The ISOLDE Solenoidal Spectrometer – First measurements

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NuSpIn 24th-28th July 2019

Overview

ISOLDE Solenoidal Spectrometer

Challenges for direct reaction measurements in inverse kinematics

Solenoid technique

HELIOS

ISOLDE Solenoidal Spectrometer (ISS)

First measurements

$^{28}Mg(d,p)^{29}Mg$

$[^{206}Hg(d,p)^{207}Hg]$

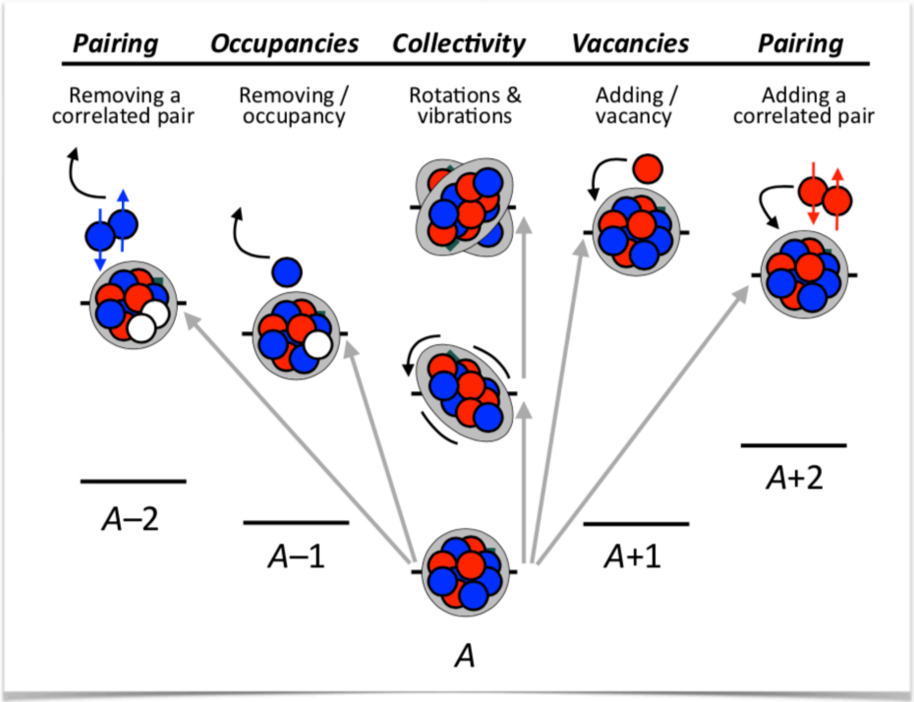
Future upgrades for ISS

Nuclear structure from direct light-ion reactions

- ***Single-particle states***, *E(ex and sp), ℓ values, spectroscopic factors.*
  Examples (d,p), (p,d), (^{3}He,d), (d,^{3}He)…..

- ***Pair correlations***
  Examples (p,t), (t,p), (^{3}He,n)….

- ***Collective properties***
  - *Examples (p,p'), (d,d'), (a,a')…..*



Direct reactions with stable beams (normal kinematics)

Measurements with stable targets and stable beams have been made for many decades.

Beam currents of 10s nA – µA (10^{10}-10^{12} pps) of light ions incident on ~100ug/cm^2 targets.

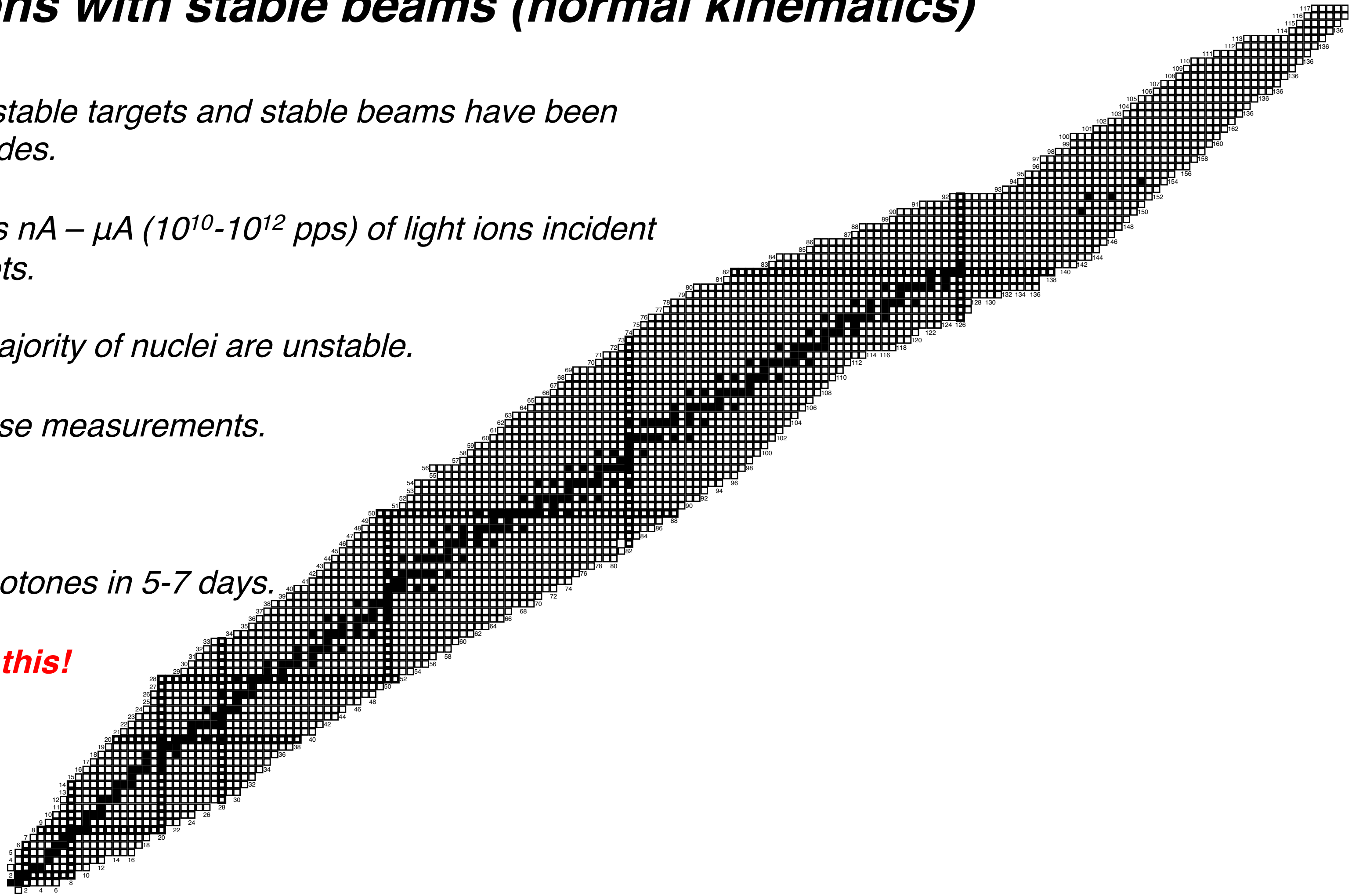
Limited in scope – majority of nuclei are unstable.

Can make very precise measurements.

Resolution 10s keV.

Chains of isotopes/isotones in 5-7 days.

Fewer places to do this!



Direct reactions with radioactive beams (inverse kinematics)

Beam currents of 100 fA – 10pA (10^4-10^6 pps) of radioactive nuclei incident on ~0.1-1mg/cm^2 CD_2 targets.

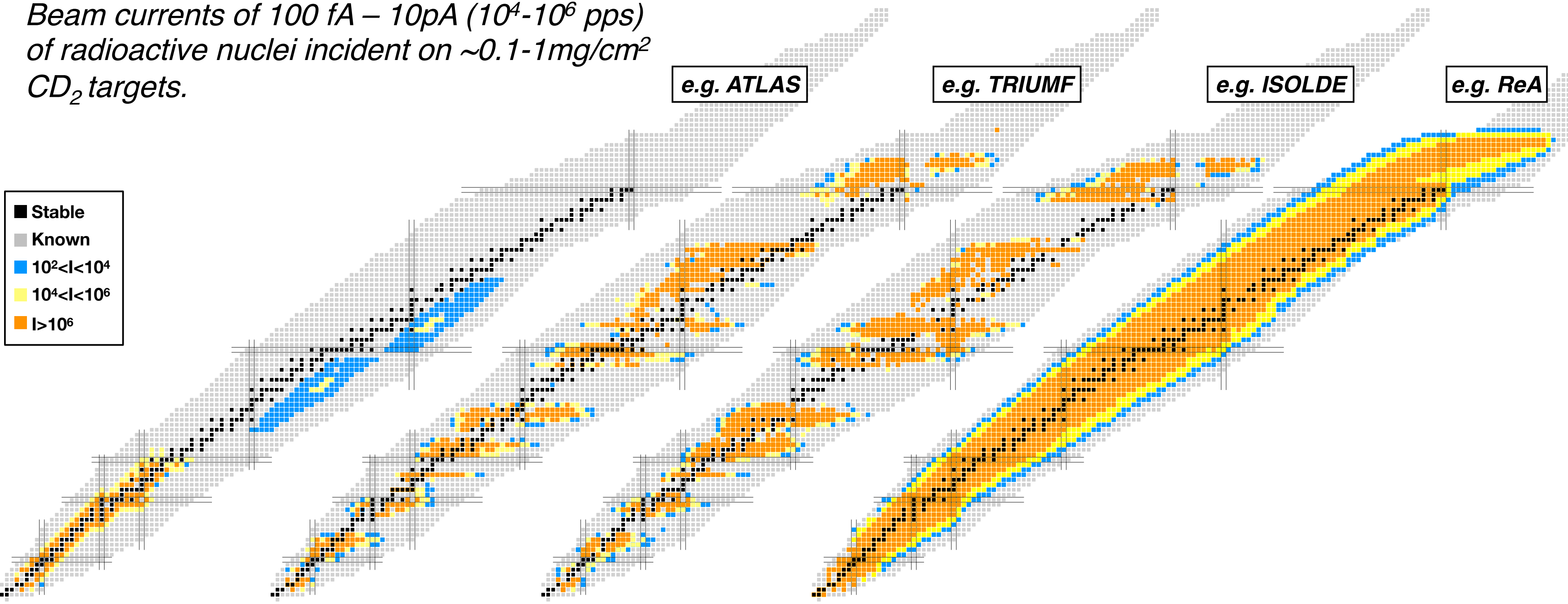


Figure courtesy of B Kay

Direct reactions in inverse kinematics

In inverse kinematics Q-value spectrum affected by kinematic effects on the measured ejectile energies in lab frame - leading to poor resolution.

