Experimental aspects of nuclear (giant) resonances

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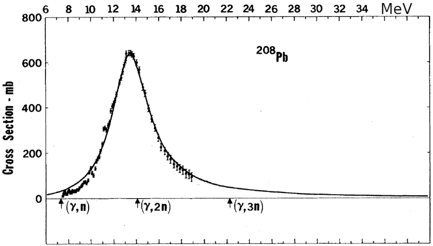
Overview

Giant Resonances Properties

Giant Resonances

Discovered in 1937 Bothe et al. **Z. Phys.** 71 (1937) in photo-absorption ;
Theoretically described in 1944 Migdal **J. Phys, (USSR)** 8 (1944)

Berman et al. **Rev. Mod. Phys.** 47 (1975)



Described/fitted by a Lorentzian (Breit-Wigner)

$$\sigma_\gamma(E) = \frac{\sigma_{\max}}{1 + \left[\frac{E^2 - E_r^2}{E\Gamma_r}\right]^2}$$

Complex plane: (E,Γ)

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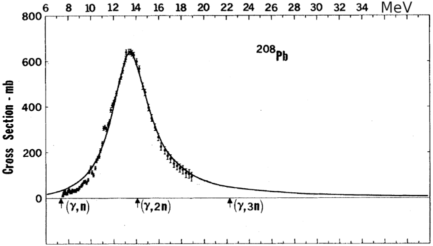

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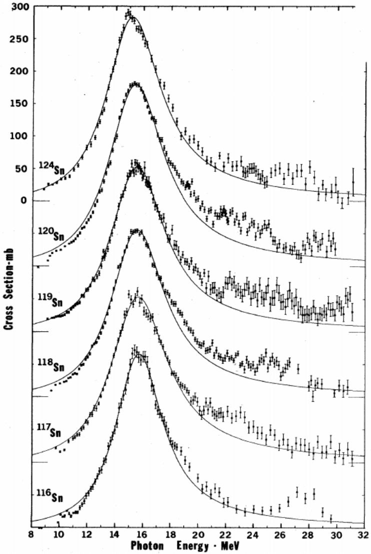

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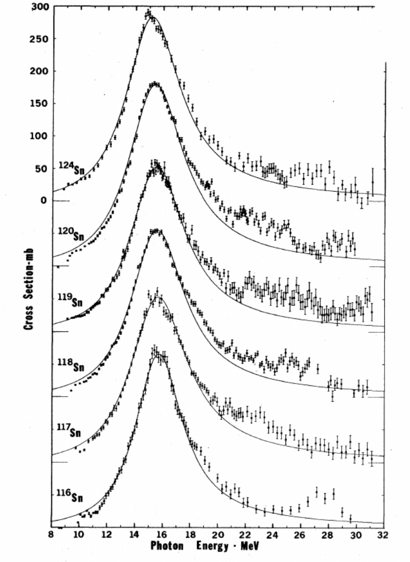
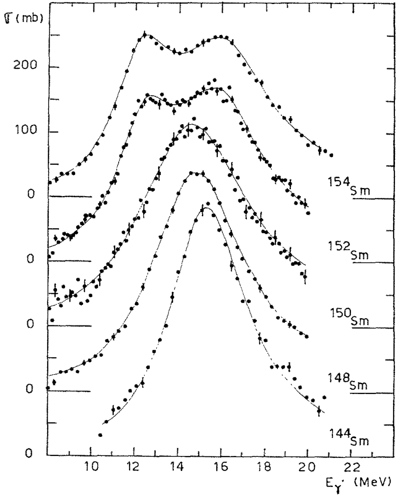




Deformation Carlos et al. **Nuclear Physics A** 225 (1974)

Giant Resonances

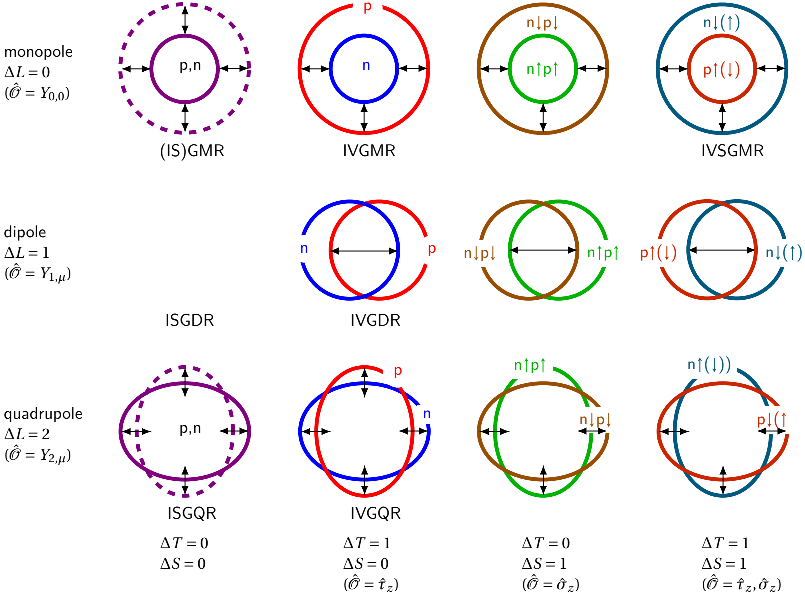
Hydrodynamic models

Giant Resonances

Giant resonances are high-frequency collective excitation of atomic nuclei
Macroscopic/Hydrodynamic models: Coherent vibrations nucleonic fluids
(well described with liquid drop model(s))

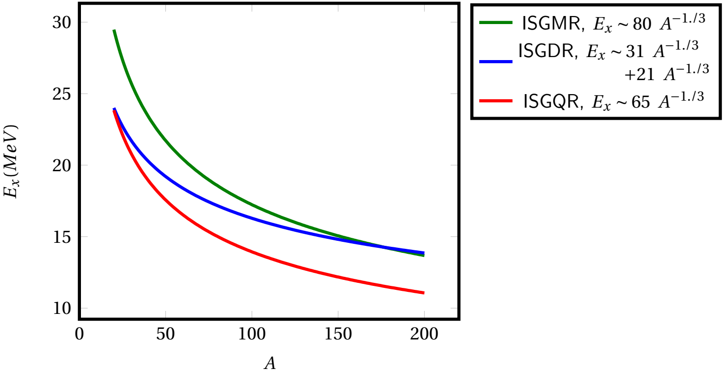
Giant Resonances

Hydrodynamic models



Giant Resonances

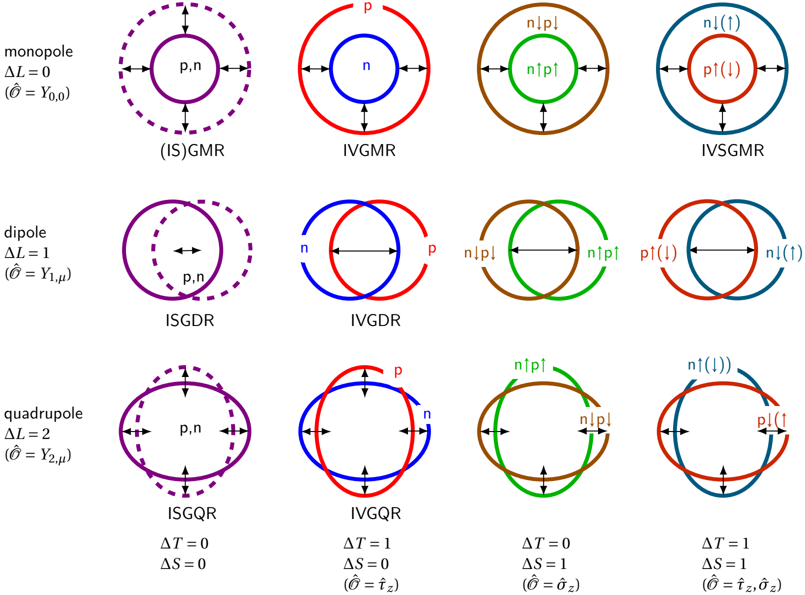
Energies



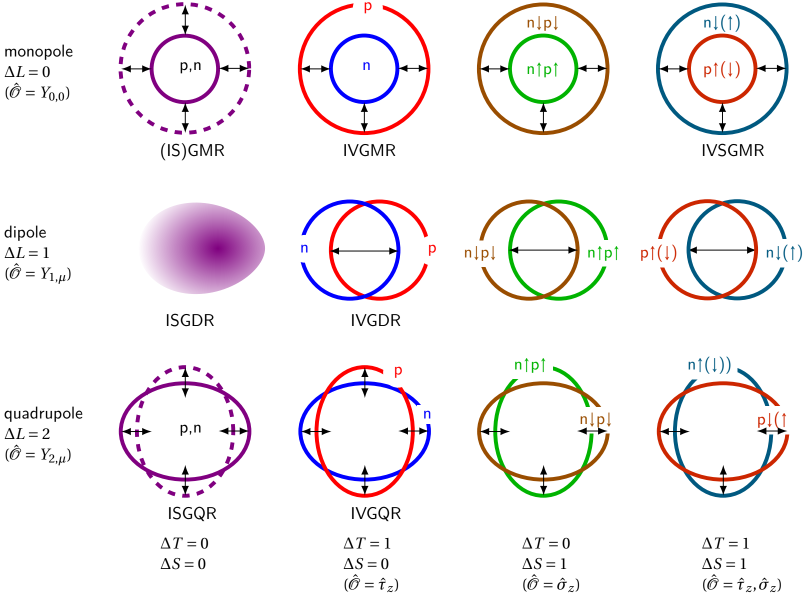
Harakeh et al. (2001)

Giant Resonances

Hydrodynamic models

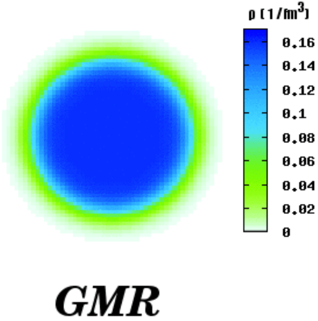


Hydrodynamic models

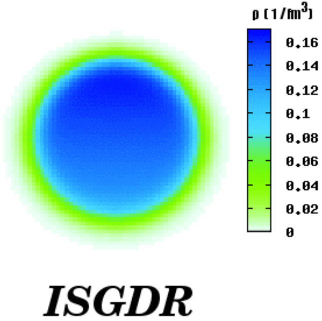


Giant Resonances

Macroscopic/Hydrodynamic models: Coherent vibrations nucleonic fluids
Compression modes: ISGMR, ISGDR



Giant Monopole Resonance



IsoScalar GDR

Giant Resonances

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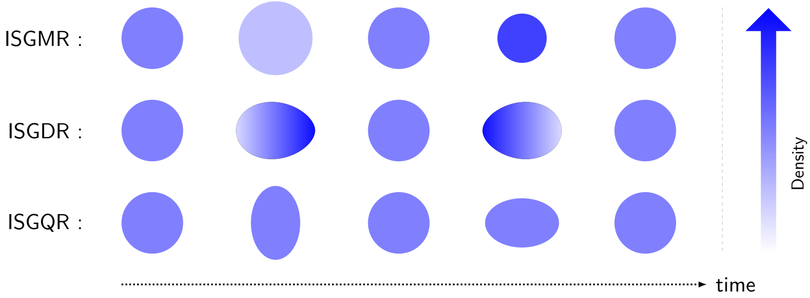

Giant Resonances

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Compression modes: ISGMR, ISGDR

$$E_{\text{ISGMR}} = \hbar\sqrt{\frac{K_A}{m<r^2>}}$$

$$E_{\text{ISGDR}} = \hbar\sqrt{\frac{7}{3}\frac{K_A + \frac{27}{25}\epsilon_F}{m<r^2>}}$$

Stringari **Phys. Lett. B** 108 (1982) Bagchi **PhD** (2015)

Nuclear incompressibility

K_A(finite matter) $\neq K_\infty = \left[9\rho_0^2 \frac{\partial^2(\mathcal{E}/A)}{\partial\rho^2}\right]_{\rho_0}$ (infinite matter)

ISGMR, ISGDR ⇒ Incompressibility + symmetry energy

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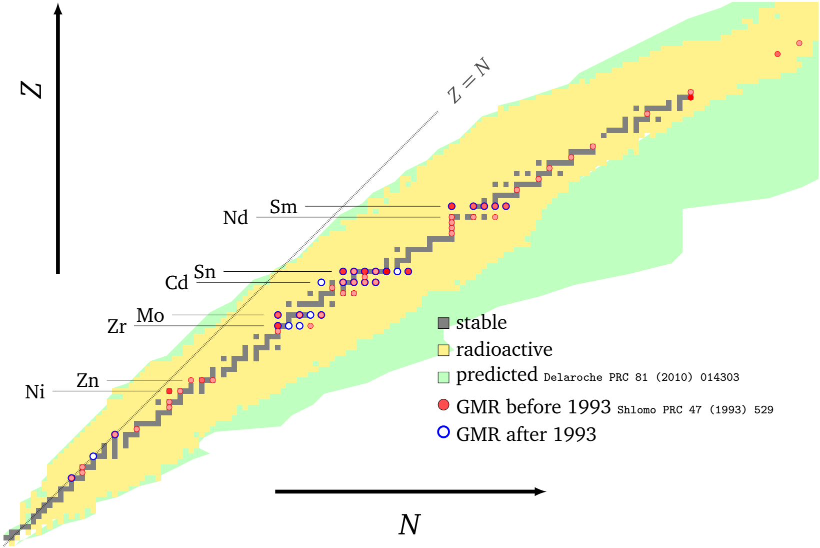
Nuclear incompressibility

$$K_A = K_\infty + K_s A^{-1/3} + K_\tau \underbrace{\left[\frac{N-Z}{A}\right]^2}_{\delta^2} + K_c \left[\frac{Z}{A^{1/3}}\right]^2 \text{ (scaling model)}$$

ISGMR, ISGDR ⇒ Incompressibility + symmetry energy

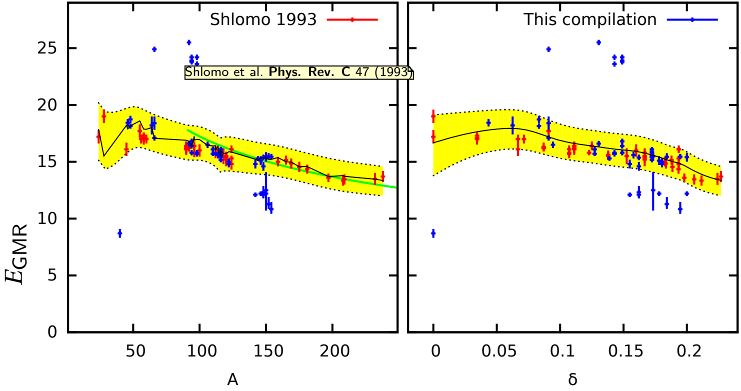
Giant Monopole Resonances

Status: stables nuclei only



Giant Monopole Resonances

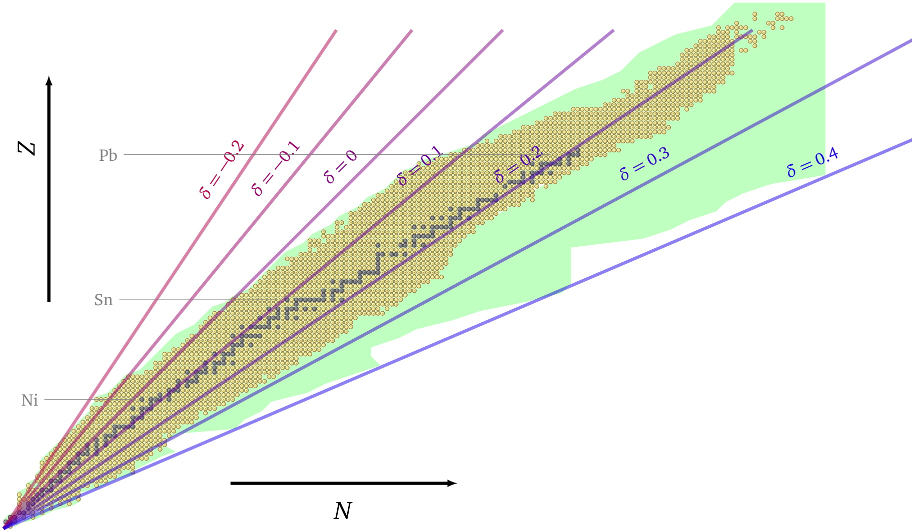
Incompressibility parameters



	This work				Shlomo
K_∞	220	240	260	235 ± 20	244 ± 15
K_τ	-28 ± 104	-222 ± 166	-416 ± 112	-194 ± 158	-142 ± 133

Giant Monopole Resonances

Towards exotic nuclei



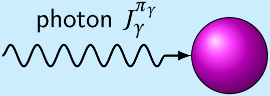
Experimental considerations

Properties of the probes

Selection rules

Historically GRs discovered by photon absorption (IVGDR)

Electromagnetic probes ?



