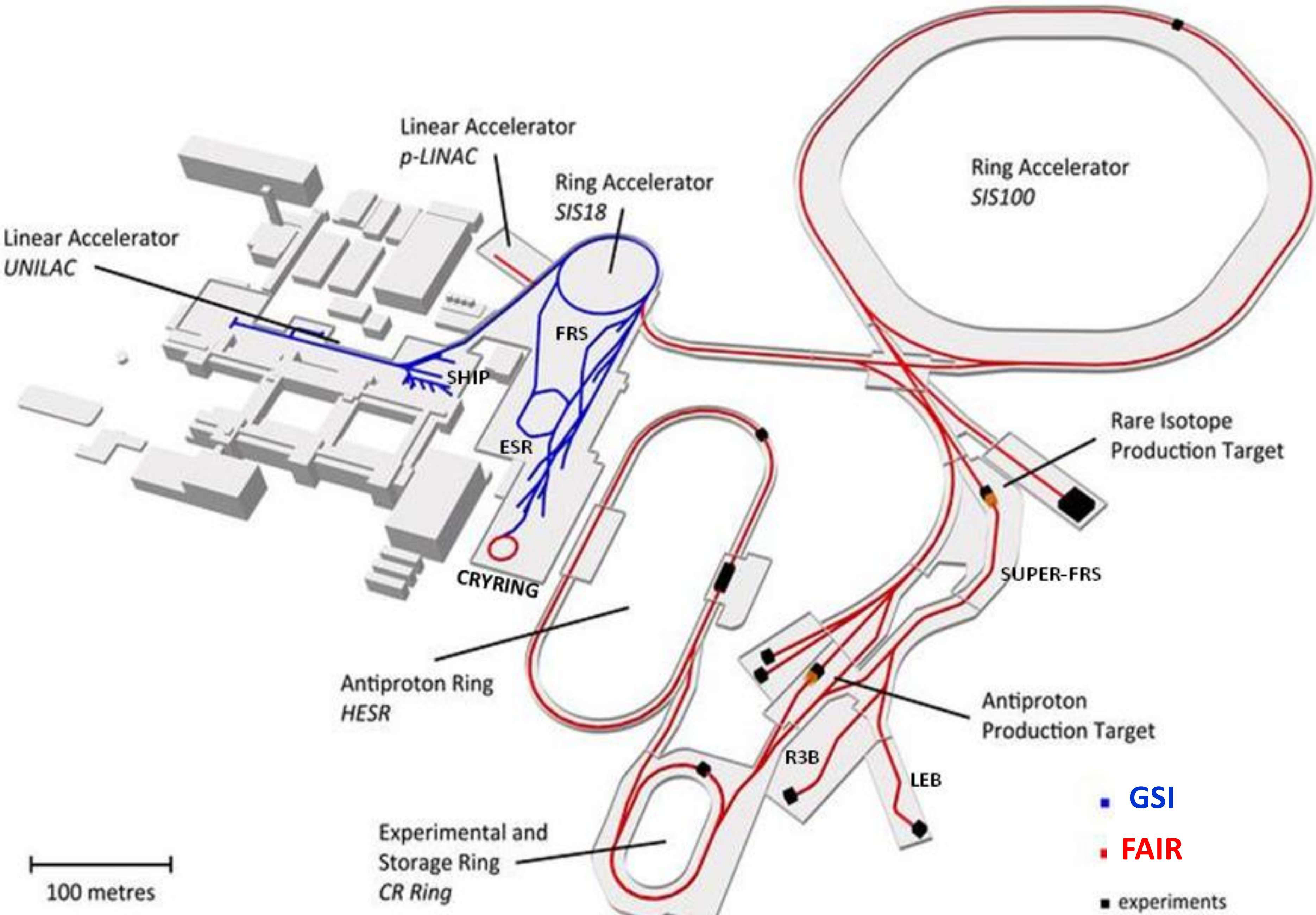
Nuclear Physics at GSI/FAIR
(Facility for Antiproton and Ion Research)

The GSI/FAIR facility

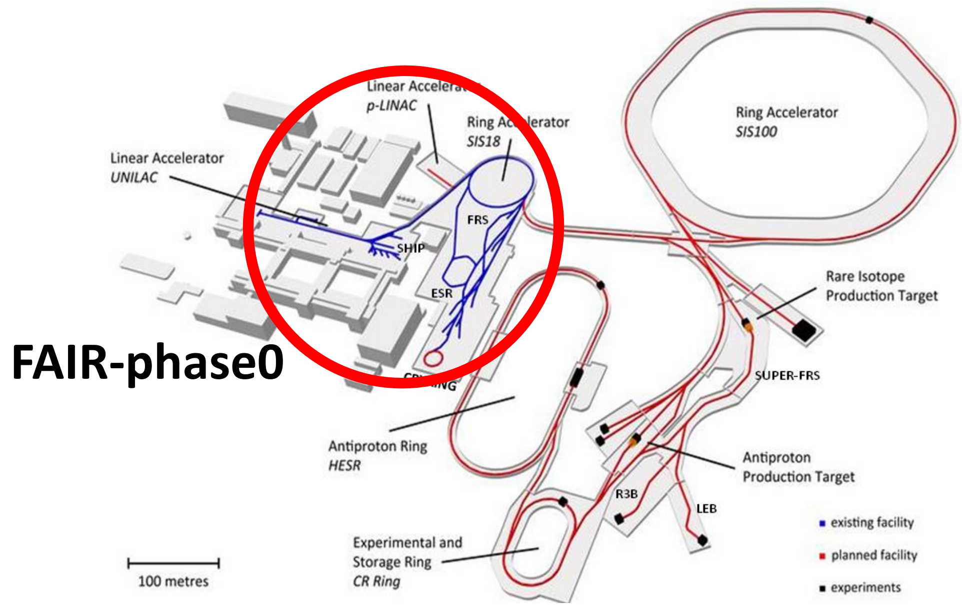


Strengths of GSI/FAIR

- Only facility world-wide able to provide a $^{238}U^{28+}$ beam at 1.5 A GeV with ~10^{11} pps
- World-record intensities for radioactive beams of fully stripped ions up to the heaviest masses near U
- Large variety of energies (stopped, A MeV, >1 A GeV)
- High-quality radioactive beams (beam cooling at rings), unrivalled experience
- State of the art detection systems are or will be available

Experiments at GSI/FAIR

- **FAIR-phase0 is running, current experiments benefit from the upgrade of UNILAC and SIS-18, and from CRYRING**



- **First experiments using the Super-FRS expected towards the end of 2025**

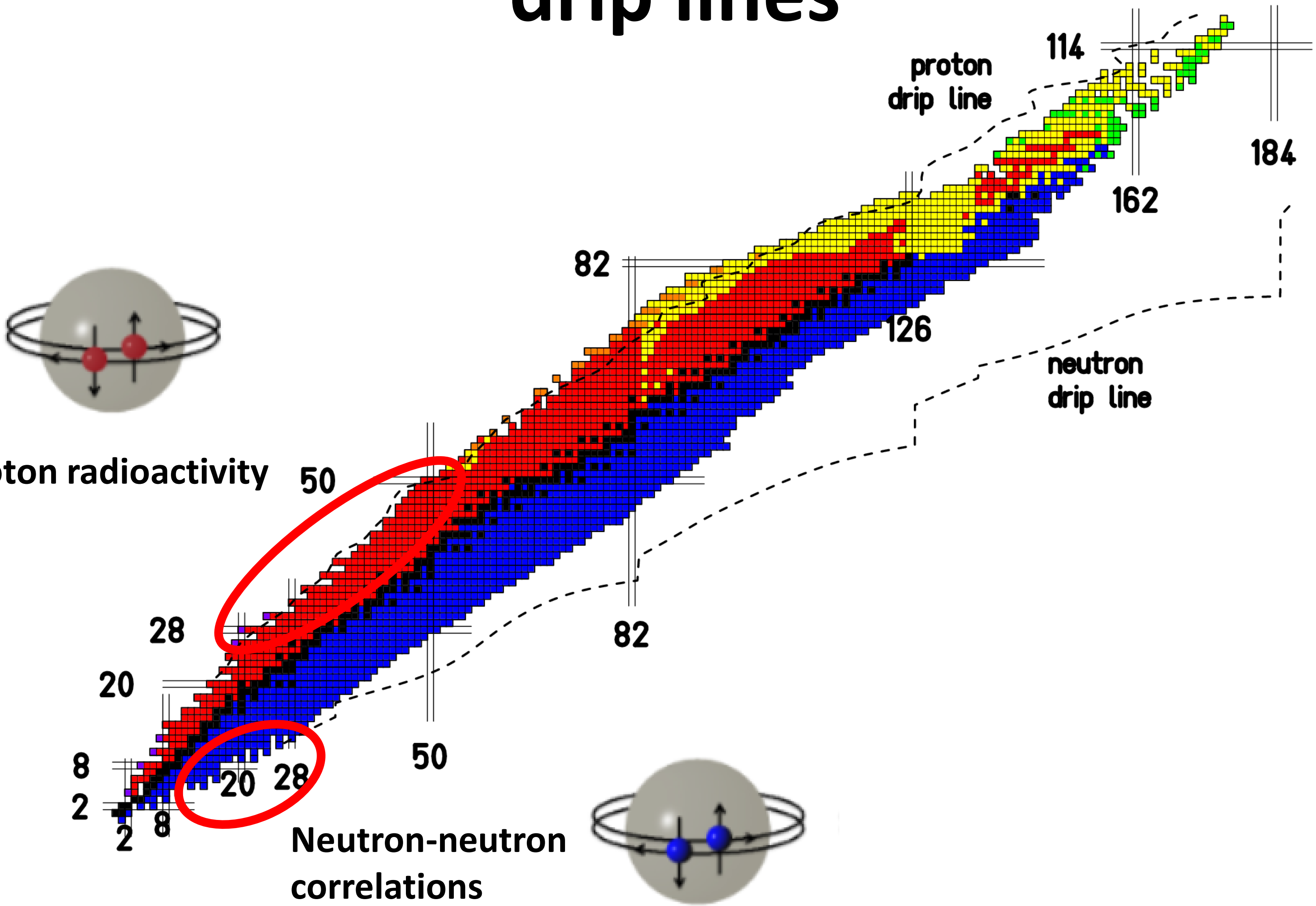
- **France is one of the 10 share-holders of FAIR and enables its scientific community the access to FAIR**

Nuclear-physics projects at GSI/FAIR coordinated by IN2P3 scientists (2020-2024)

→For AGATA@FAIR, see talk by A. Lopez-Martens

→Ideas for experiments with GRIT@FAIR, see talk by D. Baumel

Pairing correlations at the drip lines



2-proton radioactivity

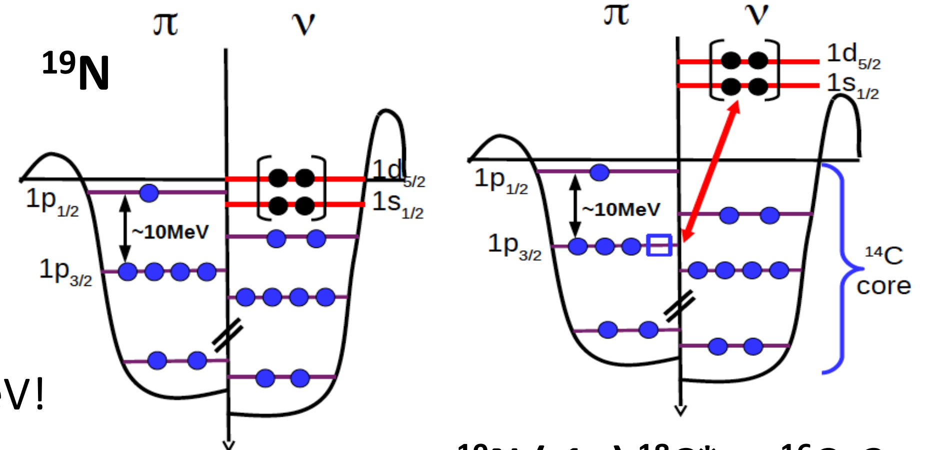
Neutron-neutron correlations

Evolution of pairing correlations towards the neutron dripline from di-neutron and tetra-neutron correlations

O. Sorlin, GANIL

Pairing correlations towards the neutron dripline

- Evolution of pairing scheme towards drip-line, from BCS to BEC ? (Hagino et al. PRL99 (2007))
- Existence of an ensemble of 4 interacting neutrons? (Marques et al.,PRC 65 (2002), Kisamori et al. PRL 116 (2016))



^{19}N (-1p) ^{18}C* -> ^{16}C+2n

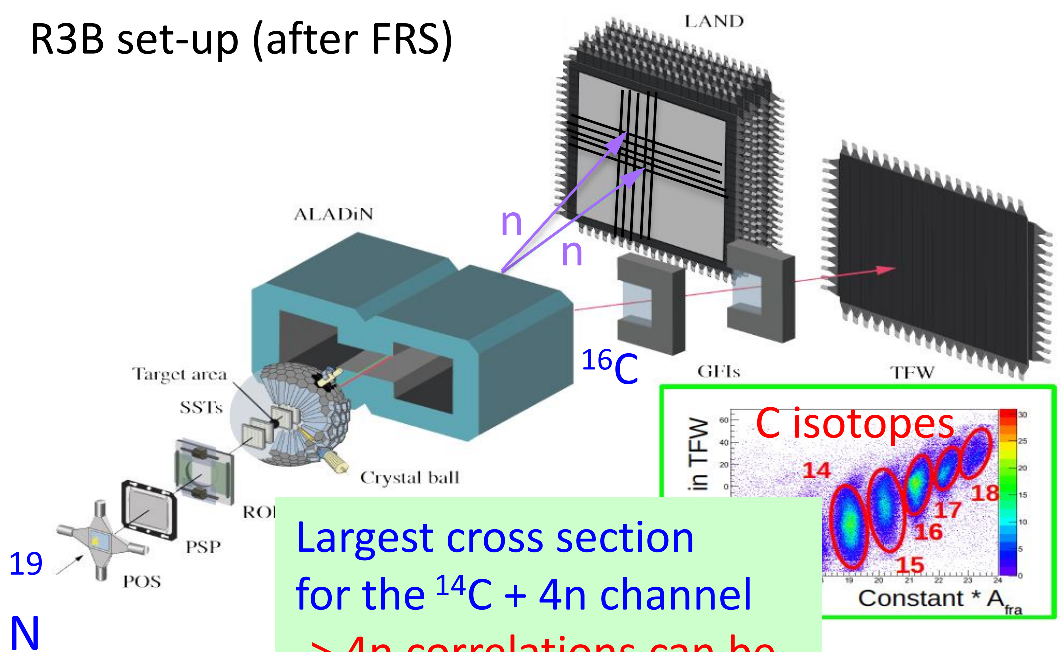
High-energy proton knockout:

Particularly well suited reaction mechanism to investigate 2n or 4n correlations:

Suddenly promotes neutrons into the continuum without affecting the n-n correlations!

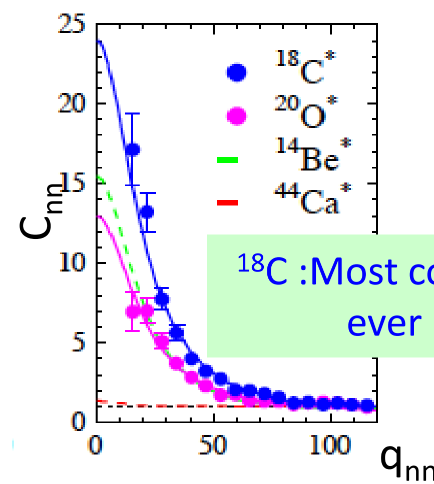
Need of high energy projectile beams ~400 A MeV!

R3B set-up (after FRS)



Largest cross section for the ^{14}C + 4n channel

-> 4n correlations can be investigated in the future

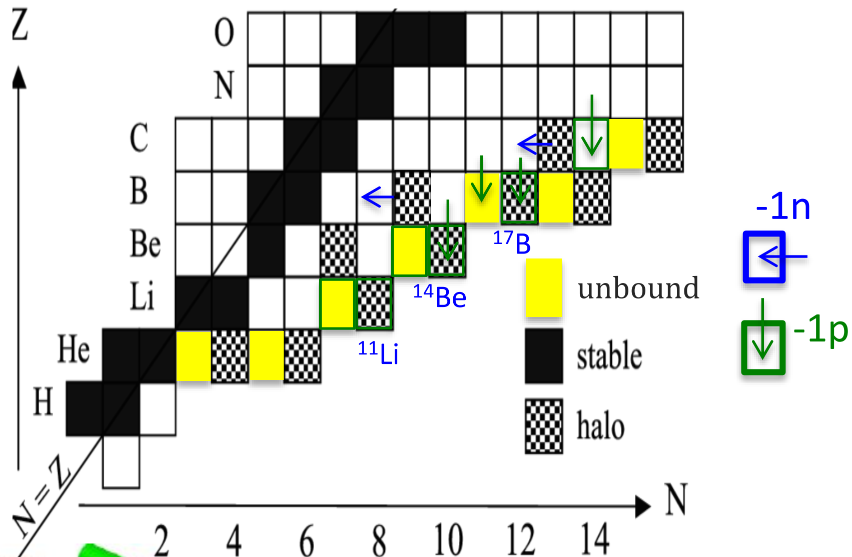


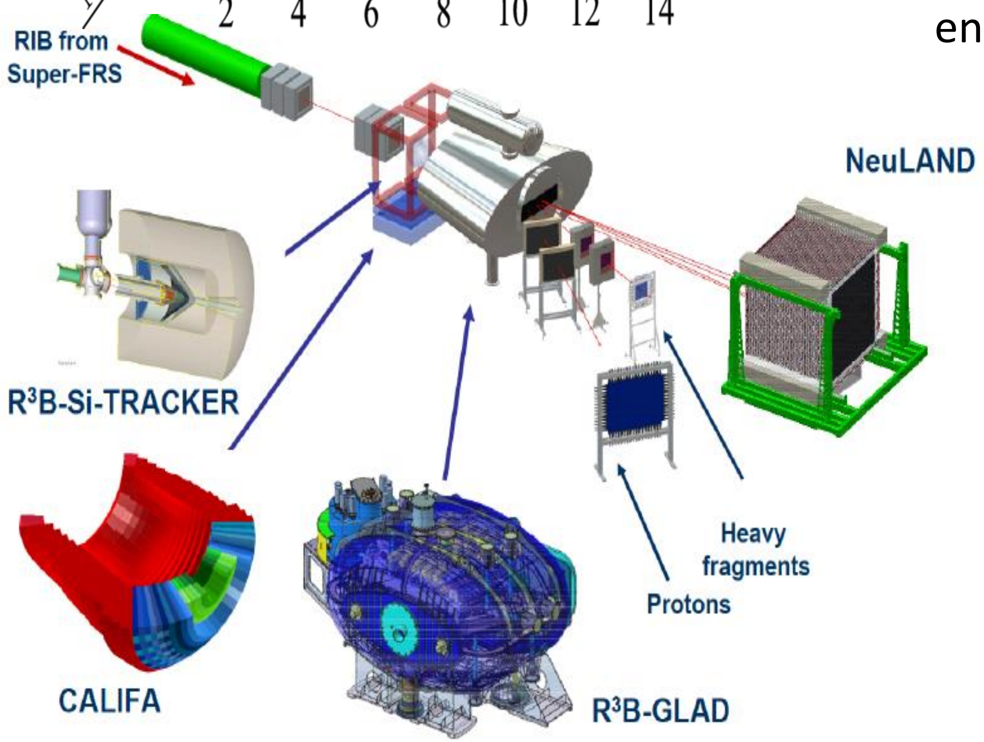
^{18}C :Most correlated system ever observed!