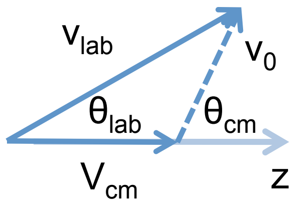
via kinematic shift often limits resolution of any detector with finite acceptance.

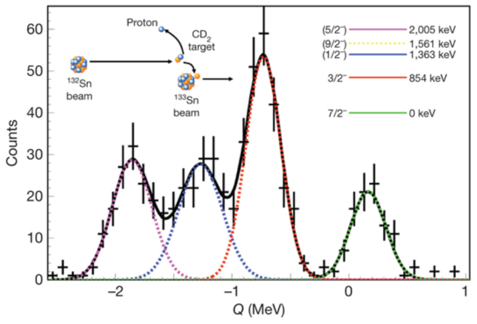
via kinematic compression dictates the separation of different excited states in ion energy.

BOTH affect the resolution obtained in a Q-value spectrum. 100s keV.

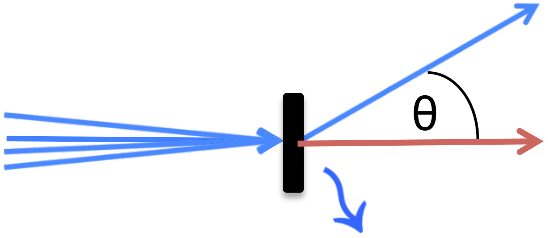
Despite same velocity in CM, LAB velocity changes with angle; resolution implications.

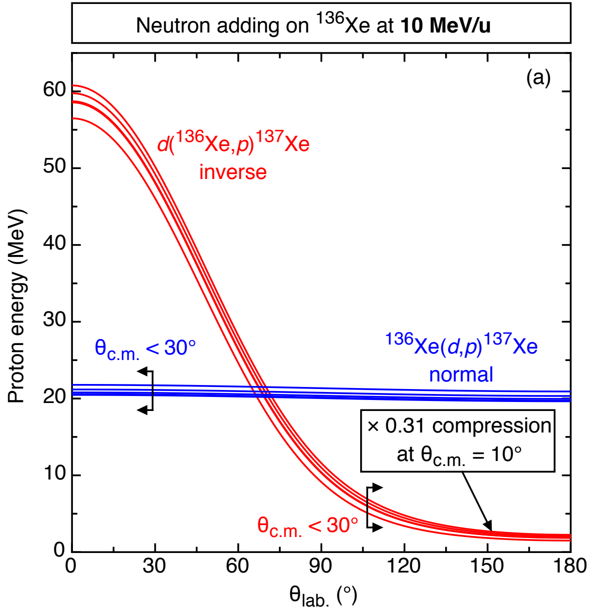
Kinematic shift: $$\kappa = \frac{1}{p}\frac{\mathrm{d}p}{\mathrm{d}\theta}$$





K.L. Jones *et al.* Nature **465** (2010) 7297



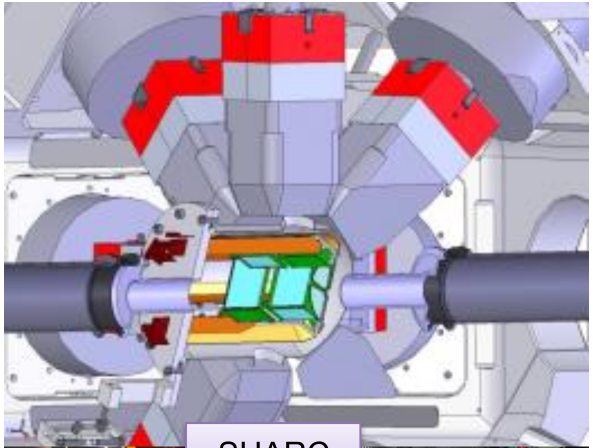


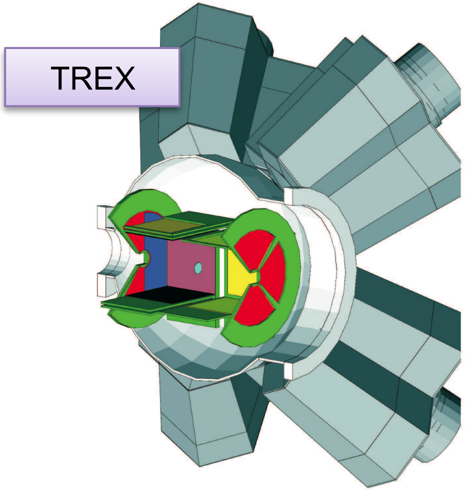
Direct reactions in inverse kinematics

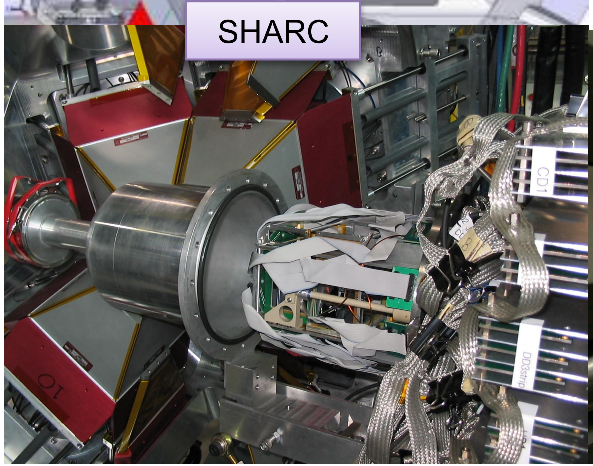
Particle detection at fixed angles using silicon arrays surrounding the target. (SHARC, T-REX, GODDESS).

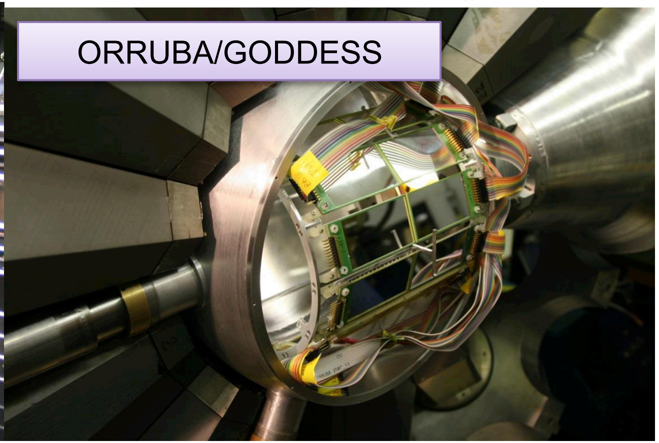
Positioned inside arrays of high-resolution germanium detectors. (TIGRESS, MiniBall, Gammasphere).

Use information from gamma-rays to extract energies, proton yields.

