THE UNIVERSITY of York

HELIOS: a new approach to studying transfer reactions in inverse kinematics*

(and potential for the use of a HELIOS-like spectrometer at HIE-ISOLDE)

Benjamin P. Kay
The University of York

ISOLDE Workshop and Users meeting
8-10 December 2010

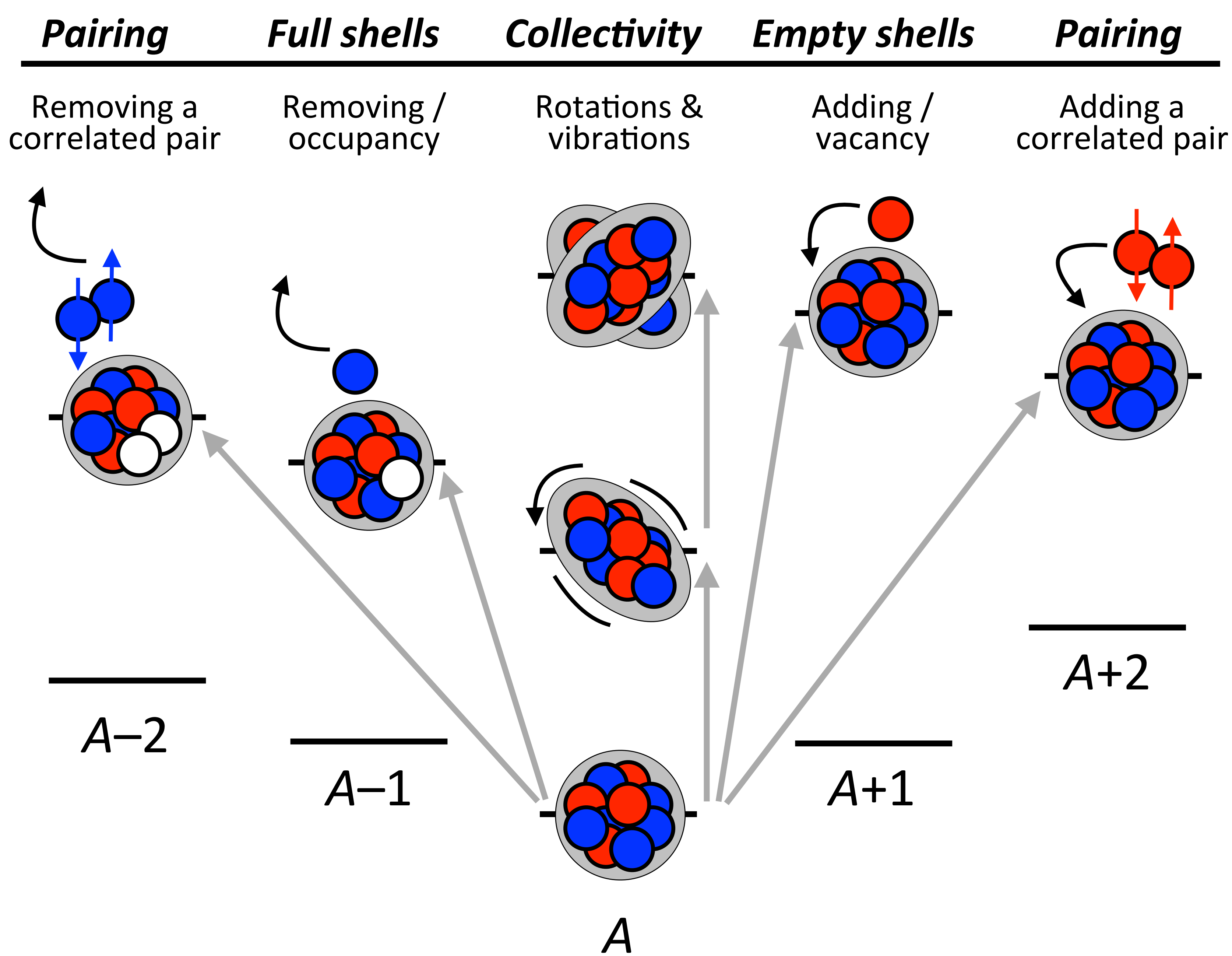
*This work is supported by the US Department of Energy, Office of Nuclear Physics under Contract No. DE-AC02-06CH11357 and Grant No. DE-FG02-04ER41320, NSF Grant No. PHY-02-16783, and the UK Science and Technology Facilities Council

Motivation – nuclear structure with radioactive beams

(via single- and multi-nucleon transfer reactions)

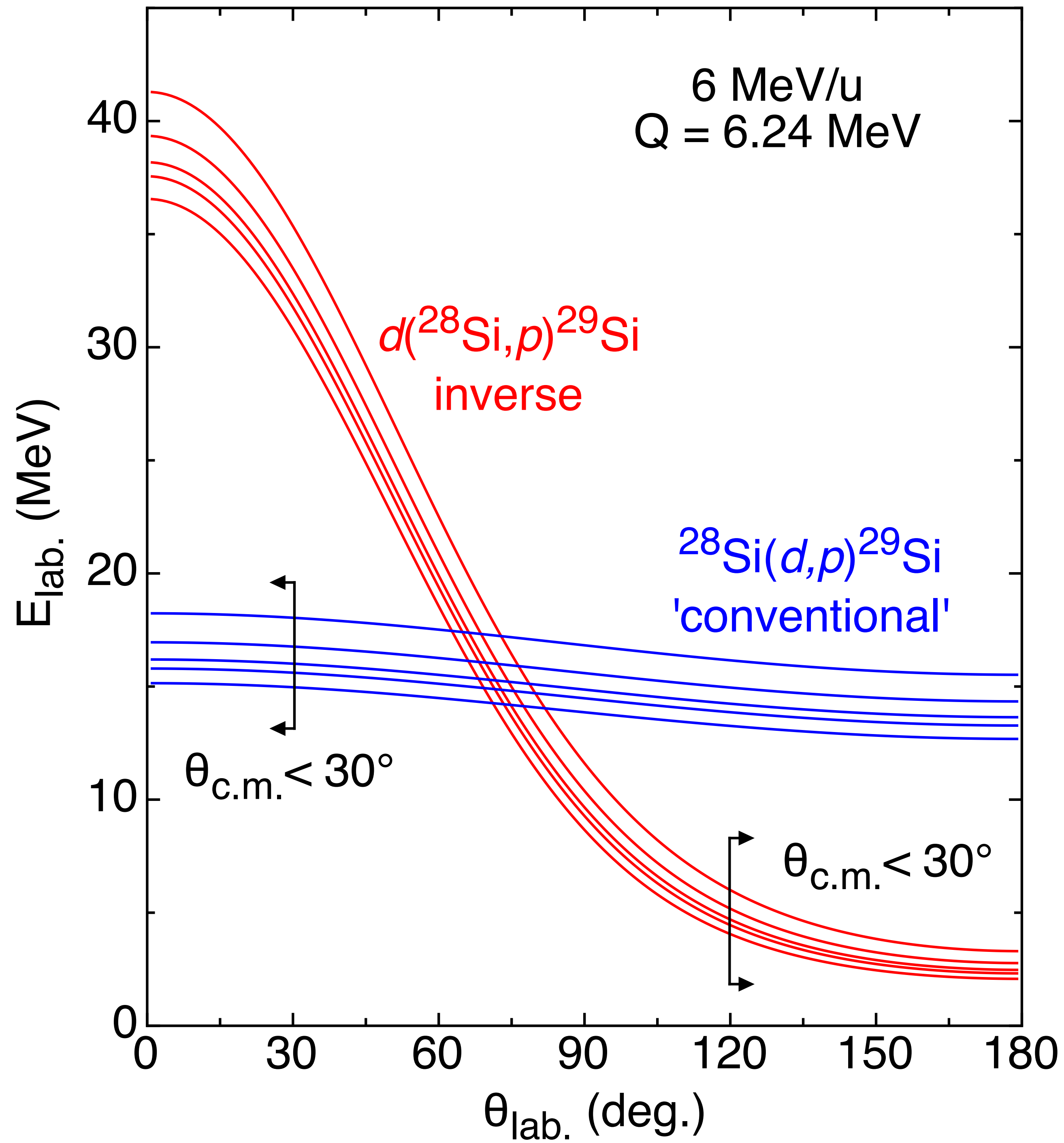
Explore:

- single-particles states; shell structure evolution,
- pair correlations with two-nucleon transfer e.g. (*p*,*t*), (*t*,*p*),
- collectivity, β decay, moments, Coulomb excitation,
- Clustering, *np* pairing, test ab-initio methods ... etc.



The problem with inverse kinematics

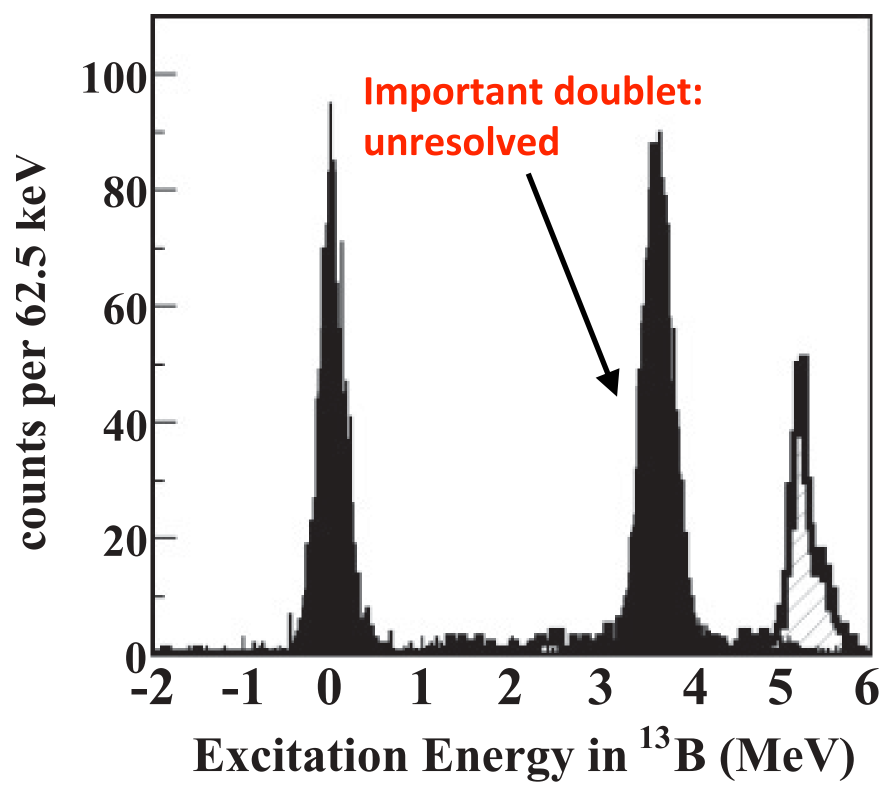
- Particle identification, ΔE-E techniques more challenging at ***low energies***
- ***Strong energy dependence*** with respect to laboratory angle
- ***Kinematic compression*** at forward c.m. angles (in fact nearly all angles)
- Typically leading to ***poor resolution*** (100s of keV)



The problem with inverse kinematics

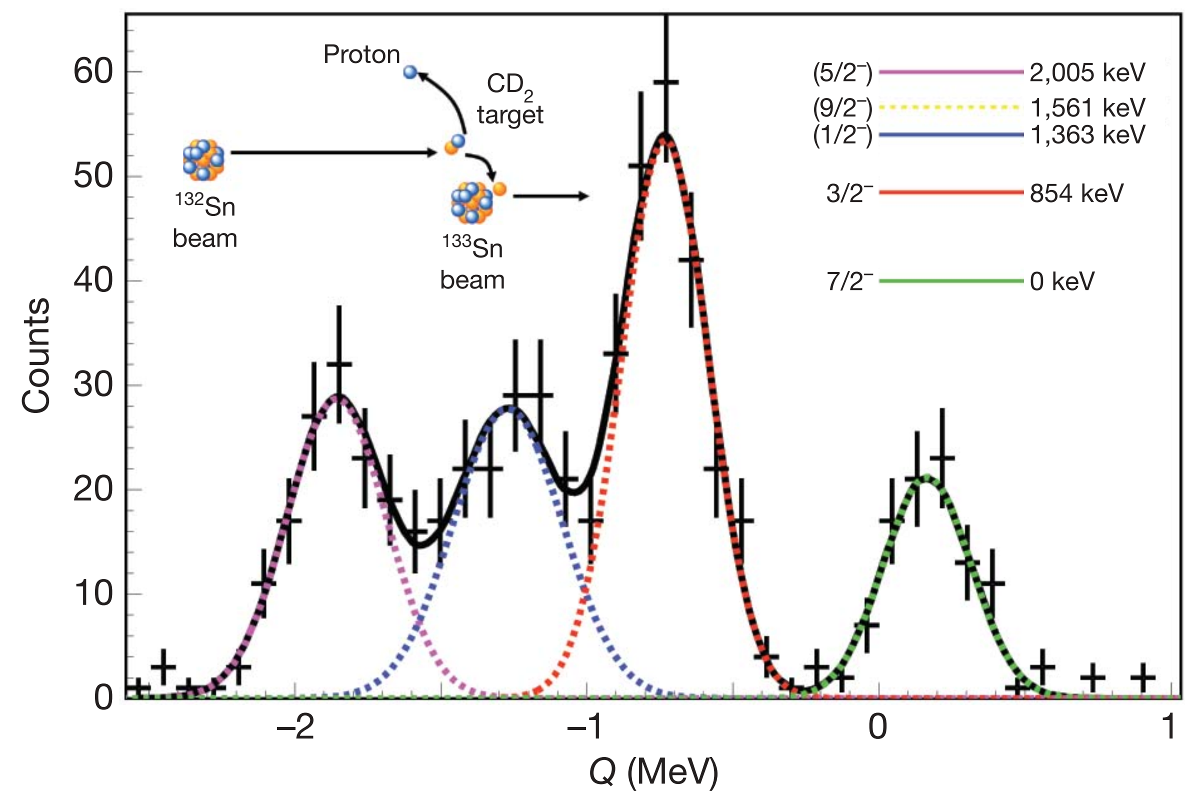
Using the traditional approach of placing a segmented Si detector at a fixed laboratory angle can result in poor excitation-energy resolution, typically of the order of ~300 keV (better can be achieved for light nuclei).

e.g. $d(^{12}B,p)^{13}B$, ~250 keV FWHM



H. Y. Lee *et al.*, PRC **81**, 015802 (2010)
(***prohibitive*** - ***more on this later***)

e.g. $d(^{132}Sn,p)^{133}Sn$, ~300 keV FWHM



K. L. Jones *et al.*, Nature **465**, 454 (2010)
(***not prohibitive - low level density***)

Is there another approach to the problem? ...

