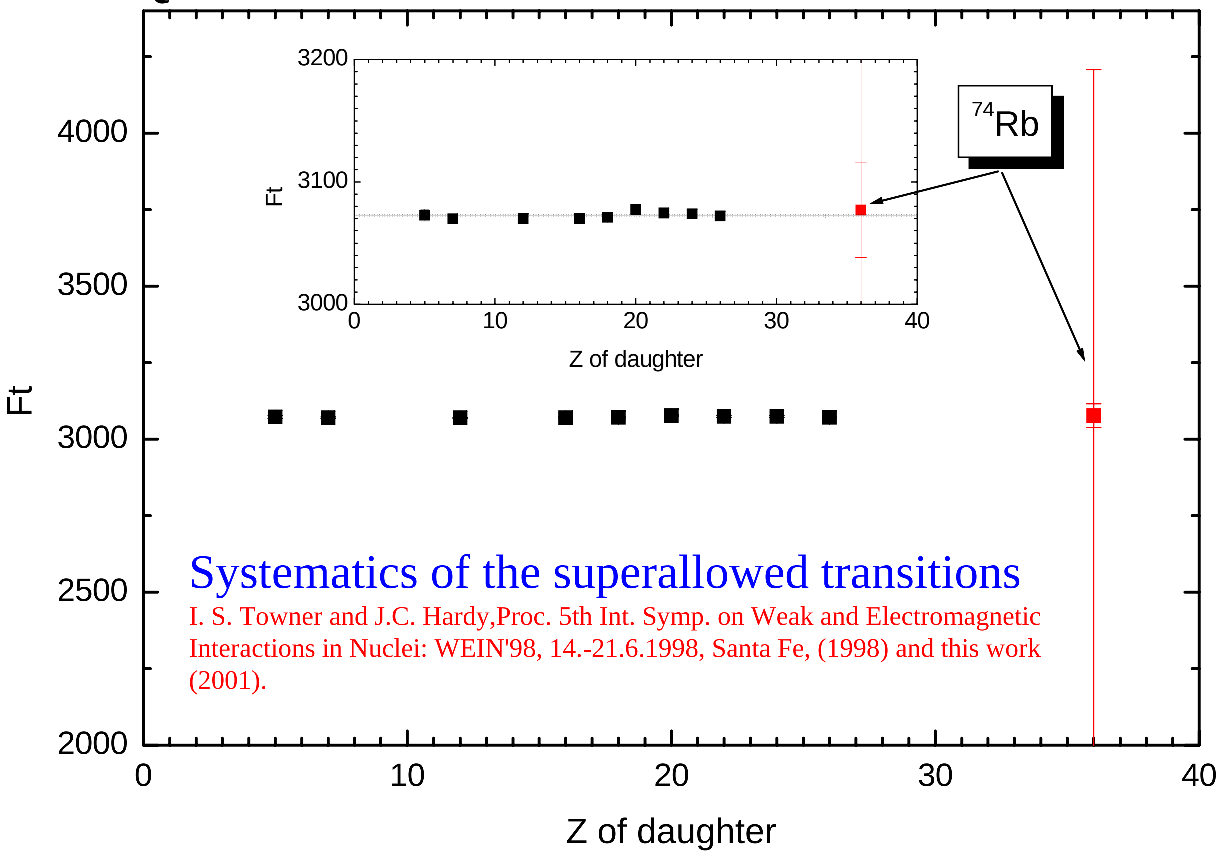
Superallowed Fermi transitions $0^+ \rightarrow 0^+, T = 1$

Test of CVC (Conserved Vector Current) hypothesis

$$ft(1+\delta_R)(1+\delta_C) \equiv \mathcal{F}t = \frac{K}{2G_V^2(1+\Delta_R)}$$

$Q-\text{value}$ halflife

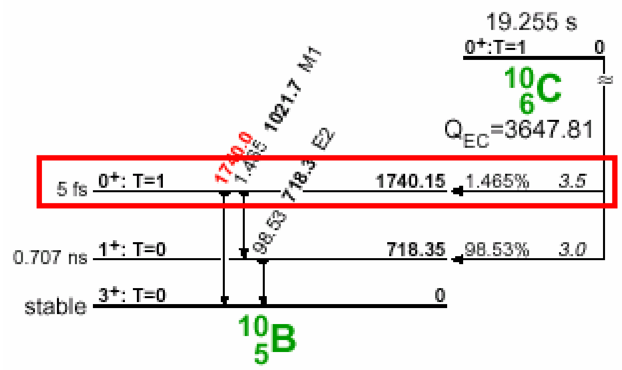
Best det. of V_{ud}



Δ_R – nuc. ind. radiative corr.

δ_R – nuc. dep. radiative corr.

δ_C – Coulomb corr.



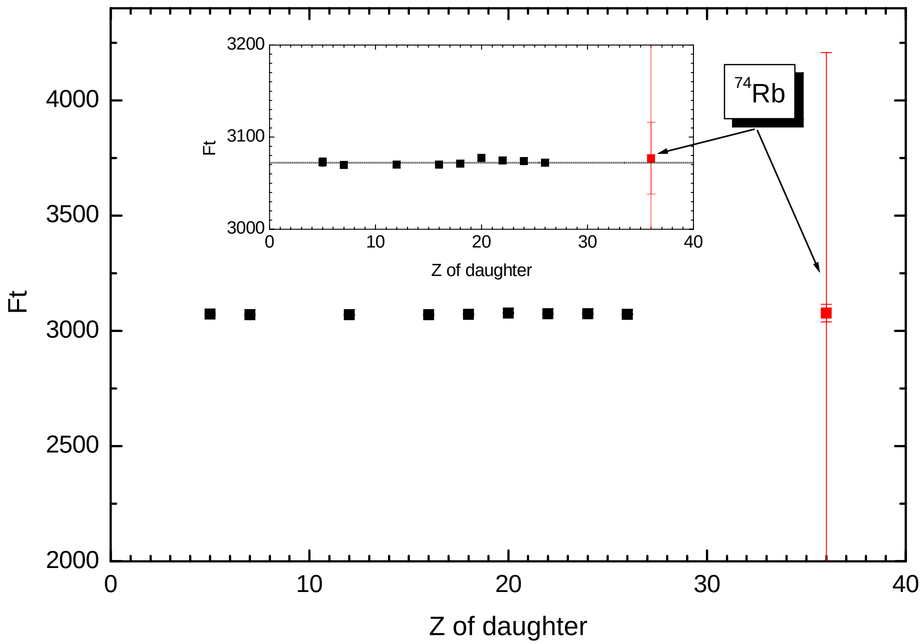
CKM (Cabibbo-Kobayashi-Maskawa) matrix unitarity

$$\mathrm{SM}: |V_{\mathrm{ud}}|^2 + |V_{\mathrm{us}}|^2 + |V_{\mathrm{ub}}|^2 = 1$$

$$\mathrm{Exp.}: |V_{\mathrm{ud}}|^2 + |V_{\mathrm{us}}|^2 + |V_{\mathrm{ub}}|^2 = 0.9968 \pm 0.0014$$

$\rightarrow$ unitarity violated by 2.2σ

$$ft(1+\delta_R)(1+\delta_C) \equiv Ft = \frac{K}{2G_V^2(1+\Delta_R)}$$



Δ_R – nuc. ind. radiative corr.

δ_R – nuc. dep. radiative corr.

δ_C – Coloumb corr.

New physics or bad corrections? Test at extreme -> ^{74}Rb (and later ^{62}Ga)

IS384 Complete spectroscopy on Fermi β-emitter ^{74}Rb

Results:

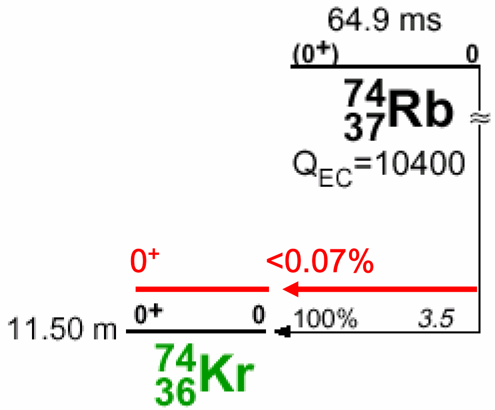
1) non-analog $0^+ \rightarrow 0^+$ transition observed

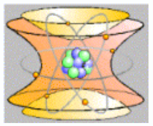
$\rightarrow$ estimate for the Coulomb mixing

2) mass of ^{74}Rb (ISOLTRAP & MISTRAL)

3) mass of the daughter ^{74}Kr (ISOLTRAP)

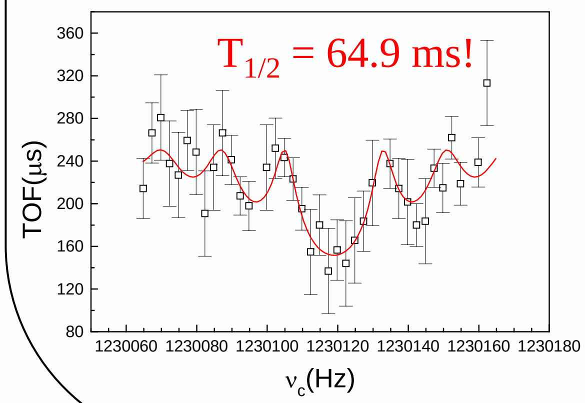
2) & 3) $\rightarrow$ Q_{EC} value

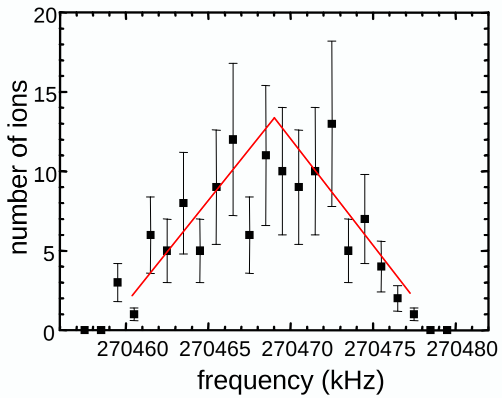


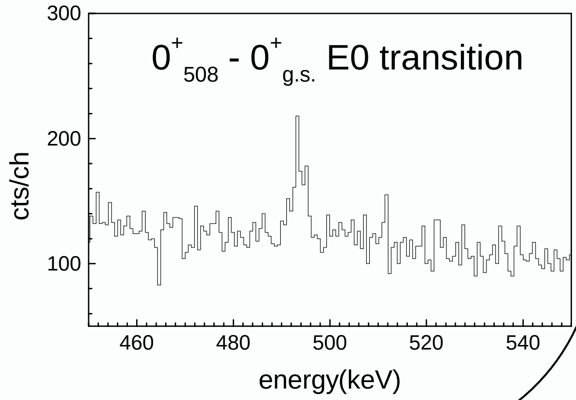


ISOLTRAP

MISTRAL







CKM (Cabibbo-Kobayashi-Maskawa) matrix unitarity

$$\mathrm{SM}: |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

$$\mathrm{Exp.}: |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9968 \pm 0.0014$$

→ unitarity violated by 2.2σ

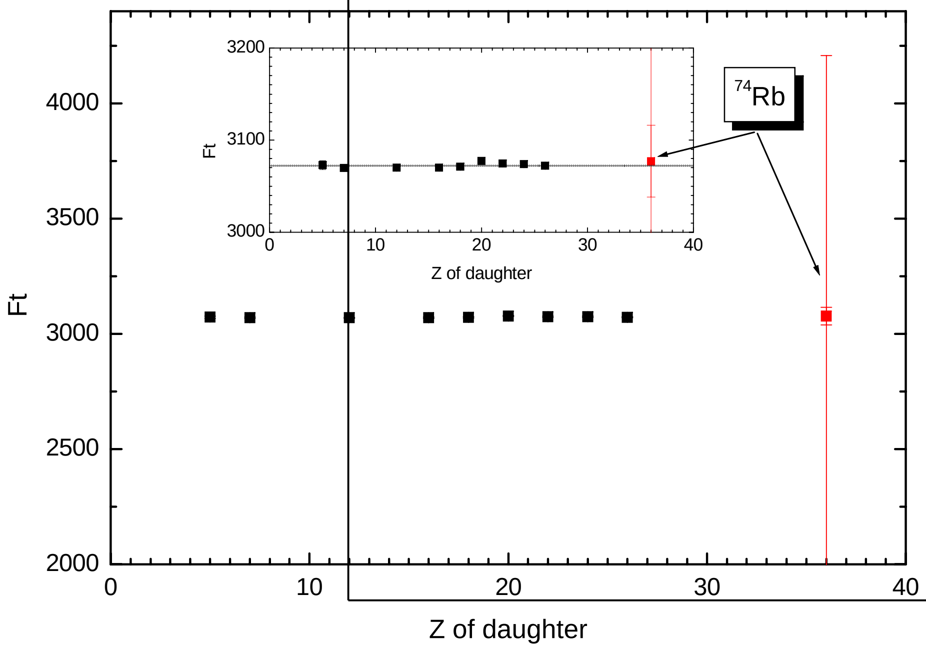
Vus remeasured – unitarity restored! Cabibbo et al, hep/th-?

$$ft(1+\delta_R)(1+\delta_C) \equiv Ft = \frac{K}{2G_V^2(1+\Delta_R)}$$

Δ_R – nuc. ind. radiative corr.

δ_R – nuc. dep. radiative corr.

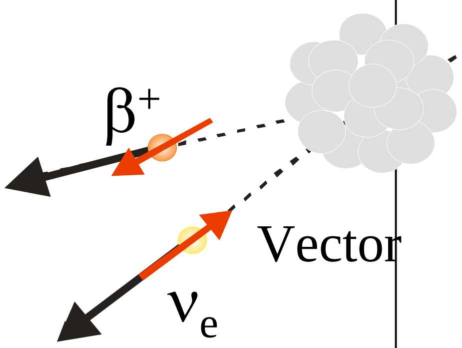
δ_C – Coloumb corr.

