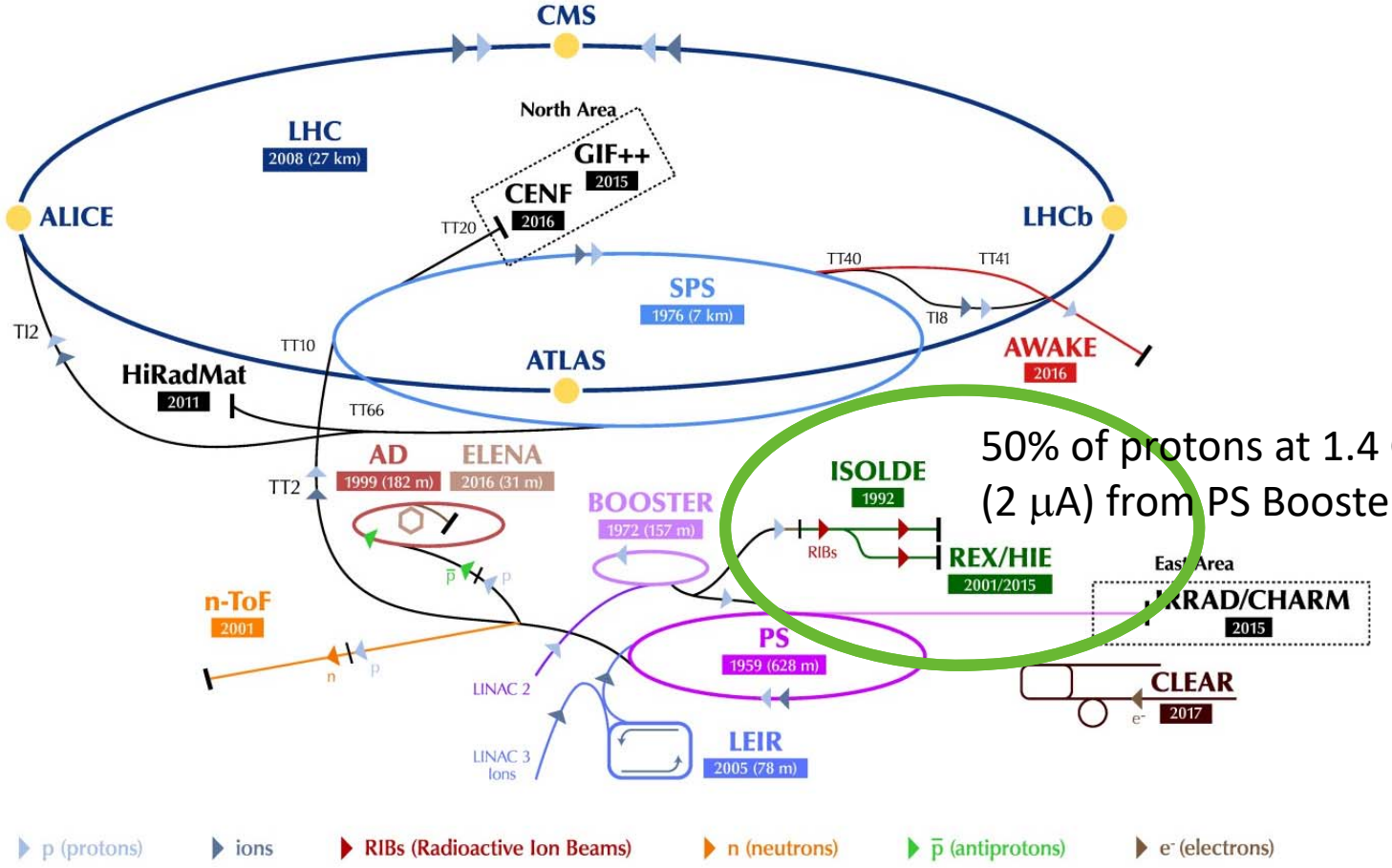
A variety of physics using radioactive beams at ISOLDE and HIE-ISOLDE @ CERN

Gerda Neyens
ISOLDE Collaboration Spokesperson
CERN (Switzerland) and KU Leuven (Belgium)

CERN's Radioactive Ion Beam (RIB) facility

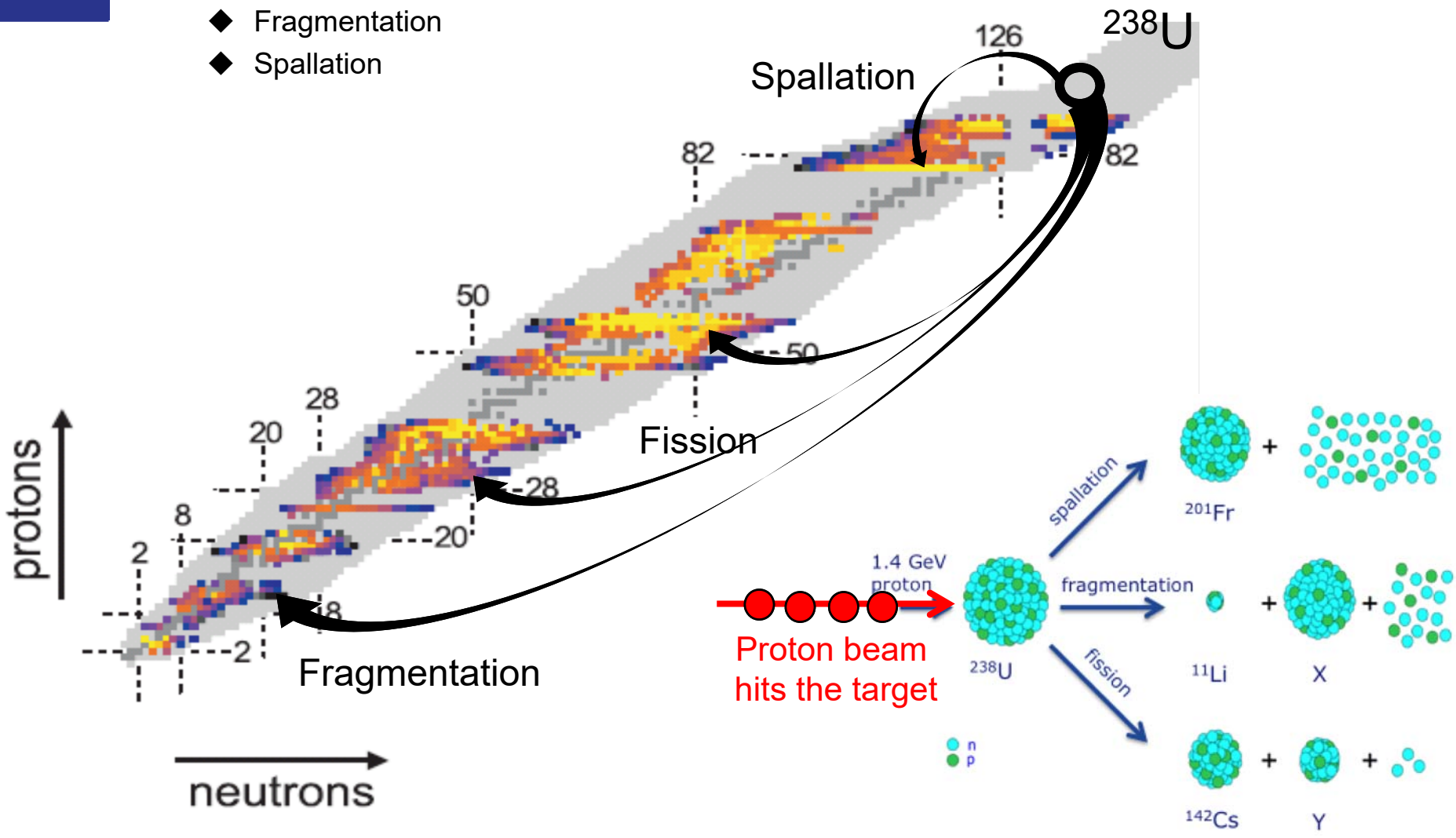


50% of protons at 1.4 GeV, (2 μA) from PS Booster.

LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE - Radioactive EXperiment/High Intensity and Energy ISOLDE // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n-ToF - Neutrons Time Of Flight //

Production of RIB's at ISOLDE

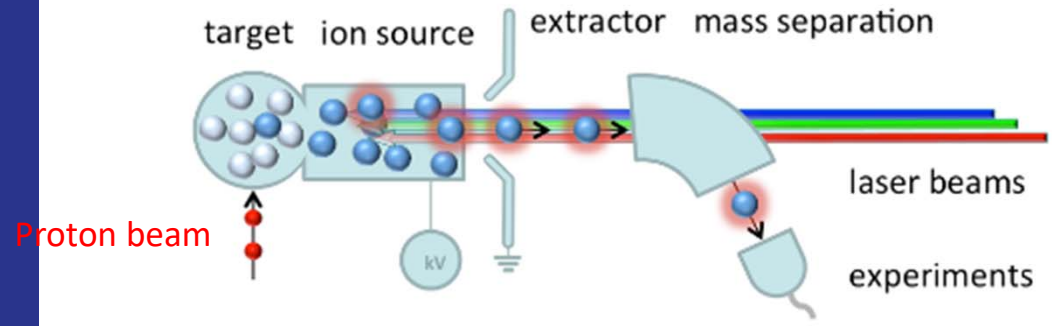
- Unique worldwide: high energy (1.4 GeV) protons onto a thick target, e.g. ^{238}U
- The protons split up the heavy nucleus in one of three ways
  - Fission
  - Fragmentation
  - Spallation

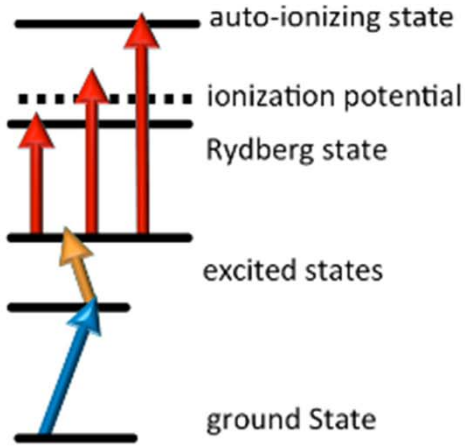


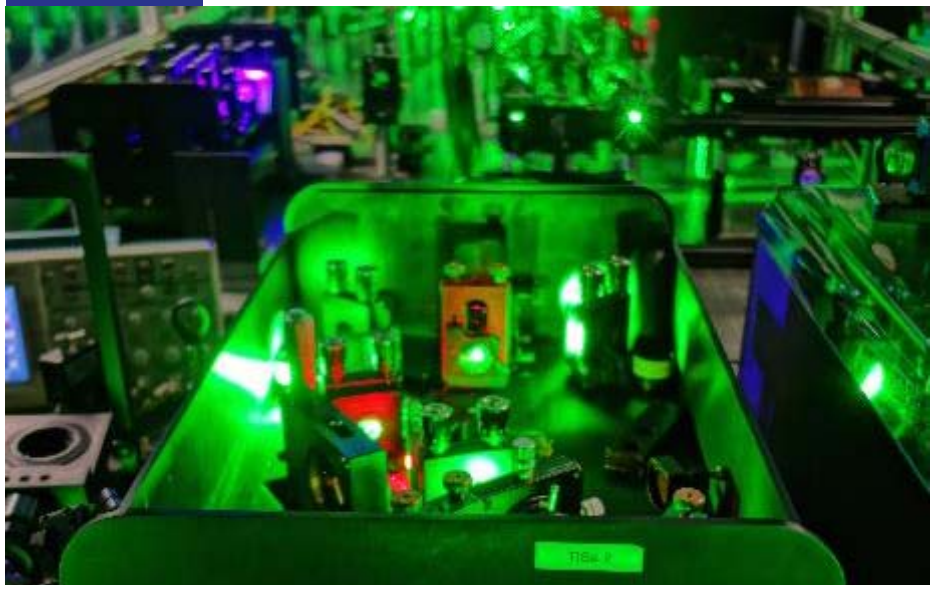
Producing purified beams: RILIS

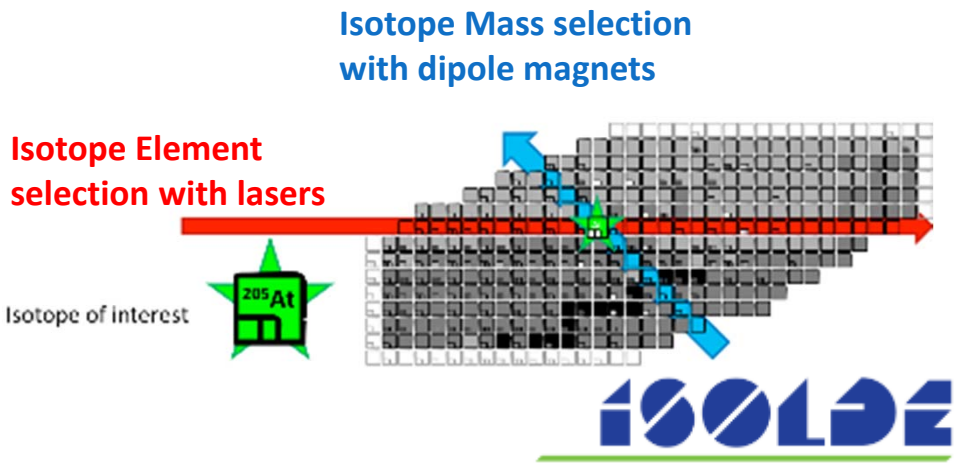
- Resonance Ionization Laser Ion Source (since 1994)
- **Selective and efficient ionization of one particular element** (e.g. Tin)