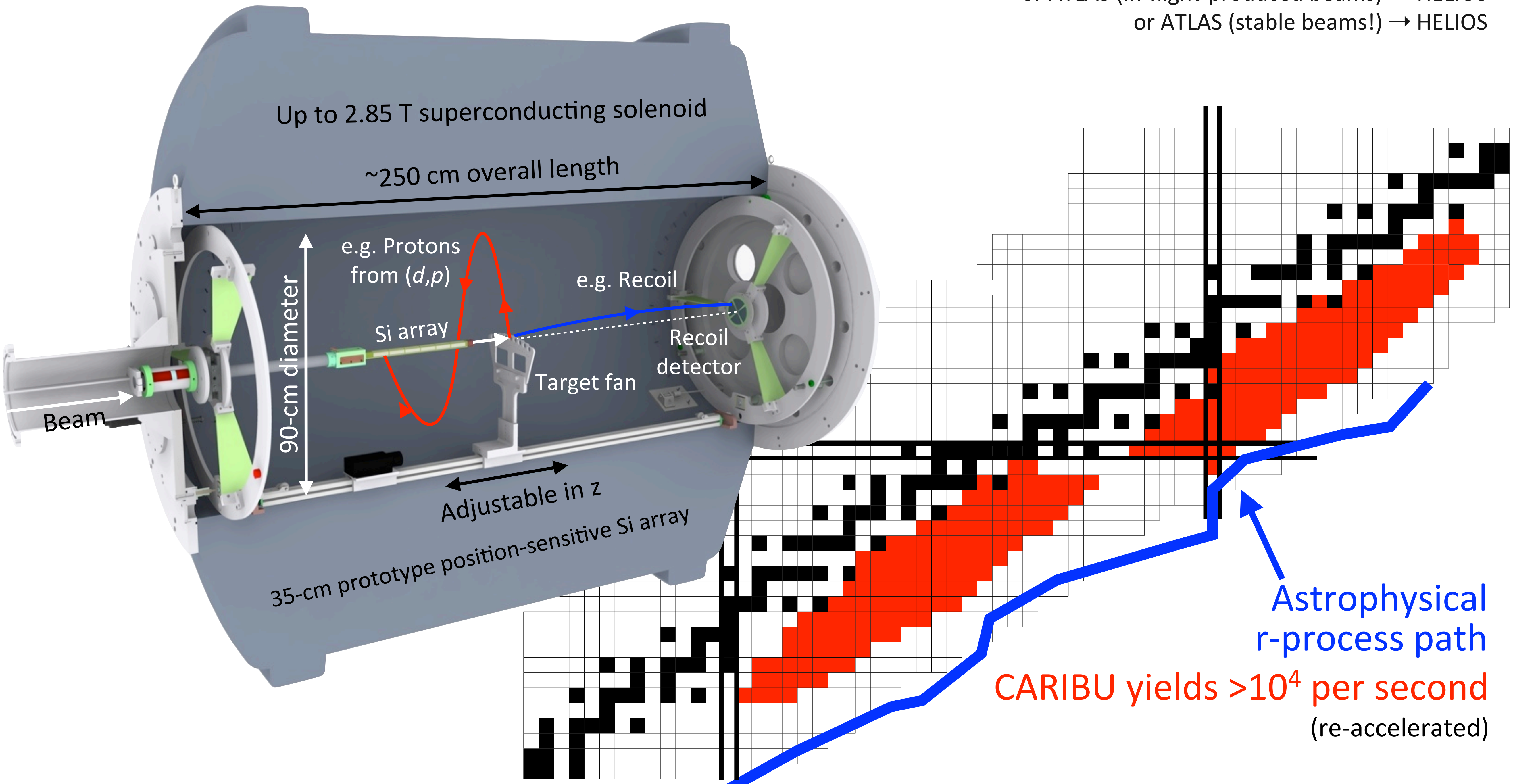
... HELIOS

A new type of spectrometer – the helical orbit spectrometer. Born out of the necessity to perform direct reactions in inverse kinematics with good excitation-energy resolution *and* with low intensity beams.

CARIBU → ATLAS → HELIOS

or ATLAS (in-flight-produced beams) → HELIOS

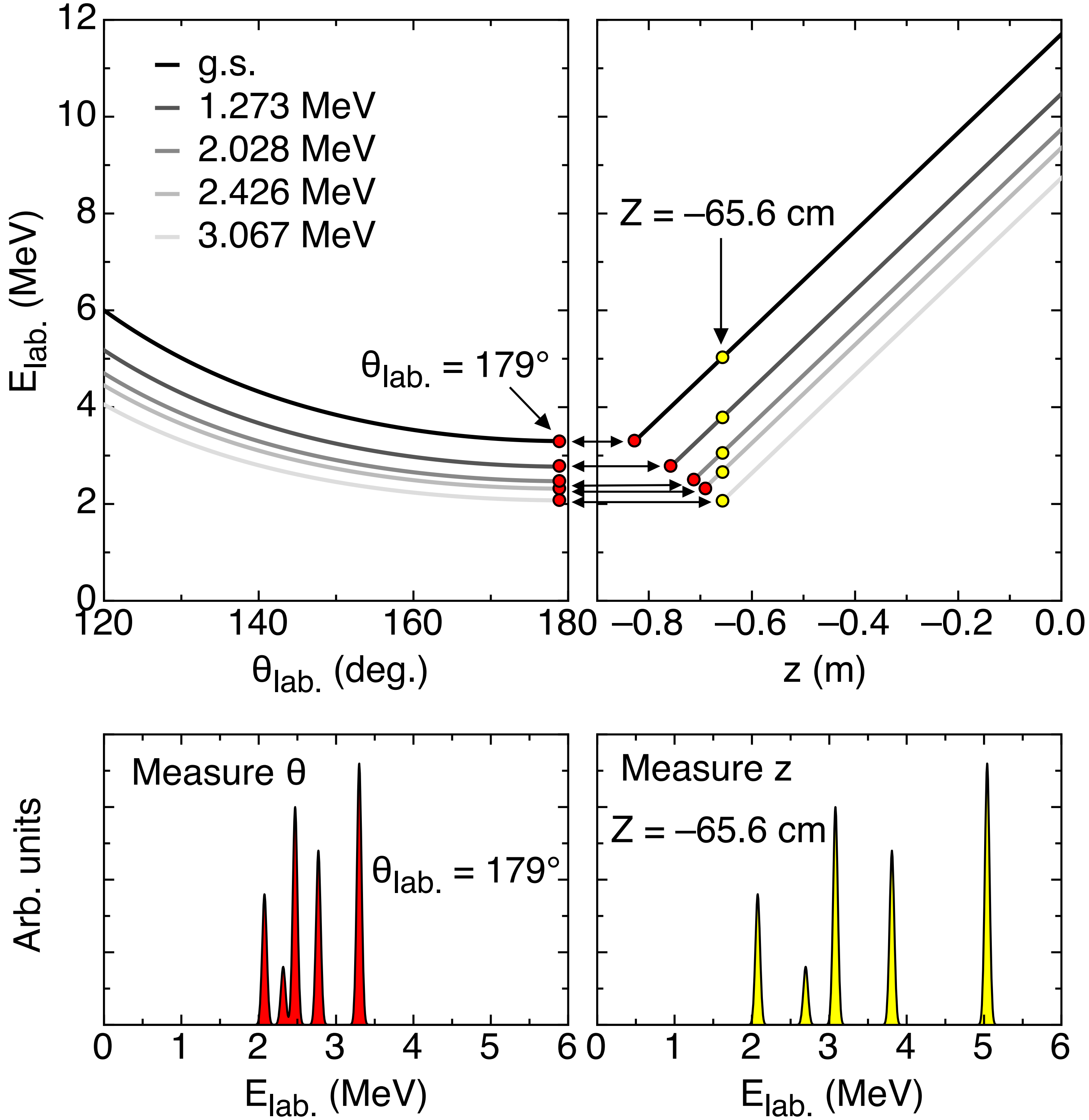
or ATLAS (stable beams!) → HELIOS



CARIBU: G. Savard et al., Nucl. Instrum. Methods Phys. Res. **B226**, 4086 (2008)

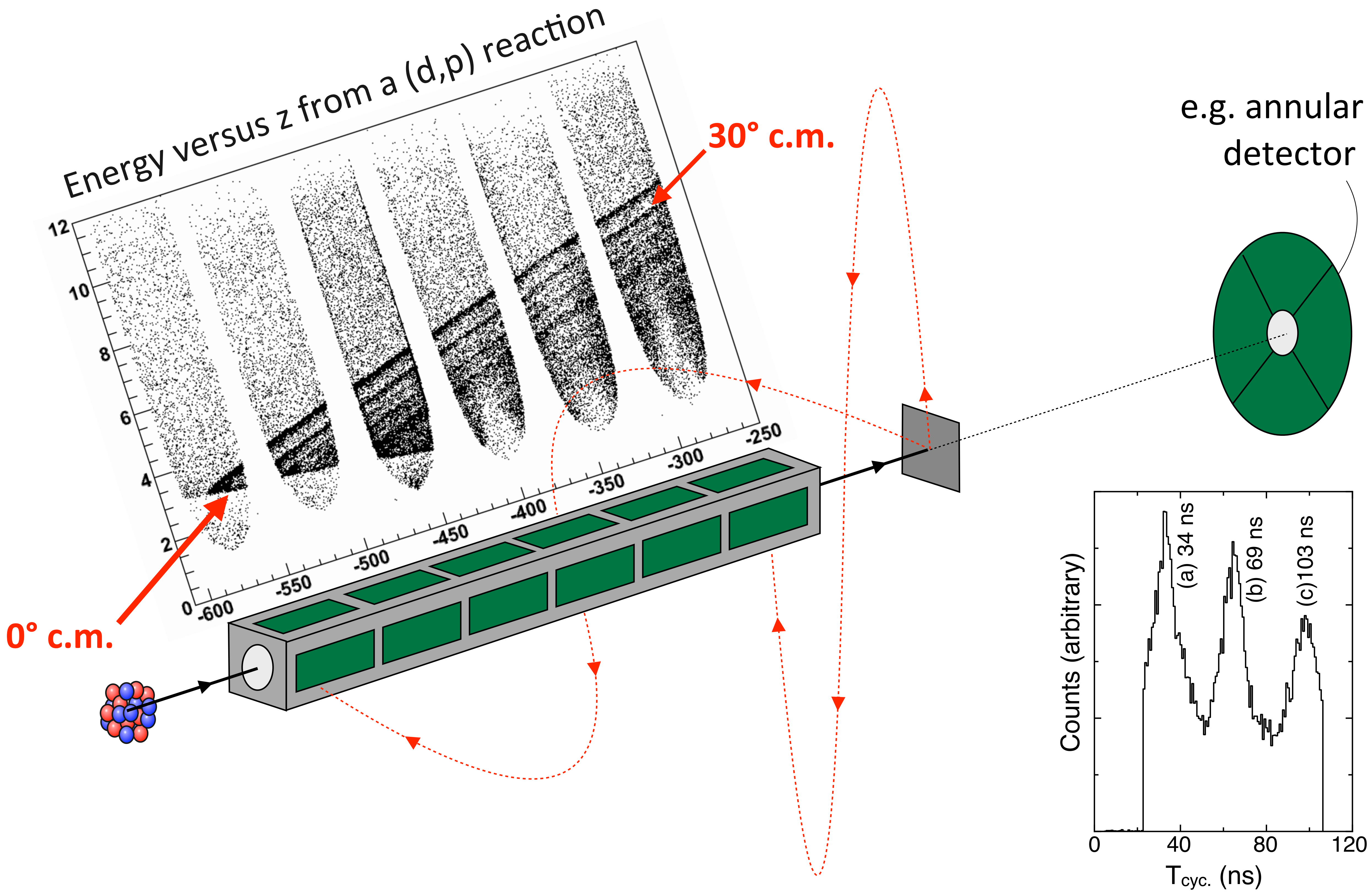
The advantages of HELIOS

Example: $d(^{28}\text{Si},p)$ at 6 MeV/u with a 2-T field

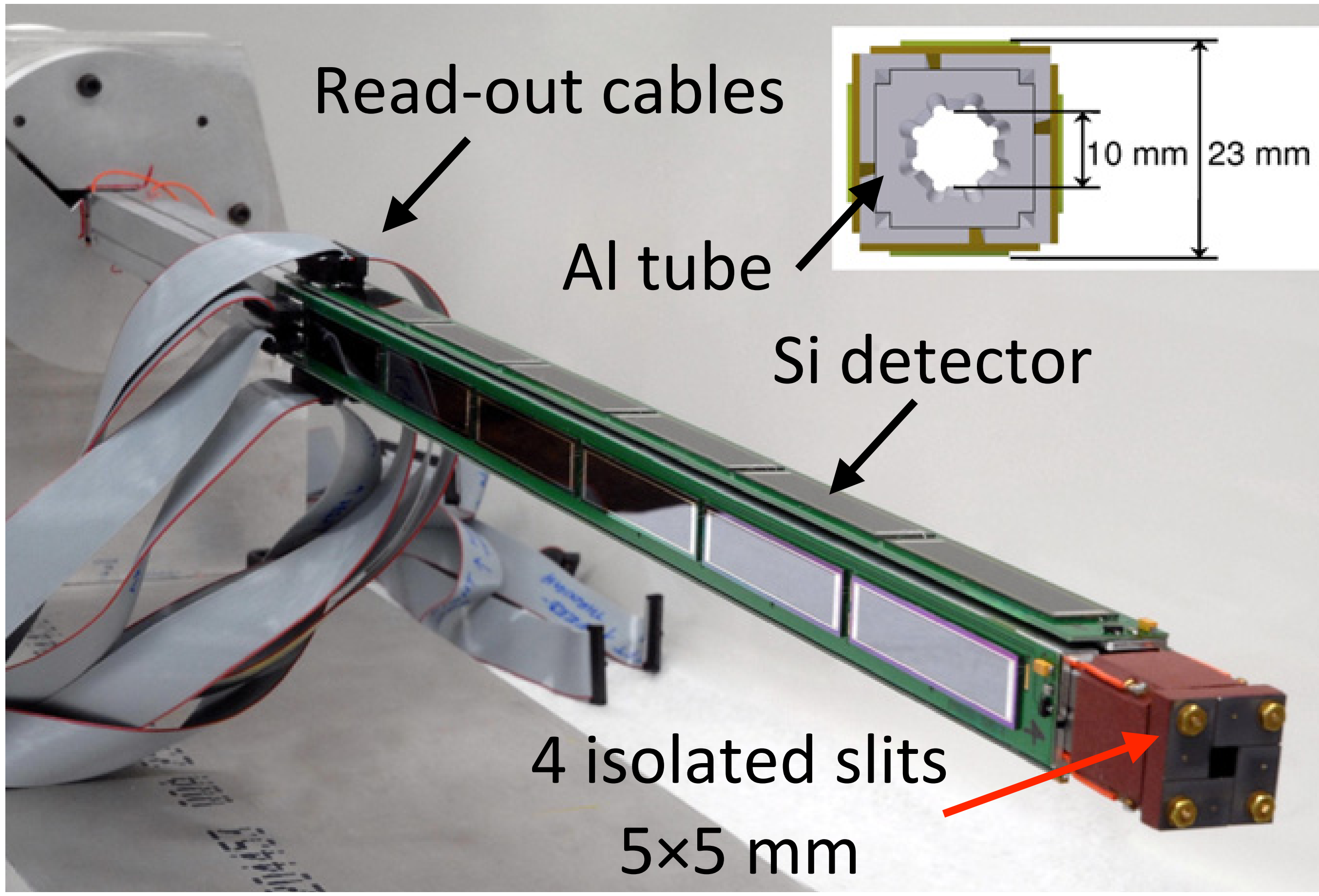


- A simple ***linear*** relationship between energy and z, where the energy separation is (nearly) ***identical*** to the excitation energy in the residual nucleus.
- Avoids the problems of kinematic ***compression***.
- Factor of ~2.4 improvement in resolution (for this example)