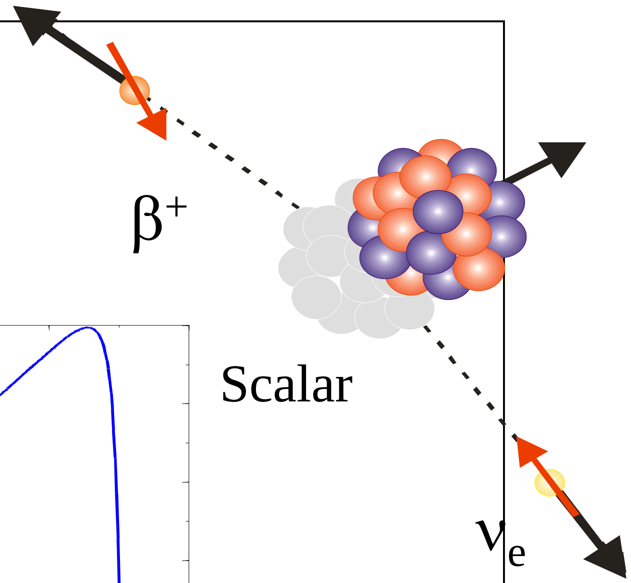


New physics or bad corrections? Test at extreme -> ^{74}Rb (and later ^{62}Ga)

WITCH – Weak Interaction Trap for CHarged particles

cooler & decay Penning trap + retardation spectrometer

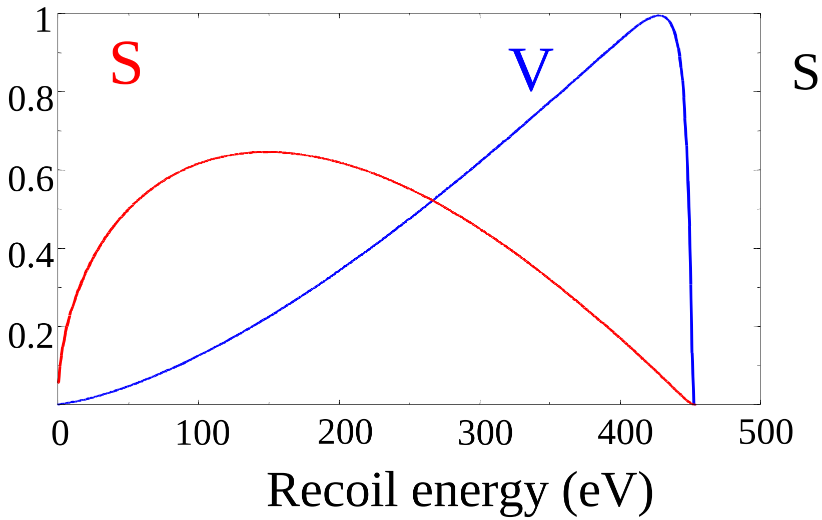




Pure Fermi decay $0^+ \rightarrow 0^+$:

$$dW = dW_0\left(1 + a\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e}\right)$$

a<1 ➞ **Scalar currents**



First goal :

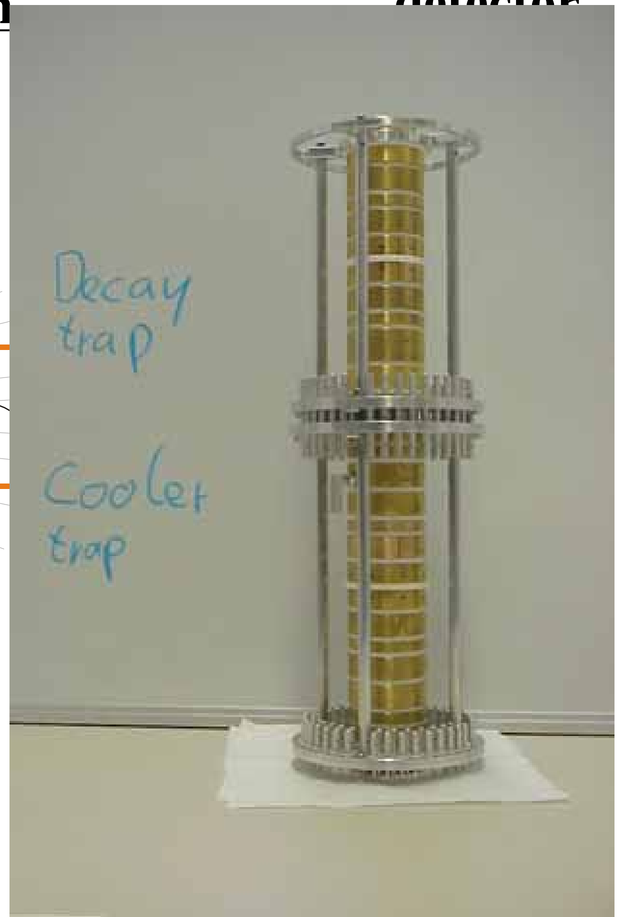
search for scalar weak interaction
by measuring
shape of recoil ion energy spectrum
after β-decay

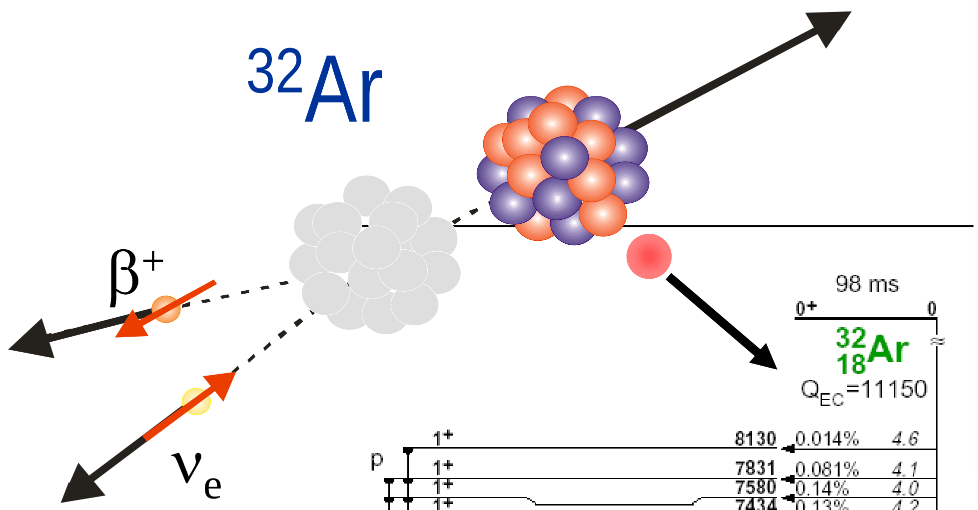
Other physics possibilities :

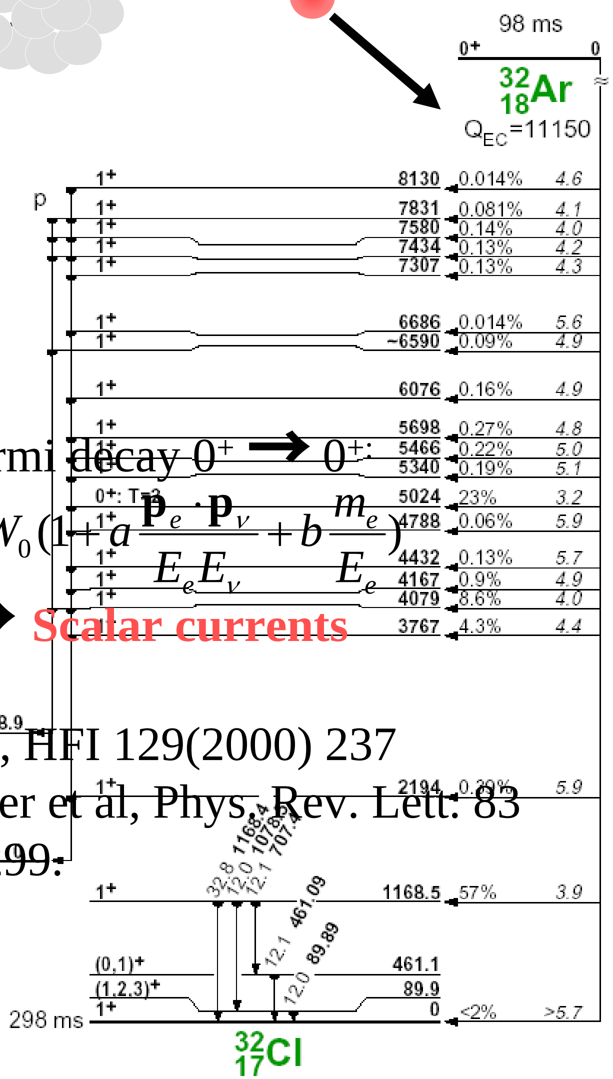
- in-trap spectroscopy
- determination of EC/β^+ ratios
- determination of Q_β-values
- measure charge state distributions

WITCH retardation spectrometer

detector







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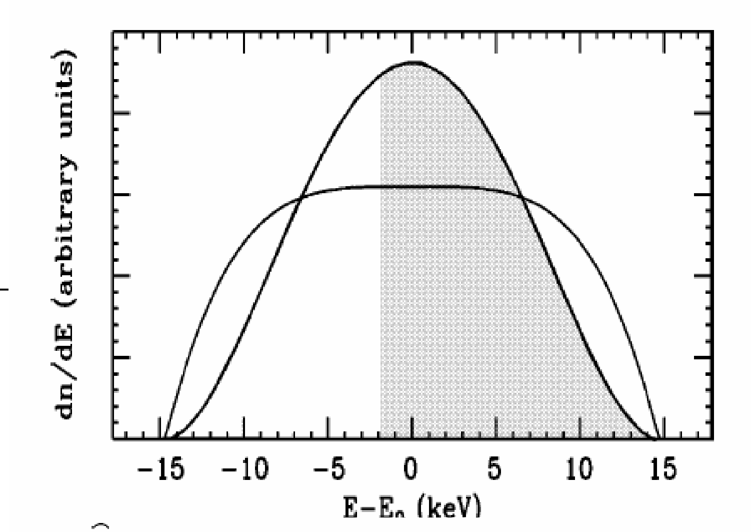
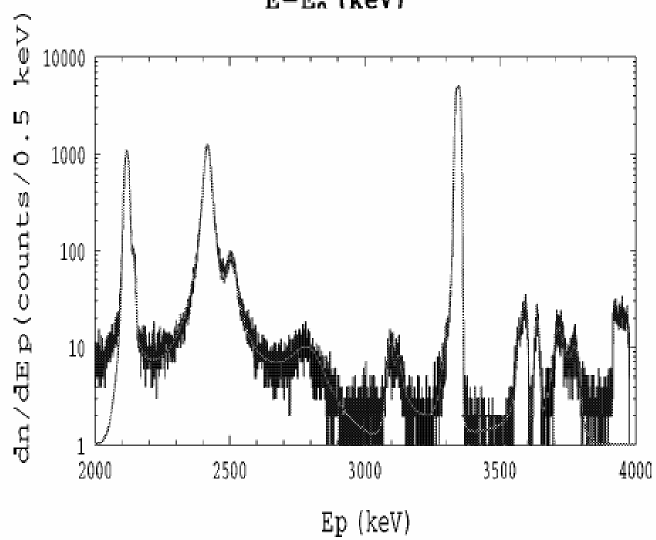
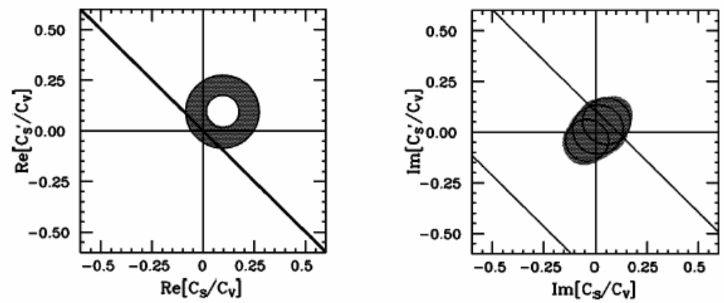
a<1 → **Scalar currents**

A. Garcia et al, HFI 129(2000) 237

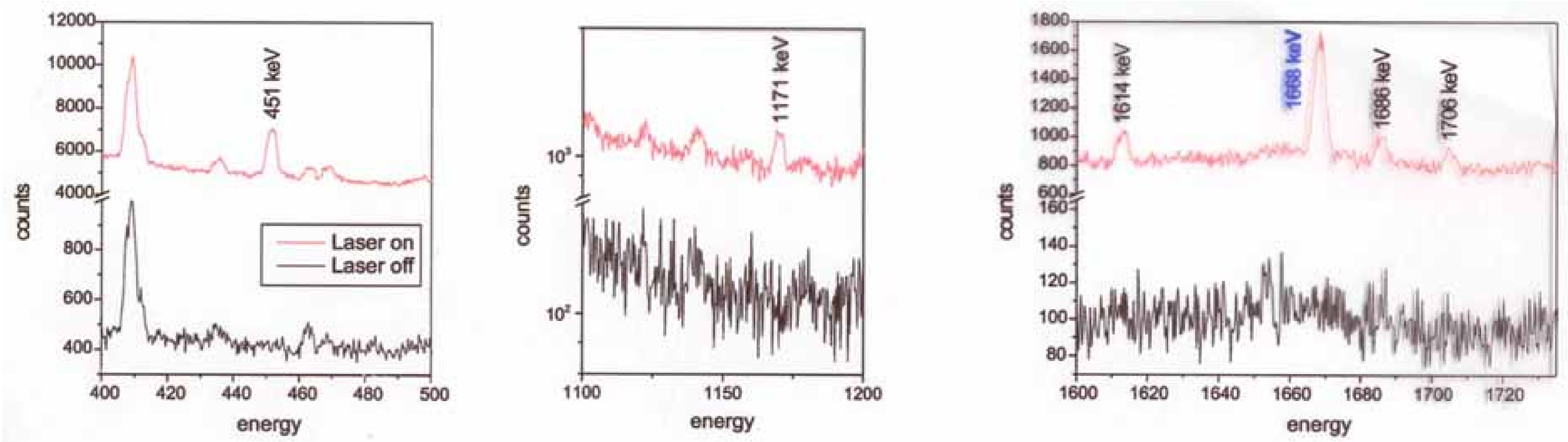
E.G. Adelberger et al, Phys. Rev. Lett. 83 (1999) 1299.

