Nuclear Structure Studies at JYFL

and Future Prospects for In-beam Spectroscopy

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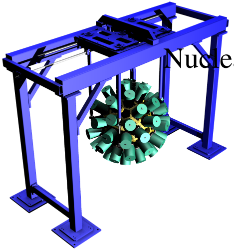

Nuclear SPectroscopy INstrumentation Workshop
26.06.-29.06.2017
GSI Darmstadt, Germany

Outline

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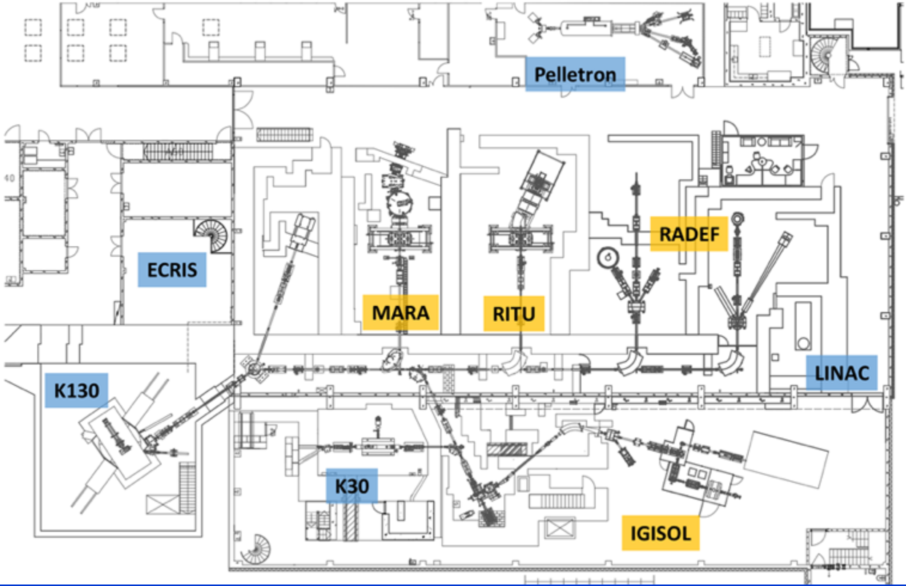
JYFL Accelerator Laboratory

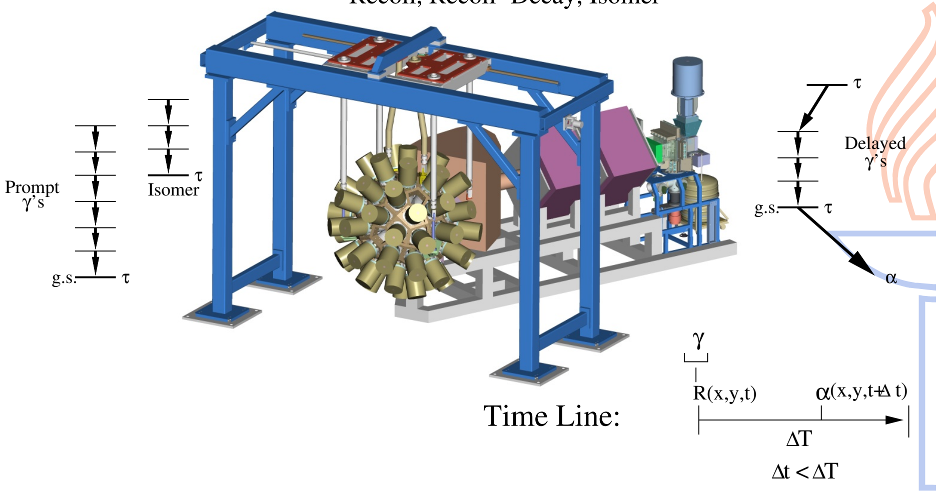
JYFL Accelerator Laboratory



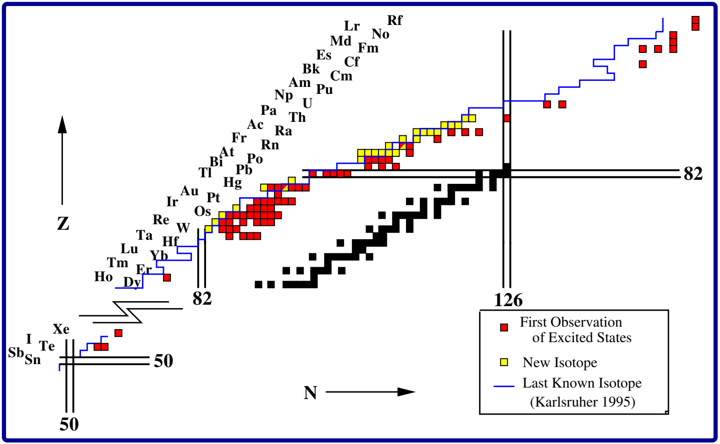
Principles of RDT

Tagging Techniques

Recoil, Recoil–Decay, Isomer

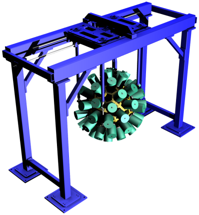


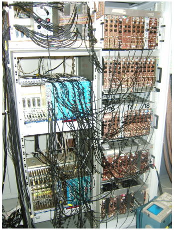
Regions of Study at RITU

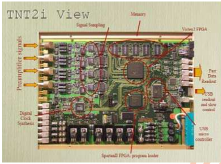


- Shell-stabilized transfermium nuclei
- Shape co-existence in light Pb and Po region
- Proton dripline nuclei
- K-isomerism in the A=140 region
- Collectivity close to ^{100}Sn
- N=Z nuclei in A=70-80 region

