Single-particle behaviour towards the "island of inversion" - $^{28,30}Mg(d,p)^{29,31}Mg$ in inverse kinematics

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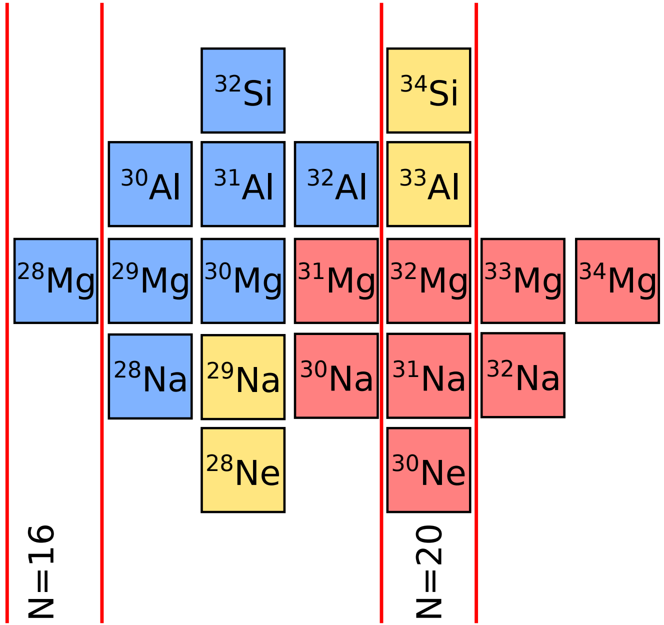
Requested shifts: 33
Beam: ^{28}Mg and ^{30}Mg at 7.5 MeV/u (5.5 MeV/u also possible)
Target: Deuterated polyethylene $(CD_2)_n$
Installation: ISOL Solenoid Spectrometer

INTC meeting, June 29th 2016

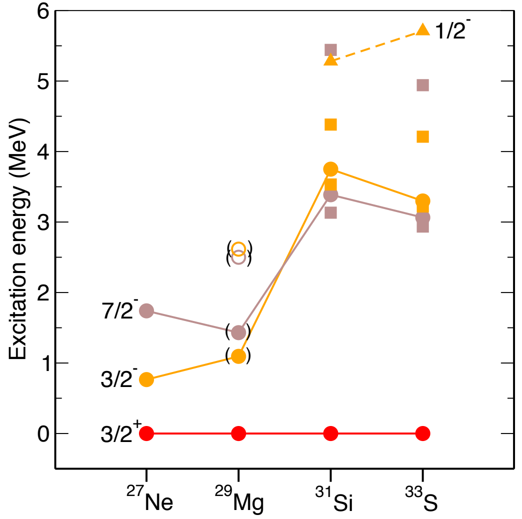
Motivation - Island of inversion

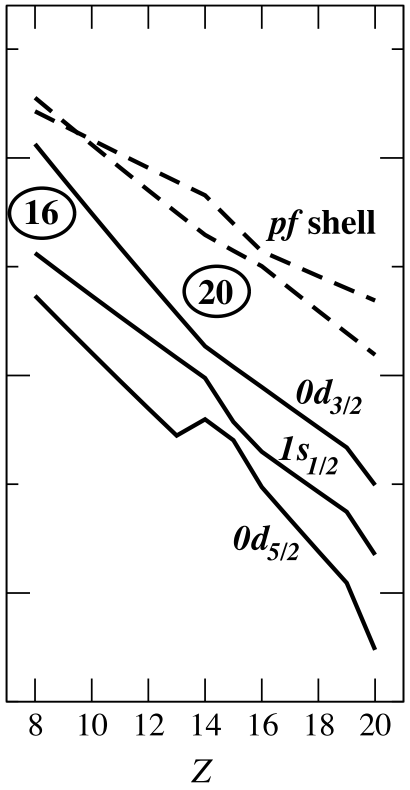
- Ground states and low-lying excitations from intruder configurations have been observed.
- Prevalence of intruder orbitals is indicative of **weakening *N=20* shell closure**.
- In the Ne, Al and Na isotopes there is a **soft transition** to a deformed ground state.
- In Mg isotopes this transition 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 $1d_{3/2}$ and $1f_{7/2}$ and $1f_{7/2}$ and $2p_{3/2}$ which define the $N=20$ and 28 shell gaps.



Motivation - Changing shell structure

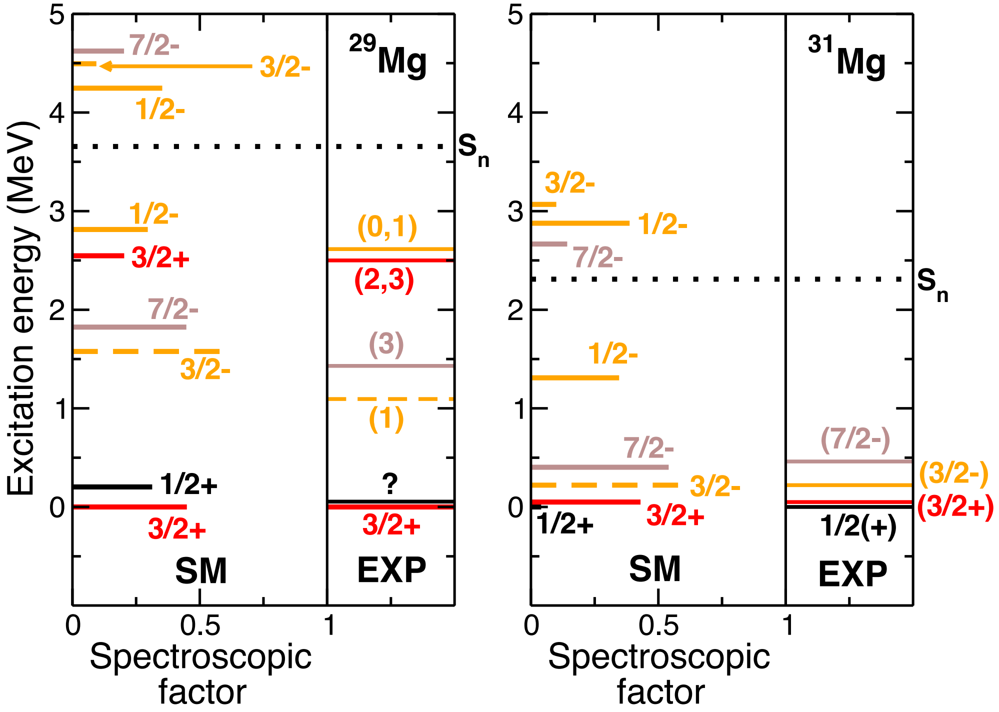
- The island of inversion is indicative of a **weakening shell gap.**
- In the oxygen isotopes the *N=20* shell gap has been shown to disappear with **the emergence of an *N=16*** shell gap in ^{24}O.
- Again measurement of the single-particle states involved in this evolution of single-particle structure will provide valuable comparison with theory.
- ^{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)