→ CAN ALSO BE USED FOR SPECTROSCOPY



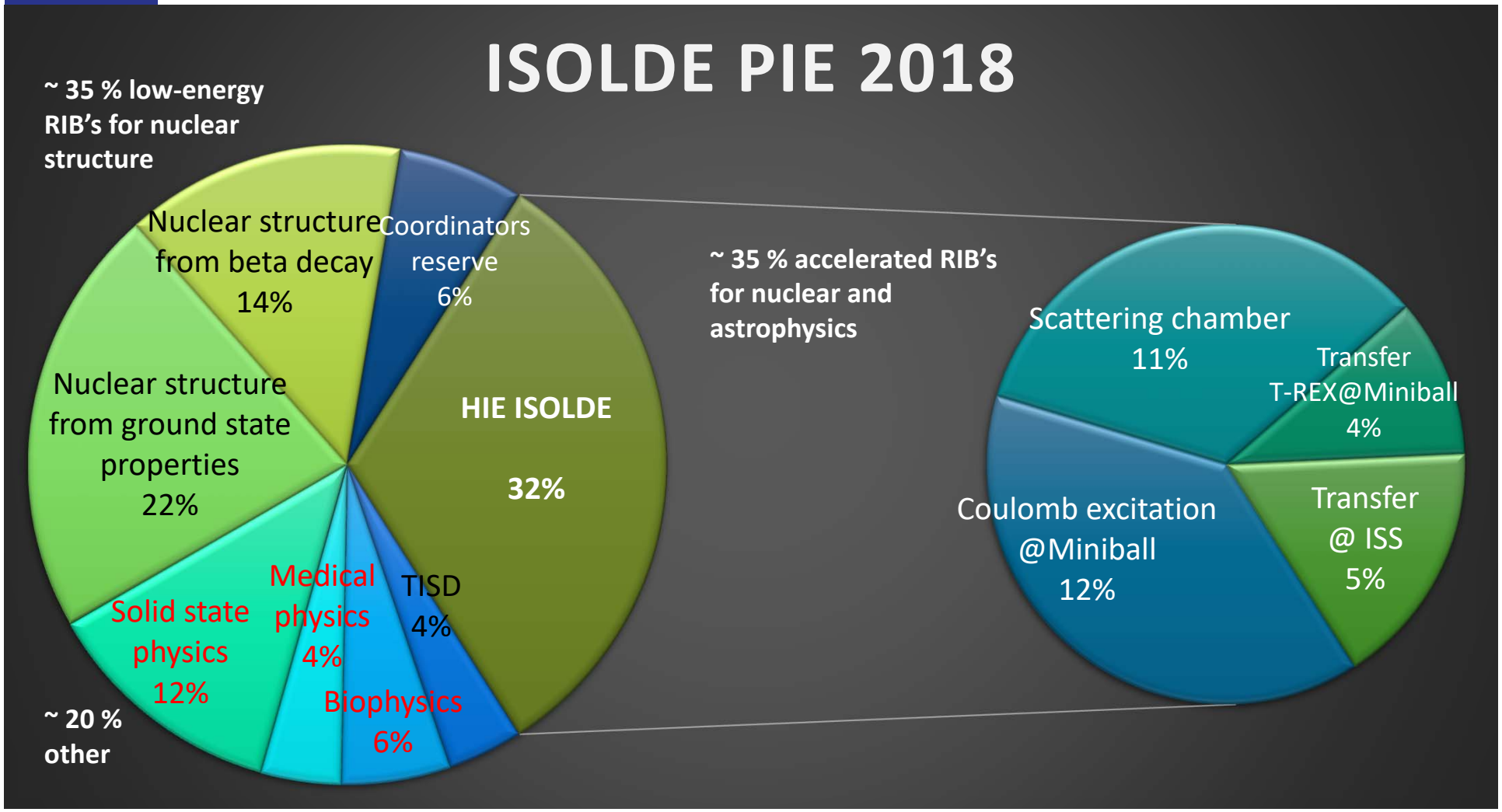






A diverse research program

in 15 experimental set-ups

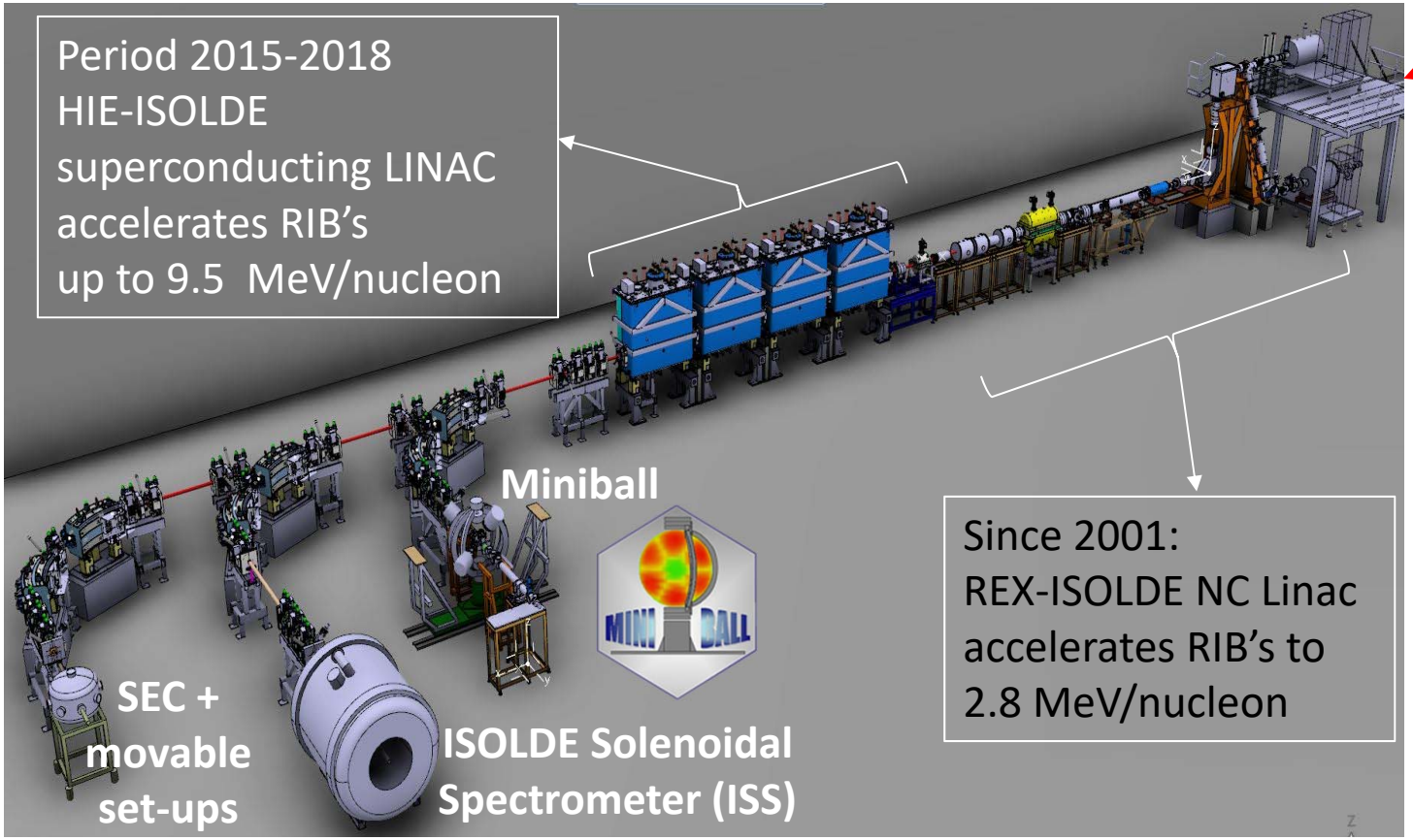


HIE-ISOLDE

An accelerator of Radioactive Ion Beams (RIB's)

Now 3 experimental set-ups available

40-60 keV
RIB from ISOLDE



Recent highlights from HIE-ISOLDE

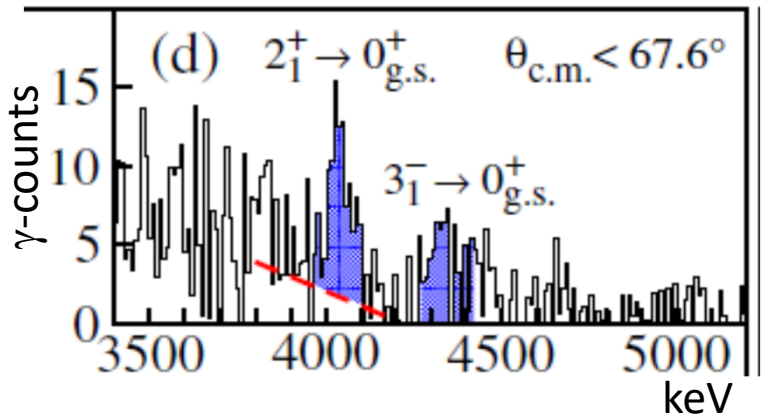
Safe Coulex on ^{132}Sn

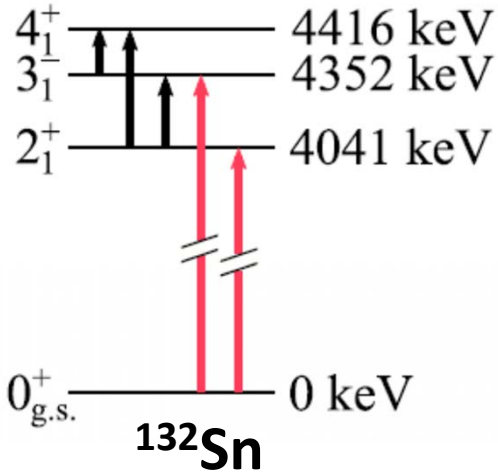
D. Rosiak et al., PRL 121, 252501 (2018)

^{132}Sn,

5.49 MeV/u, 3.10^5 ions/s

→ Precision on B(E2) improved by more than factor 10 !





$I_i \rightarrow I_f$	E_γ (keV)	$E\lambda$	$B(E\lambda; I_i \rightarrow I_f)$ (e^2b^λ) Present	Previous
$0_{g.s.}^+ \rightarrow 2_1^+$	4041.2	$E2$	0.087(19)	0.14(6) [15,16] 0.11(3) [17,18]
$0_{g.s.}^+ \rightarrow 3_1^-$	4351.9	$E3$	0.11(4)	> 0.0512 [33]
$2_1^+ \rightarrow 3_1^-$	310.7	$E1$	$9.1(31) \times 10^{-6}$	$> 3.97 \times 10^{-6}$ [33]

→ Enhanced B(E2) as compared to $^{130\text{-}134}$Sn confirmed

→ Enhanced B(E3)

^{132}Sn is doubly magic and spherical

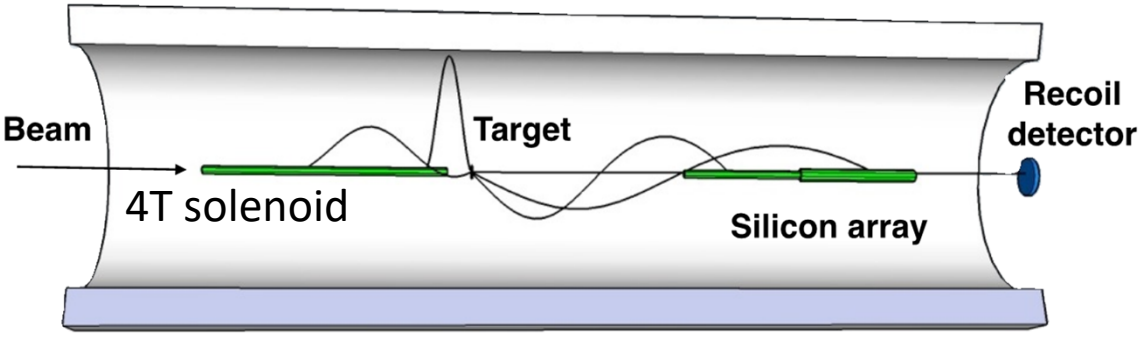
ISOLDE Solenoidal Spectrometer

- 4T superconducting (former MRI) solenoid from UQ hospital, Brisbane to ISOLDE in 2017

Helical orbit spectrometer principle

Target on the field axis + array of Si detectors.

MEASURE: position z, cyclotron period T_{cyc} and energy E_p of emitted protons from transfer reaction



Suffers <u>no kinematic compression</u> of the Q-value spectrum.

