



Investigation of ISGMR in Nickel isotopes

ESNT Workshop

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May, 19th 2025



Contents of this talk

Theoretical aspects

What is a ISGMR ?

What are the observables ?

What do we learn from them ?

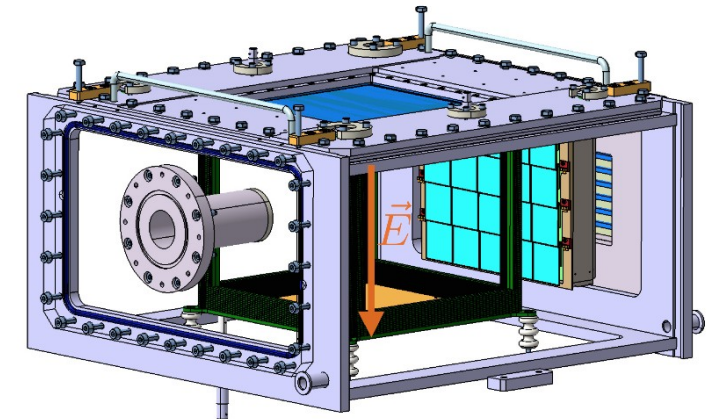
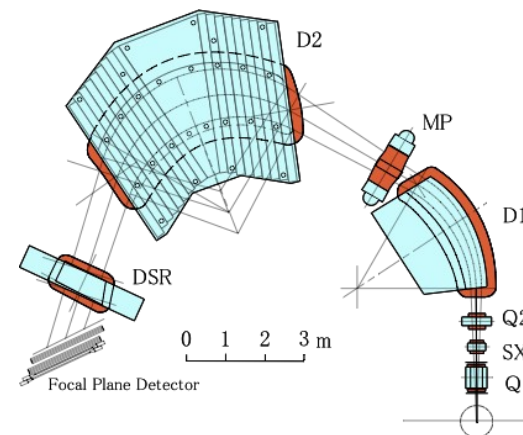
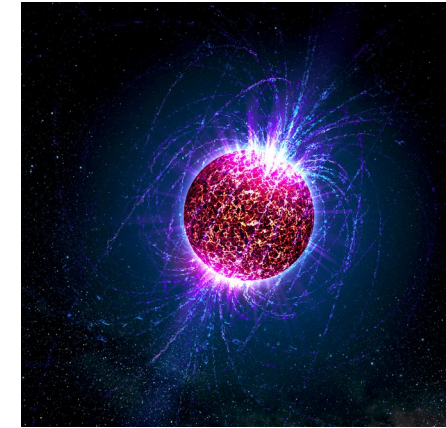
Experimental aspects

How do we experimentally measure the ISGMR

... in direct kinematics, and what are the limitations ?

... in inverse kinematics, and what are the limitations ?

Conclusion



Giant resonances

Definition :

Collective mode of **nuclear excitation** involving a **large part** of the nucleons

Microscopic interpretation : **linear combination of all 1p-1h transitions** between SM states induced by single-particle operators

Classified using **three quantum numbers** :

T = 0 or 1

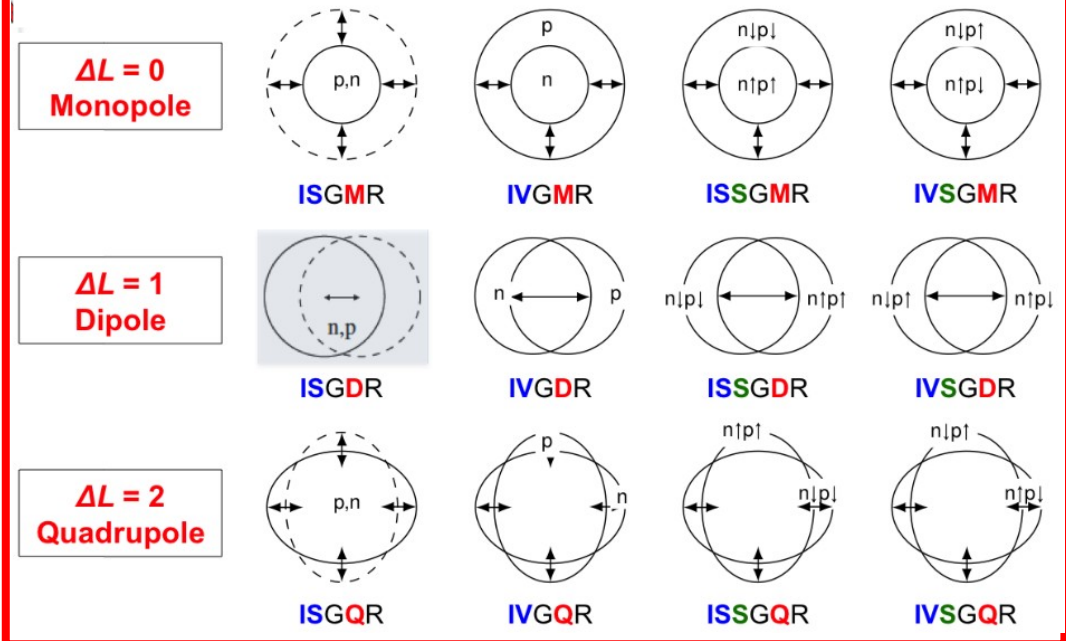
isoscalar or isovector

S = 0 or 1

electric or magnetic

L = 0, 1, 2, ...

multipolarity



Giant resonances

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Collective mode of **nuclear excitation** involving a **large part of the nucleons**

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Isoscalar electric giant monopole resonance (ISGMR) :
Compression/dilatation oscillation of the nucleus
They can be related to the **nucleus incompressibility K_A**

Classified using **three quantum numbers** :

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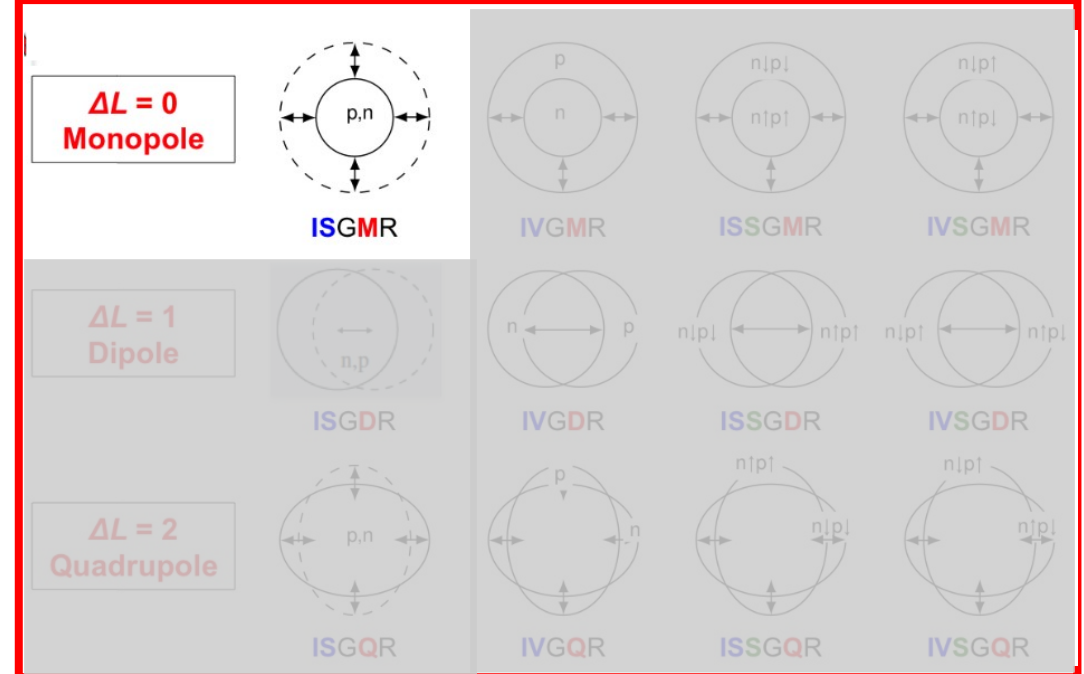
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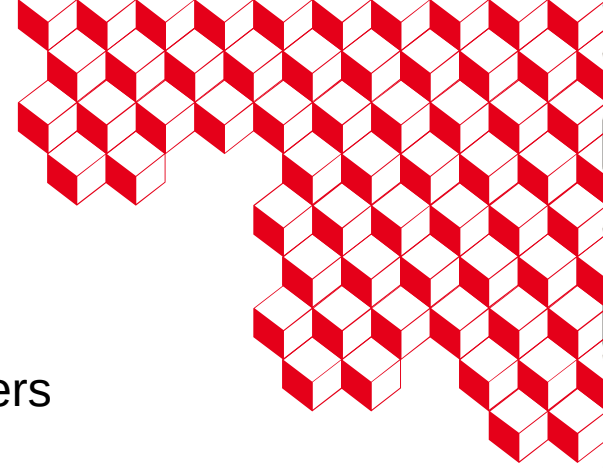
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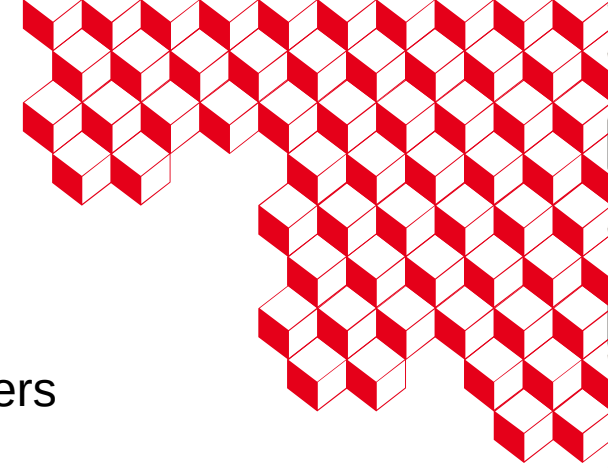
Giant resonances general properties



Some general properties of GR :

- **Excitation energy** (E_x)
 - **Width** (Γ)
 - **Sum rule** strength, usually expressed as a fraction of the theoretical sum rule (ex : %EWSR)
- } For spherical nuclei with $A > 90$ these are the parameters of a Breit-Wigner distribution

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Strength function : response of the ground state to the action of an operator \hat{O}

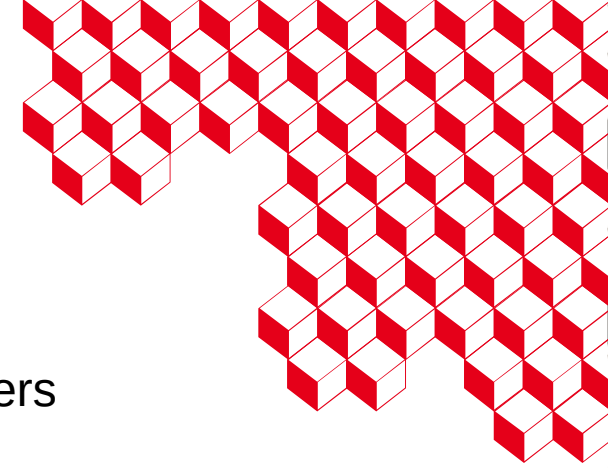
$$S(E) = \sum_k |\langle k | \hat{O} | 0 \rangle|^2 \delta(E - E_k)$$

Moments of the strength function :

$$m_n = \int_0^\infty S(E) E^n dE = \sum_k E_k^n |\langle k | \hat{O} | 0 \rangle|^2 = \langle 0 | \hat{O}^\dagger (H - E_0)^n \hat{O} | 0 \rangle$$

$E_{p,p-1} = \frac{m_p}{m_{p-1}}$	$\frac{m_1}{m_0} = E_{mean} \quad \sqrt{\frac{m_3}{m_1}} = E^S \quad \sqrt{\frac{m_1}{m_{-1}}} = E^C$
$E_{p,p-2} = \sqrt{\frac{m_p}{m_{p-2}}}$	$m_1 = \frac{\hbar^2}{2m} A \langle r^2 \rangle \stackrel{\text{def}}{=} EWSR$

Giant resonances general properties



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In order to use these data to compute values such as the incompressibility module, one has to be sure **that almost 100 % of the sum rule is exhausted by the observed strength !**

What do we learn from ISGMR ?

Related to the **nucleus incompressibility** through the relation

$$E_{ISGMR} = \sqrt{\frac{\hbar^2 K_A}{m \langle r^2 \rangle}}$$

The latter can be related to the **incompressibility of infinite symmetric nuclear matter** K_∞ (i.e when the nuclear density is at saturation)

The relation depends on the approach :

Macroscopically :
$$K_A = K_{vol} + K_{surf} A^{-1/3} + K_{sym} \delta^2 + K_{coul} \frac{Z^2}{A^{4/3}} \quad \delta = \frac{N-Z}{A}$$
$$K_{vol} = \alpha K_\infty$$

Problem : α depends on the model used to determine K_A (scaling or constraint)

Microscopically : Apply self-consistent mean-field calculation and RPA calculation with a set of effective interactions that differ in their prediction of K_∞ but provide good ground state properties

Experimental observation of ISGMR

Inelastic scattering reaction of (mainly) α particles (isoscalar probe)

Kinematic properties of the reaction (scattering angle, energies, ...) in the lab frame -----> **Excitation energy and angle in the CM frame.**

From that, one also computes the **differential cross-sections** of the reaction from which one can extract **the strength of each multipolarities.**

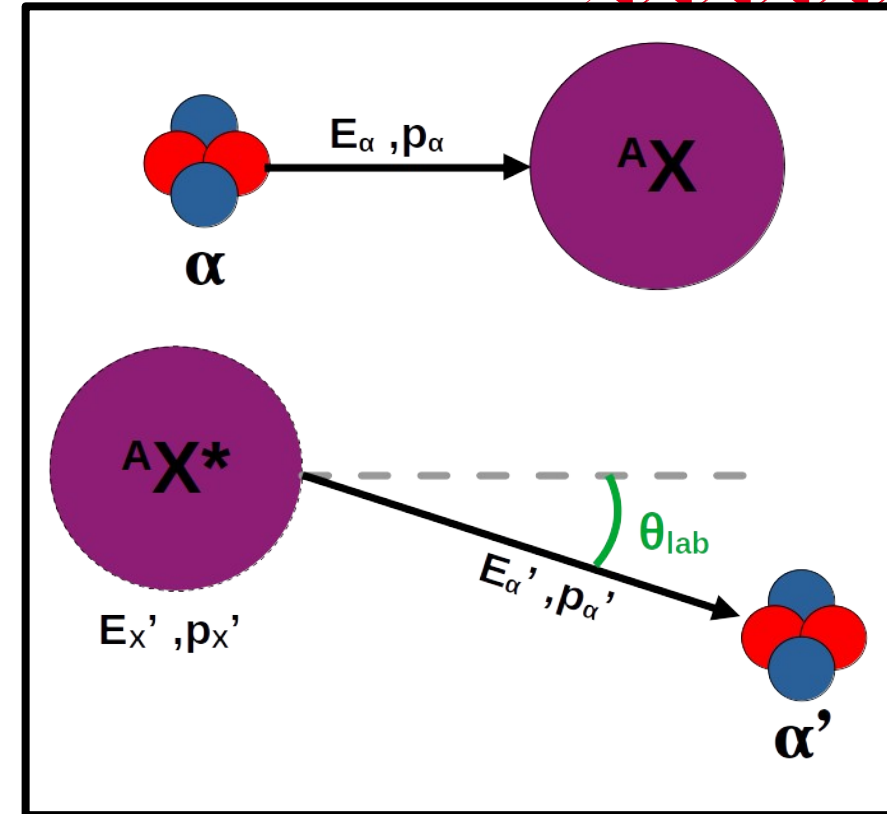
The case of light nuclei ($A < 90$)

Strength is much more **fragmented**

Strong **overlap in energy** between the different multipolarities

- the strength are difficult to properly measure
- there is often a **large part of the sum rule that is missing**

