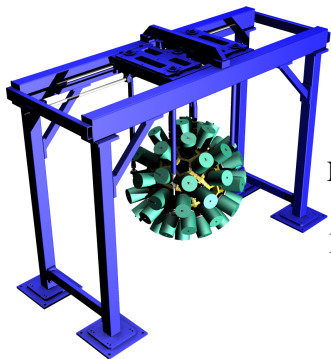


# Gamma-ray and Conversion Electron Spectroscopy at JYFL

Paul Greenlees

Department of Physics  
University of Jyväskylä

Nu-Ball Workshop  
19.05.2016  
IPN Orsay, France

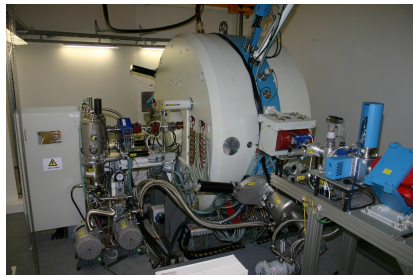


# Outline

- 1 Introduction
- 2 Past Studies
- 3 Present and Future Studies



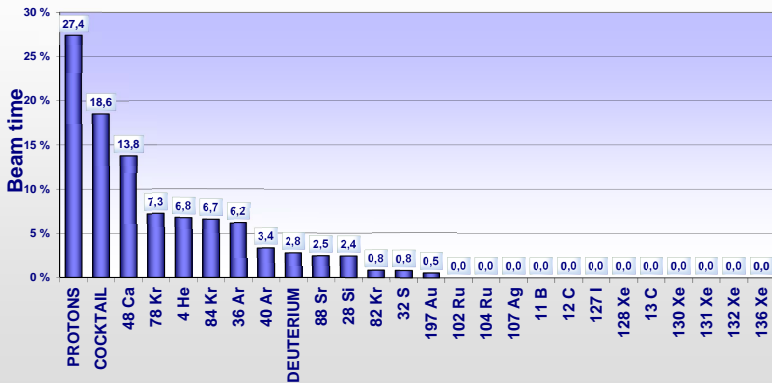
# Accelerator Facilities



# K130 Cyclotron Facility

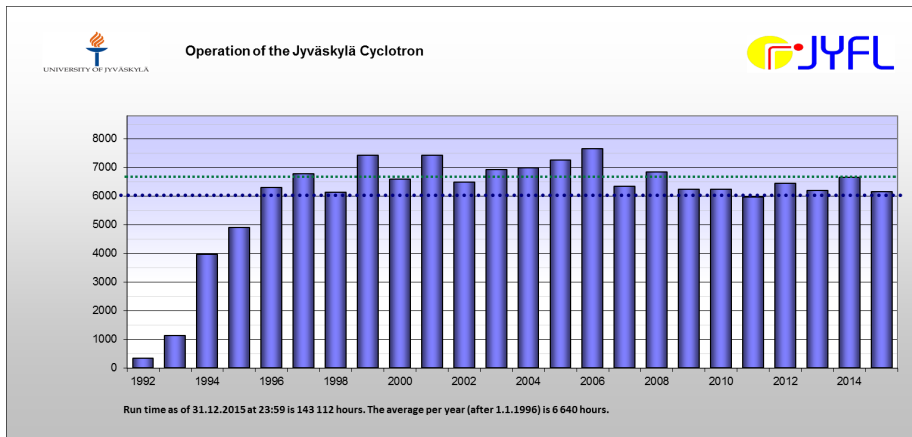


## Accelerated Ions in 2015 (All)



Charts

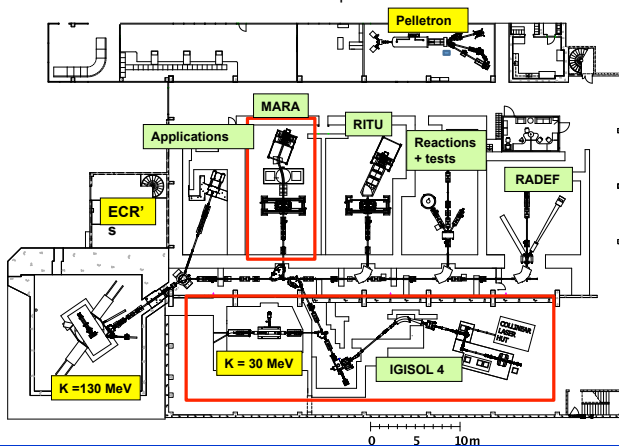
