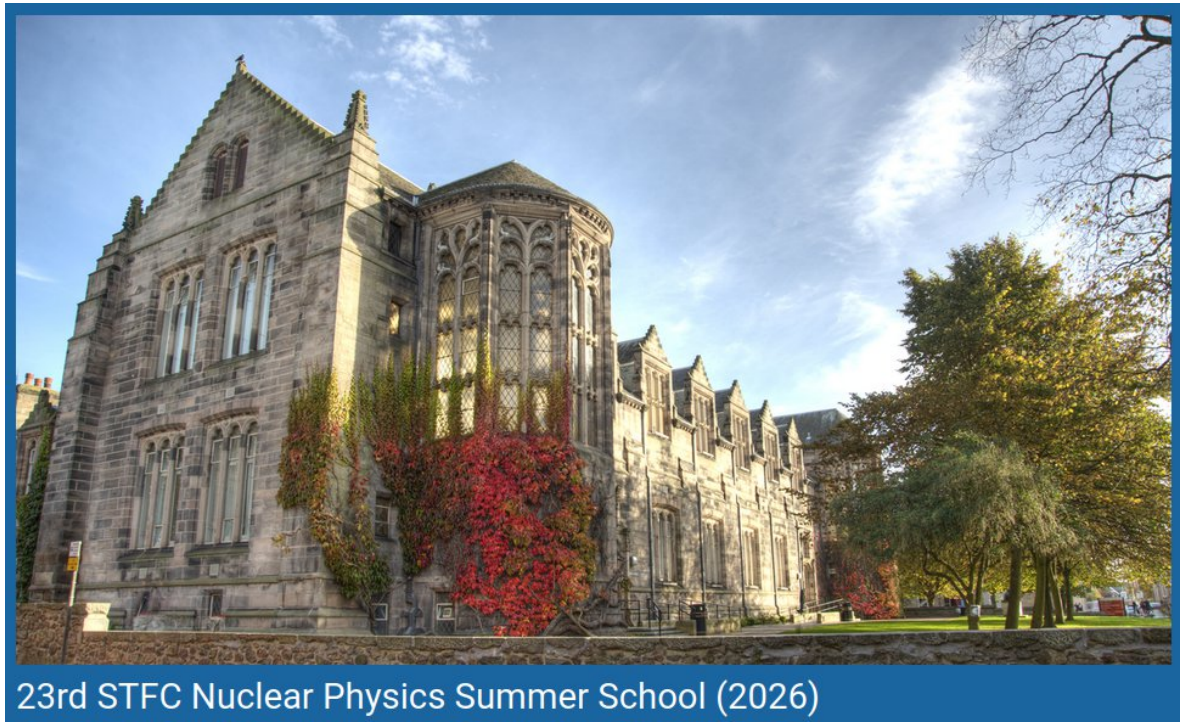


New and future nuclear research facilities

Helena May Albers
GSI/FAIR
h.albers@gsi.de

July 26th - August 8th 2026

University of Aberdeen, Scotland

Overview:

L1: Introduction
- RIB production
  - ISOL and in-flight fragmentation
  - Primary beams
- Next generation separators
- Importance of instrumentation

L2:
- In-flight fragmentation in
  - North America
  - Asia
  - Europe
- (plus some other highlights)

Some additional reading:

- Khasanov *et al.*, Major radioactive ion beam facilities: a brief global overview, Eur. Phys. J Plus 140 (2025) 638
- H. Watenabe *et al.*, Nuclear decay studies of rare isotopes, Eur. Phys. J. A (2019) 55: 19, DOI 10.1140/epja/i2019-12677-6
- Y. Blumenfeld, T. Nilsson and P. Van Duppen, Facilities and methods for radioactive ion beam production, Phys. Scr. T152 (2013) 014023
- G. Savard *et al.*, CARIBU: a new facility for the study of neutron-rich isotopes, Hyperfine Interact (2011) 199:301–309
- S. Akkoyun *et al.*, AGATA—Advanced GAmma Tracking Array, NIM A 668 (2012), 26-58
- Philip Walker and Zsolt Podolyák, 100 years of nuclear isomers—then and now, Phys. Scr. 95 (2020) 044004 (11pp)
- H. Schatz, Trends in nuclear astrophysics, J. Phys. G: Nucl. Part. Phys. 43 (2016) 064001
- L. Fraile *et al.*, Advanced scintillators for fast-timing applications, NIM B 463 (2020) 394–397
- M.R. Mumpower *et al.*, The impact of individual nuclear properties on r-processnucleosynthesis, Progress in Particle and Nuclear Physics 86 (2016) 86–126
- T. Marchi et al., The SPES facility at Legnaro National Laboratories, J. Phys.: Conf. Ser. 1643 (2020) 012036

About me

Staff scientist at the **Gesellschaft für Schwerionenforschung** (or, just GSI).

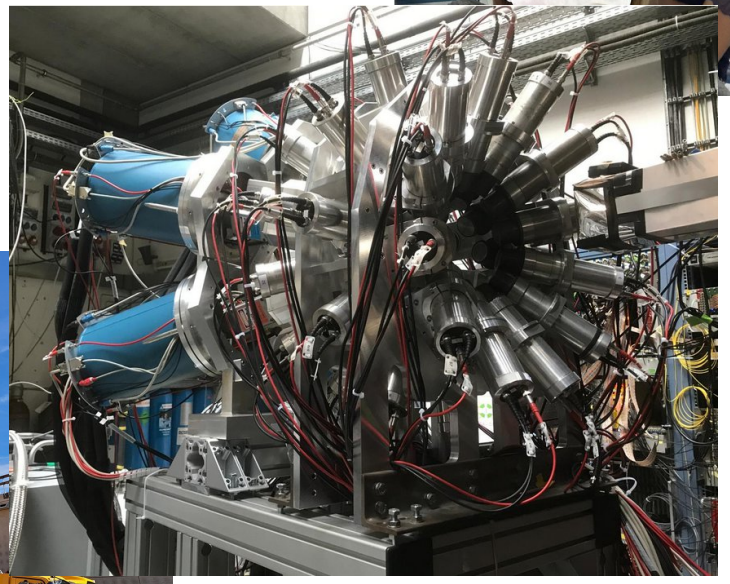
Masters in Mathematics (with Physics) from **Durham University**, followed by a year working at the **DSTL**.

PhD in Nuclear Physics from the **University of Edinburgh** 2009-2013 (N~Z, A~60 nuclei).

Postdoc at **Argonne National Lab (ANL)** 2014-2015 (GRETINA, GAMMASPHERE, FMA).

Postdoc at **GSI in SHE chemistry group** 2015-2019 (reaction mechanisms for SHE formation).

2019-today in **Nuclear Spectroscopy Group**, **Project Lead for NUSTAR** and **Group Leader for NUSTAR Experiment Coordination**



23rd STFC Nuclear Phy

July 26, 2026 to August 8, 2026

Europe/London timezone

Aside...

1. Associative learning (or, learning by association)
   - Visual association

1. Repetition repetition repetition ...

1. Write it down!

23rd STFC Nuclear Physics Summer School (2026)

July 26, 2026 to August 8, 2026

Europe/London timezone

NewScientist

Sign in | Enter search keywords

News Features Newsletters Podcasts Video Comment Culture Crosswords | This week's magazine

Health Space Physics Technology Environment Mind Humans Life Mathematics Chemistry Earth Society

Mind

Writing things down may help you remember information more than typing

Writing words down increases connectivity linked to memory and learning between different areas of the brain, with the same not being true when things are typed out on a computer

By Chen Ly

26 January 2024

What topics will be covered?

facility

noun

UK /fəˈsɪl.ə.ti/ US /fəˈsɪl.ə.ţi/

facility *noun* **(BUILDING)**

Add to word list

B1 [C]

a place, especially including buildings, where a particular activity happens:

- *a nuclear research facility*
- *a military facility*
- *a new sports facility*

facilities

phrase [plural]

Add to word list

B1

the buildings, equipment, and services provided for a particular purpose:

- *shopping facilities*
- *medical facilities*
- *sports facilities*

the facilities

phrase

[plural]

a polite way of referring to a toilet in a public place:

- **use the facilities** *There is no running water in the annex, so students have to go over to the main buildings to use the facilities.*

https://dictionary.cambridge.org

23rd STFC Nuclear Physics Summer School (2026)

July 26, 2026 to August 8, 2026

Europe/London timezone

The important questions

How can the nuclei be produced?

Which beam species? Stable or radioactive?

How many do I need for statistical significance?

Are the right states populated?

Do the ions need to be reaccelerated? Or slowed down?

What do I want to study?
(shell evolution, exotic decays, nuclear shapes,...)

Are appropriate targets available?

Are the nuclei short-lived?

Do I have the right instrumentation?

Do I need separation? Or identification? Or both?

How long do I need to measure?

What level of cleanliness is required?

The important questions

How can the nuclei be produced?

Which beam species? Stable or radioactive?

How many do I need for statistical significance?

Are the right states populated?

Do the ions need to be reaccelerated? Or slowed down?

What do I want to study?
(shell evolution, exotic decays, nuclear shapes,...)

Are appropriate targets available?

Is the right expertise available?

Are the nuclei short-lived?

Do I have the right instrumentation?

Do I need separation? Or identification? Or both?

How long do I need to measure?

What level of cleanliness is required?

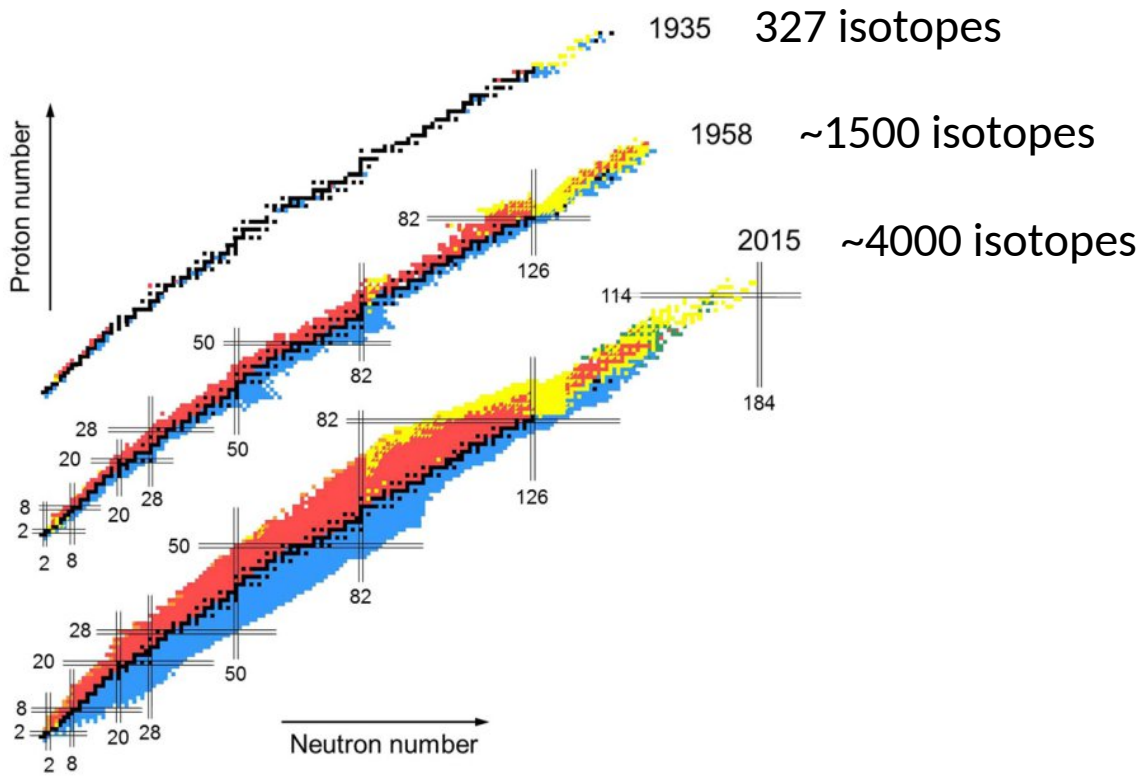
23rd STFC Nuclear Physics Summer School (2026)