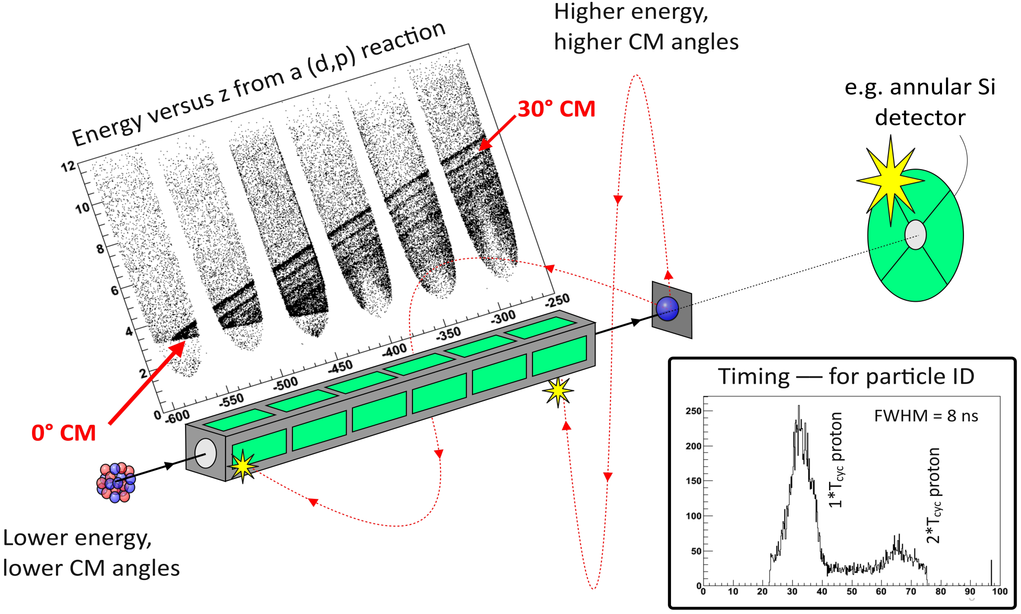




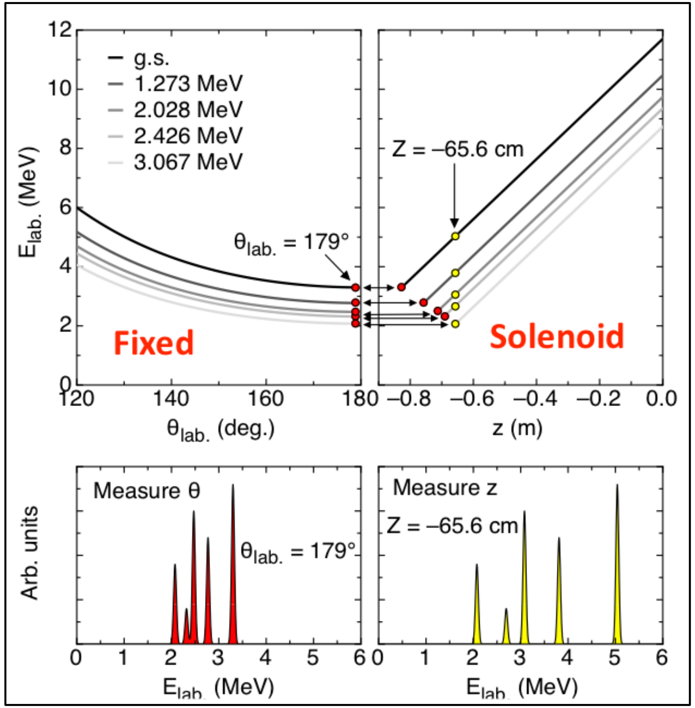




“New” Technique for Magnetic Spectrometers: Solenoid



$$E_{\mathrm{cm}} = E_{\mathrm{lab}} + \frac{mV_{\mathrm{cm}}^2}{2} - \frac{mzV_{\mathrm{cm}}}{T_{\mathrm{cyc}}}$$



MEASURED QUANTITIES: position z, cyclotron period T_{cyc} and lab particle energy E_p

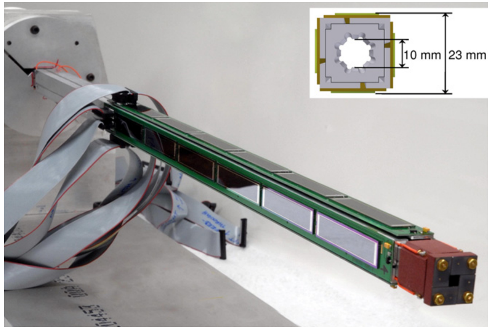
$$T_{\mathrm{cyc}} = \frac{2\pi}{B}\frac{m}{qe}$$

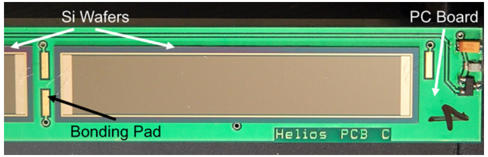
Suffers <u>no kinematic compression</u> of the Q-value spectrum

Linear relationship between E_{cm} and E_{lab}

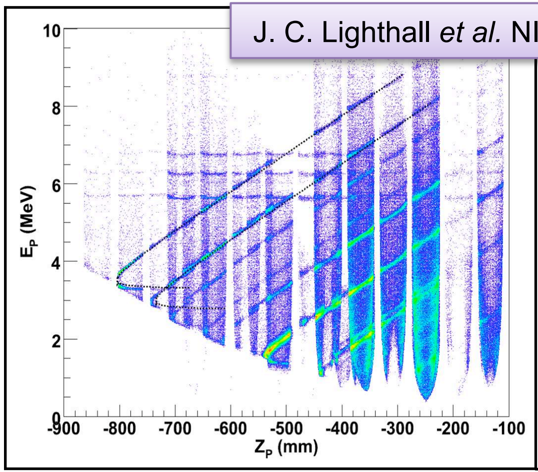
A. Wuosmaa *et al.* NIMA **580** (2007) 1290

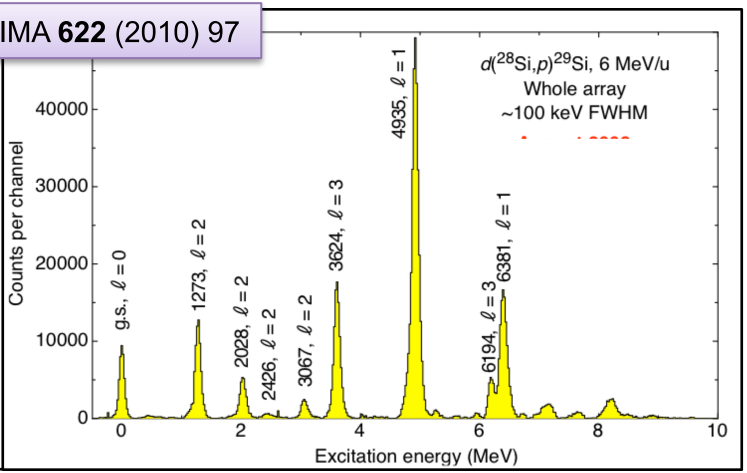
HELIOS@ANL

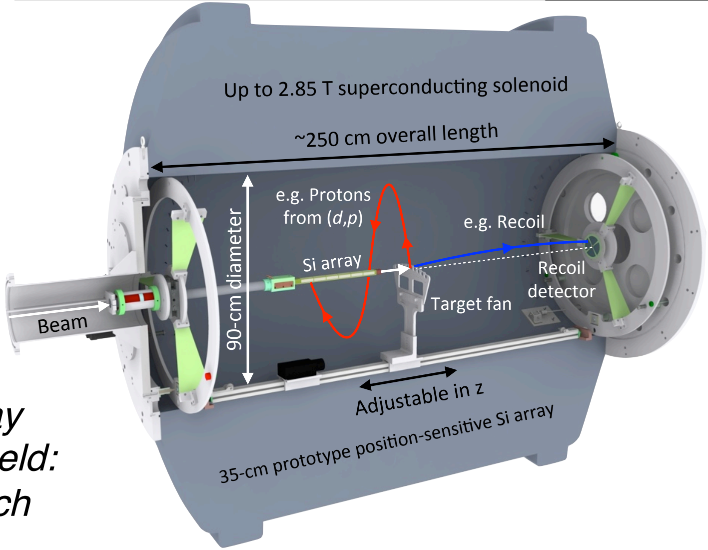




J. C. Lighthall *et al.* NIMA **622** (2010) 97



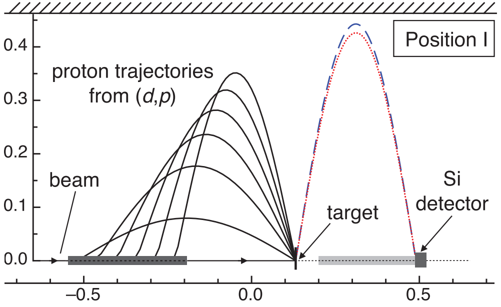




Square barrel of 6 PSD per side
700µm, resistive division
active area 9mm x 51mm

Acceptance depends on bore, array length, target-array distance and field: e.g. d(^{28}Si,p) @ 6 MeV/u 2.0 T, each detector 21 msr, total 0.50 sr

Expectations confirmed by d(^{28}Si,p) @ 8 MeV/u, 1.9 T, 84 µgcm^{-2} CD_2:

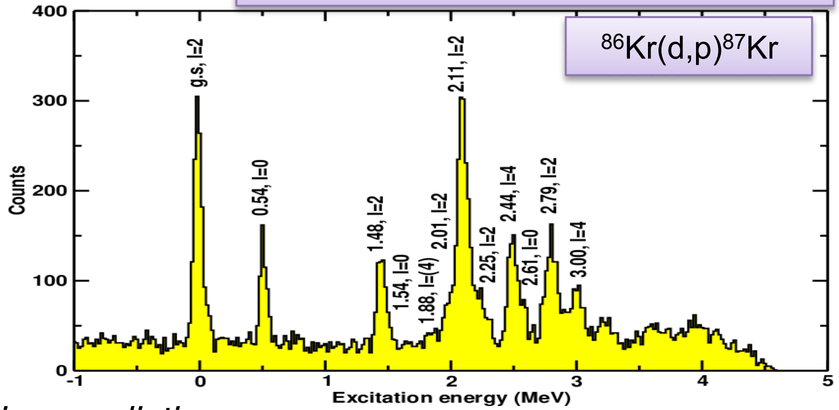


Results from HELIOS@ANL

D.K. Sharp *et al*, Phys.Rev.C **87** 014312 (2013)

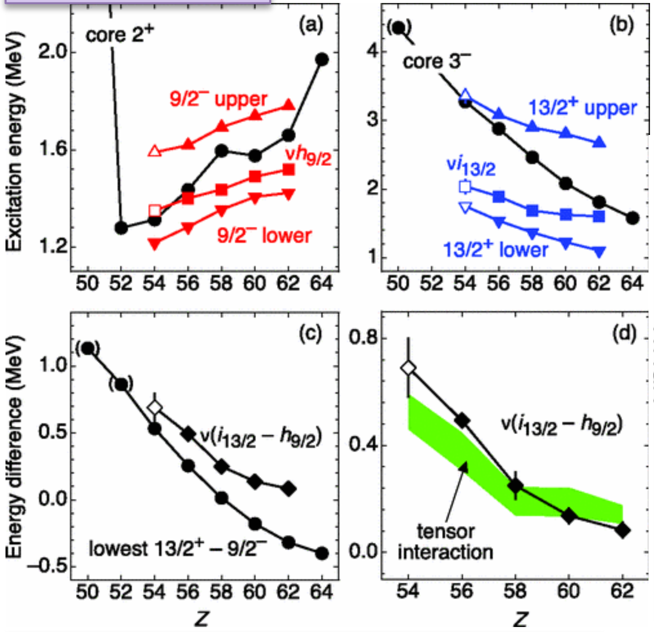
Early experiments using stable beams of varying mass with intensity similar to strong RIBs ~1e⁷ pps
Energy resolution of ~75 keV achieved.

