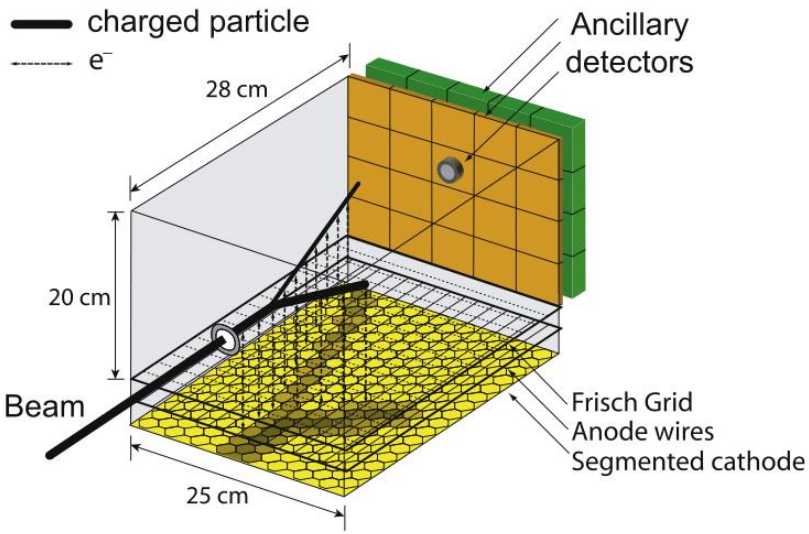
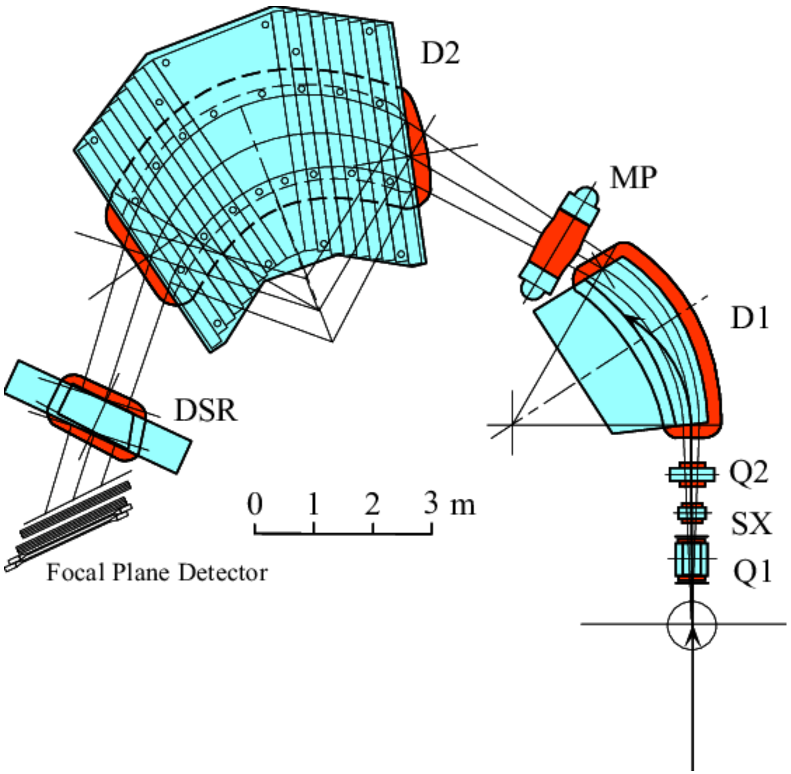
Measurements of the GMR in direct kinematics at RCNP and in unstable nuclei with the MAYA active target





SOUMYA BAGCHI

INDIAN INSTITUTE OF TECHNOLOGY, DHANBAD, INDIA

Outline

- Giant Monopole Resonance (GMR), nuclear incompressibility, and its importance
- GMR in ^{56}Ni using active target Maya at the GANIL facility
- GMR in Nd isotopes using Grand Raiden Spectrometer at the RCNP facility
- Summary

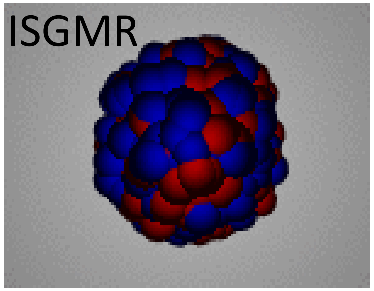
Giant Resonances

Collective excitations: Coherent superposition of 1p-1h transitions

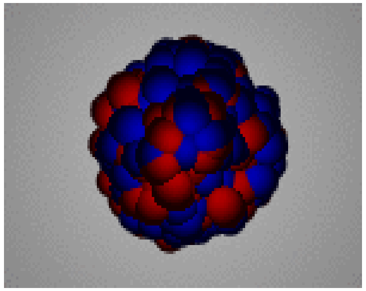
Isoscalar (In phase)
$\Delta T = 0$

Isovector (Out of phase)
$\Delta T = 1$

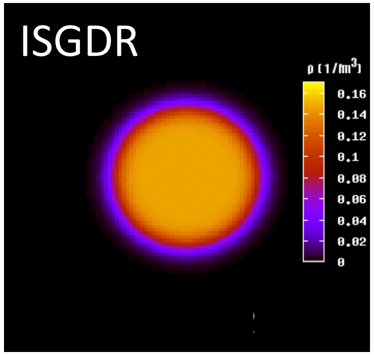
Monopole
$\Delta L = 0$
(GMR)



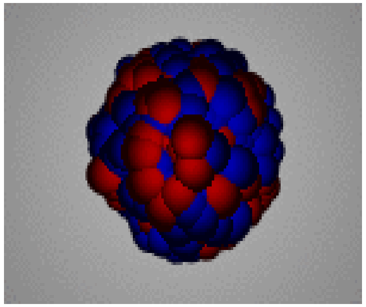
IVGMR



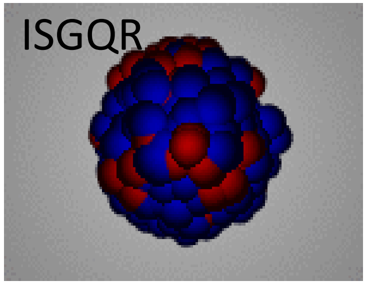
Dipole
$\Delta L = 1$
(GDR)



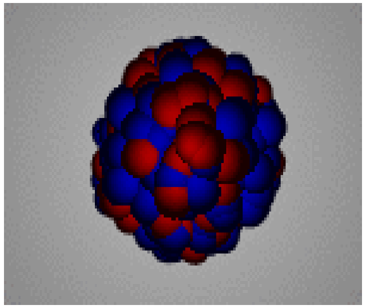
IVGDR



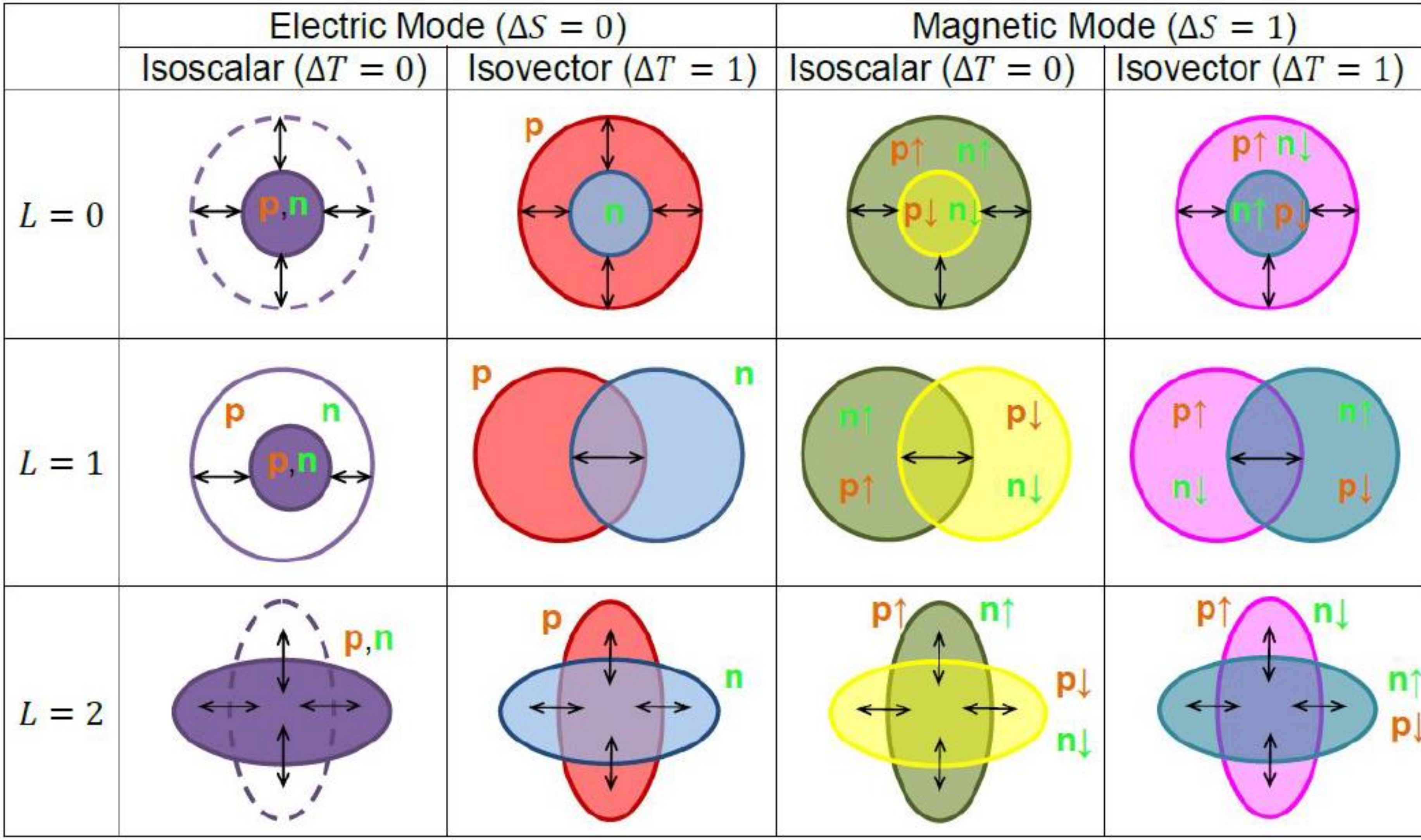
Quadrupole
$\Delta L = 2$
(GQR)



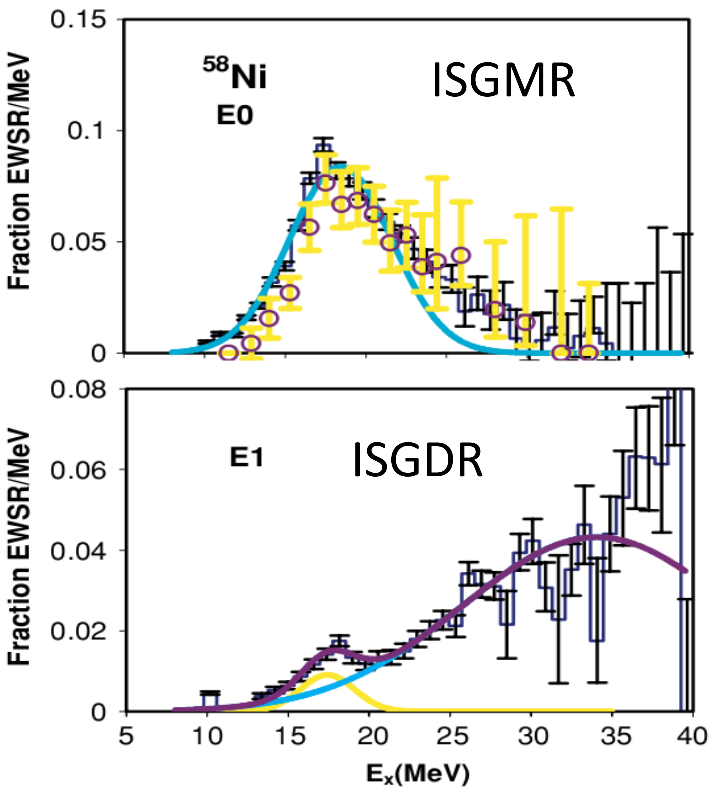
IVGQR



Schematic of Giant Resonances

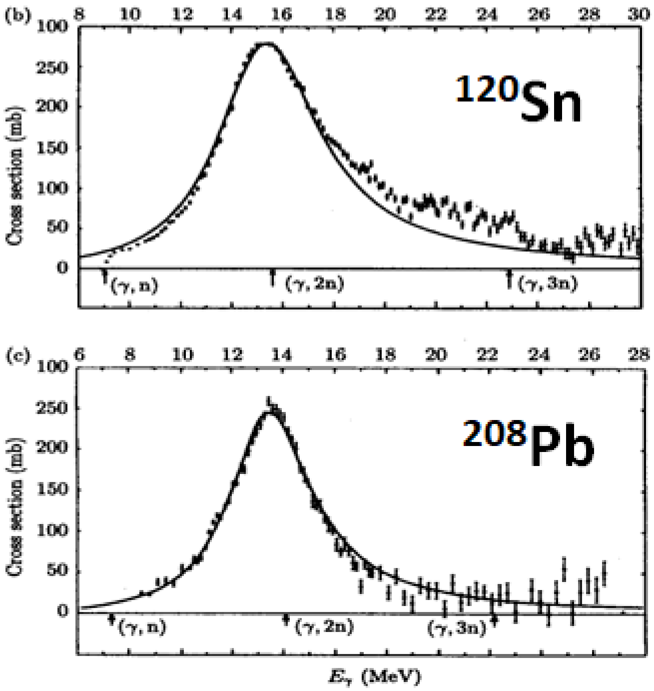


Giant Resonances: Strength Distribution of Isoscalar / Isovector Resonances



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

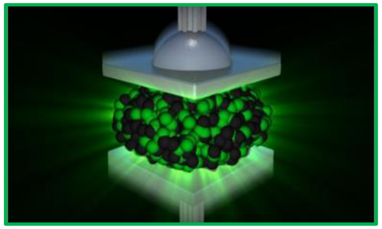
Photo neutron cross-sections (γ,n)



Berman and Fultz, Rev. Mod. Phys. 47 (1975) 47

- Giant resonances are characterized by excitation energies higher than the particle-emission threshold (10 – 30 MeV)
- Broad resonance widths

Why study Giant Monopole resonance?



Nuclear Incompressibility

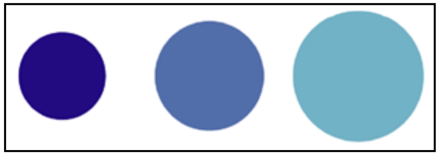
Incompressibility:
A measure of the resistance of matter to uniform compression

Why study nuclear incompressibility?