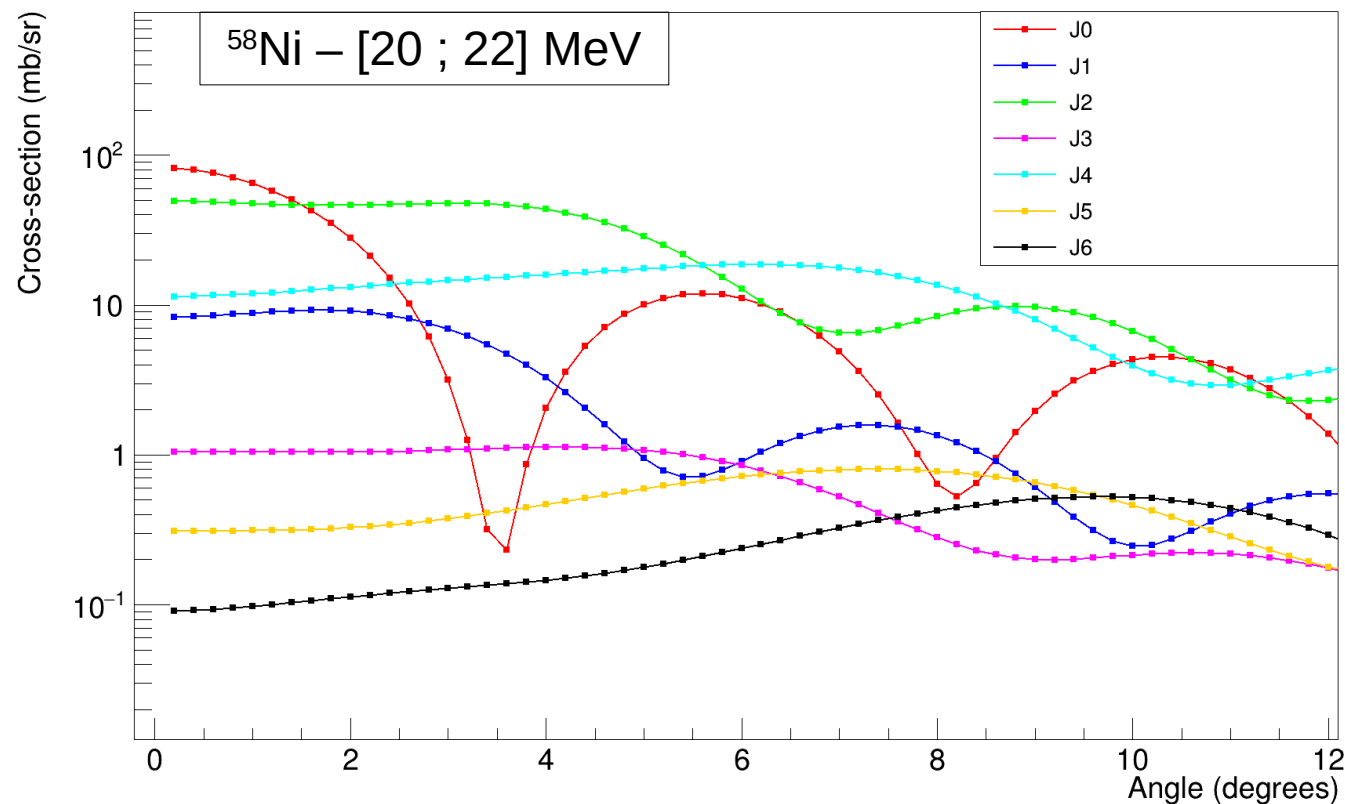
The first experiments found at most 30 % of the ESWR in nuclei with $A < 90$



Untangling the different strength

Use of the **Multipole Decomposition Analysis (MDA)** method

$$\left. \frac{d\sigma}{d\Omega} \right|_{\text{exp}} (\theta_{CM}, E^*) = \sum_{L=0}^N S_L(E^*) \left. \frac{d\sigma_L}{d\Omega} \right|_{\text{th}} (\theta_{CM}) + f_{bckg}(\theta_{CM})$$



Prediction of excited states and transitions :
RPA calculations



Cross-section calculation from the latter :
DWBA calculations

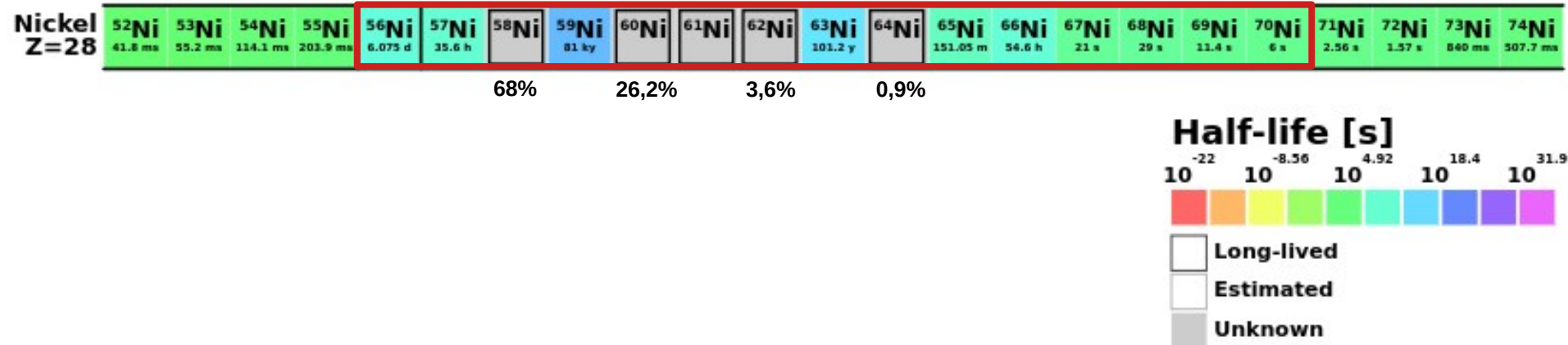
Why is Nickel interesting ?

Magic nuclei = **mostly spherical**

No (few) effect of deformation on the resonances

« Easy » case of light nuclei to measure

Large number of isotopes accessible



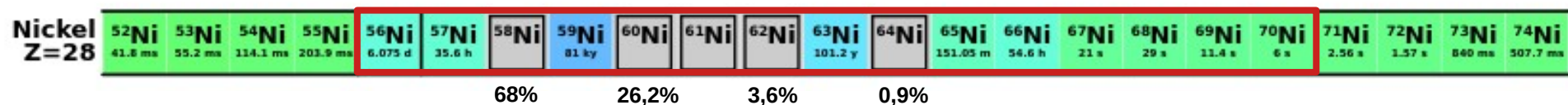
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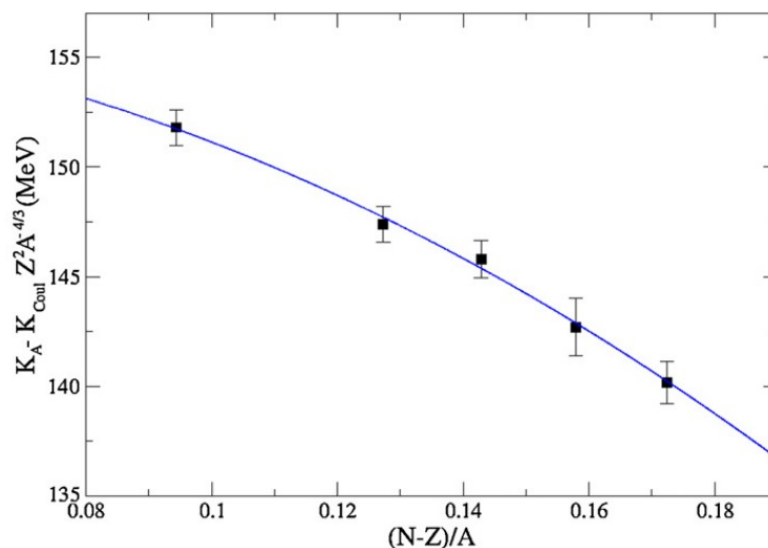
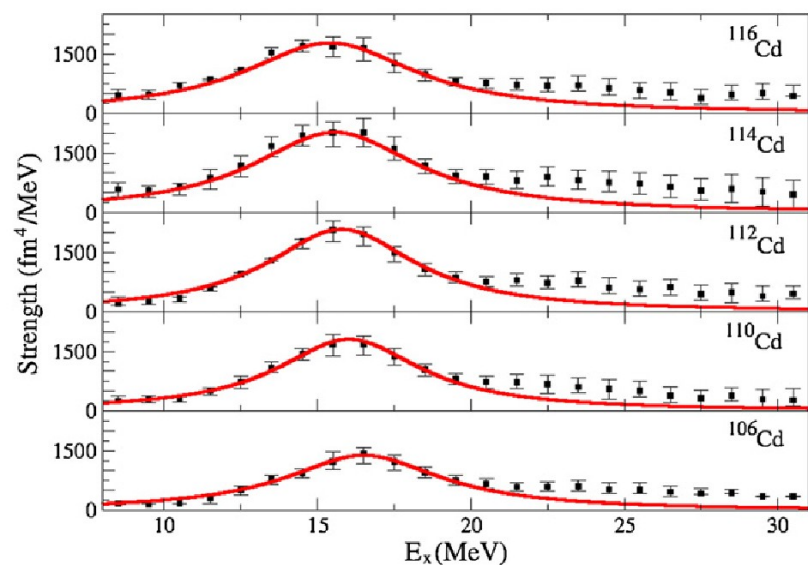
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$$K_A = K_{vol} + K_{surf} A^{-1/3} + K_{sym} \delta^2 + K_{coul} \frac{Z^2}{A^{4/3}}$$

$$K_A - K_{coul} \frac{Z^2}{A^{4/3}} \simeq const + K_{sym} \delta^2$$

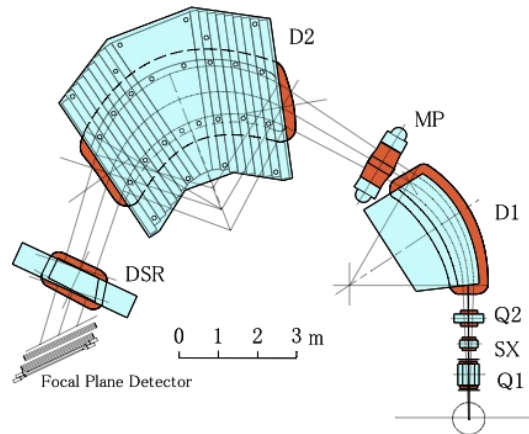
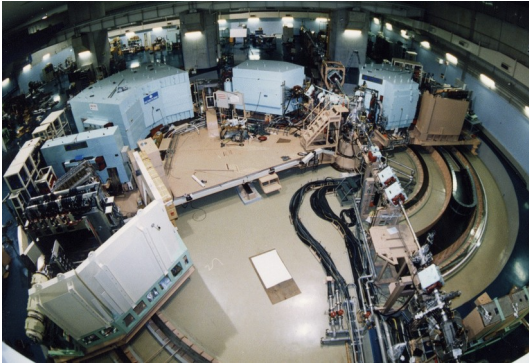


$$K_{sym} = 555 \pm 75 \text{ MeV}$$

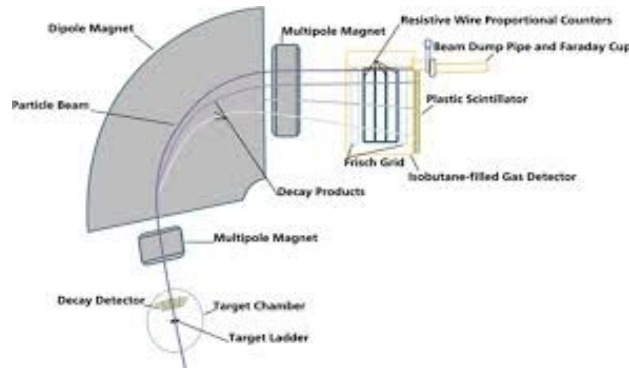


Experiments performed in direct kinematics

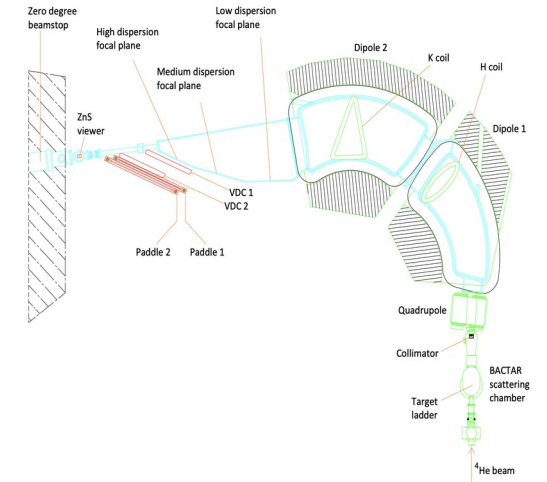
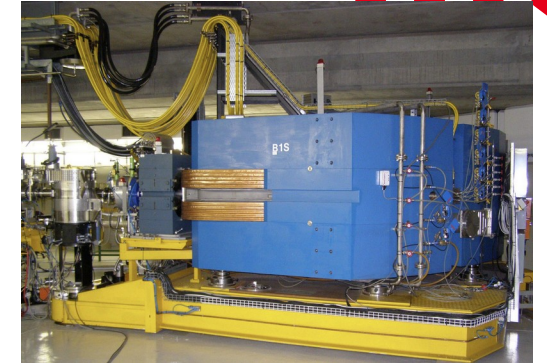
Studies with a magnetic spectrometer



Spectrometer Grand Raiden @RCNP



M2M spectrometer @Texas A&M



K600 spectrometer @iThemba LABS

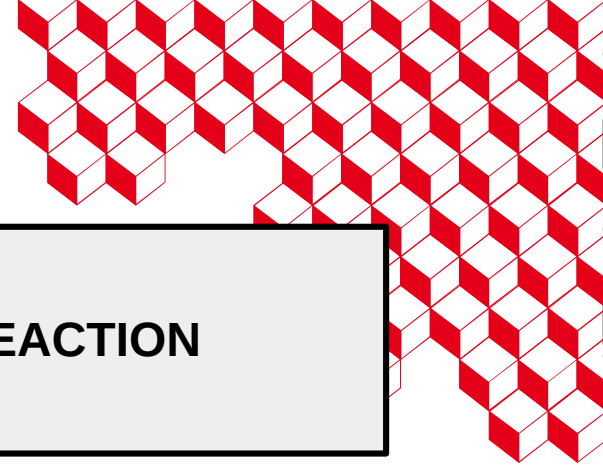
Studies with a magnetic spectrometer

Beam of α particles at an energy **between 150 and 400 MeV**

Target of the nucleus to study (generally **few mg/cm²**, preferentially pure)

REACTION

Studies with a magnetic spectrometer



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REACTION

Main characteristics of a spectrometer :

Angular acceptance ($\sim 1^\circ$)

Momentum resolution ($p/\Delta p \sim 40000$)

Resolving power

Limited aberration

SPECTROMETER

Set at the angle θ_{lab} we want to perform the measurement

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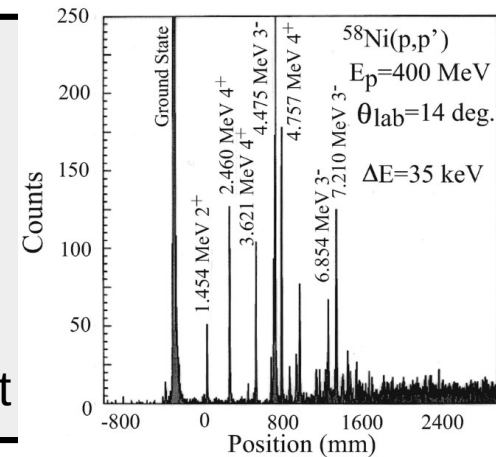
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SPECTROMETER

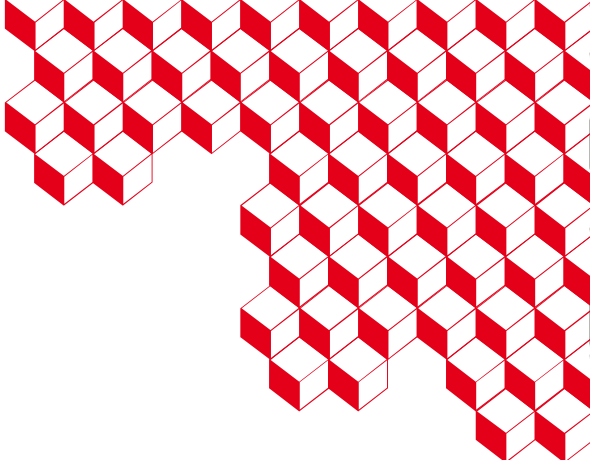
Scattered particle energy can be calculated from the measure position at the focal plane using **a multi-wire drift counter (MWDC)**

Position \rightarrow Energy

**CHARGED PARTICLE
DETECTOR**

Problem : Properties of ISGMR imply a measurement close to $0^\circ \rightarrow$ **Background**

How to tackle with the background ?