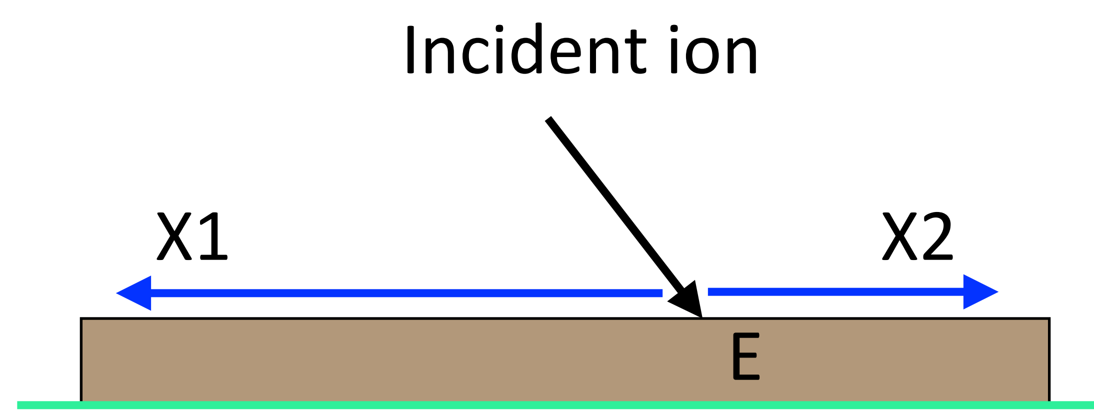
Motion of ions in HELIOS (cartoon)



*The Si (prototype) array**



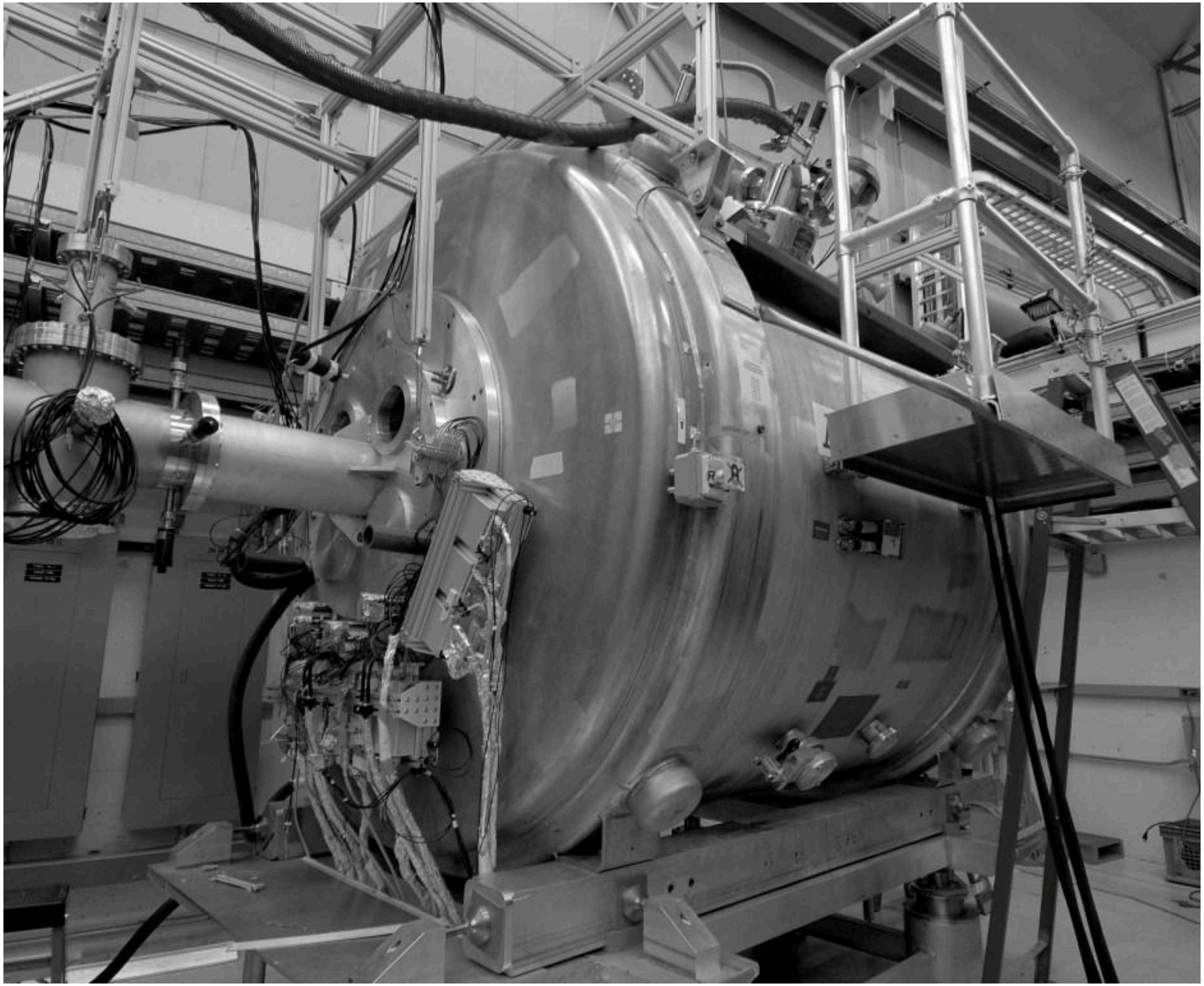
- 4 sides, 6 elements long
- Detector size, 9×50 mm
- 700-µm thick (e.g. ~10 MeV protons)
- Φ coverage, ***0.48 of 2π***
- $\Omega_{element}$ = 21 msr
- Ω_{array} = ***493 msr***



Position ≈ (X1–X2)/E

J .C. Lighthall et al., Nucl. Instrum. Methods Phys. Res.* ***A662**, 97 (2010)*

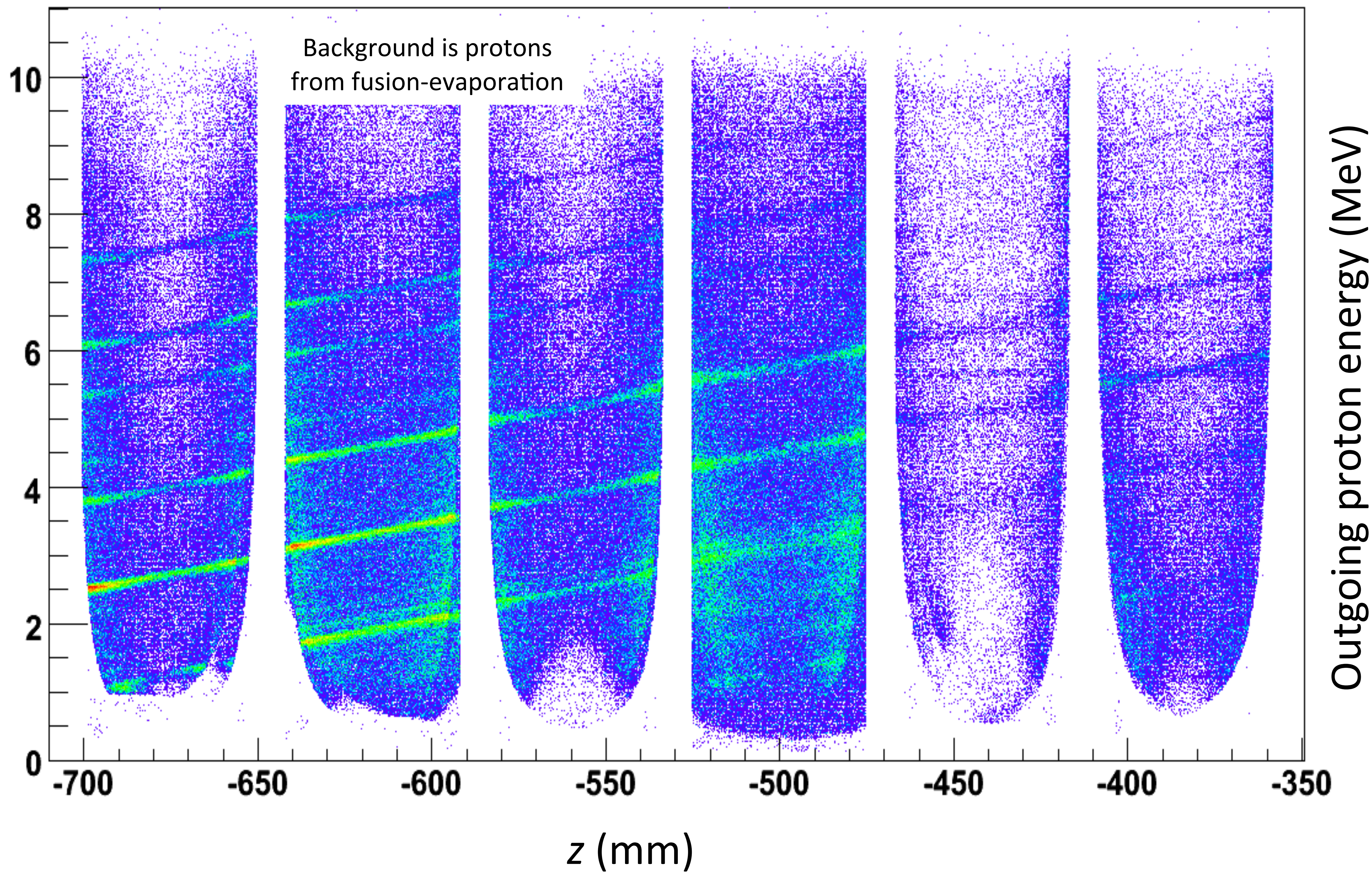
*Photograph from upstream**



**Photograph courtesy of A. H. Wuosmaa*

It works as planned, d(^{28}Si,p) at 6 MeV/u, 2 T

We measure E vs. *z*, which ***is*** the excitation-energy spectrum of the residual nucleus



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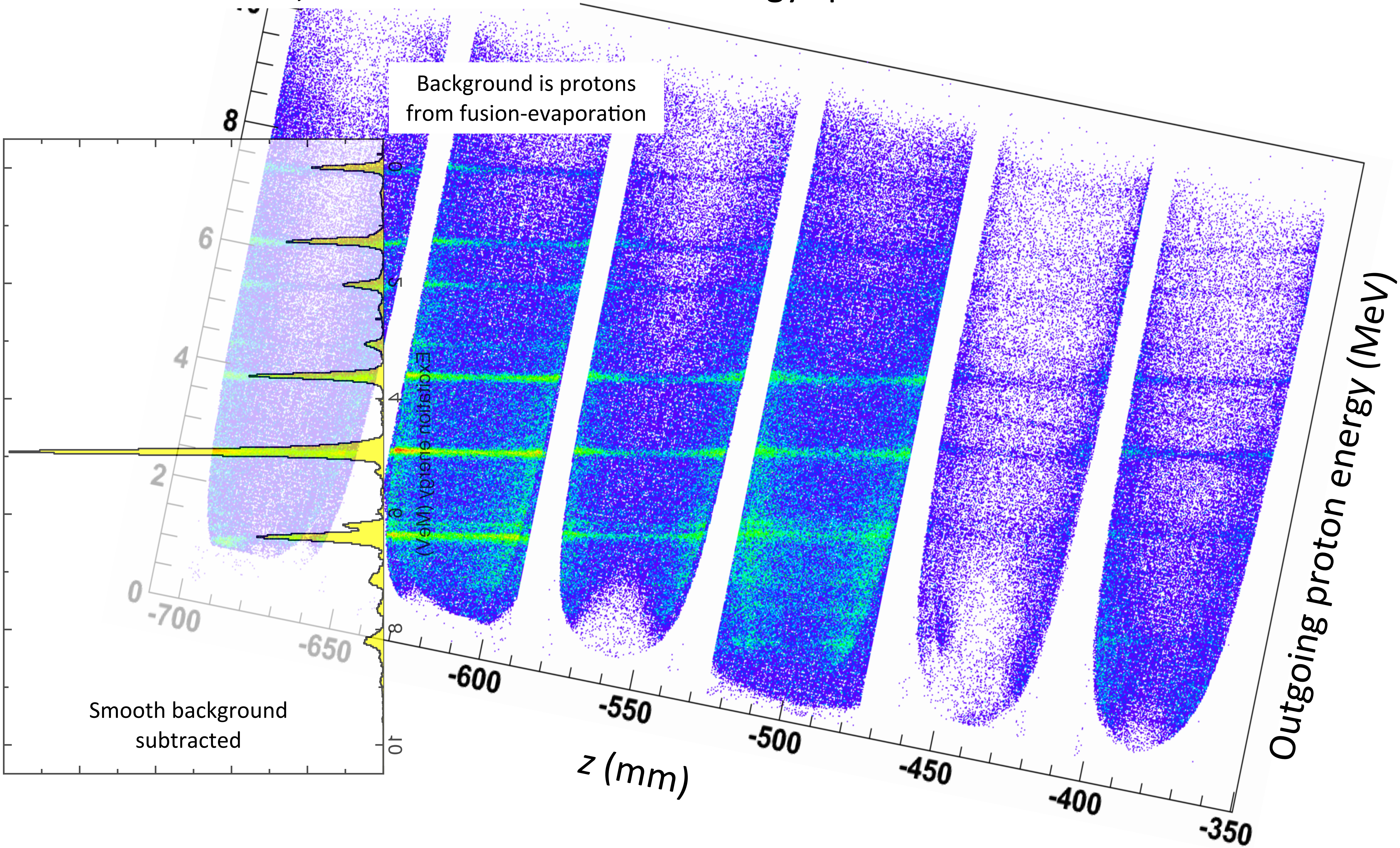