- Key input to the EoS of the nuclear matter

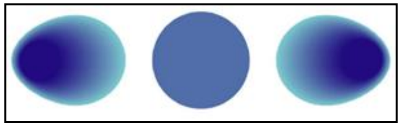
- Core collapse and supernovae explosion
- Formation of neutron star
- Collisions of heavy ions

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



See talks on Thursday

Giant Dipole resonance



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

Isoscalar (In phase)
$\Delta T = 0$

Nuclear Incompressibility

$$K_A = K_\infty + K_{Surf} A^{-1/3} + K_\tau \left(\frac{N-Z}{A}\right)^2 + K_{Coul} Z^2 A^{-4/3}$$

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

Once K_A is found.

$$K_A \xrightarrow[\text{calculation}]{\text{RPA}} K_\infty$$

From GMR data on ^{208}Pb and ^{90}Zr and other nuclei,

$K_\infty = 240 \pm 10$ MeV

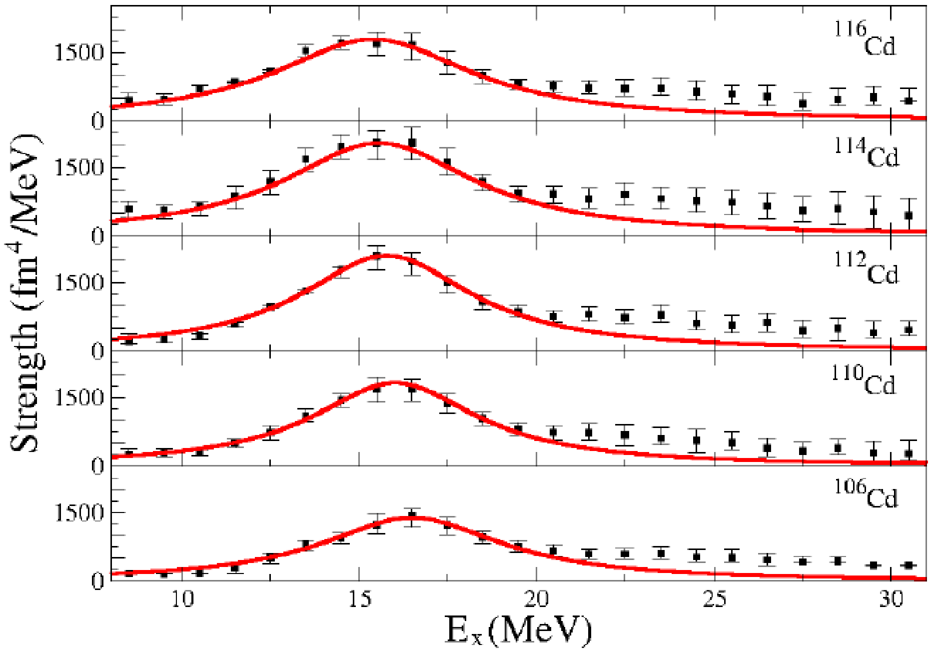
[See, e.g., G. Colò et al., Phys. Rev. C 70 (2004) 024307]

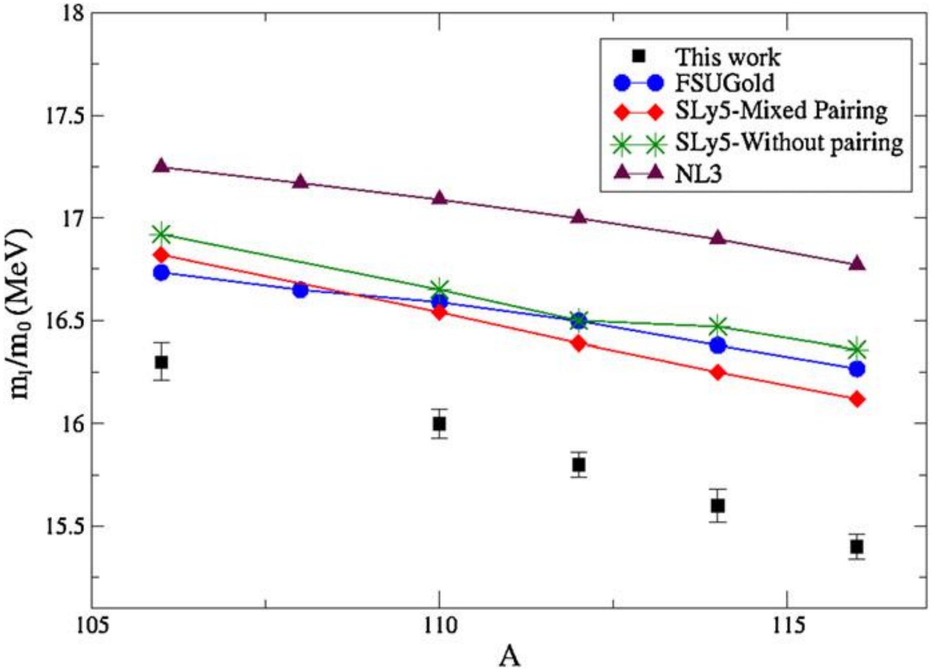
Fitting the centroid energies of soft Sn isotope and stiff Pb isotope simultaneously yielded a smaller value of K_∞ with large uncertainty, i.e., 230 ± 40MeV.

E. Khan, J. Margueron, I. Vidaña, PRL 109 (2012) 092501.
E. Khan, J. Margueron, PRC 88 (2013) 034319.

Softness of nucleus

Cd isotopes





D. Patel et al Physics Letters B 718 (2012) 447–450

Similar situation in Sn isotopes T. Li, PRL **99,** 162503 (2007)

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

Why the Tin and Cadmium are fluffy?

$$K_A \xrightarrow[\text{calculation}]{\text{RPA}} K_\infty$$

Previous works on Giant Monopole Resonance in Ni isotopes:

^{56}Ni : ISGMR, ISGQR	[^{56}Ni(*d,d'*)^{56}Ni*]	C. Monrozeau et al., PRL **100,** 042501 (2008)
^{58}Ni : ISGMR, ISGDR, ISGQR	[^{58}Ni(α,α')^{58}Ni*]	Y. Lui et al., PRC **73**, 014314 (2006)
^{60}Ni : ISGMR, ISGDR, ISGQR	[^{60}Ni(α,α')^{60}Ni*]	Y. Lui et al., PRC **73**, 014314 (2006)
^{68}Ni : ISGMR, ISGQR	[^{68}Ni(α,α')^{68}Ni*]	M. Vandebrouck et al., PRL 113, 032504 (2014)
^{68}Ni : ISGMR, ISGQR	[^{68}Ni(d,d')^{68}Ni*]	M. Vandebrouck et al., PRC **92**, 024316 (2015)

Best probe for Isoscalar Resonances:
α-particle or deuteron ($\Delta T = 0$)

α-particle probe is better:
- Cross section: Reaction with α-particle > Reaction with deuteron
- Background: Deuteron breaks at low energy
- Deuteron has spin 1 and α-particle has spin 0

^{56}Ni(α,α')^{56}Ni*

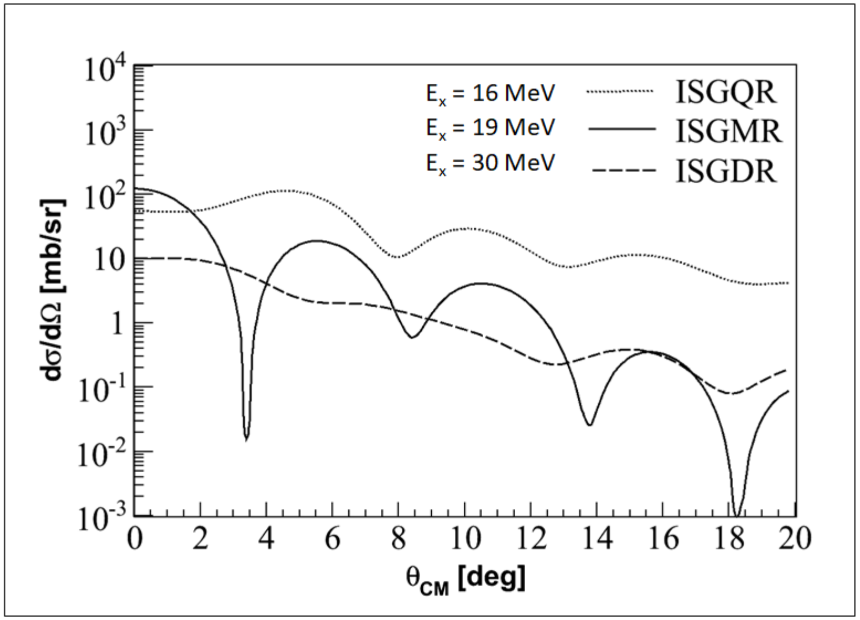
Measurement at forwarding angles and inverse kinematics

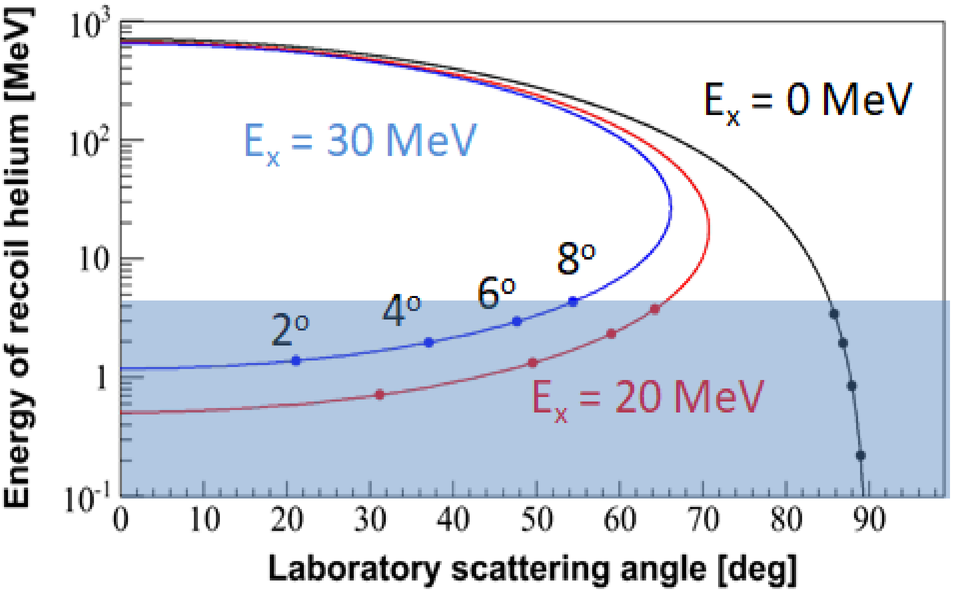
Exotic beam (half life < seconds): Inverse kinematics (can not be a target)

Intensity of exotic beams very low (~$10^4 - 10^5$ pps)

Reasonable yields: thick target is needed

$^{56}Ni(\alpha,\alpha')^{56}Ni^*$
α = Target
^{56}Ni = Projectile





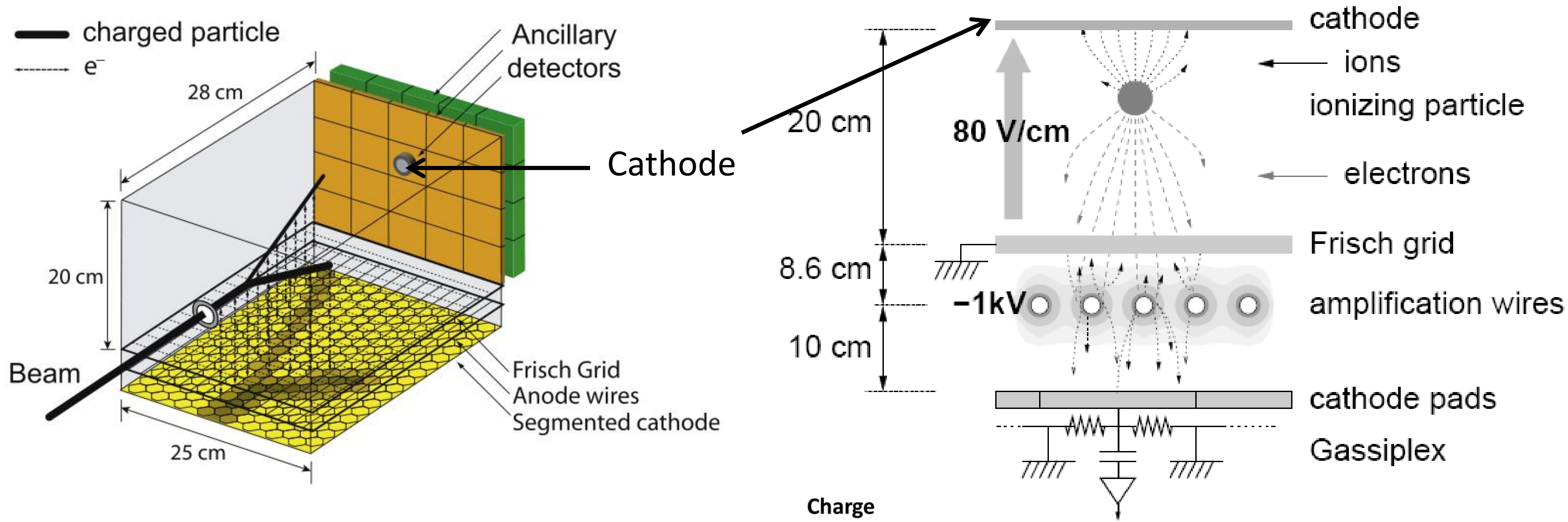
Forward angles characteristic of multipoles

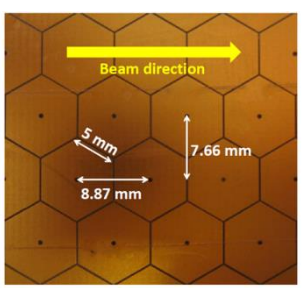
Very low energy (~ sub MeV) recoil particle will not come out of the thick target

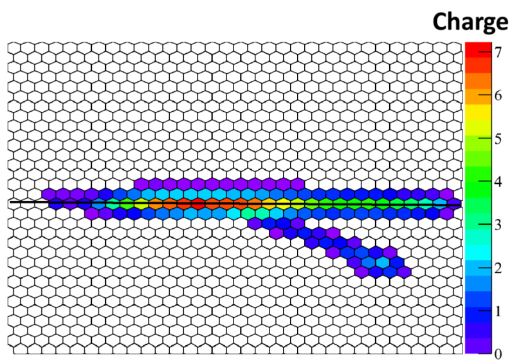
Active target

A gas detector where the target gas also acts as a detector

- Angular coverage
- Effective target thickness can be increased without much loss of resolution
- Detection of very low energy recoil particle is possible



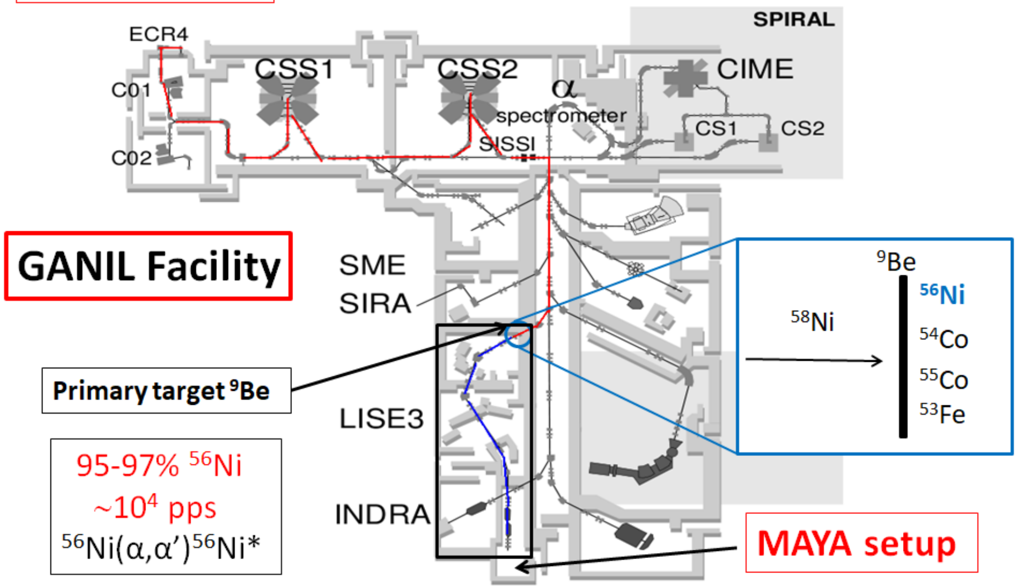


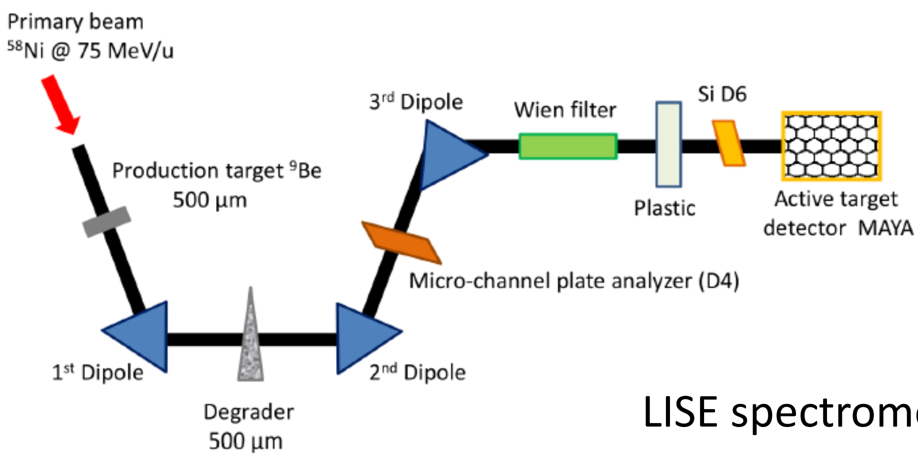


MAYA

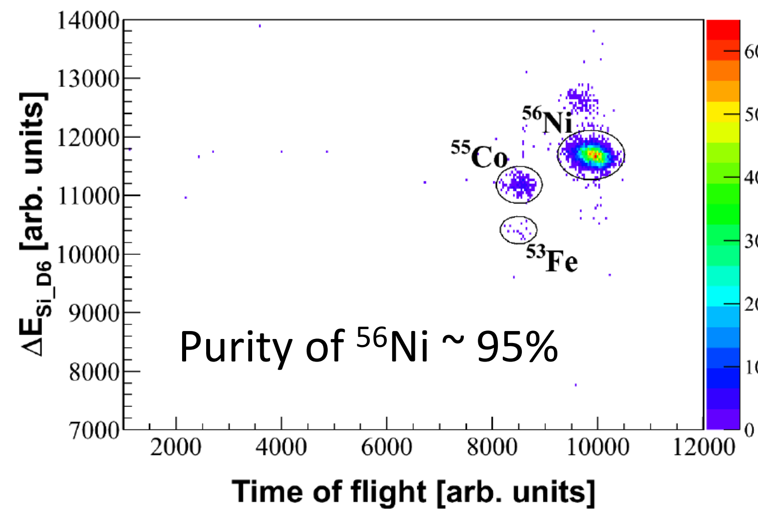
Experimental Area at GANIL, France

Primary Beam: ^{58}Ni at 75 MeV/u → Primary Target: ^{9}Be (thickness 525.6 μm) → Secondary Beam: ^{56}Ni at 50 MeV/u

