Nuclear Reactions

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RIA Summer School 2006

Outline

- Lecture 1
  - Overview of nuclear reactions - new techniques related to the use of radioactive beams
- Lecture 2
  - Approximations and models - an aperçu of different concepts in nuclear reaction theory
- Lecture 3
  - Knockout reactions: example of an emerging technique to study the structure of very exotic nuclei efficiently

Nuclear reactions: What are they used for?

- Produce nuclei far from stability
  - The most successful method for producing nuclei away from stability is by reacting them together in various ways
  - See lectures by Brad Sherrill
- Explore the structure and static properties of nuclei
  - One of the major tools to study nuclear structure
  - Often relies heavily on reaction models
- Probe the dynamical characteristics of nuclei and nuclear matter
  - Study of the Equation of State of nuclear matter
  - Also relies heavily on models for extracting observables

Many names

- Nuclear reaction have many names: transfer, knockout, Coulomb excitation, fusion-evaporation, fission, etc…
  - This abundance of names reflects the complexity and variety of possible scenarios when reacting two nuclei together
  - Helpful in establishing mental pictures of the mechanisms involved
  - Dangerous because they create "semantics boundaries" between these different pictures which are not realistic
  - Definition of names can vary among physicists depending on their background
  - Transition between one reaction type to another is smooth in reality, and depends on many parameters (energy, mass, impact parameter…)

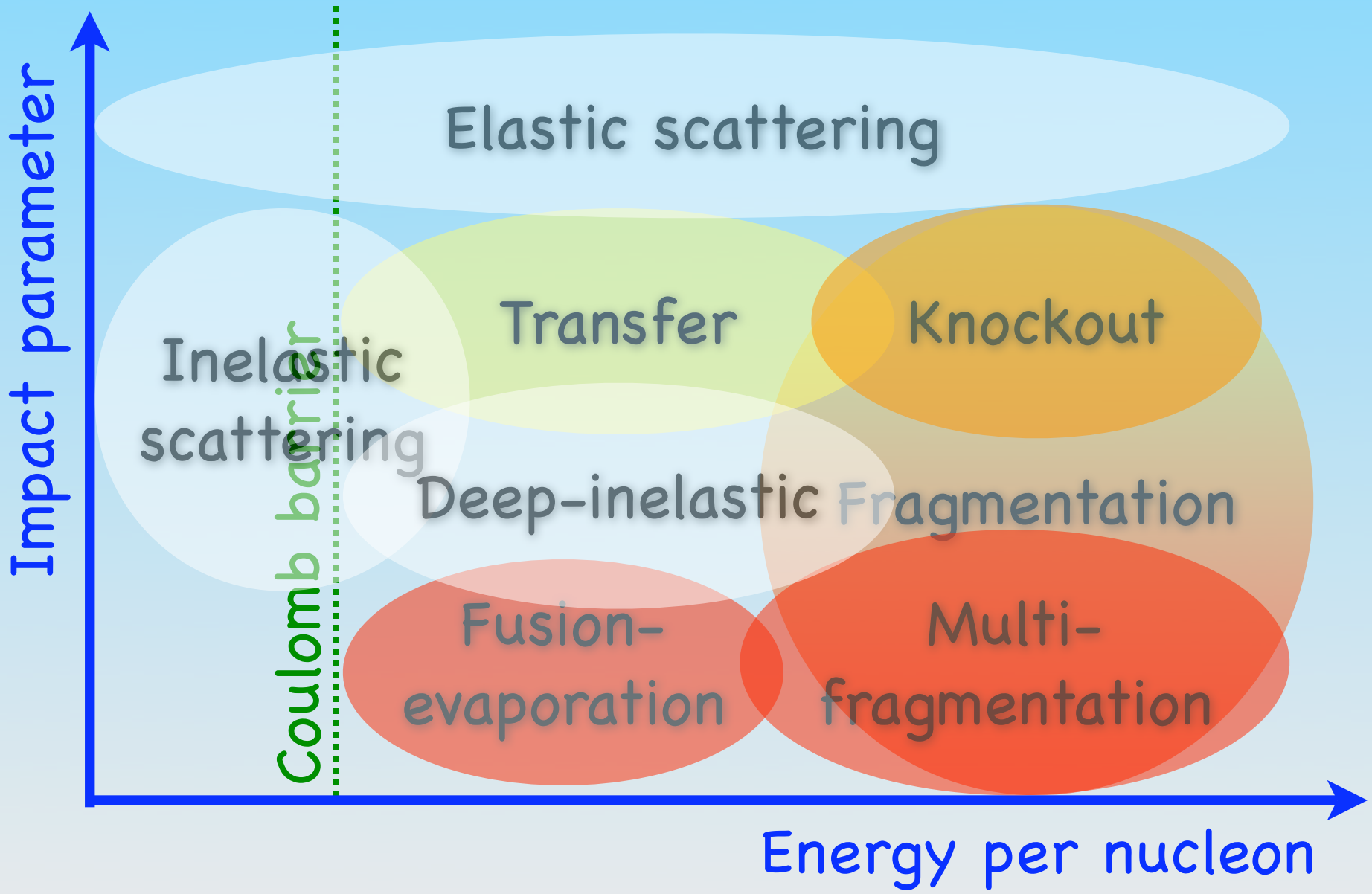
Many theories

- Quantum many-body problem
  - Cannot be solved exactly for static systems
  - Same story for dynamic systems such as a nuclear reaction
- Simplifications and approximations in models
  - Necessary to calculate anything
  - Driven by mental pictures and therefore limited in description scope
  - Difficult to establish links between different models

Many experimental techniques

- Exclusive experiments
  - Only detect part of the reaction products
  - Incomplete observables (no energy balance, missing mass, etc…)
  - Theory needs to match experimental conditions
  - Easy to put together
- Inclusive experiments
  - Detect all reaction products
  - Use energy and momentum conservation
  - No experimental bias of theoretical calculations
  - Difficult to impossible to put together

Schematic classification of some nuclear reactions



Reaction types

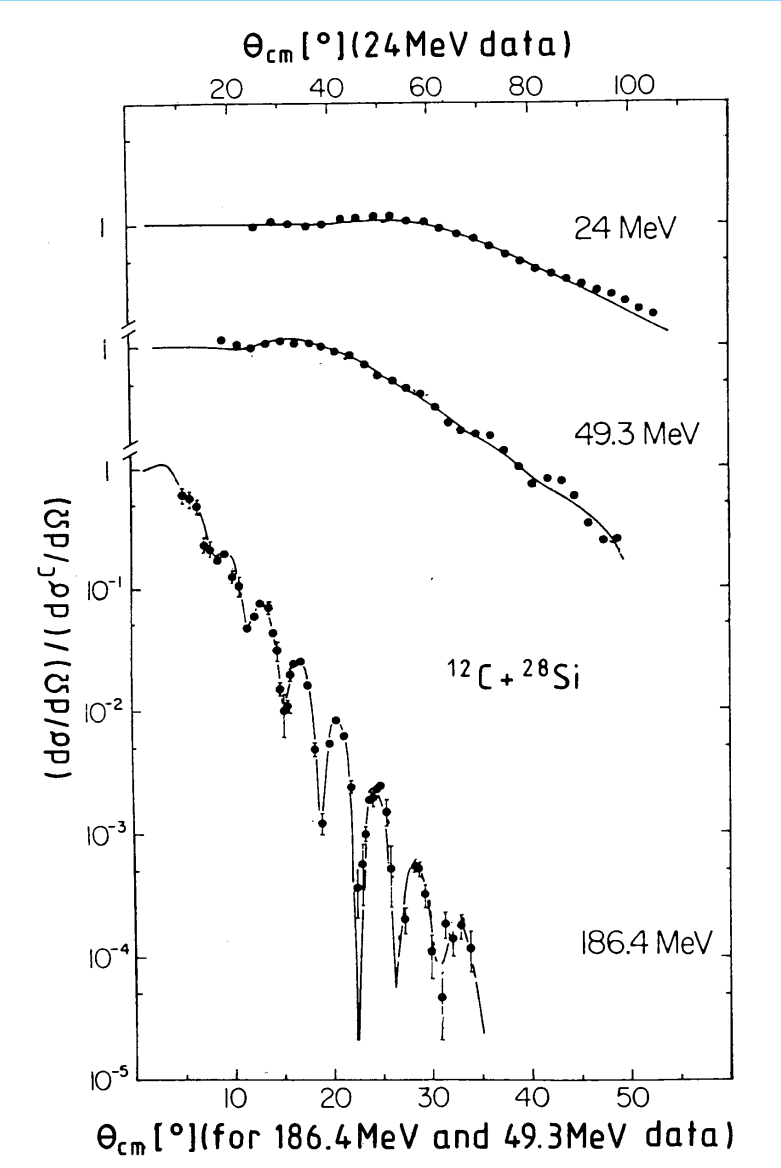
- Direct reactions
  - Proceed in a single step - last time comparable to the time for the projectile to traverse the target (10^{-22} s)
  - Usually only few bodies involved in reaction
  - Excite simple degrees of freedom in nuclei
  - Mostly surface dominated (peripheral collisions)
  - Reaction theories can use simplifications (sudden approximation, perturbation theory, etc...)
  - Primarily used to study single-particle structure

Direct reactions

- Elastic scattering
  - Both target and projectile remain in their ground state
  - Nuclei can be treated as structureless particles
  - Potential scattering: determination of optical potentials (Lecture 2)
- Inelastic scattering
  - Both target and projectile nuclei retain their integrity - they are only brought to bound excited states
  - Can excite single-particle or collective modes of excitation depending on the shell configuration
  - Example: safe and unsafe Coulomb excitation (below and above Coulomb barrier)

Example of elastic scattering

- Scattering of ^{12}C on a ^{28}Si target at various energies
- At low energies (at or below the Coulomb barrier): Coulomb deflection strong enough to prevent interference between diffracted waves from opposite sides of target - Fresnel diffraction
- At higher energy: interference occurs - Fraunhöfer diffraction like from two-slit experiment



Example of inelastic scattering

- Scattering of α particles on a ^{154}Sm target
- Population of excited states of a rotational band
- Competition between direct (one-step) and indirect (two-step) becomes significant for high-lying 4^+ and 6^+ states

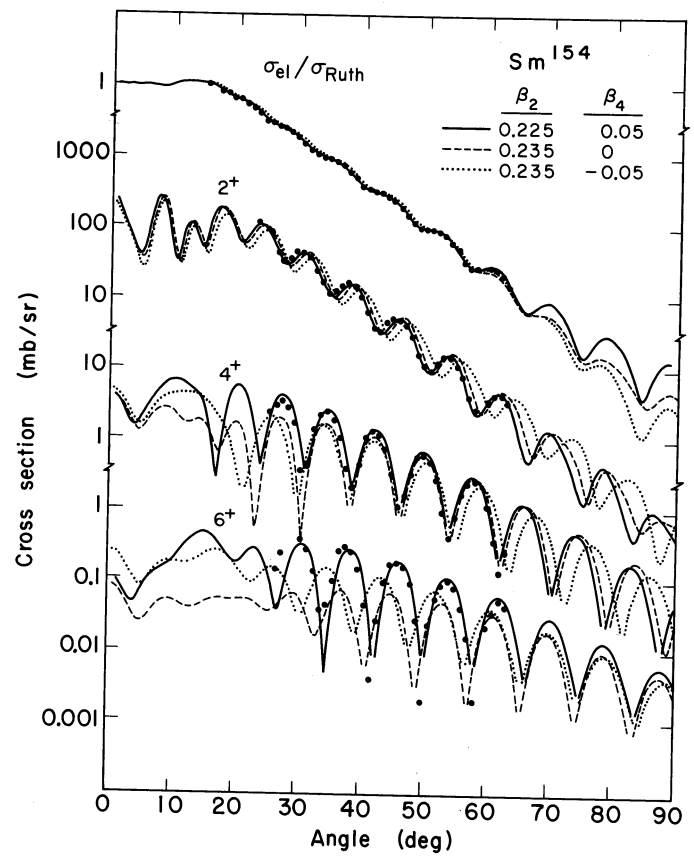


Figure 4.28 Measured and calculated cross-sections for the excitation of several states of a rotational band by the inelastic scattering of α-particles. The cross-sections for the 4^+ and 6^+ states are due largely to multiple $L = 2$ excitations but they also receive very important contributions from the $L = 4$ coupling. (From Glendenning, 1983)

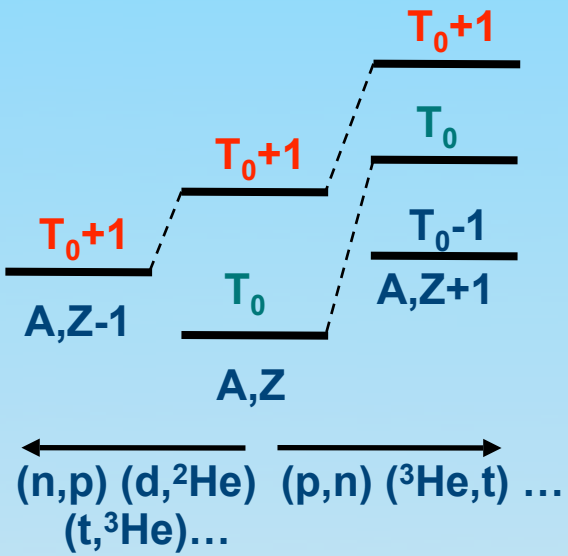
Direct reactions (cont.)

- Transfer reactions
  - One or a few nucleons are transfered between the projectile and target nuclei
  - Populates single-particle orbitals from or to which the nucleon(s) is (are) transferred
  - Characteristics of the entrance channel determines selectivity of the reaction: i. e. α particle with T=0 leads to states with same isospin as g.s., but p with T=½ leads to states with T=T±1
  - Examples are numerous: (d,p), (p,d), (t,p), (t,^{3}He), (^{3}He,t), (d,^{2}He), (^{6}Li, ^{6}He), etc…

An example in detail: charge-exchange reactions

- Reactions that exchange a proton for a neutron or vice-versa
- Net effect same as β^+ or β^- decay
- But: not limited by Q_β - can reach higher excited states and giant resonances
- Main motivation: deduce Gamov-Teller transition probabilities B(GT) - study giant resonances
- Many different probes: (p,n), (d,^{2}He), (t,^{3}He), (^{3}He,t), but also with heavy ions (^{7}Li,^{7}Be) or exotic particles (π^+, π^0), (π^-, π^0)

spin-isospin response of nuclei



Multipole operator $O=r^{\lambda}[\sigma\otimes Y_L]_J t_z$

- **isobaric analog state (IAS): $\Delta S=0$ $\Delta L=0$ $\Delta T=1$ associated with Fermi weak transitions (β-decay)**
- **Gamow-Teller Resonance (GTR): $\Delta S=1$ $\Delta L=0$ $\Delta T=1$ associated with GT weak transitions (electron-capture and β-decay)**
- **dipole excitations $\Delta S=0,1$ $\Delta L=1$ associated with forbidden weak transitions**

For GT and Fermi transitions:

$$B(GT_+) = \sum_{i,f} \frac{n_i^p n_f^h}{(2j_i+1)(2j_f+1)} \left|\langle f|\vec{\sigma}\tau_+|i\rangle\right|^2$$

$$\frac{d\sigma}{d\Omega}(q=0) = \left[\frac{\mu}{2\pi\hbar}\right]^2 \frac{k_f}{k_i} N_D |V_{\sigma\tau}|^2 \left|\left\langle f\left|\sum_k \sigma_k \tau_k\right|i\right\rangle\right|^2$$

Valid if $V_{\sigma\tau}$ (for GT) or V_τ (for Fermi) is dominant in interaction

Beam energy > 100 MeV/nucleon (multistep processes, tensor-τ interaction)

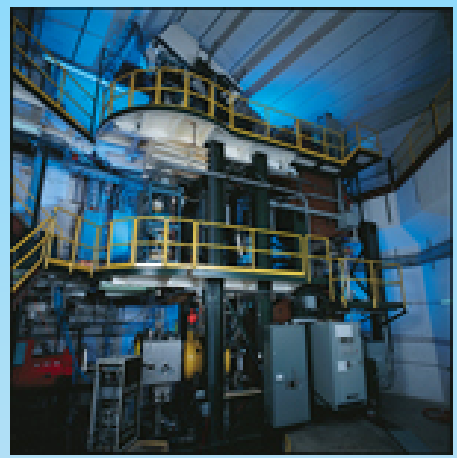
[Tadeucci et al. for (p,n)]

From: R. Zegers (private communication)

Different probes...