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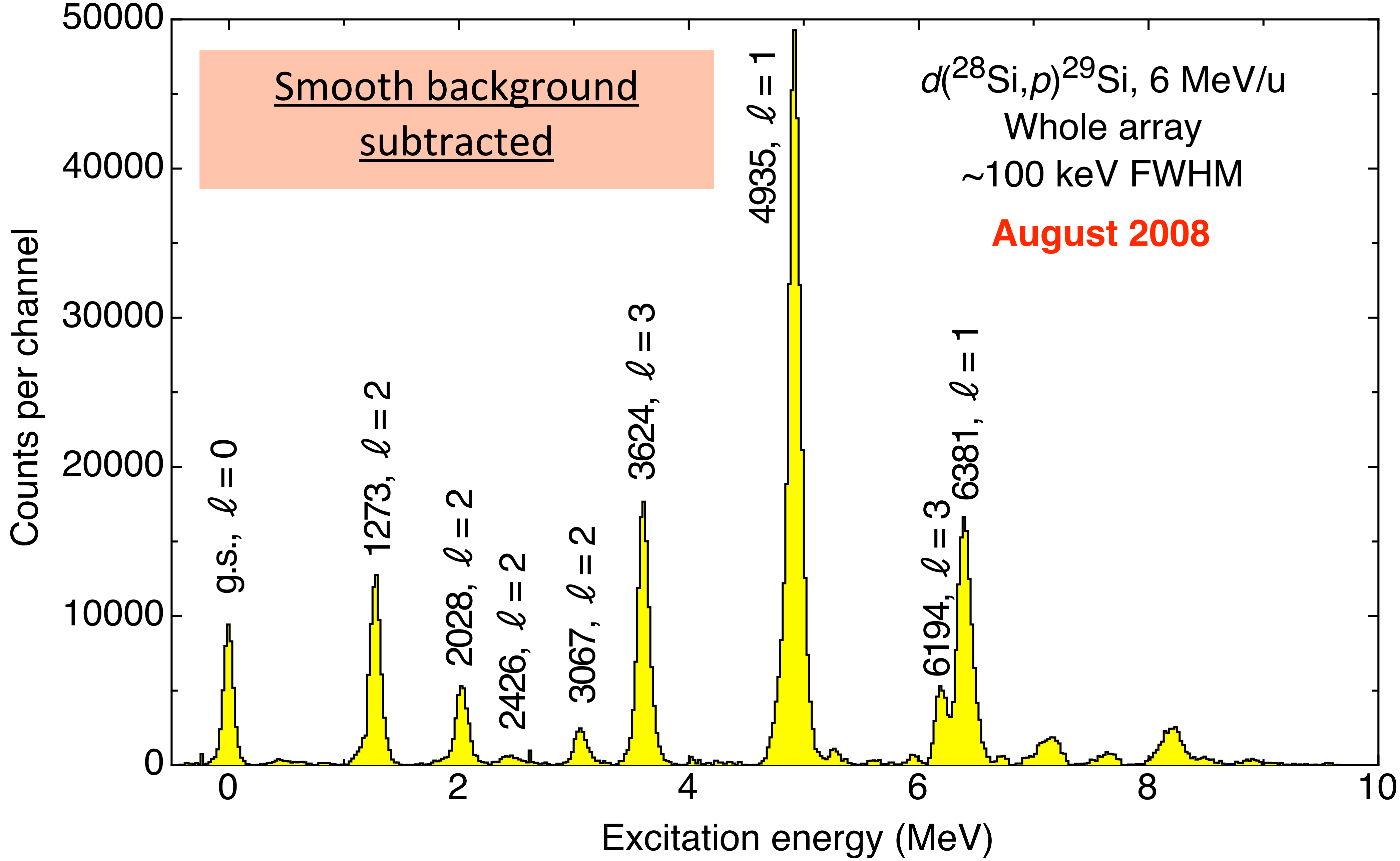
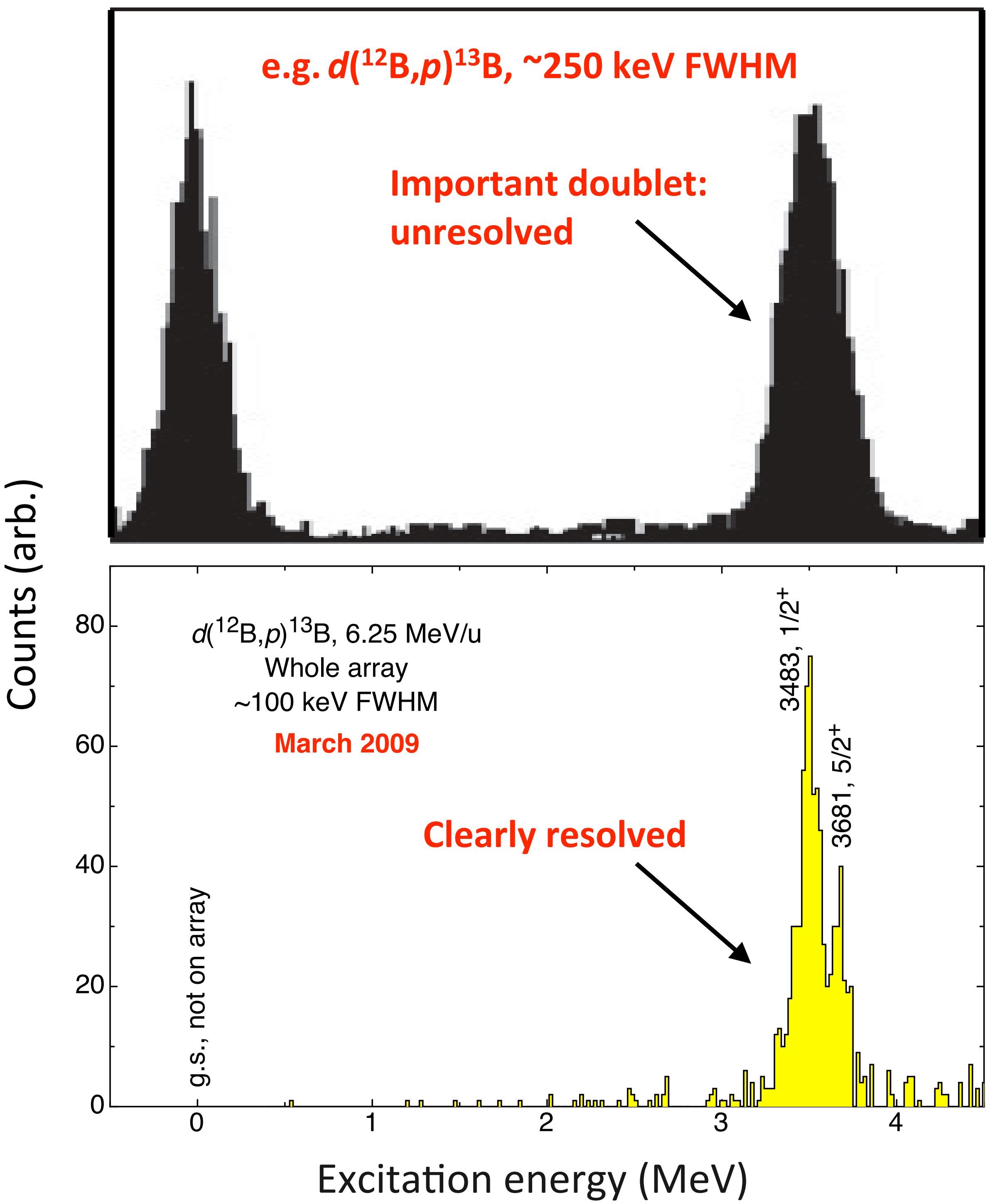
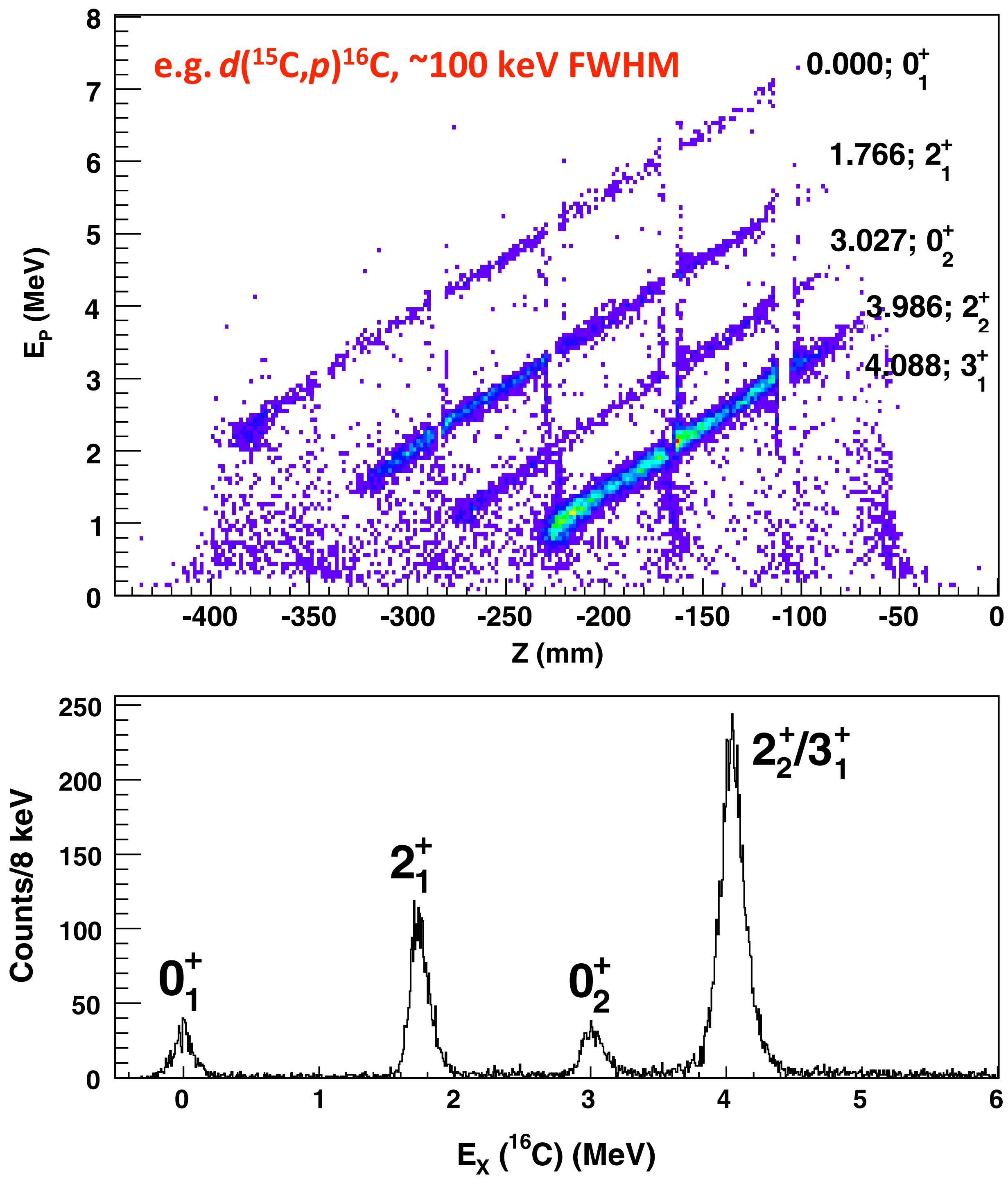


*J .C. Lighthall et al., *Nucl. Instrum. Methods Phys. Res.* ***A662***, *97 (2010)*

Other recent measurements





H. Y. Lee *et al.*, Phys. Rev. C **81**, 015802 (2010)

B. B. Back *et al.*, Phys. Rev. Lett. **104,** 132501 (2010)

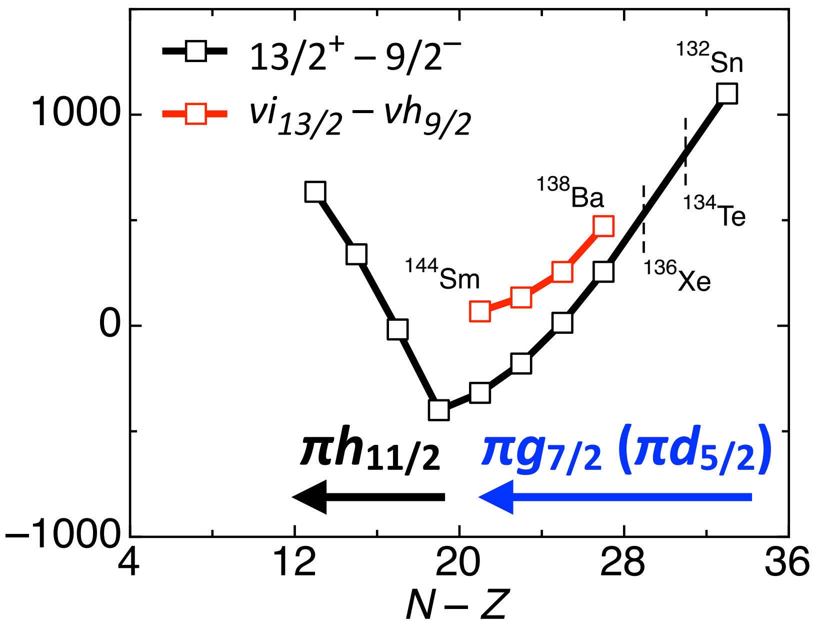
A. H. Wuosmaa *et al.*, Phys. Rev. Lett. **105,** 132501 (2010)

