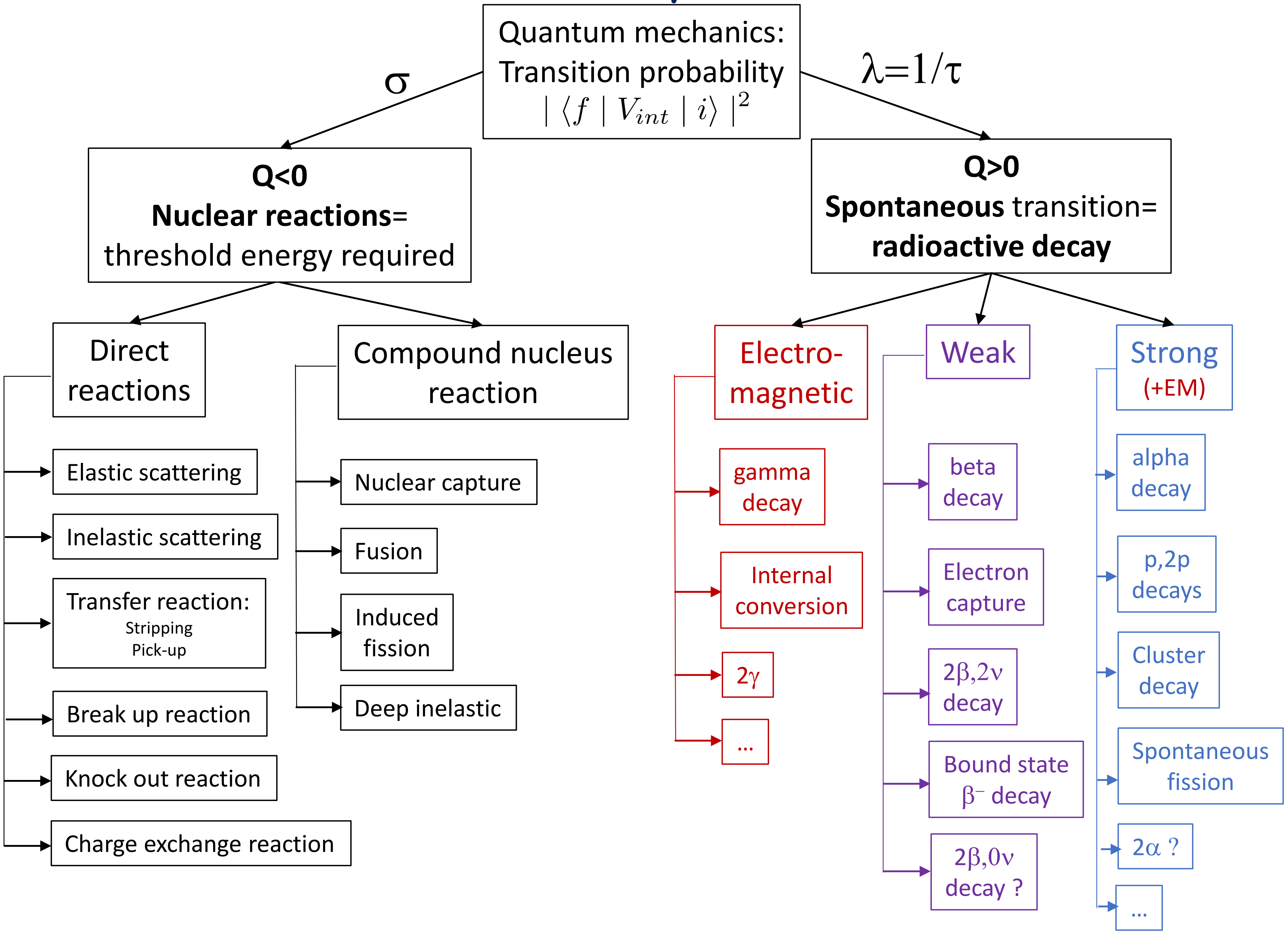
Recherche d'un nouveau type de radioactivité: la double désintégration alpha

E. Khan, Ch. Theisen / Journée annuelle P2I
9 janvier 2024

Calculations based on
F. Mercier, J. Zhao, R.-D. Lasseri, J. P. Ebran, E. Khan, T. Nikšić, and D. Vretenar, Phys. Rev. C 102, 011301(R) (2020)
F. Mercier, J. Zhao, J.-P.Ebran, E. Khan, T. Nikšić, D. Vretenar, Phys. Rev. Lett. 127, 012501 (2021)
E. Khan, L. Heitz, F. Mercier, J. P. Ebran, Phys. Rev. C 106, 064330 (2022)
J. Zhao, J. P. Ebran, L. Heitz, E. Khan, F. Mercier, T. Nikšić, and D. Vretenar, Phys. Rev. C 107 034311(2023)

Nuclear dynamics

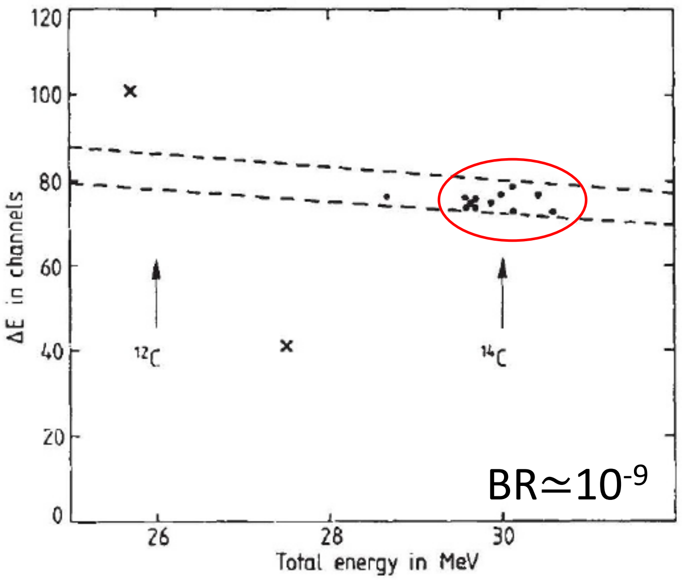


Decays

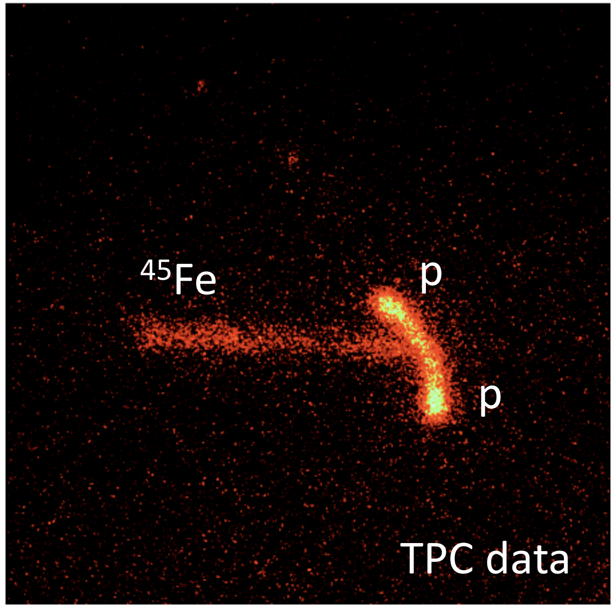
Interaction	Nom de la radioactivité (date de découverte)	Particule(s) émise(s) par le noyau
Electromagnétique	γ (1900)	photon
	Electron de conversion (1938)	e^-
Faible	β^- (1898)	e^-, $\bar{\nu}_e$
	β^+ (1933)	e^+, ν_e
	Capture électronique (1937)	ν_e
	Double β^- (1980)	$2e^-$, $2\bar{\nu}_e$
	Double capture électronique (2001)	$2\nu_e$
	β^- Etat lié (1992)	$\bar{\nu}_e$
Forte (+EM)	α (1896)	${}_2^4He$
	n, p (1970), 2p (2000), 2n (2012)	n ou p ou 2p ou 2n
	Clusters (1984)	${}^{14}C$ ou ${}^{24}Ne$ ou ${}^{32}Si$, …
	Fission (1939)	n + 2 noyaux lourds (${}^{90}Zr$, ${}^{132}Sn$, …)
	Fission ternaire (2010)	n + 3 noyaux lourds

Examples of rare decay modes by strong interaction

$^{223}Ra \rightarrow {}^{14}C + {}^{209}Pb$



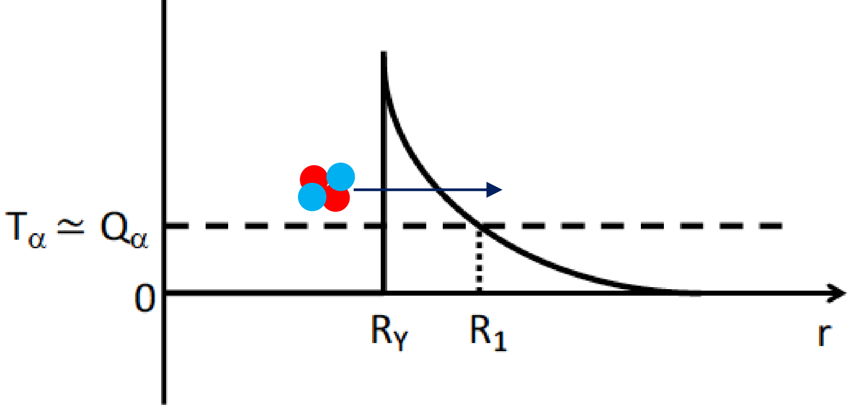
Rose and Jones, Nature, 307 (1984) 245



K. Miernik et al, Phys. Rev. Lett. 99 (2007) 192501

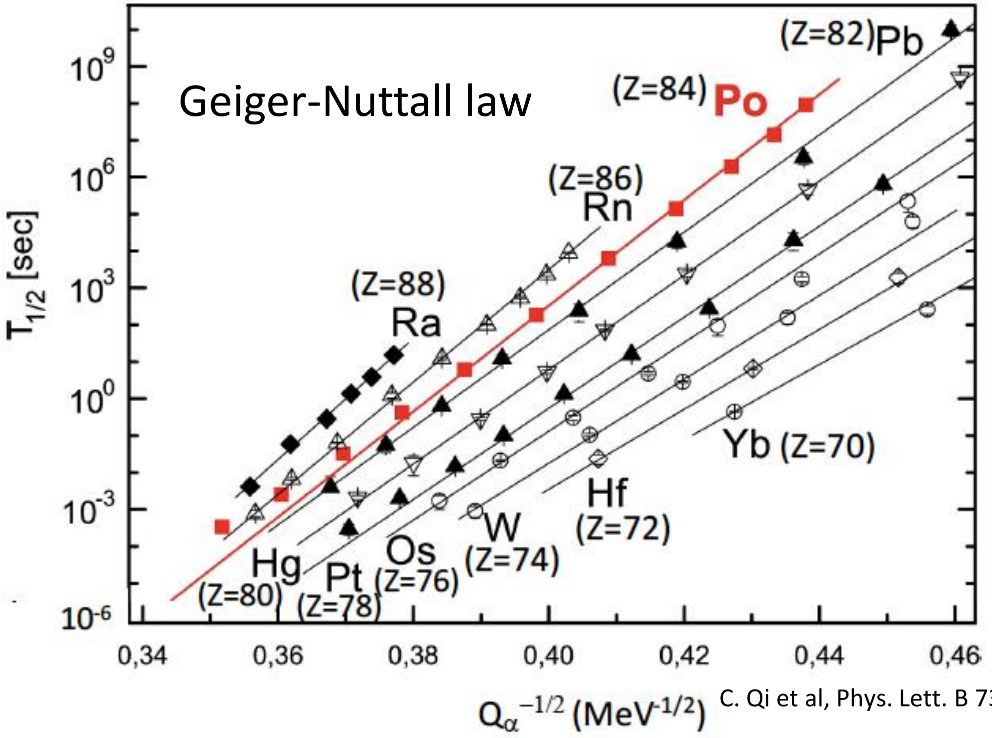
α decay from textbooks

$$P \simeq e^{-2\int_{R_Y}^{R_1} K(r)dr}$$



with

$$K(r) \equiv \frac{\sqrt{2m_\alpha(V(r) - Q_\alpha)}}{\hbar}$$



C. Qi et al, Phys. Lett. B 734, 203 (2014)

A microscopic approach to α decay

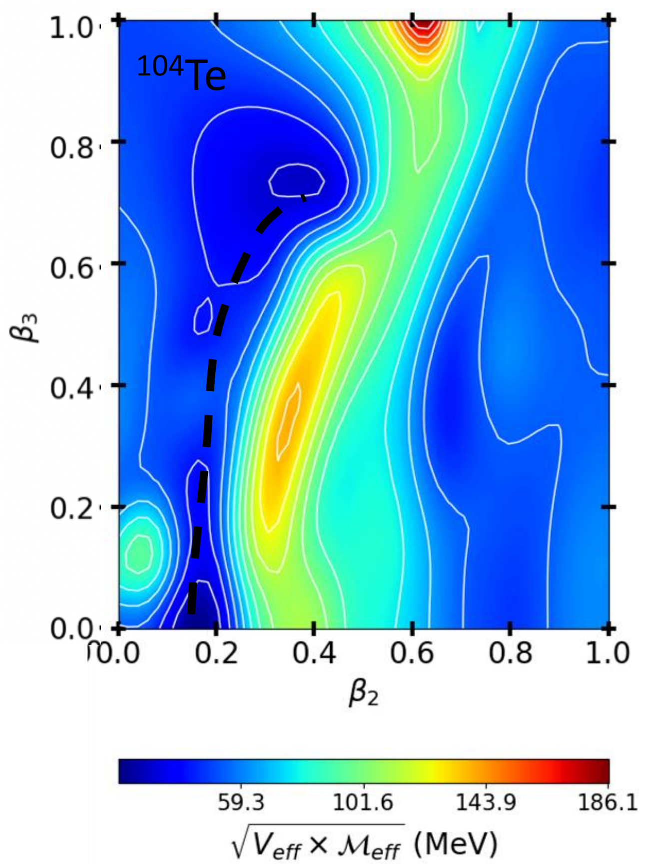
Potential energy surfaces calculated with covariant EDF