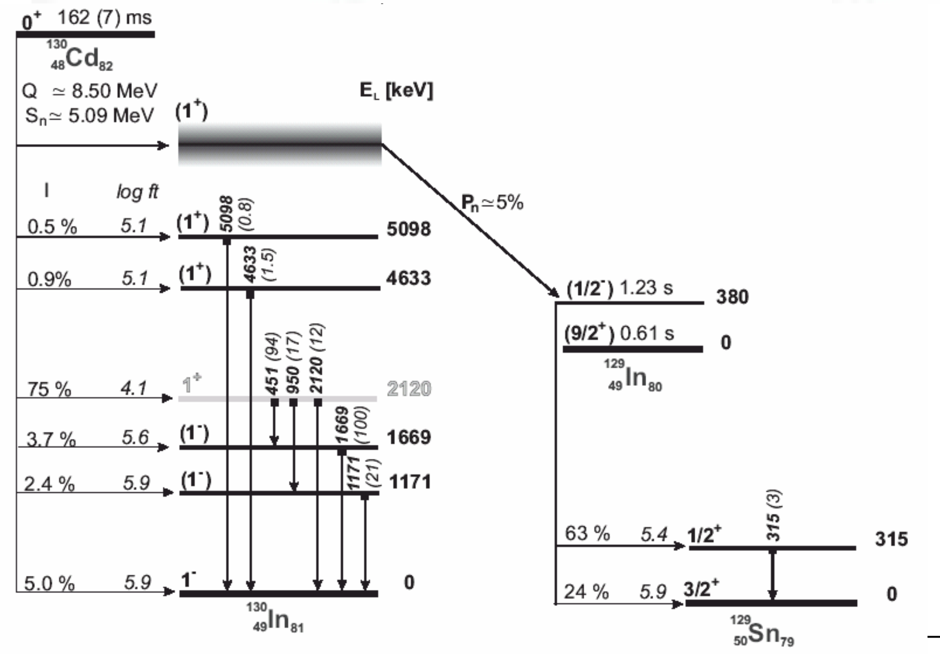


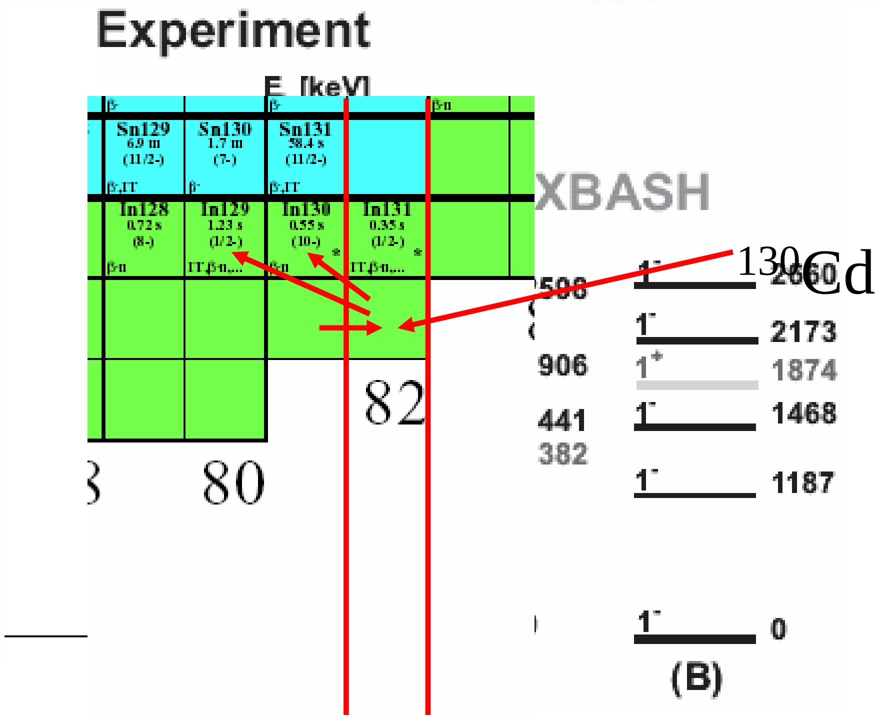




^{130}Cd - r-process waiting-point nuclide

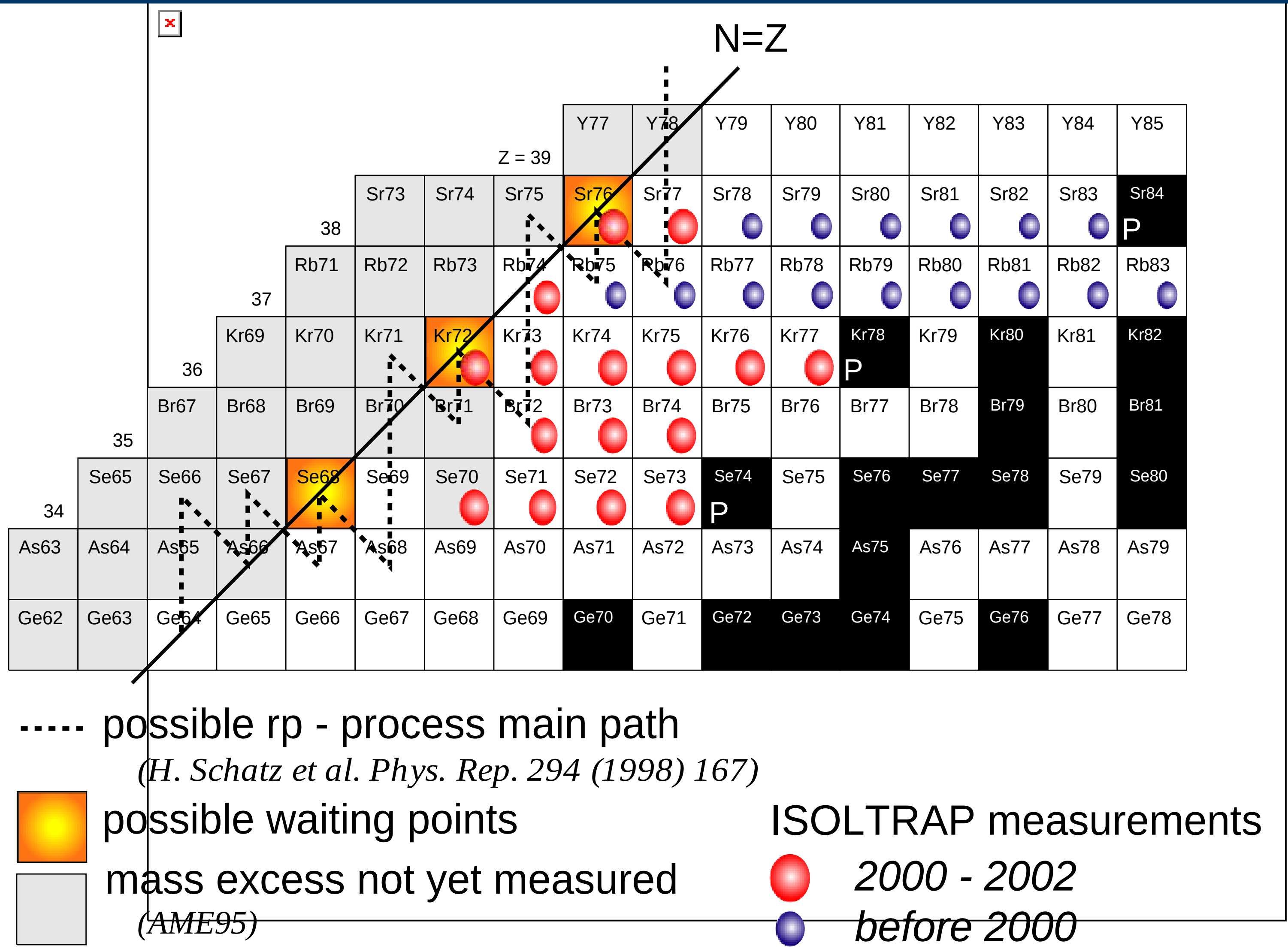






rp-process above Z = 32

Masses are the most critical nuclear physics parameters for reliable calculations in astrophysics!



Conclusions of second lecture

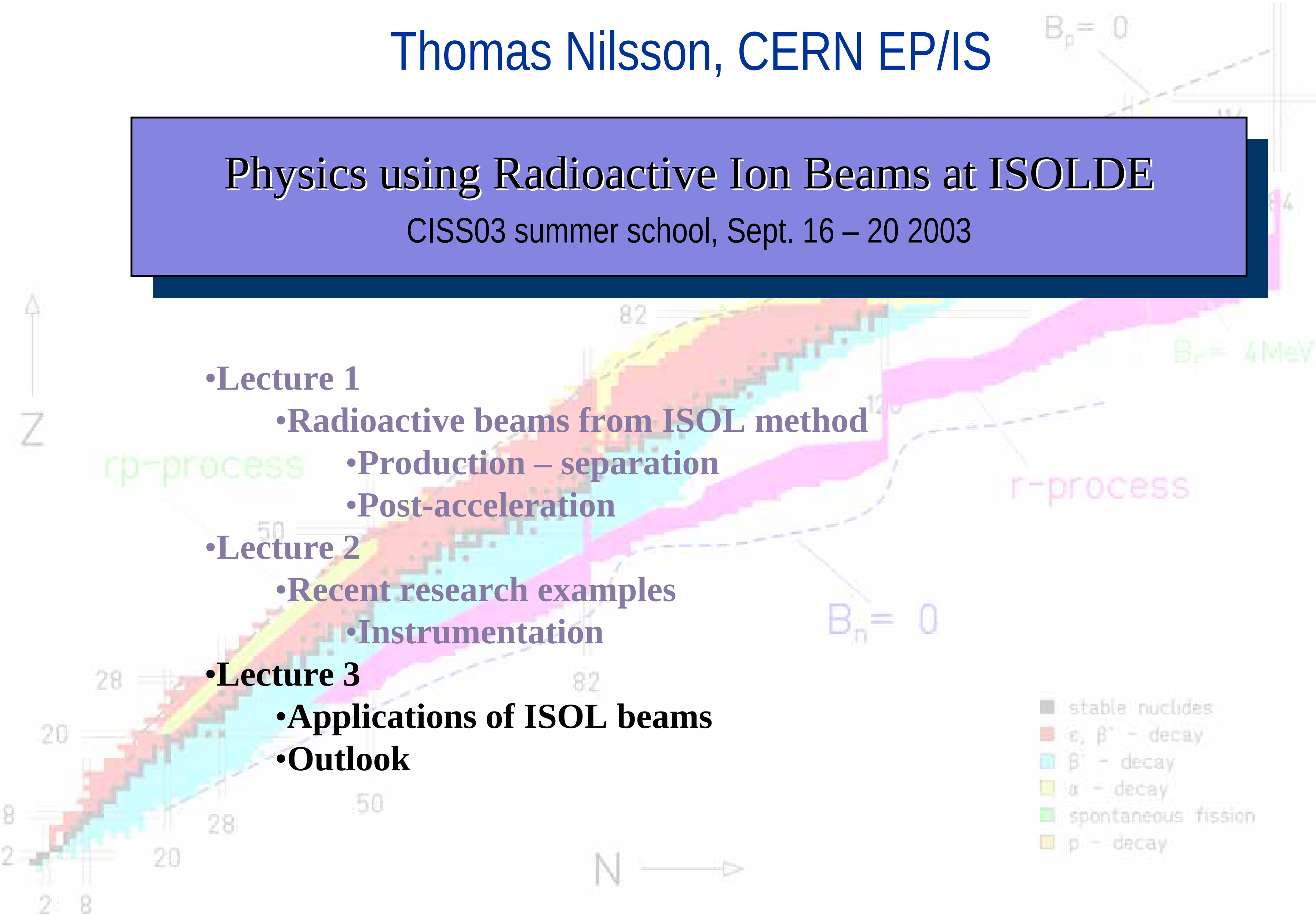
- LUNCH!

Thomas Nilsson, CERN EP/IS

Physics using Radioactive Ion Beams at ISOLDE

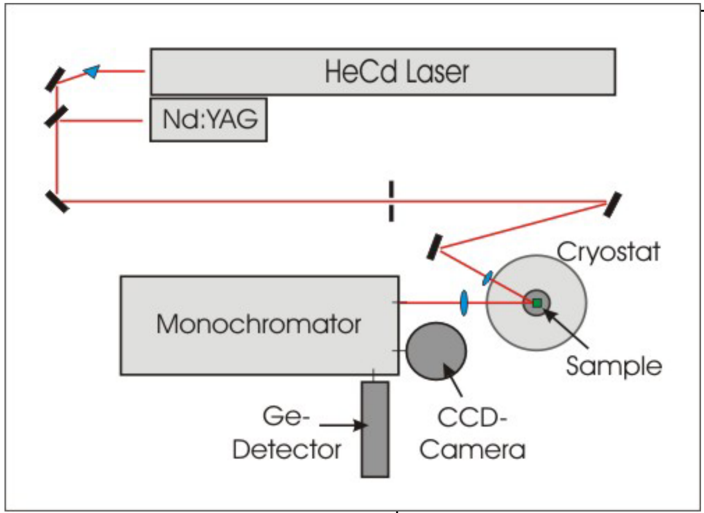
CISS03 summer school, Sept. 16 – 20 2003

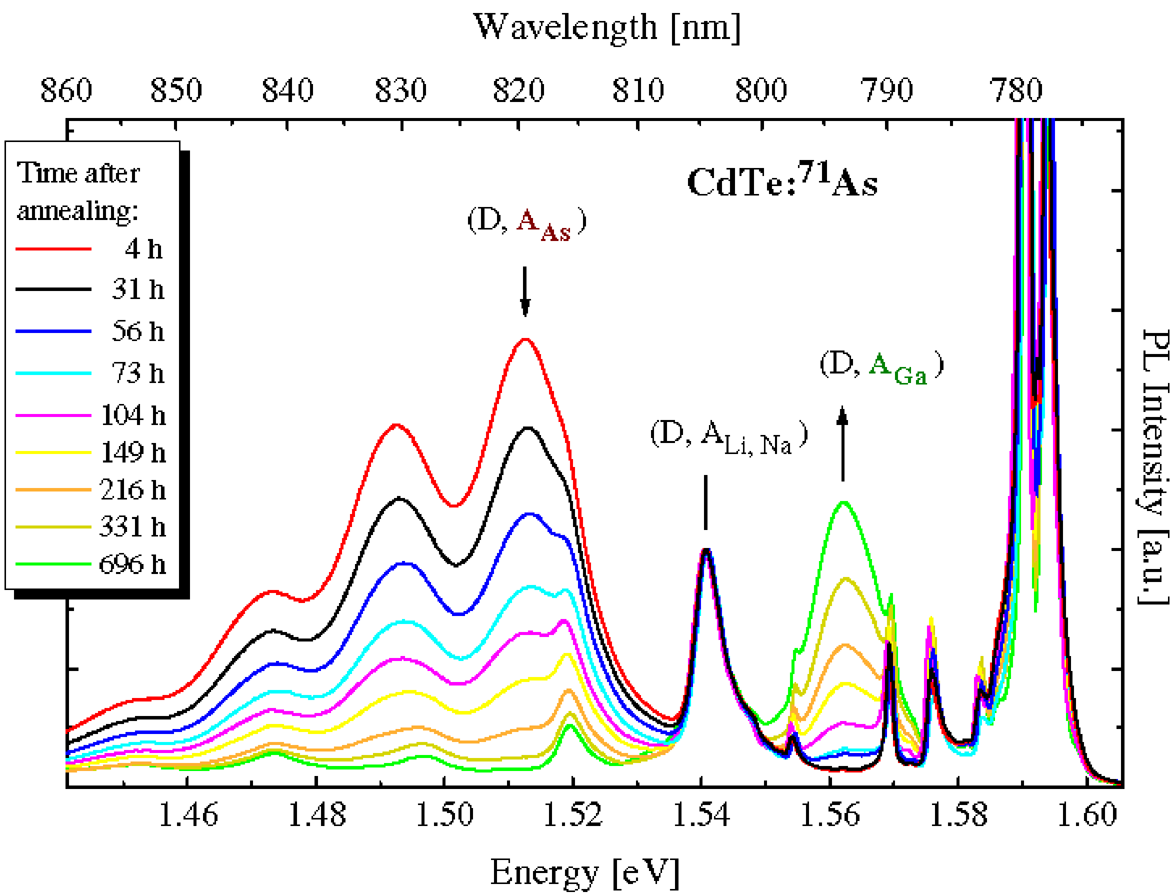
- Lecture 1
    - Radioactive beams from ISOL method
        - Production – separation
        - Post-acceleration
- Lecture 2
    - Recent research examples
        - Instrumentation
- **Lecture 3**
    - **Applications of ISOL beams**
    - **Outlook**



