

# Studying nuclei at the extremes with FRIB

*Physics in the transactinide and lead region;*  
*GasDDSAM: a TPC for lifetimes in octupole deformed actinides;*  
*A Target Recoil Tracking device for FRIB400*

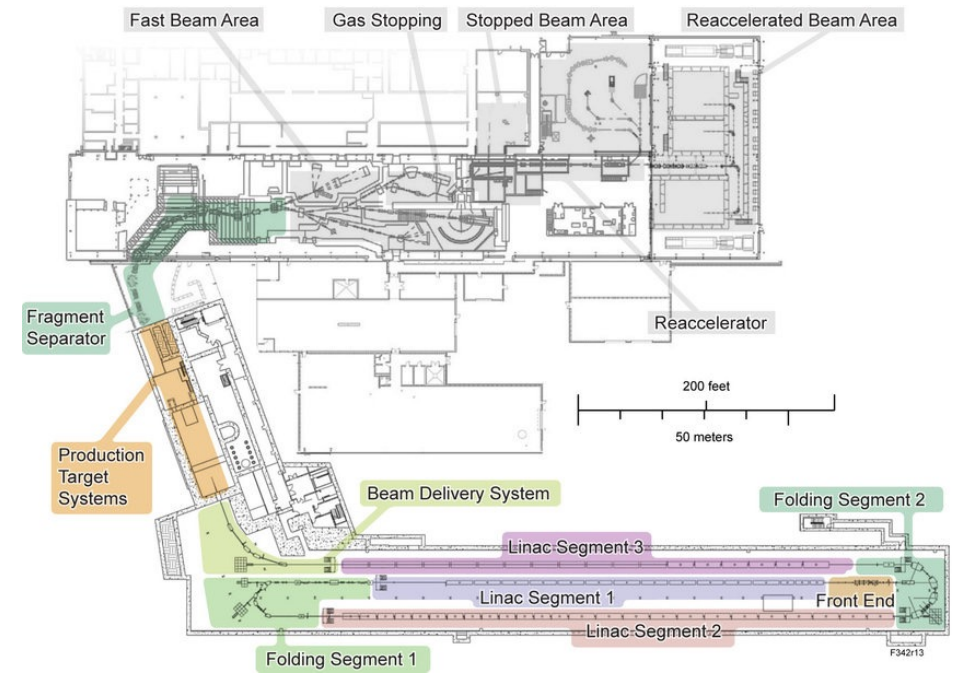
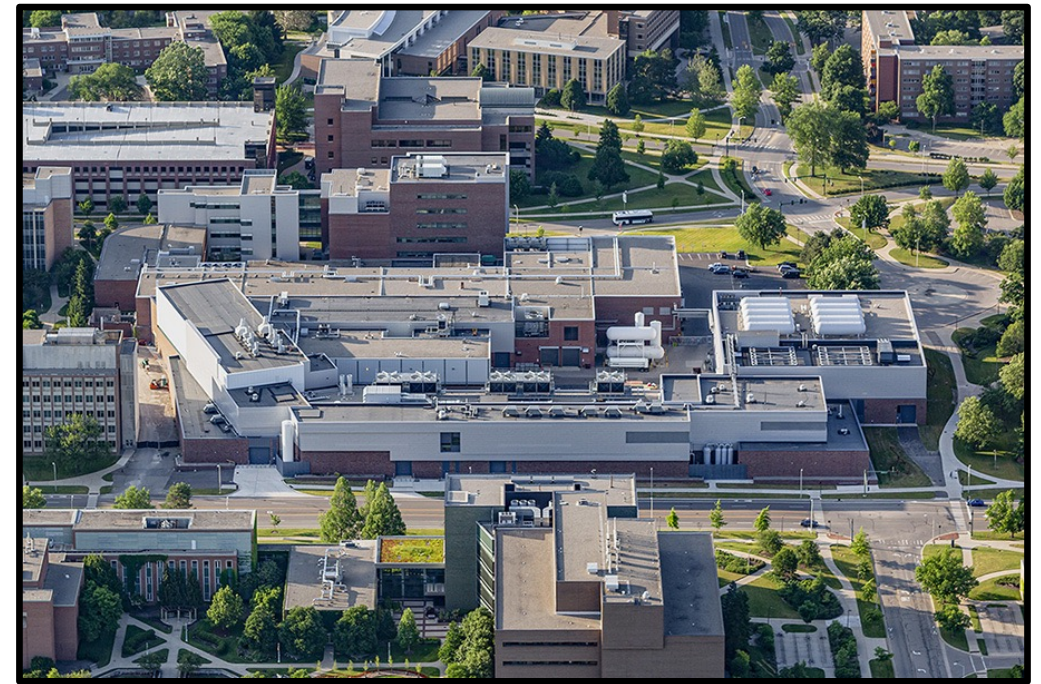
Jack Henderson – University of Surrey