# Use of the K130 Cyclotron



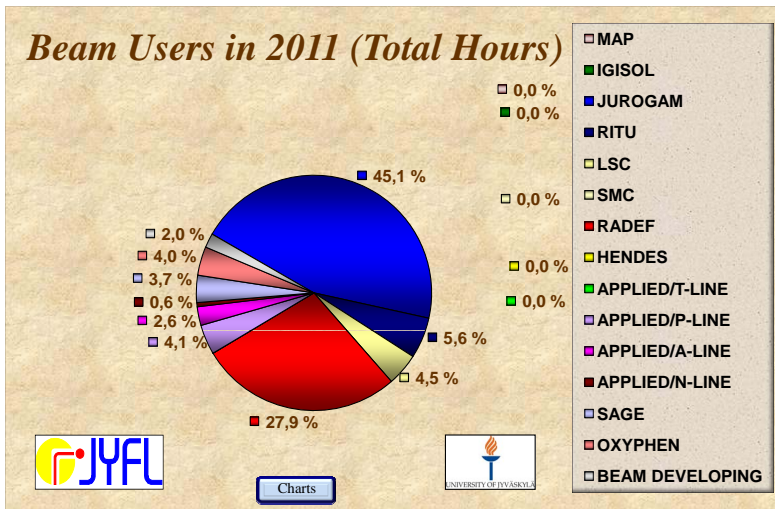
# Recent Expansion

## Upgrade of the JYFL-ACCLAB

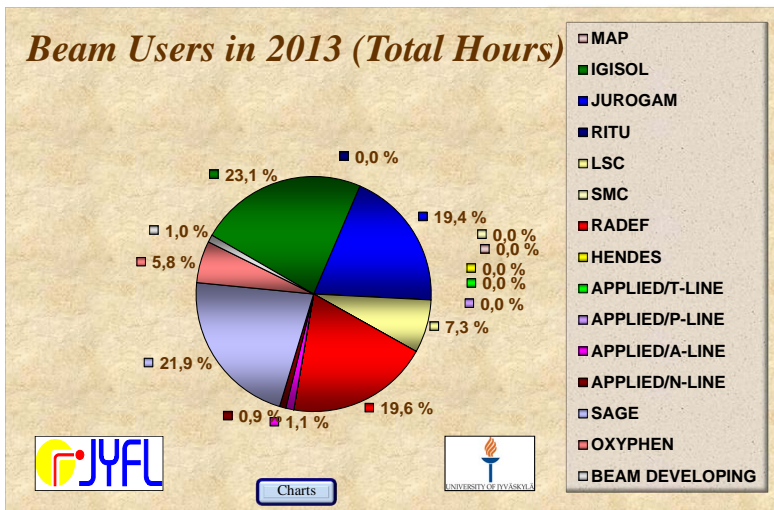
New K = 30 MeV light-ion cyclotron  
 New IGISOL 4  
 New MARA recoil separator



# Consequences: Use of the K130 Cyclotron 2011

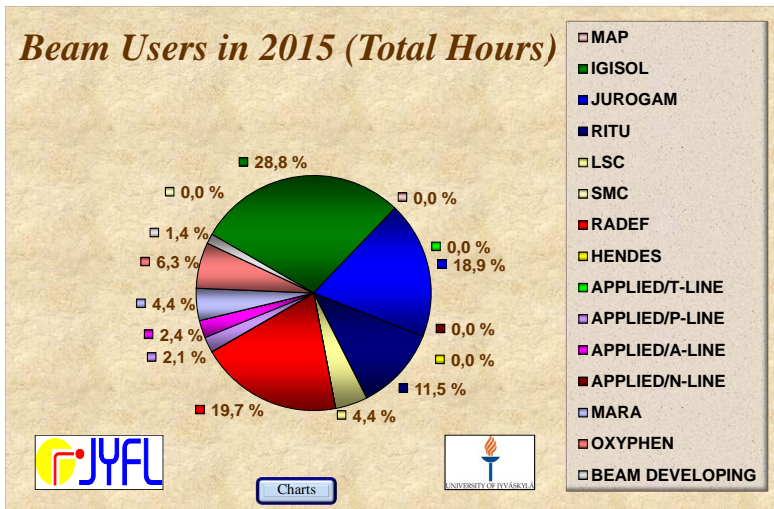


# Use of the K130 Cyclotron 2013





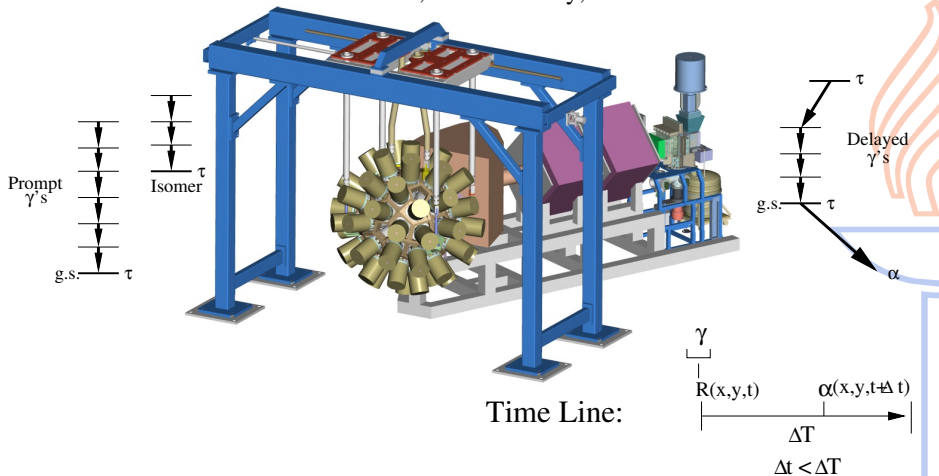
# Use of the K130 Cyclotron 2015



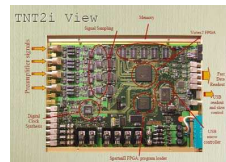
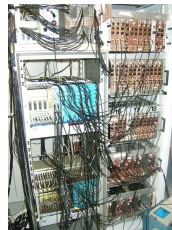
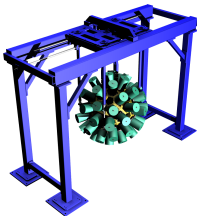
# Principles of RDT

