Thomas Nilsson, CERN EP/IS

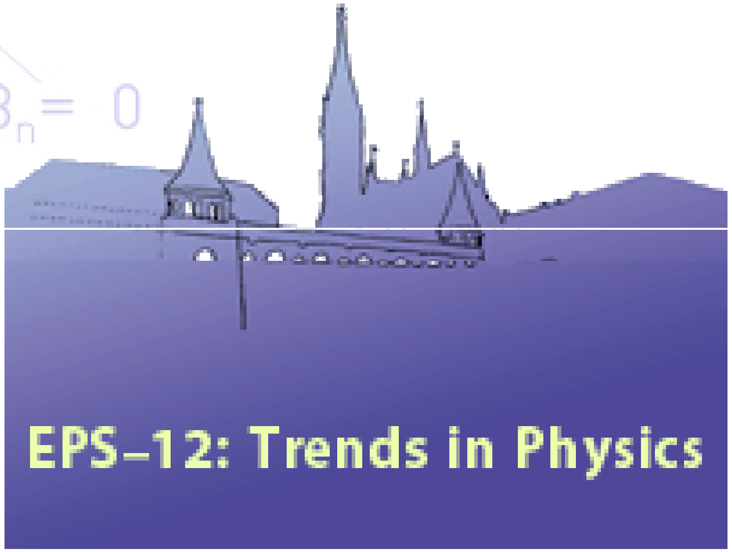
Exotic Nuclei and Radioactive Beams at Low Energy

EPS-12 Trends in Physics, Budapest August 29 2002

- Radioactive beams
  - Rationale
  - Production - separation

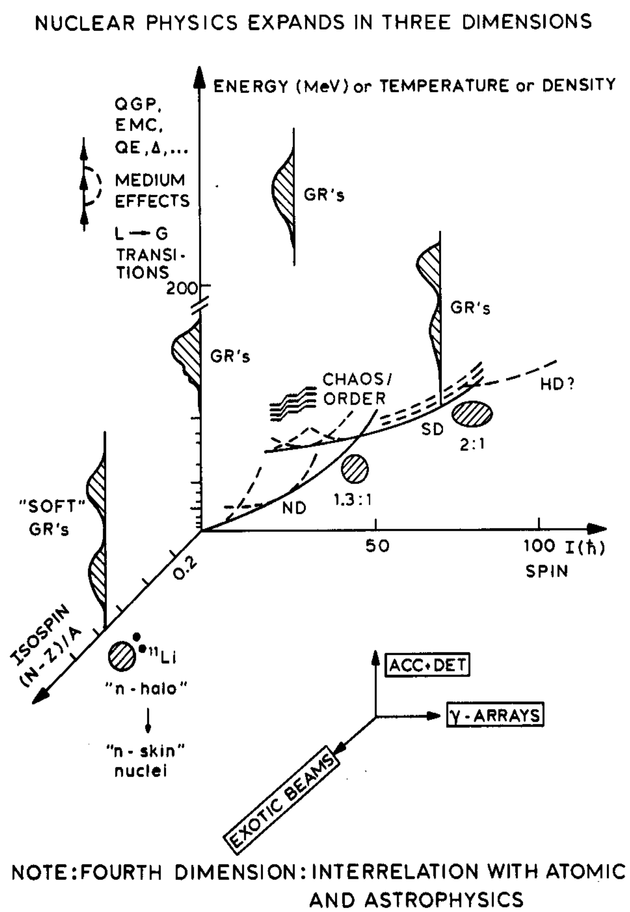
- CERN-ISOLDE
  - Research on nuclei at the driplines
  - Interdisciplinary uses of RIB
  - REX-ISOLDE

- Outlook
  - ISOLDE-RNB
  - EURISOL

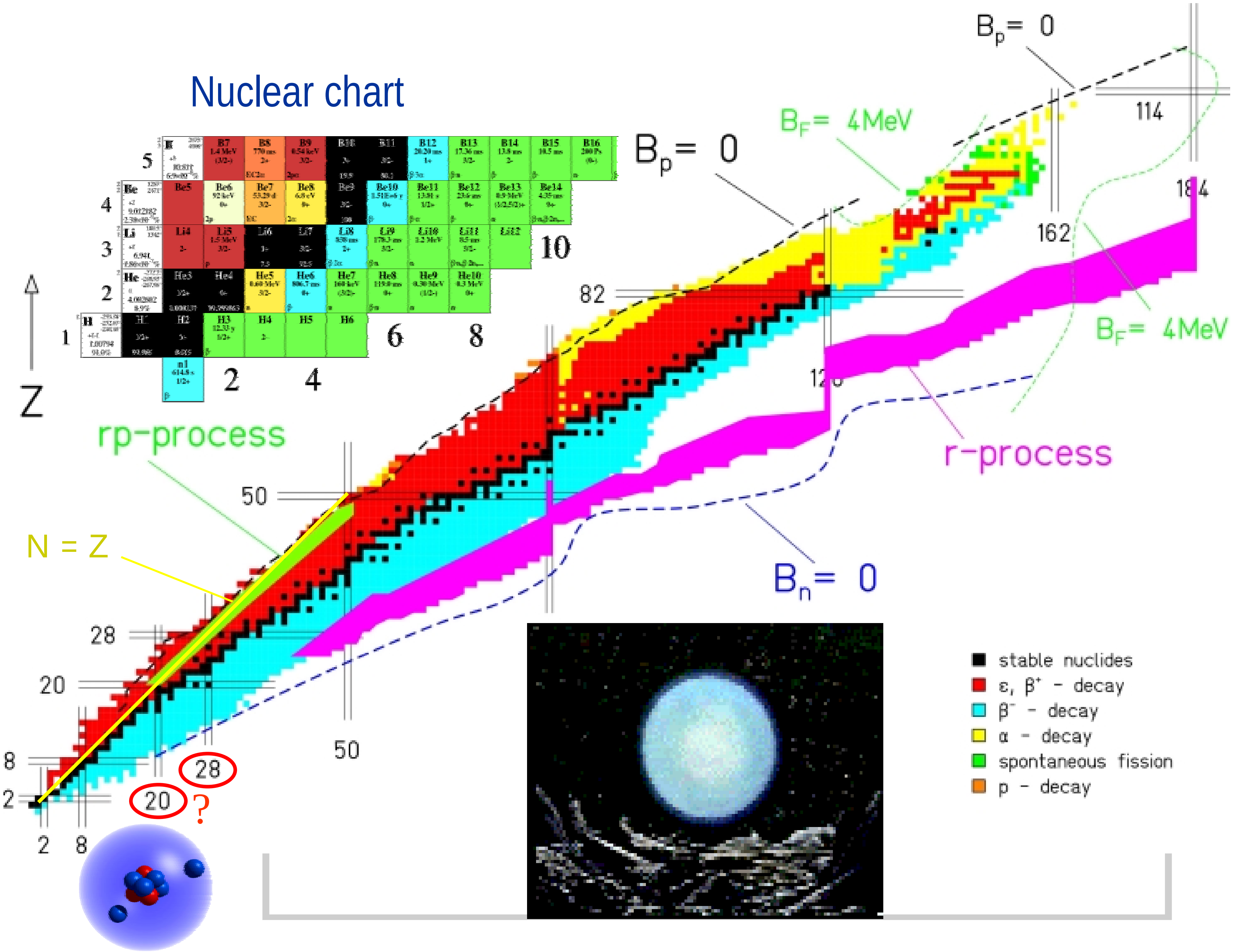


Why study the atomic nucleus?

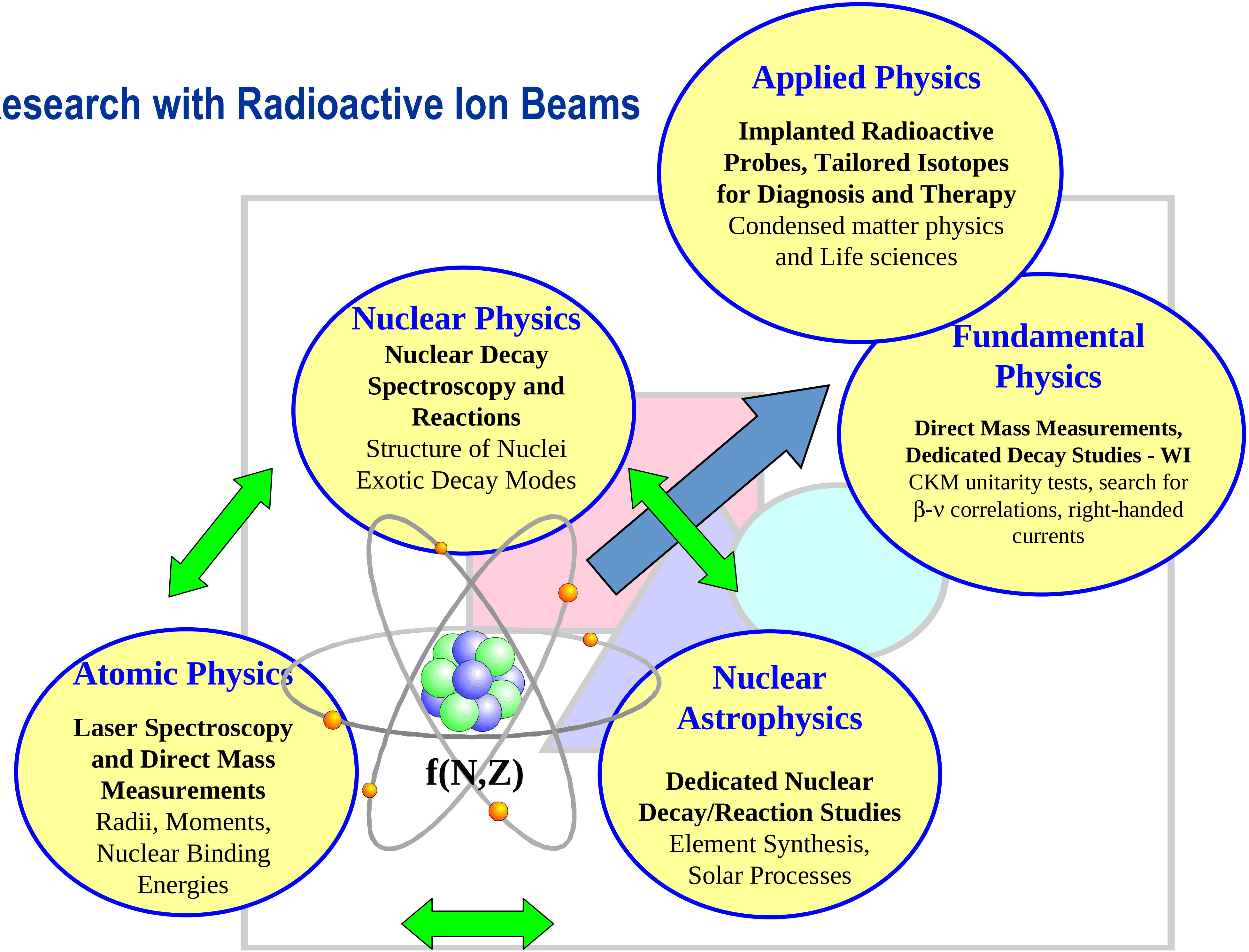
- A few-body system of hadrons (neutrons and protons) with many remaining question marks
- "Largest" system where strong and weak interaction are manifested
- "Applications"
  - Astrophysics
  - Condensed matter
  - Energy
  - Medicine