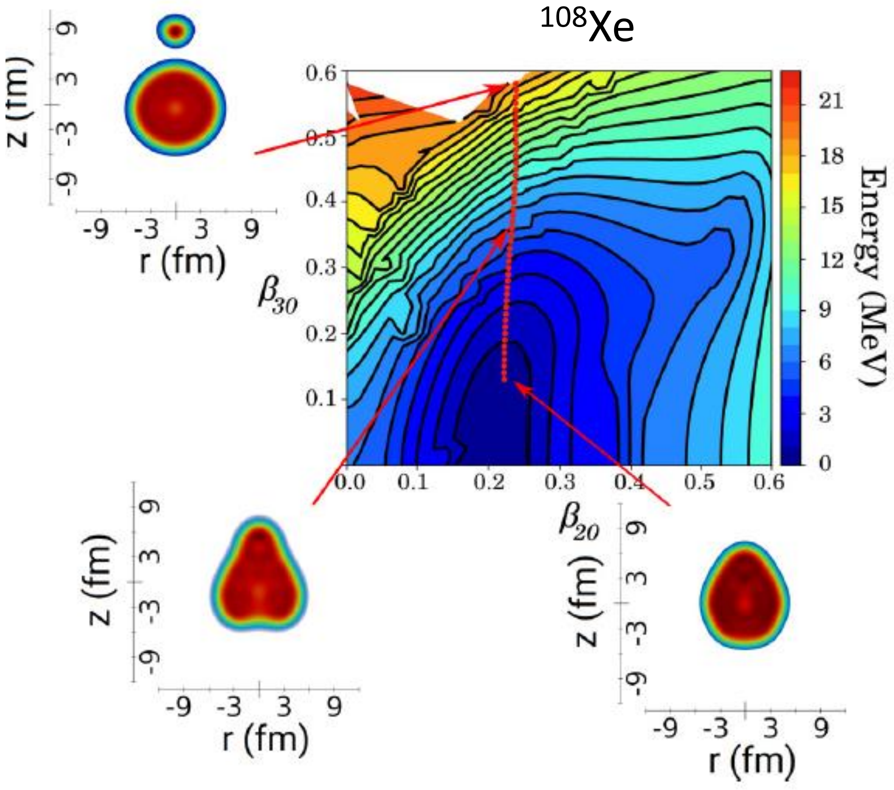
$$S(L) = \int_{s_{in}}^{s_{out}} \frac{1}{\hbar}\sqrt{2\mathcal{M}_{eff}(s)[V_{eff}(s) - E_0]}ds$$: minimization of the action integral

$$P = \frac{1}{1 + \exp[2S(L)]}$$: barrier penetration probability (WKB)

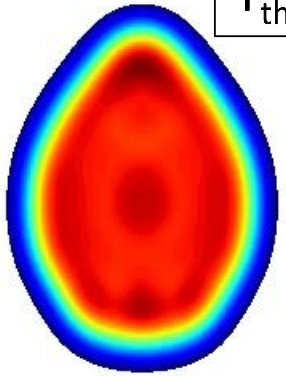
$$T_{1/2} = \ln 2/(nP)$$ n: number of assaults per unit of time

