Introducción a la física nuclear con Núcleos exóticos

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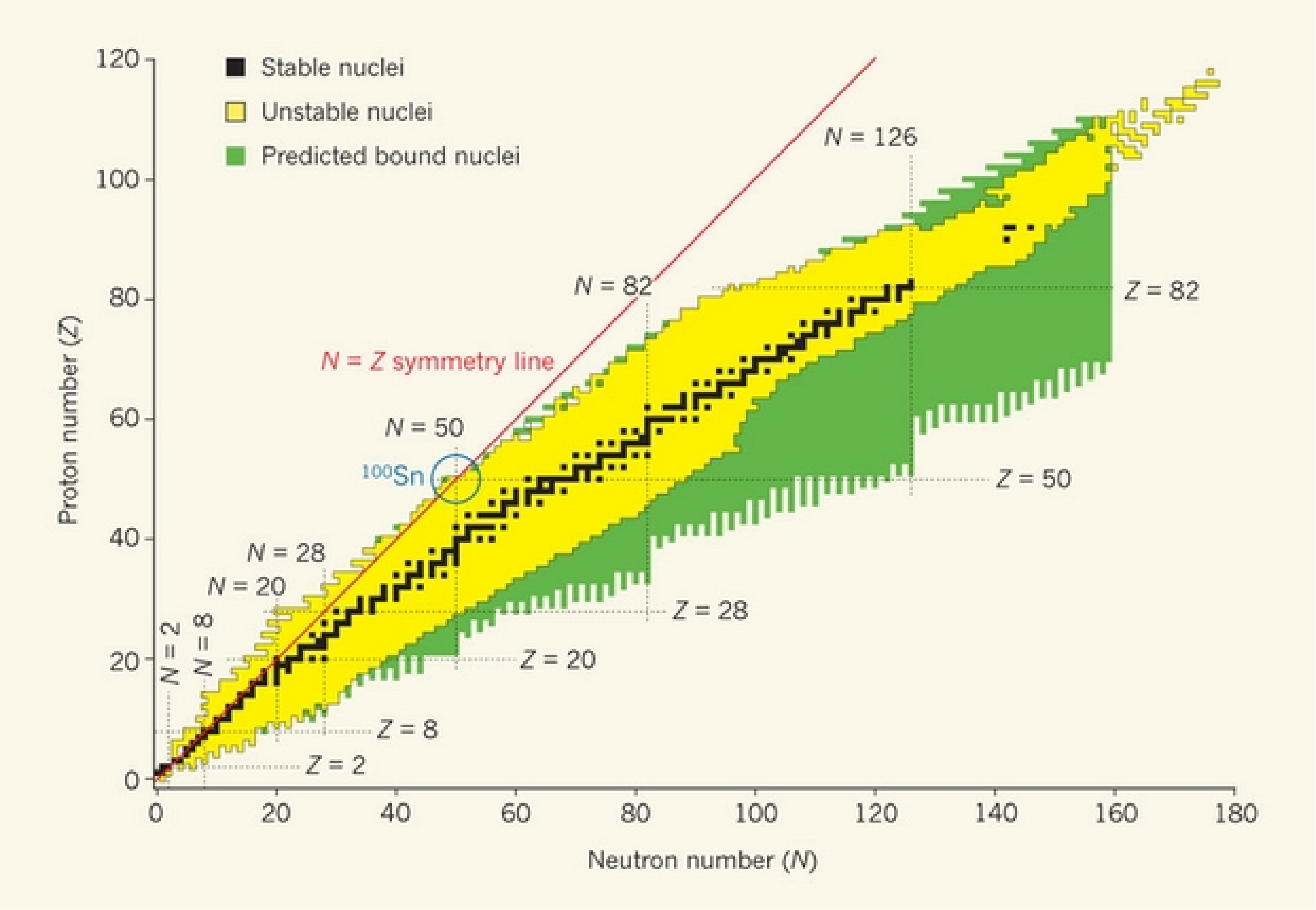
Layout

- ✓30 years of radioactive beams
- ✓Experimental investigation of the atomic nucleus
- ✓ Production of exotic beams
- ✓ Why different experimental approaches?
- ✓Few selected examples

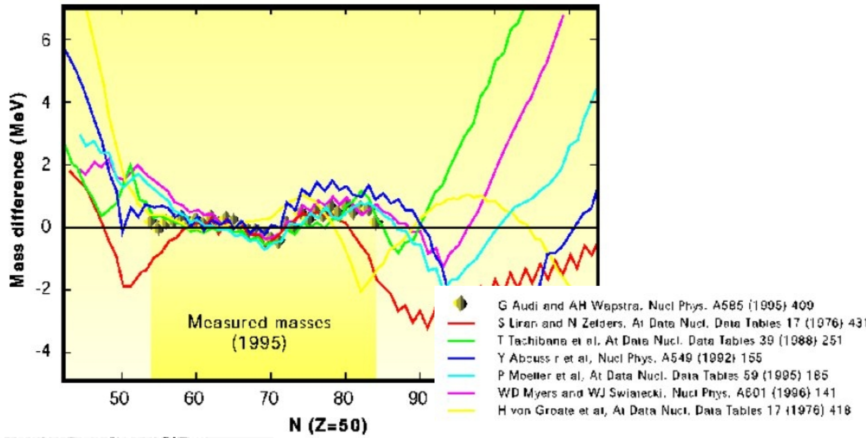
30 years of radioactive beam



Experimental investigation of the atomic nucleus

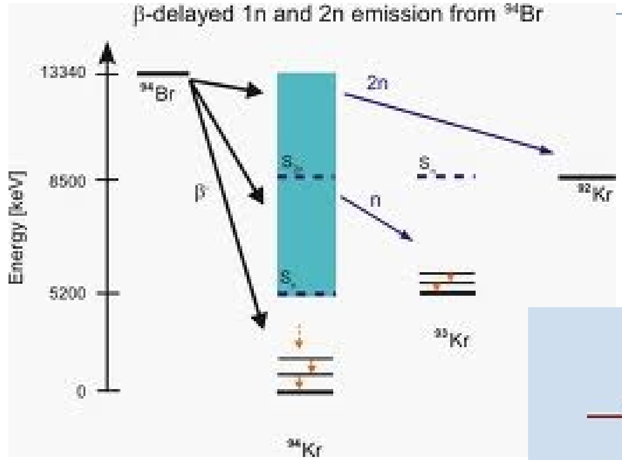
✓ Ground-state properties.

- masses
- size: matter and charge radial distributions, deformation
- electromagnetic moments



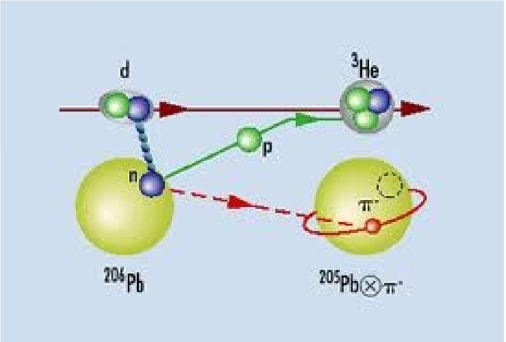
✓ Radioactive decays.

- decay properties
- beta-delayed gamma emission
- beta-delayed particle emission



✓ Nuclear reactions.

- direct reactions
- compound nucleus reactions



Experimental investigation of the atomic nucleus

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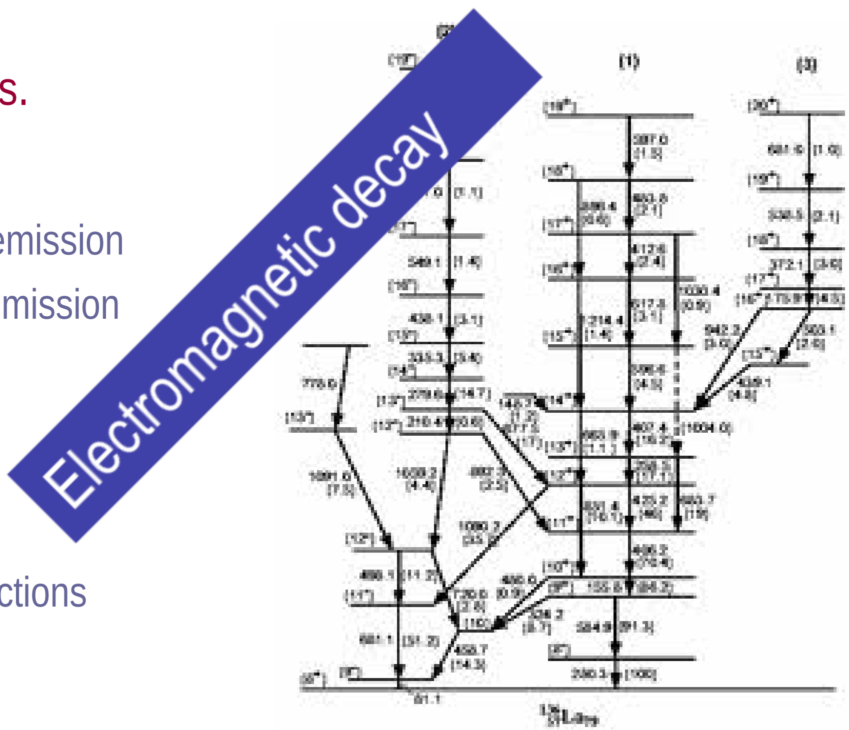
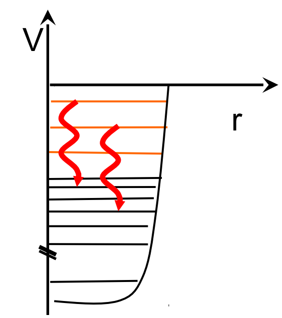
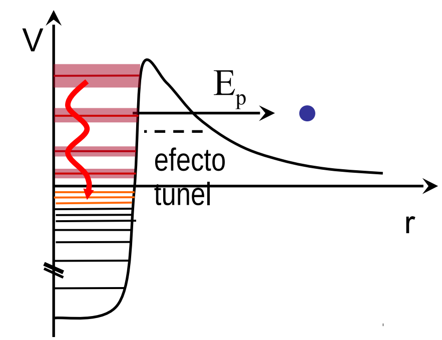
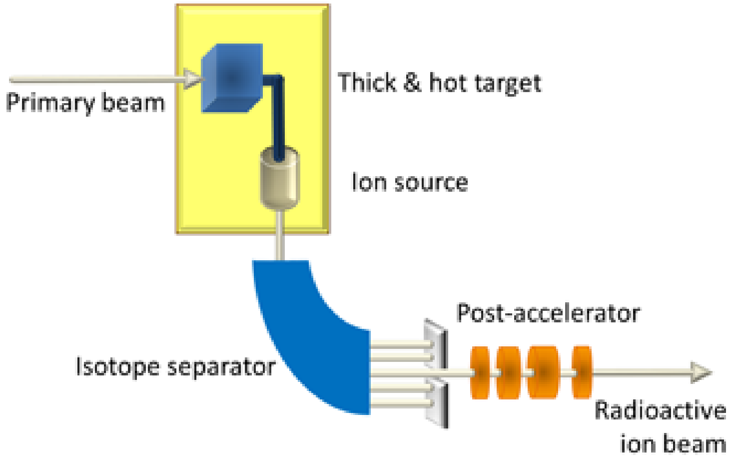