- (p,n) and (n,p)
  - 'elementary' reaction mechanisms
  - (n,p) has limited resolution (~1 MeV)
- (d,^{2}He)
  - predominately $\Delta S=1$ if e_{pp}< 1 MeV
  - complex reaction mechanism (unbound pp-system)
  - good resolution (~130 keV)
- (^{3}He,t) and (t,^{3}He)
  - Both channels with good resolutions (~30-200 keV)
  - Composite probes but reactions much like (p,n) and (n,p)
  - details can be studied using (^{3}He,t) and then applied to (t,^{3}He)
  - triton beam: made as a radioactive beam from ^{16}O fragmentation

(t,^{3}He) @ S800, NSCL



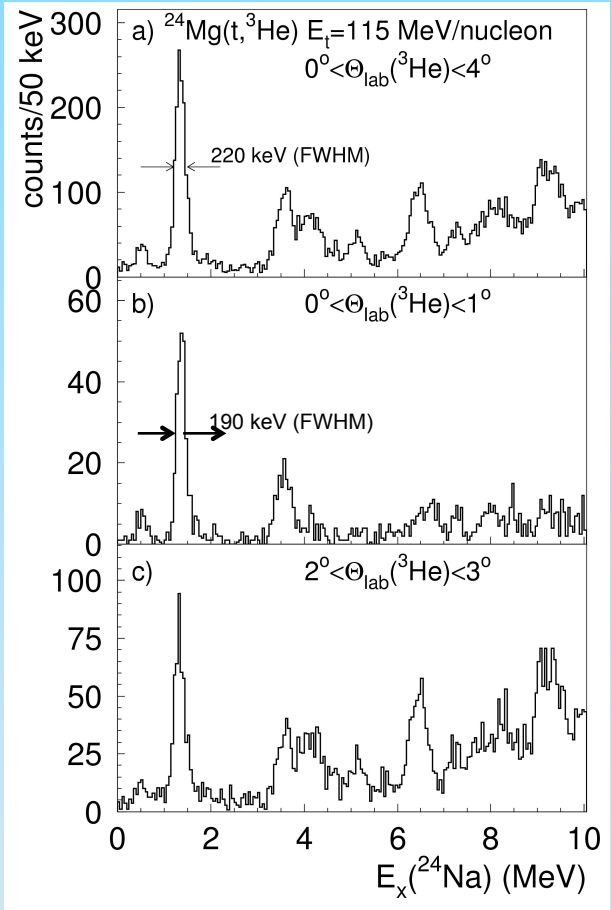
(x,y,θ_v,θ_h) focal plane

raytracing

$(y,E_{3He},\theta_h,\theta_v)$ target

missing mass

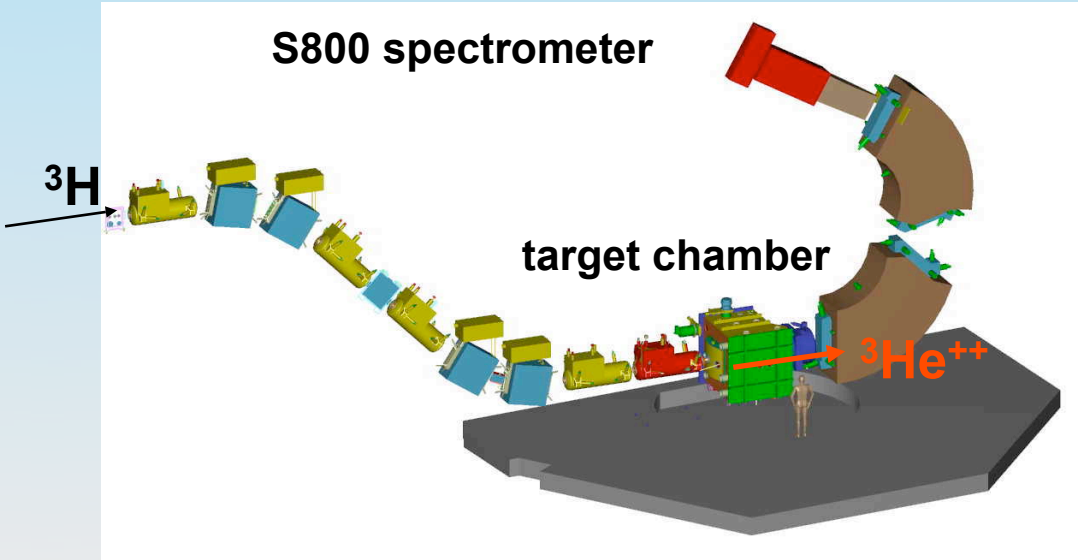
$(E_x(\text{target}),\theta_{cm})$



Dispersion matching is used to obtain good resolutions

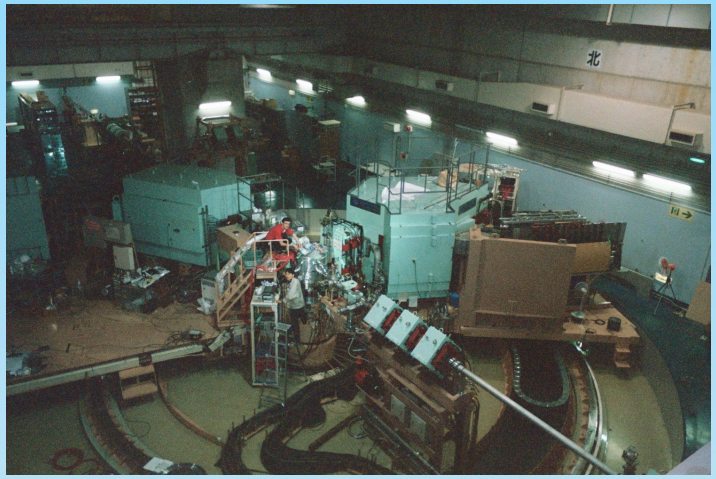
Intrinsic resolution: ~170 keV

+energy loss/straggling in target
+contribution from angular resolution } target dependent



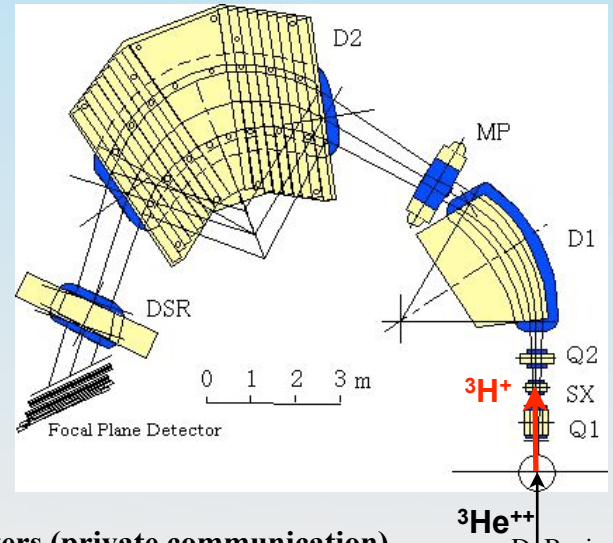
From: R. Zegers (private communication)

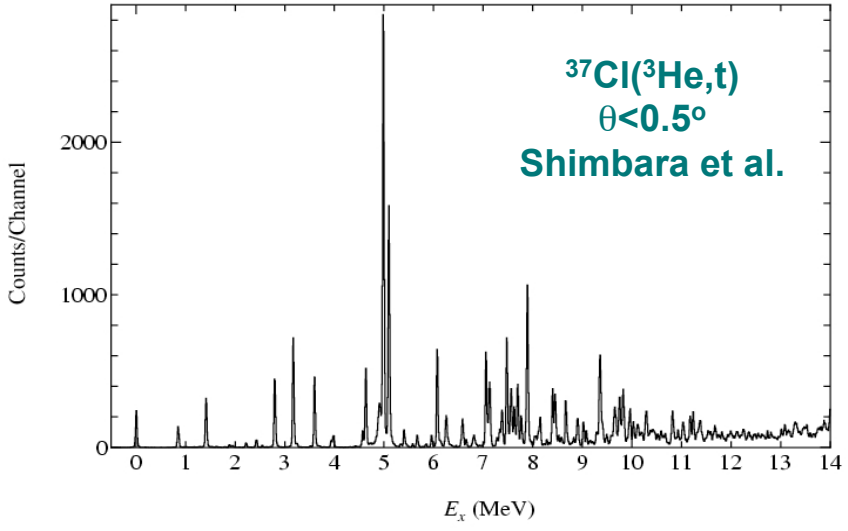
(^{3}He,t) @ Grand Raiden, RCNP



- E(^{3}He)=140 MeV/nucleon
- intensities: tens of pnA
- resolution with dispersion matching ~30 keV
  - differential cross sections?
  - Development May 2006
- resolution without dispersion matching: ~100 keV, but differential cross sections

Grand Raiden @ RCNP

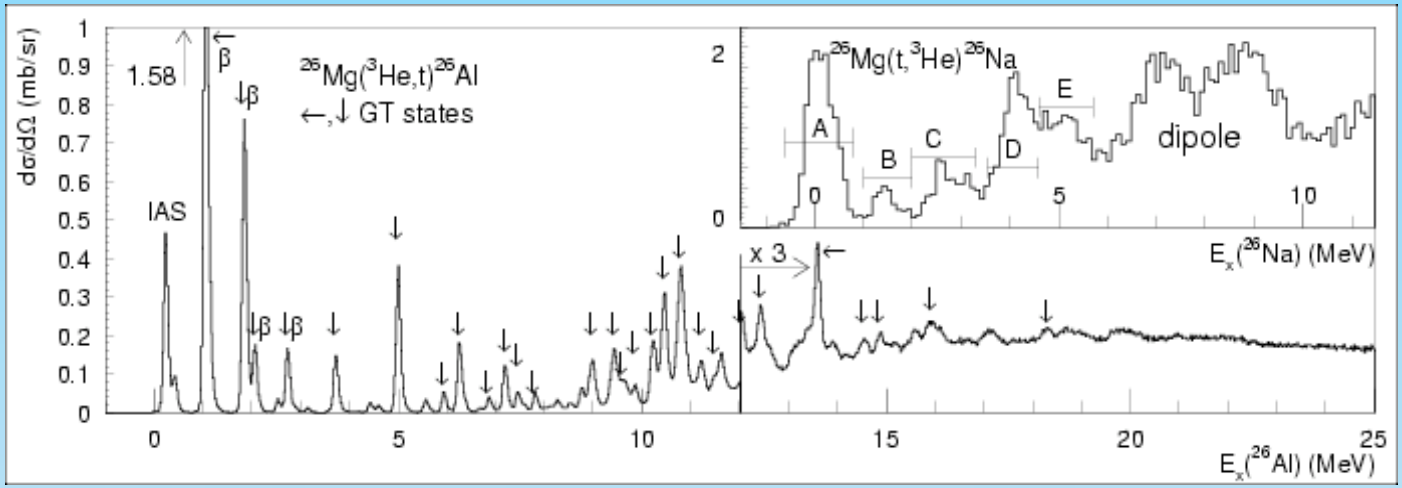


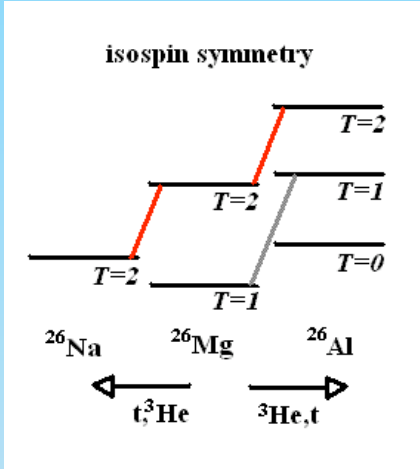


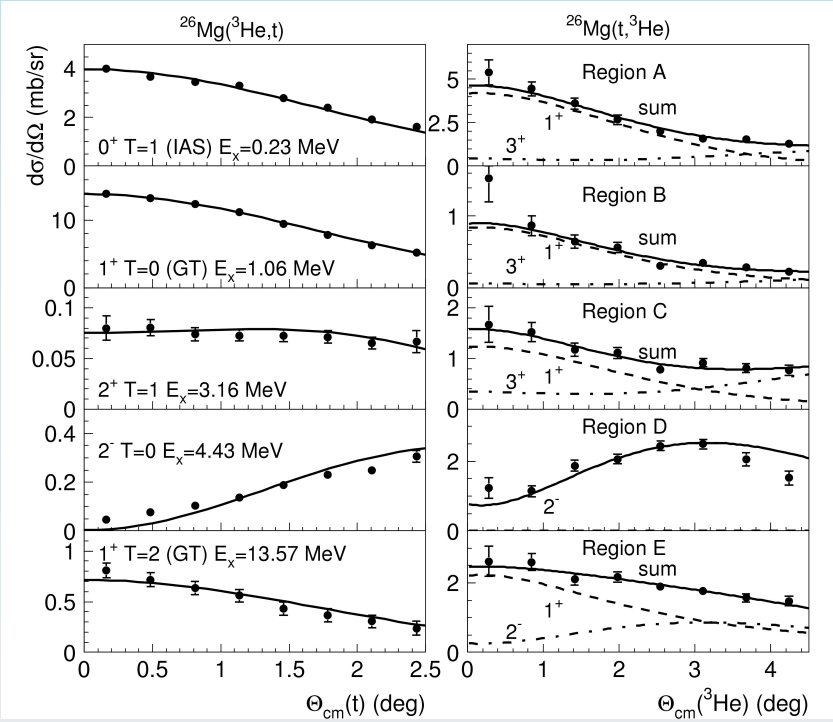
Many experiments done:
- Fujiwara et al.
- Fujita et al. (high resolution)

From: R. Zegers (private communication)

Mirror reactions on ^{26}Mg







- GT transitions are identified with angular distributions
- Calibrated with β-decay
- Good test case for study of proportionality between B(GT) and cross section at q=0
- Good test case for testing the understanding of the reaction mechanism
- DWBA approximate treatment of exchange

From: R. Zegers (private communication)

Direct reactions (cont.)