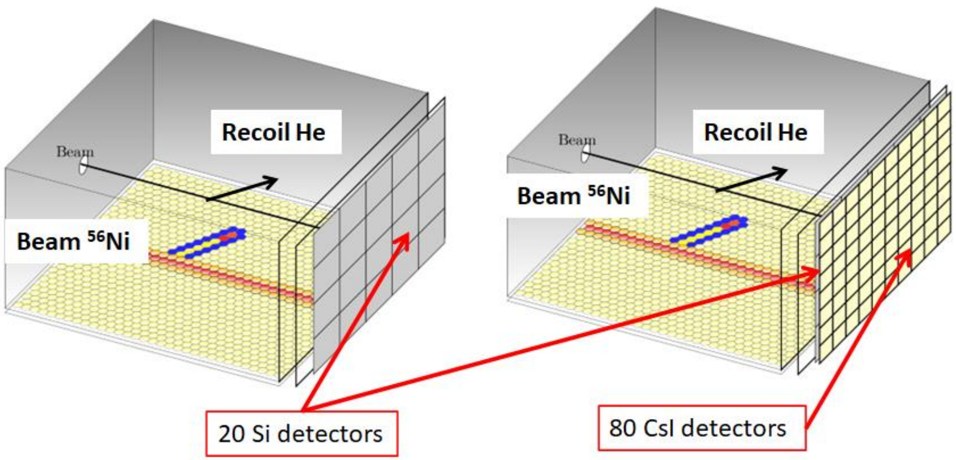


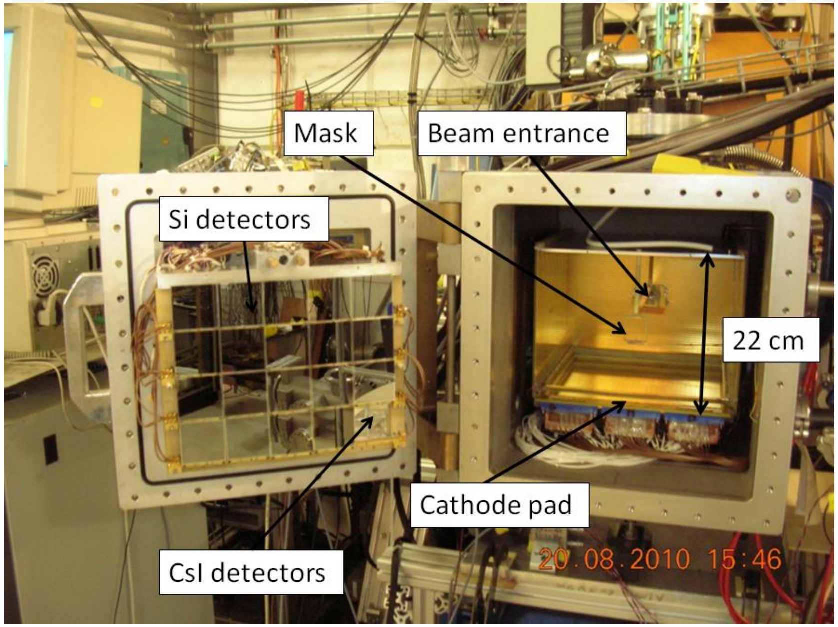


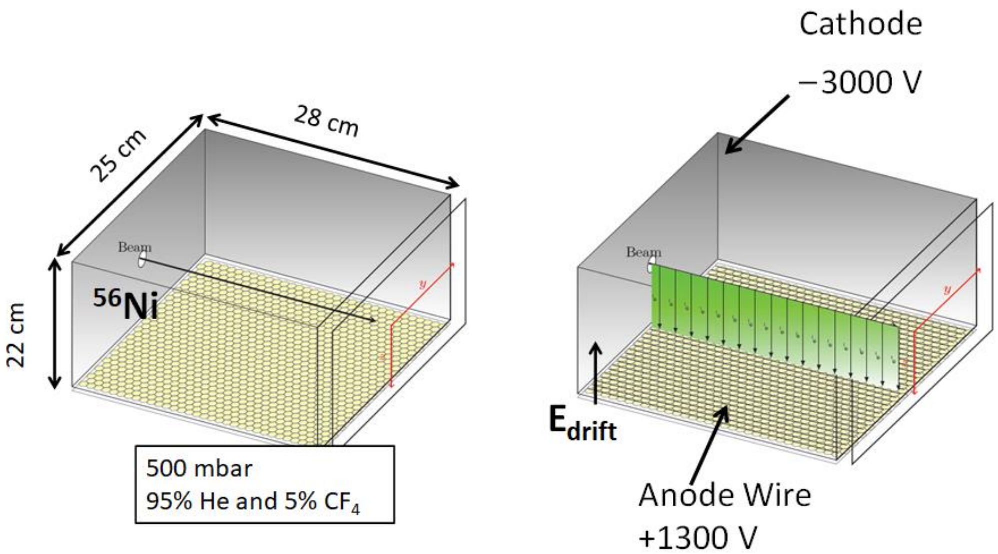
LISE spectrometer



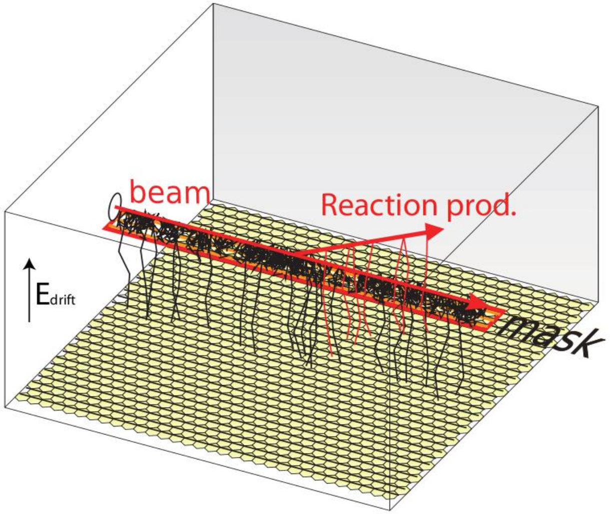
Experimental Area at GANIL, France

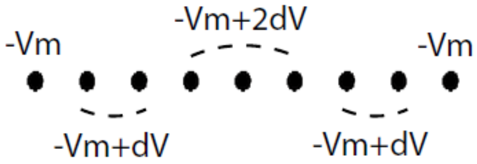




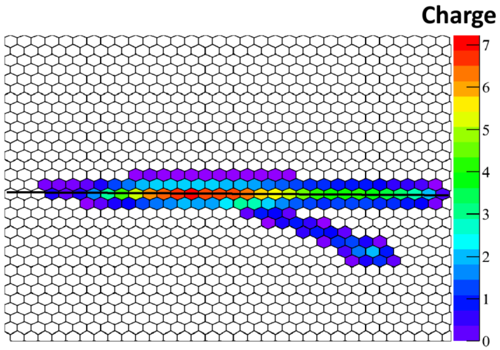


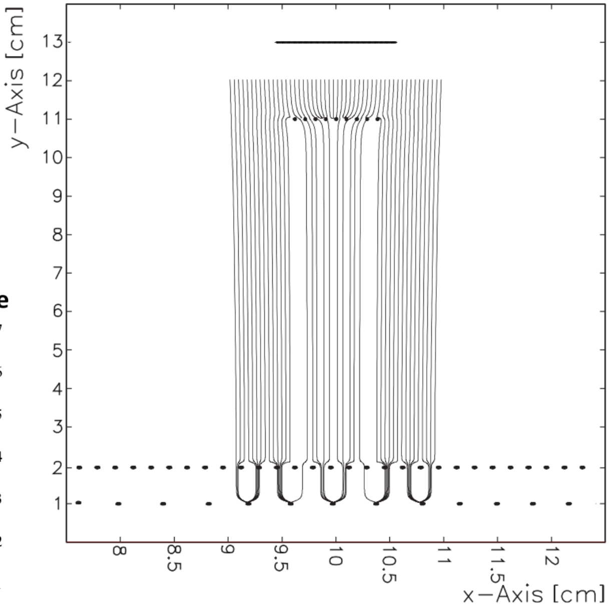
Electrostatic mask to increase the dynamic range



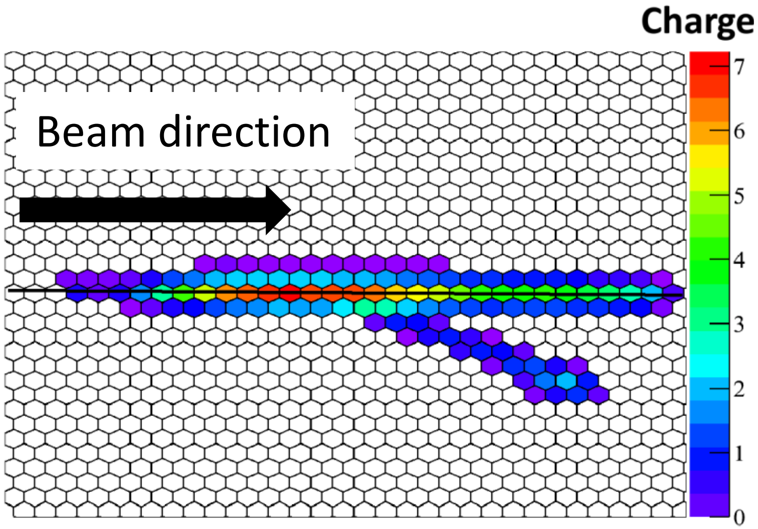


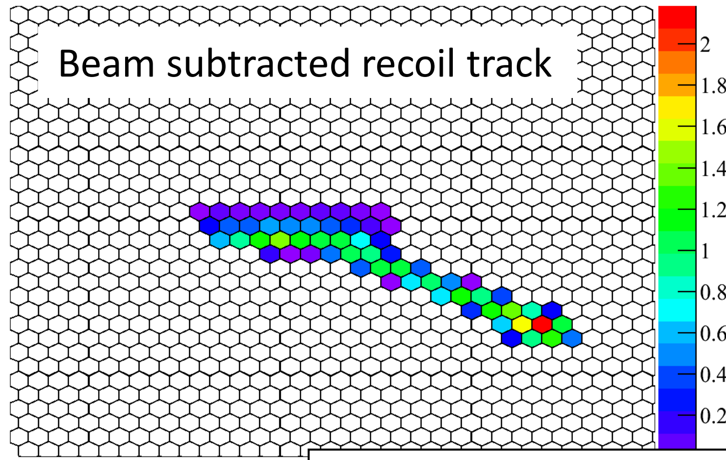
[J. Pancin et al., JINST **7** (2012) 01006]

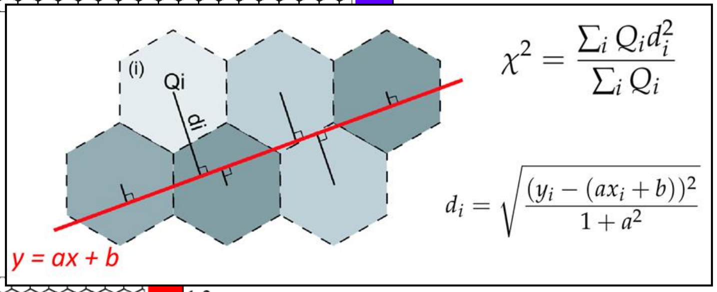




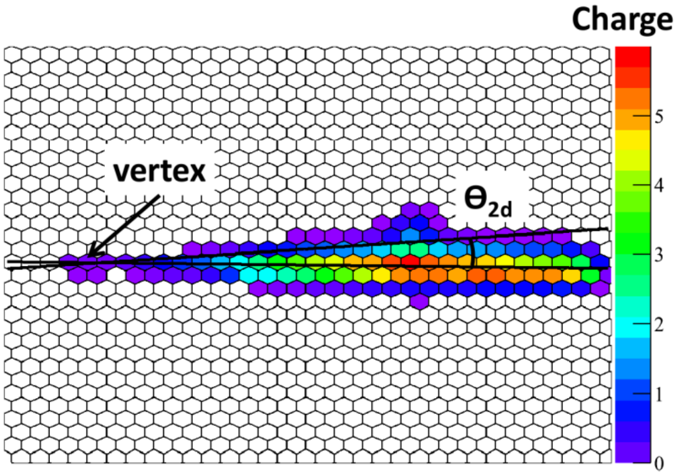
Beam Subtraction and Track Reconstruction

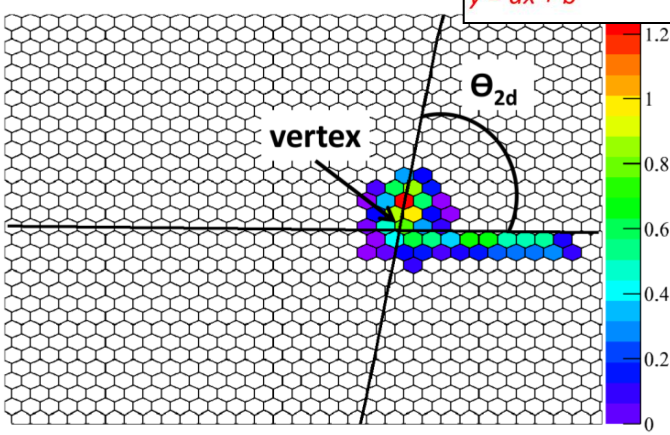




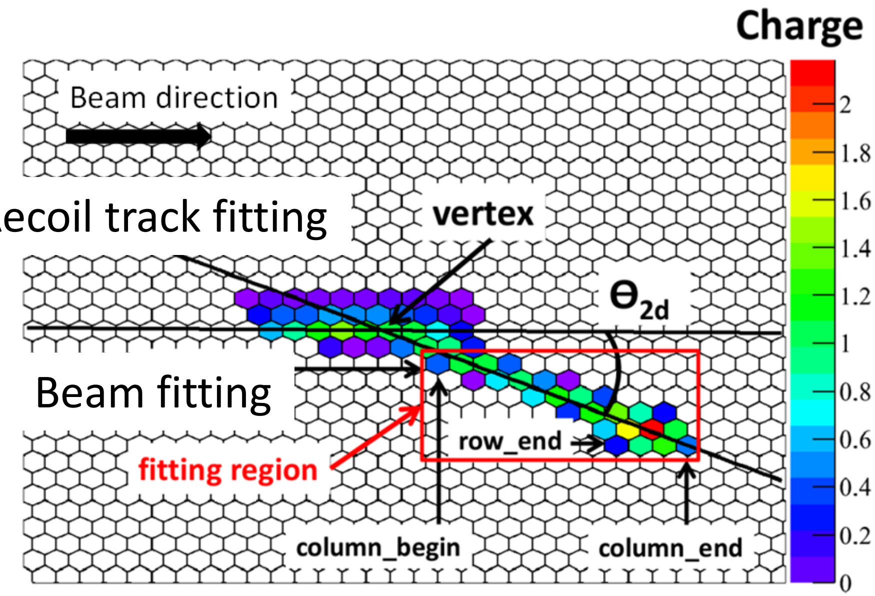


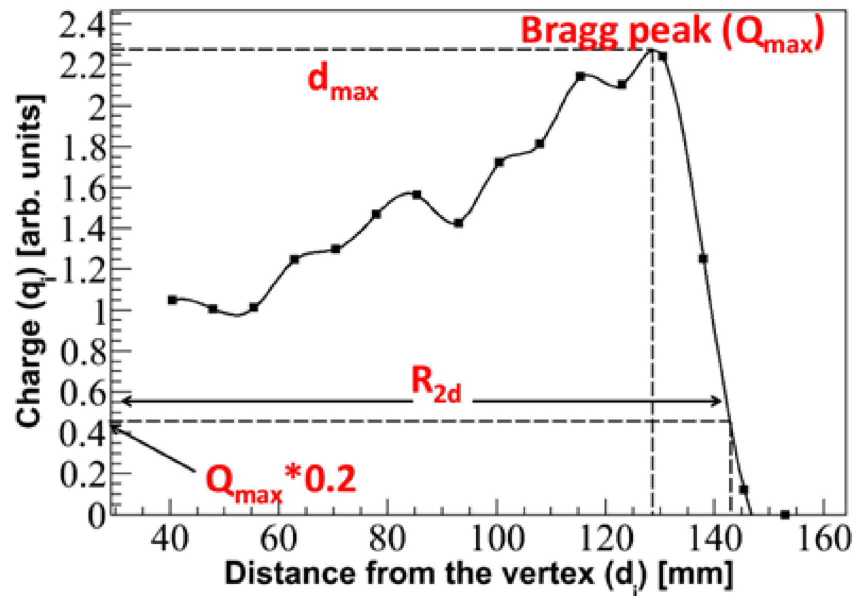
Short track reconstruction: Beam subtraction necessary