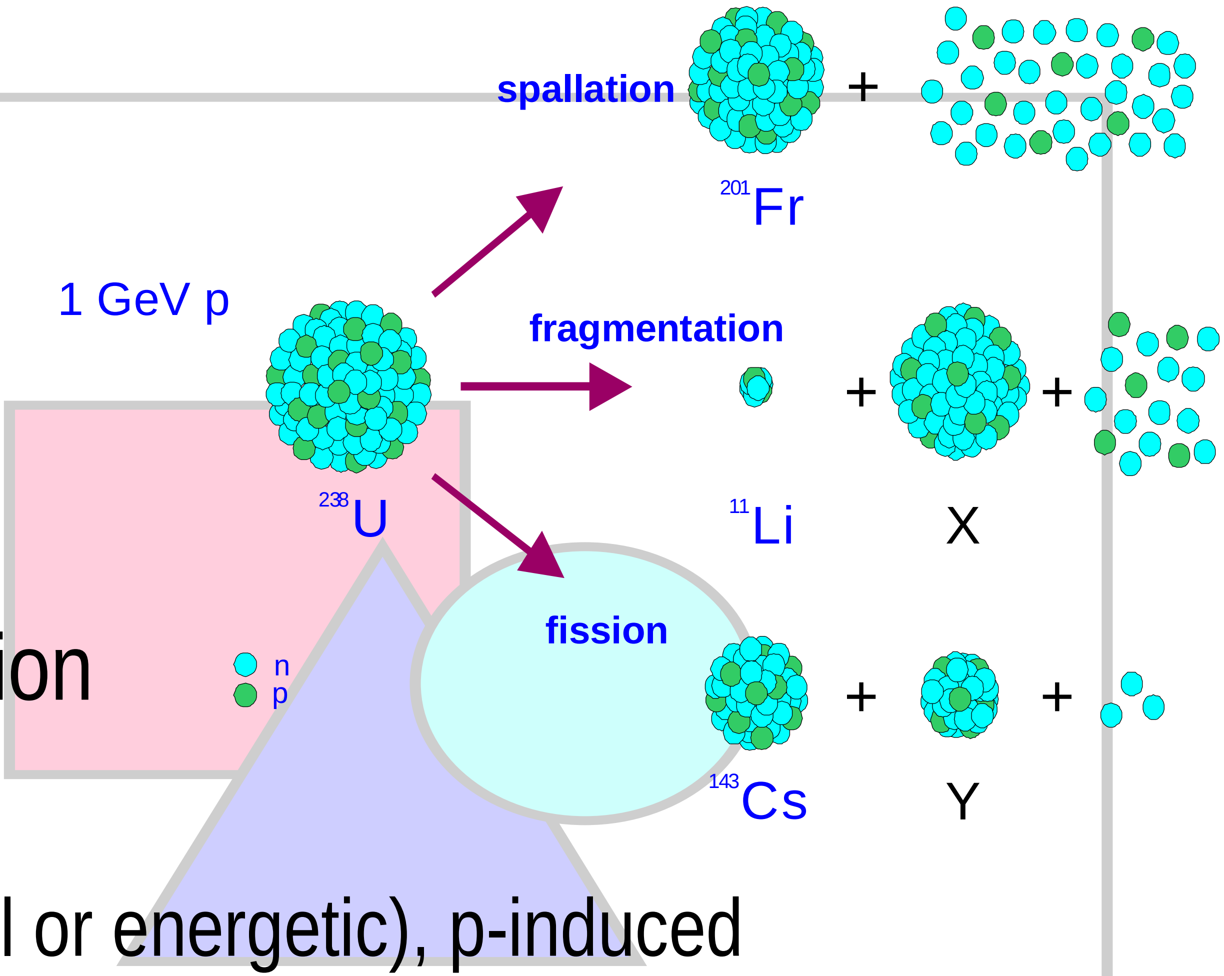
Nuclear chart



Research with Radioactive Ion Beams

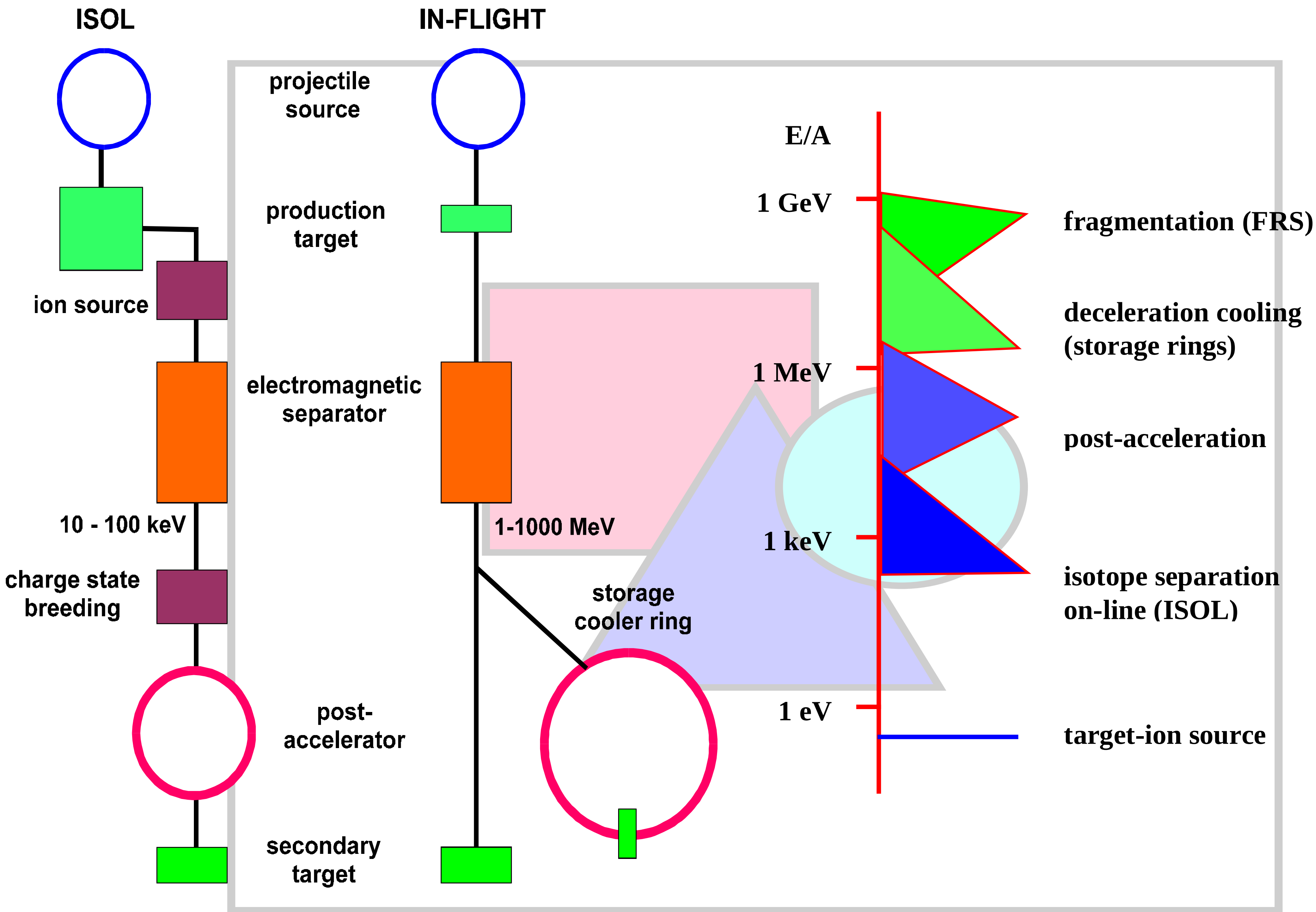


RIB - Production reactions

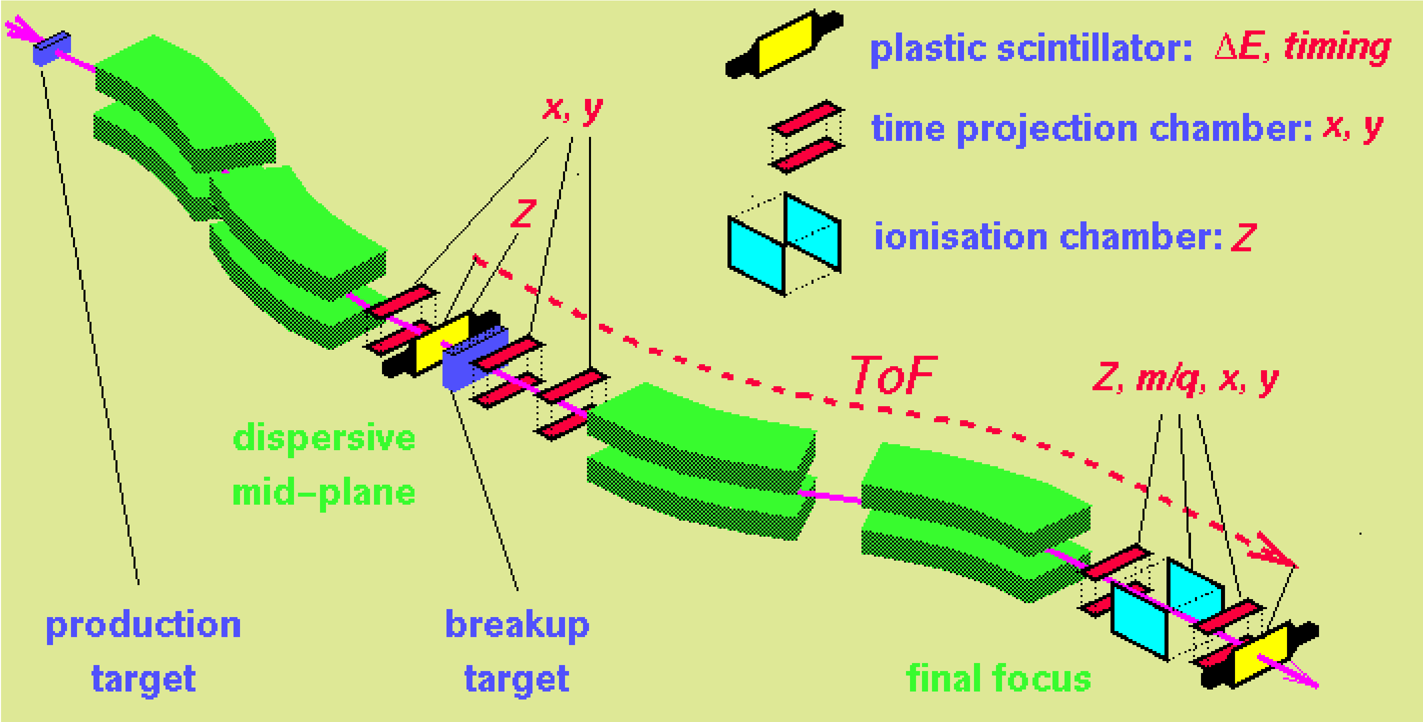


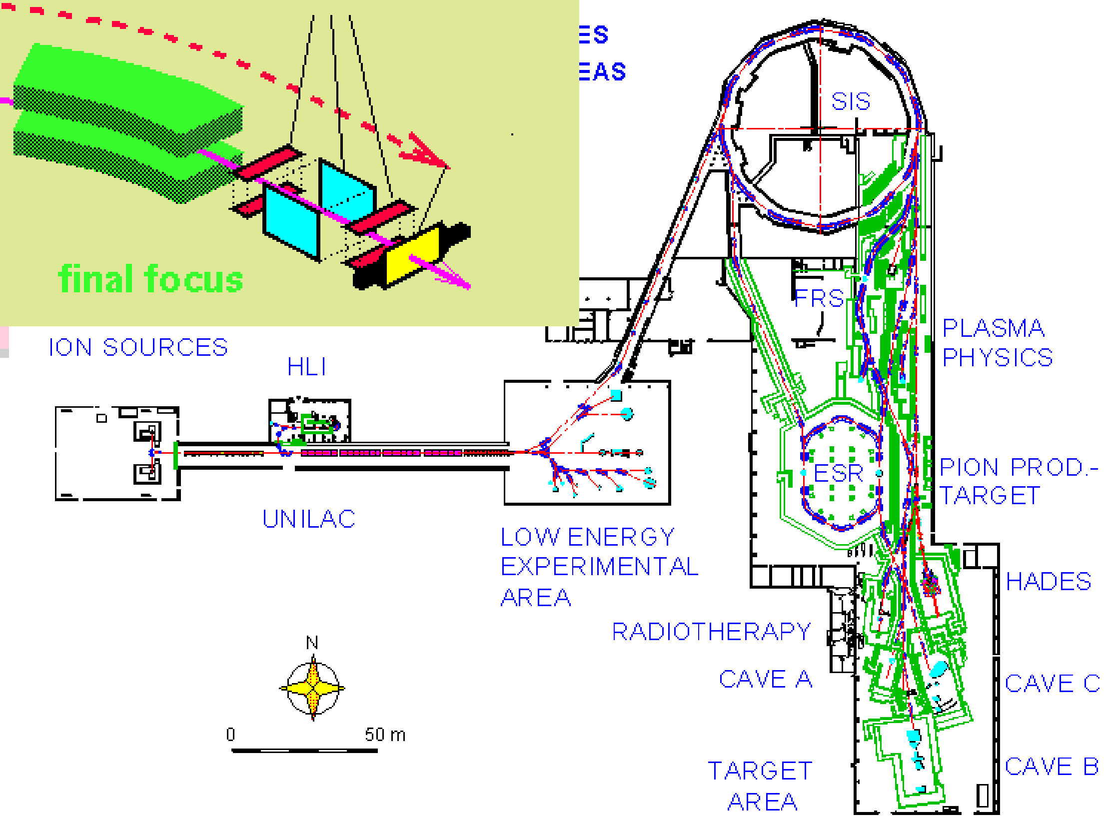
- Spallation
- Fragmentation
- Fission
  - n- (thermal or energetic), p-induced
  - Photofission (e-beam)

Radioactive beams – production and separation

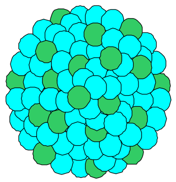


In-flight production (e.g. FRS@GSI)

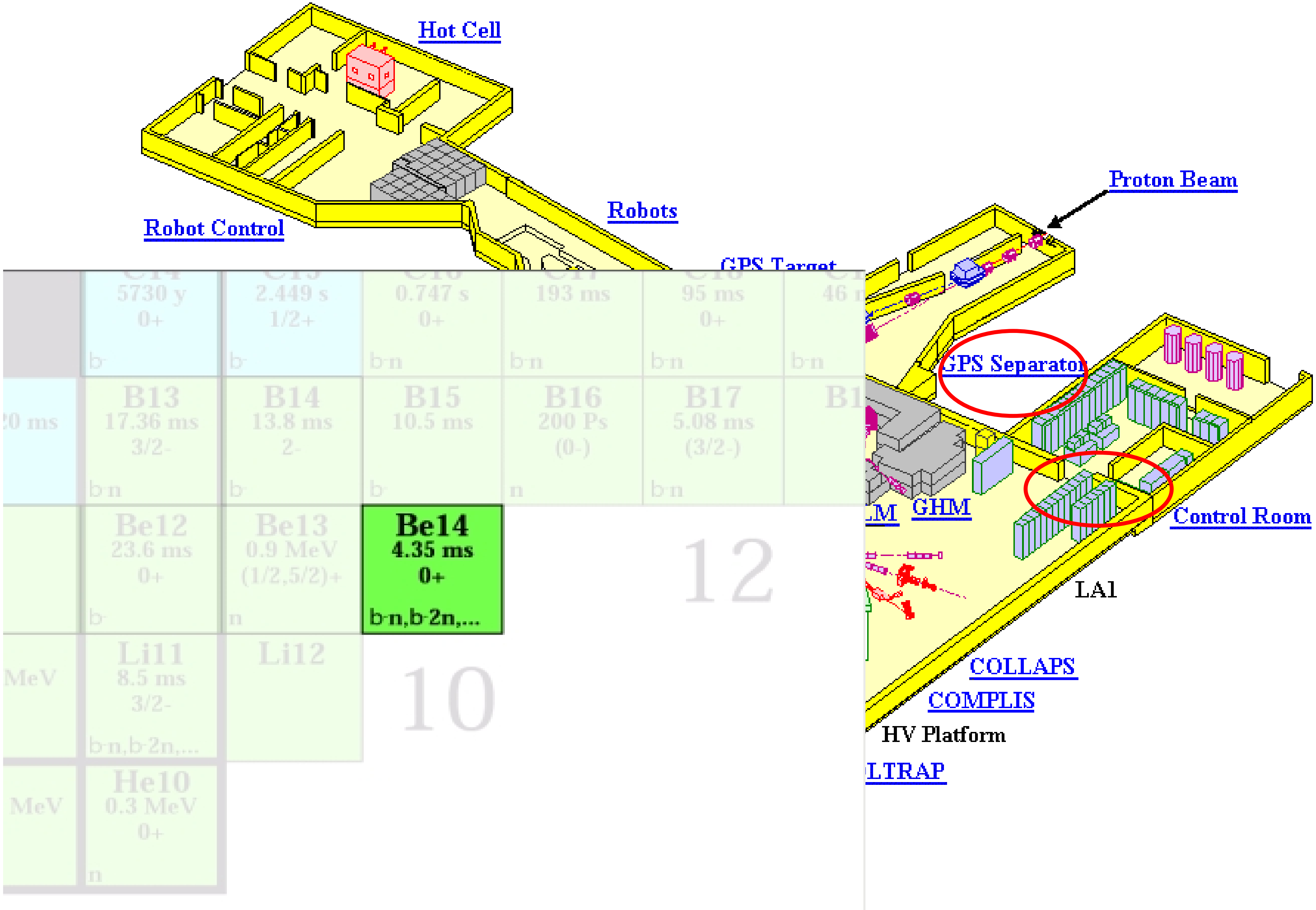




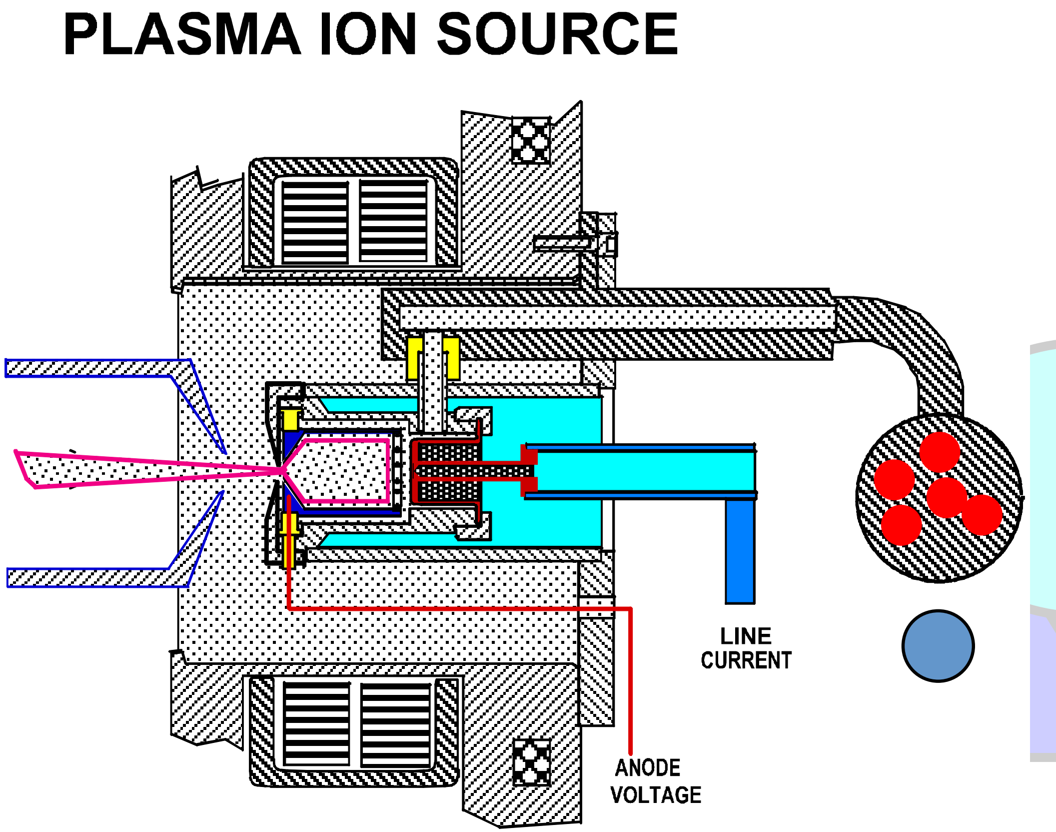
1 GeV/u U



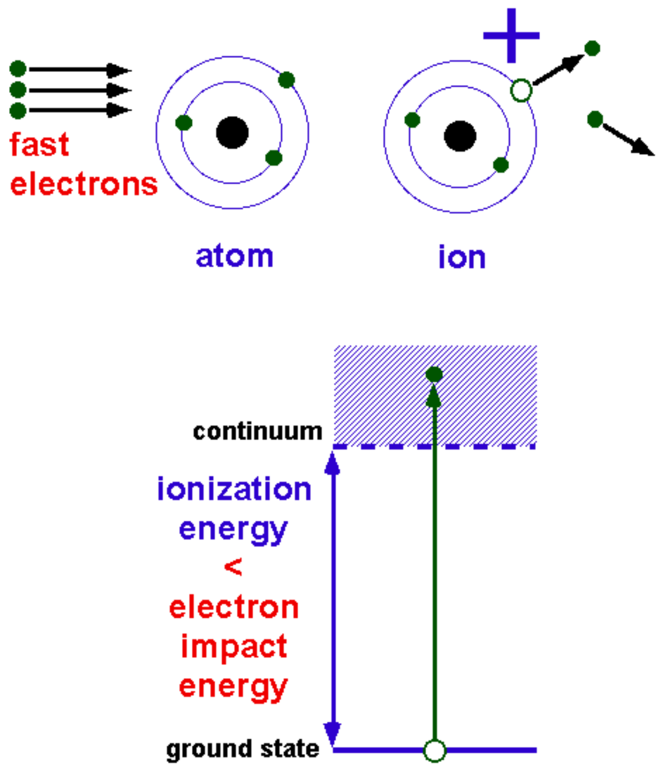
ISOL (e.g. ISOLDE@CERN)