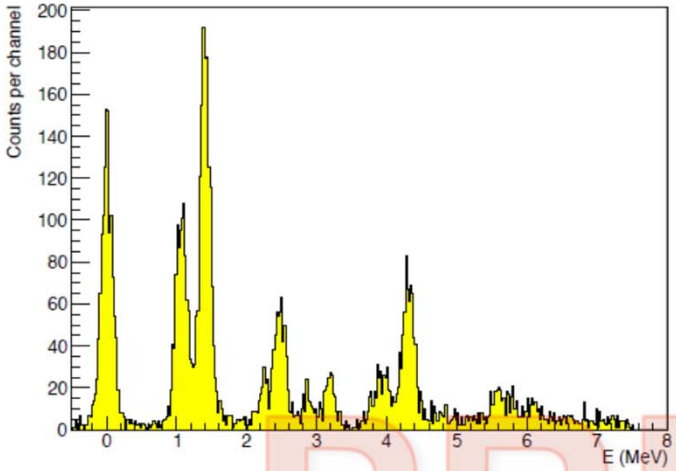
Linear relationship between E_{cm} and E_{lab}

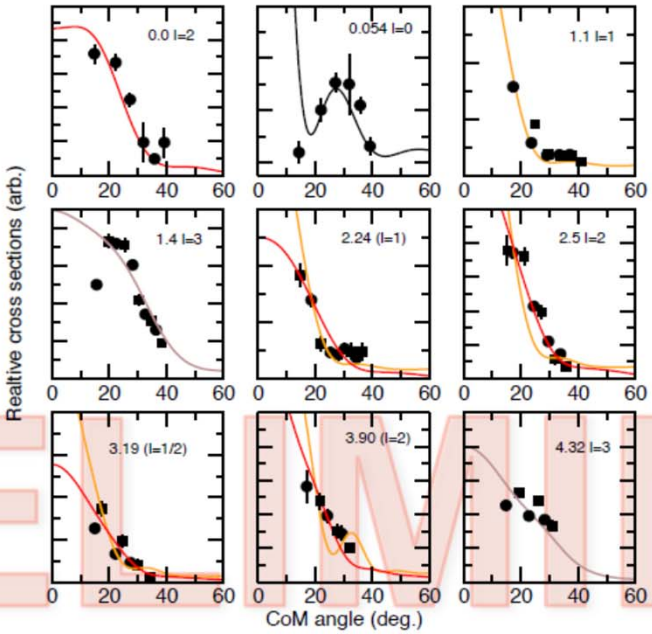
ISOLDE Solenoidal Spectrometer

- Spring-Summer 2017: construction of proper shielding around ISS
- Nov. 2017: Field mapping and beam transmission tests
- Sept. 2018: Successful commissioning with stable 22Ne beam
  and the HELIOS Si-detector array from Argonne Nat. Lab.
- October 2018: Two successful RIB experiments
  - Transfer reactions using the maximum HIE-ISOLDE beam energies

EXP #1 IS621– $^{28}Mg(d,p)^{29}Mg$ Angular distributions results

Dave Sharp, Liam Gaffney



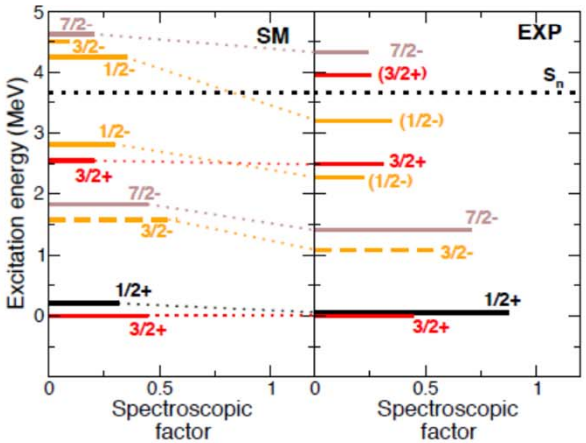


3.10^5 ^{28}Mg/s
9.5 MeV/u

FWHM <115keV

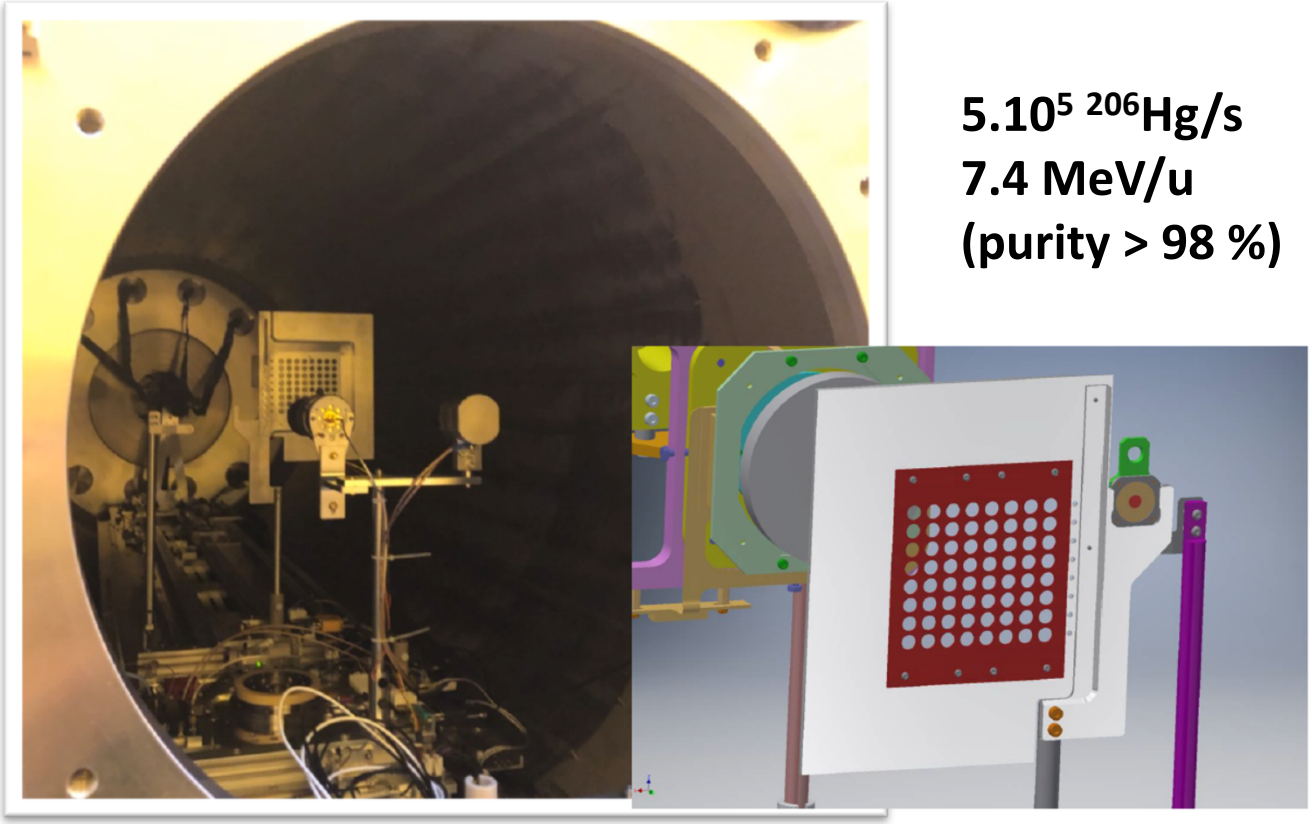
Angular distributions extracted for 9 states ***up to 4.32 MeV*** *(2 unbound).*

Compared to ***DWBA*** *calculations to make* ***preliminary*** *ℓ* ***assignments*** *– calculations extrapolated for unbound states.*



EXP#2 IS631 - $^{206}Hg(d,p)^{207}Hg$ set up

Ben Kay et al.



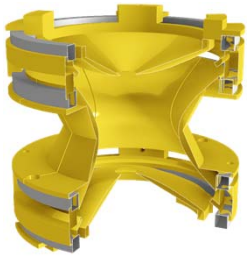
5.10^5 ^{206}Hg/s
7.4 MeV/u
(purity > 98 %)

- **30** deuterated polyethylene targets (165 mg/cm2)
  (to deal with target degradation)
- Special target ladder (automatic moving)

Experiments with low-energy RIB's

Masses

- **ISOLTRAP** (Penning trap + MR-TOF-MS)

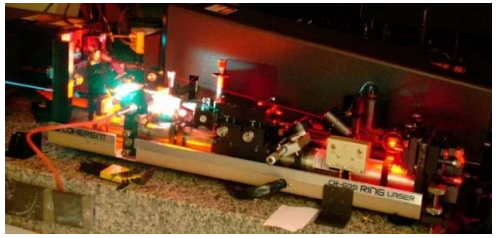


Decay spectroscopy

- **Isolde Decay Station (IDS) since 2015**

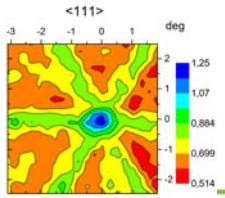
Moments, radii and spins

- **LASER SPECTROSCOPY (COLLAPS, CRIS, RILIS)**



Material research with short lived isotopes

- **Emission channeling, PAC, β-NMR, Mossbauer**

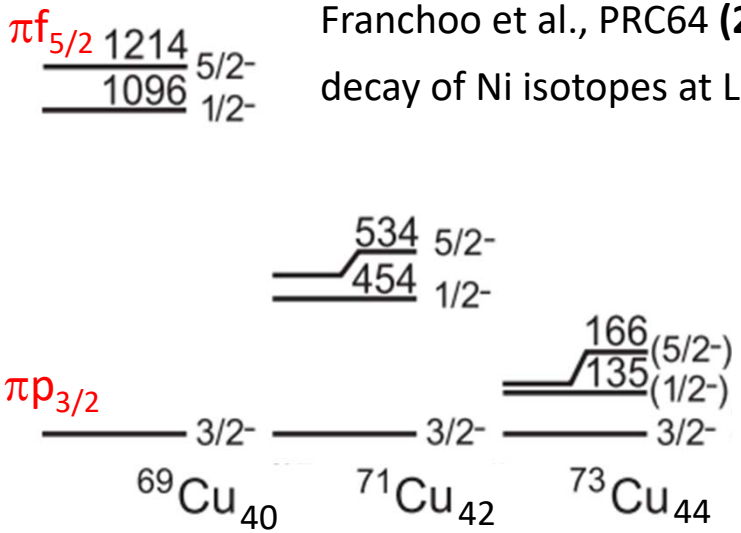


Recent highlights from low-energy ISOLDE

Evolution of single particle orbits in Cu isotopes (2001 – 2008 – 2017)