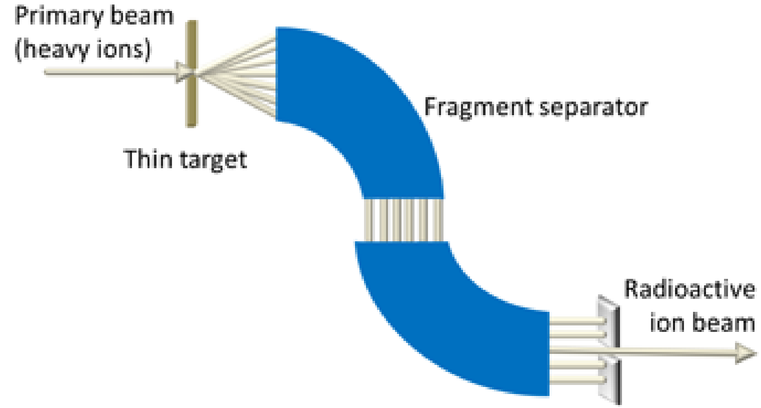
Production of radioactive beams

ISOL



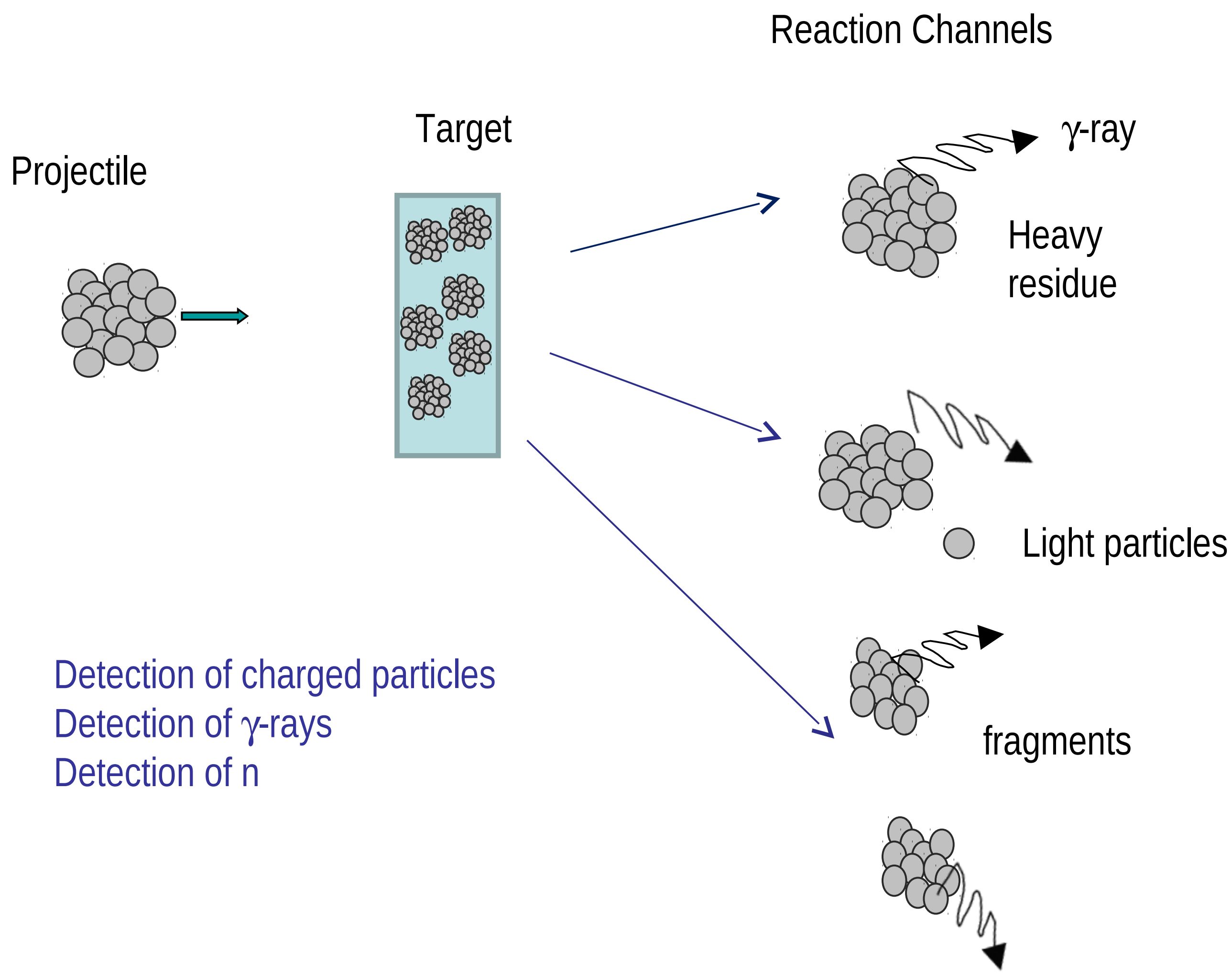
- Low energy
- ms preparation time
- good beam quality

IN-FLIGHT



- High energy
- µs flight path
- poor beam quality

Experiment with radioactive beams : detection

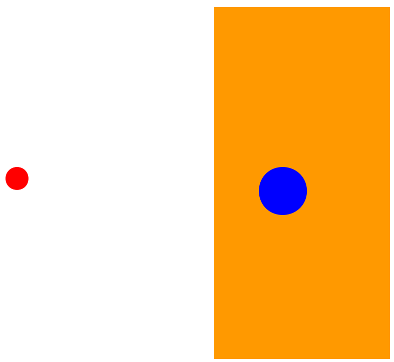


Detection of charged particles
Detection of γ-rays
Detection of n

The use of inverse kinematics

Direct kinematics

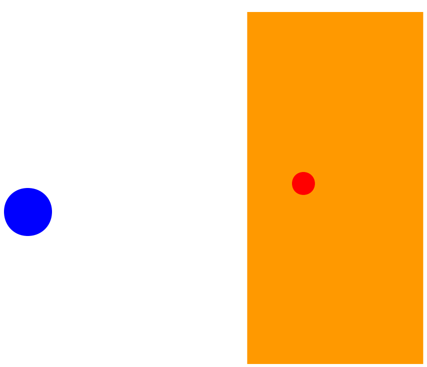
Light projectile impinging into a heavy target nucleus



- light jectiles can be detected
- target residue can only be idenfied using radiative processes

Inverse kinematics

Light projectile impinging into a heavy target nucleus



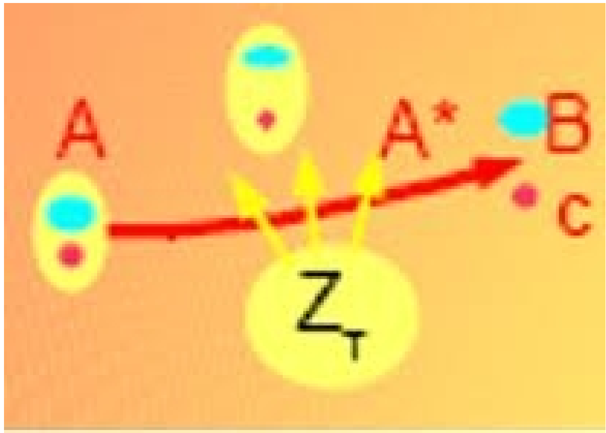
- light and heavy ectiles can be detected

The use of inverse kinematics

Advantages

✓ Reactions induced by exotic projectiles

$$^{8}B(\gamma, p)^{7}Be$$



The use of inverse kinematics

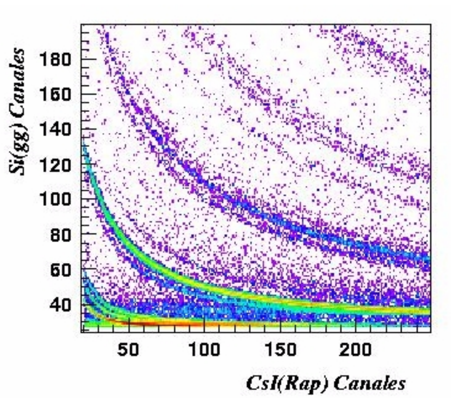
Advantages

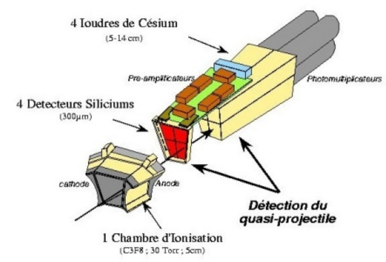
✓ Reactions induced by exotic projectiles

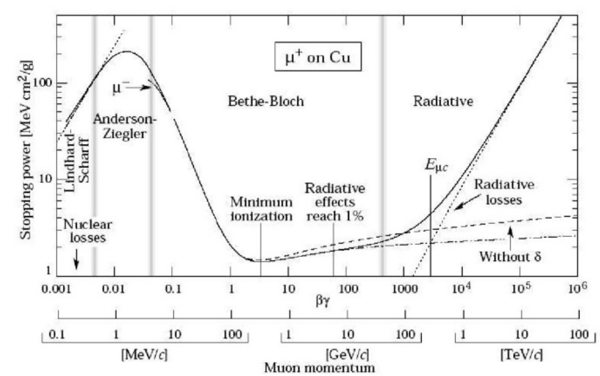
✓ Improved charge identification of reaction ejectiles

$$\frac{dE}{dx} = f(Z^2, A, \beta\gamma)$$

$$R \propto \frac{\sqrt{A \cdot E}}{Z^{2/3}}$$







The energy deposition of ions with Z > 40 and E < 1 A MeV is below the Bragg peak.

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The use of inverse kinematics

Advantages

- ✓ Reactions induced by exotic projectiles
- ✓ Improved charge identification of reaction ejectiles
- ✓ Heavy ejectiles fully identified in Z and A

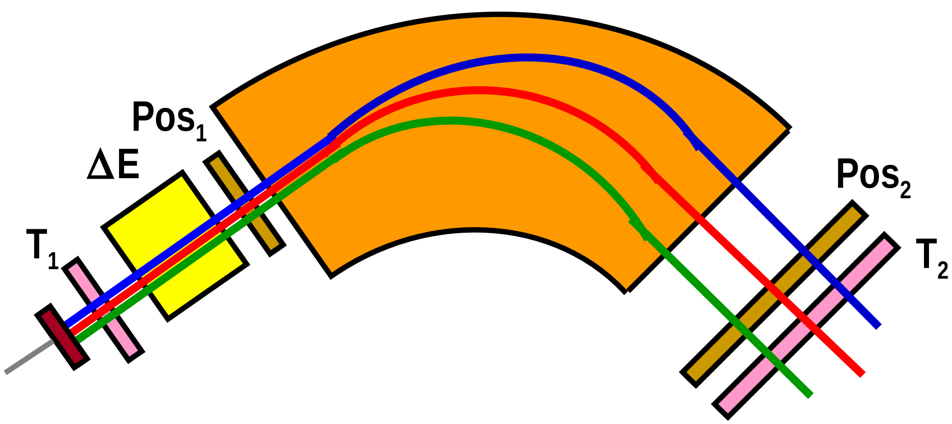
$$B\rho \propto \frac{A}{q}\beta\gamma$$

$Pos_{1}, Pos_{2} \rightarrow L_1, L_2, L_3 \rightarrow \rho_1, \rho_2, \rho_3$

$T_{1}, T_2 \rightarrow L_1, L_2, L_3 \rightarrow \beta\gamma_1, \beta\gamma_2, \beta\gamma_3$