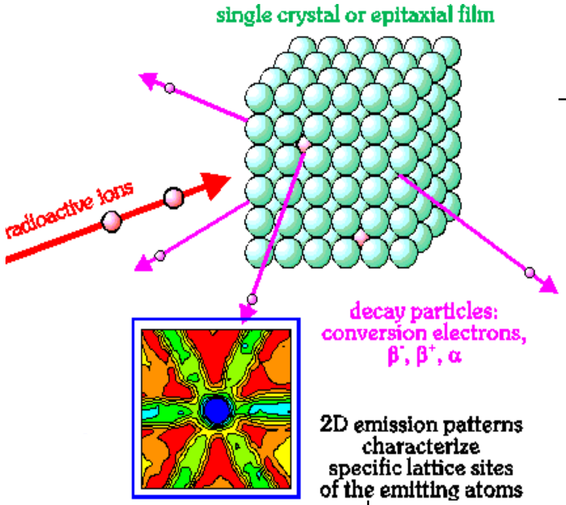
Condensed matter physics

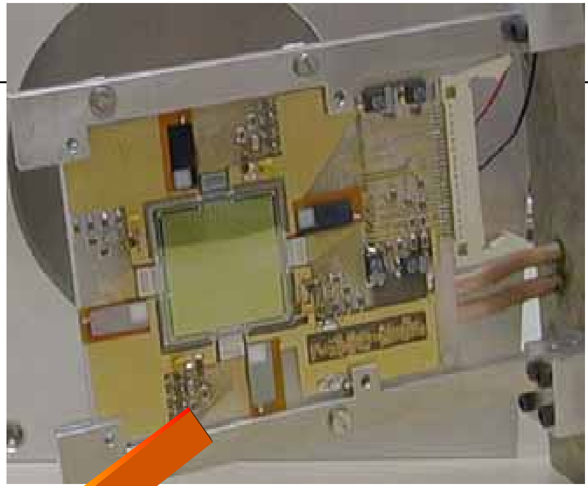
Radioactive ions as dopants in semiconductors that change with time.





New cooled 2D Si pad detector for Emission Channeling





Collaboration:

ITN Sacavém & Div.EP-ATT

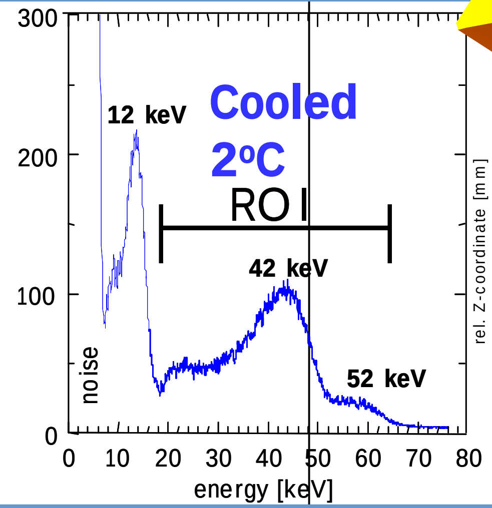
Perspectives:

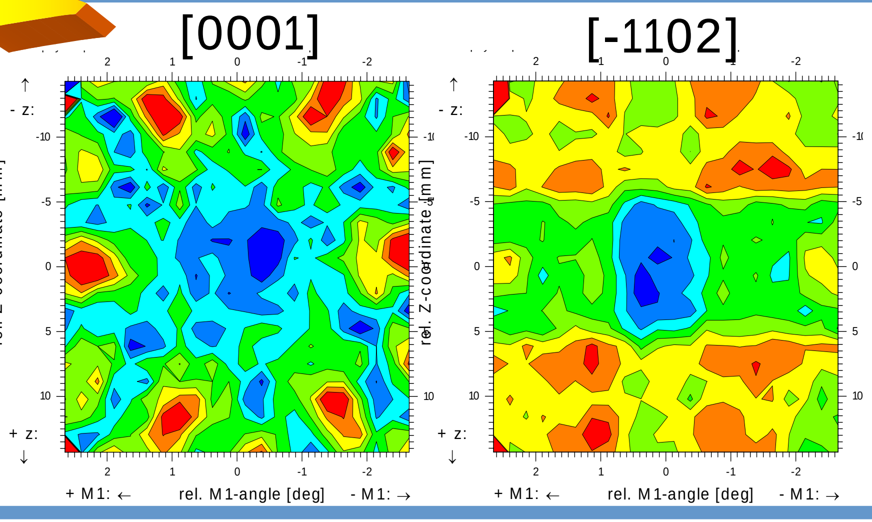
pads self-triggering

-> 5 keV trigger

-> 10kHz readout

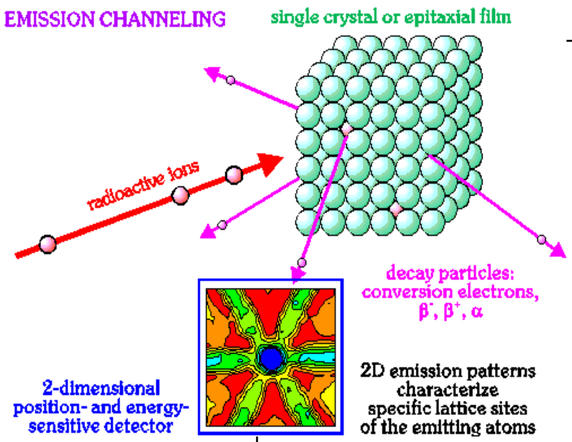
^{73}As ZnO low electron energy -IS368-



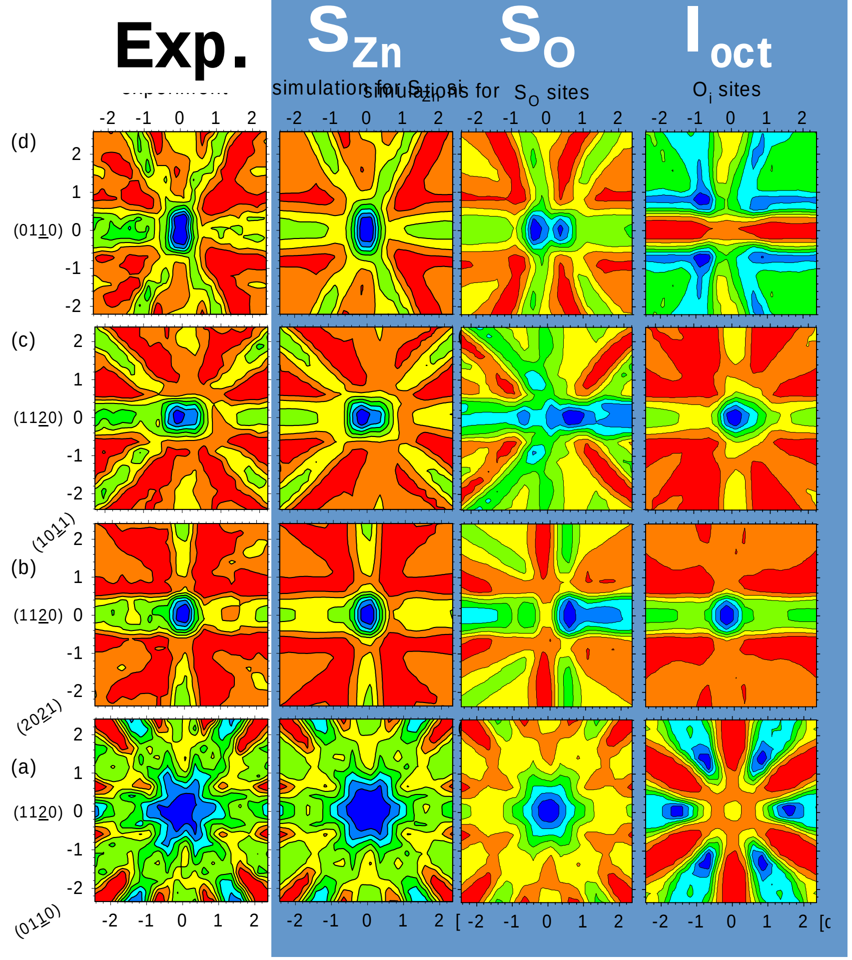


Arsenic occupies multiple sites in ZnO

IS368 - Where sits Er in ZnO ?



Conv. Elec. from ^{167m}Er

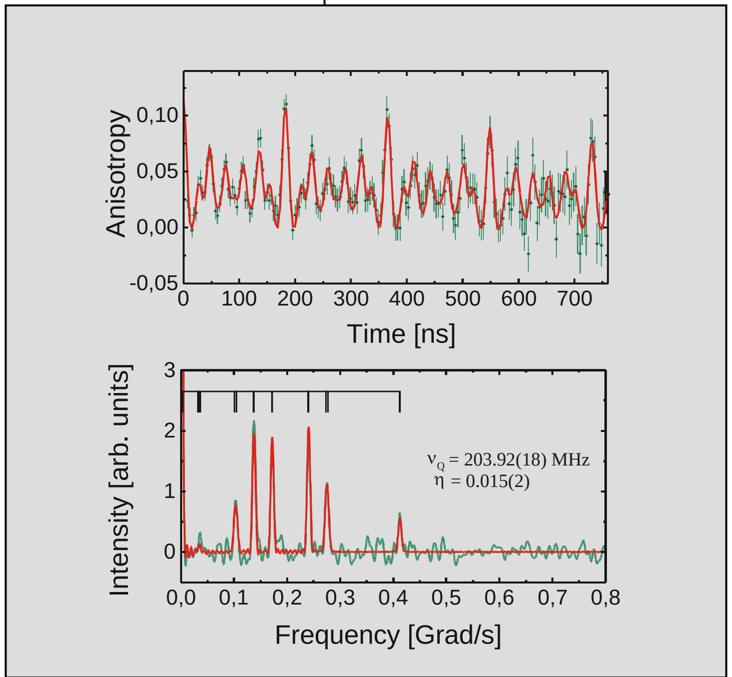


Er is substitutional at the Zn Site

(accepted by Applied Physics Letters)

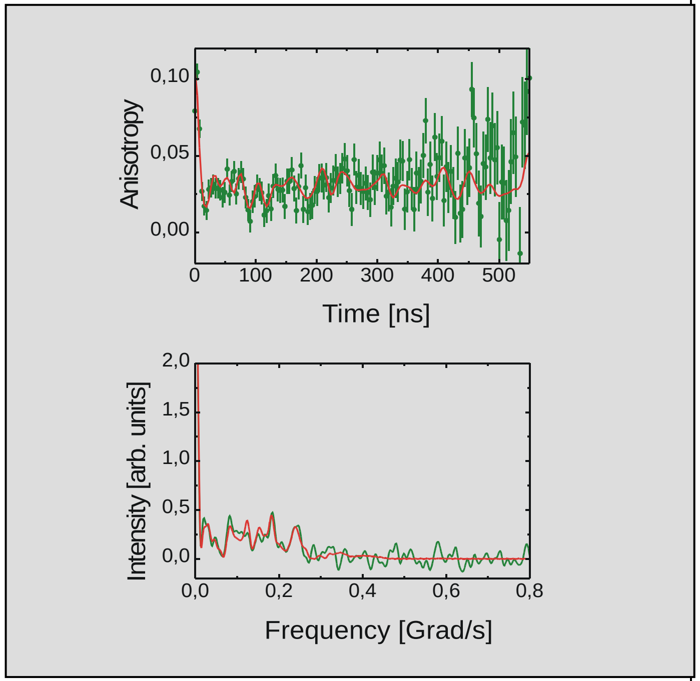
^{204m}Pb: Material & Life Sciences

^{204m}Pb in Cd metal



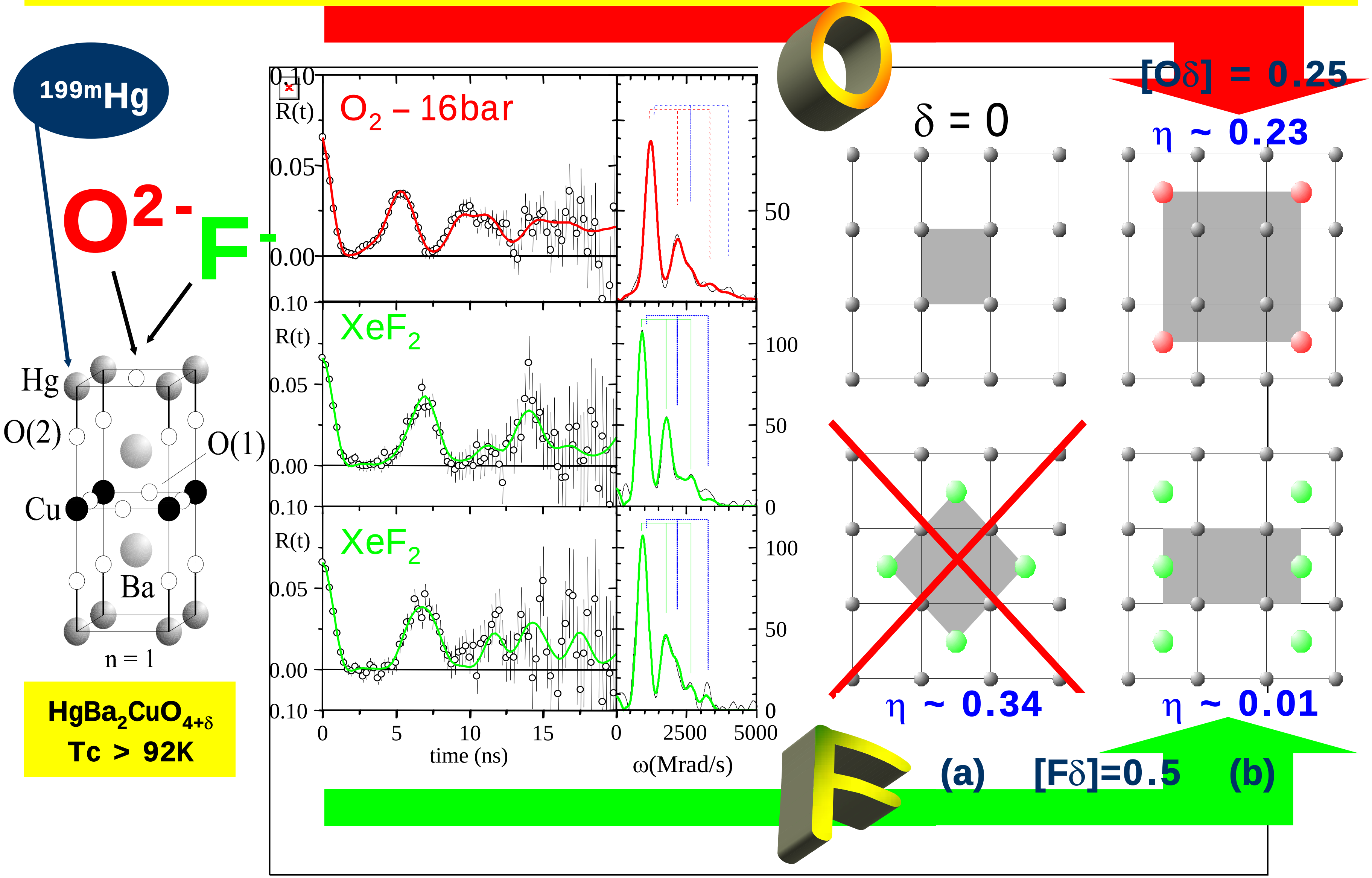
Concentration and Geometry of Defects in Solids