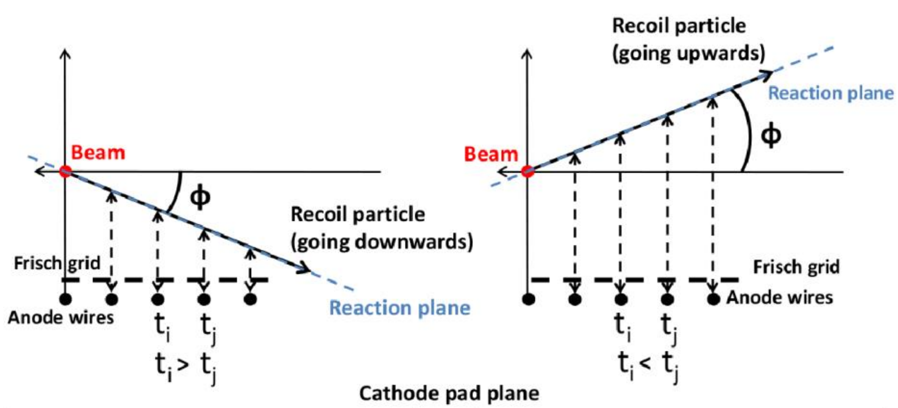


Track and kinematics reconstruction inside MAYA





Timing information from Amplification wires



θ_{2D} → Range of the recoil α particle and θ_{Lab} ← **$Range_{2D}$**

ϕ → Range of the recoil α particle and θ_{Lab}

Range of the recoil α particle and θ_{Lab}

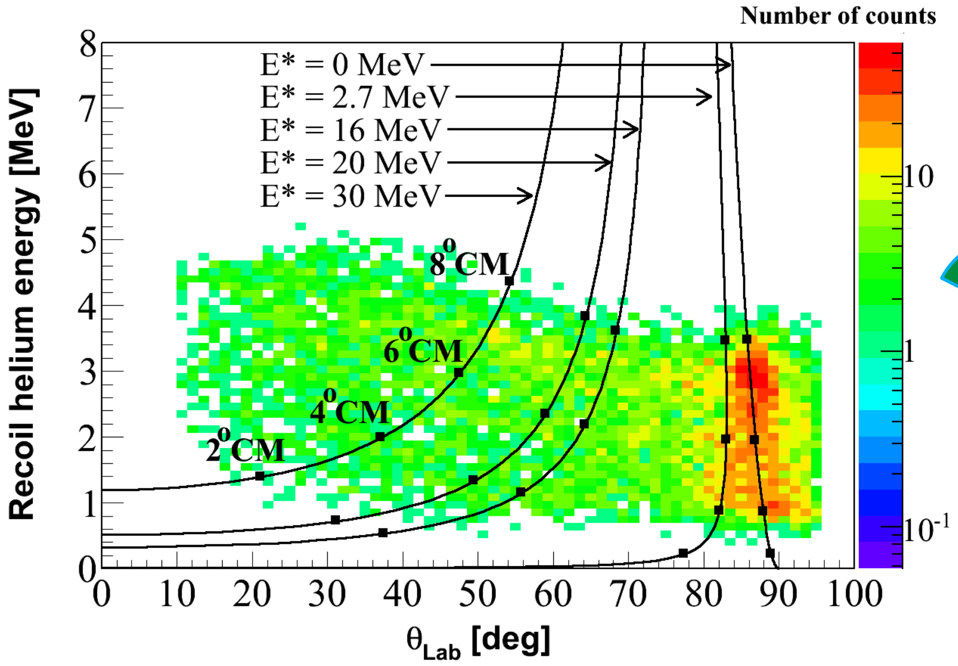
↓ SRIM: Range to Energy conversion

E_α and θ_{Lab}

↓ 2 body kinematics laws

$E^*(^{56}Ni)$ and θ_{CM}

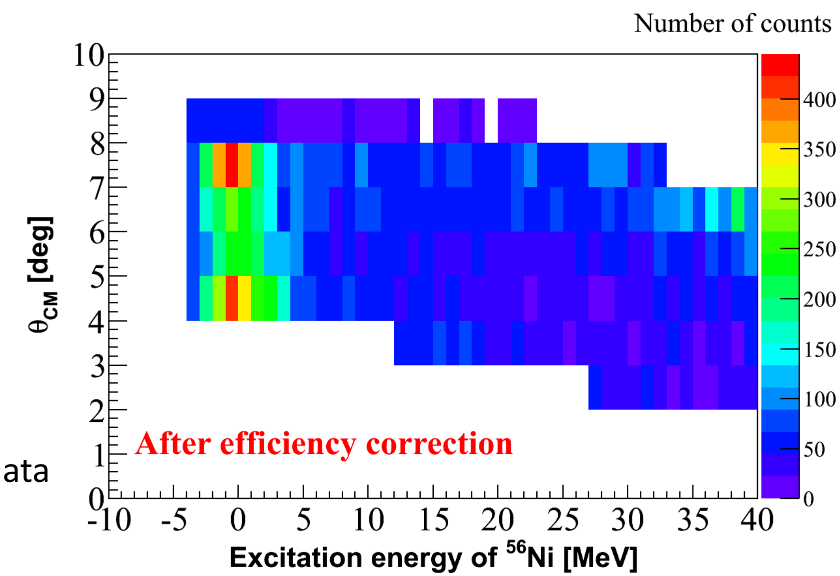
Results $^{56}Ni(\alpha, \alpha')\ ^{56}Ni^*$



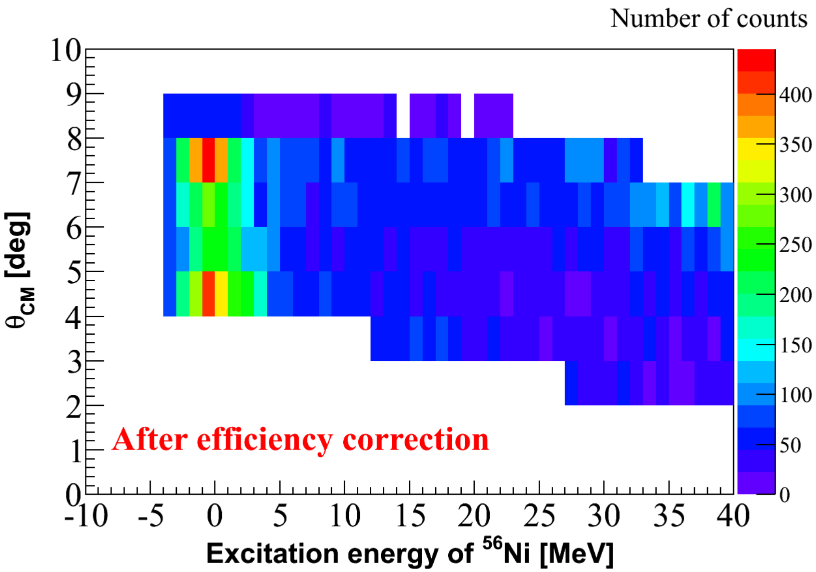
2 body reaction kinematics

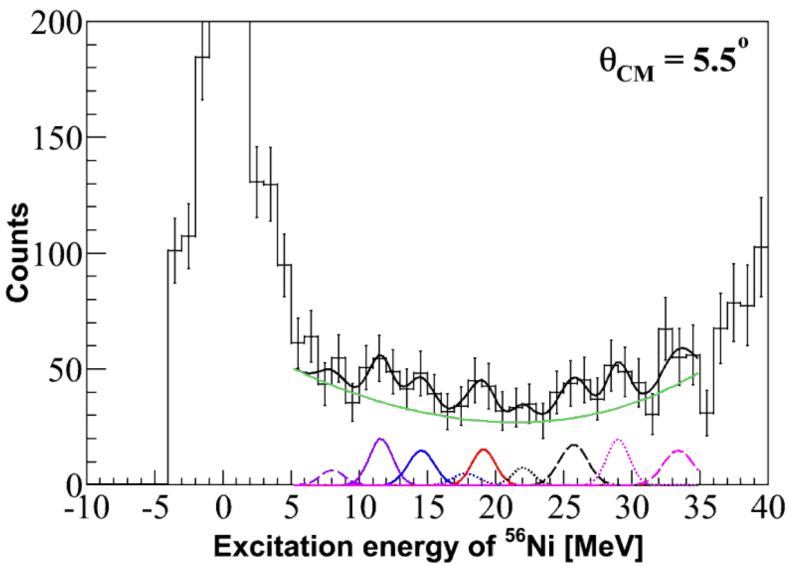
Efficiency estimated from Simulation with kinematics inputs from LISE++ and energy-to-range inputs from SRIM

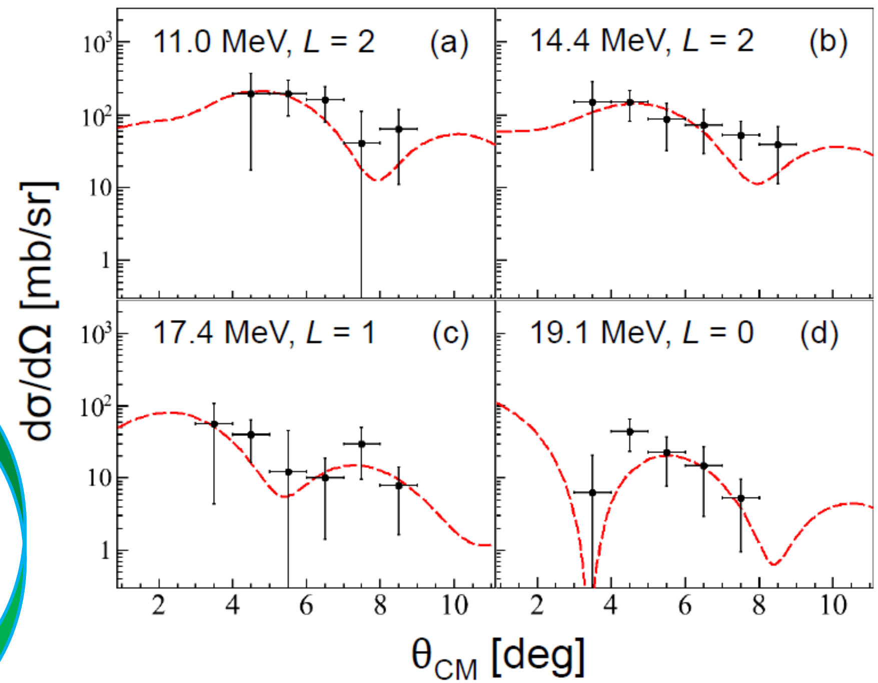
Efficiency corrected data



Results ^{56}Ni (α, α’) ^{56}Ni*: Excitation energy spectra fitting







Monopole: L = 0
19.1 ± 0.5 MeV

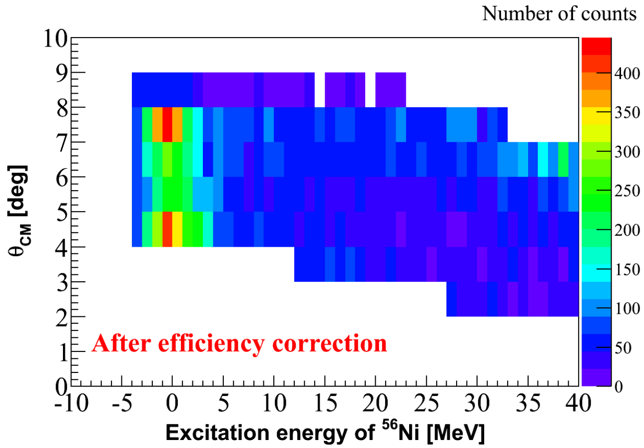
S. Bagchi et al., PLB 751 (2015) 371

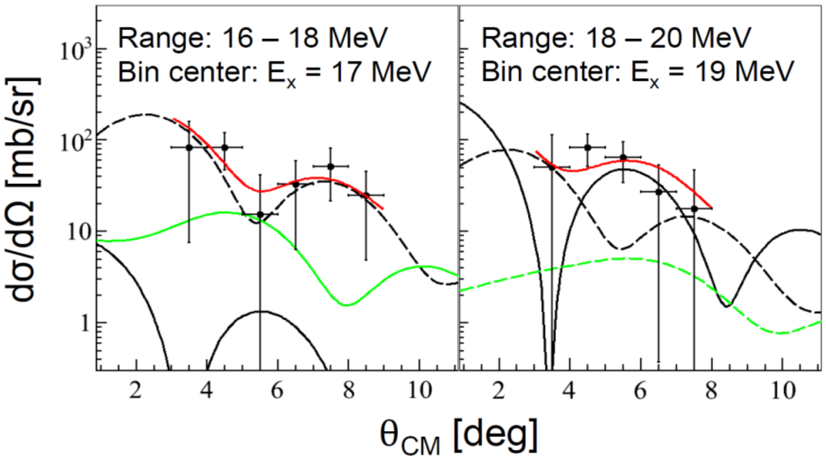
Optical model from α (^{58}Ni, α’)

H.L. Clark et al., Nucl. Phys. A **589** (1995) 416.

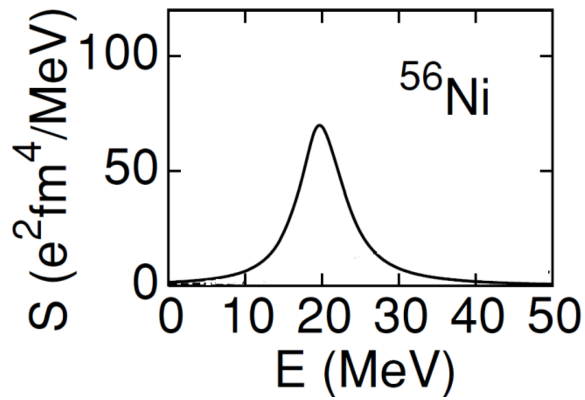
Results ^{56}Ni (α, α') ^{56}Ni* : Multipole Decomposition Analysis

$$\frac{d^2\sigma}{d\Omega\, dE}(\theta_{CM}, E^*)\bigg|_{exp} = \sum_{L=0}^{L=3} a_L(E^*)\frac{d^2\sigma_L}{d\Omega\, dE}(\theta_{CM}, E^*)\bigg|_{theory}$$





S. Bagchi et al., PLB 751 (2015) 371

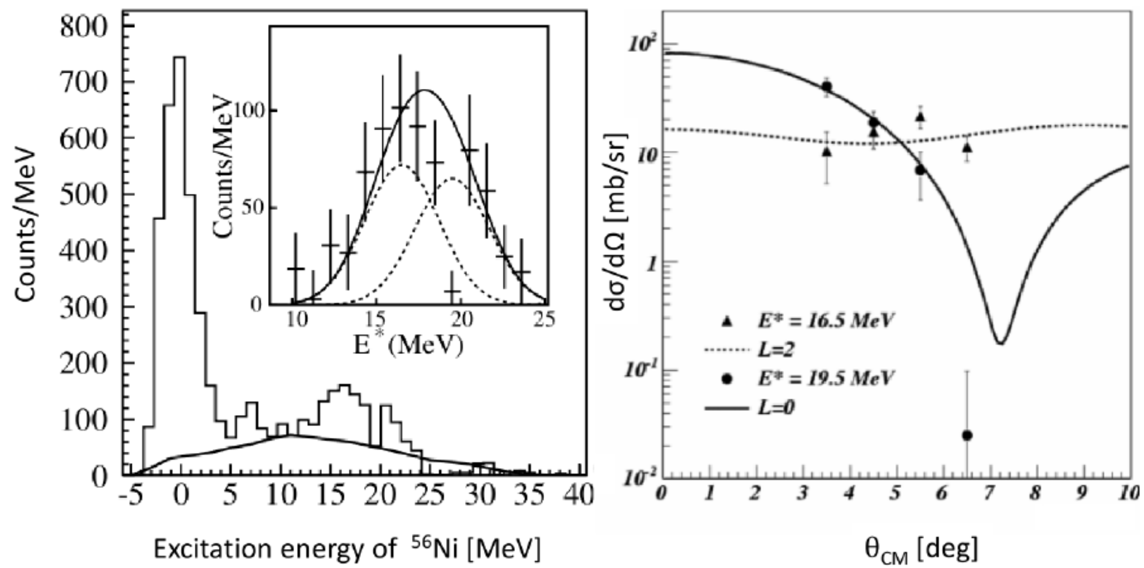


J. Terasaki & J. Engel, PRC **74**, 044301 (2006)

L = 0

Peak fitting (this work)	MDA (this work)	^{56}Ni (d,d')^{56}Ni PRL 100 (2008) 042501
19.1 ± 0.5 MeV	18.4 ± 1.8 MeV	19.3 ± 0.5 MeV