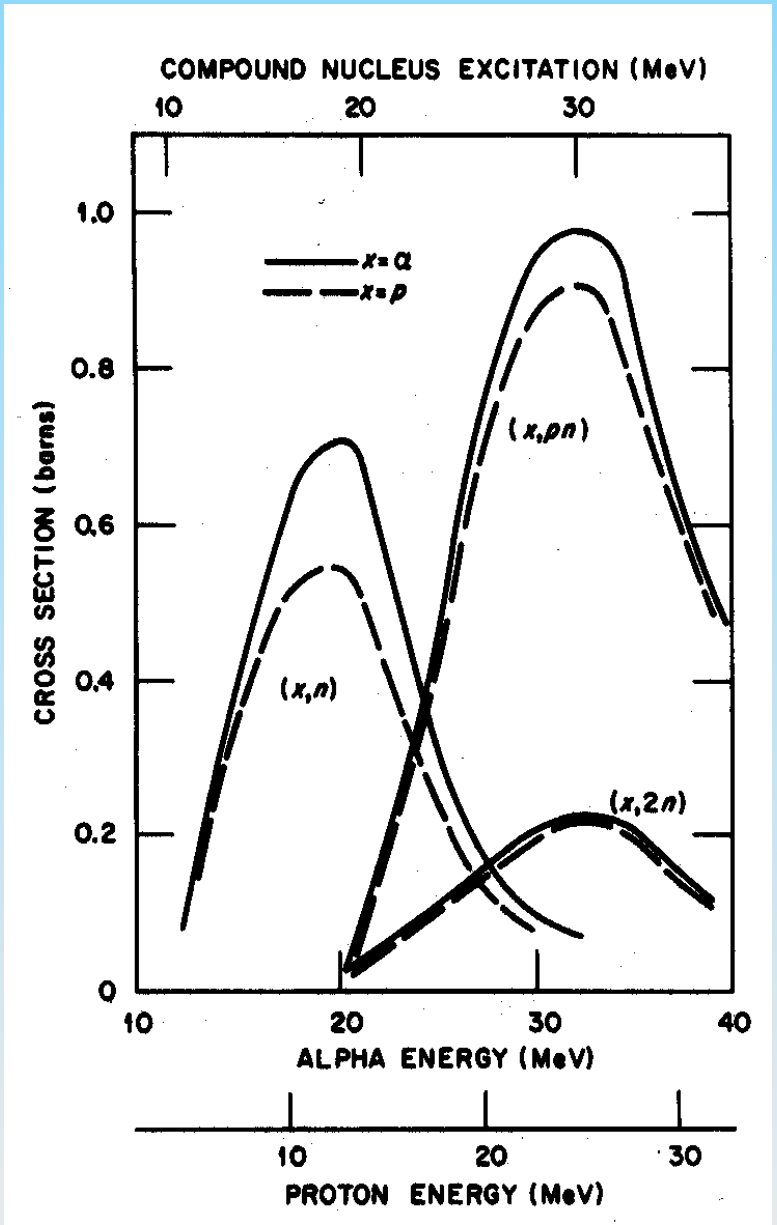
- Knockout reactions
  - One or a few nucleons are ejected from either the target and/or the projectile nuclei, the rest of the nucleons being spectators
  - Exit channel is a 3-body state
  - Becomes dominant at intermediate and high incident energies
  - Like transfer reactions removing nucleons, populates single-hole states from which spectroscopic information can be derived (Lecture 3)
  - Examples: (p,2p), (p,pn), (e,e'p), heavy ion induced knockout (^{9}Be,X)
  - See Lecture 3

Reaction types (cont.)

- Compound nucleus
  - The two nuclei coalesce and form an excited compound fused system that lasts for a relatively long time (10^{-20} to 10^{-16} s)
  - De-excitation stage follows by combination of particle evaporation and/or γ decay
  - Compound system has no memory of the entrance channel - cross section of exit channel independent
  - Found at low energy (around Coulomb barrier) and for central collisions
  - Can excite low to high energy resonances in the compound nucleus depending on the incident energy of projectile

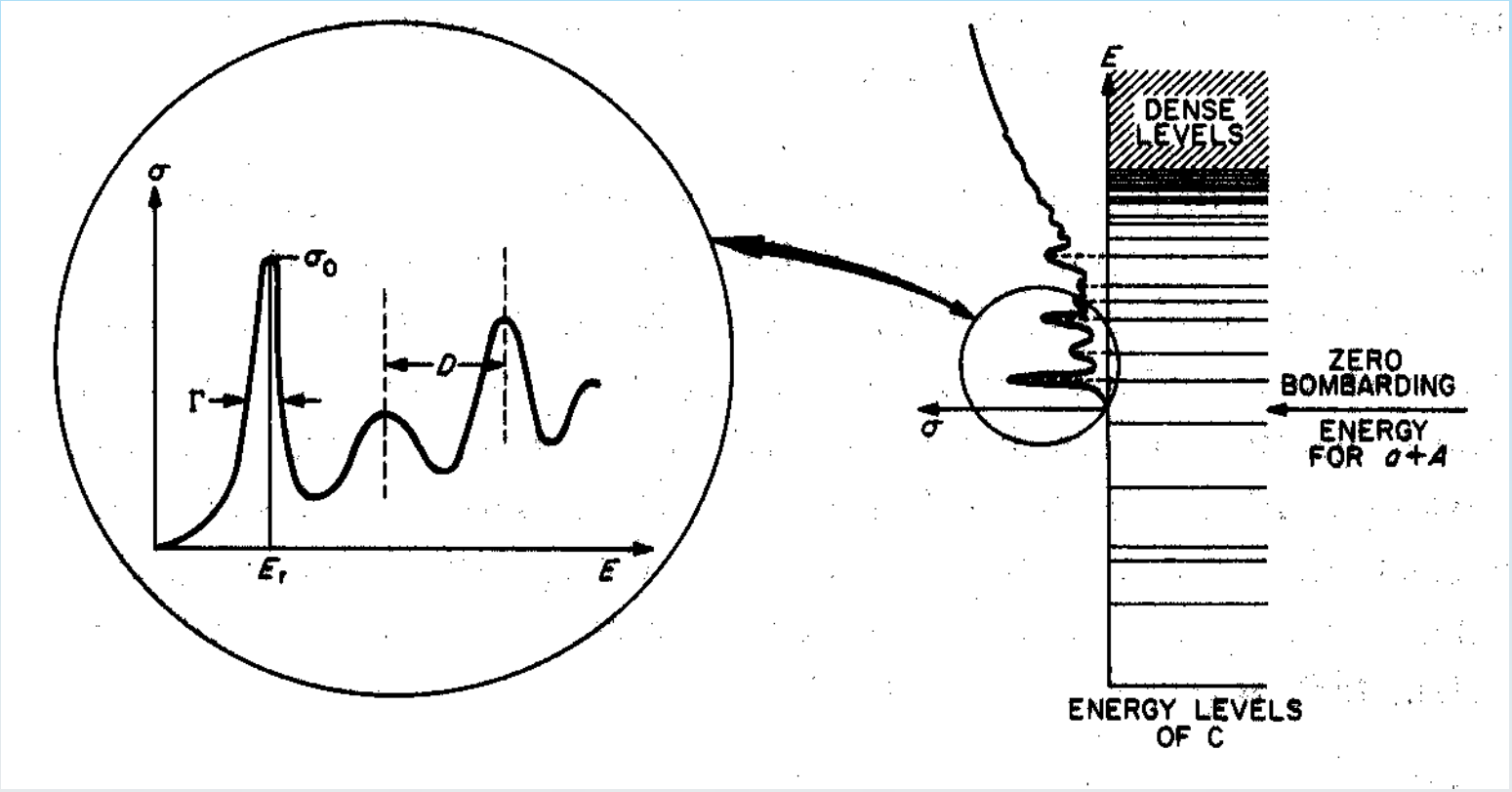
Exit channel independent

- Comparison between cross section of various reaction channels after formation of ^{64}Zn compound nucleus from $^{63}Cu+p$ and $^{60}Ni+\alpha$
- Energy scales for p and α adjusted corresponding to same excitation energy in compound nucleus



Compound resonances

- Excitation energy shared among several nucleons
- Compound system survives longer than 10^{-22} s
- Resonance width directly related to lifetime



Reaction types (cont.)

- Between direct and compound: multi-step processes
  - Cannot be described by either approaches
  - More complex theories needed such as coupled channel

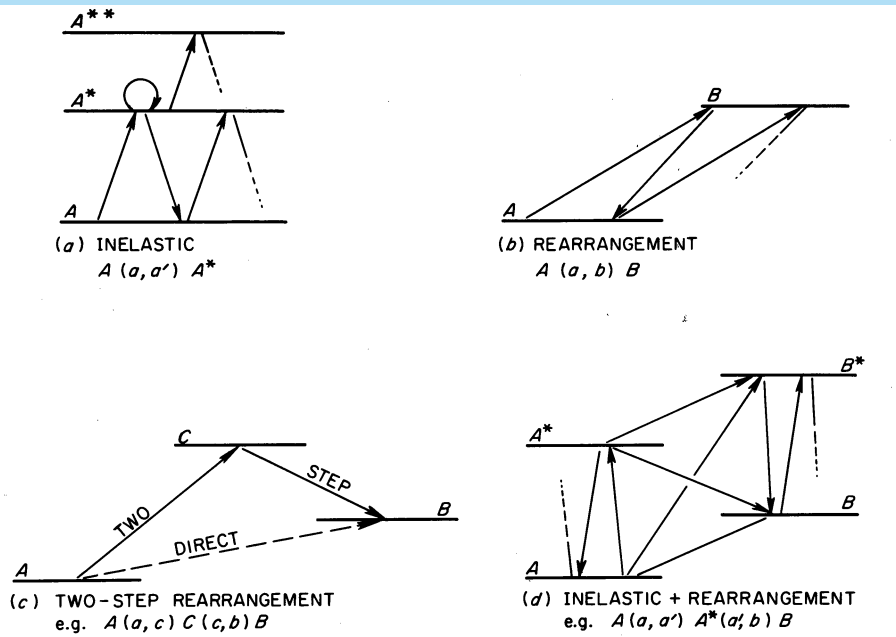
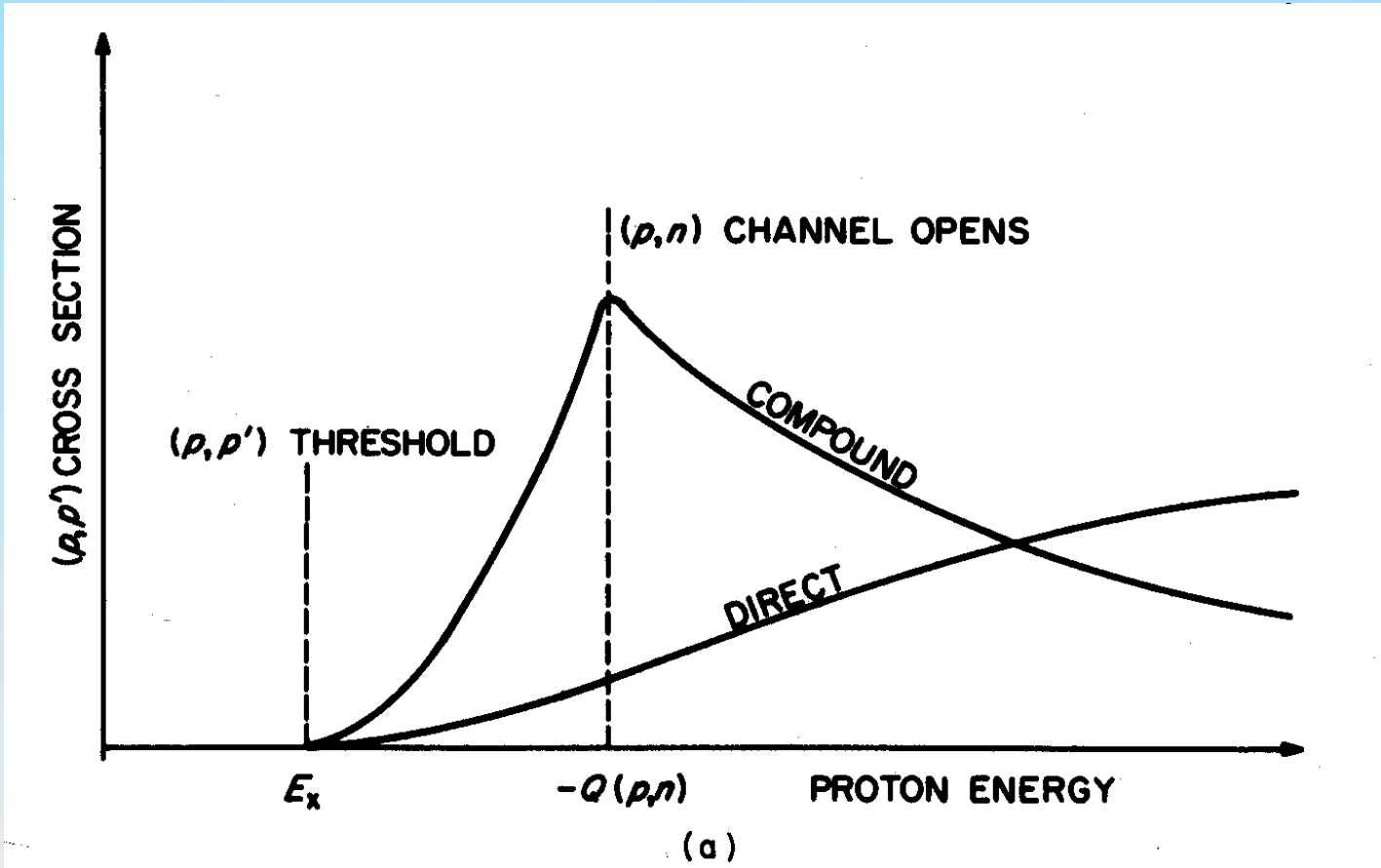


Figure 4.27 Illustrating various types of multi-step processes which may occur in direct reactions. Each arrow indicates one action by the interaction potential V. The Born approximation takes into account only one such arrow

Coexistence of reaction mechanisms

- For a given incident energy, reaction mechanisms leading to the same final state can coexist because of variation with impact parameter



Radioactive beams: new opportunities and challenges

- During past 50 years or so, only stable or close to stability nuclei could be studied using nuclear reactions
- Accessibility of nuclei far from stability as beams opens a wealth of new possibilities to study nuclear structure and dynamics in unknown territory
- Old techniques might not be applicable to radioactive beams: inverse kinematics poses new experimental challenges
- Take advantage of radioactive beams characteristics in developing new experimental techniques
- Examples: in-beam gamma-ray spectroscopy and heavy-ion knockout reactions

Old techniques on new beams?