	^{104}Te	^{108}Xe
T_{exp}	<18ns	58 μs
T_{theo}	197ns	50 μs



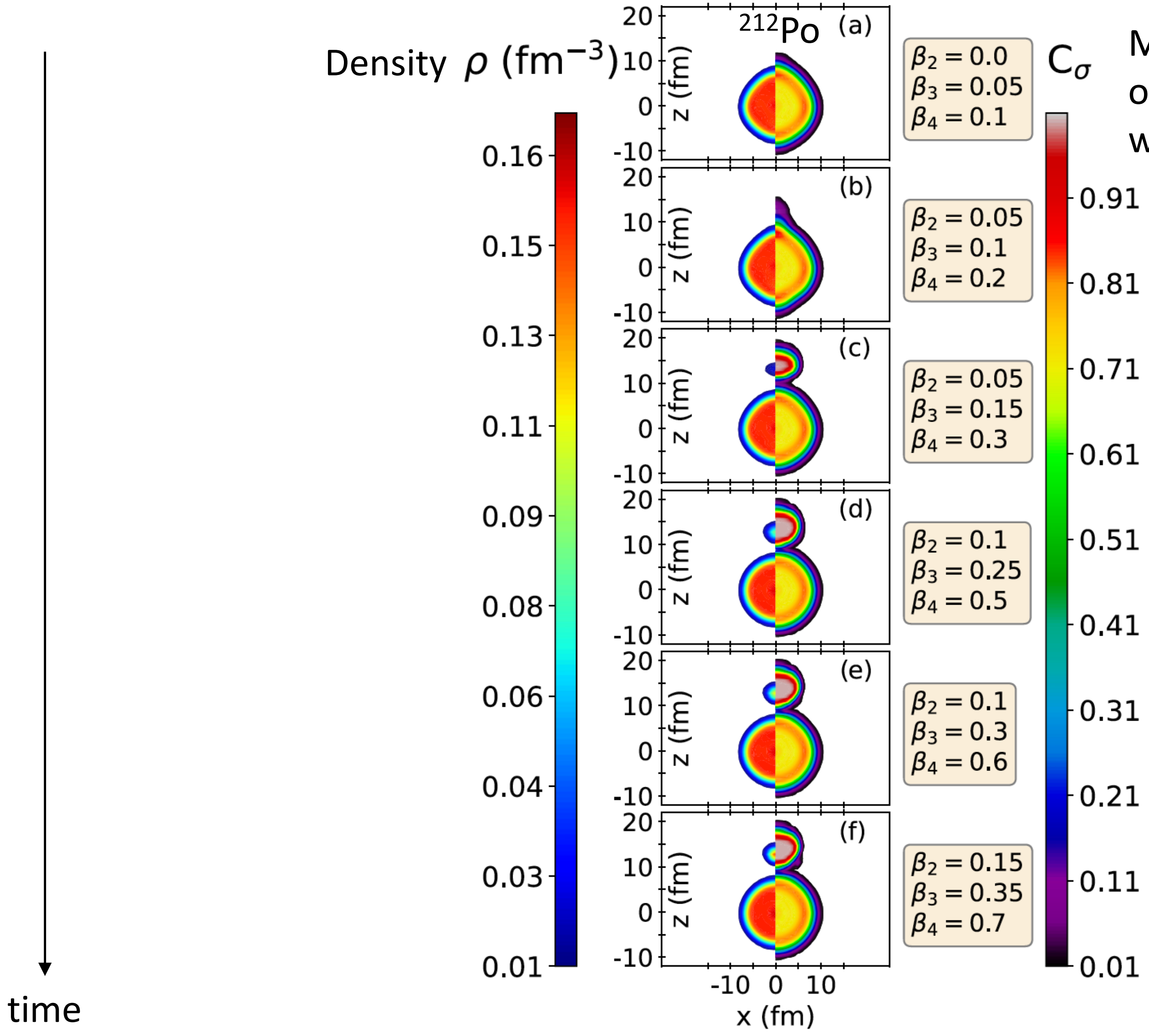


	^{224}Ra
T_{exp}	3.6 d
T_{theo}	5.7 d



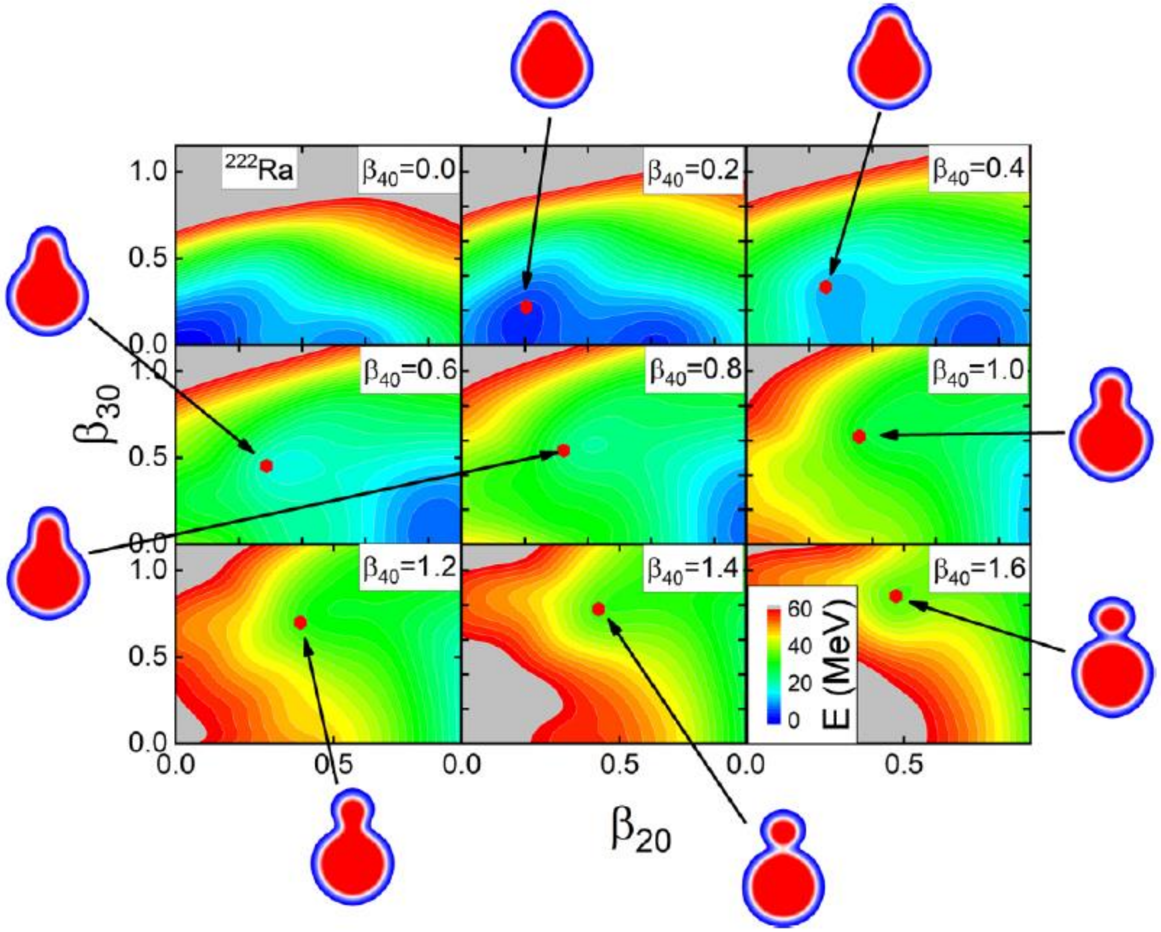
RHB density plots

Microscopic insight on the origin of the α decay mechanism

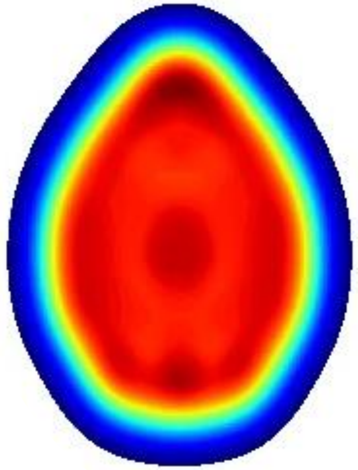


Measure of the purity of the (2n+2p) wave function

^{14}C cluster decay in $^{222,224}Ra$



^{224}Ra

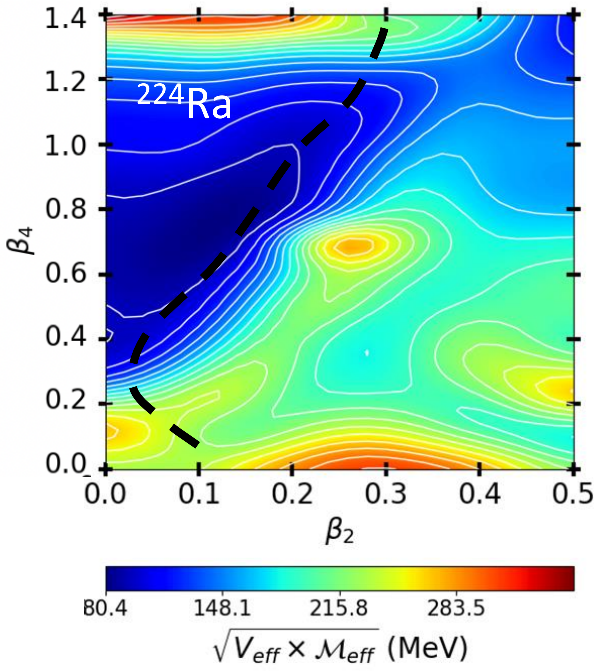


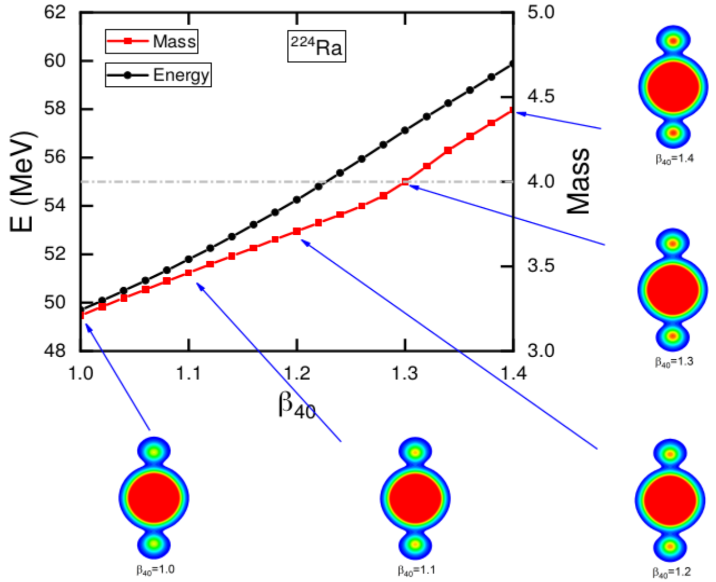
RHB density plots

	T_{expt}	T_C^{2D}	T_C^{3D}
^{222}Ra	11.01	13.61	14.82
^{224}Ra	15.86	15.87	

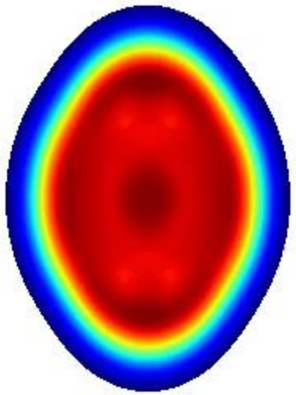
The 2α decay

	^{14}C	^{8}Be	2α
T_{theo}	$10^{15.87}$ s	$10^{27.87}$ s	$10^{13.03}$ s
T_{exp}	$10^{15.86}$ s	??	??





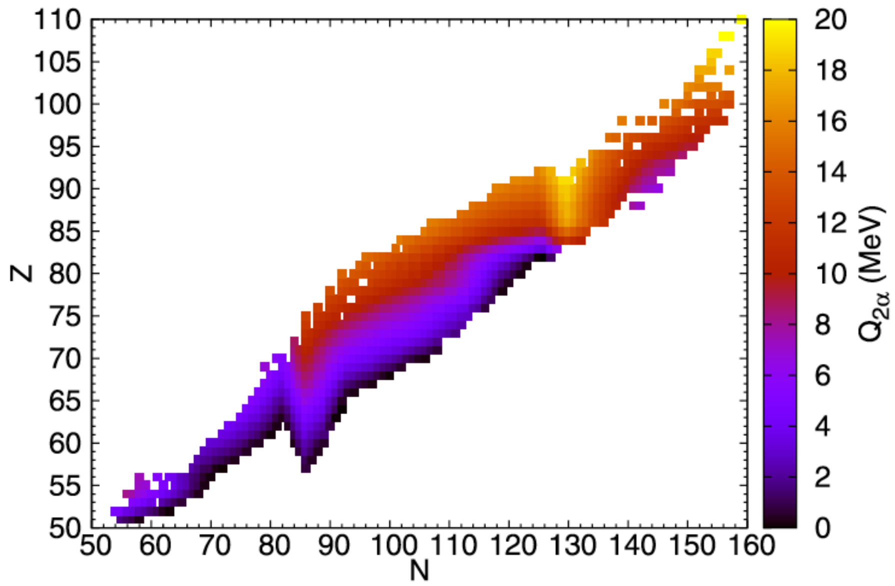
^{224}Ra

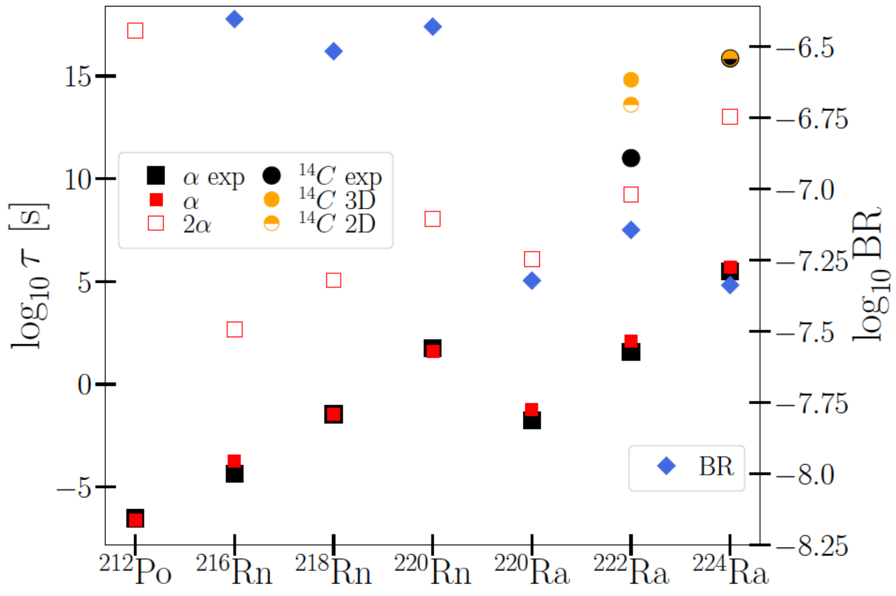


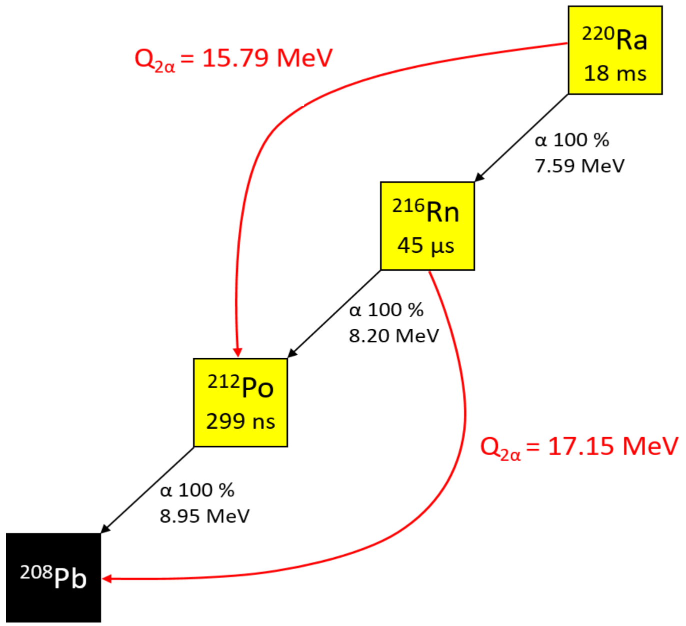
RHB density plots

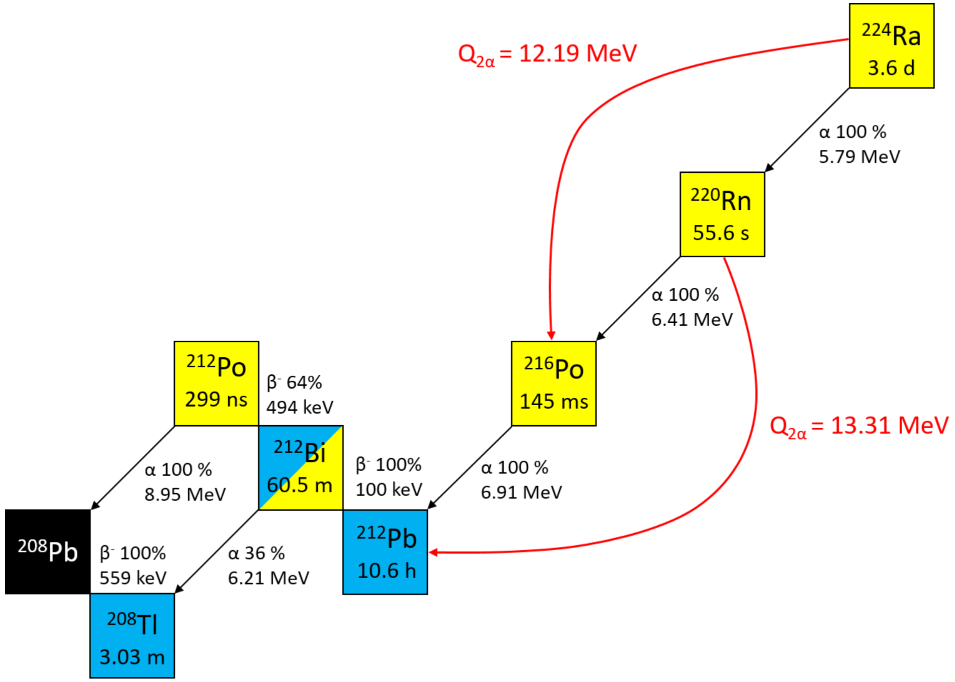
- Unobserved for now
- 2α decay predicted since several decades as ^{8}Be cluster emission: negligible BR
- Here, separate emissions of the 2 α , BR larger than observed ^{14}C cluster emission

Best 2α decay candidates ?









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2α

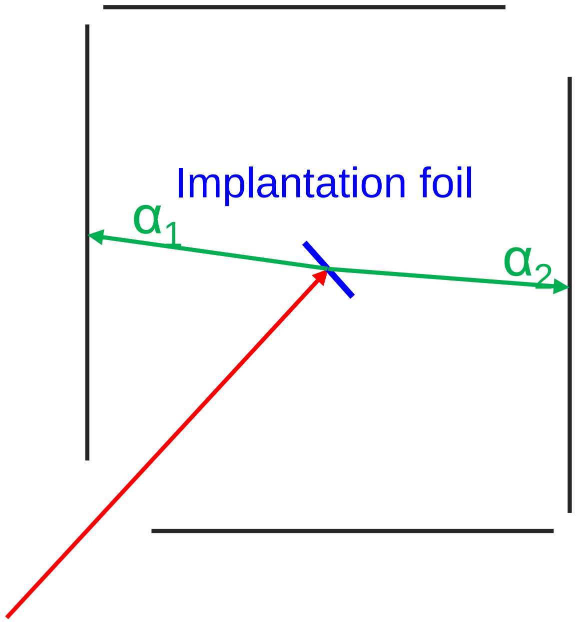
Double alpha

How to detect double alpha decay

- Measure in coincidence alpha particles
  - Energy (sum $E_{\alpha 1} + E_{\alpha 2} = Q_{2\alpha}$)
  - Timing
  - Position (back to back and eventually asymmetric double alpha decay)