July 26, 2026 to August 8, 2026

Europe/London timezone

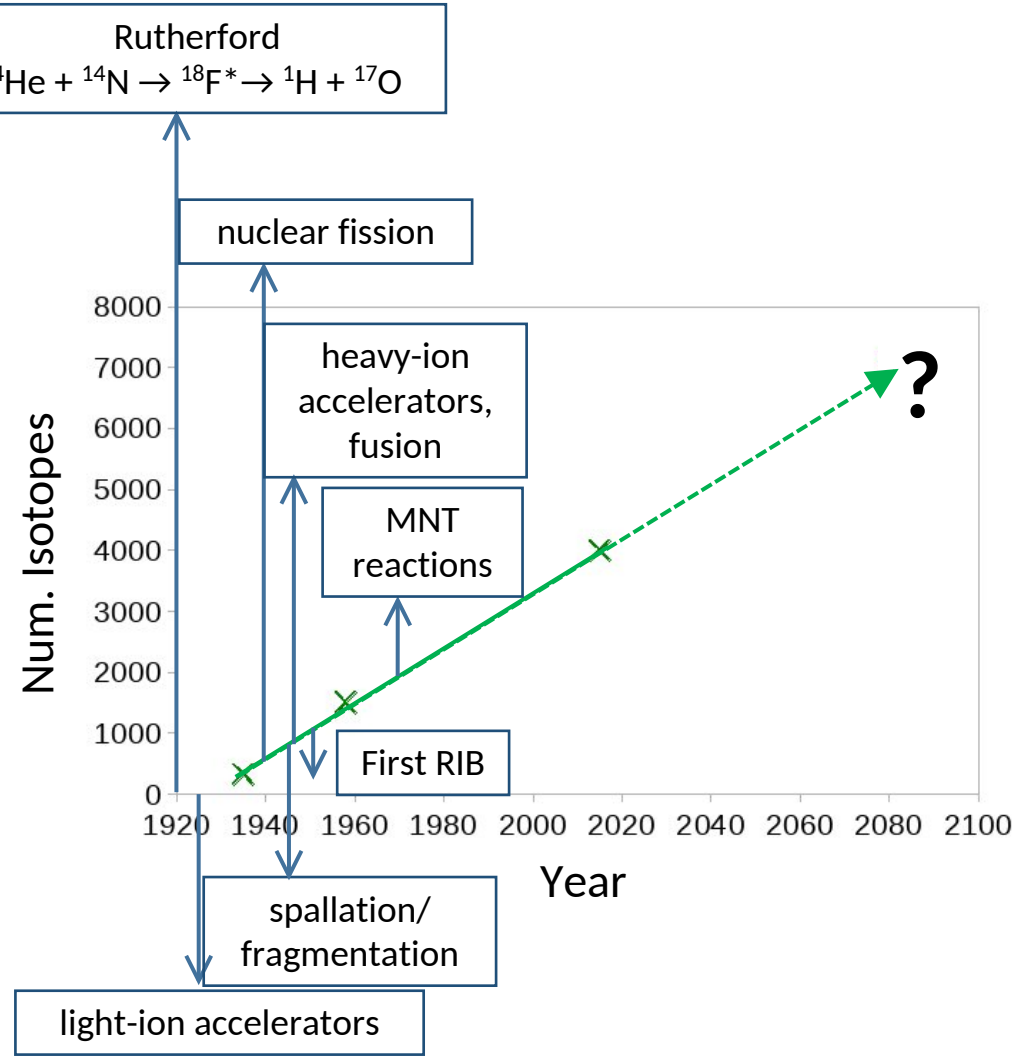
Why do we need new facilities?
How are (exotic) nuclei produced?

- Past ~century - about 4000 isotopes discovered, 118 chemical elements
- Most undiscovered territory on the **neutron-rich side**



Modified from Adamian *et al.*, Eur. Phys. J. A (2020) 56:47

first artificially-induced nuclear reaction!



Example: Nuclear physics data for astrophysical processes

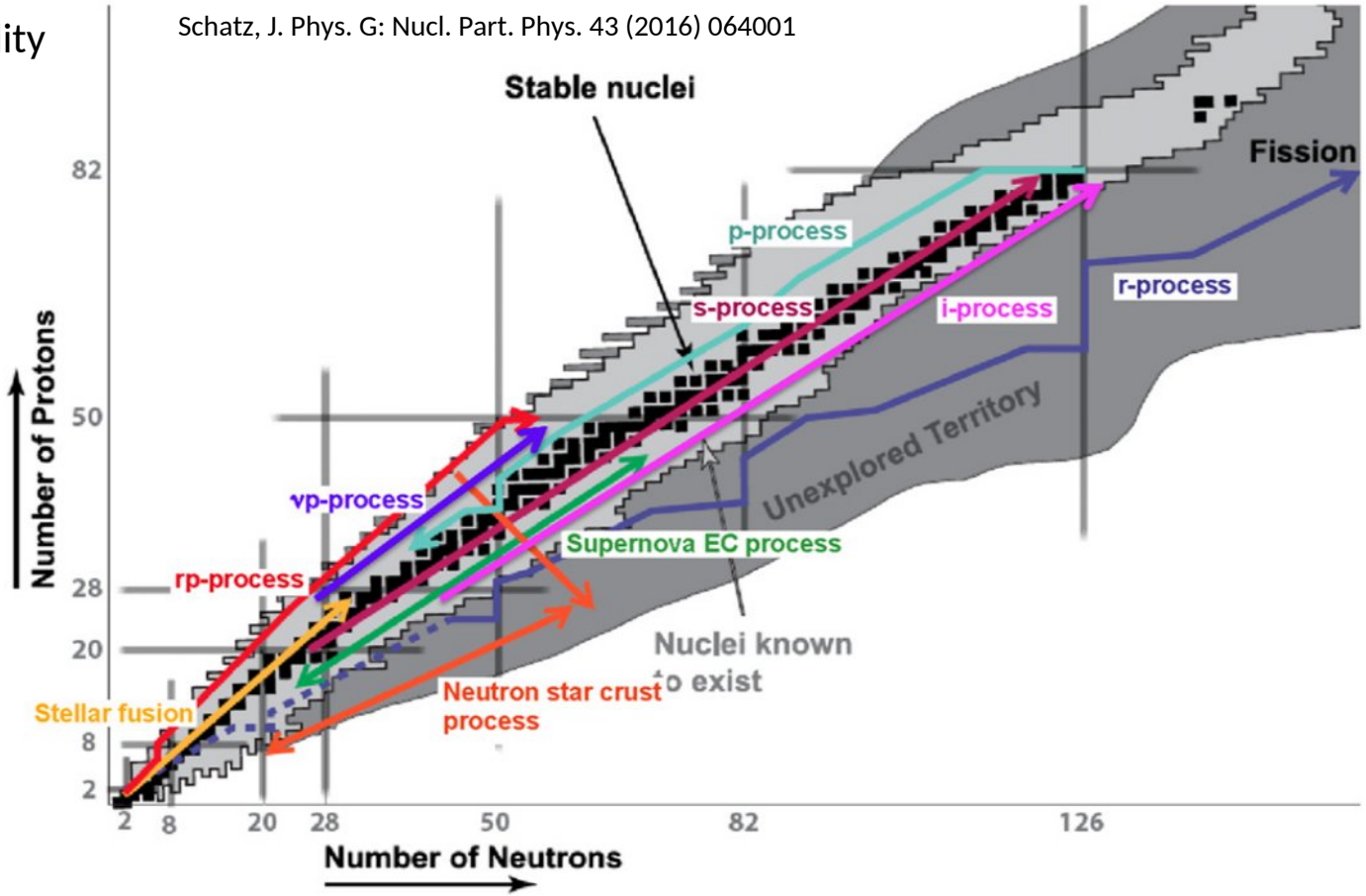
…typically, half-lives get shorter when moving away from stability

208Pb STABLE 52.4%	209Pb 3.235 h β⁻=100%	210Pb 22.2 y β⁻=100% α=1.9e-6%	211Pb 36.165 min β⁻=100%	212Pb 10.628 h β⁻=100%	213Pb 10.2 min β⁻=100%	214Pb 27.06 min β⁻=100%	215Pb 142 s β⁻=100%
207Tl 4.77 min β⁻=100%	208Tl 3.053 min β⁻=100%	209Tl 2.162 min β⁻=100%	210Tl 1.3 min β⁻=100% β⁻n=0.007%	211Tl 79.6 s β⁻=100% β⁻n=2.2%	212Tl 30.9 s β⁻=100% β⁻n=1.8%	213Tl 23.8 s β⁻=100% β⁻n=7.6%	214Tl 11 s β⁻=100% β⁻n=34%
206Hg 8.32 min β⁻=100%	207Hg 2.9 min β⁻=100%	208Hg 135 s β⁻=100%	209Hg 6.3 s β⁻=100%	210Hg 63.7 s β⁻=100% β⁻n=2.2%	211Hg 26.4 s β⁻=100% β⁻n=6.3%	212Hg β⁻=100% β⁻n ?	213Hg β⁻=100% β⁻n ?
205Au 32 s β⁻=100%	206Au 47 s β⁻=100%	207Au β⁻=100% β⁻n ?	208Au β⁻=100% β⁻n ?	209Au β⁻=100% β⁻n ?	210Au β⁻=100% β⁻n ?		
204Pt 10.7 s β⁻=100%	205Pt β⁻=100%	206Pt β⁻=100% β⁻n ?	207Pt β⁻=100% β⁻n ?	208Pt β⁻=100% β⁻n ?			
203Ir β⁻=100%	204Ir β⁻=100% β⁻n ?	205Ir β⁻=100% β⁻n ?					

Seconds
>10+15 10-01
10+10 10-02
10+07 10-03
10+05 10-04
10+04 10-05
10+03 10-06
10+02 10-07
10+01 10-15
10+00 <10-15
Unknown

https://www.nndc.bnl.gov/

Schatz, J. Phys. G: Nucl. Part. Phys. 43 (2016) 064001



- Nuclear physics data ***across the nuclear chart*** are critical for the understanding of stellar processes
- Vast areas remain ***undetermined***

-> State-of-the-art techniques and ***new facilities!***

And what about reactions?