$^{86}Kr(d,p)^{87}Kr$



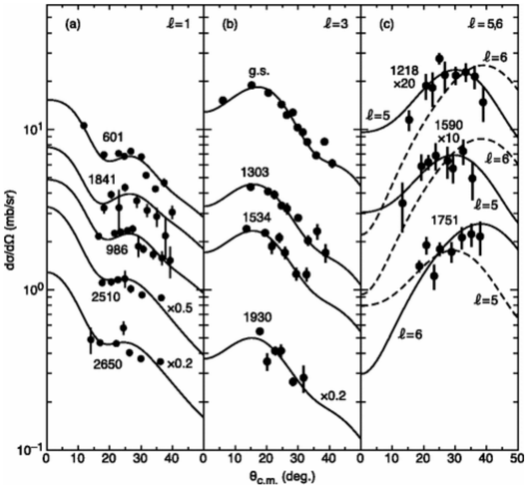
Evolution of single-particle levels at N=51 and N=83.

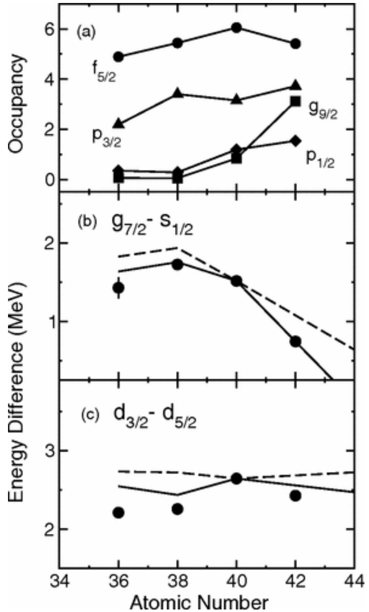
$^{136}Xe(d,p)^{137}Xe$



B. P. Kay *et al*, Phys.Rev.C **84** 024325 (2011)

Test of tensor-interaction predictions.





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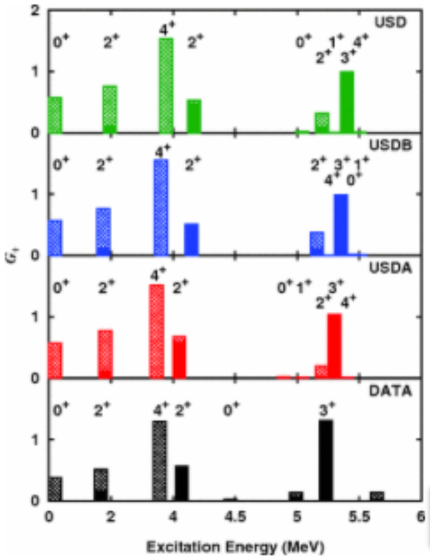
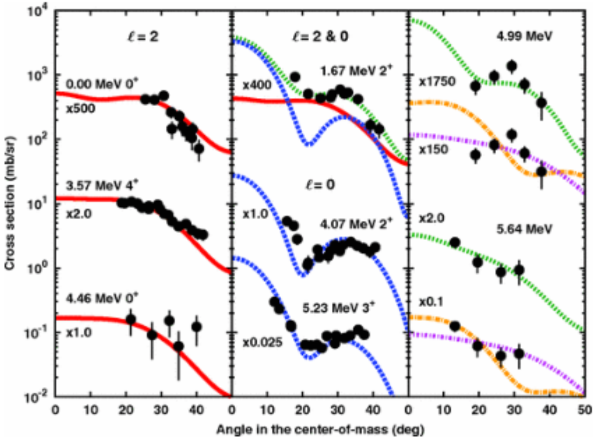
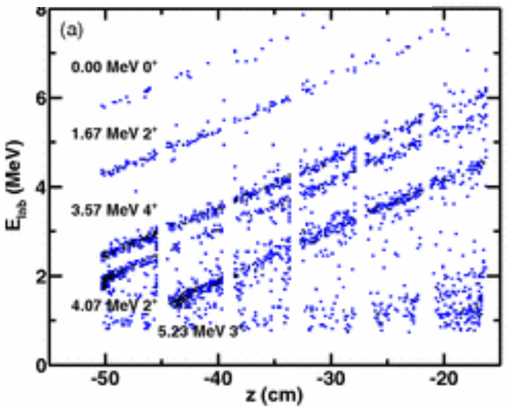
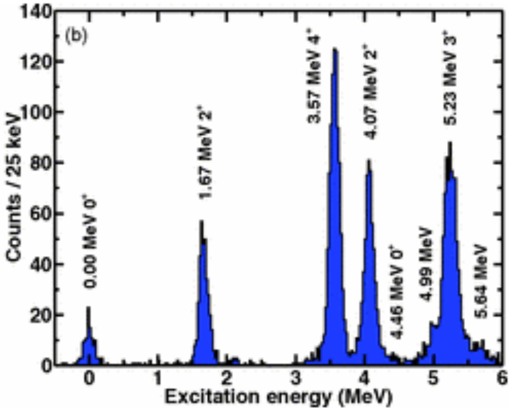




$^{19}O(d,p)^{20}O$





Radioactive beams produced using in-flight facility at ANL – example $^{19}O(d,p)$.

Studying evolution of single-particle levels across isotopic chain.

Results compared to shell-model calculations using USD interaction. Test assumptions on shell closures and understanding of 4p-0h states.

Many others – not limited to (d,p)
- *$^{12,13}B$, ^{15}C, $^{18}N(d,p)$*
- *$^{14,15}C(d,^{3}He)$*
- *$^{14,15}C(d,\alpha)$*

And more stable beam work
- *$^{20}Ne(\alpha,p)$*
- *$^{10}B(p,p')$*

C. R. Hoffman *et. al.*, Phys. Rev. C **85**, 054318 (2012)

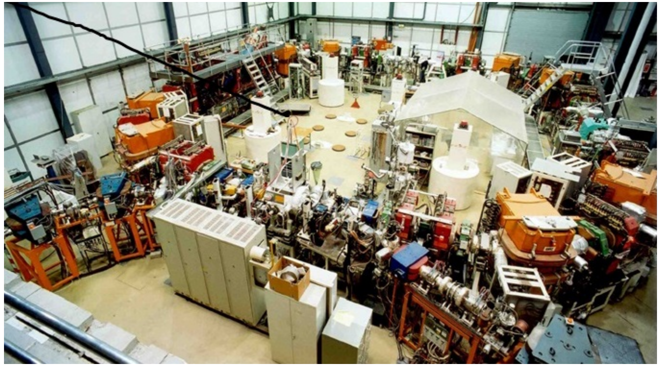
A solenoid at a radioactive beam facility

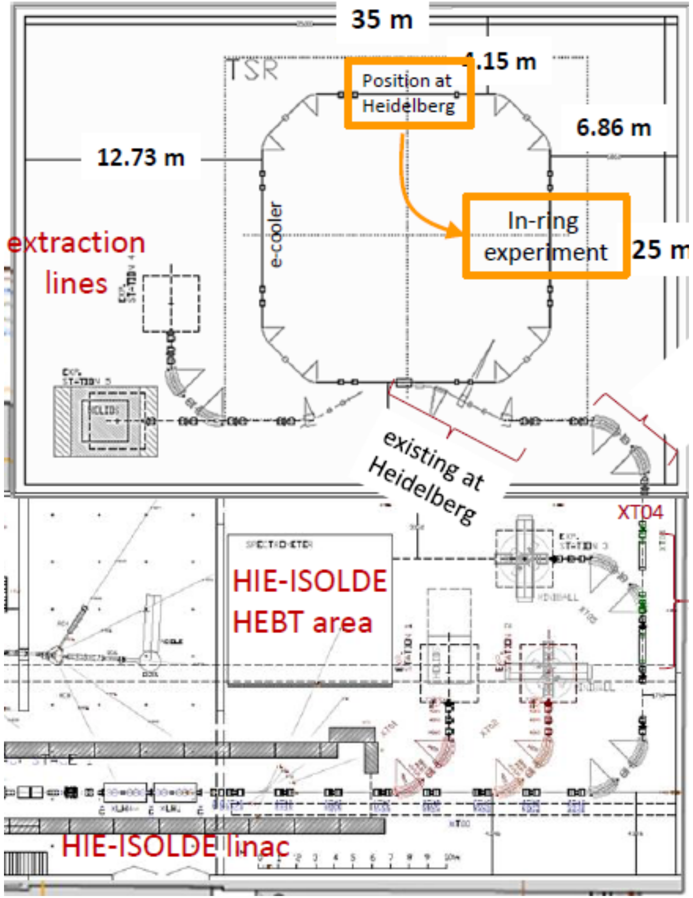
Solenoid part of ISOL-SRS project. Originally meant to be external spectrometer for the TSR.

The TSR would have provided better quality beams than currently available from HIE-ISOLDE.

TSR removed from ISOLDE-CERN medium-term plan.