Measurements in ^{56}Ni and ^{68}Ni with Maya

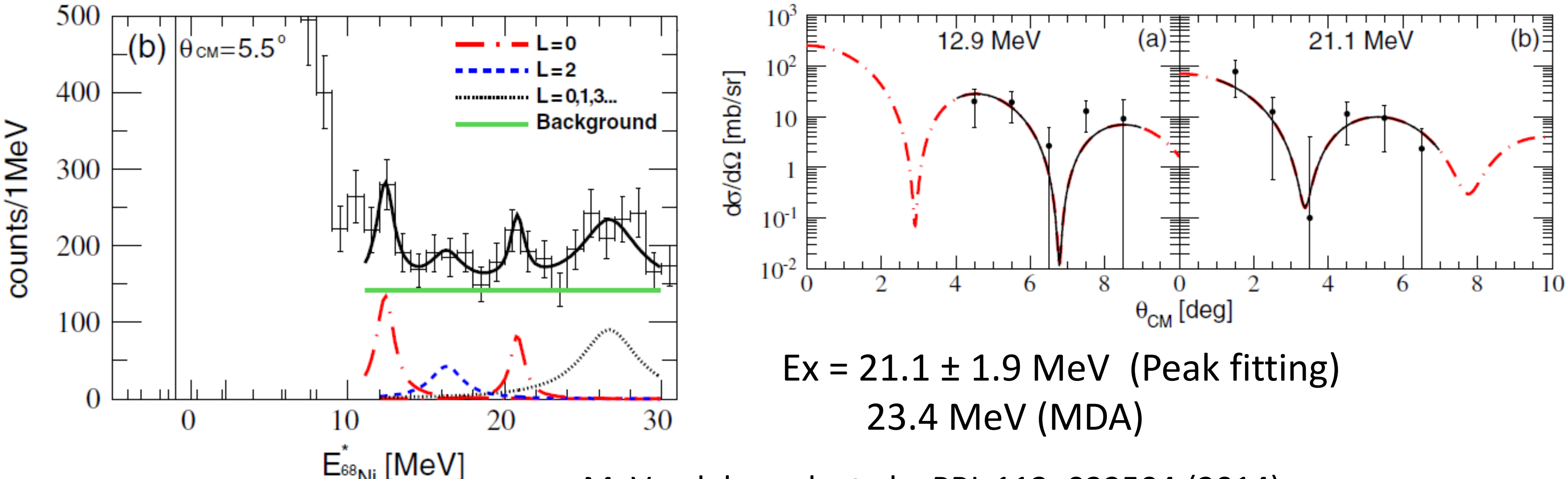


C. Monrozeau et al.,
PRL 100, 042501 (2008)

^{56}Ni (d,d')^{56}Ni

Ex = 19.3 ± 0.5 MeV (MDA analysis)
19.5 ± 0.3 MeV (Peak fitting)

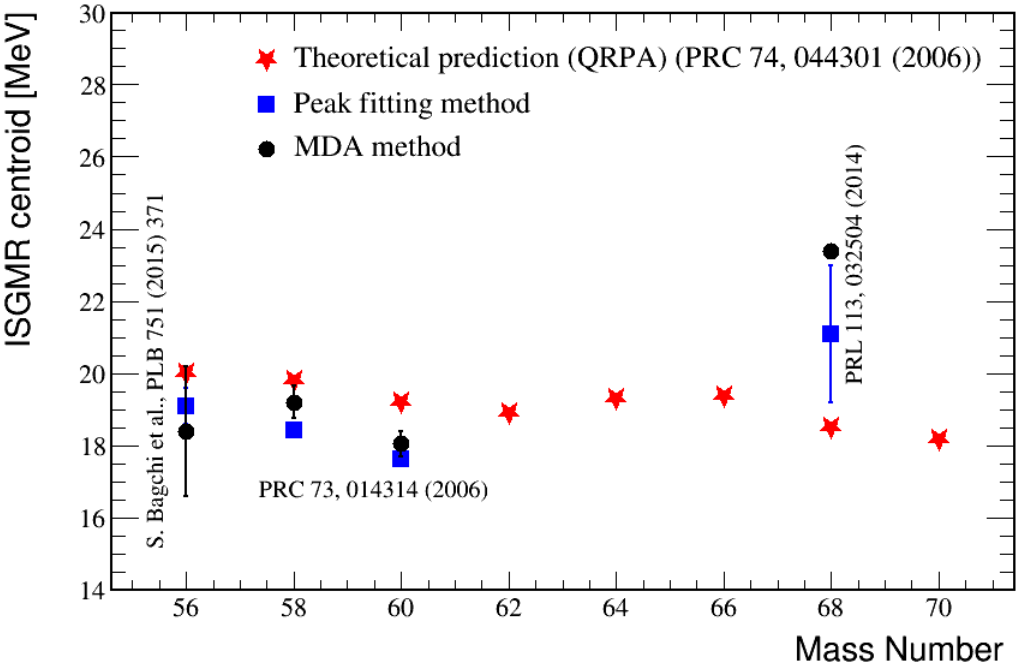
^{68}Ni (α,α') ^{68}Ni

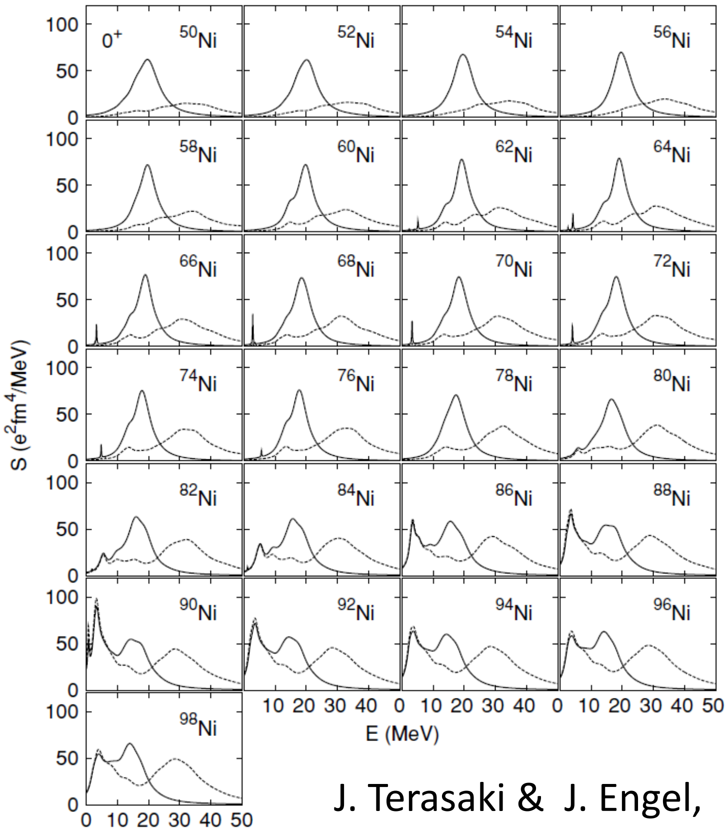


Ex = 21.1 ± 1.9 MeV (Peak fitting)
23.4 MeV (MDA)

M. Vandebrouck et al., PRL 113, 032504 (2014)

Giant resonances in Ni isotopes: Status



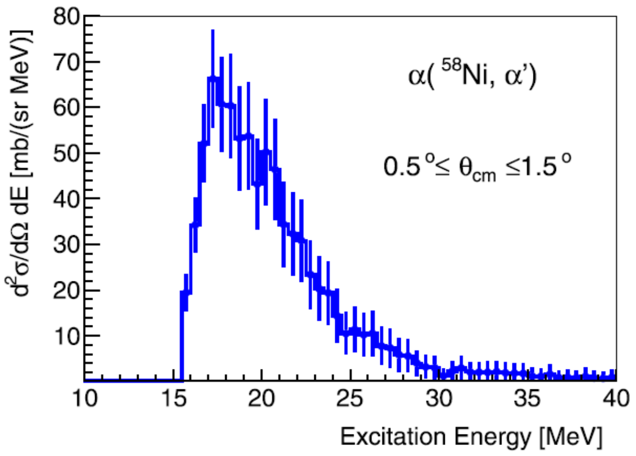


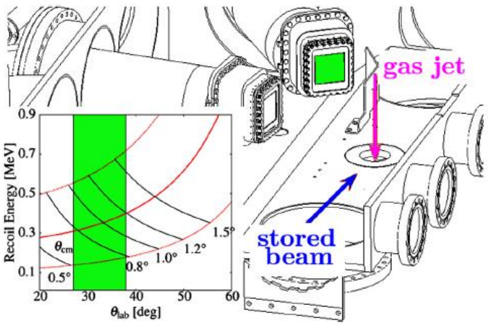
J. Terasaki & J. Engel, PRC **74**, 044301 (2006)

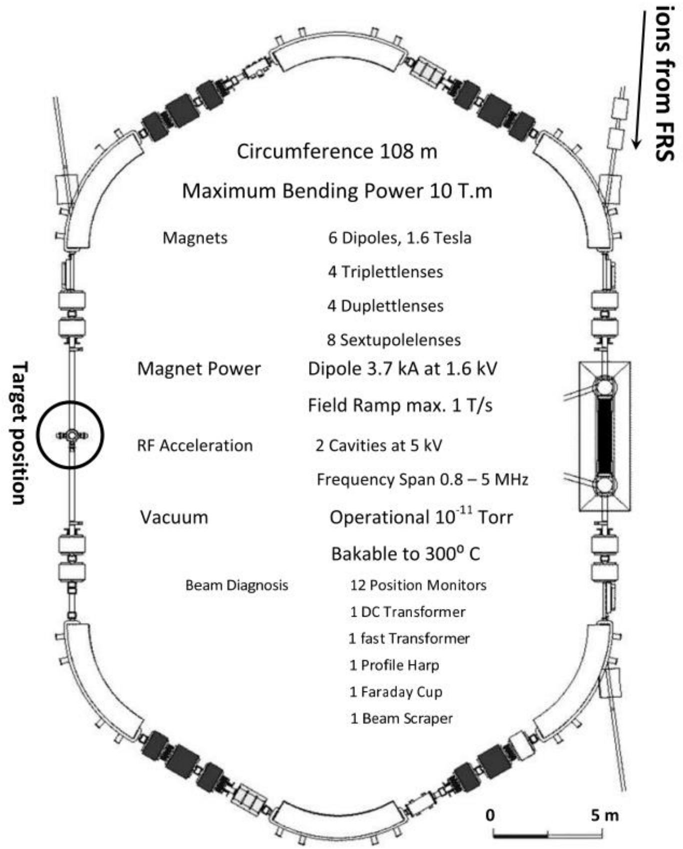
- Measurements of Ni isotopes from neutron-deficient to neutron-rich in one experimental setup (ACTAR setup!!)

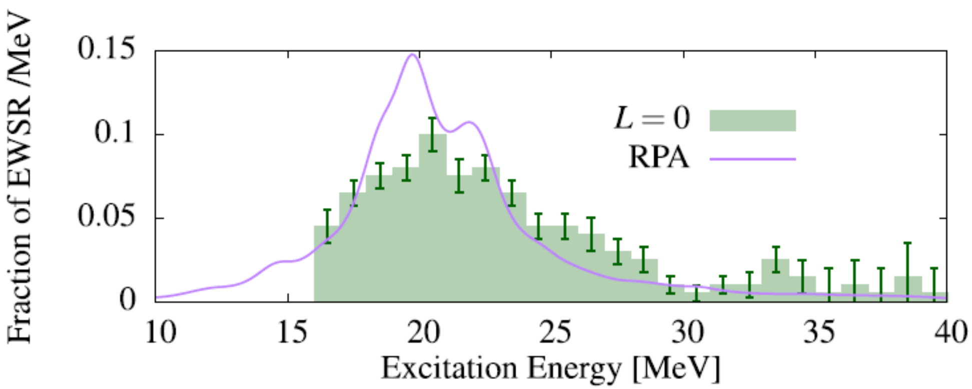
Storage Ring

Experimental storage ring at GSI:
Luminosity: $10^{26} – 10^{27}$ $cm^{-2}s^{-1}$









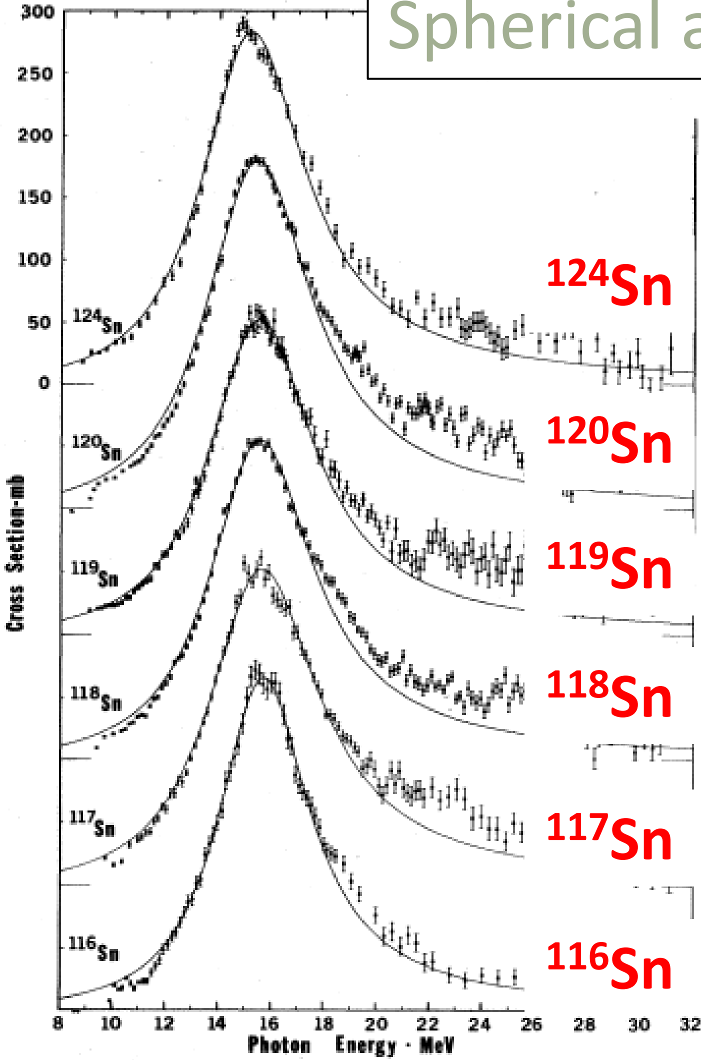
J.C. Zamora et al., PLB 763 (2016) 16–19

LOI: Investigation of the ISGMR in ^{56}Ni at the GSI Experimental Storage Ring (Continuation of the Proposal E105): J. C. Zamora and O. Kiselev et al.,