$\Delta E_{1}, \Delta E_2, \Delta E_3\ (q=Z) \rightarrow Z_1, Z_2, Z_3$

$\Big\}\ A_1, A_2, A_3$



The use of inverse kinematics

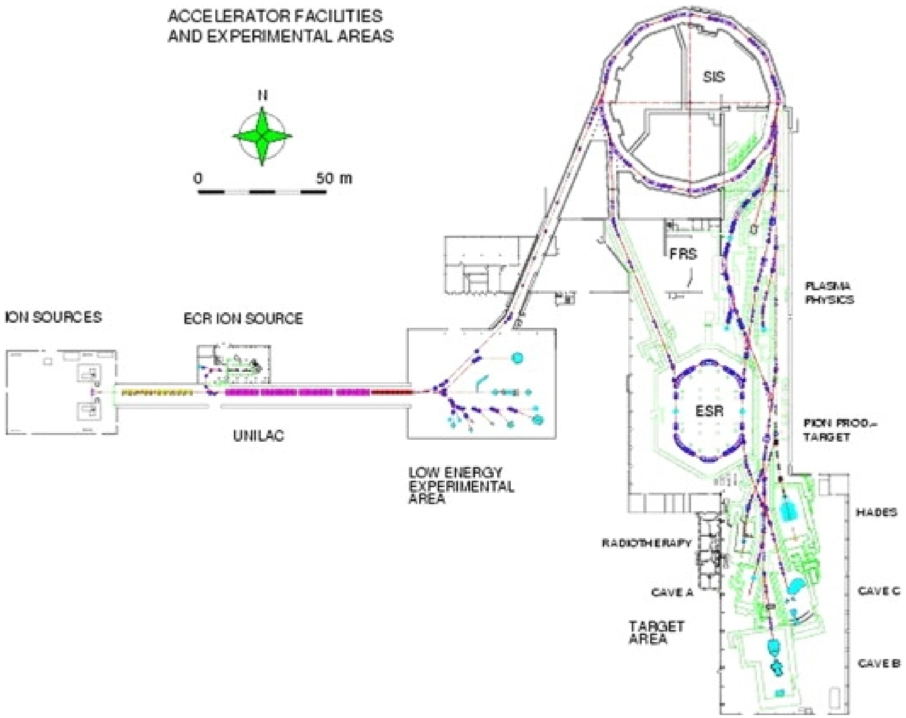
Drawbacks

✓ Complex heavy-ion accelerators with limited beam intensities

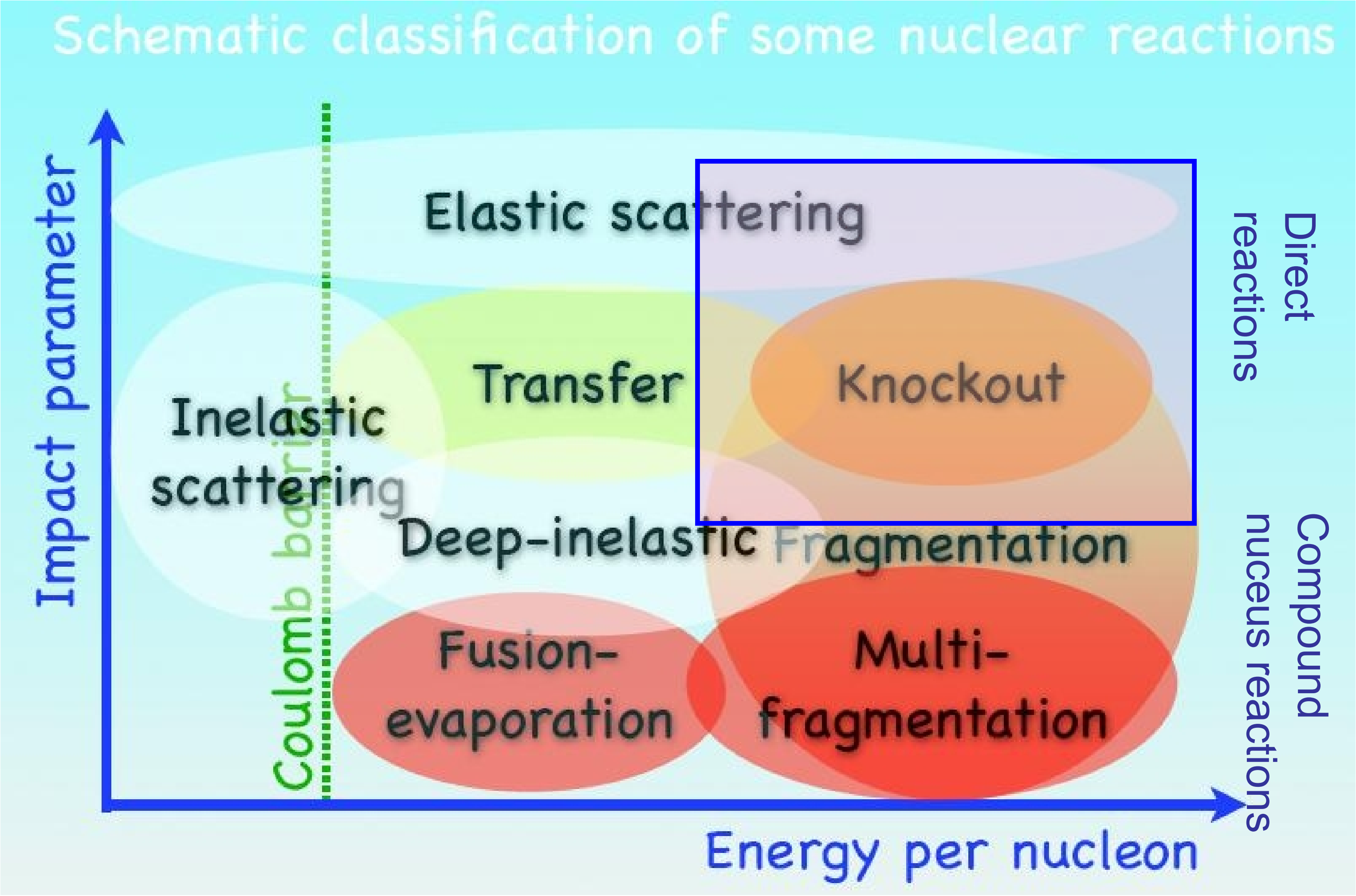
Present acceleration technologies:

- proton accelerators ~ 10^{16} p/s

- heavy-ion accelerators ~ 10^{12} ions/s



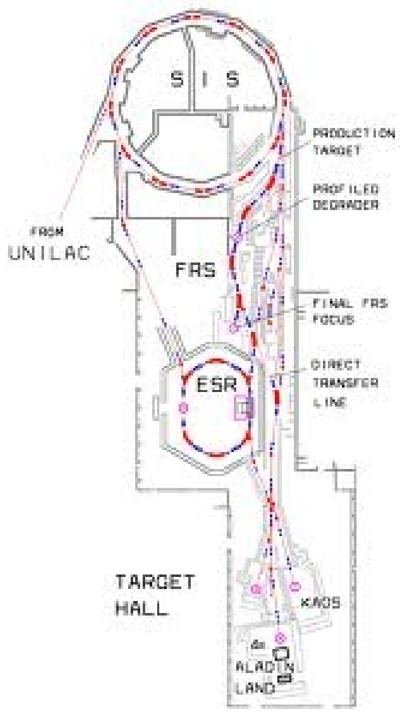
Exploring the nucleus

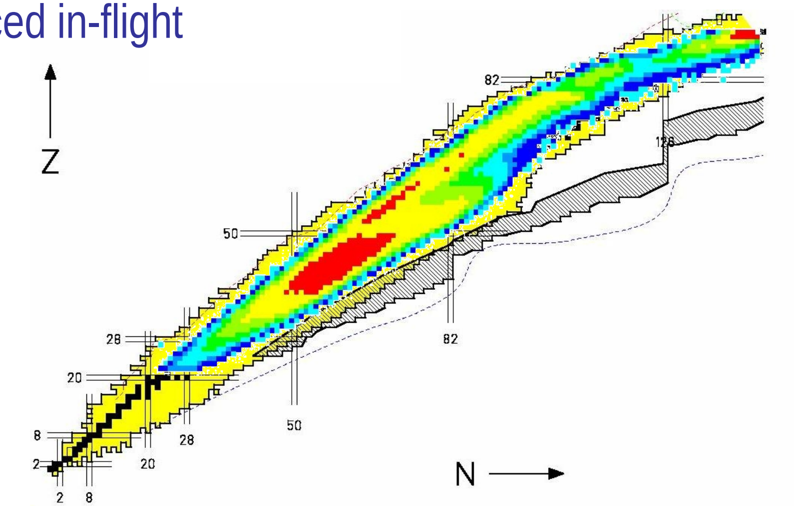


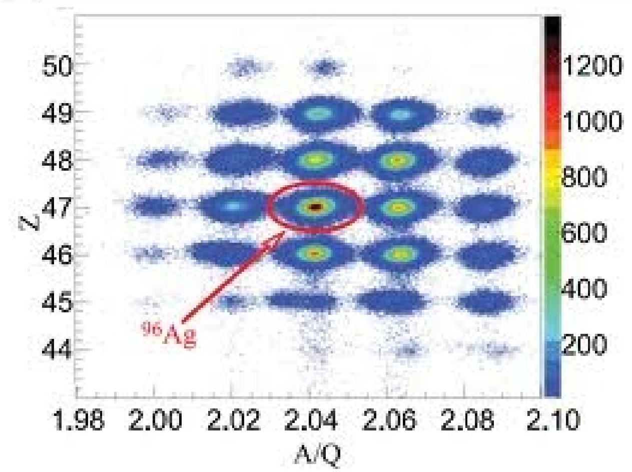
The use of relativistic energies

Advantages

- ✓ Exotic nuclei can be produced in-flight



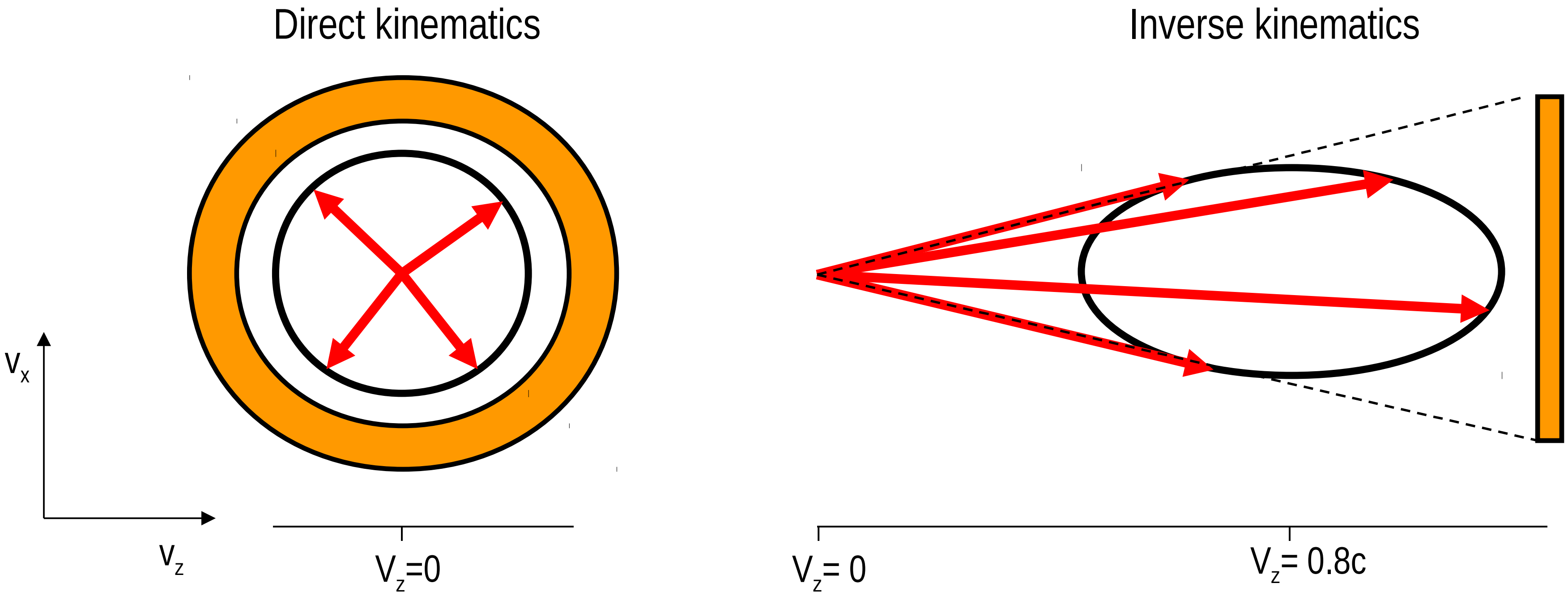




The use of relativistic energies

Advantages

- ✓ Exotic nuclei can be produced in-flight
- ✓ Detectors with smaller angular acceptance



The use of relativistic energies

Advantages

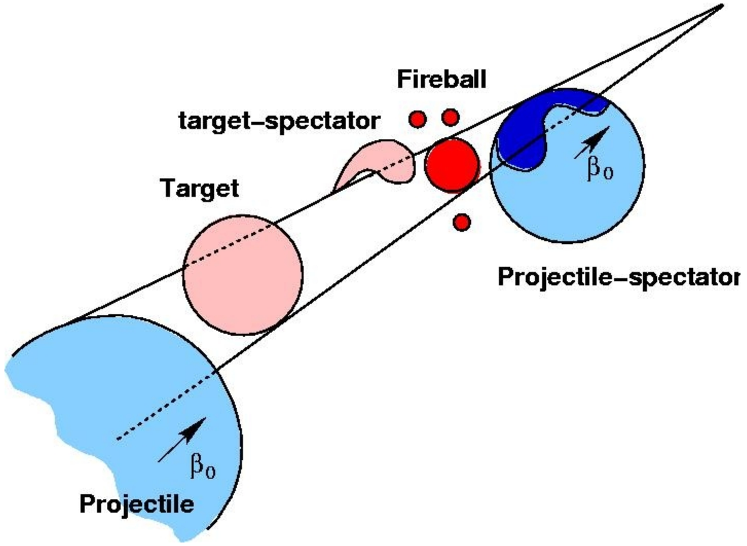
- ✓ Exotic nuclei can be produced in-flight
- ✓ Detectors with smaller angular acceptance
- ✓ Thicker targets
- ✓ Simpler description of the reaction mechanism

Glaubel picture:

- adiabatic approximation

- eikonal approximation (out-going plane wave): direct reactions

- participant-spectator picture: compound nucleus reactions



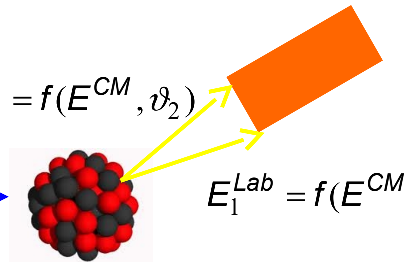
The use of relativistic energies

Drawbacks

- ✓ Gamma rays are Lorentz boosted

$$DF = \frac{E^{Lab}}{E^{CM}} = \frac{1}{\gamma(1-\beta\cos\vartheta)}$$

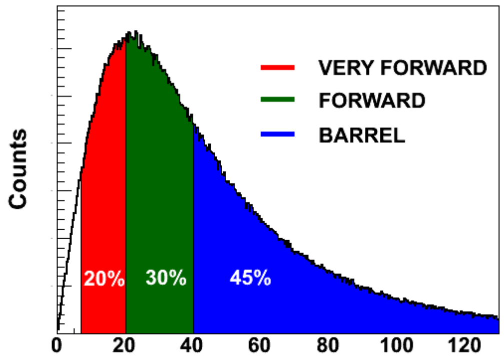
$$E_2^{Lab} = f(E^{CM}, \vartheta_2)$$

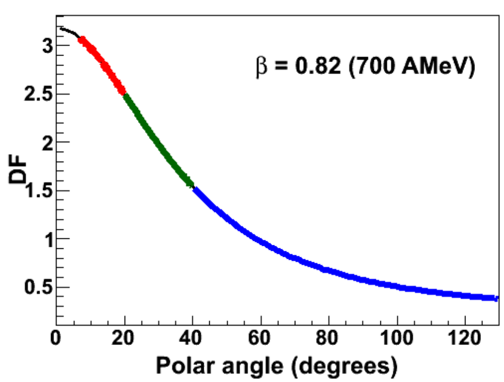


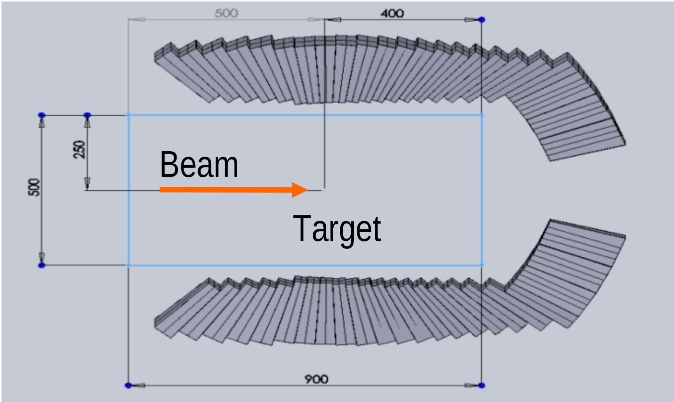
β ~ 0.8 c

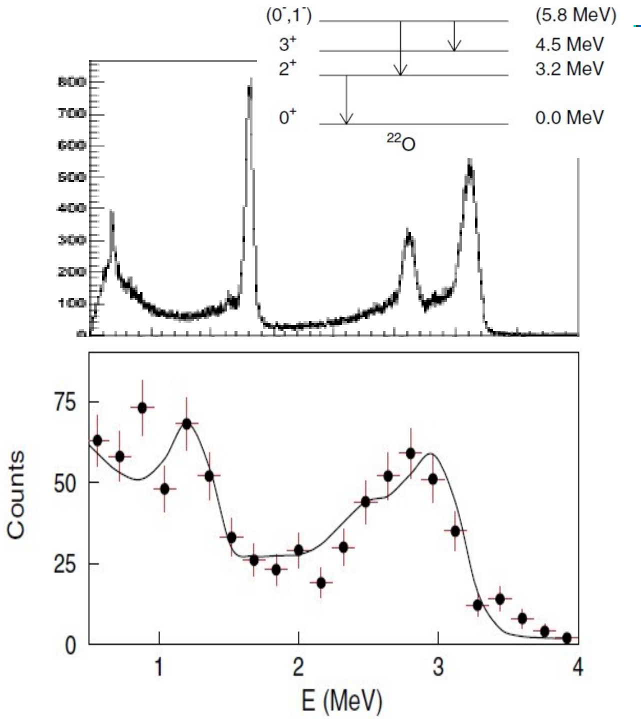
$$E_1^{Lab} = f(E^{CM}, \vartheta_1)$$

$$\frac{\Delta E^{Lab}}{E^{Lab}} = \frac{\beta\sin}{1-\beta\cos\vartheta}\Delta\vartheta$$





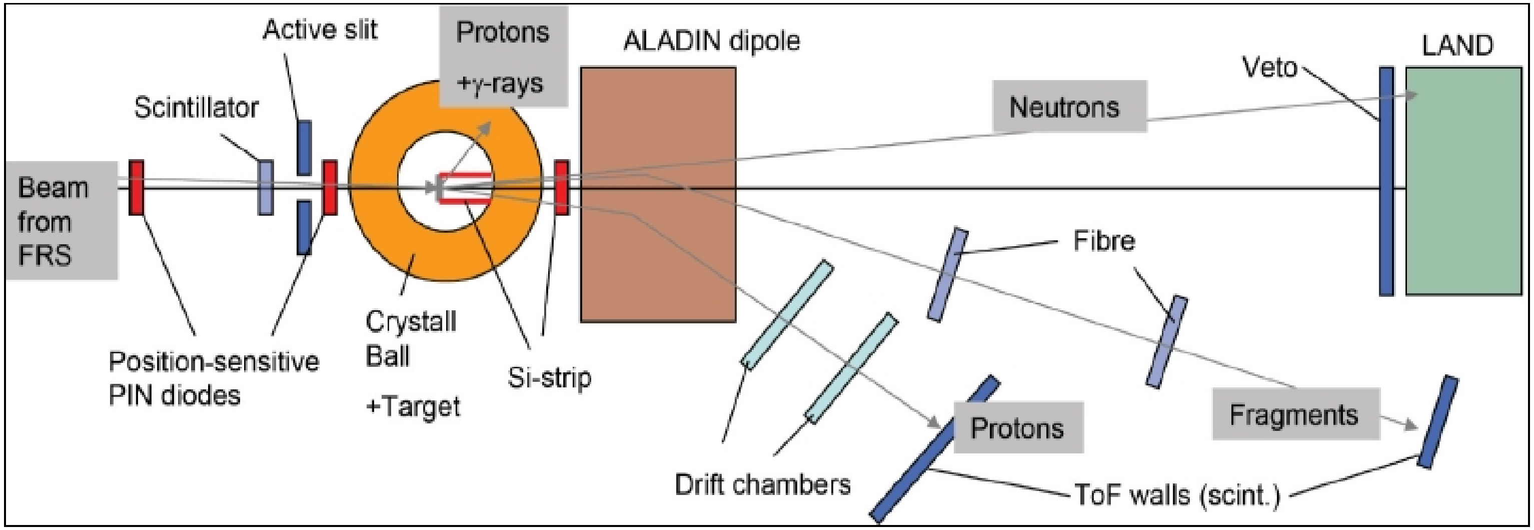




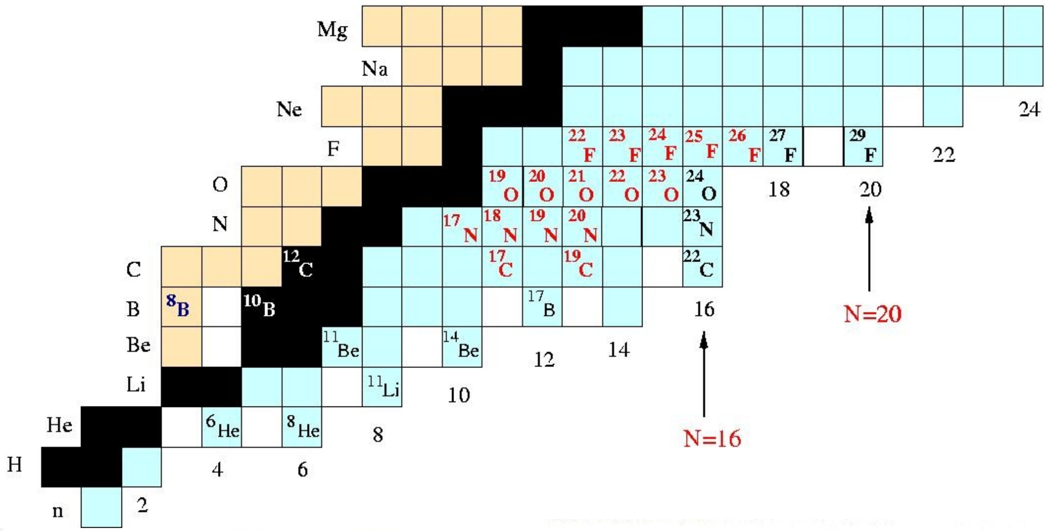
The use of relativistic energies

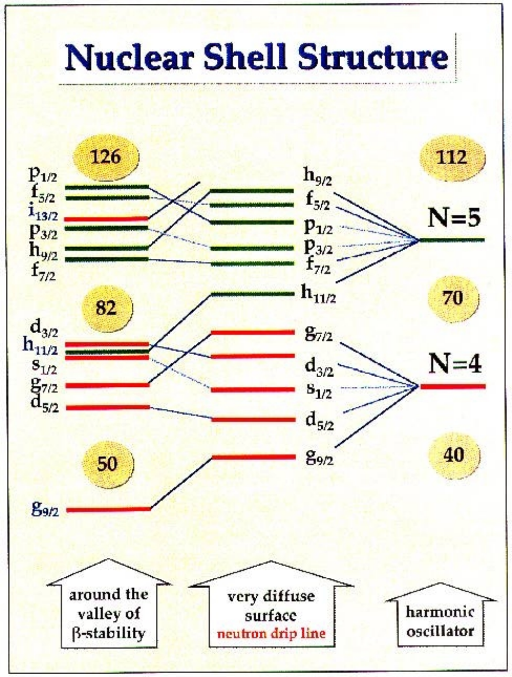
Drawbacks

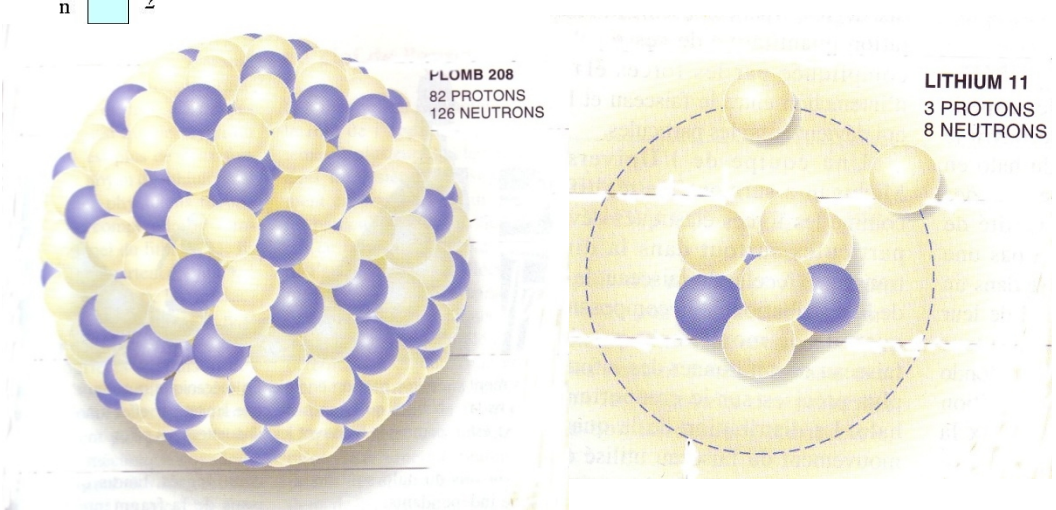
- ✓ Gamma rays are Lorentz boosted
- ✓ Light ejectiles require complex detectors



Exotic phenomena







- Núcleos muy poco ligados ➔ extensión espacial
- Presentan topologías y efectos estructurales exóticos
- Accesibles experimentalmente

Nuclear structure investigations

Knock-out reactions

This is a "quasi-free" scattering on the valence nucleons leading to a bound residual nucleus (A-1) not necessarily on its ground state

The accurate measurement of the longitudinal momentum of the residual nucleus in inverse kinematics, and the possible gamma rays emitted during the knock-out charactarize the ground state of the projectile nucleus.