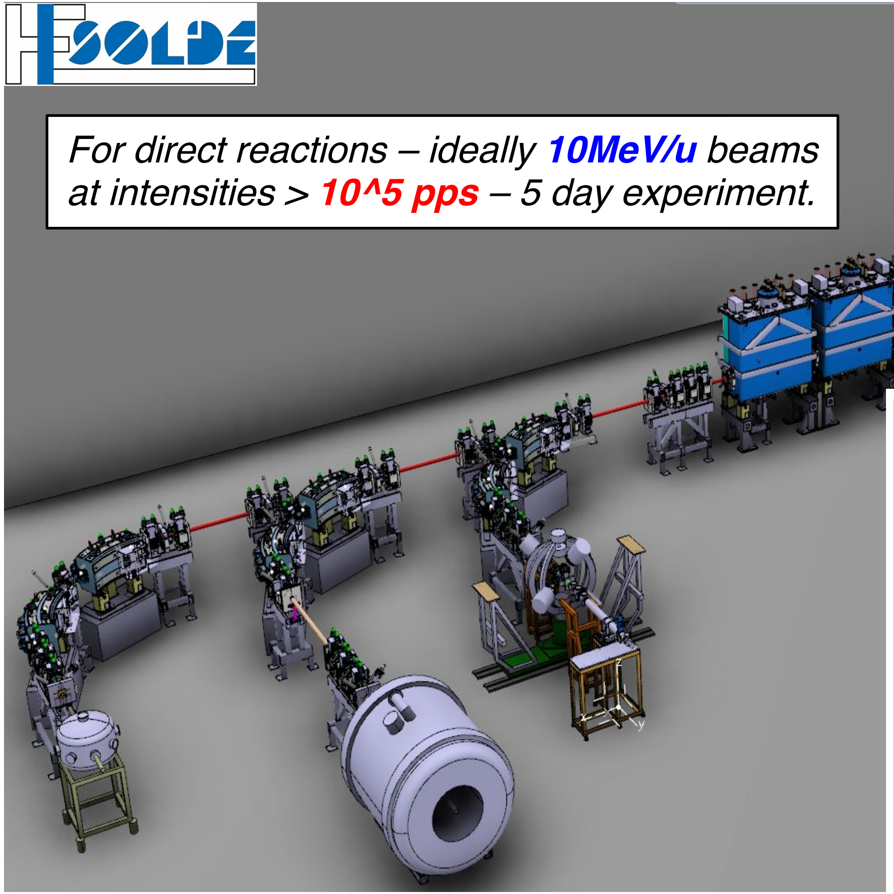
Solenoid could still take beam directly from HIE-ISOLDE.

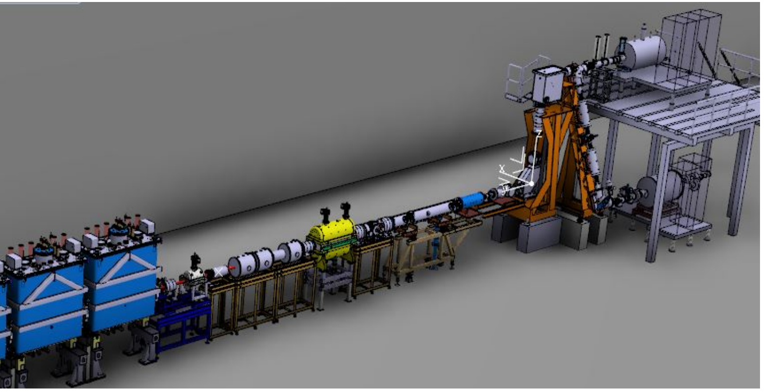


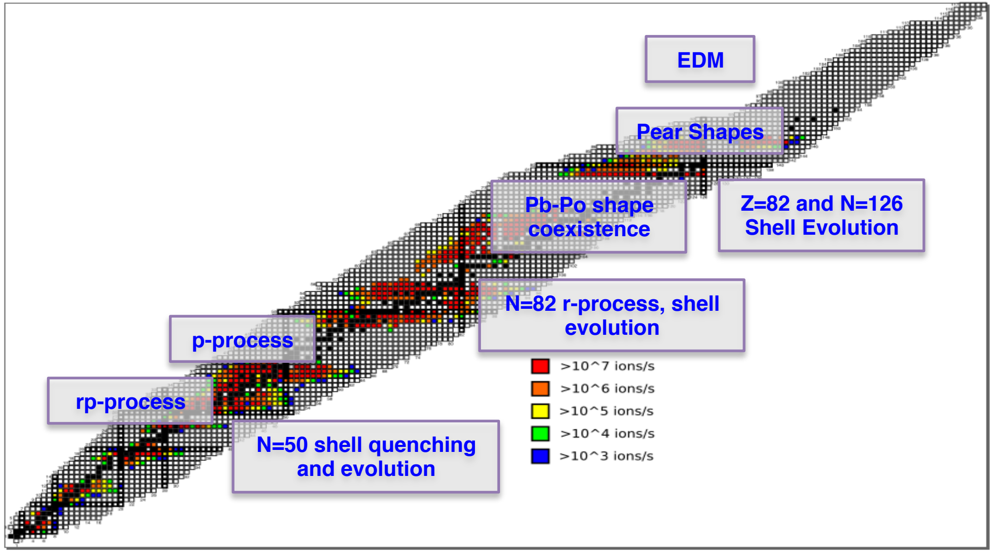


Physics at HIE-ISOLDE with a solenoid

For direct reactions – ideally ***10MeV/u*** *beams at intensities >* ***10^5 pps*** *– 5 day experiment.*







Getting a magnet

OR66 4T ex-MRI magnet.

Only 10 ever made -> Argonne found three of them!
#2 SOLARIS -> FRIB
#10 ANL HEP
#5 ISS -> ISOLDE

Magnet available from Brisbane (UQ).

Calicanto Bridge

Getting a magnet

Sarah

ISOLDE Solenoidal Spectrometer

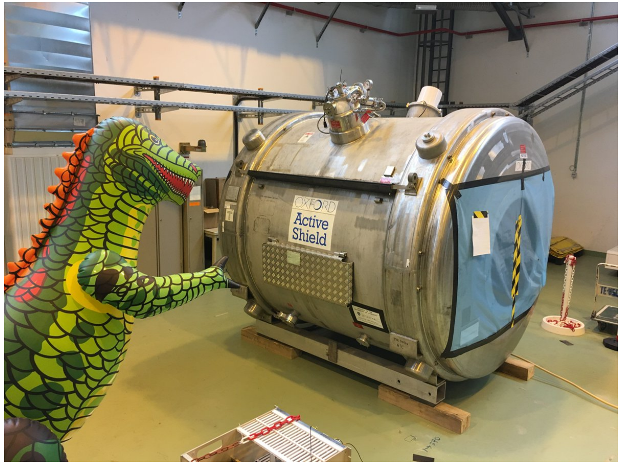
Delivered - April 2016

Cooled and energized - January 2017/ Feb 2017

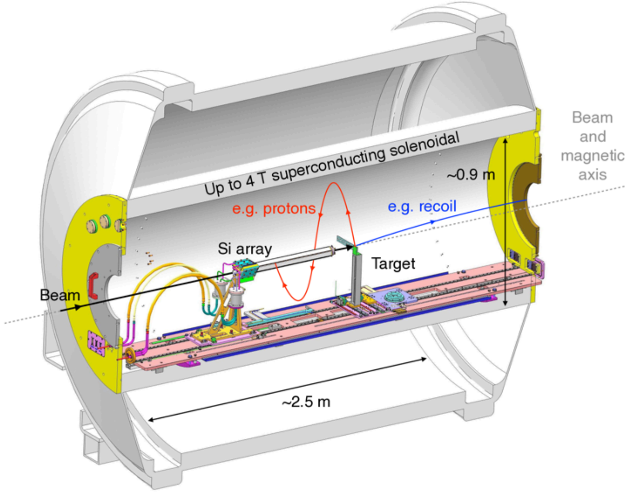
Moved in to hall - March 2017

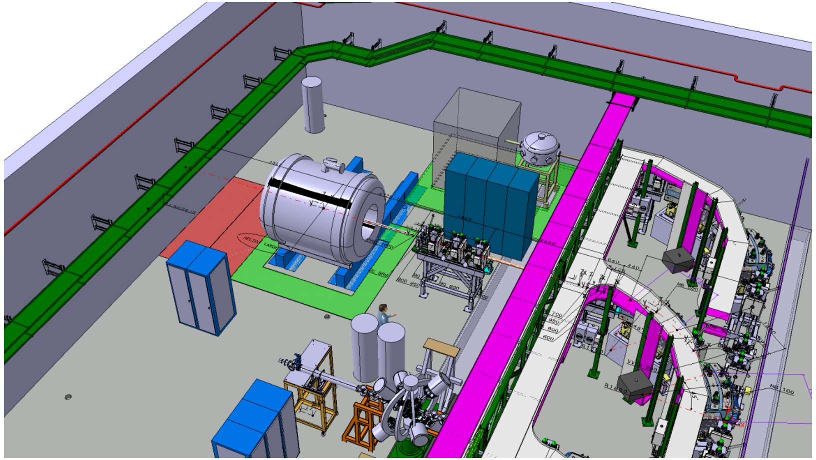
Field Mapping - November 2017

Stable beam tests - May 2018



Miniball's (and the SC's) new neighbour





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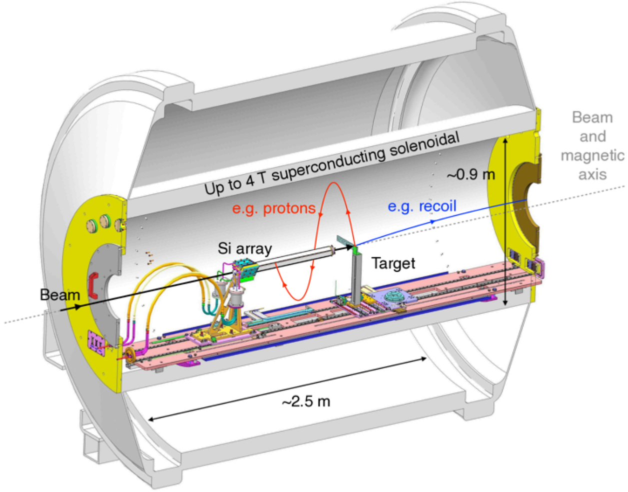
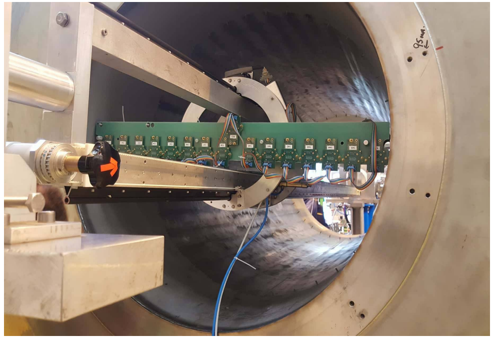
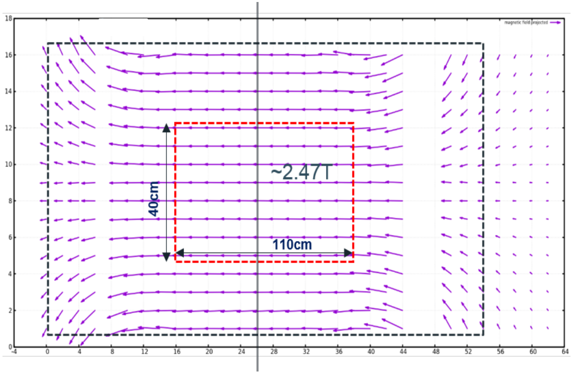


Uniformity and field pattern as expected.





