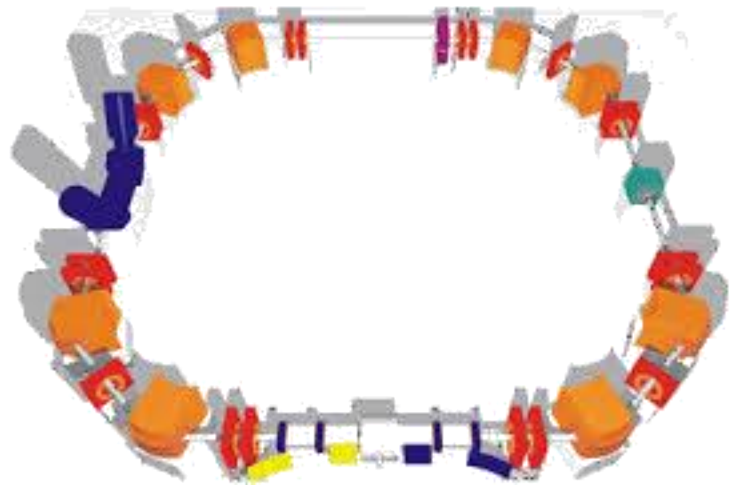
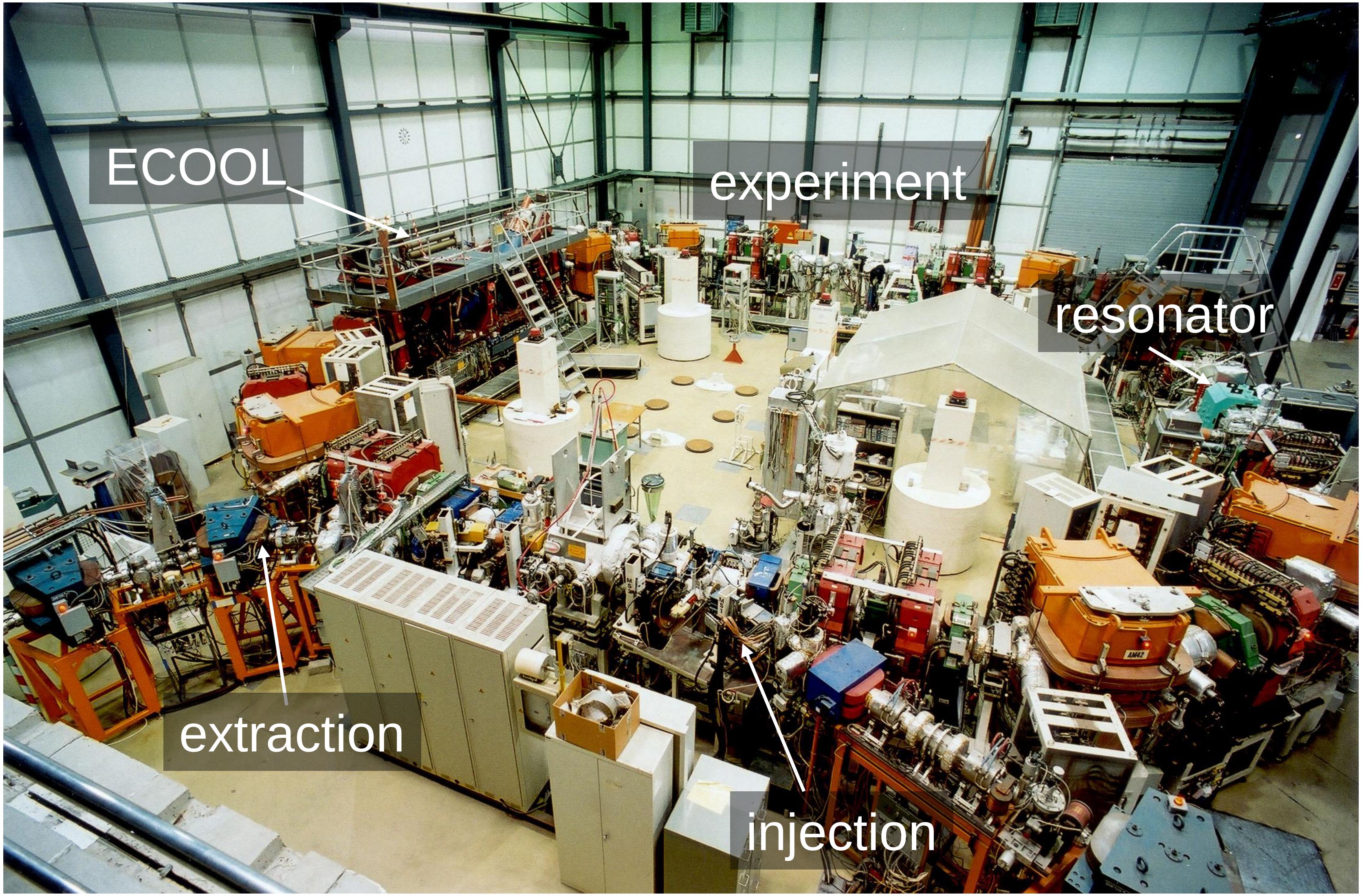
STATUS REPORT



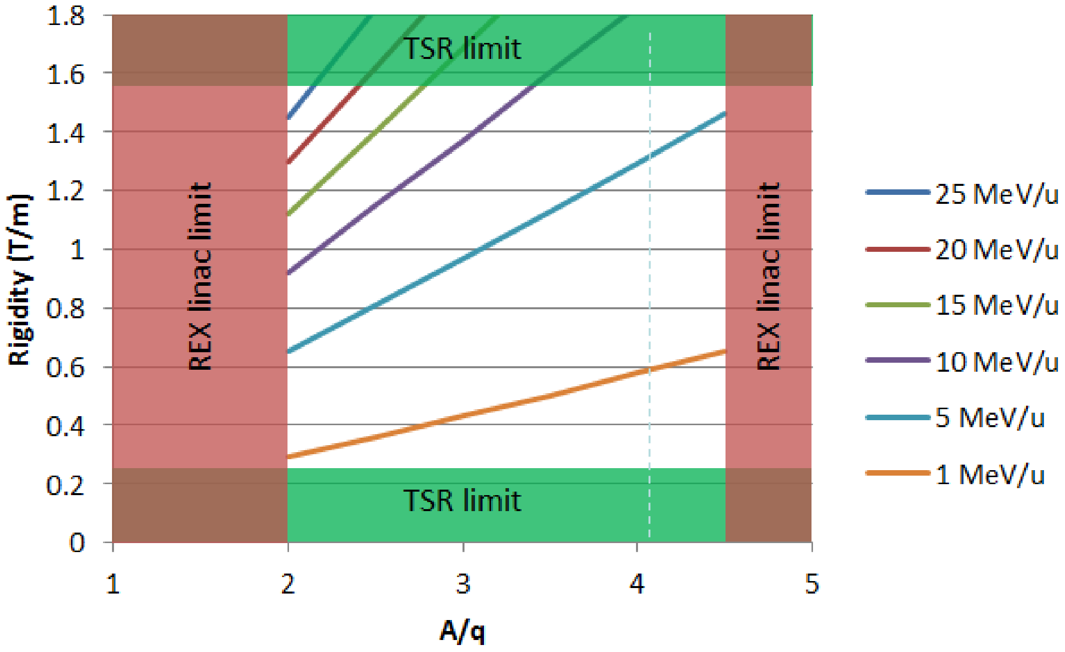
Peter Butler **University of Liverpool**

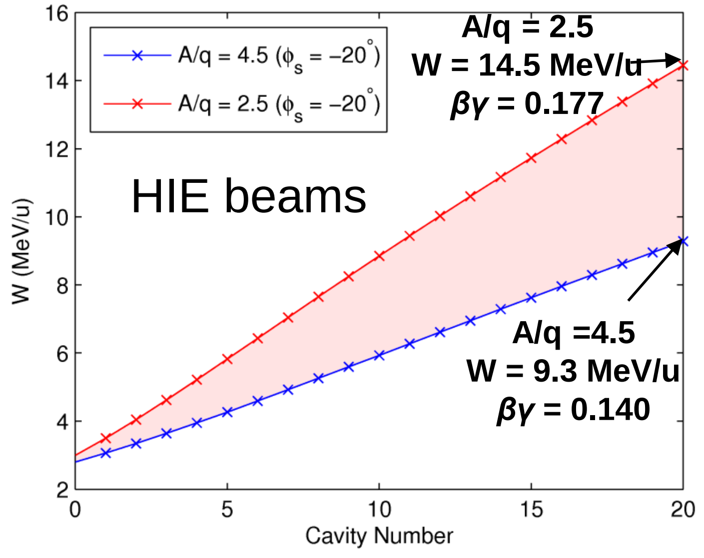
The heavy ion storage ring TSR
MPIK Heidelberg