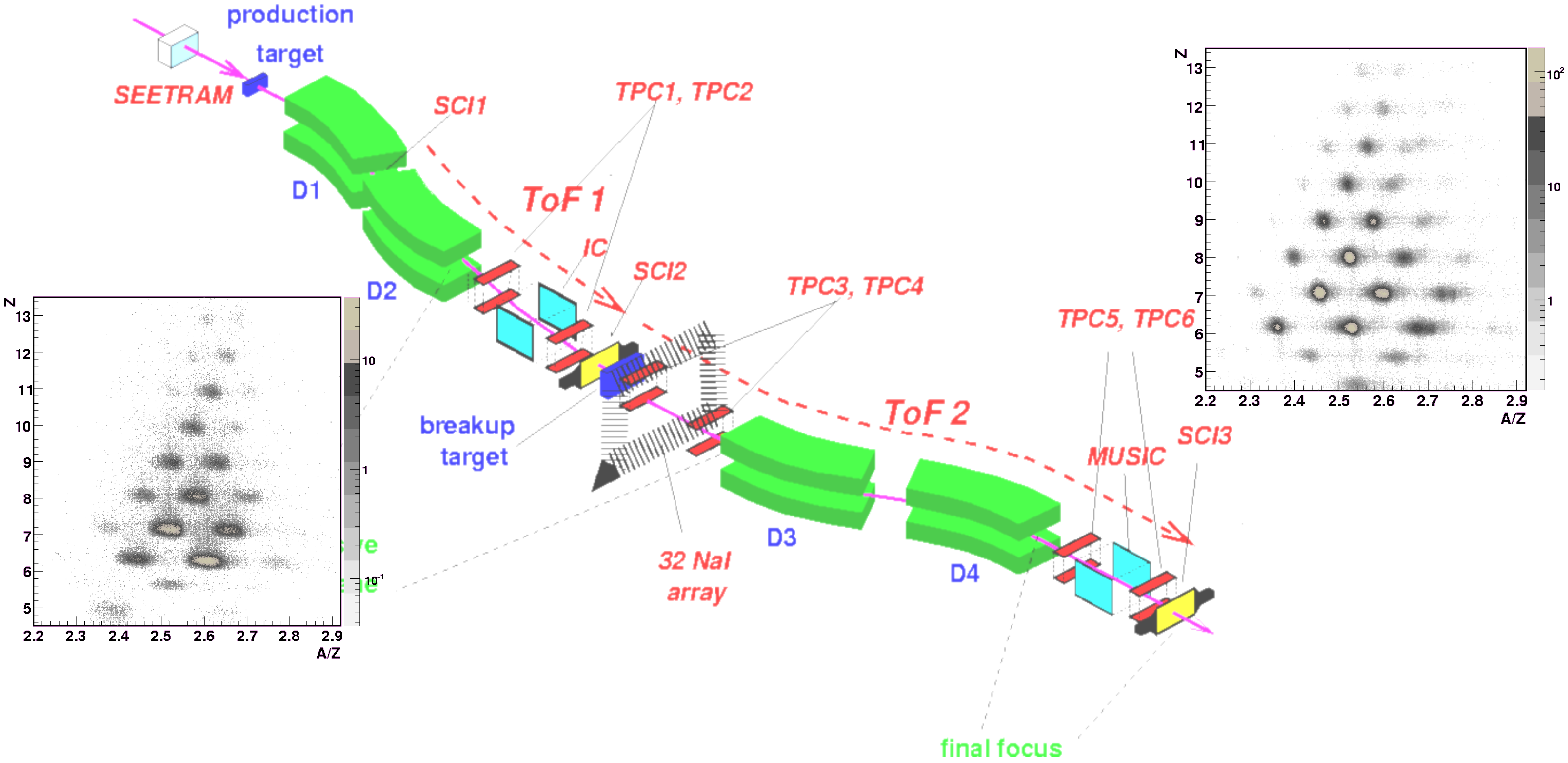
$$|P\rangle = \sum C^2S \left(|C\rangle \otimes |n\rangle \right)$$

- $|P\rangle$: Ground state of the exotic projectile
- C^2S: Spectroscopic factor → Cross-sections
- $|C\rangle$: $^{A-1}$ X fragment → Gamma ray tagging
- $|n\rangle$: removed neutron → $^{A-1}$ X fragment momentum distribution

Nuclear structure investigations

Knock-out reactions

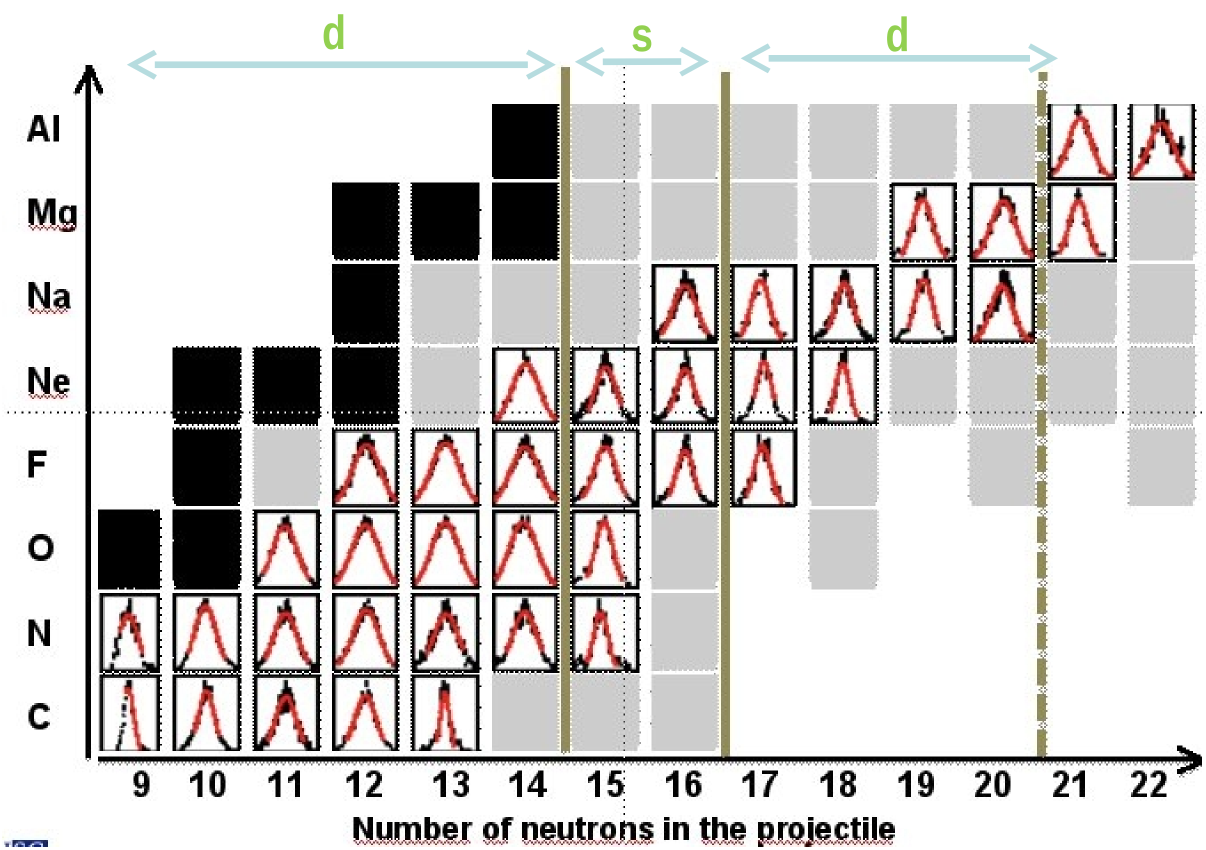
The accuracy in the measurement of the longitudinal mometum of the recoiling projectile residue requires the use of a high-resolving power magnetic spectrometer such as the FRS at GSI.

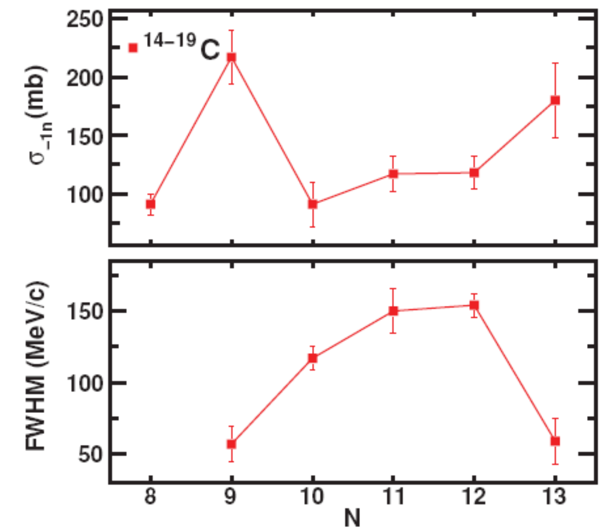


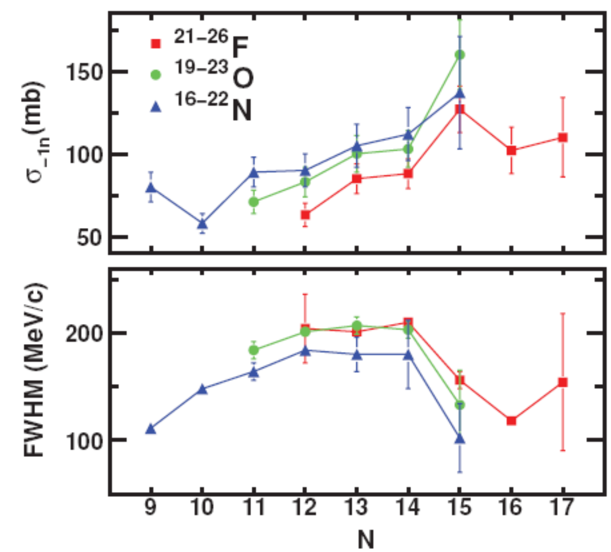
Nuclear structure investigations

Knock-out reactions

1-n knock-out cross section and the width of the momentum distributions reveal halo structures and shell evolution.





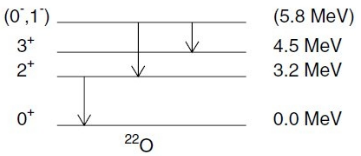


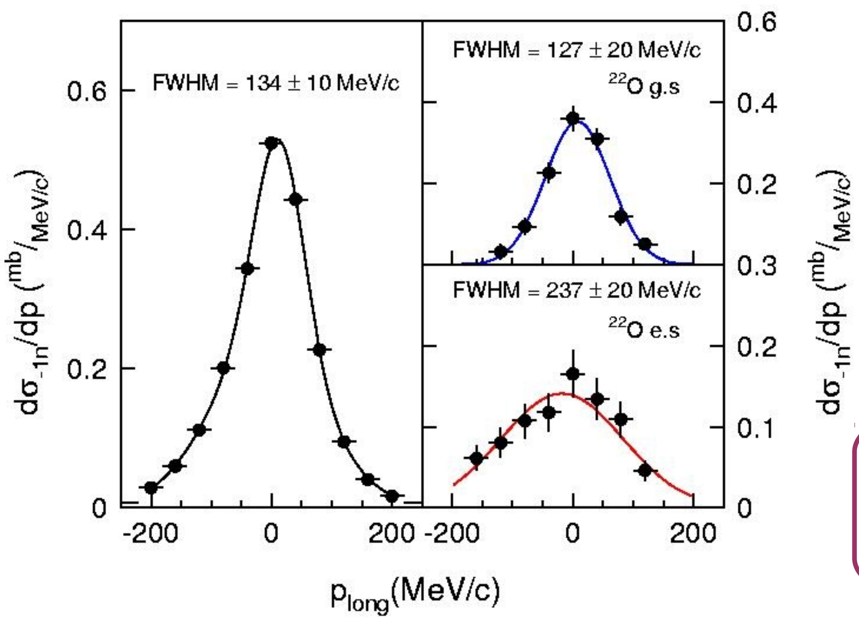
Nuclear structure investigations

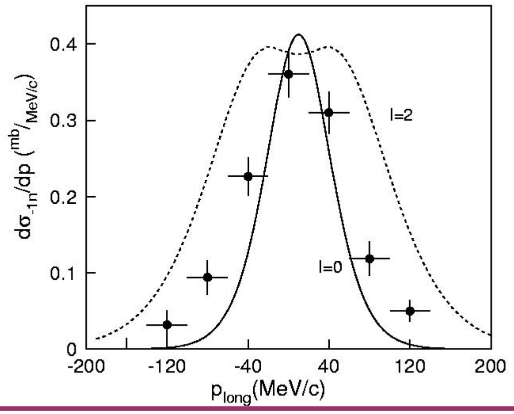
Knock-out reactions

Knock-out with gamma tagging allow for detailed spectroscopic studies.