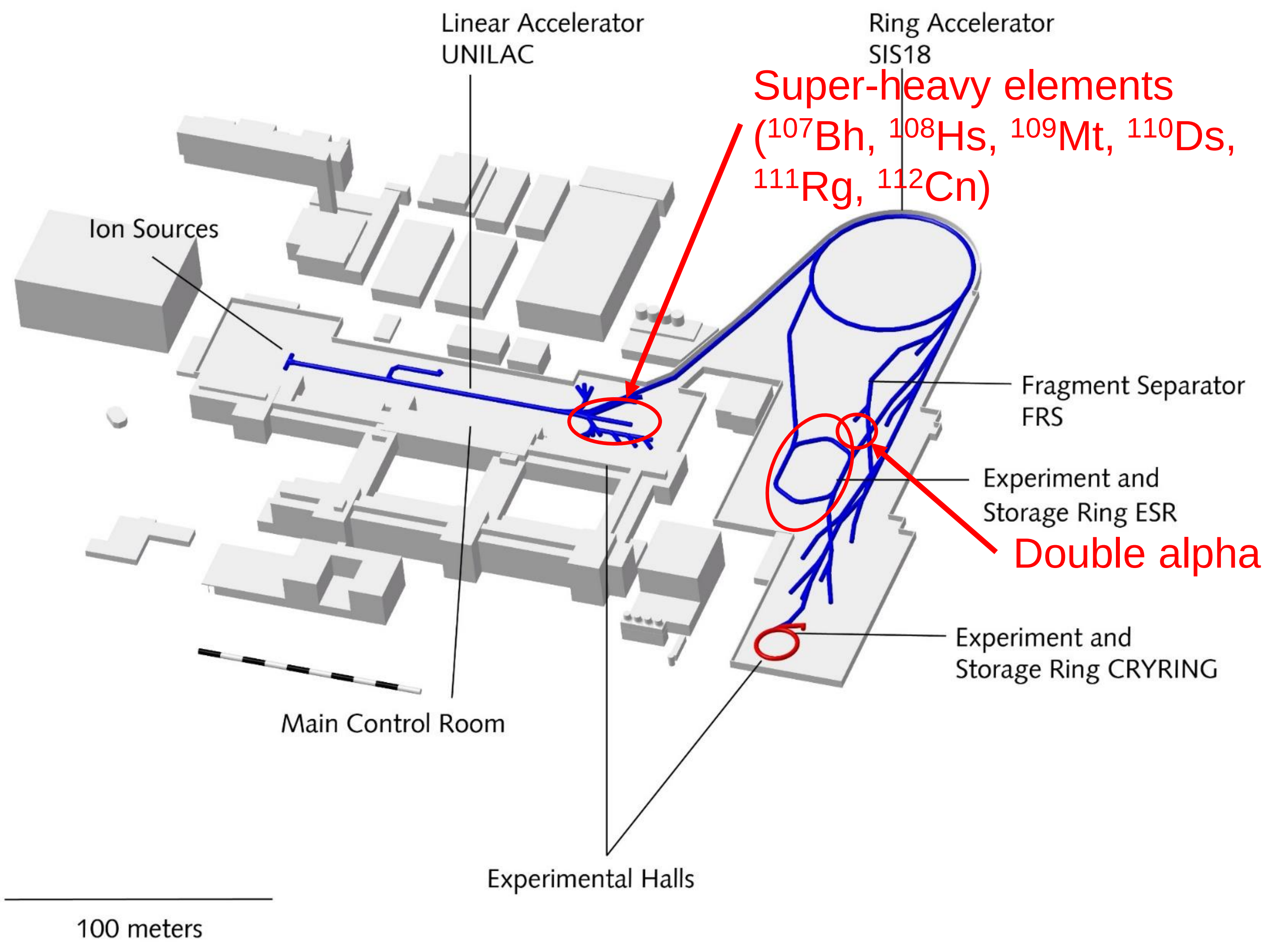
Basic idea = implant nuclei of interest in a catcher + measure alpha with position sensitive detectors

Statistics needed >> 1/Branching Ratio



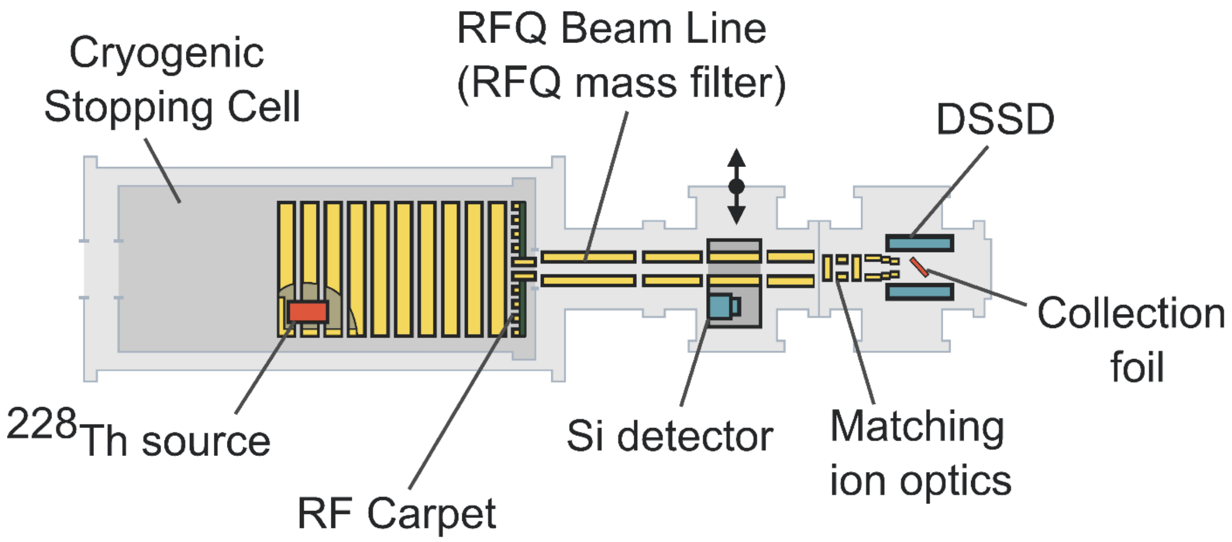
Experimental approaches

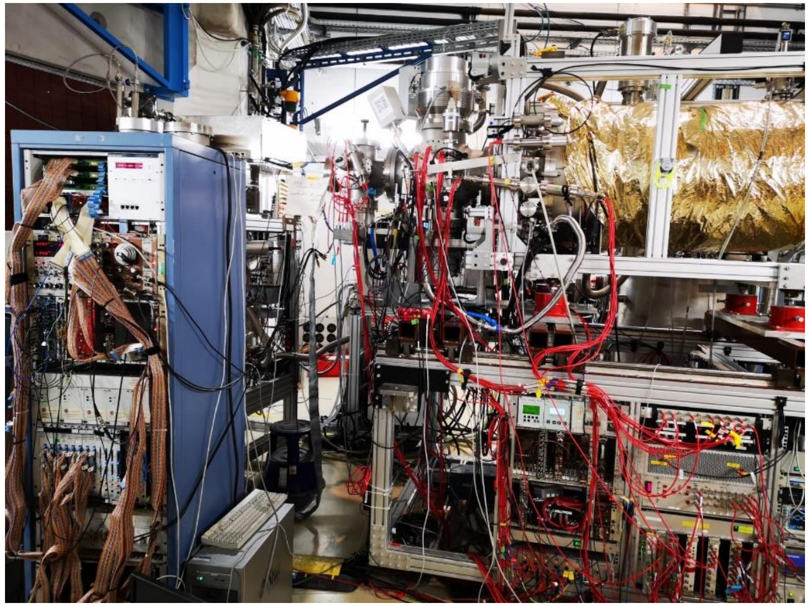
GSI 2022 ^{224}Ra. Basic principle : do an experiment as fast as possible with as much as possible existing setup.

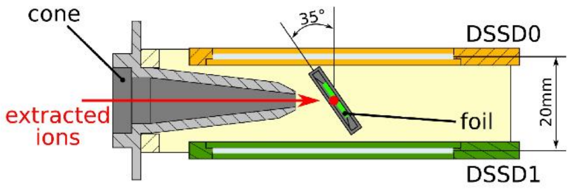


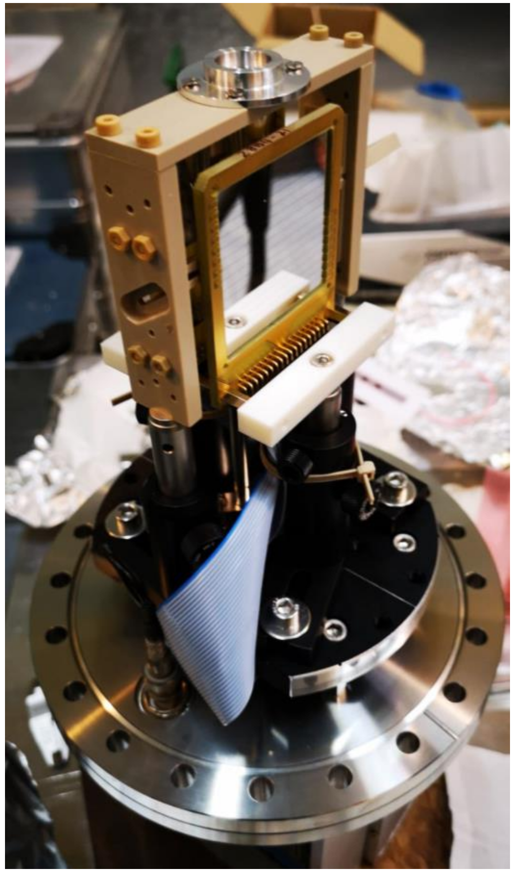
CERN/Isolde : setup with better perfomances and more relevant isotope(s)

The GSI experiment, FRS cryogenic stopping cell



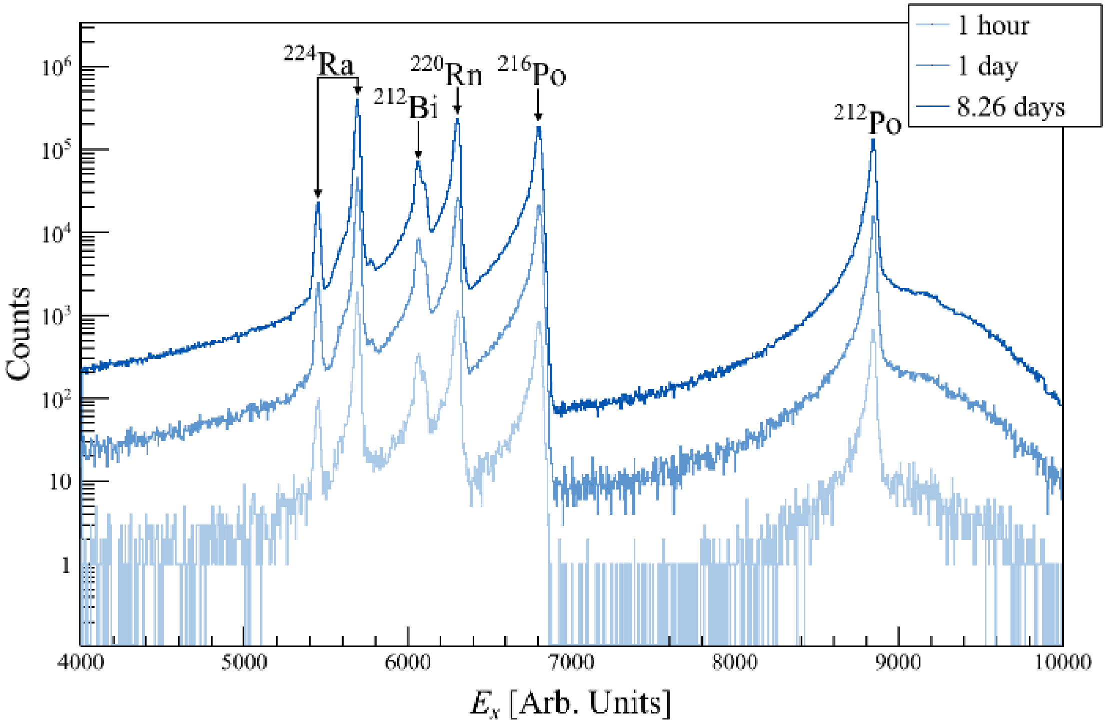






The GSI experiment

Measurement Feb – July 2022, 123 days



A novel device to perform rare decay searches using the FRS Ion Catcher

L. Varga[a,b], H. Wilsenach[c,f], O. Hall[a], T. Dickel[b,c], M. P. Reiter[a], D. Amanbayev[c], T. Davinson[a], D. J. Morrissey[d], I. Pohjalainen[b], N. Tortorelli[b,e], J. Yu[b], J. Zhao[b], S. Ayet[h,b,a], S. Beck[b], J. Bergmann[c], Z. Ge[b], H. Geissel[b,c], L. Heitz[i,m], C. Hornung[b], N. Kalantar-Nayestanaki[j], E. Khan[m], G. Kripko-Koncz[c], I. Mardor[f,g], M. Narang[j,b], W. Plass[b,c], C. Scheidenberger[b,c,l], M. Simonov[c], S. K. Singh[b], A. State[k], C. Theisen[i], M. Vandebrouck[i], P. J. Woods[a], FRS Ion Catcher Collaboration

