MAGNEX: studying exotic nuclei and isospin with FRIBs and stable beams

Clementina Agodi on the behalf of DREAMS collaboration

HIB@LNS 14-15 dicembre 2015

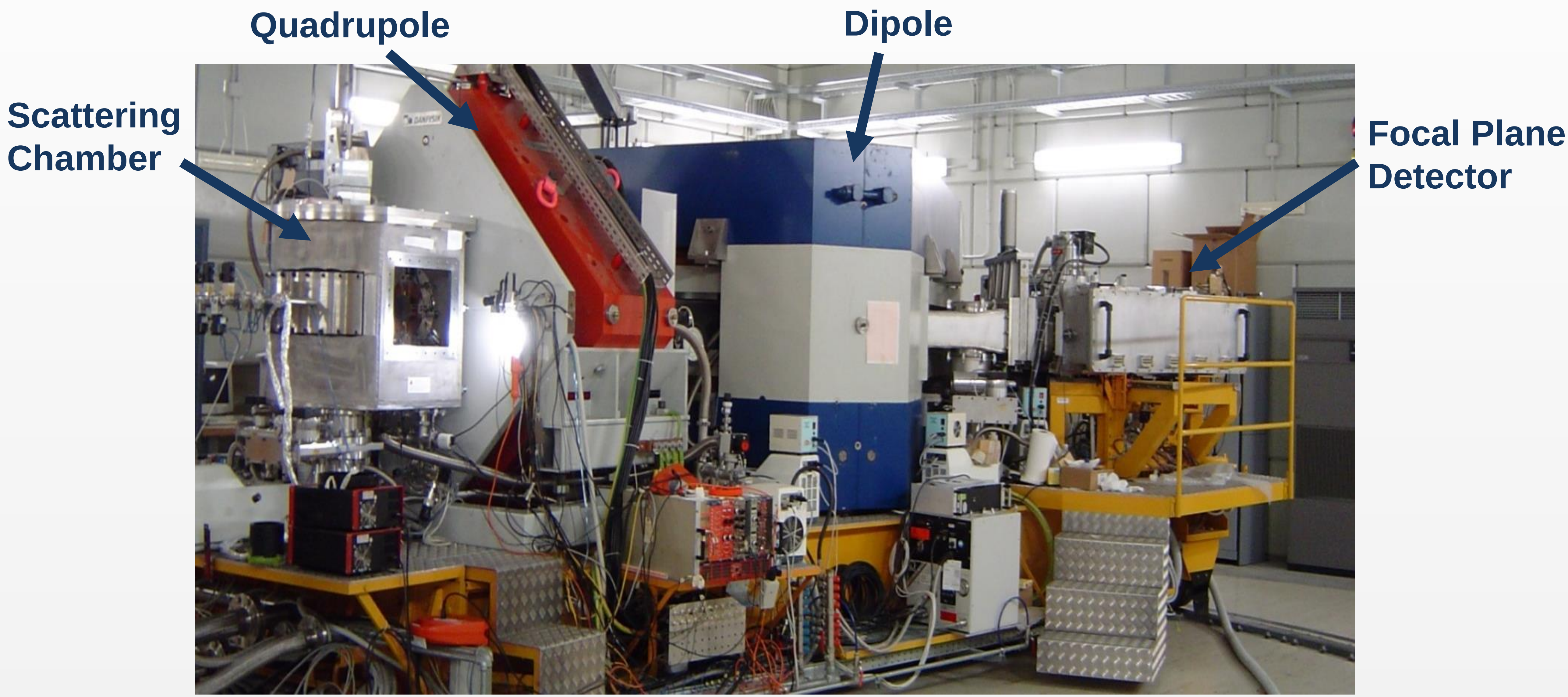
- Introduction
- Experimental Set-Up
- Experimental approaches to nuclear spin- isospin responses
- Outlook