23rd STFC Nuclear Physics Summer School (2026)

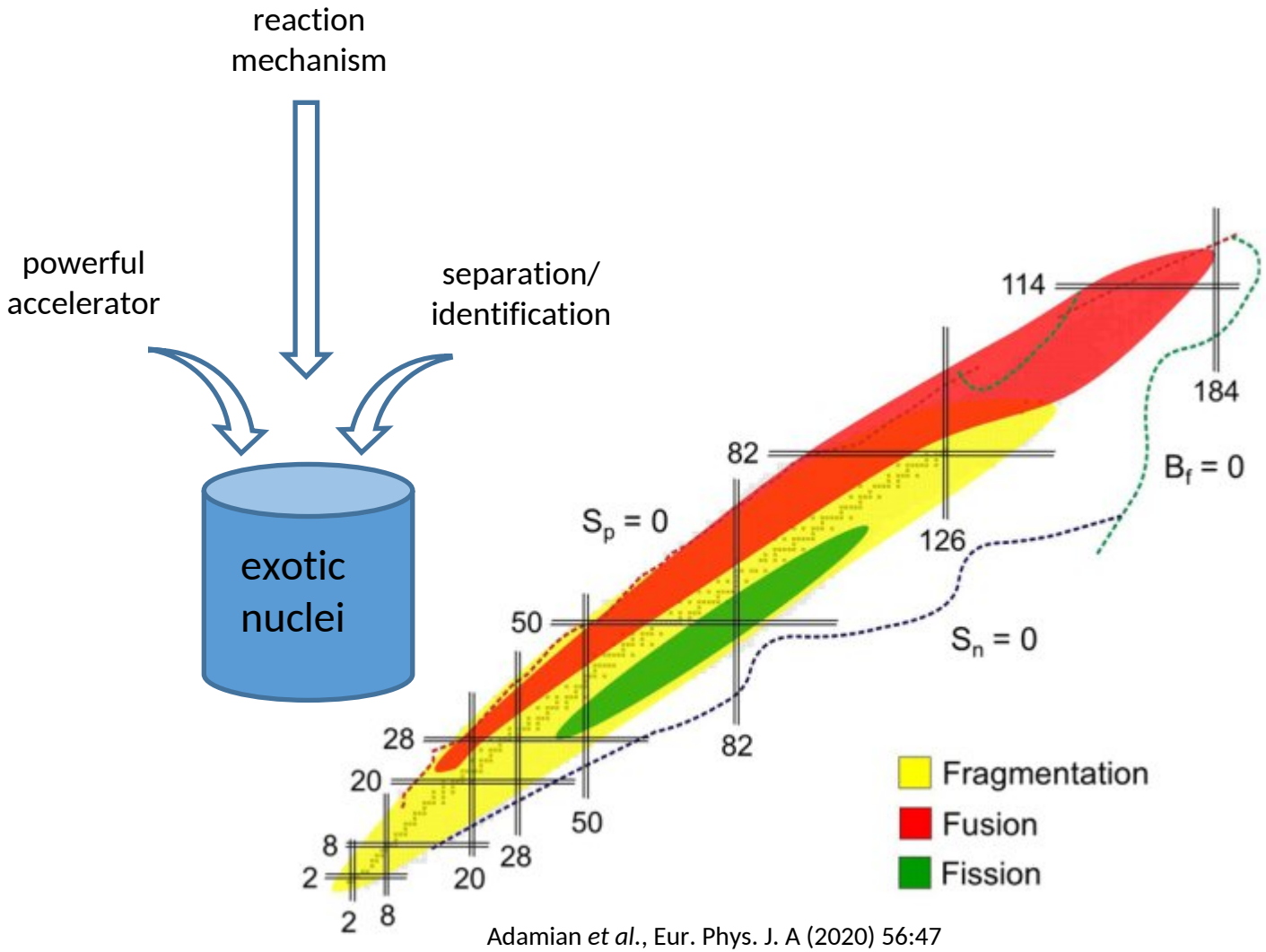
July 26, 2026 to August 8, 2026

Europe/London timezone

Reaction mechanisms

Sources	Excited states after nuclear disintegration
Coulex (Coulomb excitation)	EM excitation, stable beams or RIBs
Fusion-evaporation reactions	Neutron-deficient nuclei, high-spin states
Fusion-fission reactions	Neutron-rich nuclei
Direct reactions	Removal or pickup e.g. (d,p), (p,d)…
MNT (multi-nucleon transfer)	More exotic, neutron-rich nuclei
Fragmentation	Very exotic nuclei, RIBs

How to reach (very) exotic nuclei - Radioactive Ion Beams (RIBs)



Adamian *et al.*, Eur. Phys. J. A (2020) 56:47

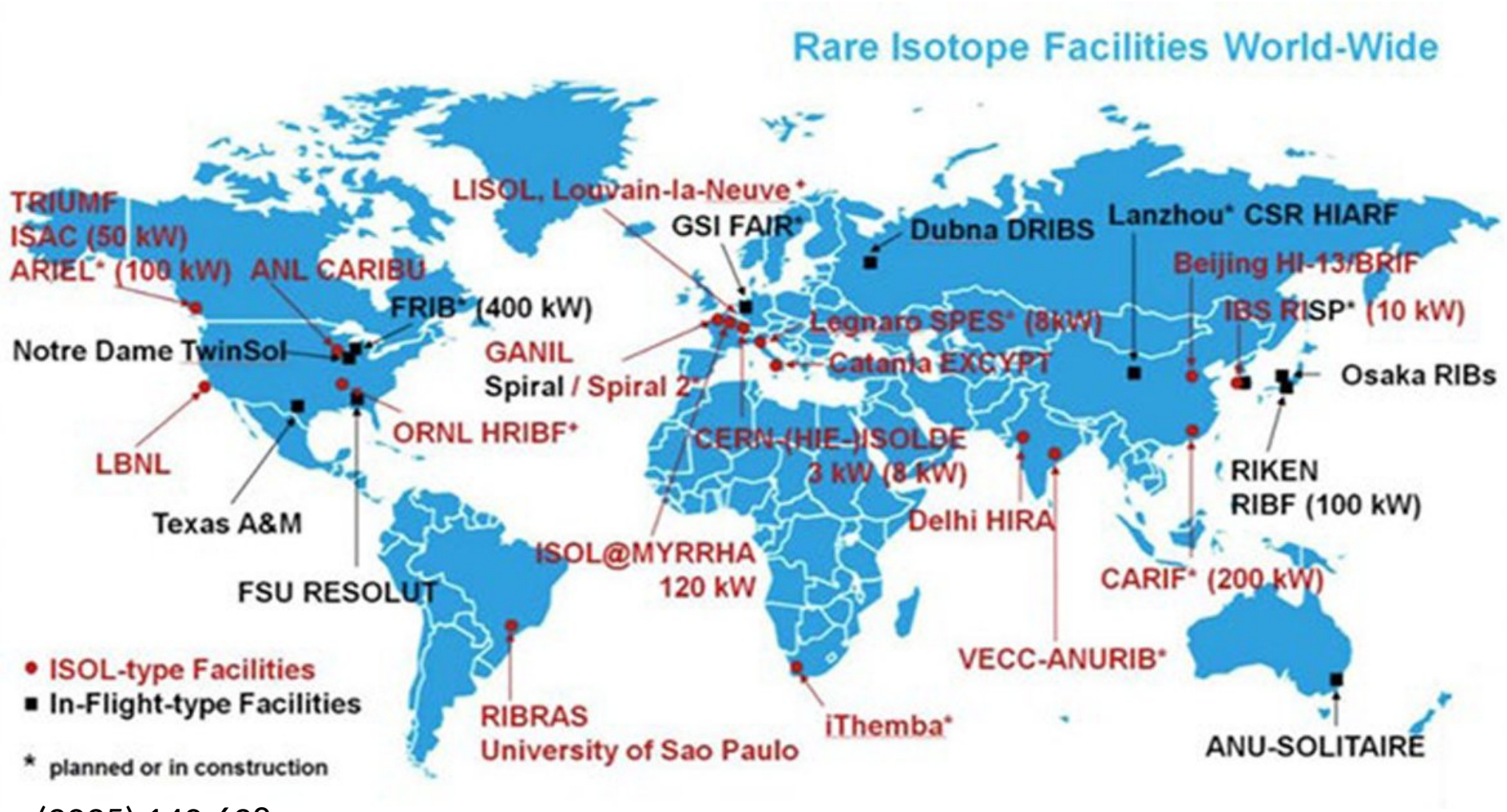
Challenges with RIB production:

low cross sections → highest-intensity beams, efficient

short half-lives → minimise time between production and experimental setup

contamination → excellent selectivity, low-background conditions

Overview of world-wide RIB facilities



Eur. Phys. J. Plus (2025) 140:638

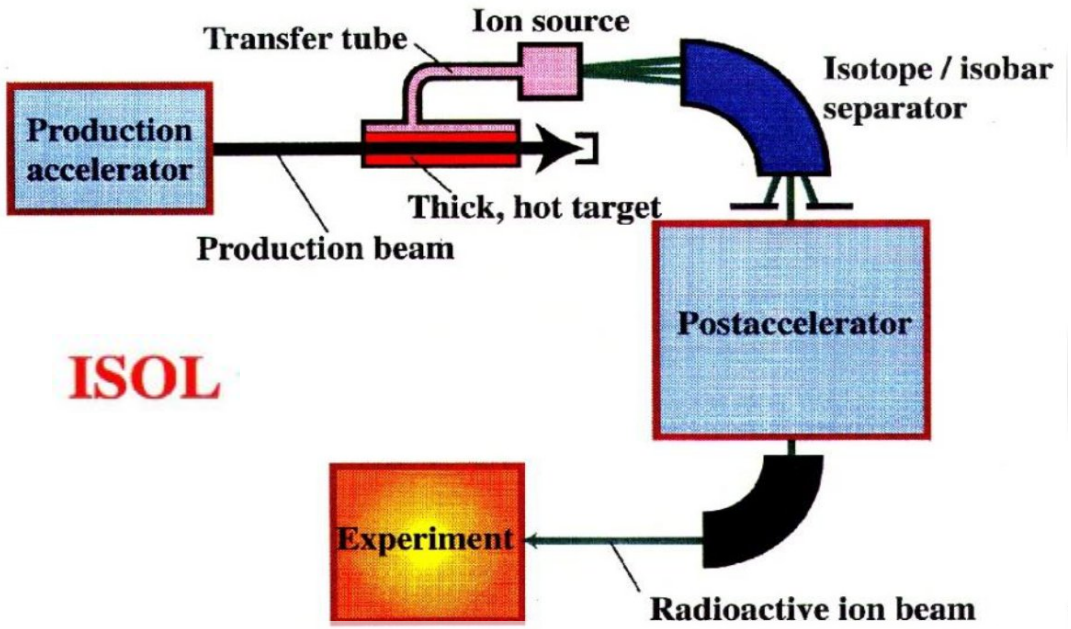
23rd STFC Nuclear Physics Summer School (2026)

July 26, 2026 to August 8, 2026

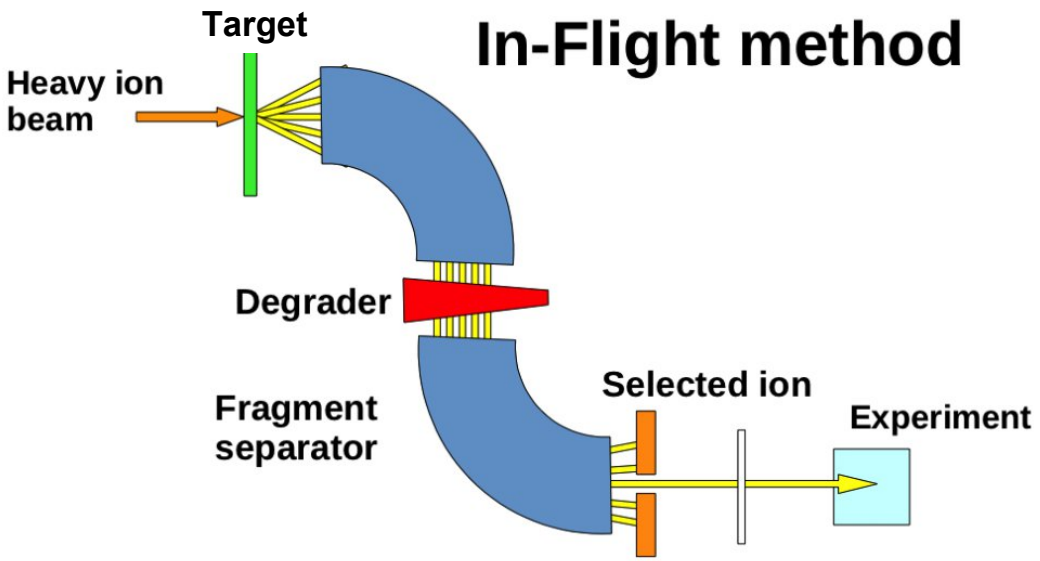
Europe/London timezone

ISOL vs In-flight methods

- Spallation/fission/fragmentation followed by chemical/physical processes to extract desired nuclei
- Products thermalised and separated
- Beams produced at very low energies (60 keV)
- Sometimes mono-isotopic!