Circumference: 55m



TSR matching to HIE-ISOLDE





Beam can be accelerated (and decelerated) inside the ring

Ion	Z	q	A/q	Breeding time (ms)
^{7}Be	4	3	2.33	20
^{18}F	9	9	2	100
^{70}Ni	30	25	2.8	350
^{132}Sn	50	39	3.38	700 *
^{182}Pb	82	53	3.43	1000 *
^{182}Pb	82	64	2.84	EBIS upgrade needed

* to be tested

World-wide storage rings

Fully-stripped ions

High-energy

ESR @ GSI
CSRe @ IMP

RI-RING @ RIKEN
CR @ FAIR
HESR @ FAIR

NESR @ FAIR
RESR @ FAIR
HIAF

($T_{1/2}$ > 1μs)

Masses, lifetimes

Low-energy

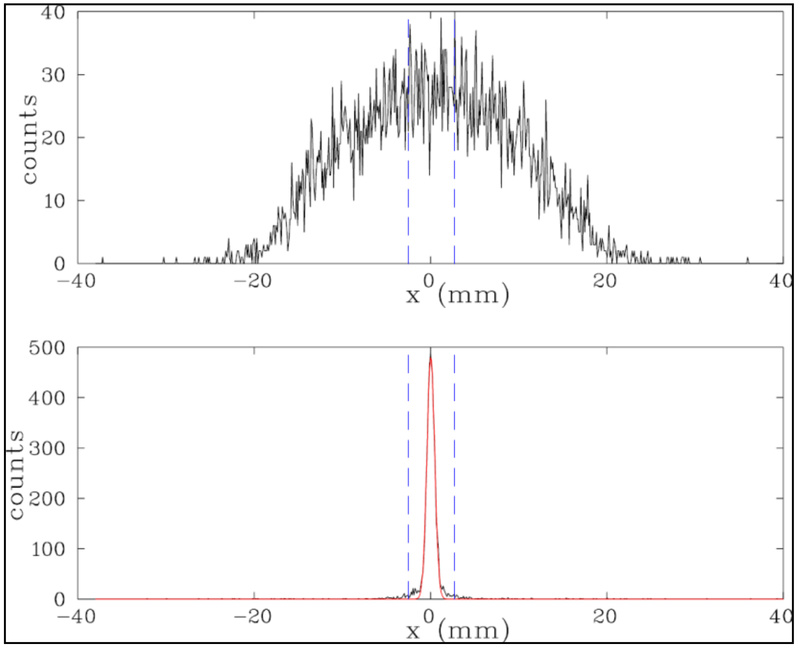
TSR @ ISOLDE
($T_{1/2}$ > 1s)

ESR @ GSI (L.E.)
or
CRYRING @ ESR
($T_{1/2}$ > 1 min or stable)

Reaction studies

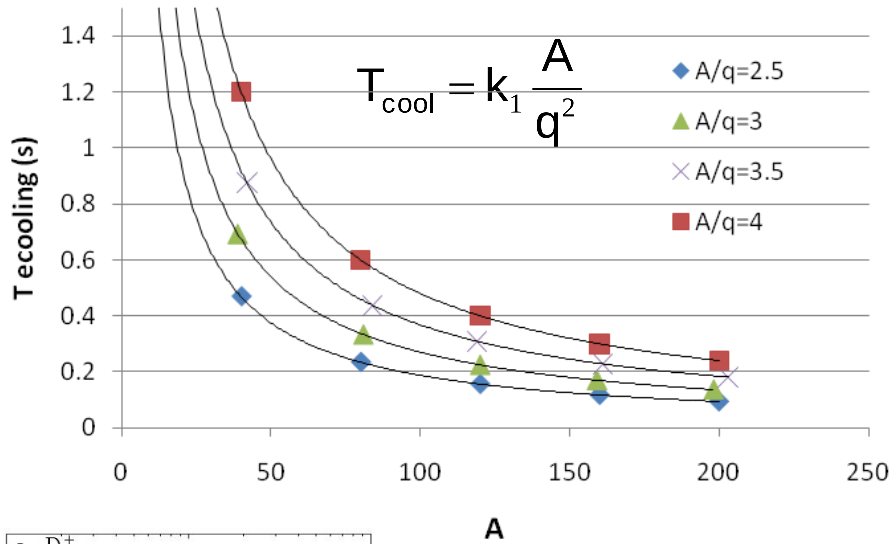
Highly-charged ions

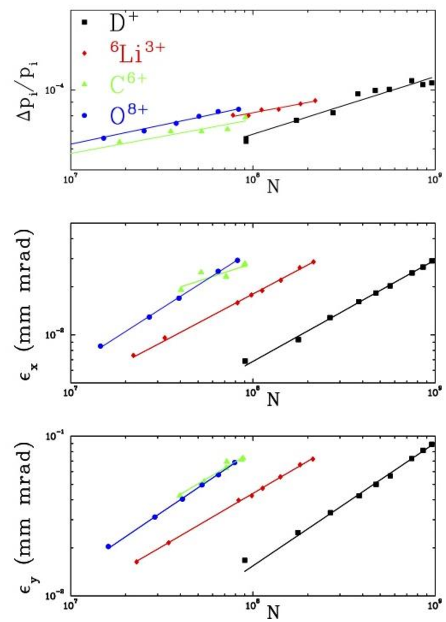
TSR: electron cooling



Radial beam extension

Light elements easiest to reach low A/q



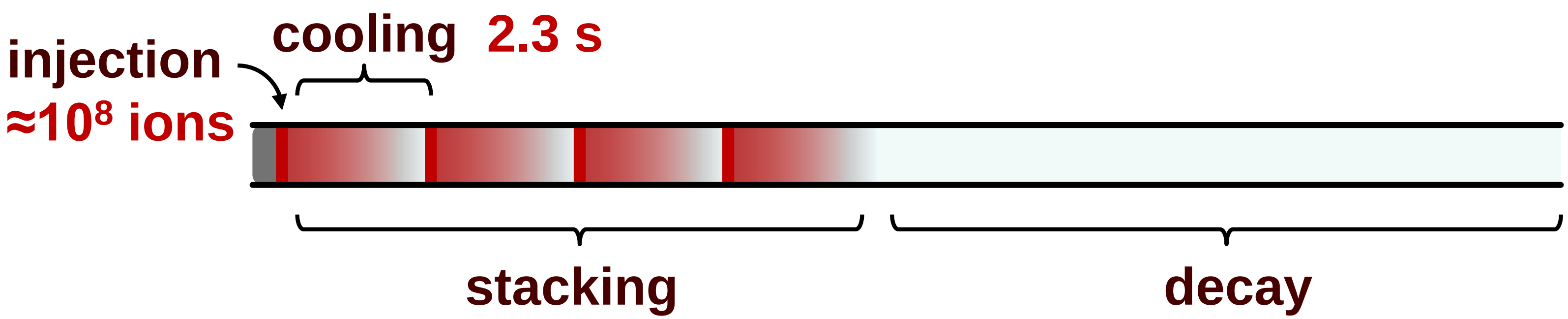


10^7 10^8 10^9 ions in ring

TSR versus linac alone

	HIE-ISOLDE	HIE+TSR
Beam structure	Macrostructure	DC
Beam x-y	few mm	~ mm
Beam energy resolution	1.4E-3	1E-4 - 1E-5
Transverse emittance	0.1 mm-mrad	0.03 mm-mrad
Beam purity	A/q contamination possible	better than 1 in 5000
Target z-extent	negligible	5mm or less
Target thickness	~ 100μg/cm^2	negligible
Target purity	e.g. CH_2	pure gas
Vacuum requirement	SHV	UHV

In-ring measurements



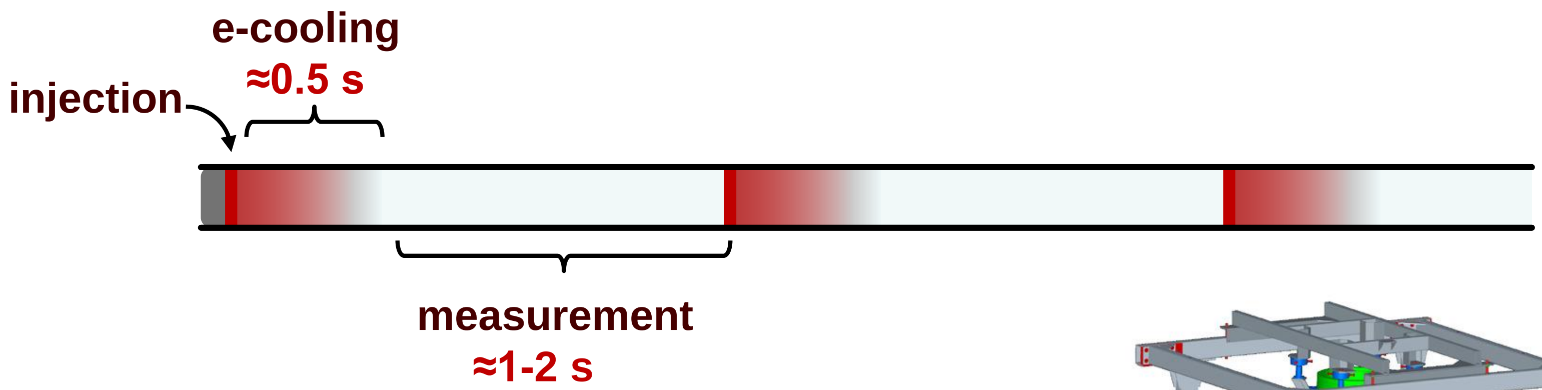
Beam is stored in REXTRAP ~ 1-2 s
Charge bred in REXEBIS 100 ms – 1 s
Injected into TSR within 35 μs
Stacking possible ≈$T_{1/2}$