## Tagging Techniques

Recoil, Recoil–Decay, Isomer



# Recent history of JUROGAM



- Fifth and final campaign ended May 2008
- 2003 - 2008: 67 experiments, 11000 hours beam on target
- 2008: Fully instrumented with TNT2 digital electronics
- TNT2 cards in collaboration with CNRS/IN2P3 GABRIELA
- Superseded by JUROGAM II

PRL 102, 212501 (2009)

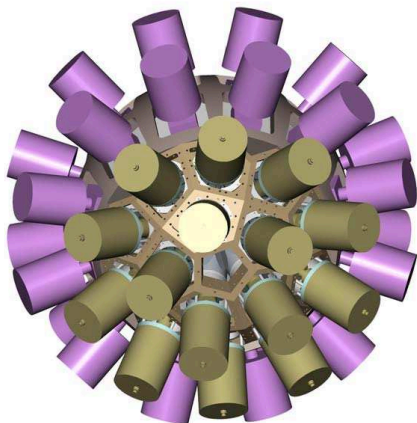
PHYSICAL REVIEW LETTERS

week ending  
29 MAY 2009

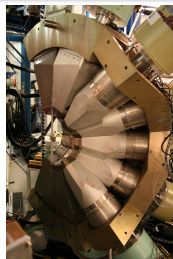
## $\gamma$ -Ray Spectroscopy at the Limits: First Observation of Rotational Bands in $^{255}\text{Lu}$

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

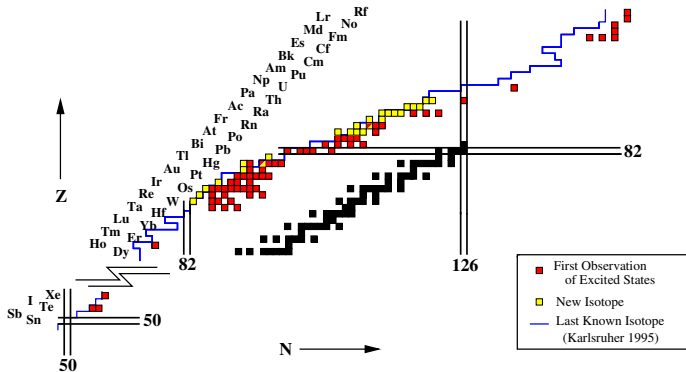
# The JUROGAM II Germanium Array



- 24 Clover and 15 Tapered Ge detectors - GAMMAPOOL resource
- Total Photopeak Efficiency 5.2% @ 1.3 MeV
- Excellent  $\gamma$ - $\gamma$  efficiency
- Autofill system built by University of York, part of GREAT
- Instrumented with Lyrtech digital electronics
- Higher counting rates, higher beam intensities
- June 2015: 1200 days devoted to 168 measurements (almost 30k hrs)



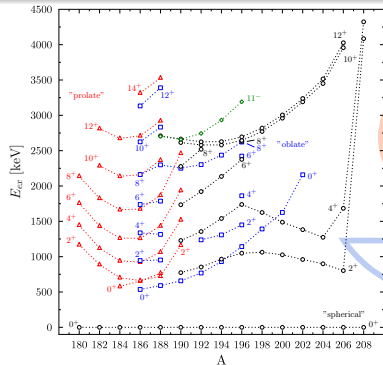
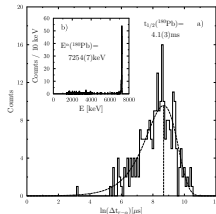
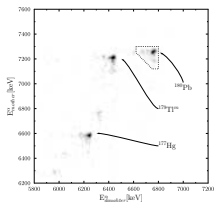
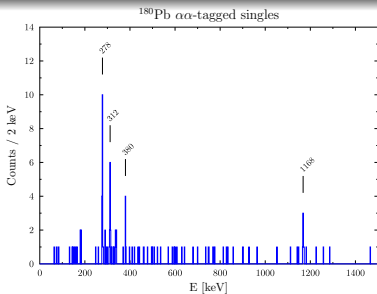
# Regions of Study at RITU



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

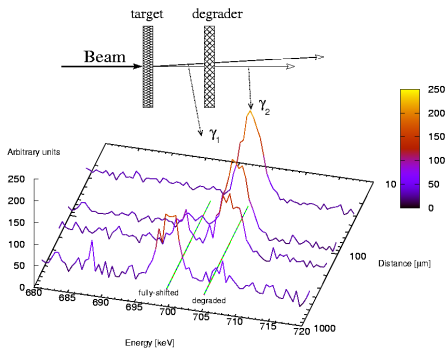
# World Record: In-beam spectroscopy at $\sigma=10$ nb

P.Rahkila et al., PRC **82**, 011303(R) (2010)  $^{90}\text{Zr} + ^{92}\text{Mo} \rightarrow ^{180}\text{Pb} + 2n$

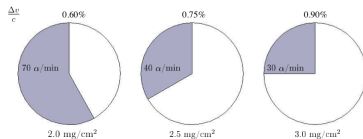


- 1 week, 7 pnA beam,  $\approx 300$  events
- c.f. Andreyev et al., PRC **80**, 054322 (2009)
- SHIP, "High intensity beam",  $\approx 100$  events