- Before radioactive beams: direct kinematics
  - Nucleus under study at rest (target) and probe particle carries momentum (beam)
  - Large intensities
  - Scattered particle escapes from target and carries final state information
- With radioactive beams: inverse kinematics
  - Nucleus under study carries momentum
  - Small intensities
  - Equivalent experiment very difficult: need to reduce target thickness to allow recoiled particle to escape ⇒ small luminosity

In-beam γ-ray spectroscopy

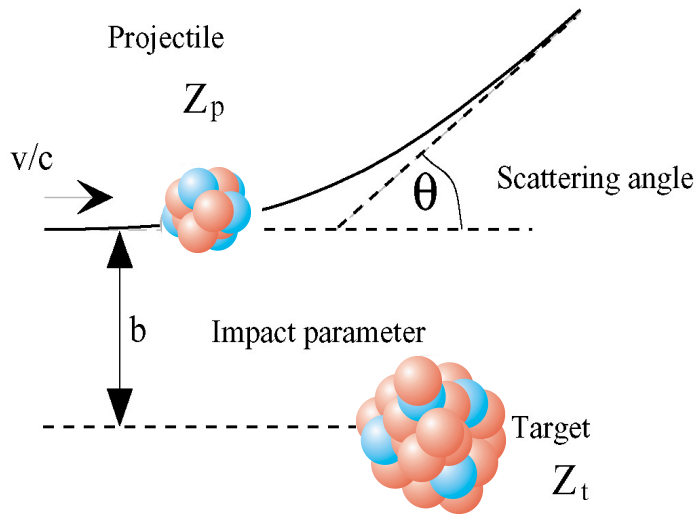
- Principle of experimental method
  - Use γ-ray emitted in flight by reacted projectile to identify final state
  - γ-ray easily escapes target ⇒ use thick targets ⇒ high luminosity
  - Projectile residue forward focussed ⇒ collect in small solid angle
- Requirements
  - High efficiency for γ-ray detection ⇒ use detector array
  - Doppler correct γ-ray energy ⇒ position resolution ⇒ segmentation
  - Filter out unwanted reaction channels ⇒ spectrometer at 0°

Examples

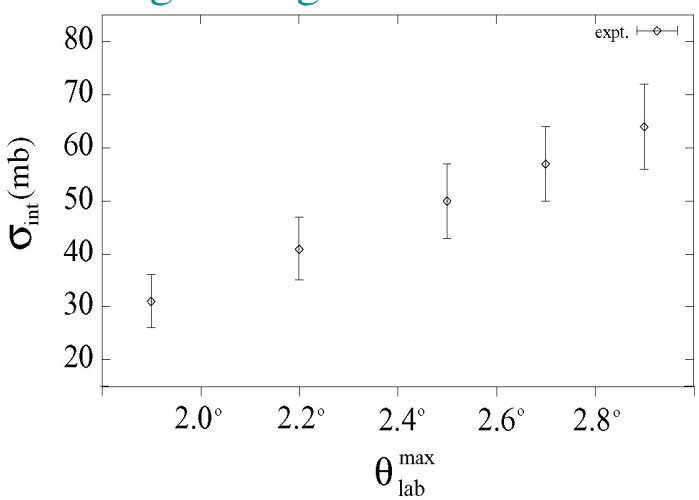
- Coulomb excitation
  - Inelastic scattering from the Coulomb field of a heavy target
- Proton inelastic scattering (p,p')
  - Inelastic scattering from the nuclear interaction
- Knockout reactions
  - Removal of one or two nucleons from the projectile - Lecture 3
- Other reactions
  - Other reactions channels involving removal or transfer of a few nucleons from/to the projectile leading to excited states of the projectile residue

Example of Coulex: ^{46}Ar

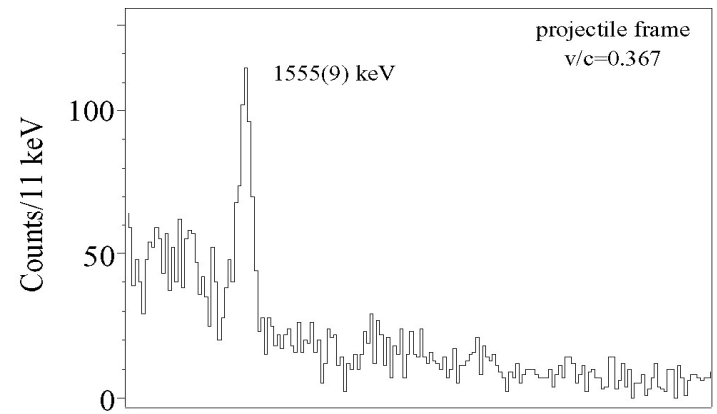
A. Gade et al., Phys. Rev. C 68, 014302 (2003).



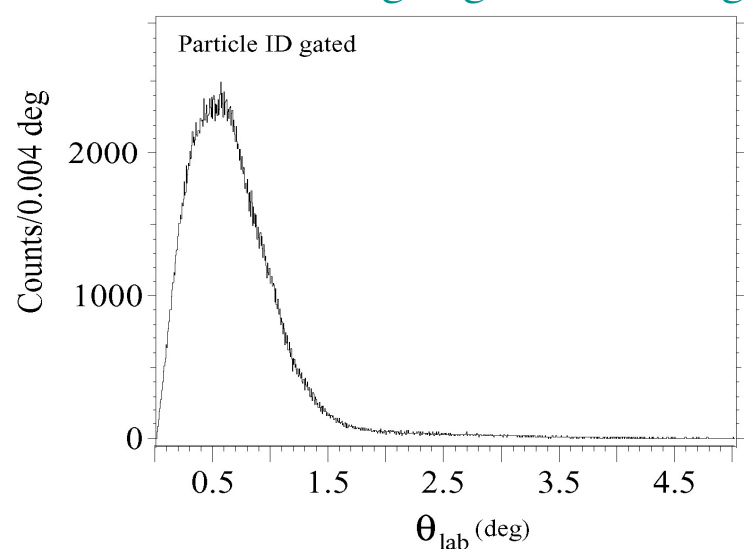
Angle-integrated cross sections



Tag the inelastic process with γ-rays

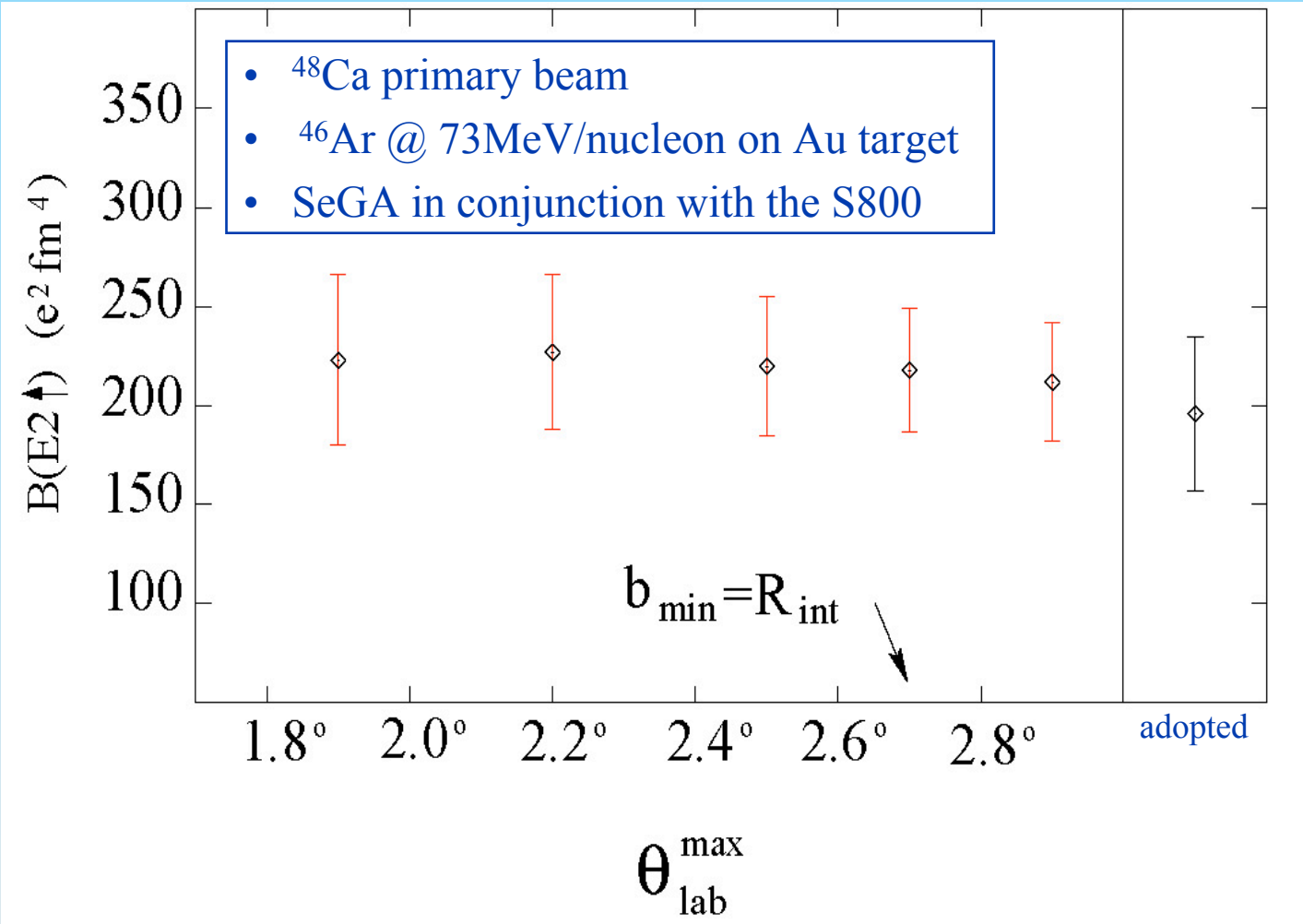


^{46}Ar scattering angle off the target



Determination of B(E2)

A. Gade et al., Phys. Rev. C 68, 014302 (2003).



- B(E2↑) constant over a broad range of impact parameters
- In good agreement with H. Scheit et al., PRL 77, 3967 (1996)

Comparison with other methods

J.M. Cook, T. Glasmacher and A. Gade, Phys. Rev. C 73, 024315 (2006).

The first:

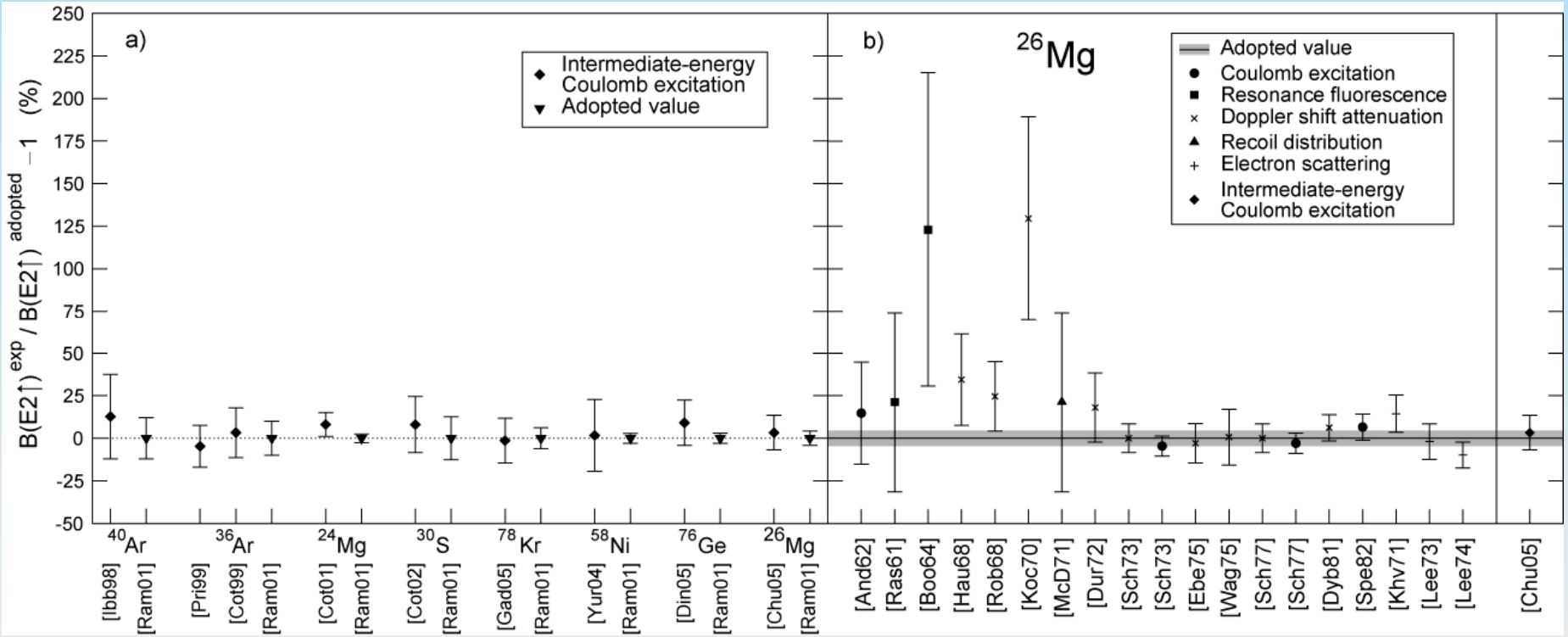
T. Motobayashi et al., Phys. Lett. B 346, 9 (1995).

The theory:

A.Winther and K. Alder, Nucl. Phys. A 319, 518 (1979).