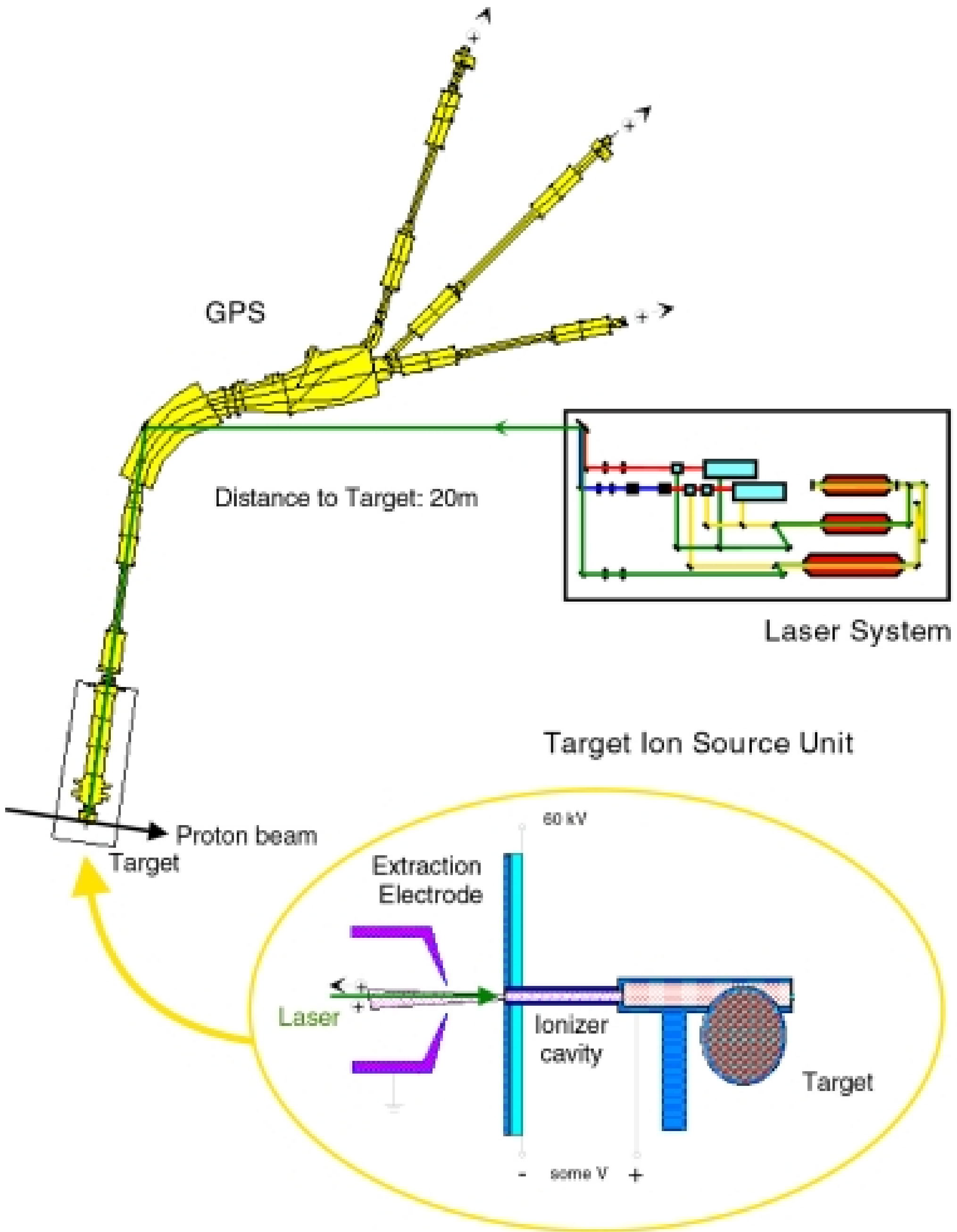
ISOL target

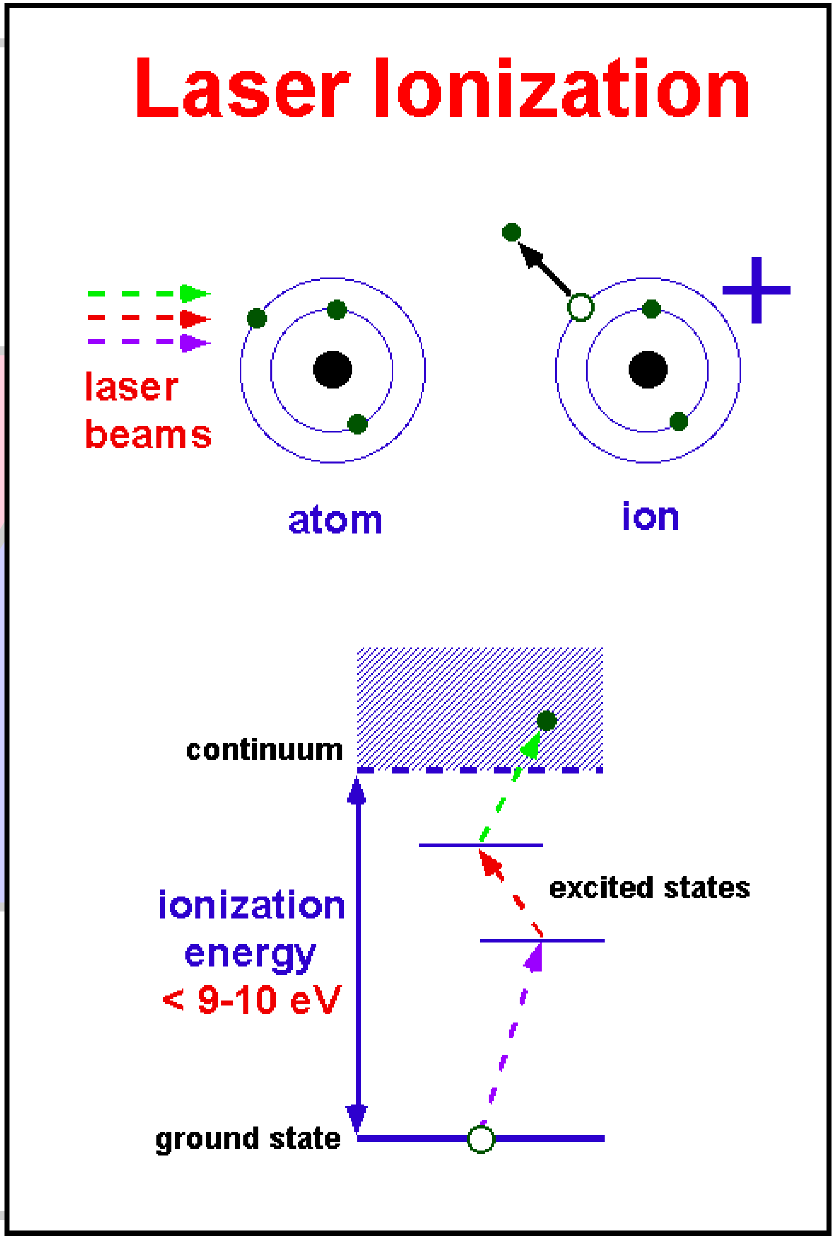


Ionization by electron impact

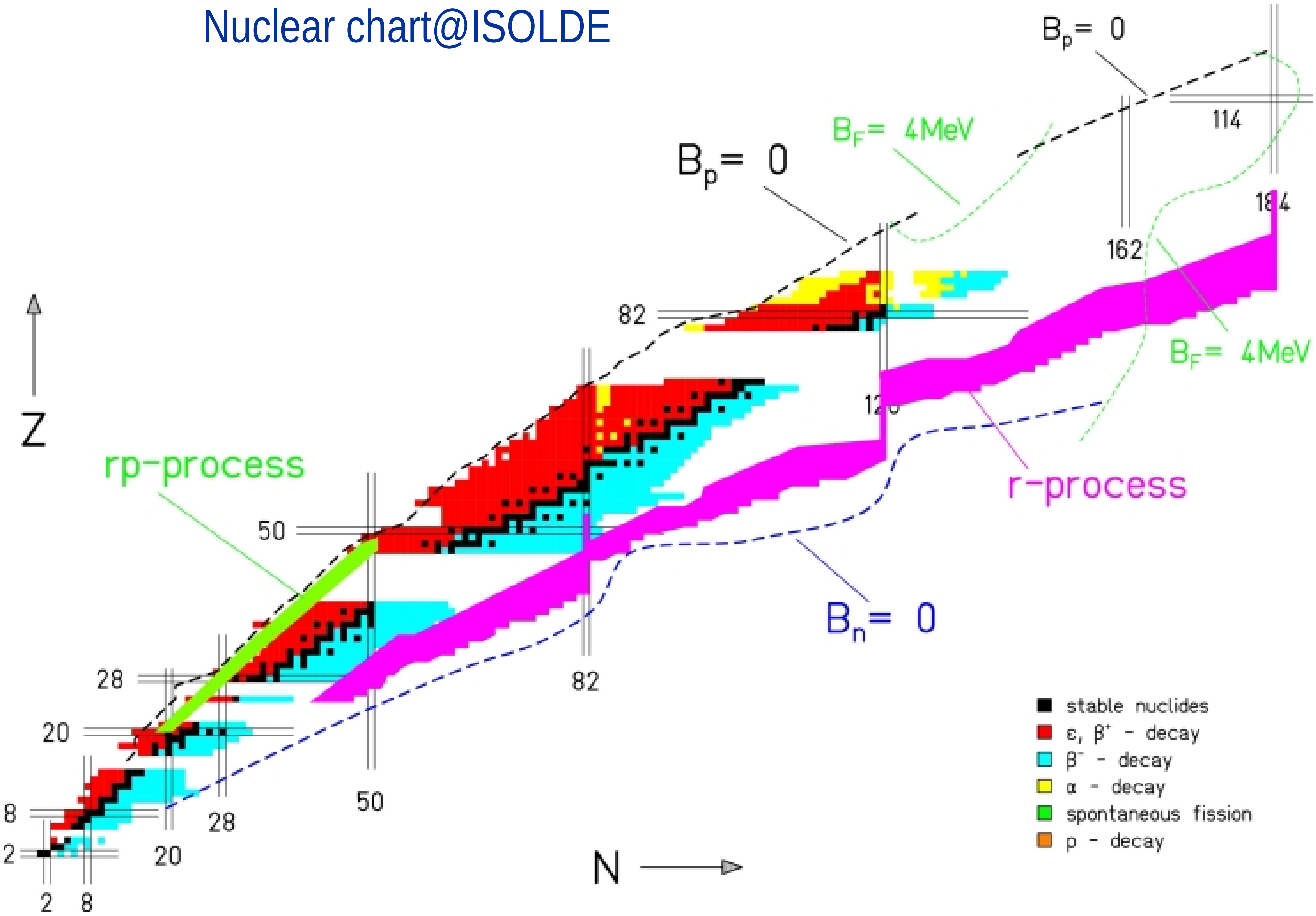


Resonant LASER Ion Source



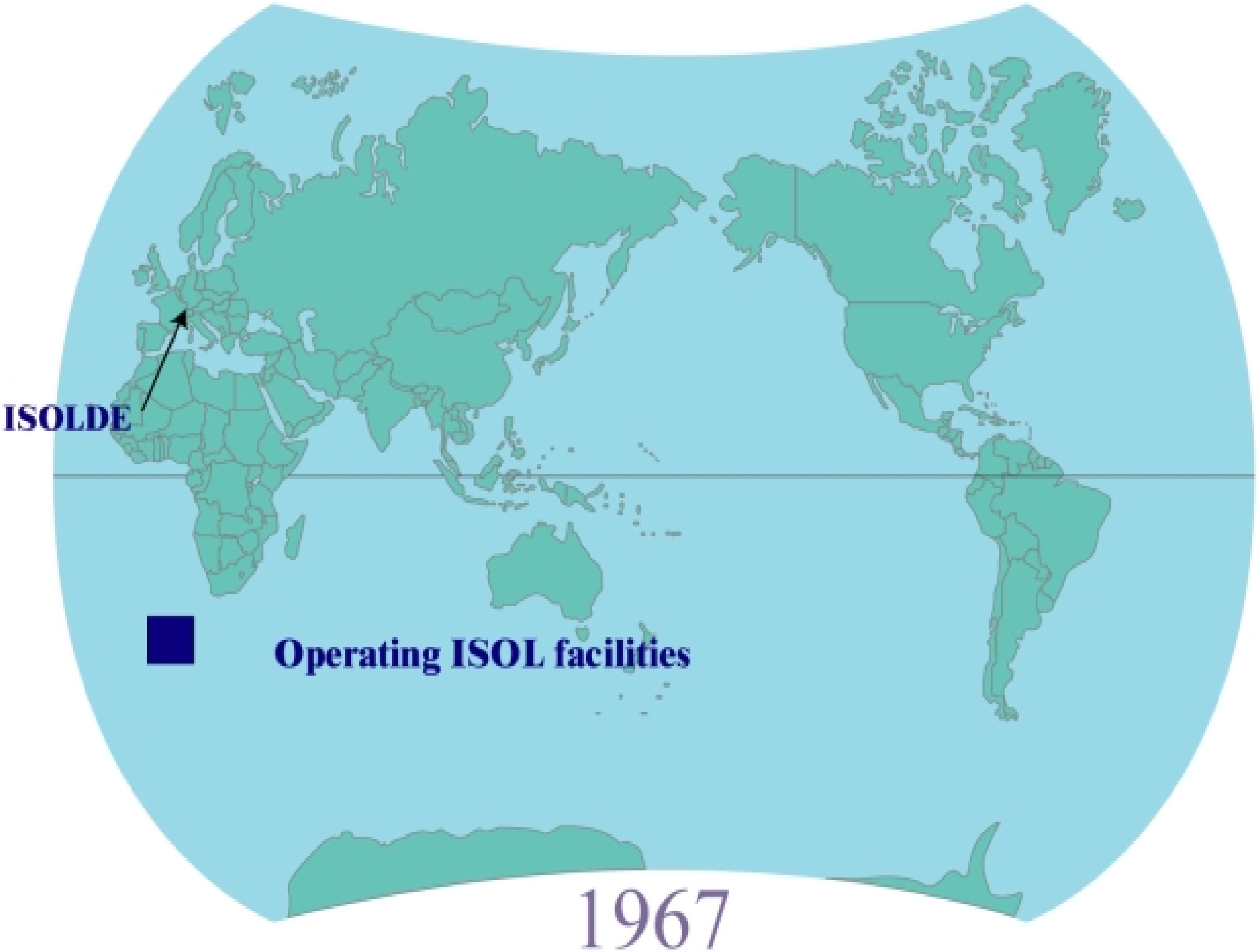


Nuclear chart@ISOLDE

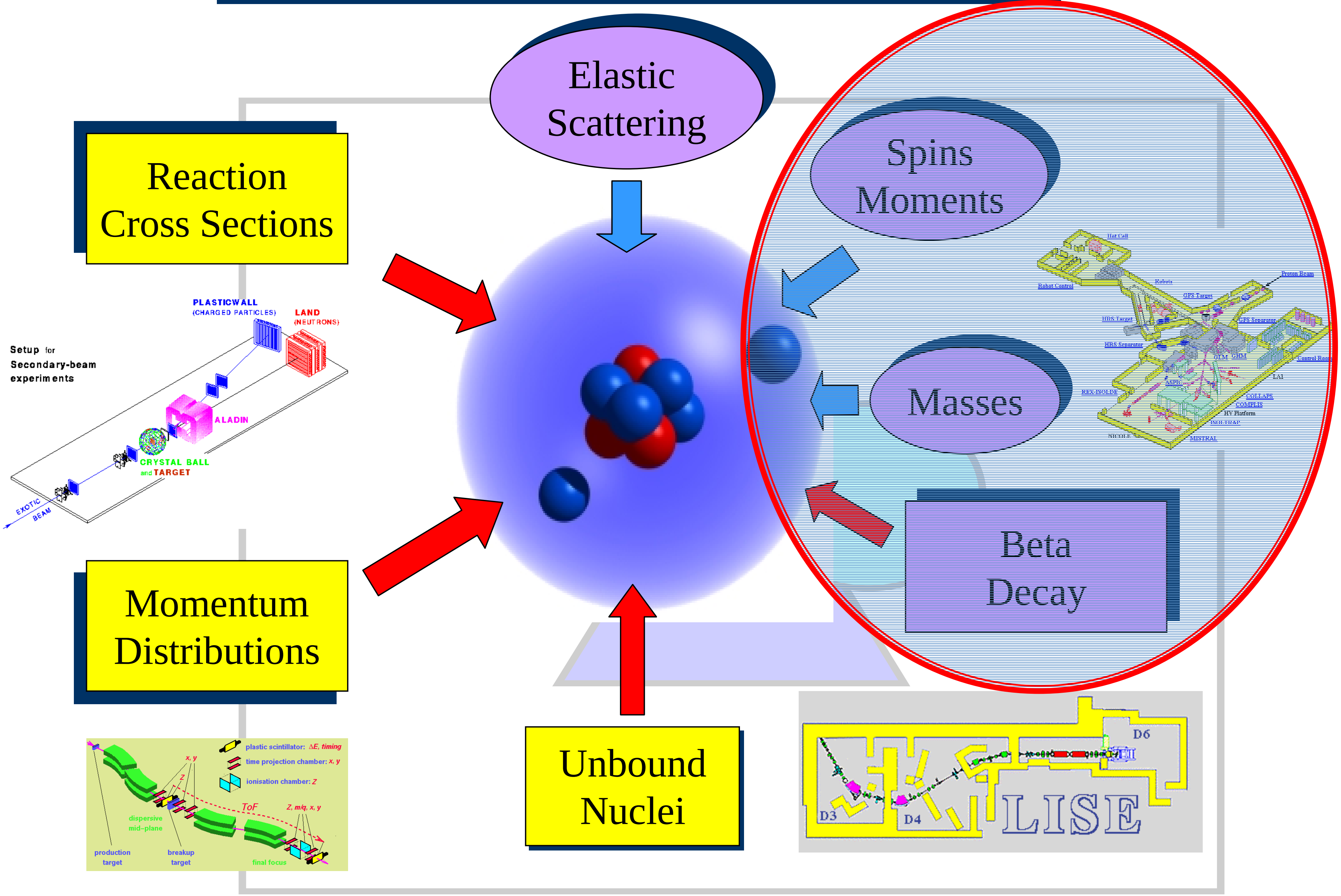


World Wide Radioactive Beam Facilities

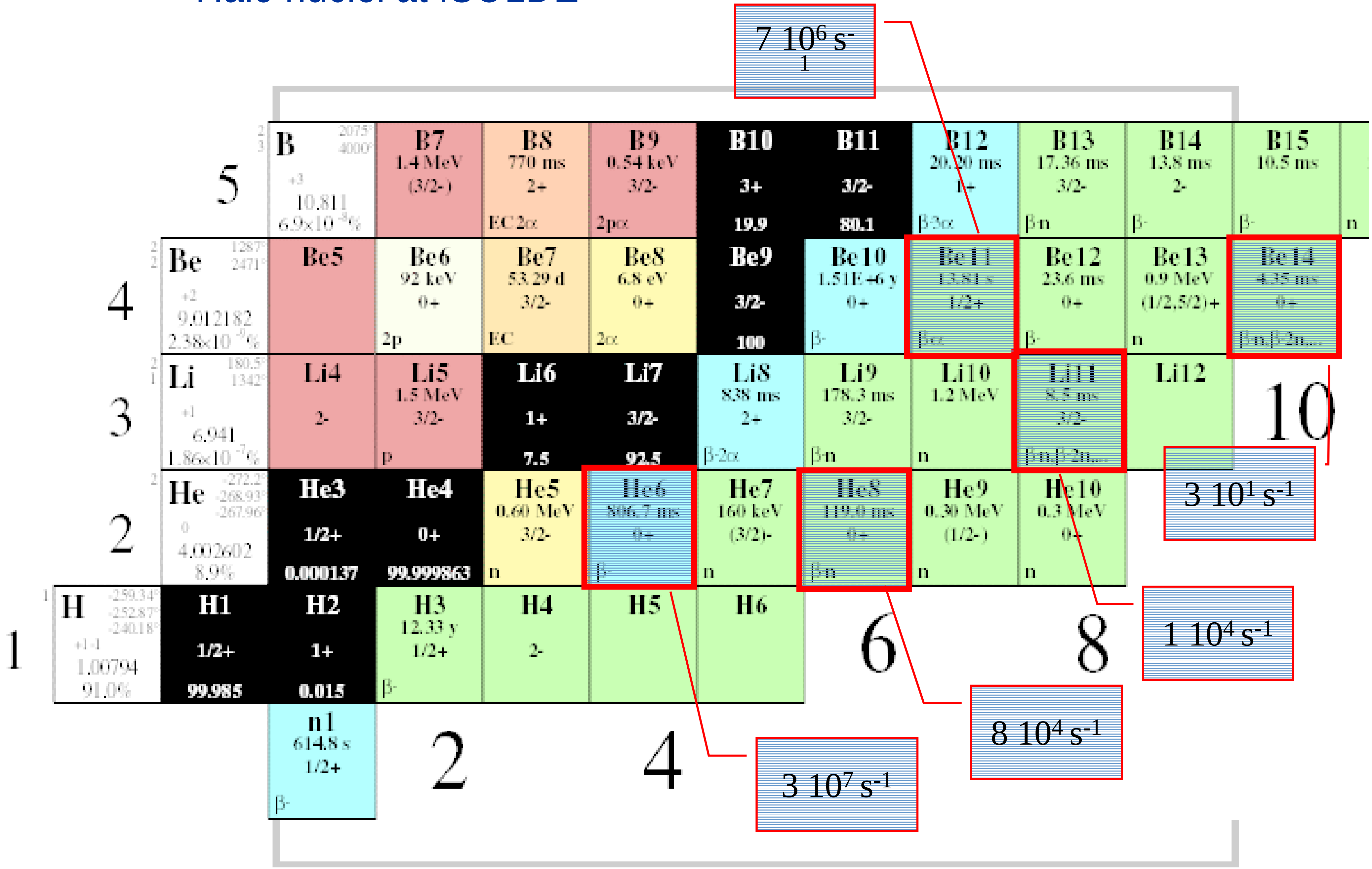
2001


ISOLDE
Operating ISOL facilities
1967

Experimental Studies of Dripline Nuclei



Halo nuclei at ISOLDE

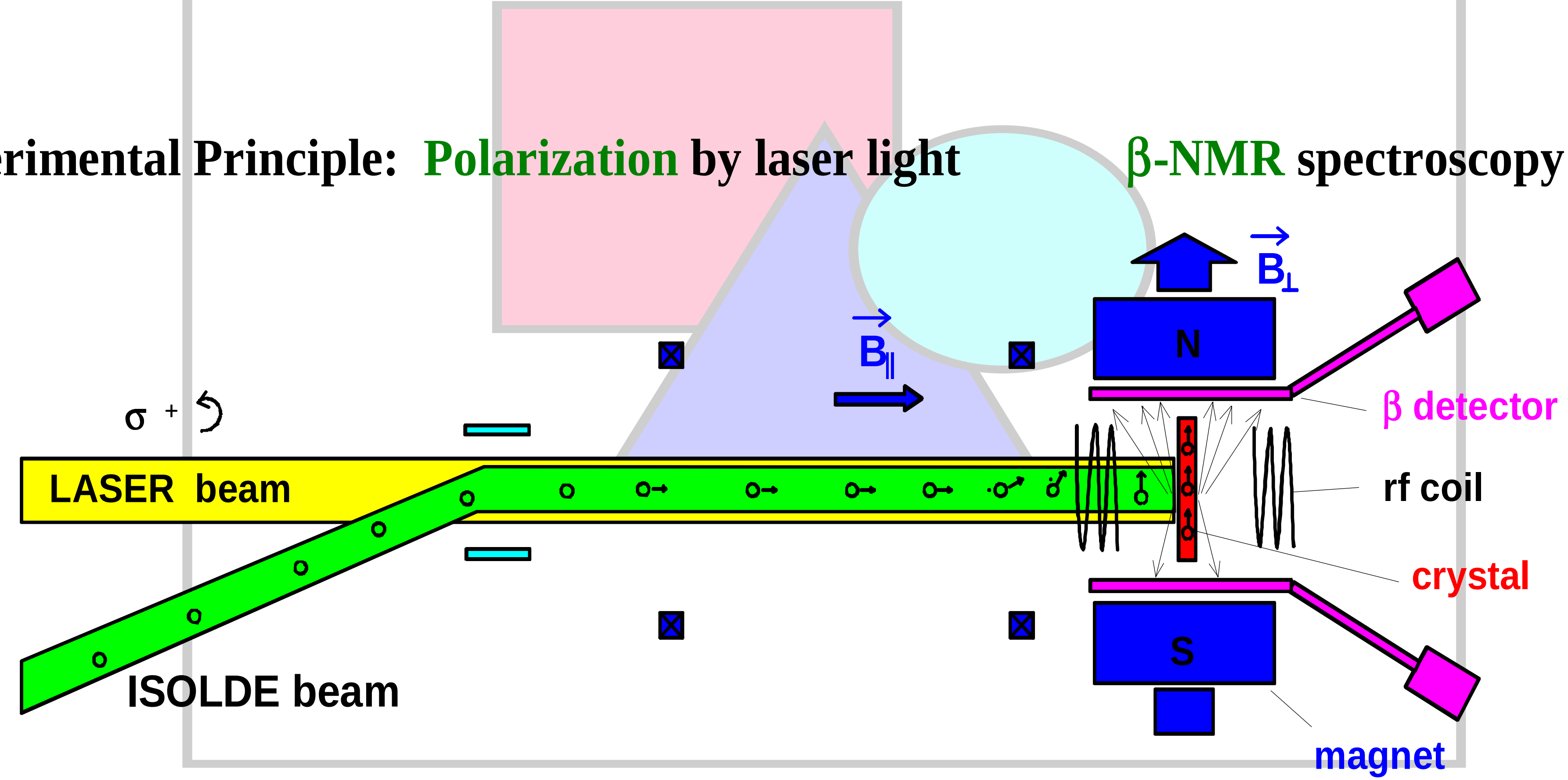


Measurement of the Magnetic Moment of ^{11}Be

^{11}Be: single neutron halo structure

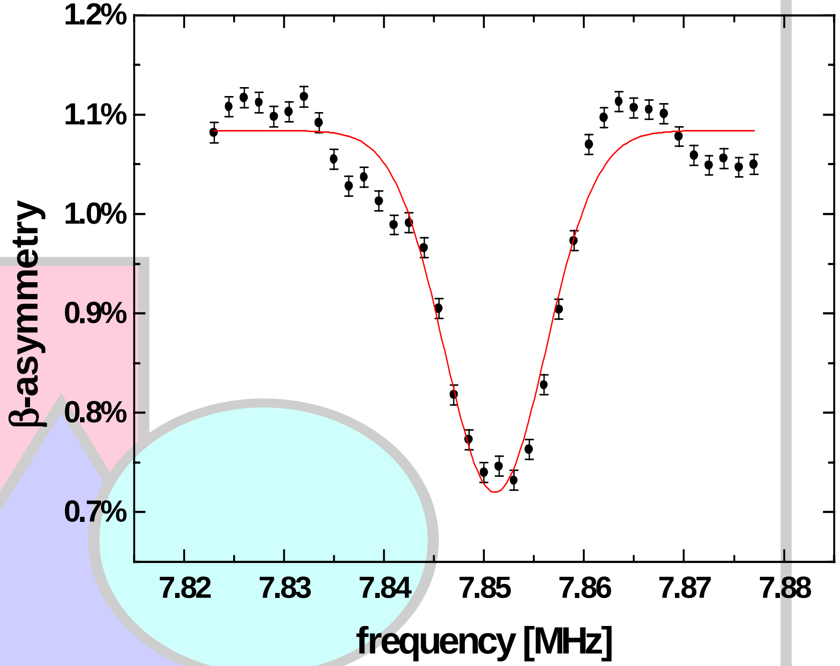
Magnetic moment: probes the state of the halo neutron