HELIOS with heavy beams

Keen to see how HELIOS performs with beams of similar mass to those around ^{132}Sn – ***in anticipation of CARIBU beams***

We performed these tests with a bit of physics in mind – ***d(^{136}Xe,p) in light of single-particle trends in the N = 82 isotones and d(^{130}Xe,p) as an early exploration of neutron vacancy (related to 0ν2β matrix elements)***

BPK *et al*., Phys. Lett. B**658**, 216 (2008)



Z < 64

'Mainly' $\pi g_{7/2}$ filling in the N = 82 cores

REPULSIVE effect with $\nu i_{13/2}$

ATTRACTIVE effect with $\nu h_{9/2}$

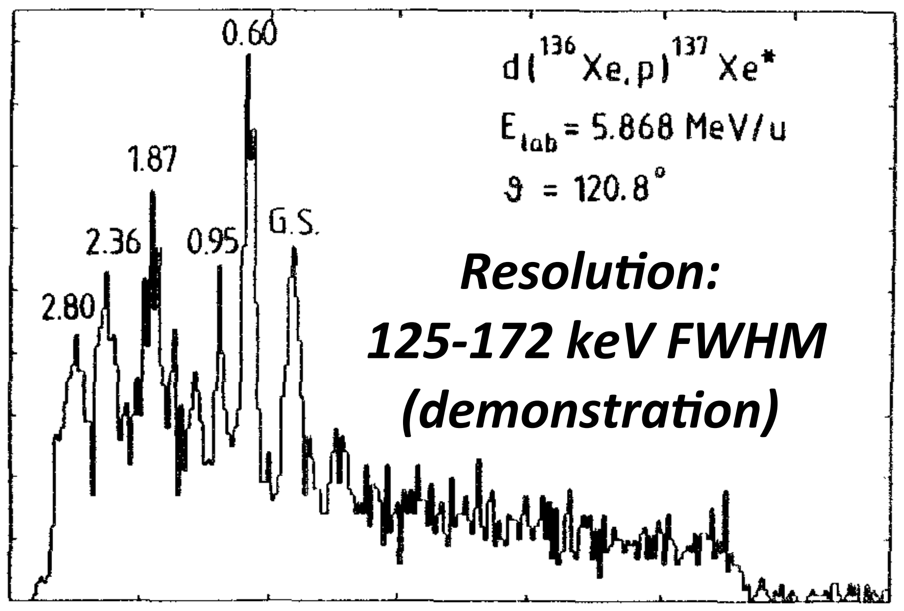
Z > 64

$\pi h_{11/2}$ filling in the N = 82 cores

REPULSIVE effect with $\nu i_{13/2}$

ATTRACTIVE effect with $\nu h_{9/2}$

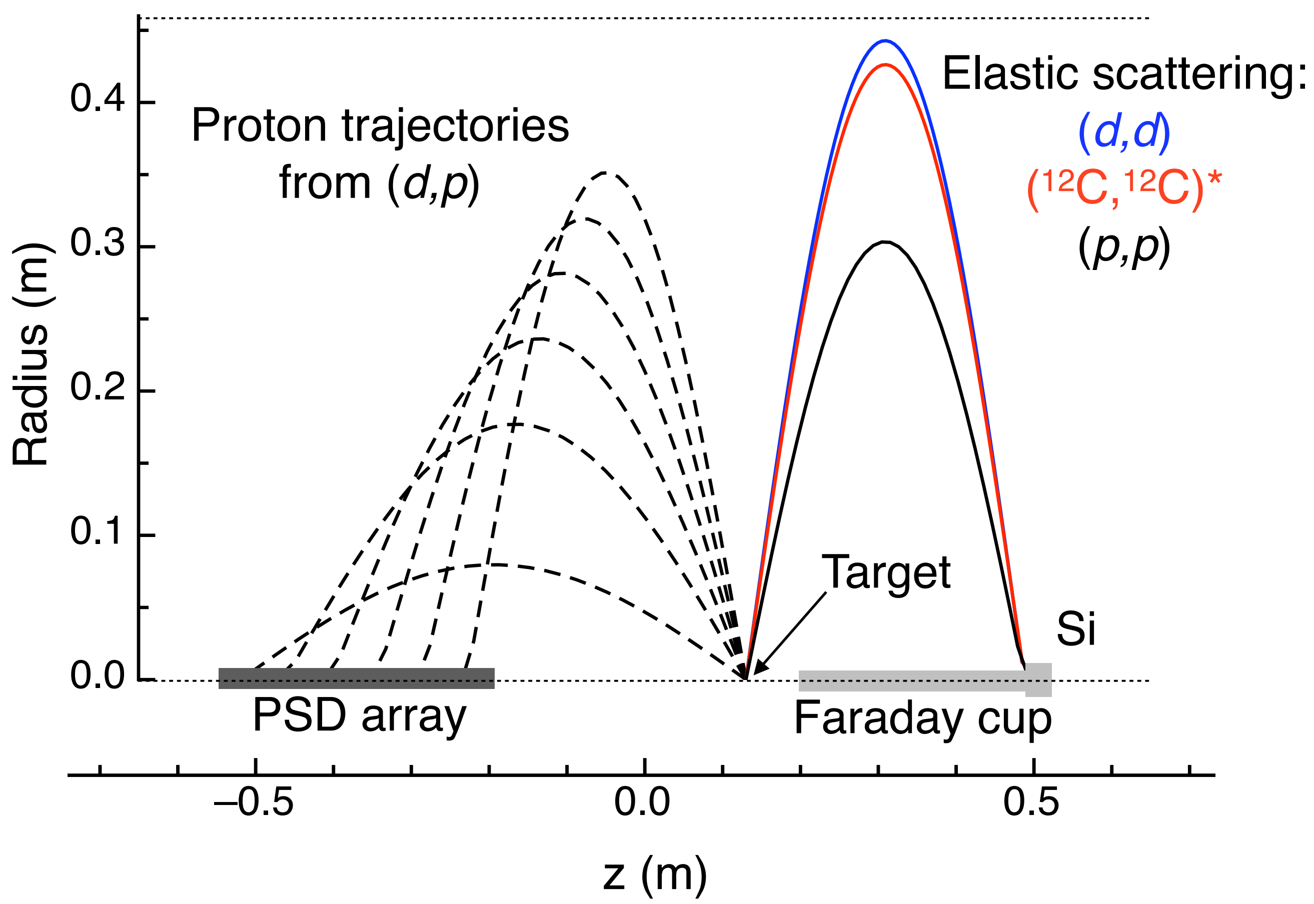
Kraus *et al*., Z. Phys. A**340**, 339 (1991)

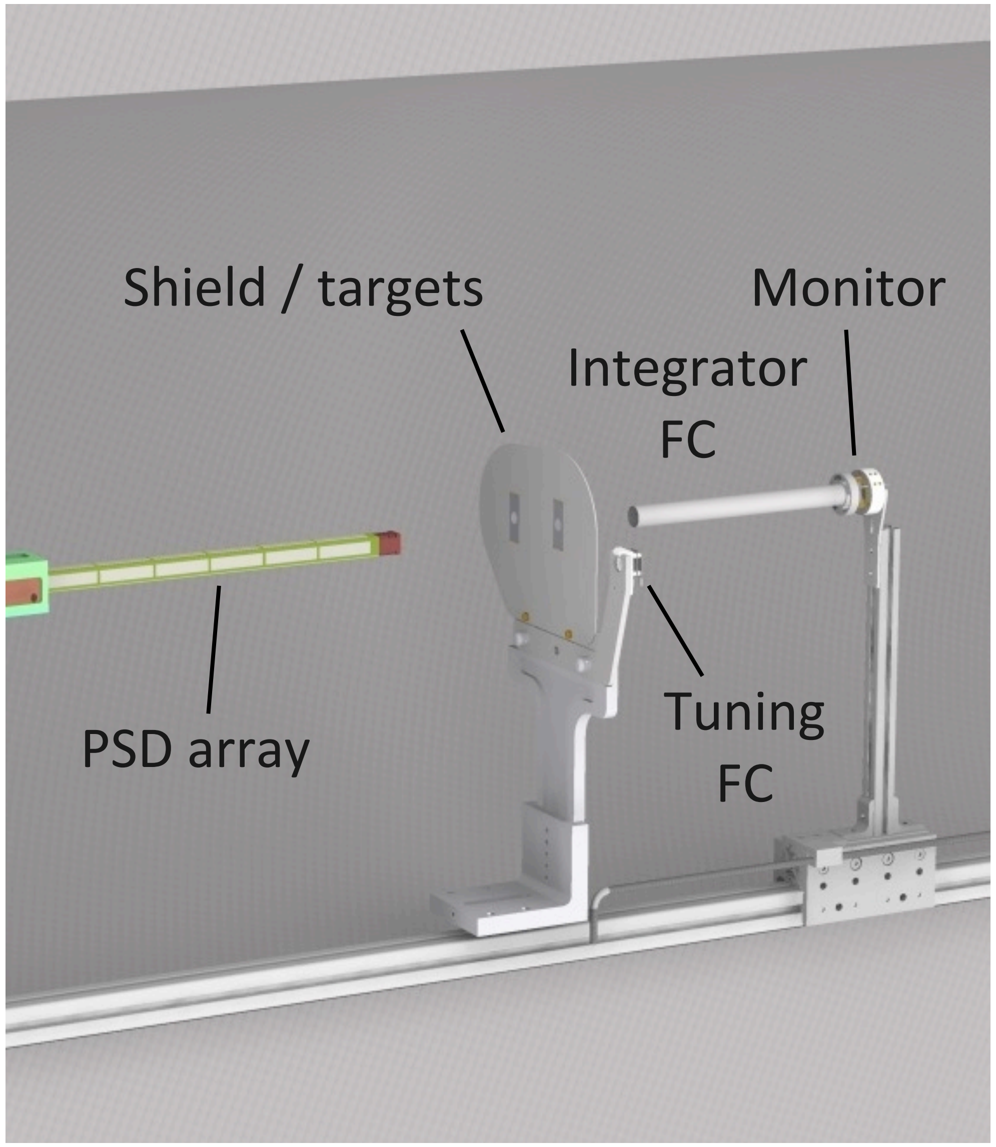


The first exploration of single-neutron transfer in inverse kinematics – GSI, 1991

Absolute cross sections

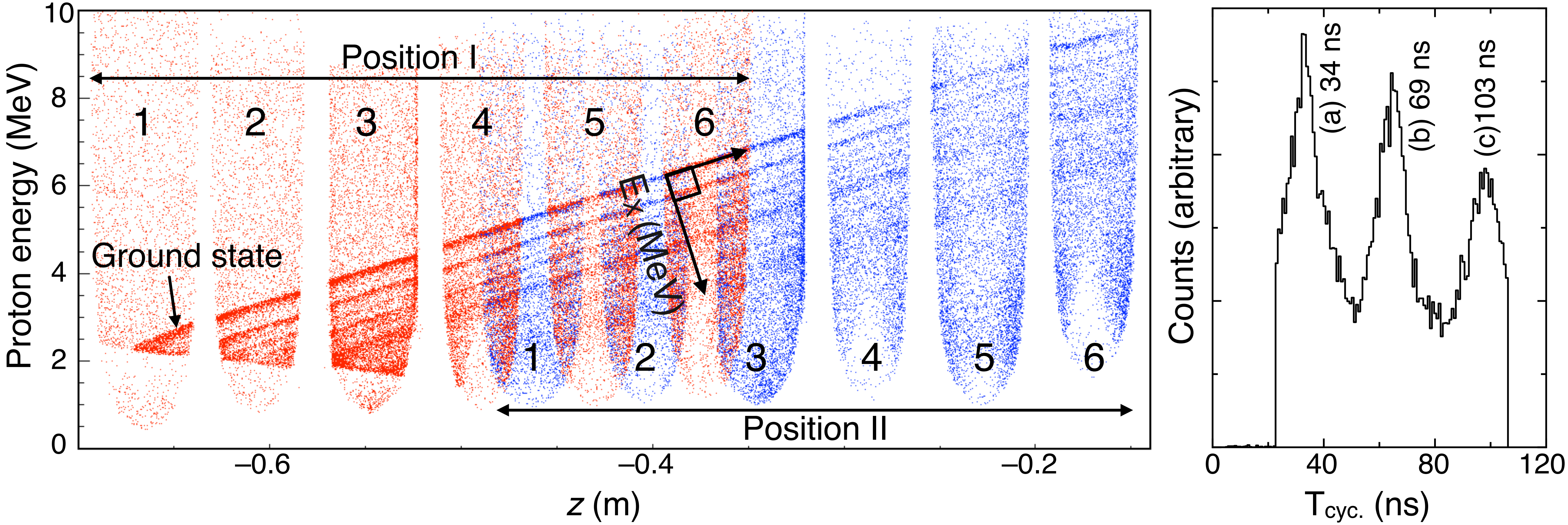
Desirable to measure absolute cross sections, target thickness, and to understand how the target degrades under beam strike. At 5 MeV/u, elastically scattering target species (deuterons, carbon ions) are within a few percent of ***Rutherford scattering*** at angles close to 90° in the lab. frame. This can be used to set an absolute cross-section scale – at 10 MeV/u the same set up (though not Rutherford) can be used to monitor the beam luminosity and target degradation.