David O'Donnell – University of the West of Scotland

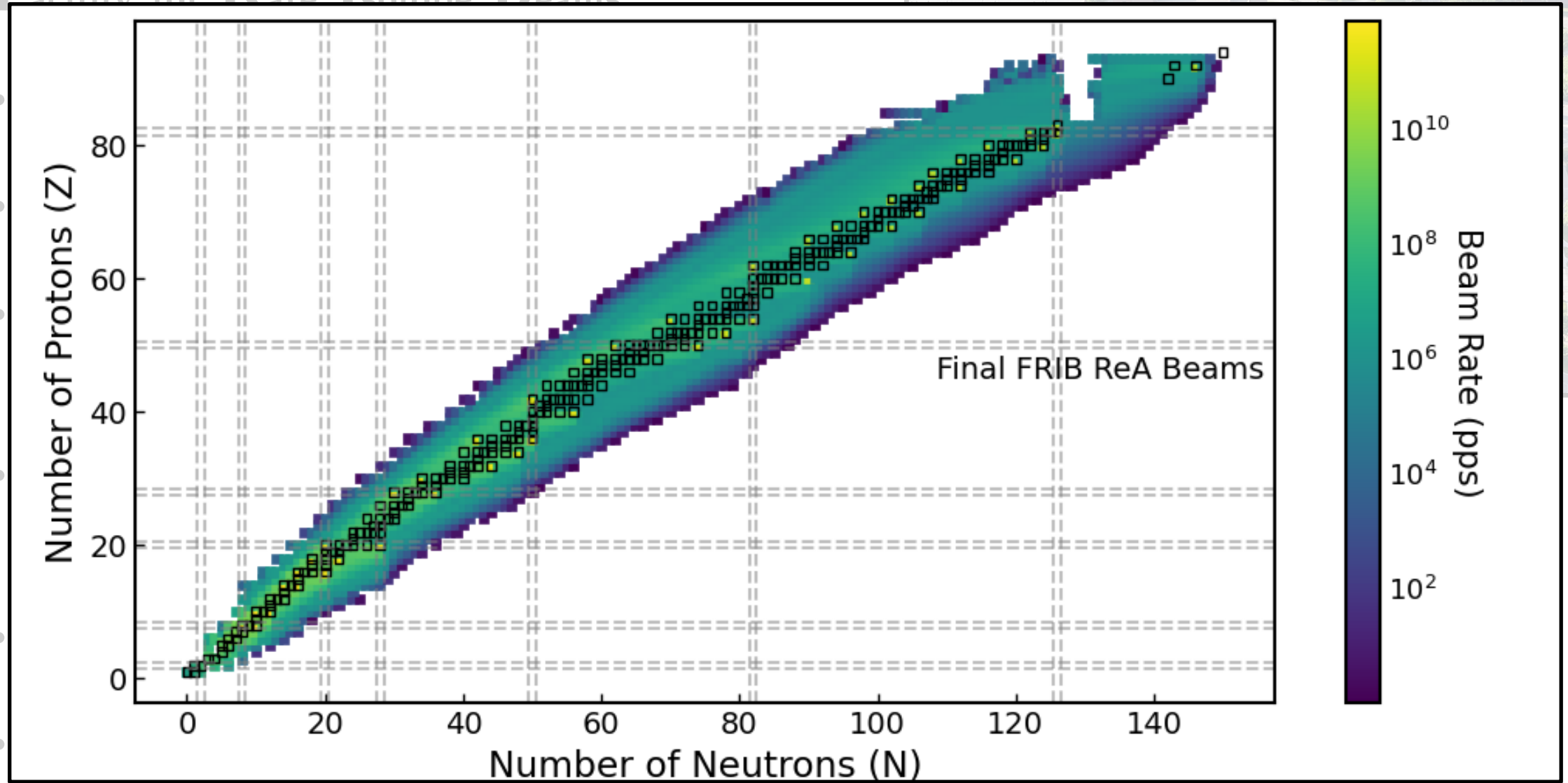
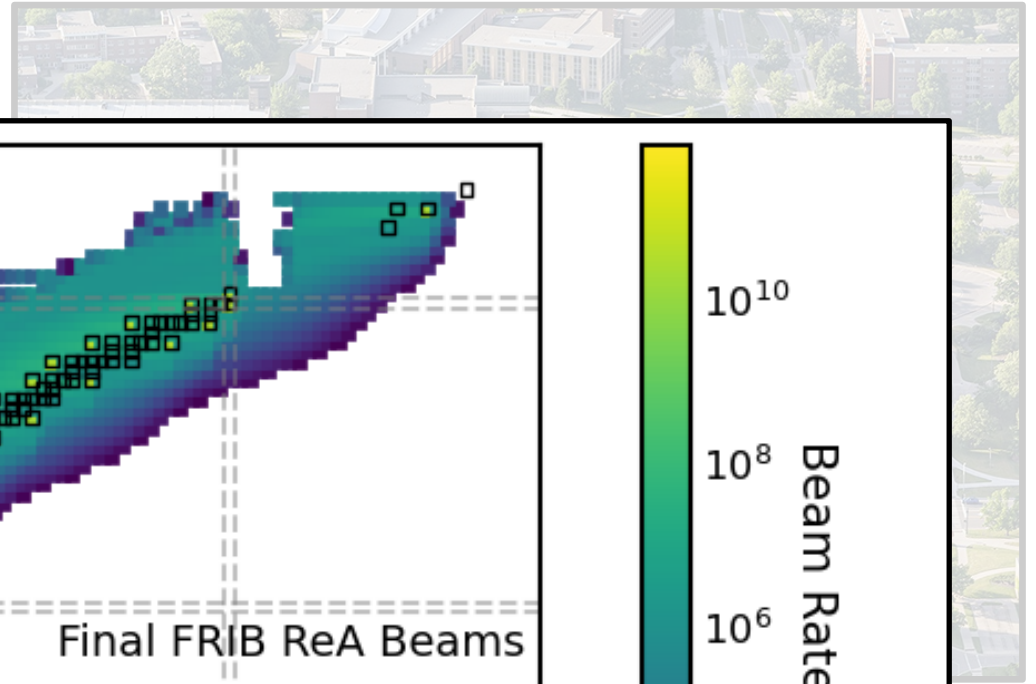
Stefanos Paschalis – University of York