^{204m}Pb: DNA



Coordination and Dynamics of Metal Sites in Proteins: Heavy Metal Sensors and Heavy Metal Detoxification

Where goes Fluorine in Hg1201 - IS360 HTcS



$HgBa_2CuO_{4+\delta}$

Tc > 92K

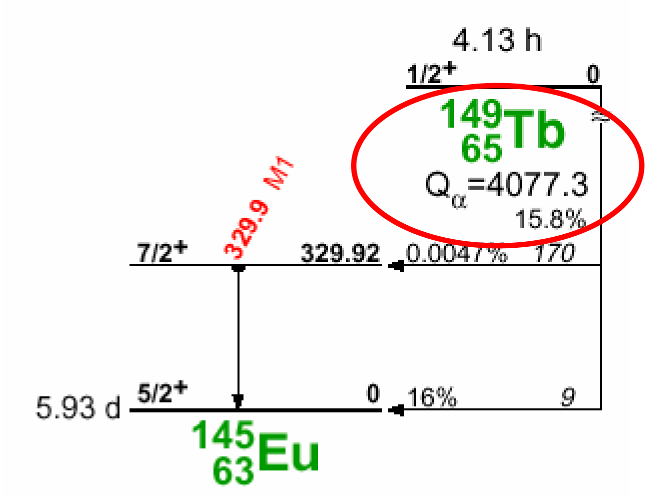
Bio Medical Research at ISOLDE

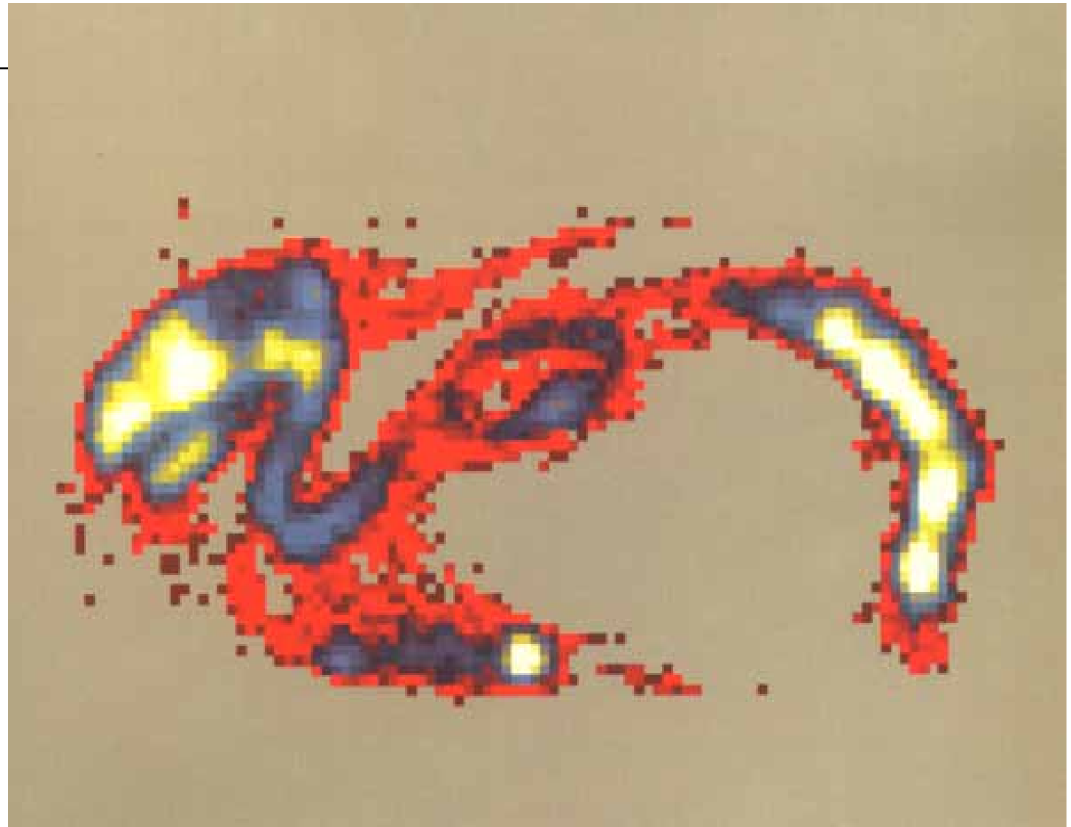
- **Example: samarium isotopes**

in vivo dosimetry by positron emission tomography (PET)

142-Sm (ε, $T_{1/2}$ = 72m) $\Rightarrow$ 142-Pm (β_+, $T_{1/2}$ = 40s)

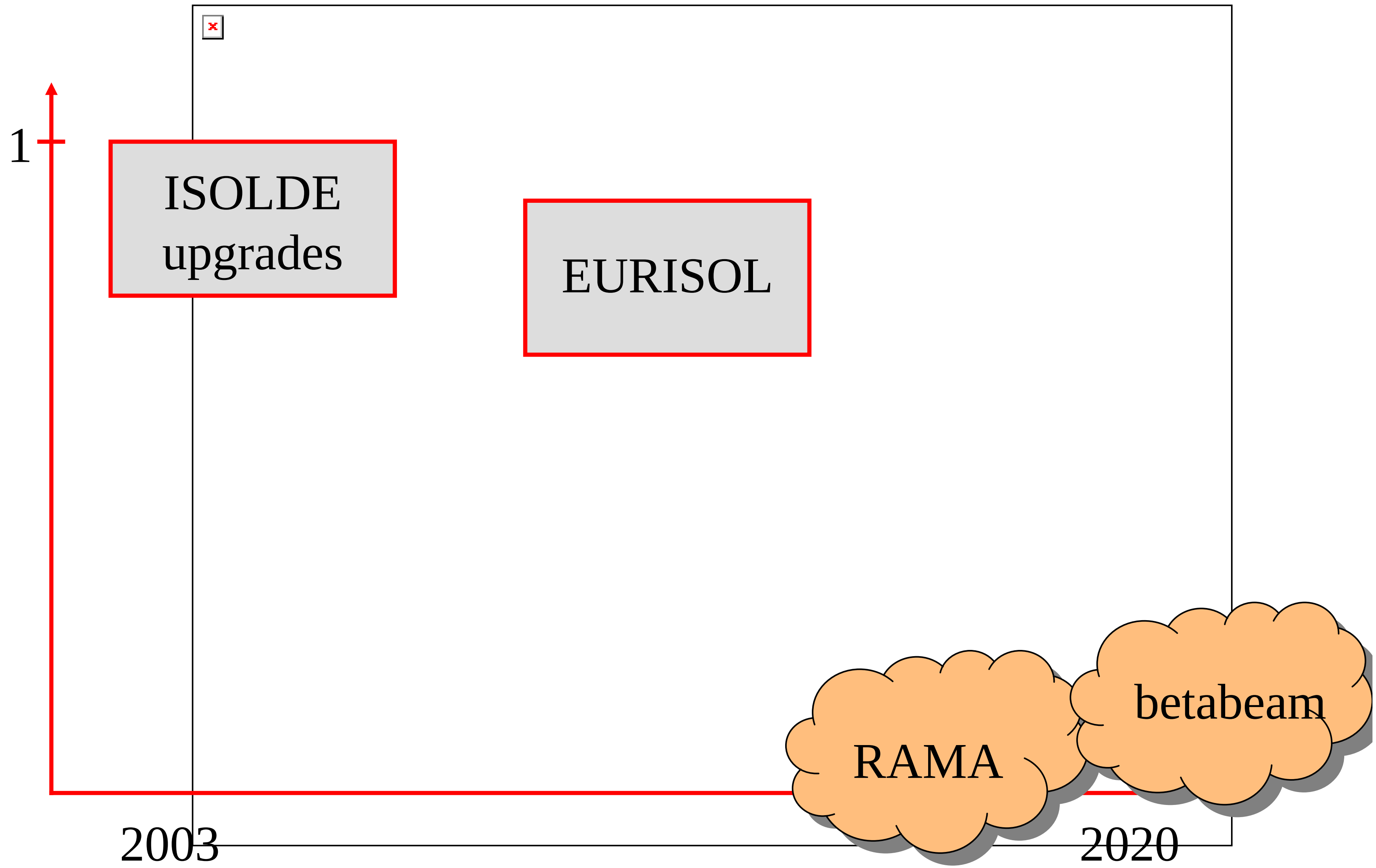
therapy 153-Sm (β_-, $T_{1/2}$ = 47h)



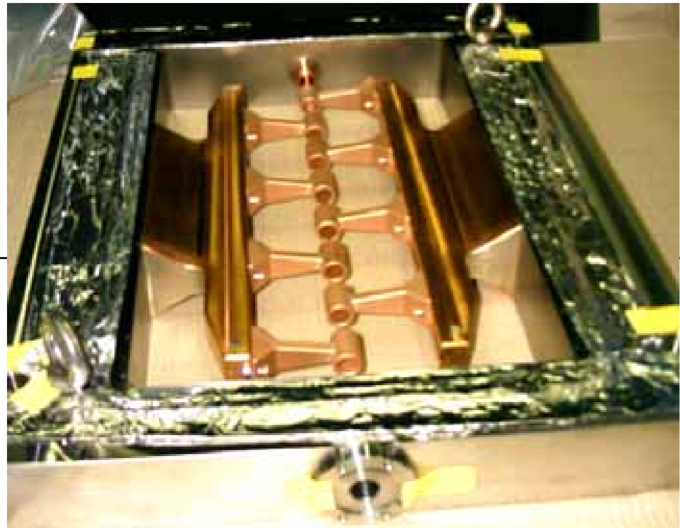


PET scan of a rabbit 60 min p.i. of ISOLDE produced
142-Sm in EDTMP solution

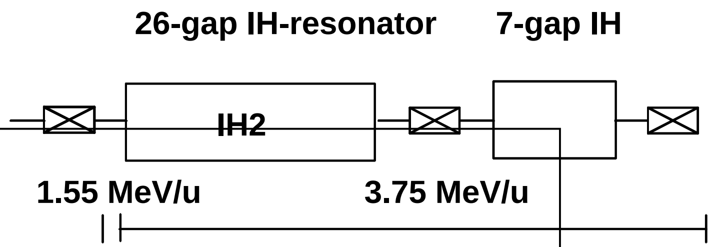
A look into the future (very personal view)



REX-ISOLDE
beams - outlook

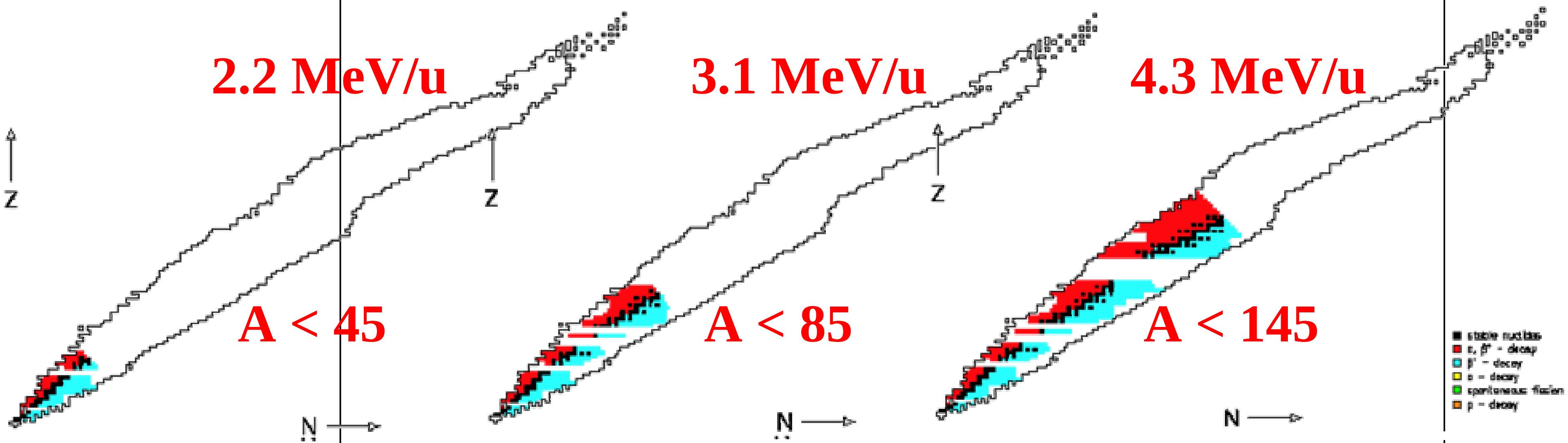


Additional 9-gap
accelerating structure



Exchange existing 7-gap
with IH accelerating
structures

2002 → **2003** → **2005-06**



RIBs reaching the Coulomb barrier

General consensus (NUPECC etc) on next-generation facilities:

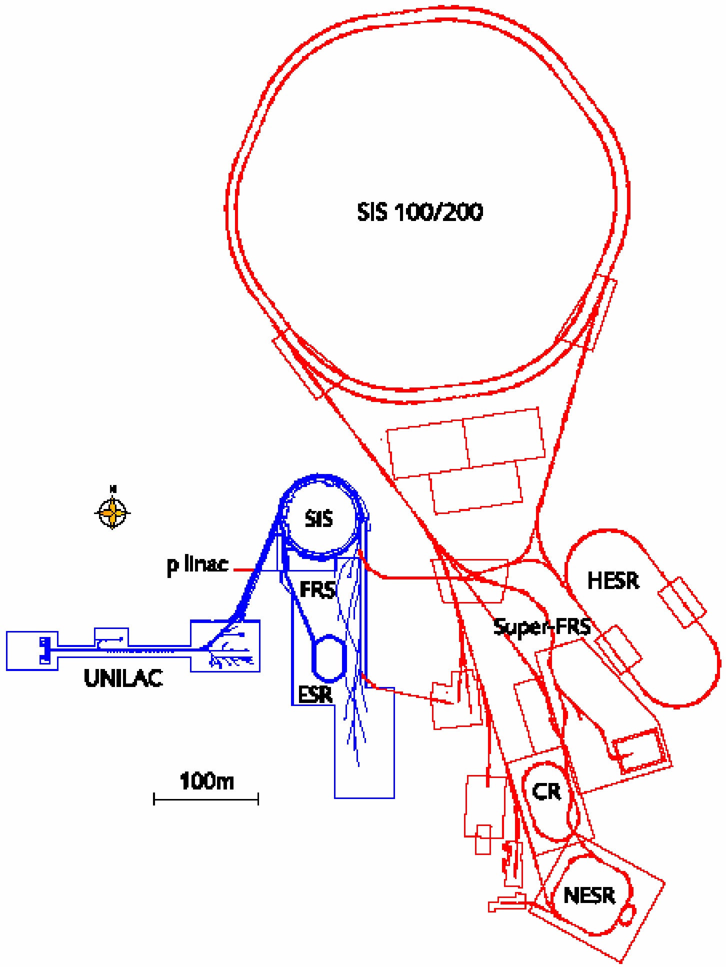
Europe needs an in-flight facility…

GSI

GESELLSCHAFT FÜR SCHWERIONENFORSCHUNG

… and an ISOL facility!