History of JUROGAM at JYFL







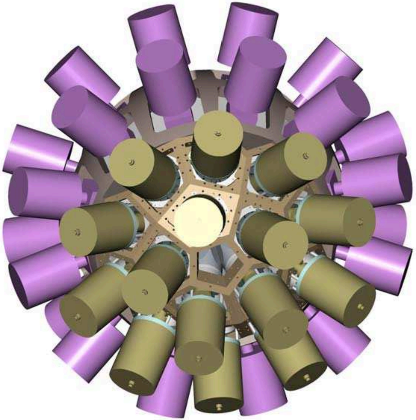
- Fifth and final campaign ended May 2008
- 2003 - 2008: 85 experiments, 13700+ beam time hours
- 2008: Fully instrumented with TNT2 digital electronics
- TNT2 cards in collaboration with CNRS/IN2P3 GABRIELA
- Superseded by JUROGAM II

PRL **102,** 212501 (2009) PHYSICAL REVIEW LETTERS week ending 29 MAY 2009

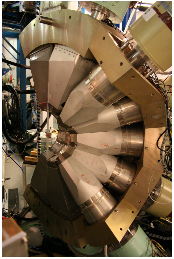
γ-Ray Spectroscopy at the Limits: First Observation of Rotational Bands in ^{255}Lr

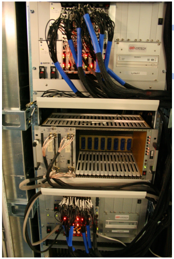
S. Ketelhut,[1,*] P. T. Greenlees,[1] D. Ackermann,[2] S. Antalic,[3] E. Clément,[4] I. G. Darby,[5,†] O. Dorvaux,[6] A. Drouart,[4] S. Eeckhaudt,[1] B. J. P. Gall,[6] A. Görgen,[4] T. Grahn,[1,‡] C. Gray-Jones,[5] K. Hauschild,[7] R.-D. Herzberg,[5] F. P. Heßberger,[2] U. Jakobsson,[1] G. D. Jones,[5] P. Jones,[1] R. Julin,[1] S. Juutinen,[1] T.-L. Khoo,[8] W. Korten,[4] M. Leino,[1] A.-P. Leppänen,[1,§] J. Ljungvall,[4] S. Moon,[5] M. Nyman,[1] A. Obertelli,[4] J. Pakarinen,[1,‡] E. Parr,[5] P. Papadakis,[5] P. Peura,[1] J. Piot,[6] A. Pritchard,[5] P. Rahkila,[1] D. Rostron,[5] P. Ruotsalainen,[1] M. Sandzelius,[9] J. Sarén,[1] C. Scholey,[1] J. Sorri,[1] A. Steer,[10] B. Sulignano,[4] Ch. Theisen,[4] J. Uusitalo,[1] M. Venhart,[3,†] M. Zielinska,[11] M. Bender,[12,13] and P.-H. Heenen[14]

The JUROGAM II Germanium Array

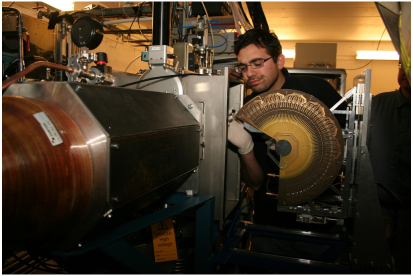


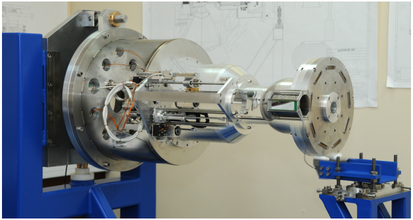
- 24 Clover and 15 Tapered Ge detectors - GAMMAPOOL resources
- Total Photopeak Efficiency 5.2% @ 1.3 MeV
- Excellent γ-γ efficiency
- Autofill system built by University of York, part of GREAT
- Instrumented with Lyrtech digital electronics
- Higher counting rates, higher beam intensities

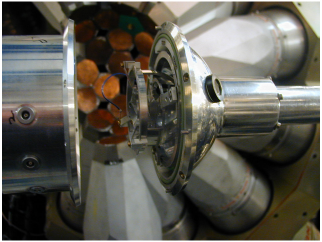


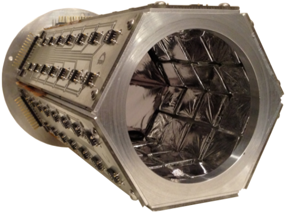


Range of Ancillary Devices



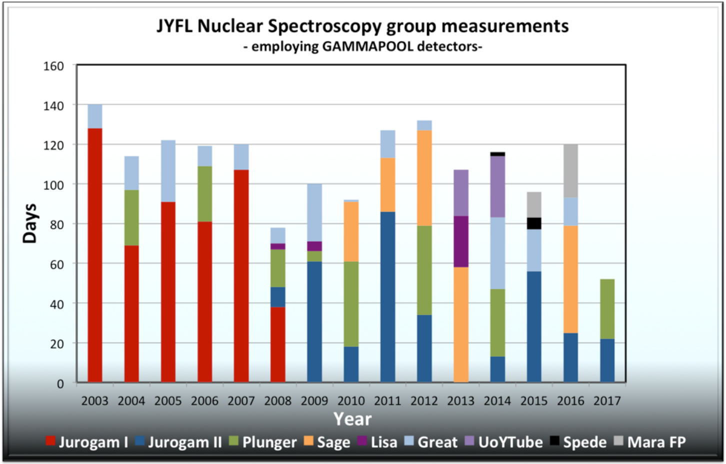






UoY Tube THE UNIVERSITY of York

Use of GAMMAPOOL Resources



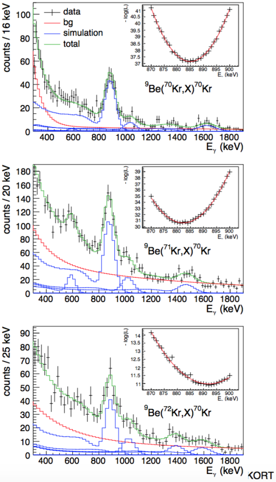
- 2003-2017: 187 experiments, over 33300 beamtime hours
- 129 refereed journal articles, 60+ conference proceedings, 65 PhD theses