# RDDS Lifetime Measurements



- $E(\theta) = E_0(1 - \frac{v}{c} \cos \theta)$
- Need high initial recoil velocity
- Degrader - 1 mg/cm<sup>2</sup> Mg, Al or 2 mg/cm<sup>2</sup> Au
- Typical velocity change 4% to 3%
- Loss of separator transmission efficiency



# RDDS Lifetime Measurements - Recent Results

PRL 97, 062501 (2006)

PHYSICAL REVIEW LETTERS

week ending  
11 AUGUST 2006

## Collectivity and Configuration Mixing in $^{186}\text{Pb}$ and $^{194}\text{Po}$

T. Grahn,<sup>1,6</sup> A. Dewald,<sup>2</sup> O. Möller,<sup>2</sup> R. Julin,<sup>1</sup> C. W. Beausang,<sup>3,1</sup> S. Christen,<sup>2</sup> I. G. Darby,<sup>1,4</sup> S. Eeckhaud,<sup>1</sup> P.T. Greenlees,<sup>1</sup> A. Görge,<sup>5</sup> K. Helariutta,<sup>1</sup> J. Jolie,<sup>2</sup> P. Jones,<sup>1</sup> S. Juutinen,<sup>1</sup> H. Kettunen,<sup>1</sup> T. Kröll,<sup>1</sup> R. Krücken,<sup>7</sup> Y. Le Coz,<sup>2</sup> M. Leino,<sup>1</sup> A.-P. Leppänen,<sup>1,3</sup> P. Maierbeck,<sup>1</sup> D.A. Meyer,<sup>1</sup> B. Melon,<sup>2</sup> P. Nieminen,<sup>1,4</sup> M. Nyman,<sup>1</sup> R.D. Page,<sup>1</sup> J. Pakarinen,<sup>1,4</sup> P. Petkov,<sup>1</sup> P. Rakhila,<sup>1</sup> B. Saha,<sup>1</sup> M. Sandzelius,<sup>1,3</sup> J. Sarén,<sup>1</sup> C. Scholey,<sup>1</sup> and J. Uusitalo<sup>1</sup>

PHYSICAL REVIEW C 80, 014324 (2009)

## Evolution of collectivity in $^{180}\text{Hg}$ and $^{182}\text{Hg}$

T. Grahn,<sup>1,2</sup> A. Petts,<sup>1</sup> M. Scheck,<sup>1</sup> P. A. Butler,<sup>1</sup> A. Dewald,<sup>2</sup> M. B. Gómez Hornillos,<sup>3,1</sup> P. T. Greenlees,<sup>4</sup> A. Görge,<sup>1</sup> K. Helariutta,<sup>1</sup> J. Jolie,<sup>2</sup> P. Jones,<sup>1</sup> R. Julin,<sup>1</sup> S. Juutinen,<sup>1</sup> S. Kettelhut,<sup>1</sup> R. Krücken,<sup>7</sup> T. Kröll,<sup>1,1</sup> M. Leino,<sup>4</sup> J. Ljungvall,<sup>2</sup> P. Maierbeck,<sup>1</sup> B. Melon,<sup>2</sup> M. Nyman,<sup>1</sup> R. D. Page,<sup>1</sup> Th. Pissulla,<sup>1</sup> P. Rakhila,<sup>1</sup> J. Sarén,<sup>1</sup> C. Scholey,<sup>1</sup> A. Semchenkov,<sup>2,3</sup> J. Soori,<sup>1</sup> J. Uusitalo,<sup>1</sup> R. Wadsworth,<sup>1</sup> and M. Zieliska<sup>1,1</sup>

PHYSICAL REVIEW C 80, 014323 (2009)

## Collectivity of $^{180}\text{Po}$ at low spin

T. Grahn,<sup>1,2</sup> A. Dewald,<sup>2</sup> P. T. Greenlees,<sup>1</sup> U. Jakobsson,<sup>1</sup> J. Jolie,<sup>2</sup> P. Jones,<sup>1</sup> R. Julin,<sup>1</sup> S. Juutinen,<sup>1</sup> S. Kettelhut,<sup>1</sup> T. Kröll,<sup>1</sup> R. Krücken,<sup>1</sup> M. Leino,<sup>1</sup> P. Maierbeck,<sup>1</sup> B. Melon,<sup>2</sup> M. Nyman,<sup>1</sup> R. D. Page,<sup>1</sup> P. Peura,<sup>1</sup> Th. Pissulla,<sup>1</sup> P. Rakhila,<sup>1</sup> J. Sarén,<sup>1</sup> C. Scholey,<sup>1</sup> J. Soori,<sup>1</sup> J. Uusitalo,<sup>1</sup> M. Bender,<sup>1,6</sup> and P.-H. Heenen<sup>1</sup>