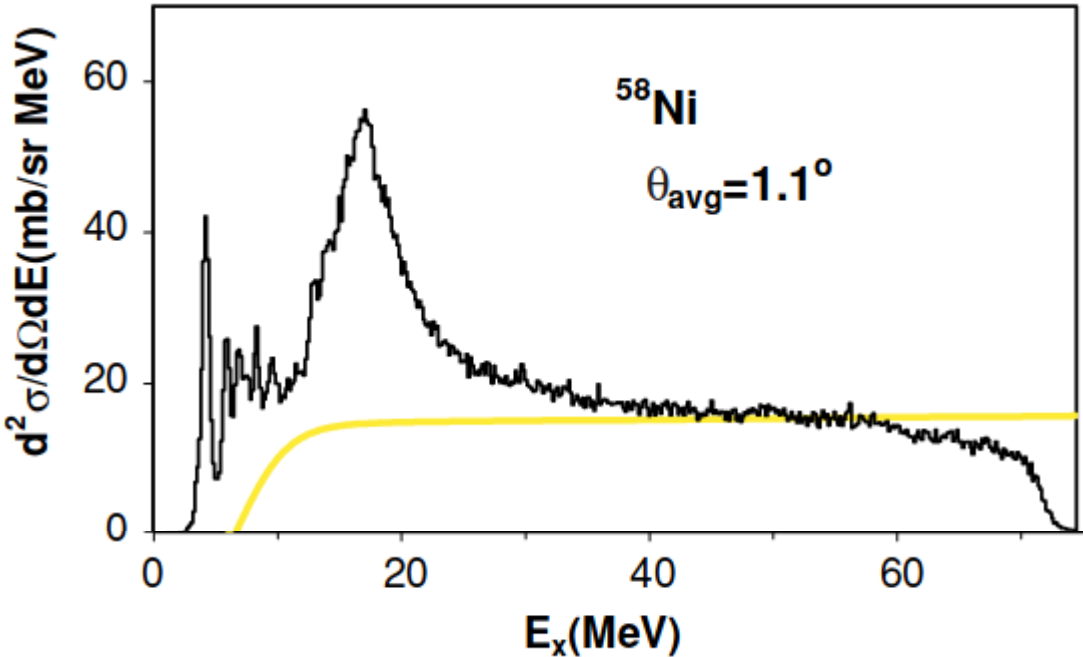


BACKGROUND	
Physical	Instrumental
Unreacted beam 3-body reactions Other resonance modes	Unwanted scattering Electronic noise

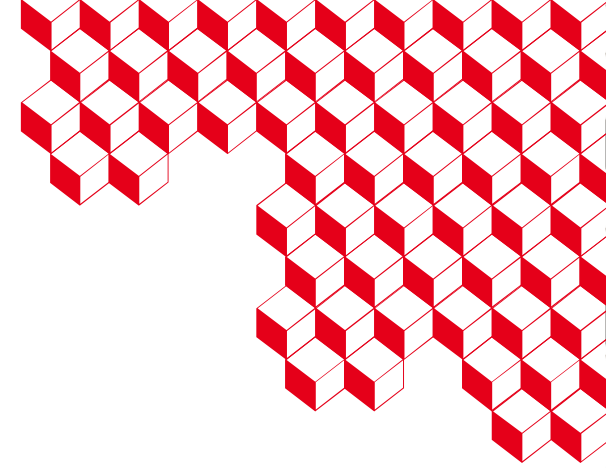
Impossible to fully modelise it !

How do we do usually ?

Subtraction of an **empirical background**
Flat at high excitation energy
Goes to 0 below few MeV



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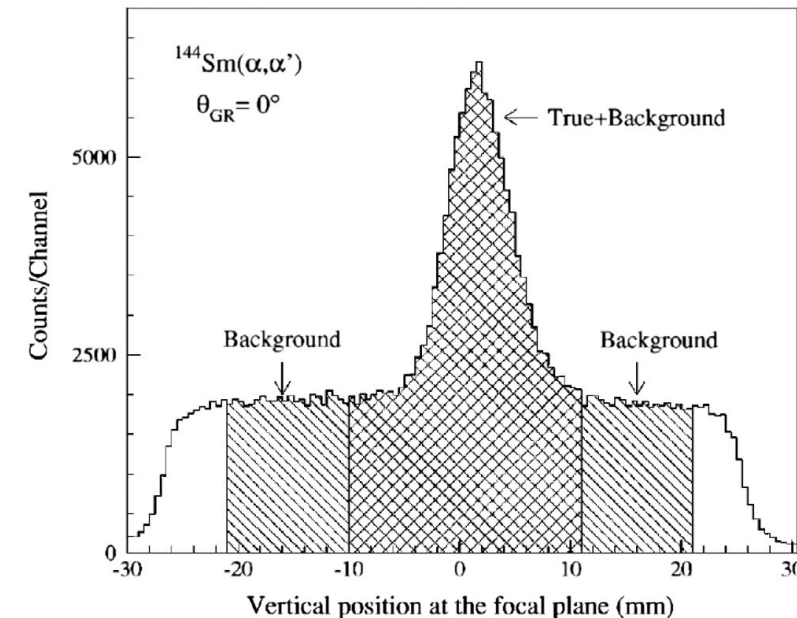
Subtraction of an **empirical background**

Flat at high excitation energy

Goes to 0 below few MeV

Some experimental efforts are done to develop methods to better reduce it (instrumentally or during analysis)

At RCNP : The optics make the particles scattered from the target **focused vertically** at the focal plane, while the background coming from other scattering is **flat**.



How to tackle with the background ?

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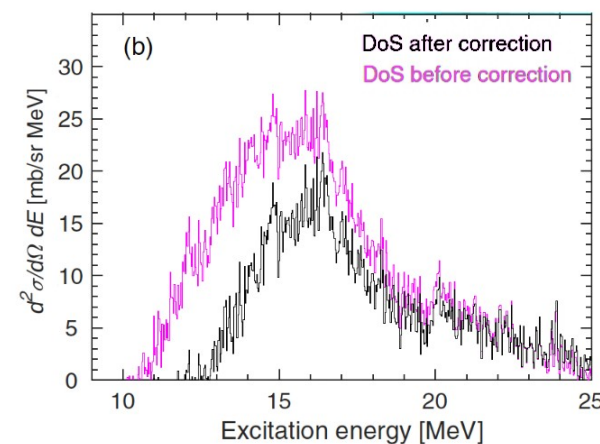
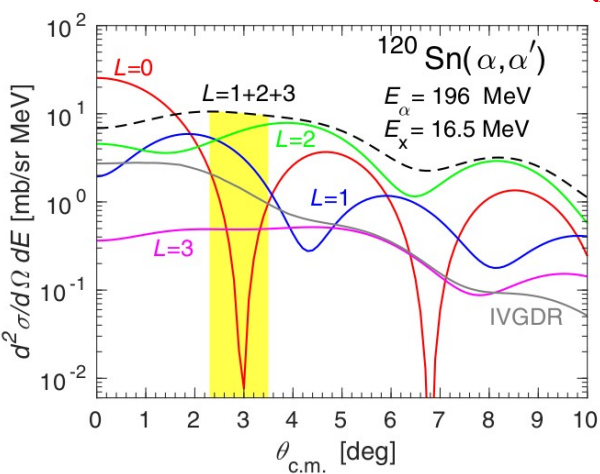
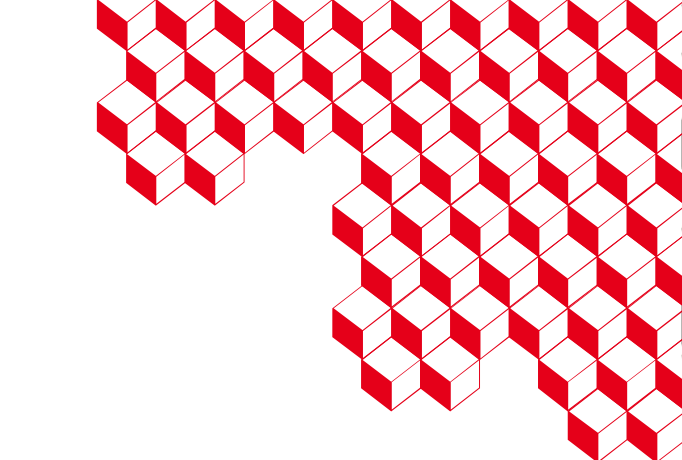
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iThemba : Difference of Spectra (DoS) method for the extraction of the **monopole strength**. Measure the $L>0$ contributions where the monopole is almost 0 then subtract it to the region where it is not.



Some results on Nickel and limitations

G. Duhamel *et al.*, Phys. Rev. C **38**, 2509-2513 (1988)

$E^*(^{58}\text{Ni})_{\text{ISGMR}} = 17.3 \text{ MeV}$
 $\text{EWSR}(^{58}\text{Ni})_{\text{ISGMR}} = 23 \pm 5 \%$

ISN Grenoble
(α, α') @ 152 MeV

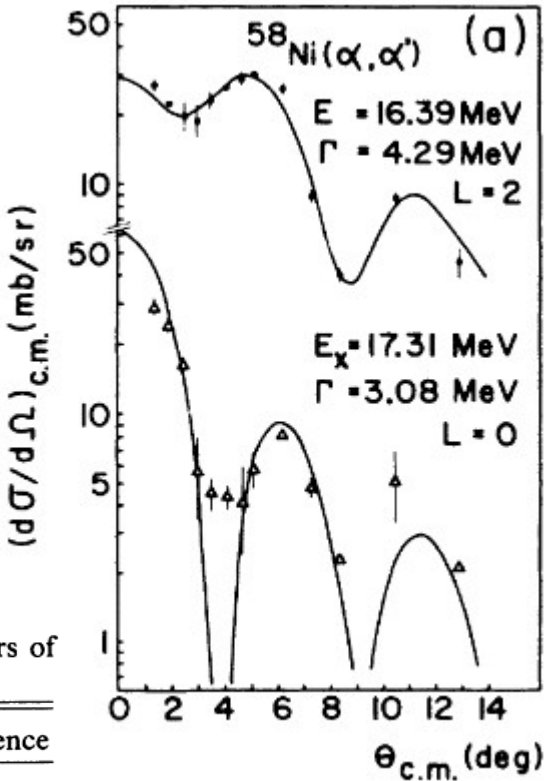
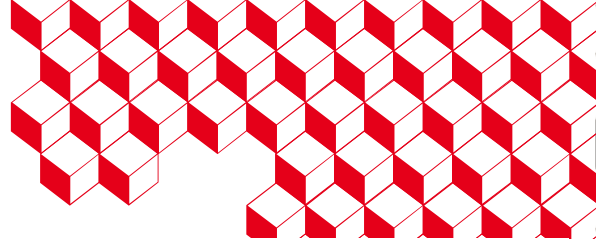


TABLE III. Comparison of the experimental parameters of the GMR.

Nucleus	E_x (MeV)	Γ (MeV)	EWSR (%)	Reference
^{58}Ni	17.1 ± 0.3	2.5 ± 0.3	10 ± 2	1
	20.0 ± 0.5	3.0 ± 0.5	40 ± 10	1
	17.3 ± 0.2	3.1 ± 0.2	23 ± 5	This work
^{92}Mo	16.35 ± 0.3	4.0 ± 0.3	24 ± 5	1
	16.2 ± 0.2	4.8 ± 0.3	84.5 ± 17	This work
^{90}Zr	16.4 ± 0.25	3.6 ± 0.25	39 ± 8	1
	16.2 ± 0.5	3.5 ± 0.3	90 ± 20	2
^{120}Sn	15.45 ± 0.25	3.25 ± 0.3	50 ± 10	1
	15.2 ± 0.5	4.1 ± 0.6	~ 180	2
	15.4 ± 0.4	4.0 ± 0.3	110 ± 22	This work

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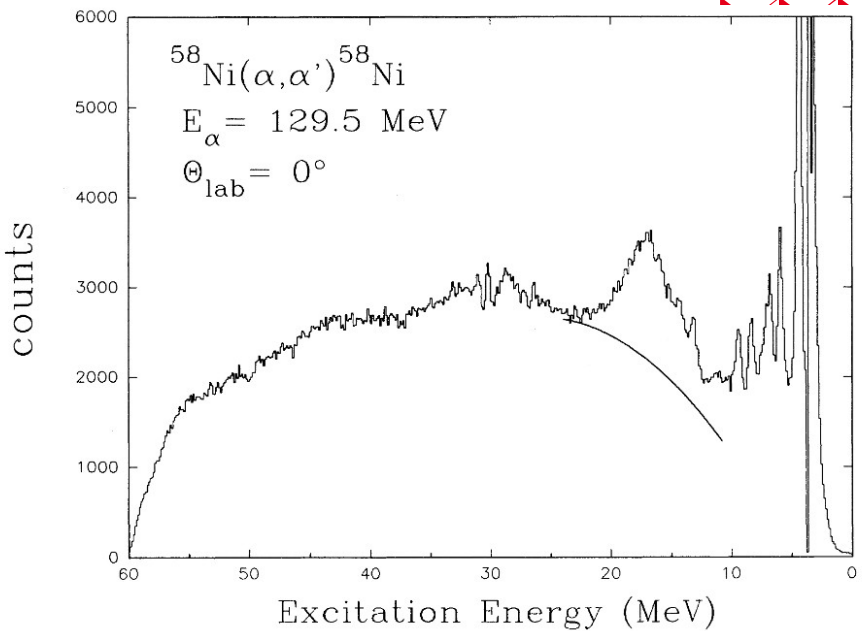
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Texas A&M
(α, α') @ 129 MeV

+ small contribution around 20 MeV (3% EWSR)



E_x (MeV)	Γ (MeV)	Sum rule ^a (%)	Reference
16.1 ± 0.2	4.7 ± 0.2	$E2 \ 52 \pm 8$	This work
16.4 ± 0.2	4.3 ± 0.2	$E2 \ 38 \pm 8$	[6]
17.0 ± 0.3	4.0 ± 0.3	$E0 \ 19 \pm 10$	This work
17.3 ± 0.2	3.1 ± 0.2	$E0 \ 23 \pm 5$	[6]
20.4 ± 0.3	4.4 ± 0.2	$E0 \ 2.9^{+2.1}_{-2.9}$ $E2 \ 6.9 \pm 2.0$	This work
20.2 ± 0.2	3.8 ± 0.75		[6]

^aSatchler version 1 form factor for $E0$.