Experimental Principle: Polarization by laser light β-NMR spectroscopy



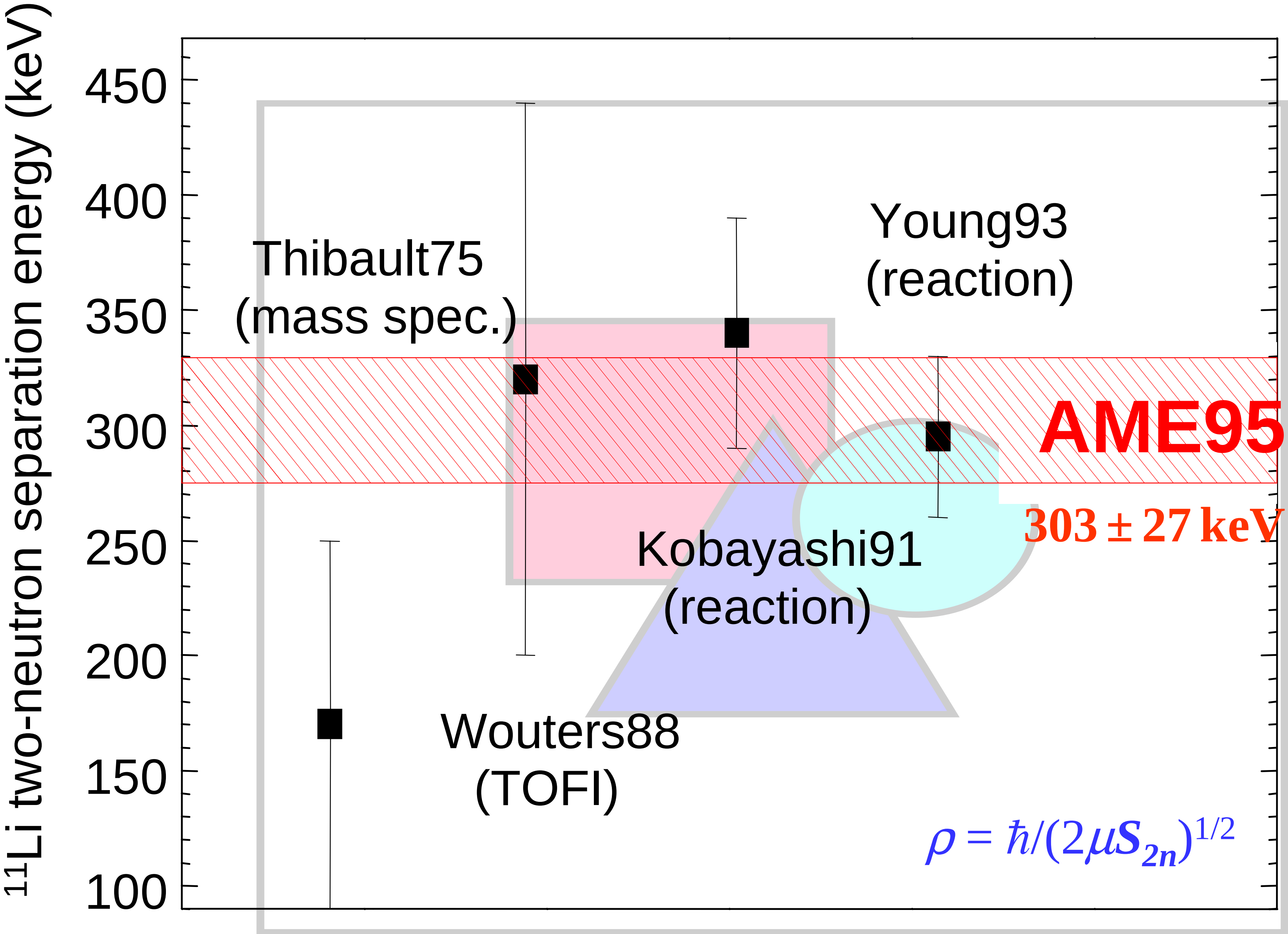
^{11}Be

- The large radius of ^{11}Be: halo structure or deformation?
- $\mu_I(^{11}Be) = -1.682(3)\ \mu_N$
- Comparison to theoretical approaches
- $-1.5\ \mu_N < \mu_I(^{11}Be) < -1.6\ \mu_N$
- for: strong small degrees of deformation
- Result indicates a rather pure halo structure with hardly any additional deformation



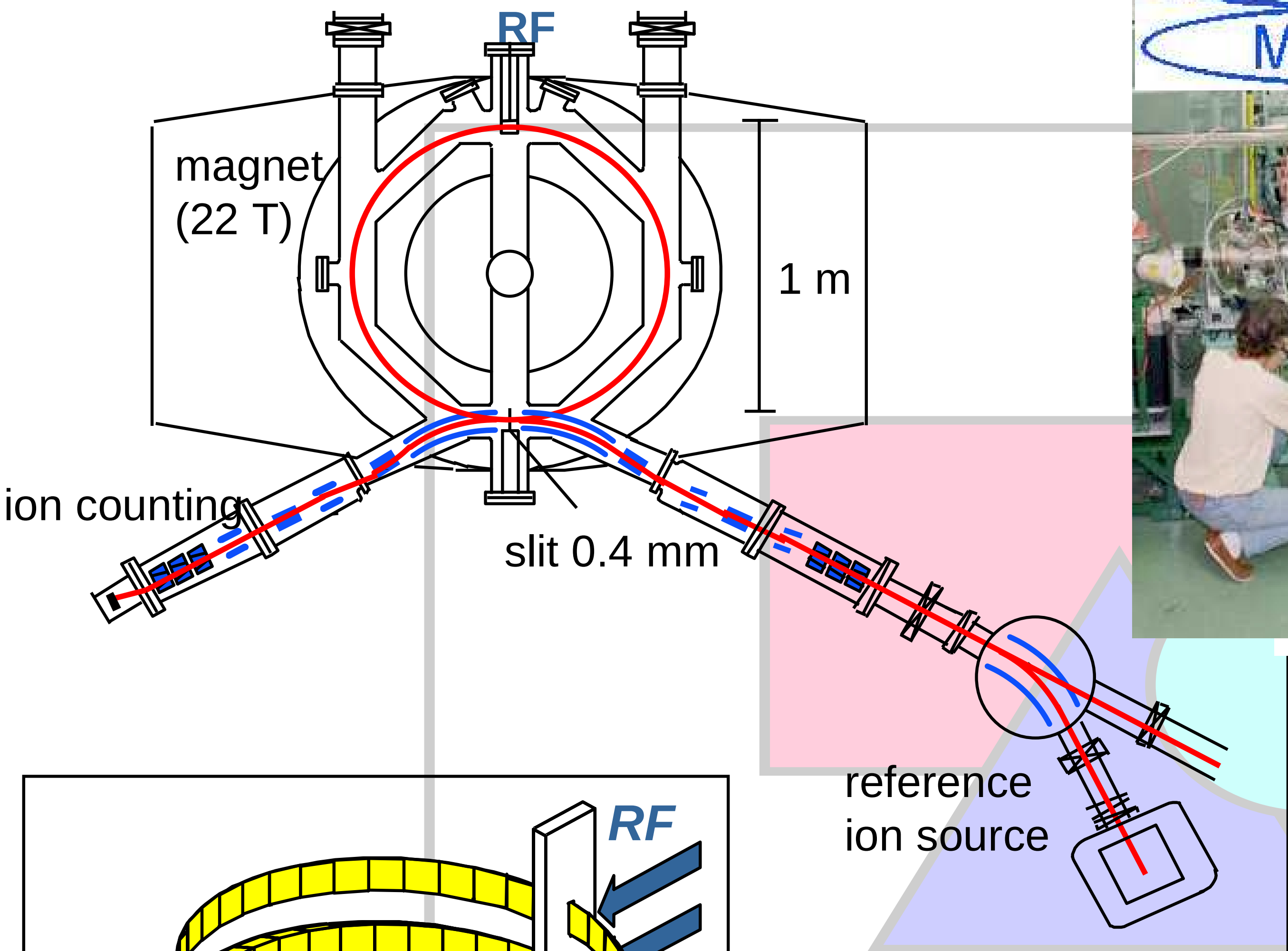
W. Geithner et al., PRL 83 (1999) 3793

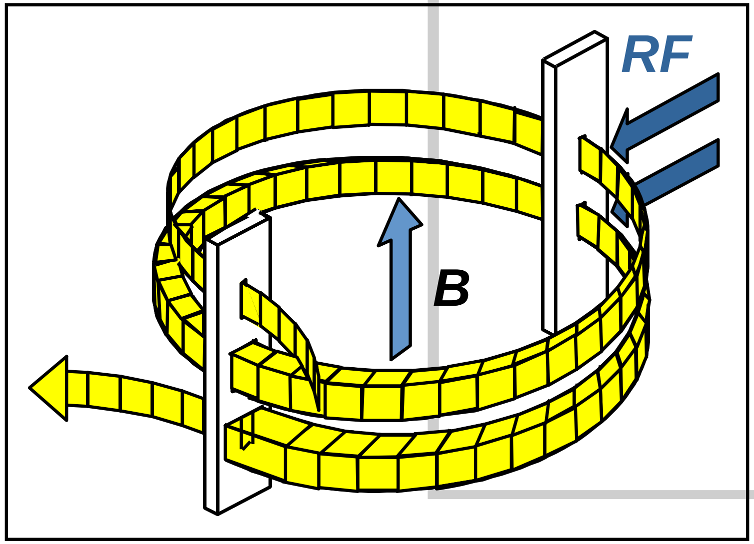
mass measurements of ^{11}Li

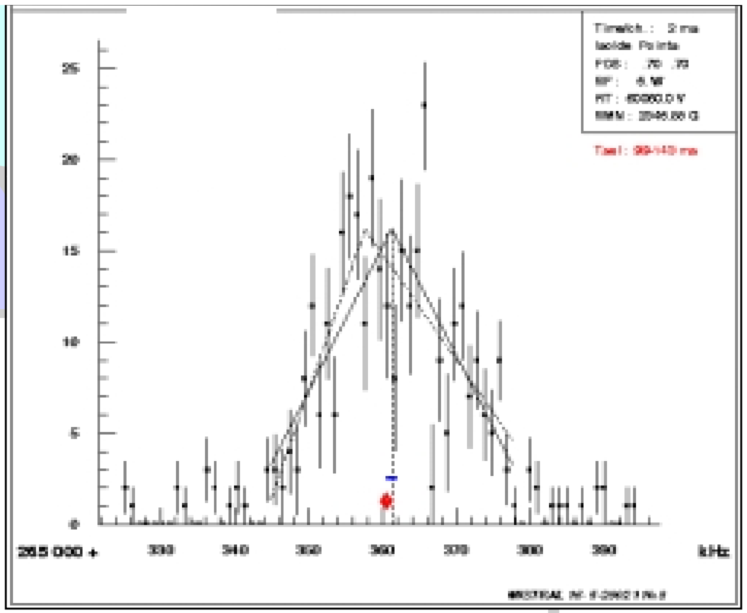


D. Lunney

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





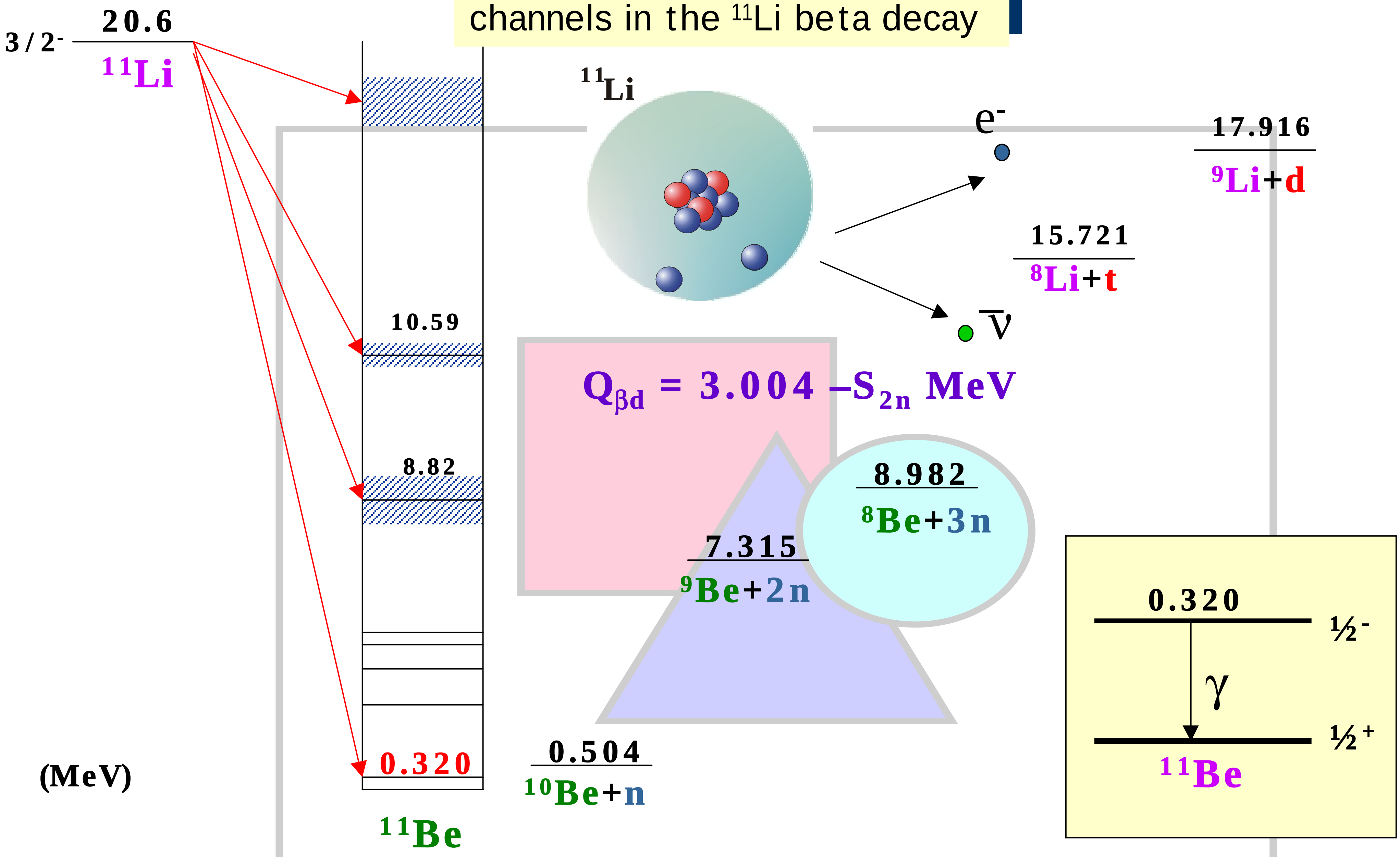


AME: S_{2n} = 303 ± 27 keV

Mistral should achieve < 20 keV

D. Lunney

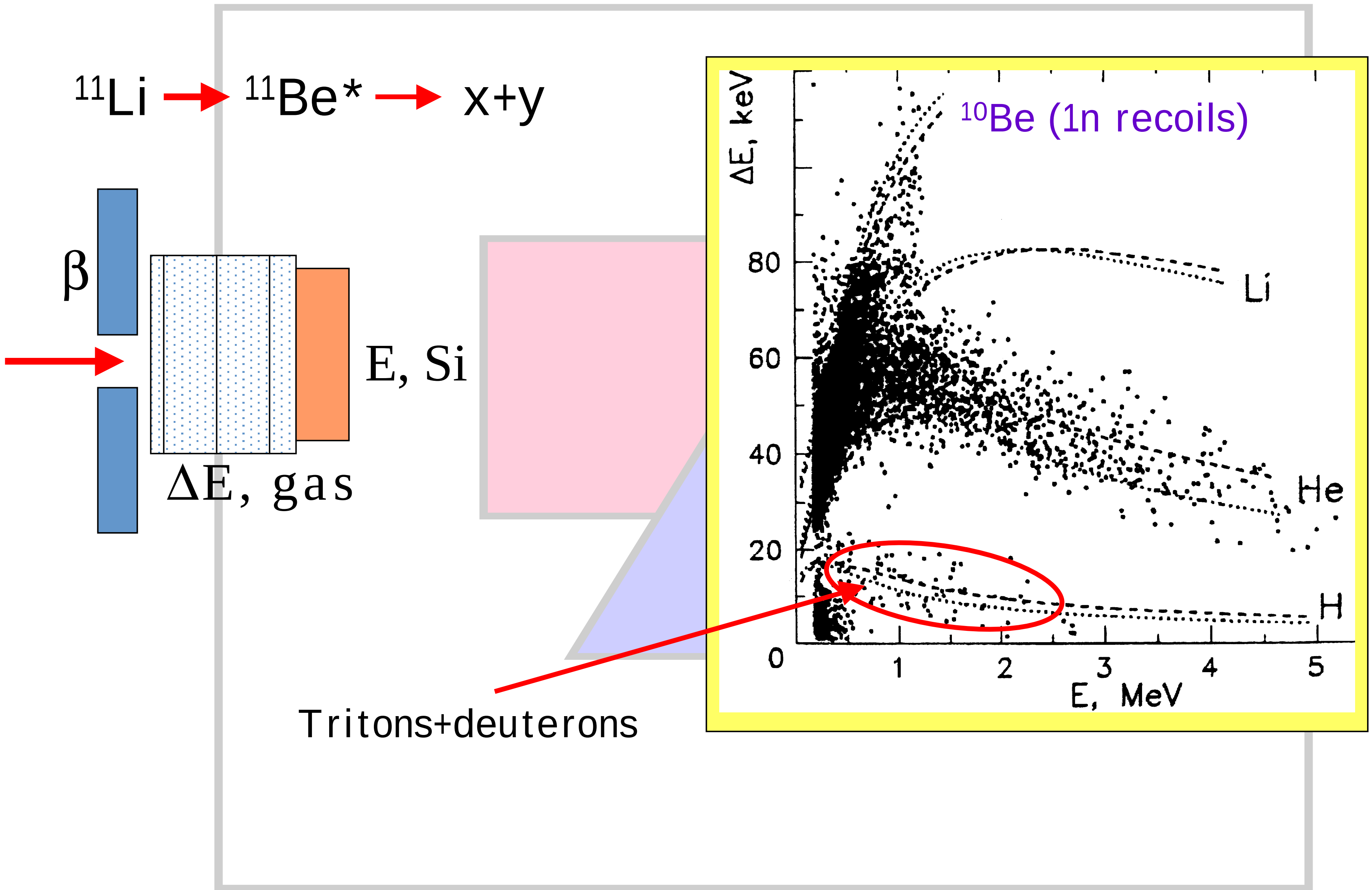
Open delayed-particle channels in the ^{11}Li beta decay