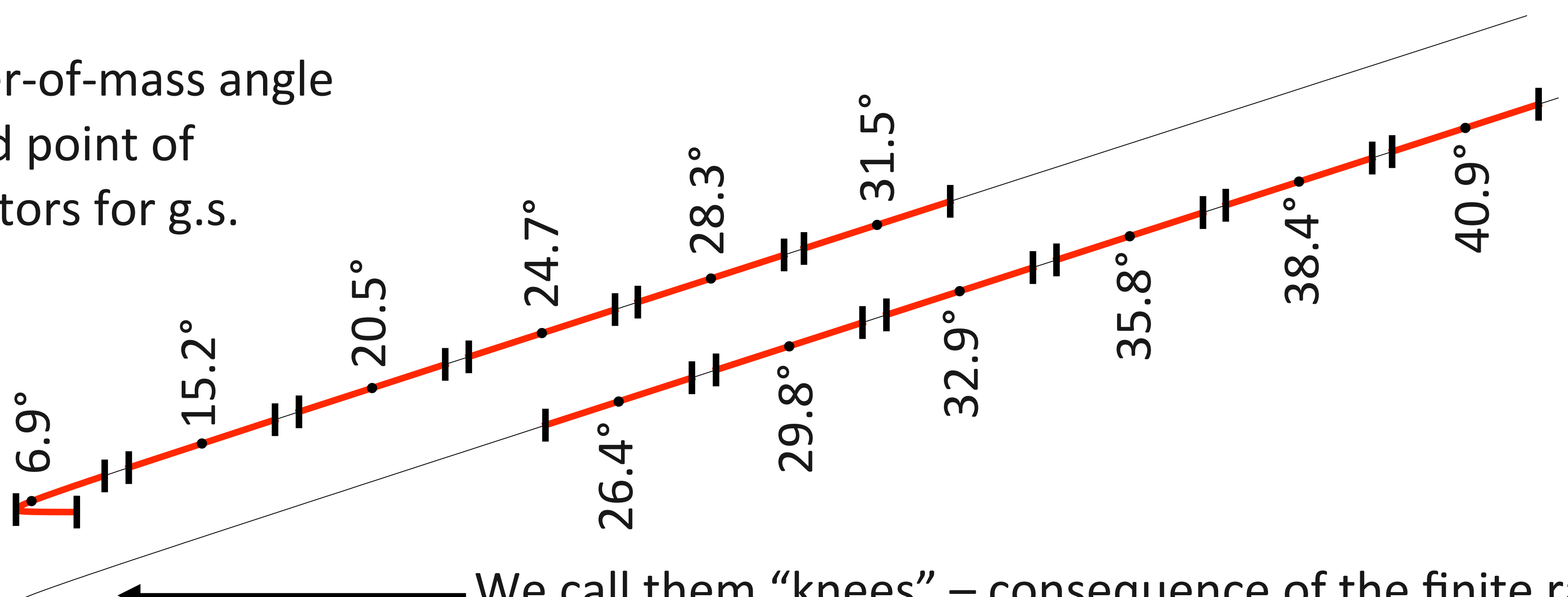


What we measure

As measured: ^{136}Xe(d,p) at 10 MeV/u with a 2-T field



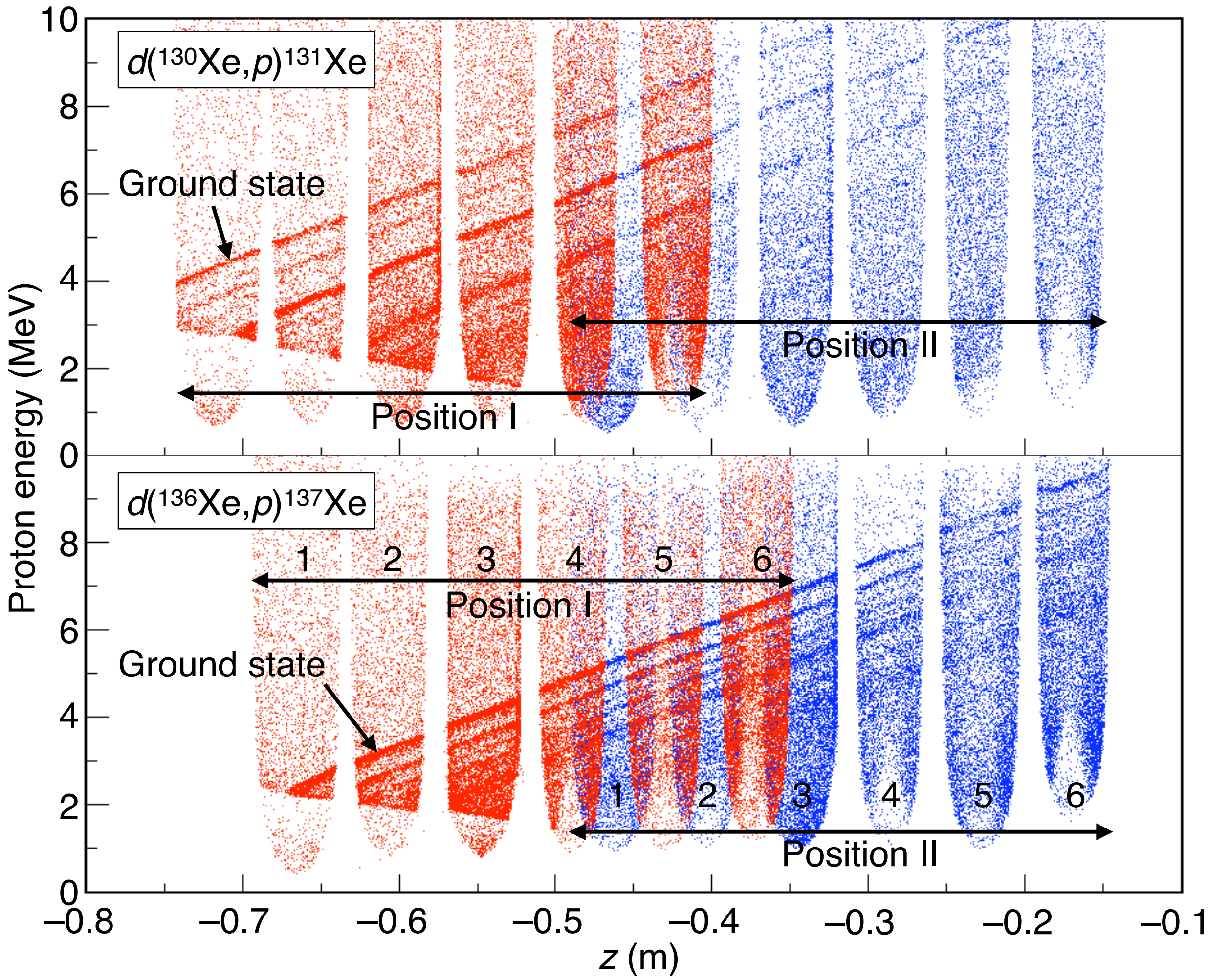
Center-of-mass angle at mid point of detectors for g.s.

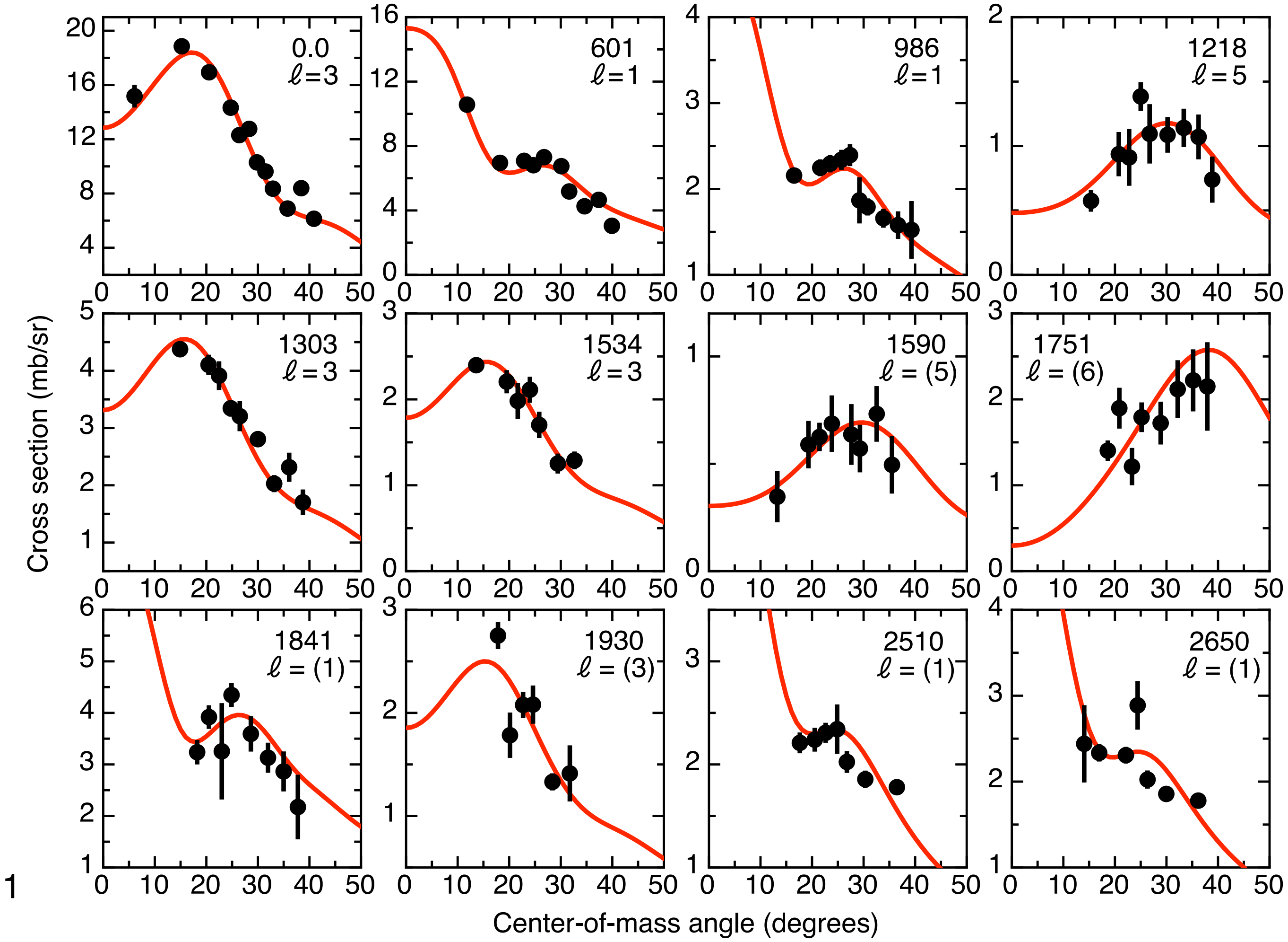


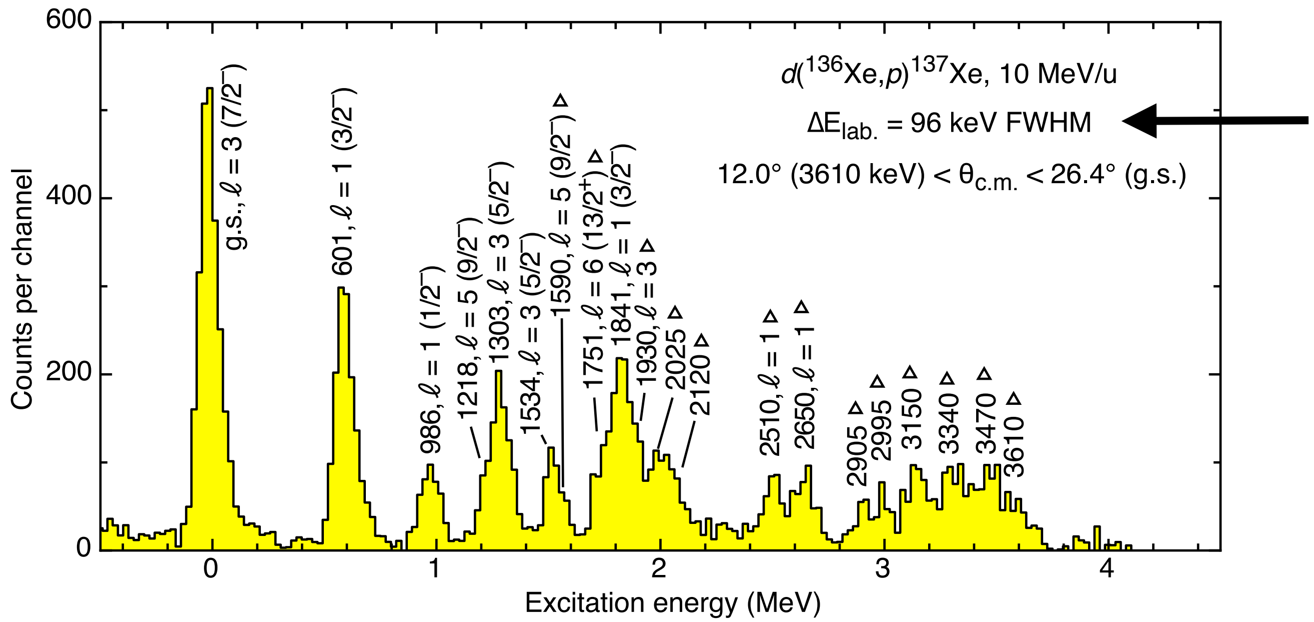
Example signal-RF spectrum from Position I, detector 6. Here we observe protons executing 1, 2, and 3 complete orbits.

We call them “knees” – consequence of the finite radius of the detector

Detailed spectroscopy of ^{137}Xe (^{131}Xe)







Over a factor of 3 improvement compared to other approaches. Allowed for a detailed spectroscopic analysis, such as angular distributions for 12 states, including 9/2⁻ states and the lowest lying 13/2⁺ state.

Significant addition to prior knowledge of ^{137}Xe.