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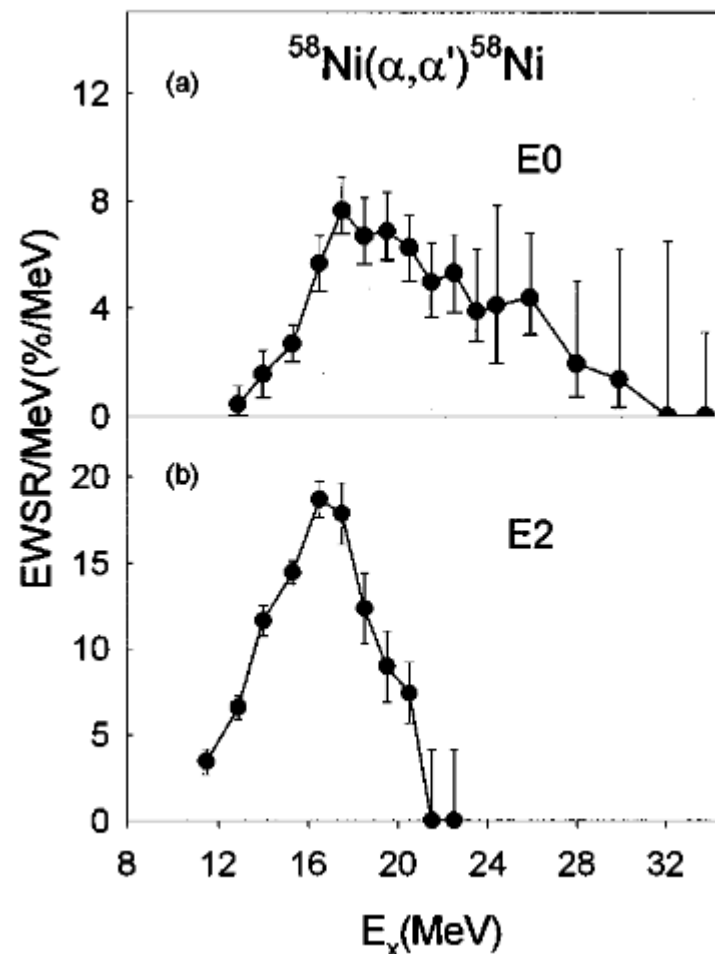
Y.-W. Lui *et al.*, Phys. Rev. C **61**, 067307 (2000)

$$E^*(^{58}\text{Ni})_{\text{ISGMR}} = 20.3 \text{ MeV}$$

$$\text{EWSR}(^{58}\text{Ni})_{\text{ISGMR}} = 74 \pm 19 \%$$

Texas A&M

(α, α') @ 240 MeV



Some results on Nickel and limitations

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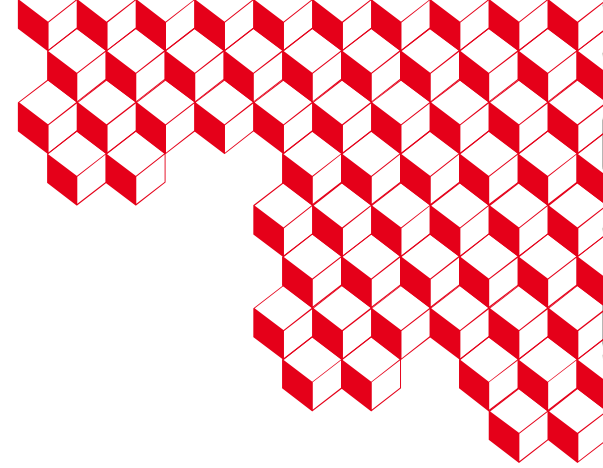
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Y.-W. Lui *et al.*, Phys. Rev. C **73**, 014314 (2006)

$E^*(^{58}\text{Ni})_{\text{ISGMR}} = 18.43 \text{ MeV}$ Texas A&M
 $\text{EWSR}(^{58}\text{Ni})_{\text{ISGMR}} = 82 \pm 10 \%$ (α, α') @ 240 MeV
 $E^*(^{60}\text{Ni})_{\text{ISGMR}} = 17.62 \text{ MeV}$
 $\text{EWSR}(^{60}\text{Ni})_{\text{ISGMR}} = 67 \pm 10 \%$
+ in agreement with calculation giving $K_\infty = 225 \text{ MeV}$

^{58}Ni	Moments			
	$E0$	$E1$	$E2$	$E3$ and higher
$m_1(\text{Frac. EWSR})$	$0.85^{+0.13}_{-0.10}$	$0.68^{+0.20}_{-0.15}$	0.82 ± 0.10	0.87 ± 0.10
$m_1/m_0 \text{ (MeV)}$	$19.20^{+0.44}_{-0.19}$	$27.78^{+0.47}_{-0.30}$	$16.31^{+0.17}_{-0.10}$	23.20 ± 0.30
rms width (MeV)	$4.89^{+1.05}_{-0.31}$	$6.96^{+0.30}_{-0.25}$	2.45 ± 0.10	8.24 ± 0.12
$(m_3/m_1)^{1/2} \text{ (MeV)}$	$20.81^{+0.90}_{-0.28}$			
$(m_1/m_{-1})^{1/2} \text{ (MeV)}$	$18.70^{+0.34}_{-0.17}$			
	Gaussian fits			
	$E0$	$E1$ peak 1	$E1$ peak 2	$E2$
Centroids (MeV)	18.43 ± 0.15	17.42 ± 0.25	34.06 ± 0.30	16.64 ± 0.12
FWHM (MeV)	7.41 ± 0.13	$3.94^{+0.36}_{-0.34}$	$19.52^{+0.41}_{-0.40}$	$5.81^{+0.16}_{-0.11}$
Frac. EWSR	$0.82^{+0.11}_{-0.09}$	0.04 ± 0.02	0.86 ± 0.12	0.81 ± 0.10

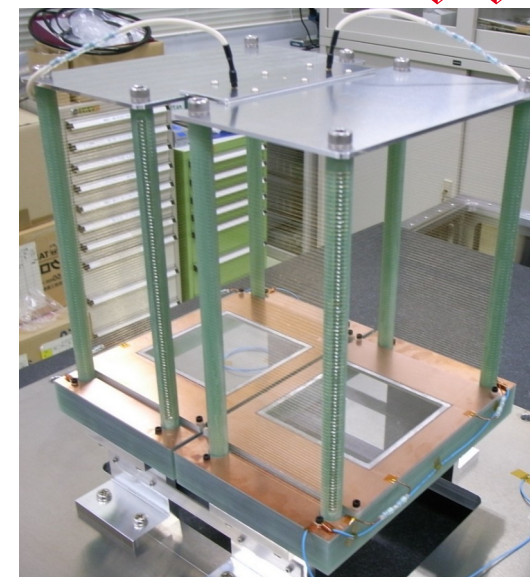
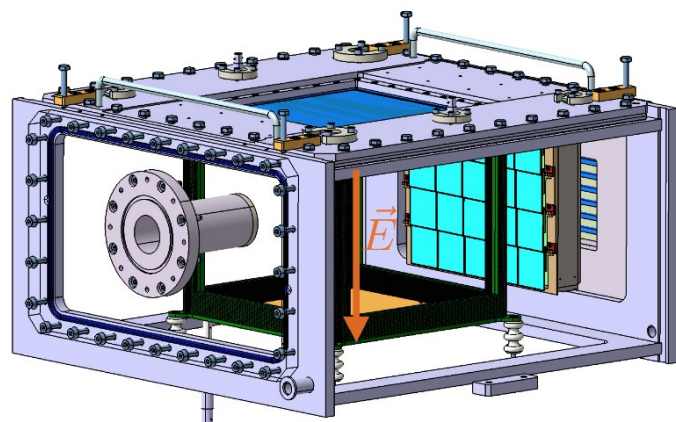
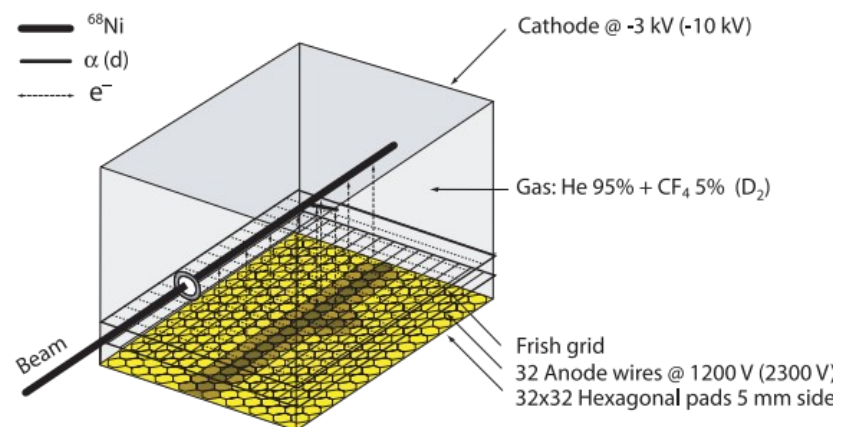
^{60}Ni	Moments			
	$E0$	$E1$	$E2$	$E3$ and higher
$m_1(\text{Frac. EWSR})$	$0.82^{+0.13}_{-0.11}$	0.72 ± 0.17	0.71 ± 0.10	0.88 ± 0.10
$m_1/m_0 \text{ (MeV)}$	$18.04^{+0.35}_{-0.23}$	24.93 ± 0.46	$15.84^{+0.18}_{-0.10}$	24.40 ± 0.26
rms width (MeV)	$4.50^{+0.97}_{-0.22}$	7.65 ± 0.27	2.92 ± 0.10	7.65 ± 0.18
$(m_3/m_1)^{1/2} \text{ (MeV)}$	$19.54^{+0.78}_{-0.23}$			
$(m_1/m_{-1})^{1/2} \text{ (MeV)}$	$17.55^{+0.27}_{-0.17}$			
	Gaussian fits			
	$E0$	$E1$ peak 1	$E1$ peak 2	$E2$
Centroids (MeV)	17.62 ± 0.15	16.01 ± 0.20	$36.11^{+0.29}_{-0.27}$	16.05 ± 0.12
FWHM (MeV)	7.55 ± 0.13	$4.41^{+0.34}_{-0.22}$	$27.13^{+0.43}_{-0.42}$	$6.61^{+0.16}_{-0.11}$
Frac. EWSR	$0.67^{+0.12}_{-0.09}$	0.06 ± 0.03	1.20 ± 0.16	0.71 ± 0.10



Experiments performed in inverse kinematics

Studies with TPCs and active targets

Some examples of TPC that are used in the world especially to measure GMR



CNS active target (CAT)
Riken (Japan)

Studies with TPCs and active targets

Using a TPC as an active target :

Choice of the gas ?

At first, no pure Helium because the gain was too low → use of **deuterium**
But huge background due to its breaking (separation energy ~ 2 MeV)

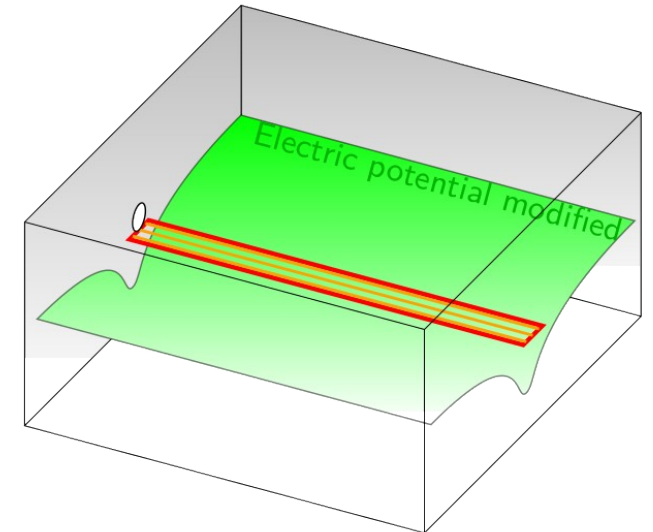
Use of **He** possible if admixed with a **quencher** (good example : CF_4)
Find the good compromise between purity and gain (usually **95 – 5 %**)

What pressure ?

The pressure will define the **range of energy accessible**, but it affects also the cross-section
Usually : few **100s mbar**

The beam ?

Energy loss by beam \gg Energy loss by scattered particle → Dynamic problem
Need to « **mask** » the beam to reduce the measured intensity
→ Modify the electric potential in the beam area to reduce the gain



Some results on Nickel and limitations

Several studies of ISGMR have been performed in the Nickel isotopic chain with MAYA at GANIL

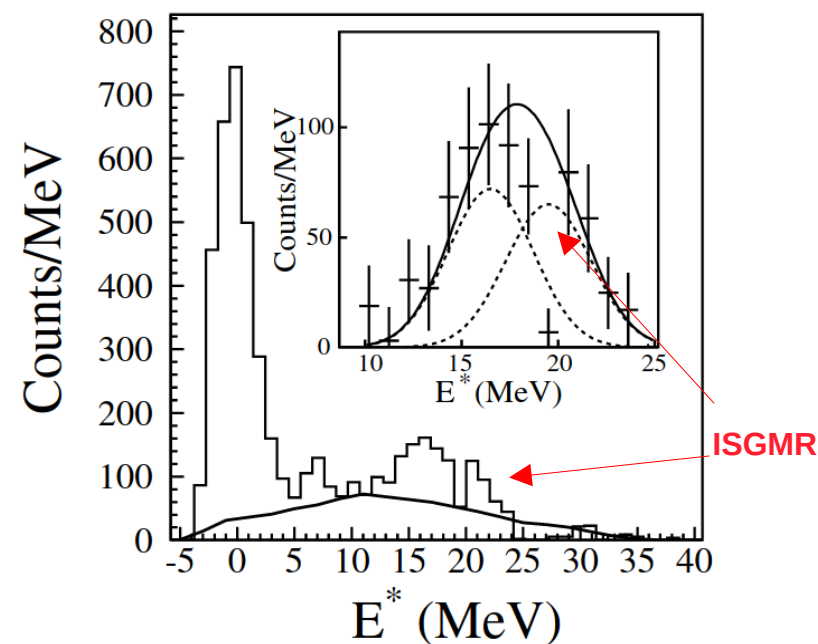
C. Monrozeau et al. Phys. Rev. Lett. **100**, 042501 (2008)

$$E^*(^{56}\text{Ni})_{\text{ISGMR}} = 19.3 \pm 0.5 \text{ MeV}$$

$$\text{EWSR}(^{56}\text{Ni})_{\text{ISGMR}} = 136 \pm 27 \%$$

SPEG + MAYA @GANIL (2005)

(d, d')



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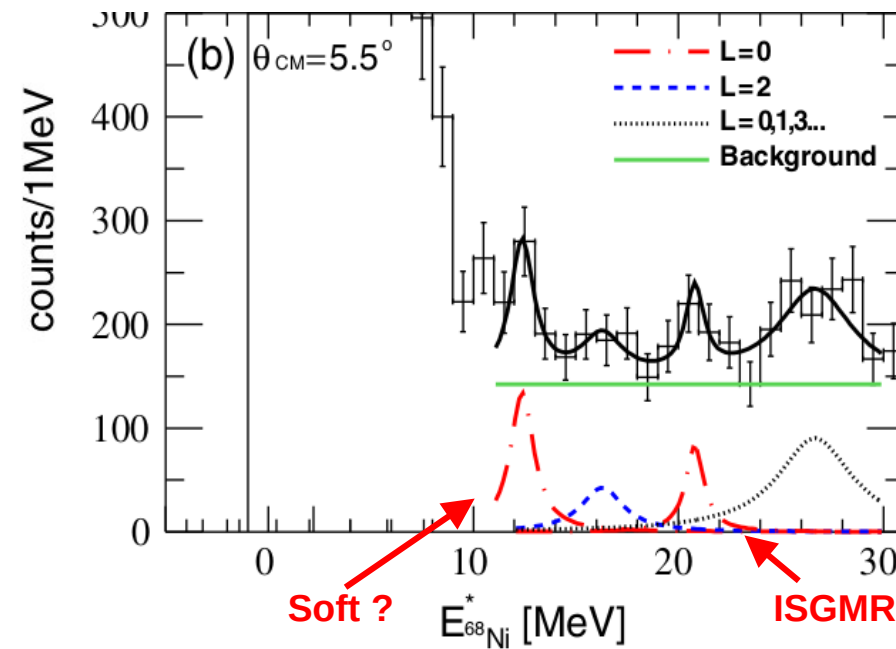
M. Vandebrouck et al., Phys. Rev. Lett. **113**, 032504 (2014)

$$E^*(^{68}\text{Ni})_{\text{ISGMR}} = 20.9 \pm 1.0 \text{ MeV (d,d')}$$

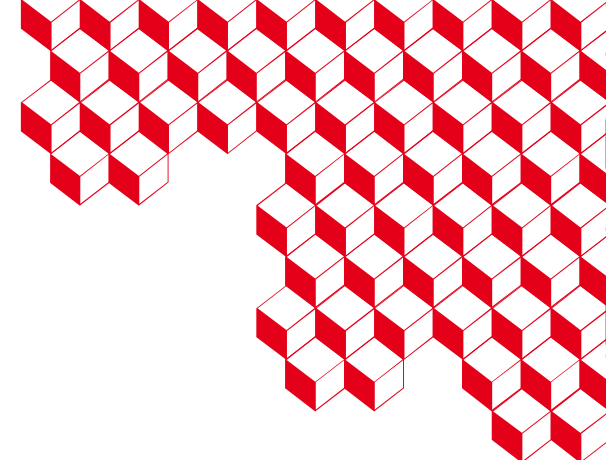
LISE + MAYA @GANIL (2010)

$$E^*(^{68}\text{Ni})_{\text{ISGMR}} = 21.1 \pm 1.9 \text{ MeV } (\alpha, \alpha')$$