Outline

Isospin symmetry in ^{70}Kr

Irfu cea saclay

First spectroscopy of ^{70}Kr



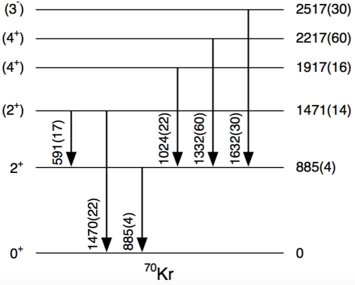
Comparison of 3 different reactions:

- inelastic scattering on Be target
- 1n knock-out from ^{71}Kr
- 2n knock-out from ^{72}Kr

→ consistent transition energies (through likely-hood fits)

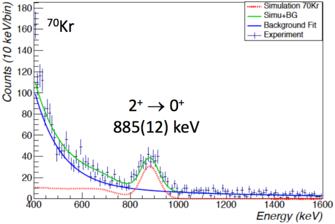
→ **level scheme** through energy differences and (partial) coincidences

→ **spin-parities** by comparison with ^{70}Se



Isospin symmetry in ^{70}Kr

Electromagnetic excitation of ^{70}Kr on Au target



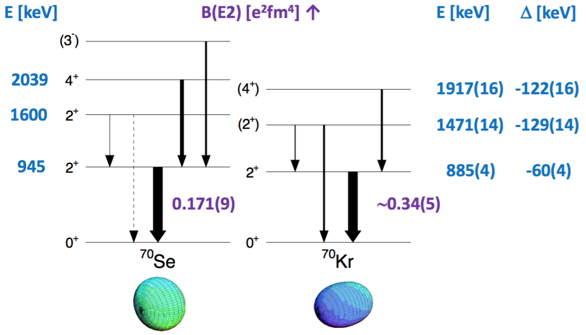
	^{70}Kr	^{68}Se	^{70}Br	^{72}Kr
Au target				
$\sigma_{2_1^+}$ [mb]	281(28)	231(3)	157(9)	339(5)
$\sigma_{2_2^+}$ [mb]		20(2)		41(3)
Be target				
$\sigma_{2_1^+}$ [mb]	18(3)	22(1)	17(1)	26.0(10)
$\sigma_{2_2^+}$ [mb]		4.4(4)		4.5(3)

- measurement of **absolute, integrated cross section** Au(^{70}Kr,^{70}Kr*)Au
- nuclear contributions taken from inelastic scattering on Be target
- feeding corrections from (observed) higher-lying states included
- preliminary result: **B(E2; $0^+ \rightarrow 2^+$) = 3400(500) e^{2}fm^4**
- final uncertainty, statistic and systematic, expected to be ~20 %

Wolfram KORTEN – ARIS 2017

Isospin symmetry in ^{70}Kr

Collectivity of A=70 T=1 mirror nuclei



Lower E(2⁺,4⁺) and **higher B(E2)** in **^{70}Kr** than in mirror ^{70}Se

→ may indicate shape change between A=70 T=1 mirror nuclei ?

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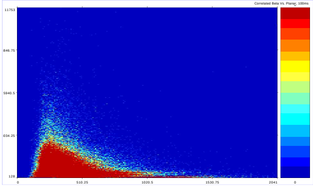
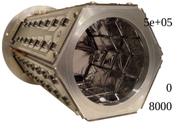
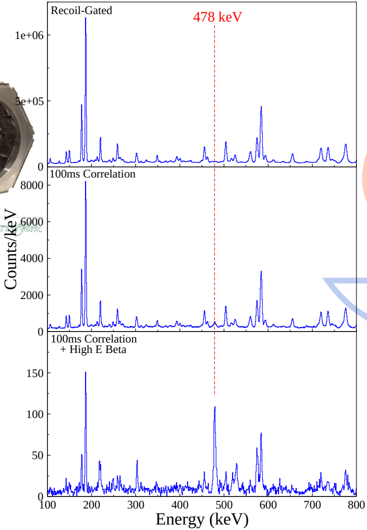
Recoil-β Tagging





UoY Tube The University of York



- Proof-of-Principle Experiment 2006
- Complemented with UoYTube charged particle detector
- Access to excited state structure of N=Z superallowed β-emitters
- A.N. Steer et al., NIMA **565**, 630 (2006)

Isospin symmetry in ^{70}Kr

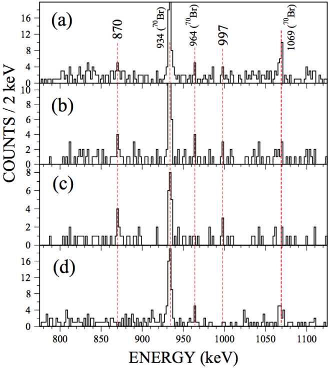


FIG. 1. γ-ray spectra obtained with JUROGAM II for different tagging conditions. (a) requires that a β-decay event occurs within 400 ms of the correlated recoil ion implant, that it has a high-energy positron (>2 MeV) recorded in the GREAT planar detector and that no coincident charged particles were recorded in UoYTube; (b) has the same gating conditions as (a) except that the β-ion correlation time in this case was up to 100 ms, (c) has the same conditions as (b) plus a time restriction on the DSSSD-planar coincidence times to select the medium-energy β particles. This reduced the ^{70}Br events in the spectrum—see text for details; (d) same as (c) but with one charged particle explicitly demanded in UoYTube.

PHYSICAL REVIEW C **94**, 054311 (2016)

Spectroscopy of ^{70}Kr and isospin symmetry in the $T = 1$ fpg shell nuclei

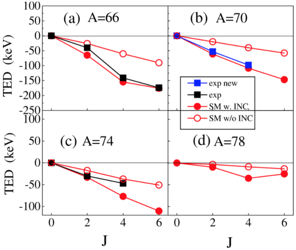


FIG. 3. Triplet energy differences as a function of spin, J, for the $A = 66, 70, 74$, and 78 triplets. Black squares show the experimental values for the $A = 66$ and 74 systems, blue squares show the new experimental values for the $A = 70$ triplet, whilst the solid (open) red circles show the results from shell model calculations with (without) the INC term.