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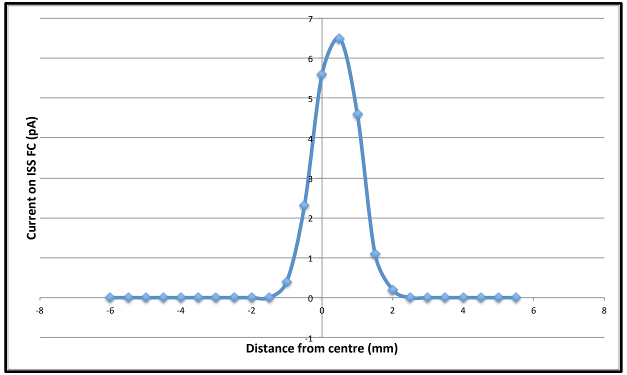
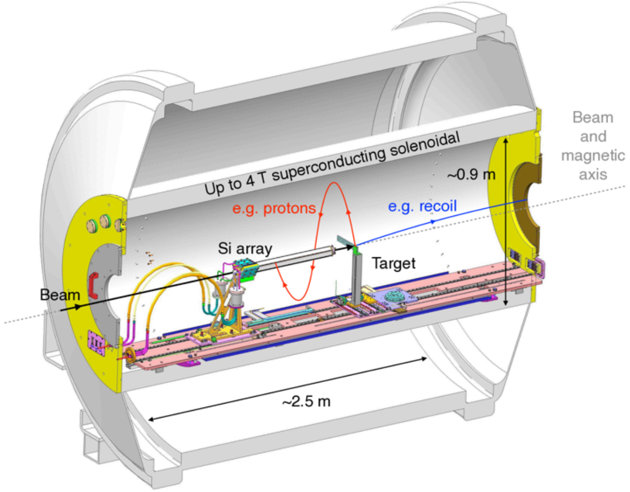
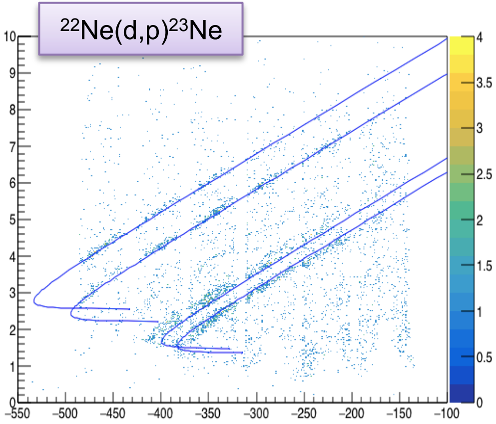
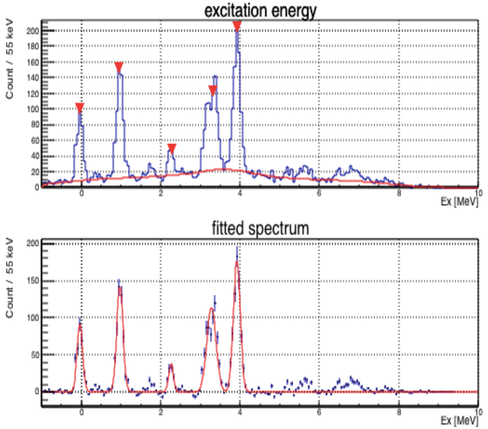


Beam profile scans – FWHM<1.5mm
Test of ANL array and DAQ - ~110keV FWHM (200ug target) – comparable with simulations.







EXP #1 IS621 – Changing shell-structure near Island of Inversion

Ground states and low-lying excitations from intruder configurations have been observed.

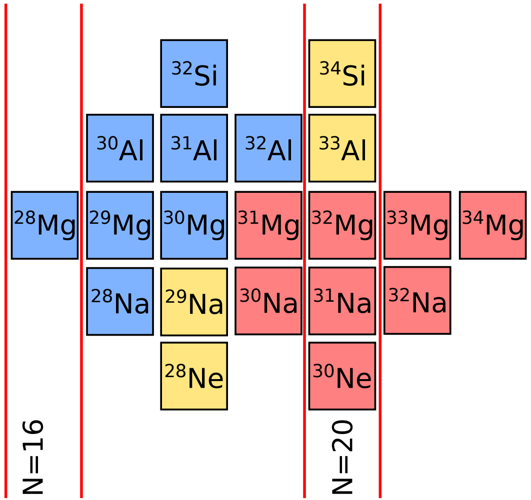
Prevalence of negative-parity states is indicative of ***cross-shell excitations****.*

In the Ne, Al and Na isotopes there is a **soft transition** to a deformed ground state.

In Mg isotopes this transition is **sharper** with ^{31}Mg inside the island and ^{30}Mg outside.

Measurements of the ***single-particle properties*** *moving in to the island of inversion provide important systematic information on the behavior of the relevant orbitals and shell gaps.*

In particular the ***difference*** *between the $d_{3/2}$ orbitals and fp - shell which define the N=20 shell gap.*



EXP #1 IS621 – Changing shell-structure near Island of Inversion

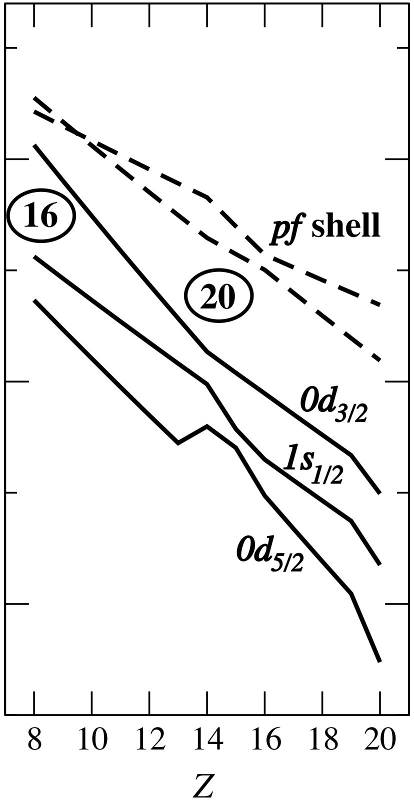
The island of inversion is indicative of a ***weakening shell gap.***

In the oxygen isotopes the N=20 shell gap has been shown to disappear with ***the emergence of an N=16*** *shell gap in ^{24}O.*

Again measurement of the single-particle states involved in this ***evolution of single-particle structure*** *will provide valuable comparison with theory.*

Along N=16 $\pi d_{5/2}$ is emptying. Differing overlaps with $\nu d_{3/2}$, $\nu f_{7/2}$ and $\nu p_{3/2}$ results in ***different monopole shifts****.*

^{29}Mg is an N=17 isotone – single-particle structure outside N=16 informative in *tracking disappearance of N=20 shell gap*.

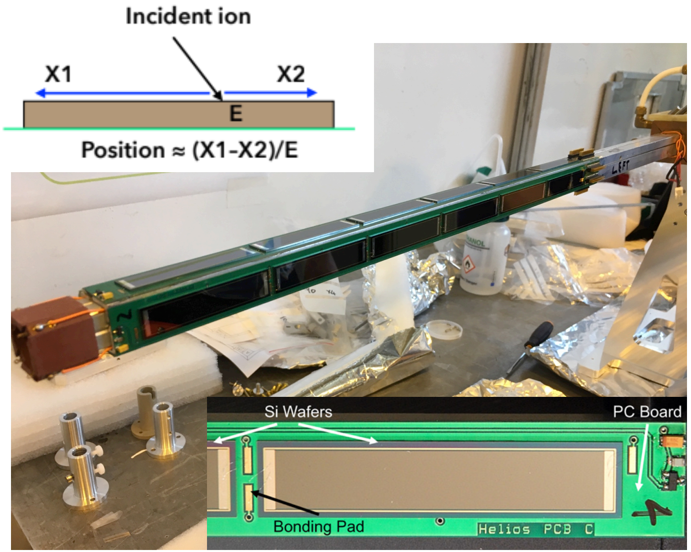


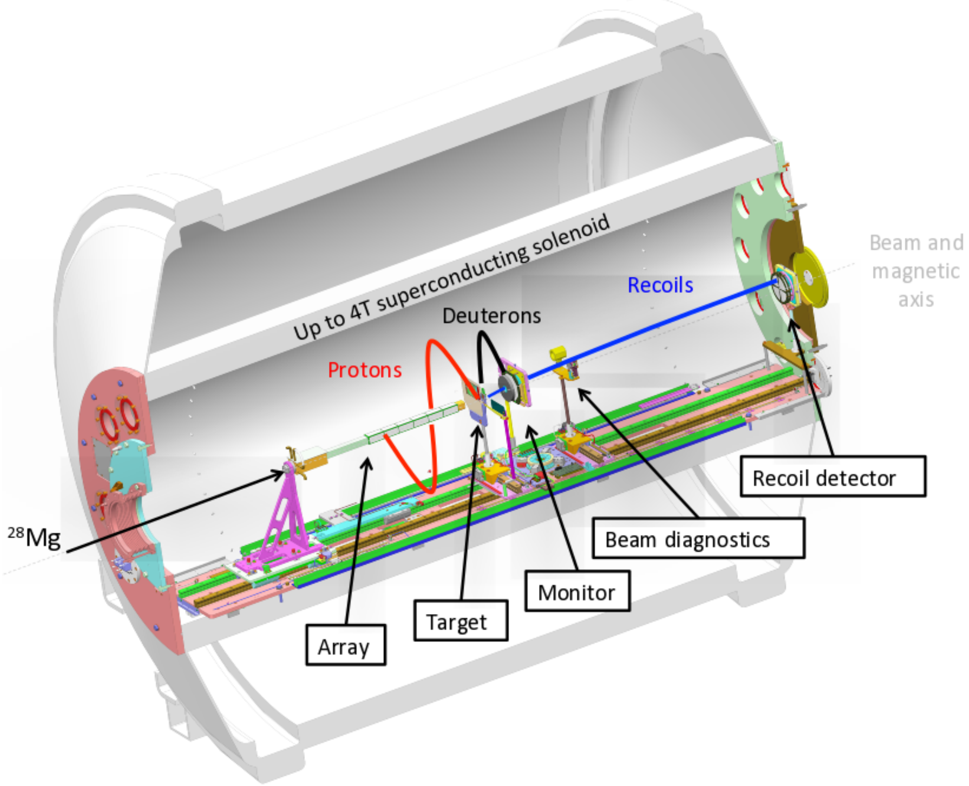
T. Otsuka *et. al.*, Eur. Phys. J. A 15, 151–155 (2002)

EXP #1 IS621– $^{28}Mg(d,p)^{29}Mg$

10^6 pps 9.473 MeV/u (dE/E = 0.3%) beam – **highest HIE-ISOLDE RIB beam energy per nucleon**.