Experimental indication of « **soft-monopole** » mode



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S. Bagchi et al., Phys. Lett. B **751**, 371 (2015)

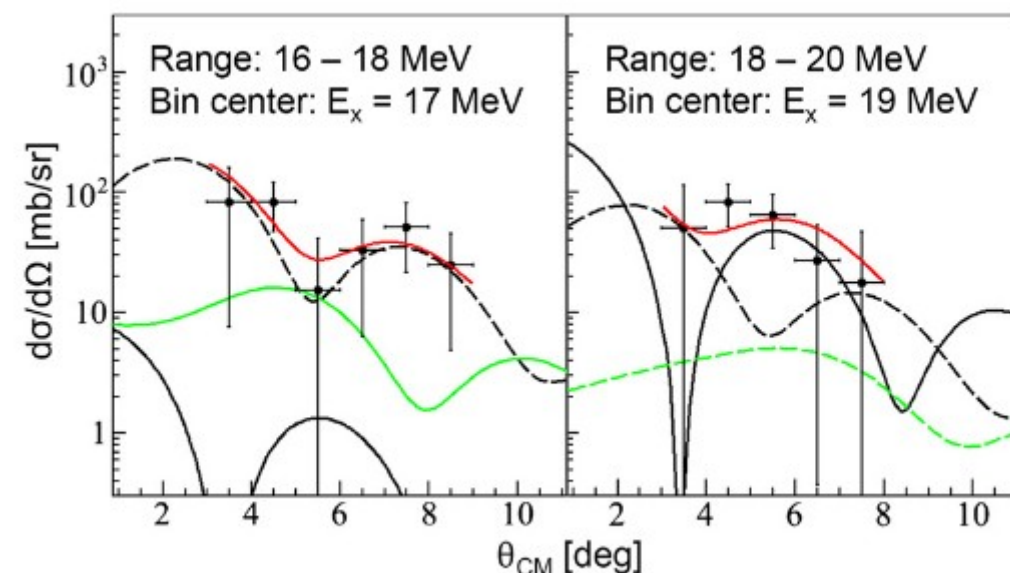
$$E^*(^{56}\text{Ni})_{\text{ISGMR}} = 19.1 \pm 0.5 \text{ MeV}$$

LISE + MAYA @GANIL (2011)

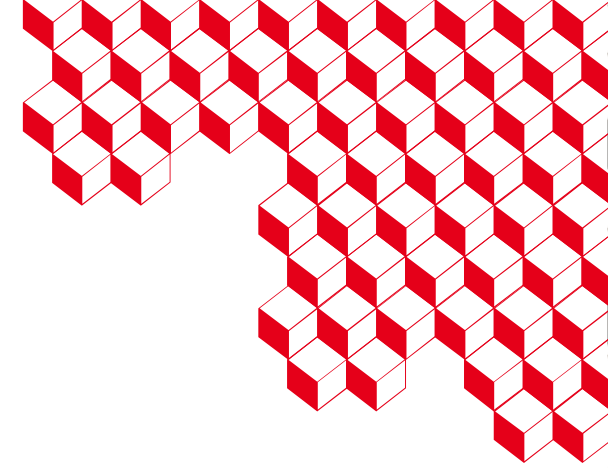
$$\text{EWSR}(^{56}\text{Ni})_{\text{ISGMR}} = 240 \pm 120 \%$$

(α , α')

Limitation of MAYA: **efficiency and angular resolution** for low energy particles



Studies with TPCs and active targets



$^{58}\text{Ni}(\alpha, \alpha')^{58}\text{Ni}^*$ inverse kinematics Benchmark

$E_{\text{beam}} = 49.7 \text{ MeV/u}$

Intensity $\sim 10^5 \text{ pps}$

Gas mixture : 98 % He + 2 % CF_4 @400 mbar

Beam time : ~ 85 hours in 4 days

$^{68}\text{Ni}(\alpha, \alpha')^{68}\text{Ni}^*$ inverse kinematics Investigating the soft-monopole mode

$E_{\text{beam}} = 48.9 \text{ MeV/u}$

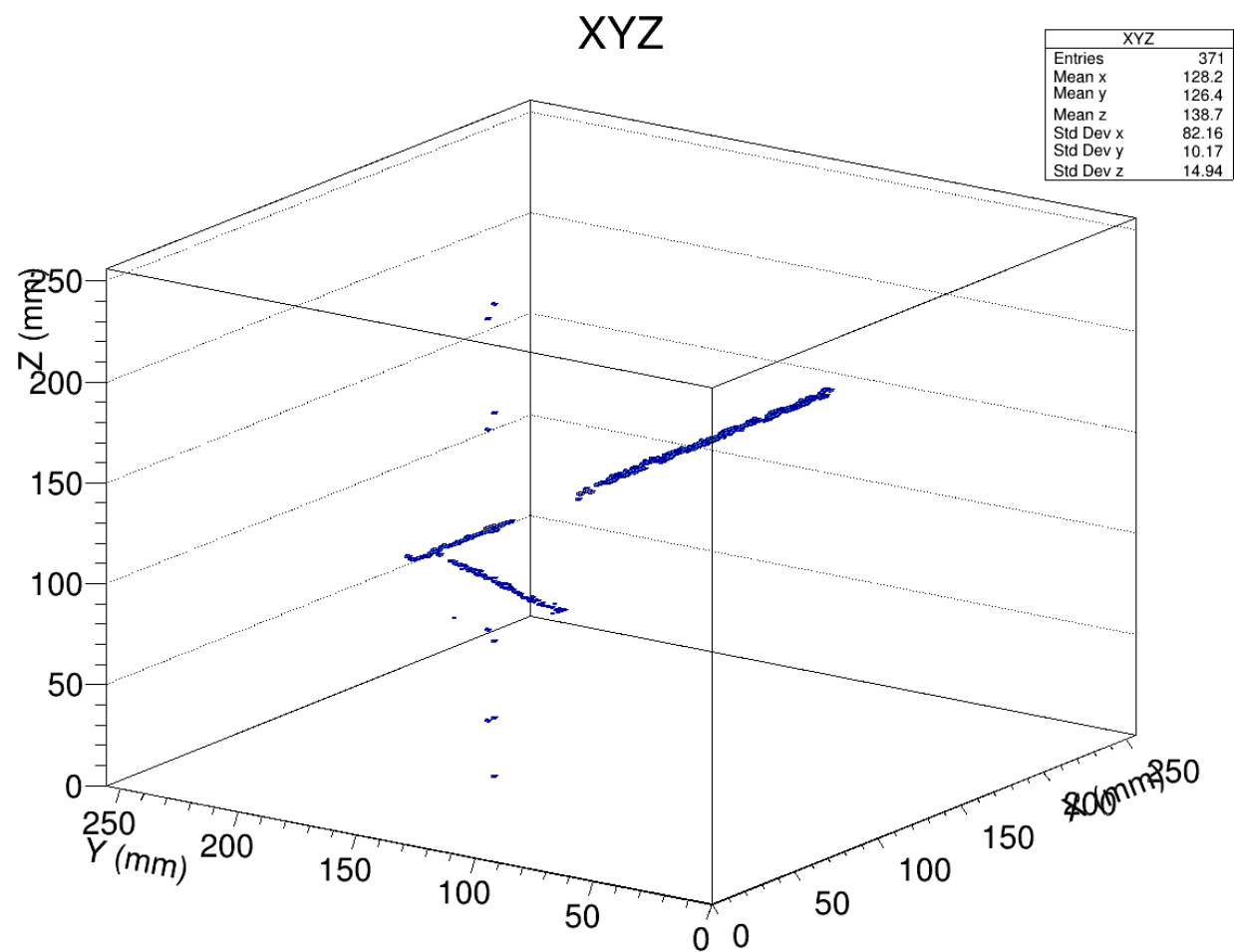
Intensity $\sim \text{few } 10^4 \text{ pps}$

Gas mixture : 98 % He + 2 % CF_4 @400 mbar

Beam time : ~ 80 hours in 4 days

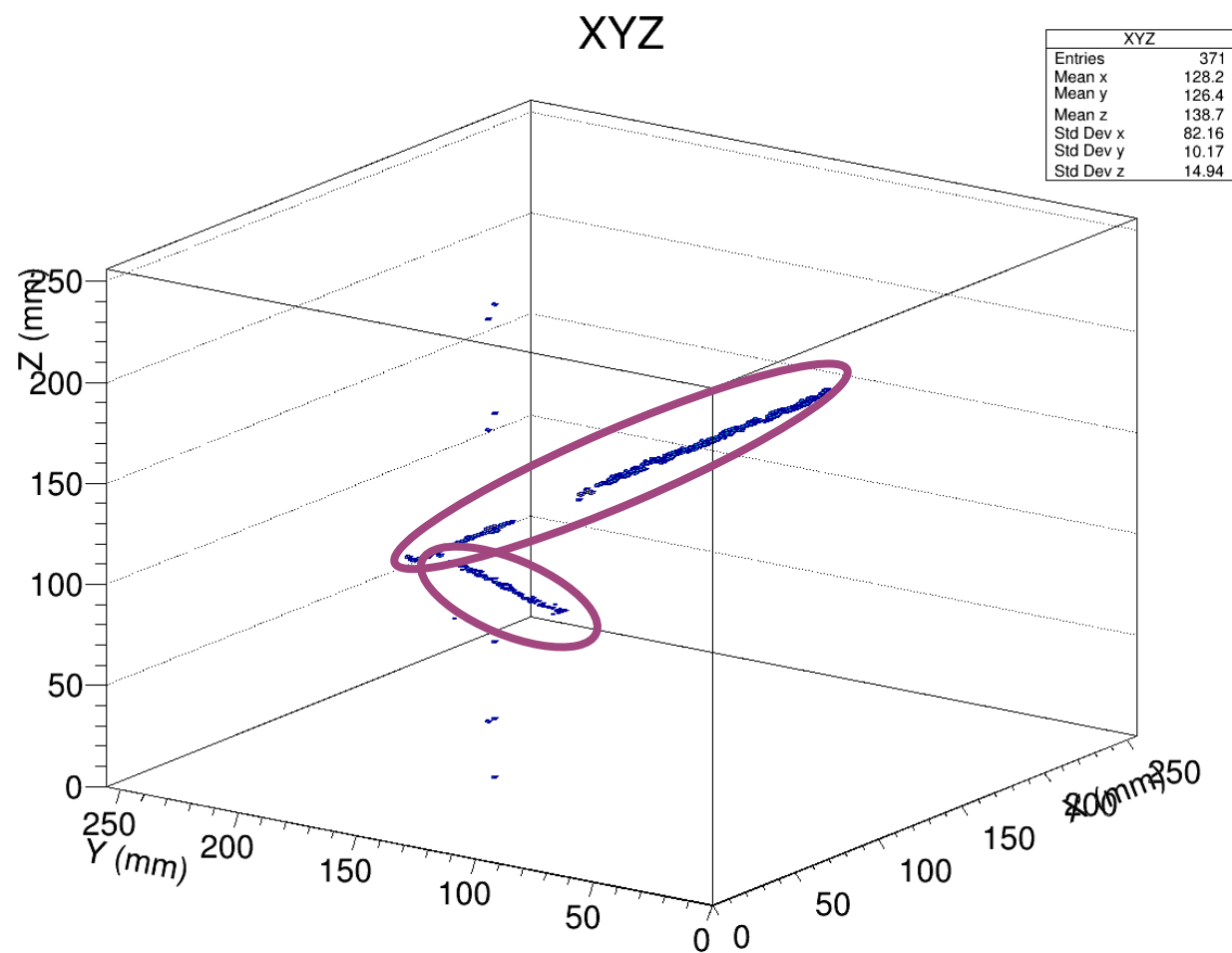
The first two experiments of ACTAR at GANIL were dedicated to the study of ISGMR in ^{58}Ni and ^{68}Ni in 2019