# Facility for Rare Isotope Beams

- LINAC driven rare-isotope beam facility
- Beams produced by *fragmentation*
- *Fast, slow/stopped* and *reaccelerated* experimental areas
- Fast beams: “traditional” NSCL physics, i.e. GRETINA + S800, decay spec., etc.
- Slow beams: mass, laser and decay spec.
- Reaccelerated beams: transfer, Coulomb excitation, SECAR...



# Facility for Rare Isotope Beams



excitation, SECAR...

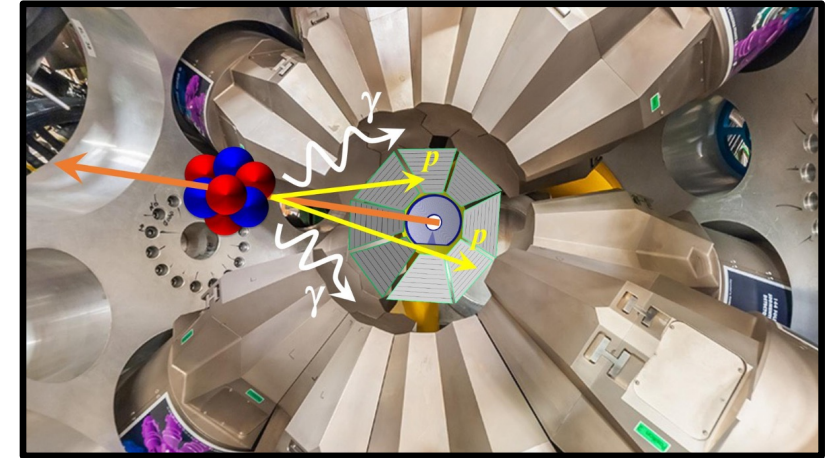




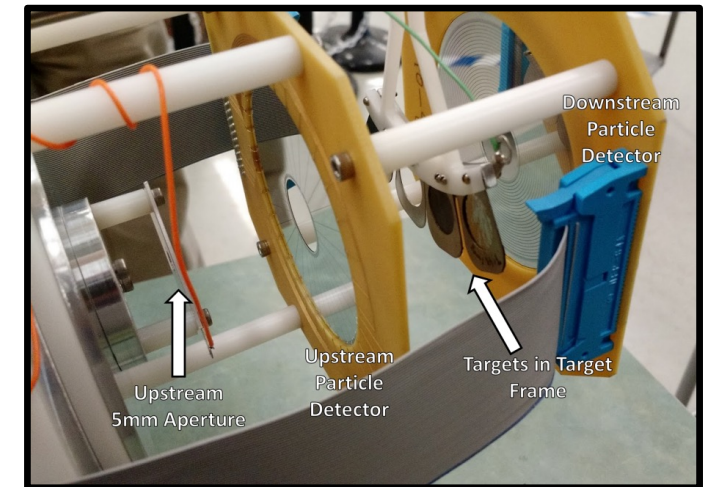
# Facility for Rare Isotope Beams

- Exploring the p-process with SECAR (M. Williams, Surrey)
- Shape coexistence in  $N=Z$   $^{44}\text{Ti}$  (LLNL, MSU, Surrey)