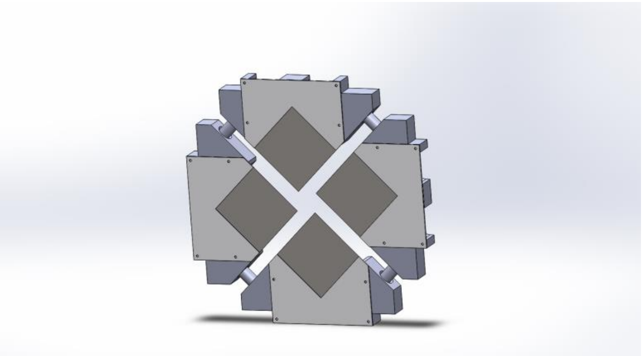
Half life of H-like ^{7}Be in the Sun

β-delayed proton emission of ^{11}Be

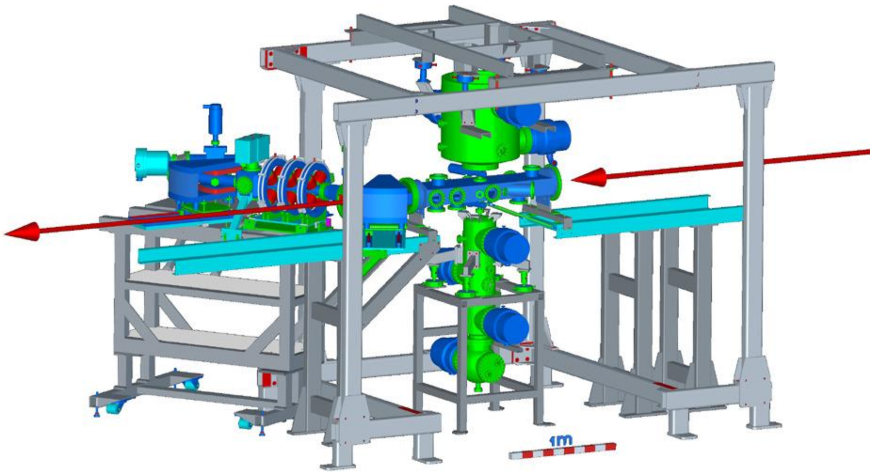
laser spectroscopy

Measurements using internal target

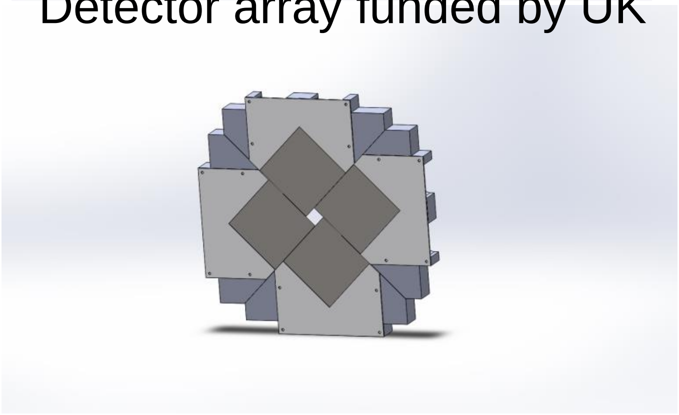




Detector array funded by UK



Gas-jet proposed by DK+S



p-capture

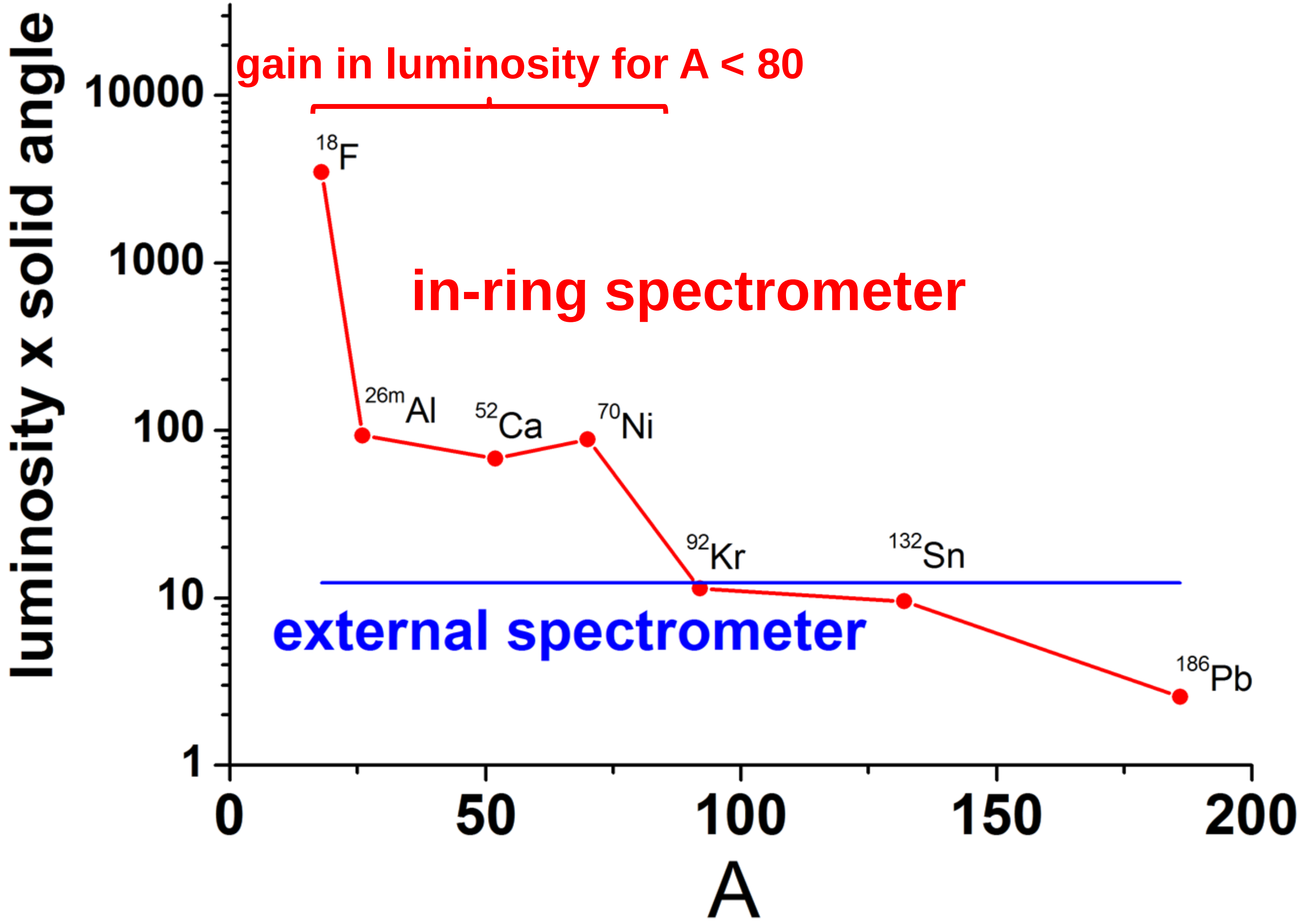
Direct measurement of (p,γ) or (α,γ) rates

(^{3}He,d) as surrogate of (p,γ)