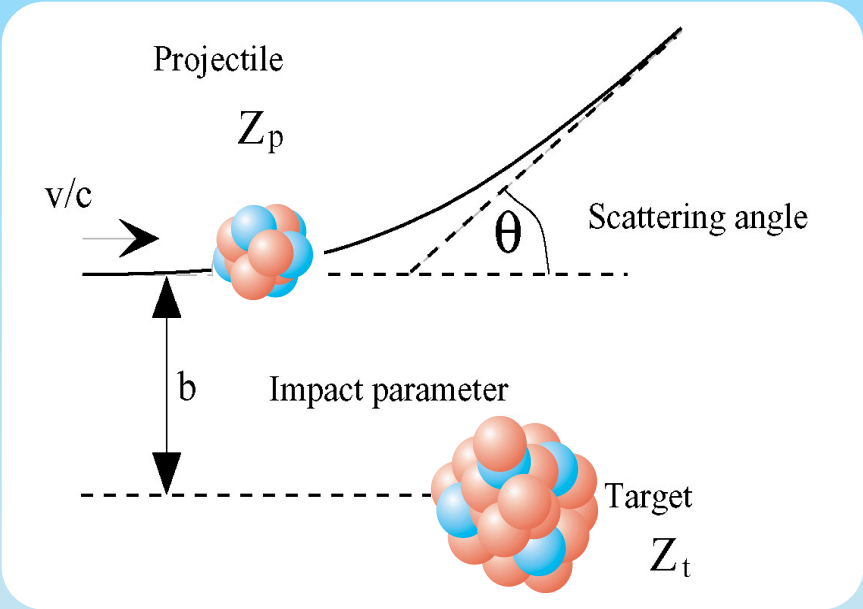
Adopted and measured B(E2↑) values for stable nuclei

B(E2↑) values from different methods for ^{26}Mg



Safe Coulex above barrier

Assumption: electromagnetic interaction dominates for $b > R_{int}$



for given v/c:
impact parameter $b=b(\theta)$

Experiment:
Scattering angle determines b

$$R_{int} = C_t + C_p + 4.49 - \frac{C_p + C_t}{6.35}$$

Electromagnetic interaction radius

$$C_i = R_i(1 - 1/R_i^2) \qquad i=t,p$$

Radius for diffuse (Fermi) mass distribution

$$R_i = 1.28\,A_i^{1/3} - 0.76 + 0.8\,A_i^{-1/3}$$

Radius for homogenous ("sharp") distribution

Parametrization: W.W. Wilcke et al., At. Data Nucl. Data Tables 25, 389 (1980)

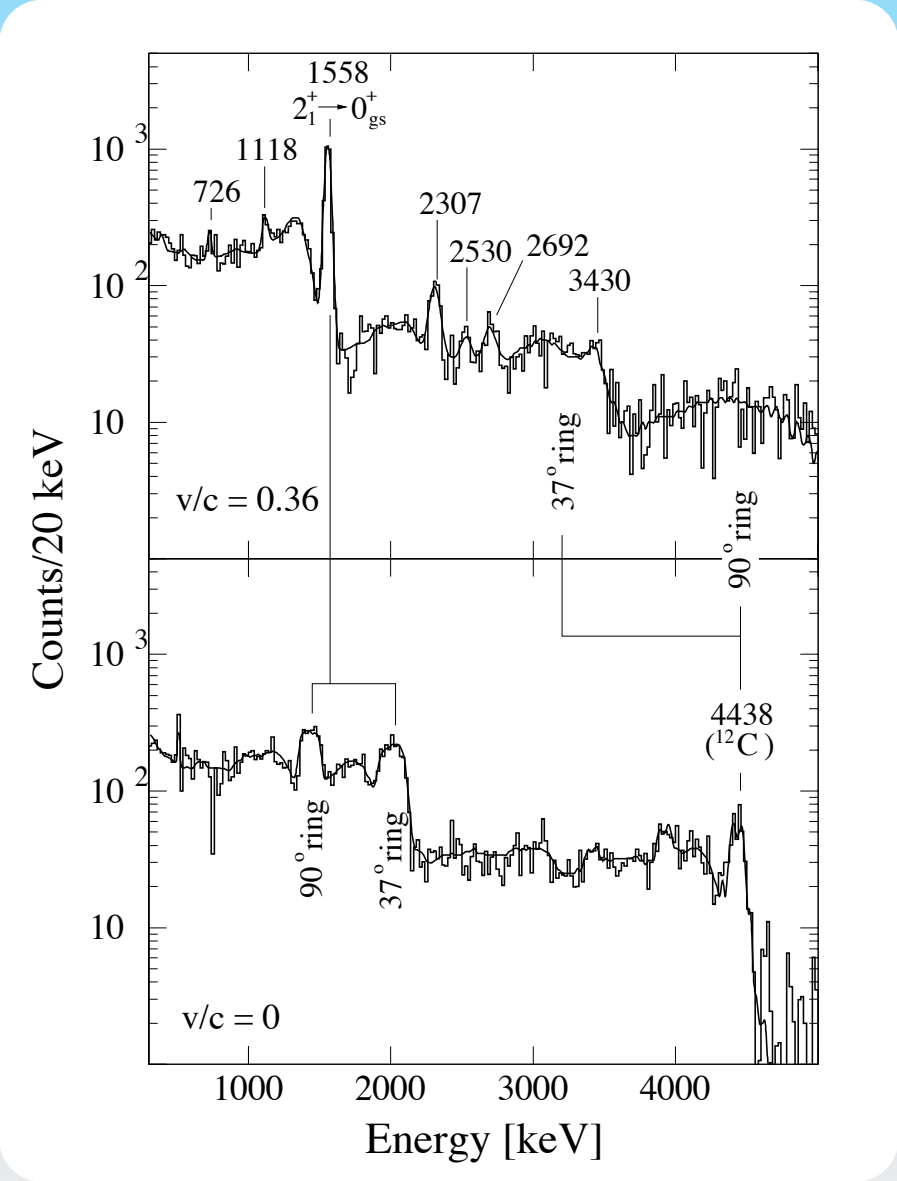
Inverse kinematics inelastic proton scattering

- Coulex only provides information on the deformation of proton shell via B(E2)
- Proton inelastic scattering is sensitive to both neutron and proton shell structures
- Combining both measurements can help disentangle the contributions of
- Use thick targets ⇒ high luminosity
- CH_2 target requires ^{12}C background measurement
- Cryogenic proton target

$^{46}Ar(p,p')$ on a CH_2 target

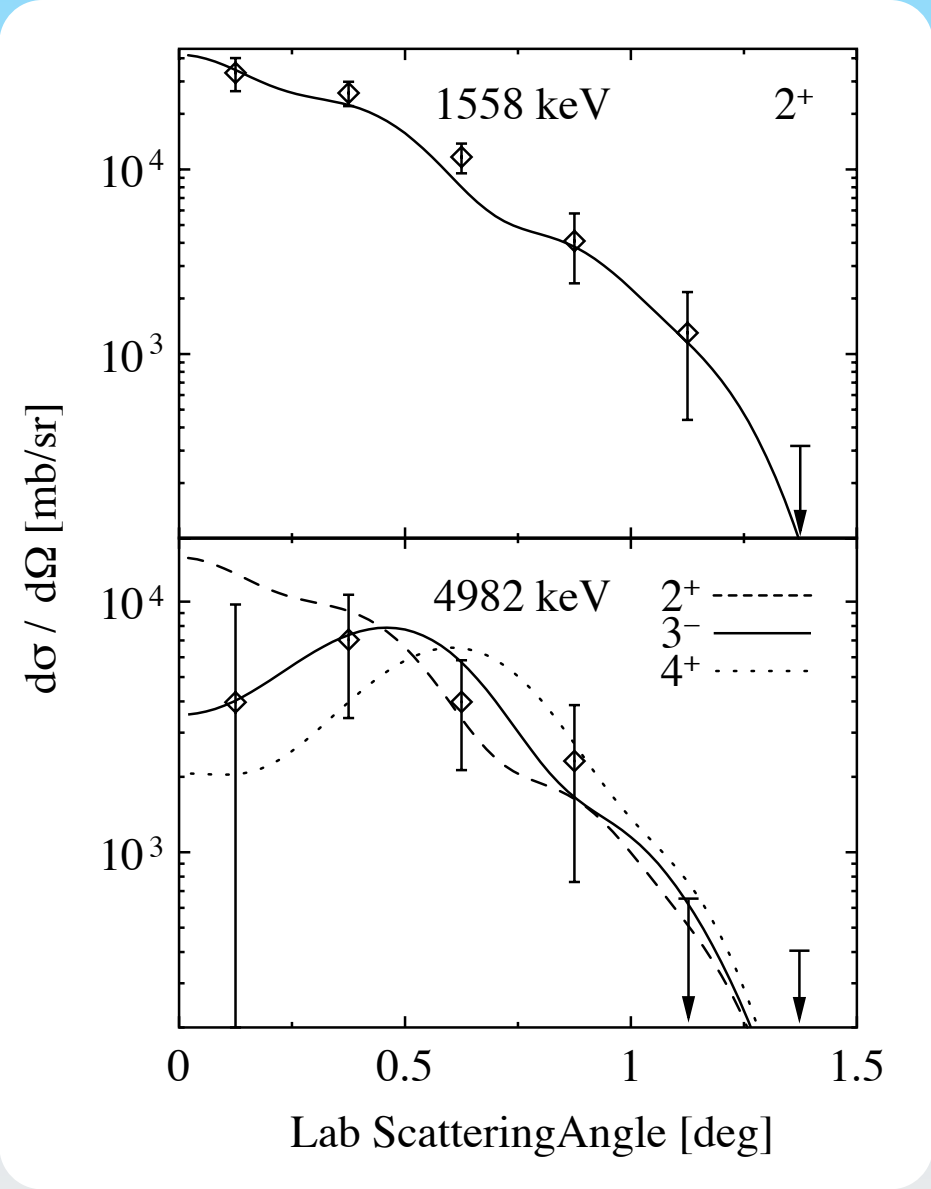
L. Riley et al., Phys. Rev. C 72, 024311 (2005)

- Doppler-corrected γ spectrum shows strongest peak ($2^+ \rightarrow 0^+$) as for Coulex
- Other excited states not seen in Coulex also populated
- Lab frame γ spectrum shows first excited state in ^{12}C
- Line shapes simulated using Geant



Angular distributions

- Angular distributions of scattered ^{46}Ar measured in S800 spectrograph in coincidence with γ-rays
- Comparison with coupled-channels code ECIS95 helps to identify spin-parity of states
- Calculations performed using a global optical potential fitted on stable nuclei (see lecture 2)

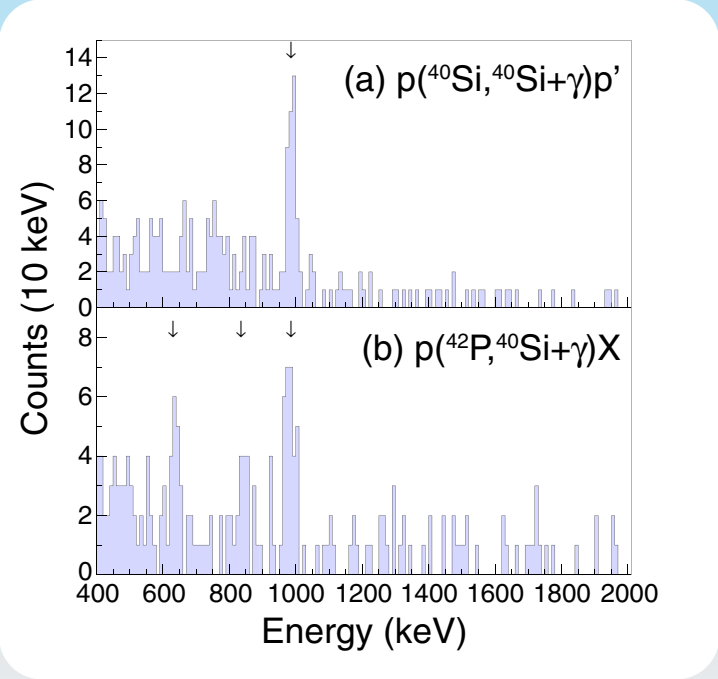


Knockout reactions

- Remove one or two nucleons from projectile by highly absorptive target (usually ^{9}Be)
- Momentum of heavy residue directly related to momentum of removed nucleon(s) - used to deduce its (their) angular momentum
- Final state of heavy residue known from in-flight γ-rays
- Total and partial cross sections lead to spectroscopic factors using eikonal theory to calculate single-particle cross sections
- Very high sensitivity (down to 1 particle/second)
- More details in Lecture 3

Other reactions

- Depending on the energy of the radioactive beam, other reactions involving a few nucleons are used to populate excited states of resulting nucleus
- Like in normal kinematics experiments, different reaction channels lead to different populations of excited states - reaction selectivity
- When using different radioactive beams (as in cocktail beams for instance), the same final nucleus can be produced via different reactions, which can help pinpoint spin-parity



From C. Campbell et al., to be submitted to Phys. Rev. Lett.

Unbound resonances

- Nuclei close to drip-lines have fewer bound excited states
  - Cannot use in-beam γ-ray spectroscopy when particle emission becomes dominant channel (in particular towards neutron-rich side)
  - Complete kinematics methods are required where as much of the reaction products as possible are detected
- Invariant mass method
  - Identify and measure momentum of all particles before and after the reaction - kinematically complete
  - Difficult experimentally - multi-detectors needed and low coincidence rates

Low-lying E1 strength in ^{11}Li

- ^{11}Li is a "Borromean" system (2n and ^{10}Li both unbound) S_{2n} = 0.3 MeV
- ^{11}Li is bound by nn correlations
- Coulomb breakup of ^{11}Li by a Pb target leads to ^{9}Li+n+n
- All 3 particles identified and have their momentum vector measured
- Cross section as a function of ^{11}Li excited state invariant mass