- Collectivity and Shape North of Sn (MSU, LLNL, Surrey)
- Shell evolution at  $N=28$  studied through sub-barrier Coulomb excitation (MSU, LLNL, Surrey)
- *Evolution and isospin-dependence of quadrupole collectivity in the heaviest  $N=Z$  systems* (M. Bentley, R. Wadsworth, York)
- *Constraining the Ni-Cu cycle in X-ray bursts and Core Collapse Supernovae: Spectroscopy of  $^{60}\text{Zn}$*  (G. Lotay, Surrey)
- LoI for development of actinide beams (UWS, Liverpool)

## Current UK involvement:



## FAUST (Surrey, Daresbury, York)



## JANUS (MSU, LLNL, Surrey)

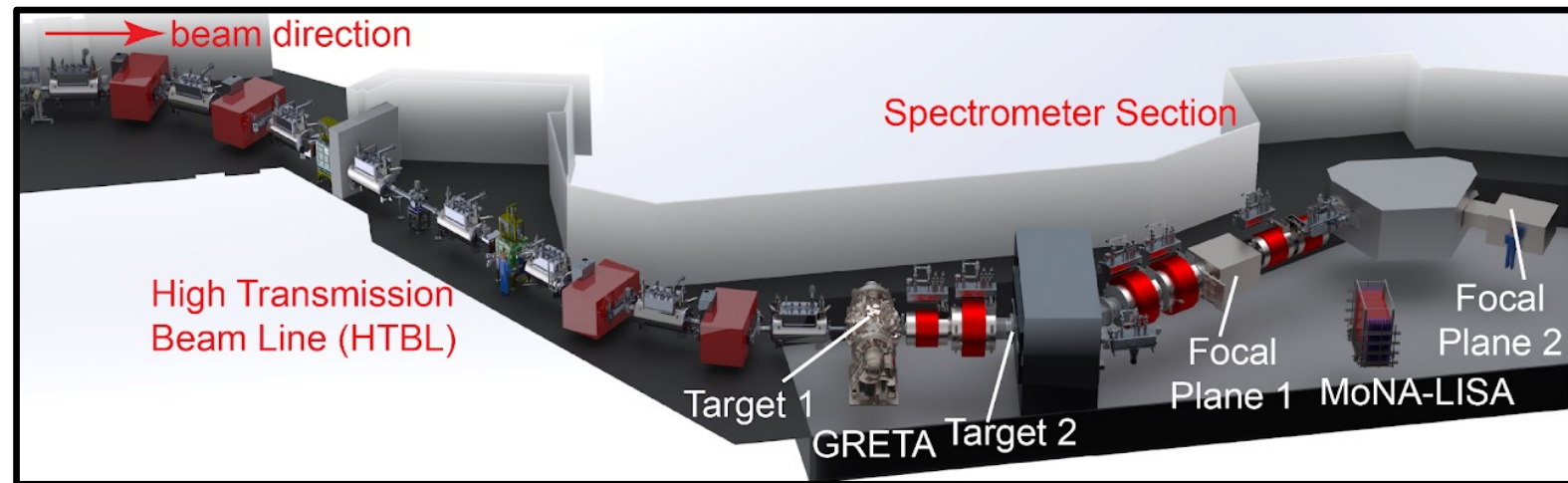
# Facility for Rare Isotope Beams

Future developments:

**High-Resolution Spectrometer (HRS):** A replacement for the existing S800 spectrograph, optimized for high-rates and efficiencies up to the FRIB400 energies

**Status:** Funded (\$115 million)

**FRIB400:** Upgrade of the FRIB LINAC to 400 MeV/u to increase production of exotic nuclei



**Status:** Whitepaper(s) submitted and endorsed in the 2023 Long Range Plan

**Gamma-Ray Tracking Array (GRETA):** Complete  $4\pi$  tracking array with upgraded electronics

**Status:** Fully funded and nearing completion

# Facility for Rare Isotope Beams

## Intersections with UK interests:

Fast beams delivered to GRETA + S800 / HRS for *knockout followed by  $\gamma$ -ray spectroscopy* (York) and *transfer reactions* (Surrey, York)

Reaccelerated beam (ReA) area can provide high-quality beams for *Coulomb excitation* (Liverpool, Surrey, UWS), direct measurements for *nuclear astrophysics* (Surrey, York) and transfer reactions with *solenoidal spectrometers* (Liverpool, Manchester)

Both fast and stopped beam areas allow for decay spectroscopy (silicon deposition or tape station) for *isomeric* and  *$\beta$ -decay* studies (Brighton, Surrey, York)

Stopped beam area for *laser* (Liverpool, Manchester) and *mass spectroscopy* (Edinburgh)

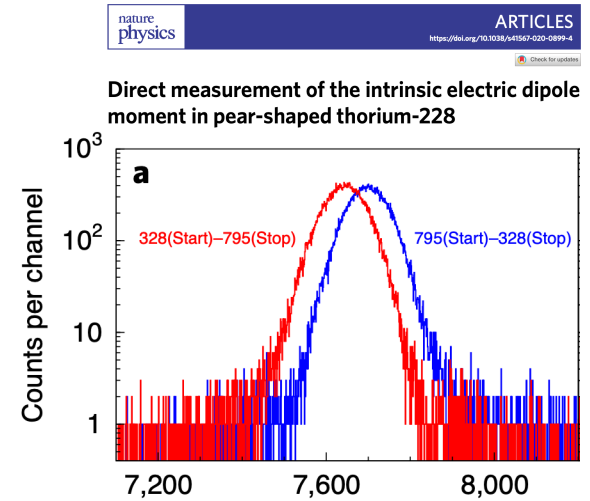
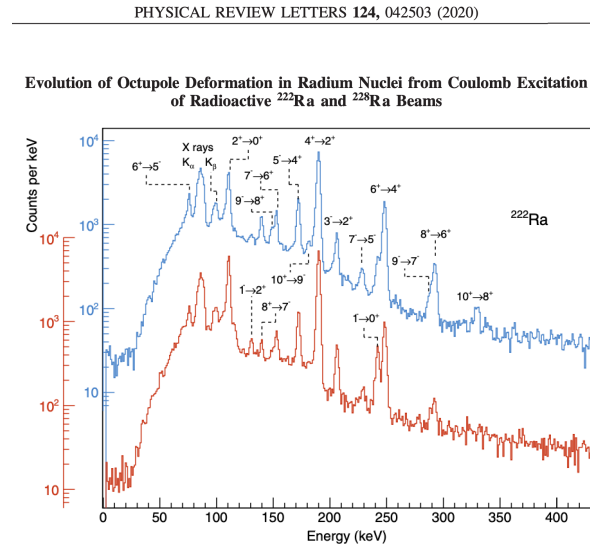
*Active-target TPCs* in use for low- and mid-mass beams (Birmingham, Sheffield Hallam)

*FRIB Theory Alliance*, bringing together nuclear theorists across the USA (Surrey, York)

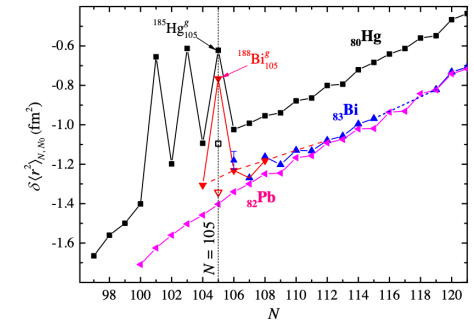
# Physics in the trans-lead and actinide regions

(Liverpool, Manchester, Surrey, UWS, York)