LNS
INFN Istituto Nazionale di Fisica Nucleare

MAGNEX : magnetic spectrometer @ LNS

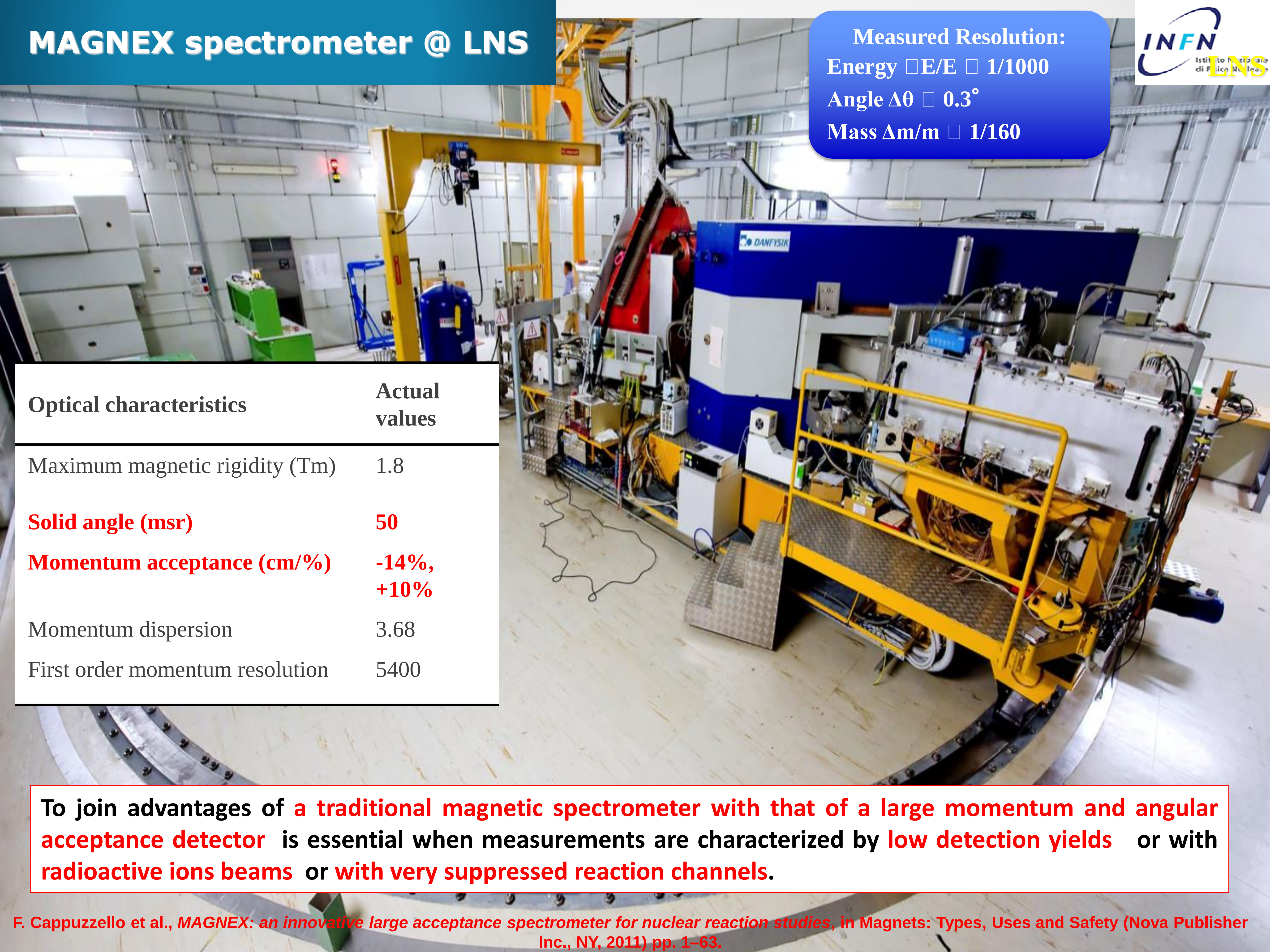
MAGNEX consists of two magnetic elements:

- **The Quadrupole: vertically focusing (Aperture radius 20 cm, effective length 58 cm. Maximum field strength 5 T/m)**
- **The Dipole: momentum dispersion and horizontal focus (Mean bend angle 55°, radius 1.60 m. Maximum field ~ 1.15 T)**



It was designed to study different processes, characterized by **very low yields**, in **different nuclear physics fields,** from nuclear structure to characterization of reaction mechanisms in a large energy and mass range.
The high-order aberrations originated by the large acceptance are calculated and **corrected by means** of a software ray-reconstruction **based on differential algebric methods.**

MAGNEX spectrometer @ LNS



Measured Resolution:
Energy □E/E □ 1/1000
Angle $\Delta\theta$ □ 0.3°
Mass $\Delta m/m$ □ 1/160

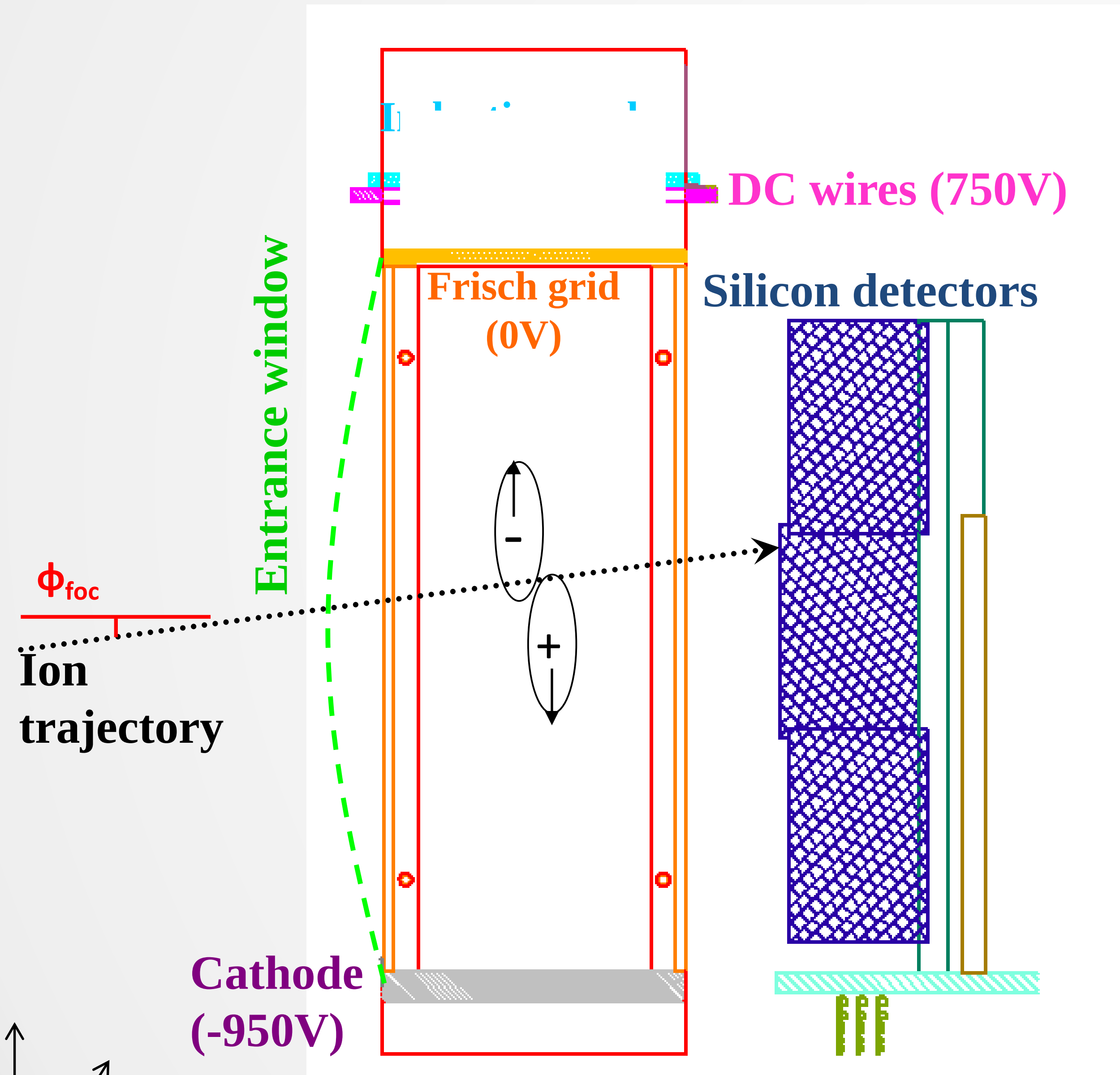
Optical characteristics	Actual values
Maximum magnetic rigidity (Tm)	1.8
Solid angle (msr)	**50**
Momentum acceptance (cm/%)	**-14%, +10%**
Momentum dispersion	3.68
First order momentum resolution	5400