Franchoo et al., PRC64 **(2001)**

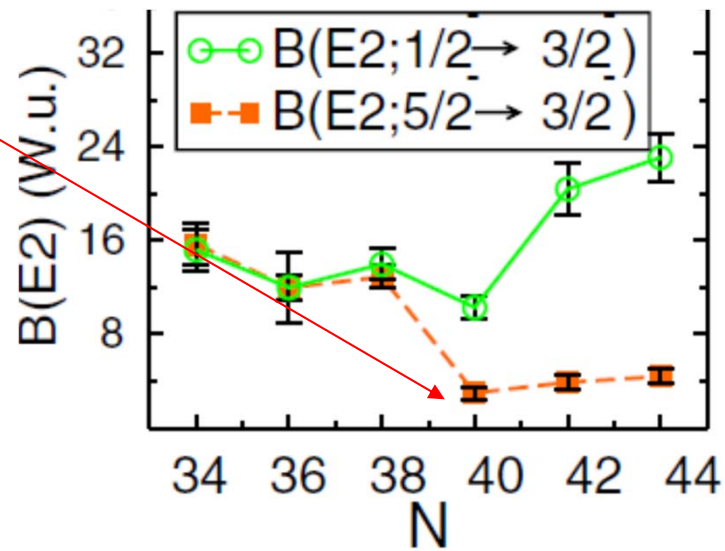
decay of Ni isotopes at LISOL (LLN)



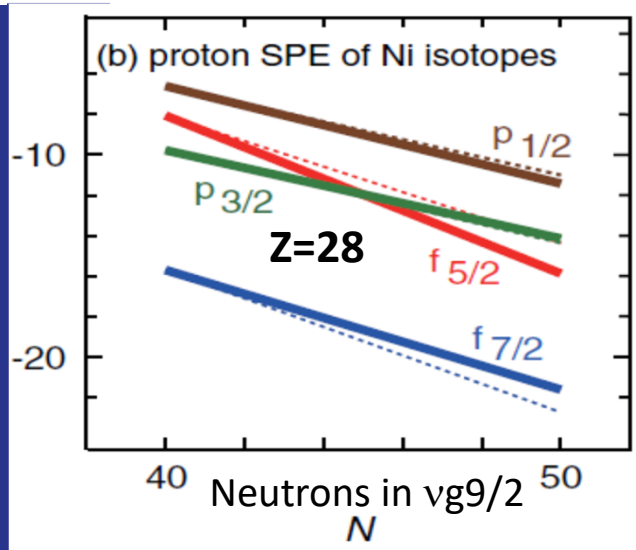
I. Stefanescu et al., PRL 100 **(2008)**

Coulex at REX-ISOLDE up to ^{73}Cu

→ 5/2- level is single-particle like !



T. Otsuka et al, PRL **95**, 232502 **(2005)**



Lowering of $\pi f_{5/2}$ when filling $\nu g_{9/2}$
(due to strong p-n interaction, enhanced due to tensor force)

→ Inversion of levels predicted from 75Cu onwards

Inversion of the $\pi f_{5/2}$ and $\pi p_{3/2}$ levels in ^{75,77}Cu

Collinear laser spectroscopy on bunched beams (ISCOOL)

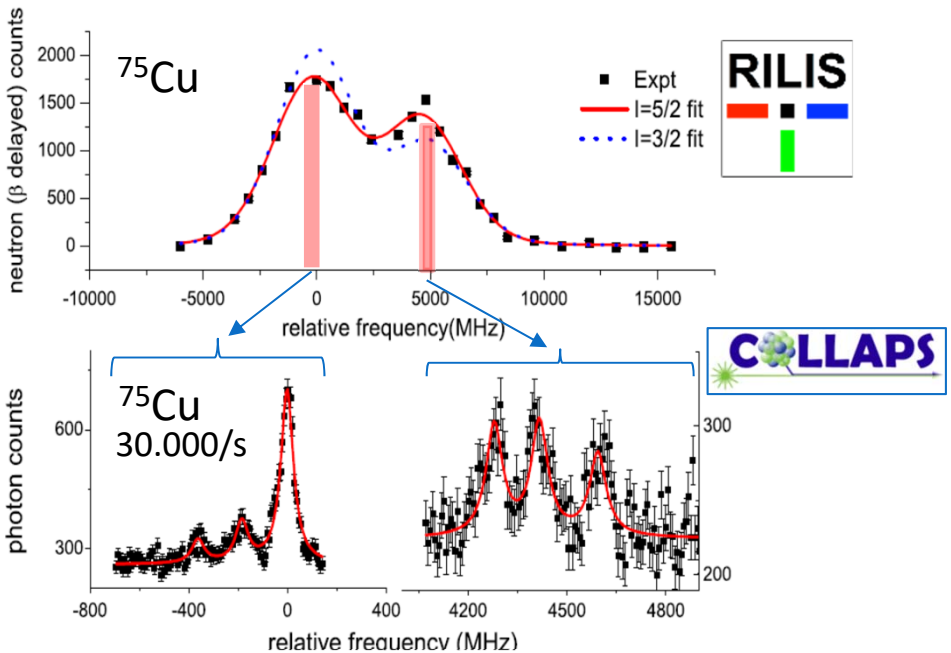
Model-independent spin determinations: 5/2

Magnetic moments: proton occupies πf5/2

Experimental sensitivity improved by factor 200

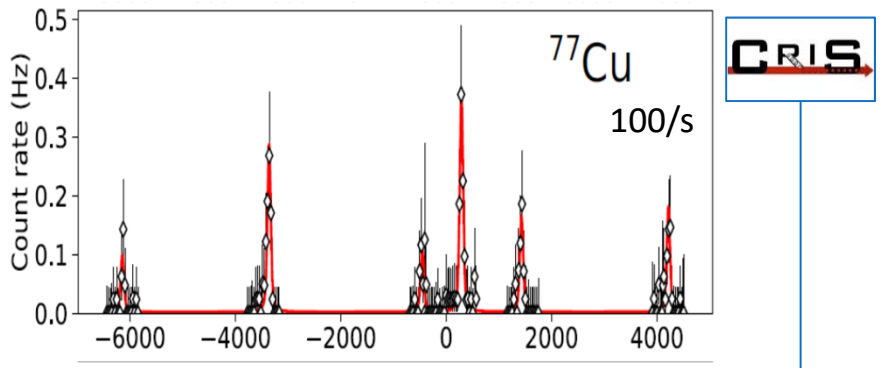
K.T. Flanagan et al., PRL 103 **(2009)**