Shell model calculations



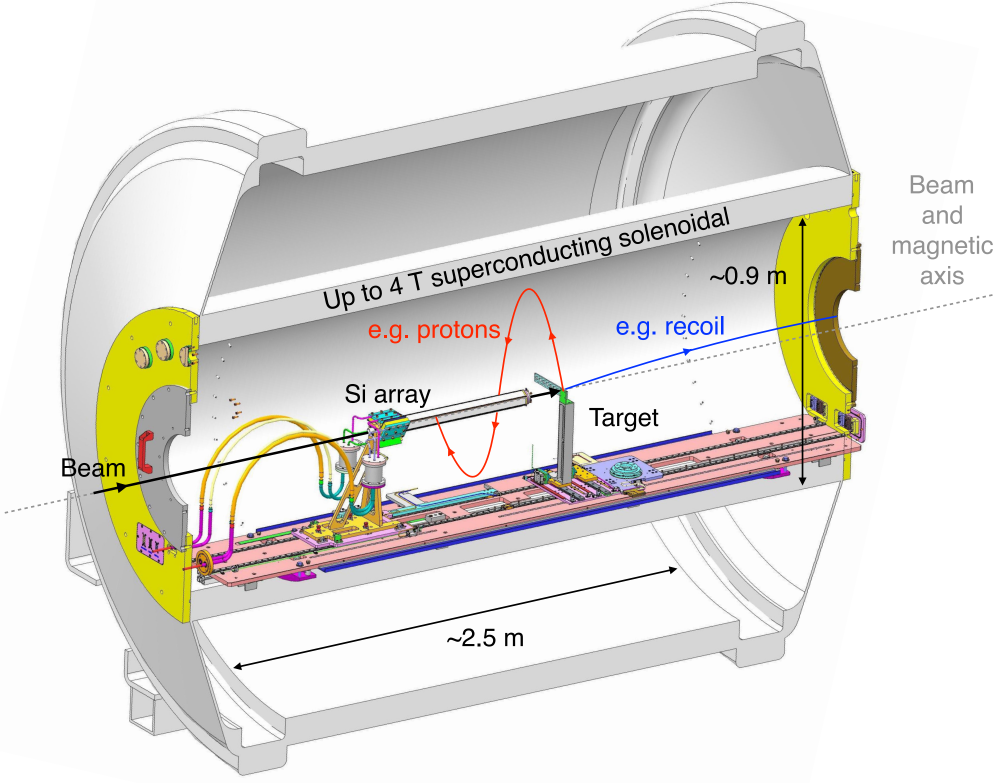
- Calculations using the **SDPF-MU** interaction with **0p-0h** excitations only for the positive-parity states.
- **1p-1h** excitations for the negative-parity states.
- Are **higher order excitations** (2p-2h, 3p-3h) needed to describe the observed spectra?
- At what point are they needed?
- Observation of **previously unobserved** and unbound 1/2- states will provide further important quantities for comparison with SM.

Proposed measurements

Propose measurement of ^{28}Mg and ^{30}Mg(d,p) reactions at 7.5 MeV/u using the ISOL Solenoid Spectrometer (ISS)

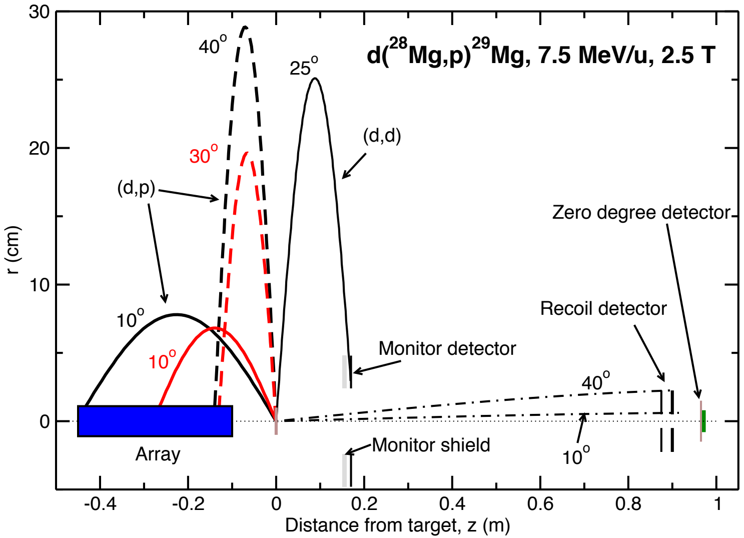
- States of interest are intruder states from above the valence shell.
- Neutron-adding reactions ideal probe for studying single-particle properties of these states.
- Complement knock-out data which probe occupied states.
- Generally perform reactions at ~5-10MeV/u to maximize direct reaction cross section.
- ^{28}Mg – no published data, ^{30}Mg was an early TREX experiment, suffered from low statistics and gamma-ray detection efficiency due to long-lived states.
- Challenges in inverse kinematics due to kinematic compression for fixed angle measurements. Solution proposed here is use a solenoid.

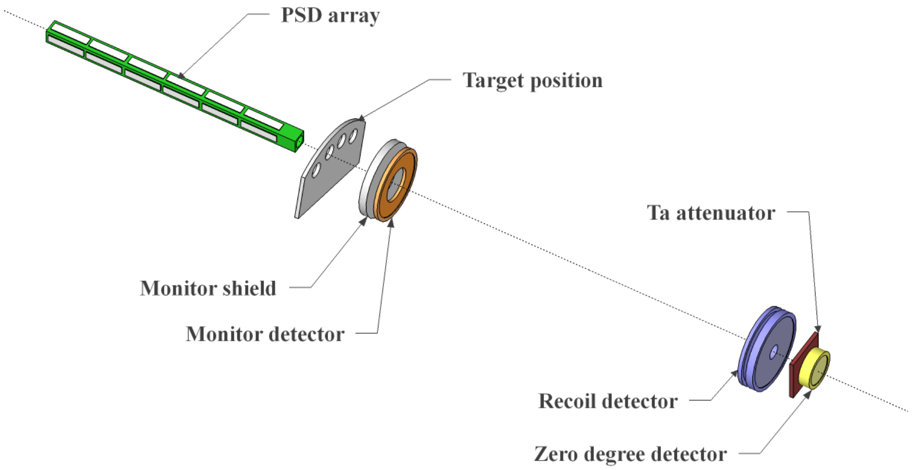
ISOL Solenoid Spectrometer



- 4T superconducting former MRI magnet. To be installed on 2nd beamline in ISOLDE hall.
- Same principles as **successfully implemented at ANL in HELIOS.**
- Does not suffer from **any kinematic compression**.
- **~75 keV** Q-value resolution achieved for charged particles.
- Does not require coincident γ-ray detection **- not affected by lifetime of states.**