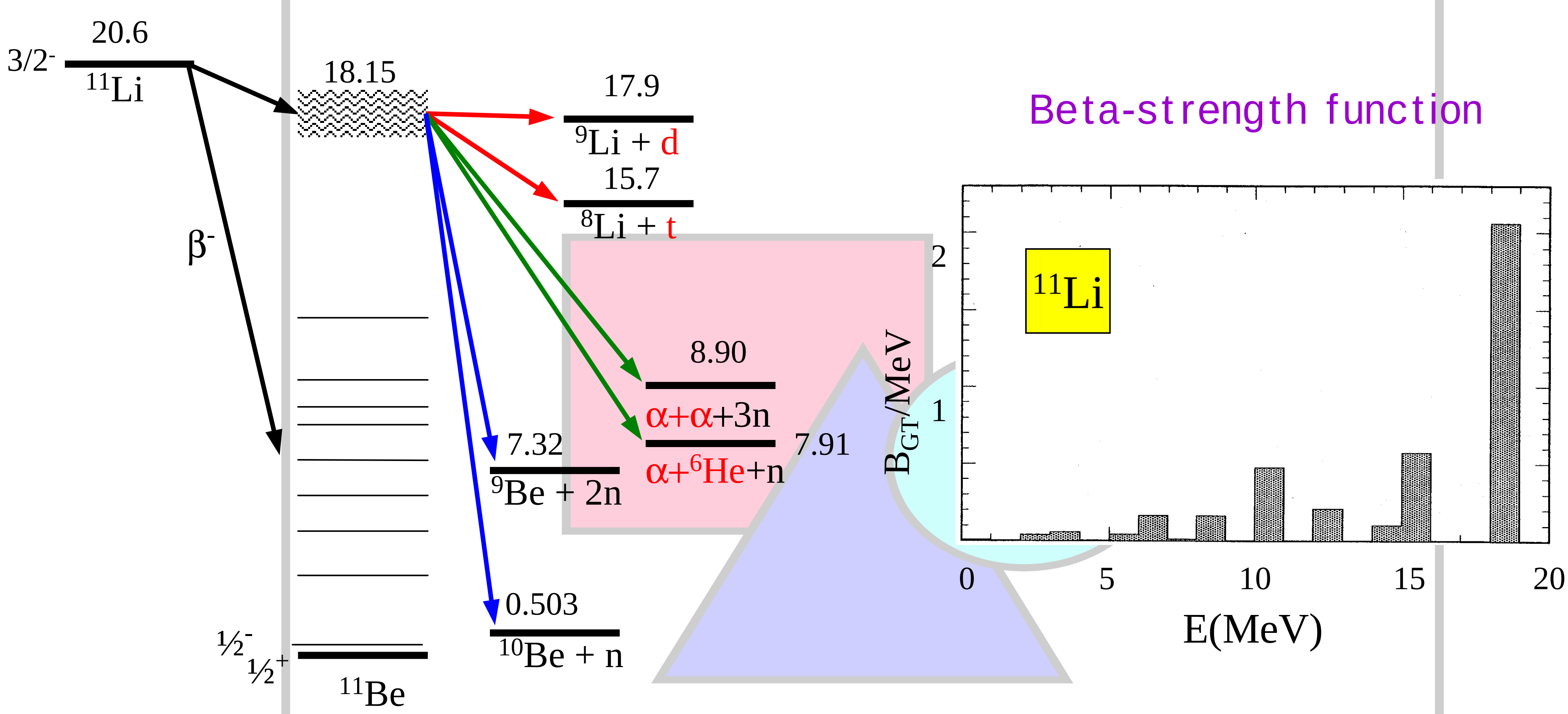
$$\mathcal{O}_\beta|\text{halo state}\rangle = \mathcal{O}_\beta\big(|\text{core}\rangle|\text{halo}\rangle\big) = \big(\mathcal{O}_\beta|\text{core}\rangle\big)|\text{halo}\rangle + |\text{core}\rangle\big(\mathcal{O}_\beta|\text{halo}\rangle\big)$$

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

^{11}Li, charged particles



^{11}Li



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

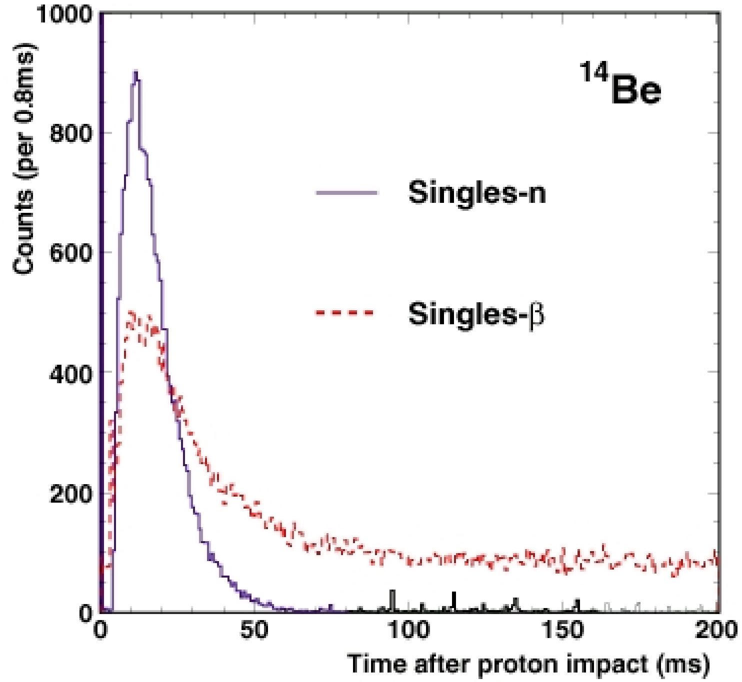
I.Mukha et al., PL B367 (1996) 65

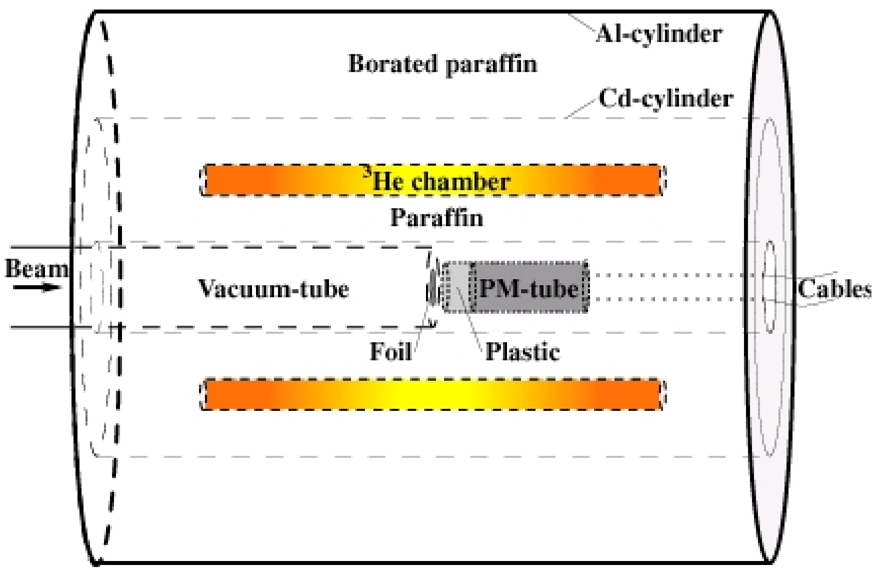
M.J.G. Borge et al.. Nucl. Phys. A613 (1997) 199

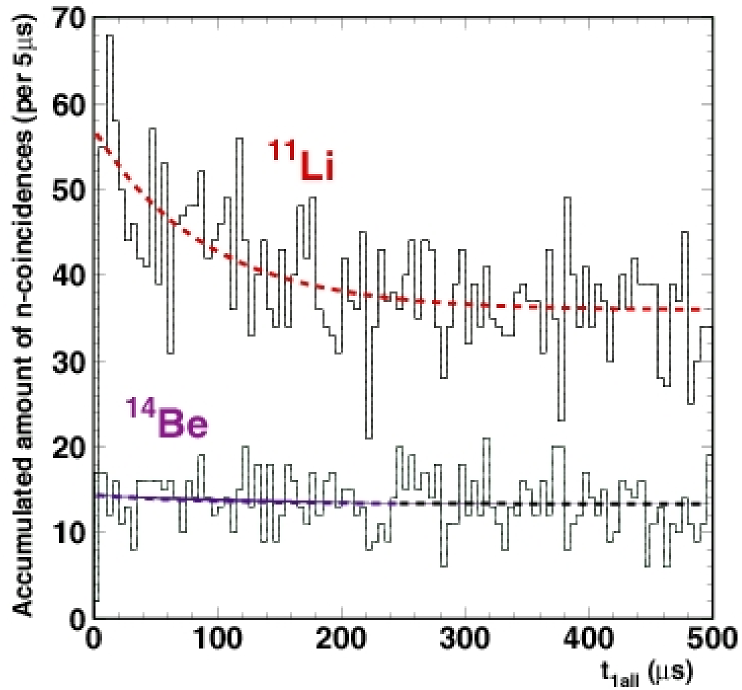
Beta-delayed neutrons from ^{14}Be

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

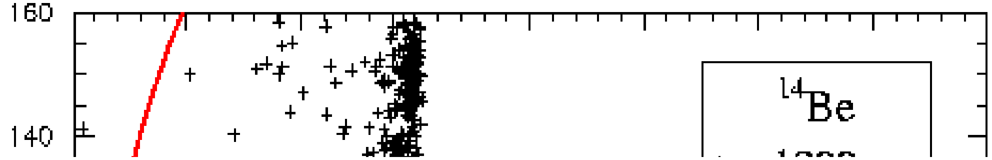
$$P_{2n} + 3P_{3n} = 0.8(8)\ \%$$



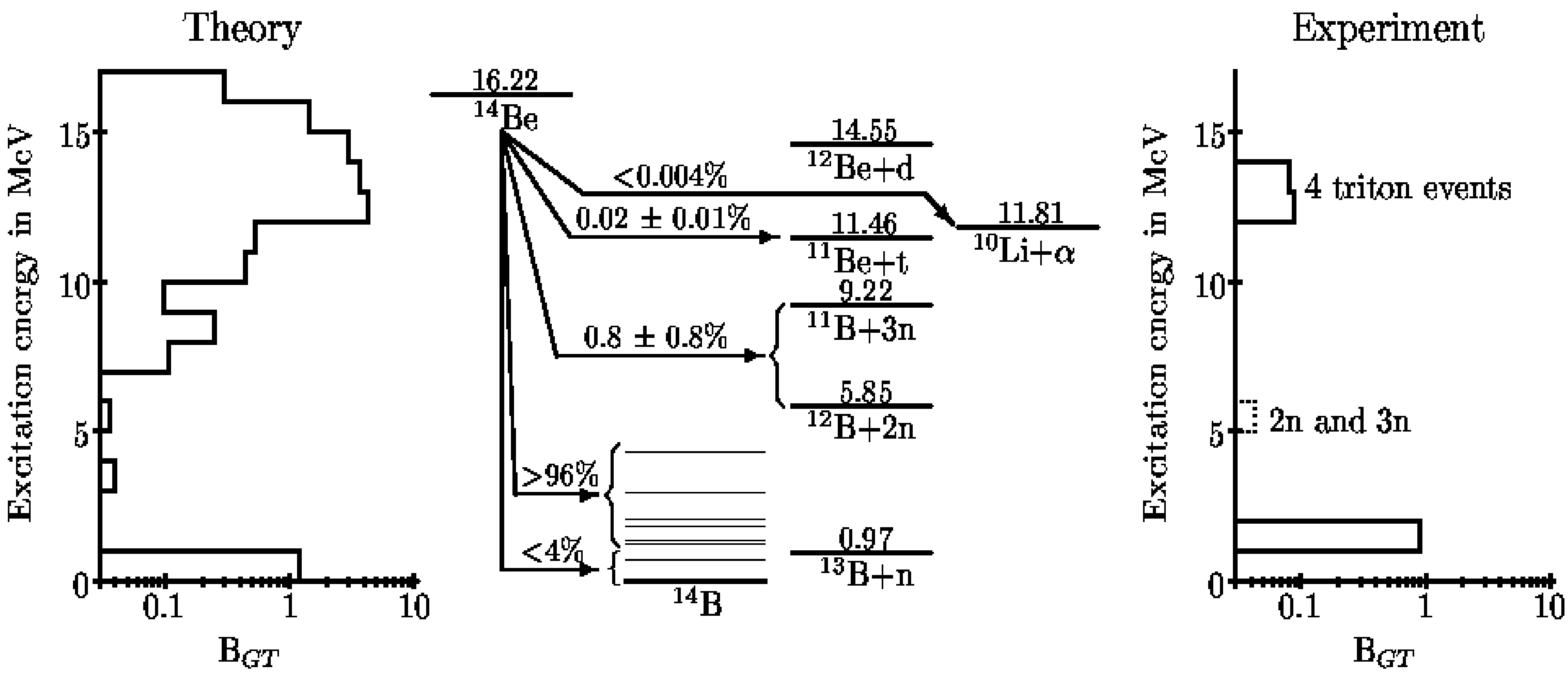




14Be

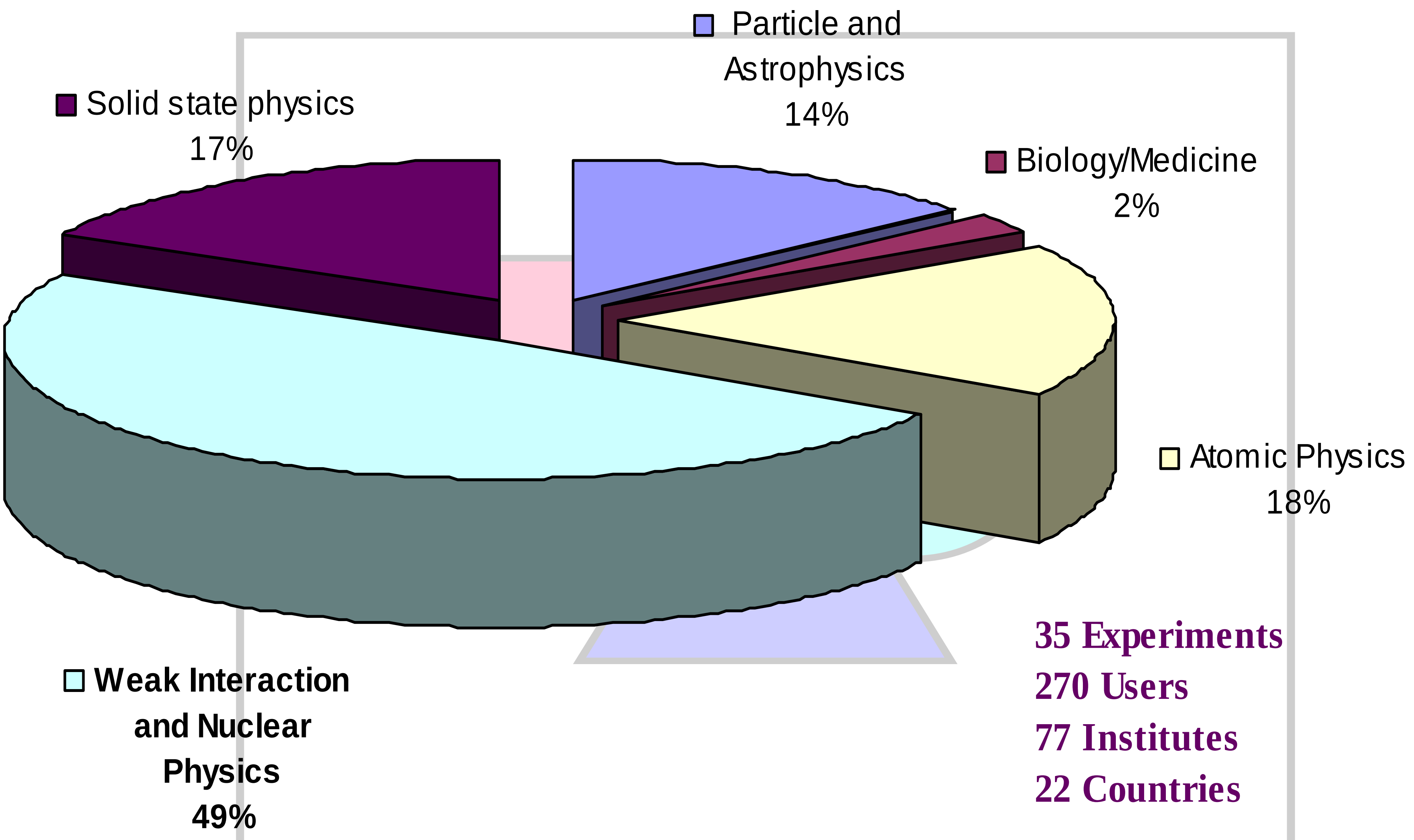


160
140
^{14}Be



Theory
Experiment
Excitation energy in MeV
B_{GT}
0
5
10
15
0.1
1
10
16.22
^{14}Be
<0.004%
0.02 ± 0.01%
0.8 ± 0.8%
>96%
<4%
14.55
^{12}Be+d
11.46
^{11}Be+t
9.22
^{11}B+3n
5.85
^{12}B+2n
0.97
^{13}B+n
^{14}B
11.81
^{10}Li+α
4 triton events
2n and 3n