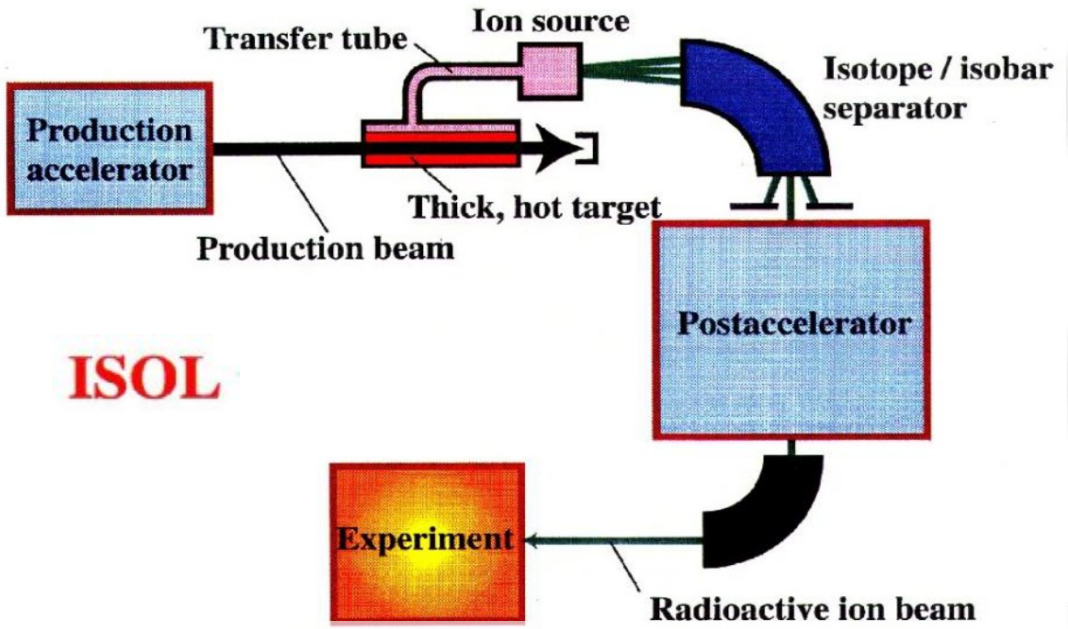


- Relativistic fragmentation/fission of heavy nuclei on targets
- > 50 MeV/u → production of cocktail beams containing several species
- Separator for separation and identification - long time of flight (~100s ns)

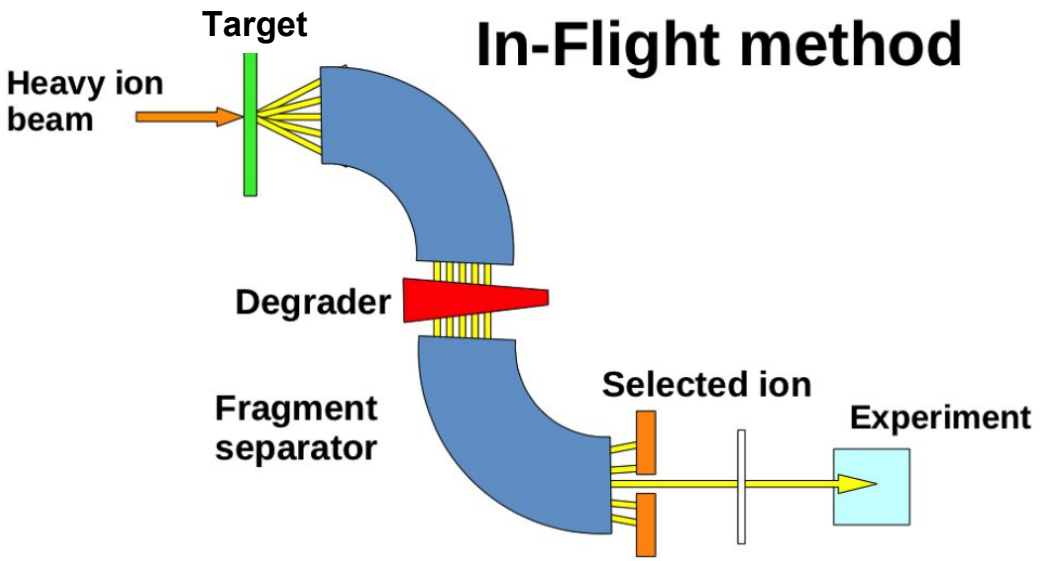


ISOL vs In-flight methods

- ✓ (Relatively) high cross sections
- ✓ No need for re-acceleration
- ✓ Rates can be higher
- x Short-lived species might not be accessed easily
- x Refractory elements difficult
- x Isobaric contamination



- ✓ Cocktail beam: many nuclei can be studied at once
- ✓ Larger range of lifetimes possible
- ✓ Measurements possible with very few ions
- x Low cross sections
- x Rate limitation
- x Limitations due to ToF



Aside - the development of ISOL

Short-Lived Krypton Isotopes and Their Daughter Substances

O. KOFOED-HANSEN AND K. O. NIELSEN
Institute for Theoretical Physics, University of Copenhagen, Copenhagen, Denmark
(Received February 9, 1951)

THE isotopes Kr^{89}, Kr^{90}, Kr^{91}, and their daughter substances have been investigated. Krypton formed in fission of uranium was pumped through a 10-m long tube directly from the cyclotron into the ion source of the isotope separator. The cyclotron and the isotope separator were operated simultaneously, and the counting could begin immediately after the interruption of the separation. The rubidium and strontium daughter substances were separated chemically; strontium was precipitated as carbonate. Half-lives were measured and an absorption analysis of the radiations was carried out. The results are given in Table I.

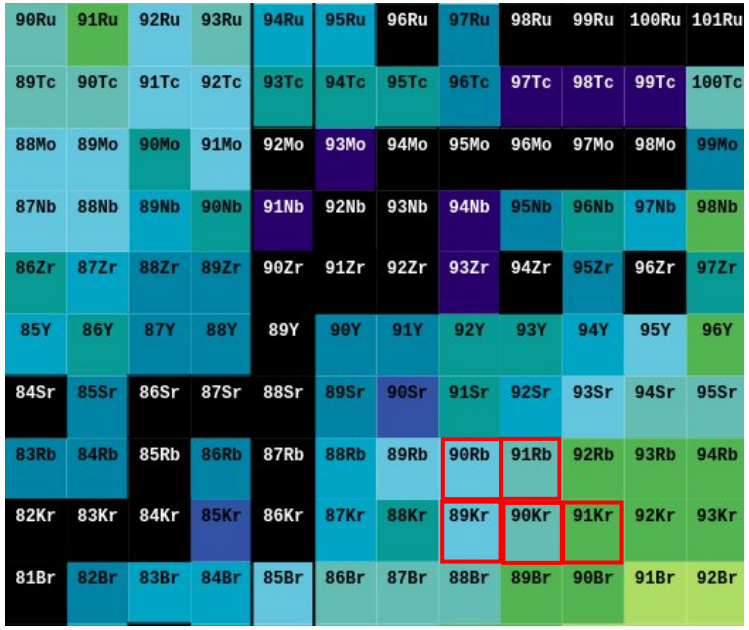
TABLE I. Observed radiations.

Isotope	Half-life	Radiation	E_{β}^{max}	Spectrum
Kr^{89}	3.18 min (2.6)	β^-, γ	4.0 Mev	Complex
Kr^{90}	33 sec (33)	β^-, γ	3.2 Mev	Complex
Rb^{90}	2.74 min	β^-, γ	5.7 Mev	Complex
Kr^{91}	10 sec (9.8)	β^-, γ probable	~3.6 Mev	Complex
Rb^{91}	100 sec	β^-, γ	4.6 Mev	Complex
Rb^{91}	14 min	β^-, γ	3.0 Mev	Complex

- First ISOL beam - 1951 at the Niels Bohr Institute in Denmark (Kofoed-Hansen and Nielsen, Phys. Rev. 82 (1951) 96)

- Two-stage method:
  - Deuterons accelerated by a cyclotron impinged on a target to produce neutrons
  - Neutron-induced fission in secondary uranium target
- More ISOL facilities came online in the following years
- 1964 - ISOLDE established…

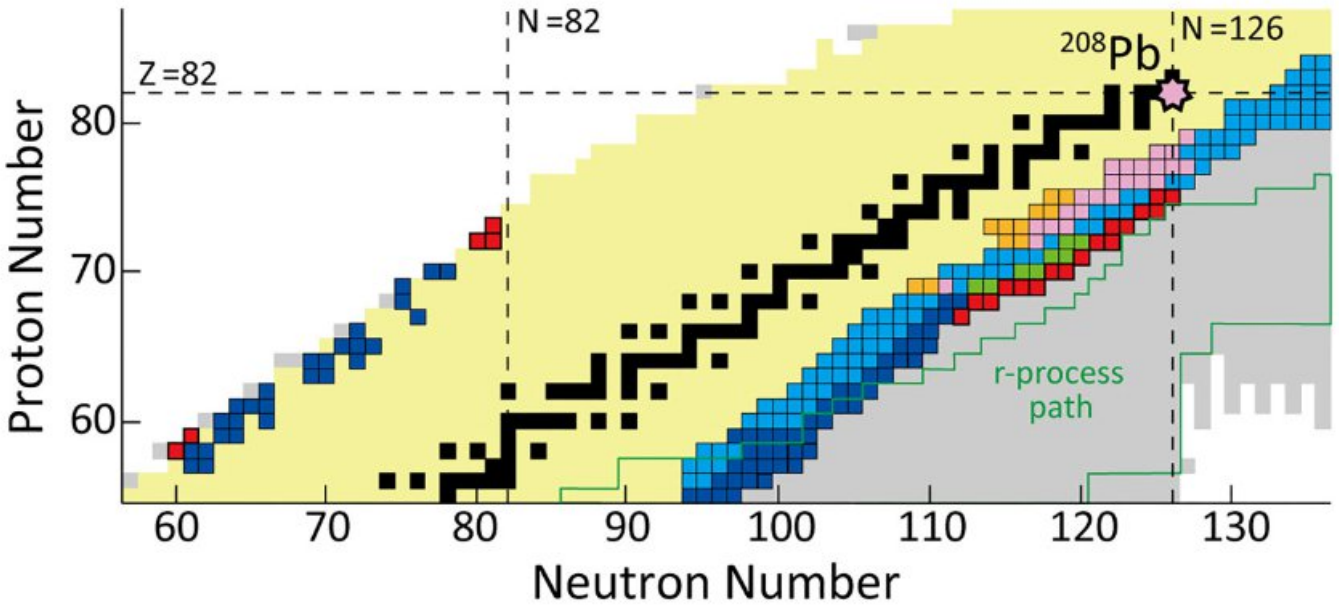
^{89}Kr 3.15(4) min
^{90}Kr 32.32(9) s
^{90}Rb 158(5) s