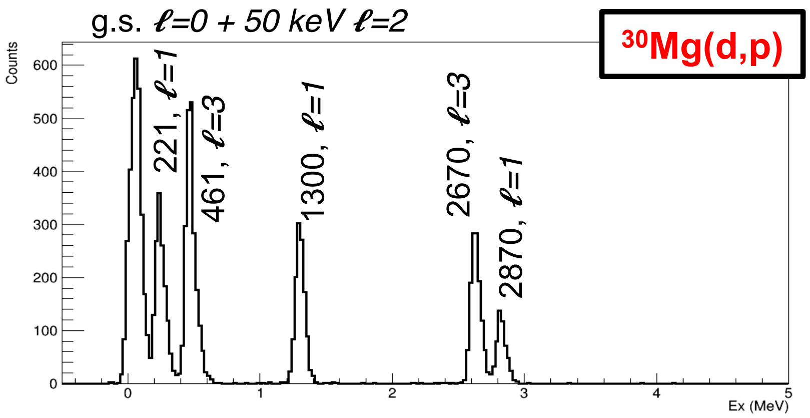
Experimental set up

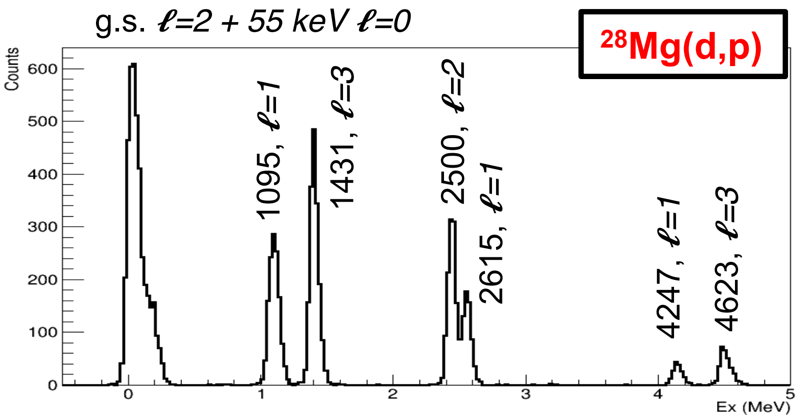


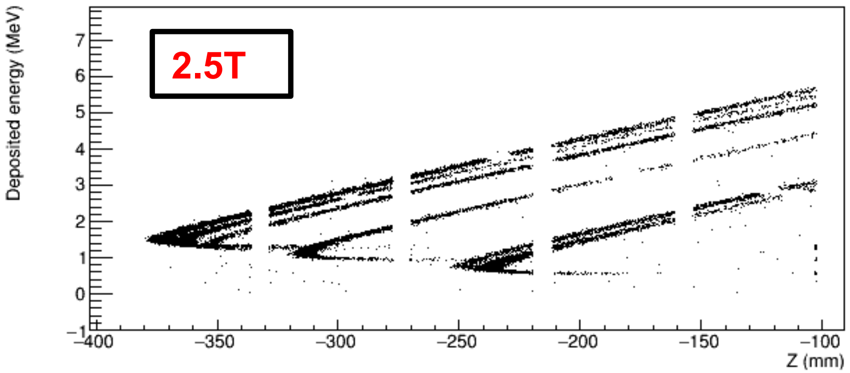


- **Monitor detector** to monitor target thickness.
- **ΔE-E recoil detector** (annular silicon) used to remove beam contamination.
- **Zero-degree detector** to ascertain degree of contamination and monitor beam intensity.
- Target ladder can hold **multiple CD_2 targets**.

Solenoid spectrometer simulations







Expected resolution ~**80 keV** assuming:

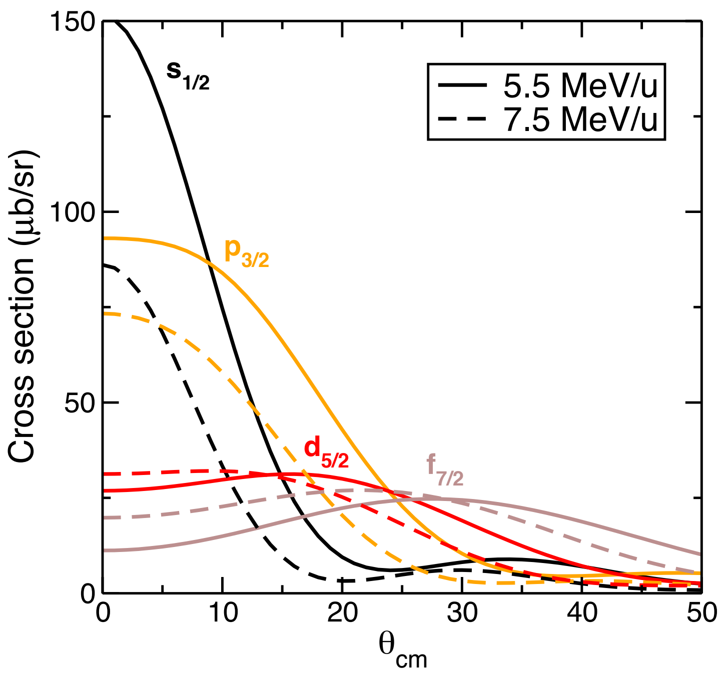
- **40 keV intrinsic detector resolution**
- **100 µg/cm^2** CD_2 targets
- **HIE-ISOLDE beam properties**. (2.3mm beam spot, divergence = 1.8 mrad, ΔE = 0.26%)
- **ANL array** geometry.
- Comparable **to achieved resolution** at ANL.

Angular distributions – choice of beam energy

Generally aim to measure transfer reactions at **5-10MeV/u** to maximise direct reaction contribution.

7.5 MeV/u chosen as a trade off between **high cross sections** and **angular coverage** of finite silicon array.

These measurements **could run at 5.5 MeV/u** but with reduced angular coverage. This affects the higher energy states proportionately more.



Comments on contamination

- **^{28}Mg – 50% ^{28}Al** contamination. **^{30}Mg – 10% ^{30}Al** contamination.

- Recoil detection used to select reaction of interest so **contamination levels are not limiting for this measurement**. Majority of scattered beam passes through center of recoil detector.

- For ^{28}Mg increased rate due to Al contamination is within limit for recoil detection. Recoil detectors have been used with beams of >10^7 at ANL within this limit. Total expected beam with 50% contamination is ~10^6 giving expected recoil rate of 3kHz.

- Kinematics of Al(d,p) very different to Mg(d,p) – only states above 6 MeV incident on array in region of interest.

- **Reduction in ^{28}Al is not critical to measurement** – but reduced rate without loss of Mg intensity would always be welcome. Release characteristics can be used to reduce ^{28}Al.

Summary of request

- Request a total of **33 shifts**.

- **9 shifts** for ^{28}Mg(d,p) at 7.5 MeV/u. Assuming 100ug/cm^2 targets and 6x10^5 expect ~800-1500 counts a day in the whole array for a state with S=1. Coverage is 50% in azimuthal angle and 85% in theta angle. Target is <5% statistical error on absolute cross section.

- **21 shifts** for ^{30}Mg(d,p) at 7.5 MeV/u. Assuming 6x10^4 expect ~80-150 counts a day in the whole array for a state with S=1. Target is <10% statistical error on absolute cross section.