Available online at www.sciencedirect.com



ScienceDirect

Nuclear Physics A 801 (2008) 83–100

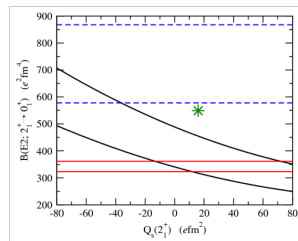
NUCLEAR  
PHYSICS A

www.elsevier.com/locate/nucphysa

## Lifetimes of intruder states in $^{186}\text{Pb}$ , $^{188}\text{Pb}$ and $^{194}\text{Po}$

T. Grahn<sup>a,b,c</sup>, A. Dewald<sup>c</sup>, O. Möller<sup>c-1</sup>, R. Julin<sup>a</sup>, C.W. Beausang<sup>d,2</sup>, S. Christen<sup>e</sup>, I.G. Darby<sup>b,3</sup>, S. Eeckhaud<sup>a</sup>, P.T. Greenlees<sup>a</sup>, A. Görge<sup>e</sup>, K. Helariutta<sup>f</sup>, J. Jolie<sup>e</sup>, P. Jones<sup>a</sup>, S. Juutinen<sup>a</sup>, H. Kettunen<sup>a</sup>, T. Kröll<sup>g</sup>, R. Krücken<sup>g</sup>, Y. Le Coz<sup>e</sup>, M. Leino<sup>a</sup>, A.-P. Leppänen<sup>a,4</sup>, P. Maierbeck<sup>h</sup>, D.A. Meyer<sup>d,5</sup>, B. Melon<sup>e</sup>, P. Nieminen<sup>a,6</sup>, M. Nyman<sup>a</sup>, R.D. Page<sup>h</sup>, J. Pakarinen<sup>a,b</sup>, P. Petkov<sup>a</sup>, P. Rakhila<sup>a</sup>, B. Saha<sup>e</sup>, M. Sandzelius<sup>a,7</sup>, J. Sarén<sup>a</sup>, C. Scholey<sup>a</sup>, J. Uusitalo<sup>a</sup>, M. Bender<sup>1</sup>, P.-H. Heenen<sup>1</sup>

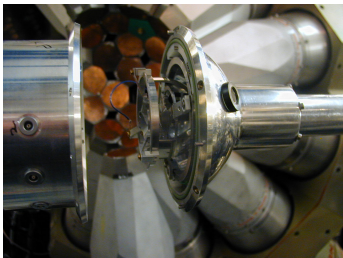
- Confirm ideas concerning development of collectivity based on level energies alone
- Complements our Coulex studies with REX-ISOLDE collaboration
- Lifetime measurements needed to constrain fits in analysis of Coulex data
- Analysis of  $^{182}\text{—}^{188}\text{Hg}$  and  $^{188}\text{—}^{198}\text{Pb}$  in progress



J.Ljungvall et al., PRL 100, 102502 (2008)



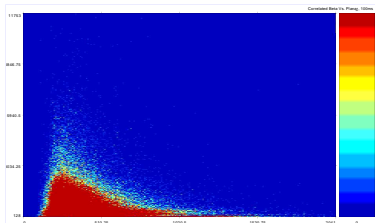
# RDDS Lifetime Measurements - New DPUNS Plunger



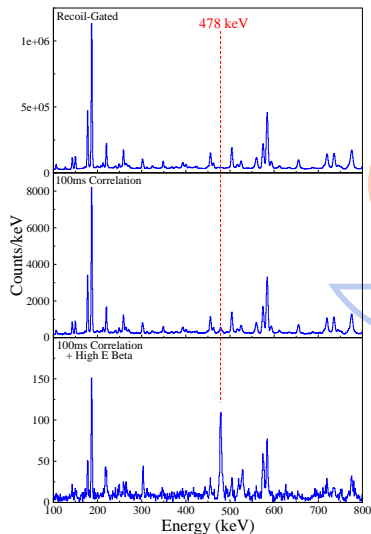
- Copy of Köln plunger for dedicated use in JYFL
- Collaboration between JYFL, IKP Köln, University of Manchester, University of Liverpool
- Mostly funded by STFC via Manchester, Liverpool
- Build up expertise in JYFL, reduce reliance on Köln support
- Triple foil plunger under development at Manchester



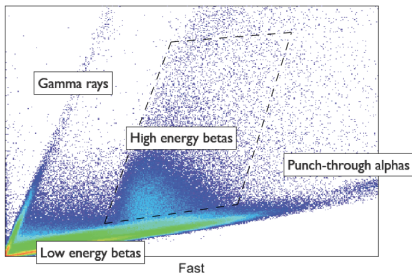
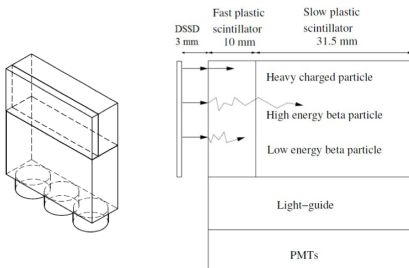
# Recoil- $\beta$ Tagging



- Proof-of-Principle Experiment
- One of GREAT Project Design Goals
- Access to excited state structure of  $N=Z$  superallowed  $\beta$ -emitters
- A.N. Steer et al., NIMA **565**, 630 (2006)



# Recoil- $\beta$ Tagging



PHYSICAL REVIEW C **88**, 024320 (2013)

## Recoil- $\beta$ tagging study of the $N = Z$ nucleus $^{66}\text{As}$

P. Ruotsalainen,<sup>1,2</sup> C. Scholey,<sup>1</sup> R. Julin,<sup>1</sup> K. Hauschild,<sup>1,2</sup> K. Kaneko,<sup>3</sup> B. S. Nara Singh,<sup>4</sup> R. Wadsworth,<sup>4</sup> D. G. Jenkins,<sup>4</sup> T. S. Brock,<sup>5</sup> P. T. Greenlees,<sup>1</sup> J. Henderson,<sup>2</sup> U. Jakobsson,<sup>1</sup> P. Jones,<sup>1,2</sup> S. Juutinen,<sup>1</sup> S. Ketelhut,<sup>1,2</sup> M. Leino,<sup>1</sup> N. M. Lumley,<sup>2</sup> P. J. R. Mason,<sup>6</sup> P. Nieminen,<sup>1</sup> M. Nymann,<sup>1</sup> I. Paterson,<sup>2</sup> P. Peura,<sup>1</sup> M. G. Procter,<sup>2</sup> P. Rähkila,<sup>1</sup> J. Sarén,<sup>1</sup> J. Sorri,<sup>1</sup> and J. Uusitalo<sup>1</sup>