$\Delta J = J_\gamma > 0$ and
$\pi_\gamma = (-1)^{J_\gamma}$ (E) or $(-1)^{J_\gamma+1}$ (M)

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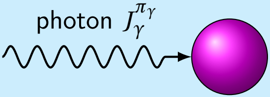

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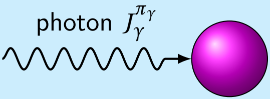

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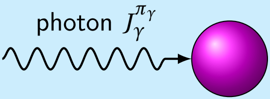

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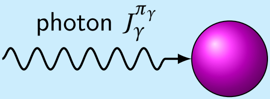

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Inelastic scattering (α, α')

$$\left\{ \begin{array}{lcl} \vec{T}_i + \Delta\vec{T}_{GR} & = & \vec{T}_f \\ T_{z_i} + \Delta T_{z_{GR}} & = & T_{z_f} \end{array} \right. \quad \text{and} \quad \left\{ \begin{array}{lcl} \vec{T}_i + \vec{T}_\alpha & = & \vec{T}_f + \vec{T}_{\alpha'} \\ T_{z_i} + \cancelto{0}{T_{z_\alpha}} & = & T_{z_f} + \cancelto{0}{T_{z_{\alpha'}}} \end{array} \right.$$

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α($T = 0$): perfect probe for isoscalar modes ($+\ S_{n,p,d\ldots} \gtrsim 20\,\text{MeV}$)

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proton ($T = 1/2$): isoscalar and isovector mixed (used in conjonction)

More general probes

	$\Delta S=0$ $\Delta T=0$ $\Delta A=0$	$\Delta S=1$ $\Delta T=0$ $\Delta A=0$	$\Delta S=0$ $\Delta T=1$ $\Delta A=0$	$\Delta S=1$ $\Delta T=1$ $\Delta A=0$	ΔS ΔT $\Delta A=2$
Variable	Number density	Spin density	Isovector density	Isovector spin density	Pair density
Property	Incompressibilit	Magnetism	Symmetry energy		Pair condensation
Probe	(α,α), (d,d)	(p,p), (^{6}Li,^{6}Li*)	(^{7}Li,^{7}Be*), (^{6}He,^{6}Li*)	(p,n), (n,p), (d,2p)...	(α,^{6}He), (α,^{6}Li), (α,d), (α,pn), (d,α), (n,^{3}He), (^{3}He,n)

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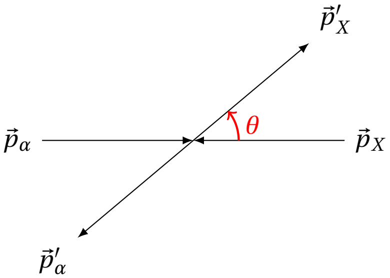
Angular distribution : General considerations

Classical approach

$$^{A}X(\alpha,\alpha')^{A}X^{\star}$$



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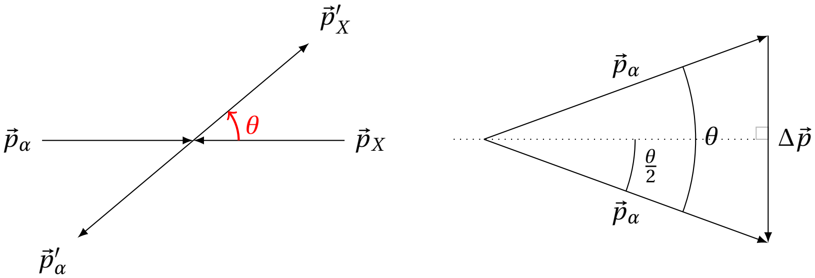

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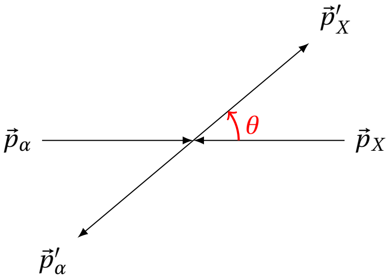

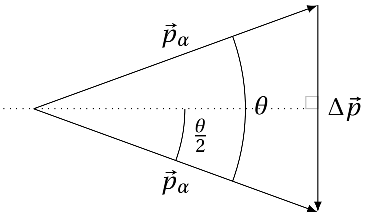

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If we assume $p_\alpha \sim p'_\alpha$: $\sin\frac{\theta}{2} \sim \frac{|\Delta\vec{p}/2|}{|\vec{p}_\alpha|}$

with $\vec{l}_\alpha = \vec{r}_\wedge \Delta\vec{p} \Rightarrow l_\alpha = r\,\Delta p \Rightarrow \Delta p = l_\alpha / r \Rightarrow \sin(\theta/2) = \frac{l_\alpha}{2p_\alpha r} \Rightarrow \theta = 2\arcsin\left(\frac{|\vec{l}_\alpha|}{2|\vec{p}_\alpha||\vec{r}|}\right)$

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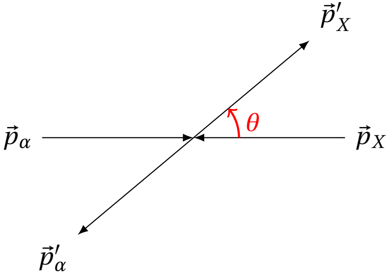

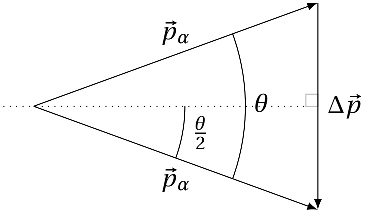

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$$\theta \propto l$$

Angular distribution shape

With interferences

Sharp edge Fraunhofer (approximation w/o Coulomb)

Garg et al. **Progress in Particle and Nuclear Physics** 101 (2018) Bernstein (1969)

(Analogy w/ optics)

$$\left(\frac{d\sigma}{d\Omega}\right)_{0^+\to 0^+} \propto \left|J_0\left(qR_D\right)\right|^2,$$
$$\left(\frac{d\sigma}{d\Omega}\right)_{0^+\to 1^-} \propto \left|J_1\left(qR_D\right)\right|^2,$$
$$\left(\frac{d\sigma}{d\Omega}\right)_{0^+\to 2^+} \propto \left[\frac{1}{4}J_0\left(qR_D\right)^2 + \frac{3}{4}J_2\left(qR_D\right)^2\right] \not\propto J_2^2\left(qR_D\right)$$

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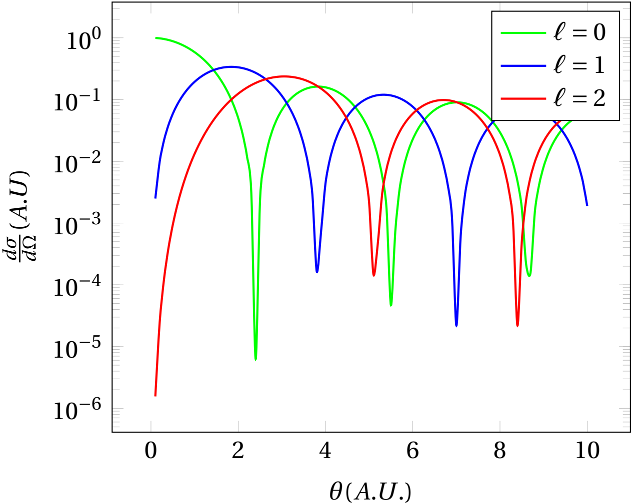
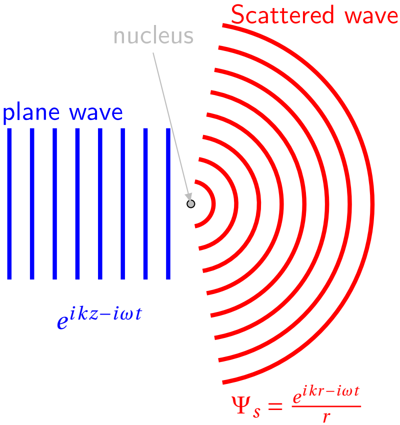


Angular distribution calculation

In pratice: optical potential, DW . . .



Angular distribution calculation

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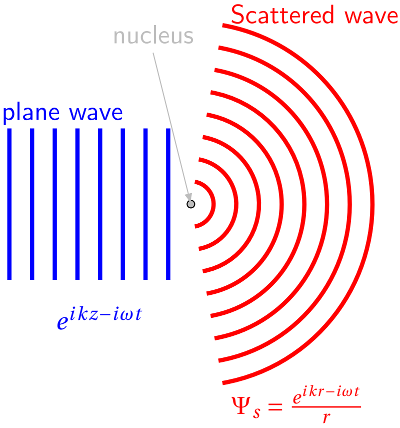

Total wave function:

$$\psi_{\text{tot}}(\theta) \underset{r\to\infty}{\longrightarrow} \left[e^{ikz} + \underbrace{f(\theta)\frac{e^{ikr}}{r}}_{\psi_s} \right] e^{-i\omega t}$$

Angular distribution calculation

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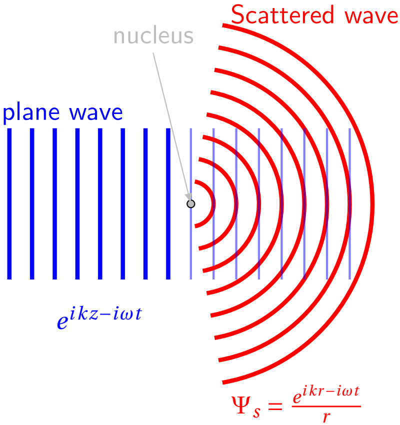

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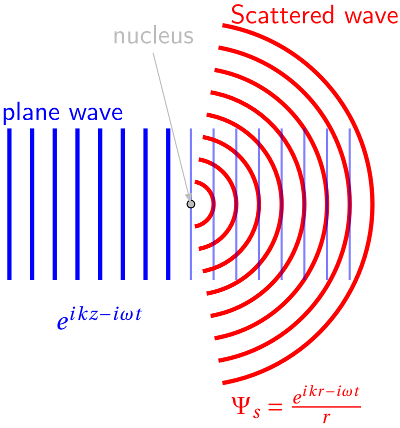

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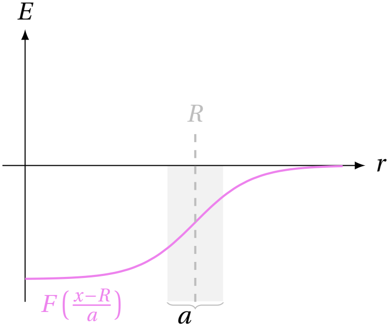
Angular distribution

$$\frac{d\sigma}{d\Omega} = \left| f(\theta) \right|^2$$

Angular distribution calculation

In pratice: optical potential, DW . . .

Nucleus representation:

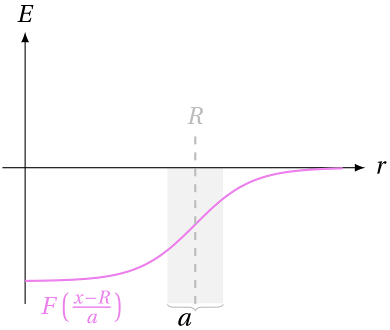


Wood saxon potential
(w/o Coulomb)

Angular distribution calculation

In pratice: optical potential, DW ...

Nucleus representation:



Wood saxon potential
(w/o Coulomb)

To calculate ψ :

$$\left[-\frac{\hbar^2}{2\mu}\nabla^2 + \mathbf{V}(r)\right]\psi = E\psi$$

with *ad minima*

$$\mathbf{V}(r) = -(\mathcal{V} + i\mathcal{W})\, F\left(\frac{r-R}{a}\right)$$

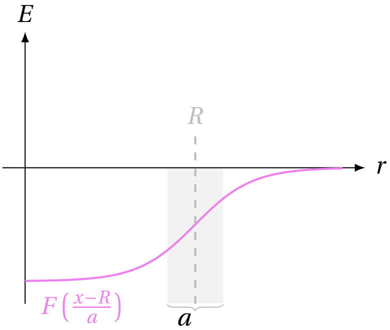
and

$$F(x) = \frac{1}{1+e^x}$$

Angular distribution calculation

In pratice: optical potential, DW ...

Nucleus representation:



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and

$$F(x) = \frac{1}{1+e^x}$$

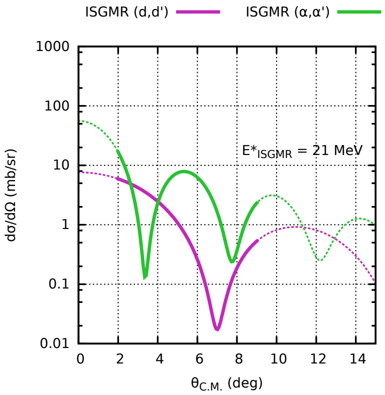
$$\psi = \sum_l \sum_{m=-l}^{l} \alpha_{l,m}(k)\,\frac{u_l(k,r)}{r}\,Y_l^m(\theta,\psi)$$

+ deformation/rotation + form factor (Harakeh et al. **Physical Review C** 23 (1981))...

Giant Resonances

Experimental techniques?