Analysis procedure



A typical scattering event in ACTAR

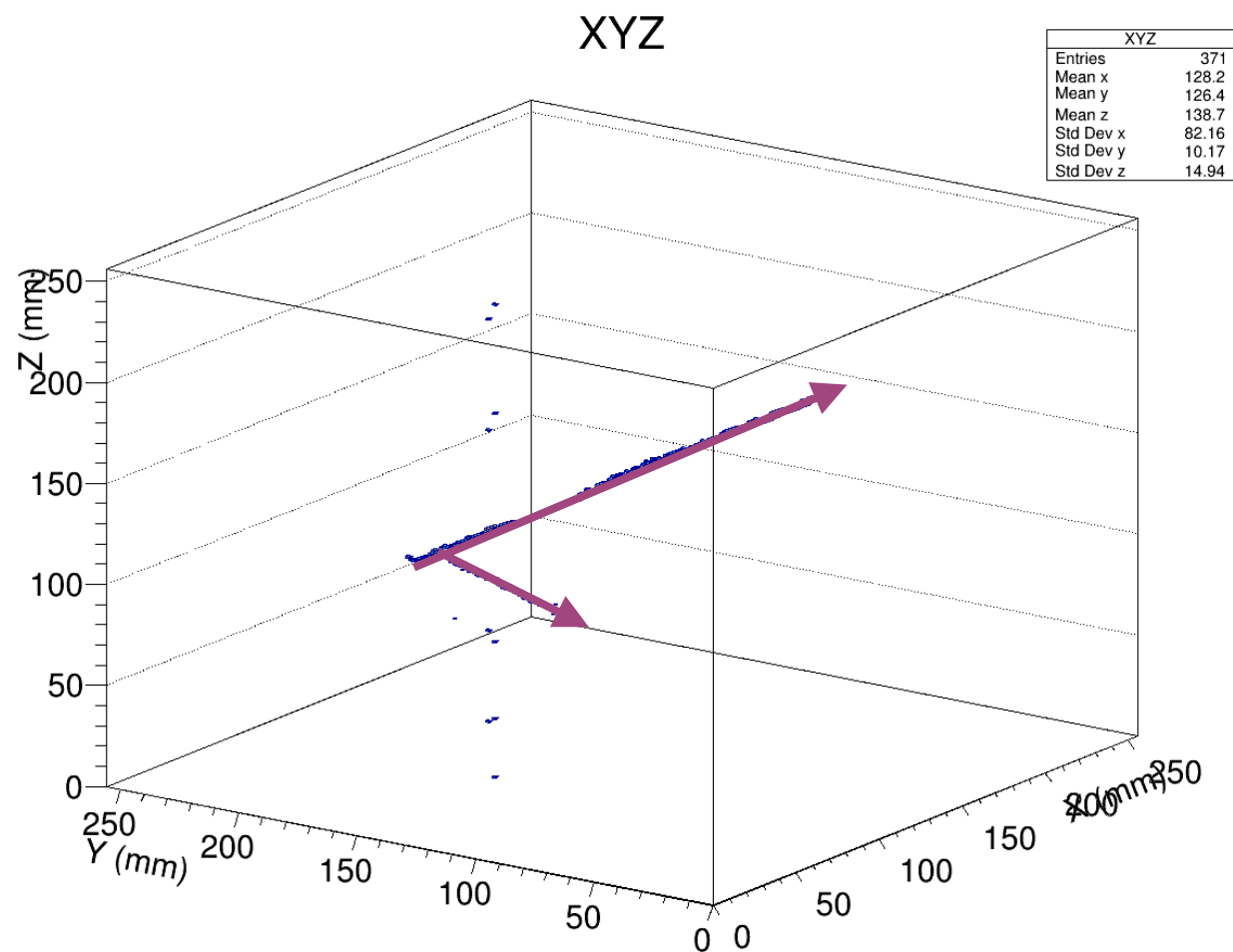
Analysis procedure



A typical scattering event in ACTAR

RANSAC

Analysis procedure



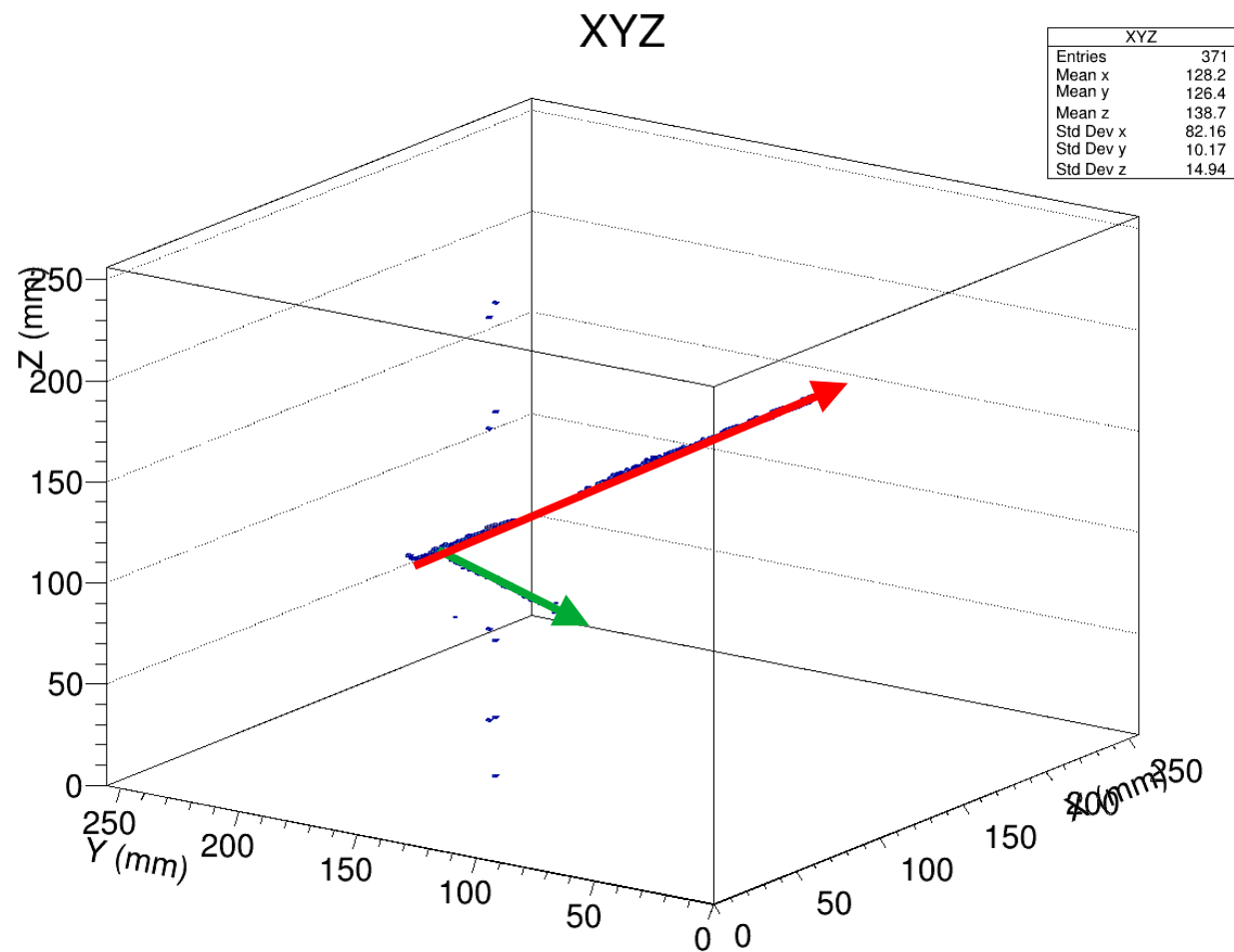
A typical scattering event in ACTAR

RANSAC

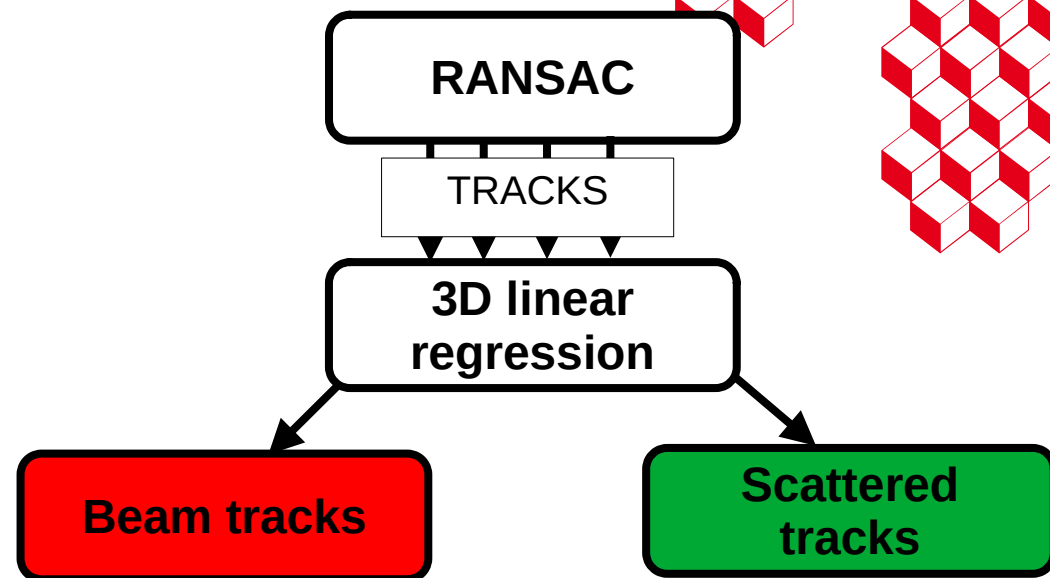
TRACKS

**3D linear
regression**

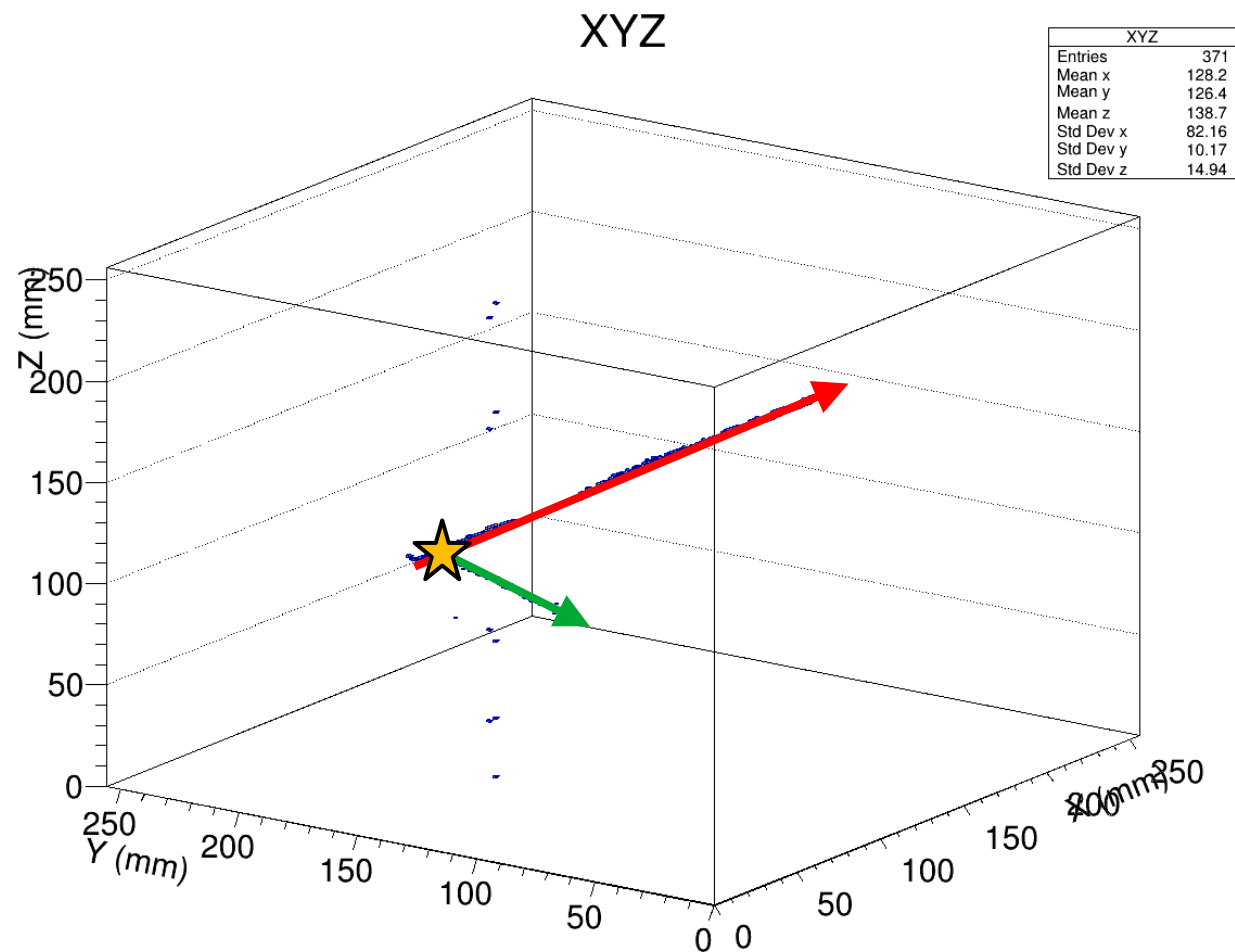
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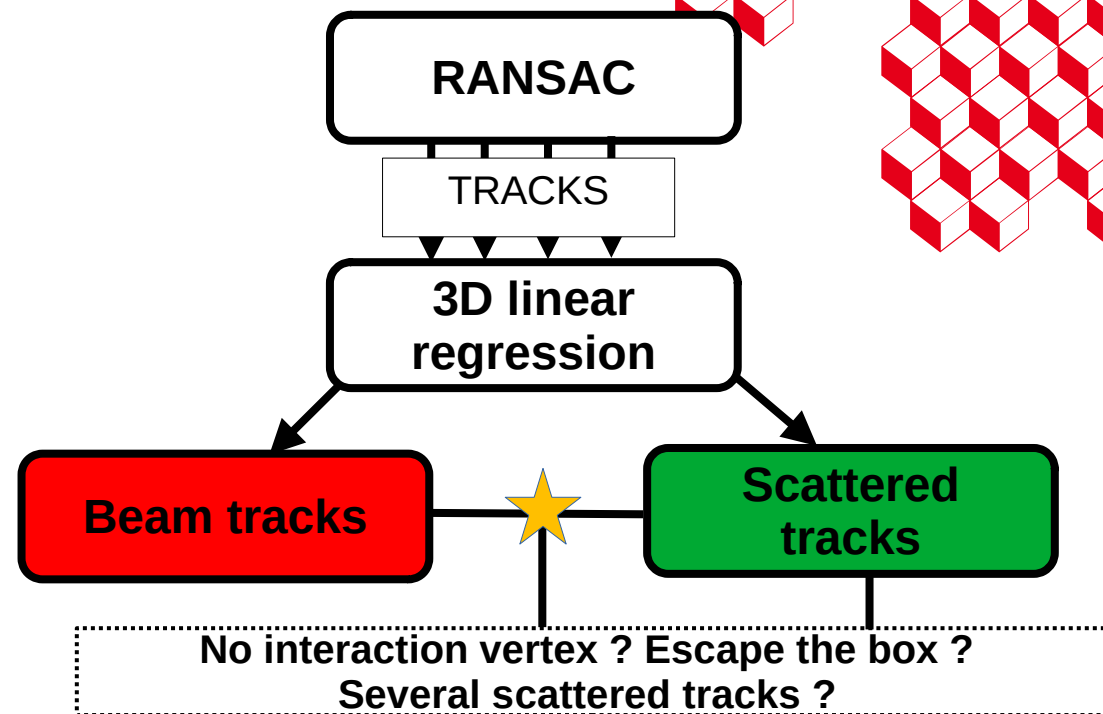
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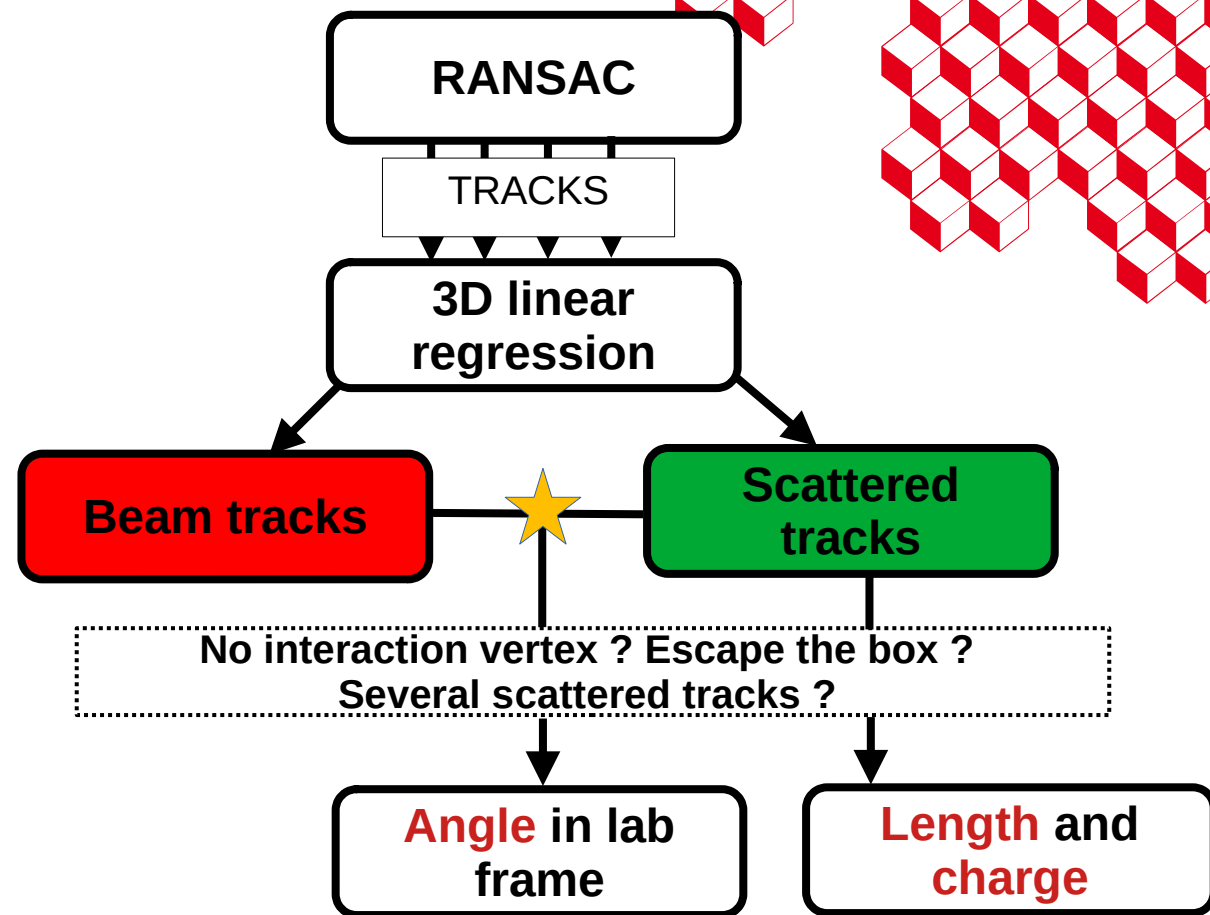
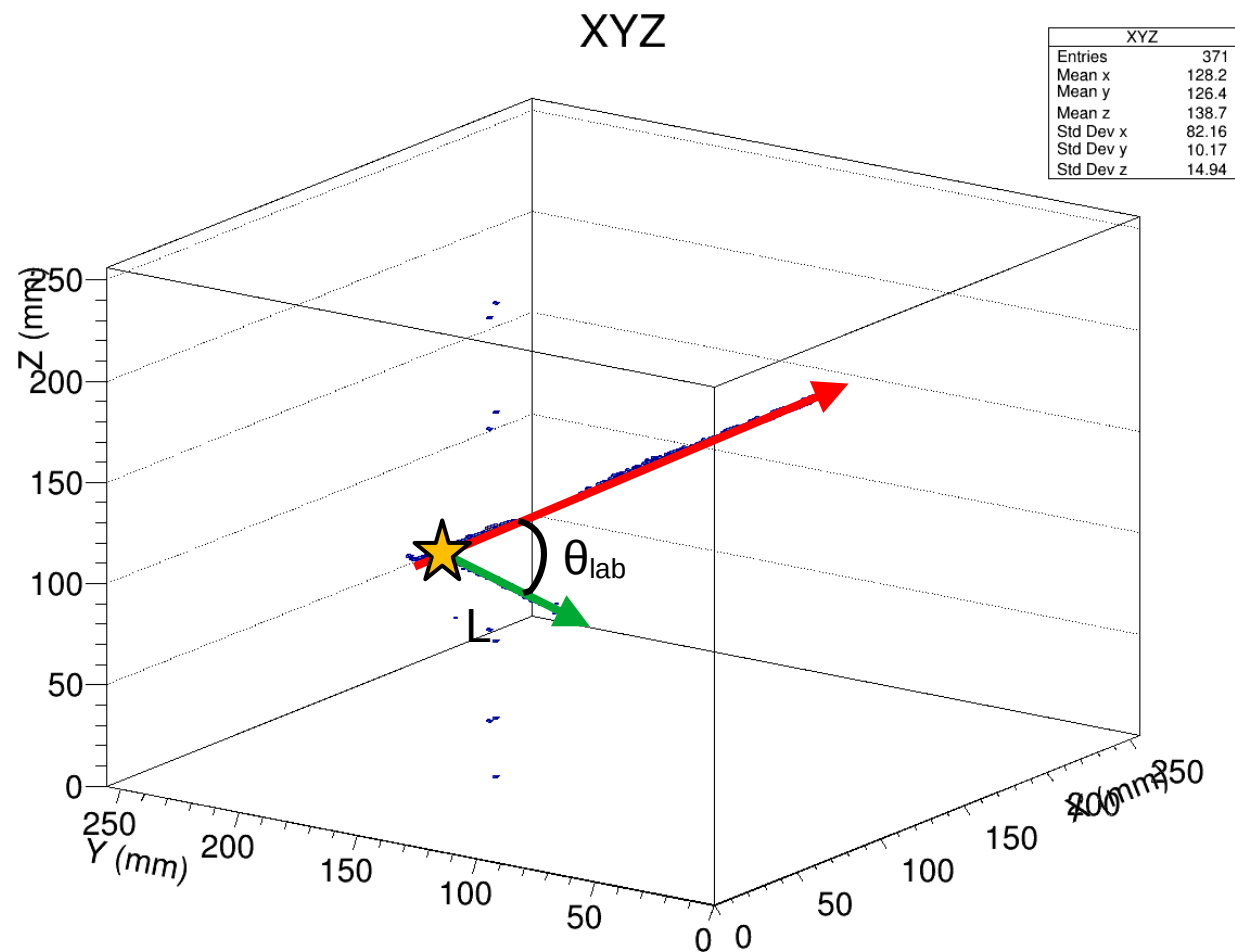
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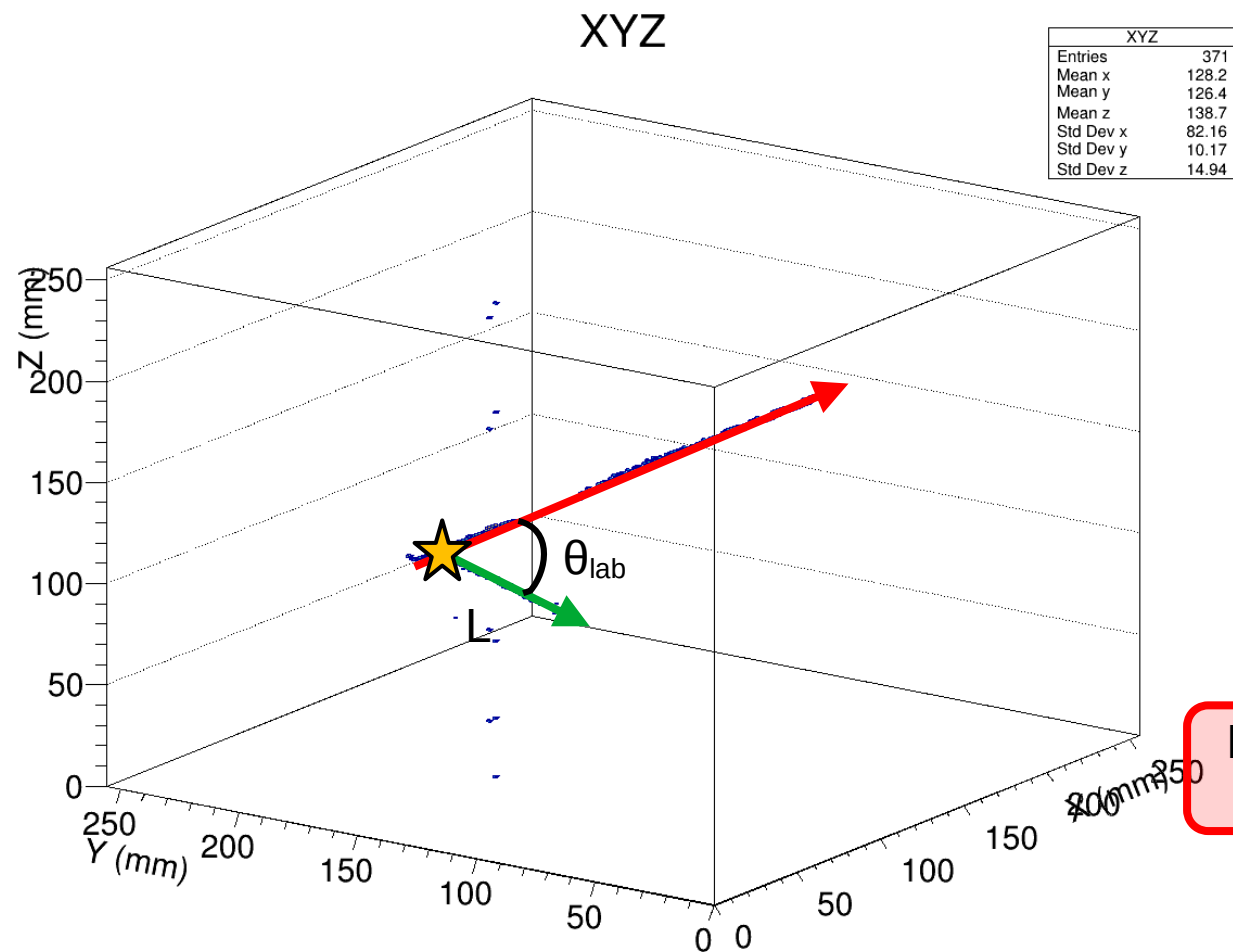
A typical scattering event in ACTAR