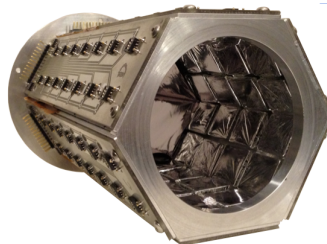
RAPID COMMUNICATIONS

PHYSICAL REVIEW C **88**, 041308(R) (2013)

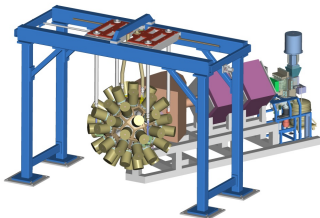
## Spectroscopy of proton-rich $^{66}\text{Se}$ up to $J^\pi = 6^+$ : Isospin-breaking effect in the $A = 66$ isobaric triplet

P. Ruotsalainen,<sup>1,2</sup> D. G. Jenkins,<sup>3</sup> M. A. Bentley,<sup>2</sup> R. Wadsworth,<sup>2</sup> C. Scholey,<sup>1</sup> K. Auranen,<sup>1</sup> P. J. Davies,<sup>2</sup> T. Graham,<sup>1</sup> P. T. Greenlees,<sup>1</sup> J. Henderson,<sup>2</sup> A. Herzli,<sup>4</sup> U. Jakobsson,<sup>1</sup> P. Joobi,<sup>2</sup> R. Julin,<sup>1</sup> S. Juutinen,<sup>1</sup> J. Koski,<sup>1</sup> M. Leino,<sup>1</sup> G. Lotay,<sup>2</sup> A. J. Nichols,<sup>2</sup> A. Obertelli,<sup>4</sup> J. Pakarinen,<sup>1</sup> J. Partanen,<sup>1</sup> P. Peura,<sup>1</sup> P. Rähkila,<sup>1</sup> M. Sandzelius,<sup>1</sup> J. Sarén,<sup>1</sup> J. Sorri,<sup>1</sup> S. Stolz,<sup>1</sup> and J. Uusitalo<sup>1</sup>

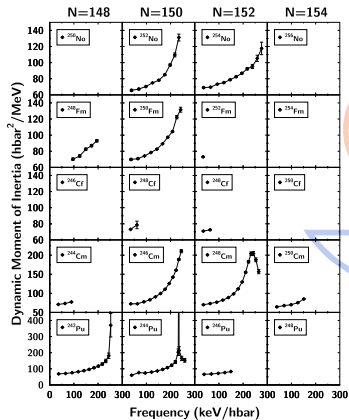
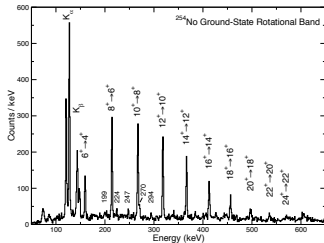
UoY Tube THE UNIVERSITY of York



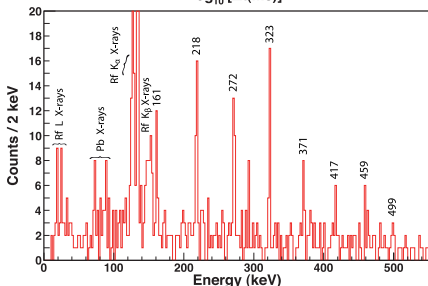
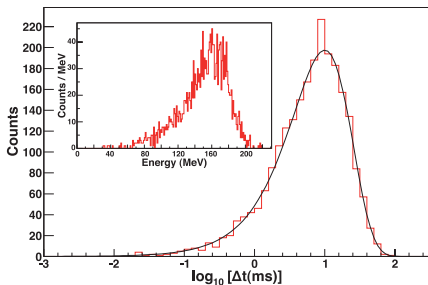
# In-beam studies in region of $^{254}\text{No}$



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



# In-beam spectroscopy of SHE: $^{256}\text{Rf}$



## Experimental Details

- $^{50}\text{Ti} + ^{208}\text{Pb} \Rightarrow ^{256}\text{Rf} + 2\text{n}$
- JUROGAM II, RITU, GREAT
- Enriched  $^{50}\text{Ti}$  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)

# Conversion-Electron Spectroscopy of $^{254}\text{No}$

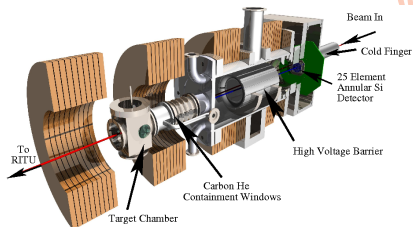
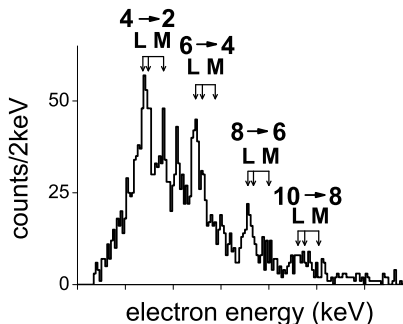
VOLUME 89, NUMBER 20