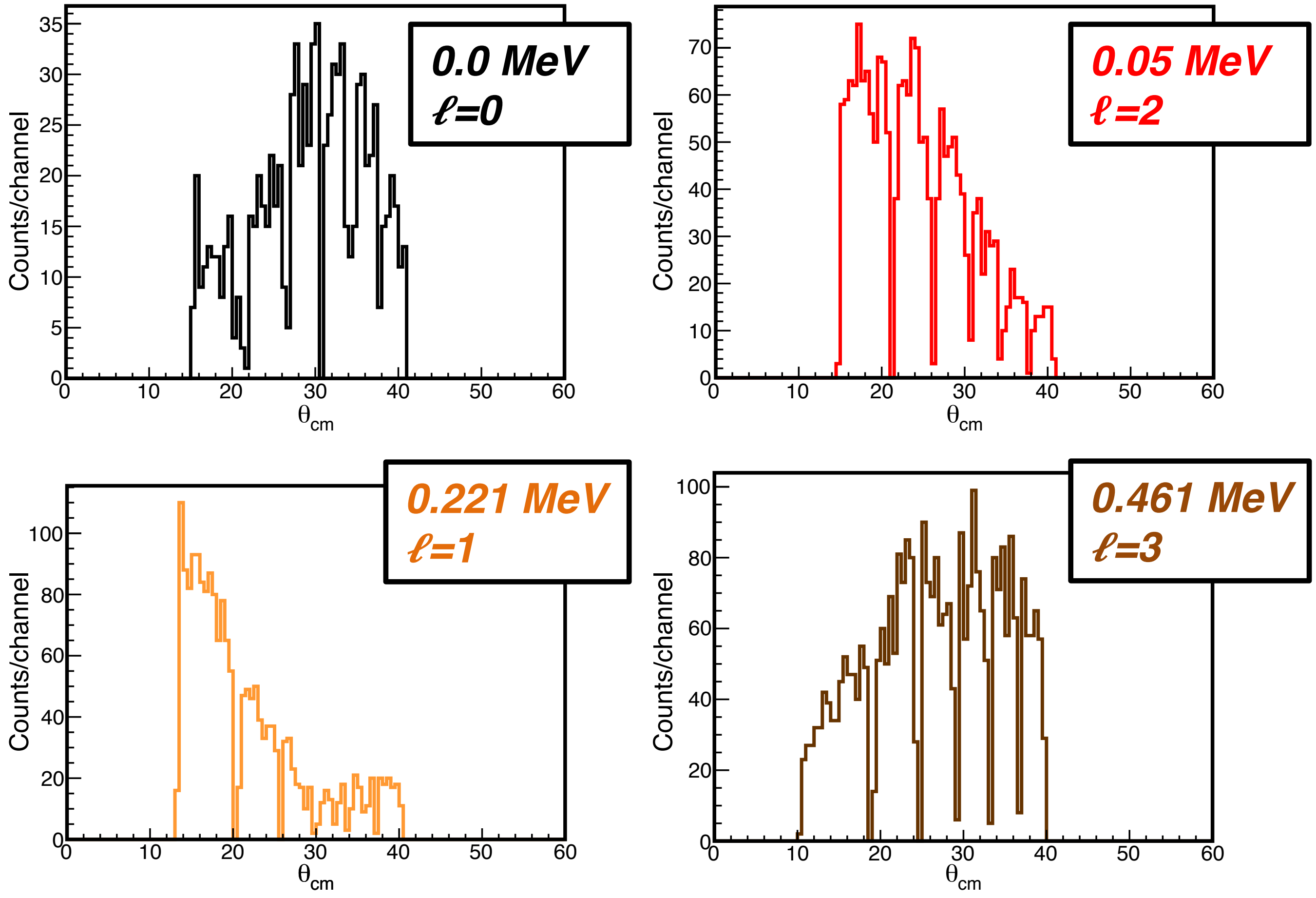
- **3 shifts** for optimizing tune of RIBs in to ISS and change of beam between reactions.

- Beams delivered to **ISOL Solenoid Spectrometer**.

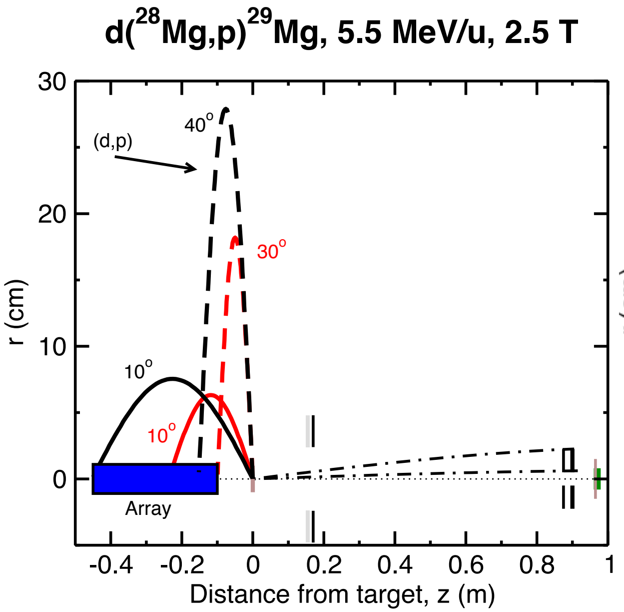
- Experiment could be performed at 5.5 MeV/u if necessary.