A. Revel et al. Phys. Rev. Lett . 120, 152504 (2018)

Future studies of 2n and 4n correlations in atomic nuclei at FAIR/GSI

Experiment accepted, planned in 2020





Program:

Use of quasi-free proton knockout mechanism to promote 1n, 2n or 4n in the continuum

Study of 2n or 4n correlations as a function of nuclear structure and the proximity of the drip line
-> Evolution of nuclear superfluidity

Spectroscopy of drip-line nuclei with excellent energy resolution -> shell evolution

Means:

Study of all steps of the reaction with full kinematics for ions and neutrons

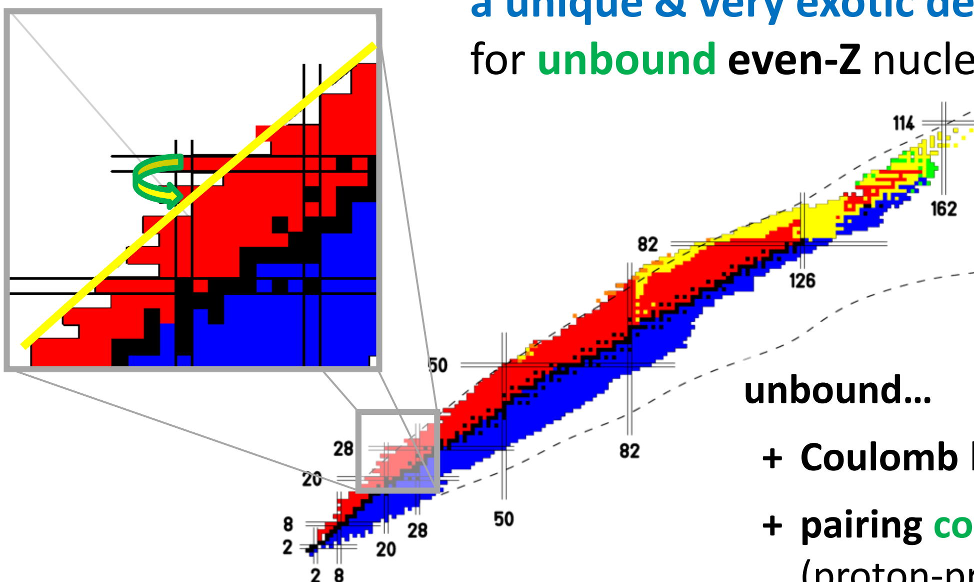
Very good (neutron) energy resolution (NEULAND), Highest efficiency worldwide

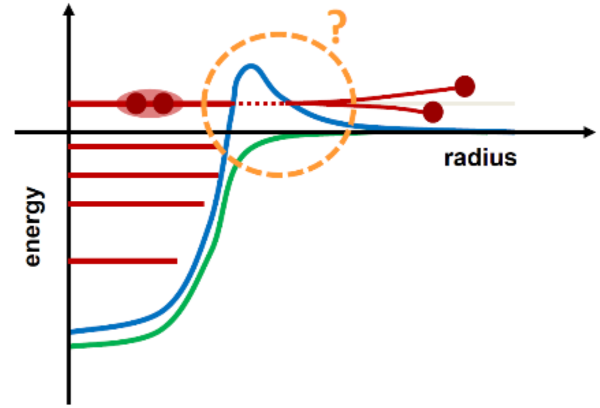
Good γ energy resolution and efficiency (CALIFA)

Two-proton radioactivity
J. Govinazzo, CENBG

2-proton radioactivity

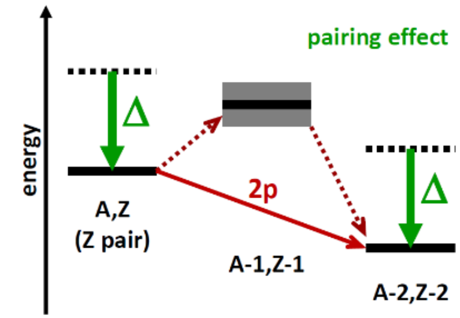
a unique & very exotic decay mode
for **unbound** **even-Z** nuclei





unbound…

- **+ Coulomb** barrier
- **+ pairing correlations** (proton-proton)



physics motivation (beyond drip-line)

- **pairing**
- **drip-line and masses**
- **tunnel effect**
- **nuclear structure**

- predicted in the 60's
  indirect evidence in the 2000's
  observed cases: ^{45}***Fe*** (GANIL, GSI), ^{48}***Ni*** (GANIL,NSCL), ^{54}***Zn*** (GANIL), ^{67}***Kr*** (RIKEN)
- correlations (tracking exp., TPC): ^{45}***Fe*** [+ poor data on ^{54}***Zn***]

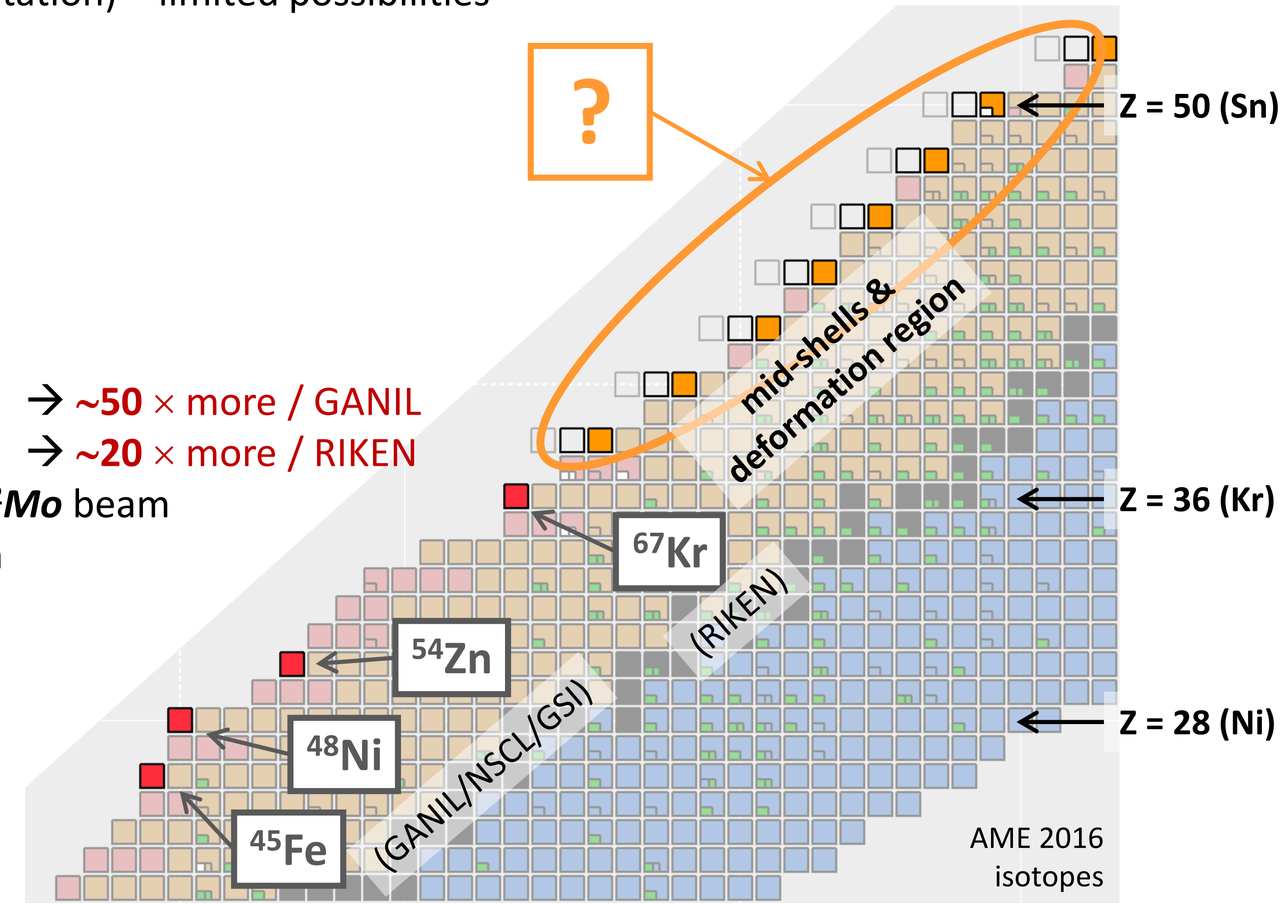
difficult theoretical interpretation

- combine decay **dynamics** & nuclear **structure**
- new calculations (deformation) → Gamow coupled channels

need for various cases
orbital configurations / deformation

2-proton radioactivity @ GSI/FAIR

- **current facilities** (proj. fragmentation) – limited possibilities
  - ▷ **GANIL** (95 MeV/A)
  - ▷ **NSCL** (160 MeV/A)
  - ▷ **RIKEN** (350 MeV/A)



- **FAIR (FRS / Super-FRS)**

  rate estimates (courtesy of B. Blank)

  ~70 ^{48}***Ni*** / day with ^{58}***Ni*** beam → **~50** × more / GANIL

  ~200 ^{67}***Kr*** / day with ^{78}***Kr*** beam → **~20** × more / RIKEN

  ~100 ^{71}***Sr***, ~60 ^{75}***Zr*** / day with ^{92}***Mo*** beam

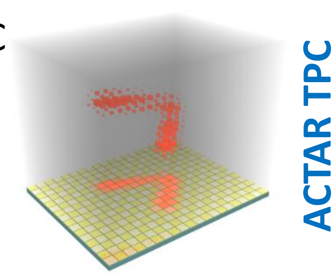
  ~10 ^{79}***Mo*** /day with ^{92}***Mo*** beam

  ~10 ^{98}***Sn*** /day with ^{124}***Xe*** beam

- **2-step experiments**
  - ▷ **search for candidates**

    decay identification (DSSD)

    → NUSTAR / DESPEC
  - ▷ **correlations (tracking exp.)** → ACTAR TPC
  - ▷ **equipment already available**



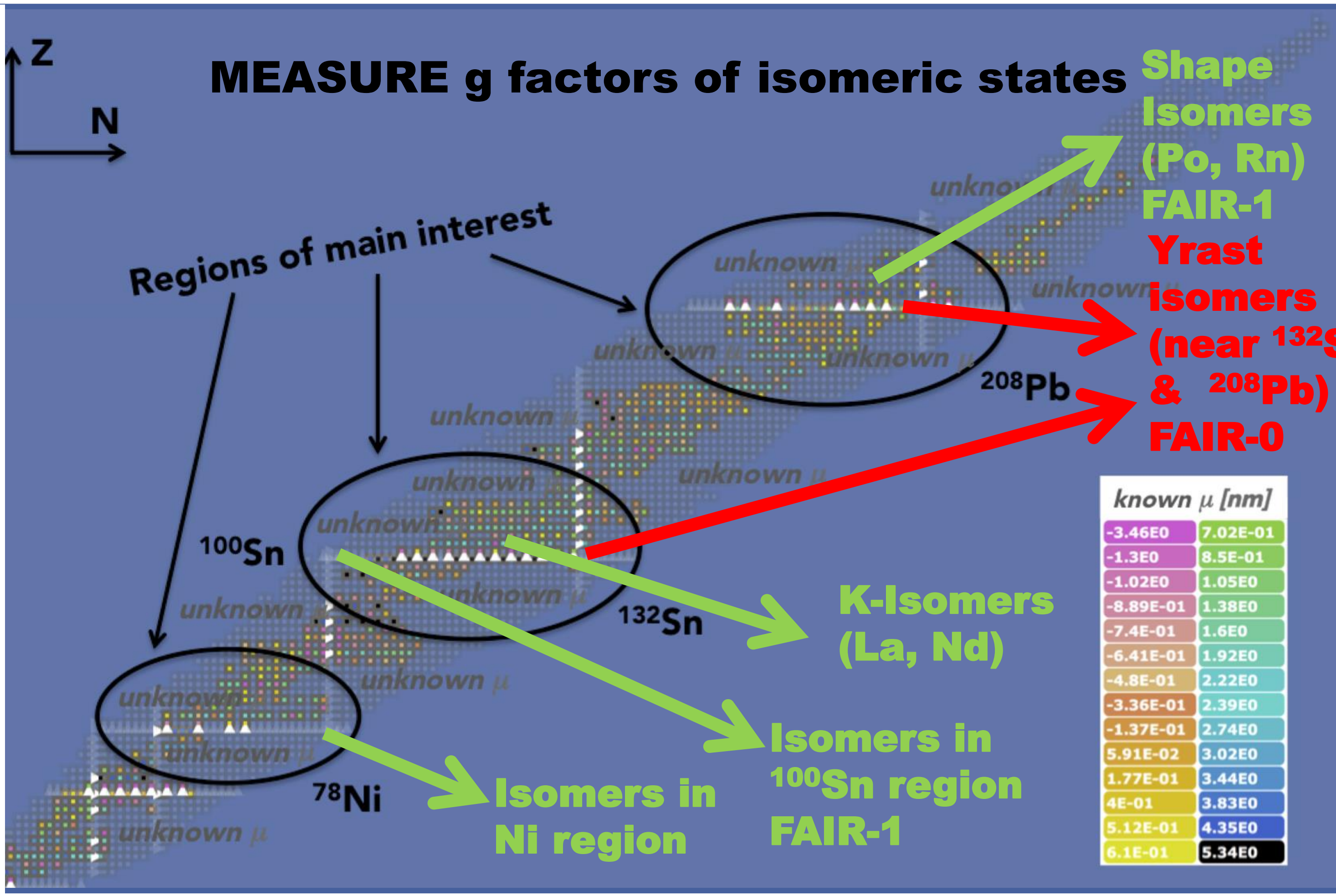
Nuclear magnetic moments of isomeric states
R. Lozeva, CSNSM

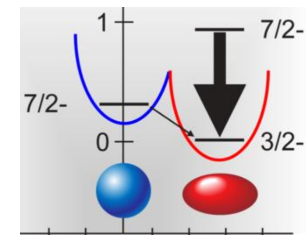
gSPEC@FAIR Scientific motivation

Unknown g factors for excited isomeric states : unknown configuration

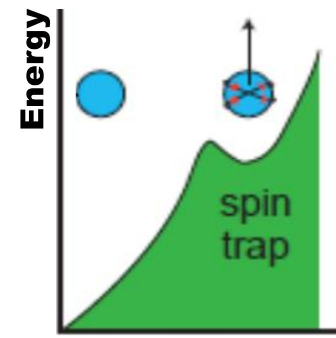
- g factor : the dimensionless magnetic moment, M1 operator
- measure of the valence nucleon configuration
- single-particle excitations, orbital evolution, development of collectivity & deformation

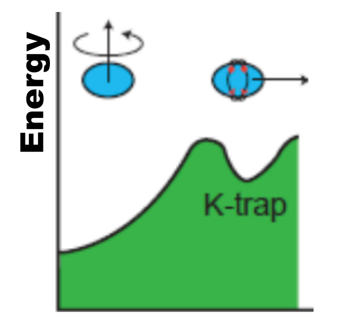
18 collaboration LoIs @gSPEC workshop 2018





Nuclear Shape
PRL 102, 092501 (09)





Nuclear Spin

HI 240, 55 (19) and references therein

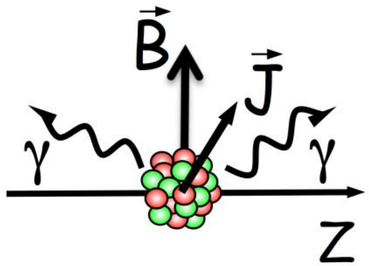
Nature 399, 35 (99)

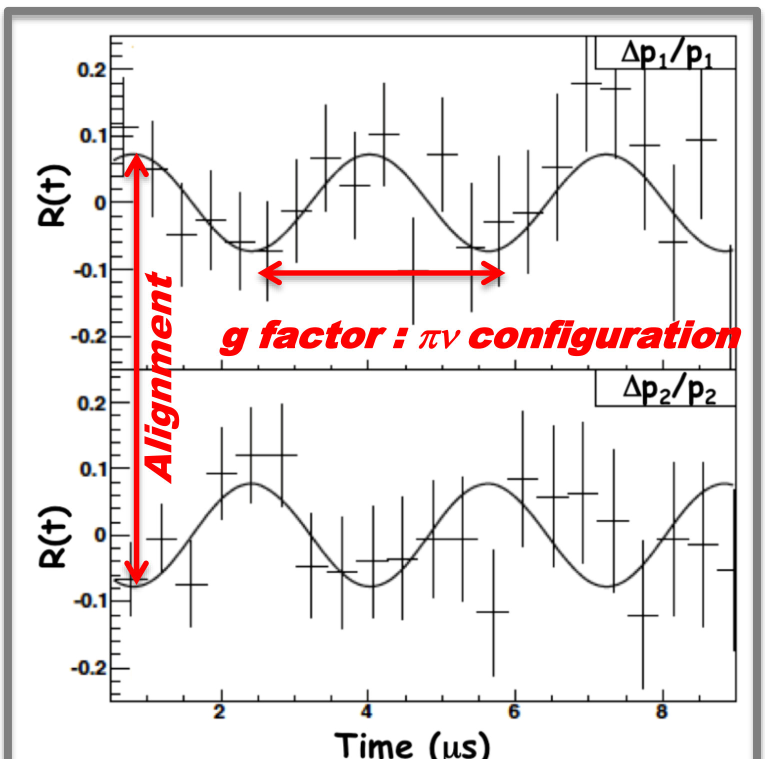
gSPEC@FAIR

Experimental method

Well established!