Galactic abundance of γ-ray emitter ^{26}Al

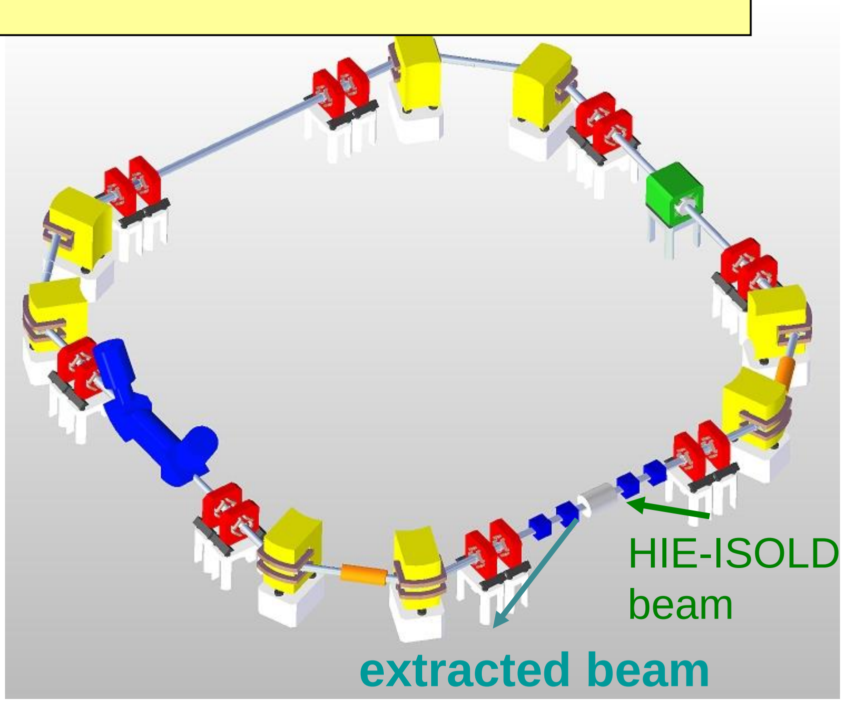
Measure ^{26m}Al(d,p)^{27}Al transfer reaction

Internal versus external detectors



External target: beam extraction

- Extraction times can be reduced to ~ 1s
- Efficiency (cooled beam) ≈90%
- Properties similar to those of the cooled beam



cooling + extraction ≈ 1.5 s

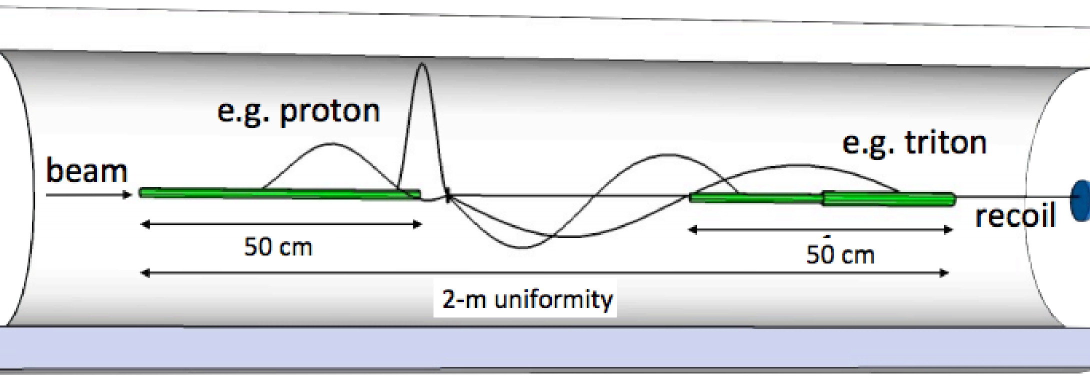
injection
≈10^5 ions

probe tensor interaction:
N=82 using ^{146}Gd, ^{148}Dy, ^{150}Er (d,p)
N=126 using ^{206}Hg, ^{212}Rn, ^{214}Ra (d,p)

pear-shaped nuclei for EDM
^{225}Ra(d,d')

Isol(de) Solenoidal Spectrometer

Funded by UK



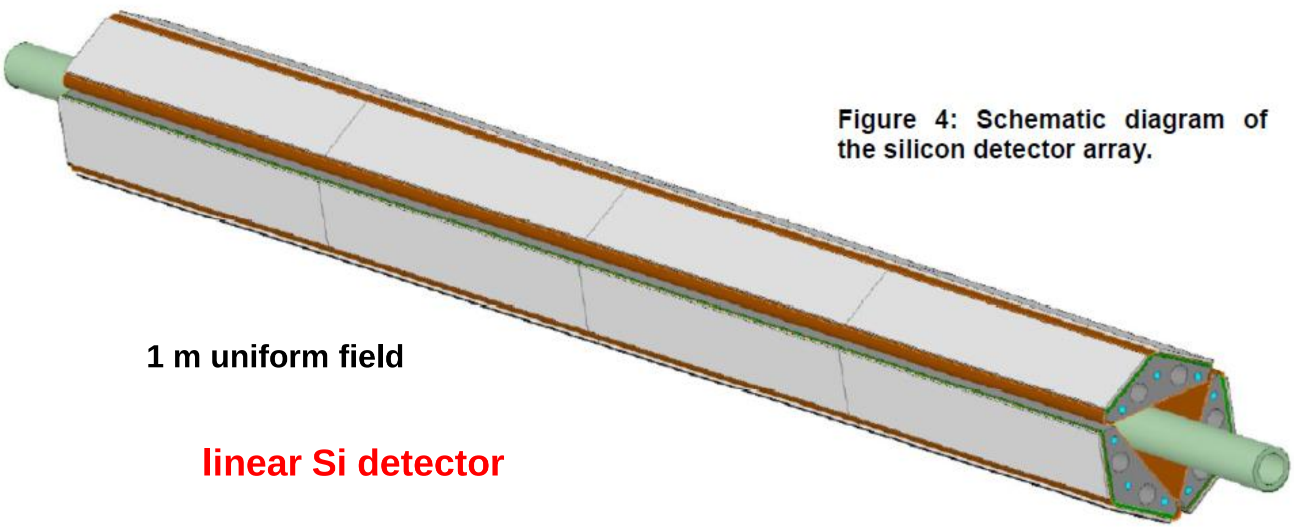


Figure 4: Schematic diagram of the silicon detector array.

1 m uniform field

linear Si detector

4 x 125 x 25 mm; 1 mm strips
R^3B-type ASIC readout

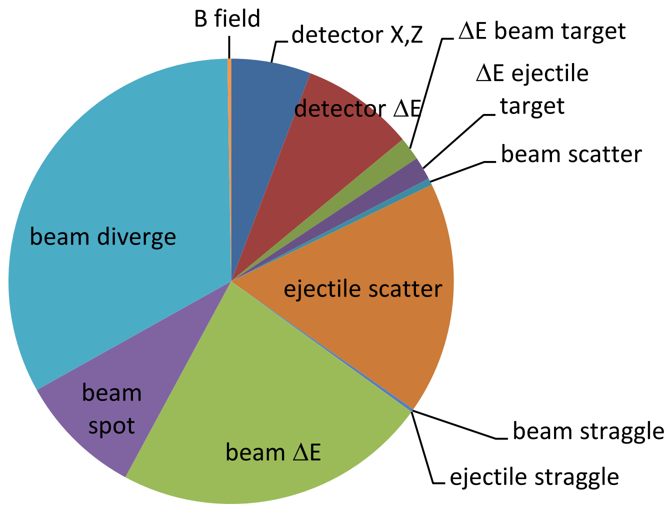
ISS installation

- Presently in building 190
- Cool down with dewars or in SM18
- Magnet is energised prior to final move
- Field mapping
- Move to building 170 January 2017
- Install magnetic shielding (upstream and downstream)
- Install Si array (ANL), electronics , DAQ
- Source tests, stable beam line to commission beam line
- Ready for beam 2018
- Install ISOL-SRS Si array (UK) & recoil detector 2019-2020
- Upgraded detector ready for beam 2021
- Move ISS to TSR hall 2022?