Systematic: cross sections ±15%
Relative spectroscopic factors ±15%

Previous work

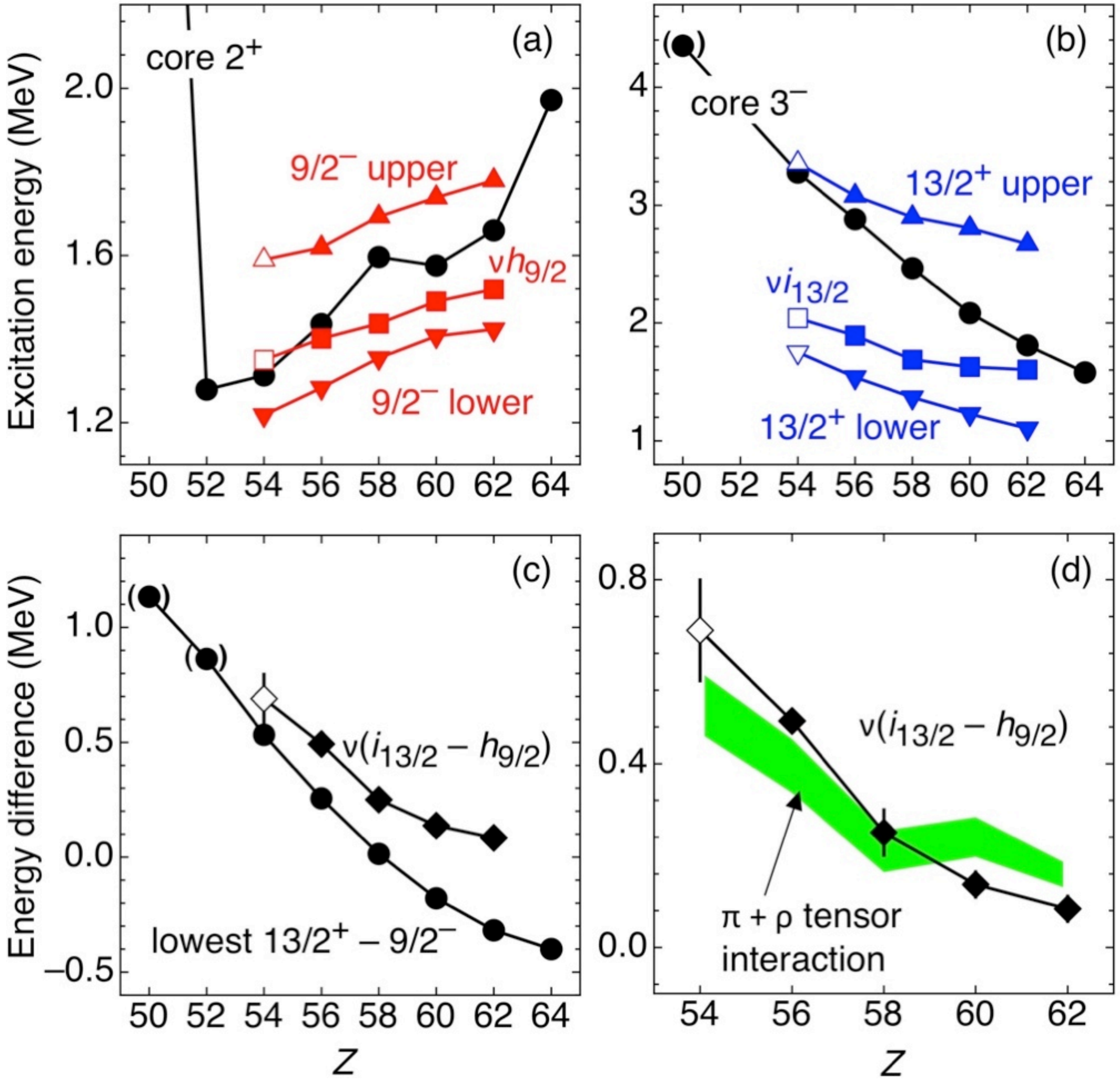
E (keV)	*ℓ*	J^{π}	σ(θ) (mb/sr)	C^2S	C^2S (1)	C^2S (2)	C^2S (3)
0.0	3	$7/2^-$	18.8, 15.2°	1.00	0.70	0.58	0.73
601	1	$3/2^-$	10.6 (11.8°)	0.55	0.41	–	0.40
986	1	$1/2^-,3/2^-$	2.2 (16.5°)	0.37	0.13	–	0.27
1218	5	$9/2^-$	1.1 (33.3°)	0.46	–	–	–
1303	3	$5/2^-$	4.4 (14.9°)	0.23	–	–	–
1534	3	$5/2^-,7/2^-$	2.2 (19.2°)	0.13	–	–	–
1590*	(5)	$9/2^-$	0.7 (32.5°)	0.25	–	–	–
1751	(6)	$13/2^+$	2.2 (37.9°)	0.89	–	–	–
1841	(1)	$3/2^-$	3.9 (24.9°)	0.31	–	0.30	0.18
1930*	(3)	$5/2^-,7/2^-$	2.8 (17.8°)	0.11	–	–	–
2025*	(1,3)?	–	2.1 (19.7°)	0.22 / 0.16	–	–	–
2120*	(1,3)?	–	0.9 (19.4°)	0.10 / 0.06	–	–	–
2510*	(1)	$1/2^-,3/2^-$	2.0 (22.6°)	0.20	–	0.13	0.15
2650*	(1)	$1/2^-,3/2^-$	2.1 (22.1°)	0.17	–	–	–
~2900*	(1,3)?	–	0.8 (15.6°)	0.08 / 0.05	–	–	–
~2990*	(1,3)?	–	1.4 (21.1°)	0.17 / 0.05	–	–	–
~3150*	–	–	0.3 (35.1°)	0.12**	–	–	–
~3310*	–	–	0.3 (34.7°)	0.12**		–	–
~3470*	–	–	0.5 (34.4°)	0.18**	–	–	–
~3610*	–	–	0.4 (34.1°)	0.14**	–	–	–

*Determined in this work
**If assumed $13/2^+$

(1) G. Kraus *et al.*, Z. Phys. A340, 340 (1991)
(2) E. J. Schneid and B. Rosner, Phys. Rev. **148**, 1241 (1966)
(3) P. A. Moore *et al.*, Phys. Rev. **175**, 1516 (1968)

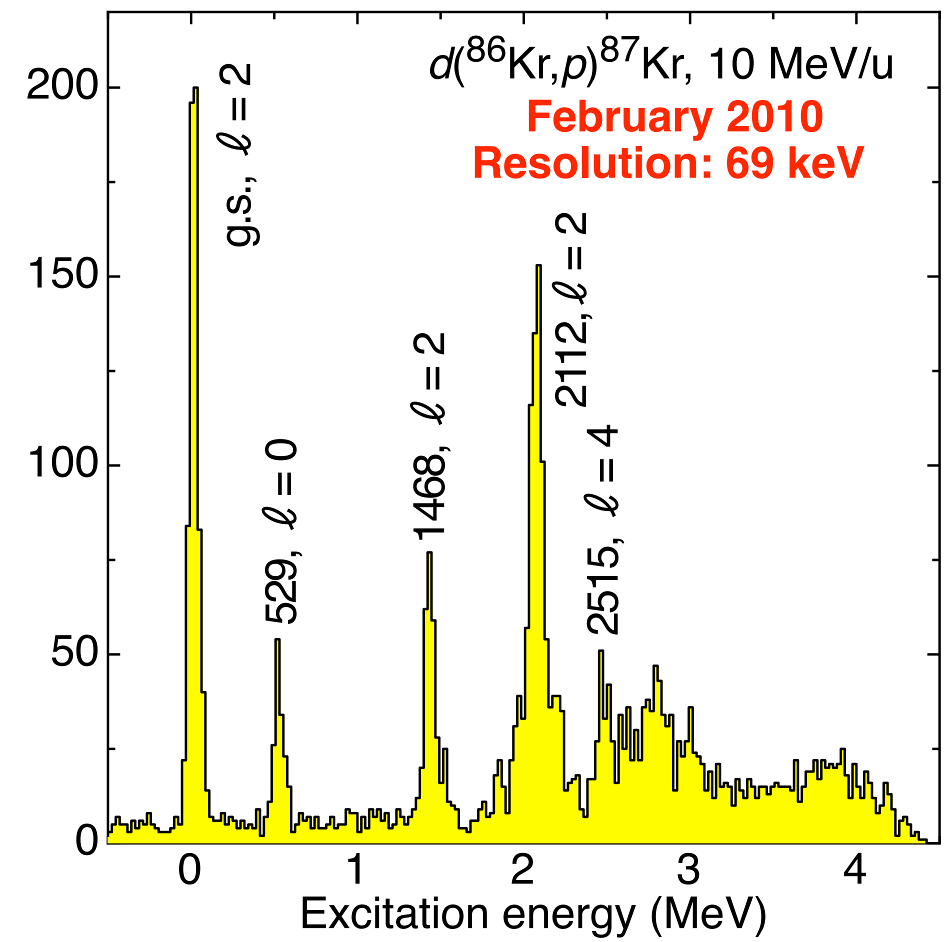
Latest work ...

Extends our knowledge of single-particle trends outside *N* = 82. With CARIBU, measurements with ^{134}Te and ^{132}Sn soon.



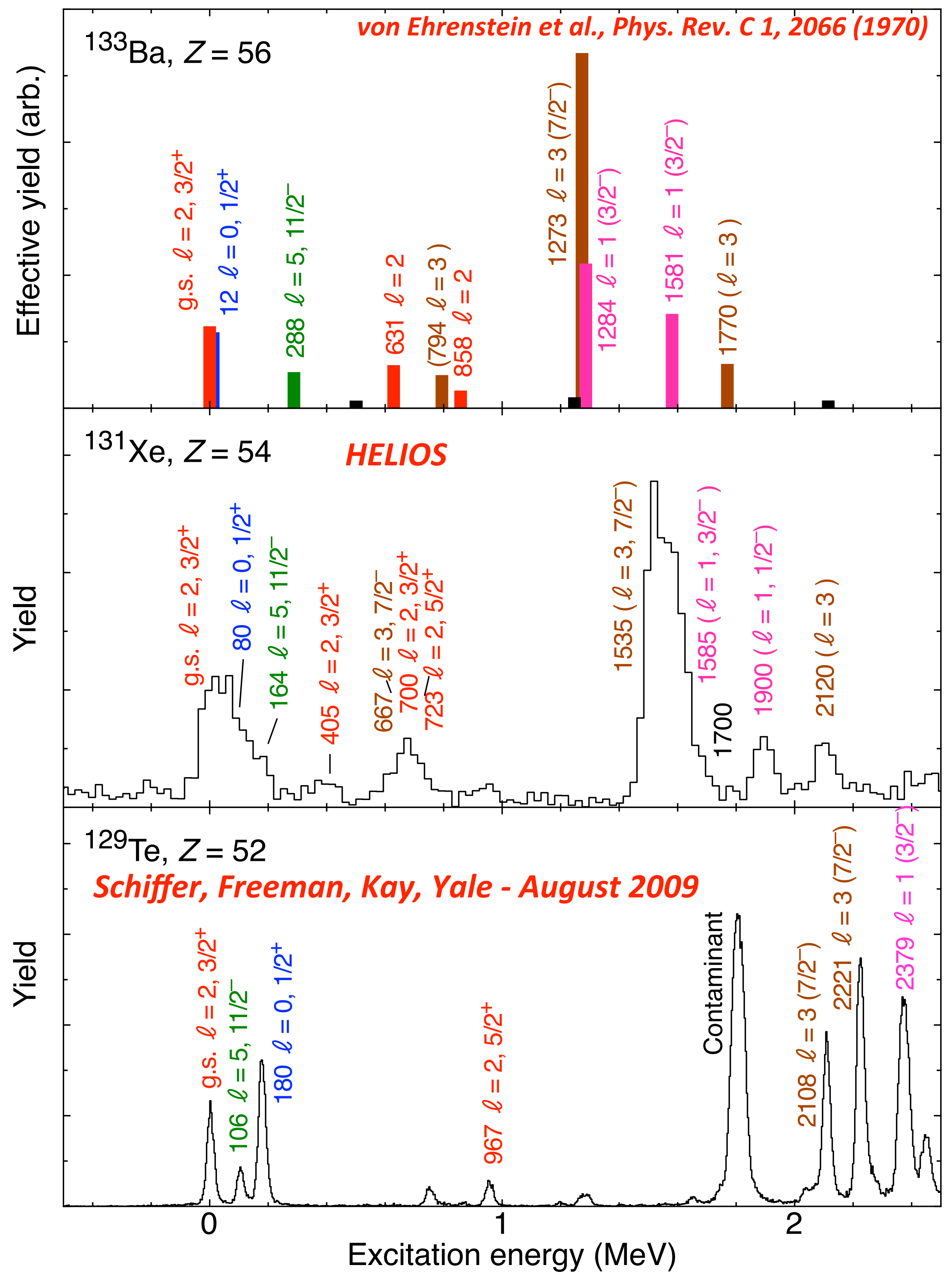
BPK, preliminary. Manuscript in preparation.

Achieved a resolution of ~70 keV in a recent measurement with a stable, lower *Z* beam ... [Part of thesis work by ***D. K. Sharp***, Manchester]



Part of an ongoing exploration of s.p. trends outside *N* = 50. Limited to the stable targets (beams) at Argonne (***in this region***)

d(^{130}Xe,p) and the N = 76 isotones



Radioactive beams

CARIBU opens up an interesting region to study many characteristics of nuclei. HELIOS will be an excellent tool to perform measurements with these beams.

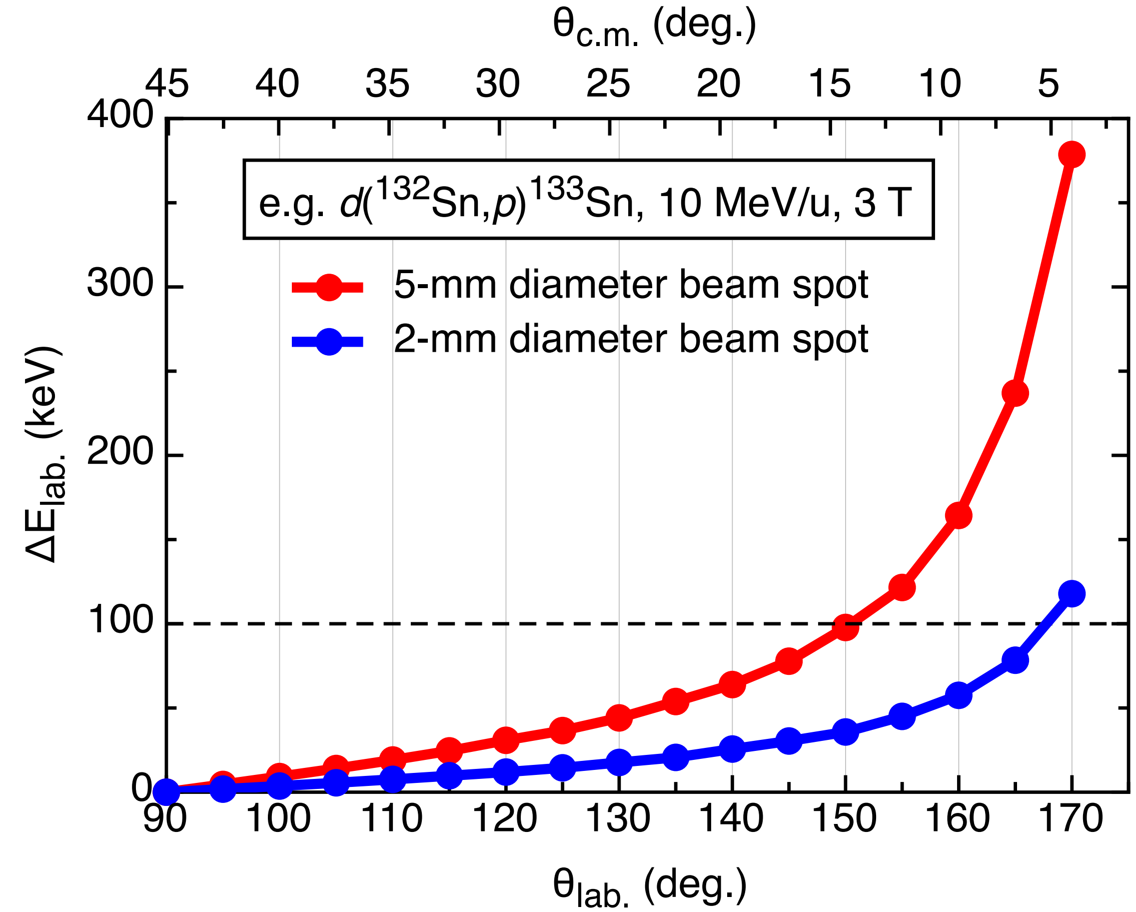
Clear we need to go further – facilities such a SPIRAL2 and HIE-ISOLDE offer a ***wider range*** of beams and potentially ***orders of magnitude*** more intensity.