^{68}Ni$(\alpha, \alpha')^{68}$Ni*

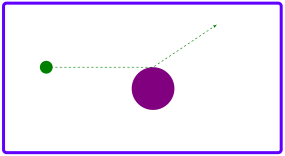


Physics of interest $\sim 0^{\circ}$

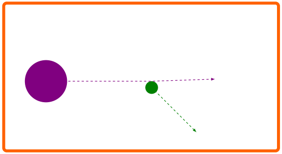
Kinematics

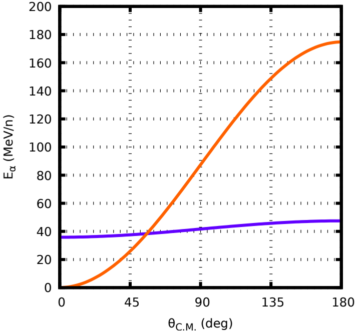
Example : α on $A \sim 60$ with $T \sim 50\,\mathrm{MeV/n}$

Direct kinematics



Reverse kinematics





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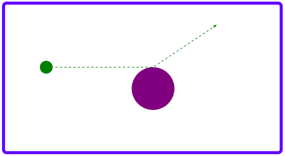

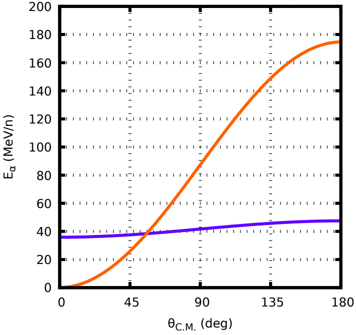

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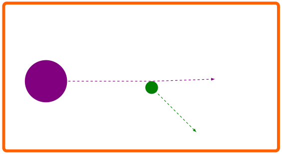

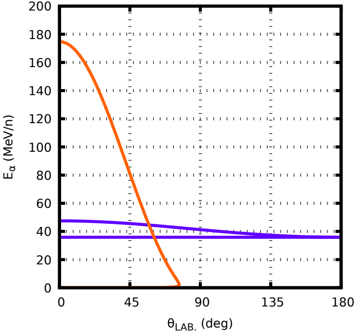

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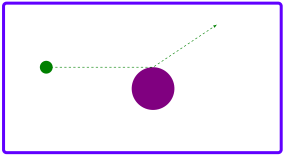

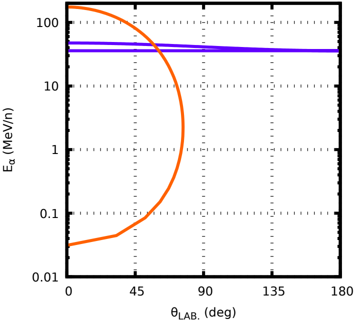

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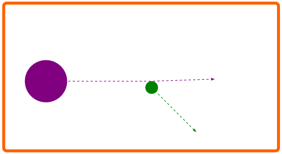

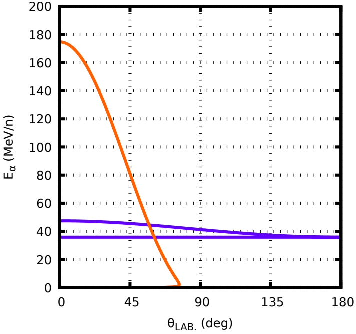

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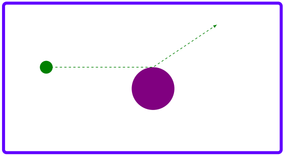

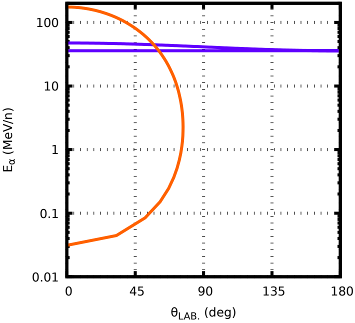

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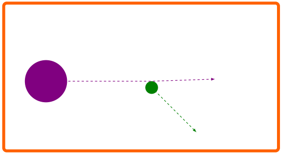
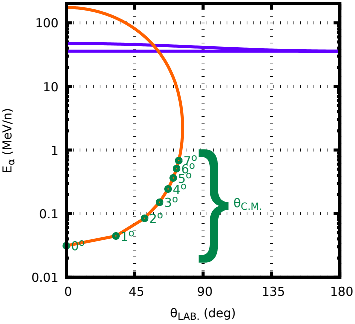
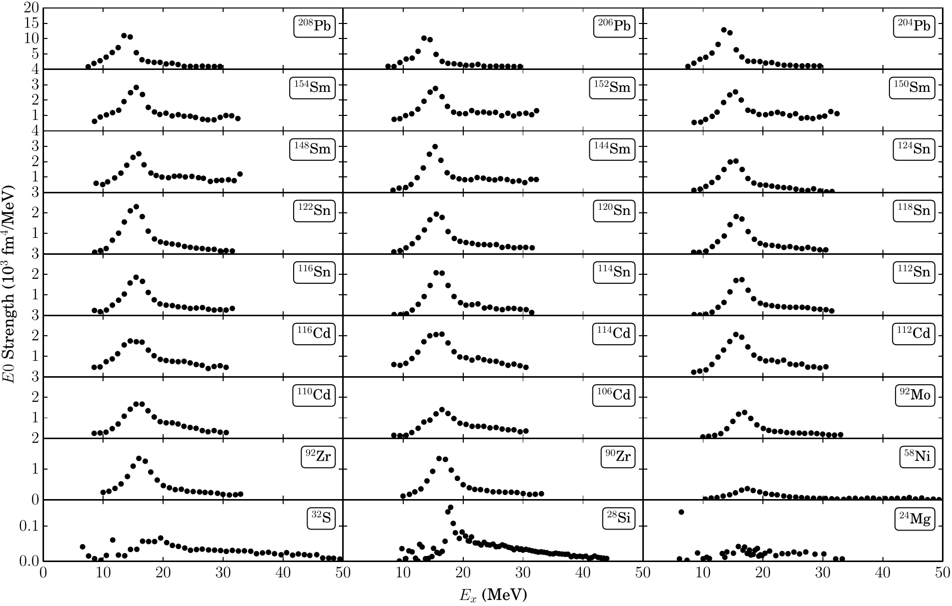




Example of experiments with stable nuclei

Systematics on stable nuclei

Garg et al. **Progress in Particle and Nuclear Physics** 101 (2018)



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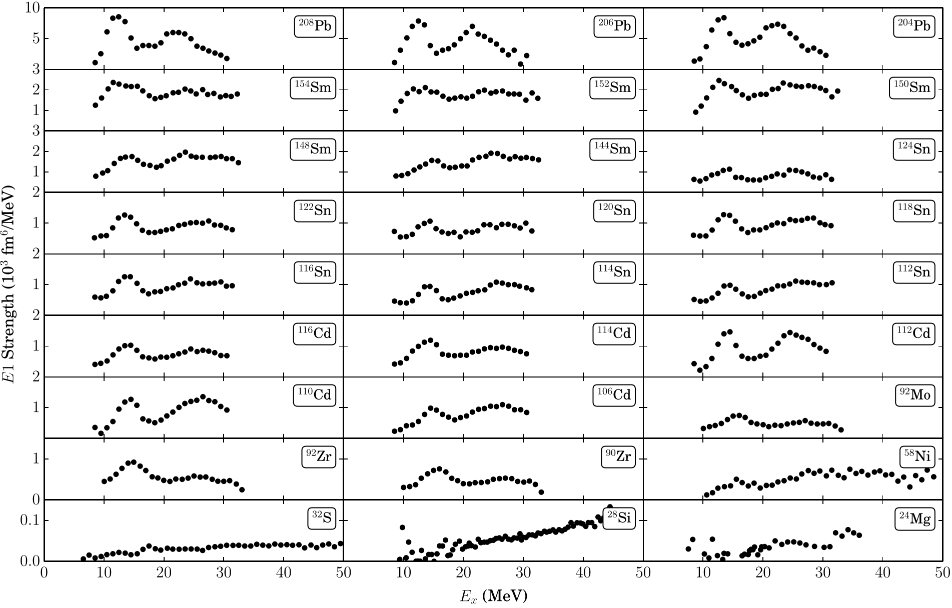
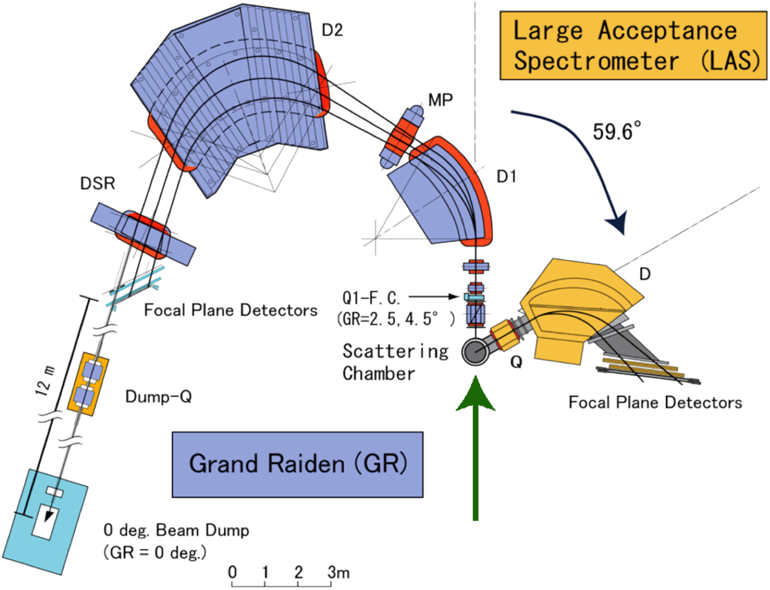


Systematics on stable nuclei

Experimental details

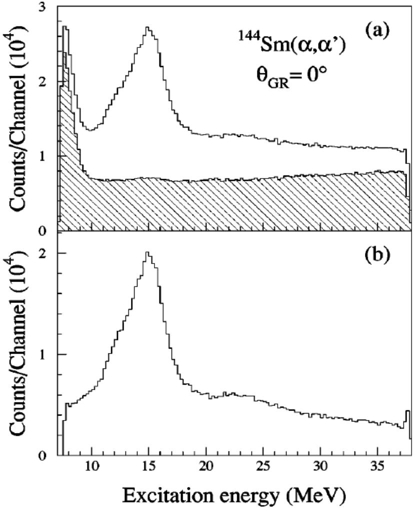
Itoh et al. **Phys. Rev. C** 68 (2003)

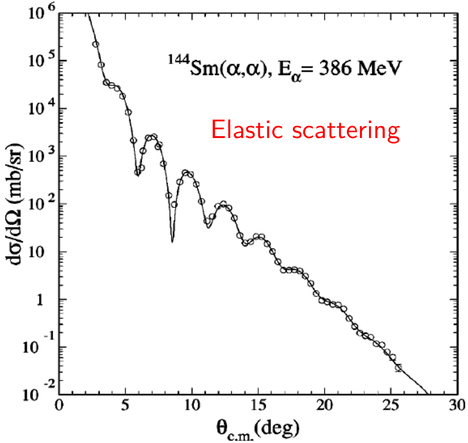


Systematics on stable nuclei

Experimental details

$$\alpha + {}^{144}\text{Sm} \rightarrow \alpha' + {}^{144}\text{Sm}^{\star}$$





Elastic scattering

Systematics on stable nuclei

Experimental details Itoh et al. **Phys. Rev. C** 68 (2003)

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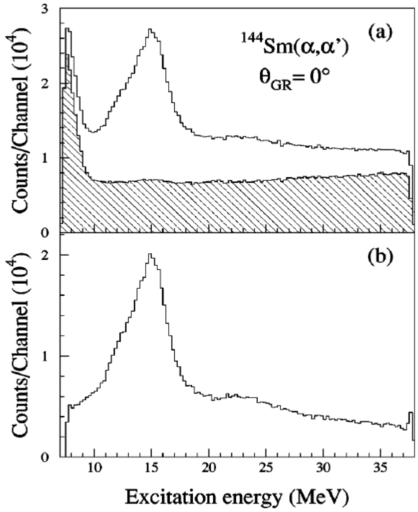

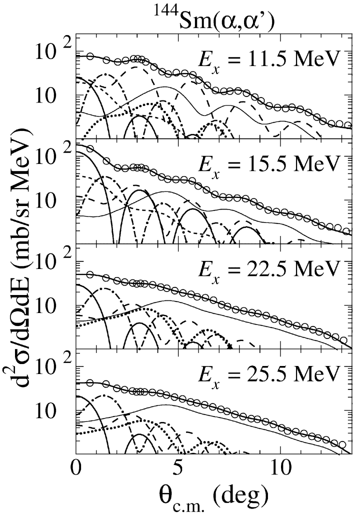

Systematics on stable nuclei

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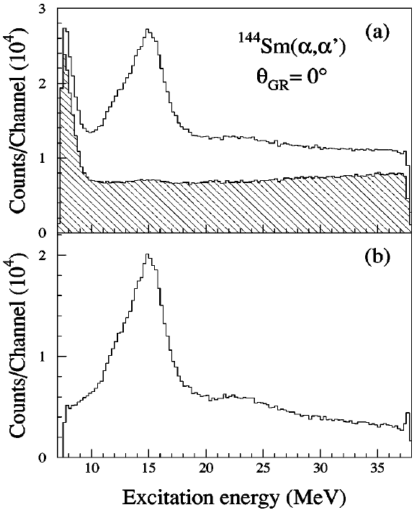
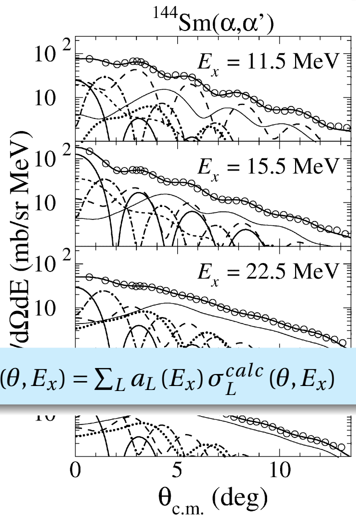
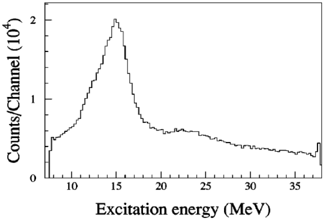




$$\sigma^{exp}(\theta, E_x) = \sum_L a_L(E_x)\,\sigma_L^{calc}(\theta, E_x)$$

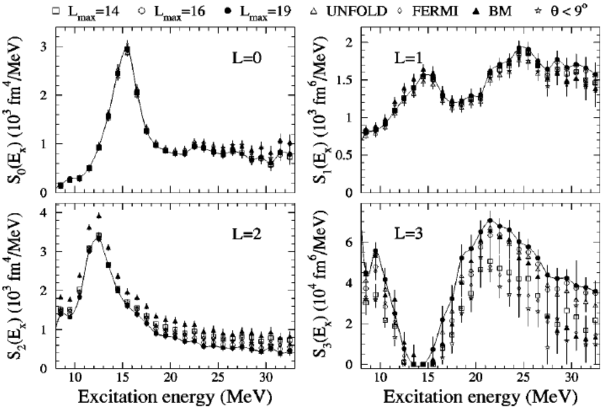
Systematics on stable nuclei

Analysis details Itoh et al. **Phys. Rev. C** 68 (2003)



$\alpha + {}^{144}\text{Sm} \rightarrow \alpha' + {}^{144}\text{Sm}^\star$

Multiple Decomposition Analysis (MDA)



Systematics on stable nuclei

Analysis details Itoh et al. **Phys. Rev. C** 68 (2003)

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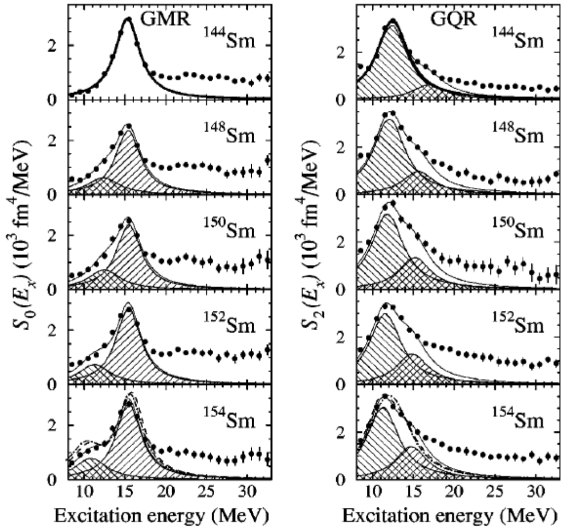


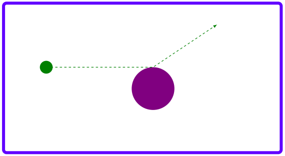
Finally fit
with Lorentzian
⇓
position
width
"amplitude"
(X-section)

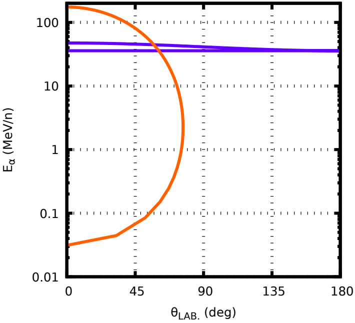
Example of experiments with unstable nuclei

Kinematics

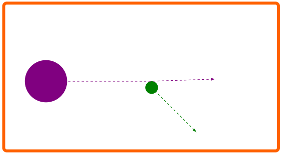
Example : α on $A \sim 60$ with $T \sim 50\,\text{MeV/n}$

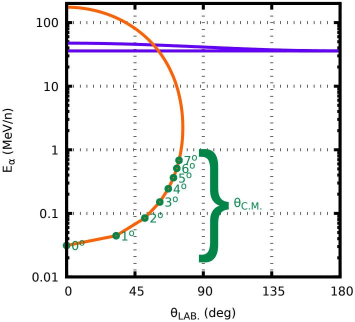
Direct kinematics





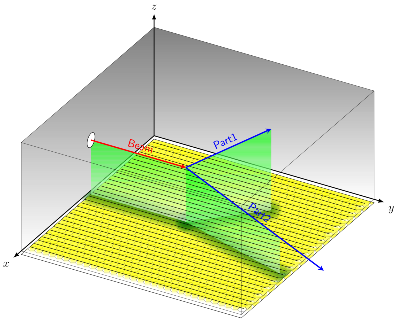
Reverse kinematics





Reverse kinematics ⇒ very low energy recoil ⇒ gas detector/target!