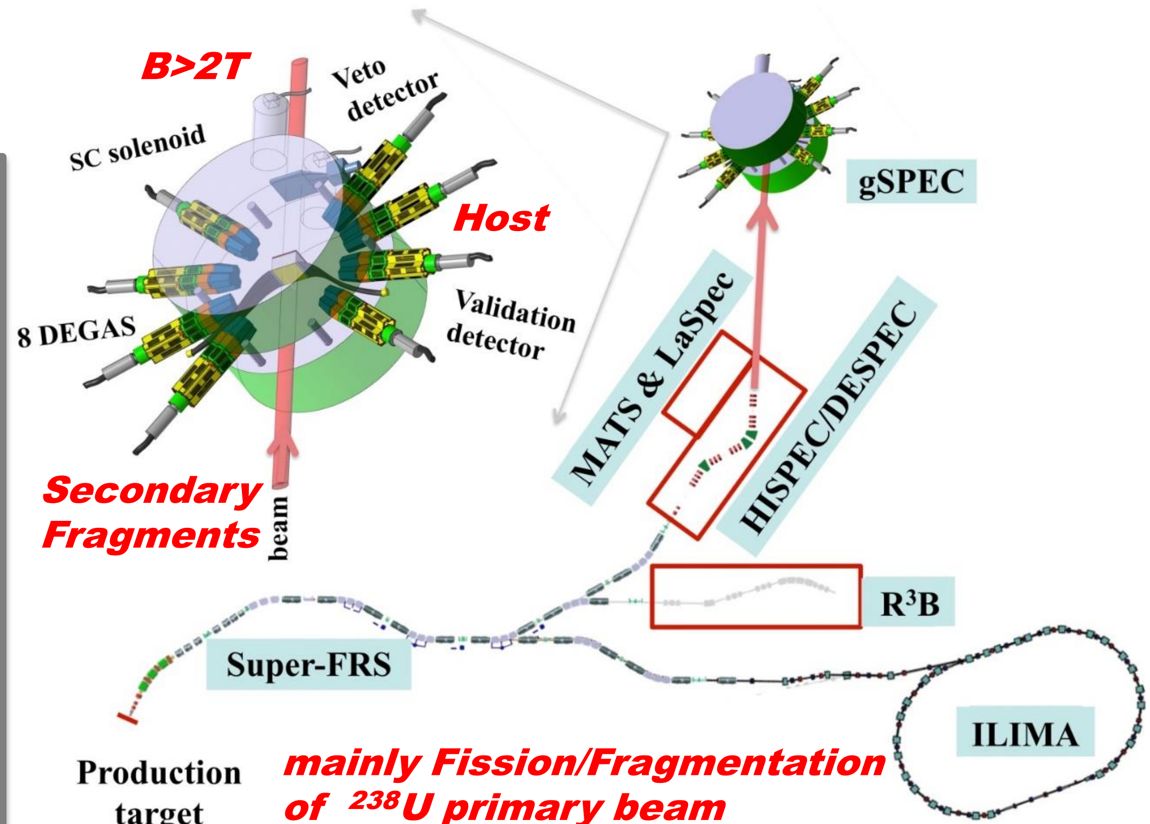
Spin (J) precession in Field (B)



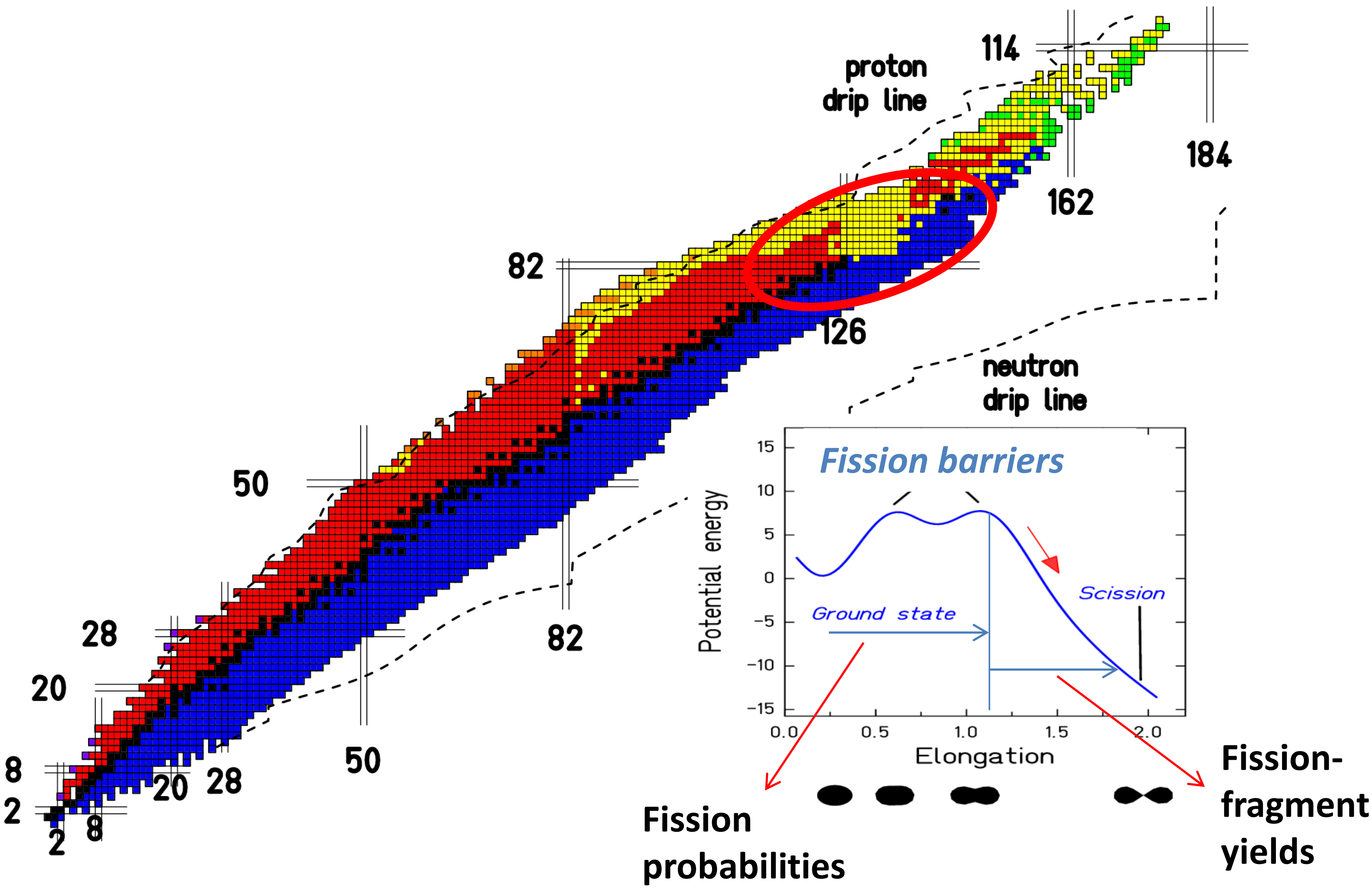


Main experimental SETUP

Magnet + HpGe detectors + ancillary
(x,y) detectors for high B + host => R&D needed!

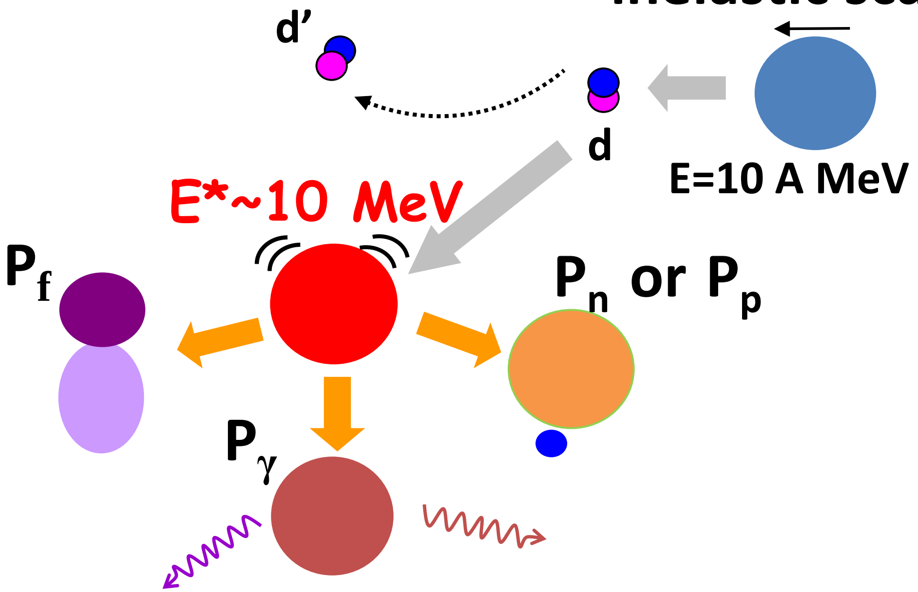


Nuclear fission, extreme deformation



High-precission decay-probability measurements at CRYRING
B. Jurado, CENBG

The interest of measuring decay probabilities induced by transfer or inelastic scattering reactions

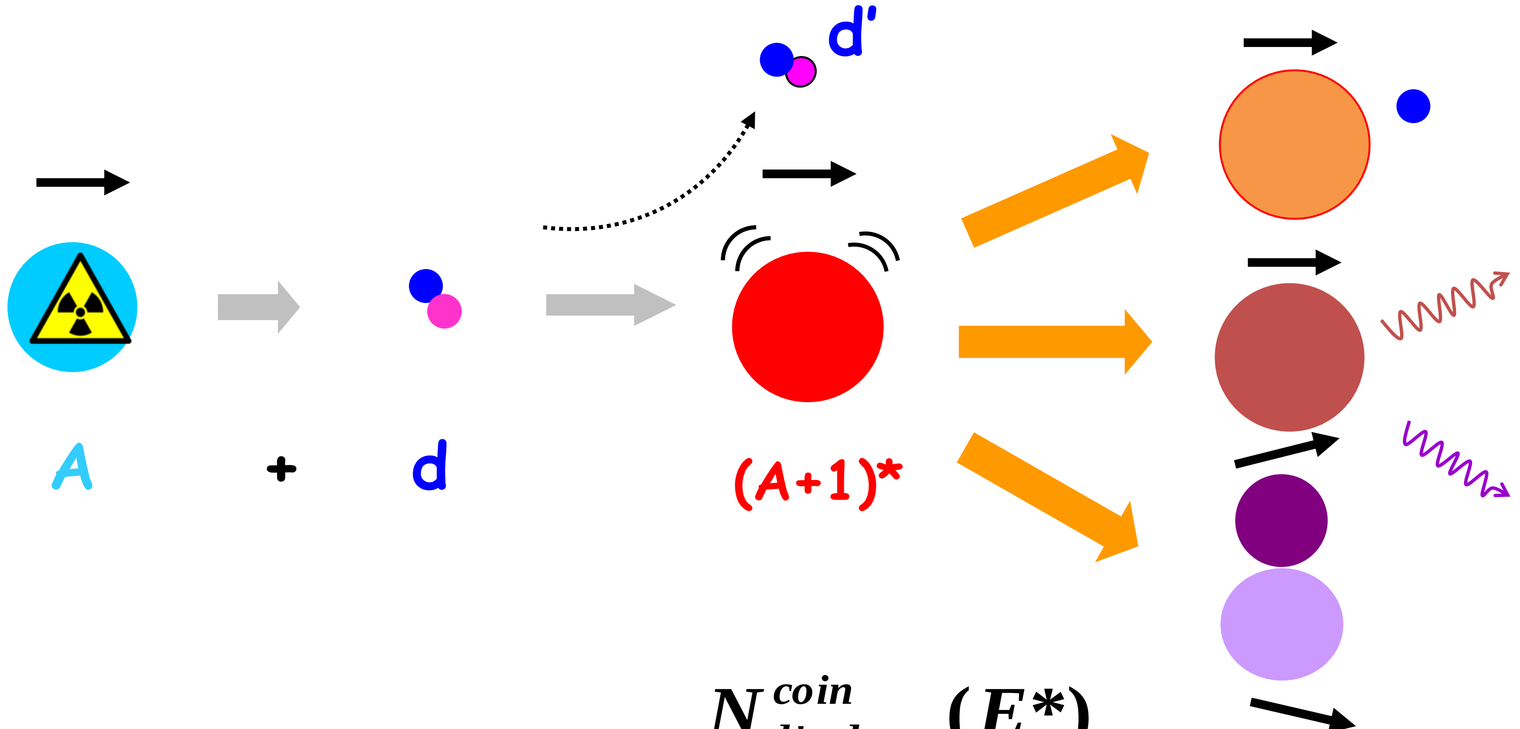


Decay probabilities depend on:
Low-lying level structure, fission barriers particle transmission coefficients, level densities, γ-ray strength functions, …
Model calculations for these quantities can completely diverge if no data are available!!

Transfer or inelastic scattering reactions in inverse kinematics make possible:
- Systematic studies with different reactions and in different regions
- Simultaneous measurement of all probabilities to completely constrain model calculations

Significant improvement of model predictions of n-induced cross-sections far from stability needed for e.g. understanding the origin of the elements in nuclear astrophysics!

Decay-probability measurements in inverse kinematics

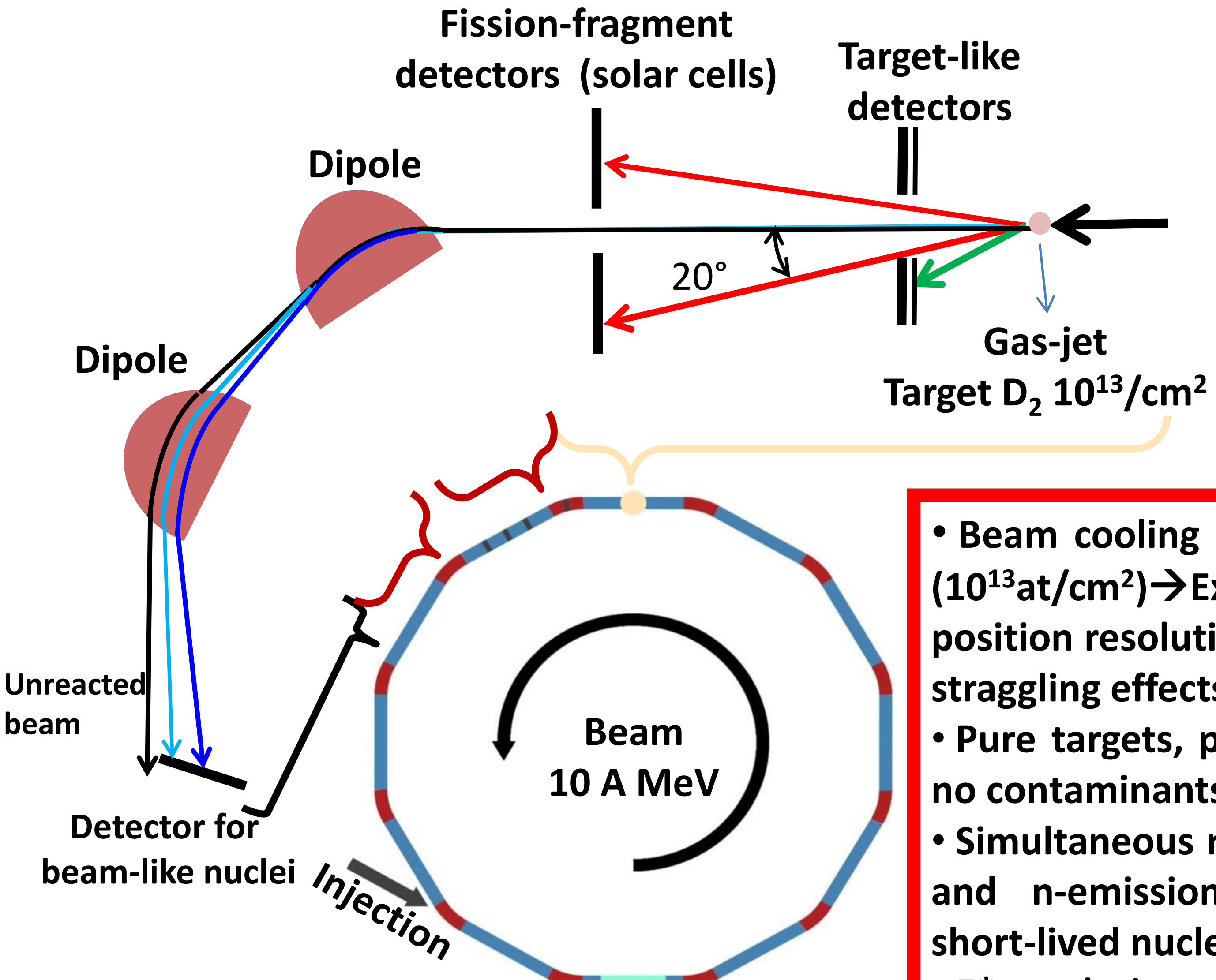


$$P_{decay}(E^*) = \frac{N^{coin}_{d'-decay}(E^*)}{N^{sing}_{d'}(E^*) \cdot \varepsilon_{decay}(E^*)}$$

Required E* resolution ~ few 100 keV!
Target contaminants and target windows have to be avoided!

STORAGE RINGS!

High-precision decay-probability measurements at CRYRING

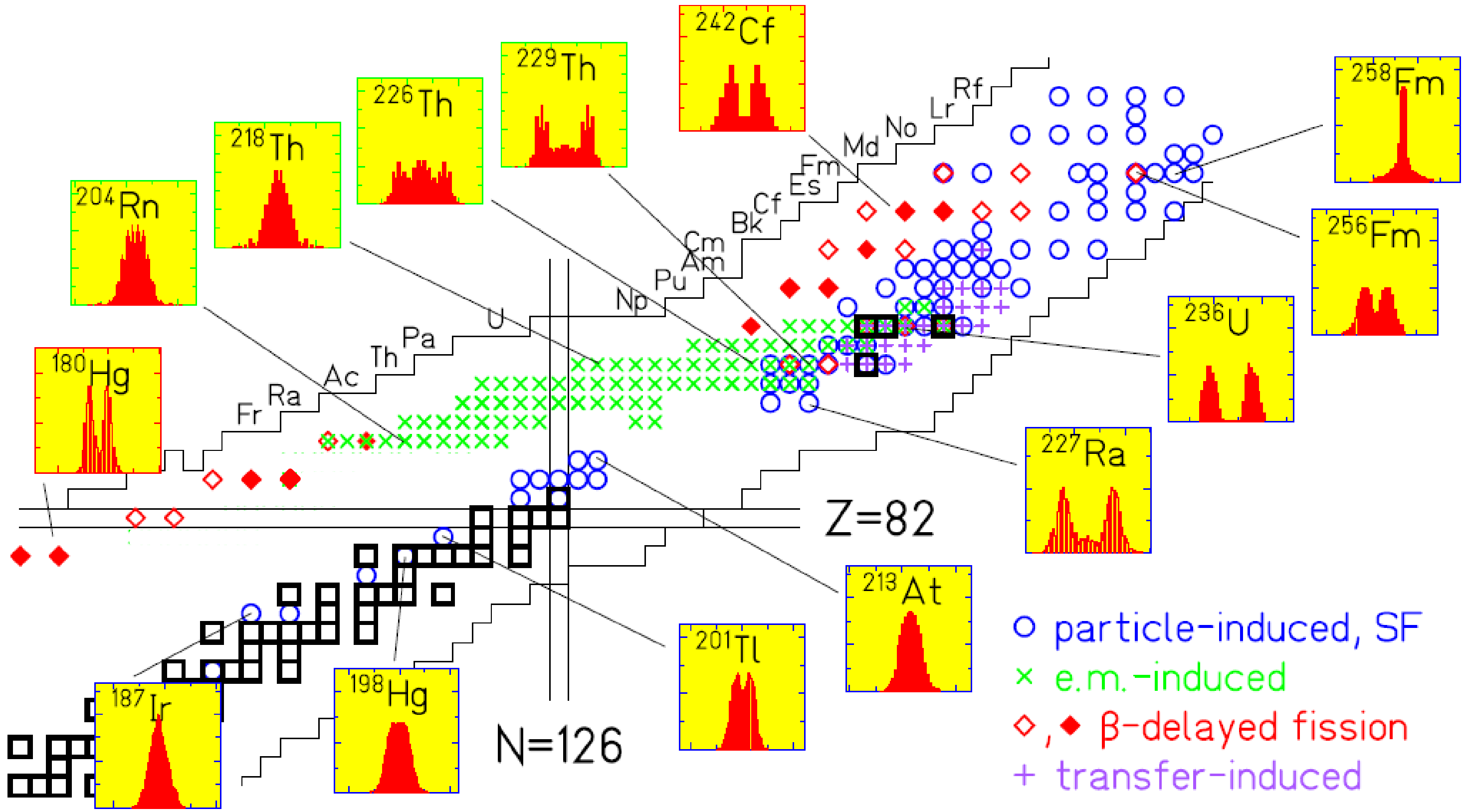


- Beam cooling & ultra-thin gas-jet target (10^{13}at/cm^2)→Excellent energy and position resolution of the beam, negligible straggling effects
- Pure targets, pure beams, (no windows, no contaminants)
- Simultaneous measurement of fission, γ- and n-emission probabilities of many short-lived nuclei
- E* resolution ~200 keV
- Nearly 100% detection efficiency for all reaction products

High-precision nuclear fission studies with SOFIA

L. Audouin, IPNO

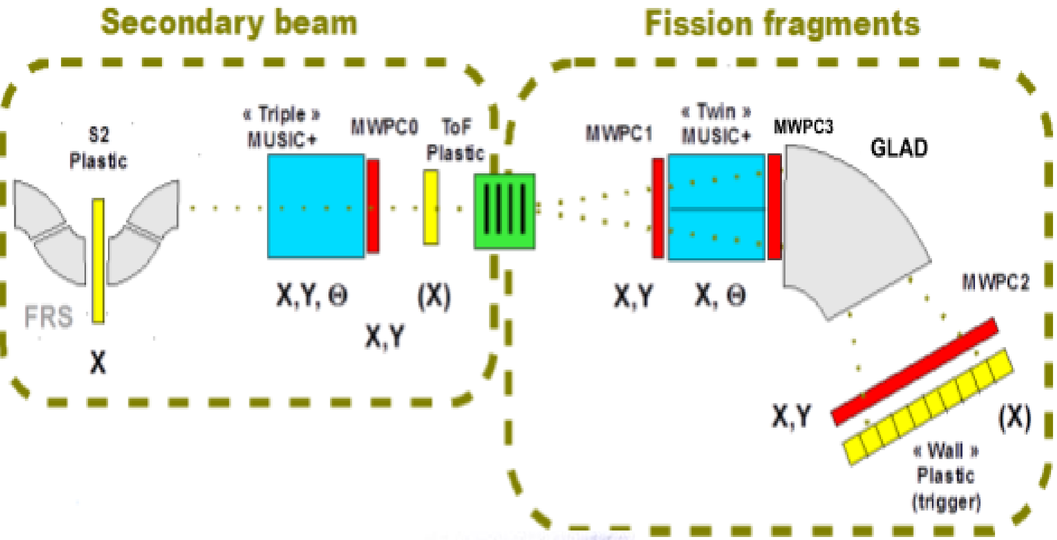
The big puzzle of fission fragment yields



•Asymmetric fission in the U-Pu region
Explained (recently!) by deformed (octupole) shell effects (Z~54)
Scamps & Simenel, Nature 564 (2018) 382
•Transition from asymmetric to symmetric fission in the Ra-Th region
•New asymmetric region around 180Hg!
•Lack of high-precision data in trans-uranium region
•Completely unexplored region of neutron-rich pre-actinides

SOFIA has contributed and will significantly contribute to understand the complexity of fission-fragment yields!