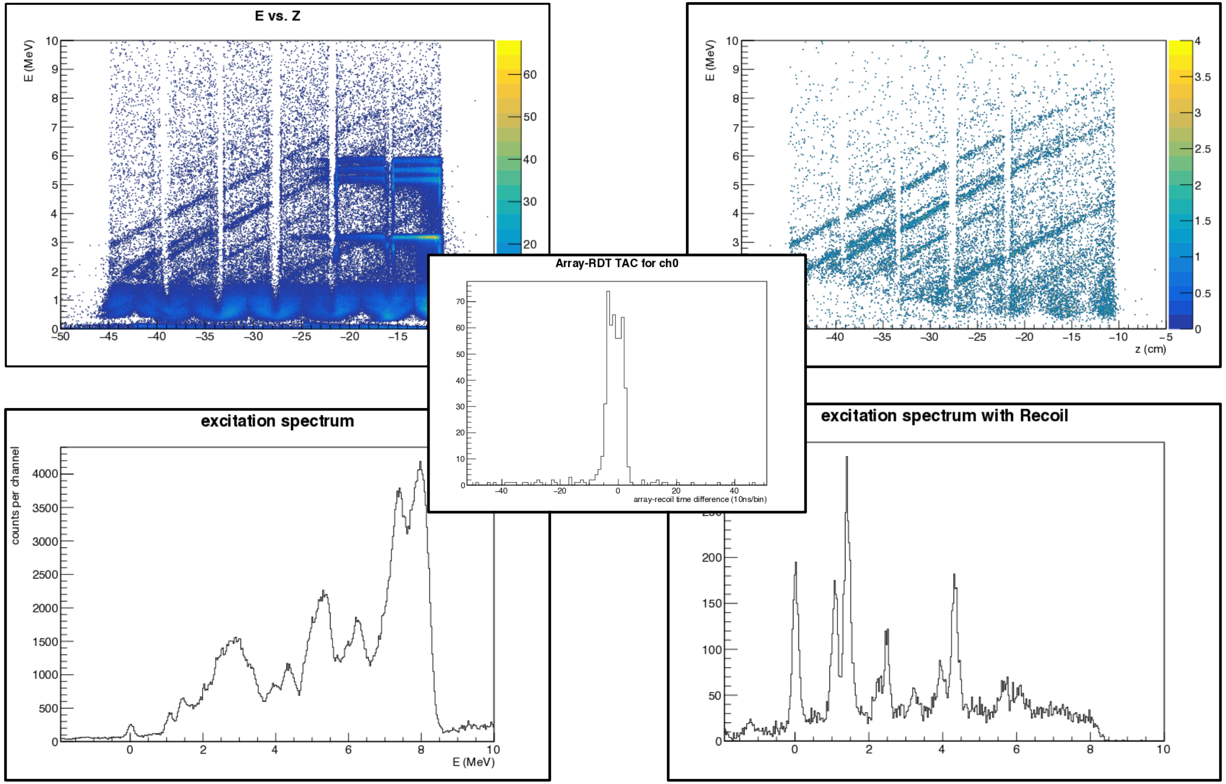
ISS set at a field of ***2.5T*** *– 2 target-array positions used to cover $10^o<\theta_{cm}<40^o$ for states up to ~ 4MeV.*





EXP #1 IS621– ^{28}Mg(d,p)^{29}Mg reaction gating

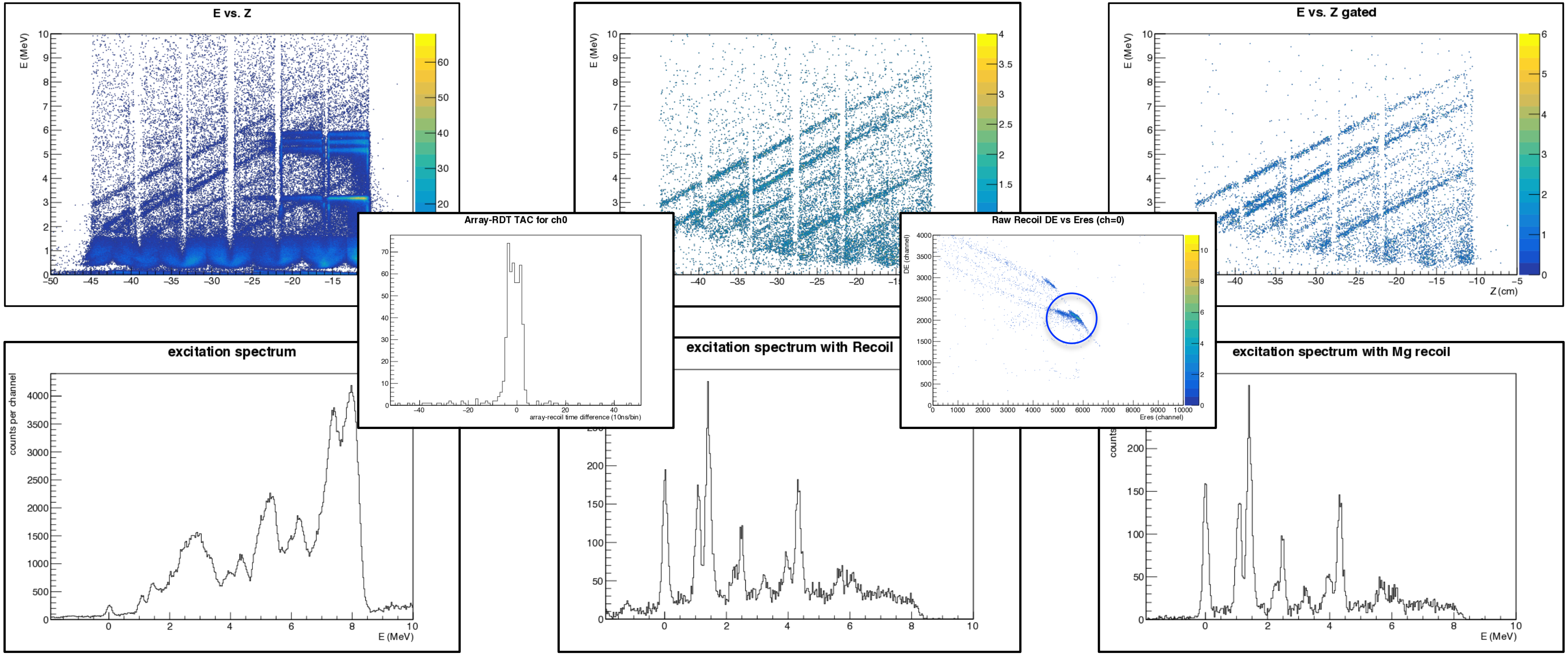
recoil-array timing



EXP #1 IS621– ^{28}Mg(d,p)^{29}Mg reaction gating

recoil-array timing

recoil energy gate



Slides courtesy of B Kay

EXP#2 IS631 - ^{206}Hg(d,p)^{207}Hg

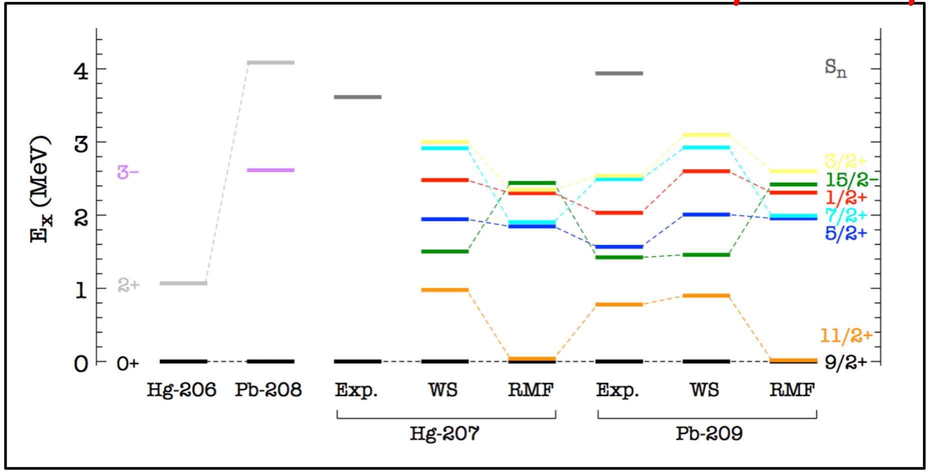
N=127 istones below Pb

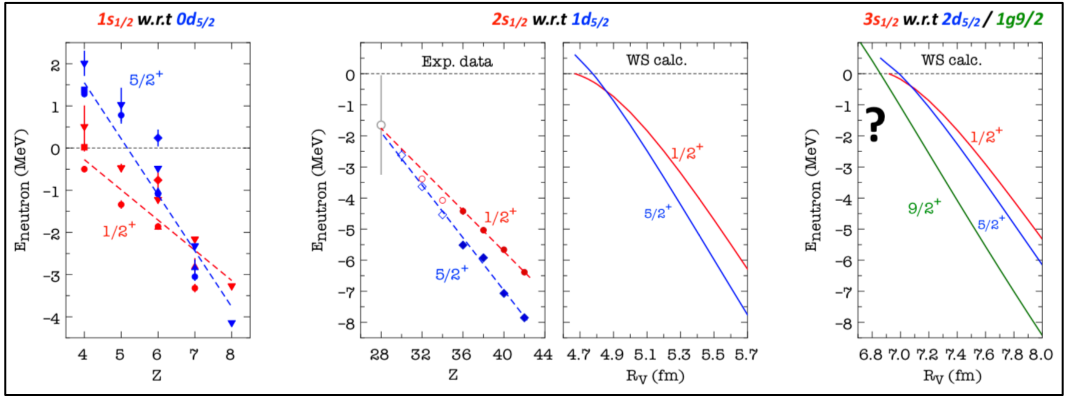
Below Pb, around N=126 very little is known.