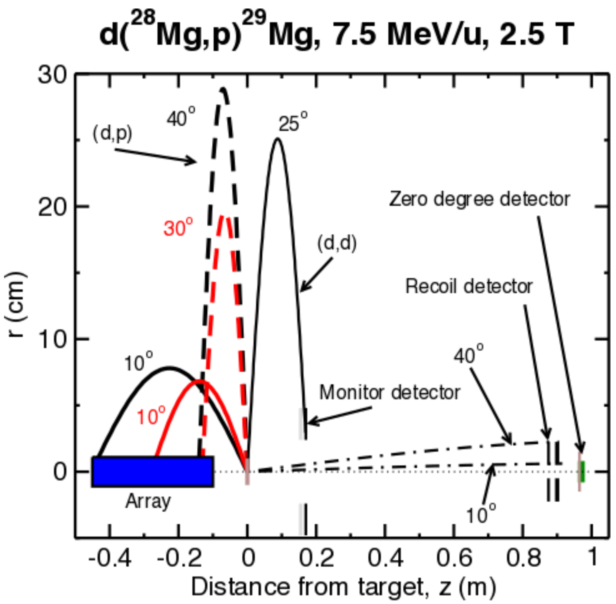
Simulated distributions

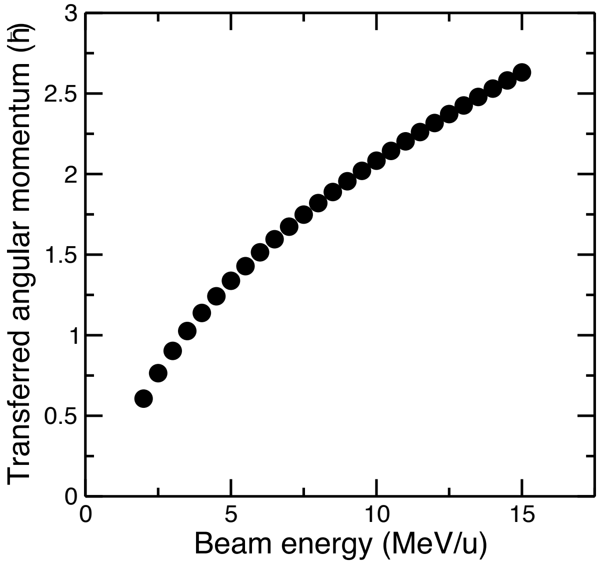
$^{30}Mg(d,p)$



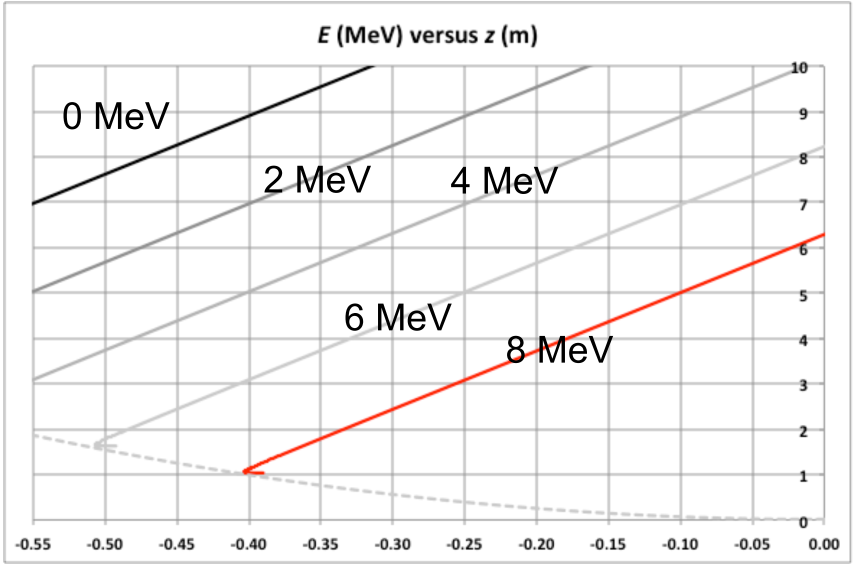
Choice of beam energy



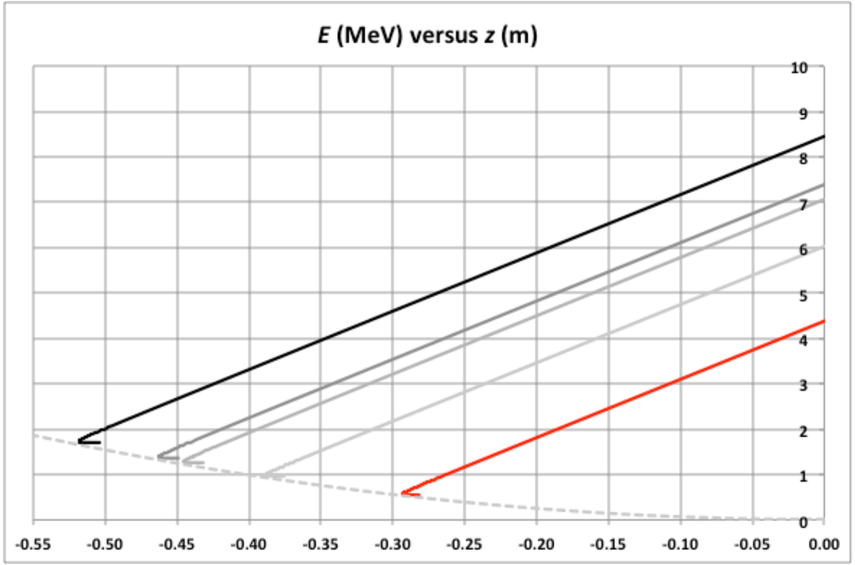




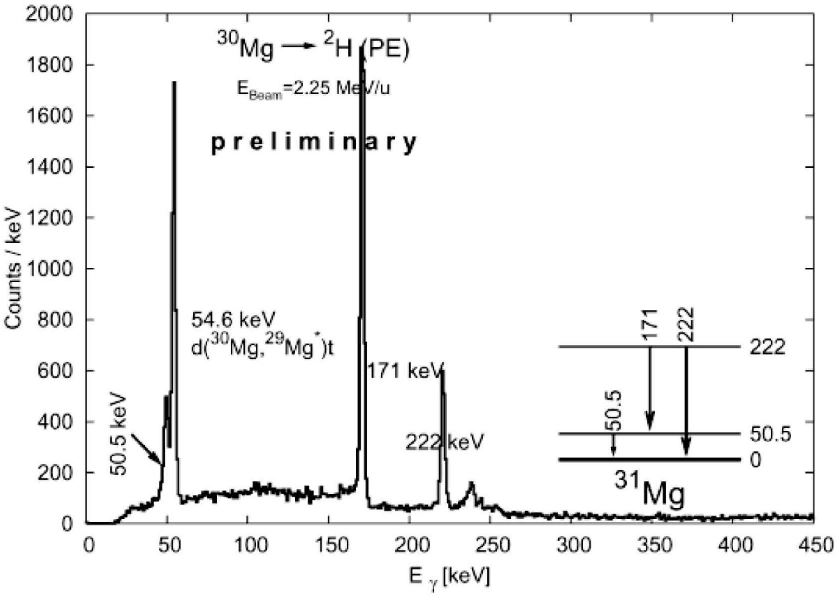
^{28}Al(d,p)

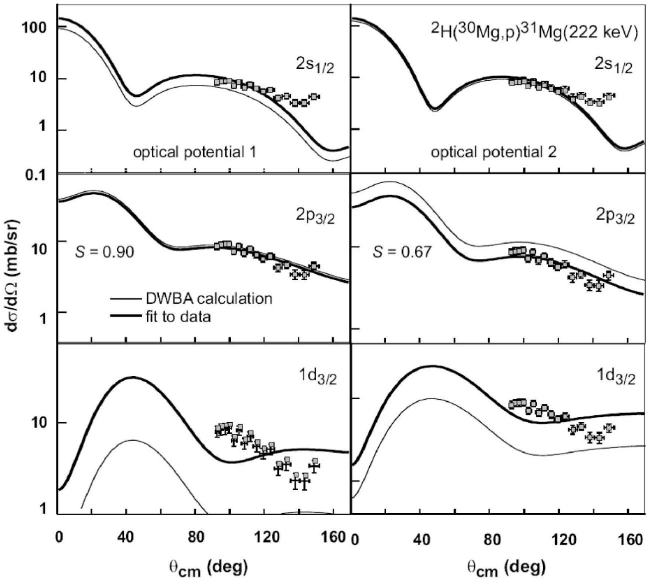


^{28}Mg(d,p)

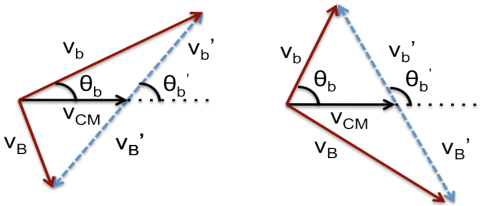


Previous ^{30}Mg(d,p) measurements at ISOLDE





- Angular momentum assignments difficult due to limited angular coverage.
- Only identified fist two excited states.
- Some issues with gamma-ray efficiency due to long lived states.