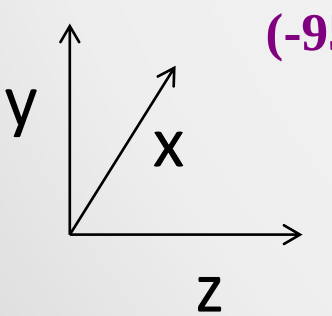
To join advantages of a traditional magnetic spectrometer with that of a large momentum and angular acceptance detector is essential when measurements are characterized by low detection yields or with radioactive ions beams or with very suppressed reaction channels.

F. Cappuzzello et al., *MAGNEX: an innovative large acceptance spectrometer for nuclear reaction studies*, in Magnets: Types, Uses and Safety (Nova Publisher Inc., NY, 2011) pp. 1–63.

MAGNEX Focal Plane Detector

The reaction ejectiles, momentum-analyzed by MAGNEX, are detected by the **Focal Plane Detector (FPD)**: a **gas drift chamber** divided in five sections, each one working also as proportional counter and four of which being position-sensitive. A wall of **60 stopping silicon pad detectors** is located at the back of the gas section.



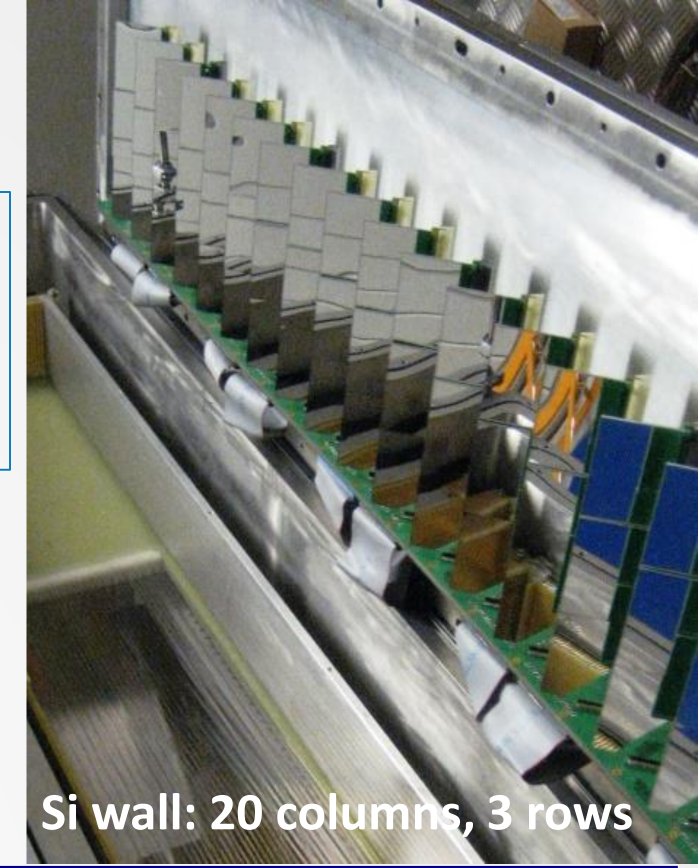


Section view

- Gas-filled hybrid detector

Drift chamber 1400mm x200mmx100mm

Pure isobutane pressure range: 5-100mbar; 600-800 Volt,wires 20 micron



60 Silicon Detectors
→ E_{res}

5 Proportional Wires
→ ΔE

4 Induction Strip
→ X_1, X_2, X_3, X_4
→ X_{foc}, θ_{foc}

4 Drift Chamber (DC)
→ Y_1, Y_2, Y_3, Y_4
→ Y_{foc}, Φ_{foc}

Ion identification

Ray-reconstruction

•*C.Boiano et al., IEEE 55 (2008) 3563*

•*M.Cavallaro et al. EPJ A 48: 59 (2012)*

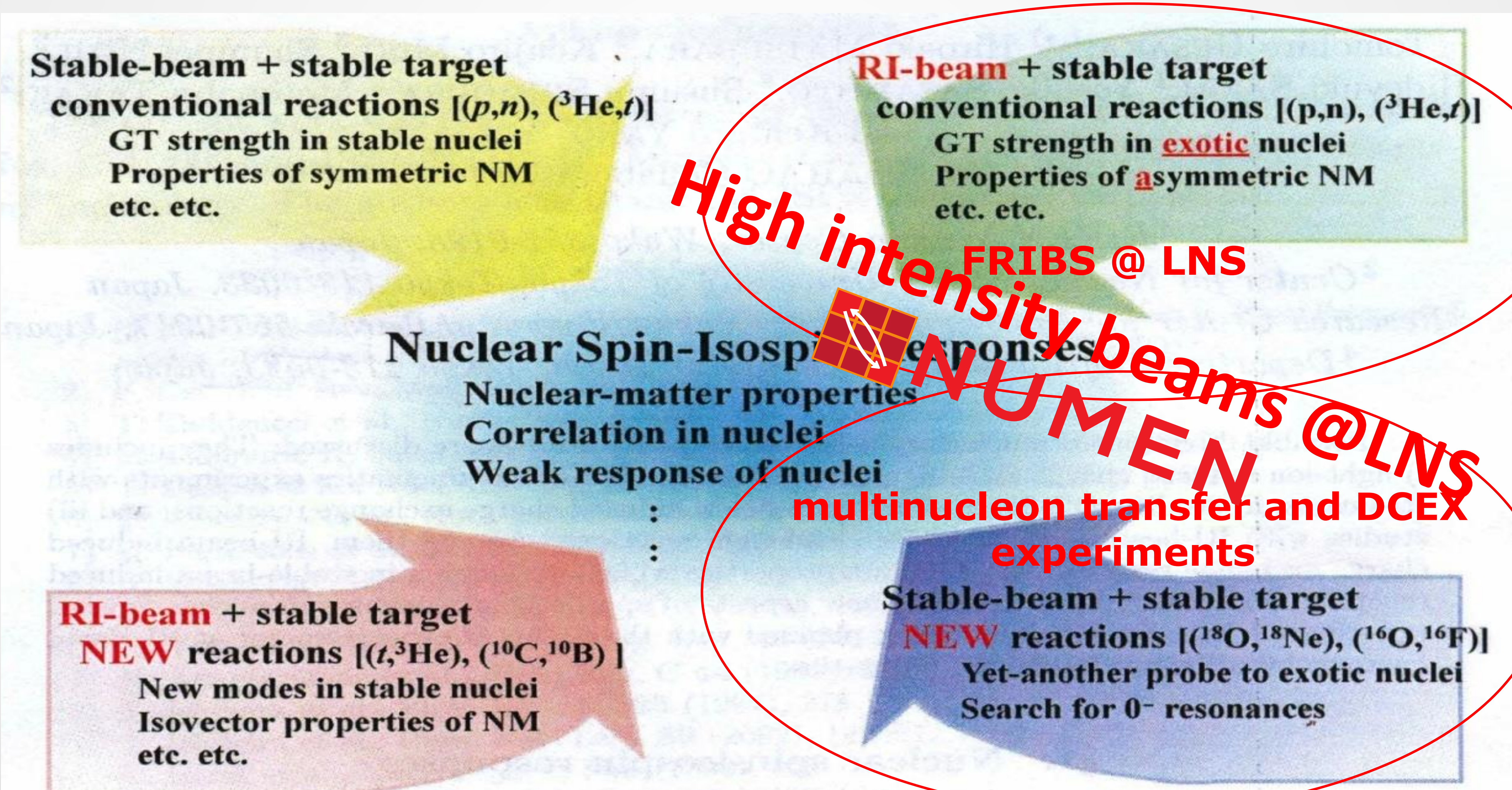
•*D.Carbone et al. EPJ A 48: 60 (2012)*

Some experimental approaches to nuclear spin- isospin responses

Experimental approaches to nuclear spin- isospin responses

Study of spin-isospin responses in nuclei forms one of core items in nuclear physics.
Since 1990s RI-beams → physics of unstable nuclei, which would shed new light on the spin-isospin studies.

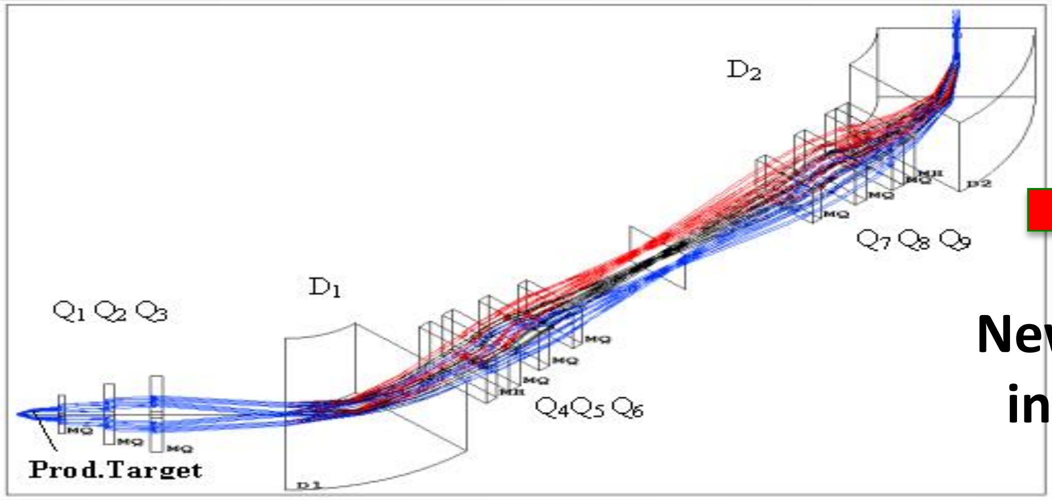
Experimentally, possible extensions from the traditional light ion studies are considered :