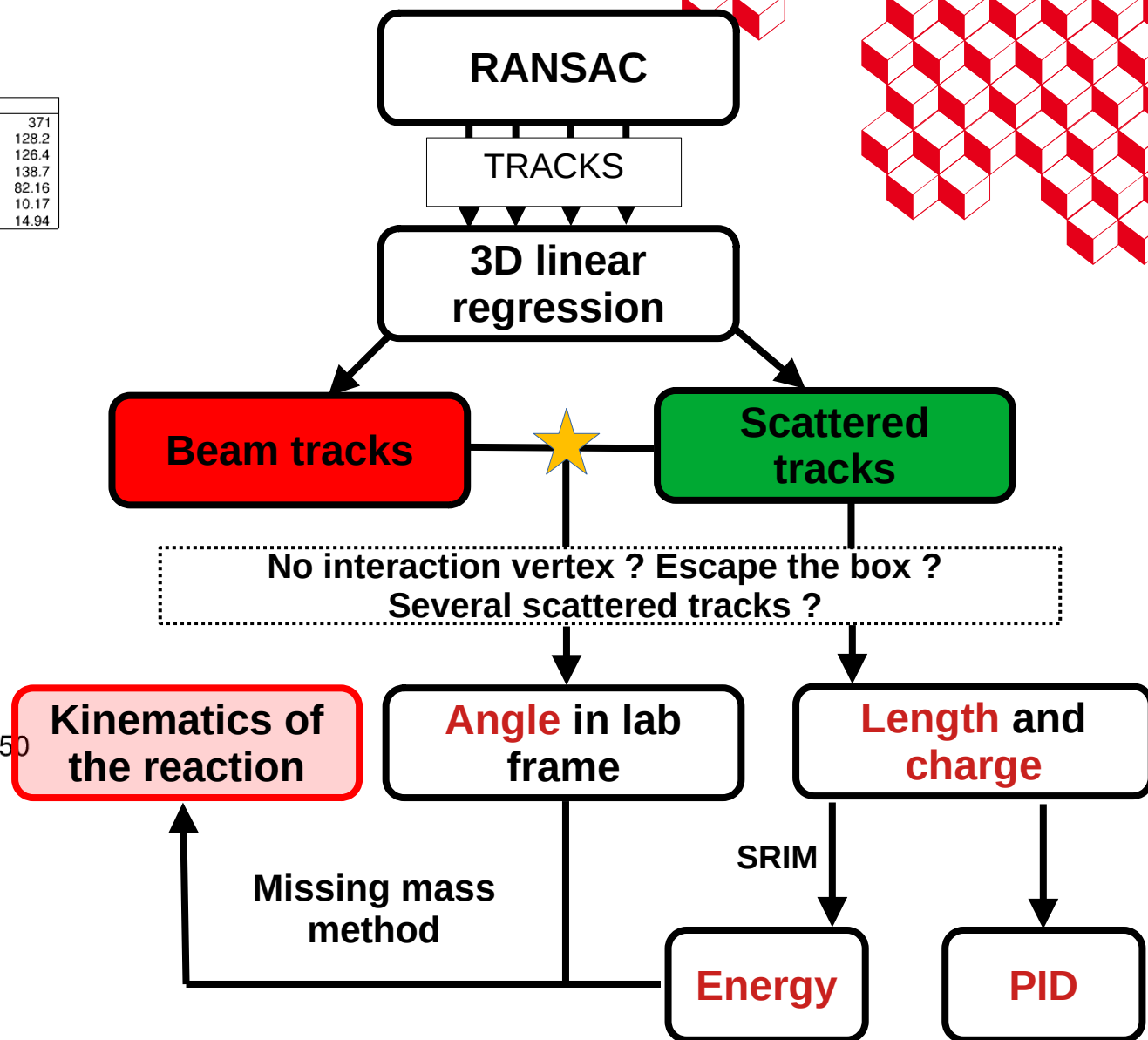
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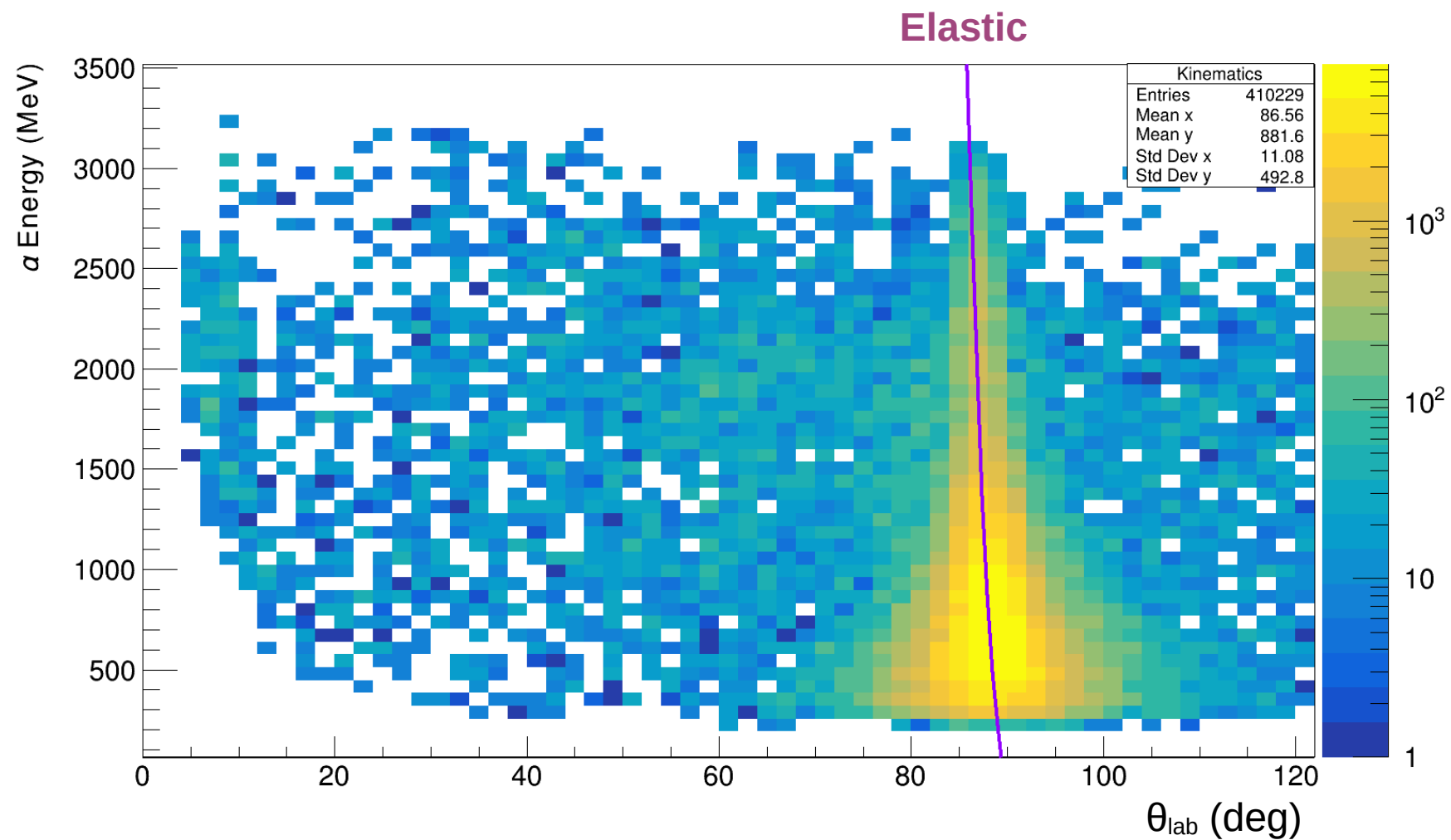
Analysis procedure