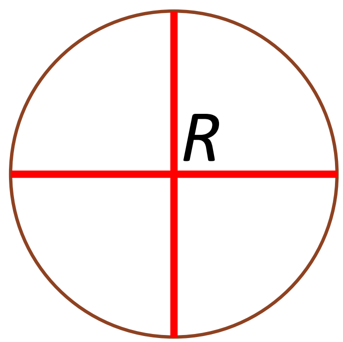
See talk by J. Zamora

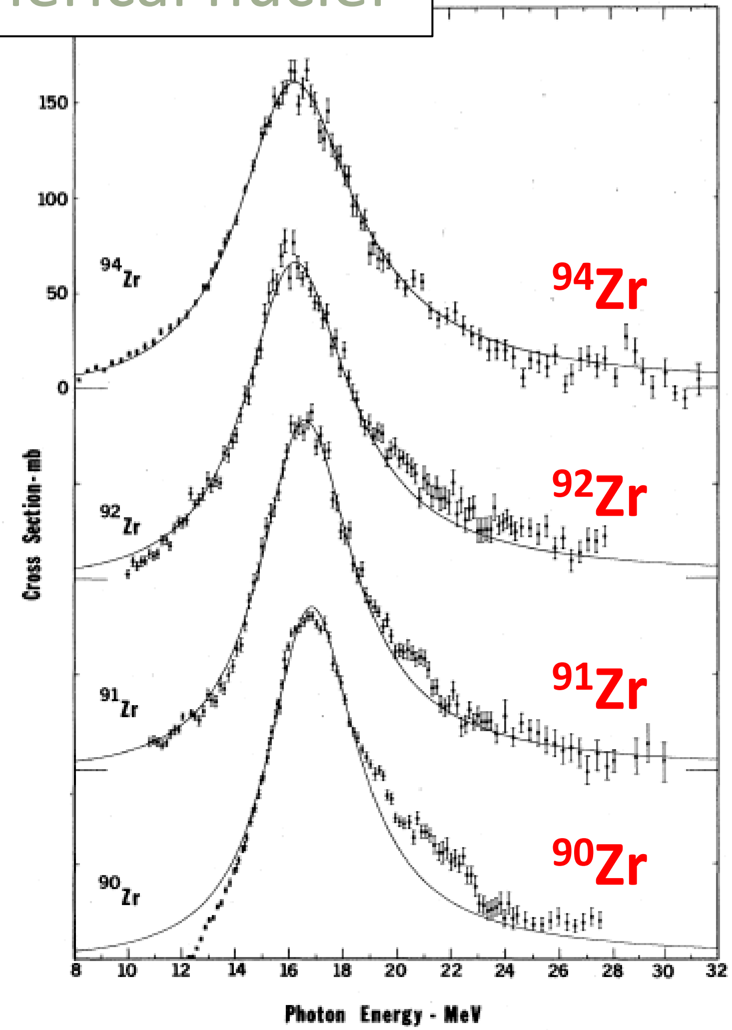
Isovector Giant Dipole Resonances: Photo-neutron cross-section

Spherical and nearly spherical nuclei



$$\omega \propto \frac{1}{R}$$





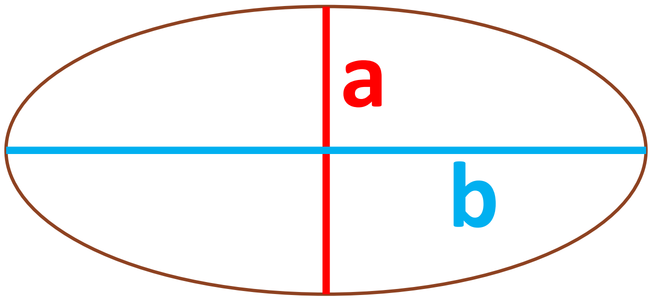
B. L. Berman and S. C. Fultz, Rev. Mod. Phys. 47, 713 (1975)

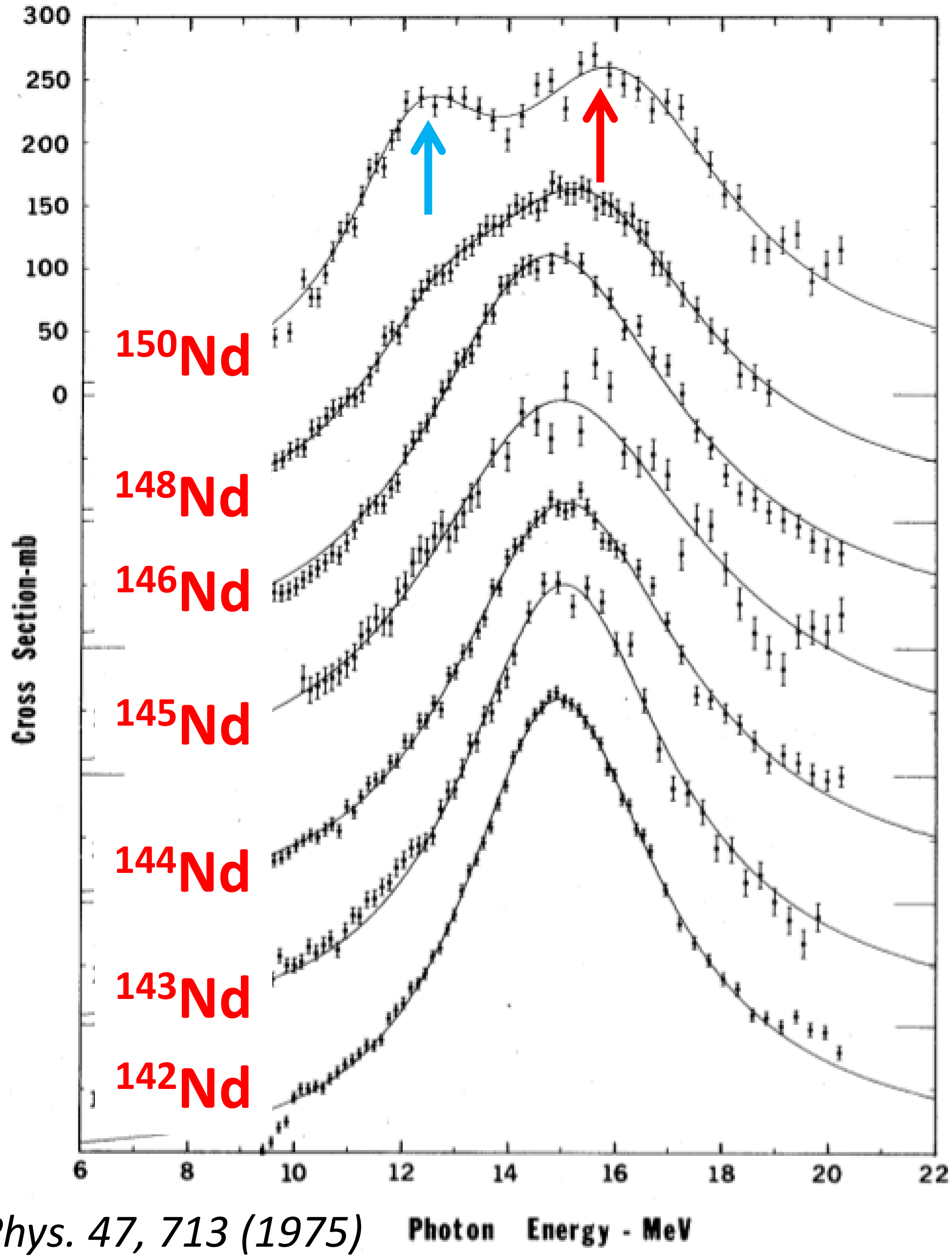
Photo-neutron cross-section in deformed nuclei:

Deformed Nucleus

$$R(\theta,\varphi)=R_0(1+\beta_2 Y_{20}(\theta,\varphi))$$

$$\beta_2\ (^{150}Nd) = 0.285(3)$$





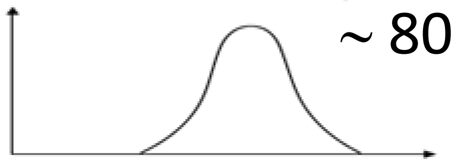
B. L. Berman and S. C. Fultz, Rev. Mod. Phys. 47, 713 (1975)

Isoscalar resonances in deformed nuclei

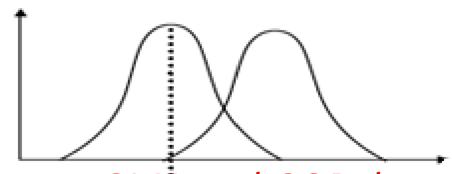
Spherical Nucleus

Prolately Deformed Nucleus

Monopole
$\Delta L = 0$

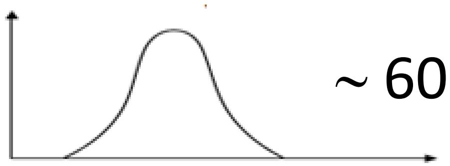


$\sim 80\ A^{-1/3}$ MeV

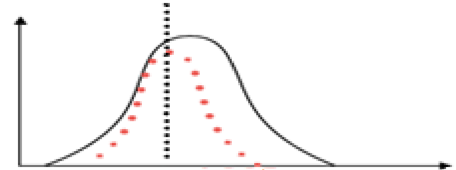


Coupling between GMR and GQR due to deformation

Quadrupole
$\Delta L = 2$



$\sim 60\ A^{-1/3}$ MeV



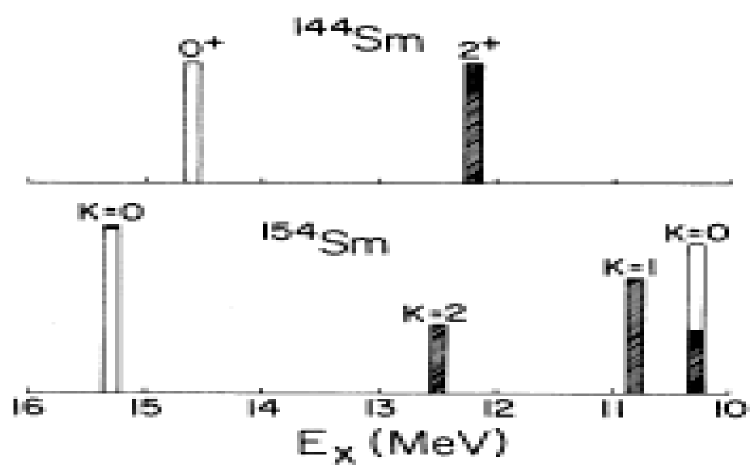
K = 0 component of GQR

Adapted from U. Garg

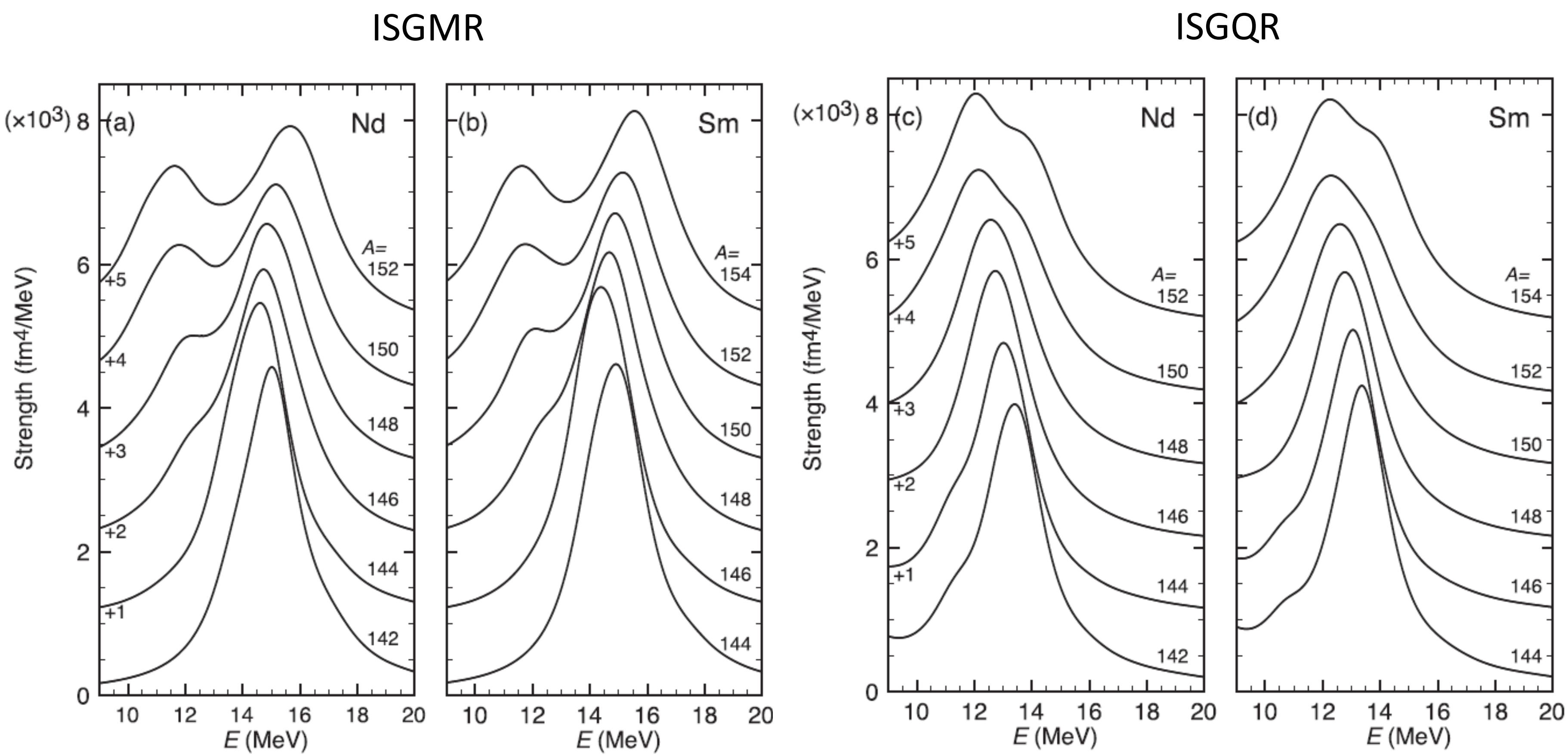
Spherical Nucleus ^{144}Sm, β_2 = 0.0881 (13)

Deformed Nucleus ^{154}Sm, β_2 = 0.339 (3)

Coupling between GMR and GQR due to deformation



Isoscalar resonances in deformed nuclei:

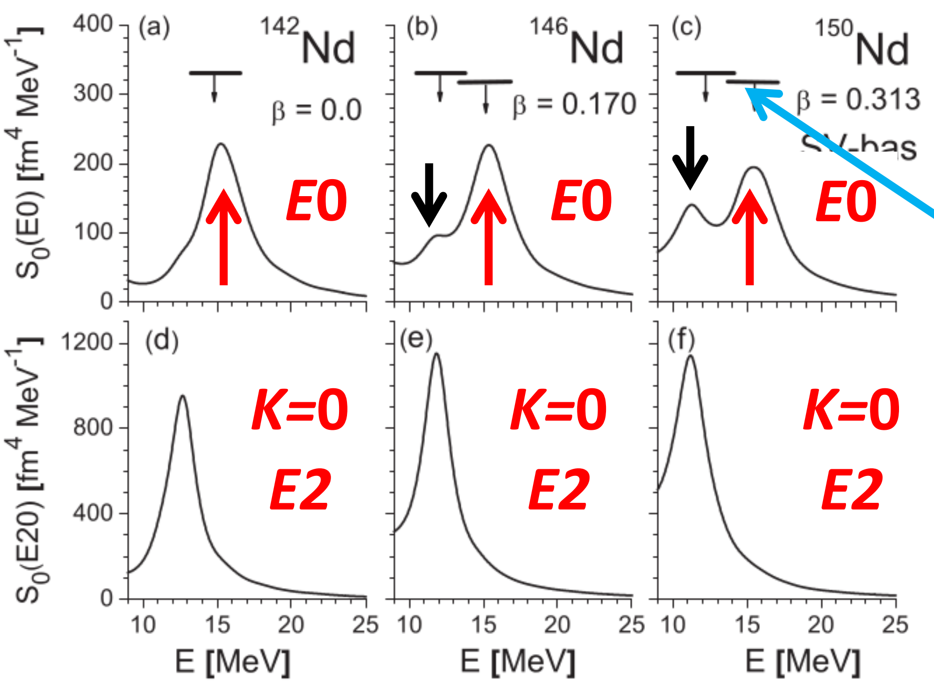


QRPA calculations with Skyrme energy-density functional   Yoshida and Nakatsukasa, PRC **88**, 034309 (2013)

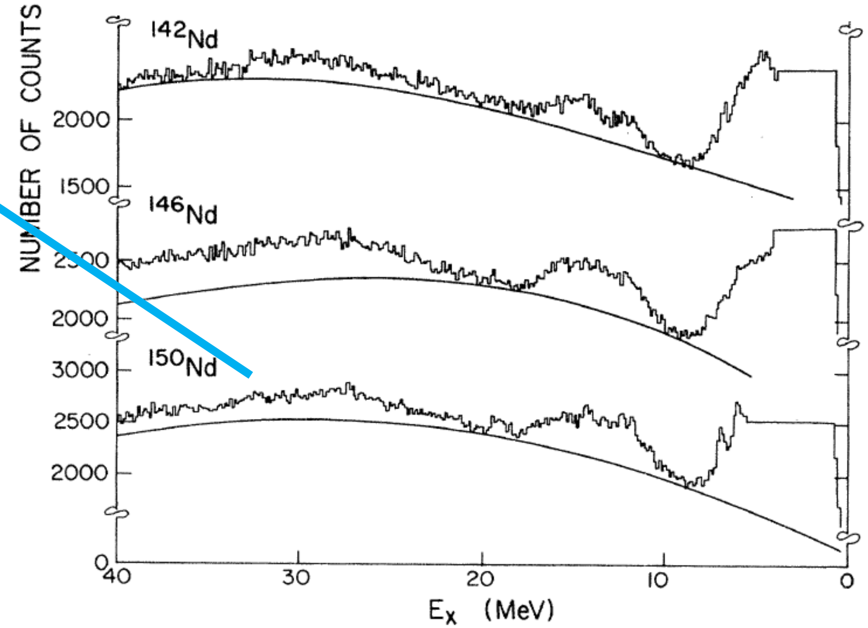
Isoscalar GR has been studied in Sm isotopes, ^{24}Mg, ^{28}Si, Mo isotopes.