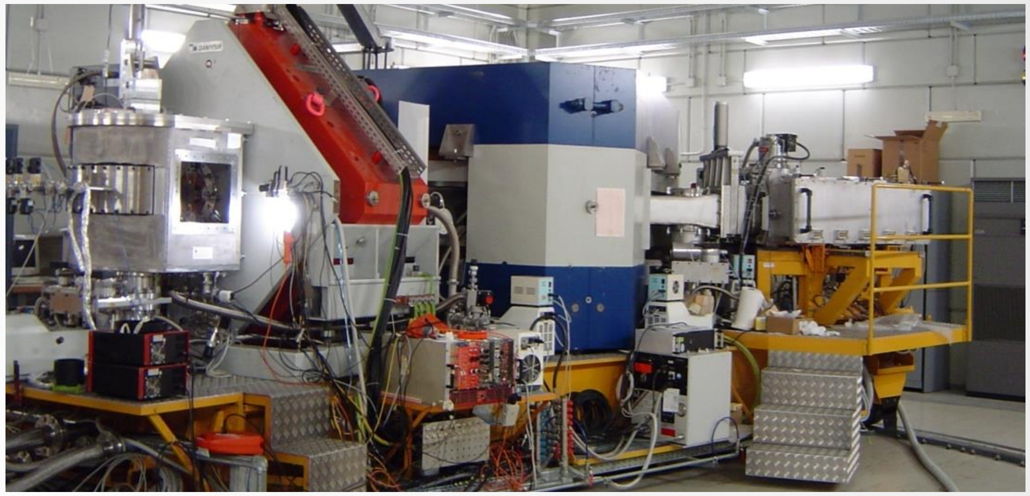
Tomohiro Uesaka et. al. Progress of Theoretical Physics Supplement No. 196, 2012