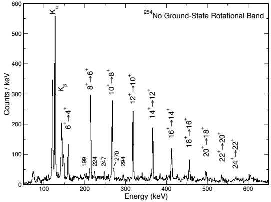
TABLE I. Quadrupole moments (in efm^2) predicted by the shell model using the JUN45 interaction in the fpg model space (with the INC interaction included) for the yrast states in the $A = 70$ triplet nuclei.

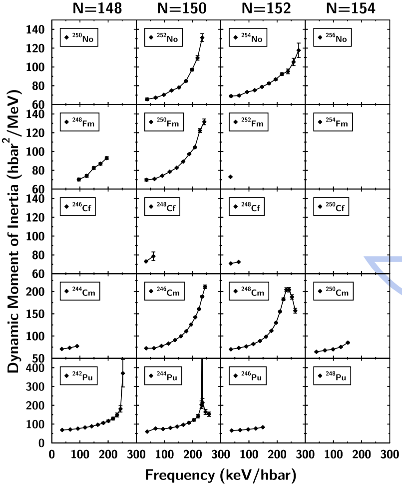
J^{π}	^{70}Se	^{70}Br	^{70}Kr
2^+	37.3	39.8	44.4
4^+	49.7	54.2	59.6
6^+	55.1	59.9	65.7

Outline

Rotational Properties of Heavy Nuclei

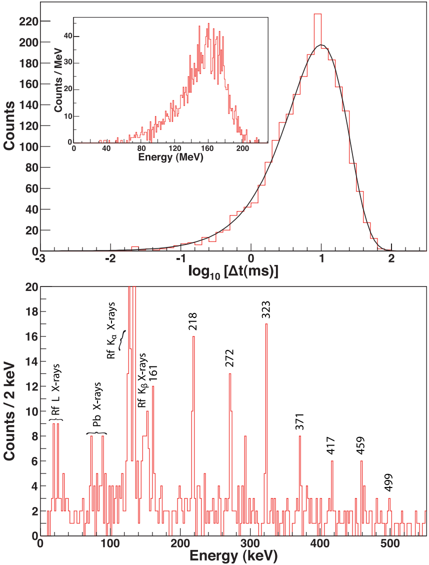
S. Eeckhaudt, P.T. Greenlees et al., EPJA **26**, 227 (2005)





- Confirmed deformed nature of nuclei around ^{254}No
- Showed fission barrier robust with spin ($> 20\hbar$)
- Faster alignment at N=150 compared to N=152 ($\pi i_{13/2}, \nu j_{15/2}$)
- Excellent testing ground for theory; e.g.
  Duguet et al., NPA **679**, 427 (2001),
  Bender et al., NPA **723**, 354 (2003),
  Afanasjev et al., PRC **67**, 024309 (2003),
  Egido and Robledo, PRL **85** 1198 (2000)
- Provides test of pairing properties
- Many new theory papers prompted by latest data

In-beam spectroscopy of SHE: ^{256}Rf

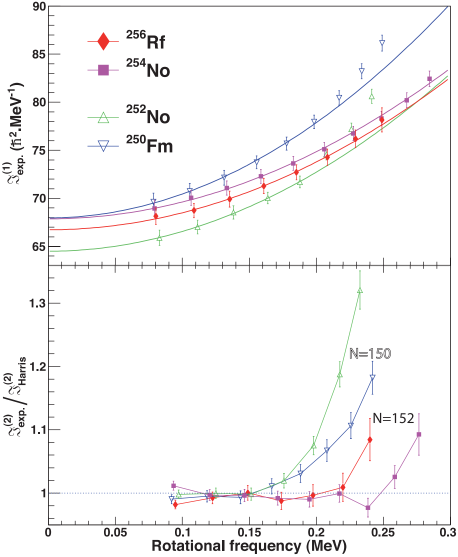


Experimental Details

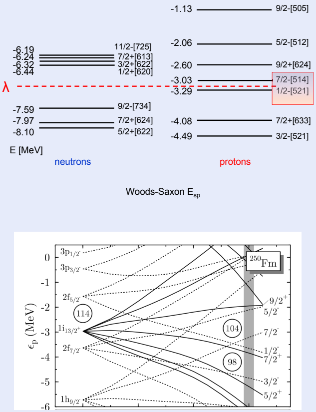
- ^{50}Ti + ^{208}Pb ⇒ ^{256}Rf + 2n
- JUROGAM II, RITU, GREAT
- Enriched ^{50}Ti beam from MIVOC
- 450 hours, 29pnA beam, 2210 observed fissions
- Cross section 17 nb

P.T.Greenlees, J.Rubert et al., PRL **109**, 012501 (2012)

In-beam spectroscopy of SHE: ^{256}Rf



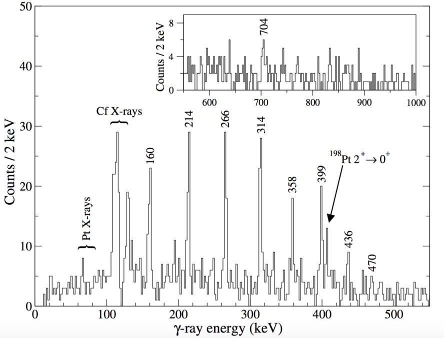
Single-particle energies

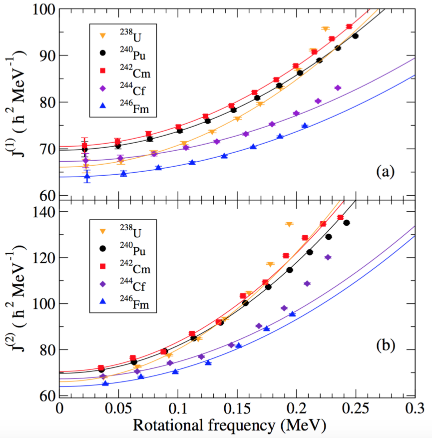


P.T.Greenlees, J.Rubert et al., PRL **109**, 012501 (2012)