See talks by A. Pastore, L. Usman

Effect of deformation on ISGMR strength in Nd isotopes



J. Kvasil et al., Phys. Rev. C 94, 064302 (2016)



TAMU data

Phys. Rev. C 29, 93 (1984).

- QRPA calculation: Position of the low-energy *E*0 peak matches with the position of the ISGQR (*K* = 0) peak suggesting the *E*0-*E*2 coupling
- TAMU data: Excitation energy spectra suffer from instrumental background as well as nuclear continuum; bombarding energy of α-beam 129 MeV
- At RCNP we can perform the experiment without instrumental background and much lower nuclear continuum background; bombarding energy of α-beam 400 MeV

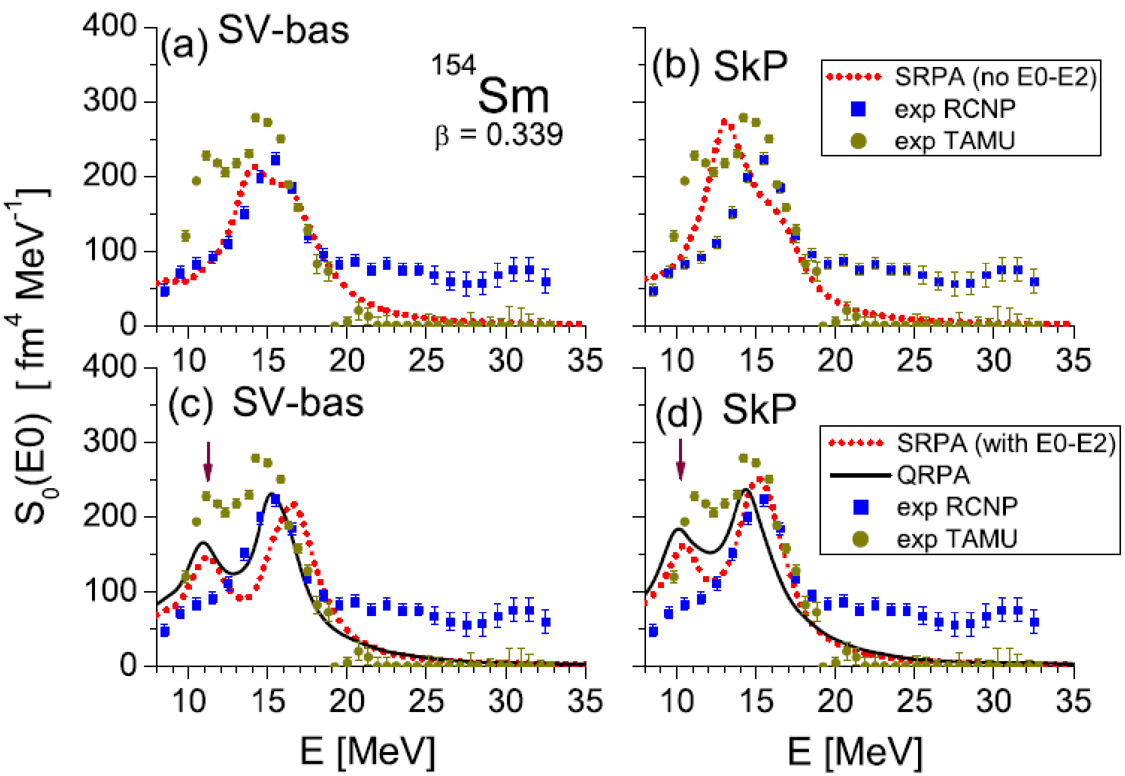
Discrepancy in ISGMR strength distribution in deformed ^{154}Sm

RCNP data

Phys. Rev. C 68, 064602 (2003)

TAMU data

Phys. Rev. C 69, 034315 (2004)



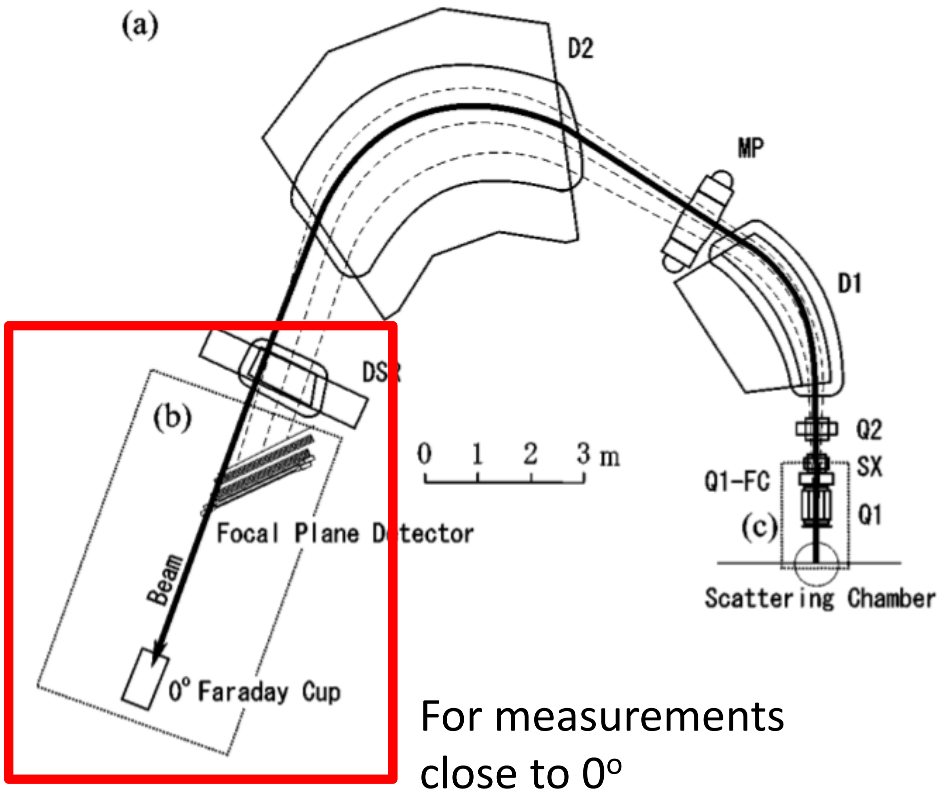
- EWSR of the low-energy ISGMR component to that of the high-energy ISGMR component is not consistent in these two different sets of data
- Discrepancy may be due to different bombarding energies of the beam

J. Kvasil et al., Phys. Rev. C 94, 064302 (2016)

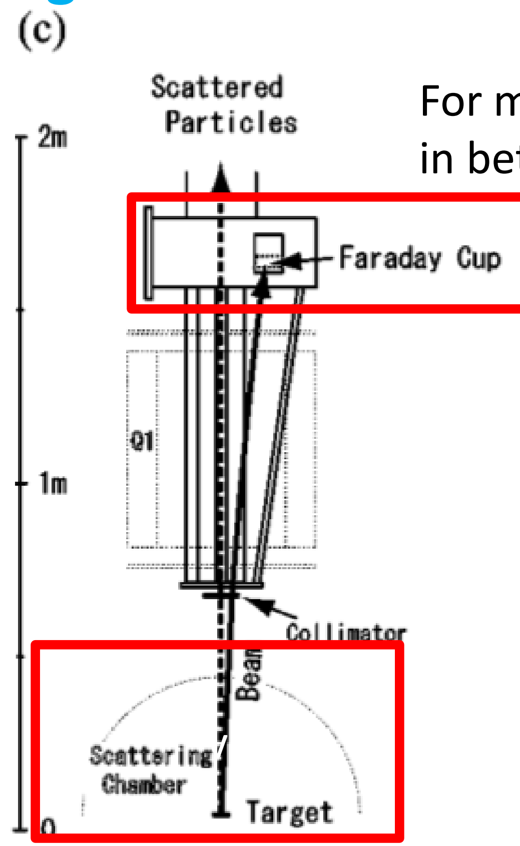
- Need investigation of another nucleus having strong deformation

Experimental Setup

Faraday cup positions for different angles measurements



For measurements close to 0°



For measurements in between 2°-6°

For > 6° measurements

Requirements:

- α-beam to be halo free
- Beam energy ~ 386 MeV
- Intensity ~ 10 nA

7 different angular settings of the spectrometer: 0°, 2.5°, 3.5°, 5°, 6.5°, 8°, and, 9.5°

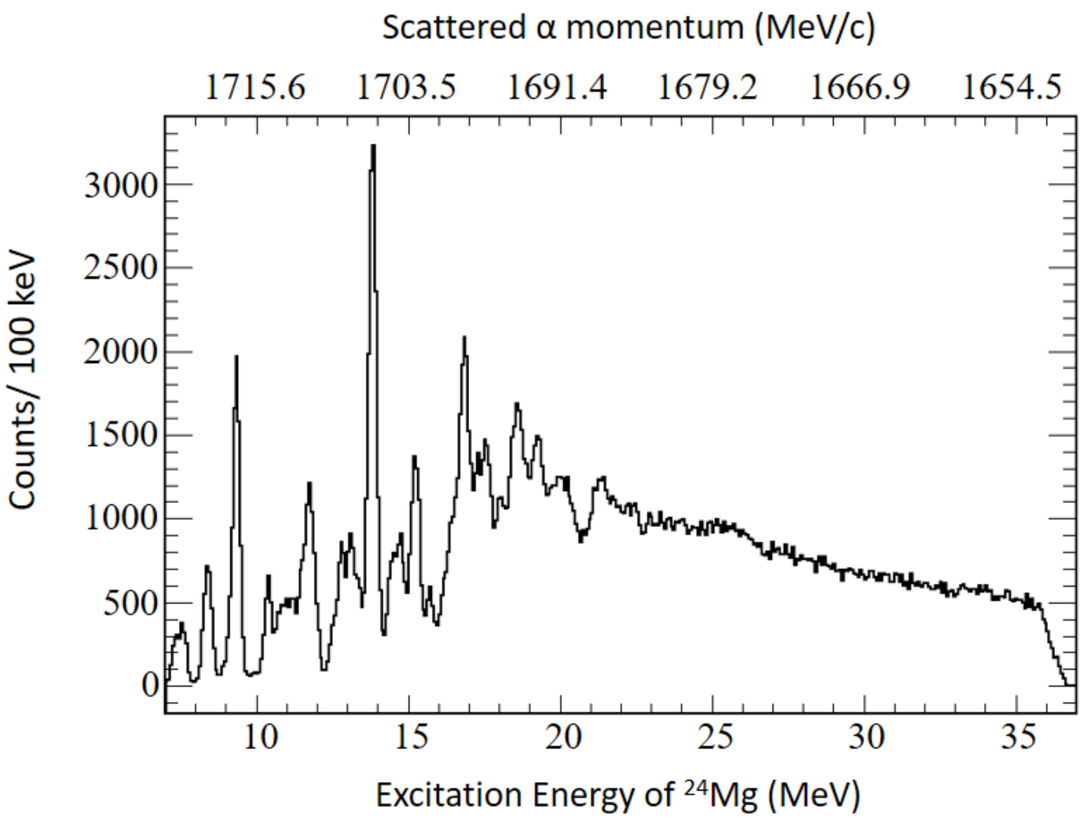
Research Center for Nuclear Physics: Grand Raiden Spectrometer

Coupled AVF and ring cyclotrons deliver 386 MeV α-particles

Enriched (> 95%) $^{142, 146, 148, 150}$Nd targets (~ 5 mg/cm^2)

Focal plane: position-sensitive MWDCs and plastic scintillators for momentum analysis and particle identification.

Calibration with ^{24}Mg (α,α')

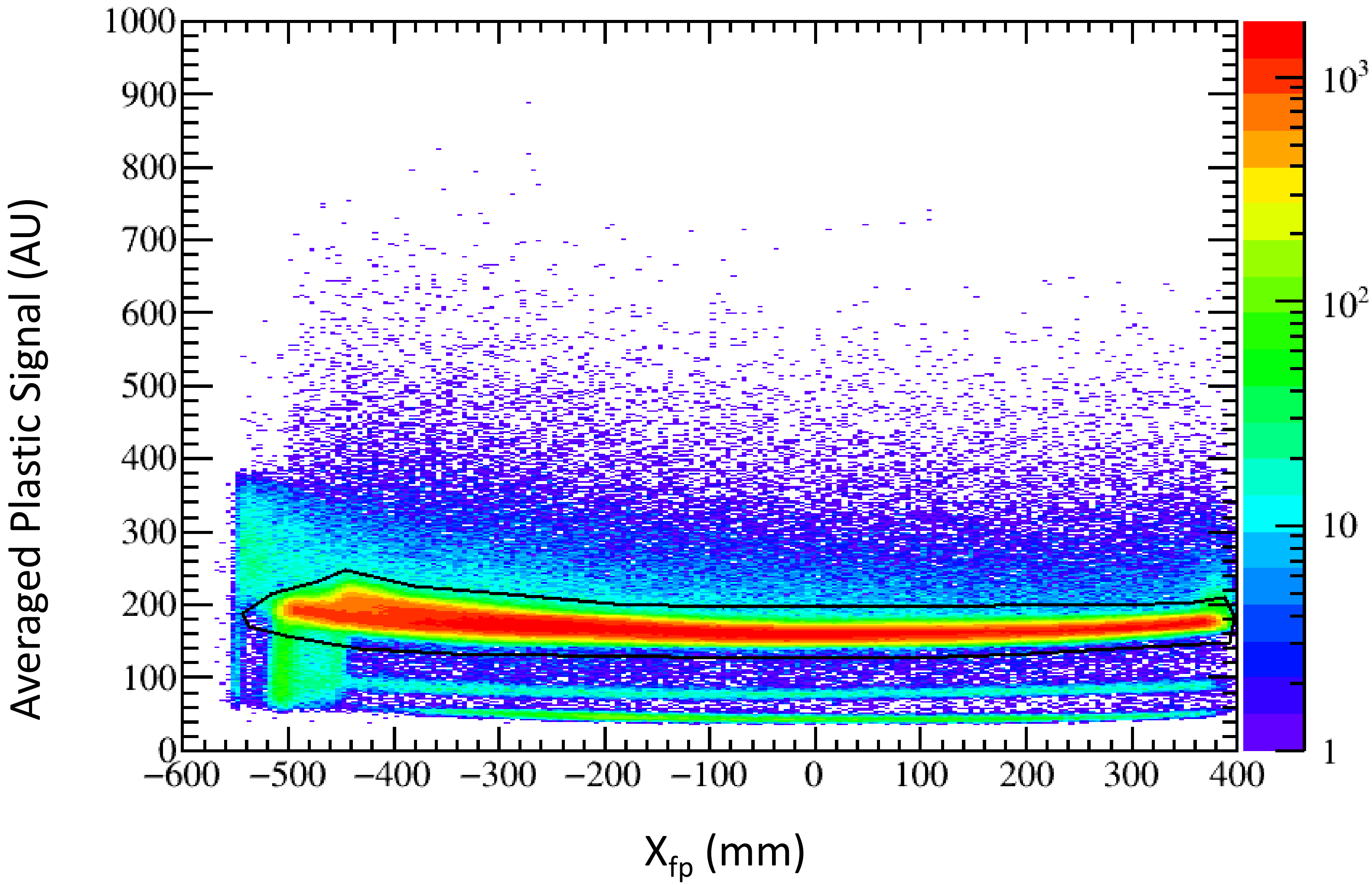


In ^{24}Mg, well-known low-lying discrete states

High-resolution reference spectra obtained from T. Kawabata

Calibration parameters were obtained using the kinematical relations between the incident particle, the target nucleus, and the scattered α particle.