EURISOL

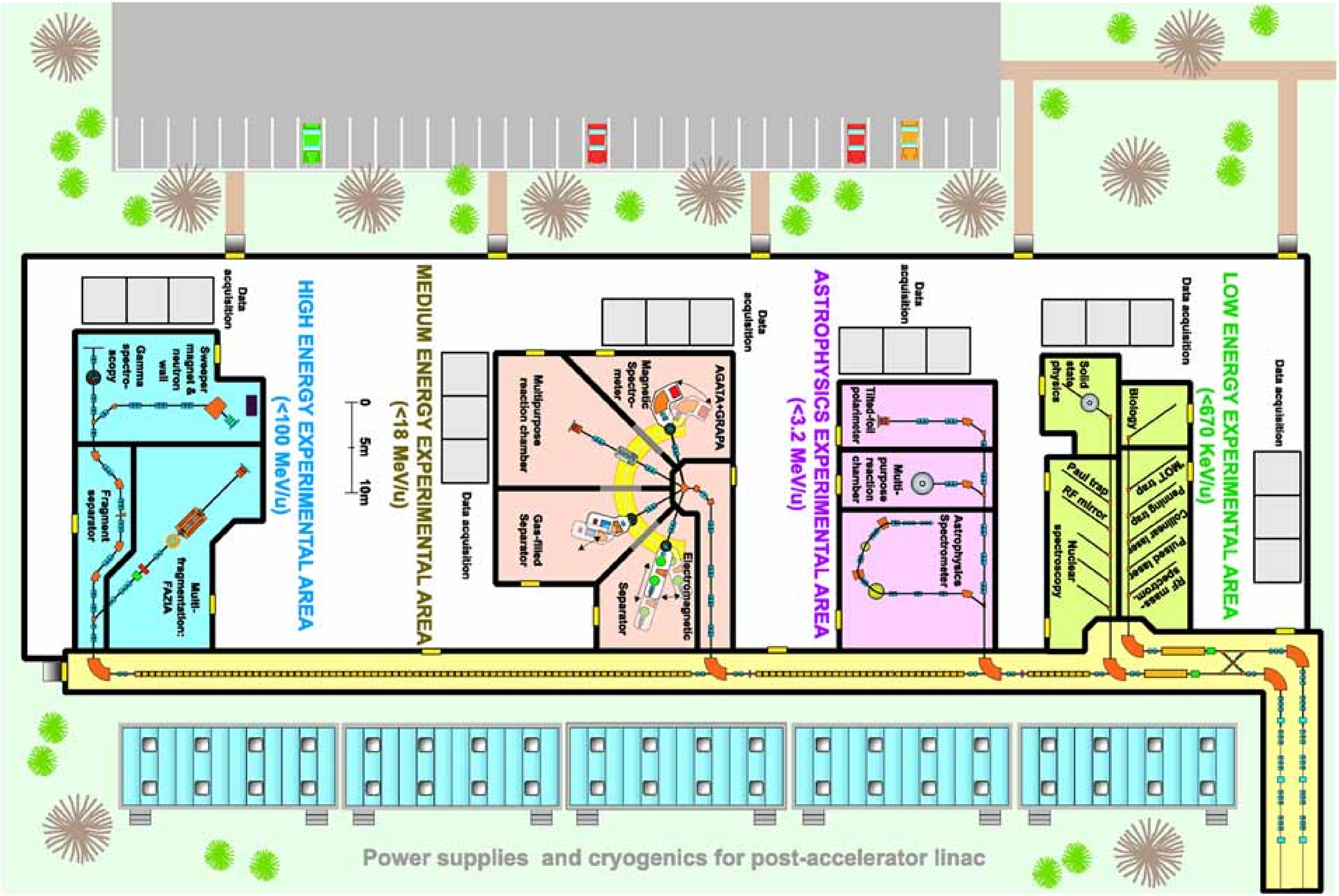


EURISOL

- Aim: increase intensities 1000 times compared to today
- Preliminary design study done
  - http://www.ganil.fr/eurisol
  - 1 GeV SC proton LINAC
    - 100 mA direct production
    - 4 mA on neutron spallation targets
  - Advanced target/ion source techniques
    - Key elements – Be, Ar, Ni, Ga, Kr, Sn, Fr
  - SC LINAC as post-accelerator (100 MeV/u)
  - Innovative new instrumentation

EURISOL

- Key experiments identified
  - Superheavies creation through ^{132}Sn fusion
  - Drip-line nuclei (N<70) through secondary fragmentation of ^{132}Sn
  - Neutron-rich nuclei as high-spin probe
    - Hyperdeformation
  - Detailed information of r-process path
  - …
- Real DS starting 2004?
- Site?

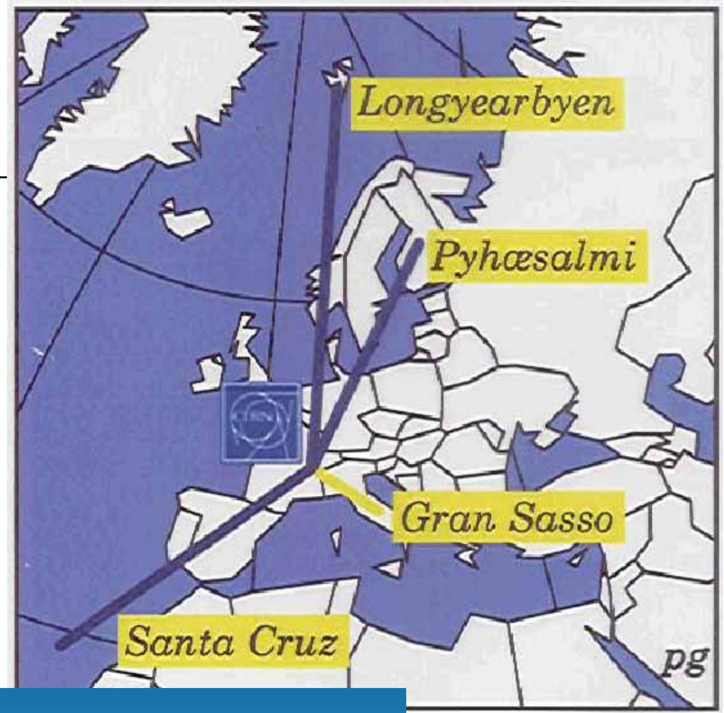


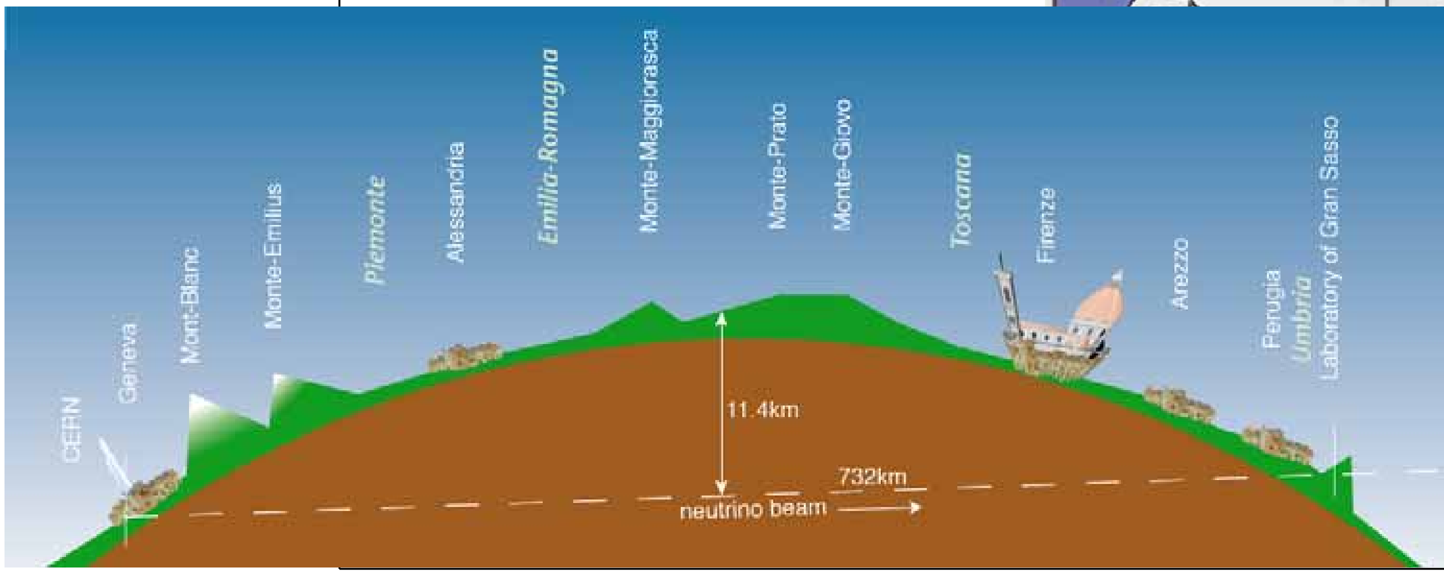
HIGH ENERGY EXPERIMENTAL AREA (<100 MeV/u)
MEDIUM ENERGY EXPERIMENTAL AREA (<18 MeV/u)
ASTROPHYSICS EXPERIMENTAL AREA (<3.2 MeV/u)
LOW ENERGY EXPERIMENTAL AREA (<670 KeV/u)
Data acquisition
Sweeper magnet & neutron wall
Gamma spectroscopy
Fragment separator
Multi-fragmentation: FAZIA
0 5m 10m
AGATA+GRAPA
Magnetic Spectrometer
Multipurpose reaction chamber
Gas-filled Separator
Electromagnetic Separator
Tilted-foil polarimeter
Multi-purpose reaction chamber
Astrophysics Spectrometer
Solid state physics
Biology
Paul trap
RF mirror
Nuclear spectroscopy
MOT trap
Penning trap
Collinear laser
Pulsed laser
RF mass-spectrom.
Power supplies and cryogenics for post-accelerator linac

Long base-line ν experiments

- Solar neutrino deficit
- Neutrino oscillations (Super-K, LSND, SNO)
- Accelerator based exp. – look for