^{71,73,75}Cu

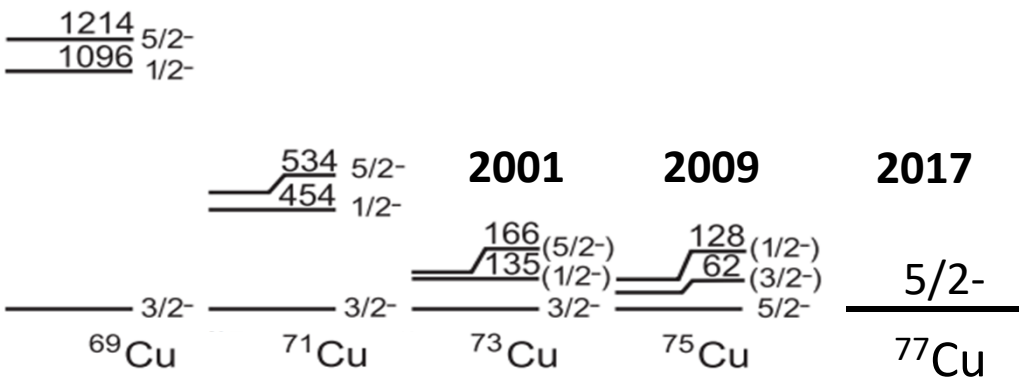


R.P. de Groote et al., PRC 96 **(2017)**

^{73,75,77}Cu



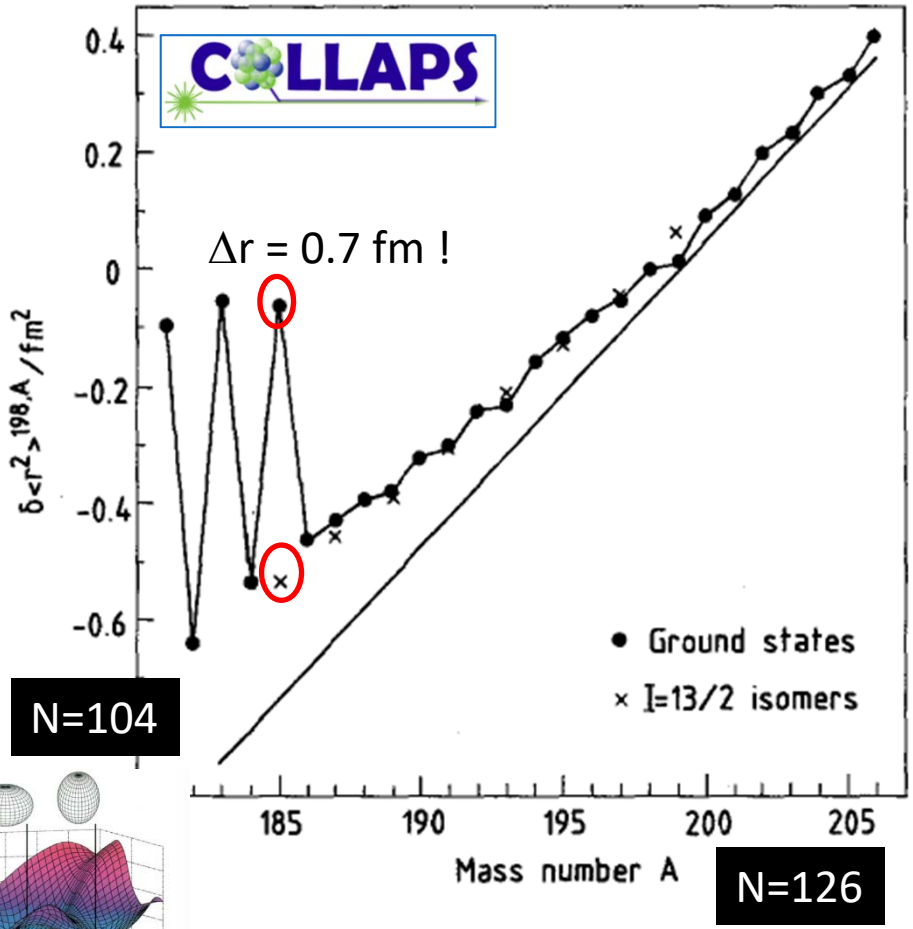
Experimental sensitivity improved by another factor 300

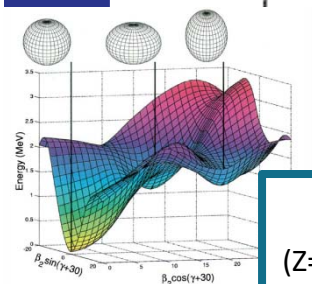


Shape coexistence in Hg isotopes (1972 – 1986)

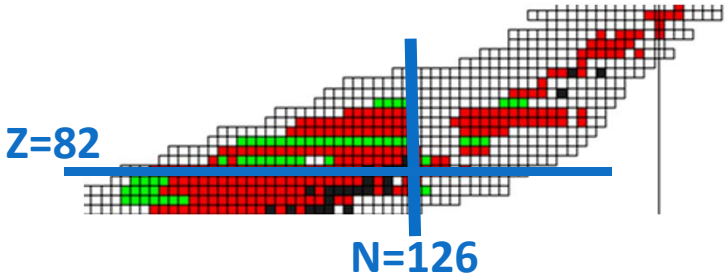
Hg: Z=80

G. Ulm et al., Z. Phys. 325, 247–259 **(1986).**





^{186}Pb
(Z=82, N=104)



Shape coexistence established in 185Hg !

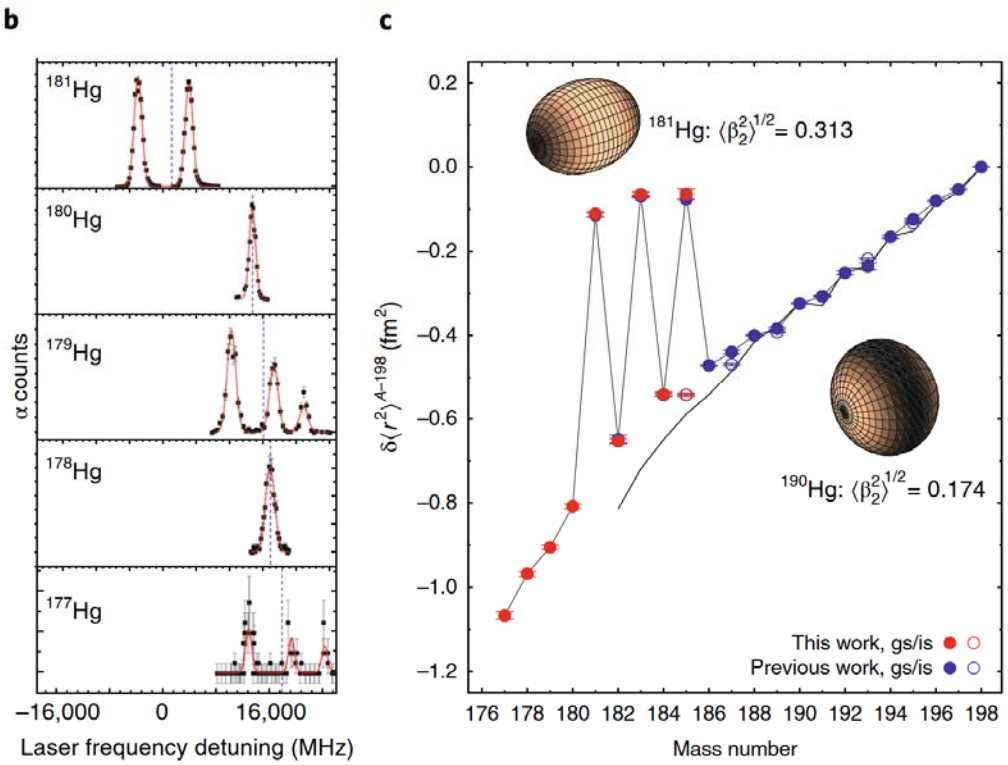
Huge increase in the charge radii of neutron-deficient 181,183,185Hg (N=101,103,105 → neutron mid-shell)

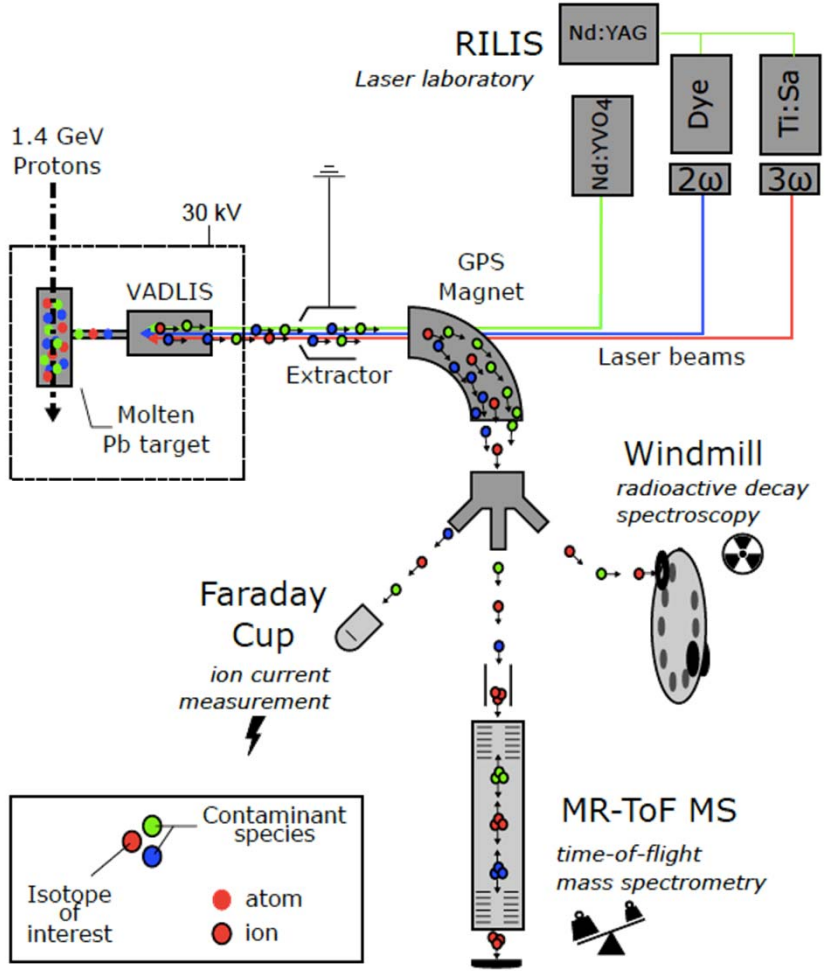
Microscopic description remained unexplained for more than 30 years !

Remove more neutrons: what happens ??