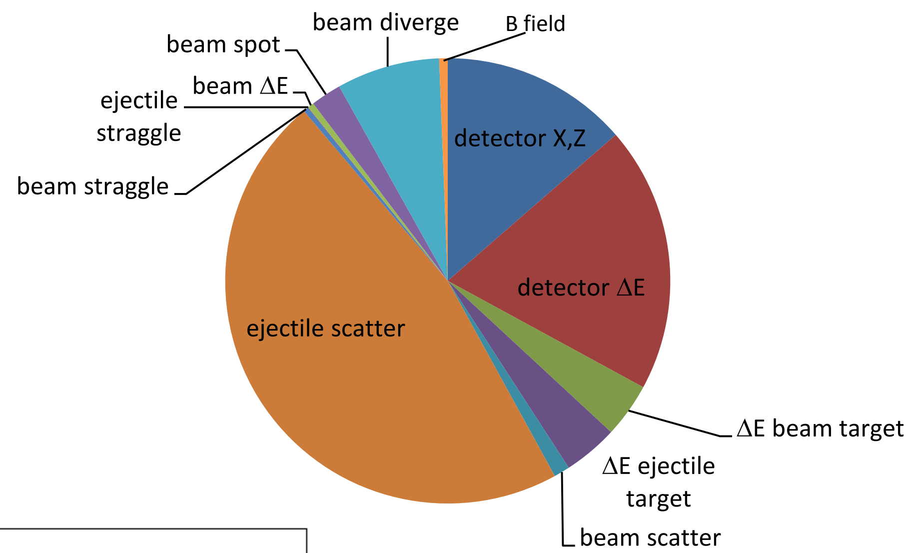
Q-value energy resolution

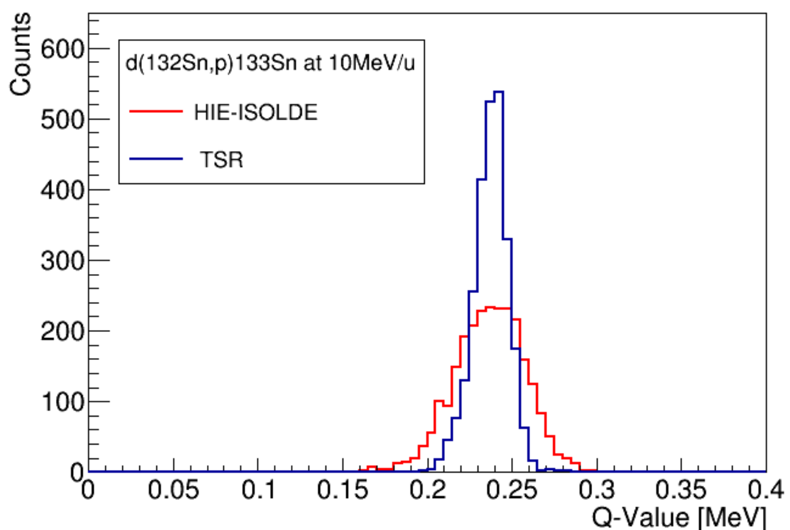
d(^{132}Sn,p)^{133}Sn @ 10 MeV/u

With HIE-ISOLDE beam: ~**50 keV**



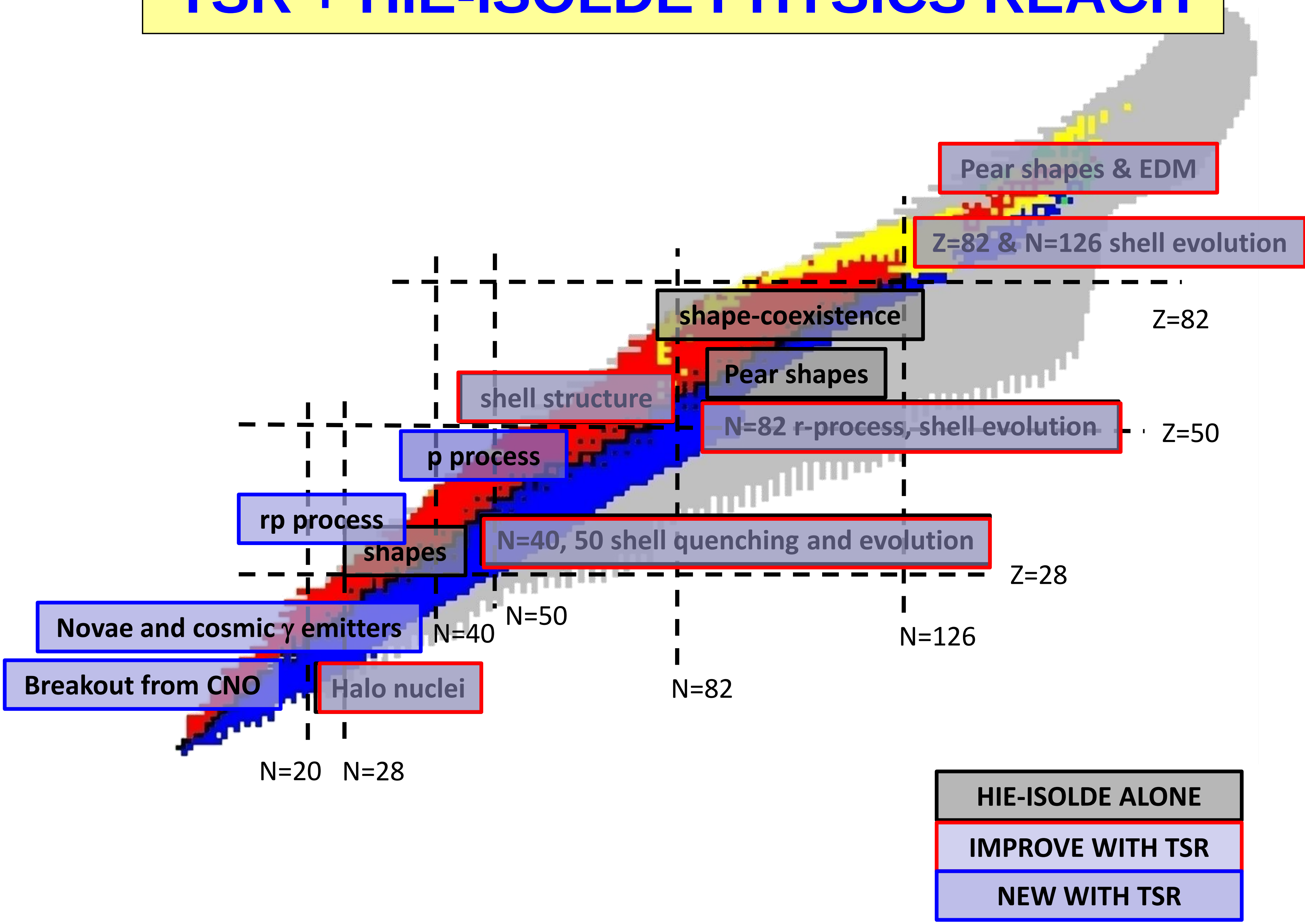
With cooled TSR beam: ~**20 keV**



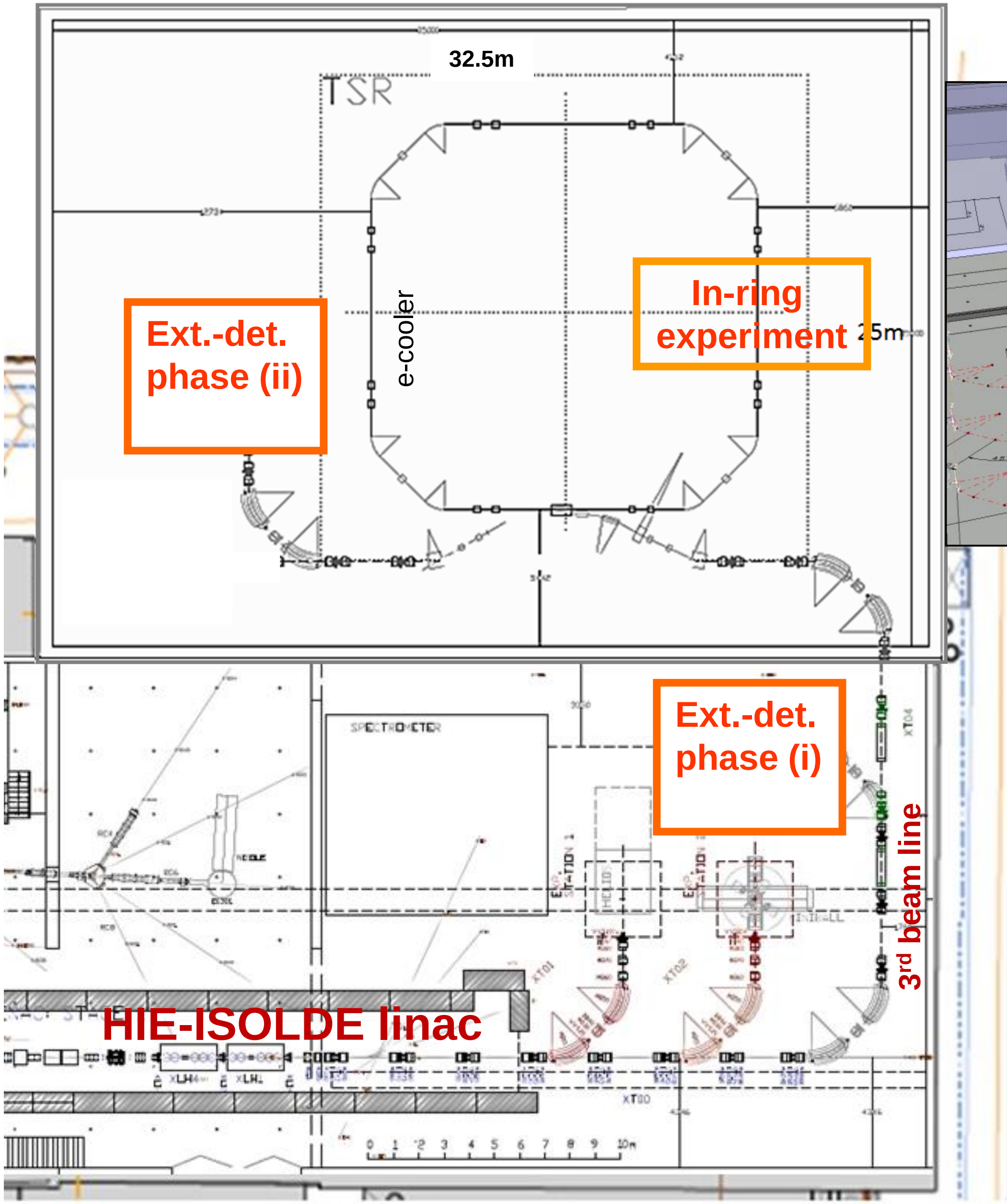


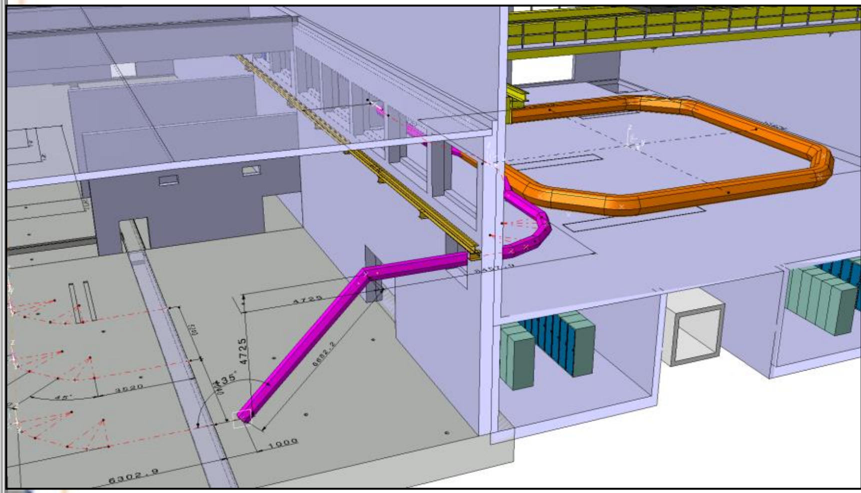
Argonne HELIOS
~ **100 keV**
(limited beams)

TSR + HIE-ISOLDE PHYSICS REACH



Beam-line layout





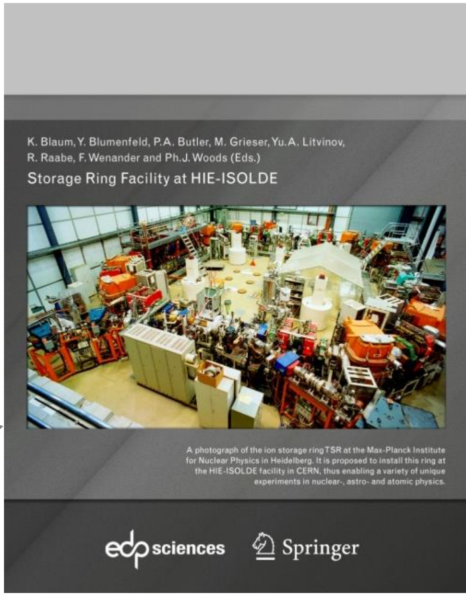
Time-line

TSR@ISOLDE workshop at MPI-K Heidelberg
evaluated the future for TSR Oct 2010

ISOLDE and Neutron Time-of-Flight Committee endorsed Jan 2012

TSR technical design report **129 co-authors (47 institutions)**

EPJ Special Topics **207** 1-117 May 2012



Approved by CERN Research board, May 2012

"The installation of TSR, as an experiment to be included in the HIE-ISOLDE programme, was approved by the Research Board.

The timescale will be defined once the study of its Integration has been completed."

Presentation of the integration study to the CERN Research Board Nov 2013

UK internal + external detectors (ISOL-SRS) ~£5M funded, project 2015-2019

External detector phase (i): exploit HIE-ISOLDE beams (3rd beam-line) from 2018

Internal detector & external detector phase (ii): exploit TSR from 2023

TSR budget