RI beam + stable target: the idea…

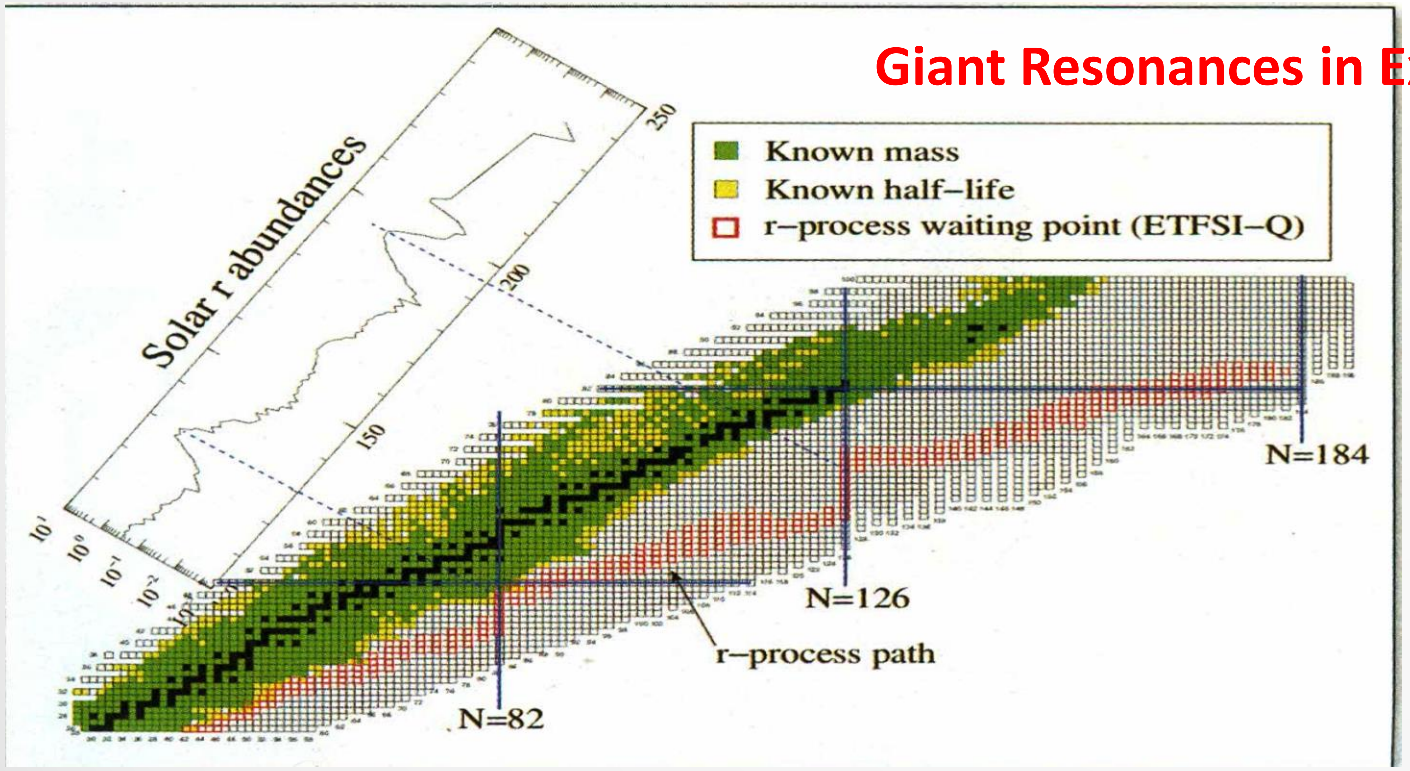
FRIBS & MAGNEX

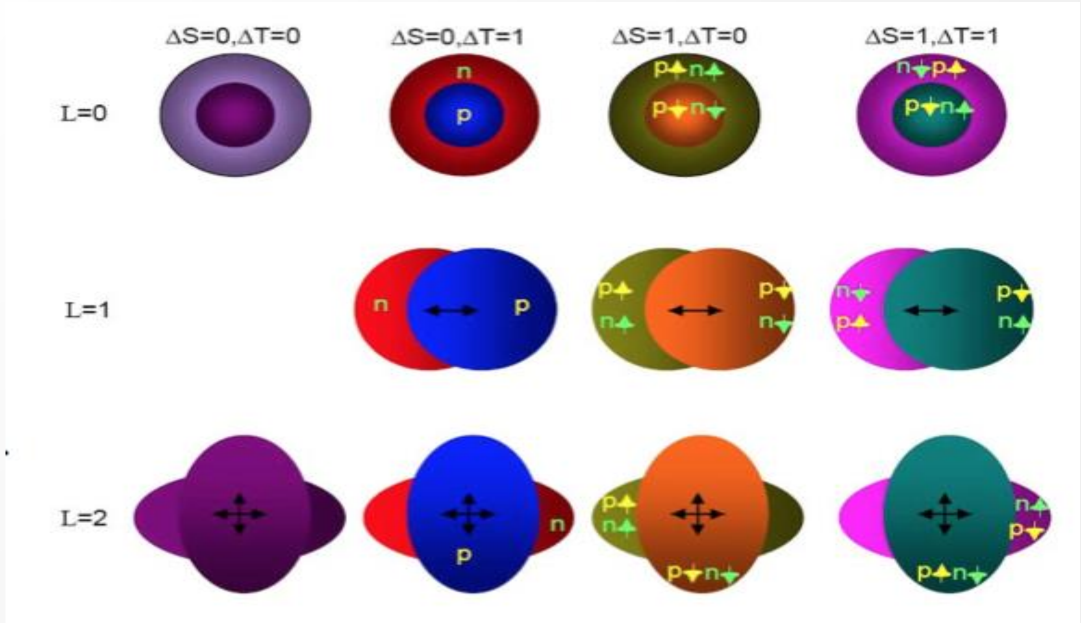


New opportunities to study interesting physics cases.



Giant Resonances in Exotic Nuclei

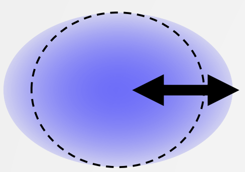




Measure the Isoscalar Giant Monopole Resonance in exotic nuclei

Physics motivations