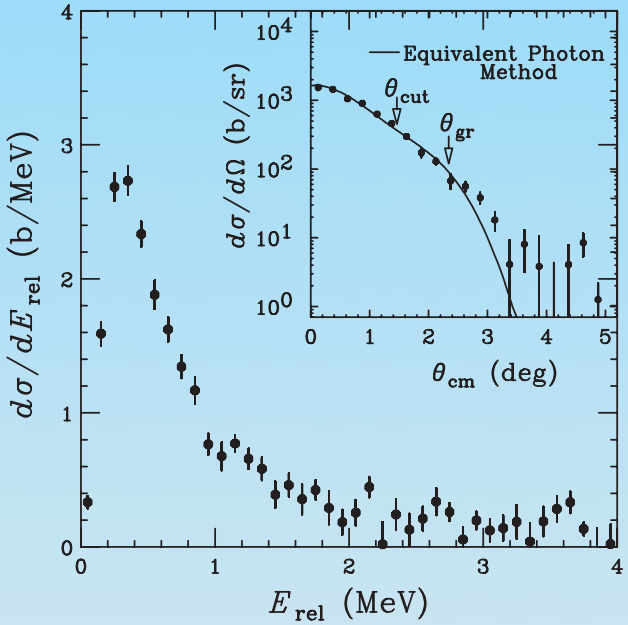


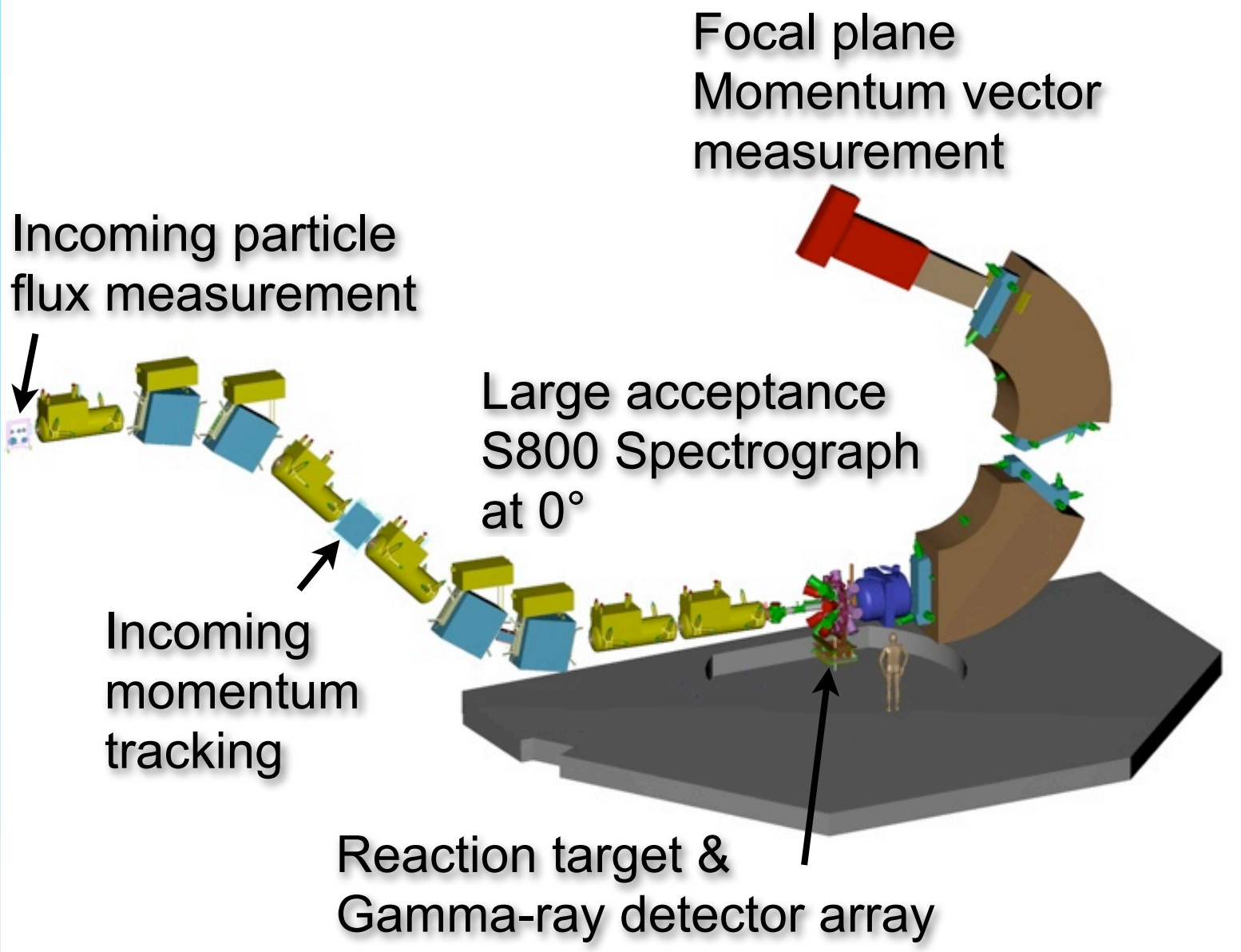
FIG. 2. Breakup cross sections for ^{11}Li + Pb at 70 MeV/nucleon as a function of the three-body relative energy for data with $\theta_{cm} \leq 5°$. Inset: Angular distribution of ^{11}Li (the ^{9}Li + n + n c.m.) scattered by the Pb target in the range $0 \leq E_{rel} \leq 4$ MeV. θ_{gr} denotes the grazing angle (2.34°). The calculation using the equivalent photon method is shown by the solid curve.

T. Nakamura et al., PRL 96, 252502 (2006)

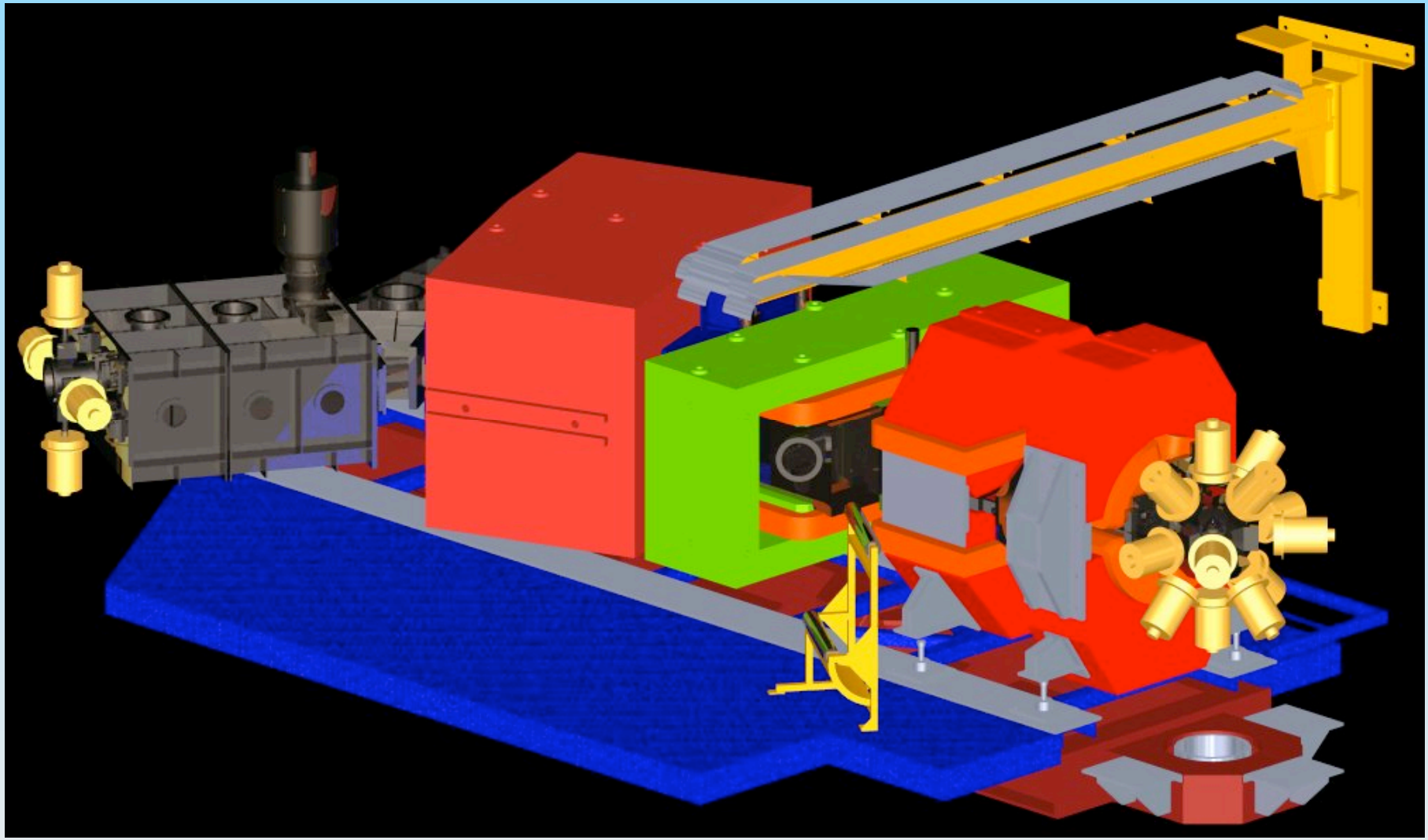
Some instruments used in radioactive beam reaction studies

- Zero degree filtering device (spectrometer) to collect and identify heavy reaction residue
- Detector array surrounding reaction target to capture γ-rays emitted during the reaction
- For complete kinematics experiments: light particle detector array(s) at small angles
- Neutron detection particularly challenging - energy by time-of-flight - efficiency important issue