In-beam study of ^{244}Cf

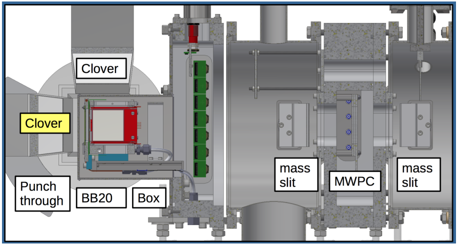
- ^{48}Ca + ^{198}Pt, J. Konki, B. Sulignano et al., In preparation

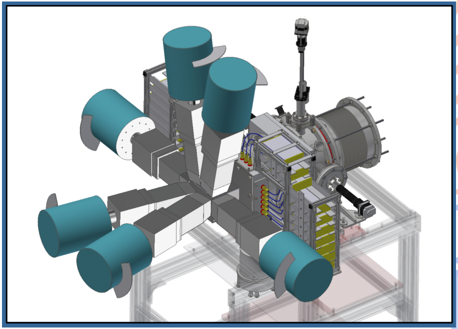




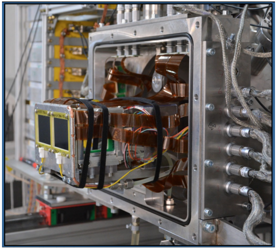
Outline

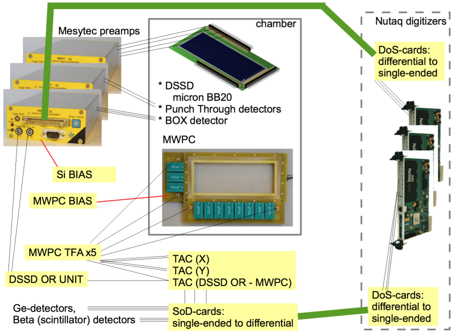
MARA - Focal Plane (Courtesy Jan Sarén)

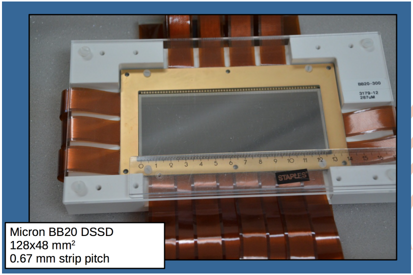


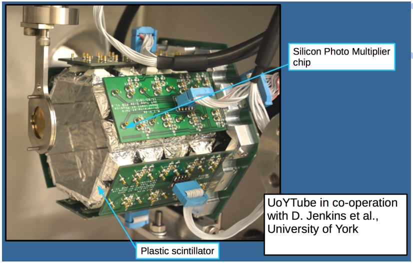


MARA - Instrumentation (Courtesy Jan Sarén)

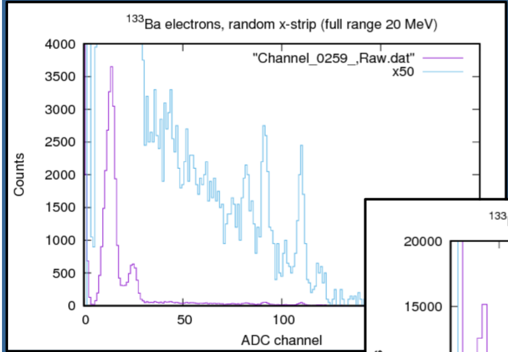






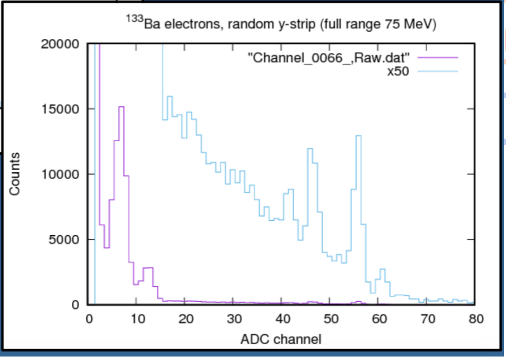


Commissioning of MARA - Examples (Courtesy Jan Sarén)

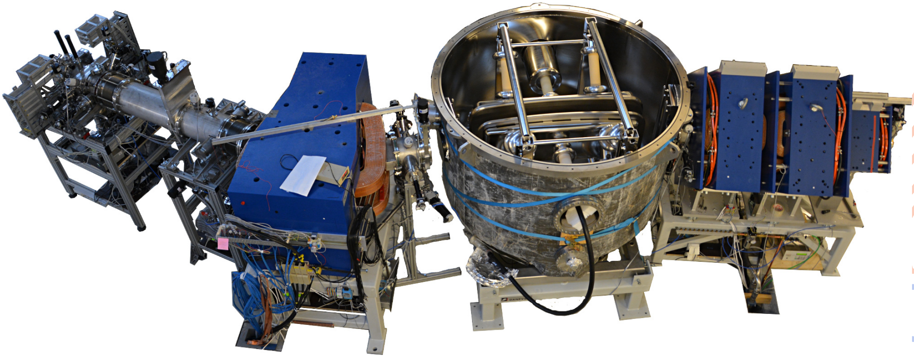


BB20 is promising:

- Threshold below 45 keV.
- Only one strip missing currently
- Resolution (FWHM) around
  - ~20 keV for alphas
  - ~9 keV for electrons