Constrain the Nuclear Matter Equation of State



ISGMR ⟷ Nuclear incompressibility

J.P. Blaizot, Phys. Rep. 64, 171 (1980)

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

$$K_A = K_\infty + K_{surf}A^{-1/3} + K_\tau\delta^2 + K_{Coul}\frac{Z^2}{A^{4/3}}$$

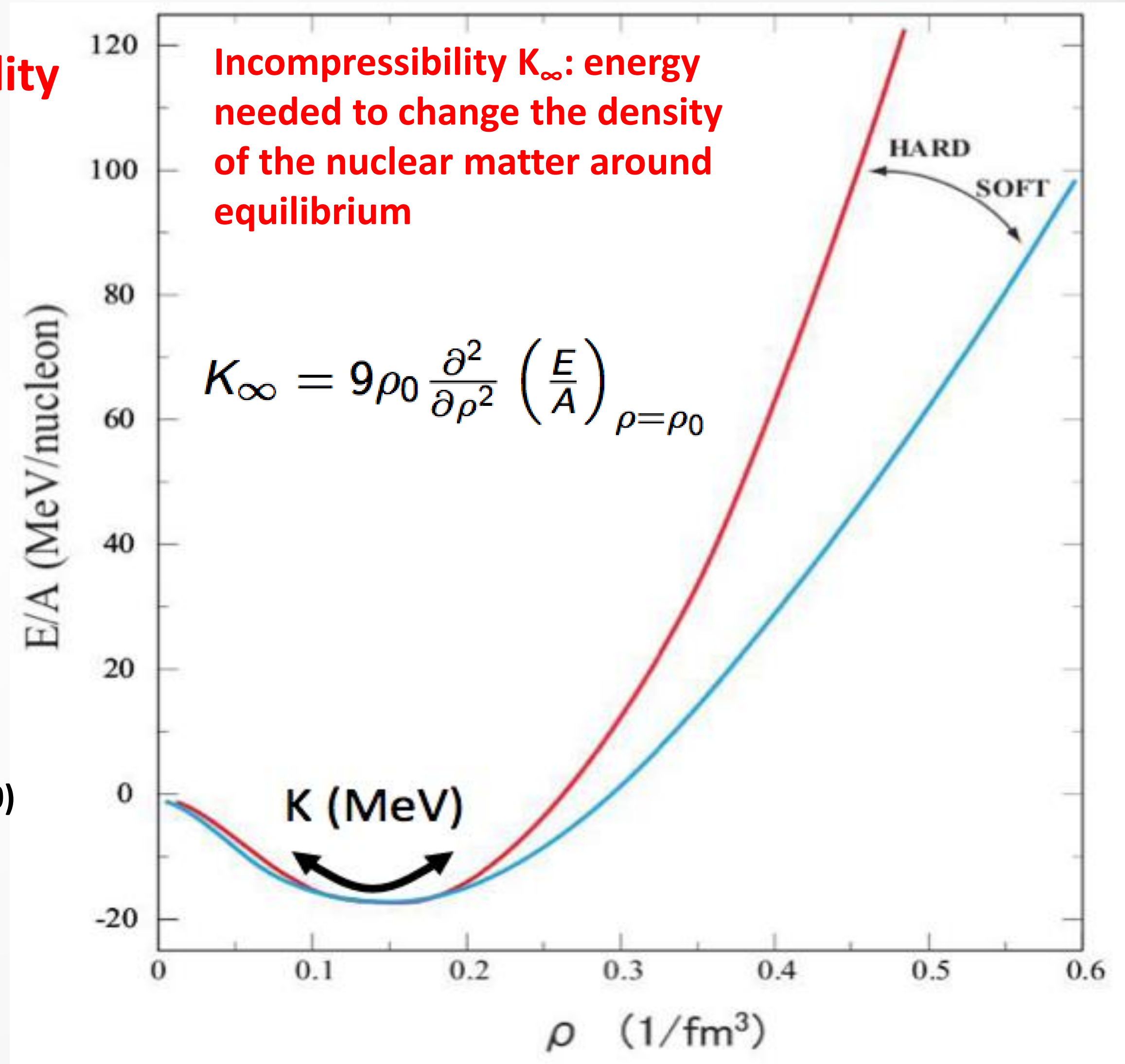
Nucleus (mass A) — *Nuclear Matter* — *Isospin Dependence*