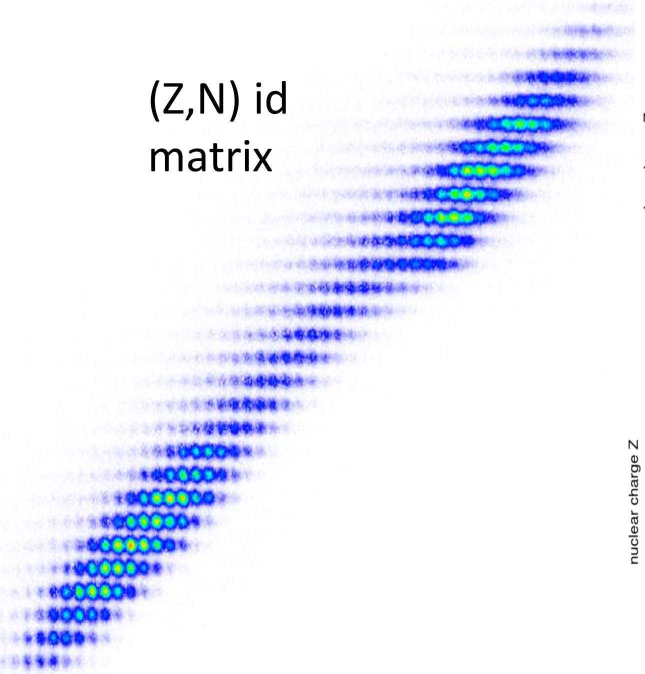
SOFIA@GSI/FAIR : a unique tool for fission studies

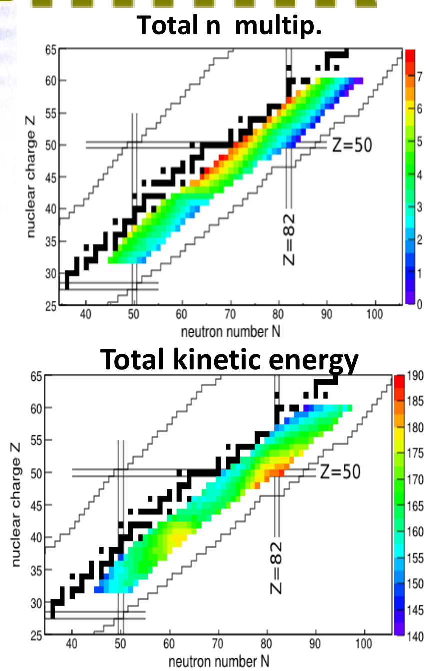


Strengths :

- Unique range of secondary beams (ms isotopes)
- Excellent selection and definition of the secondary beam (FRS)
- High fission efficiency due to extreme forward-focusing + large GLAD acceptance
- Identification (A, Z) of both fission fragments (ΔE-Bρ-ToF technique)
- Unprecedented Z resolution and excellent precision in A (tailored detectors + high kinetic energy)
- Event-by-event determination of the emitted neutron number
- Precise total kinetic energy measurement

(Z,N) id matrix





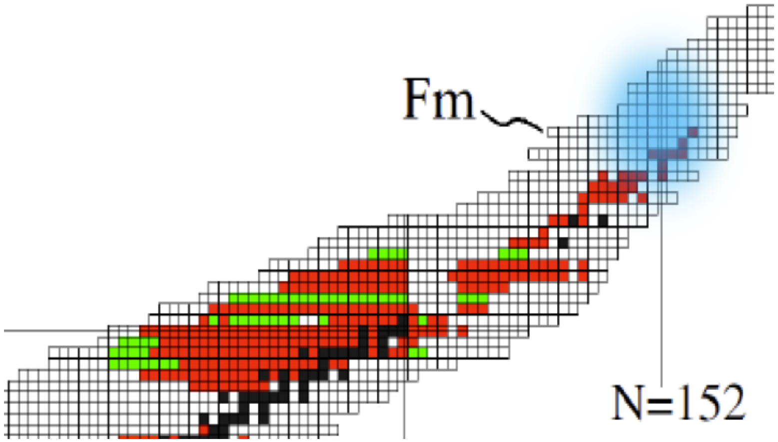
Experiment accepted to explore the 180Hg region in 2020!

A. Chatillon et al. Phys. Rev. C 99 (2019) 054628
E. Pellereau et al. Phys. Rev. C 95 (2017) 054603

High-resolution Laser spectroscopy of super-heavy nuclei

N. Lecesne, GANIL

High resolution laser spectroscopy of super heavy nuclei



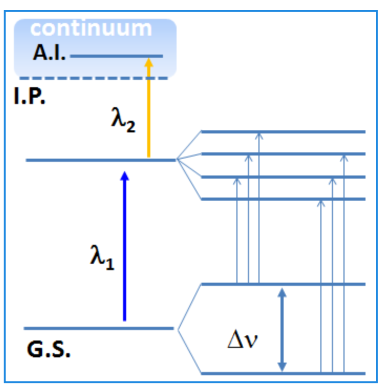
Blaum K., et al., Phys. Scr. T152 (2013) 014017

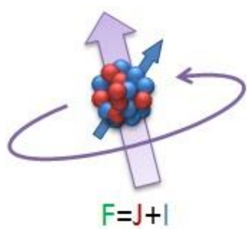
North-eastern limit of existence?
How do the magic numbers evolve?
Is there an island of stability?

Make use of the atomic structure of transfermium elements (Z>100) to infer nuclear properties of the heaviest elements (spin, moments, sizes, shapes)

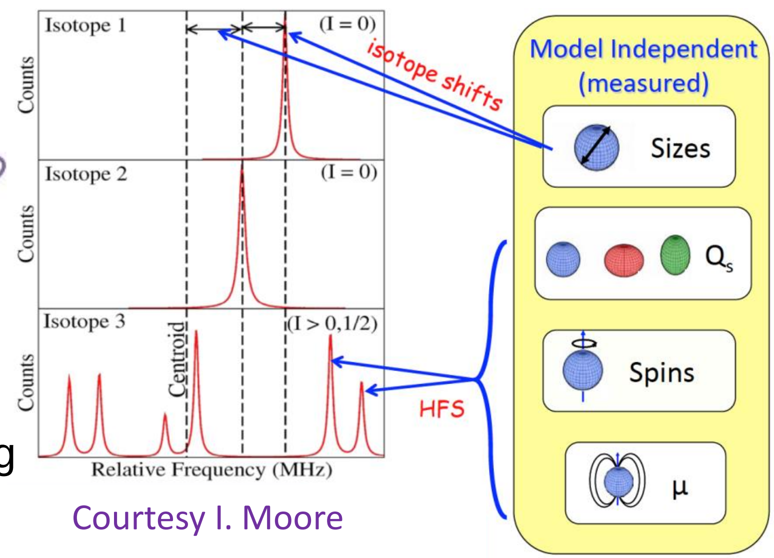
Synergies: atomic physics methods and nuclear structure studies

Resonant Ionisation Laser Spectroscopy





Hyperfine structure due to coupling of e$^-$ orbitals with nucleus



Courtesy I. Moore

- **Isotope shifts:** Change in the mean-square charge radii between the two isotopes
- **Hyperfine structure:** Nuclear spins and moments

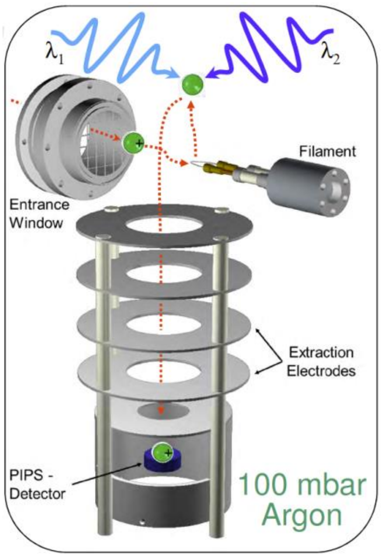
Model independent!

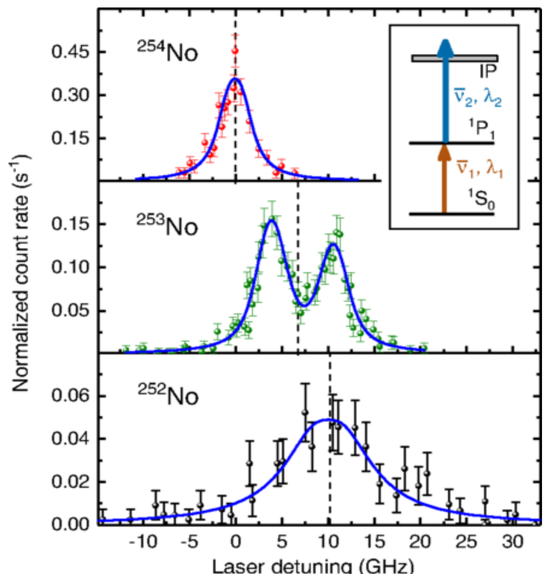
Laser spectroscopy of super heavy nuclei at SHIP

Very challenging!

Very low production cross sections and lack of knowledge on optical transitions

RADRIS (Radiation Detected Resonant Ionization Spectroscopy)





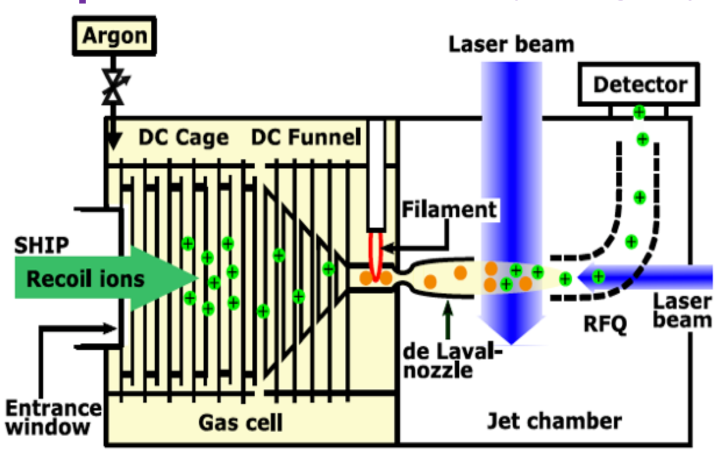
M. Laatiaoui et al., **Nature** (London) 538, 495 (2016)

P. Chhetri et al., **PRL** 120, 263003 (2018)

S. Raeder et al., **PRL** 120, 263003 (2018)

⇒**7 years were necessary to find the 1st No(Z=102) gs transition experimentally !**

Perspectives: New set-up, in-gas-jet resonance ionisation spectroscopy



⇒**Improved resolution**

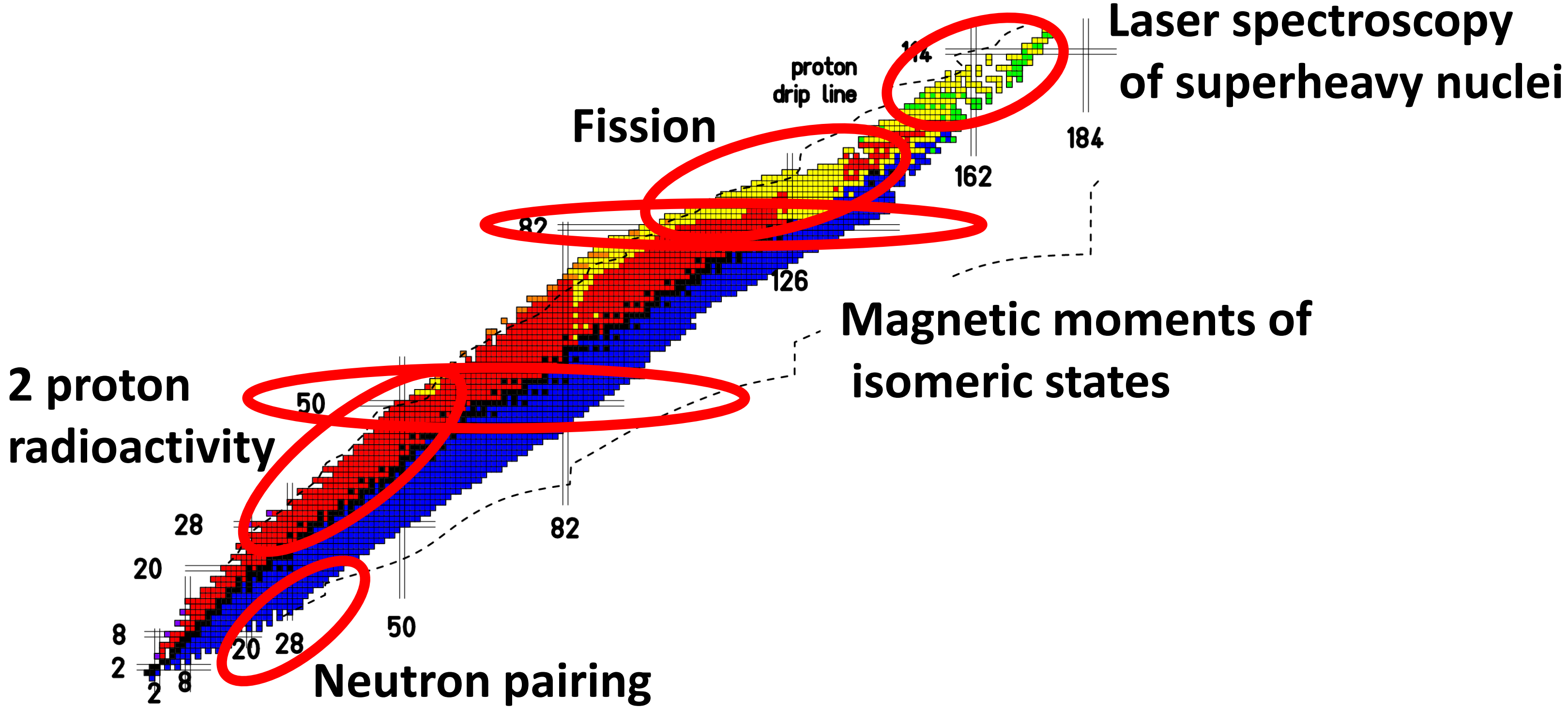
⇒**Experiments foreseen to study more exotic No isotopes and Lr (Z=103)**

⇒**New laser system 10kHz required**

⇒**Preparatory phase for S^{3}LEB at SPIRAL2**

Conclusions

•Six projects from IN2P3 researchers to be conducted between 2020-2024, within FAIR-Phase0



•GSI/FAIR is currently the only facility where the proposed experiments can be performed

•Most of the projects open bright perspectives for future measurements beyond FAIR Phase-0

Back-up slides
FAIR

Uniqueness of the NUSTAR Day-1 program

- **Understanding the 3rd r-process peak** by means of comprehensive measurements of lifetimes, masses, neutron branching ratios, dipole strength, and the level structure along the **N=126 isotones**;
- **Equation of State (EoS) of asymmetric nuclear matter** by measuring the dipole polarizability and neutron-skin thicknesses of **heavy neutron-rich isotopes** (in combination with the results of the first highlight);
- **Exotics**: **Hypernuclei** with large N/Z asymmetry and **nucleon excitations** in nuclei

Competitiveness of NUSTAR

- RIB energies and Super-FRS performance
  - Competitive luminosity and highest purity, in particular for heavy isotopes (Z>70)
  - New excitation modes accessible (“hypernuclei”)
  - High-resolution spectrometer mode (at 20 Tm)
- Storage ring experiments
  - World-wide unique range from keV to GeV
  - Largely unrivalled experience
- New and improved instrumentation, e.g.,
  - R3B dipole magnet
  - Cryogenic Stopping Cell for low-energy beams

The road towards FAIR MSV

Facility	U beam intensity/spill at production target	Luminosity [fb^{-1}]
Today at GSI with **FRS** (Phase 0)	1...2×10^{9}	~0,1
Super-FRS with upgraded **SIS18**	5×10^{9}	2
Commissioning phase **SIS100**	2×10^{10}	5
Full final intensity with **SIS100**	4×10^{11}	100

Phase 0 → **Day-1** → **Full MSV**

preparation → **discovery** → **detailed studies**

- **0.1 fb^{-1}** → **2-5 fb^{-1}** → **100 fb^{-1}**
- (near) stability → exotic → very exotic nuclei

GSI/FAIR expected intensities

	SIS-18	SIS-100
Reference primary ion	**U^{28+}**	**U^{28+}** / U^{92+}
Reference energy	**0.2**	**1.5** / 10 GeV/u
Ions per cycle	1.2E11	**4E11** / 1E10
cycle rate (Hz)	2.7	**0.5** / 0.1
Intensity (ions/s)	3E11	**2E11** / 1E9

Today= 2015

	UNILAC today	FAIR	2017
Reference primary ion	**U^{28+}/U^{73+}**	**U^{28+}**	**U^{73+}**
Current (mA)	5/1	15	3
Emittance, 4σ (h, mm mrad)	**7/7**	**5**	**7**
Momentum spread (2σ)	**1E-3/1E-3**	**5E-4**	**5E-4**

	SIS-18 today	FAIR design	2017
Reference primary ion	**U^{28+}/U^{73+}**	**U^{28+}**	**U^{73+}**
Reference energy GeV/u	0.2/1	0.2	1
Ions per cycle	**4E10/4E9**	**1.5E11**	**2E10**
cycle rate (Hz)	0.5 Hz	2.7 Hz	2 Hz
Long. dilution	**> 2**	**1.5**	**2**

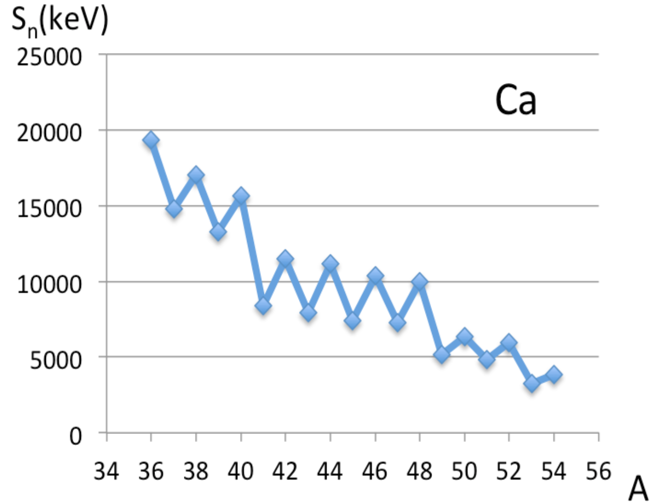
Construction of the SIS100 Tunels
May 2019