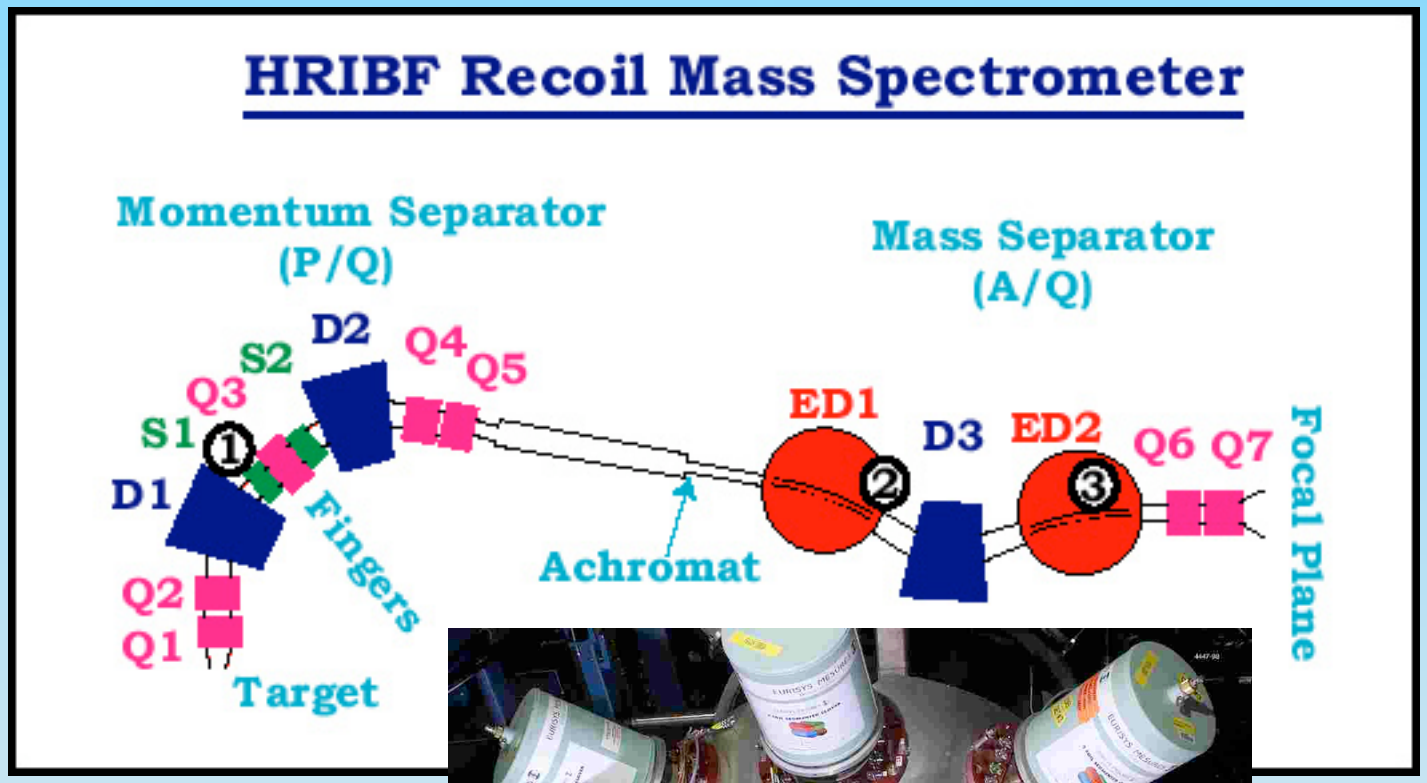
S800 + SeGa @ NSCL



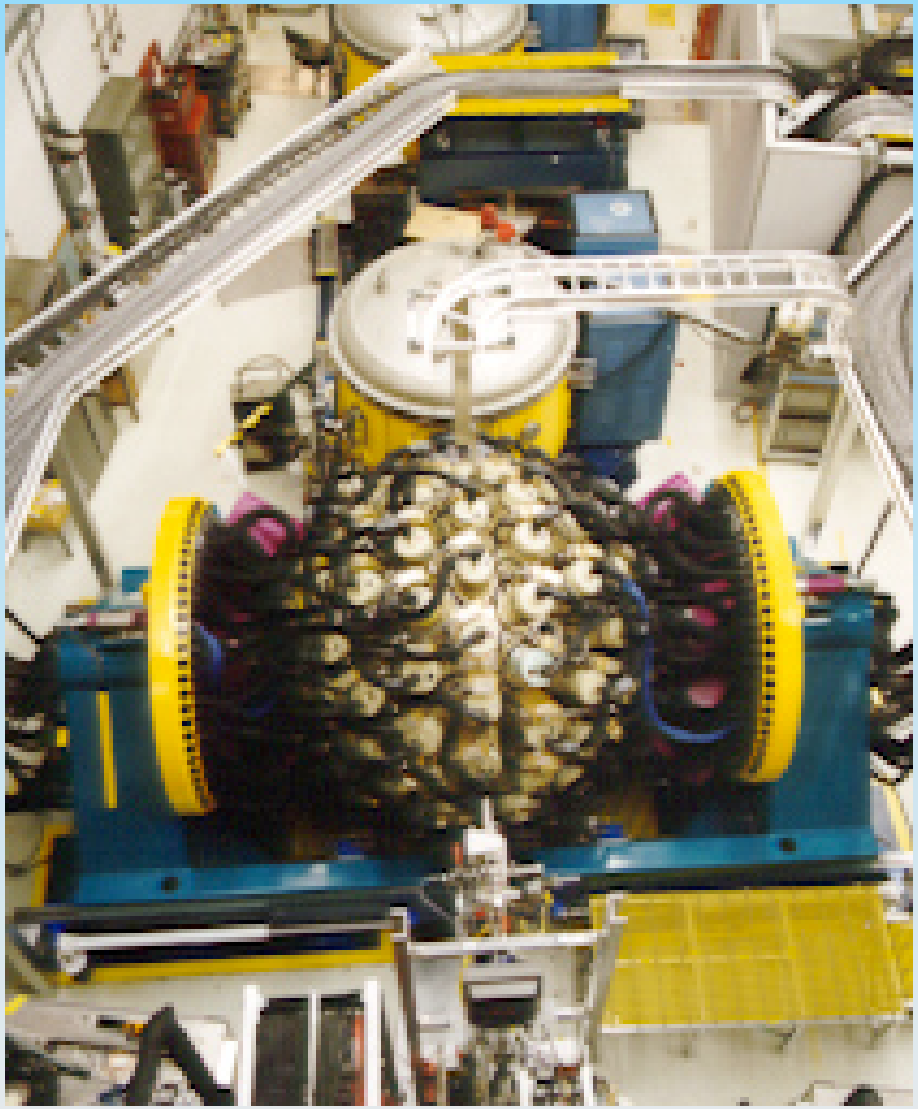
VAMOS + Exogam @ GANIL



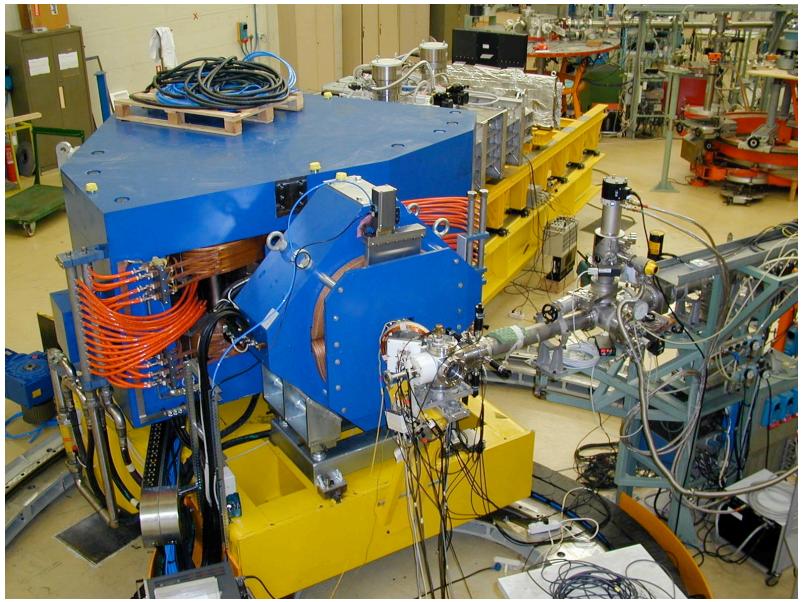
RMS + CLARION @ HRIBF

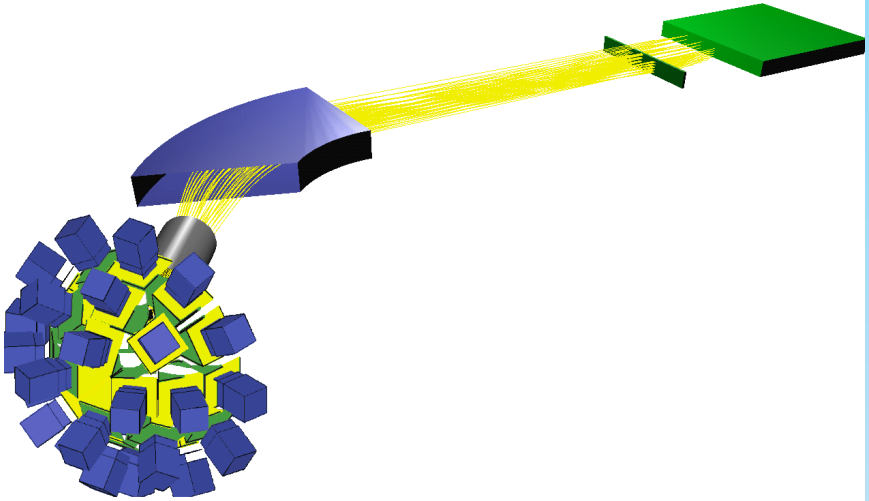


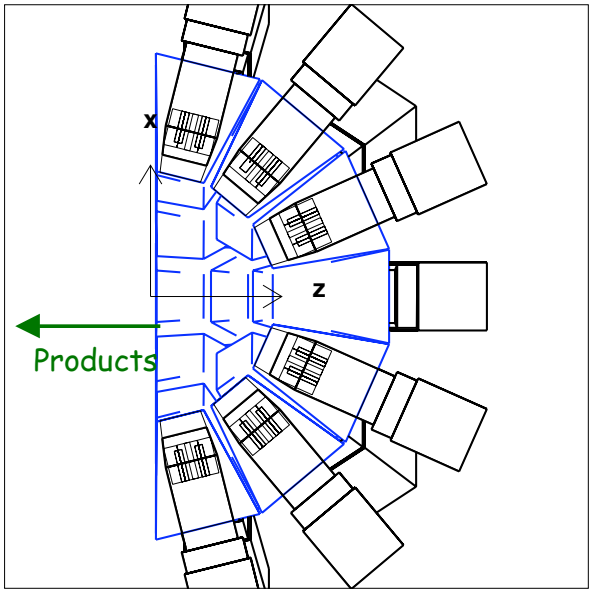
FMA + GammaSphere @ ANL



Prisma + Clover array @ Legnaro

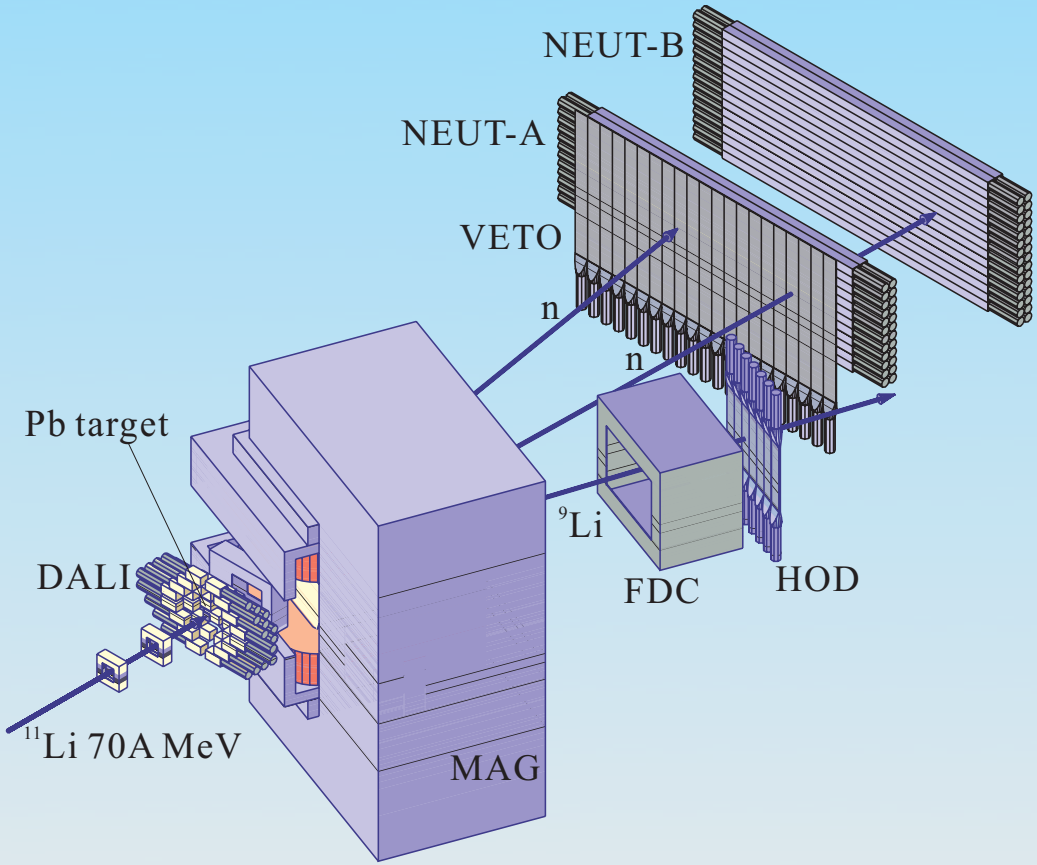




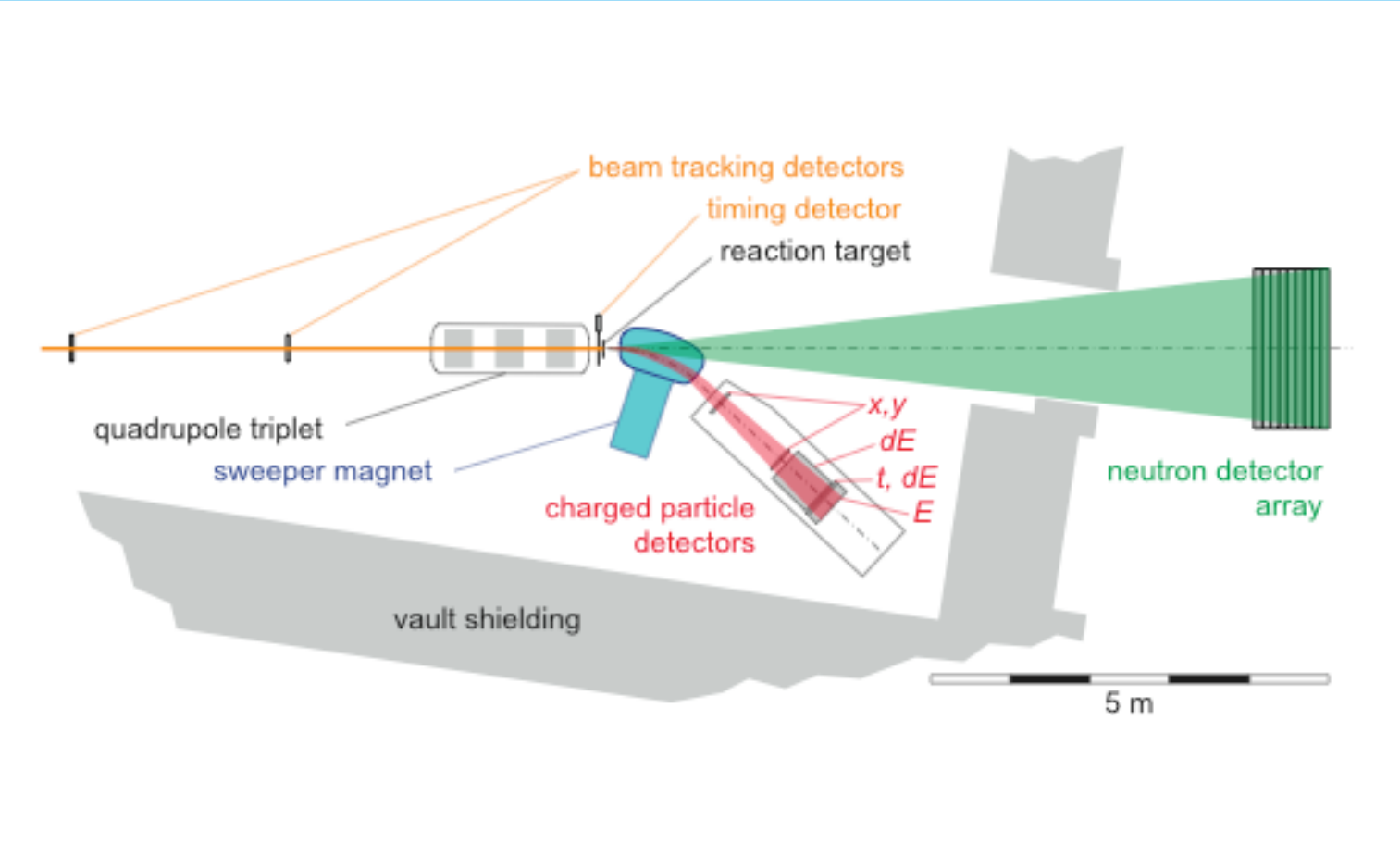


- 24 to 25 Clovers setup
- Efficiency ~ 3 %
- Peak/Total ~ 50 %
- Position θ = 104°-156°
- FWHM ~ 10 keV for E_γ = 1.3MeV
  at v/c = 10 %