The case of $^{23}O \rightarrow {}^{22}O+n$

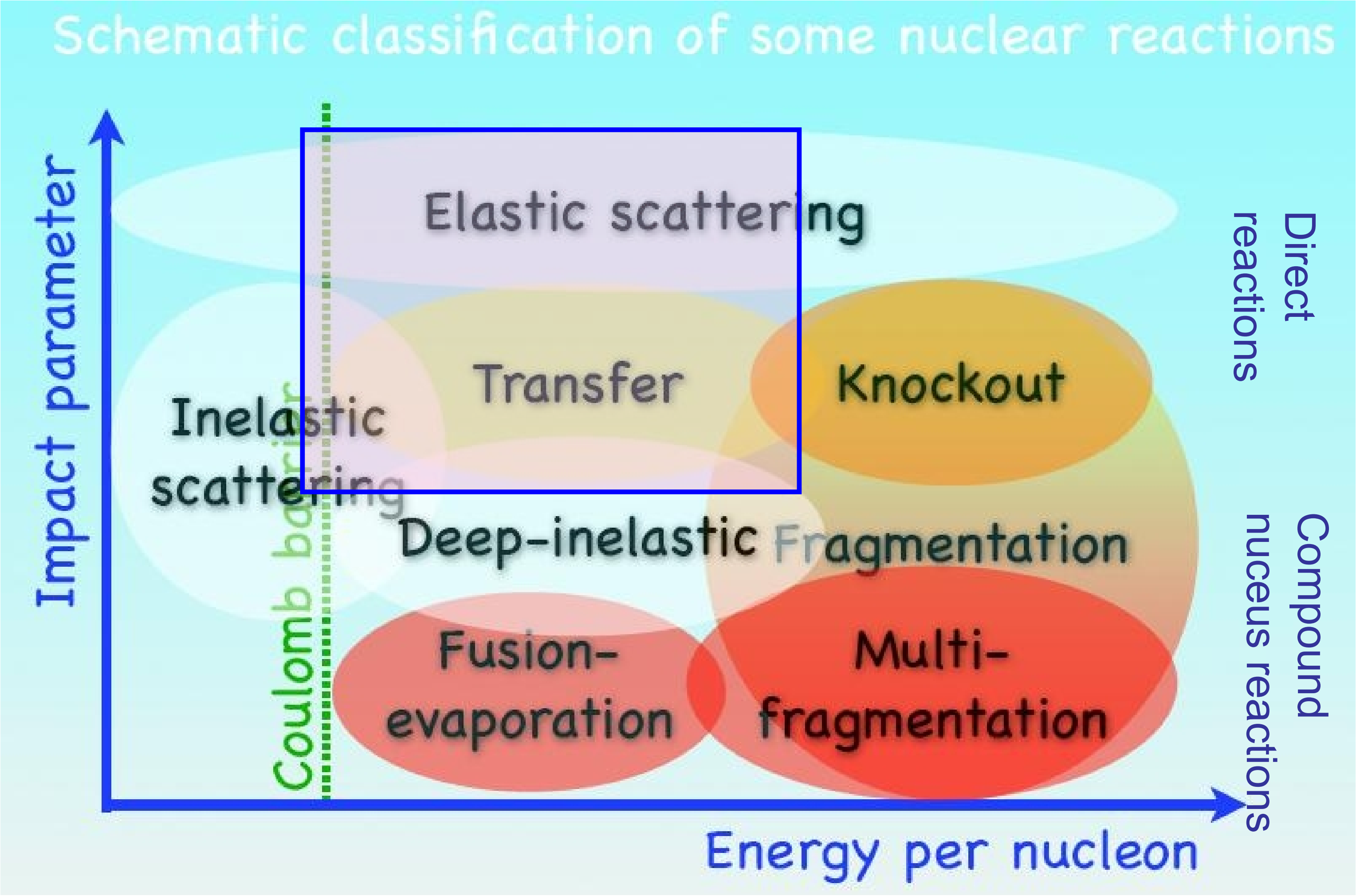






$$|1/2^{+}\rangle = a|\,0^{+} \otimes 2s_{1/2}\rangle + b|\,2^{+} \otimes 1d_{5/2}\rangle$$

Exploring the nucleus



The use of low energy beams

TRIUMF –ISAC II

ISOL facility

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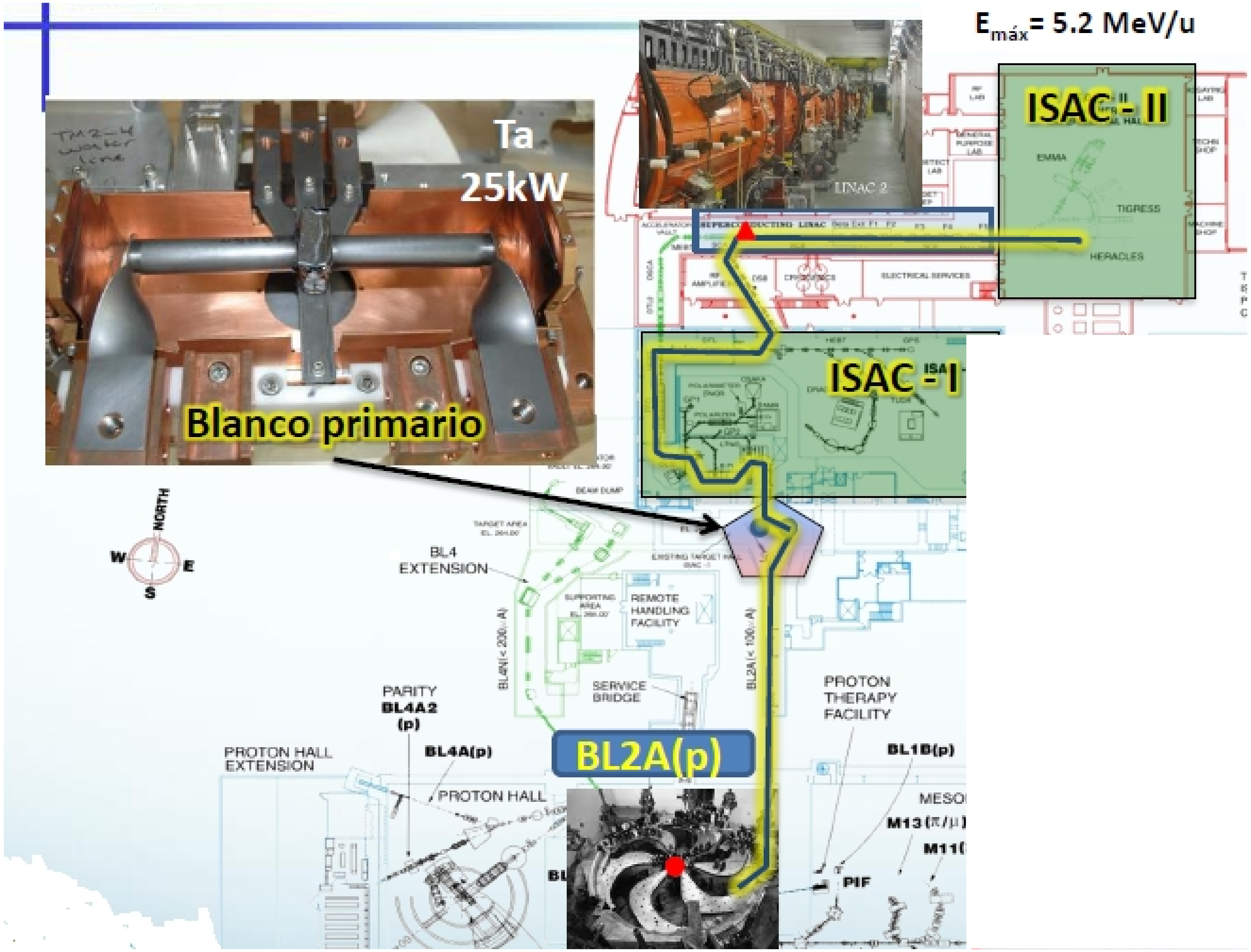
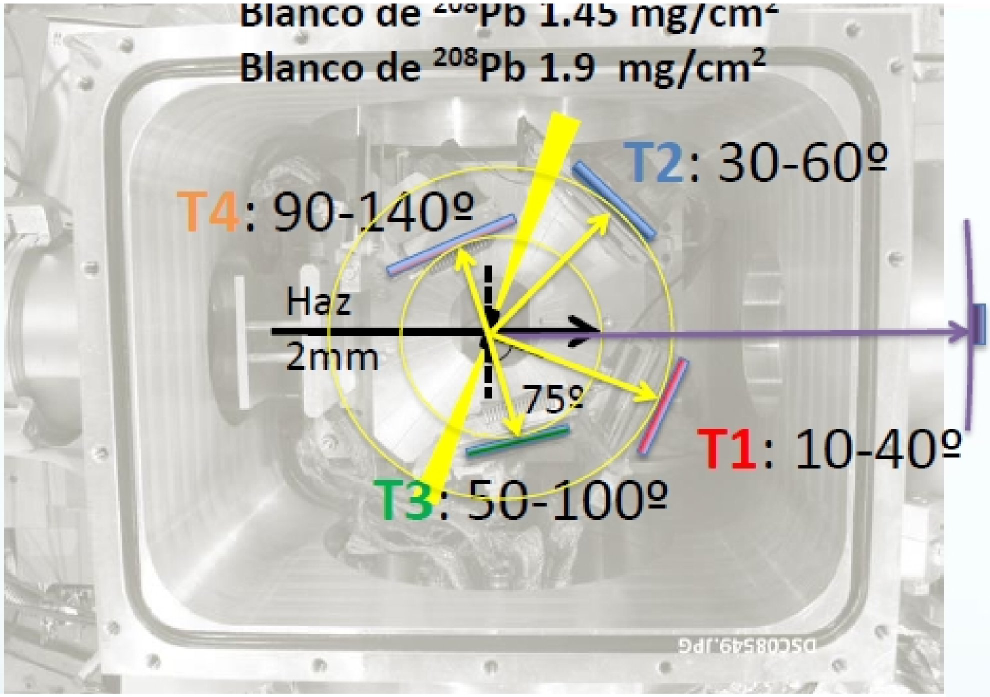
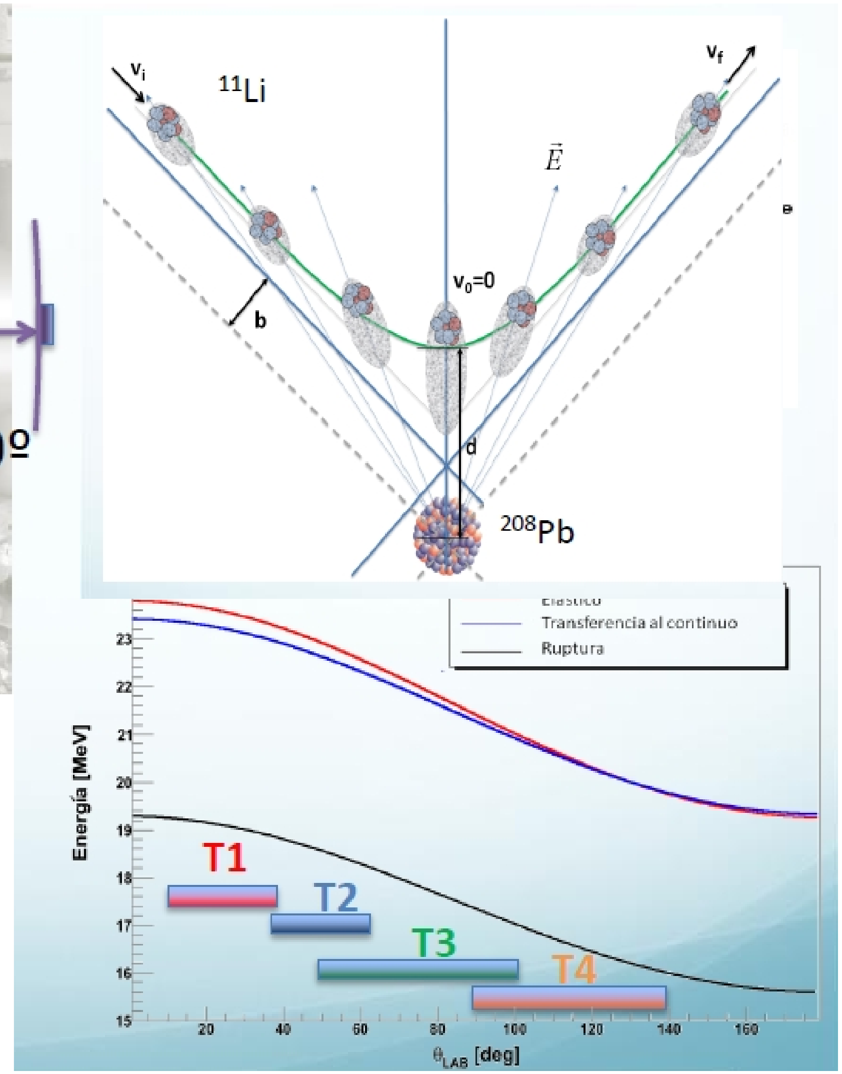


The use of low energy beams

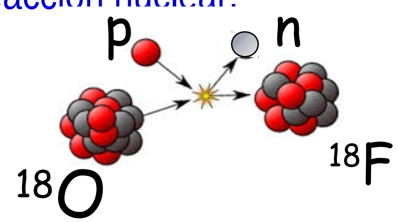




- ✓ Elastic scattering of ^{11}Li on heavy target 11Li+208Pb and 9Li+208Pb @ 29.5 MeV.
- ✓ Direct kinematics
- ✓ Detection of light charge particles

Sección eficaz de una reacción

La **sección eficaz** es una medida de la probabilidad de ocurrencia de una determinada reacción nuclear. Podemos distinguir los siguientes casos:



-**Sección eficaz total**: probabilidad de cualquier reacción entre dos núcleos.