Active target



Gas detector w/ gas = target

Pros

High efficiency (3D)

Low detection threshold

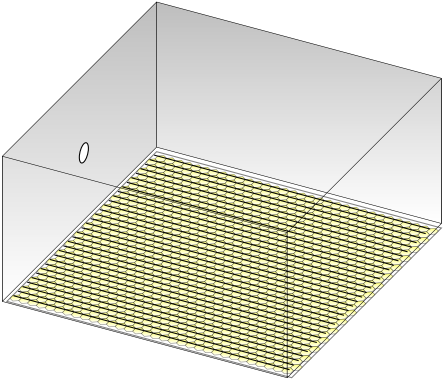
Thick target (≈10 mg/cm^2)

Cons (as for MAYA)

Beam rate limited (10^5 pps)

Capricious (!)

MAYA: concept



MAYA

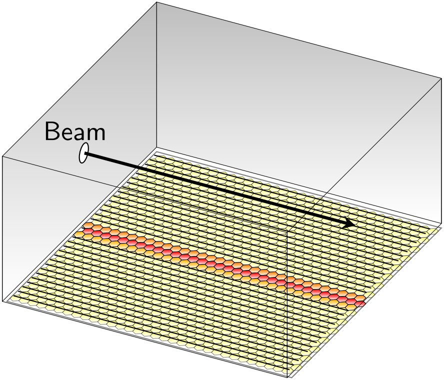
$283 \times 258 \times 200\ \text{mm}^3 \equiv 30$ L of gas

⇒ thick target

⇒ gas detector

Demonchy et al. **Nucl. Instrum. Methods Phys. Res., Sect. A** 583 (2007)

MAYA: concept



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⇒ thick target
⇒ gas detector

Inside :

2D proj. (honeycomb struct.)

Demonchy et al. **Nucl. Instrum. Methods Phys. Res., Sect. A** 583 (2007)

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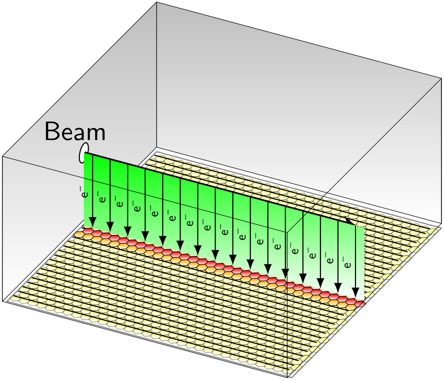

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2D proj. (honeycomb struct.)

3D using drift time

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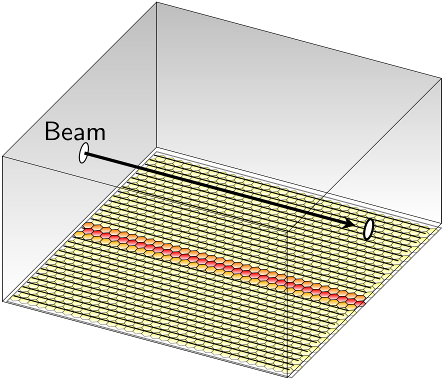

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Inside :

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3D using drift time

Ancillary detectors :

Diamond

Demonchy et al. **Nucl. Instrum. Methods Phys. Res., Sect. A** 583 (2007)

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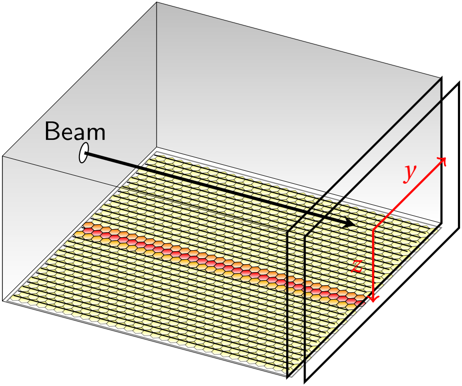

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⇒ thick target

⇒ gas detector

Inside :

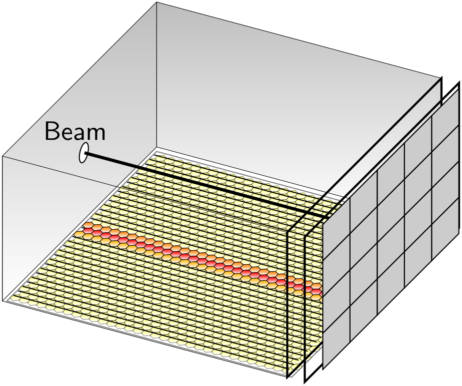
- 2D proj. (honeycomb struct.)
- 3D using drift time

Ancillary detectors :

- Diamond
- Drift chamber

Demonchy et al. **Nucl. Instrum. Methods Phys. Res., Sect. A** 583 (2007)

MAYA: concept



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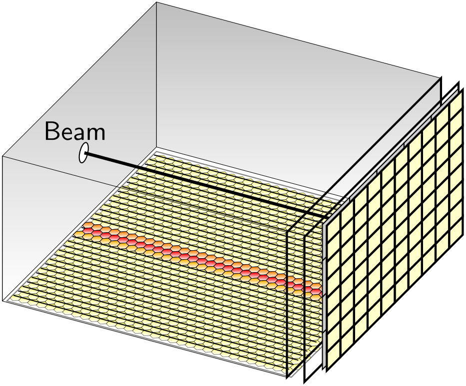
Inside :

- 2D proj. (honeycomb struct.)
- 3D using drift time

Ancillary detectors :

- Diamond
- Drift chamber
- 4×5 Si (5×5cm^2, 700 μm)

MAYA: concept



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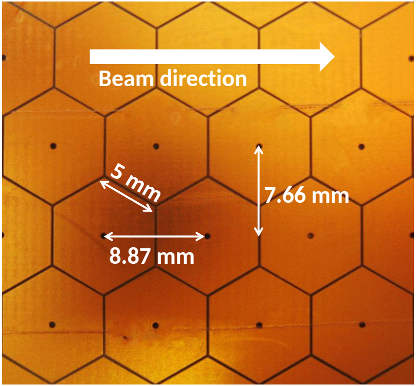
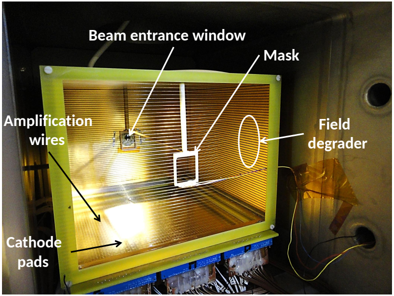
Ancillary detectors :

- Diamond
- Drift chamber
- $4{\times}5$ Si ($5{\times}5$cm^2, 700 μm)
- $8{\times}10$ CsI ($2.5{\times}2.5$cm^2)

Setup: pictures

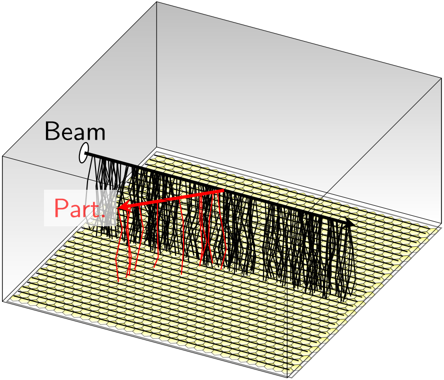




Setup: Improvement

Mask

Beam energy loss ≫ scattered particles ⇒ dynamics issues.



Pancin et al. **J. Instrum.** 7 (2012)

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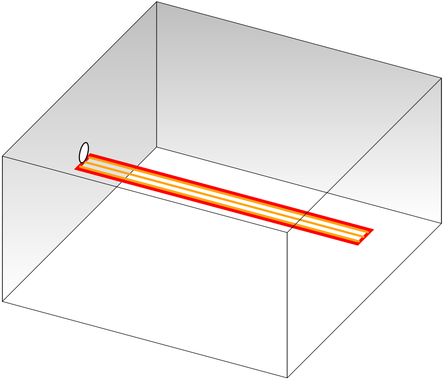

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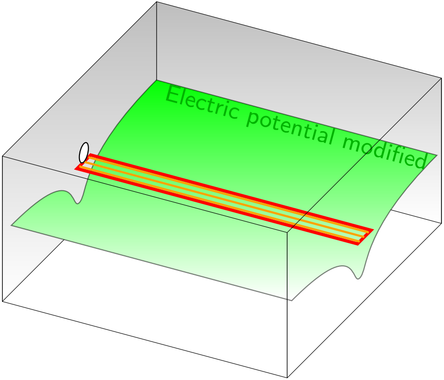

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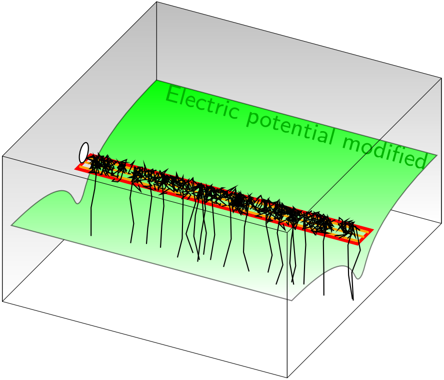
Beam energy loss $\gg$ scattered particles $\Rightarrow$ dynamics issues.



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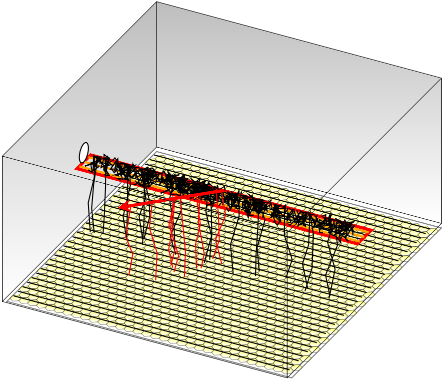

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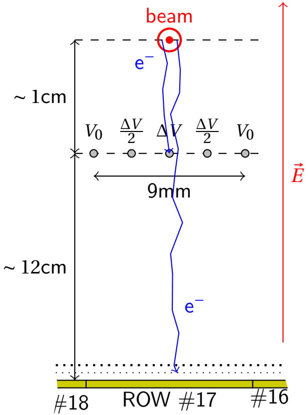
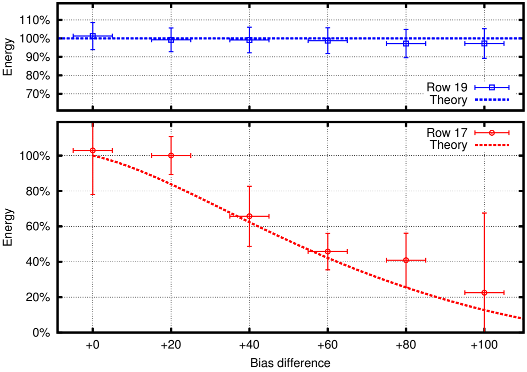
Mask



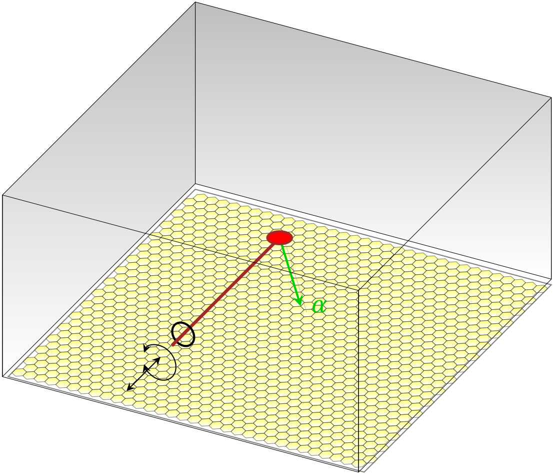


Bias difference (ΔV) added to mask central wire ; Energy $\propto N_{e^-}$

Pancin et al. **J. Instrum.** 7 (2012)

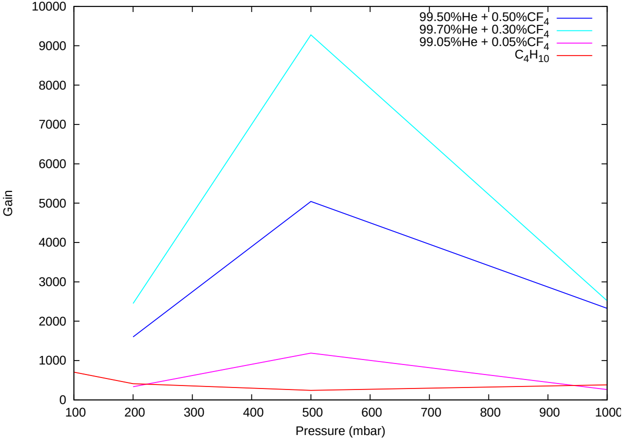
Setup: Improvement

Retractable source, allows regular monitoring.



Setup: Improvement

Gas: Helium feasible with CF_4 as quencher



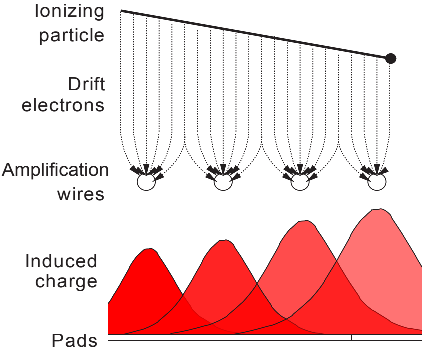
Test performed w/ "Mayaito"

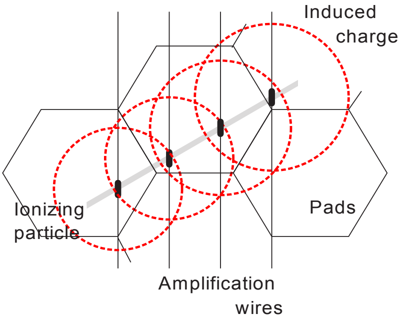
With MAYA and during experiment ~500mbar, 5% CF_4.

Some MAYA analysis techniques:

Roger et al. **Nucl. Instrum. Methods Phys. Res., Sect. A** 638 (2011)

Trajectory reconstruction

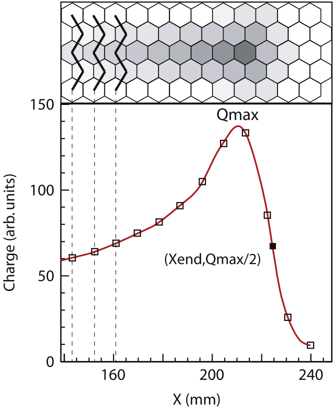




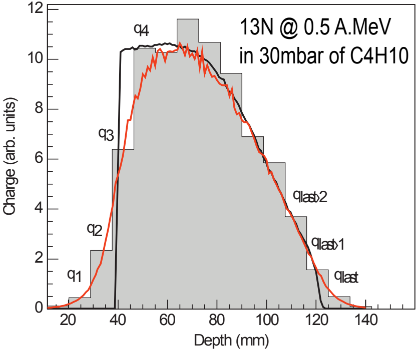
Some MAYA analysis techniques:

Range measurement

In case of a "clear" Bragg pic: smoothing w/ spline ⇒ error ≤ 1 mm



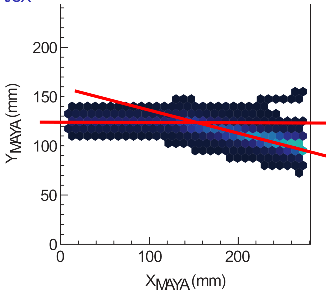
Otherwise: depends on the experiment/simulation (typically last charge/position combinaison. . .)