Shape coexistence in Hg isotopes (1972 – 1986 – 2018)

Combining resonance laser ionisation in the RILIS ion source with detection in 3 different experimental stations !

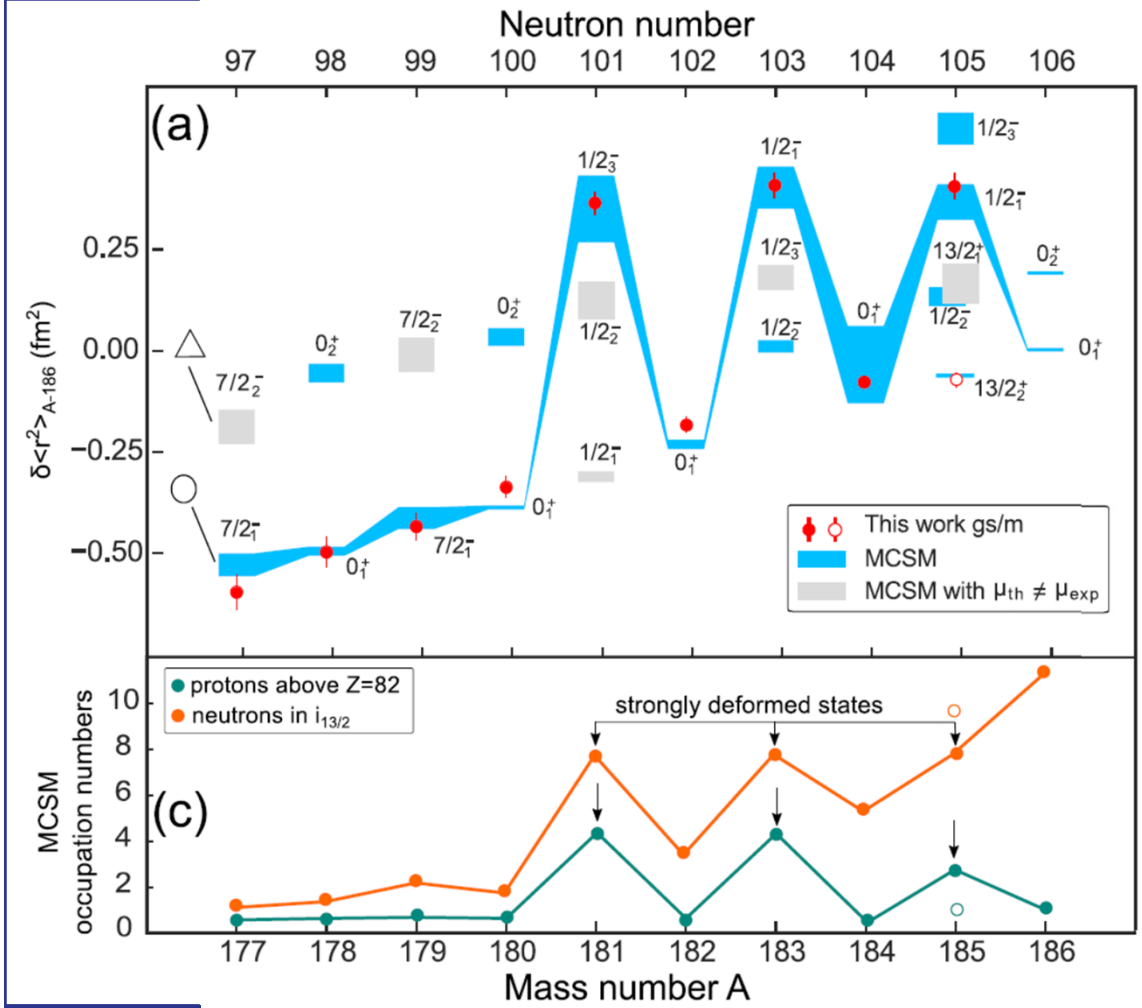




B. March et al., Nature Physics 14, 1163 (2018)

S. Sels et al., Phys. Rev. C 99, 044306 (2019)

Hg mean square charge radii



FIRST large scale MCSM calculations in this heavy mass region (Otuska et al.)

→ origin of the staggering is understood microscopically !

→ Due to enhanced (tensor) interaction between $\nu i_{13/2}$ and $\pi h_{9/2}$

→ Favors occupations of these orbits, leading to increased deformation and lowering of the energy

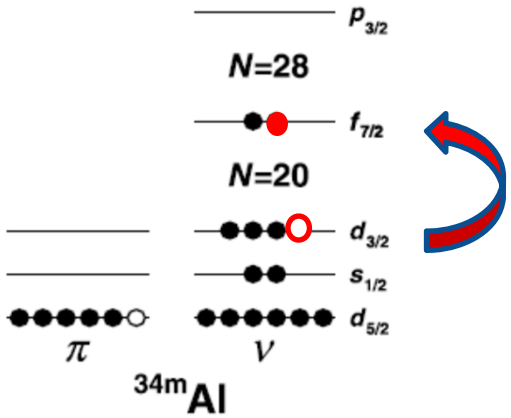
$$E_{\mathrm{mon}} = f(j_p, j_n) n_\pi(j_p) n_\nu(j_n)$$

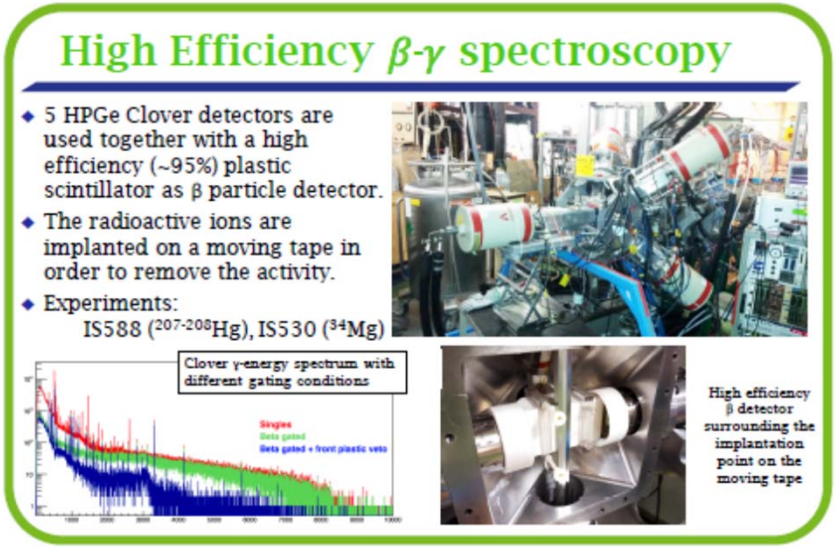
B. March et al., Nature Physics 14, 1163 (2018)

S. Sels et al., Phys. Rev. C 99, 044306 (2019)

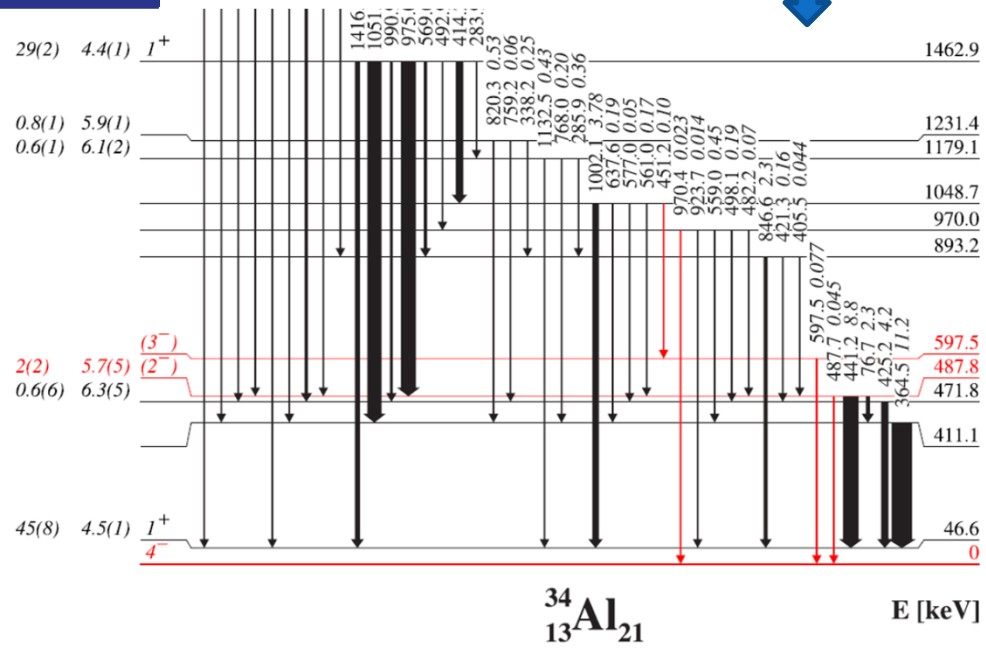
E(1⁺) intruder isomer energy in ^{34}Al

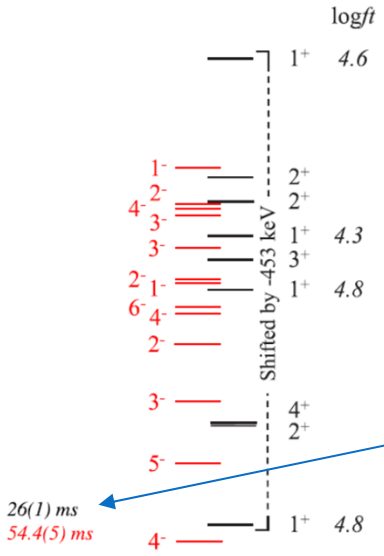
R. Lică et al., PRC 95, 021301(R) (2017)