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

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

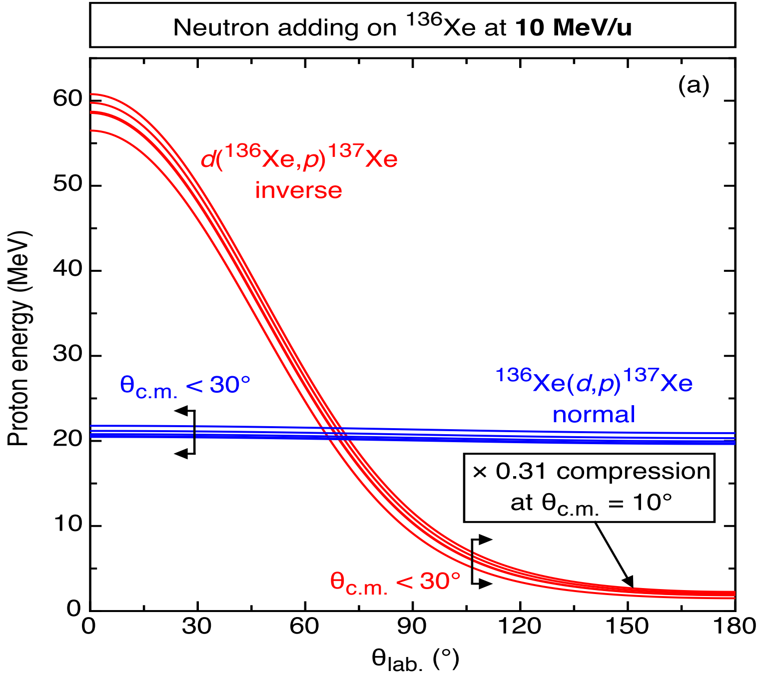
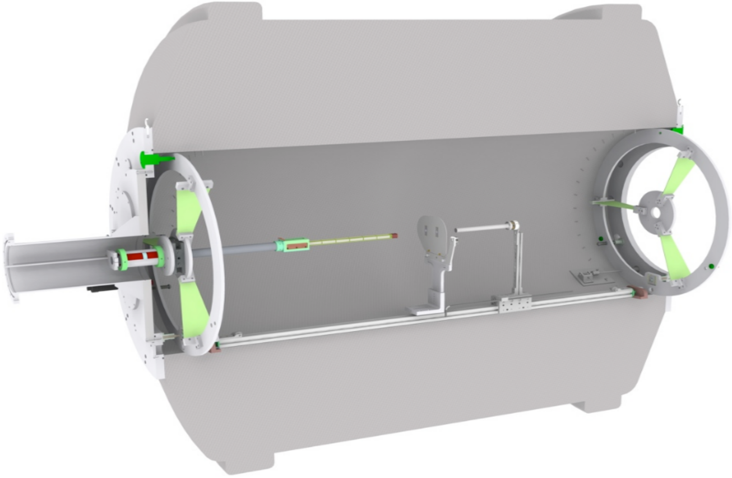


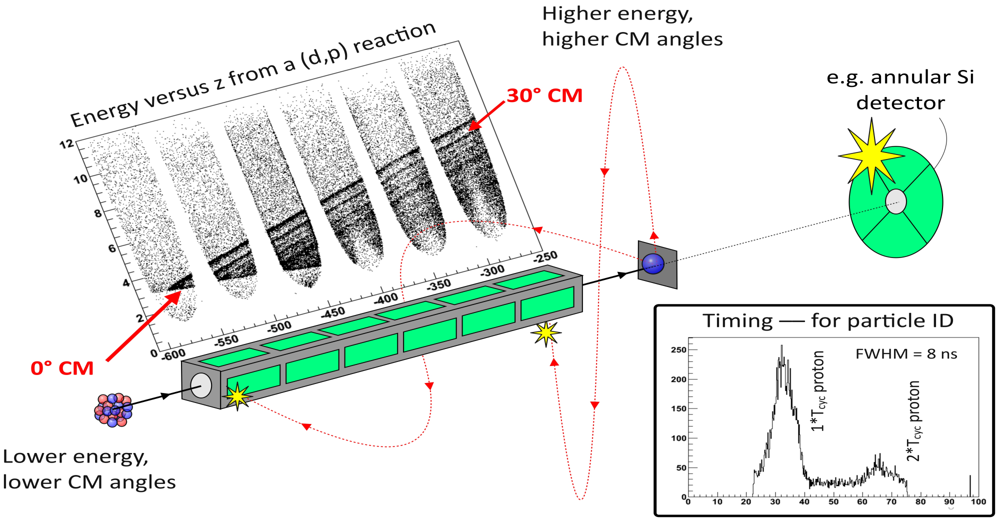
Figure courtesy of Benjamin Kay

Kinematic effects:

- via *kinematic shift* often limits resolution of any detector with finite acceptance.
- via *differential kinematic shift* dictates the separation of different excited states in ion energy.
- BOTH affect the resolution obtained in a Q-value spectrum.



Light particle from reaction follow helical orbits, returning to the axis after one orbit where they are detected in position sensitive silicon detectors.



Measured quantities:

- position, z
- cyclotron period T_{cyc}
- particle energy

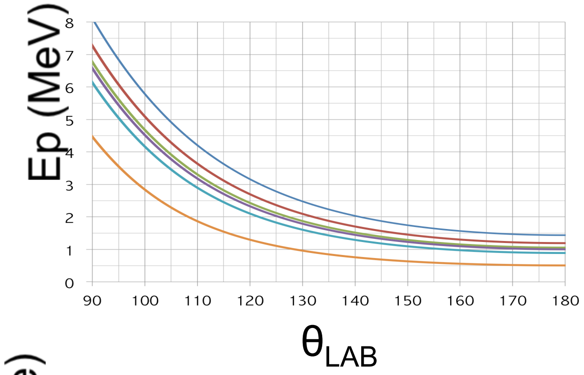
For a particular E*, different CM angles have different lab velocities leading to different z.

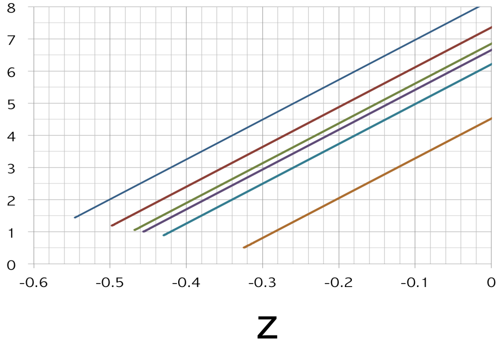
For a particular z, energies in CM and ion energies in LAB related by an additive offset.

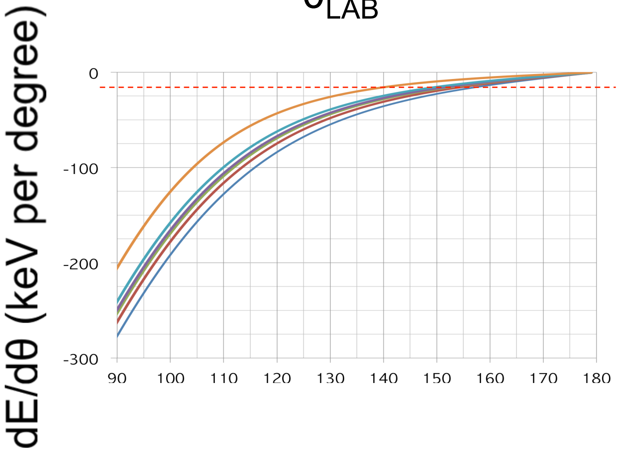
$$E_{\rm cm} = E_{\rm lab} + \frac{mV_{\rm cm}^2}{2} - \frac{mzV_{\rm cm}}{T_{\rm cyc}}$$

Eliminates differential kinematic shift; spacing of energies in CM same as in LAB.

Contribution due to position resolution small (~15keV).