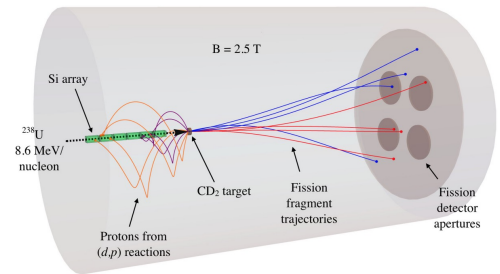
- UK has a wealth of experience and interest in the region
- Challenges:
  - Low-energy  $\gamma$ -ray spectroscopy
  - Neutron detection
  - Charged-particle detection
  - Nuclear theory
- Project:
  - BEGe detectors, neutron detectors, charged-particle R&D
  - Subdivisible and portable
  - *Robust theoretical work-package* to support and direct experimental work
- ECR-led project



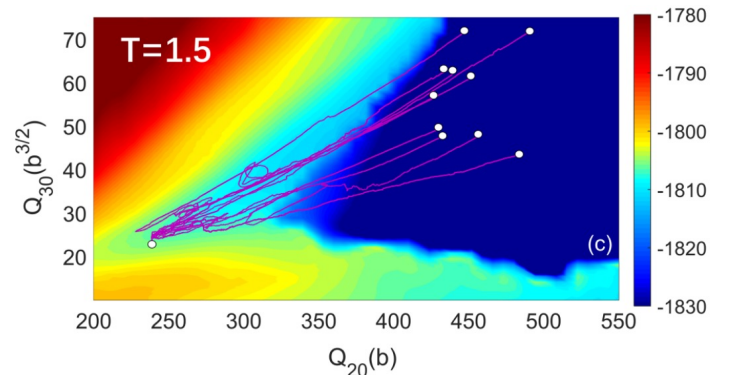
## Large Shape Staggering in Neutron-Deficient Bi Isotopes



## Direct Determination of Fission-Barrier Heights Using Light-Ion Transfer in Inverse Kinematics



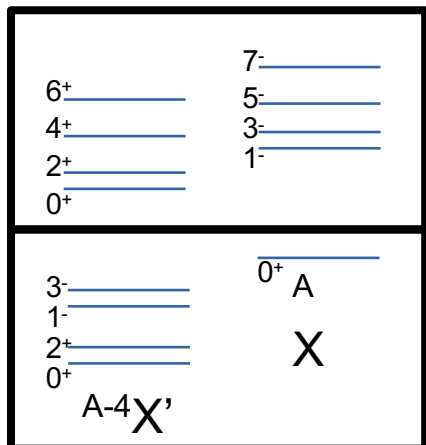
## Fission dynamics of compound nuclei: Pairing versus fluctuations



# GasDDSAM: a TPC for the measurement of lifetimes in octupole-deformed actinide nuclei – David O'Donnell (UWS)

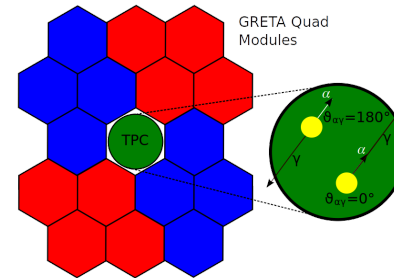
## Motivation:

- Level lifetimes essential for quadrupole and octupole deformation
  - $B(E1)$ ,  $B(E2)$  and  $B(E3)$ ...
- Identify candidate nuclei for future EDM searches
- Test and refine theoretical models
- High yields of actinide nuclei to be available at FRIB
- Levels of interest are expected to be too short for fast-timing
- Levels not populated as a result of fusion-evaporation
- Levels are populated following alpha decay: use  $\alpha$ - $\gamma$  correlations