	2014 integration study	*2016 integration study*	*revision?*
Capital	16 MCHF	22 MCHF	19 MCHF
FTE	26	44	28

(increases due to extraction line, hall infrastructure, vacuum infrastructure, project management, commissioning/operation)

Infrastructure contributions

Germany	4 FTEs
UK	2 FTE (*to be confirmed*)
ISOLDE collaboration	??

Detectors

UK (includes FTE)	6.9 MCHF
Belgium	0.2 MCHF
Denmark/Sweden	(0.5 MCHF *proposed)*
other opportunities	….

Back Up

Summary

Several areas of HIE-ISOLDE research area will strongly benefit from TSR.

New opportunities, particularly nuclear astrophysics, will come from the TSR.

New UK detection systems:
first phase will exploit HIE-ISOLDE (3rd beam-line) but will require TSR (and was funded on its promise).

TSR should have its building in the near future (maintenance and expert manpower issue).

TSR transfer lines & integration scheduled after LS2.

Internal target: beam lifetimes

Survival times

Dominated by electron capture and stripping

Residual gas and gas target

Effective target thickness:
(gas target thickness) x (revolution frequency) x (lifetime

Internal gas target

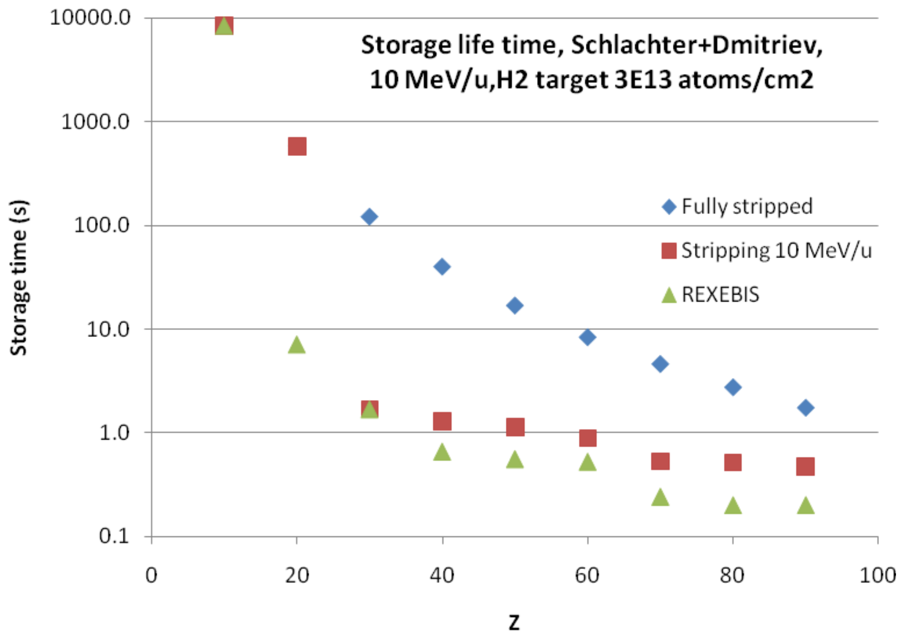
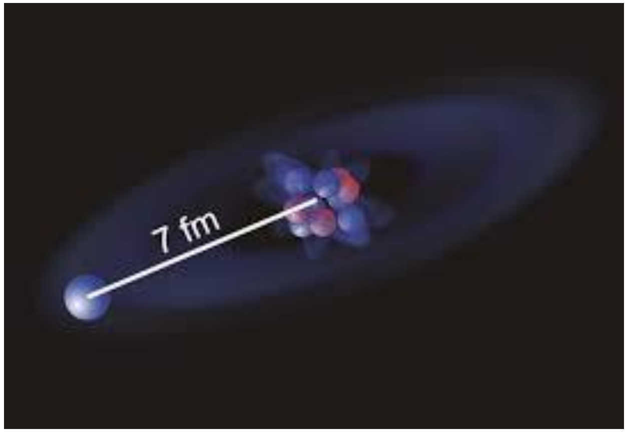


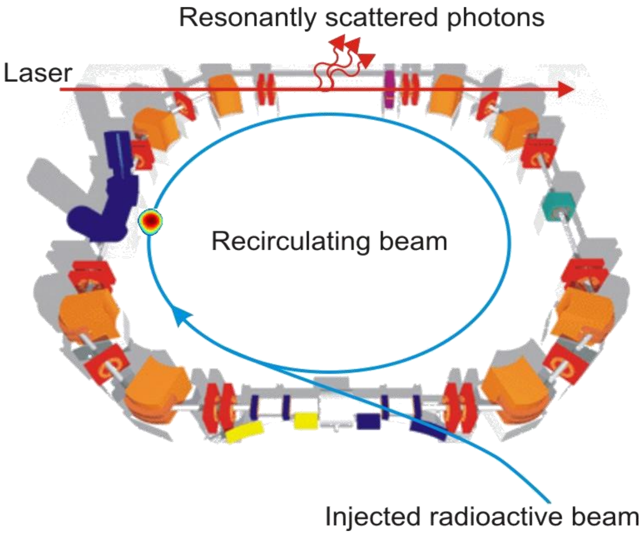
Table 1: Parameters of beams circulating in the TSR. See text for details.