So what are the beam and infrastructure requirements for a HELIOS-like device?

Beam and infrastructure requirements, I

Q-value resolution set by longitudinal emittance. A 2 MeV energy spread for a 1 GeV mass 100 beam implies 20 keV contribution to q-value resolution.

Beam spot of less than 5 mm contributes less than ~100 keV at angles of interest.



Current Si array has an acceptance of ~10 π.mm.mrad. For the HIE-LINAC* a normalised transverse emittance of <0.3 π.mm.mrad with a βγ~0.15 for 10 MeV/u beams implies an actual beam emittance of ~2 π.mm.mrad. More than sufficient.

Beam purity – with adequate recoil detection (technique depends on beam), impure beams can be tolerated.

*http://hie-isolde.web.cern.ch/hie%2Disolde/Beams_specifications.htm

Beam and infrastructure requirements, II

RF period of the beam ***needs to be ~100 ns***. (At ATLAS it is 82 ns.)

Time resolution of ~1-2 ns can be tolerated (as demonstrated).

(*many other measurements would benefit from a RF structure on the order of 100 ns e.g. in-beam gamma-ray spectroscopy, RDT, ..., isomer tagging, neutron detection TOF, ...*)

	$T_{cyc.}$ (ns)		
Species	1 T	2 T	3 T
p	65.6	32.8	21.9
d	131.2	65.6	43.7 **(=2p)**
t	196.4	98.2	65.6 **(=3p)**
^{3}He	98.2	49.1	32.7 **(=3/2p)**
^{4}He	131.2	65.6	43.7 **(=d,2p)**
^{12}C (6^{+})	131.2	65.6	43.7 **(=d,2p)**

Other:

The current footprint of the HELIOS setup, including space for recoil detectors is ~6.5 × 4 m^2

Helium consumption (at Argonne) is about ***250 litres per month***. Additional losses when powering up and down (~500 litres for a complete cycle).

**http://hie-isolde.web.cern.ch/hie%2Disolde/Beams_specifications.htm*

Future challenges

Build on initial successes:

Reactions with the array in a forward position e.g. (d,^{3}He), (d,t) (***spring 2011***)

Development of a gas-cell target of α and ^{3}He induced reactions (***in progress***)

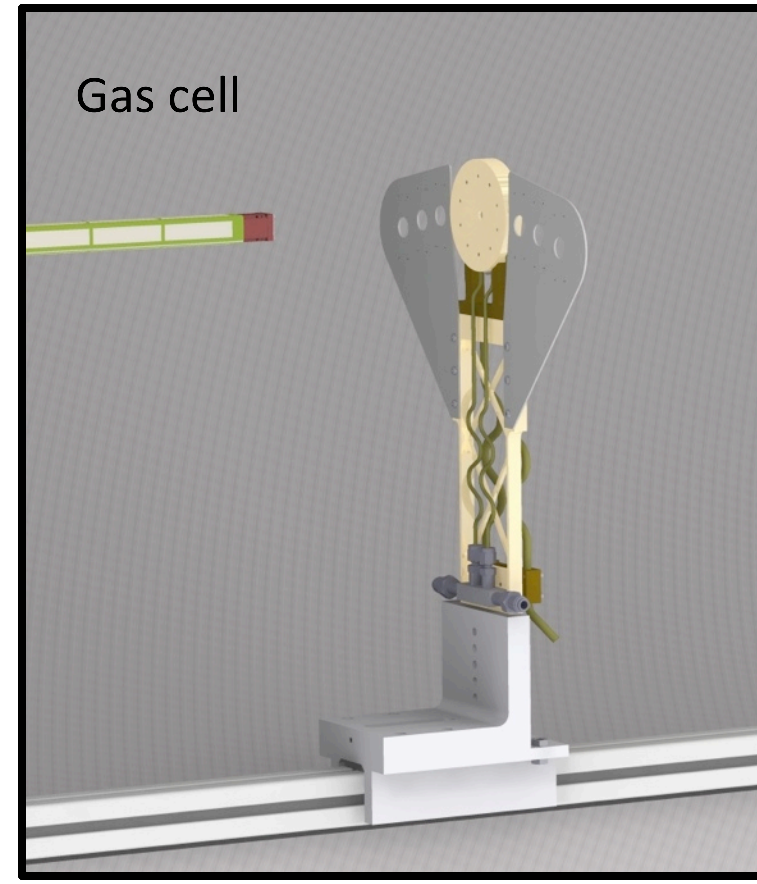
Replace the prototype array with a new, large-acceptance, 6-sided (10-sided) modular position-sensitive Si array (***in progress***)

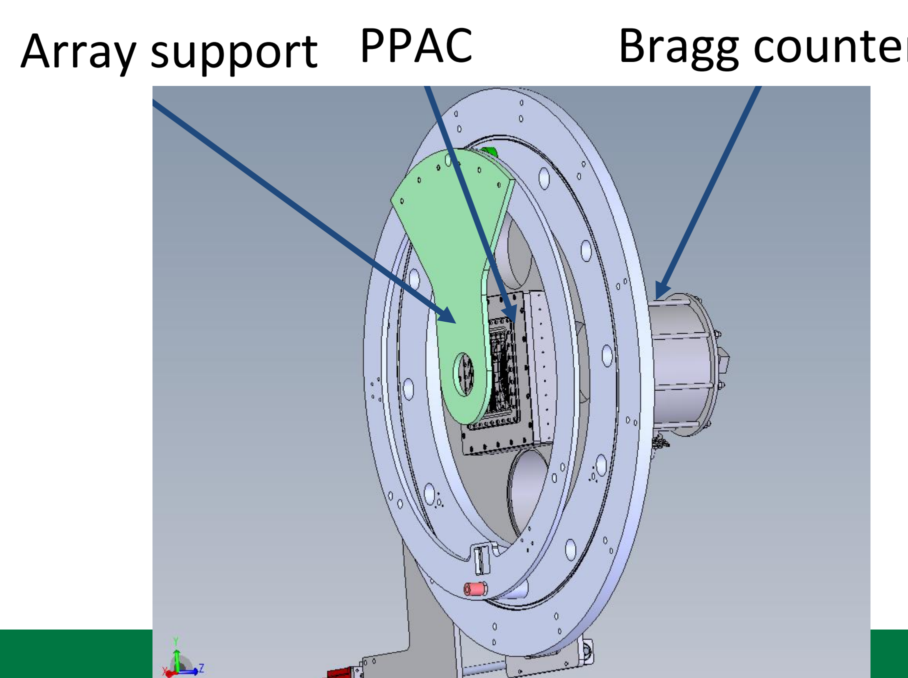
CARIBU beams – ***imminent***

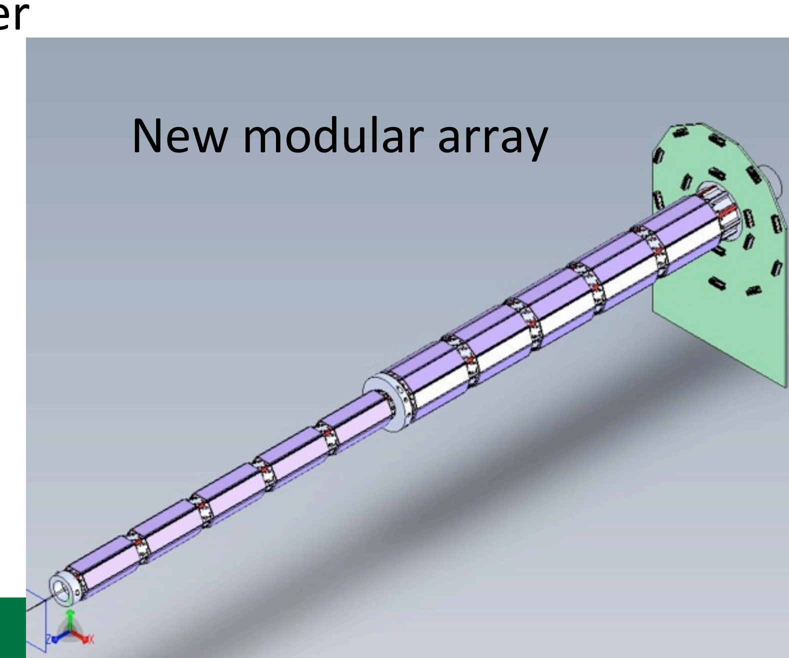
Utilise Manchester-built gas-ionisation chamber for recoil detection

Gamma-ray detection?

... and more ...







Acknowledgements

*The HELIOS collaboration**

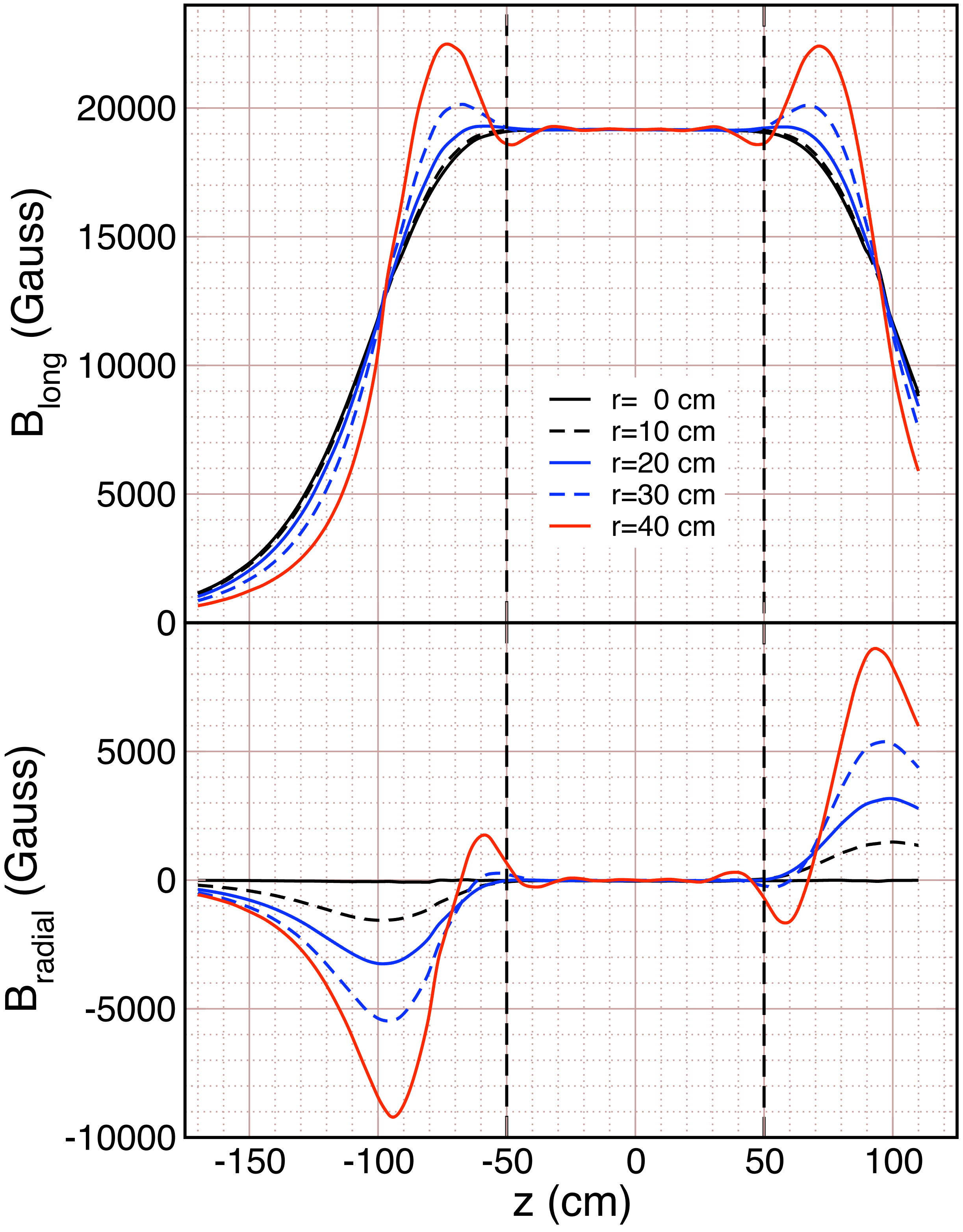
N. Antler[1], B. B. Back[1], S. I. Baker[1], J. A. Clark[1],
C. M. Deibel[1], B. J. DiGiovine[1], S. J. Freeman[2],
N. J. Goodman[3], Z. Grelewicz[1], S. Heimsath[1],
C. R. Hoffman[1], B. P. Kay[1,4], H. Y. Lee[1], C. J. Lister[1],
S. T. Marley[1,3], P. Mueller[1], R. Pardo[1], K. E. Rehm[1],
A. M. Rogers[1], J. Rohrer[1], J P Schiffer[1], D. Shetty[3],
J. Snyder[3], M. Syrion[1], J. C. Lighthall[1,2], A. Vann[1],
J. R. Winkelbauer[1,3], A. Woodward[1], A. H. Wuosmaa[3]

[1]Argonne National Laboratory, USA
[2]University of Manchester, UK
[3]Western Michigan University, USA
[4]University of York, UK

**Many have moved institution since the collaboration was formed*

Spares

HELIOS field map



A 21,240-point field map was measured (J. C. Lighthall, J. Winkelbauer)