PHYSICAL REVIEW LETTERS

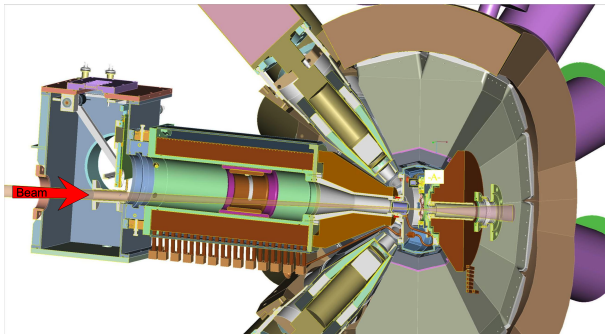
11 NOVEMBER 2002

## Conversion Electron Cascades in $^{254}_{102}\text{No}$

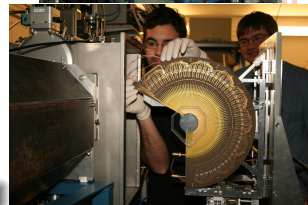
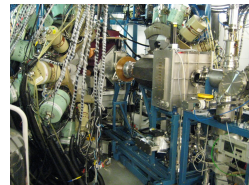
P. A. Butler,<sup>1</sup> R. D. Humphreys,<sup>1</sup> P. T. Greenlees,<sup>2</sup> R.-D. Herzberg,<sup>1</sup> D. G. Jenkins,<sup>1</sup> G. D. Jones,<sup>1</sup> H. Kankaanpää,<sup>2</sup> H. Kettunen,<sup>2</sup> P. Rakkila,<sup>2</sup> C. Scholey,<sup>1,2</sup> J. Uusitalo,<sup>2</sup> N. Amzal,<sup>1</sup> J. E. Bastin,<sup>1</sup> P. M. T. Brew,<sup>1</sup> K. Eskola,<sup>3</sup> J. Gerl,<sup>4</sup> N. J. Hammond,<sup>1</sup> K. Hauschild,<sup>5</sup> K. Helariutta,<sup>4</sup> F.-P. Heßberger,<sup>4</sup> A. Hürstel,<sup>5</sup> P. M. Jones,<sup>2</sup> R. Julin,<sup>2</sup> S. Juutinen,<sup>2</sup> A. Keenan,<sup>2</sup> T.-L. Khoo,<sup>6</sup> W. Korten,<sup>5</sup> P. Kuusiniemi,<sup>2</sup> Y. Le Coz,<sup>5</sup> M. Leino,<sup>2</sup> A.-P. Leppänen,<sup>2</sup> M. Muikku,<sup>2</sup> P. Nieminen,<sup>2</sup> S. W. Ødegård,<sup>7</sup> T. Page,<sup>1</sup> J. Pakarinen,<sup>2</sup> P. Reiter,<sup>8</sup> G. Sletten,<sup>9</sup> Ch. Theisen,<sup>5</sup> and H.-J. Wollersheim<sup>4</sup>



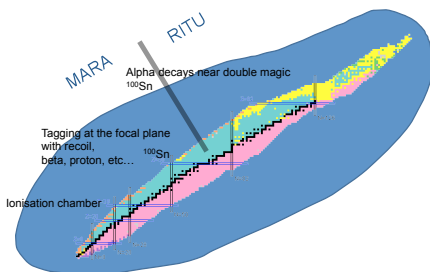
# The SAGE Spectrometer



P. Papadakis et al., AIP Conf. Proc. **1090**, 14 (2009)



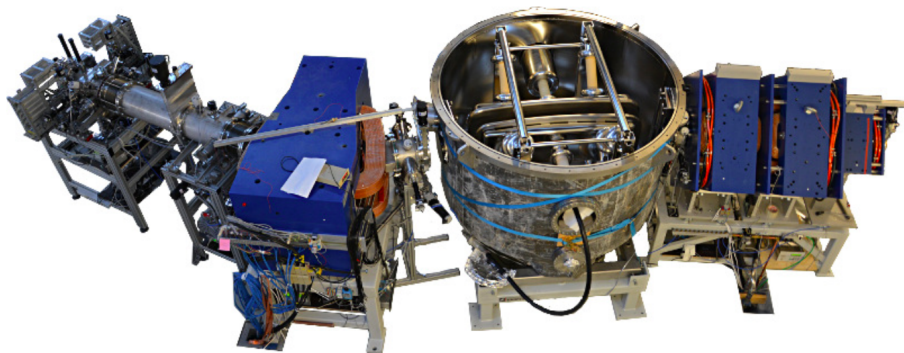
# Future studies of light nuclei - MARA



- Decay spectroscopy (proton and  $\alpha$  emitters)
- In-beam spectroscopy at proton drip line
- Nuclear structure related to astrophysical processes (isomers, etc)
- Studies of  $N \simeq Z$  nuclei
- Super- and hyper-deformation ( $N \simeq Z \simeq 40$ )
- Mirror nuclei
- Combination with existing/new devices (LISA/SAGE/DPUNS/UoYTube...)