Back-up slides
O. Sorlin

Physics case: Signs of superfluidity and their evolution towards the drip line

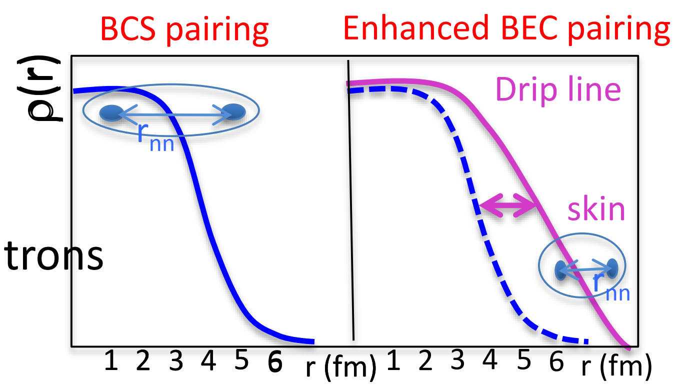
Pairing correlations play essential role in atomic nuclei and in neutron stars (NS)

- oscillations in S_n values
- g.s. spin 0^+ of even-even nuclei
- Moment of inertia << rigid value
- Enhanced pair transfer
- cooling of NS, glitches

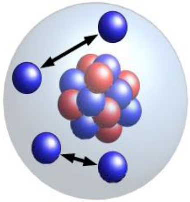


Evolution of pairing scheme towards drip-line, from BCS to BEC ? *(e.g. Hagino et al. PRL99 (200*

Few information available
-> Study of n-n correlations in various systems
-> Evolution with binding energy ?
-> Determine average distance r_{nn} between neutrons
-> Amount of sequential / direct decay

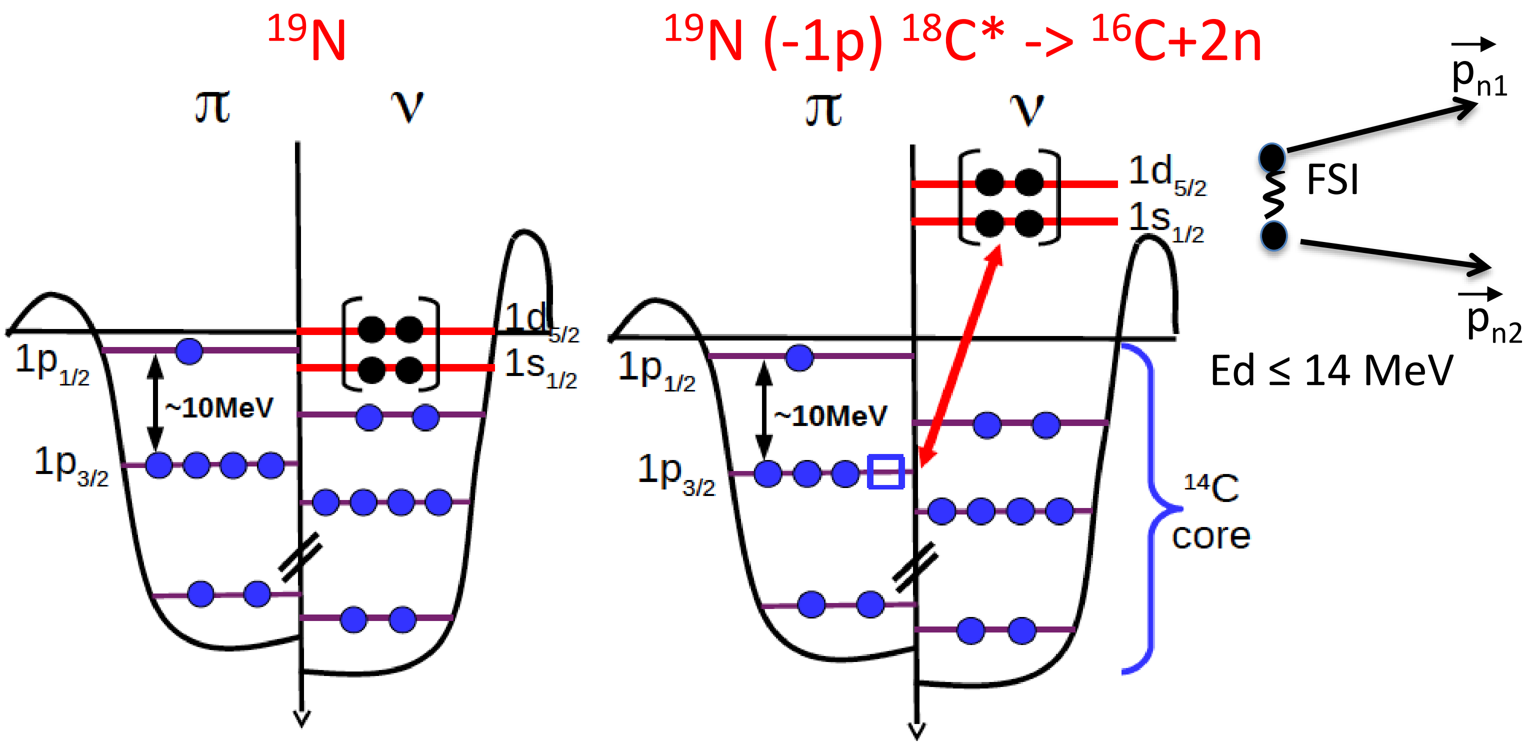


Possible existence of a narrow 4n resonance *(e.g. Marquès, Shimura)*
4n correlations could play a role in describing the nuclear superfluidity
-> Role not yet revealed or studied in atomic nuclei



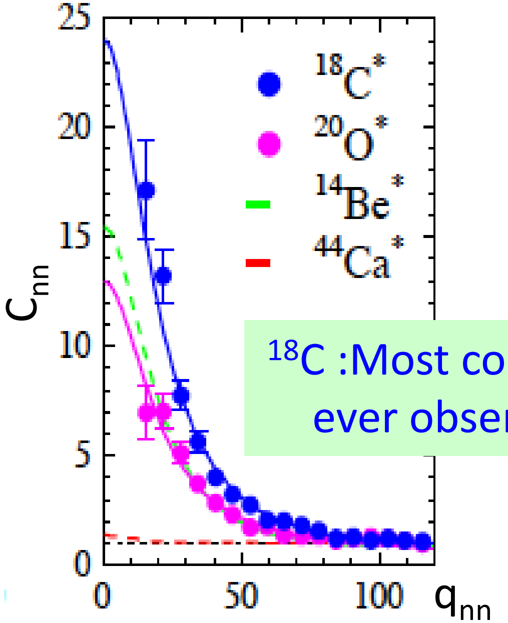
Previous work: Experimental method to study neutron correlations (in ^{18}C

$^{18}C \approx {}^{14}C$ core +4n valence neutrons

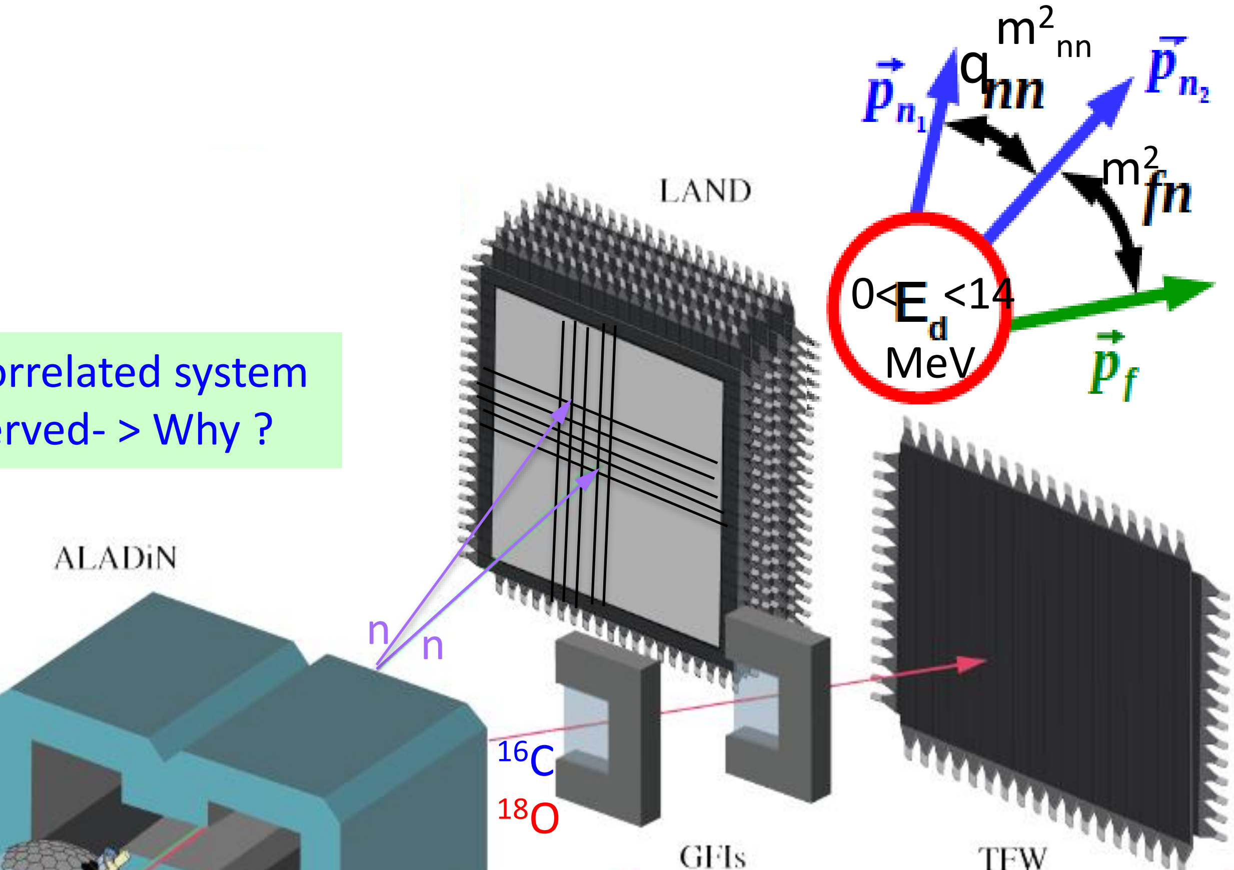


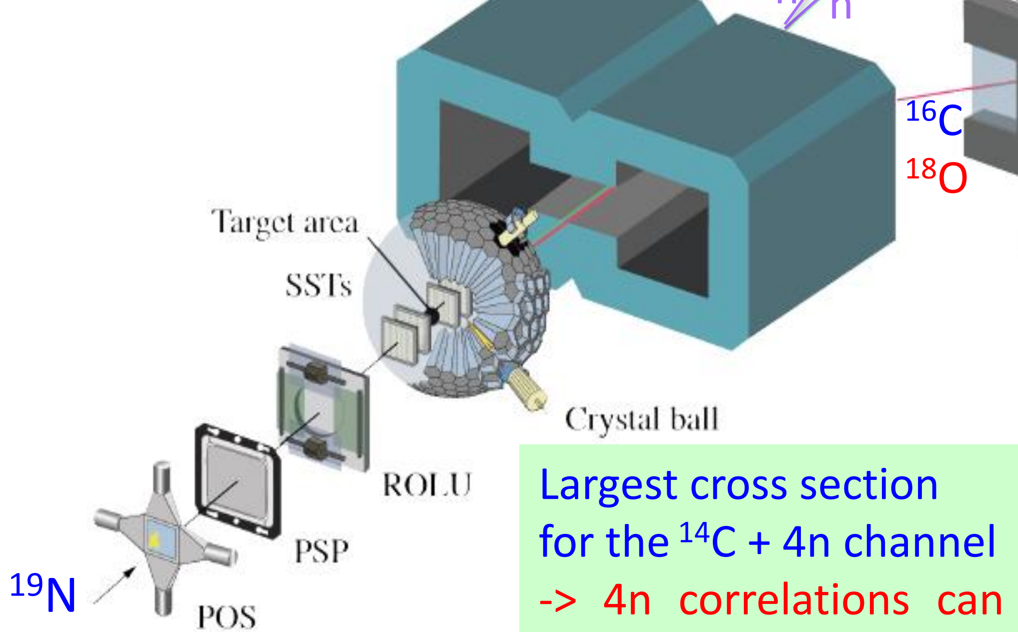
- High energy *proton* knock-out reaction (p,2p) at GSI (400A.MeV) *-> quasi-free mechanism*
- Deeply bound *proton* orbitals *-> energy piston to promote neutrons into the continuum*
- Sudden approximation *-> neutron correlations weakly affected by proton knock-out*
- Deduce information on the n-n correlations from their observed decay patterns

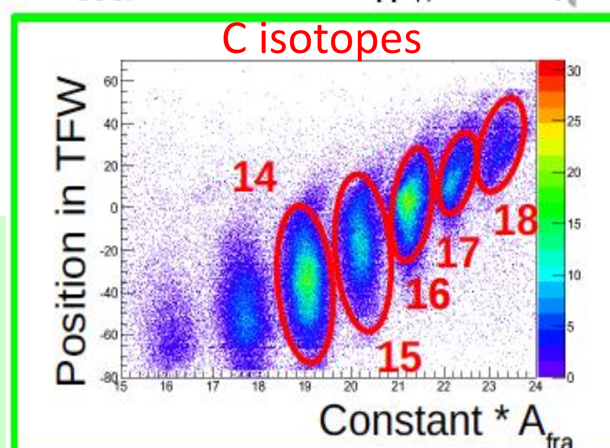
Results: Study of n-n correlations in ^{18}C and ^{20}O at R3B



^{18}C :Most correlated system ever observed- > Why ?

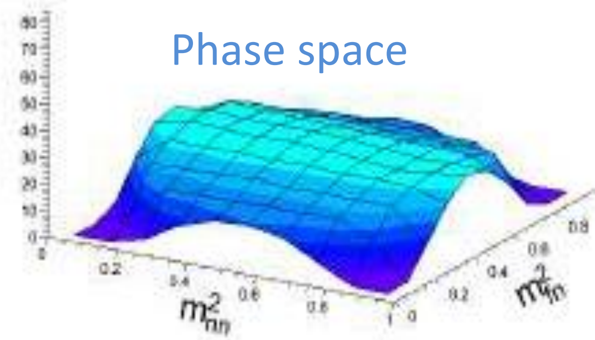


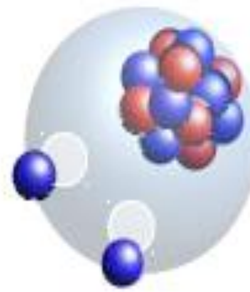




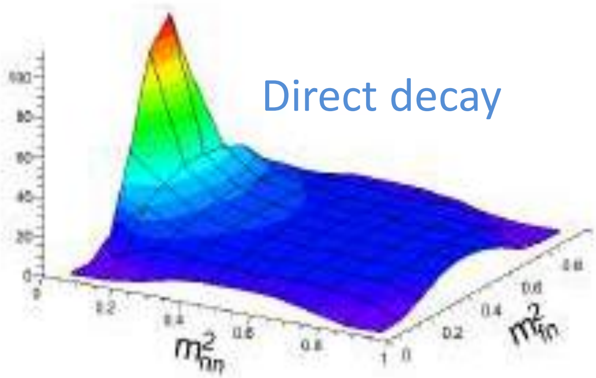
Largest cross section for the ^{14}C + 4n channel
-> 4n correlations can be

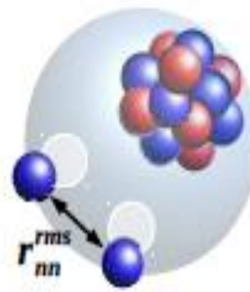
Results: Dalitz plots and n-n correlations in ^{18}C and ^{20}O (core + 4n syste

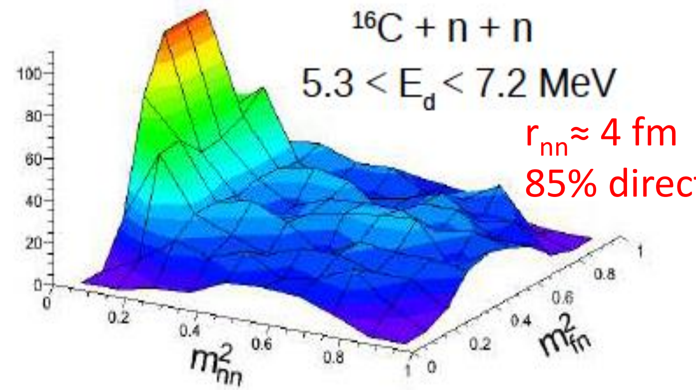


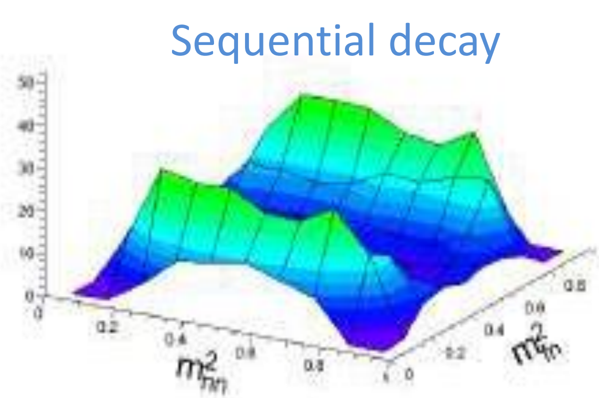


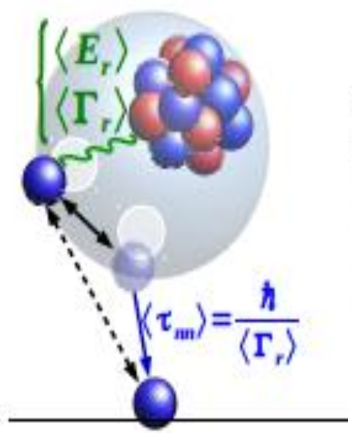
A. Revel et al Phys. Rev. Lett. 112 (2018)

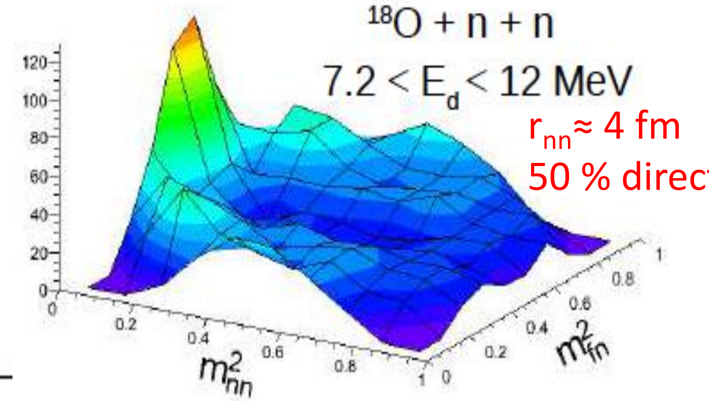






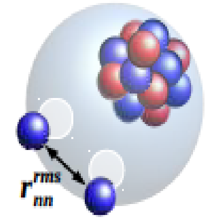




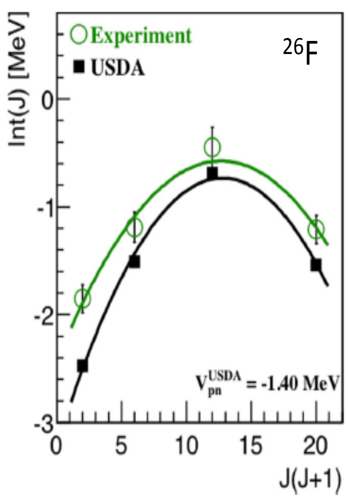


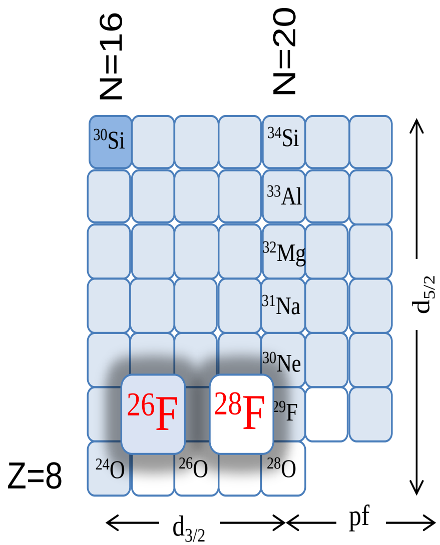
Summary of results from the previous experiment