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Abstract

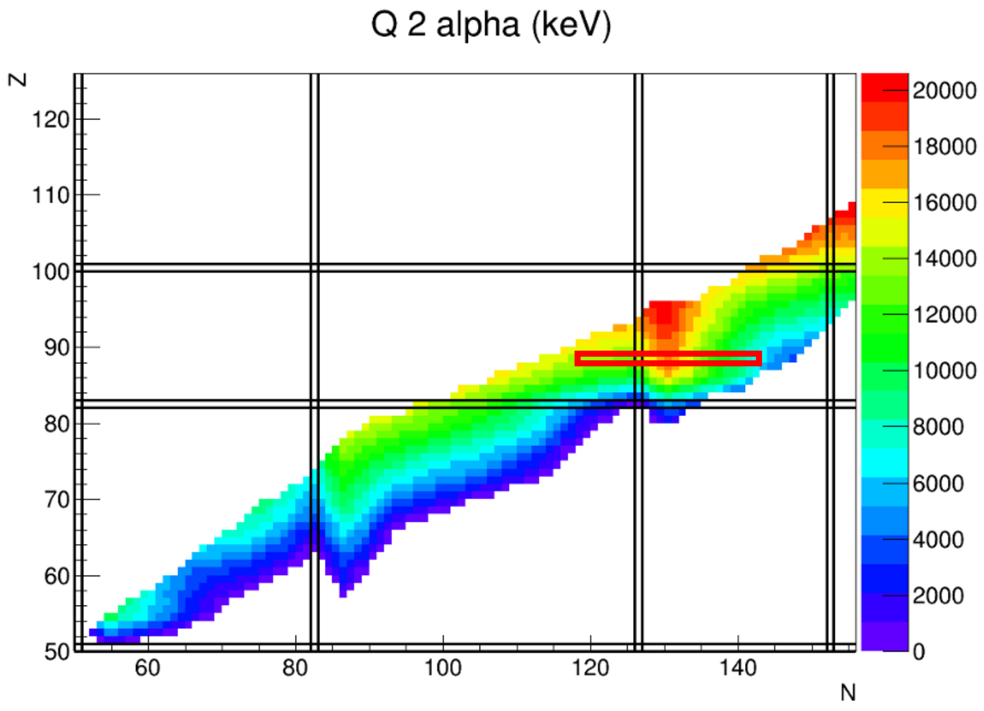
A novel system has been developed to detect simultaneous double-alpha emission from purified and weightless sources. The system includes the collection of ^{224}Ra low-energy recoils in purified helium buffer gas from the decay of ^{228}Th. The recoil products are thermalized and collected in a cryogenic buffer gas cell and extracted into an RF-ion guide for mass selection. The mass-separated ions are implanted at low kinetic energy into a thin carbon foil placed between two large-area double-sided silicon strip detectors to observe correlated alpha-particle emission. The apparatus is described in detail, including insights into its experimental performance.

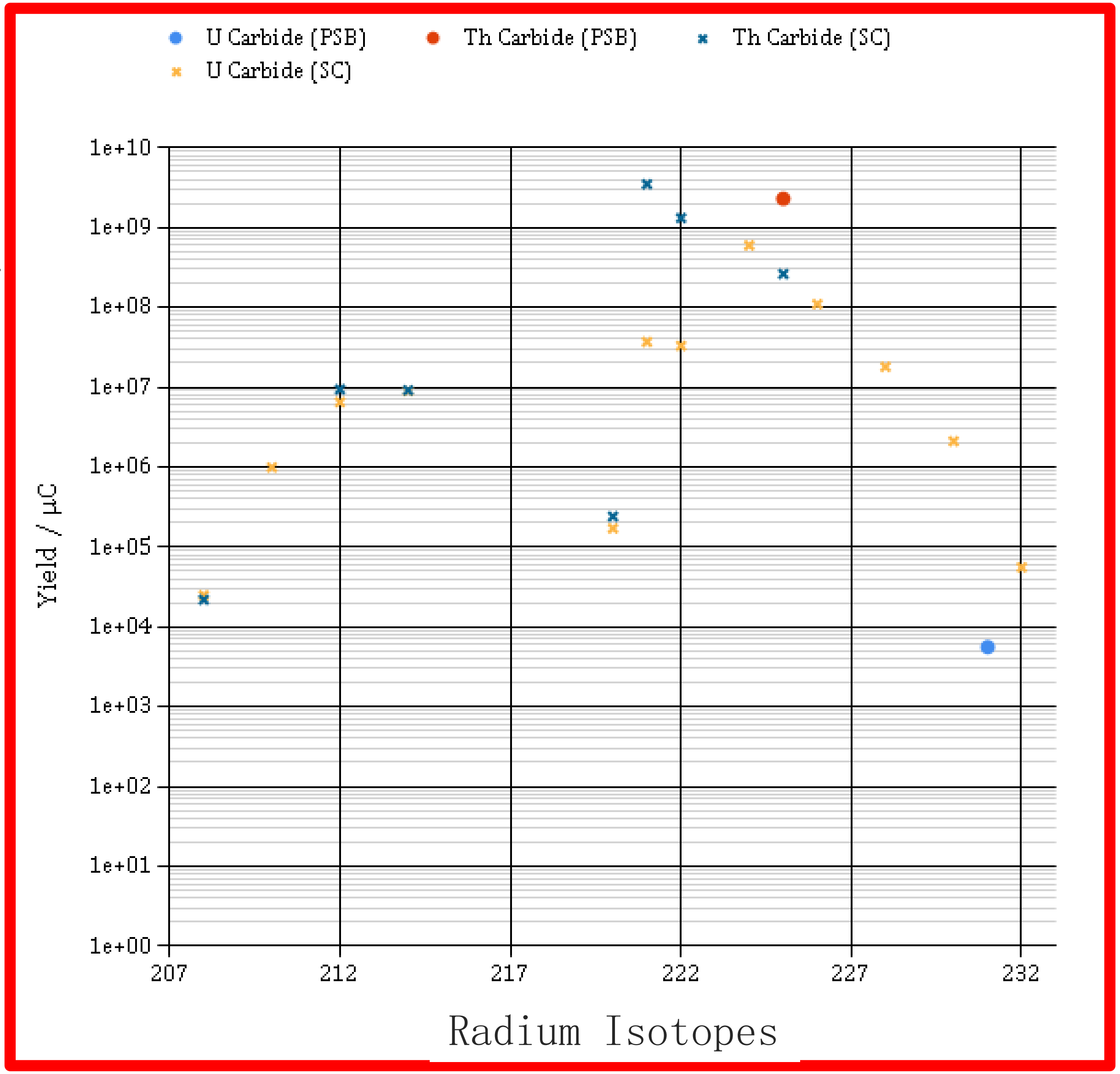
Keywords: double-alpha decay, 224-Ra, cryogenic stopping cell, DSSD, exotic radioactive decay modes

Submitted to NIMA

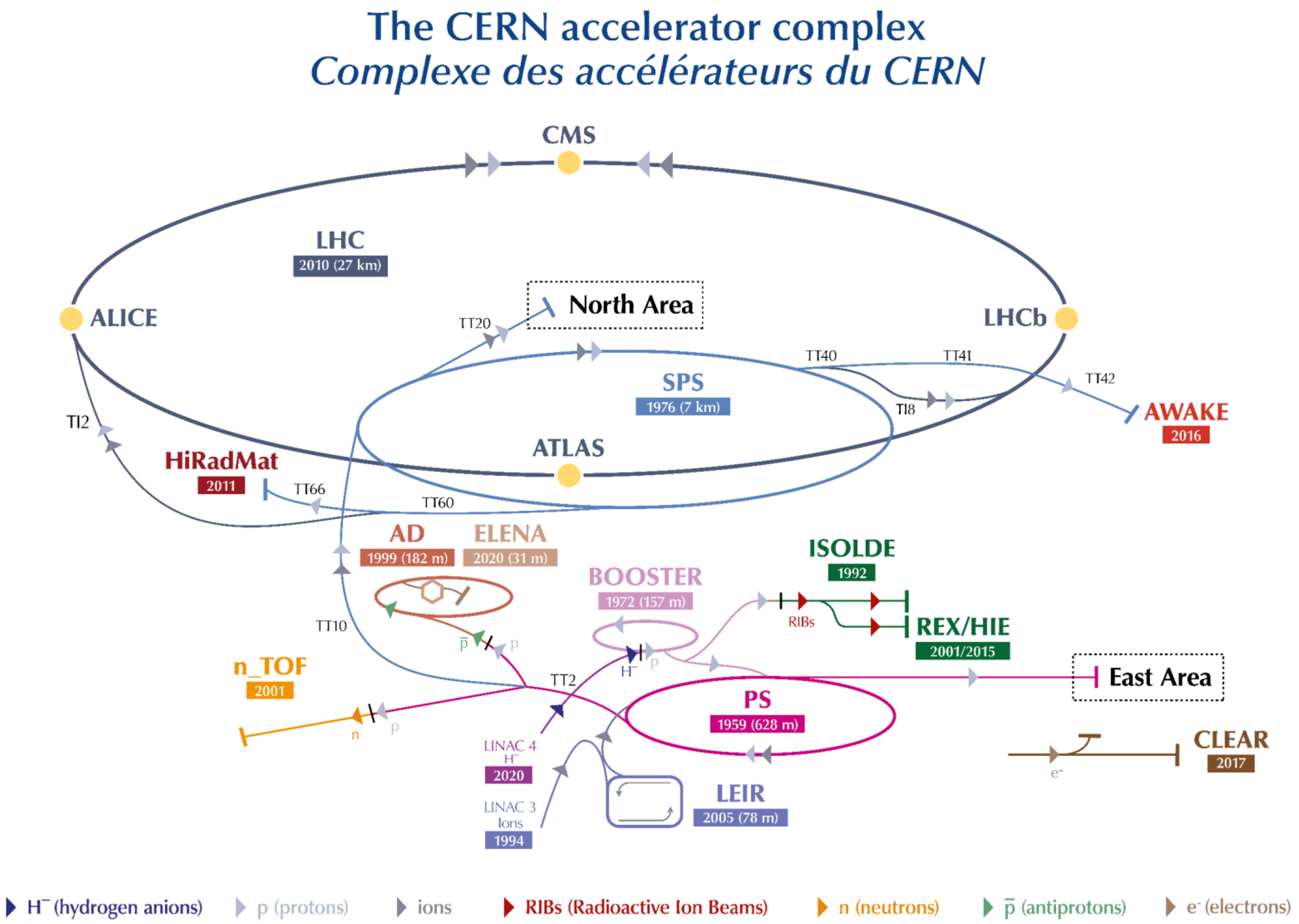
Isolde experiment : why ?

- A wide range of available isotope
- Spallation reactions. Protons 1.4 GeV on various target
- Low energy beam 30-60 keV : perfect for implantation in a catcher
- Option molecular beams to avoid isobar contamination