N=50

Why primary beam matters

- Choice of primary beam species **can have a huge effect**
- Example: development of ^{208}Pb primary beam at RIBF RIKEN
- Production cross sections for nuclei of interest (N~126, Z~75) from ^{238}U and ^{208}Pb are comparable, but:



PTEP
Prog. Theor. Exp. Phys. **2026** 061D01 (12 pages)
DOI: 10.1093/ptep/ptag082

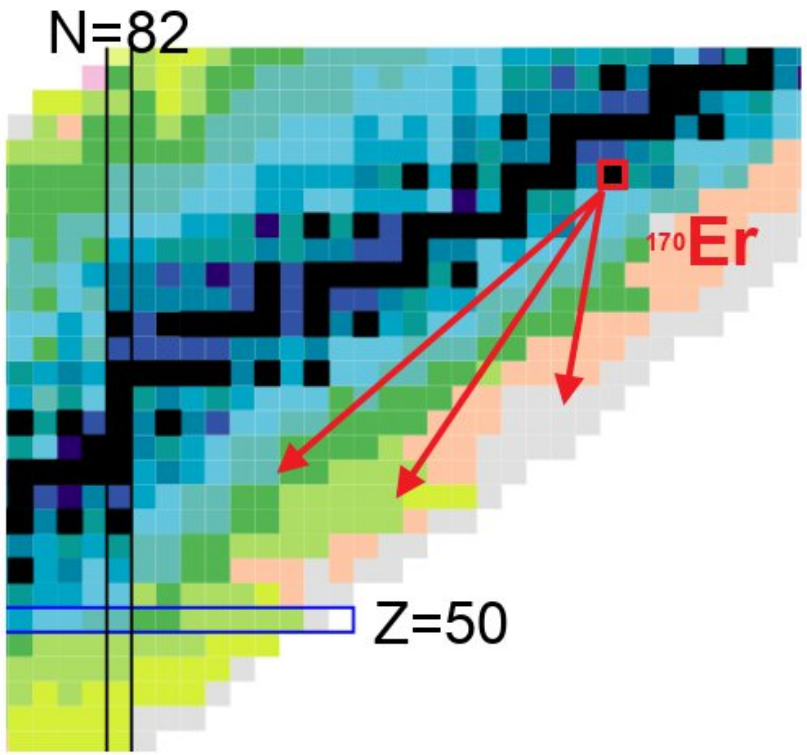
First Observation of 22 Exotic Isotopes Using a ^{208}Pb Primary Beam at the RI Beam Factory

N. Fukuda[1,*], S. Michimasa[1,†], H. Suzuki[1,‡], Y. Shimizu[1], H. Takeda[1], Y. Togano[1], M. Yoshimoto[1], Y. Yanagisawa[1], K. Kusaka[1], M. Ohtake[1], H. Sato[1], T. Sumikama[1], K. Yoshida[1], S. Motomura[1], H. Baba[1], Y. Ichinohe[1], N. Kitamura[2,3,1], K. G. Tanaka[2,1], K. Kasai[2,1], D. Suzuki[2,3,1], N. Imai[4], R. Yokoyama[4], Y. Yamamoto[4], S. Hanai[5], Y. Funasaka[6], R. Tsuchiya[7], N. Matsuoka[7,1], N. Fukunishi[1], and H. Sakurai[1]

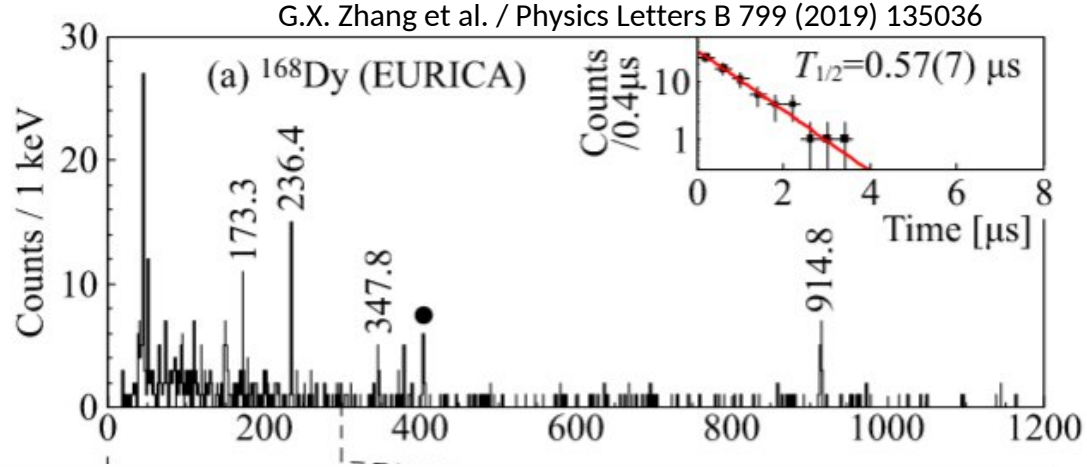
No fission product contamination ->higher-purity beams!

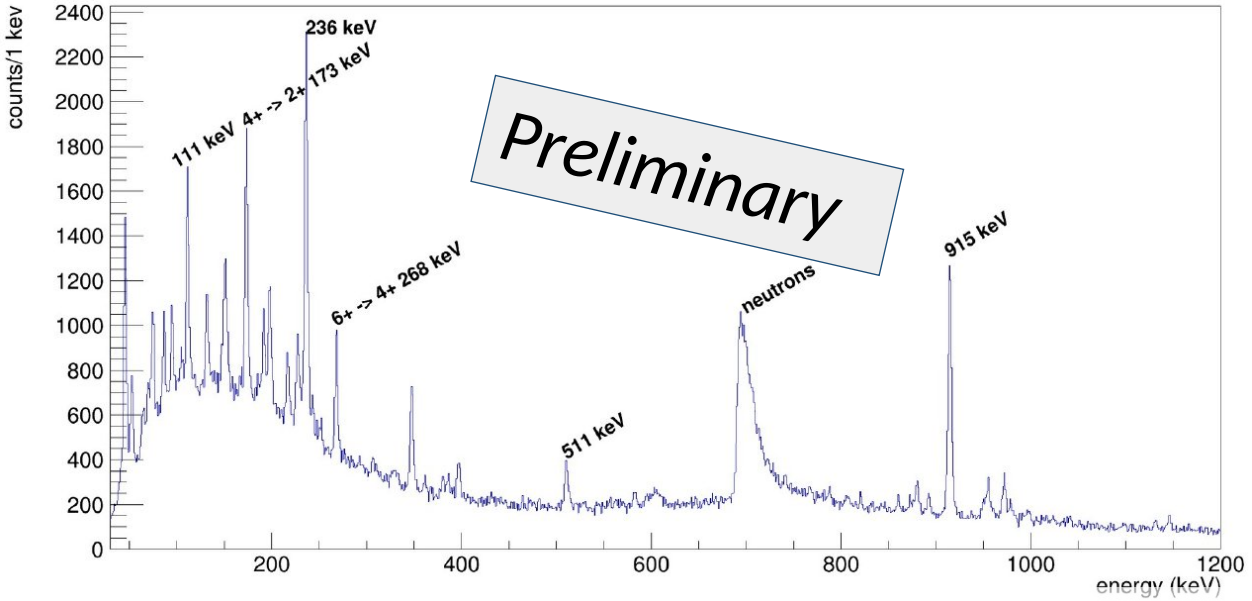
Why primary beam matters

- Example: neutron-rich rare-earth nuclei studied at RIBF using high-intensity U beams
- Region accessed using primary ^{170}Er beam @ 1 GeV/u at GSI



G.X. Zhang et al. / Physics Letters B 799 (2019) 135036



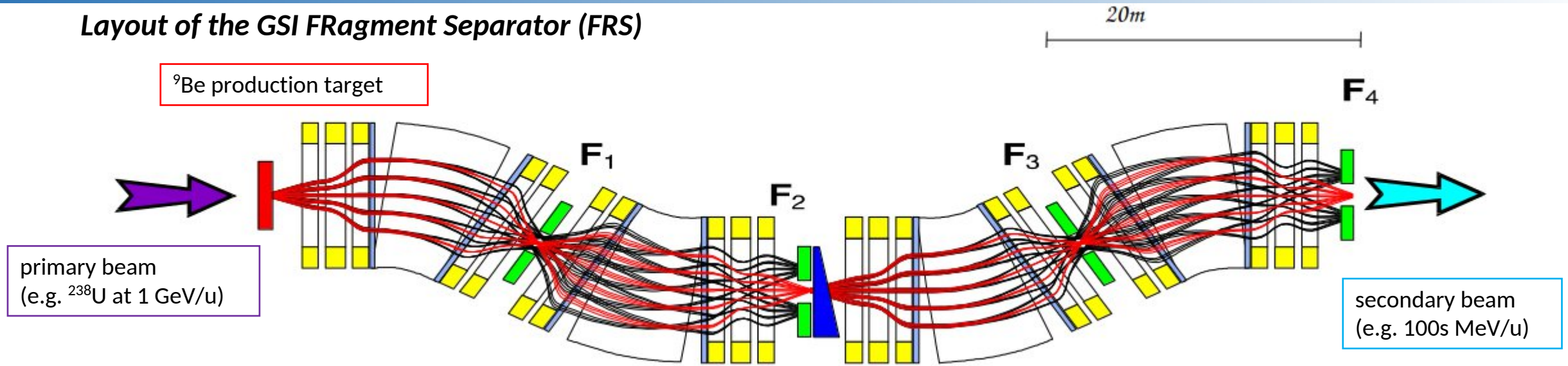


PhD work of J. Bormans, J.E.L. Larsson

Beam energy also matters.....

Fragment separation and identification

Layout of the GSI FRagment Separator (FRS)



- 'Cocktail beam' of ions produced in fragmentation reactions.
- Transmission typically 20-70% for fragments.
- High-energy primary beams - excellent separation, 5-18 Tm magnetic rigidities.
- Magnetic spectrometer - uses Bρ-ΔE-Bρ selection method.

FRS Optical Elements:

- Four stages, each with a 30° bending dipole.
- Quadrupoles for focussing.
- Correction of aberrations with sextupoles.
- Steerers deflect the beam in the vertical direction.