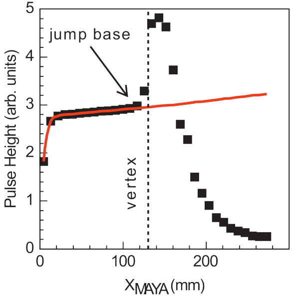


Roger et al. **Nucl. Instrum. Methods Phys. Res., Sect. A** 638 (2011)

Some MAYA analysis techniques:

Vertex





First order

intersection point of tracks

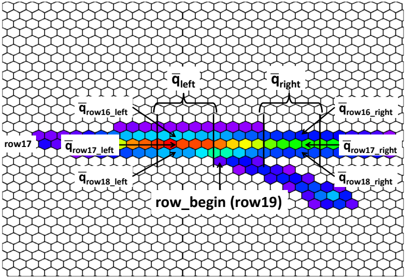
Refinement

enhancement of the deposited charge around the vertex. (simulation)

Some MAYA analysis techniques:

Vertex

Thanks to the mask, beam can be seen and substracted, to allow fitting of small tracks (few pads)



Some MAYA analysis techniques:

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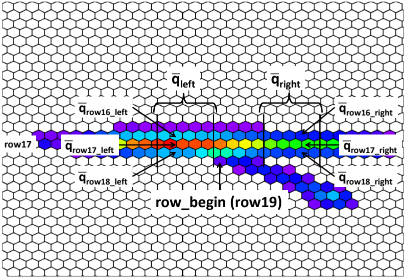
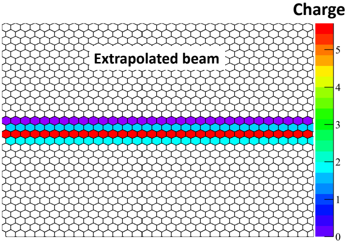
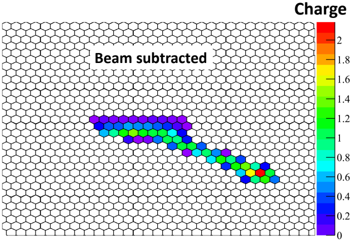






Mounting MAYA !

https://www.youtube.com/watch?v=aUxC68zb6sI

^{56}Ni : ISGMR & ISGDR

^{54}Ni ^{55}Ni ^{56}Ni ^{57}Ni ^{58}Ni ^{59}Ni ^{60}Ni ^{61}Ni ^{62}Ni ^{63}Ni ^{64}Ni ^{65}Ni ^{66}Ni ^{67}Ni ^{68}Ni ^{69}Ni ^{70}Ni ^{71}Ni ^{72}Ni

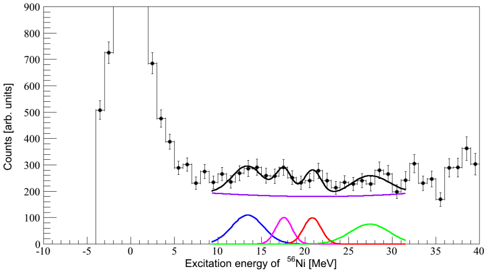
ISGMR : two experiments

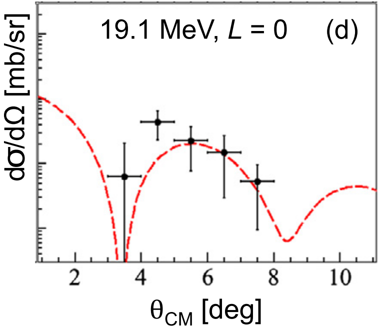
^{56}Ni$(d,d')^{56}$Ni*: Monrozeau et al. **Phys. Rev. Lett.** 100 (2008) Monrozeau **PhD** (2007)

$E^{*}_{\text{ISGMR}} \approx 19.5$ MeV

^{56}Ni$(\alpha,\alpha')^{56}$Ni*: Bagchi **PhD** (2015) Bagchi et al. **Phys. Lett. B** 751 (2015)

$E^{*}_{\text{ISGDR}} = 19.1 \pm 0.5$ MeV





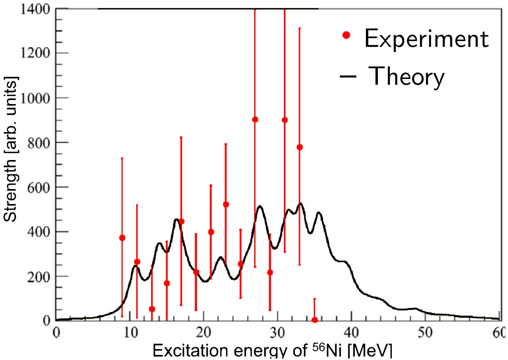
^{56}Ni : ISGMR & ISGDR

^{54}Ni ^{55}Ni ^{56}Ni ^{57}Ni ^{58}Ni ^{59}Ni ^{60}Ni ^{61}Ni ^{62}Ni ^{63}Ni ^{64}Ni ^{65}Ni ^{66}Ni ^{67}Ni ^{68}Ni ^{69}Ni ^{70}Ni ^{71}Ni ^{72}Ni

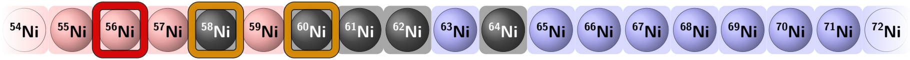
ISGDR

^{56}**Ni**$(\alpha,\alpha')^{56}$**Ni*****:** Bagchi et al. **Phys. Lett. B** 751 (2015)

$$E^{*}_{\text{ISGDR}} = 17.4 \pm 0.7 \text{ MeV}$$



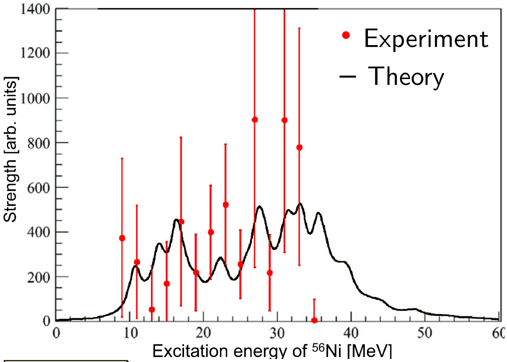
^{56}Ni : ISGMR & ISGDR



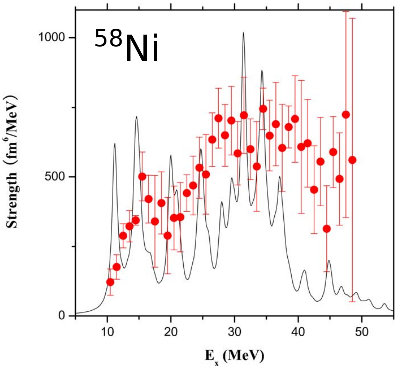
ISGDR

^{56}Ni(α,α')**^{56}Ni*:** Bagchi et al. **Phys. Lett. B** 751 (2015)

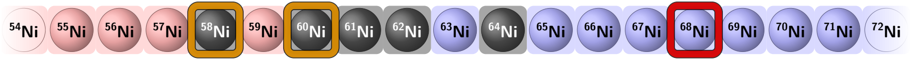
$$E^{*}_{\mathrm{ISGDR}} = 17.4 \pm 0.7 \text{ MeV}$$



This work



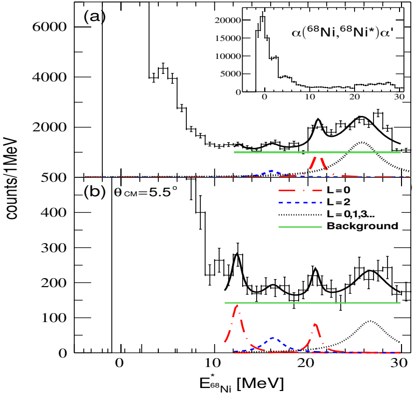
Nayak et al. **Phys. Lett. B** 637 (2006)

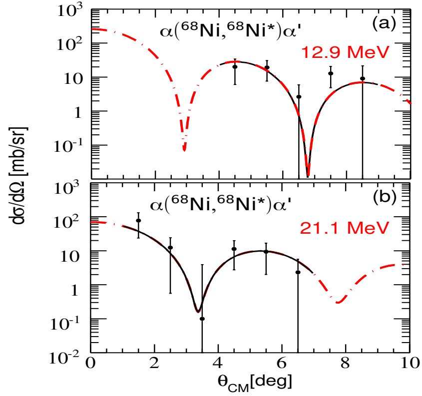


One proposal: two experiments (M. Vandebrouck's PhD)

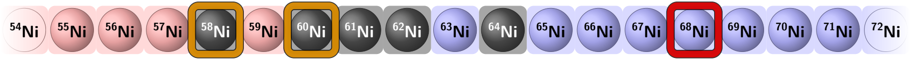
^{68}Ni$(\alpha,\alpha')^{68}$Ni*: $E^* = 12.9 \pm 1.0$ & 21.1 ± 1.9 MeV

^{68}Ni$(d,d')^{68}$Ni*: $E^* = 12.6 \pm 0.3$ & 20.8 ± 0.6 MeV





^{68}Ni : ISGMR



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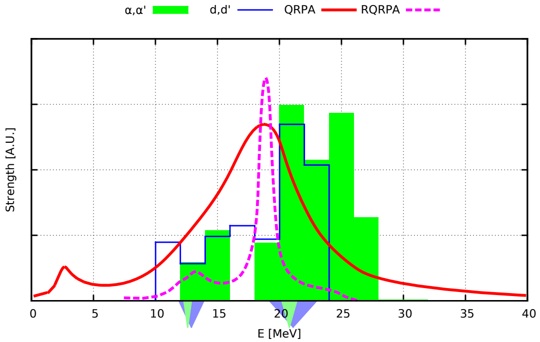
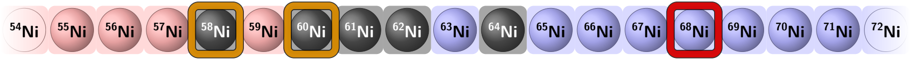


QRPA: Terasaki et al. **Phys. Rev. C** 74 (2006) RQRPA: Khan et al. **Phys. Rev. C** 84 (2011)

^{68}Ni : ISGMR



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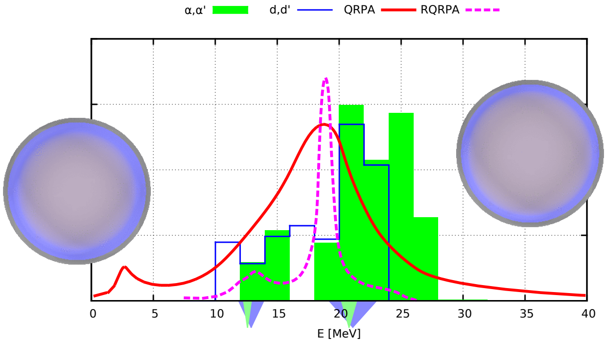
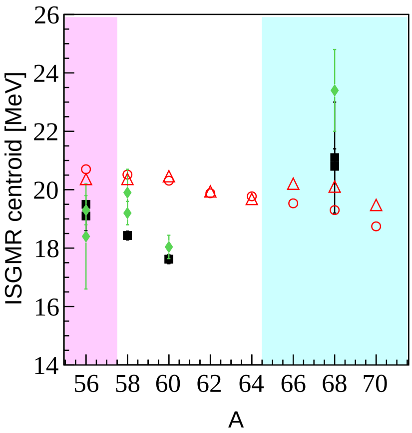


QRPA: Terasaki et al. **Phys. Rev. C** 74 (2006) RQRPA: Khan et al. **Phys. Rev. C** 84 (2011)

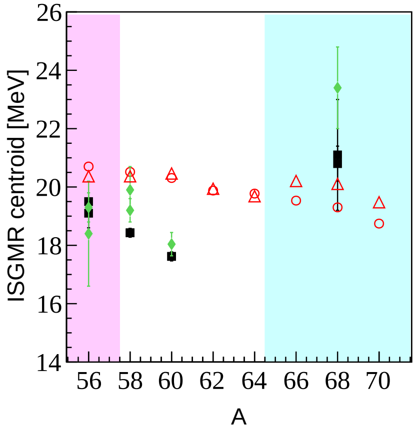
ISGMR : summary in Nickel's chiain



Experiment :
■ **Fitting method**
♦ **MDA**

Theory :
○ **QRPA (S. Peru, private comm.)**
△ **RQRPA (E. Litvinova, private comm.)**

ISGMR : summary in Nickel's chiain



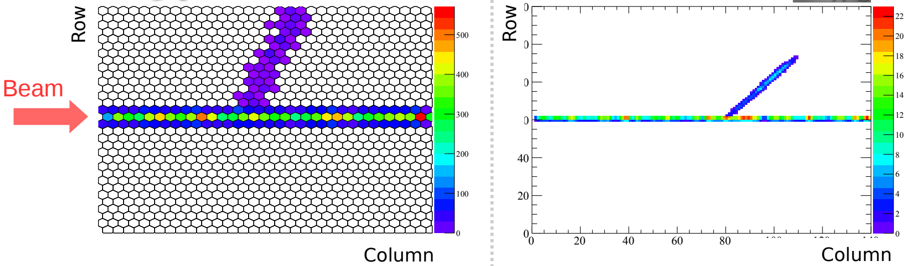
Experiment :
■ **Fitting method**
♦ **MDA**

Theory :
○ **QRPA (S. Peru, private comm.)**
△ **RQRPA (E. Litvinova, private comm.)**

More points needed?

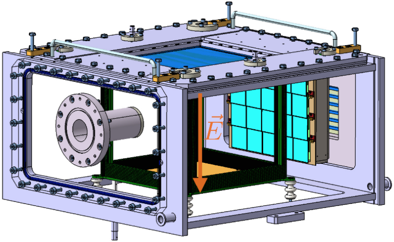
Improve measurement on $^{58,68,(70)}$Ni

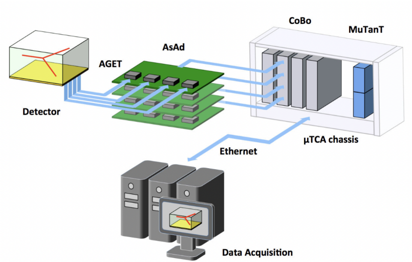
^{68}Ni(α,α')^{68}Ni* (E*=20MeV)



;

ACTAR TPC : ACTive TARget





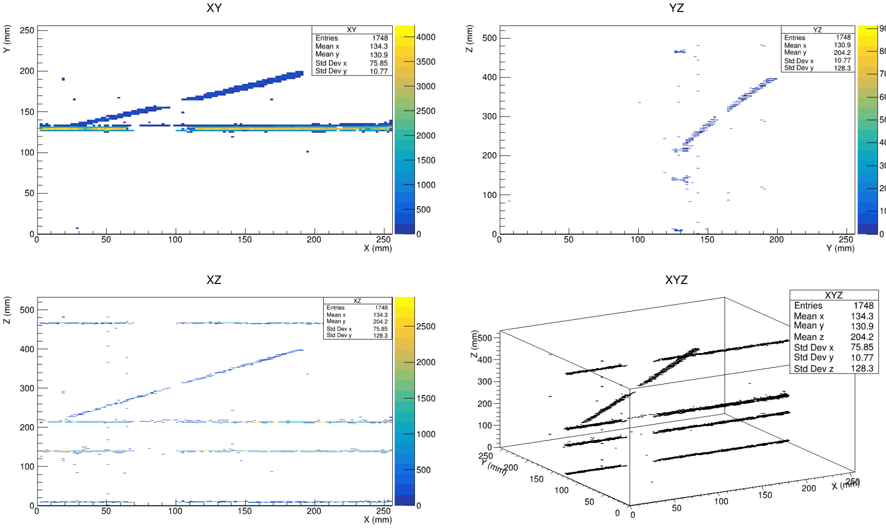
Roger et al. **Nucl. Instrum. Methods Phys. Res., Sect. A** 895 (2018)

128×128 pixels of $2\,\mathrm{mm}^2$

16 384 channels in a square of 25.6 x 25.6 cm^2 (~ 10 more than MAYA)

Dedicated (compact) electronics

ACTAR TPC : ACTive TARget



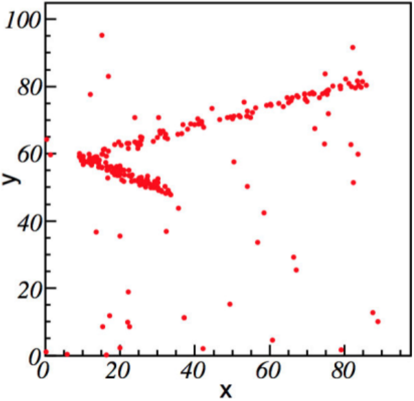
How to identify each individual track ?