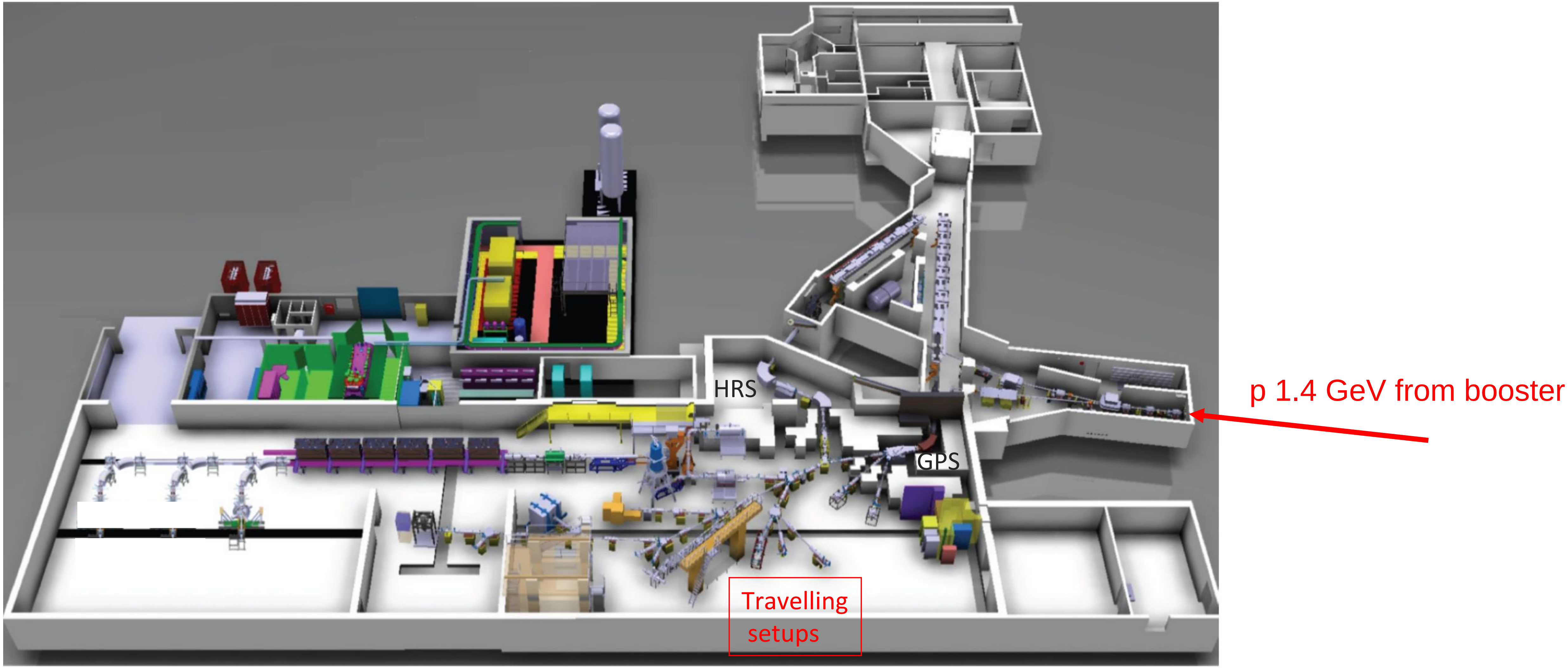


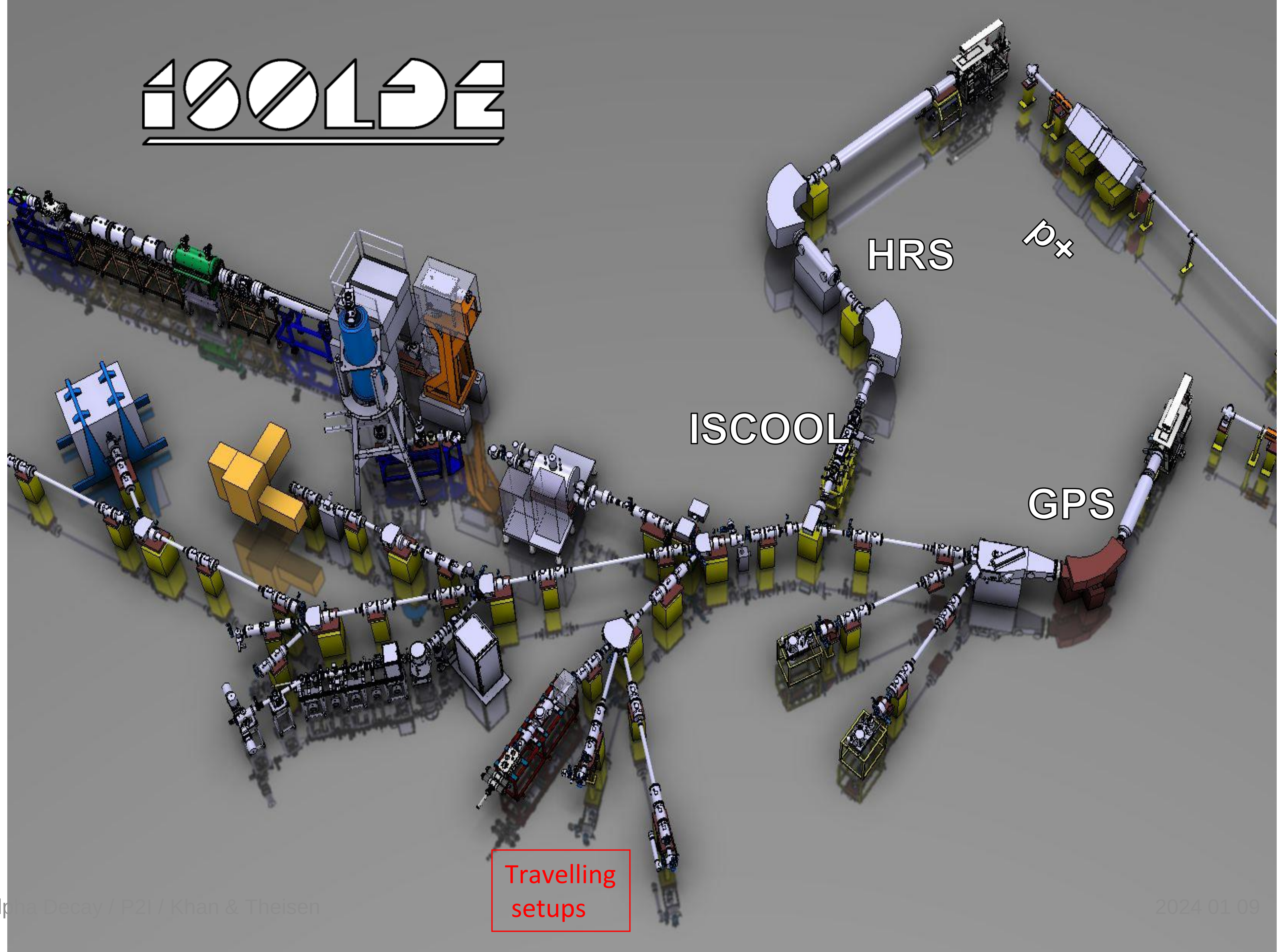


What is Isolde ?



Isolde




ISOLDE
HRS
p+
ISCOOL
GPS
Travelling setups

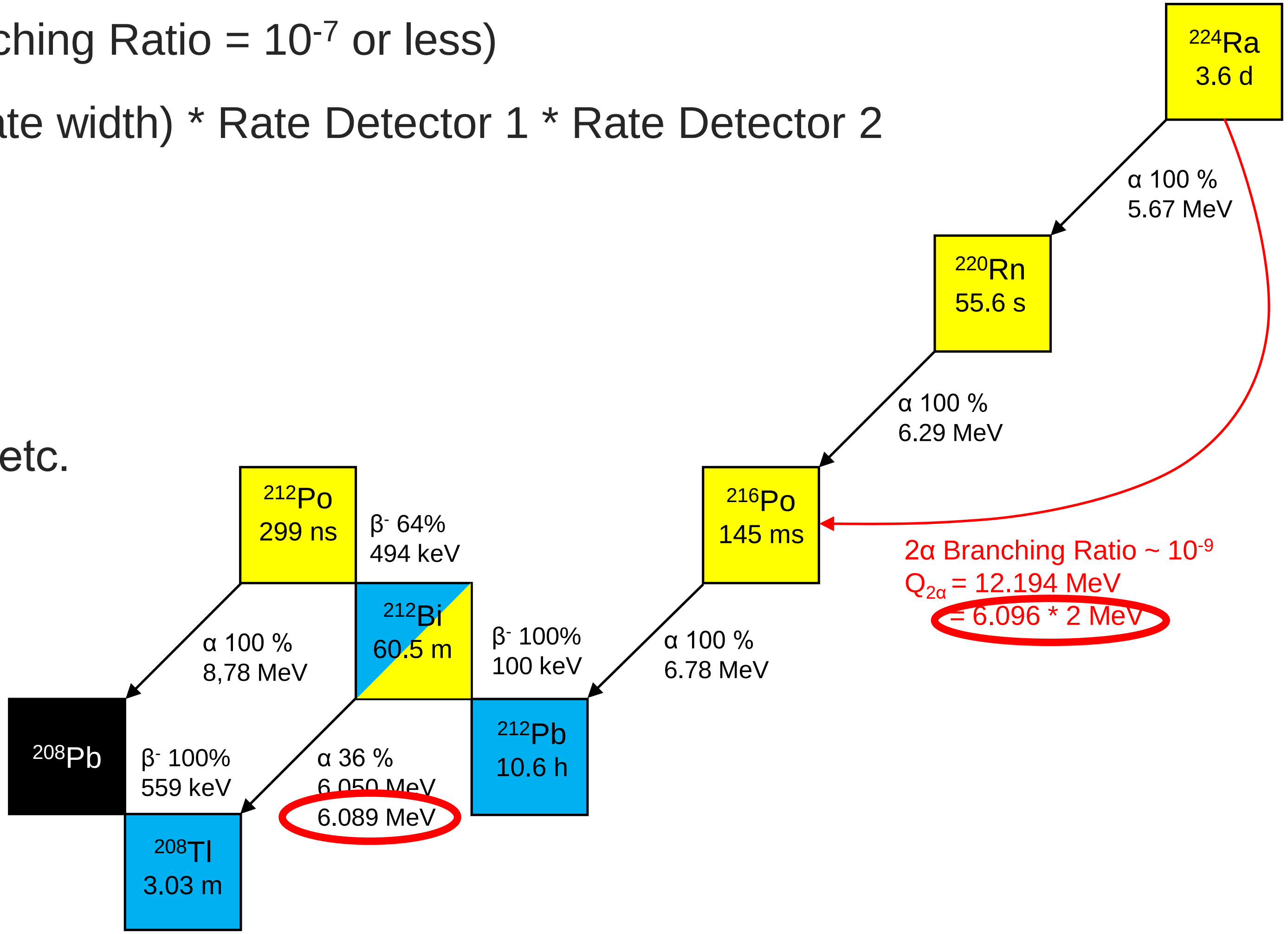
Which beam ?
Random coincidences and contamination

- Random coincidence (remember low Branching Ratio = 10^{-7} or less)

  Random coincidence rate = 2 ΔT (gate width) * Rate Detector 1 * Rate Detector 2

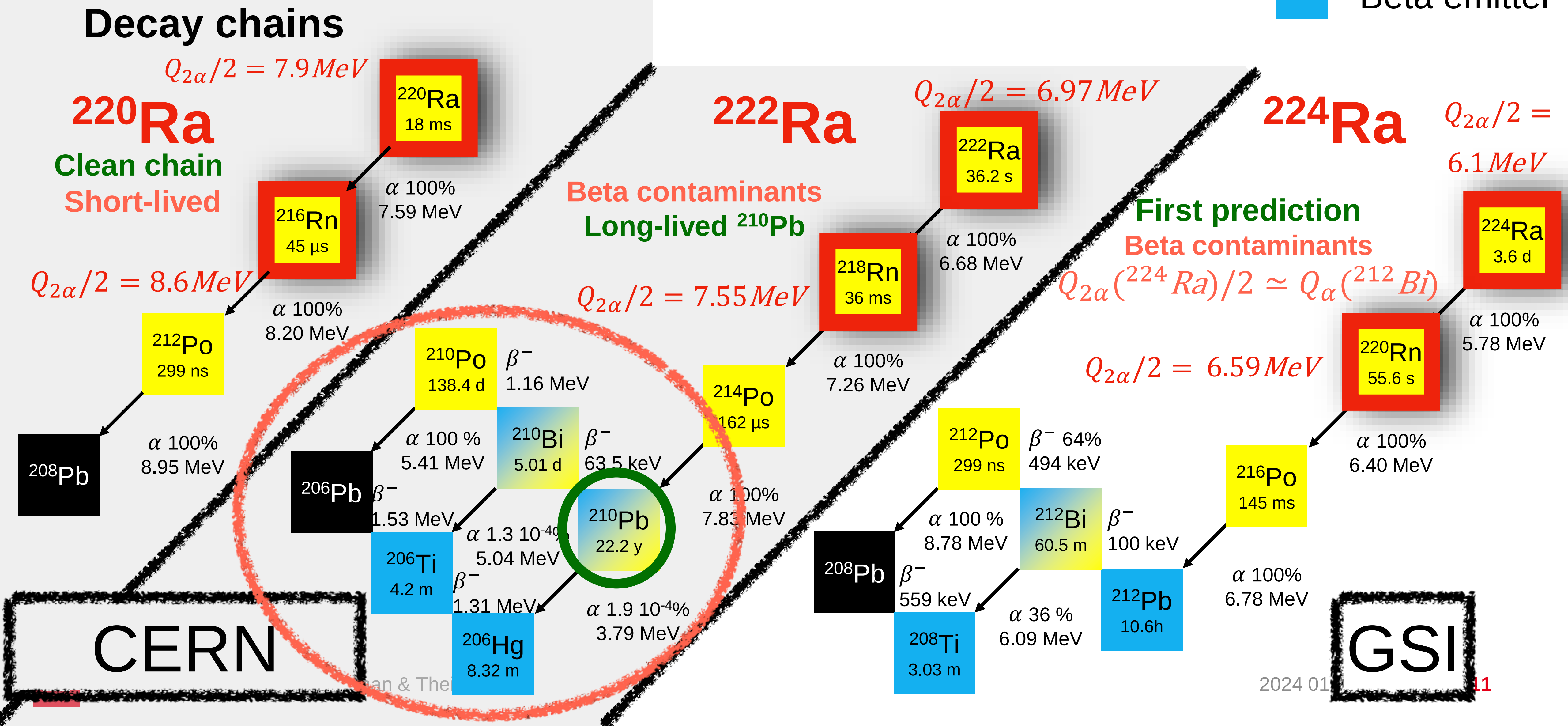
- Contamination in the region of interest

→ choice of the decay chain, beam intensity, etc.



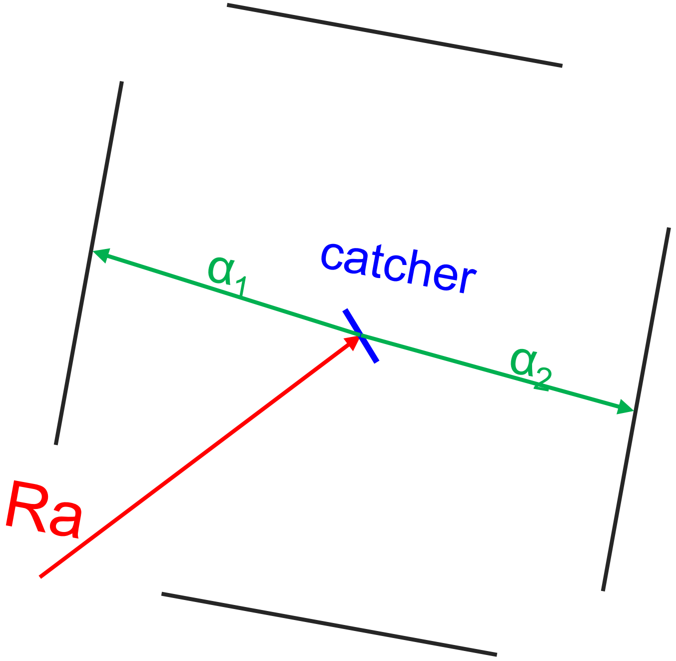
Which isotope ?