Ion	Nuclear lifetime	Energy (MeV/u)	Cooling time	Beam lifetime in residual gas	H_2 target (atoms/cm^2)	Beam lifetime in target	Eff. target thickness (μg/cm^2)
^{7}Be 3+	(53 d)	10	2.3 s	370 s			
^{18}F 9+	100 m	10	0.7 s	280 s	1×10^{14}	236 s	31000
^{26m}Al 13+	6.3 s	10	0.5 s	137 s	5×10^{14}	23 s	4200
^{52}Ca 20+	4.6 s	10	0.4 s	58 s	5×10^{14}	9.6 s	3000
^{70}Ni 28+	6.0 s	10	0.25 s	30 s	2×10^{14}	12 s	1600
^{70}Ni 25+	6.0 s	10	0.3 s	26 s	2×10^{13}	2.1 s	60
^{132}Sn 30+	40 s	4	0.4 s	1.5 s	1×10^{12}	1.4 s	1.2
^{132}Sn 45+	40 s	4	0.2 s	1.4 s	5×10^{12}	1.6 s	7
^{132}Sn 39+	40 s	10	0.25 s	7.4 s	2×10^{12}	3.6 s	9.5
^{132}Sn 45+	40 s	10	0.2 s	10 s	5×10^{13}	1.3 s	90
^{186}Pb 46+	4.8 s	10	0.25 s	4 s	2×10^{12}	1.5 s	4
^{186}Pb 64+	4.8 s	10	0.13 s	5 s	1×10^{13}	1.7 s	20

In-ring collinear laser spectroscopy

LASER SPECTROSCOPY:
Measure charge radii and moments of previously inaccessible unstable light nuclei. Use interaction of lasers with ions recirculating in the ring to induce fluorescent emission and study hyperfine structure.





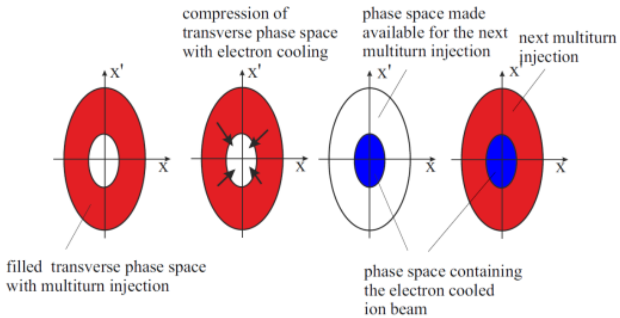
Produce He-like ions in EBIS of HIE-ISOLDE (allows high precision in use of atomic models for calibration)

Inaccessible transition energies Doppler-shifted

Recirculation of the beam

Polarisation & purification possible

STACKING



stacking ≈$T_{1/2}$

SLOW BEAM EXTRACTION

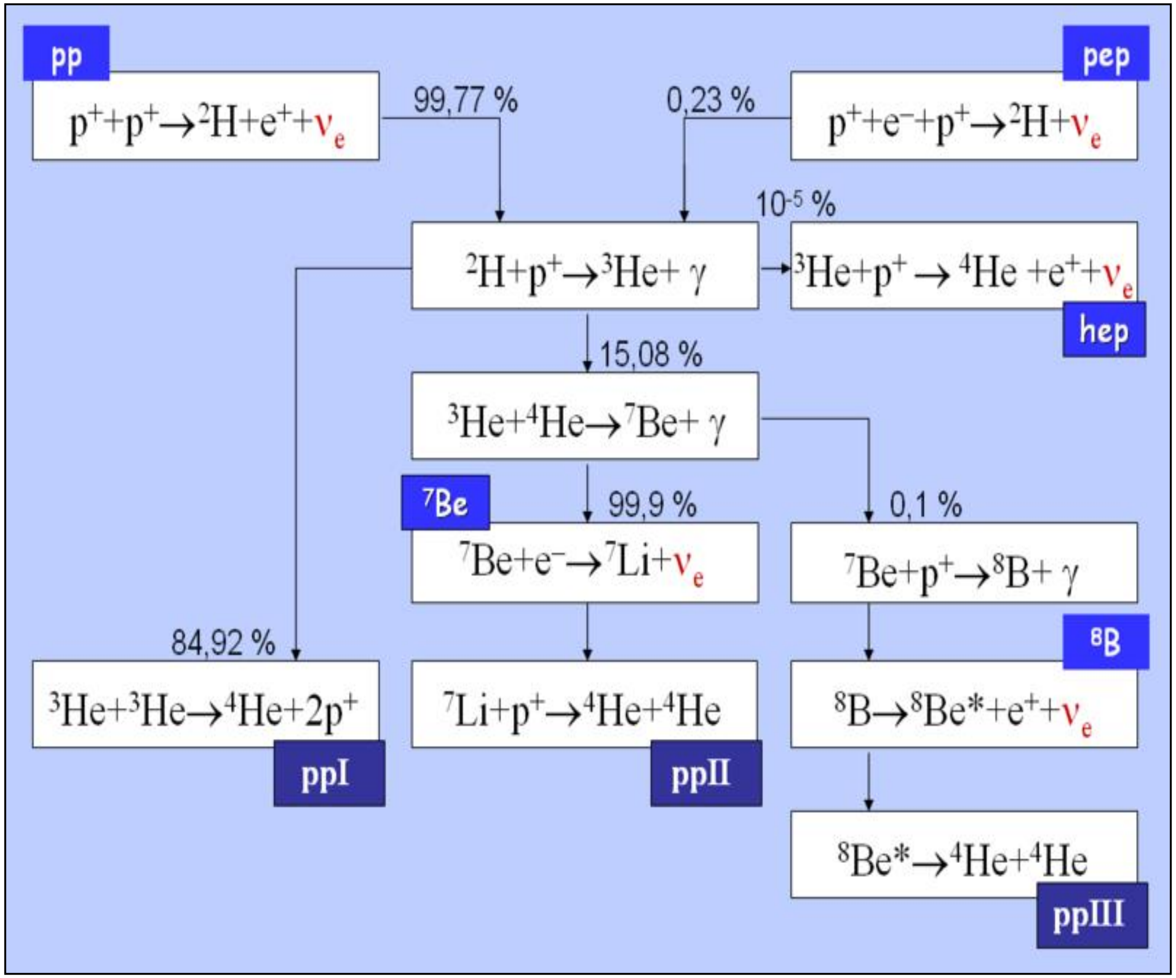
e-cool for 1 s

Shift Q_x close to resonance 8/3

Apply 30 kHz (bandwidth) noise on extraction kicker

Horizontal emittance increase -> beam extraction

In-ring measurements

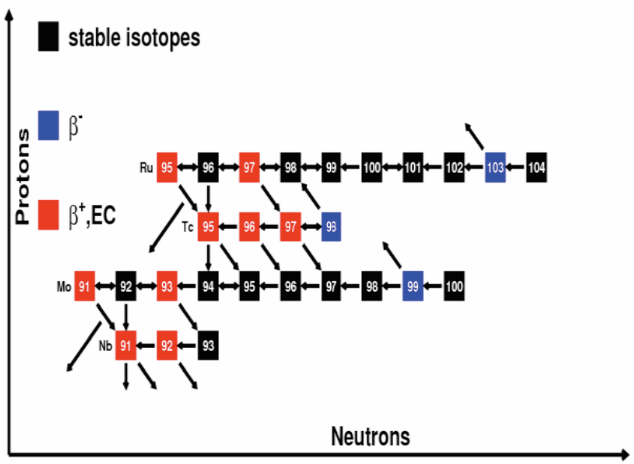


Example: p-nuclei

proton-rich isotopes between Z=34 & Z=80
not accounted for by s- or r-process

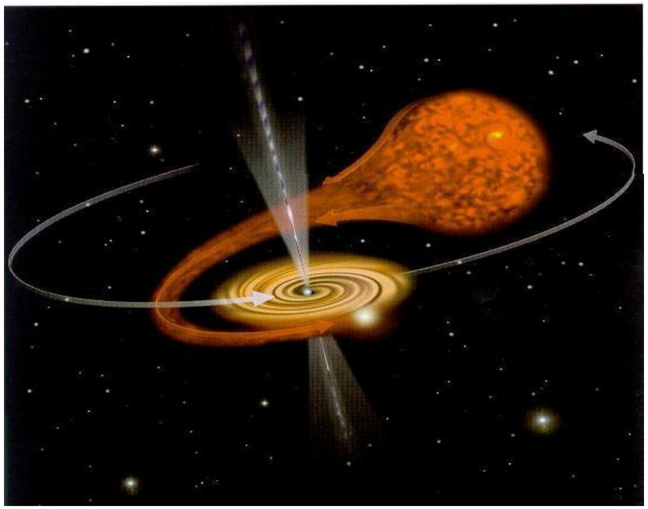
p-process: reaction flow carried by (γ,n), (γ,p) or (γ,α)

rp-process: reaction flow carried by (p,γ)



require high temperatures 2-3 GK
possible sites are:

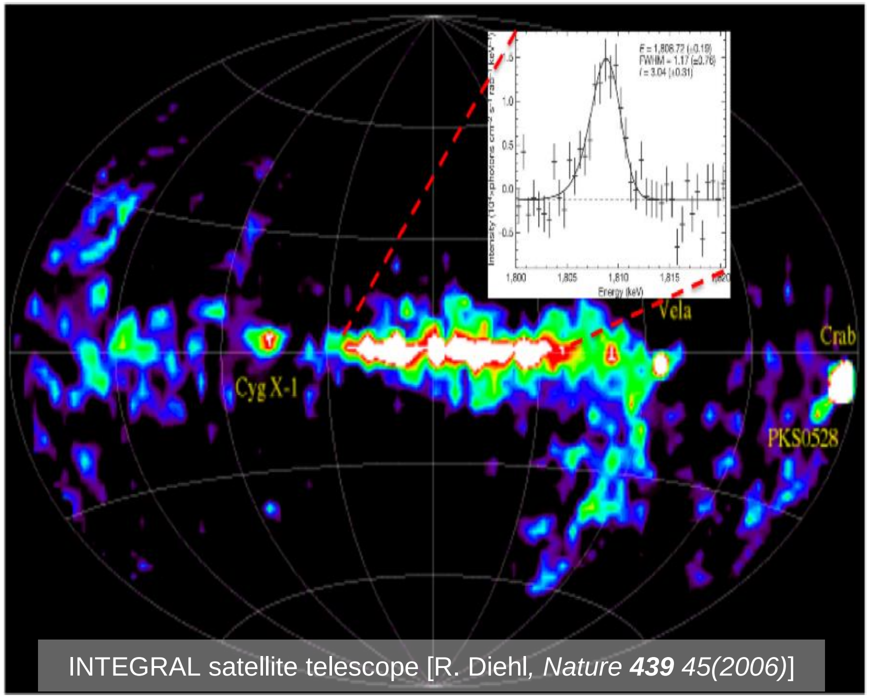
- **SN type II**
- **Novae**
- **X-ray bursters (accreting binary systems)**
- **SN Ia**



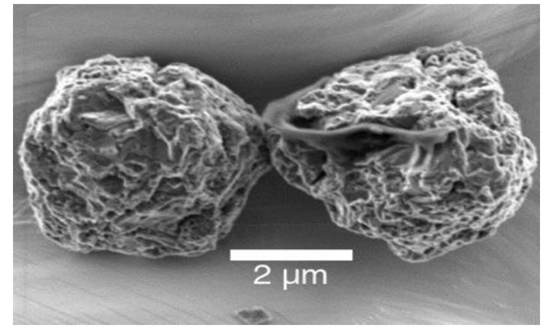
Direct measurement of (p,γ) or (α,γ) rates in the Gamow window
(^{3}He,d) as surrogate of (p,γ)
(p,α) as inverse of (α,p)

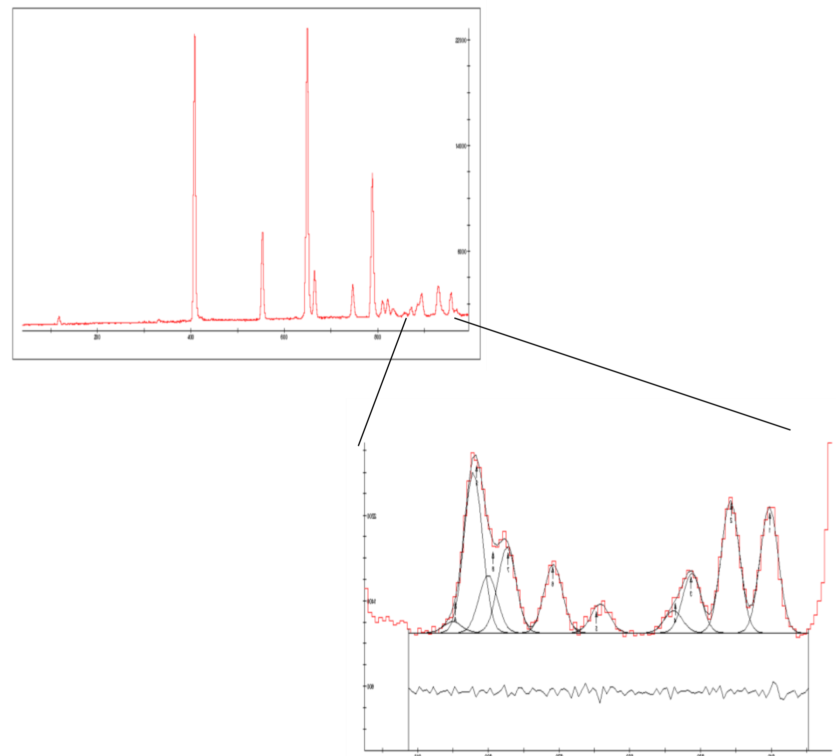
Example: galactic abundance of γ-ray emitter ^{26}Al

Phil Woods



INTEGRAL satellite telescope [R. Diehl, *Nature* ***439*** *45(2006)*]





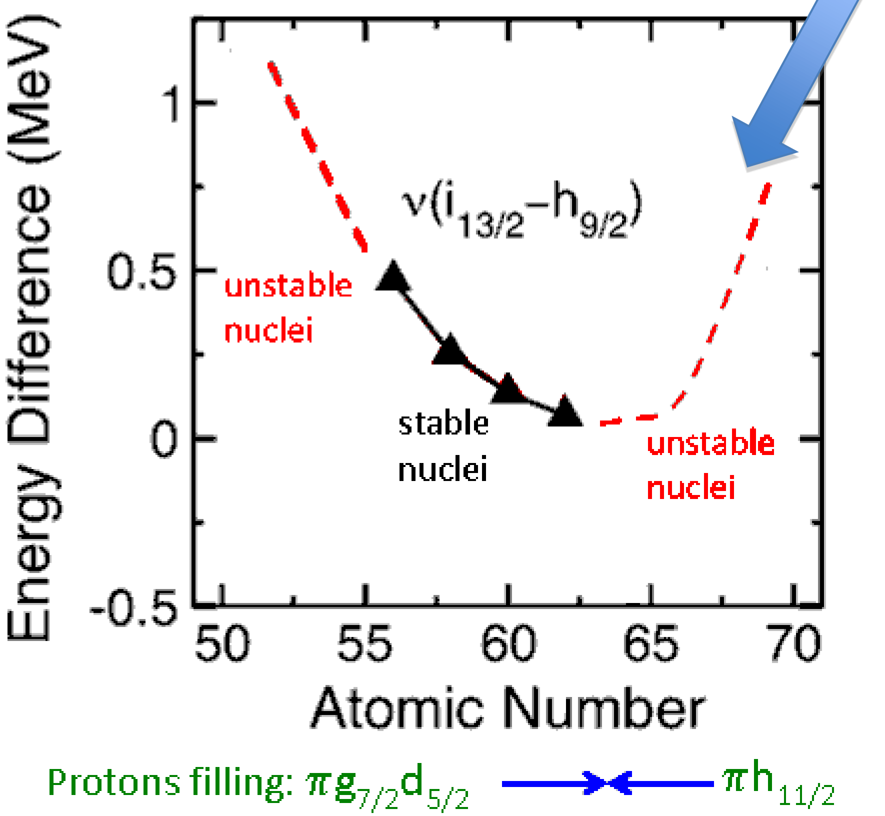
Isomer can be excited in core collapse supernovae.
'Extinct' ^{26}Al observed in meteorites as excess ^{26}Mg.

Measure ^{26m}Al(d,p)^{27}Al transfer reaction.

Example: probe tensor interaction

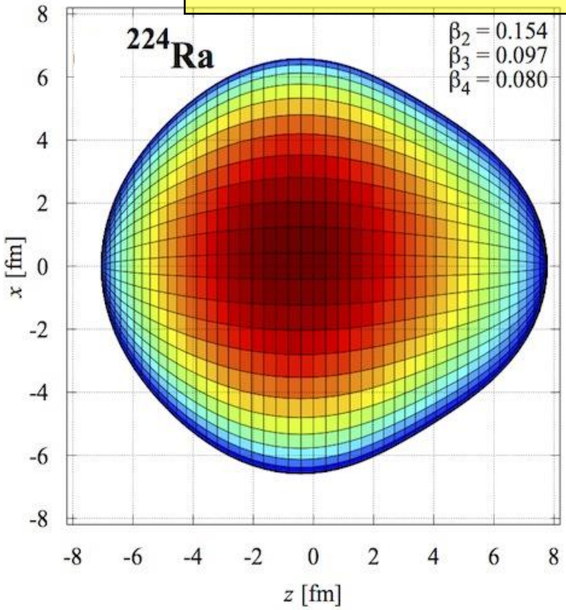
Transfer reaction measurements to locate single-neutron *particle* states outside *inert core*.

Expect turnaround in trend, if tensor force drives changes, for higher Z.



Test outside N=82 using ^{146}Gd, ^{148}Dy, ^{150}Er

Example: pear-shaped nuclei and EDMs



Schiff moment related to Q_3 P,T-violating n-n interaction

$$S = -2\frac{J}{J+1}\frac{\langle \hat{S}_z \rangle \langle \hat{V}_{PT} \rangle}{\Delta E}$$

energy splitting of parity doublet