ISOLDE Physics programme 2001



35 Experiments
270 Users
77 Institutes
22 Countries

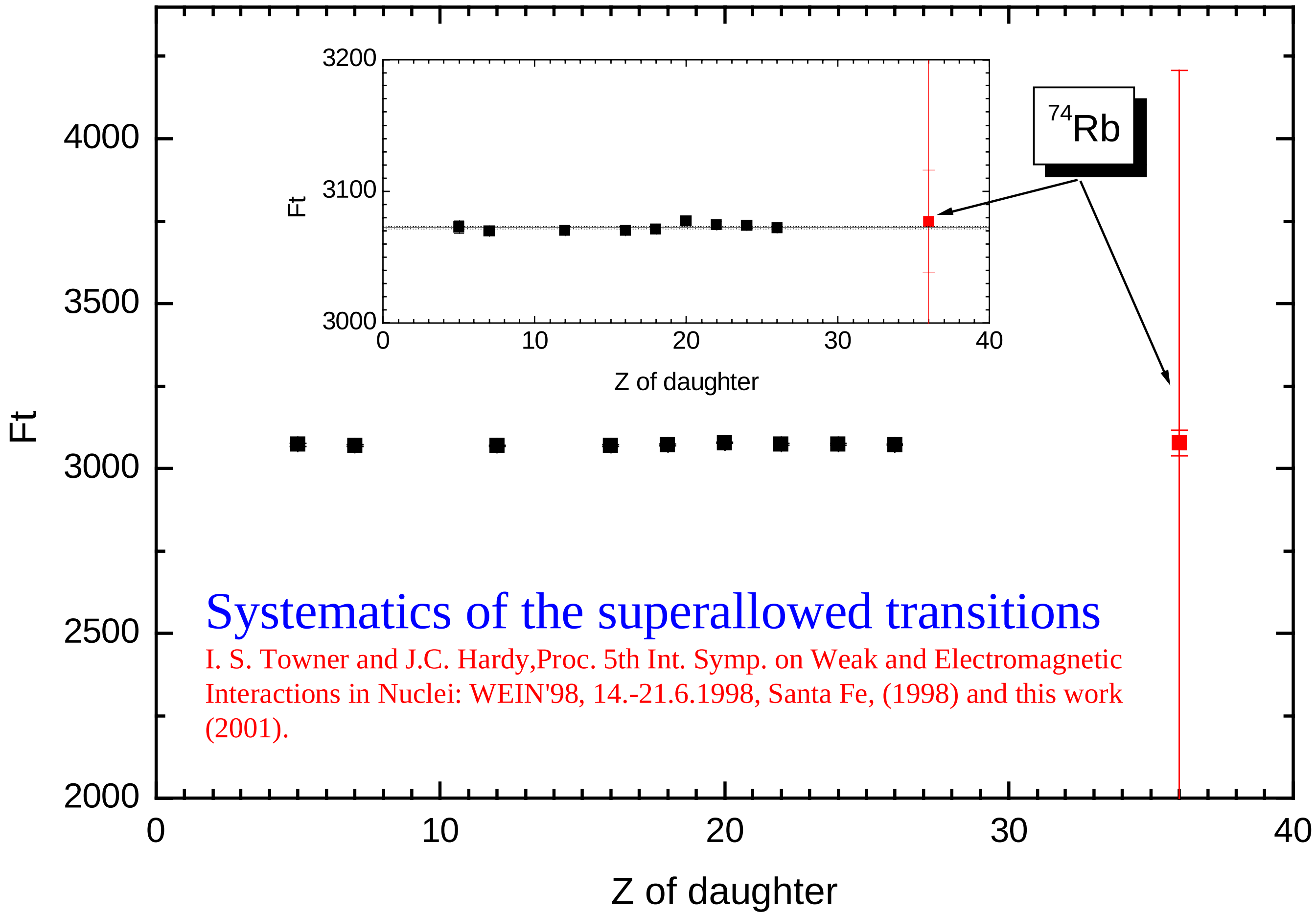
Superallowed Fermi transitions $0^+ \rightarrow 0^+, T=1$

Test of CVC (Conserved Vector Current) hypothesis

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

$Q-$value halflife

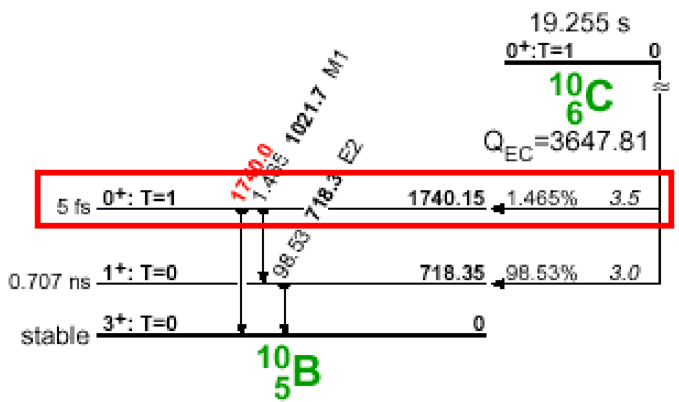
Best det. of V_{ud}



Δ_R – nuc. ind. radiative corr.

δ_R – nuc. dep. radiative corr.

δ_C – Coulomb corr.



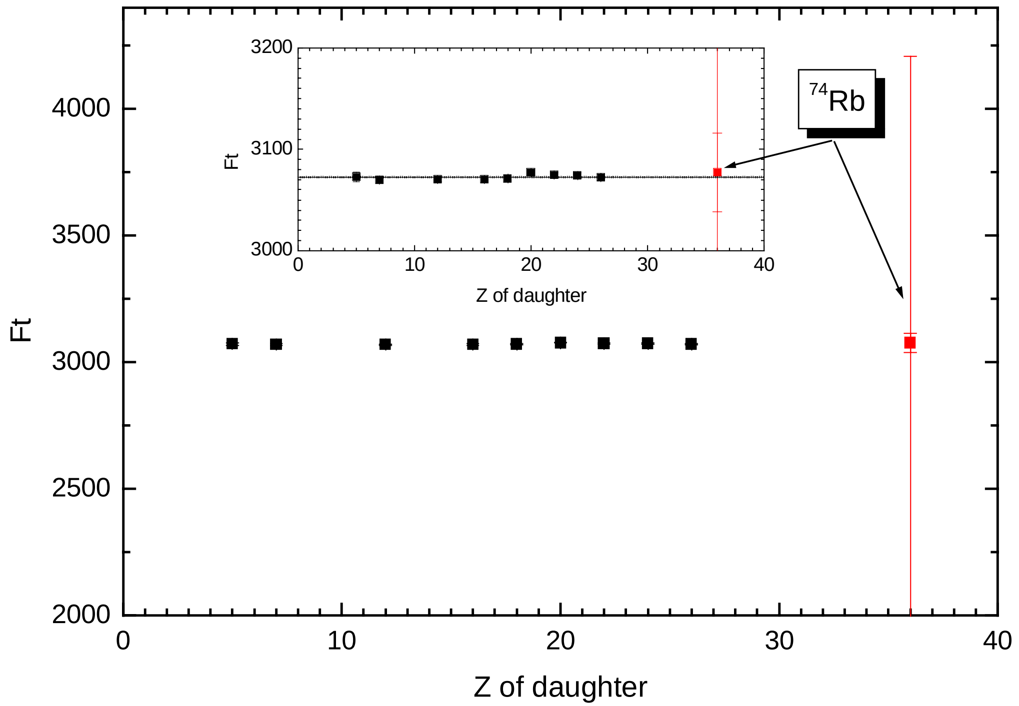
CKM (Cabibbo-Kobayashi-Maskawa) matrix unitarity

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

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

$\rightarrow$ unitarity is 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

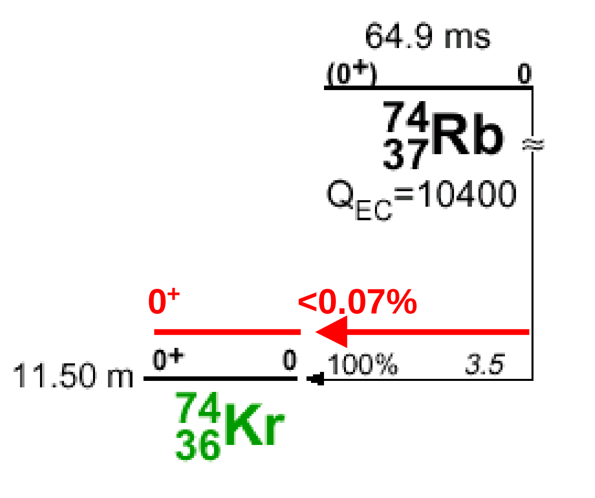
… and later ^{62}Ga

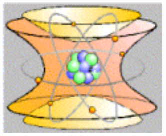
IS384 Complete spectroscopy on Fermi β-emitter ^{74}Rb

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)

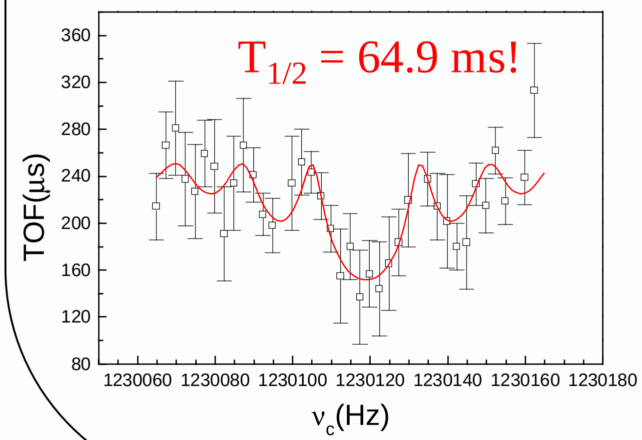
2) & 3) $\rightarrow$ Q_{EC} value

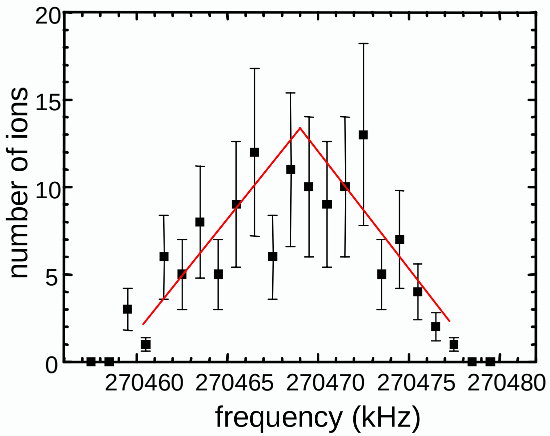


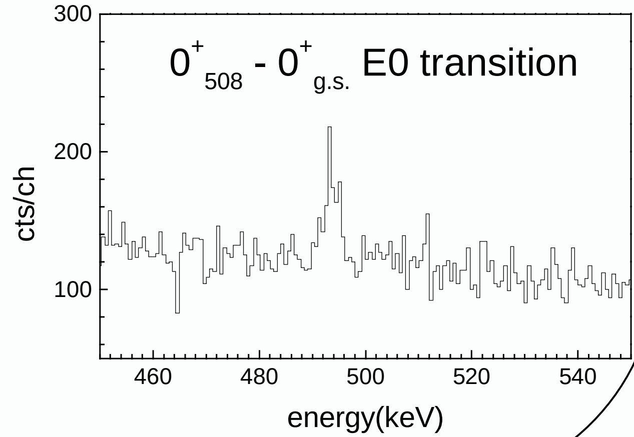


ISOLTRAP

MISTRAL

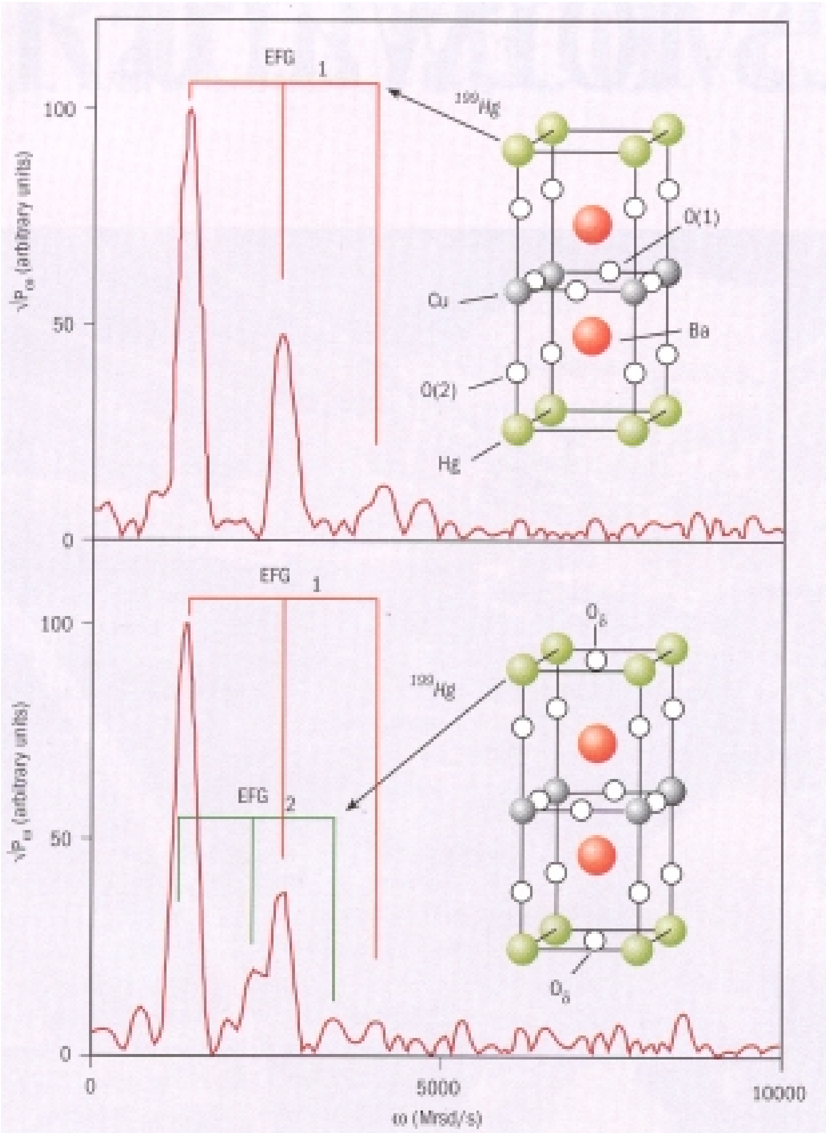




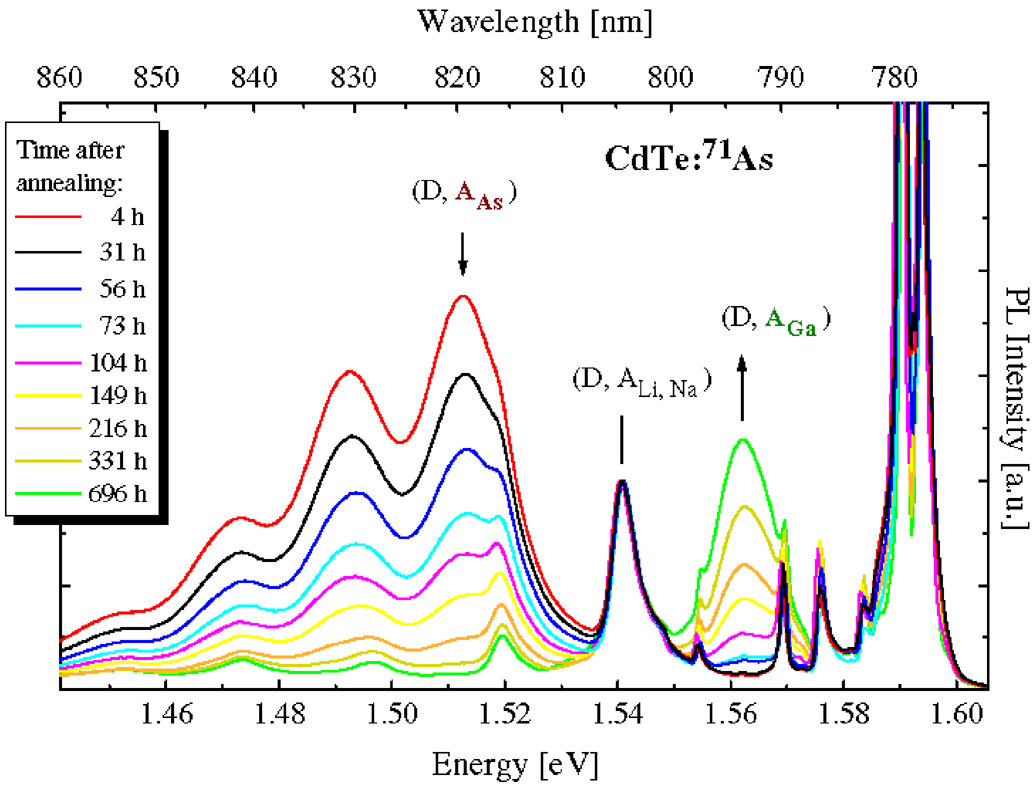


Condensed matter physics

Radioactive ions as “spies” (PAC) in high-T_c superconductors…



… or as dopants in semiconductors that change with time.