K_τ= -550 ± 100 MeV

T. Li, U. Garg et al., Phys. Rev. C 81, 034309 (2010)

K_∞= 240 ± 10 MeV

J. Li, G. Colò and J. Meng, Phys. Rev. C 78, 064304 (2008)



Part of this uncertainty is due to our poor knowledge of the Isospin dependence K_τ

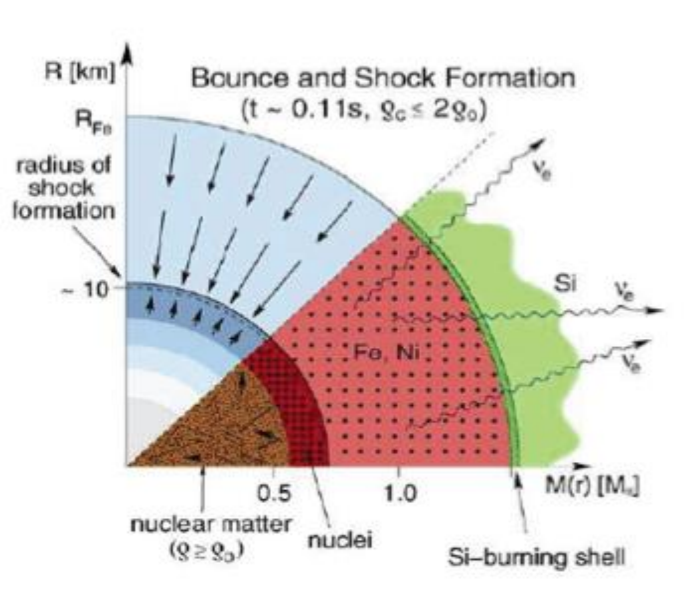
Measuring the GMR in exotic nuclei will open the possibility to study the isospin dependence of the incompressibility

Physics Motivation

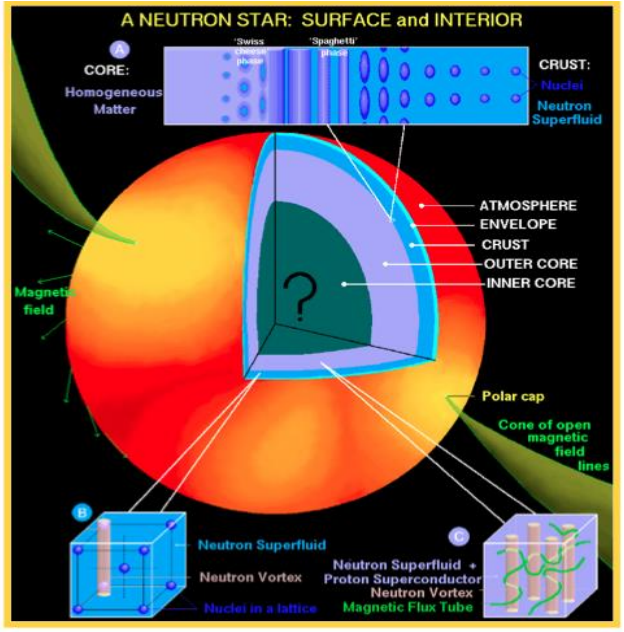
Determine the Incompressibility of Asymmetric nuclear matter

Impact on Astrophysical systems: **behavior of neutron- rich matter, whose equation of state (EOS)** is essential for the **understanding of complex astrophysical objects such as core-collapse supernovae and neutron stars.**