Commissioning of MARA



Commissioning Runs

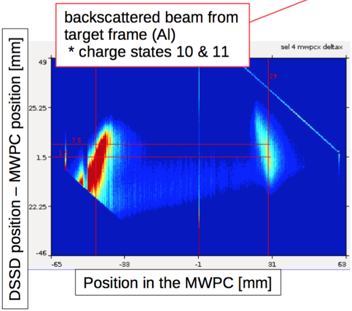
- $^{78}Kr + ^{98}Mo \rightarrow ^{176}Pt^*$
- $^{78}Kr + ^{58}Ni \rightarrow ^{136}Gd^*$

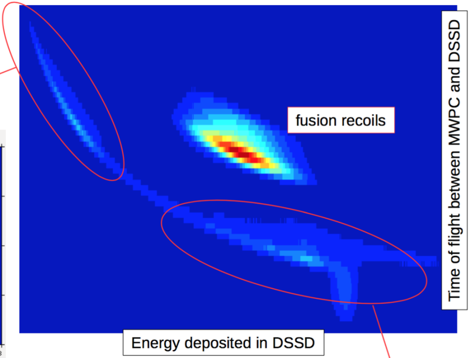
- $^{40}Ca + ^{45}Sc \rightarrow ^{85}Nb^*$
- $^{40}Ca + ^{nat}Ca \rightarrow ^{80}Zr^*$
- $^{40}Ar + ^{124}Sn \rightarrow ^{164}Er^*$
- $^{58}Ni + ^{106}Cd \rightarrow ^{164}Os^*$

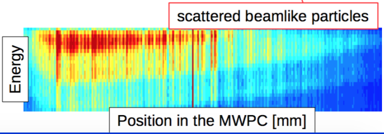
Commissioning of MARA - Examples (Courtesy Jan Sarén)

Separation of the fusion recoils and background by ($ToF_{MWPC\text{-}DSSD}$, E_{DSSD})

Example: reaction 58Ni + 106Cd → 164Os



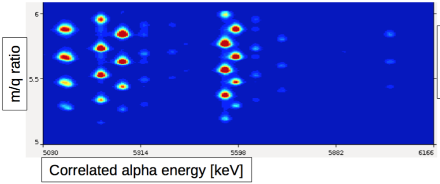


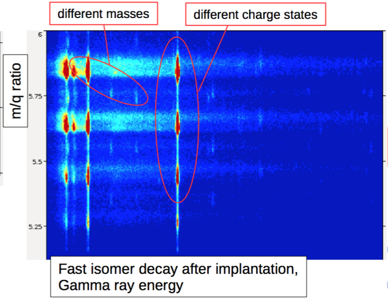


These are the main background types seen in all commissioning experiments. Rate of these have been about the same as the rate of fusion recoils. The backscattered beam m/q peaks might be slightly challenging in some experiments.

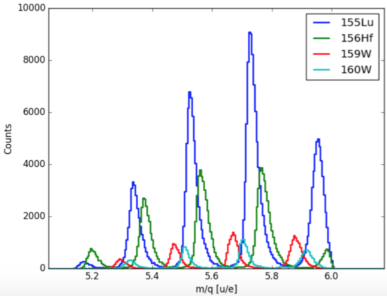
Commissioning of MARA - Examples (Courtesy Jan Sarén)

Mass/charge ratio of fusion products
Example: reaction 58Ni + 106Cd → 164Os





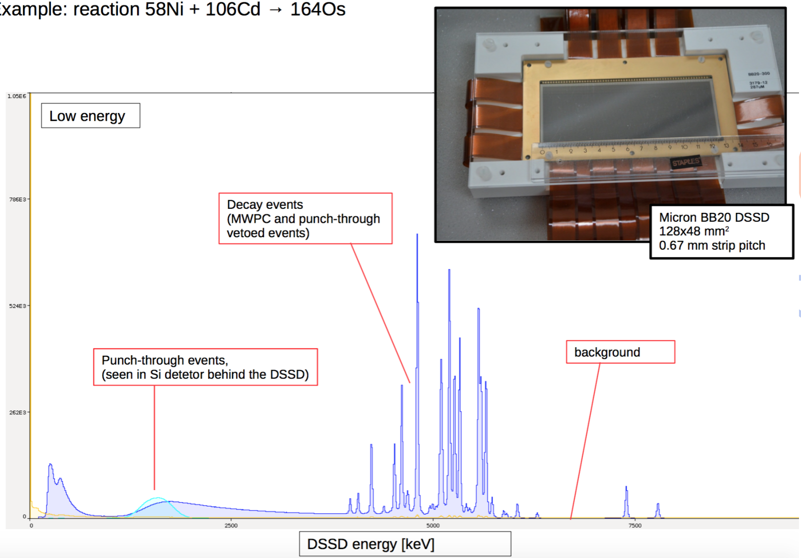
Isomeric gamma decay tagging selectivity can be enhanced by the mass resolving power.



Mass resolving power of 140-150 was obtained in this reaction. It is strongly affected by beam spot size and aberrations. If required, mass resolving power can be increased by apertures or by using a so called high resolution mode.

Commissioning of MARA - Examples (Courtesy Jan Sarén)

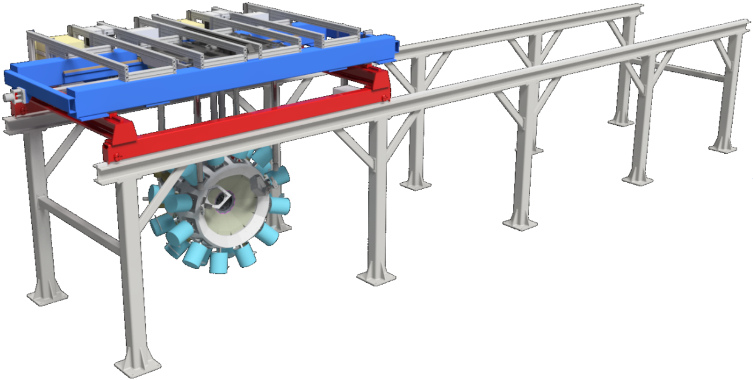
Classification of DSSD events
Example: reaction 58Ni + 106Cd → 164Os