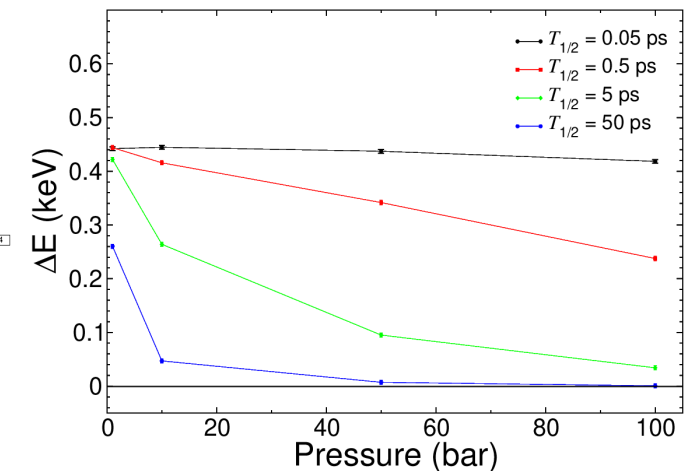
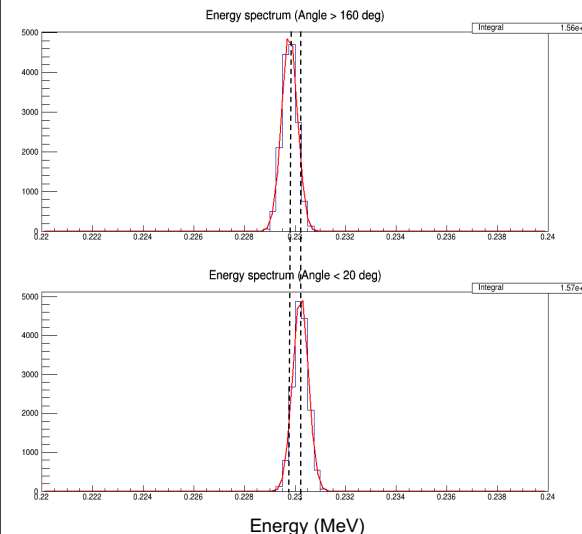


Z	225U	226U	227U	228U	229U	230U	231U	232U	
92	8.73E8	5.64E8	8.73E8	1.09E9	1.32E9	1.56E9	1.82E9	2.06E9	
	224Pa	225Pa	226Pa	227Pa	228Pa	229Pa	230Pa	231Pa	
	1.17E9	1.04E9	1.17E9	1.23E9	1.24E9	1.23E9	1.18E9	1.11E9	
	223Th	224Th	225Th	226Th	227Th	228Th	229Th	230Th	
90	6.81E8	6.78E8	6.64E8	6.02E8	5.29E8	4.49E8	3.68E8	2.90E8	
	221Ac	222Ac	223Ac	224Ac	225Ac	226Ac	227Ac	228Ac	229Ac
	1.51E8	3.57E8	3.08E8	2.54E8	2.03E8	1.55E8	1.14E8	7.95E7	5.29E7
	220Ra	221Ra	222Ra	223Ra	224Ra	225Ra	226Ra	227Ra	228Ra
88	9.47E6	1.37E8	1.05E8	7.73E7	5.44E7	3.65E7	2.33E7	1.40E7	7.88E6
	132	134	136	138	140				

## Solution:



- TPC with Xe gas held at high, variable pressure
- Surround TPC with HPGe tracking detectors
- Fast ions implanted into gas volume
- Detect  $\alpha$  particle in TPC volume and  $\gamma$ -ray in HPGe





# Target Recoil Tracker for FRIB400 (MeV/A) at HRS

– Stefanos Paschalis (University of York)

## Physics cases and the international landscape for FRIB400

- Structure of the most exotic systems such as multi-neutron systems → see SAMURAI tetra-neutron result
- Structure studies through gamma-ray spectroscopy with thick LH2 target → See MINOS/SEASTAR campaign at RIKEN
- Studies of clustering (through, e.g.,  $(p,p\alpha)$ ,  $(p,pd)$  QFS reactions) → New physics programme at R3B and at SAMURAI (ONOKORO/TOGAXSI)
- Fission barrier heights determined through  $(p,2p)$  reactions → New physics programme at R3B and at SAMURAI
- Short-range correlation (SRC) studies with exotic beams and hadronic probes → New programme at R3B

Apparatuses in fragmentation facilities share complementary physics goals and similar technological challenges:

[HRS at FRIB400](#), R3B at FAIR, SAMURAI at RIBF

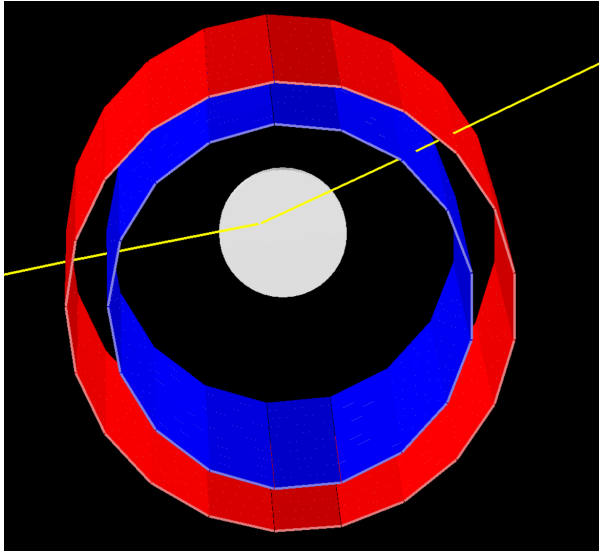
The regime of beam energies with a few hundred MeV/A:

- Enables studies of dense asymmetric nuclear matter
- Ideal for certain types of nuclear reactions (quasi-free scattering:  $p,2p$   $p,pd$   $ppa$ )
- Optimal for increasing luminosity and the yield of exotic isotope production and in particular heavy ions

# Target Recoil Tracker for FRIB400 (MeV/A) at HRS

– Stefanos Paschalis (University of York)

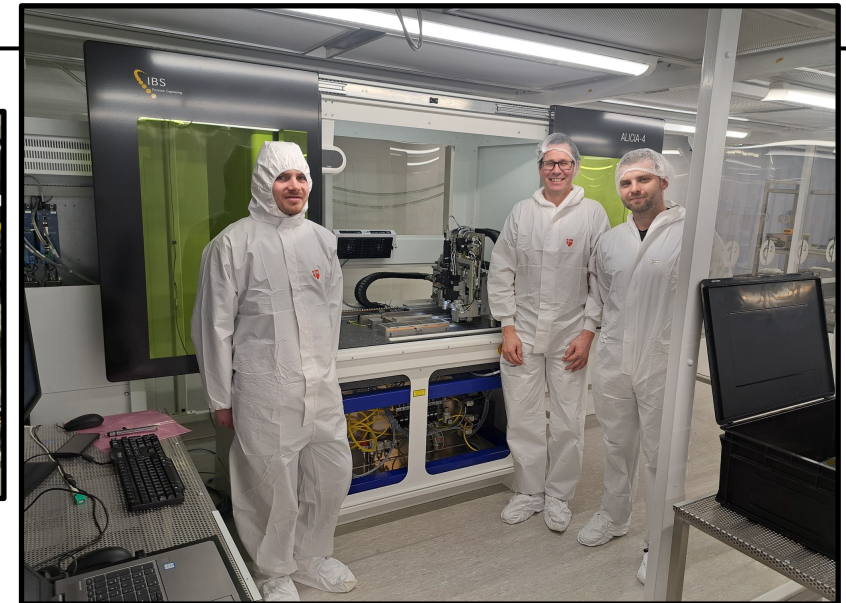
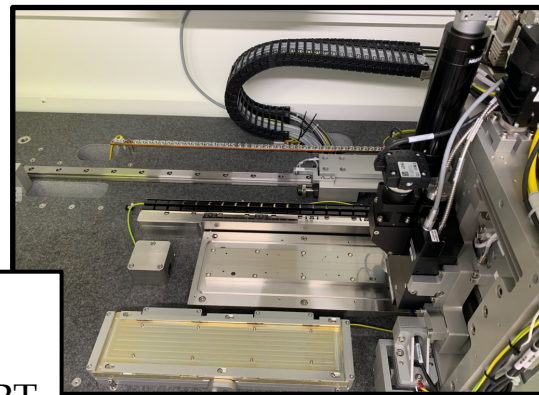
High-precision Target Recoil Tracker is an essential instrument for reaction vertex reconstruction and missing-mass measurements with high energy beams



Capitalising on existing UK expertise → excellent value for money and low risk:

- Currently leading the construction of the R3B TRT device at Daresbury
- Leading relevant physics programmes at R3B (p,pd M. Petri ) and SAMURAI (ONOKRO)

ALICIA machine installed at Daresbury for R3B TRT



# SECAR: Separator for Capture Reactions

– Matthew Williams (University of Surrey)

New recoil separator in ReA3 Hall, optimised to measure  $(p,\gamma)$  and  $(\alpha,\gamma)$  reactions for astrophysics.

Presently undergoing in-beam commissioning, expected to carry out first experiments by end of 2024/early 2025.

First approved radiative capture reaction to measure  ${}^{77}\text{Br}(p,\gamma){}^{78}\text{Kr}$  for p-process  
– PI: Matt Williams (Surrey)