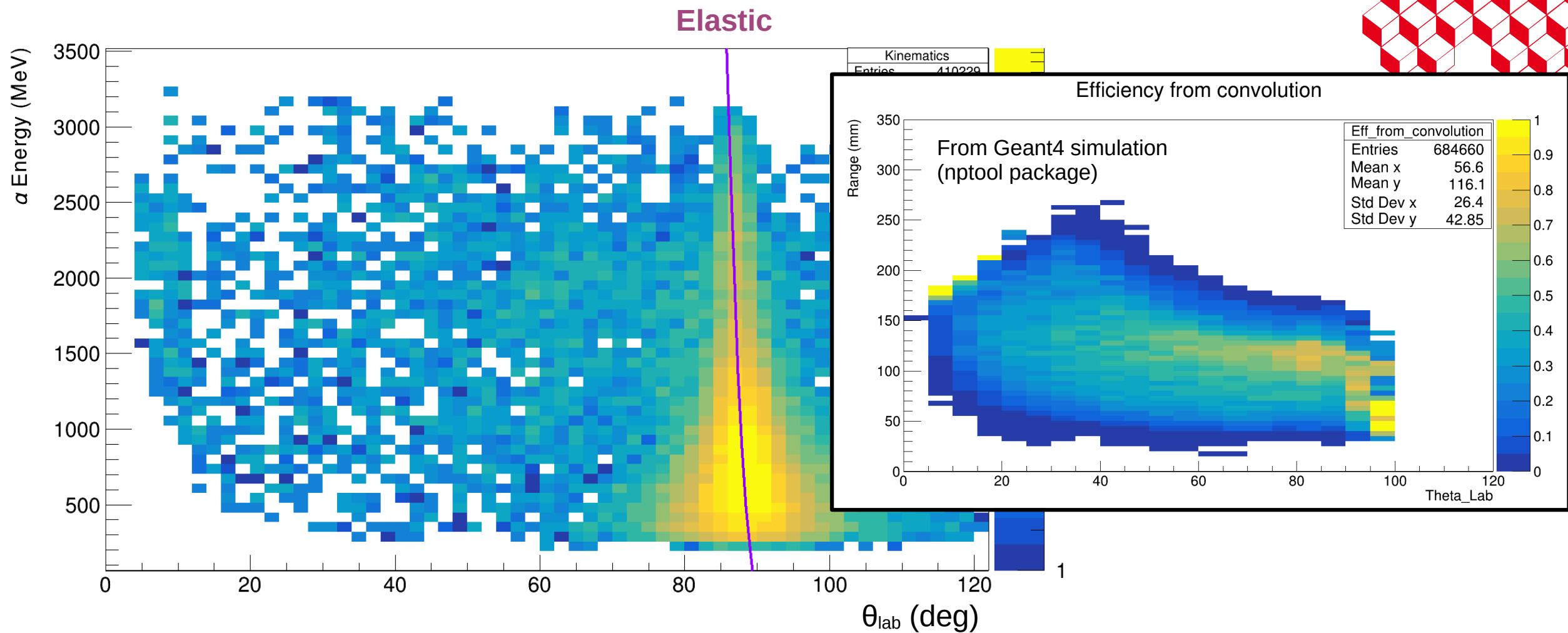
A typical scattering event in ACTAR



Results - ^{58}Ni ; Lab Frame

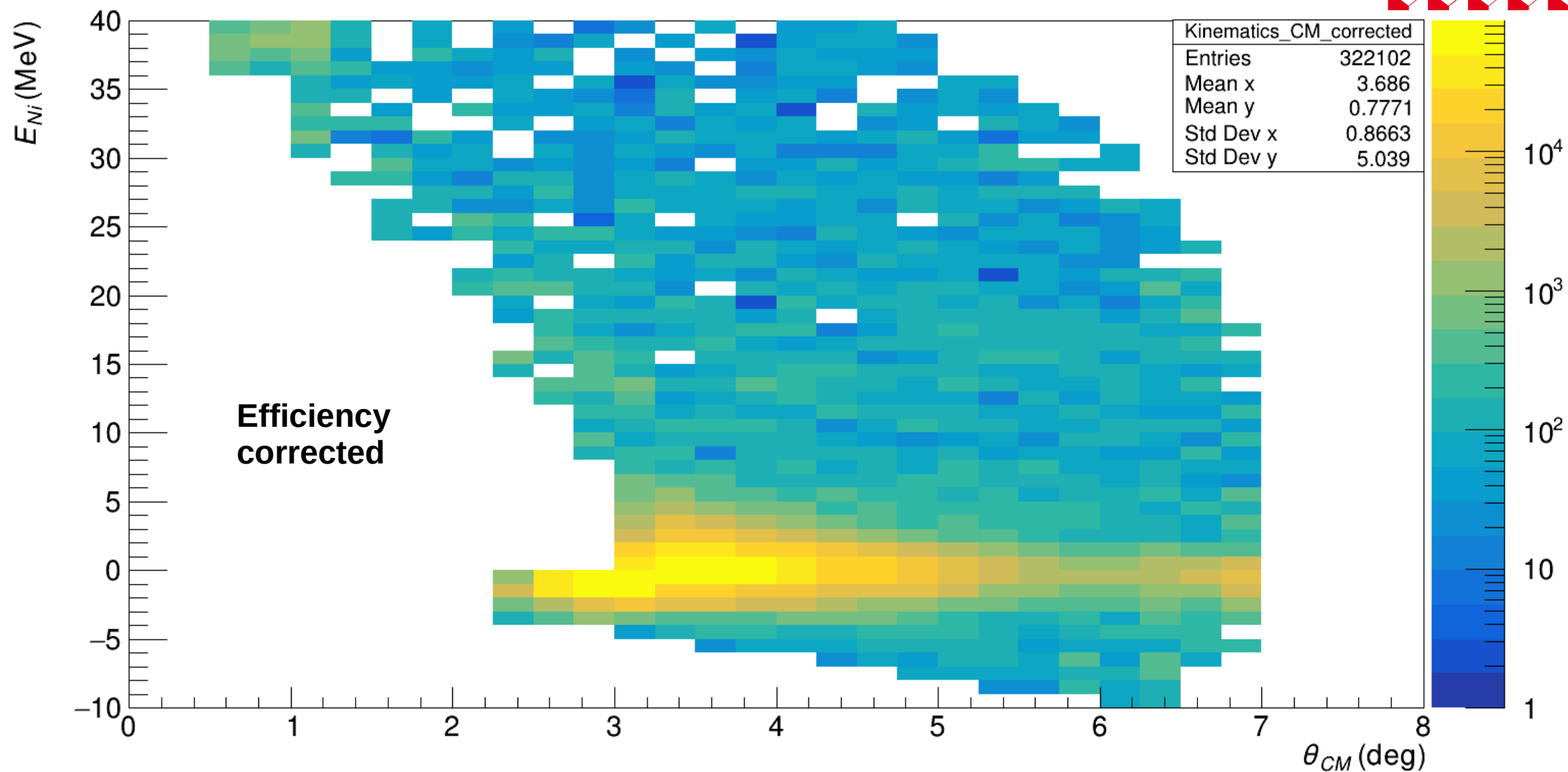


Results - ^{58}Ni ; Lab Frame

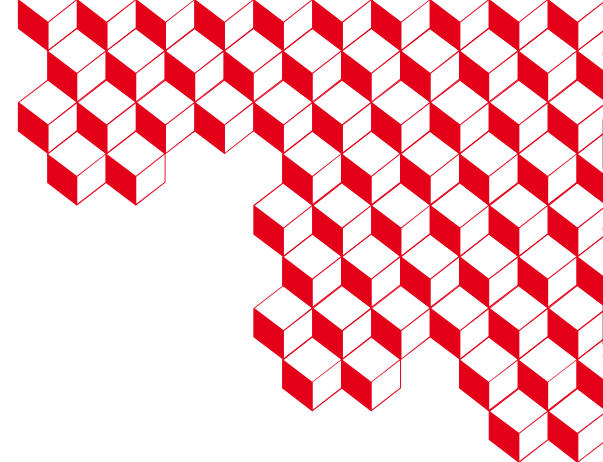


Efficiency correction + missing mass method → **Distribution in CM frame**

Results - ^{58}Ni ; CM Frame



Some results on Nickel and limitations



Results from the ACTAR analysis for ^{58}Ni :

$$\frac{d\sigma}{d\Omega}(\theta_{CM}) = \frac{dN(\theta_{CM})}{2\pi \sin(\theta_{CM}) d\theta_{CM}} \times \frac{1}{\mathcal{E}(\theta_{CM}) \mathcal{N}_{cible} e \mathcal{N}_{inc}}$$

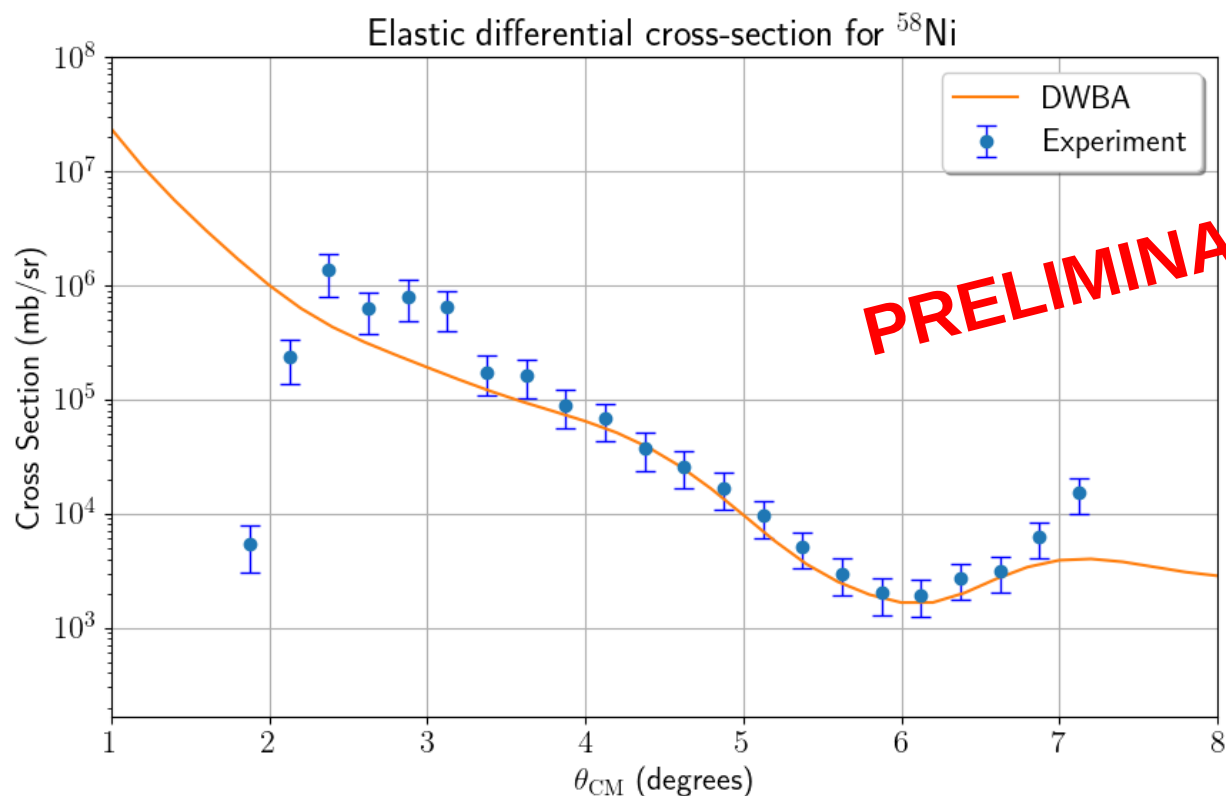
$d\theta = 0.25^\circ$

$N_{\text{target}} = 9.0 \times 10^{18} \text{ atoms/cm}^3$

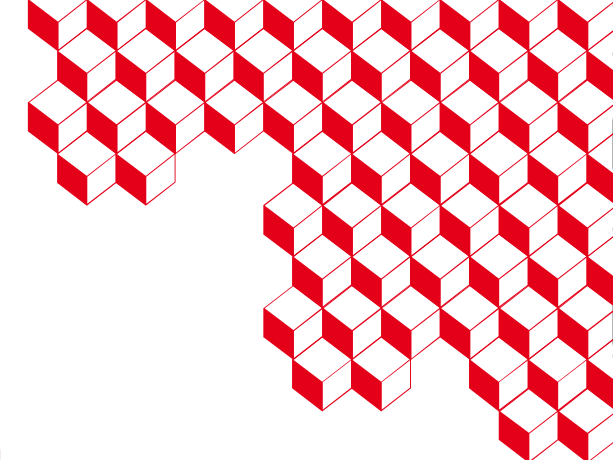
$N_{\text{inc}} = 3.95 \times 10^9 \text{ atoms}$

$e = 25.6 \text{ cm}$

Calculation by S. Peru and
M. Dupuis (CEA-DAM), Cophynu
collaboration



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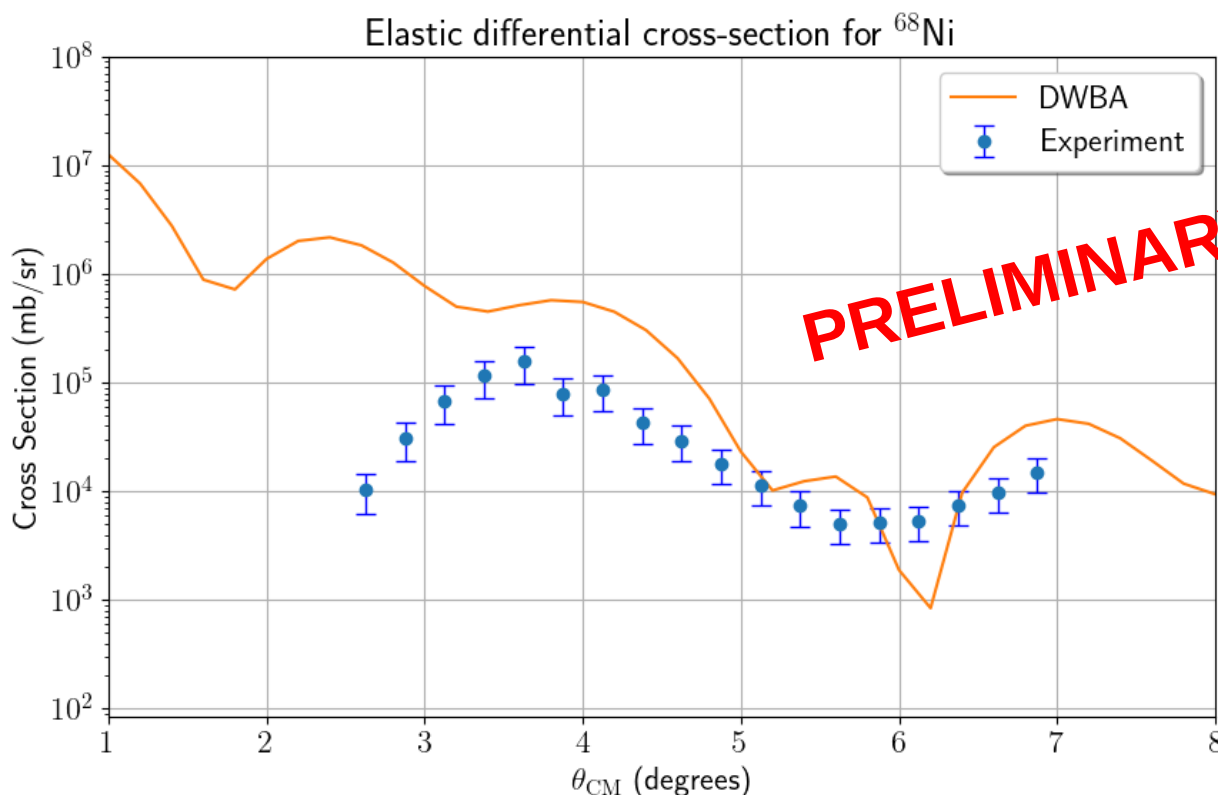
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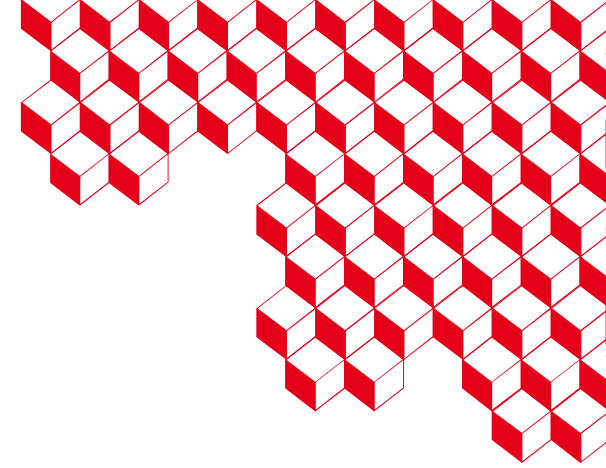
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Strong dependance on models



Range → **Energy** : dE/dX calculated from SRIM, LISE, Geant4, ...
Need to precisely know the pressure, temperature, gas composition
Check if there is no fluctuation along time

Efficiency : Calculated using GEANT4 simulations
The simulation has to be as faithful as possible (long)
Some discrepancies at the limit of detection

MDA : We depend on QRPA and DWBA calculations to perform the fit and extract the values
Is elastic scattering a good benchmark ?
What if one changes the model ?

Conclusions

The ISGMR can be related to the **incompressibility** of a nucleus and by extension to the incompressibility of nuclear matter

Experimentally, one needs to measure **100 % of the strength** to calculate faithful values.
The strength are extracted using **MDA**.

Stable nuclei are mostly studied in direct kinematics with **magnetic spectrometer**

Unstable nuclei are mostly studied in inverse kinematics with **active targets**

One can also mention the use of **storage rings** for the study of GR

The main source of uncertainties is the **estimation of the background**

An other difficulty, especially in inverse kinematics, is the **strong dependance on models**

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**Thank you for your
attention**