Two-neutron correlations in the ^{18}C, ^{20}O isotones
(A. Revel et al. Phys. Rev. Lett . 120, 152504 (2018)



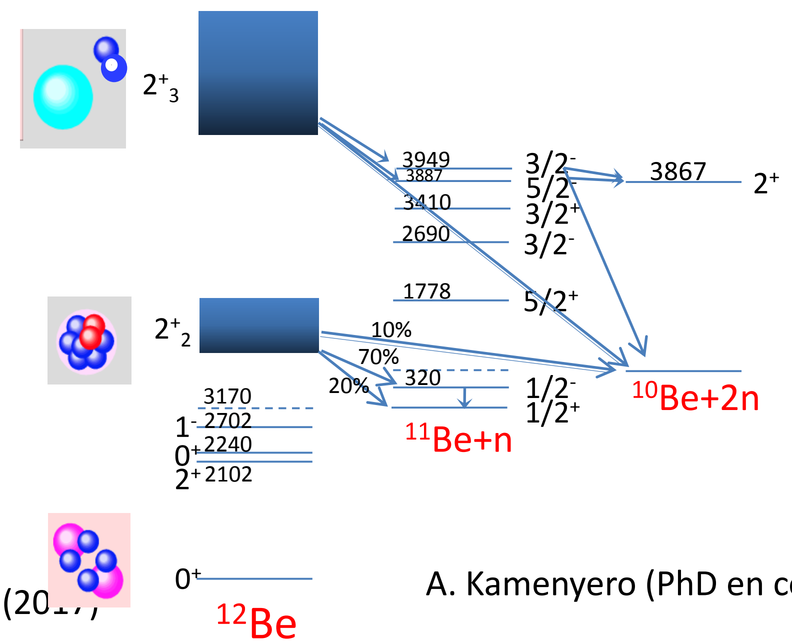
Study of pn interaction at the drip line





M. Vandebrouck, A. Lepailleur et al., Phys. Rev. C 96, 054305 (2017)

Study of the multi-facets ^{12}Be nucleus



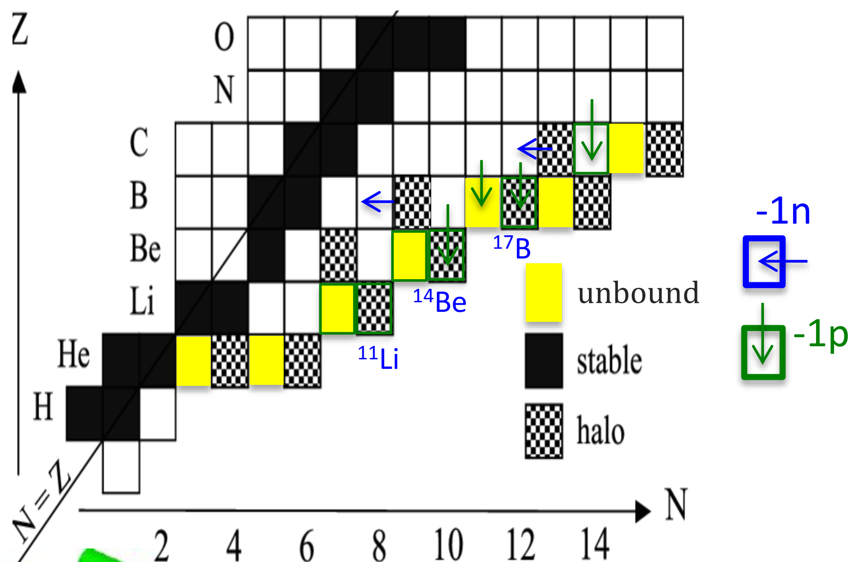
A. Kamenyero (PhD en cours)

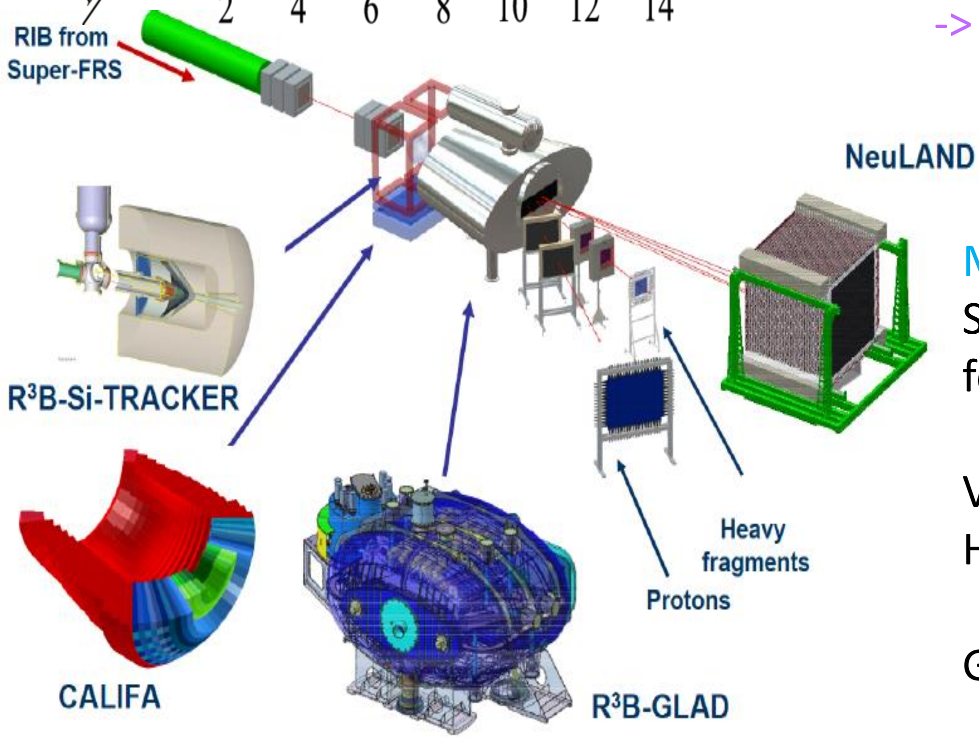
As one experiment produces a cocktail of nuclei and many reactions, it leads to several PhD thesis (3 from IN2P3 on different topics, in addition to other PHD from the collaboration)

At least two more results to be published on mirror symmetry in ^{15}C - ^{15}O and the influence of the coupling to continuum in ^{14}B

Study of 2n and 4n correlations in atomic nuclei at FAIR/GSI

Planned studies 2020 (core+4n, haloes, drip-line)





Program:

Use of quasi-free proton knockout mechanism to promote 1n, 2n or 4n in the continuum

Spectroscopy of drip-line nuclei with excellent energy resolution -> shell evolution

Study of 2n or 4n correlations as a function of nuclear structure and the proximity of the drip line
-> Evolution of nuclear superfluidity

Means:

Study of all step of the reaction with full kinema
for ions and neutrons

Very good (neutron) energy resolution (NEULAN
Highest efficiency worldwide

Good γ energy resolution and efficiency (CALIFA

Type	2020	2021	2022	2023	2024	total
NeuLAND double planes or Califa detectors	30 (1)	30	30	30	30	150 k€
Travel (k€)	3 (2) +1.5 (3)	2.5 (3+4)	2.5 (3+4)	2.5 (3+4)	2.5 (2)	14.5 k€
PhD (k€)		40	40	40		120 k€
Senior with student	1	1	1	1	1	5 k€
Total (k€)	35.5	73.5	73.5	73.5	33.5	289.5 k€

(1) Yearly contribution to buy 1 double plane of NeuLAND or two ring of CALIFA array in 5 years.

(2) For running our accepted experiment supposed to be scheduled in 2020.

(3) For 2 yearly R3B collaborations (6 people in total)

(4) For the participation of the IN2P3 researchers to other experiments of the collaboration

Human resources	2020	2021	2022	2023	2024	total
Researchers (2 GANIL+ 3 IPNO + 1 LPC) spokesperson	0.8 0.3	0.2 0.2	0.2 0.2	0.8 0.3	0.2 0.2	2.2 1.2
PhD	0.9	0.9	0.9	0.9	0.9	4.5
Total	2	1.3	1.3	2	1.3	8.9

Estimated counted time are for running experiments, attending R3B meeting, participating to tests or other experimental programs. It is assumed that another proposal will be deposited in the period (2021), with another experiment running in 2023. As for student's work, the time includes data analysis as well.

Timeline and scientific production

2011: Participation to experimental campaign with Aladin/LAND

2016: Study ^{26}F and probe the strength of the proton-neutron interaction, 1 publication

2018: Neutron pairing in ^{18}C and ^{20}O, 1 publication (PRL)

2019: The multiple facets of the ^{12}Be nucleus, PhD thesis, work in progress

2017: Proposal approved by the GSI PAC to investigate several nuclei close to the drip line

2020: Expected schedule of the experiment

2021-…**:** Participation to experiments of the collaboration, new proposals to be presented.

SWOT analysis

SCIENCE / HUMAN RESOURCES

strength

Full kinemtics of the reaction, The best existing neutron detector array

Many students in different countries can share analysis

Large european community involved in R3B

French physicists involved in the program already involved in other facilities

weakness

Not yet involved in technical development and tests. Modest knowhow on detectors / electronics / mechanics

opportunity

Big investment from CEA (magnet + cryogenic target)

Different scientific topics to be carried out with this beam line (incl. Fission)

Cross fertilize exchanges between different communities

Super FRS in 2023

threat

Unequal engagment in terms of budget and physicists ifrom France as compared to ther countries

Competition with RIKEN:
-> need to better define the contours of each scientific programs.

Additional slides
J. Giovinazzo

2-proton radioactivity – main exp. results

1996	^{45}*Fe* observation	GSI	**PRL 77**, B. Blank *et al.*
2000	^{48}*Ni* observation	GANIL	**PRL 84**, B. Blank *et al.*
2002	2P radioactivity (indirect) of ^{45}*Fe*	GANIL	**PRL 89**, J. Giovinazzo *et al.*
2002	2P radioactivity (indirect) of ^{45}*Fe*	GSI	EPJA 14, M. Pfützner *et al.*
2005	observation and 2P (indirect) of ^{54}*Zn*	GANIL	**PRL 94**, B. Blank *et al.*
2007	direct obs. of ^{45}*Fe* 2P decay	GANIL	**PRL 99**, J. Giovinazzo *et al.*
2007	*angular correl. in ^{45}Fe 2P decay*	*NSCL*	*PRL 99, K. Miernik et al.*
2011	direct obs. of ^{54}*Zn* 2P decay	GANIL	**PRL 107**, P. Ascher *et al.*
2011	*direct obs. of ^{48}Ni 2P decay*	*NSCL*	*PRC 83, M. Pomorski et al.*
2016	^{67}*Kr* observation	RIKEN	**PRC 93**, B. Blank *et al.*
2016	2P radioactivity (indirect) of ^{67}*Kr*	RIKEN	**PRL 117**, T. Goigoux *et al.*

IN2P3 / CENBG not involved
IN2P3 / CENBG involved
IN2P3 / CENBG leading

	2020	2021	2022	2023	2024	2025+	total
Researchers **- CENBG** **- ACTAR TPC** **- other IN2P3**	 **0.1**	 **0.1**	 **0.2**	 **0.4** **0.1**	 **0.8** **0.2** **0.2**	 **0.8** **0.3** **0.2**	 **2.4** **0.6** **0.4**
Engineers **- CENBG** **- ACTAR TPC**				 **0.1** **0.1**	 **0.1** **0.2**	 **0.1** **0.2**	 **0.2** **0.5**
PhD (if any)					**0.9**	**0.9** **(+2026)**	**2.7**
Collab. from abroad (incl. ACTAR TPC)					**0.3**	**0.5**	**0.8**
Total	**0.1**	**0.1**	**0.2**	**0.7**	**2.7**	**3.8**	**7.6**

type	2020	2021	2022	2023	2024	…	total
equipment					10 k€ (ACTAR TPC coupling)		10 k€
travel	1 k€(1)	1 k€(1)	2 k€(1)	2 k€(1)	15 k€(2)	15 k€(2) / exp	36 k€ (up to 2025)
PhD					40 k€(3) × 3 years	40 k€(3)	120 k€
total	1 k€	1 k€	2 k€	2 k€	65 k€	…	166 k€

- (1)for meetings with the NUSTAR collaboration, proposals preparation and PAC meeting.
- (2) for the participation of the IN2P3 researchers to the experiments: the year is an indication, but cannot be given precisely.
- (3) a first PhD is requested for the participation and analysis of the first experiments, but another PhD will be needed for the ACTAR TPC experiments.

2-proton radioactivity @ GSI/FAIR – SWOT analysis

	positive	negative
internal	**strengths** • **known exp. techniques** - standard impl./decay technique - ACTAR TPC tested • **very limited investment** • **strong visibility of IN2P3**	**weaknesses** • **manpower for analysis** (PhD funding…)
external	**opportunities** • **unprecedented prod. rates** • **join NUSTAR collaboration**	**threats** • **beam time / accepted exp.** • **beam availability**

2-proton radioactivity @ GSI/FAIR – timeline

2019 2020 2021 2022 2023 2024 2025

GANIL prog. (^{48}**Ni**/^{54}**Zn** correl./ACTAR TPC)

RIKEN prog. (^{67}**Kr** correl./ACTAR TPC)

FAIR

join NUSTAR collab., prepare proposals
(travel)

new candidates exp.
(travel, PhD…)

FRS

Super-FRS

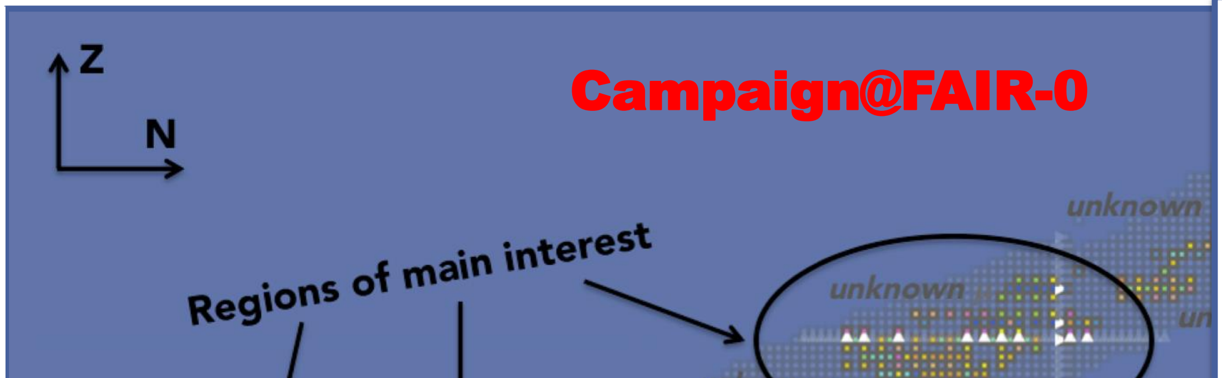
correlation exp.
(travel, PhD, engineers, setup adaptation…)

Backup gSPEC

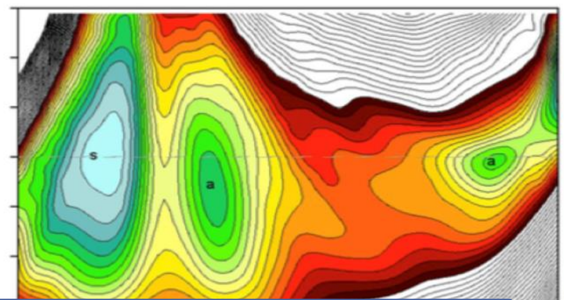
gSPEC@FAIR Scientific motivation

Unknown g factors for excited isomeric states : unknown configuration

- **g factor : the dimensionless magnetic moment, M1 operator**
- **measure of the valence nucleon configuration**
- **single-particle excitations, orbital evolution, development of collectivity and deformation**

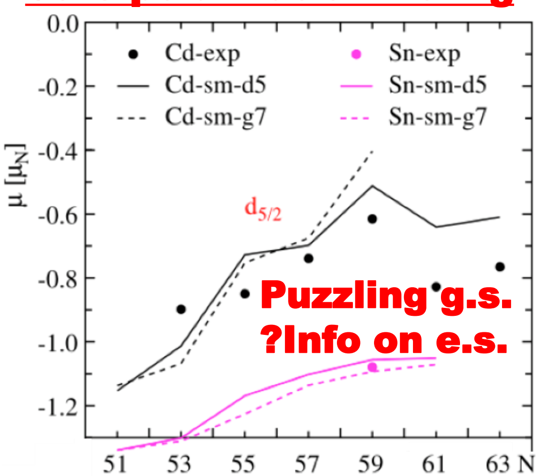


g factors of shape isomers
^{208}Pb region (Po-Rn)
=> deformation/shapes



PRL 78, 2920 (97)

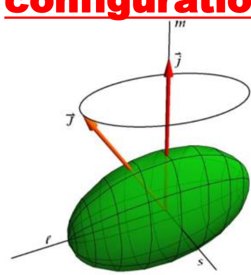
Isomers in ^{100}Sn region
=> $\pi\nu$ interaction, pairing
core polarization from g



Puzzling g.s.
?Info on e.s.