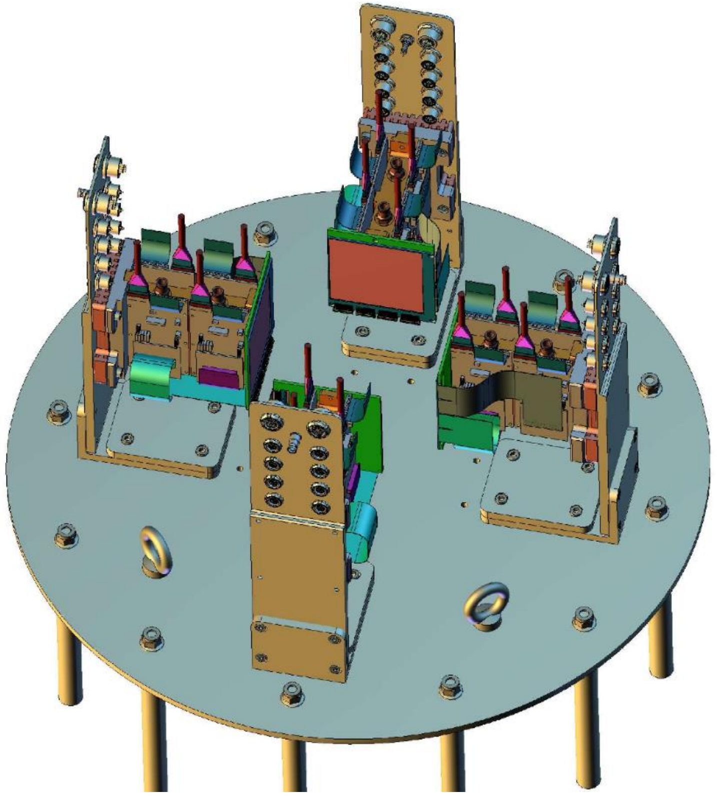
2α candidate
Alpha emitter
Beta emitter

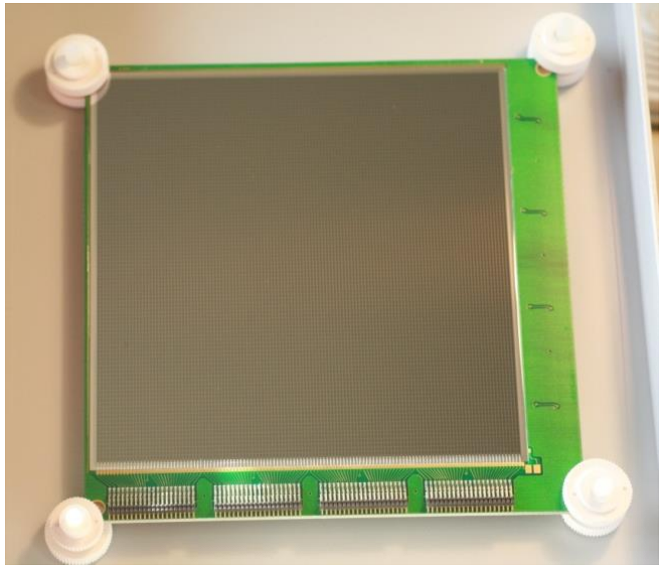


First experiment at Isolde : the setup

Array also sensitive to asymmetric double alpha decay







DSSD 10x10 cm^2, 128 (X) + 128 (Y) strips
MUSETT array

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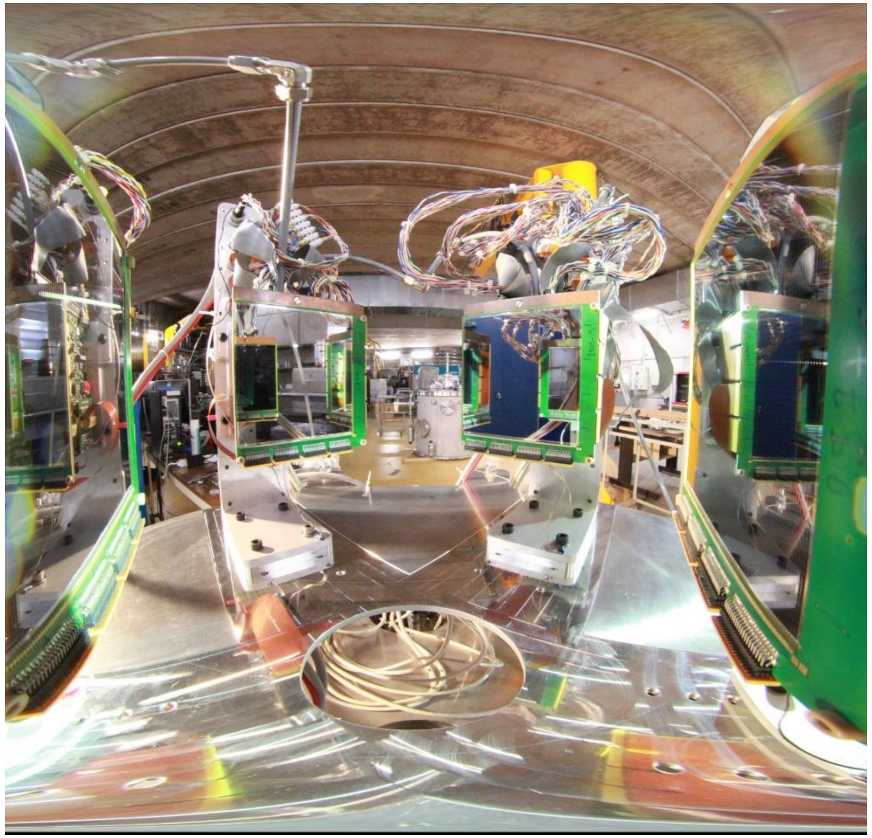
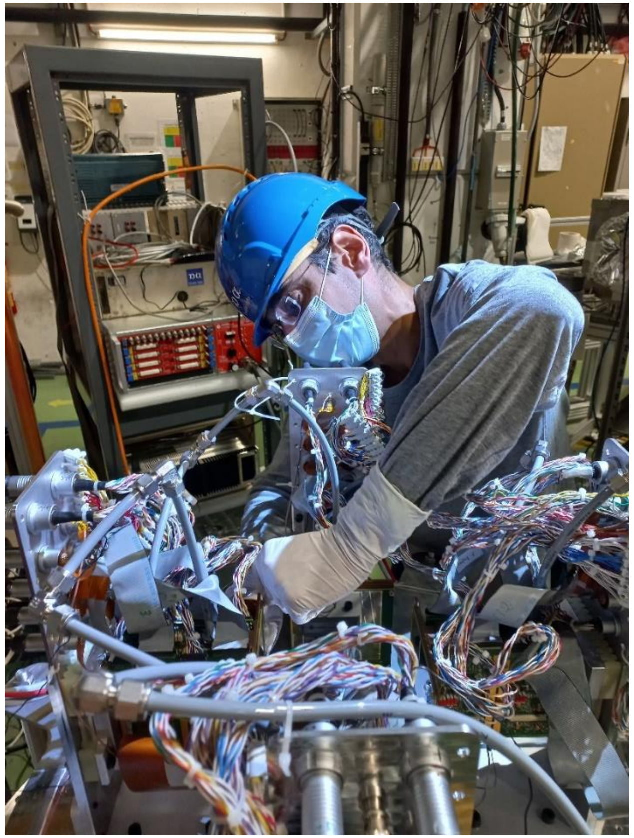
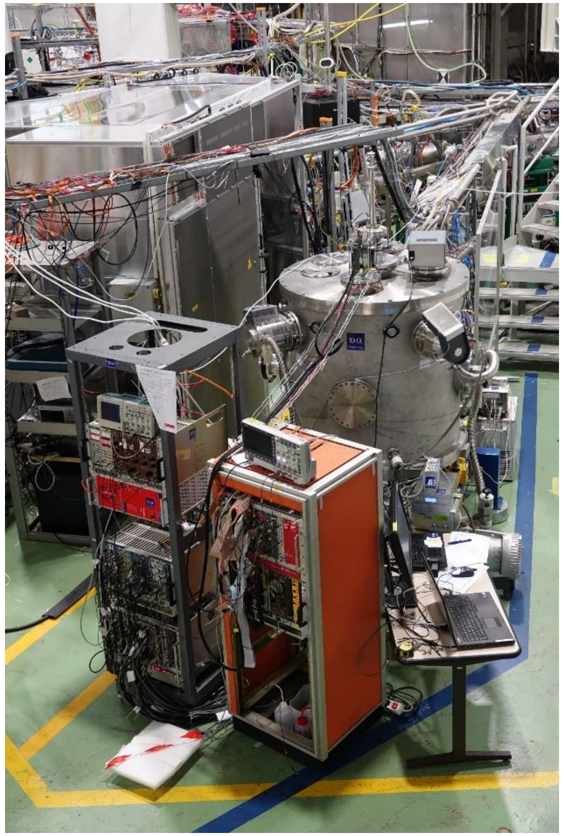
Double alpha @ Isolde



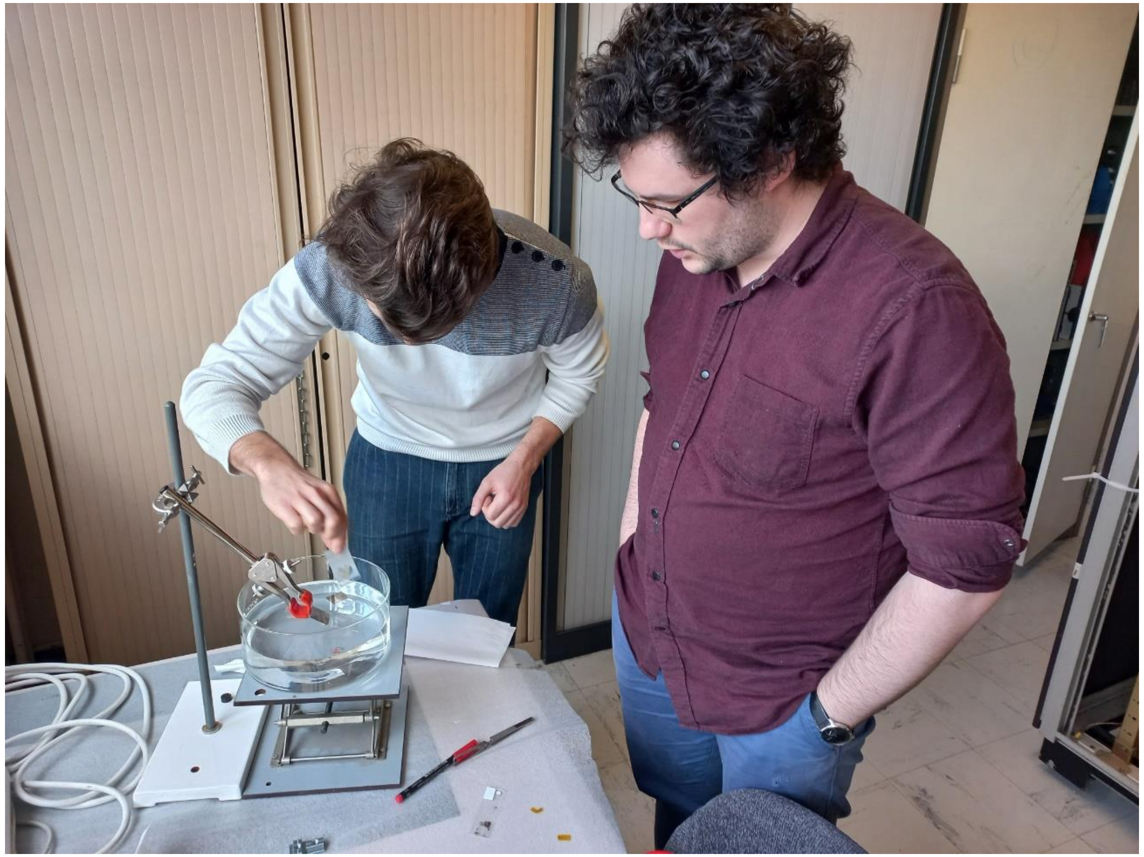


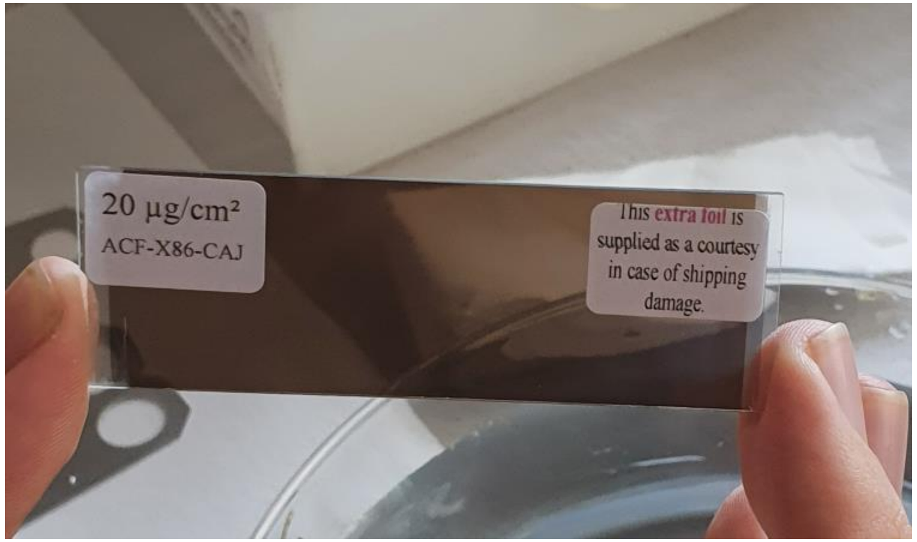


+ pumping 2 turbo + 2 dry
+ cooling for detectors and electronics

+ DSSD detector at 0 deg for beam alignment
+ HV, LV, electronics for 1024 + 32 channels
+ DAQ, online monitoring, etc.