ACTAR TPC : ACTive TARget

Identification and reconstruction of tracks

RANSAC method: iterative method to find the tracks

2D example



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RANSAC method: iterative method to find the tracks

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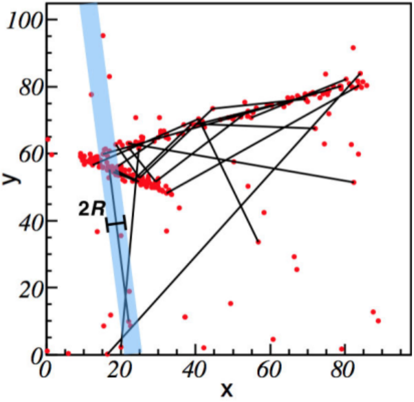
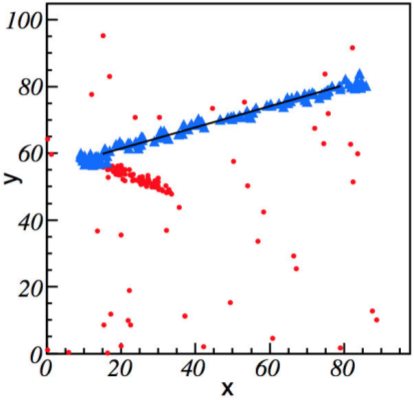


Mauss **PhD** (2018)

RANSAC method: iterative method to find the tracks

2D example



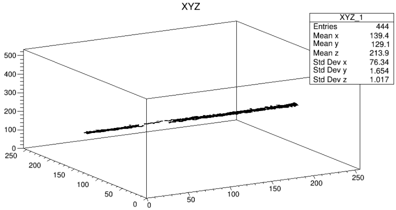
Mauss **PhD** (2018)

ACTAR TPC : ACTive TARget

Identification and reconstruction of tracks

RANSAC method: iterative method to find the tracks

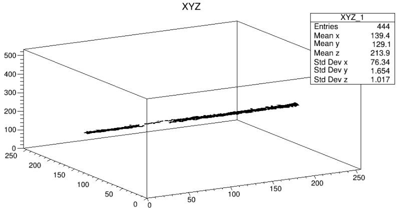
3D example iterative results

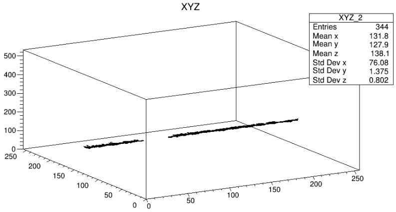


Mauss **PhD** (2018)

RANSAC method: iterative method to find the tracks

3D example iterative results





Mauss **PhD** (2018)

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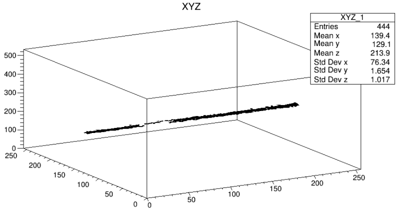
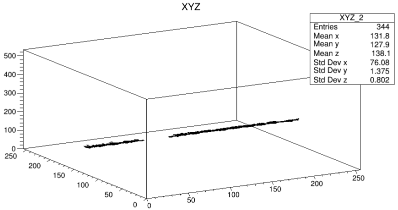
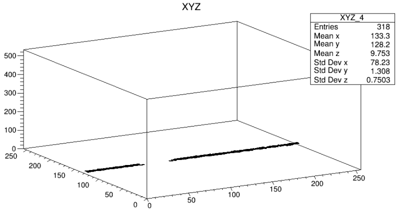


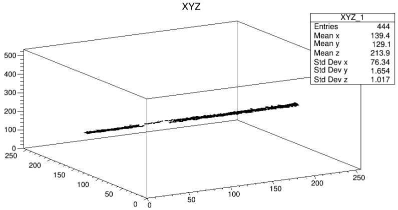


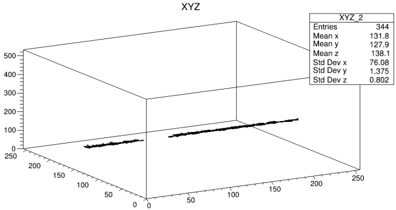


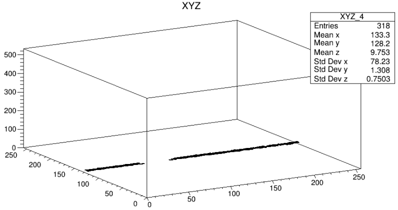
Mauss **PhD** (2018)

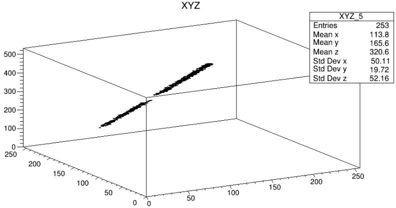
RANSAC method: iterative method to find the tracks

3D example iterative results









Mauss **PhD** (2018)

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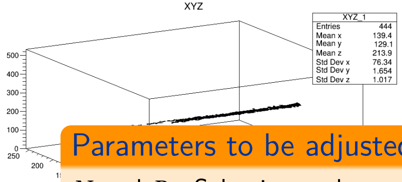
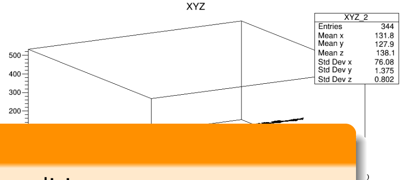
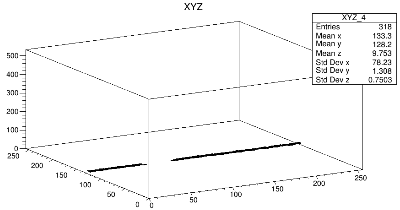
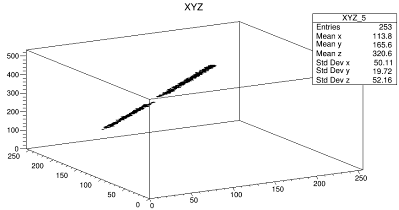




Parameters to be adjusted

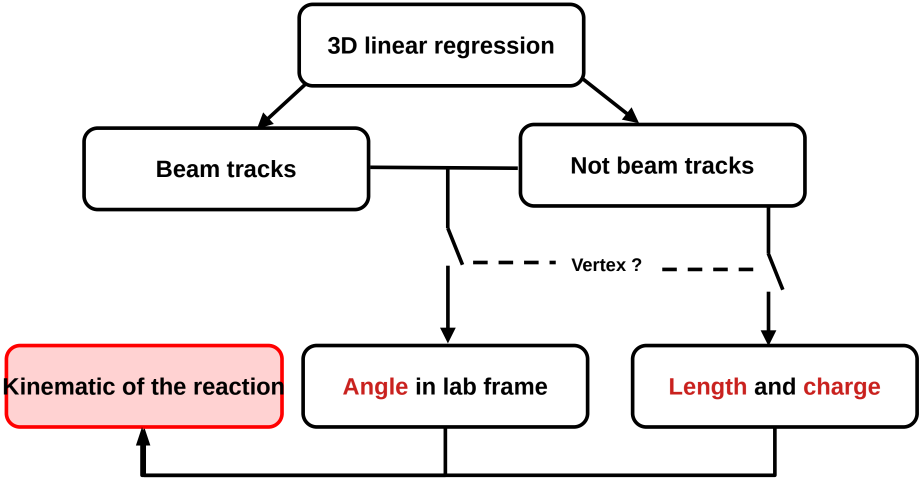
N and R ; Selection and stopping conditions





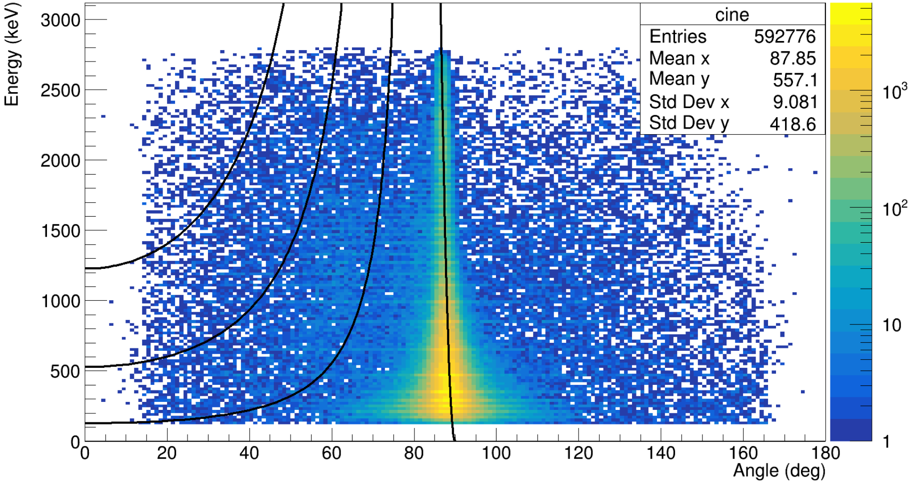
Mauss **PhD** (2018)

Measurement of the kinematics parameters



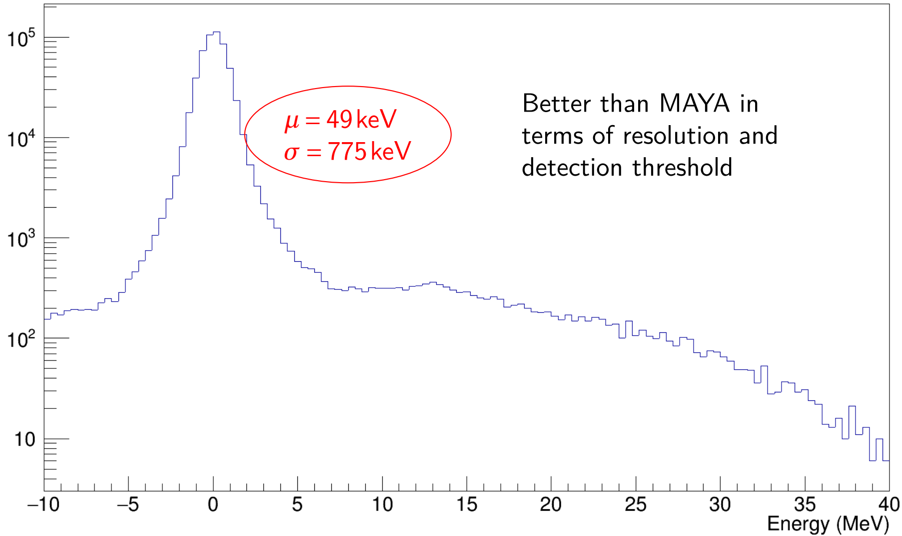
$^{58}Ni(\alpha, \alpha)^{58}Ni^{\star}$ dataset

Kinematics: lab angle vs alpha energy



^{58}Ni(α, α)^{58}Ni* dataset

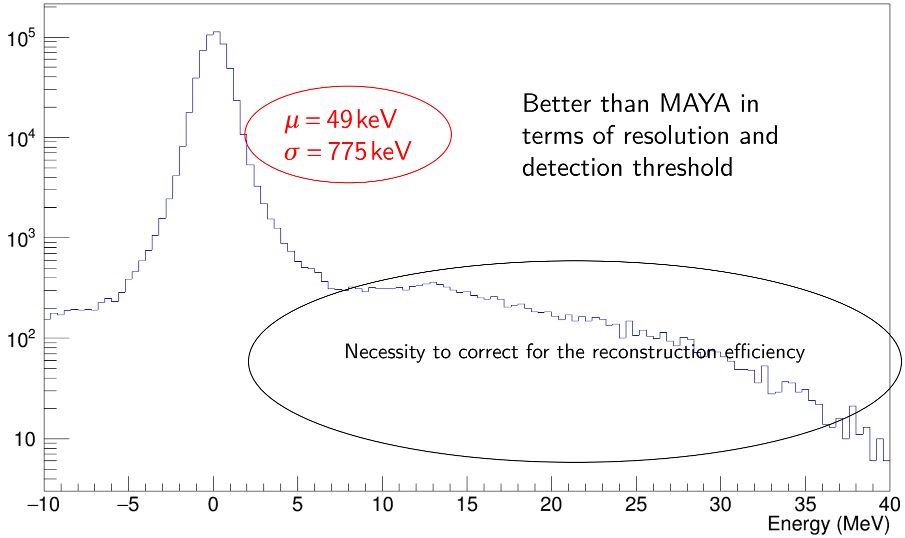
Kinematics: lab angle vs alpha energy



Better than MAYA in terms of resolution and detection threshold

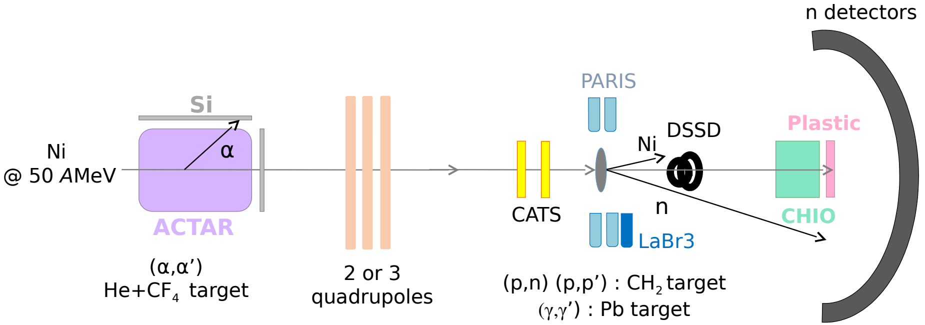
$^{58}Ni(\alpha, \alpha)^{58}Ni^{\star}$ dataset

Kinematics: lab angle vs alpha energy

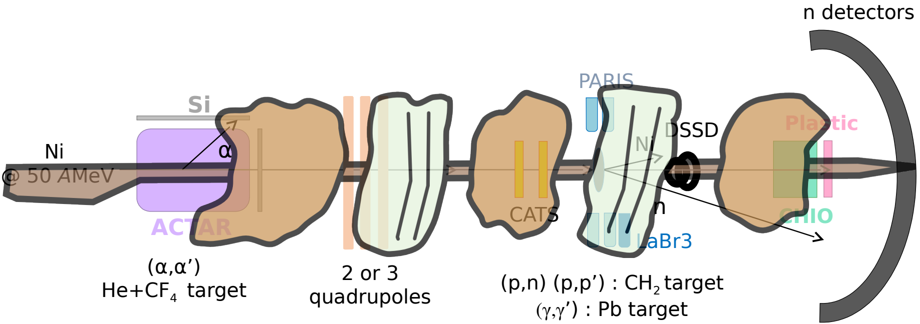


Letter of Intent/Proposal

"Yakitori" (or "Brochette" ["Skewer"]) mode



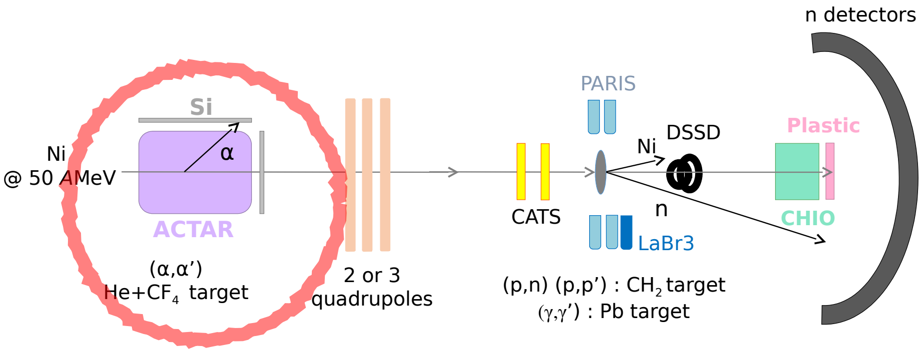
“Yakitori” (or “Brochette” [“Skewer”]) mode