Selection: Bρ-ΔE-Bρ method

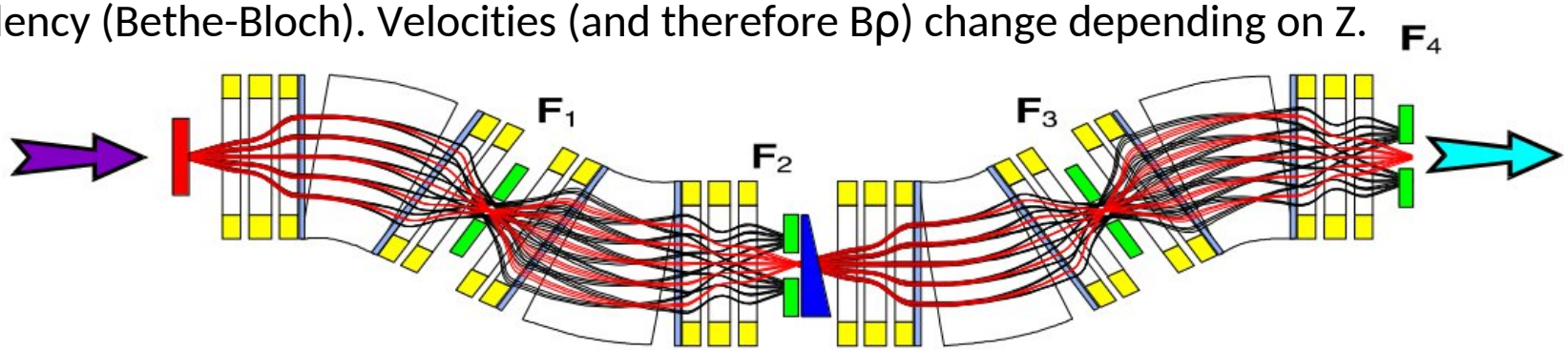
- Lorentz force $q\vec{v} \times \vec{B}$ equal to centrifugal force for ions travelling perpendicularly to a homogeneous magnetic field:

$$F_{Lorentz} = \frac{mv^2}{\rho} \qquad B\rho = \beta\gamma\frac{A}{q}uc \qquad \Rightarrow B\rho \propto \beta\gamma\frac{A}{Z}$$

where β = v/c is the fraction of the speed of light.

- Slits at the intermediate focal point 'cut' the acceptance and remove unwanted ion species based on their magnetic rigidities.

- Second stage of separation achieved by a wedge-shaped degrader system at F2 - ions deposit energy in the degrader with a Z^2 dependency (Bethe-Bloch). Velocities (and therefore Bρ) change depending on Z.



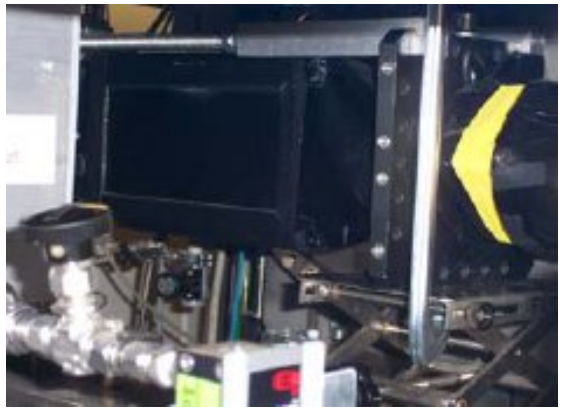
- In the last step, the final 2 dipole stages perform another Bρ filter (i.e. Z selection).

Identification: ToF-ΔE-Bρ method

- Several detectors through the separator measure the ***position, ToF and Z*** of the transmitted ions.

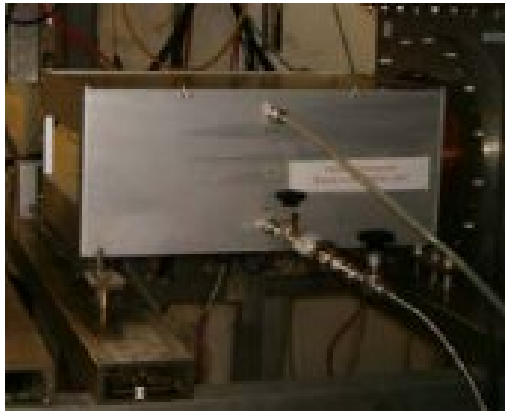
Time Projection Chambers (TPCs) at F2 and F4 measure the **position.**

Gas-filled chamber, vertical drift velocity. Excellent position resolution (~1mm in x, ~0.5mm in y).



Plastic scintillator detectors positioned at F2 and F4 measure the **time-of-flight (ToF).**

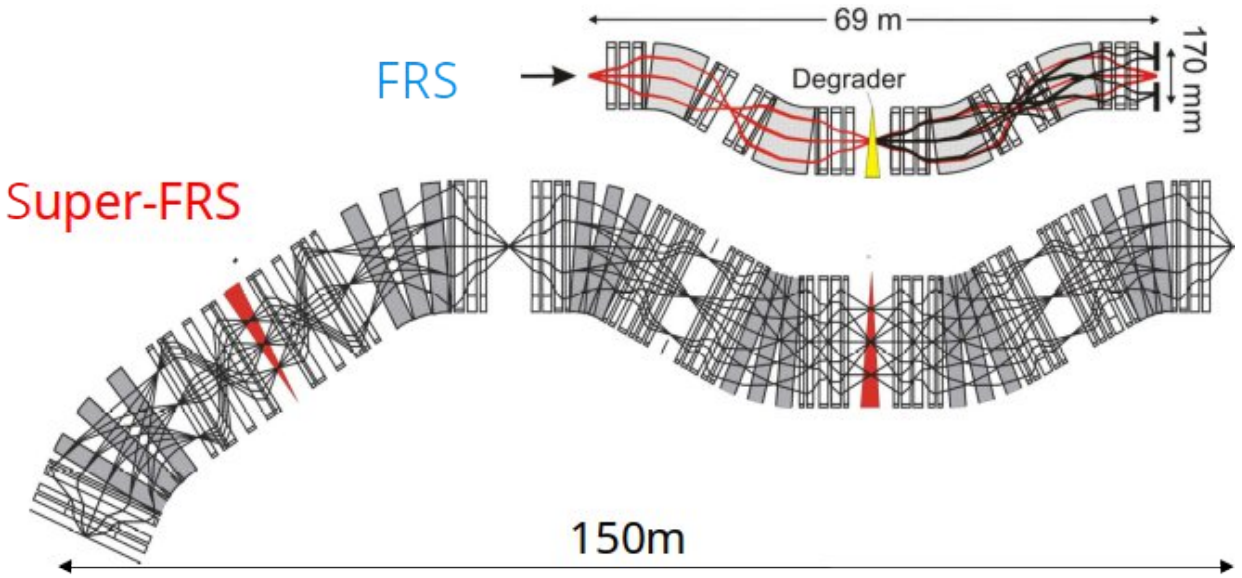
High efficiency, excellent time resolution (~40ps). Typically ~1mm thick.



MUlti Sampling Ionisation Chambers (MUSIC) at F4 measure the atomic number **Z.**

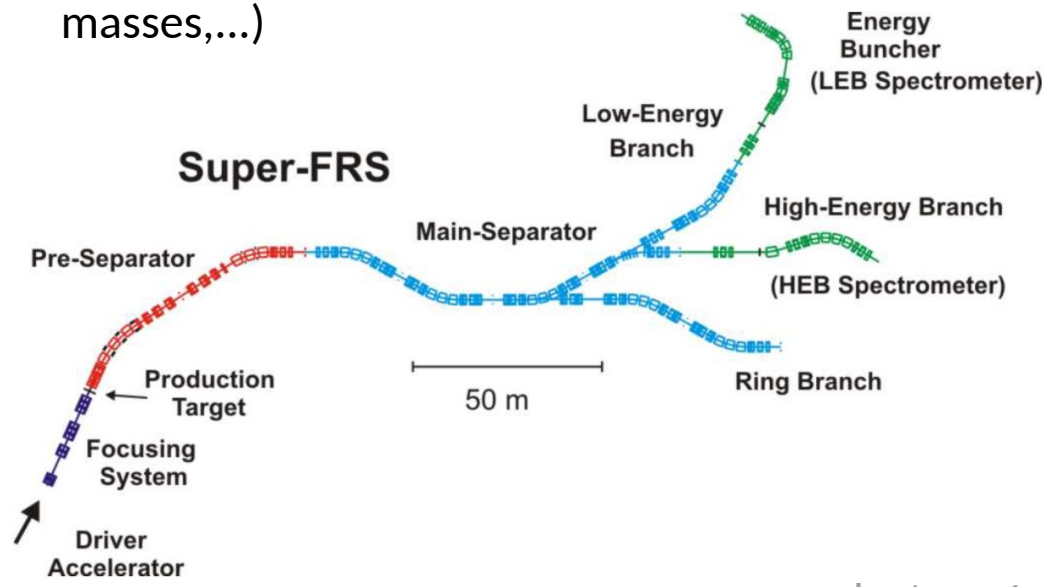
Gas-filled chamber, free electrons created in gas ionisation proportional to Z^2.

Next generation separators - e.g. Super-FRS at FAIR



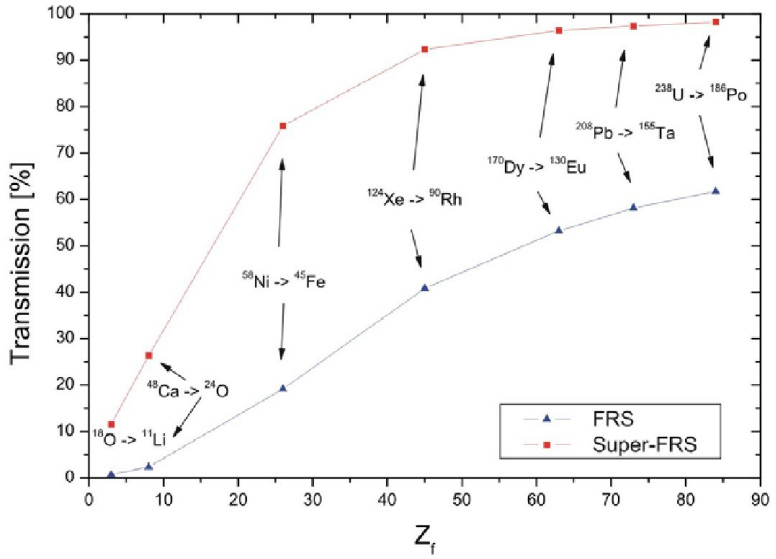
	$B\rho_{max}$	$\Delta p/p$	$\Delta\Phi_x, \Delta\Phi_y$	resolving power	gain factor ^{19}C	gain factor ^{132}Sn
FRS	18 Tm	1.0 %	±13, ±13 mrad	1500	1	1
Super-FRS	20 Tm	2.5 %	±40, ±20 mrad	1500	5	10
				including primary rate	250	20 000