M. Deicher, Europhysics News (2002) Vol. 33 No. 3

Biomedical Research at ISOLDE

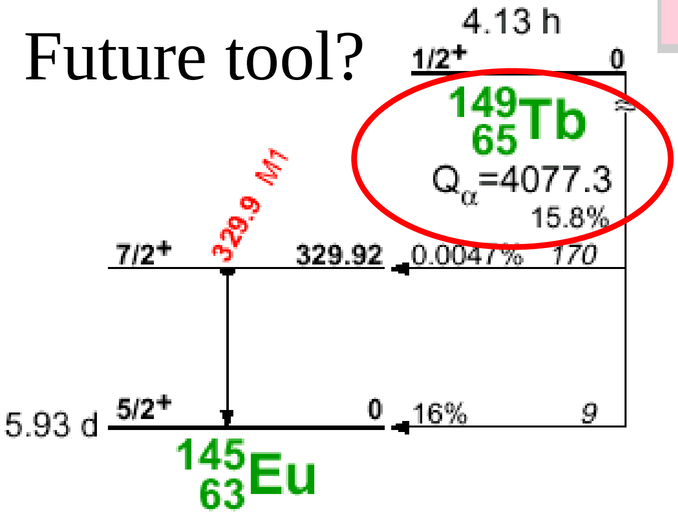
- **Example: samarium isotopes**

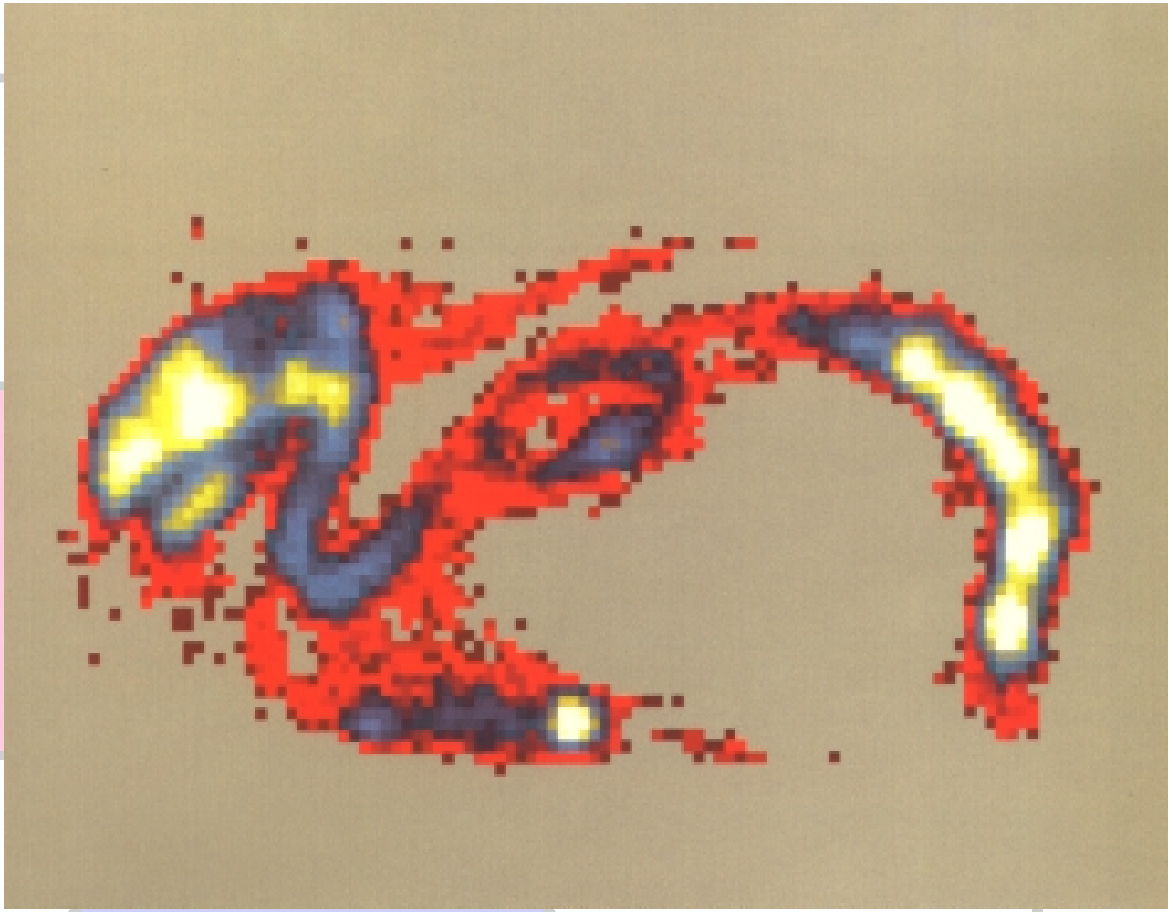
in vivo dosimetry by positron emission tomography (PET)

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

therapy 153-Sm (β_-, $T_{1/2}$ = 47h)

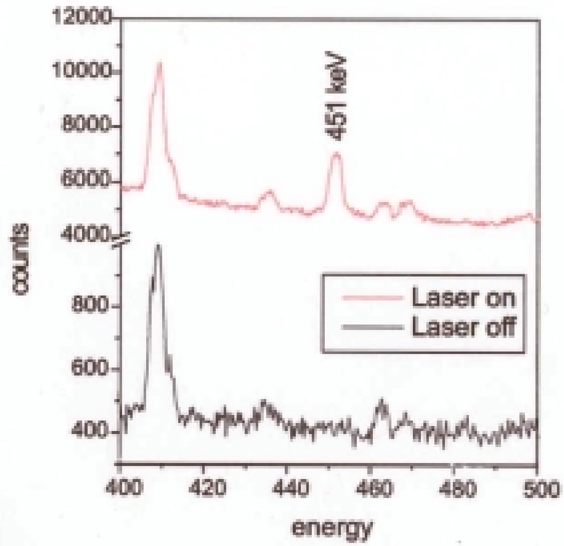
Future tool?

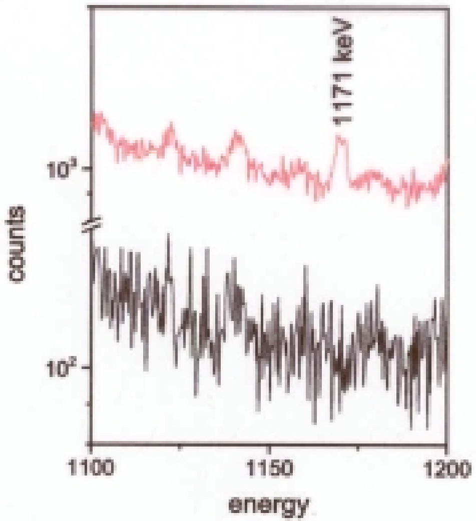


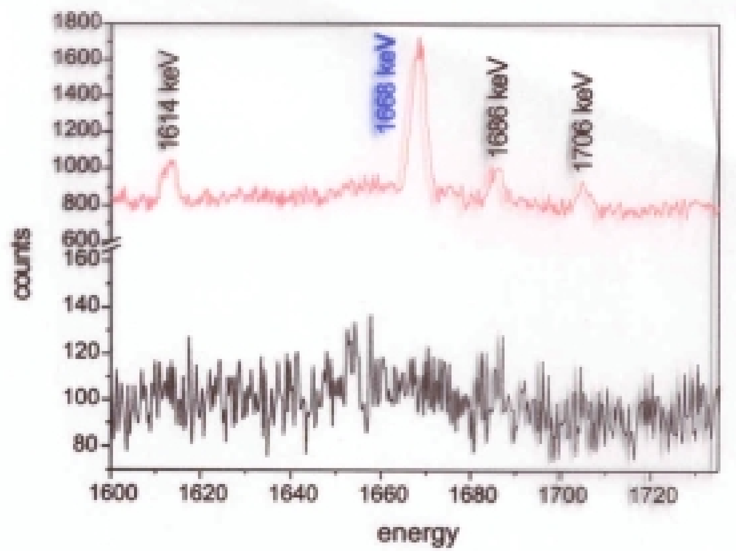


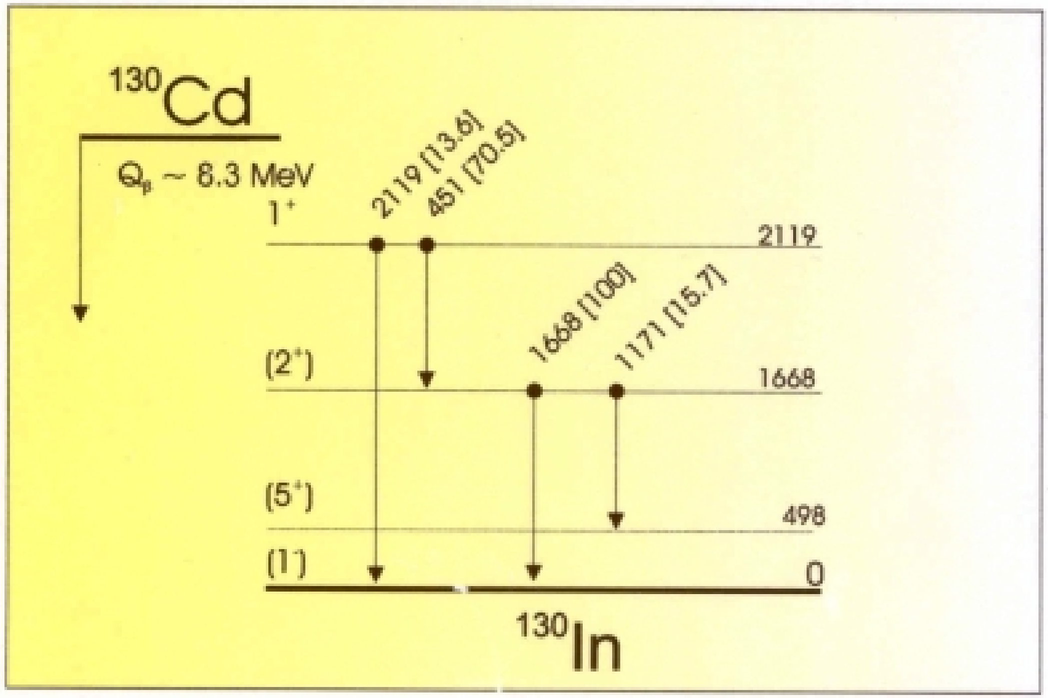
PET scan of a rabbit 60 min p.i. of ISOLDE produced
142-Sm in EDTMP solution

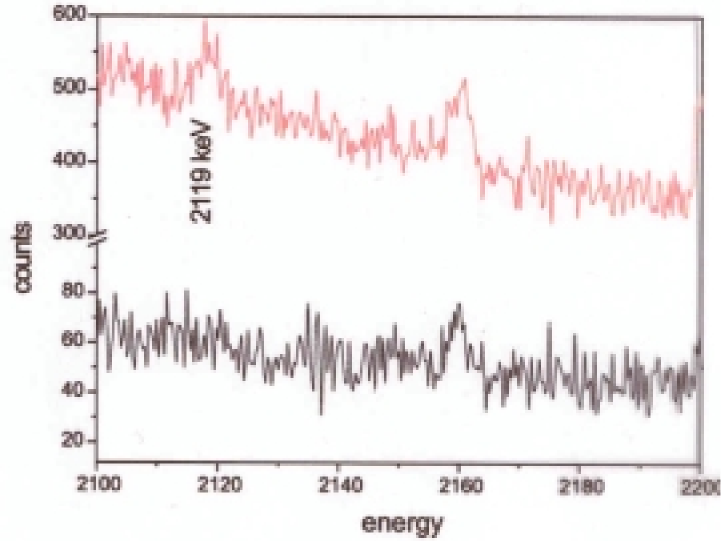
IS393 - Nuclear properties in r-process vicinity