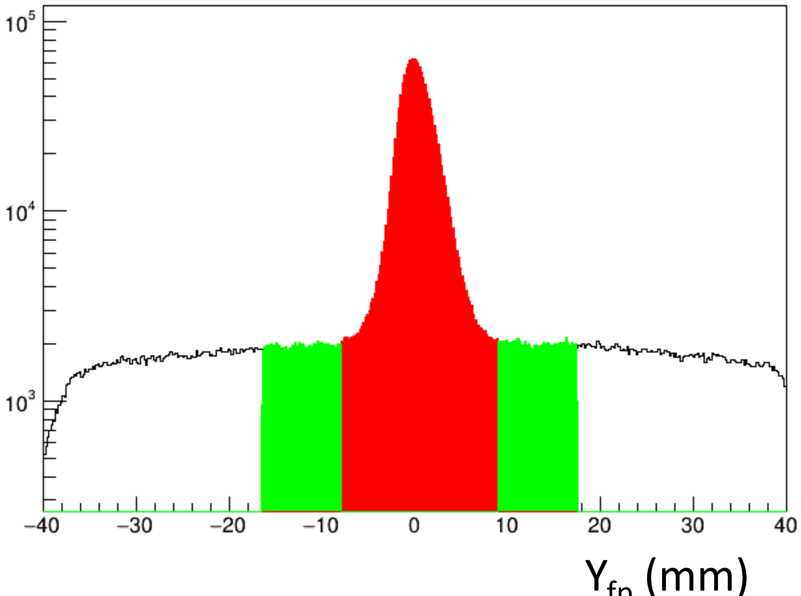
Particle Identification

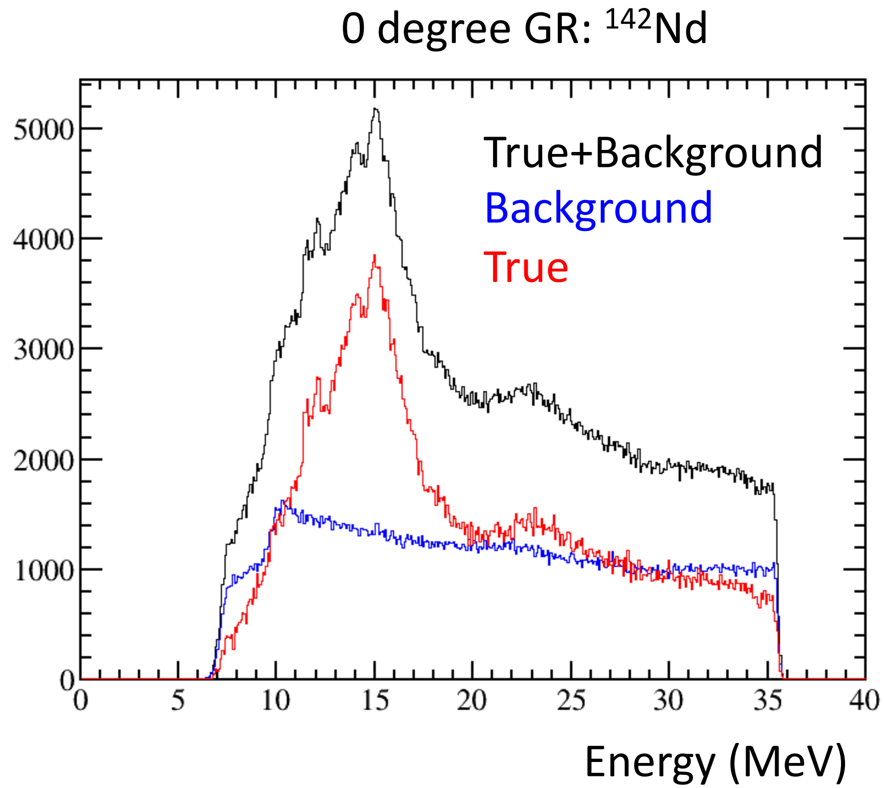


Pulse height from plastic scintillators mounted on the focal plane versus horizontal focal plane position obtained from MWDCs.

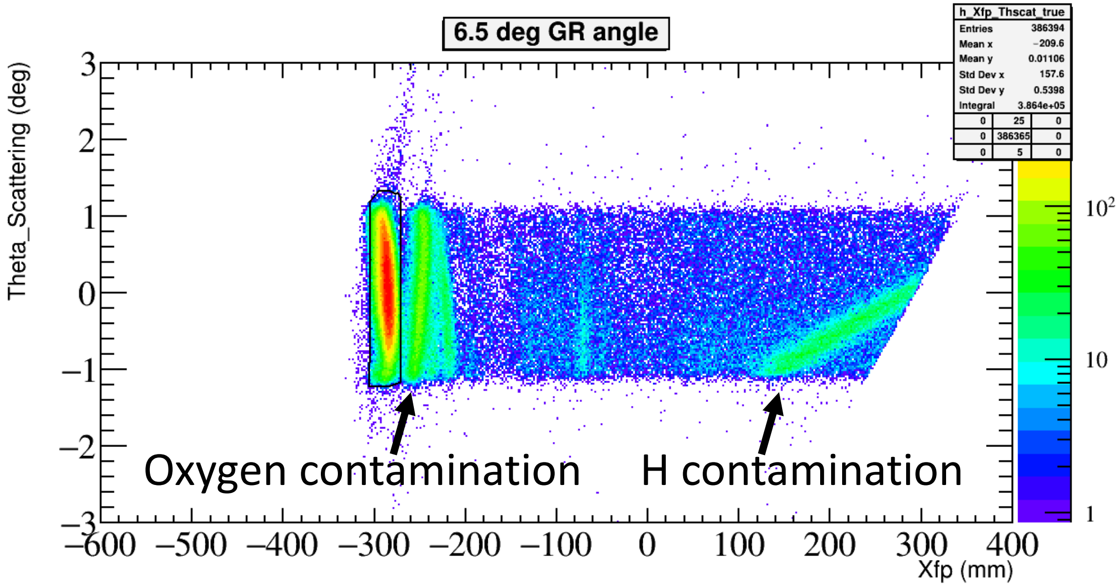
Instrumental Background

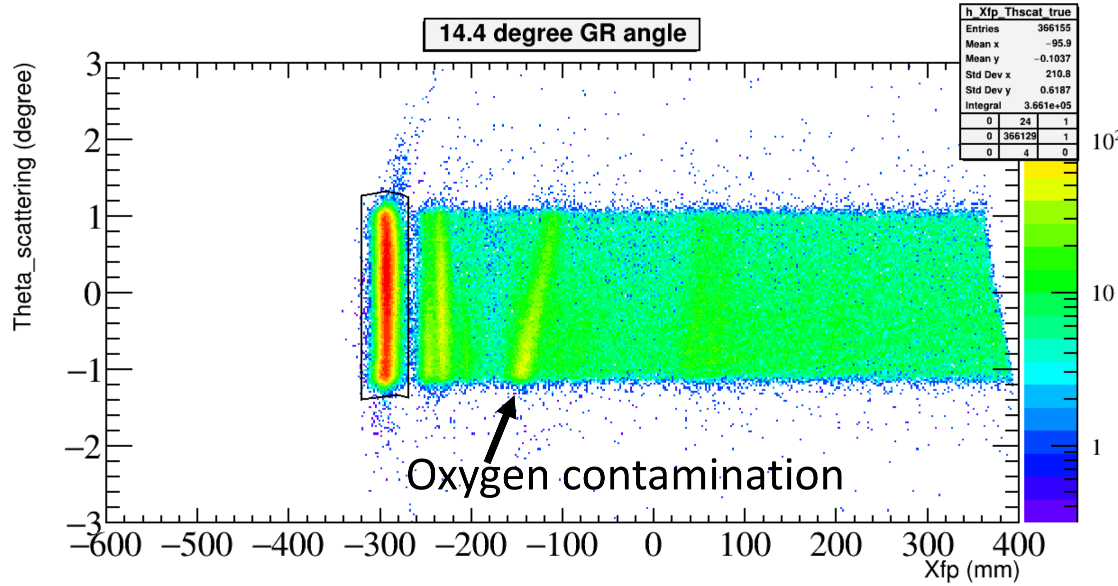
Double Focusing Mode of the Spectrometer





Elastic Scattering of α-particles with ^{142}Nd

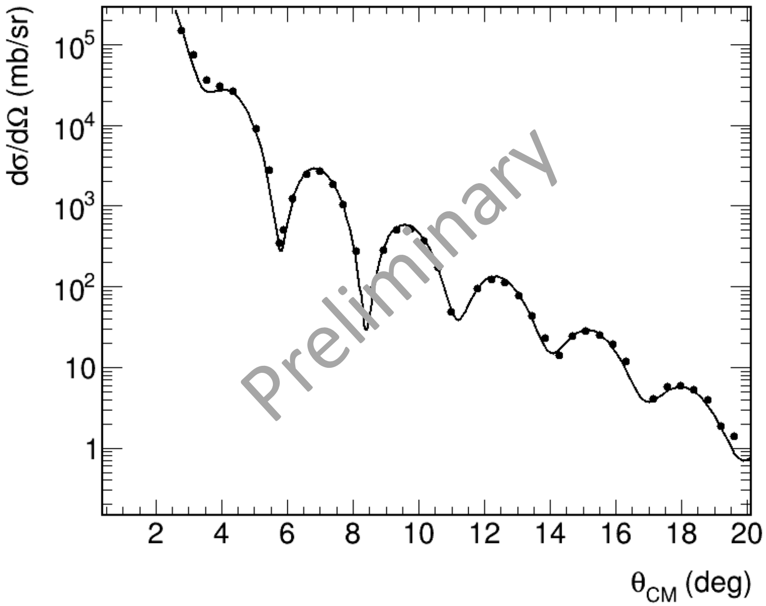




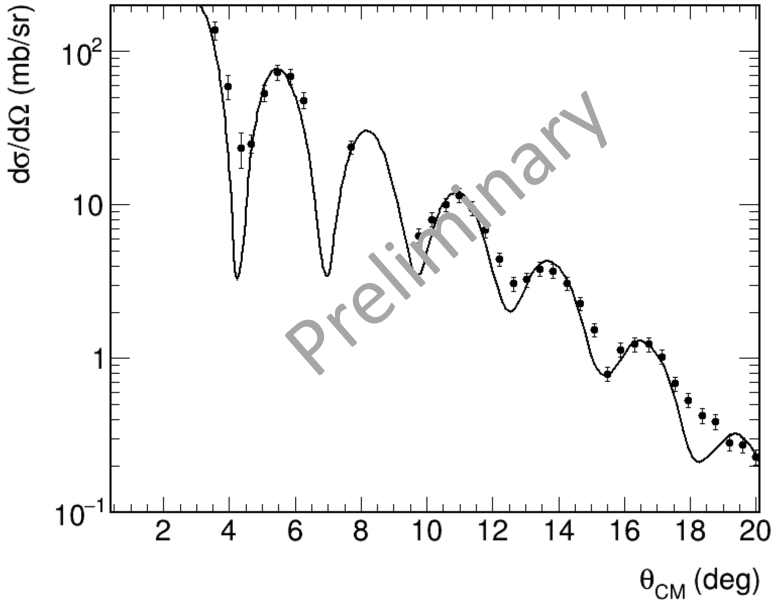
Optical Potential Parameters

Elastic α-scattering on ^{142}Nd

Fit to the elastic scattering data by chi^2 minimization



2^+ excitation energy of ^{142}Nd 1.576 MeV

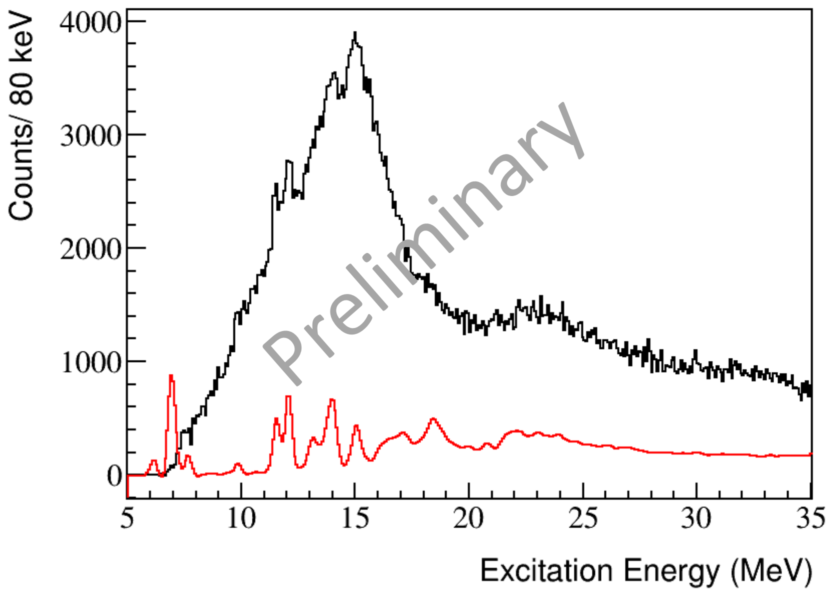


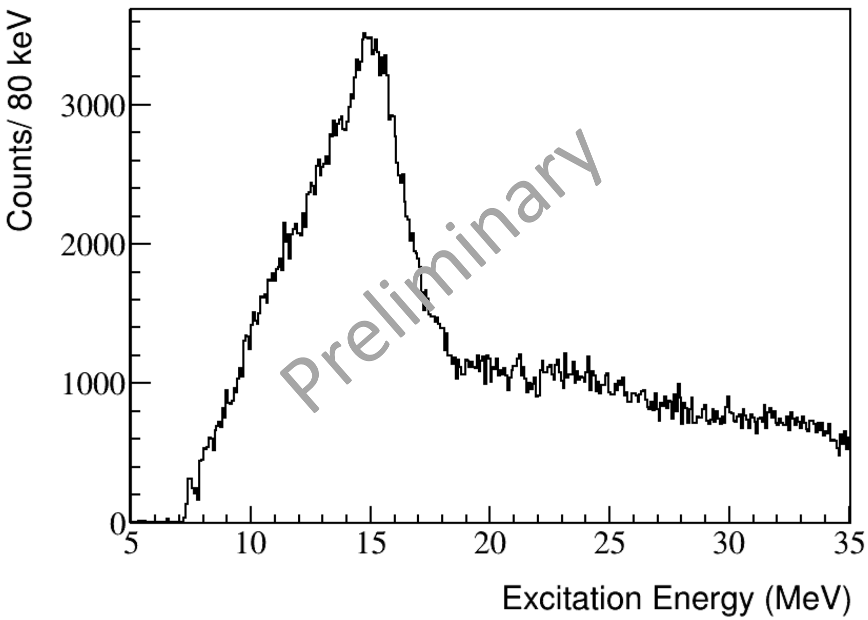
Woods-Saxon Potential

$$V(r) = -\frac{V_\circ}{1 + \exp(\frac{r-R}{a})}$$

- Low efficiency of drift chamber
- Oxygen contamination

Oxygen Contamination Subtraction





- Inelastic alpha scattering data off ^{16}O (SiO_2 target) from M. Itoh
- Beam energy is the same
- Oxygen spectrum is changed to the Nd kinematics
- Smeared to the experimental resolution
- Scaling of the spectrum done by taking the ratio of the corresponding peaks
- After scaling, the oxygen spectrum in Nd kinematics is subtracted from the Nd data

Strength distribution extraction: Multipole Decomposition Analysis

$$\frac{d^2\sigma^{exp}(\theta_{C.M.},E_x)}{d\Omega dE_x} = \sum_{\lambda} A_\lambda(E_x)\frac{d^2\sigma_\lambda^{DWBA}(\theta_{C.M.},E_x)}{d\Omega dE_x}$$

- Until L = 7 multipoles have been considered
- Optical parameters used from the elastic scattering data
- Coupled channel code (CHUCK3) was used to calculate the theoretical angular distribution at a particular energy
- IVGDR contribution has not yet been subtracted
- Energy bins used 400 keV

Summary

- Active target is an alternative to study the GMR of exotic nuclei using inelastic alpha particle scattering
- Fluffiness in some nuclei is still an open question. Need further data.
- Storage ring is another good approach to study the GMR for exotic nuclei
- Data analysis of Nd isotopes taken using the Grand Raiden Spectrometer is ongoing. Energy bins 400 keV show statistical fluctuations. 1 MeV energy bin would be better.
- IVGDR contribution has not yet been subtracted
- Data from another strongly deformed nucleus ^{172}Yb ($\beta_2 = 0.33$) was taken.

Maya Collaboration

S. Bagchi, J. Gibelin, M.N. Harakeh, N. Kalantar-Nayestanaki, N.L. Achouri, H. Akimune, B. Bastin, K. Boretzky, H. Bouzomita, M. Caamaño, L. Càceres, S. Damoy, F. Delaunay, B. Fernández-Domínguez, M. Fujiwara, U. Garg, G.F. Grinyer, O. Kamalou, E. Khan, A. Krasznahorkay, G. Lhoutellier, J.F. Libin, S. Lukyanov, K. Mazurek, M.A. Najafi, J. Pancin, Y. Penionzhkevich, L. Perrot, R. Raabe, C. Rigollet, T. Roger, S. Sambi, H. Savajols, M. Senoville, C. Stodel, L. Suen, J.C. Thomas, M. Vandebrouck, J. Van de Walle

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lpc caen

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JINR – JOINT INSTITUTE FOR NUCLEAR RESEARCH

GANIL – GRAND ACCELERATEUR NATIONAL D'IONS LOURDS – LABORATOIRE COMMUN DSM/CEA-IN2P3/CNRS

USC – UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

IPN – INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

MTA atomki DEBRECEN

GSI

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