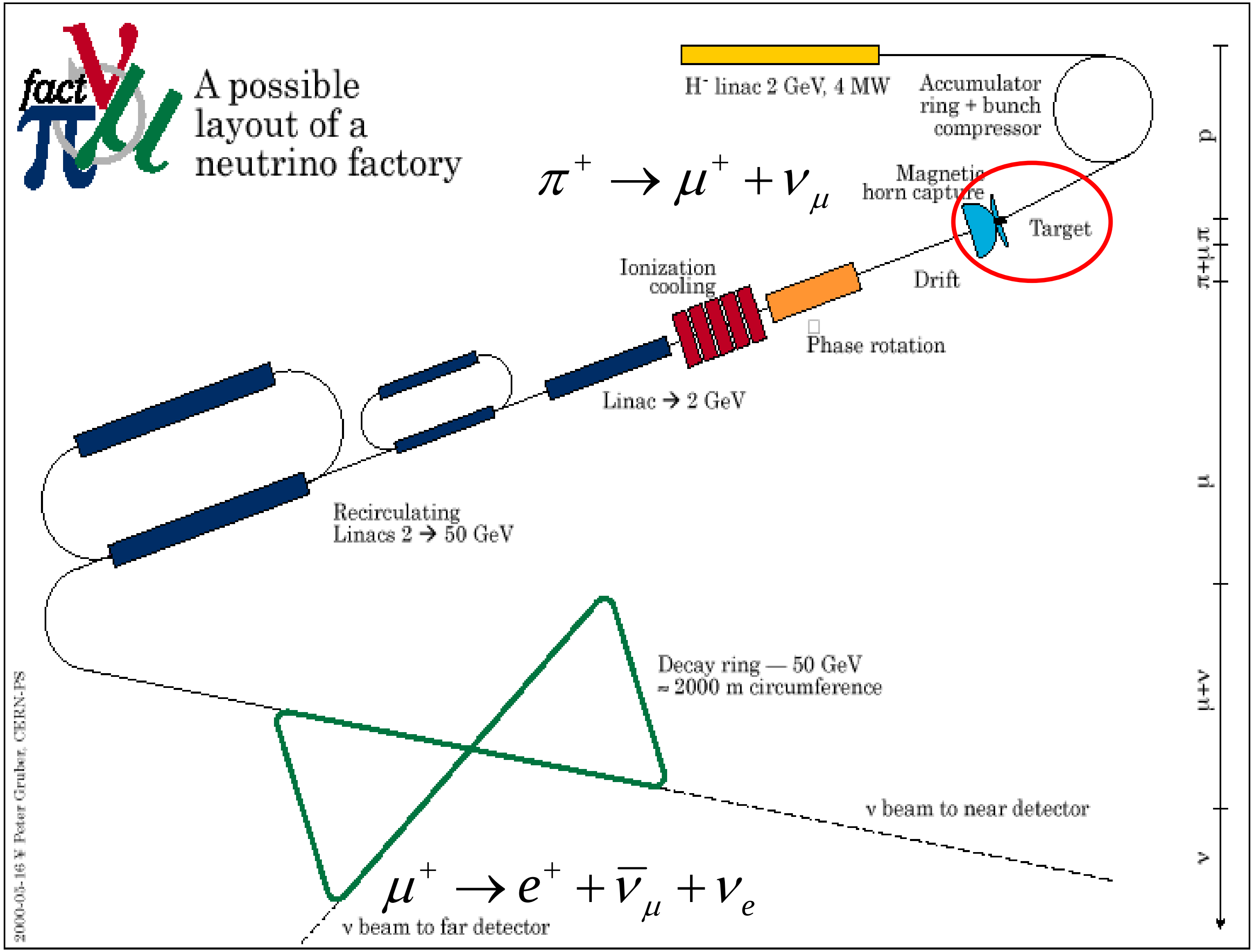
$$\nu_\mu \rightarrow \nu_\tau$$



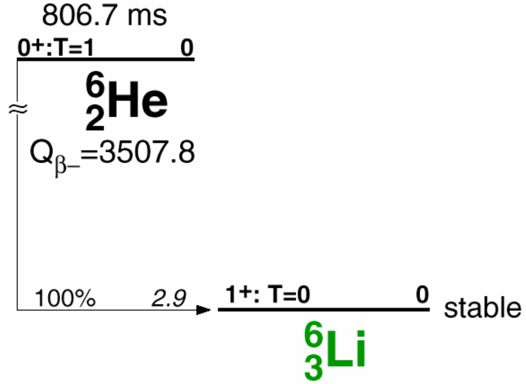


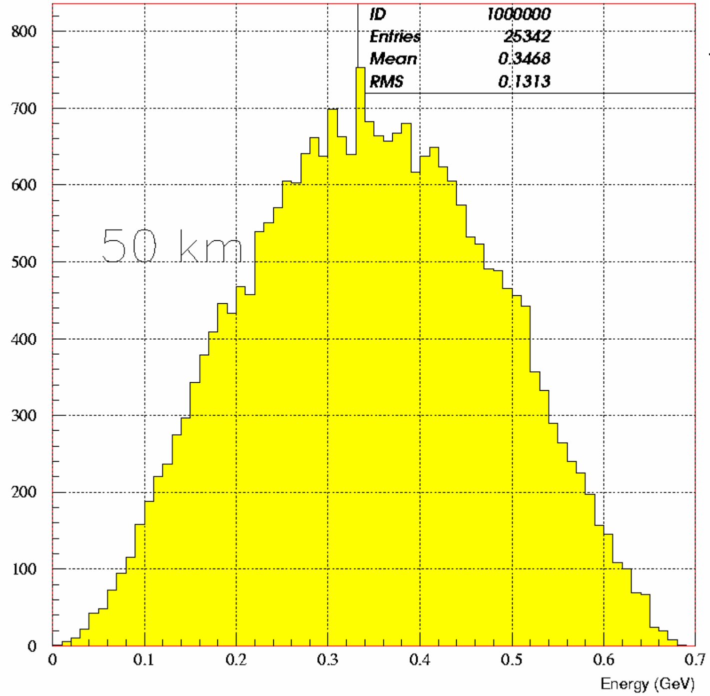
$O(10)$ events/5 y

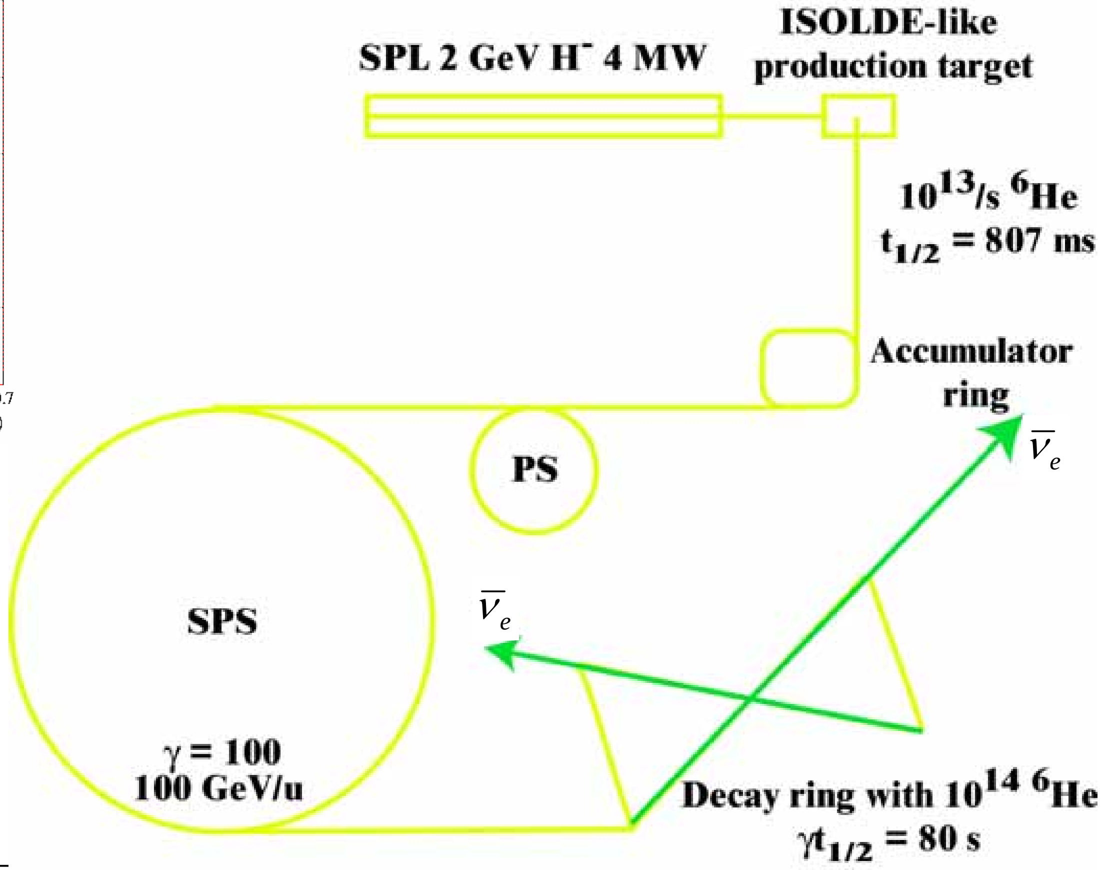
CERN ν-factory base-line scenario



The beta-beam – a serious alternative?





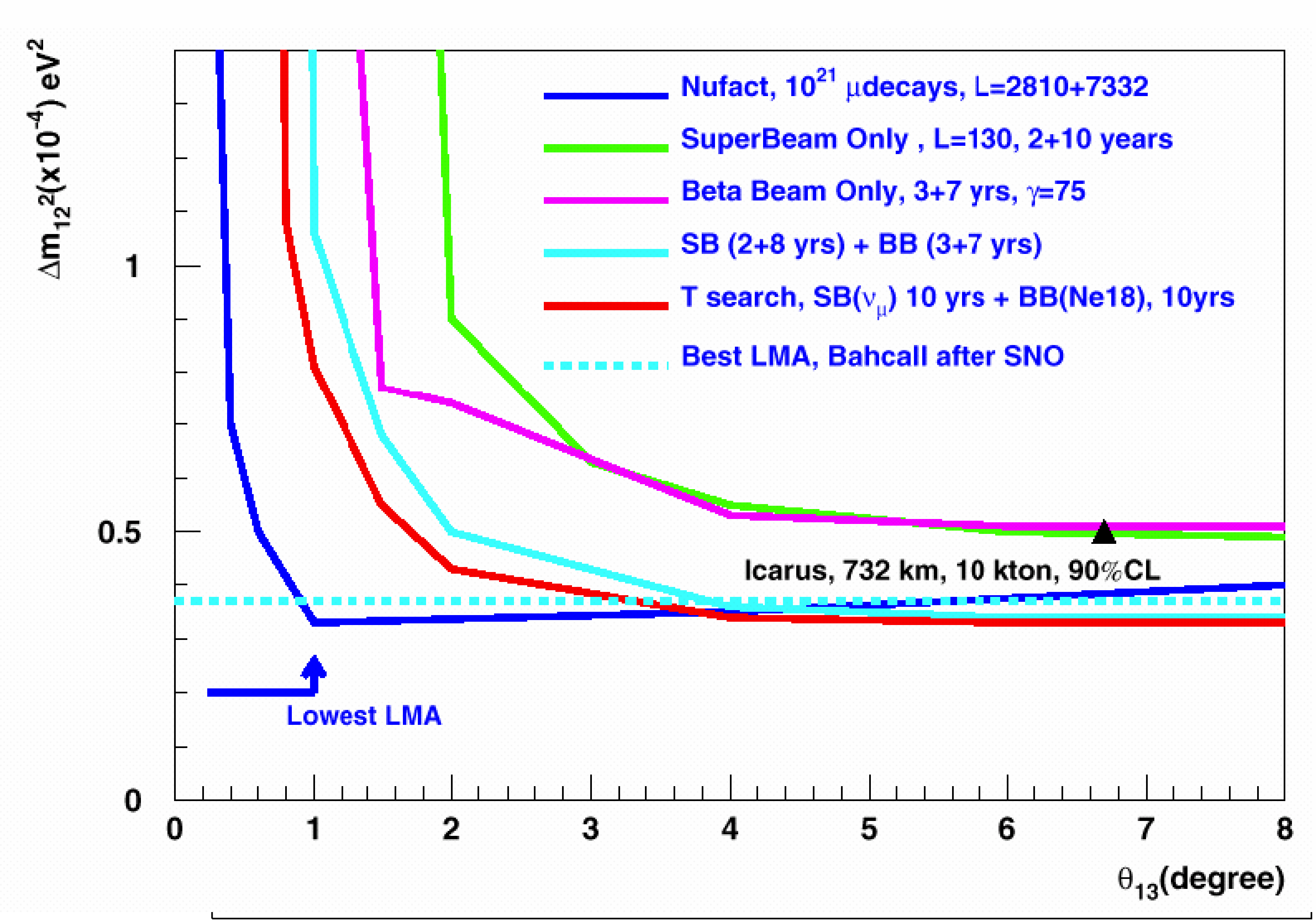


Γ=100, 350 MeV@50 Km.

Possible neutrino physics scopes (P. Zucchelli, Phys. Lett. B 532(2002) 166):

1. ν_e cross sections (astrophysics)
2. Short baseline oscillations (LSND)
3. LBL: θ_{13} (disappearance and appearance)
4. CP violation

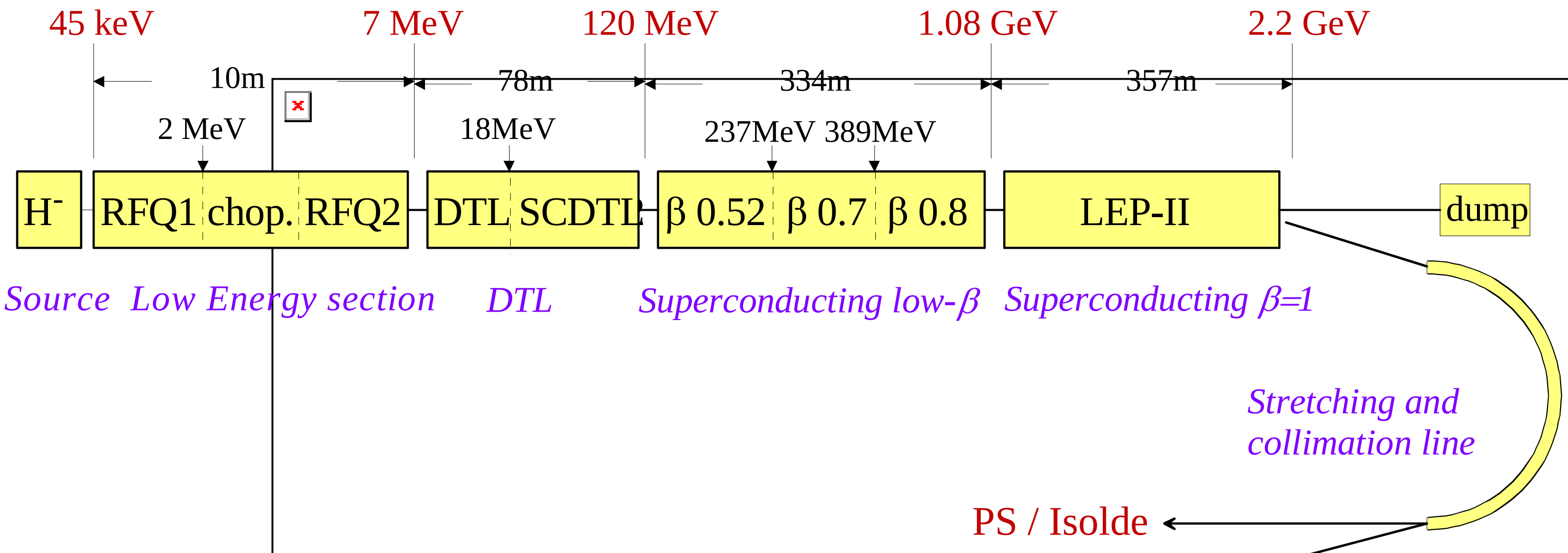
Leptonic CP violation $\nu_e \rightarrow \nu_\mu \neq \overline{\nu_e} \rightarrow \overline{\nu_\mu}$



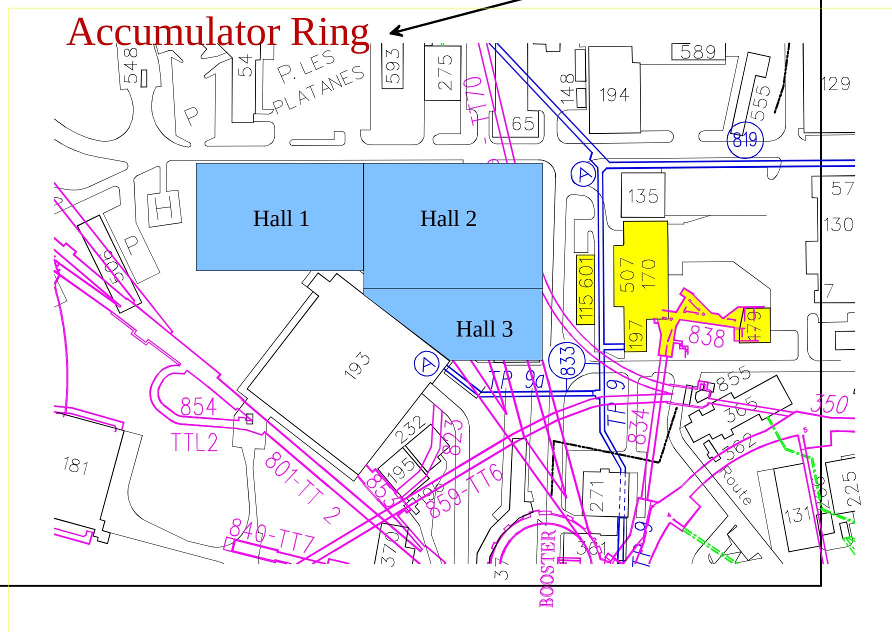
CERN needs for higher intensity proton beams

- Planned uses of high intensity proton beam and interesting directions of improvement :
  - LHC: increased beam brightness at injection
  - CERN Neutrinos to Gran Sasso (CNGS): higher proton flux
  - Anti-proton Decelerator (AD)
  - Neutrons Time Of Flight (nTOF) experiments
  - ISOLDE
- Potential uses of high intensity proton beams:
  - Fixed target Physics with low to medium energy muons and neutrinos
  - Neutrino Superbeam
  - "Neutrino Factory" based on a muon storage ring
  - "Muons Collider"

A second-generation RIB facility at CERN?