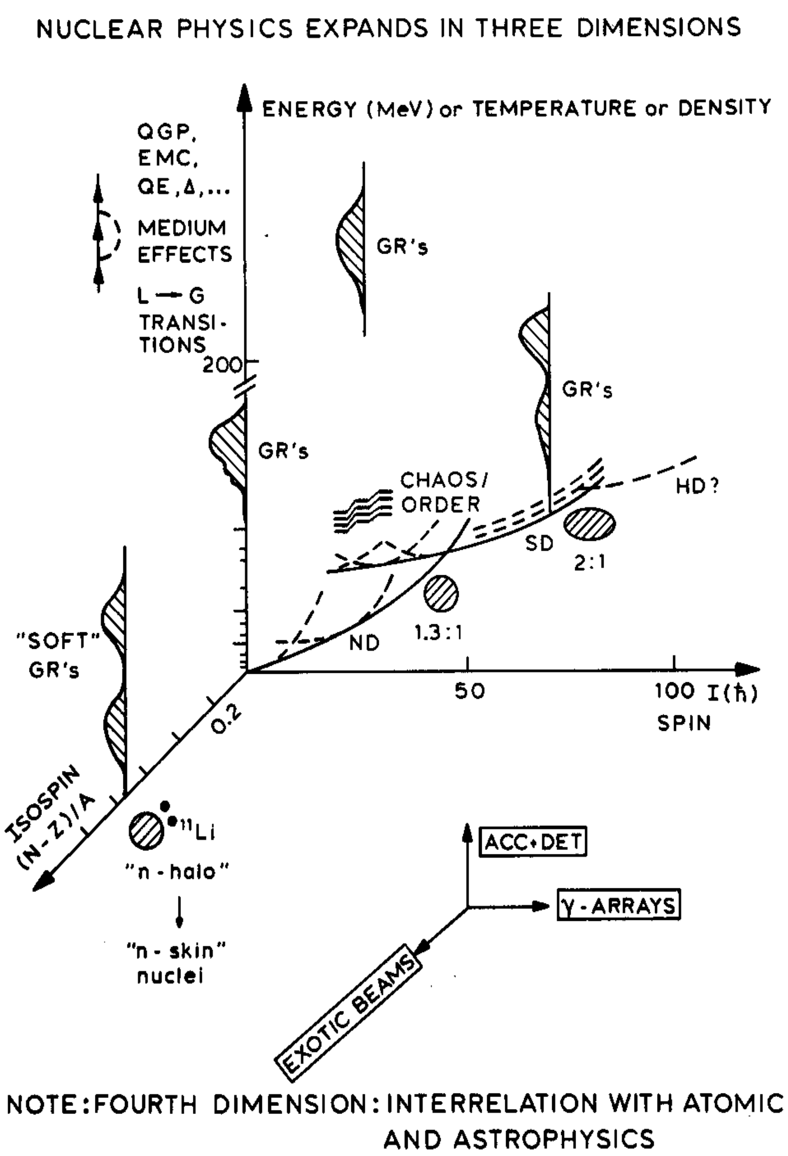


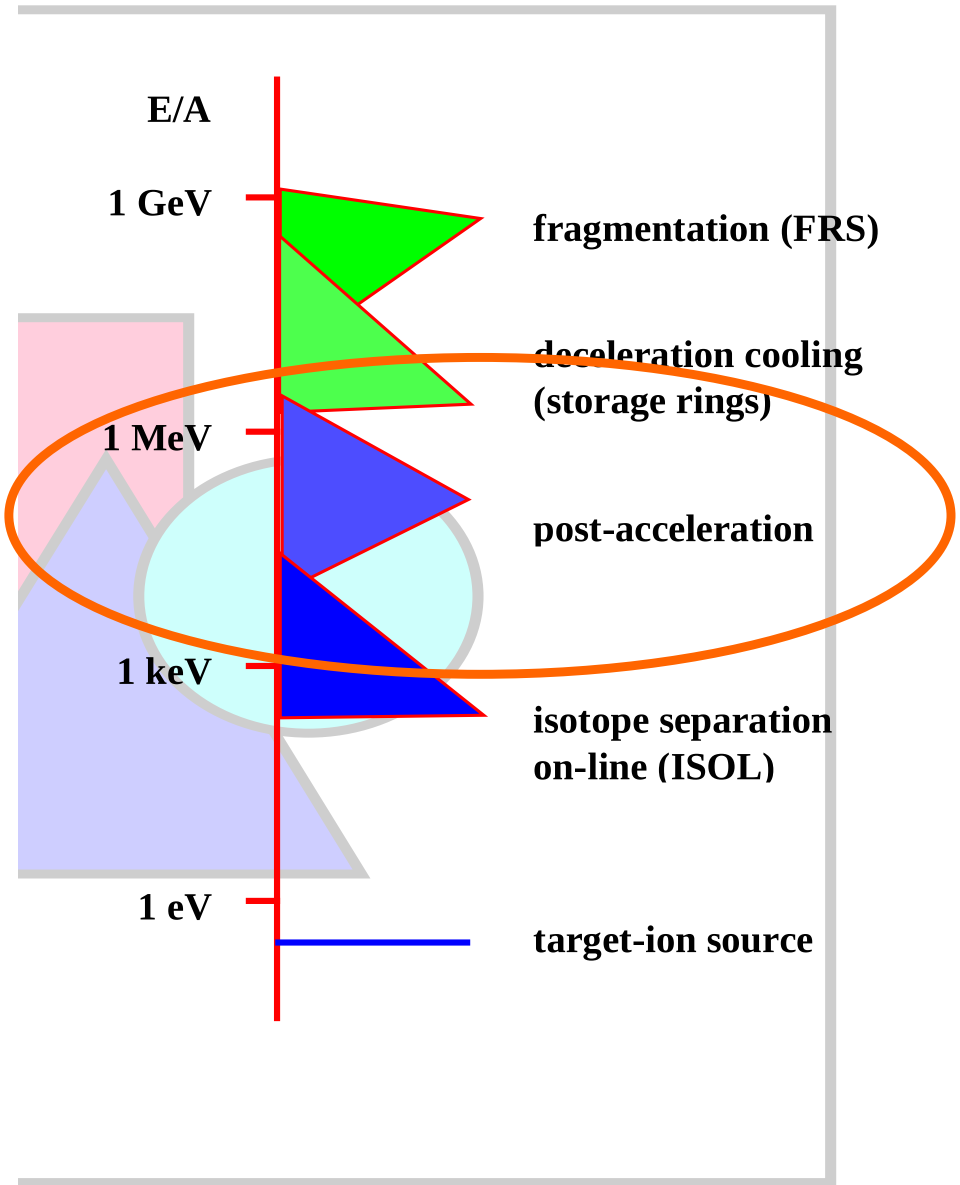


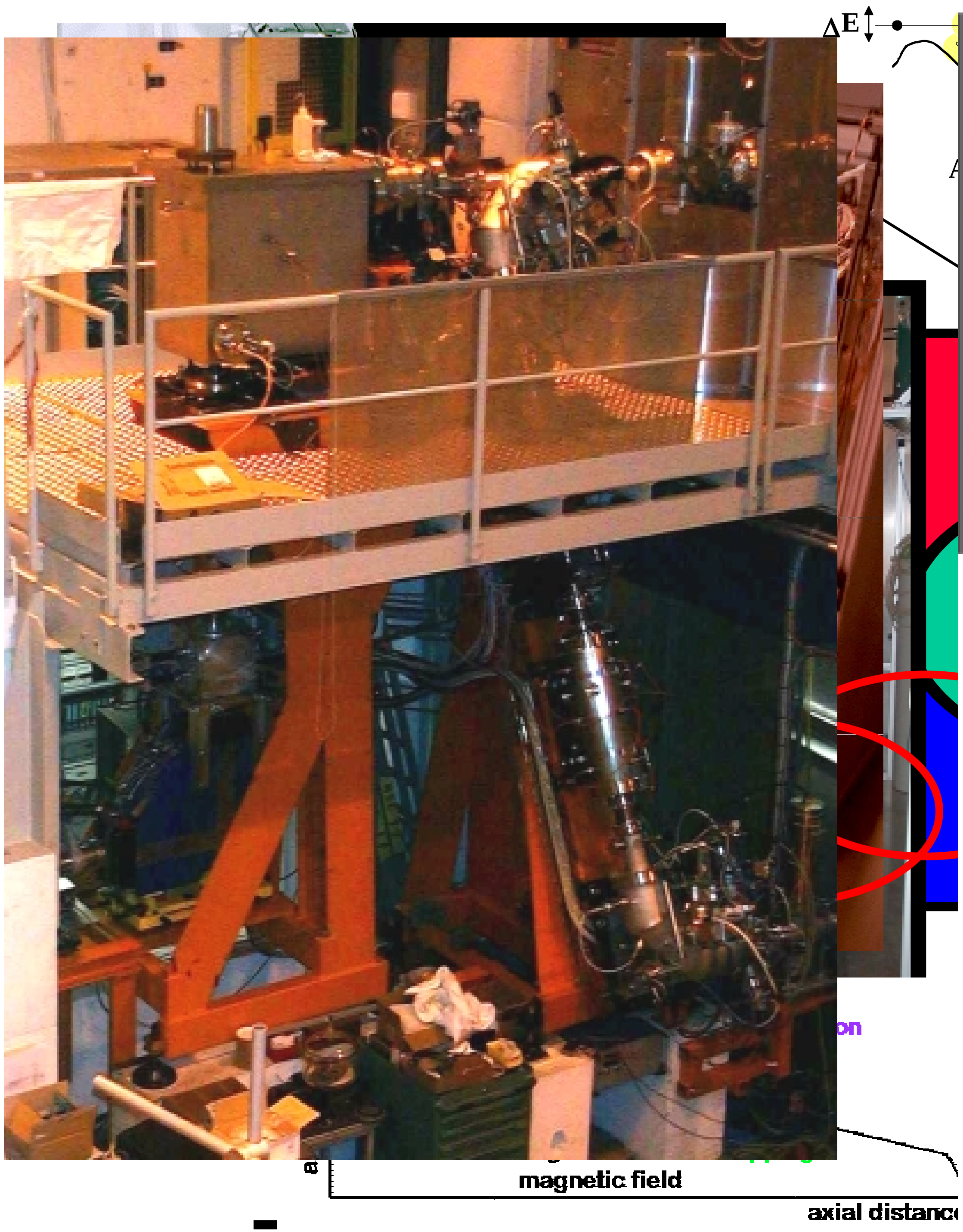


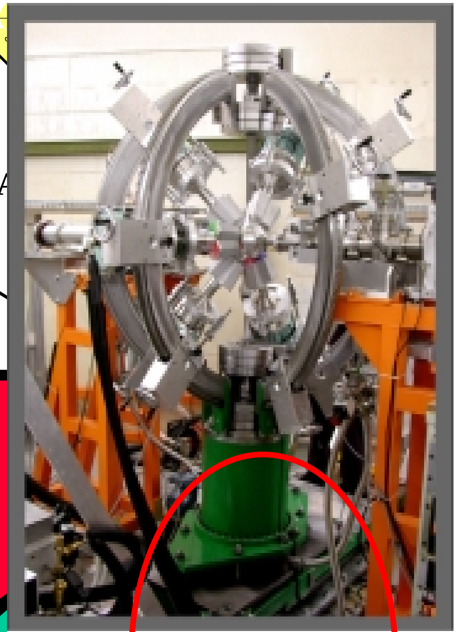


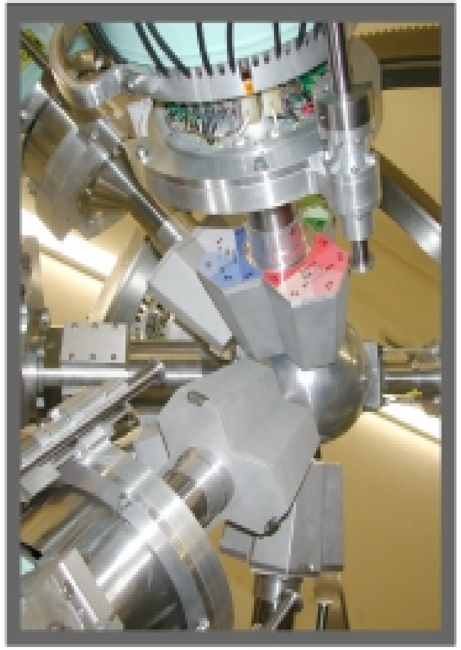
Post-acceleration

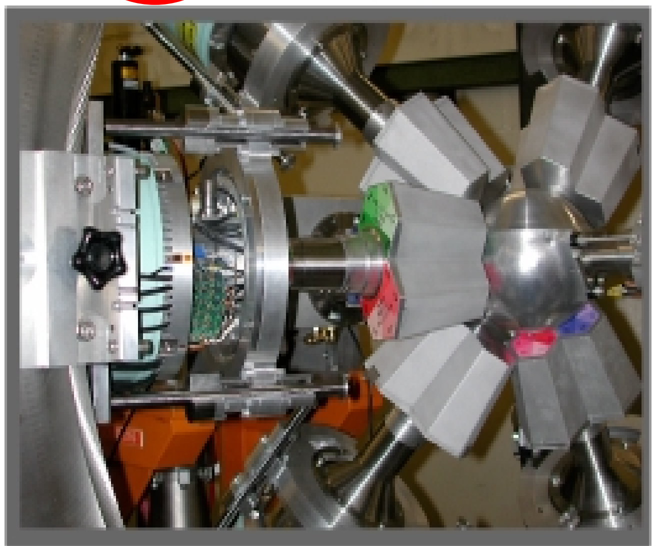




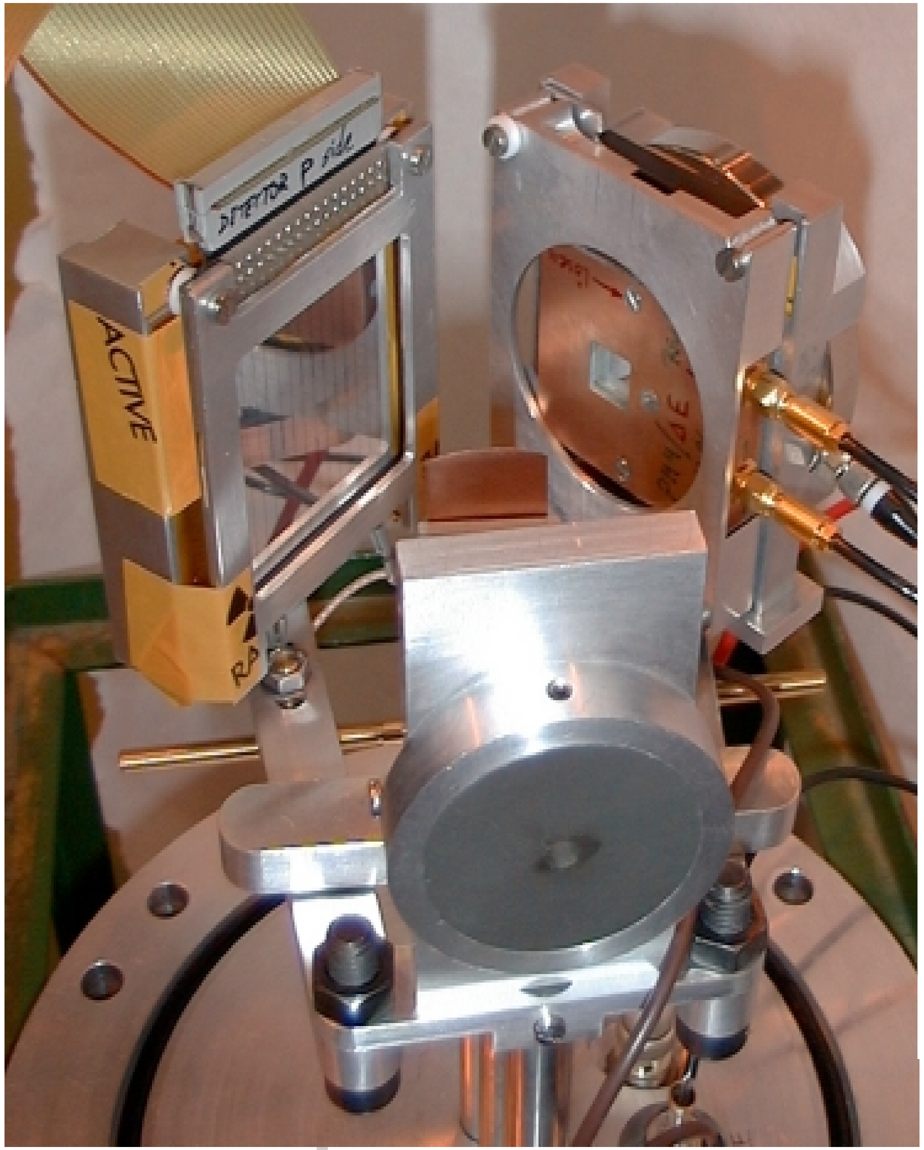

ΔE
magnetic field
axial distance

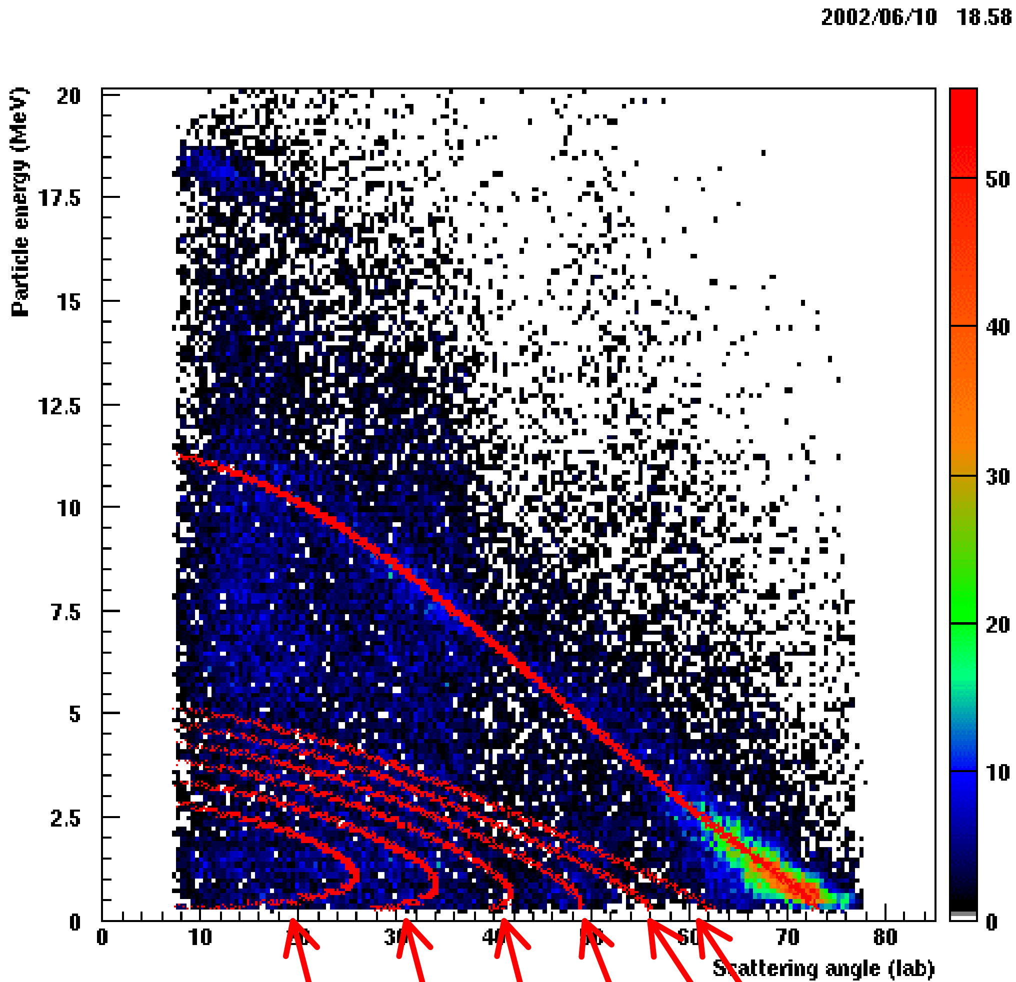






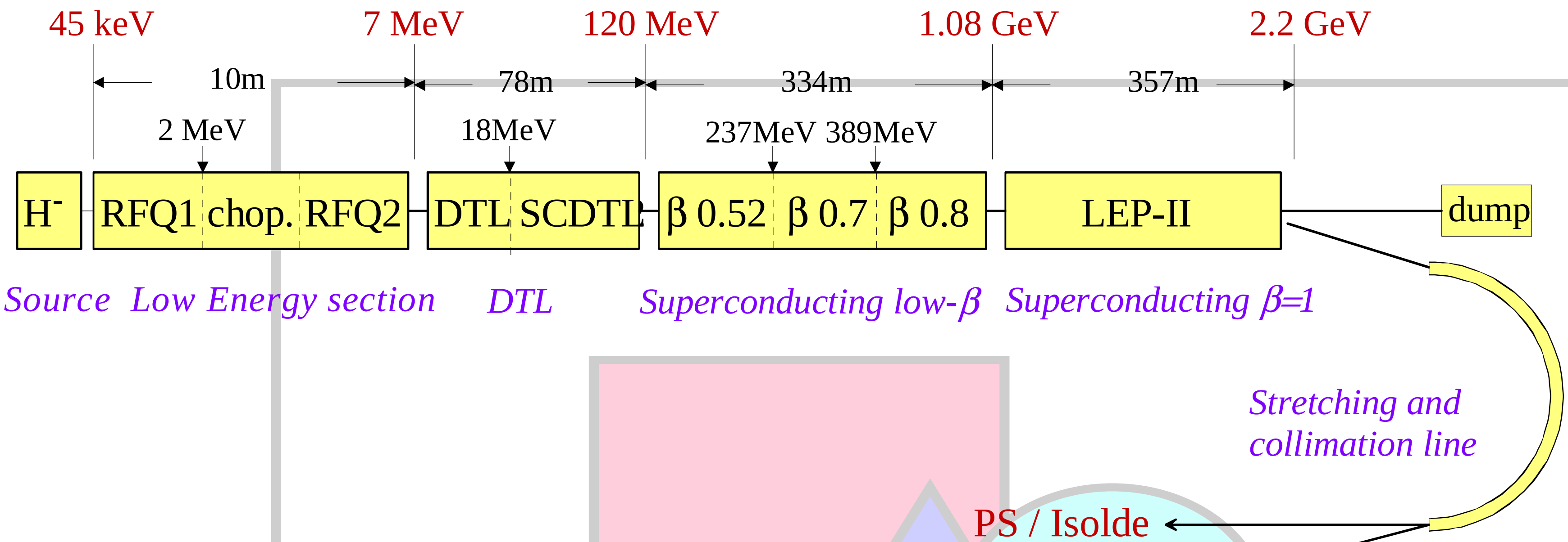
d(^{9}Li,^{10}Li*)p using REX-ISOLDE

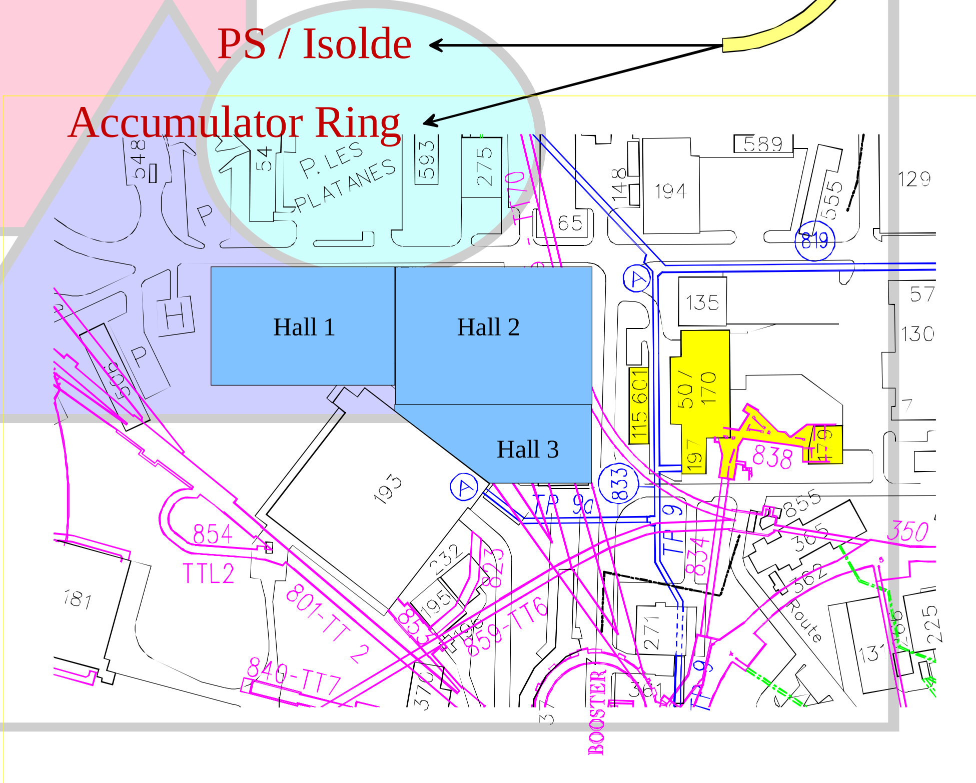




$E_{ex}(^{10}Li)$ = 1000 800 600 400 200 0 keV

A second-generation RIB facility at CERN? – ISOLDE-RNB

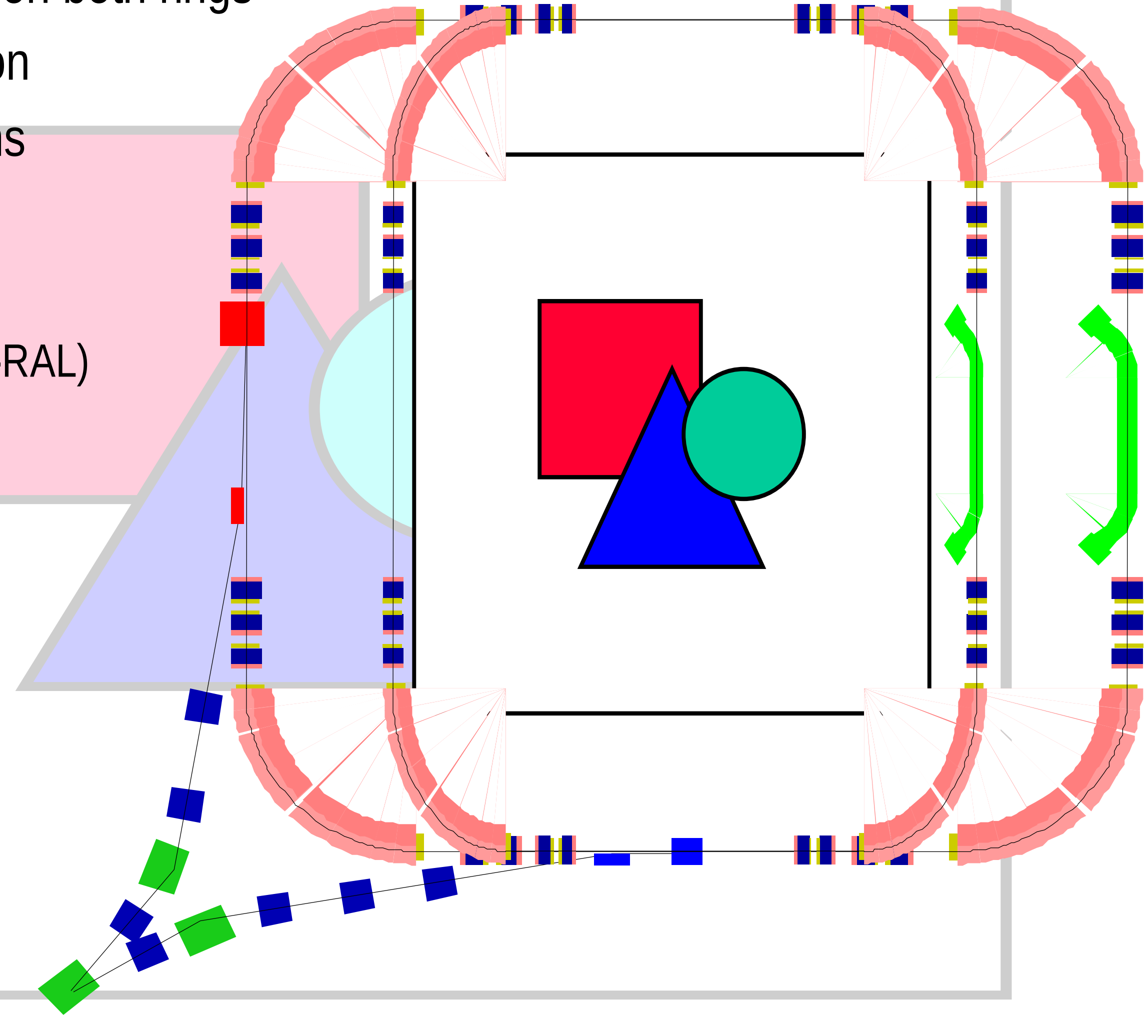




- Second generation RNB facility using the SPL as driver
- <100 µA on « traditional » ISOL targets, >100 µA on converter
- Post-acceleration to 100 MeV/u (cyclotron/LINAC)
- Storage/re-cycler ring

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

- RIB are crucial in widening our understanding of the nuclear system when stretching the parameters
- Low-energy RIBs with good beam quality is the optimal starting point for decay studies, laser physics, traps etc.
- RIB overcome partly the fact that we now only have the stable and long-lived “ashes” of astrophysical processes
- RIB and techniques used in the production and separation have important connections to other research fields
- Large physics output obtained with “first-generation” RIB facilities – time to make a major step forward

Acknowledgements

- Collaborations:
- IS304 (Mainz, Leuven, Montreal, CERN)
- IS320 (Aarhus, CERN, Darmstadt, Gothenburg, Madrid, Orsay)
- IS367 (Gothenburg , Aarhus, Madrid, CERN, Darmstadt, Örebro)
- IS374 (Caen, Gothenburg , Aarhus, Madrid, Troitsk, Orsay, Mainz, CERN, Darmstadt)
- IS376 (Gothenburg , Aarhus, Madrid, Stockholm, CERN, Darmstadt)
- IS402 (Orsay, GSI, MSU, Munich, CERN, Sao Paulo)