Letter of Intent/Proposal

"Yakitori" (or "Brochette" ["Skewer"]) mode

GMR + ISGDR w/ ACTAR

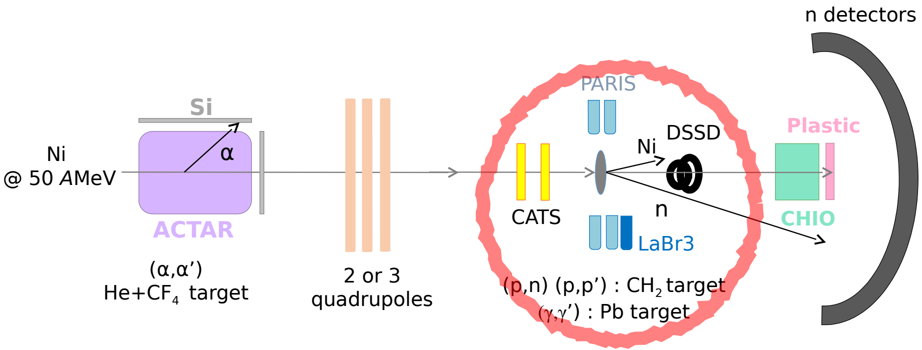


Letter of Intent/Proposal

"Yakitori" (or "Brochette" ["Skewer"]) mode

GMR + ISGDR w/ ACTAR

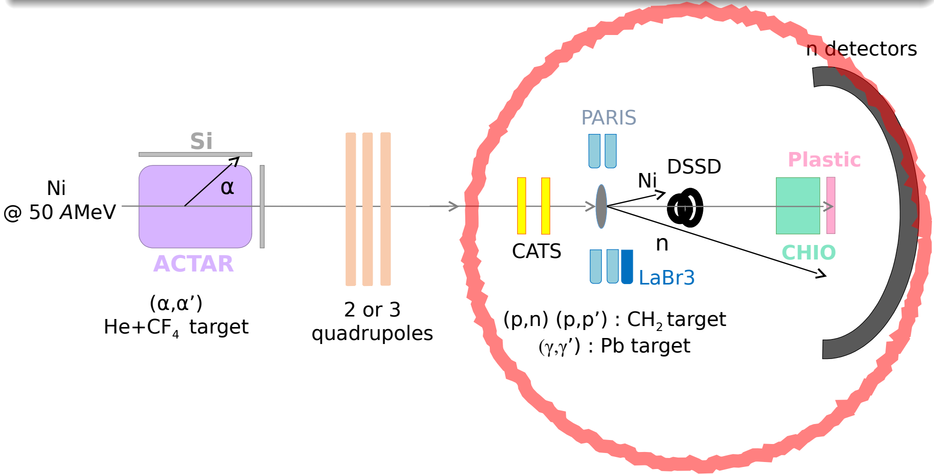
ISGDR + IVGDR w/ solid target & γ-rays



Letter of Intent/Proposal

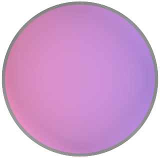
“Yakitori” (or “Brochette” [“Skewer”]) mode

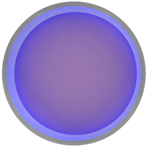
- GMR + ISGDR w/ ACTAR
- ISGDR + IVGDR w/ solid target & γ-rays



(IV) Pygmy Dipole Resonance

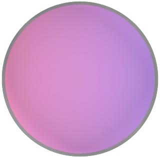
Illustration



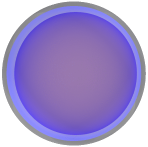


(IV) Pygmy Dipole Resonance

Illustration

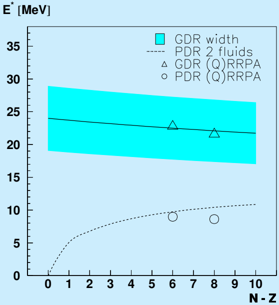


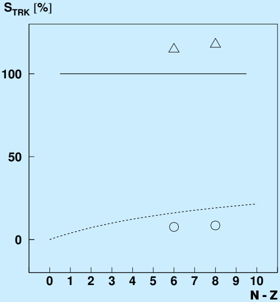
GDR



PDR

Neon isotopes



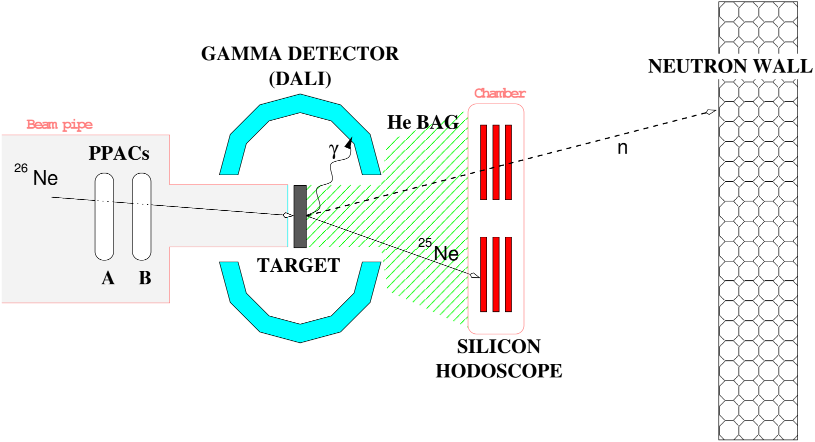


Suzuki et al. **Progress in Theoritical Physics** 83 (1990)

Cao et al. **Physical Review C** 71 (2005)

(IV) Pygmy Dipole Resonance

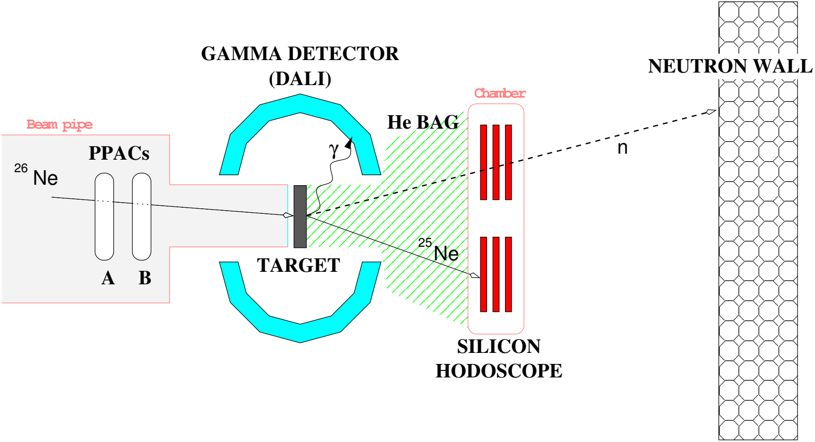
$^{26}_{10}$Ne case



$$^{26}\text{Ne} + {}^{208}\text{Pb} \rightarrow {}^{26}\text{Ne} \rightarrow {}^{26+x}\text{Ne}^{\star} + x\ n$$

(IV) Pygmy Dipole Resonance

$^{26}_{10}$Ne case



$$^{26}\mathrm{Ne} + {}^{208}\mathrm{Pb} \rightarrow {}^{26}\mathrm{Ne} \rightarrow {}^{26+x}\mathrm{Ne}^{\star} + \underbrace{x}_{x\geq 0} n$$

(IV) Pygmy Dipole Resonance

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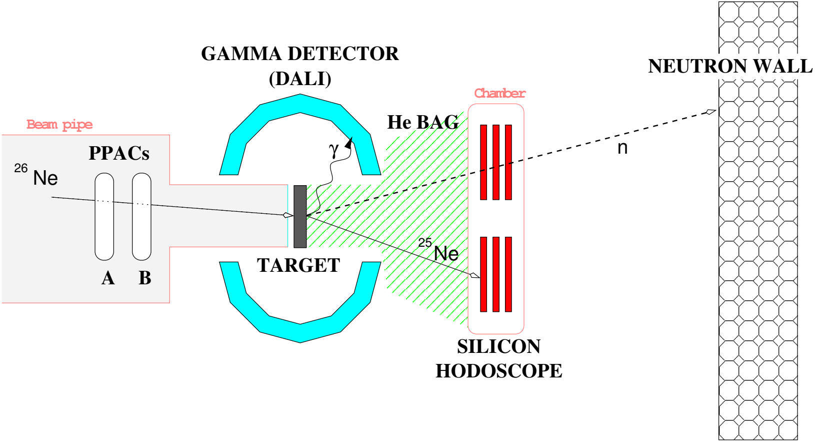
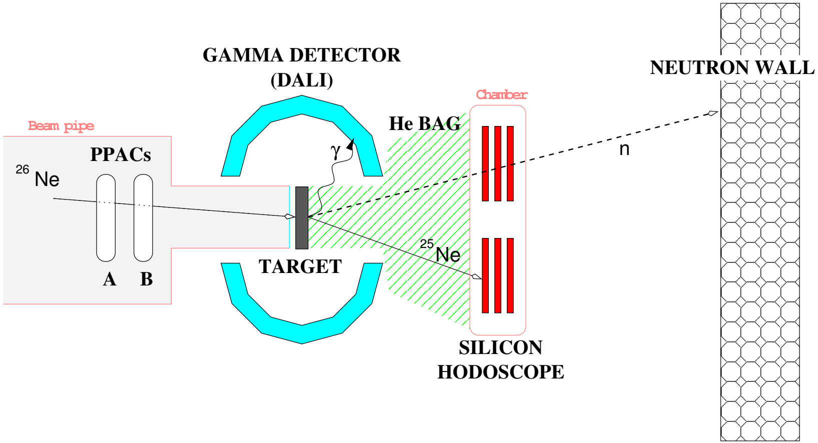


$$\underbrace{{}^{26}\text{Ne} + {}^{208}\text{Pb}}_{\Leftrightarrow {}^{26}\text{Ne}+\gamma^\star} \rightarrow {}^{26}\text{Ne} \rightarrow {}^{26+x}\text{Ne}^\star + \underbrace{x}_{x\geq 0} n$$

(IV) Pygmy Dipole Resonance

$^{26}_{10}$Ne case



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(IV) Pygmy Dipole Resonance

$^{26}_{10}$Ne case

Invariant mass method:

$$M_{\text{inv}} = M_0 + E^\star = \sqrt{\sum_i E_i^2 - \sum_i \vec{p}_i^{\,2}} \Rightarrow E^\star \sim E_{\text{rel}}(^{25}\text{Ne}, n) + E_\gamma(^{25}\text{Ne})$$

(IV) Pygmy Dipole Resonance

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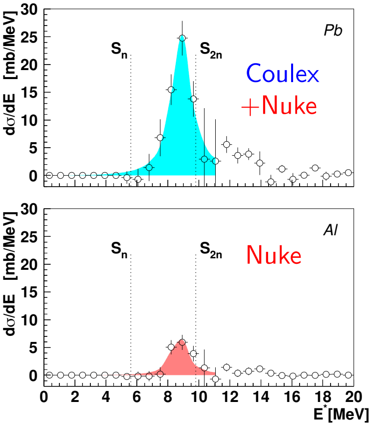

(IV) Pygmy Dipole Resonance

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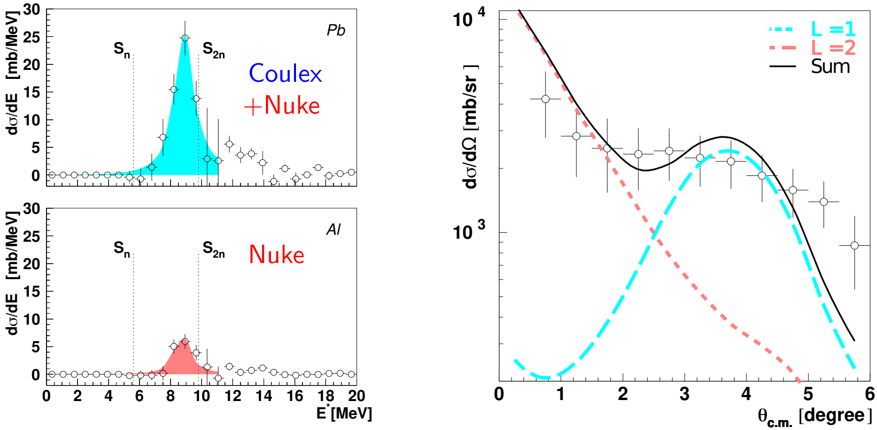
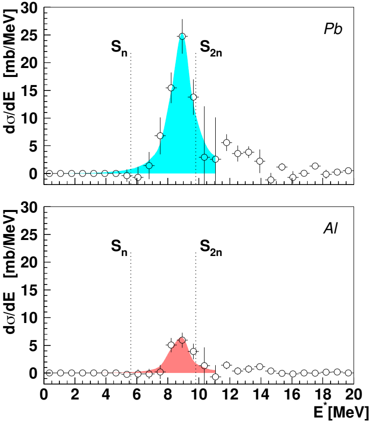
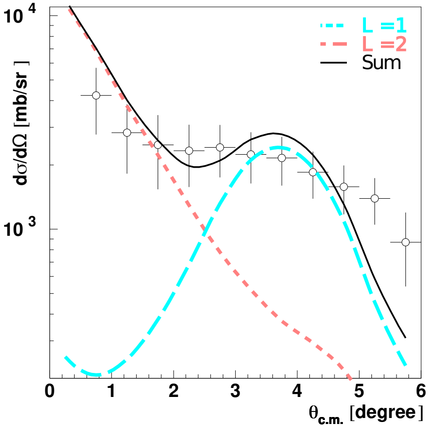


(IV) Pygmy Dipole Resonance

$^{26}_{10}$Ne case





Results

$E_x \sim 9\,\text{MeV}$ and $S_{\text{TRK}} \sim 5\,\%$

Pygmy properties vs skin thickness

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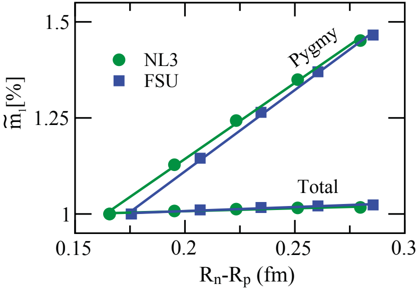
$E_x \sim 9\,\text{MeV}$ and $S_{\text{TRK}} \sim 5\,\%$

Pygmy properties vs skin thickness

Results

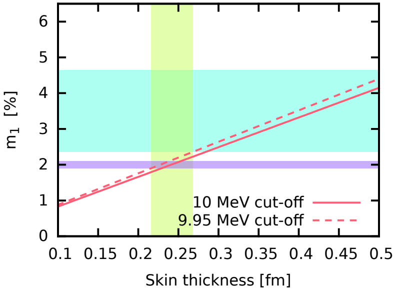
$E_x \sim 9\,\text{MeV}$ and $S_{\text{TRK}} \sim 5\,\%$

^{68}Ni



Piekarewicz **Phys. Rev. C** 83 (2011)

^{26}Ne



Inakura et al. **Phys. Rev. C** 88 (2013)

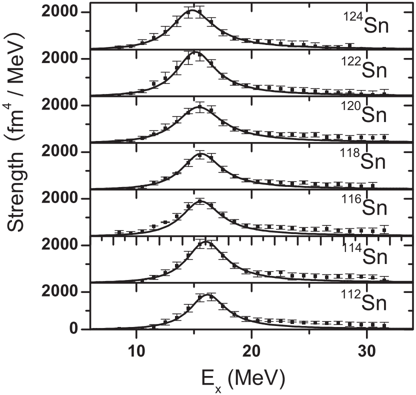
Marinova et al. **Phys. Rev. C** 84 (2011)

Gibelin **PhD** (2018)

Other setup for GMR measurement

Systematics in stable Sn isotopes

RCNP/Grand Raiden

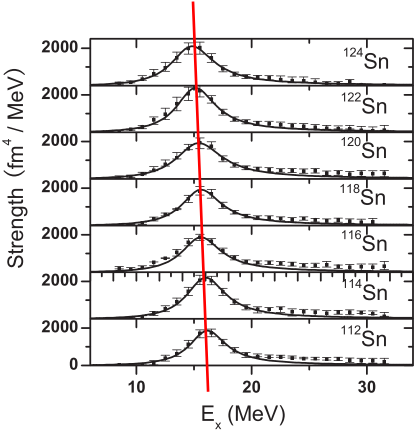


$$K_A - K_{\text{Coul}} Z^2 A^{-4/3} \sim K_{\text{vol}} \left(1 - A^{-1/3}\right) + K_\tau [(N-Z)/A]^2$$