^{34}Mg, 700 ions/s





1p-1h intruder state at E = 46.6 keV

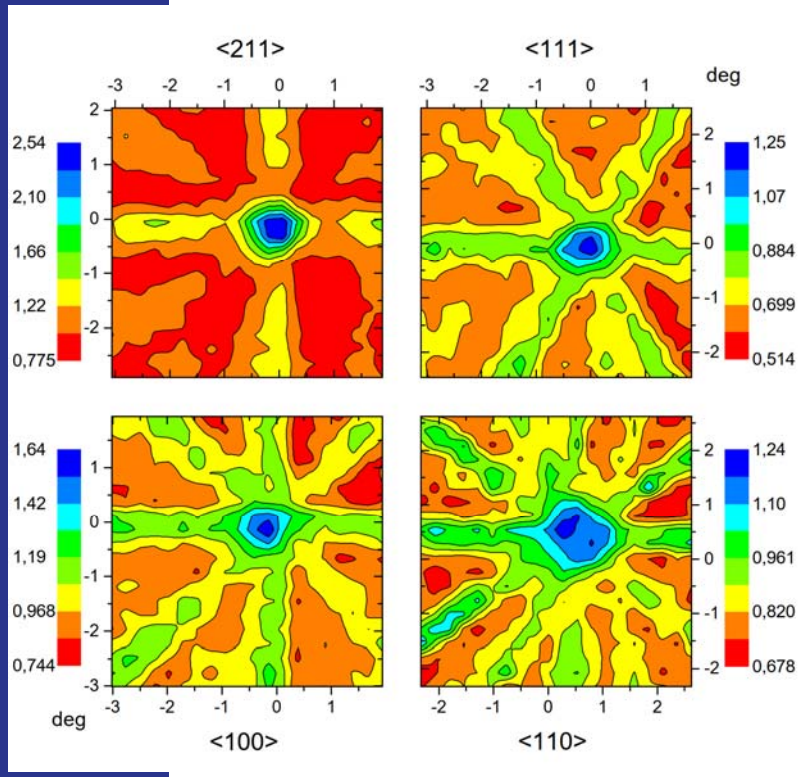
Search for ^{229}Th isomer energy

M. Verlinde et al., submitted to PRC

Nov 2018

Requirement: 229Ac should take substitutional site in CaF

Method: Emission Channeling



Idea to measure radiative decay energy:

- ✓ Produce intense beam of 229Ac
- ✓ 229Ac decays into the 229mTh isomer (13%)

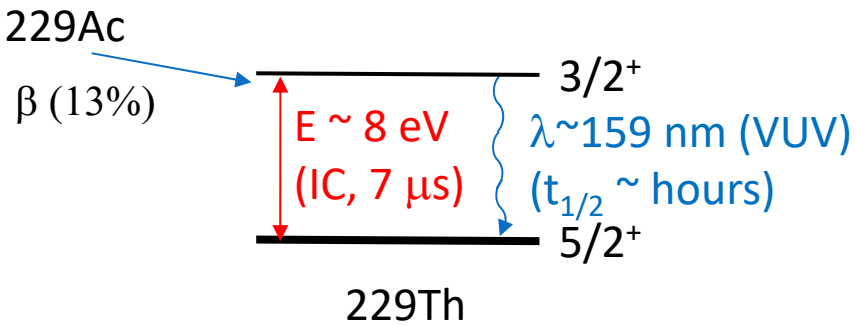
To block Internal Conversion decay

➔ implantation in wide bandgap material CaF (12 eV)

→ radiative decay dominates !

* Measure the radiative decay energy (VUV)

CaF is transparent for VUV radiation



L. von der Wense et al. Nature 533 (2016)

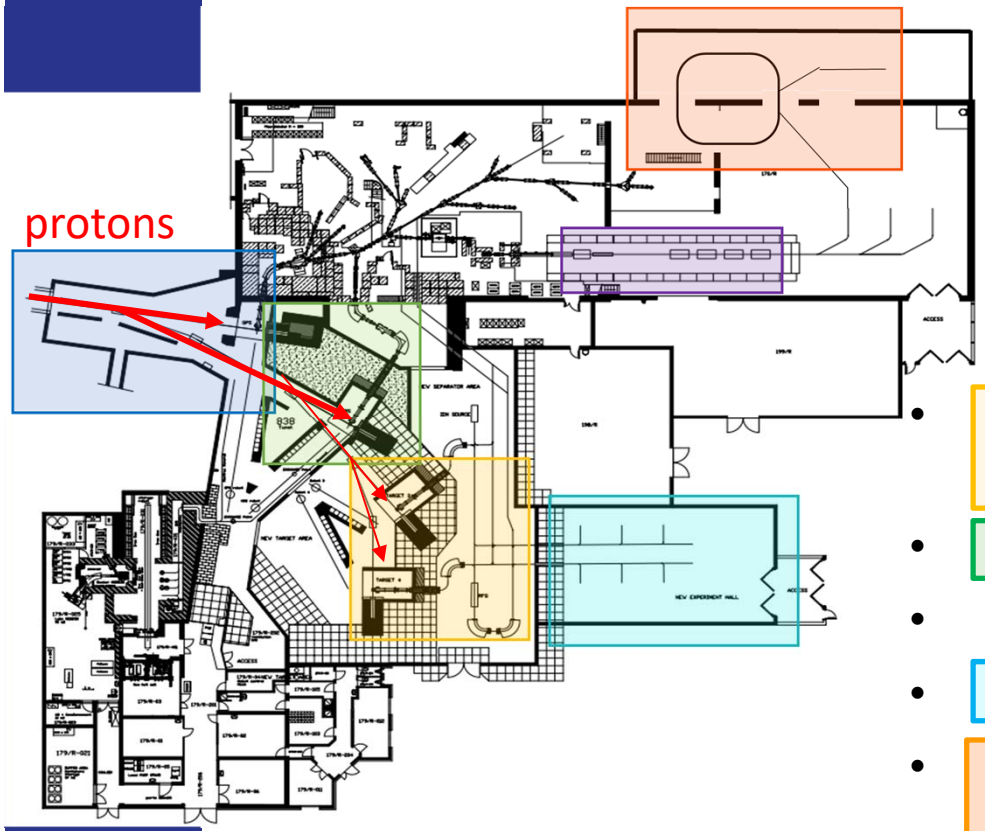
Courtesy P. Van Duppen, L. Pereira et al.

Outlook to the future

The EPIC Project: Exploiting the Potential of ISOLDE at CERN

(not yet approved by CERN)

Layout of an extended ISOLDE (colors are new/upgrades) :



The EPIC project comprises of 6 key upgrades (in no particular order):

- The addition of two new target stations and a high resolution mass separator
- Improvement of the existing beam dumps
- Provide 2 GeV protons to ISOLDE
- The addition of a second experimental hall
- Installation of a storage ring beyond the HIE-ISOLDE post accelerator
- An upgrade of the non-superconducting part of HIE-ISOLDE (REX-part)

New opportunities with EPIC@CERN

for the (European) (Nuclear) Physics Community

- **Upgrade of the HIE-ISOLDE pre-accelerator (REX)**
  - higher A/Q (up to 5.5) so more intense heavy beams, with a variable time structure and up to 10 MeV/u also for those around Pb.

- **Higher RIB beam intensities (gain factor 2 to 50)**
  - thanks to the LHC intensity upgrades (LIU) at CERN
    - ✓ Higher proton beam intensity from booster (from 2 → 4 μA)
    - ✓ Higher proton beam energy (from 1.4 → 2 GeV) from booster

- **Two new (additional) target stations + a new low-energy hall**
  - Have multiple ***simultaneous*** beams for users (low/high energy)

- **Improved mass separation capabilities**
  - Purer beams are better for ***efficient*** reacceleration

- **A new storage ring for short-lived, light and heavy ions**
  - New perspectives for precision studies in nuclear, atomic and astrophysics

Conclusions

- ISOLDE now provides **slow and accelerated RIB's (up to ~10 MeV/u)** for more than a dozen permanent experiments

  (and a few travelling setups) for studying:
  - Nuclear physics
  - Nuclear astrophysics
  - Solid state physics
  - Bio-physics
  - Fundamental interactions and symmetries

- Future upgrades are under discussion in the framework of the EPIC Project (Exploiting the Potential of ISOLDE @ CERN)

First ISOLDE-EPIC workshop: December 3-4

followed by the Annual ISOLDE Users Meeting on December 5-6

Many more results and details in several contributions at this conference

ISOLDE