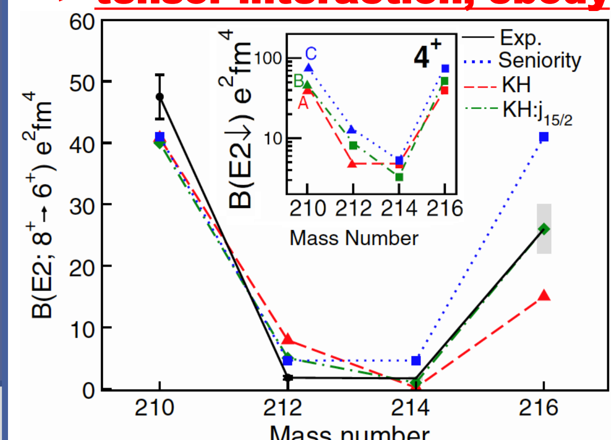
PRC 98, 011303(R) (18)

K-isomers
(La-Nd) => g
configuration



PRC 99, 014308 (19)

g factors of yrast isomers
^{208}Pb region or ^{132}Sn region
=> tensor interaction, 3body



PRL 109, 162502 (12)

18 collaboration LoIs @gSPEC workshop 2018

HI 240, 55 (19) and references therein

Budget gSPEC@FAIR

Type of budget	2020	2021	2022	2023	2024	Total
Equipment	120 k€ Detectors (ancillary) + Design magnet	780 k€ magnet	50 k€ Detector + Magnet manipulators	-	-	950 k€
Running costs	10 k€	10 k€	10 k€	10 k€	10 k€	50 k€
Travel	15 k€	15 k€	15 k€	20 k€	10 k€	75 k€
Personnel	PostDoc (75 k€)	PostDoc (75 k€)	PostDoc (75 k€) PhD (40 k€)	PhD(40 k€)	PhD(40 k€)	345 k€
Total	**220 k€**	**880 k€**	**190 k€**	**70 k€**	**60 k€**	**1420 k€**

- **Equipment : ~1 M€** (demanded contribution)
- **Outside this demand :**
  - HpGe detector R&D and production, electronics, DAQ
  - Beam tracking FRS/SuperFRS, electronics, DAQ
  - Ancillary gSPEC backend electronics & DAQ
  - All supports (table, magnet, HpGe detectors, ancillary detectors)
  - All hosts + degraders (for gSPEC)
  - Possible 2nd setup chamber+cooling (for gSPEC)
  - Possible another encapsulation HpGe (R&D+production for gSPEC)

Timeline gSPEC@FAIR

2019 | 2020 | 2021 | 2022 | 2023 | 2024

ws | m | ws | m | m | ws | meetings & workshops

*gSPEC @ NUSTAR

RIKEN exp (^{68}Ni<^{132}Sn)
light nuclei

Feasibility Simulations
R&D gSPEC *(magnet, detectors)*
***publications R&D**

TDR, LoIs **Proposals-0** **Proposals-1**
(travels on site)

***purchaise**

FRS **Super-FRS**

Installation on site & tests (magnet, detectors)
Engineers *(setup adaptations, travels on site)*

Setup adaptations & tests
(travels on site)

***gSPEC campaign-0** ***gSPEC campaign-1**

Post-doc (preparations, tests, simulations)
All *(setup, travels on site, commissioning)*

Evaluations & preparations
Some *(travels on site)*

PhD (experiments, data analysis...
(*travels on site*)

***physics results & publications**

FAIR-0 **FAIR-1**

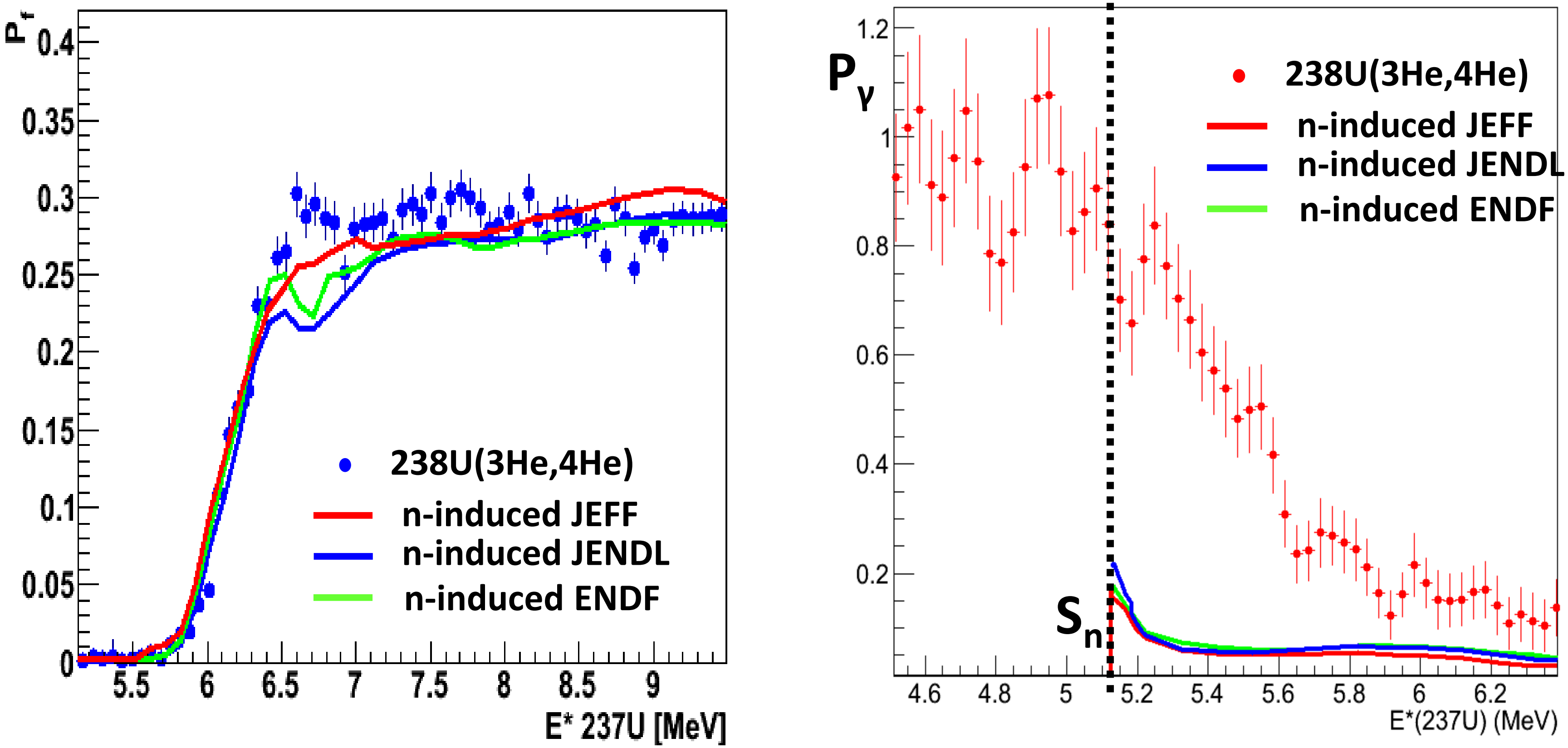
SWOT gSPEC@FAIR

<table>
<tr>
<td>Strengths
Develop, build and exploit a state-of-the-art spectrometer for g factors
Technical expertise in superconducting magnets, HPGe detectors, electronics and DAQ
Expertise in hyperfine interactions
International effort
Precision spectroscopy of exotic nuclei
Discovery potential</td>
<td>Weaknesses
International effort
Few experts</td>
</tr>
<tr>
<td>Opportunities
Involvement of a new company Design Study and possible collaboration with University-based magnet Design Study and production
New R&D on particle detectors in high magnetic field
New encapsulation HpGe in collaboration with partners
Exploitation of new techniques
Subsequent Q experimental campaigns</td>
<td>Threats
Lack of funding and Human Resources
Little beam time in the host sites may require relocation</td>
</tr>
</table>

Back-up slides
B. Jurado

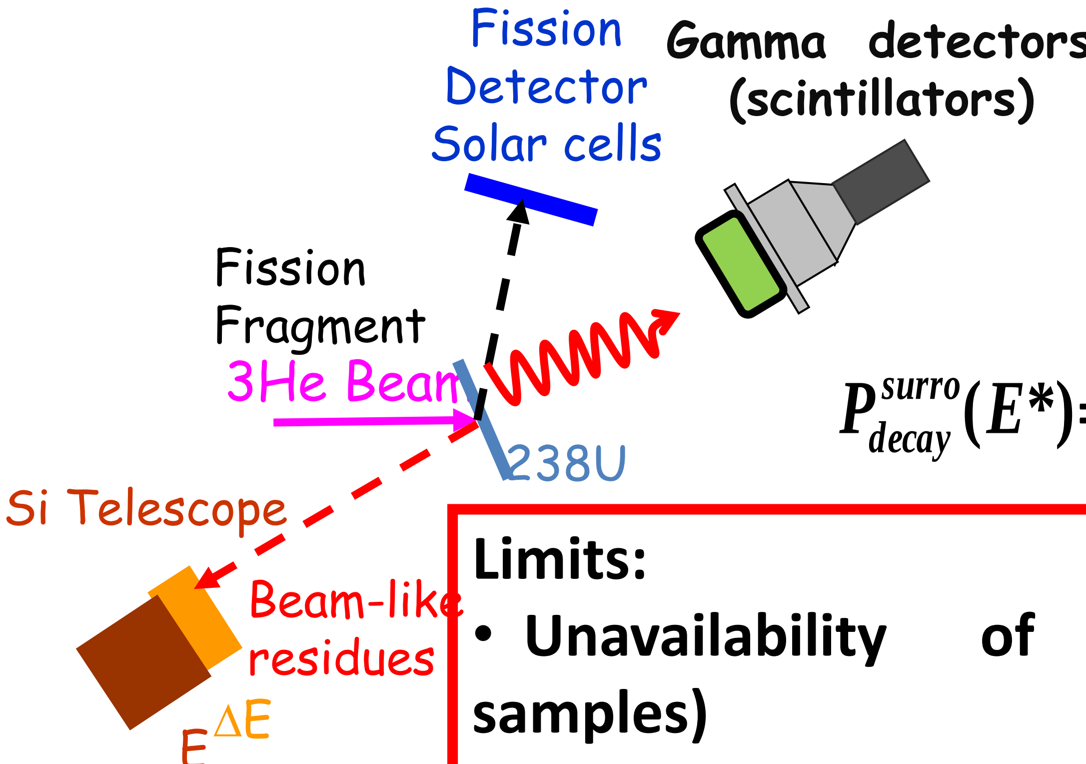
Representative results

3He+238U→4He+237U ⇔ n+236U→237U



Good agreement for fission probabilities but strong disagreement for γ-emission probabilities.
Not understood, need systematic studies involving nuclei with different nuclear structure and different reactions to define how to use surrogate reactions when no neutron data are exists.

Setup for the measurement of fission and gamma-emission probabilities in direct kinematics

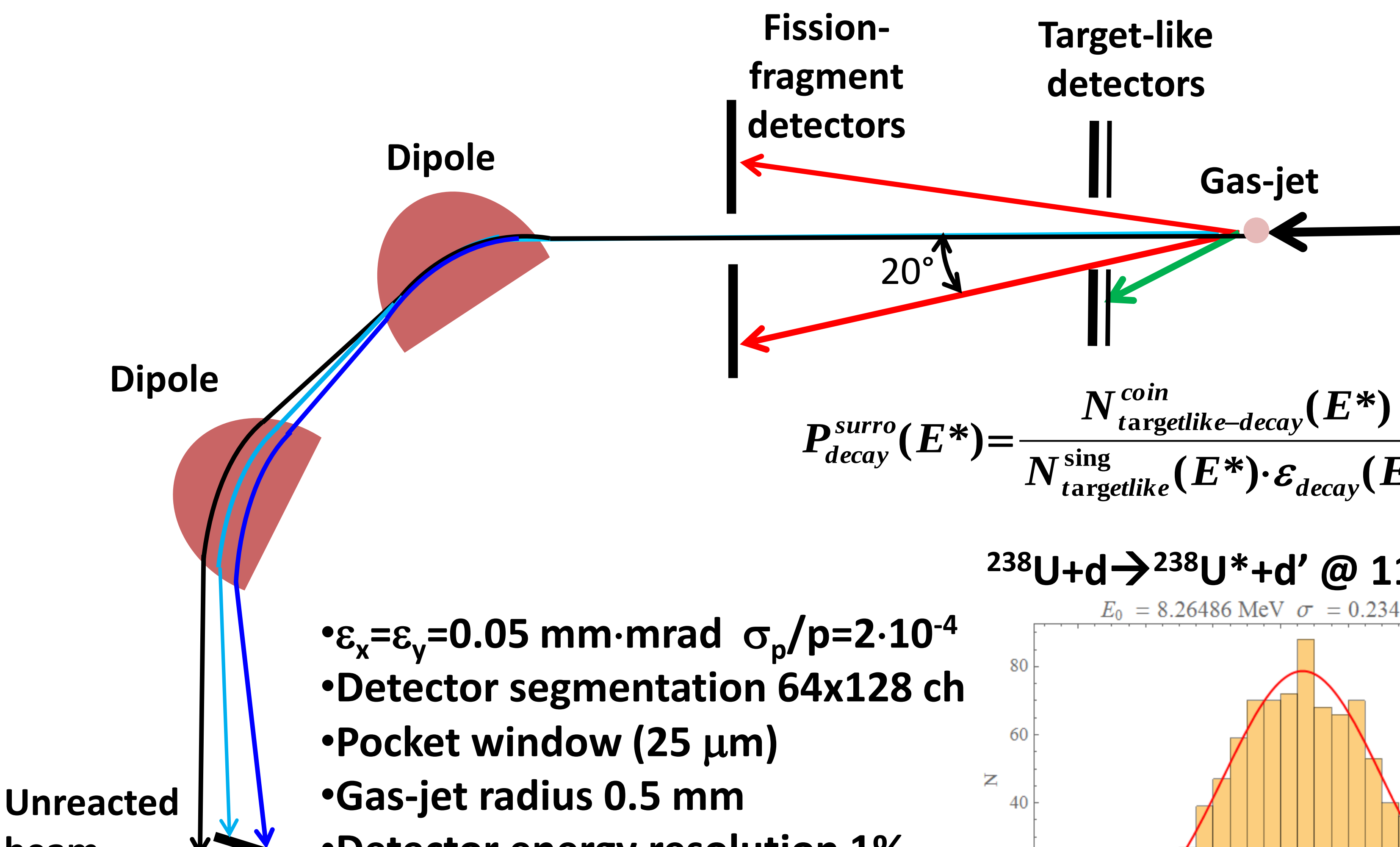


$$P^{surro}_{decay}(E^*) = \frac{N^{coin}_{beamlike\text{-}decay}(E^*)}{N^{sing}_{beamlike}(E^*)\cdot \varepsilon_{decay}(E^*)}$$

Limits:

- **Unavailability of targets (radioactive samples)**
- **Target contaminants and target support**
- **P_γ : discrimination of γ's from fission fragments, very low detection efficiency**
- **P_n: measurement of low-energy neutrons and neutron efficiency**

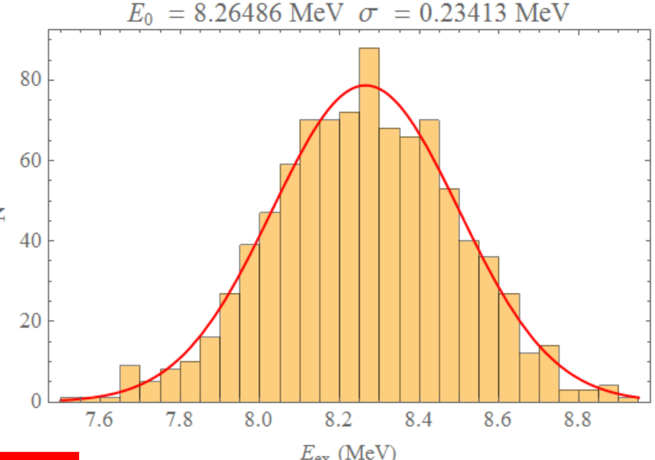
Detailed Geant 4 simulations: excitation-energy resolution



$$P_{decay}^{surro}(E^*) = \frac{N_{targetlike-decay}^{coin}(E^*)}{N_{targetlike}^{sing}(E^*)\cdot\varepsilon_{decay}(E^*)}$$

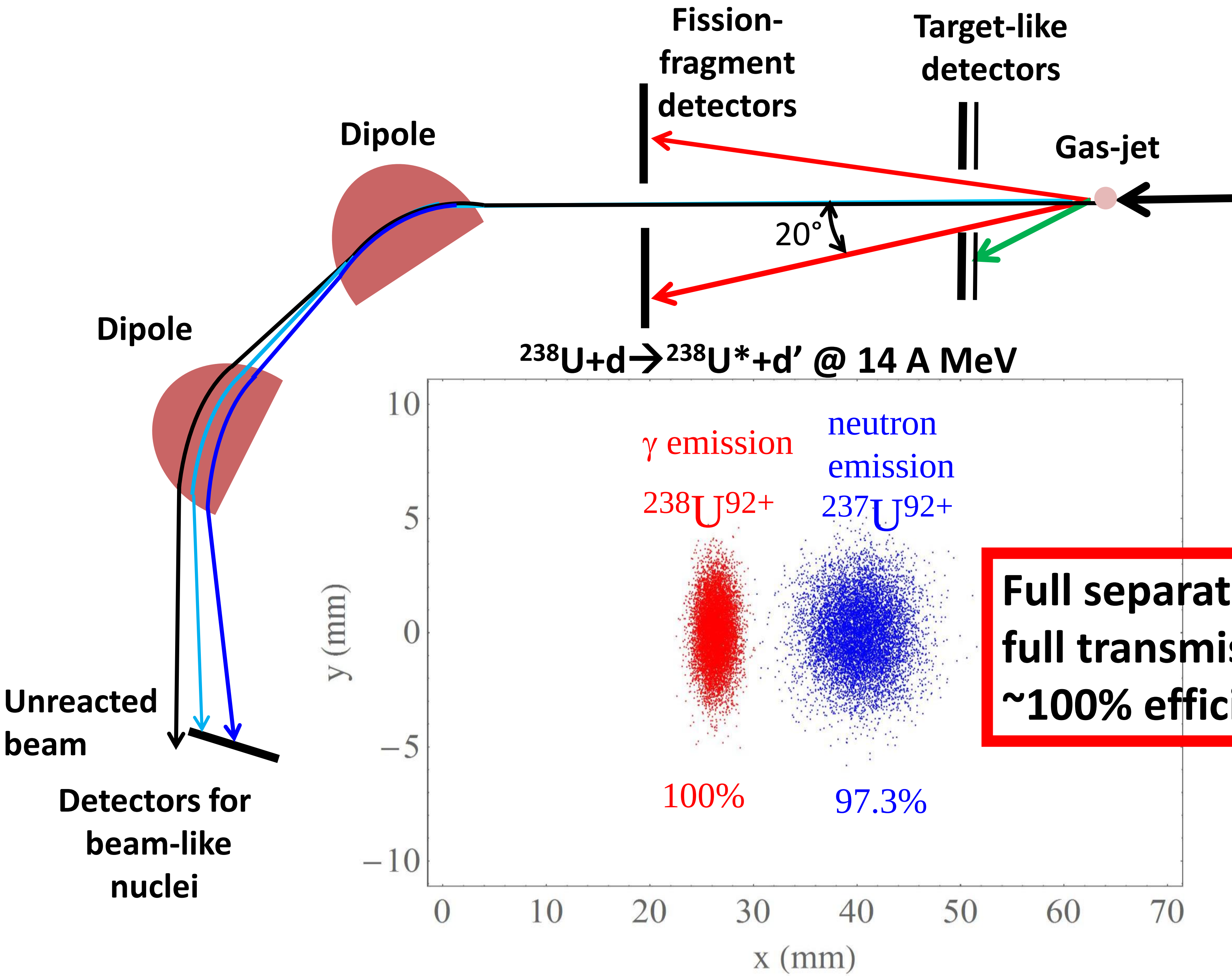
- $\varepsilon_x = \varepsilon_y = 0.05$ mm·mrad $\sigma_p/p = 2\cdot10^{-4}$
- Detector segmentation 64x128 ch
- Pocket window (25 μm)
- Gas-jet radius 0.5 mm
- Detector energy resolution 1%
- Dispersion at gas-jet 1.5 m

$^{238}U + d \rightarrow {}^{238}U^* + d'$ @ 11 A MeV



ΔE*≈200 keV

Detailed Geant 4 simulations: separation of beam-like residues



Full separation and full transmission: ~100% efficiency!

Timeline and scientific production

2017: Start of feasibility studies, presentation of the project at the CENBG Scientific Council with the conclusion: *“The scientific council strongly supports this project and their funding request.”*

2018: Detailed feasibility studies at GSI within EMMI visiting professor-ship of B. Jurado

2019: Project awarded with a Marie Curie post-doc fellowship and an international PhD of the CNRS, applications sent to French/German funding agencies ANR-DFG and to the ERC (Advanced Grant).

2020-2022: Submission of experiment proposal to the GSI/FAIR PAC and construction of set-up

2023-2024: Realization of first experiment, data analysis and publication of results

We have presented this project in more than 15 workshops and are preparing an article on the use of solar cells, many articles are expected during the set-up development and after the experiment.

Budget

Type of budget	2020	2021	2022	2023	2024	Total
Equipment	**380k€ detectors and electronics**	**420k€ reaction chambers and manipulators**	**200k€ beam monitors**			**1030 k€**
Travel	**10 k€**	**10 k€**	**10 k€**	**20 k€**	**10 k€**	**60 k€**
Personnel			**PhD (40 k€)**	**PhD(40 k€)**	**PhD(40 k€)**	**120 k€**
Total	**390 k€**	**430 k€**	**250 k€**	**60 k€**	**50 k€**	**1180 k€**

Important: We have applied for funding to the ANR-DFG and ERC in 2019. In case any of these applications is successful, our requested resources to the IN2P3 will be drastically reduced.