-**Sección eficaz parcial**: probabilidad de una determinada reacción

-**Sección eficaz diferencia**: evolución de la probabilidad de reacción respecto de una variable continua (energía, ángulo, …)

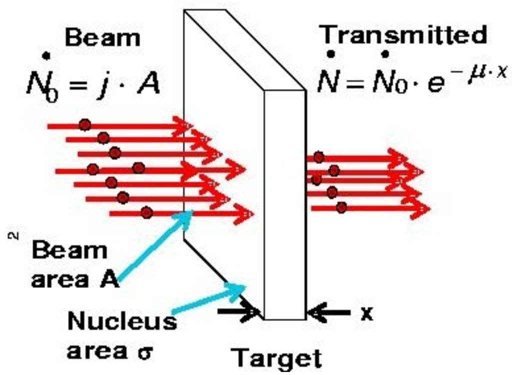
En una irradiación de un material blanco de espesor *x* y densidad de centros dispersores *n*, con un flujo N_o de partículas, el número total de reacciones es:

$$N_{reacción} = N_o - N = N_0\left(1 - e^{-x\sigma n}\right) \approx N_o x \sigma n$$

El corto alcance de la fuerza nuclear nos permite calcular a primer orden la sección eficaz total de reacción como:

$$\sigma_{total} = \pi\left(R_p + R_b\right)^2 = \pi \cdot 1.2^2\left(A_p^{1/3} + A_b^{1/3}\right)^2 \; fm^2$$

$$1\,\text{barn} = 10^{-24}\ \text{cm}^2 = 100\ \text{fm}^2$$

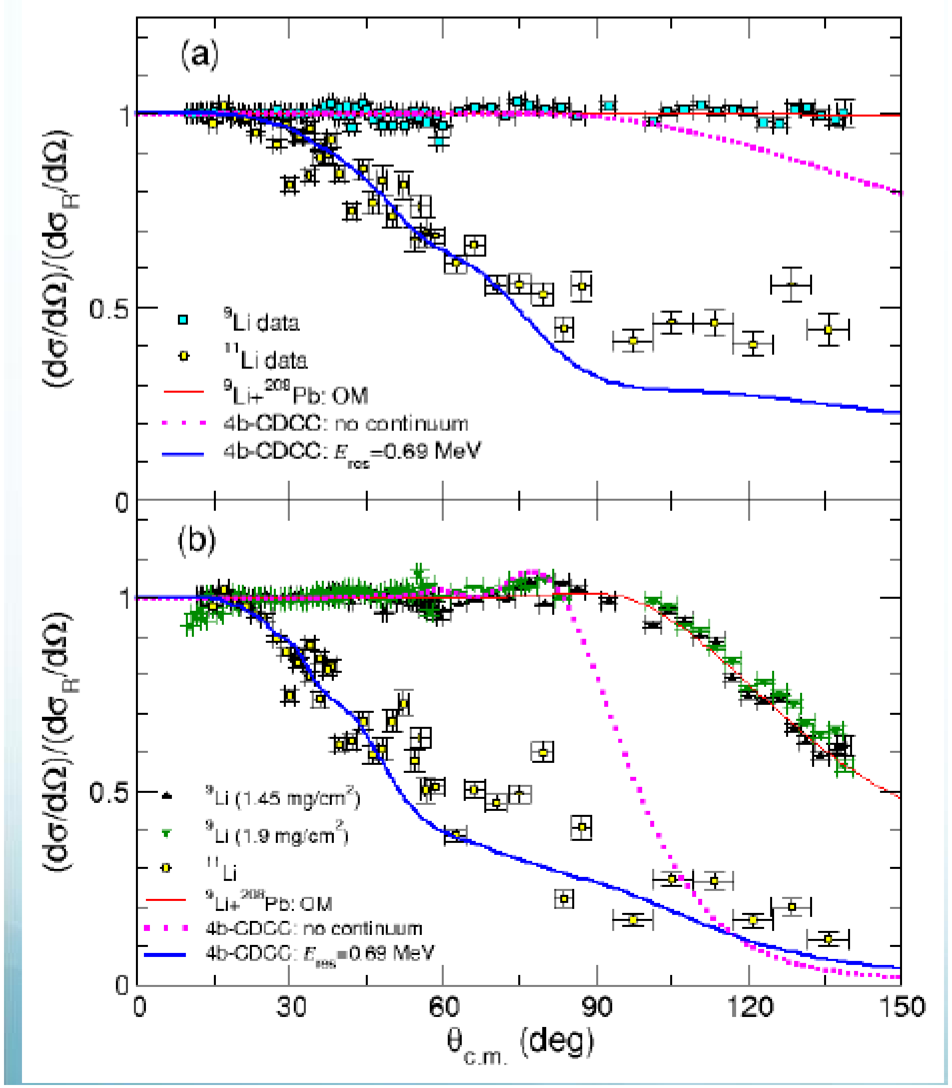


The use of low energy beams

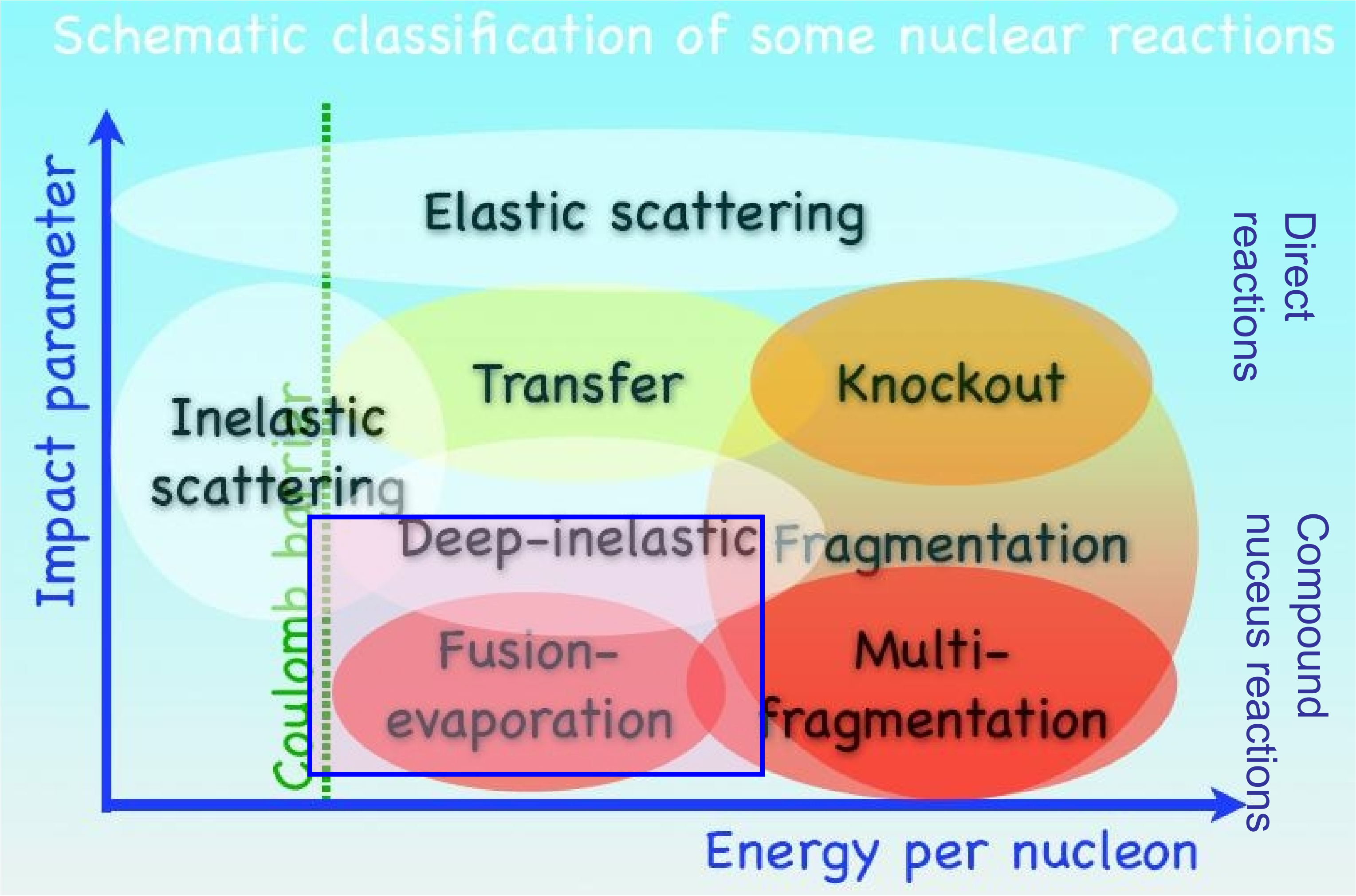
- ✓ Los datos de 9Li+208Pb son ajustados usando un modelo óptico donde la parte real se describe con el potencial de doble convolución de São Paulo (SPP) y la parte imaginaria un potencial de Woods-Saxon.

- ✓ Los datos para la dispersión de 11Li+208Pb serán comparados con cálculos CDCC a cuatro cuerpos.

- ✓ Evidencia experimental del halo del 11Li y éxito de la modelización de la reacción nuclear



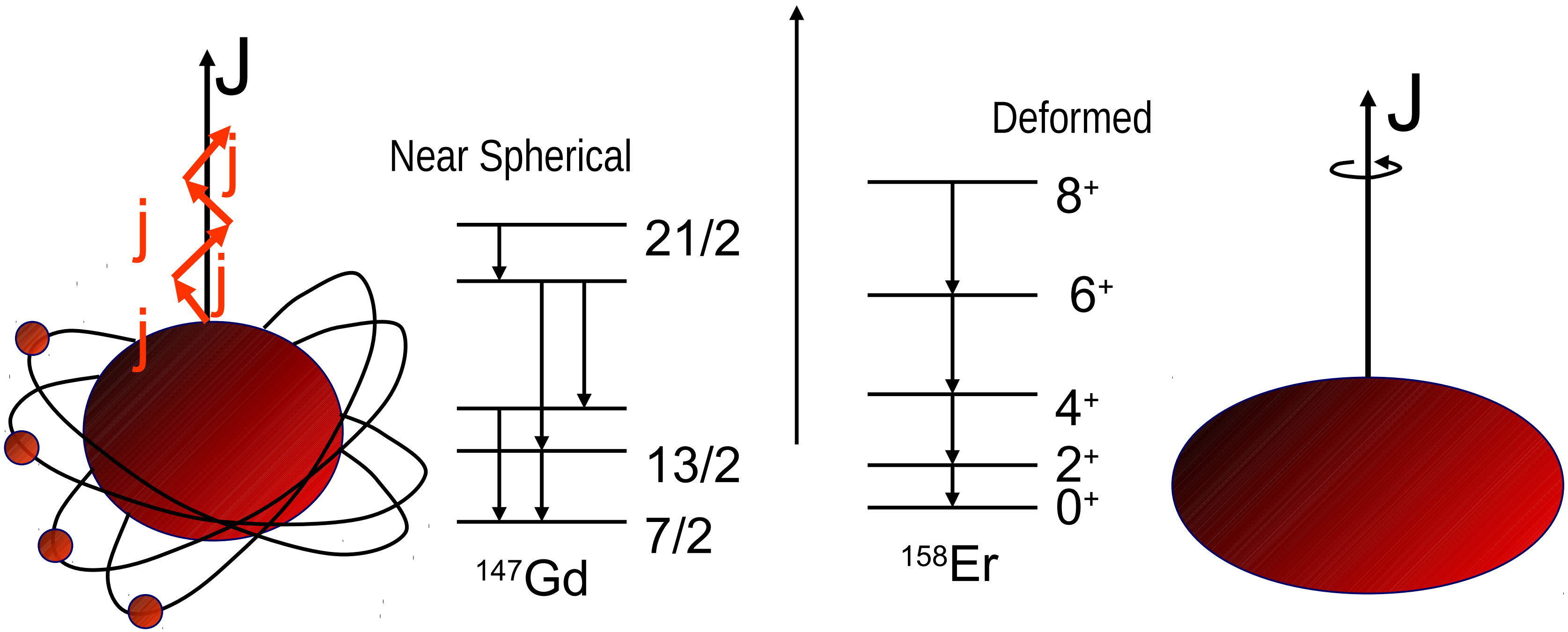
Exploring the nucleus



Single particle versus collectivity

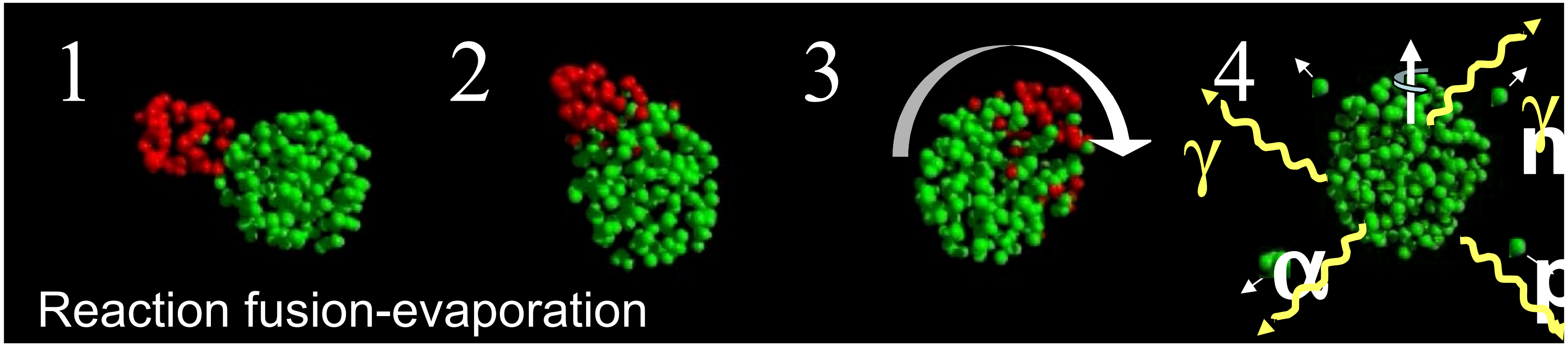
Single-particle behaviour.