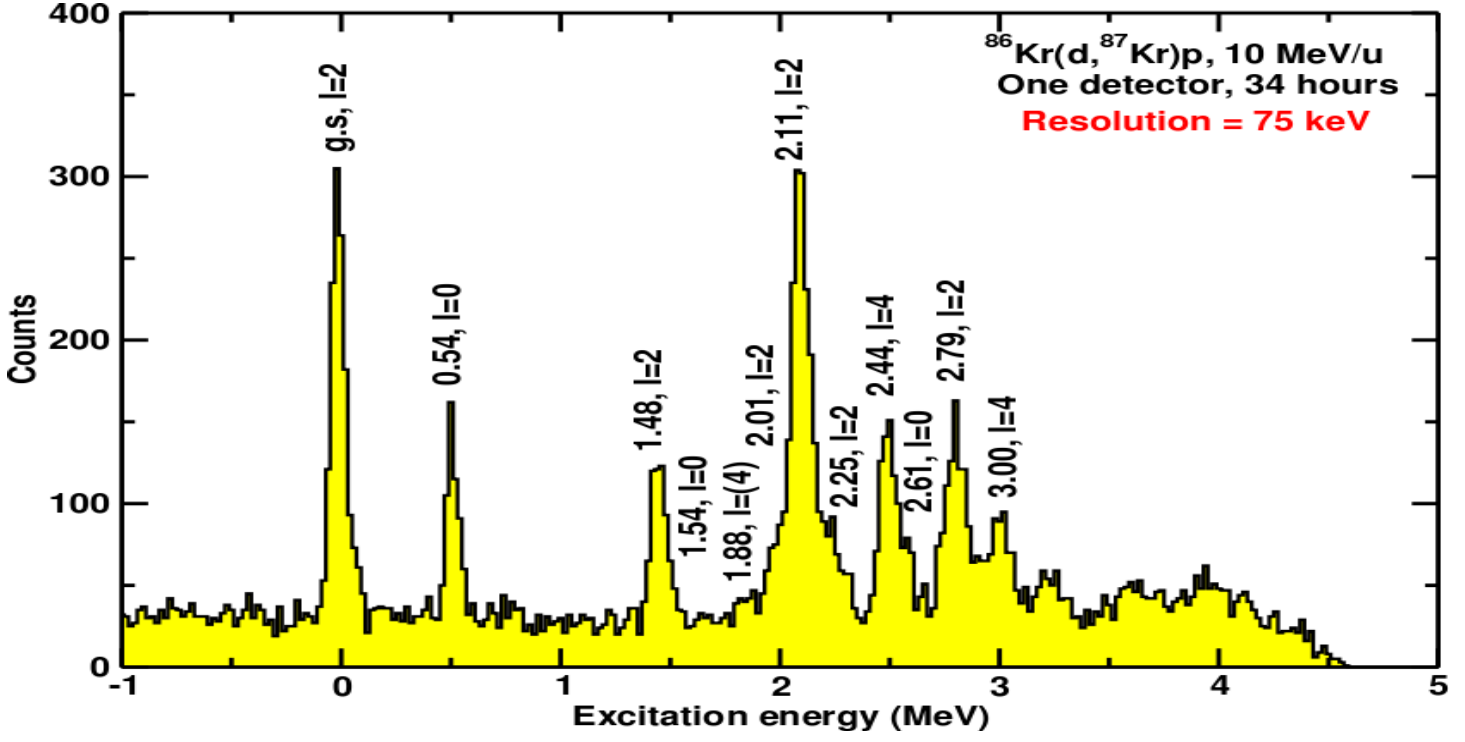


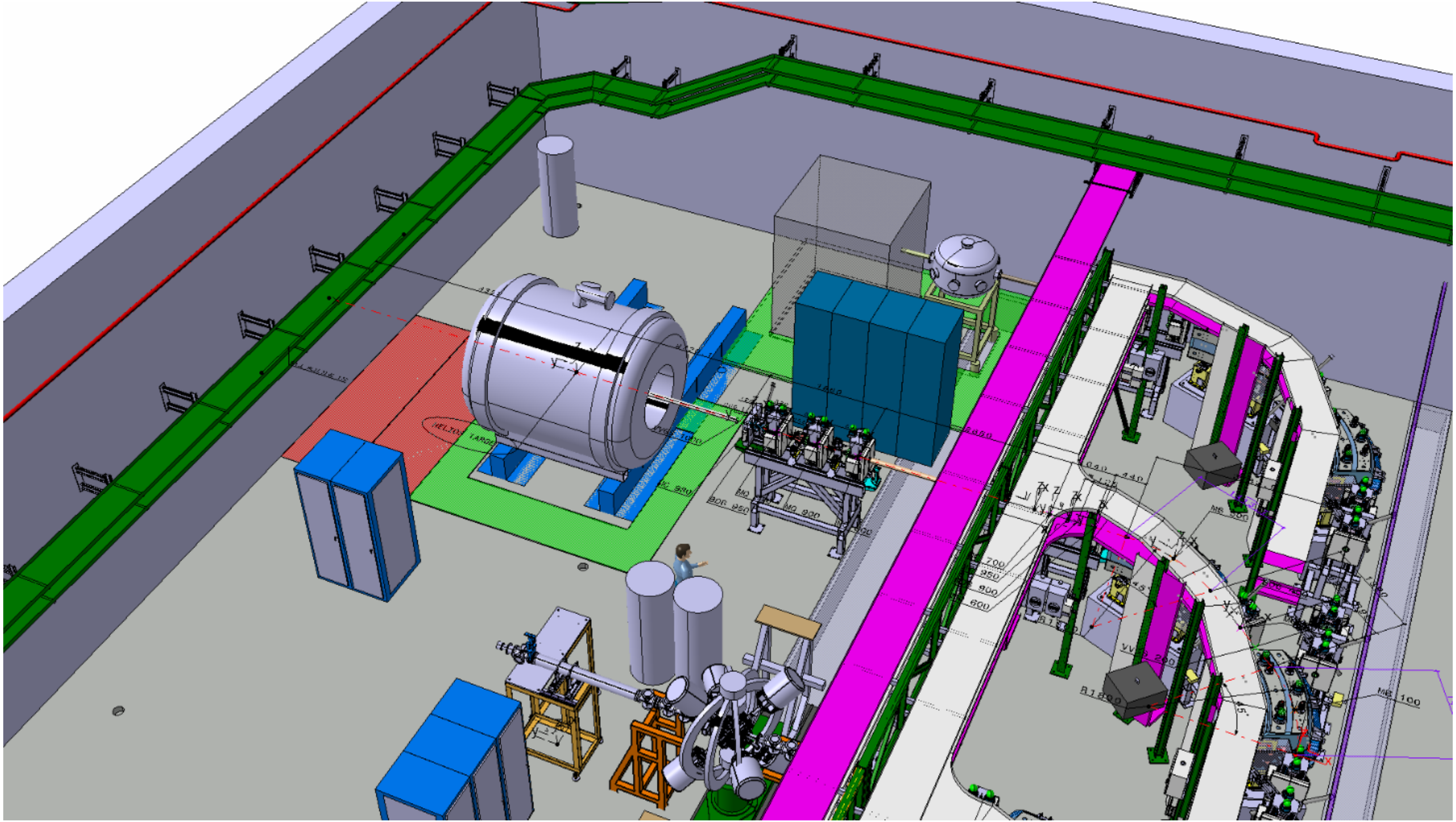




When target effects dominate ion-energy resolution, Q-value spectrum still benefits from the lack of compression.