Evolution of single-particle structure not investigated in lead region – requires heavy RIB's which HIE-ISOLDE can provide

Few theoretical studies on single-particle excitations.

***s-states in loosely bound systems** tend to linger below threshold—this feature seems to **dominate the structural changes in light nuclei**, and that results in **halo structures**. Does this characteristic of s-states play a role in loosely bound heavier systems?*





C. R. Hoffman, B. P. Kay, J. P. Schiffer, PRC **89**, 061305(R) (2014), C. R. Hoffman, B. P. Kay, J. P .Schiffer, PRC **94**, 024330 (2016), C. R. Hoffman, and B. P. Kay, Nuclear Physics News International Oct-Dec 2015. X. F. Yang et al., Phys. Rev. Le7. **116**, 182501 (2016)

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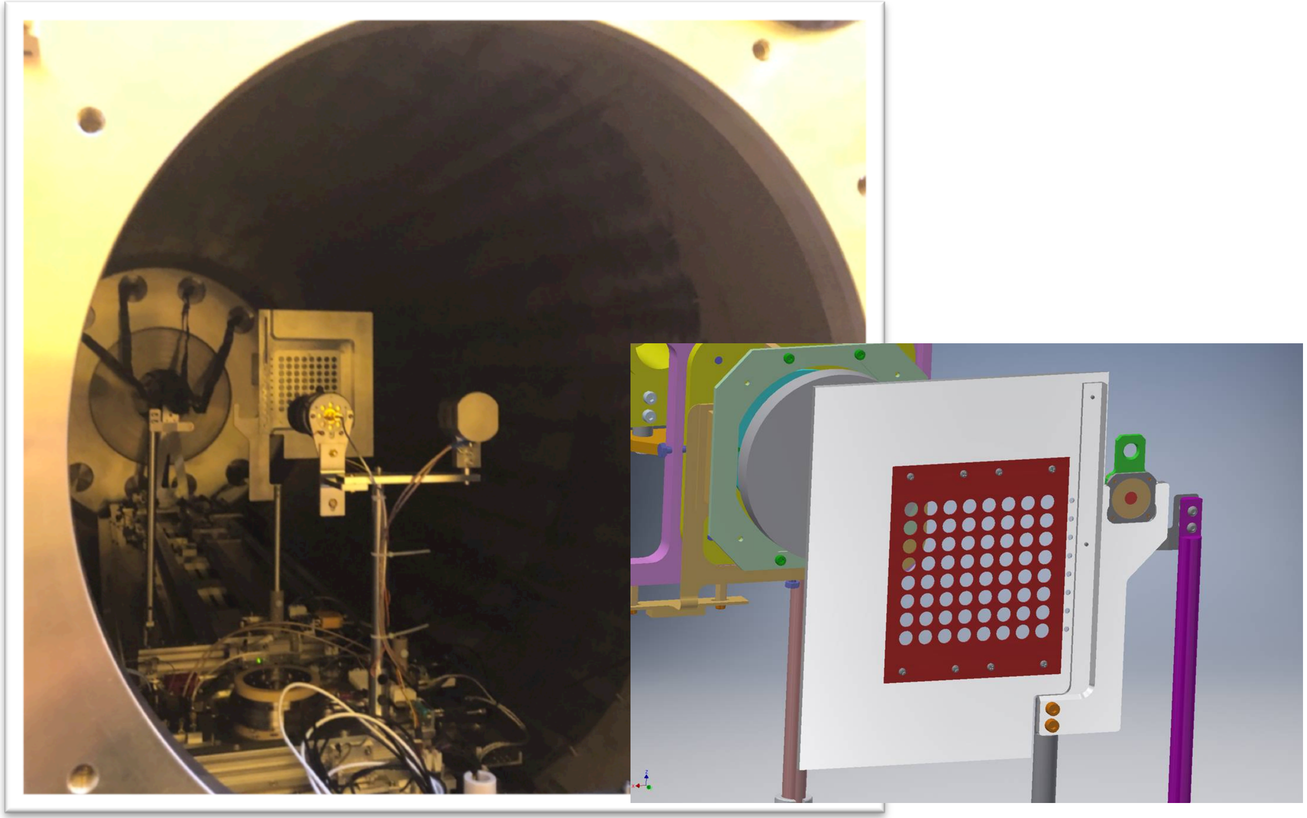
EXP#2 IS631 - ^{206}Hg(d,p)^{207}Hg set up

Slides courtesy of B Kay



Experimental info:

- *~**5x10^{5} pps** of ^{206}Hg for ~82 hours.*
- *A **7.4 MeV/u** ^{206}Hg beam **– highest total HIE-ISOLDE beam >1.5 GeV***
- *Measured in singles mode*
- *Beam purity **>98%**.*
- *Using **>30 deuterated polyethylene targets** of ~165µg/cm2*
- *ISS set to B-field of 2.5 T*

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Future developments

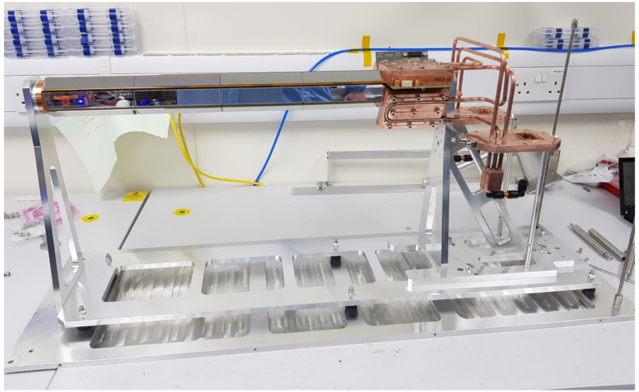
New array *(Constructed at University of Liverpool – ready to ship to CERN).*

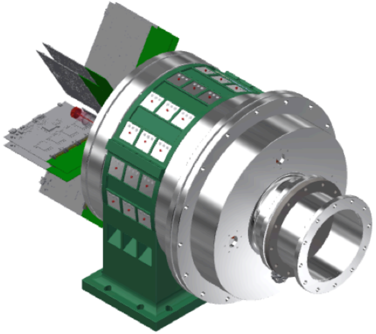
DSSDs + ASIC readout.
1mm thick.
x: 128 x 0.95mm x 4 each side.
y: 11 x 2mm x 6 sides.

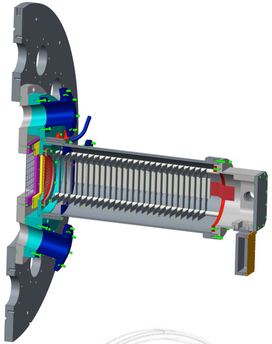
New fast-counting ionization chamber *to be constructed at The University of Manchester 2019/20.*
*Up to **100 kHz** counting.*
Segmented with digital readout – sample dE/dx along track of recoils.

SpecMat *– time projection chamber with gamma ray detection.*

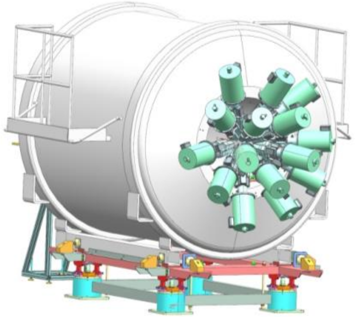
Germanium spectrometer tests *in the solenoid field.*







Riccardo Raabe



Francesco Recchia

Conclusions

First two experiments *with ISS have both been successful.*

Also for HIE-ISOLDE operating ***at new extremes of energy****.*

Operation of ISS in ***two different mass regions*** *demonstrated.*

Probing ***evolution of single-particle structure*** *along N=17 and towards IOI.*

Probing ***terra incognita region*** *south of ^{208}Pb.*

More to come after LS2!

Workshop 27th-28th August*,* ***University of Liverpool****. https://indico.cern.ch/e/ISSWorkshop2019*

ISS collaboration

MANCHESTER 1824
The University of Manchester

Argonne NATIONAL LABORATORY

ISS
ISOLDE Solenoidal Spectrometer

UNIVERSITY OF LIVERPOOL

ISOLDE

UNIVERSITY OF SURREY

UNIVERSITY OF THE WEST of SCOTLAND
UWS

KU LEUVEN

UNIVERSITY OF CONNECTICUT 1881

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro

Universidad de Huelva

THE UNIVERSITY of EDINBURGH

LSU
LOUISIANA STATE UNIVERSITY

TECHNISCHE UNIVERSITÄT DARMSTADT

lpc caen

IPN
INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

UNIVERSITÀ DEGLI STUDI DI PADOVA

UNIVERSITY of York

Science & Technology Facilities Council

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

UiO : University of Oslo