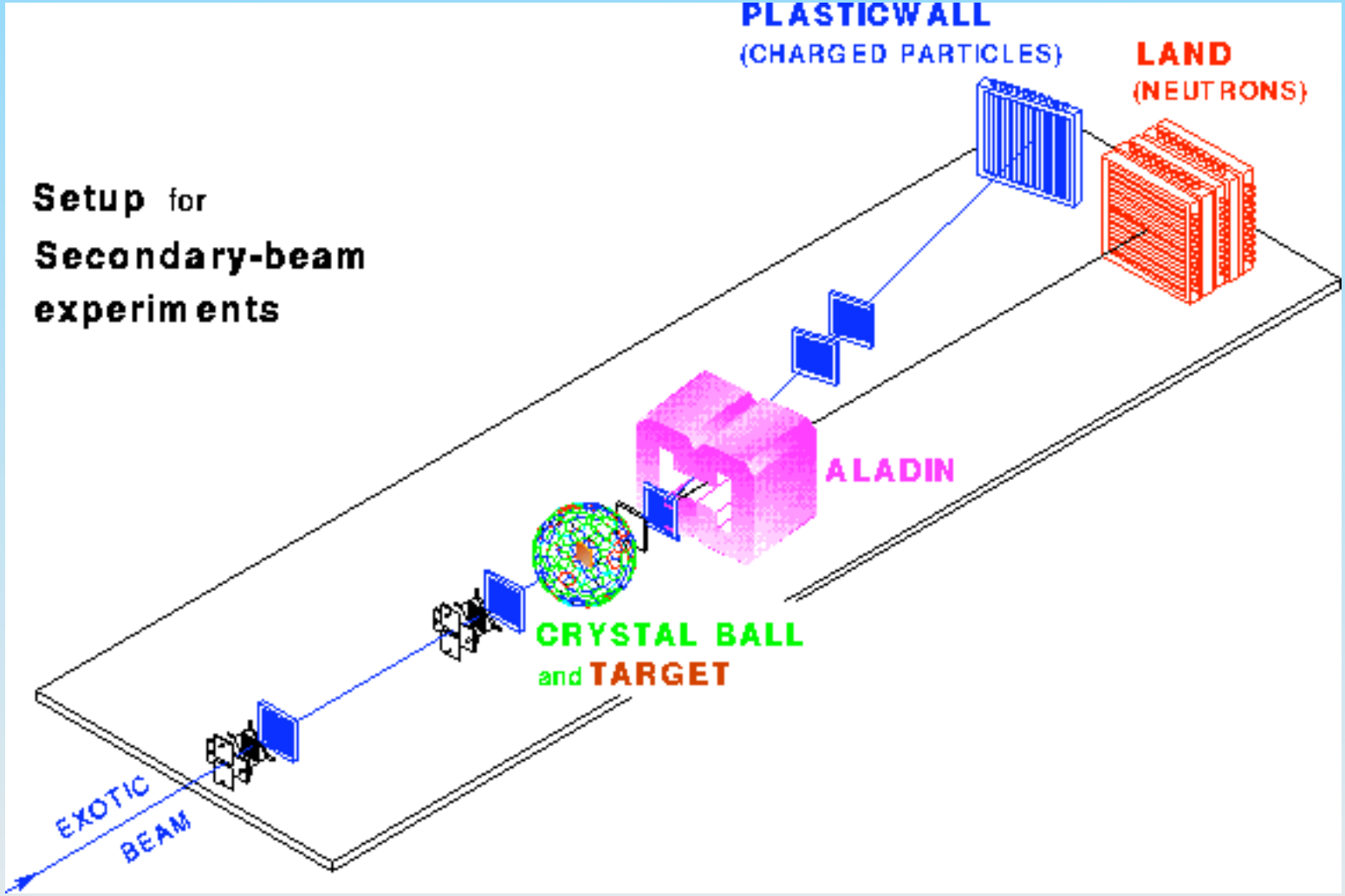
DALI + MAG @ RIKEN



Sweeper + MoNA @ NSCL

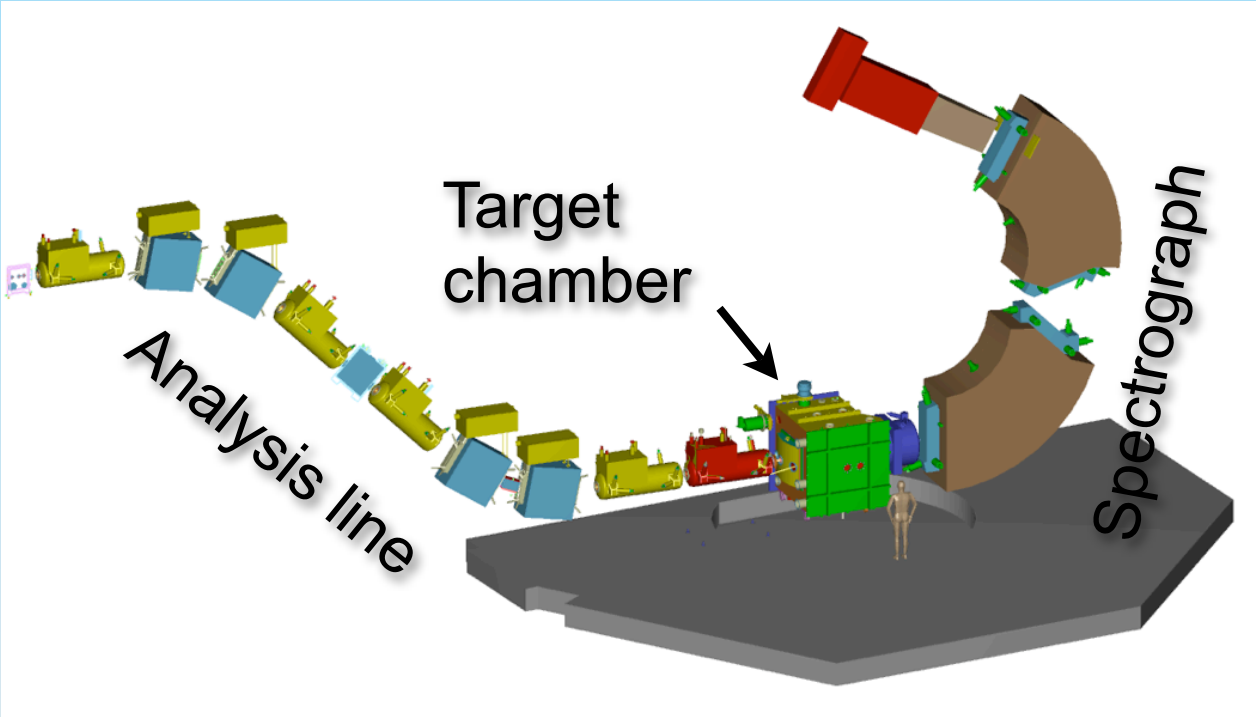


Aladin + Land @ GSI

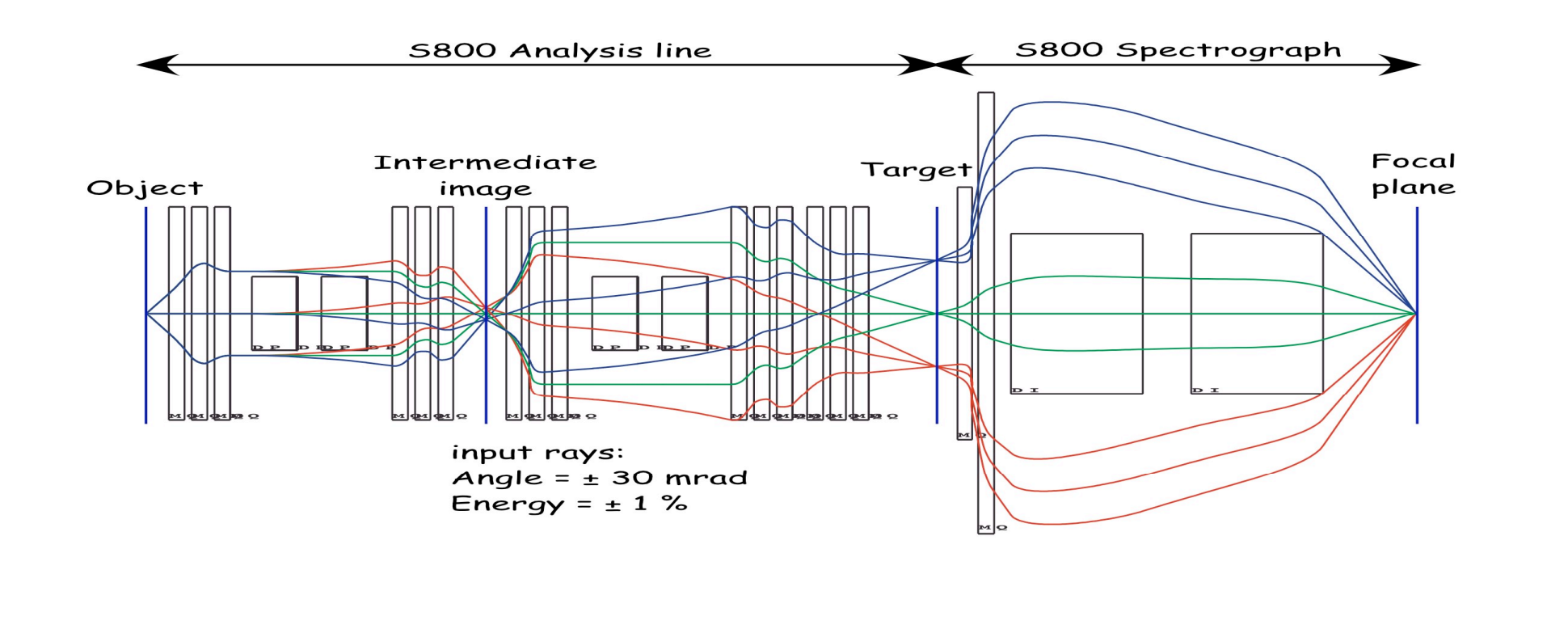


Example of experimental device: S800 as energy loss spectrograph

- Analysis line can be used in various modes, to prepare optical properties of radioactive beam
- Spectrograph is big because of large acceptances
- 10% ΔE/E, 20 msr
- 10^{-4} ΔE/E, 2 mrad scattering angle



Dispersion matching mode



- Analysis line disperses the radioactive beam at target location
- Without target: all particles refocussed in focal plane
- Position at focal plane only depends on energy lost in target, due to nuclear reaction

Trajectory reconstruction in spectrograph

- Principle of calculation
  - Calculate aberrations to order n using field maps and COSY infinity
  - Inverse transfer map S
  - Apply map to data to get energy and scattering angle at target

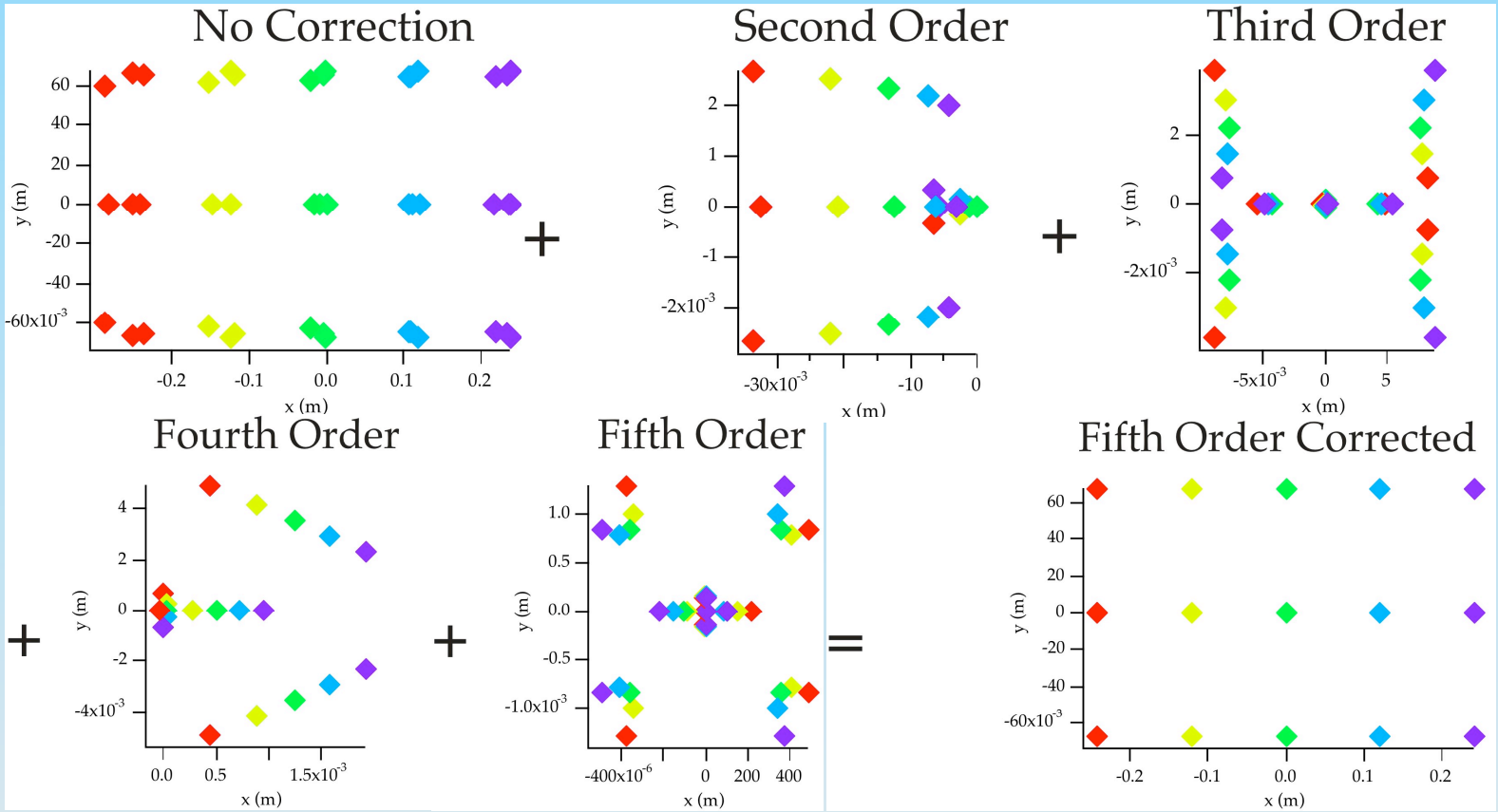
$$\begin{pmatrix} x_f \\ \theta_f \\ y_f \\ \phi_f \end{pmatrix} = S \begin{pmatrix} \delta_i \\ \theta_i \\ y_i \\ \phi_i \end{pmatrix} \quad \Rightarrow \quad \begin{pmatrix} \delta_i \\ \theta_i \\ y_i \\ \phi_i \end{pmatrix} = S^{-1} \begin{pmatrix} x_f \\ \theta_f \\ y_f \\ \phi_f \end{pmatrix}$$

$$(x_i = 0)$$

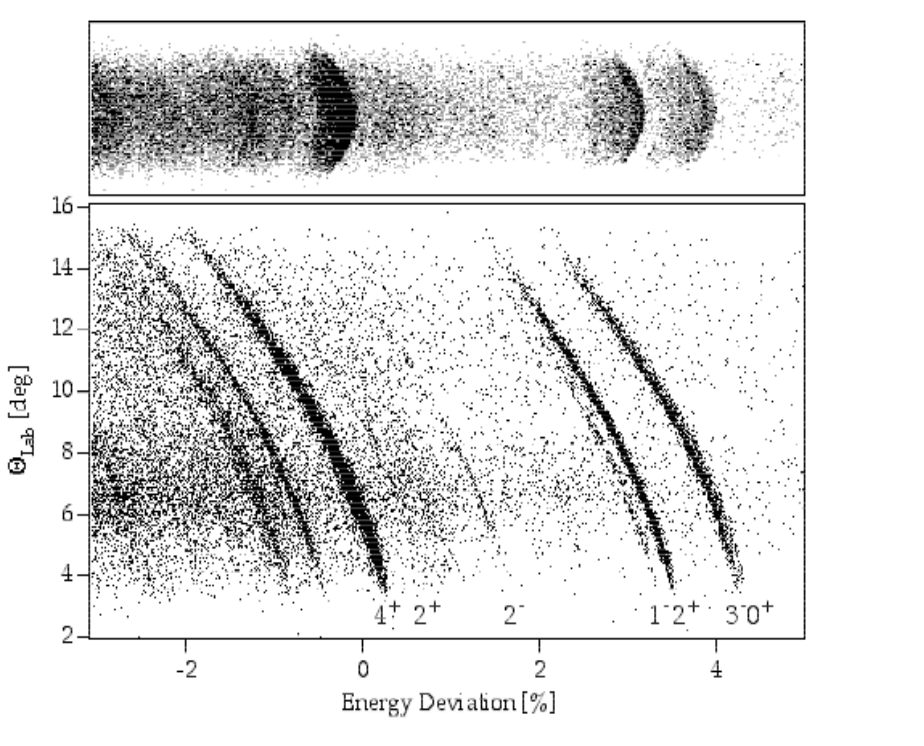
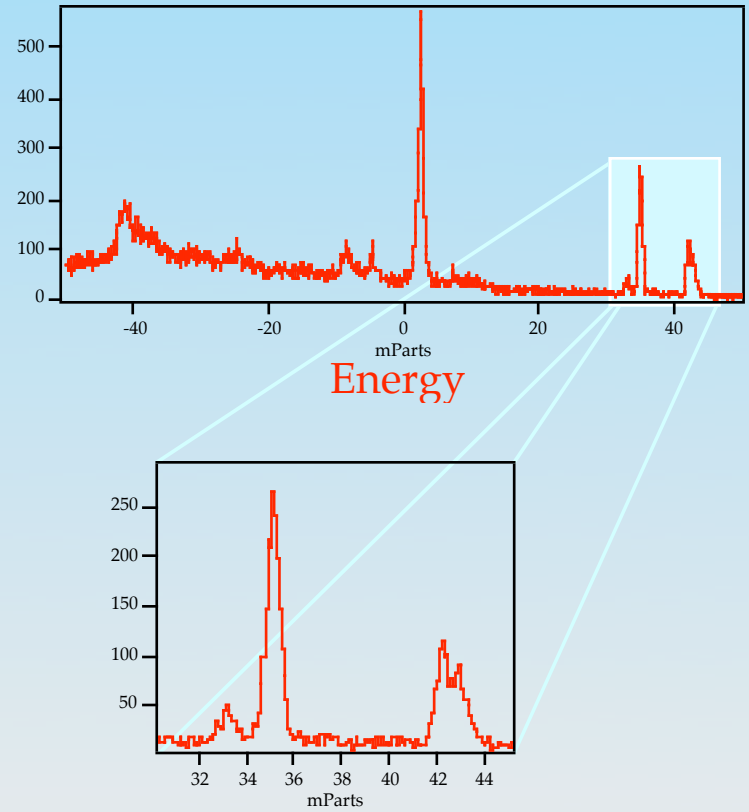
- Resolutions
  - Depend on object size (x_i), detector resolutions and accuracy of transfer map

Aberration calculations

Initial Grid: -5%<Energy<5% ; -60mr<Theta<60mr ; -90mr<Phi<90mr



Expected energy resolution for a 1mm spot size: 1 part in 5000 in Energy

Example of reconstruction

- Reaction: $^{12}C(^{7}Li,^{3}H)^{16}O$ at 19 MeV/u
  - Spectrograph rotated at 8°
  - Energy resolution of 1/1800 over full acceptance (20 msr)