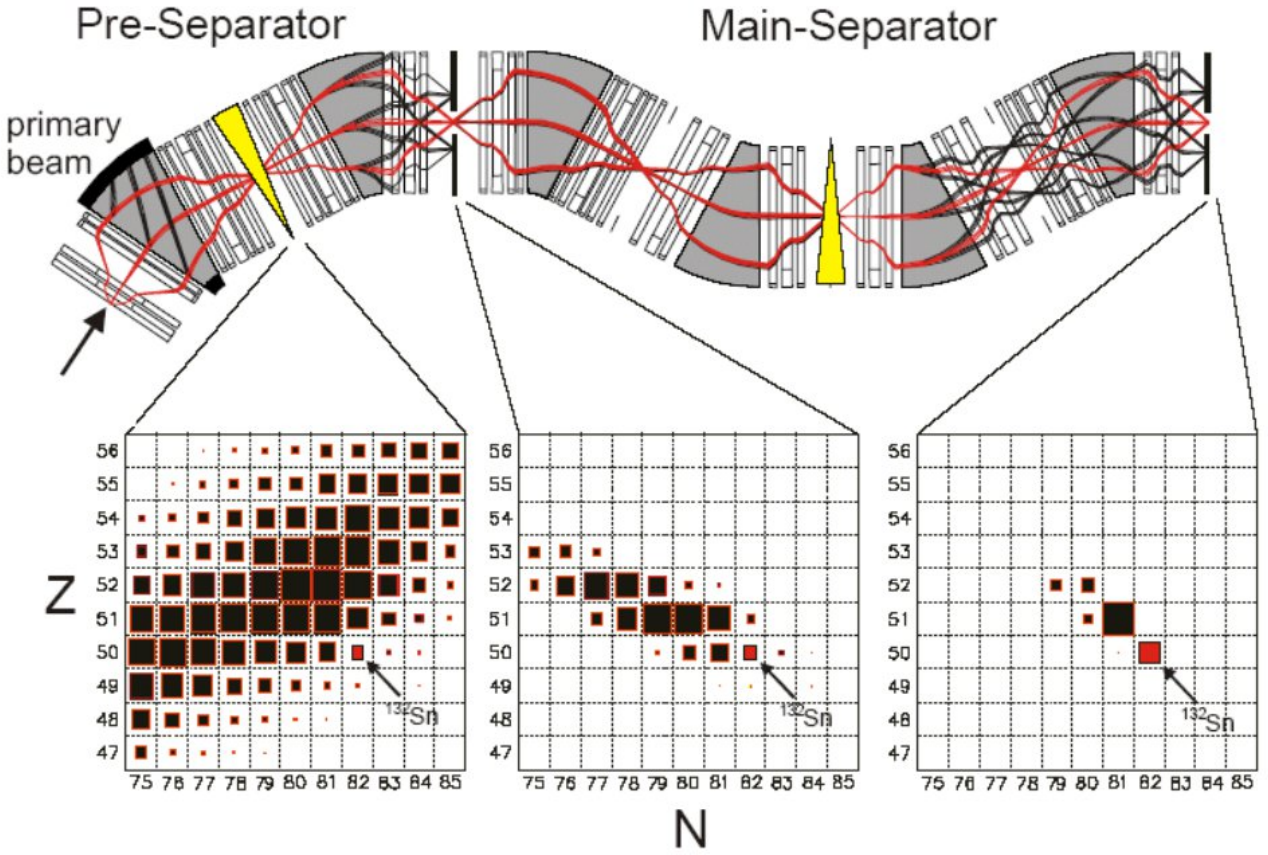
- Among world's **most powerful separators** for exotic nuclei
- Three branches to address different physics cases
  - **Low-energy branch** (High-resolution in-beam and decay spectroscopy, precision experiments with thermalised exotic nuclei, colinear laser spectroscopy,…)
  - **High-energy branch** (reactions with high-energy radioactive beams)
  - **Ring branch** (isomeric beams, lifetimes, masses,…)



Next generation separators - e.g. Super-FRS at FAIR

- Increased ***transmission***
- Specialised beam instrumentation for ***high rates***
- ***Exotic beams*** from protons to uranium up at high energy for excellent particle identification at high masses
- ***High-resolution*** spectrometer

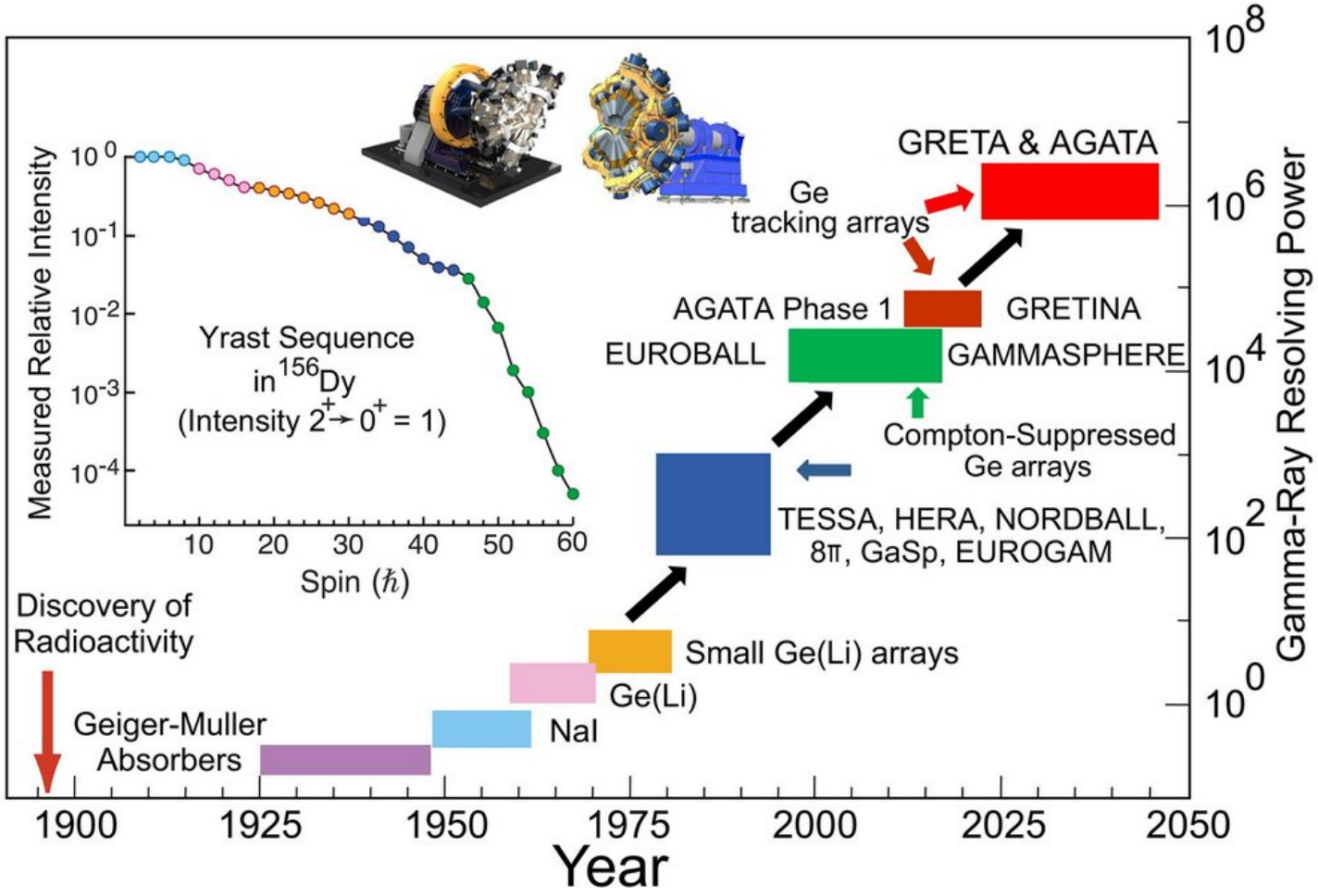


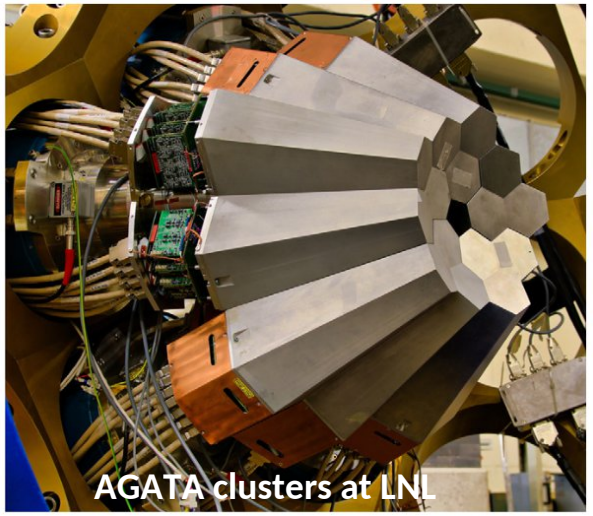


Pre-separation stage critical for high beam intensities and beam cleanliness

A facility is only as good as its instrumentation

– Example: a century of evolution for gamma-ray detection





23rd STFC Nuclear Physics Summer School (2026)

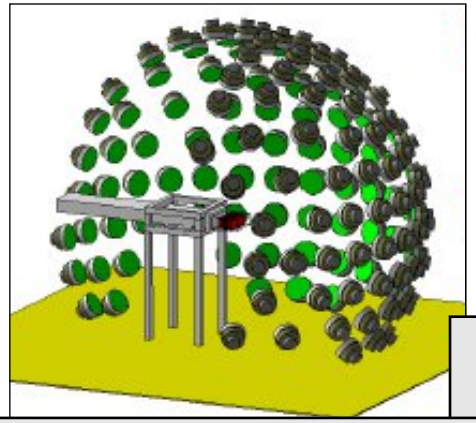
July 26, 2026 to August 8, 2026

Europe/London timezone

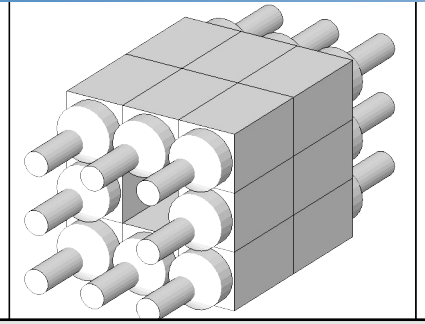
Wyss and Riley, Vol. 32, No. 2 (2022) Nucl. Phys. News

S. Akkoyun *et al.*, NIMA 668 (2012) 26–58

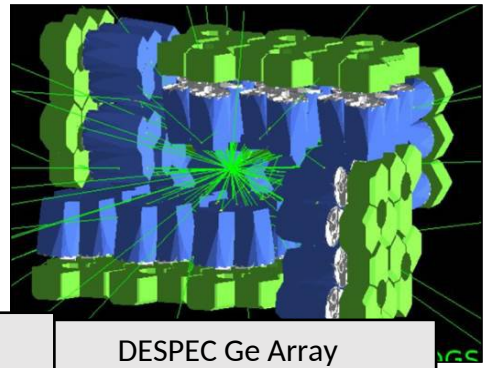
State-of-the-art detector arrays



The MOdular Neutron SpectromeTER **(MONSTER)**



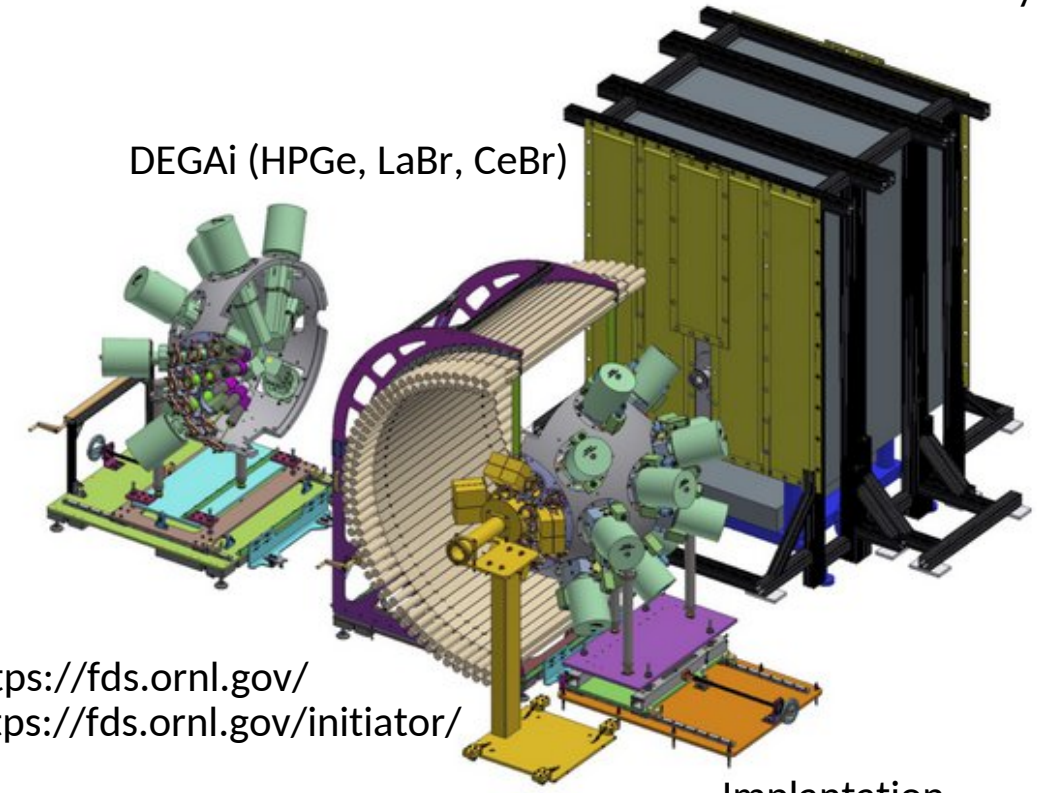
Decay Total Absorption γ-ray Spectrometer **(DTAS)**
NaI(Tl) modules