- Second generation RNB facility using the SPL as driver
- <100 μA on « traditional » ISOL targets, >100 μA on converter
- Post-acceleration to 100 MeV/u (cyclotron/LINAC)
- Storage/re-cycler ring



RAMA - "New" tools (for RIB)

Existing idea (GSI, RIKEN plans):

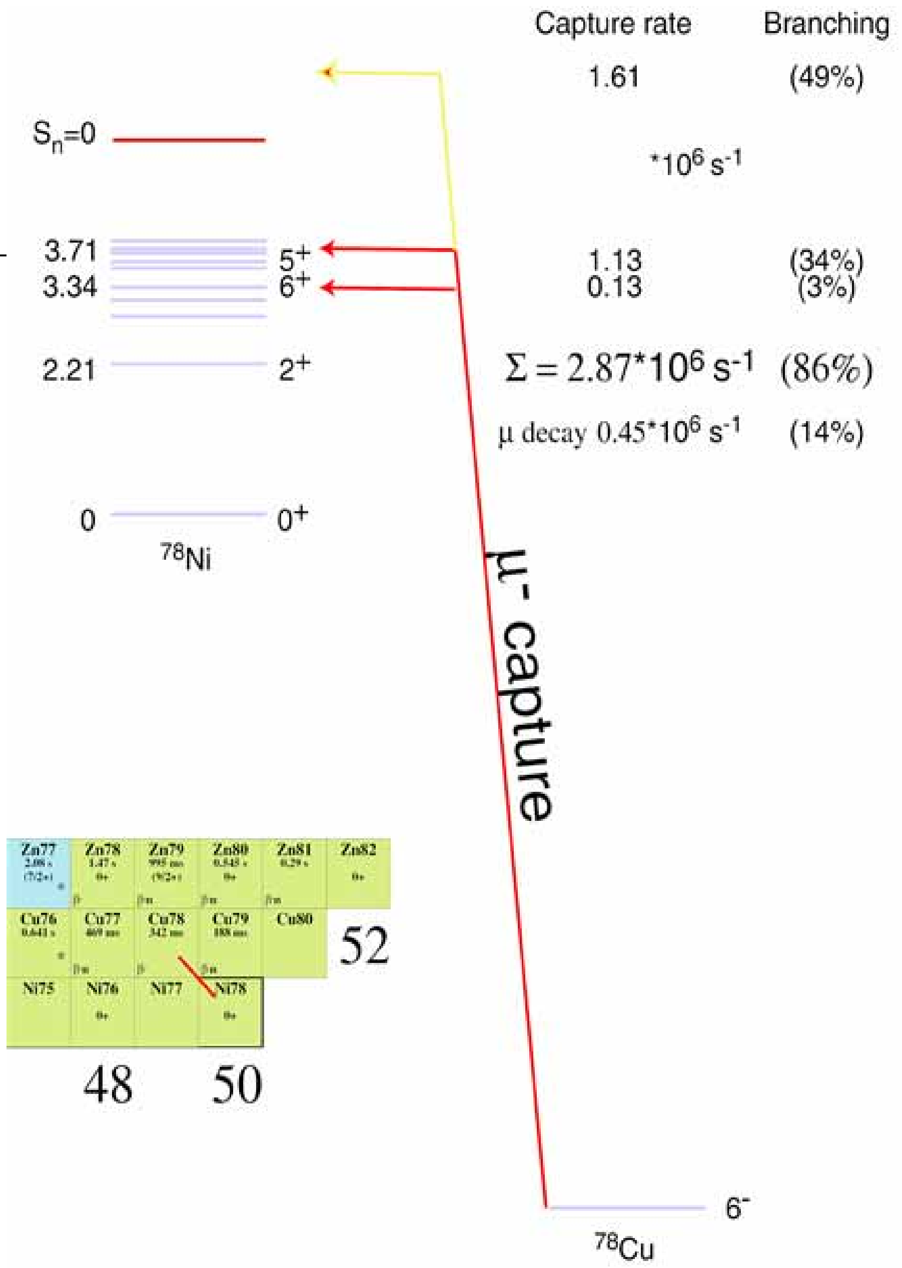
- e-scattering – Luminosity, kinematics???

With new drivers (eg. SPL@CERN) we will not only produce 10^2 – 10^3 more RI, but also >10^3 more muons (nuFact) and anti-protons (AD+) than today!

⇨Combine to Radioactive Antiprotonic and Muonic Atoms (RAMA)

Radioactive muonic atoms

Process	Observable	Deduced quantity	Physics
Capture in high orbit (atomic x-sections), cascade	Muonic x-rays *O*(MeV)	Charge distribution	High-precision data on charge radii and moments ■novel structure features far from stability ■parity non-conservation in Fr, Ra atoms
Muon capture (semi-leptonic) feeding highly excited states, high multipoles $^{A}_{Z}X + \mu^{-} \rightarrow {}^{A}_{Z-1}X + \nu_{\mu}$ N.B.: One step further from stability on n-rich side!	De-excitation γ, particles, daughter activity	Capture rates	Nuclear structure@high excitation energies ■collective excitation modes in neutron-rich nuclei ■renormalization of g_A in nuclear medium Nuclear astrophysics ■ν scattering (supernova), ■ν post-processing, … Neutrino physics



Capture rate
Branching
1.61
(49%)
S_n=0
*10^6 s^-1
3.71
3.34
5+
6+
1.13
0.13
(34%)
(3%)
2.21
2+
Σ = 2.87*10^6 s^-1
(86%)
μ decay 0.45*10^6 s^-1
(14%)
0
0+
78Ni
μ- capture
Zn77
Zn78
Zn79
Zn80
Zn81
Zn82
Cu76
Cu77
Cu78
Cu79
Cu80
52
Ni75
Ni76
Ni77
Ni78
48
50
6-
78Cu

Antiprotonic radioactive atoms

Process	Observable	Deduced quantity	Physics
Capture in high orbit (atomic x-sections), cascade	Antiprotonic x-rays *O*(MeV)	Annihilation orbit, energy shifts	Matter distributions, neutron vs. protons on nuclear surface, …
Annihilation (n>7) on peripheral nucleon	De-excitation γ, particles, daughter activity	n vs. p annihilation	

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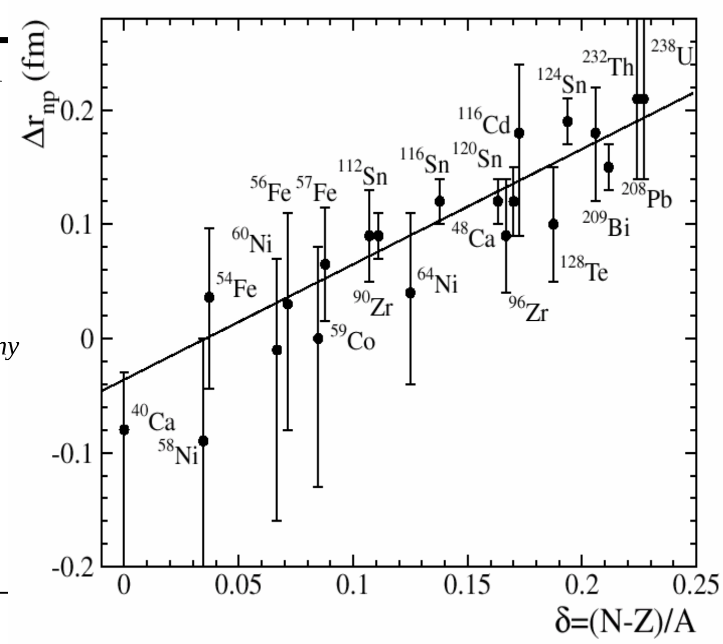
Neutron Density Distributions Deduced from Antiprotonic Atoms

A. Trzcińska, J. Jastrzębski, and P. Lubiński
Heavy Ion Laboratory, Warsaw University, PL-02-093 Warsaw, Poland
F. J. Hartmann, R. Schmidt, and T. von Egidy
Physik-Department, Technische Universität München, D-85747 Garching, Germany
B. Klos
Physics Department, Silesian University, PL-40-007 Katowice, Poland
(Received 28 March 2001; published 2 August 2001)



Combined cyclotron and ion traps

Cyclotron trap at PSI

10^5 μ^-/s @ 20…50 keV
scale by 10^6 --> $N_\mu = 10^{11}$ /s

$v_\mu = 1.5 - 30$ cm/τ_μ

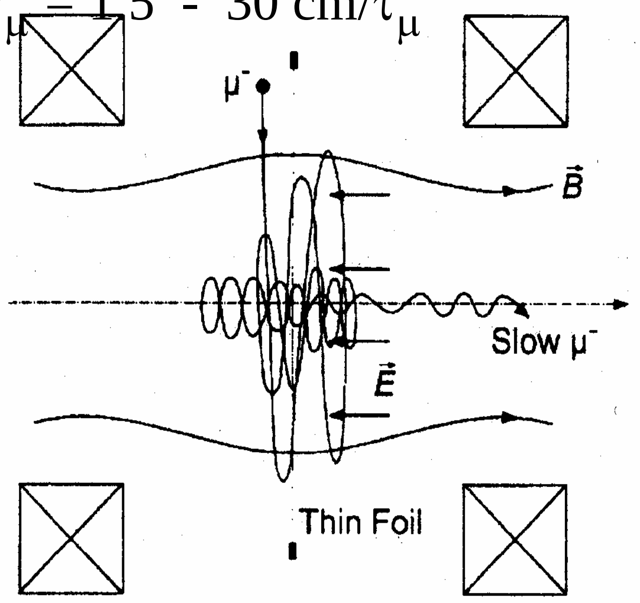


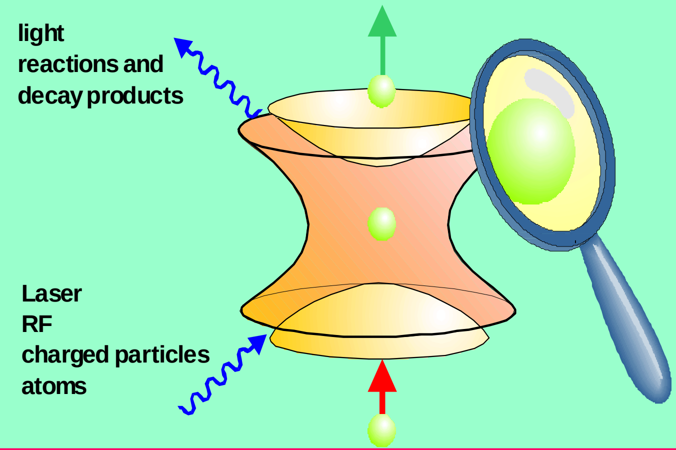
Fig. 2. Principle of the extraction method.

Ion traps at ISOLDE

$N_{ion} = 10^6$ /cm^3

Penning trap:
magnetic field + static electric field

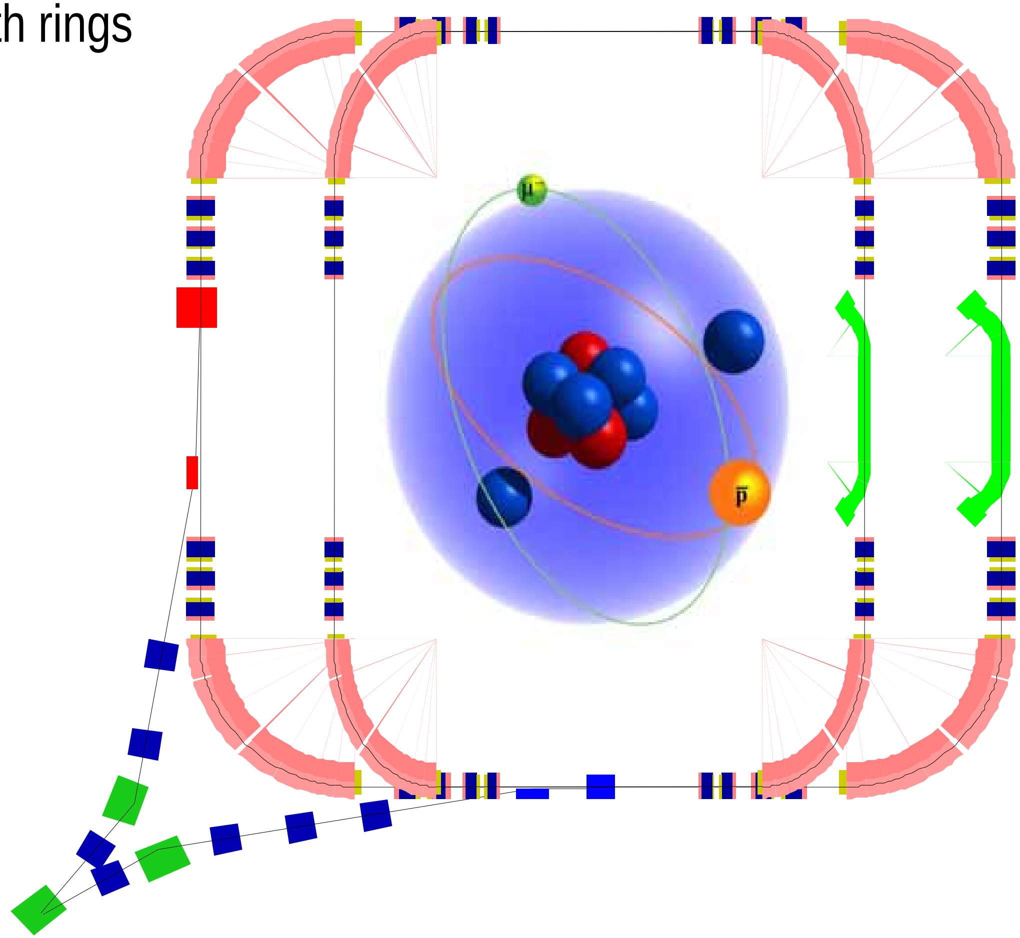
Paul (RFQ) trap:
oscillating electric field



$$N_{\mu atoms} = N_\mu \, N_{ion} \, \sigma_{capt} \, v_\mu = 6 \ldots 120 \text{ /s}$$

Ideas for exotic probes for RIB (RAMA@ECT*)

- p-bar – antiprotonic atoms
  - Intersecting storage ring with 10^9 p-bar stored
    - Electron cooling on both rings
    - Multi turn injection
    - Merging reactions
- μ^- – muonic atoms
  - Cyclotron trap (PSI)
  - Hydrogen layer (RIKEN-RAL)
  - Storage ring



Conclusions

- The ISOLDE scientific programme is very active and diverse, both within basic and applied research
- ISOL-techniques used in the production and separation have important connections to other research fields
- Large physics output obtained with “first-generation” ISOL facilities – time to make a major step forward with EURISOL
  - Due to technical and scientific synergies, CERN could be the most efficient site