# Future studies of light nuclei - MARA

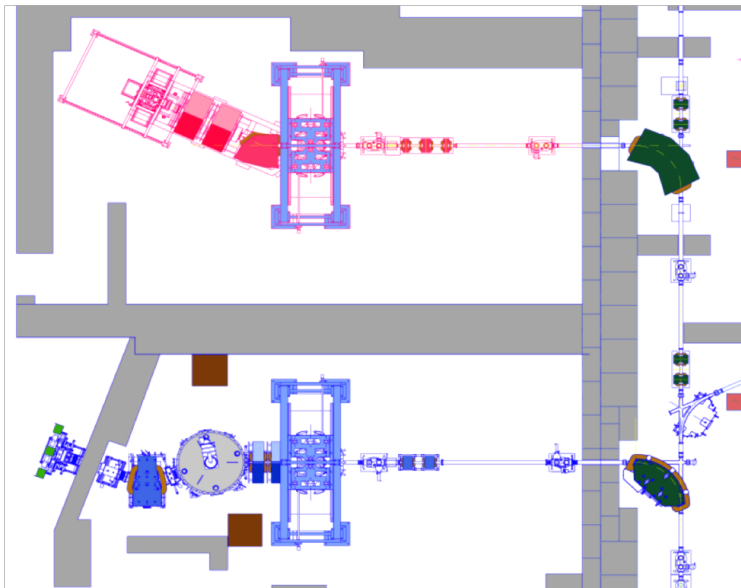


## Commissioning runs

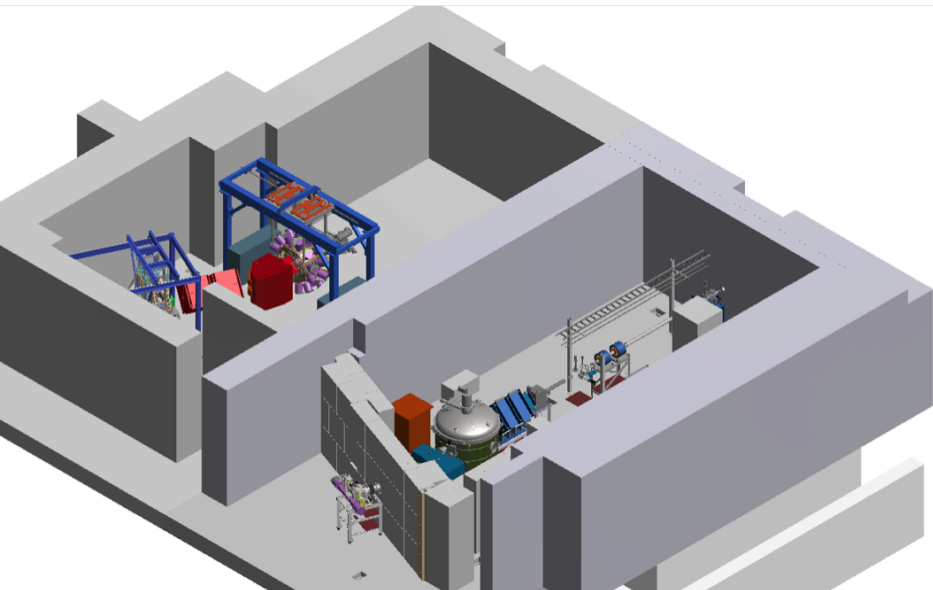
- $^{78}\text{Kr} + ^{98}\text{Mo} \rightarrow ^{176}\text{Pt}^*$
- $^{78}\text{Kr} + ^{58}\text{Ni} \rightarrow ^{136}\text{Gd}^*$

- $^{40}\text{Ca} + ^{45}\text{Sc} \rightarrow ^{85}\text{Nb}^*$
- $^{40}\text{Ca} + \textit{nat}\text{Ca} \rightarrow ^{80}\text{Zr}^*$
- $^{40}\text{Ar} + ^{124}\text{Sn} \rightarrow ^{164}\text{Er}^*$

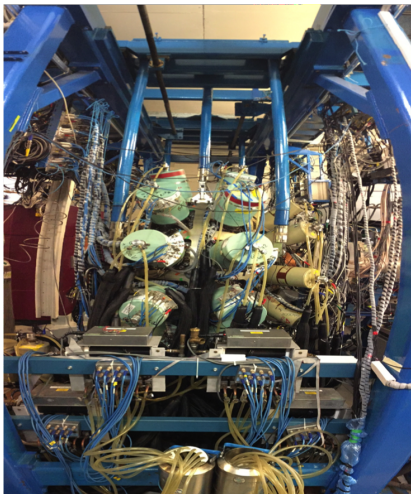
# In-beam studies at MARA



# In-beam studies at MARA



# In-beam studies at MARA



- Infrastructure funding from Finnish Academy
- Crane 150 k€
- LN2 vacuum feedline extension 50 k€
- BGO HV cards/crates 110 k€
- Total 310 k€

# Summary and Outlook

- Very successful campaigns with JUROGAM and RITU
- Range of ancillary devices: SAGE, DPUNS plunger, UoYTube, LISA
- New laboratory / accelerator - more opportunities for nuclear spectroscopy
- MARA separator - commissioned, focal plane physics 2016-2017
- MARA separator - cave reconstruction and in-beam physics 2017-2018
- Expect a broad and competitive physics program in the future