Human resources

	2020 etp	2021 etp	2022 etp	2023 etp	2024 etp	Total etp
International PhD CNRS CENBG	**1**	**1**	**1**			**3**
Marie Curie postdoc A. Henriques CENBG	**1**	**0.6**				**1.6**
Permanent IN2P3 researchers CENBG: B. Jurado, L. Mathieu, I. Tsekhanovich, CR IPNO: L. Audouin	**1.1**	**1.25**	**1.25**	**1.5**	**0.7**	**5.8**
Mechanical Engineer T. Chiron CENBG	**0.5**	**0.5**	**0.5**			**1.5**
Electronics Engineer J. Pibernat CENBG	**0.6**	**0.6**	**0.6**	**0.5**		**2.3**
Instrumentation Engineers B. Thomas, P. Alfaurt CENBG	**0.3**	**0.3**	**0.4**	**0.3**		**1.3**
Total ETP	**4.5**	**4.25**	**3.75**	**2.3**	**0.7**	**15.5**

High-precision decay-probability measurements at CRYRING

	positive	negative
internal	**Strengths** • First time ever simultaneous measurement of fission, gamma- and neutron-emission probabilities with very good E* resolution • High precision in the probabilities due to the absence of target contaminants/windows and the unambiguous separation of the reaction products, which can be detected with very large efficiencies • Cutting-edge technology • Synergy with atomic physics methods	**Weaknesses** • The detection system has to be compatible with the ultra-high vacuum (UHV) of the ring. This is challenging and we are on the way to acquire the required expertise on UHV technology
external	**Opportunities** • Our developments are beneficial for proton and e- capture cross-section measurements of heavy nuclei at CRYRING • Pioneering work: the study of nuclear reactions at rings is only possible since a few years • Our project can be the seed for a future high-level program on nuclear structure and astrophysics with transfer or inelastic scattering reactions at rings • Our solar-cell studies can be the seed for developing new monitoring methods in RIB facilities	**Threats** • Funding necessary to build the set-up not yet available • Beam availability

Back-up slides
L. Audouin

Timeline

2012: First campaign to study the U-Th region (SOFIA-1)
2014: Second campaign focussed on ^{236}U (SOFIA-2)
2020: Construction of a MWPC, revamp of the readout of all MWPC, SOFIA-3 experiment (dedicated to the study of the transition toward asymmetric fission in very neutron-deficient nuclei). Data analysis.
2021: Data analysis
2022: Preparation of the SOFIA-4 experiment (dedicated to the influence of excitation energy on the fission yields for a range of nuclei, possibly the Th chain)
2023: SOFIA-4 experiment and data analysis.
2024: Data analysis and possibly development of the Pu beam

Human resources

	2020 (etp)	2021 (etp)	2022 (etp)	2023 (etp)	2024 (etp)	Total (etp)
PhD (expected from Graduate School of Saclay)		1	1	1		3
Post-doc (CNRS)			1	1		2
Permanent researchers : L. Audouin (IPNO) B. Jurado (CENBG)	0.6	0.5	0.5	0.5	0.5	2.6
Instrumentation engineers : J. Bettane, L. Vatrinet (IPNO)	0.50		1			1.5
Electronics Engineer : T. N. Trung (IPNO)	0.20					0.2
Instrumentation technicians : M. Imre, L. Seminor, B. Geoffroy (IPNO)	1		2			3
Total	2.3	1.5	5.5	2	0.5	12.3

Budget

Type of budget	2020	2021	2022	2023	2024	Total
Equipme nt	65 k€ (detectors and electronics)		20 k€ (mechanic s)			85 k€
Travel	8 k€	2 k€	4 k€	15 k€	10 k€	39 k€
Personnel			Post-doc (1) (50 k€)	Post-doc (1) (50 k€)		100 k€
Total	73 k€ (2)	2 k€	74 k€	65 k€	10.€	224k€

SOFIA: perspectives and risk/opportunity assessment

- Coupling to the CALIFA array:

-> (p,2pf) measurement: study the influence of excitation energy on yields

- Coupling to the NeuLAND neutron wall:

-> Neutron assignation for in-depth test of the energy partition

- ^{242}Pu primary beam

-> High-precision nuclear data for energy application (yields of ^{240}Pu* !)

- (long-term) Super-FRS beams:

-> New range of exotics systems, including neutron-rich nuclei (astrophysical interest)

- Successful first experiments
- Cutting-edge technologies
- IN2P3 contribution: specific and visible
- Short, mid and long-term program

- Key position of CEA-DAM in the collaboration
- Harsh competition for beam time
- Lack of physicist manpower on IN2P3 side

Back-up slides
N. Lecesne

Timeline

2017: Proposals accepted at the GSI G-PAC for RADRIS and in-gas-jet laser spectroscopy experiments (U313, U314)

2018: Construction of the new detection set-up prototype for high-resolution spectroscopy

2019: Realization of RADRIS studies at SHIP of GSI/FAIR for ^{255}No and first tests for in-gas-jet laser spectroscopy experiments (U313, U314)

2019-2022: Realization of the in-gas-jet laser spectroscopy experiments with an improved setup (high repetition rate narrow bandwidth laser system)

2019-2021: Final construction of the S^3 LEB instrumentation and off-line commissioning at LPC Caen

2022: Mounting of LEB instrumentation at S^3, commission and first test in-beam

2023: Start of Day-1 experimental program at S^3

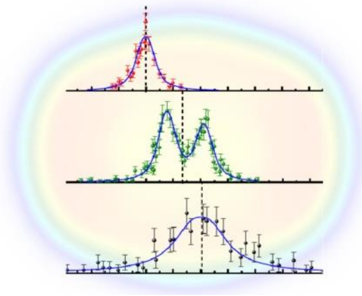
Budget

Type of budget	2020	2021	2022	2023	2024	Total
Equipment	100 k€ pump laser 10kHz	15 k€ Laser consumable	10 k€ Laser consumable			125 k€
Travel & meetings (+accord IN2P3)	2 k€	2 k€	2 k€	2 k€	2 k€	10 k€
Personnel	PhD (40 k€)	PhD (40 k€)	PhD (40 k€)			120 k€
Total	142 k€	57 k€	52 k€	2 k€	2 k€	255 k€

Human resources

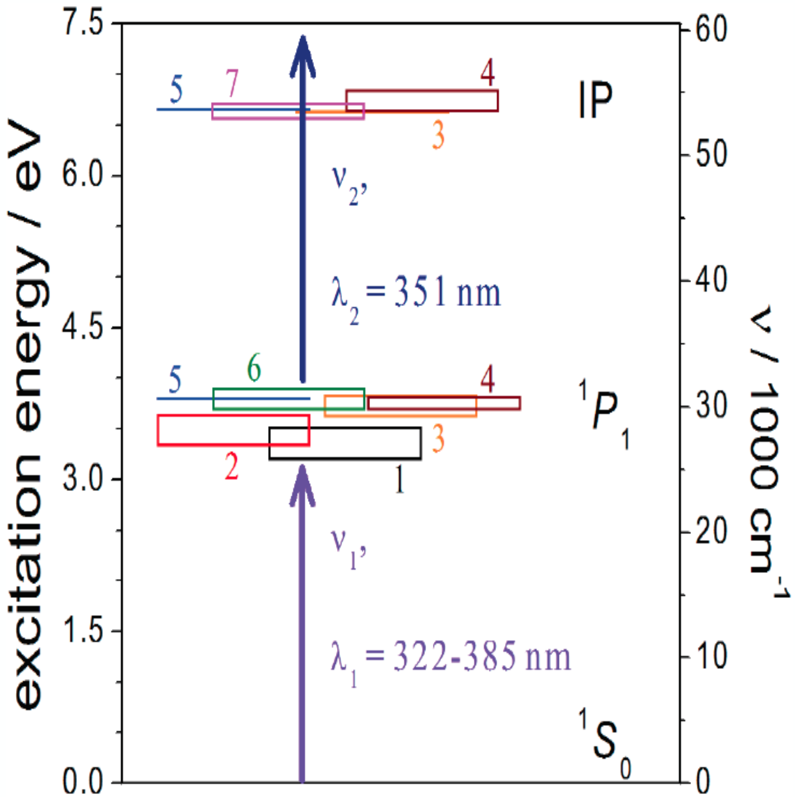
	2020 etp	2021 etp	2022 etp	2023 etp	2024 etp	Total etp
Permanent staff GANIL: N. Lecesne, H. Savajols, D. Ackermann, J. Piot, C. Stodel IPNO: E. Minaya Irfu/DPhN : M. Vandebrouck, B. Sulignano	2	2	2	2	2	10

High-resolution Laser spectroscopy of super-heavy nuclei



	positive	negative
internal	**Strengths** • Unique set-up and knowhow • High scientific impact and discovery potential • Synergies: atomic physics methods and nuclear structure studies • Strong visibility of IN2P3	**weaknesses** • Not yet strongly involved in technical development and tests (Investment budget…) • Manpower for supporting experiment and for analysis (PhD funding…)
external	**opportunities** • Complementary access to basic features of the heaviest nuclei • Set-up the course for future program at S3 Low Energy Branch • Strengthen IN2P3-NUSTAR collaboration	**threats** • Beam time / accepted exp. • Beam availability

Atomic energy level calculations: nobelium (Z=102)



1 (MCDF): S.Fritzsche, Eur. Phys. J. D 33 (2005) 15

2 (MCDF): S.Fritzsche, Eur. Phys. J. D 33 (2005) 15

3 (IHFSCC): A.Borschevsky et al., Phys. Rev. A 75 (2007) 042514

4 (RCC): V.A.Dzuba et al., Phys. Rev. A 90 (2014) 012504

5 (MCDF): Y.Liu et al., Phys. Rev. A 76 (2007) 062503

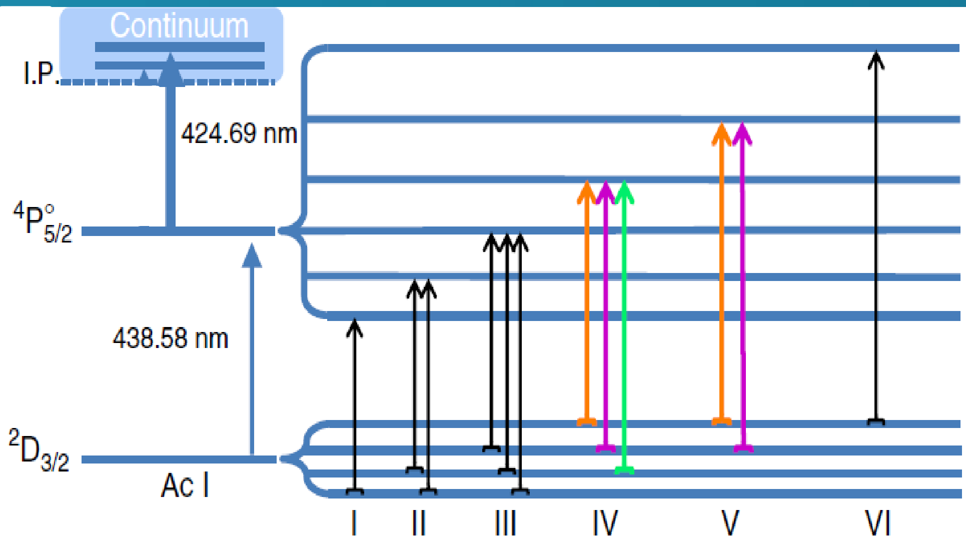
6 (MCDF): P.Indelicato et al., Eur. Phys. J. D 45 (2007) 155

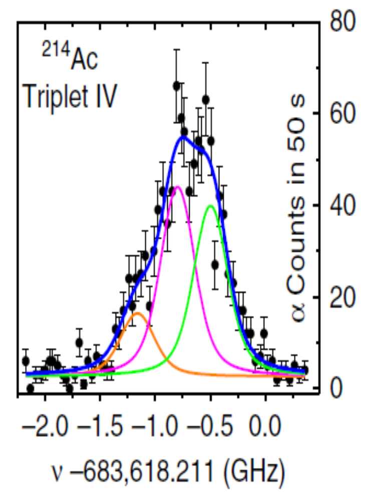
7 (extrapolation): J.Sugar, J. Chem. Phys. 60 (1974) 4103

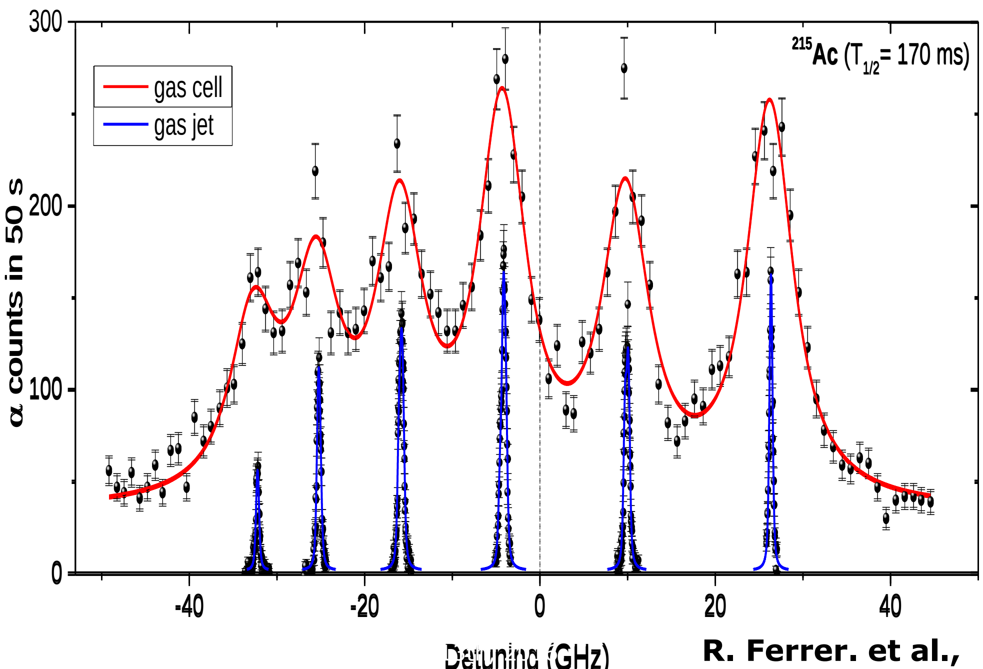
Need to scan 5000 cm^{-1} ~ 150,000 GHz (FWHM (BB dye laser) ~ 15GHz)

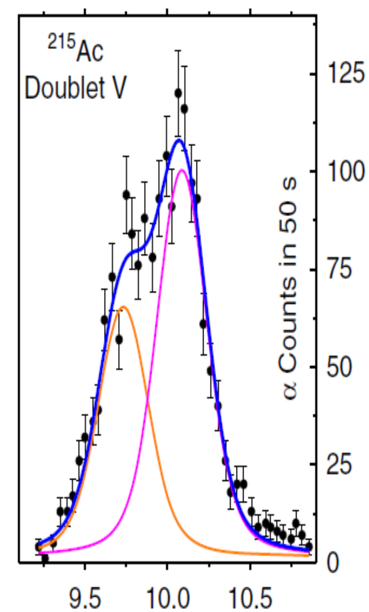
Each cycle ~ 1 minute… expect ~2 resonant counts

In-Cell vs In-Jet Spectroscopy of ^{215}Ac









R. Ferrer. et al., Nat. Commun. 8 (2017) 14520

Tables all projects

Total Budget

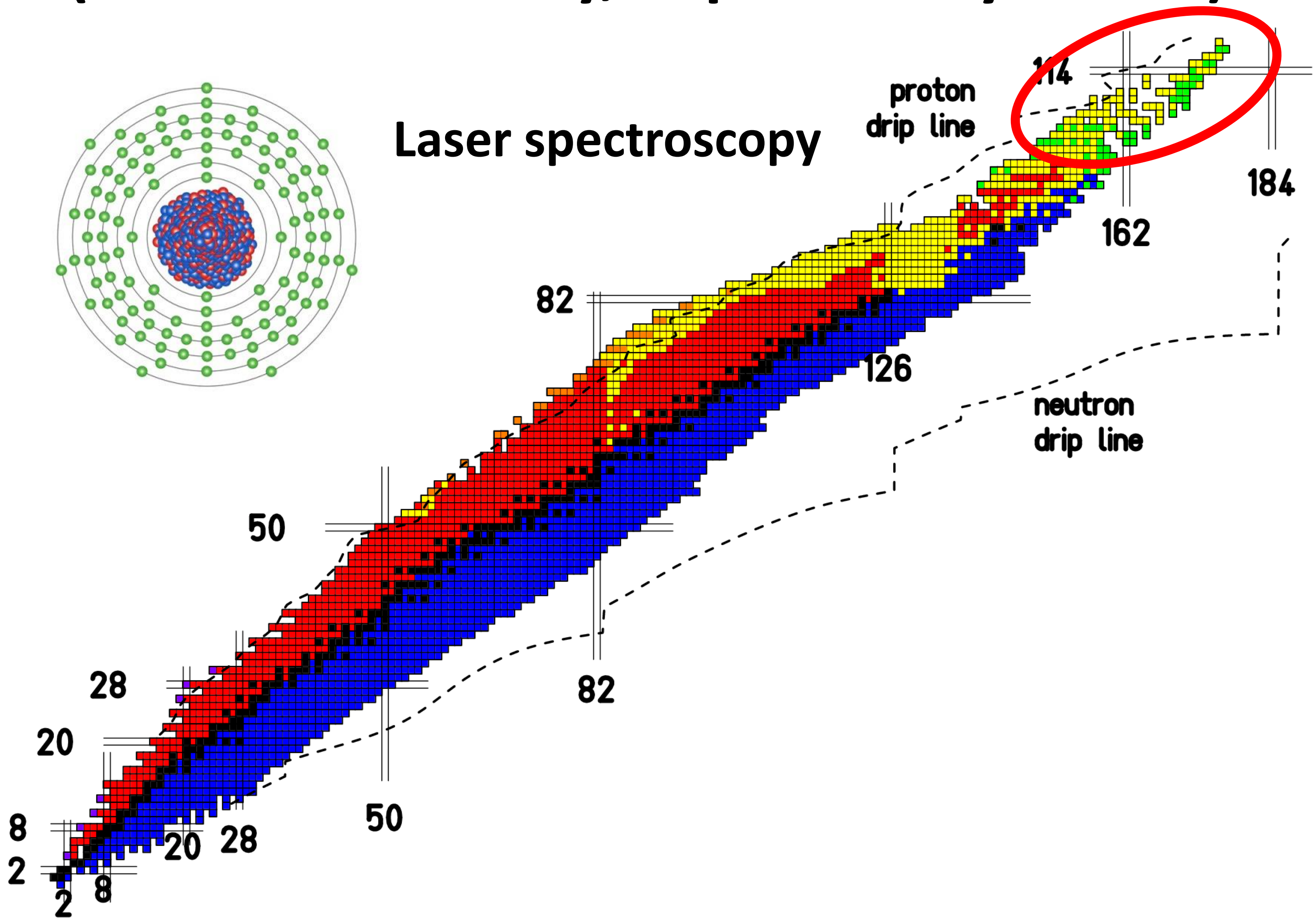
Type of budget	2020	2021	2022	2023	2024	Total
Equipment	695 k€	1245 k€	310 k€	30 k€	40 k€	2320 k€
Travel+running costs	51.5 k€	43.5 k€	46.5 k€	72.5 k€	60.5 k€	274.5 k€
Personnel (PhD +Posdocs)	115 k€	155 k€	285 k€	170 k€	120 k€	845 k€
Total	861.5 k€	1443.5 k€	641.5 k€	272.5 k€	220.5 k€	3439.5 k€

Total available human resources

	2020 etp	2021 etp	2022 etp	2023 etp	2024 etp	Total etp
PhD	1.4	1.3	1			3.7
Postdoc (Marie Curie fellow)	1	0.6				1.6
Permanent researchers (IN2P3 and University)	6.5	6.05	6.35	7.6	6.5	33
Permanent Engineers (IN2P3)	3.8	2.2	5.3	1.6	0.8	13.7
Total ETP	12.7	10.15	12.65	9.2	7.3	52

Overview of French projects
(Limits of stability, super-heavy nuclei)

Laser spectroscopy



Evolution of shells, onset of deformation and collectivity with isomers