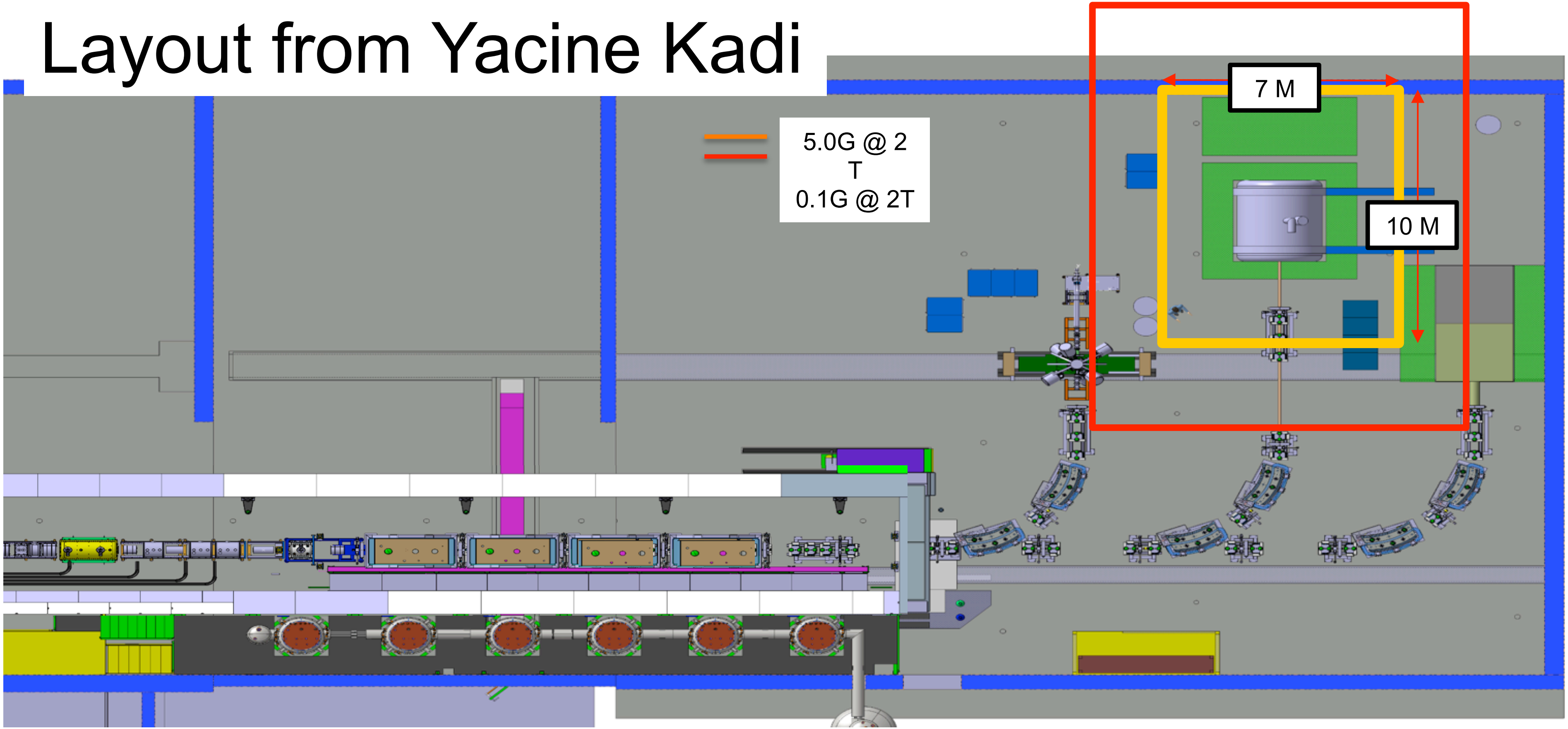
- Used HELIOS to measure d(^{86}Kr,p)^{87}Kr reaction.
- Achieved best (published) resolution to date – **75keV**.

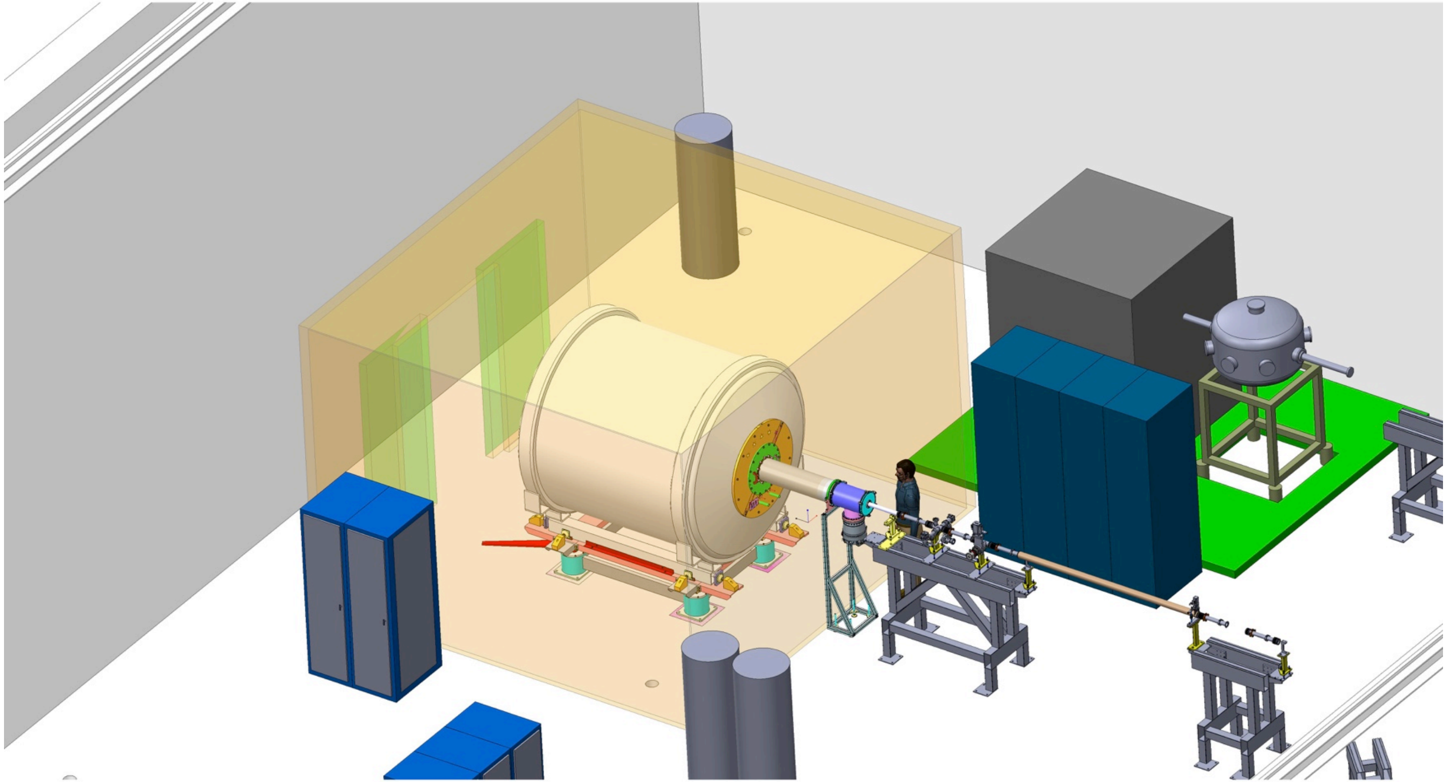




Installation in the ISOLDE Hall

Layout from Yacine Kadi





Next steps

Clean & perform vacuum tests
Cool magnet
Energise & verify field
Move to XT02 by end of January 2017
Finalise shielding calculations
Field mapping
Stable beam tuning tests from Summer 2017
Early implementation experiments 2018
Early 2019 – commission new Si array
Longer term – move to TSR