DESPEC Ge Array Spectrometer **(DEGAS)**

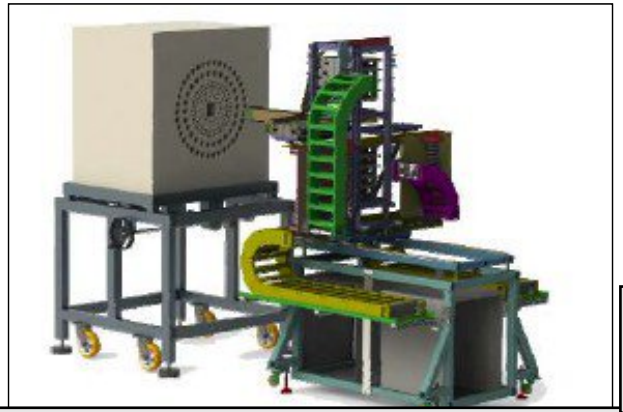
VANDLE - neutron TOF array

DEGAi (HPGe, LaBr, CeBr)

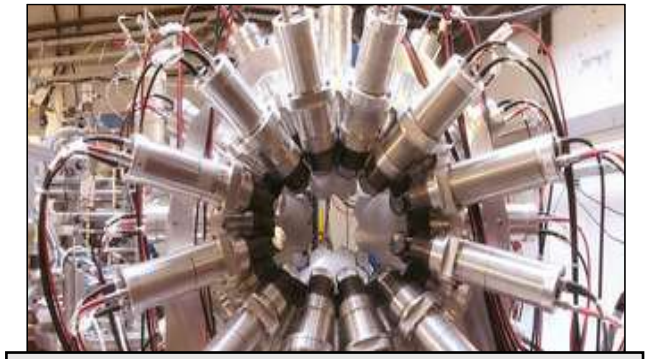


https://fds.ornl.gov/
https://fds.ornl.gov/initiator/

Implantation
XSISi - silicon array
YSO-Segmented Scintillator



BEta-deLayEd Neutron detector **(BELEN)**
48 3He cylindrical counters



FAst TIMing Array $LaBr_3(Ce)$ modules **(FATIMA)**

A.K. Mistry *et al.*, The DESPEC setup for GSI and FAIR, NIM A, 166662 (2022)

23rd STFC Nuclear Physics Summer School (2026)

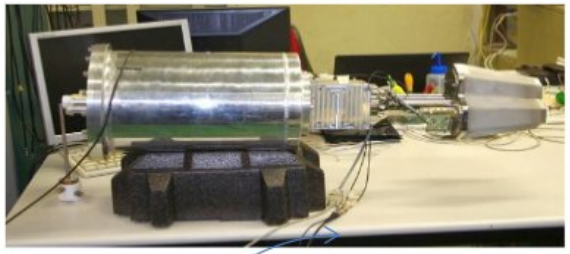
July 26, 2026 to August 8, 2026
Europe/London timezone

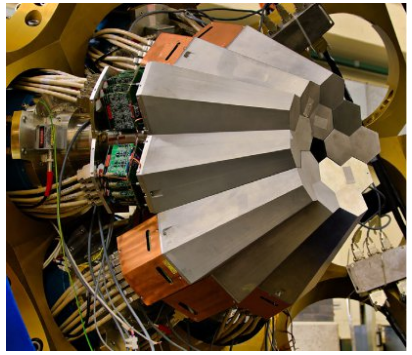
State-of-the-art detector arrays

GASP coaxial HPGe det. Of GALILEO
With new digital electronics:

- Preamplifiers
- digital sampling
- Preprocessing
- DAQ

Newly refurbished triple CLUSTER det.



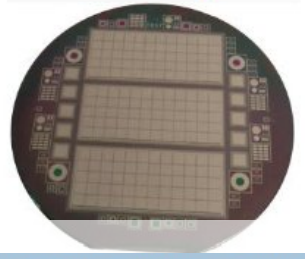


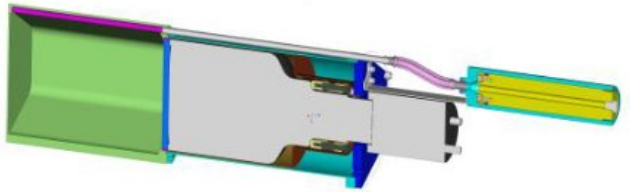
AGATA array @ LNL

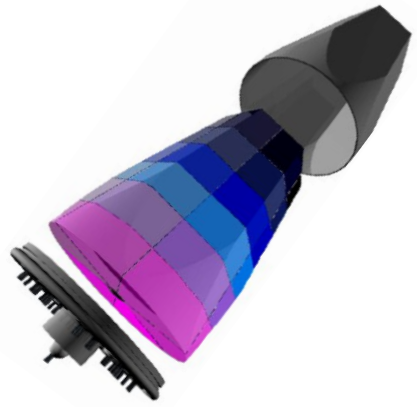
SPES LNL
Possible ancillary detectors:

* HPGe Clover/Cluster detectors
* GALILEO coaxial detectors
* Modified NEDA Neutron detectors
* TRACE Silicon detectors
* Fast responding LaBr3:Ce det. for fast time measurements
* Large volume $LaBr_3/BaF_2$ for TAS

Courtesy of G. Benzoni







S. Akkoyun et al. / Nuclear Instruments and Methods in Physics Research A 668 (2012) 26–58

Making the right choice; example: short-lived states

- Nuclear states have a huge range of lifetimes, > 30 orders of magnitude.
- Main techniques for short lifetimes:
  - Recoil Distance Doppler Shift method (RDDS) → > 1 ps
  - Doppler Shift Attenuation Method (DSAM) → < 1 ps
  - **'Fast timing' with $LaBr_3(Ce)$ detectors** → > 10s ps

HPGe or $LaBr_3(Ce)$?

- Direct timing methods (e.g. DSAM) - high energy resolution needed.
- Fast timing methods involve time differences between detector pairs - time resolution below the intrinsic detector resolution is possible.
- Ge detectors are semiconductors (need to be cooled!) - very small gap between conducting and valence bands (E gap = 0.67 eV!) 1 keV produces 300 electrons! Energy resolution scales with 1/sqrt(yield)
- LaBr3(Ce) detectors have significantly worse energy resolution, but much better timing properties than HPGe.

I Deloncle *et al.*, J. Phys.: Conf. Ser. 205 (2010) 012044

P.H. Regan *et al.*, J. Phys: Conf. Ser. 620 (2015) 012005

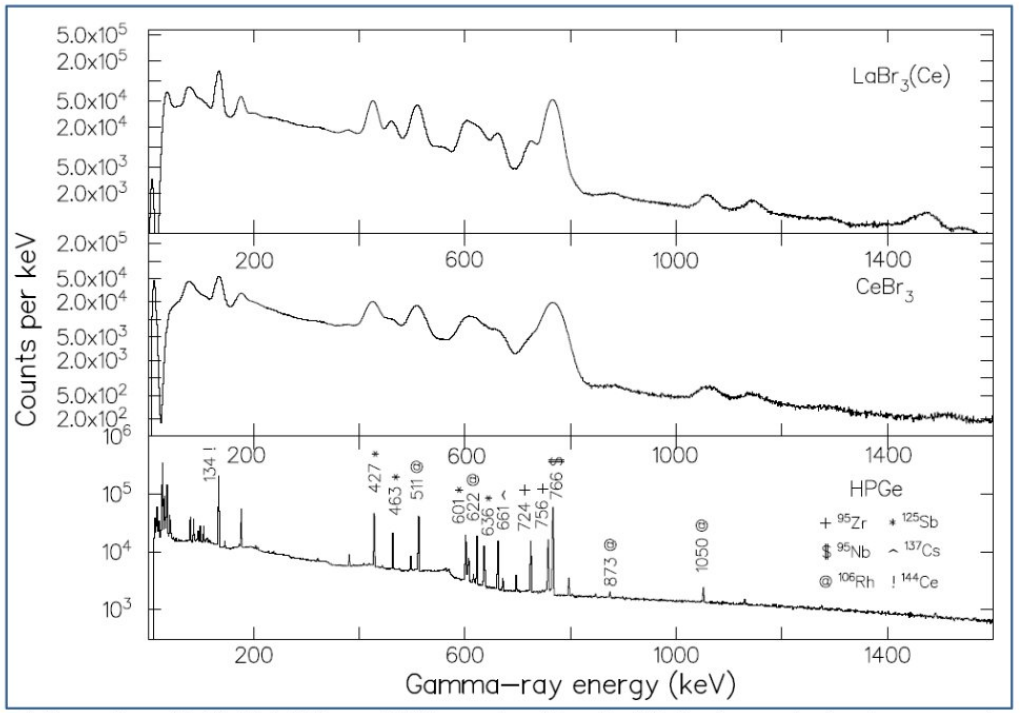


Figure 1 Comparison of $LaBr_3(Ce)$, $CeBr_3$ and HPGe spectra of long-lived fission fragments of protons on uranium. The main lines identified in the HPGe spectra arise from the decays of ^{95}Zr, ^{95}Y, ^{106}Rh, ^{125}Sb, ^{137}Cs and ^{144}Ce decays.

Table 1. Comparison of main properties of Ge and $LaBr_3$ detectors of same volume.

	Ge	$LaBr_3$
Energy range	keV to MeV	keV to MeV
Abs. Eff.(at 2,54cm from source)[6]	10^{-1} to 10^{-2}	2.10^{-1} to 5.10^{-2}
Rel. Eff. (@1.33MeV)	75%	143%
Energy resolution	1% to 1‰	20% to 3%
Typical time response	250 ns (risetime)	16ns (scint. decay time)
Time resolution	20 ns to 5ns [7]	200 ps(@511keV) [10, 11]

Tutorial discussion point

Discussion point: experiment design

Goal: to start thinking like an experimental physicist!

What are the main considerations when designing a nuclear physics experiment? Start with the question "Which physical phenomena or science questions am I trying to address?".

Note: physics goals can be vague or even fake – the idea is to start the thought process about the key points and not to worry about the details.

Think about and discuss all aspects (examples):

- How can the nuclei of interest be produced? (beams, targets)
- Do energy or intensity play an important role?
- How clean do the conditions need to be?
- How will I identify reaction products?
- Will I populate the correct states?
- Do I have the right instrumentation at the ready for the goal observables?
- Do I have the right expertise to carry out the measurement?
- How long will I need to measure?
- How will I gain access to beam time?
- …

If there is time, take the points above and try to make an outline of how you would construct a proposal for beamtime.

- How can the choice of parameters (e.g., beam, target, number of shifts, instrumentation,…) be justified?
- How to balance potentially high-impact goals with experimental feasibility?
- What other important aspects should be mentioned in a proposal? Will this change depending on the target facility?