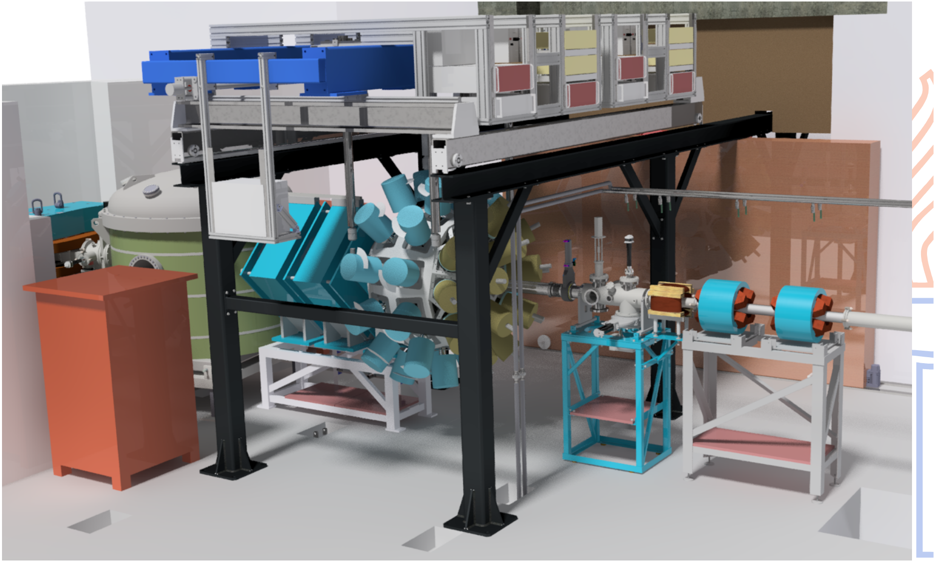
JYFL Decay Spectroscopy Pending Proposals

Exp. Code	Spokespersons	Title	Submission deadline	Days
R52	J. Uusitalo	Probing beyond the proton drip-line above lead, ^{189}At	15.3.2015	10
R53	K. Hauschildt	Decay Spectroscopy of the Transfermium Nucleus ^{255}Lr	15.9.2015	14
M2	J. Uusitalo	Beta-delayed proton decay of ^{77}Zr	15.3.2016	10
M3	D. Jenkins	Beta-delayed proton decay of ^{69}Kr	15.3.2016	14
M4	R. Wadsworth	Study of MEDs in the mass 95 mirror pair ^{95}Cd/^{95}Ag	15.3.2016	10
M5	D. Cullen	Deformation of ^{140}Dy; daughter of the deformed ^{141}Ho Proton Emitter using Fast timing with a compact array of $LaBr_3$ detectors at the MARA focal plane	15.3.2016	10
M6	N. Singh	Proof of principle test of lifetime measurements using charge plunger at MARA	15.3.2016	5
M7	B. Cederwall, J. Uusitalo	Decay spectroscopy of extremely neutron deficient Ce, La and Ba isotopes including a search for the new isotopes ^{116,118}L	15.3.2016	14
R54	R. Page	Decay spectroscopy of proton-emitting Tl isotopes	15.3.2016	10
R55	E. Parr	Studying possible K-isomeric states of ^{252}Fm	15.9.2016	5
M8	R. Page	Search for charged-particle radioactivity from ^{160}Os	15.3.2017	14
M9	J. Uusitalo, D. Joss	Search for the beta-delayed proton emitters ^{133}Gd and ^{132}Eu	15.3.2017	14
M11	U. Forsberg, M. Bentley	Investigating excited states in T_z=-3/2 nuclei in the fpg shell using beta-delayed proton tagging at MARA	15.3.2017	3