Catchers





C 20 µg/cm^2 (90 nm) ACF metal on a glass support detached by floating in water
C foils from SEASON

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First experiment at Isolde

Tuesday **June 20th**	Wednesday	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday **June 30th**
Technical stop	**Technical stop**	**^{222}Ra**	**^{222}Ra**	**^{222}Ra**	**^{222}Ra**	**^{222}Ra / ^{220}Ra**	**CERN blackout**	**^{220}Ra**	**^{220}Ra**

Use of hot GPS target to produce ^{218}Rn

Less beam time than expected due to CERN technical shutdown and Cern blackout

~4 days ^{222}Ra ~2.10^{10} implanted + ~2 days ^{220}Ra ~ 2.10^{8} implanted + 2 days ^{218}Rn ~3.10^{9} implanted

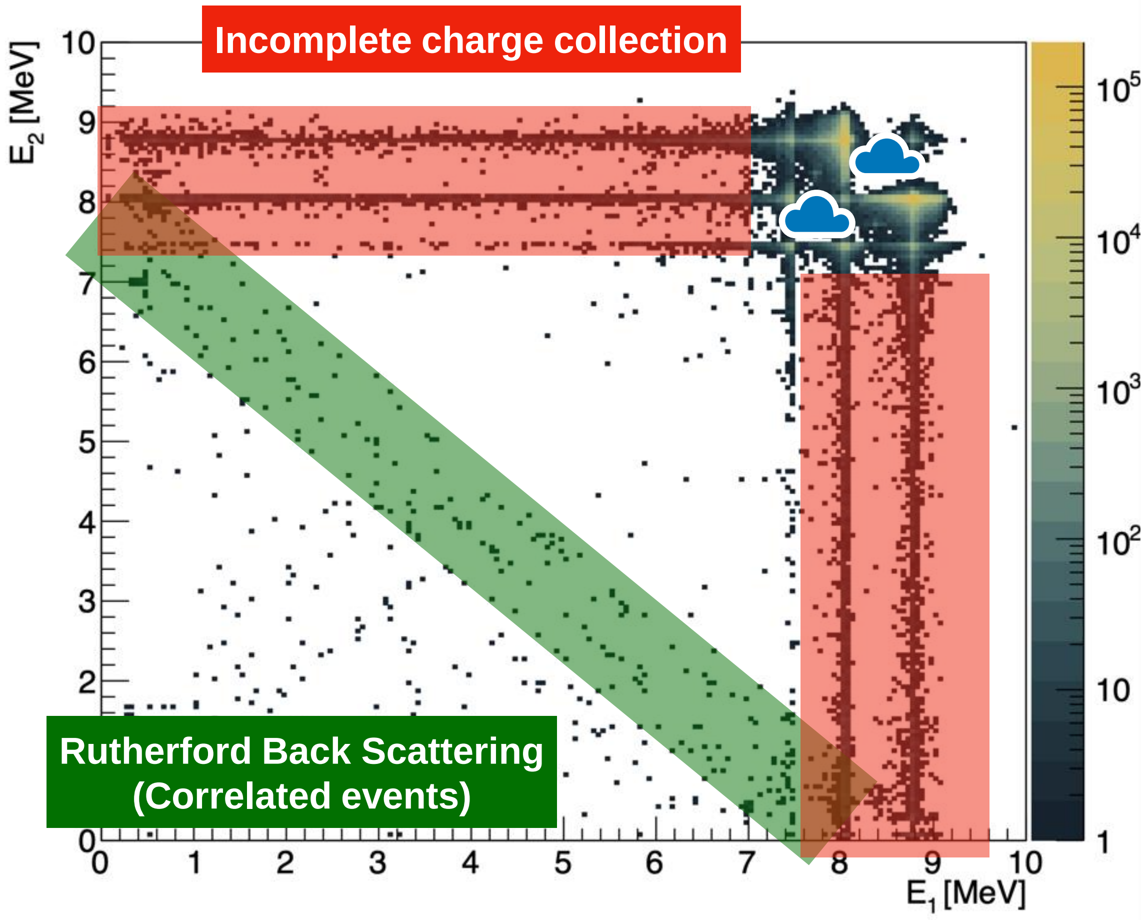
Unexpected beam contamination

Problem tuning beam position and spot size

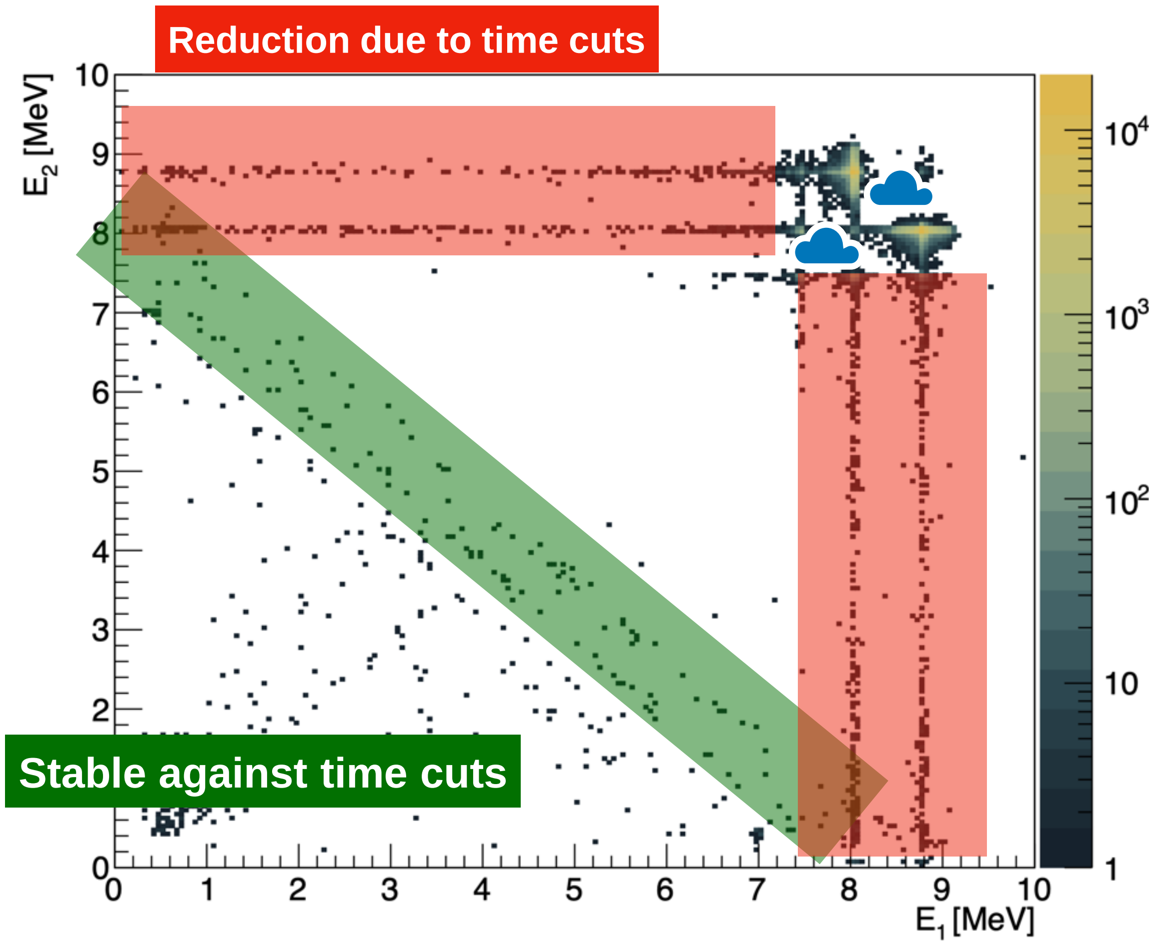
Overall good data quality

Analysis in progress

^{220}Ra alpha-alpha coincidences [PRELIMINARY]



Without time cut



With time cut $\Delta T < 20$ ns

P2I grant and continuation

P2I Grant 41 k€

→Transport (from/to ISOLDE/GANIL/SACLAY)

→ Pumping unit (Chamber and pumping were borrowed from GANIL & WISArD collaboration)

→ Cable and electronics maintenance

→ DAQ maintenance

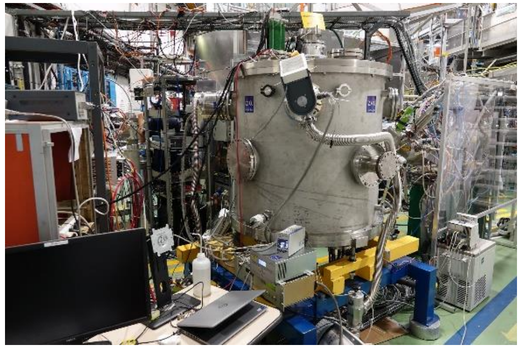
Beyond P2I

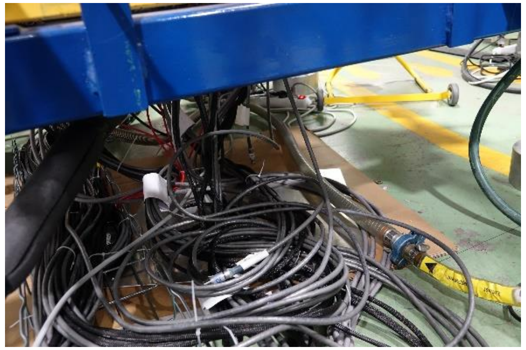
→ New target loader

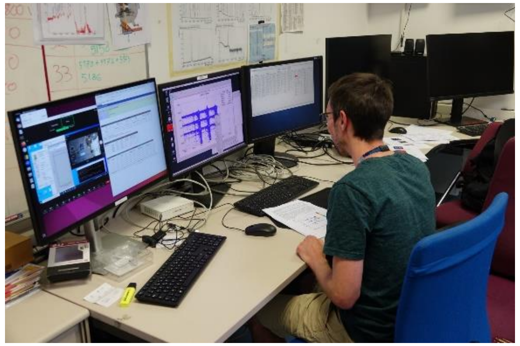
→ improved beam diagnostic e.g. MCP

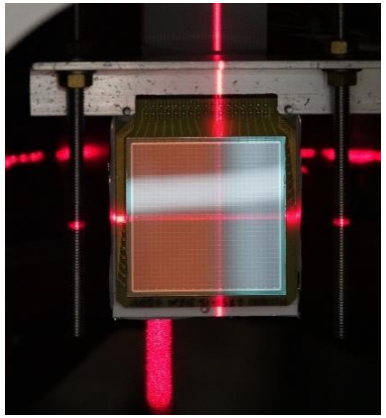
-> reasonably sized chamber

→ digital electronics (long term)









Isolde experiment

An experiment prepared rapidly to answer a burning physics question

Setup built in ~ 1 year

Most of the setup made from existing or borrowed hardware

Smooth and versatile beam conditions

Data collected on ^{222}Ra (more than expected), ^{220}Ra (less than expected but super clean), ^{218}Rn (not foreseen)

Good on-line data quality

Experiment technically successful

Some improvements to be done : beam purity, beam diagnostic and alignment, DAQ and electronics maintenance, pumping

8 UTs remaining

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This project has received funding from the European Union's Horizon Europe Research and Innovation programme under Grant Agreement N°101057511

GSI-IN2P3-DRF collaboration agreement : grants 23-90 IN2P3-GSI (Khan, Dickel) and 23-91 CEA-GSI (Theisen, Dickel) for travel to/from GSI

P2I grant « Projets P2I 2023 »

Fin