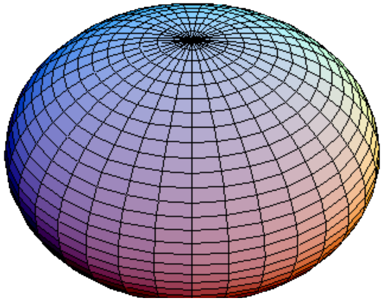
Collective behaviour.

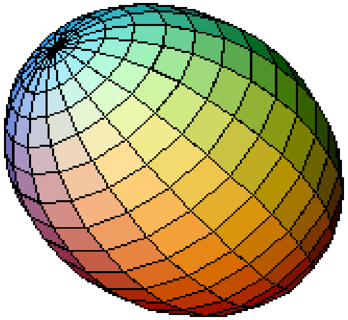


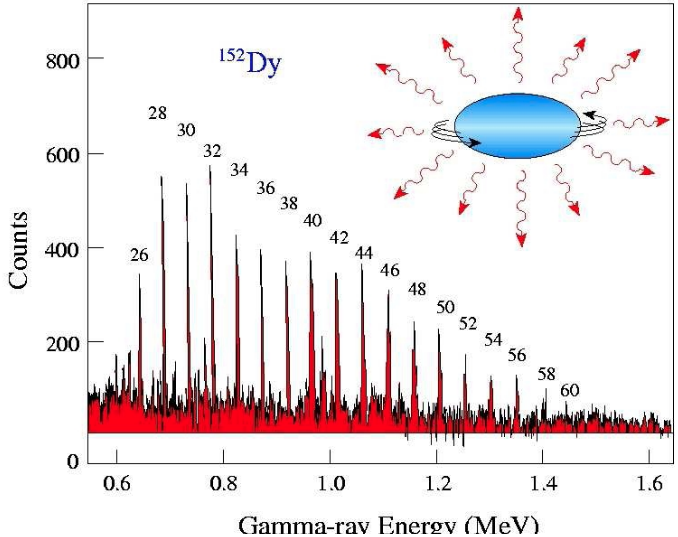
Nuclei are many-body quantal systems consisting on many nucleons, up to 300, resulting on a rich variety of quantum phenomena.

The shape of the nucleus





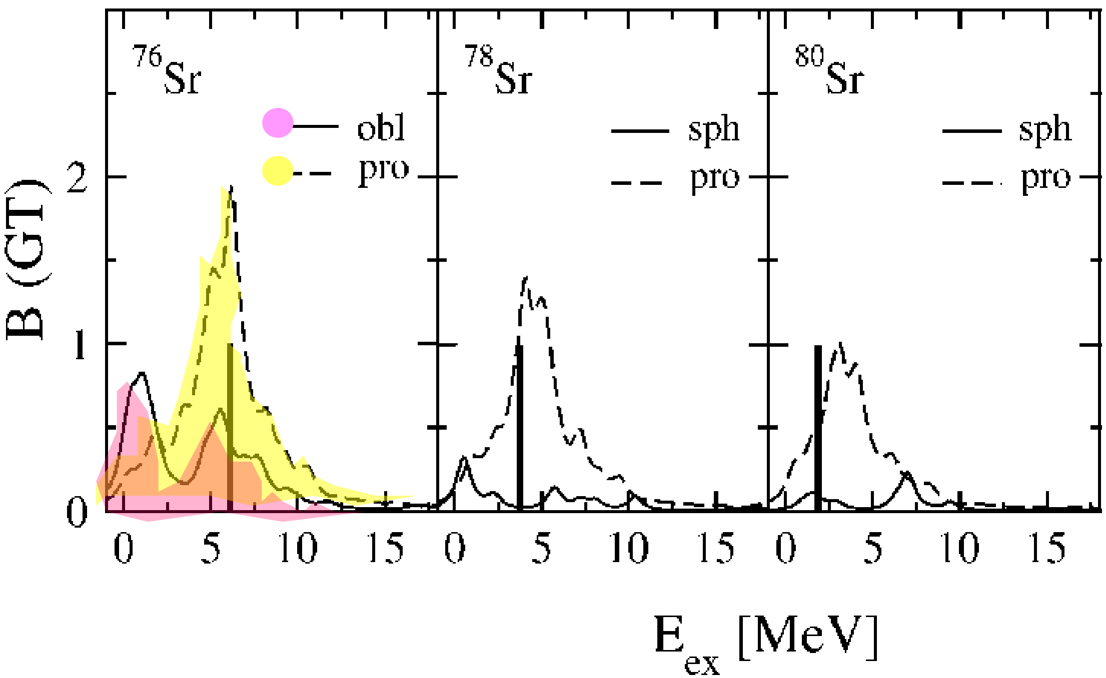


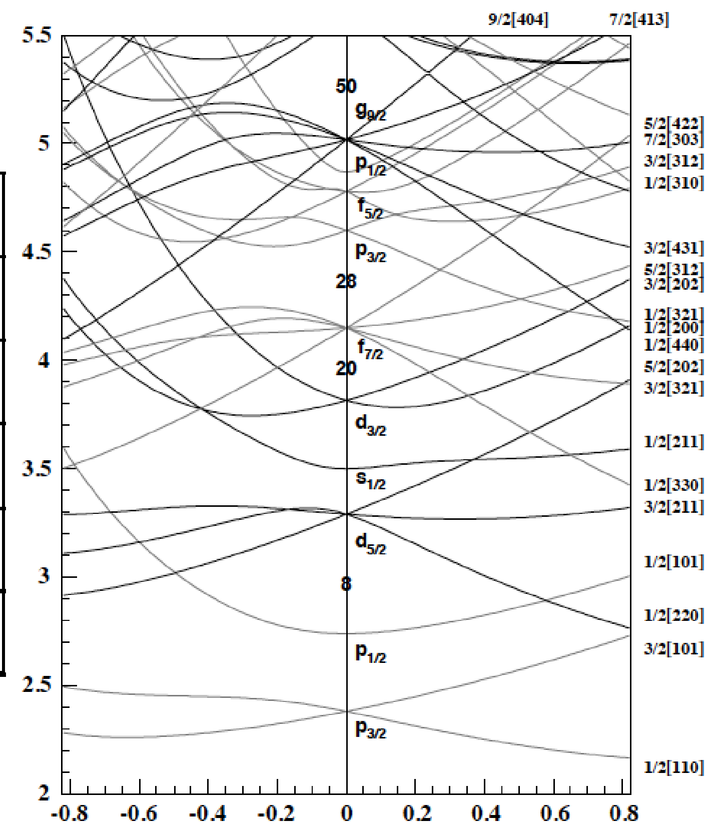


$$|Q| = \sqrt{16\pi B(E2{:}2_1^+ \rightarrow 0_1^+)} = \frac{3Ze}{\sqrt{5\pi}} R_0^2(\beta + 0.16\beta^2),$$

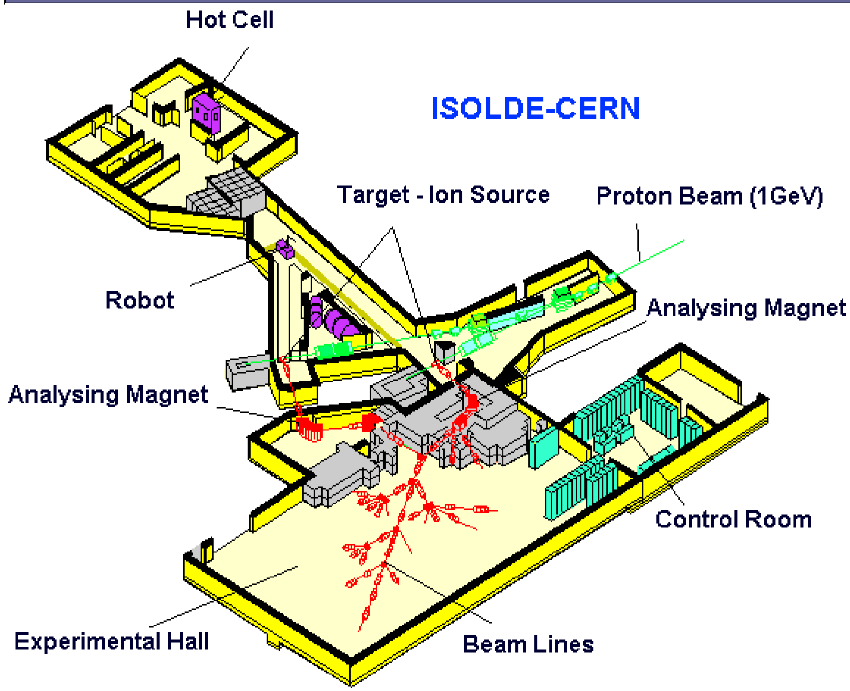
Shapes and dimensions from beta decay

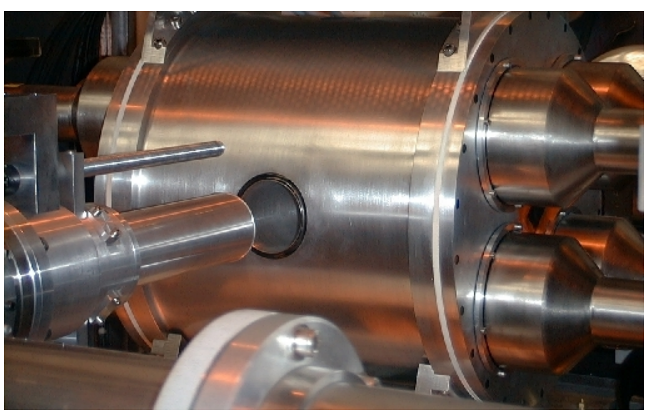
We can also learn about deformation using the dependency of the strength distribution in the daughter nucleus depending on the shape of the parent.

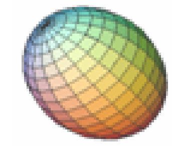




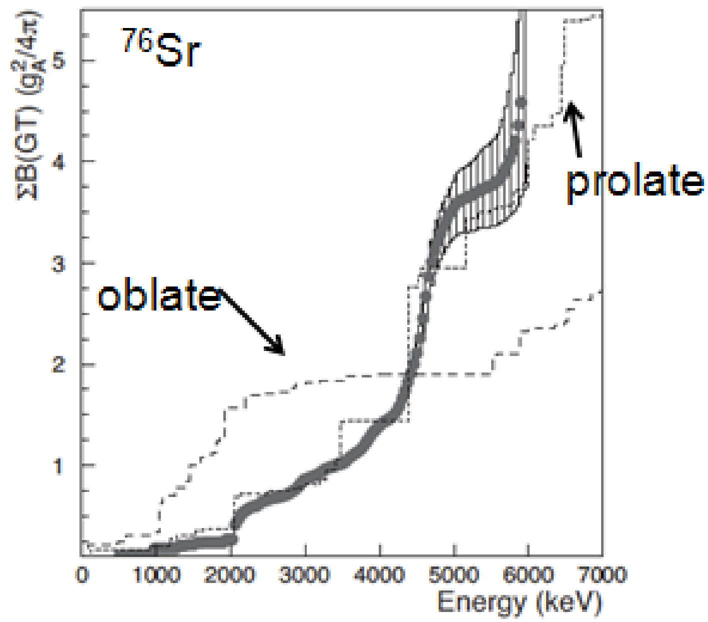
Shapes and dimensions







Very prolate N=Z nucleus



Comparación de resultados experimentales de B(GT) medidos a través de Espectroscopía de Absorción Total con cálculos teóricos