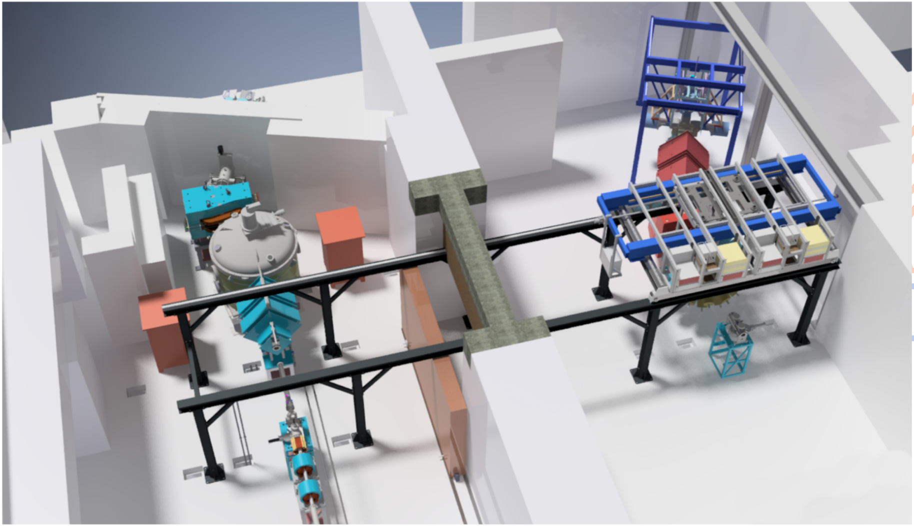
MARA - JUROGAM3 Transport System



JUROGAM3 @ MARA



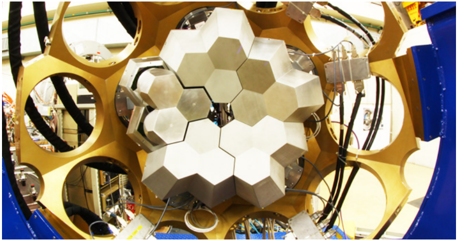
JUROGAM3 @ MARA OR RITU



MARA In-beam Spectroscopy Pending Proposals

Exp. Code	Spokespersons	Title	Submission deadline	Days
J23	S. Tandel	K isomers and rotation alignments in Am isotopes	15.3.2015	6
JR146	J. Uusitalo	Prompt and Delayed Spectroscopy of the Proton-Unbound Nucleus ^{193}At	15.9.2015	14
JR149	D. Cullen	Commissioning of TPEN: A Triple-foil Plunger for Exotic Nuclei (TPEN)	15.3.2016	5
JM1	B. Cederwall, J. Smith	In-beam study of excited states of ^{107}Te using recoil-decay tagging with JurogamIII and MARA	15.3.2017	14
JM2	D. Jenkins	Identification of excited states in ^{78}Zr	15.3.2017	9
JM3	C. Petrache	Collectivity and shape phenomena in extremely neutron deficient La, Ce, and Pr nuclei	15.3.2017	7
JM4	M. Bentley, R. Wadsworth	T=0 neutron-proton correlations in ^{94}Ag	15.3.2017	12
JM5	P. Ruotsalainen, C. Scholey	Isoscalar neutron-proton pairing in N=Z nuclei ^{84}Mo and ^{88}Ru	15.3.2017	16
JM6	D. Joss, J. Uusitalo, B. Cederwall	Excited states in the highly deformed proton emitter ^{131}Eu	15.3.2017	14
JM7	B.S. Nara Singh	Feasibility test of a lifetime measurement in ^{74}Rb using the plunger and recoil-β tagging technique	15.3.2017	4
JM8	A. Boso, D. Jenkins	Isospin Symmetry and Shape Coexistence in Mirror Nuclei ^{71}Kr-^{71}Br	15.3.2017	14
JM9	B. Cederwall, B.S. Nara Singh	Search for the isoscalar spin-aligned pairing scheme in self-conjugate ^{96}Cd	15.3.2017	10
JR150	K. Auranen	Prompt and delayed spectroscopy of neutron deficient trans-lead nuclei ^{211,213}Ac	15.3.2017	14

AGATA @ JYFL?



AGATA

- Limited involvement so far
- Signatory of MoU 2016-2021
- Bid for AGATA capsule and infrastructure
- Finnish Academy 359 k€ 2018-2019
- Conditionally granted January 2017

Physics Cases

- AGATA only coupled to zero degree spectrometer in GANIL?
- Possible coupling to MARA or RITU
- Ancillary devices (DPUNS, SAGE, UoYTube, etc)
- Stable beams up to 200 pnA from (p to Au)
- e.g. SHE, N=Z, high spin
- High level of beam time availability

Concerns

- Man and woman power!
- Cost!
- Beam line height!
- Performance (P/T, Singles, Efficiency)
- Integration with TDR DAQ

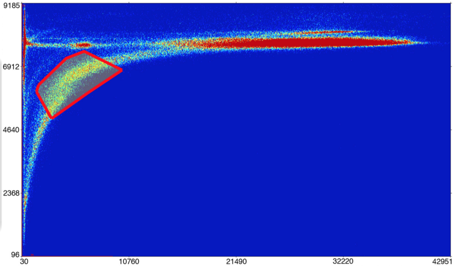
Beyond Rf?

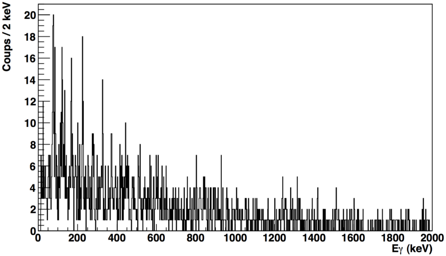
To Sg?

- e.g. ^{208}Pb(^{54}Cr,2n)^{260}Sg
- X.S. 300-500 pb (at best!)
- ^{256}Rf - 17 nb, 30 pnA, 40%, 450 hours
- Need a factor of 30-60 improvement!

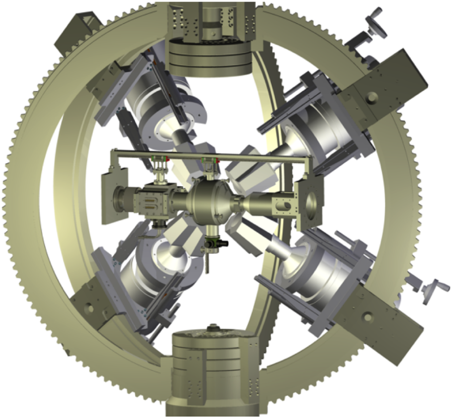
Factors

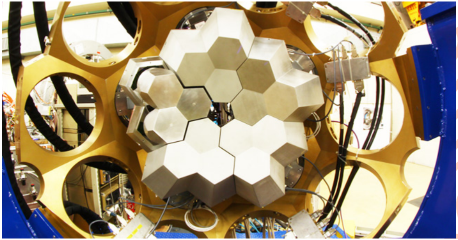
- Full(?) AGATA - 50%? (Factor 10)
- ^{260}Sg 50% alpha, 50% SF, 5 ms (Factor 0.75?)
- 60-100 pnA? Factor 2-3
- 900 hours? Factor 2
- New Separator? At most Factor 2
- Total Factor about 50?





Activities outside JYFL





AGATA

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ISOLDE

- SPEDE installed at MINIBALL
- Isolde Decay Station - DAQ and analysis
- MINIBALL DAQ upgrade based on FEBEX

Summary and Outlook

- Very successful campaigns with JUROGAM and RITU
- Range of ancillary devices: SAGE, DPUNS plunger, UoYTube, LISA
- Fusion-evaporation reactions with stable beams complementary to RIB studies
- MARA separator - commissioned, focal plane physics 2017-2018
- MARA separator - cave reconstruction and in-beam physics 2017-2019+
- Involvement in MINIBALL, AGATA
- Possible host for AGATA in far future
- Expect a broad and competitive physics program in the future!

Nuclear Spectroscopy Group