$K_{\text{Coul}} \sim$ cst

Systematics in stable Sn isotopes

RCNP/Grand Raiden



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$$K_{\text{vol}} \left(1 - A^{-1/3}\right) + K_\tau [(N-Z)/A]^2$$

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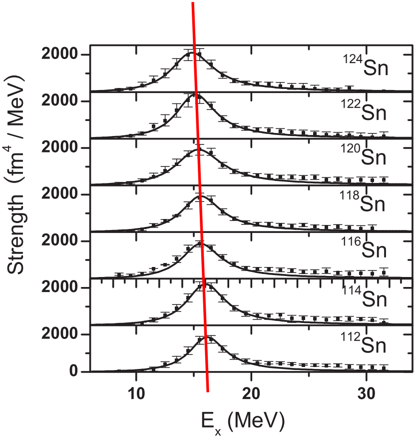

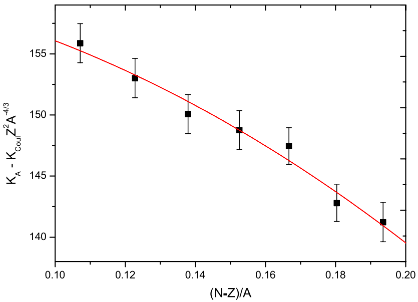

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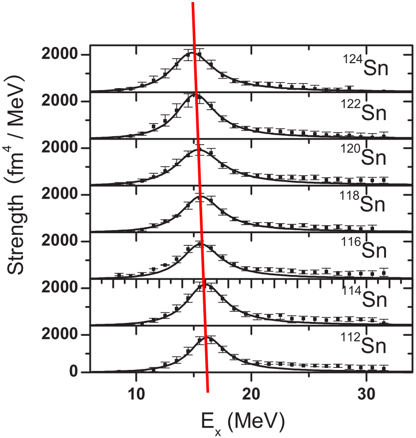
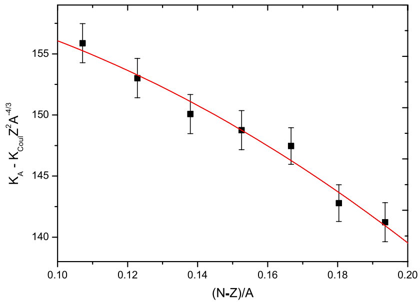
RCNP/Grand Raiden





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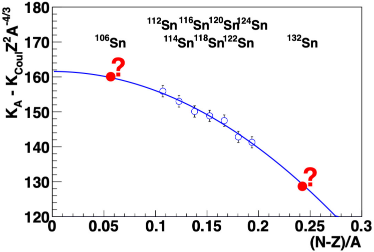
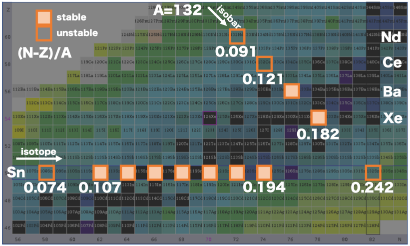
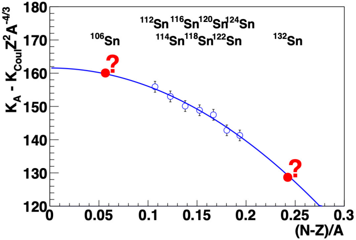
What about the radioactive Sn?

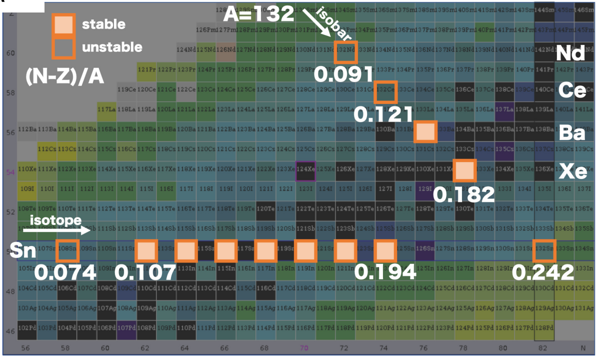




What about the radioactive Sn?



Combined measurement (RIBF + RCNP) w/ the same setup “CATS”



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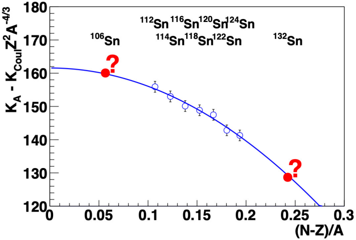

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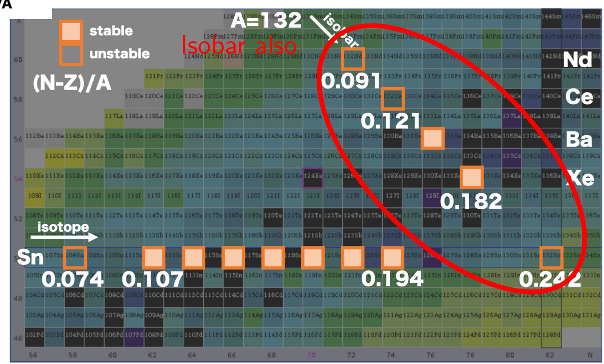
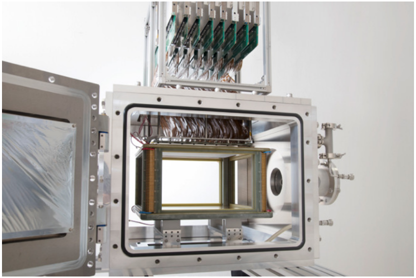
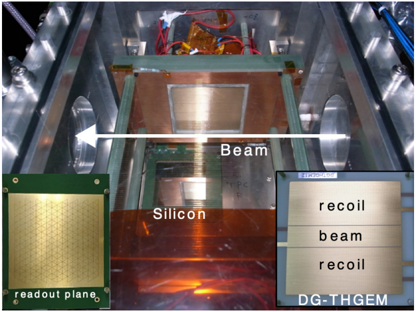


CAT (CNS Active Target)

NEAT! (yEt another Active Target!)

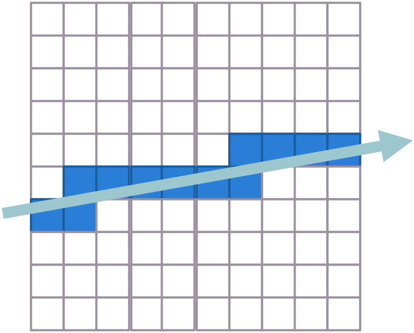




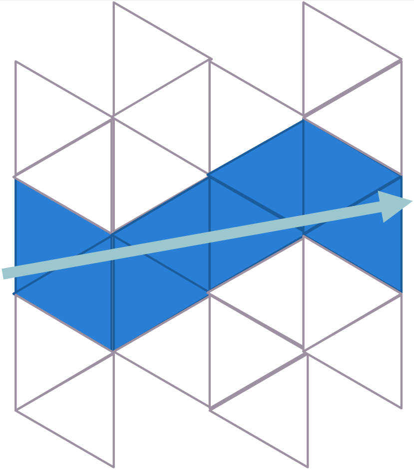
CAT (CNS Active Target)

NEAT! (yEt another Active Target!)

Concept: small number of readout channel (relatively low definition)



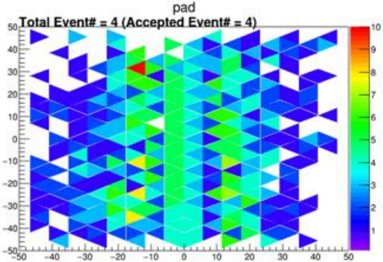
$4\,\mathrm{mm}^2 * 100 = 400\,\mathrm{mm}^2$ (4K)



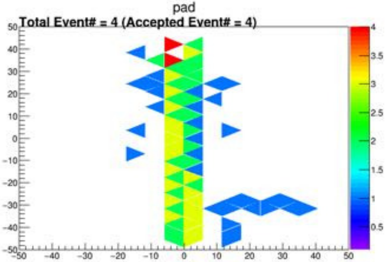
$15.6\,\mathrm{mm}^2 * 24 = 374\,\mathrm{mm}^2$ (HD) GEM technology

CAT (CNS Active Target)

NEAT! (yEt another Active Target!)



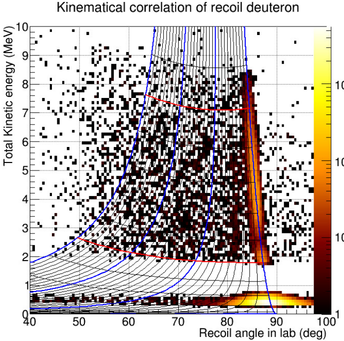
(RAW)



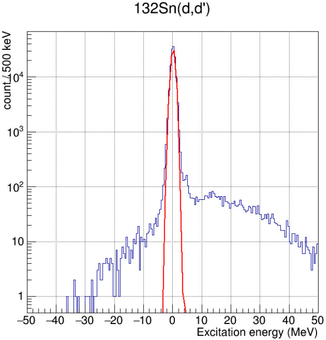
(CLEAN ⇐ Hough transform (see Radon tr.))

CAT (CNS Active Target)

(preliminary)Results ^{132}Sn(d,d') (Courtesy of S. OTA [RCNP/Japan])



Kinematics

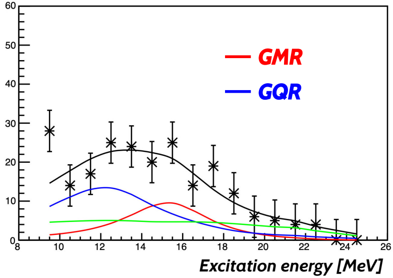


Excitation energy

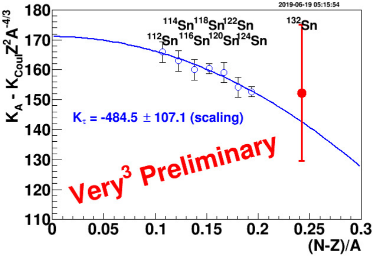
$E_x \sim 0\,\mathrm{MeV} (\sigma = 0.6\,\mathrm{MeV})$

CAT (CNS Active Target)

(preliminary) Results $^{132}Sn(d,d')$



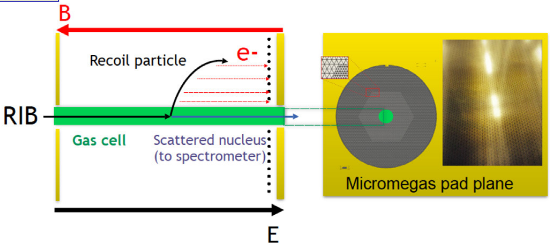
Lorentzian fit (GMR + GQR)

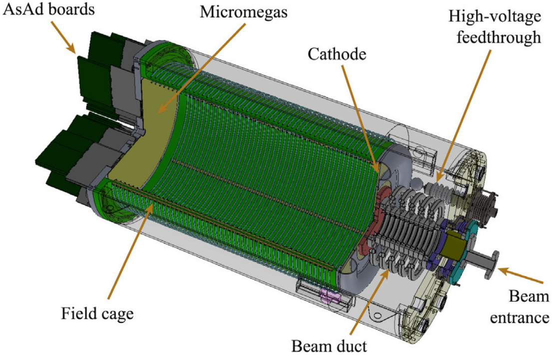


Compressibility

AT-TPC (Active Target Time Projection Chamber) – MSU

Ayyad et al. **Nucl. Phys. A** 954 (2020)





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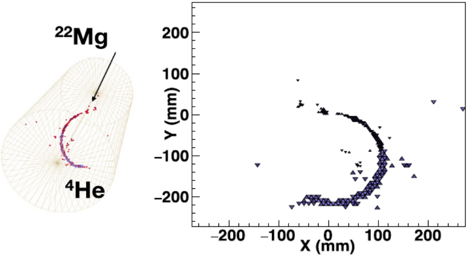

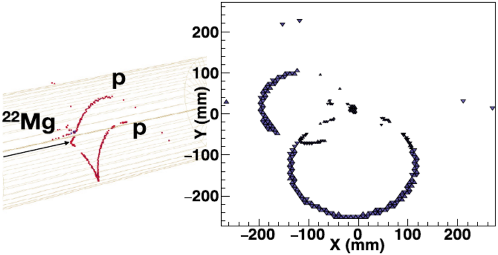

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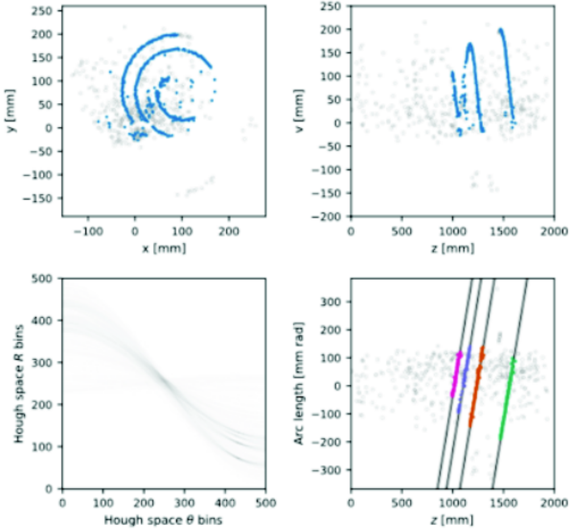
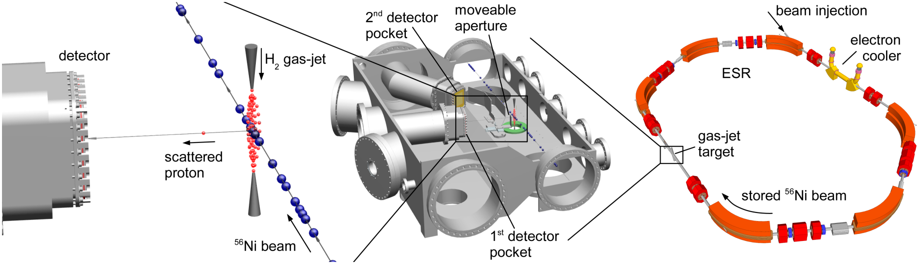


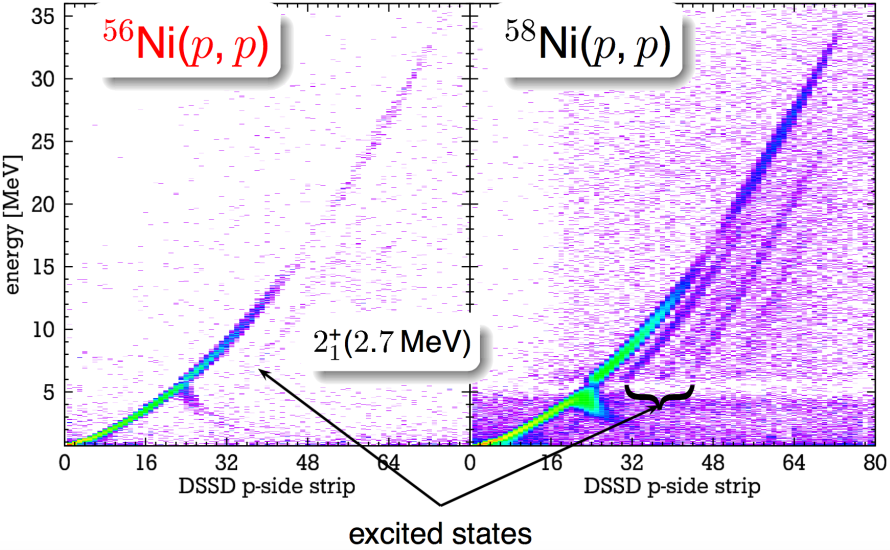
(FAIR/GSI)



Zamora et al. **Physics Letters B** 763 (2016)

EXL (Exotic nuclei studied in Light-ion induced reactions at the NESR storage ring)

(FAIR/GSI)



Zamora et al. **Physics Letters B** 763 (2016)

Overview

1. Giant Resonances Properties
2. Experimental considerations
3. Example of experiments with stable nuclei
4. Example of experiments with unstable nuclei
   - GMR (MAYA/ACTAR)
   - PDR (Coulomb excitation)
5. Other setup for GMR measurement
   - RIKEN/RCNP
   - MSU
   - EXL (FAIR/GSI)

References