Supernovae

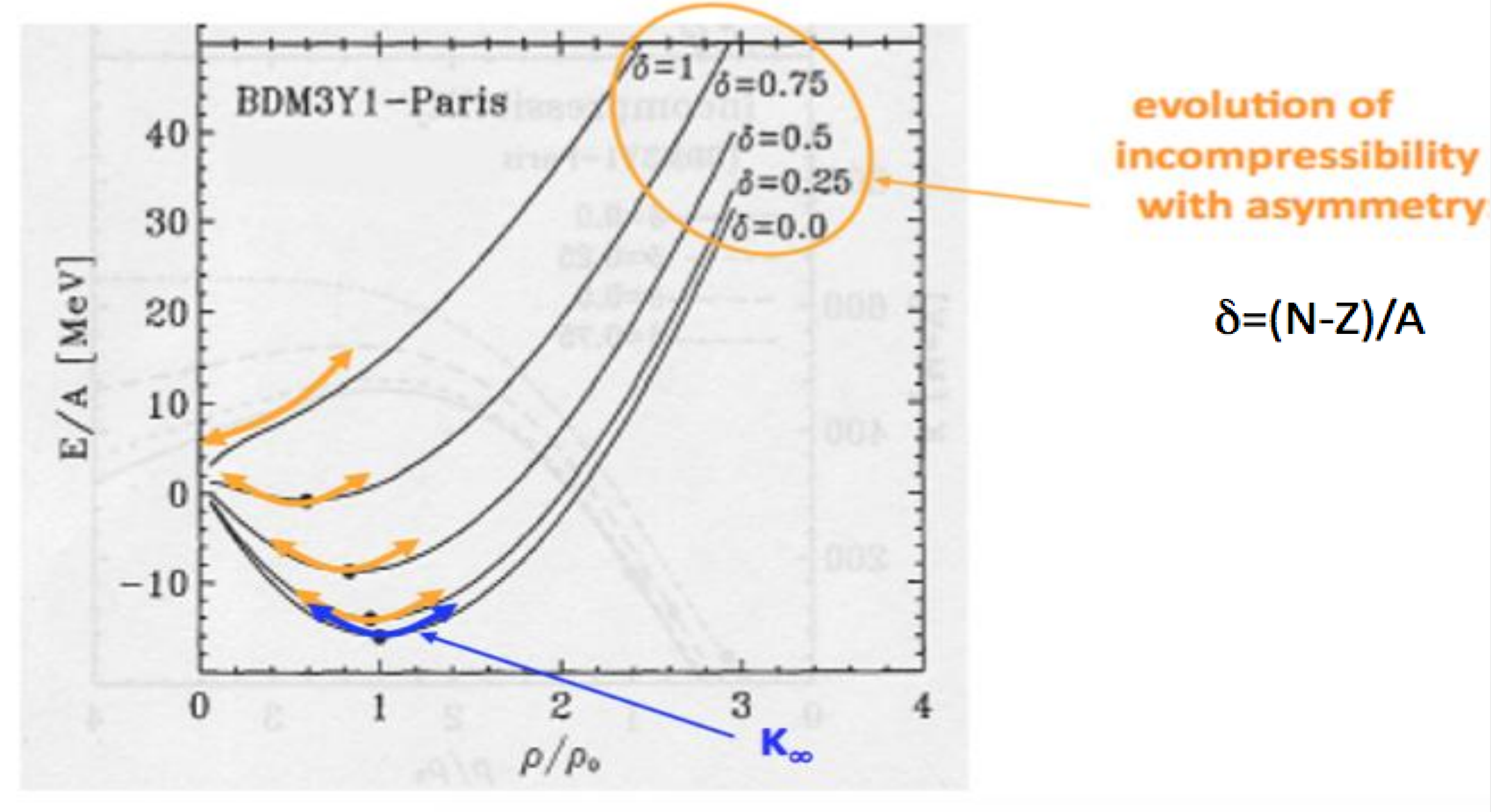


Neutron stars



J. Piekarewicz Physical Review C 91,014303 (2015)

$$E(\rho,\delta) = E(\rho,0) + a_{sym}(\rho)\delta^2$$



δ=(N-Z)/A

D.T.Khoa et al., Nucl. Phys. A602 (1996) 98

Experimental Tool

Inelastic scattering of light isoscalar probes (d,^{4}He,^{6}Li)

The GMR measurement in unstable nuclei remains a major experimental challange

☹ Low beam intensity

↓

Thick target

Experimental challange!

☹ Inverse kinematics (^{2}H,^{4}He,^{6}Li targets)

↓

Low recoil energies for the light probes

↙ ↘

Thin target | Low detection thresholds

Exotic Nuclei

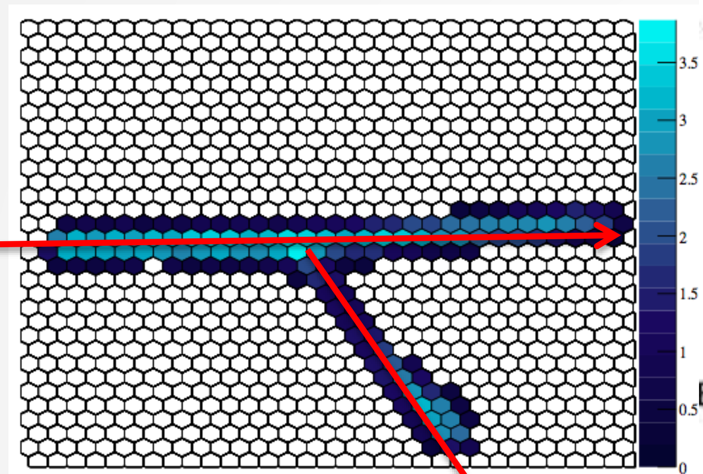
GANIL results I

1st measurement of the ISGMR and ISGQR in unstable nuclei ^{56}Ni :
$^{56}Ni(d,d')^{56}Ni^*$

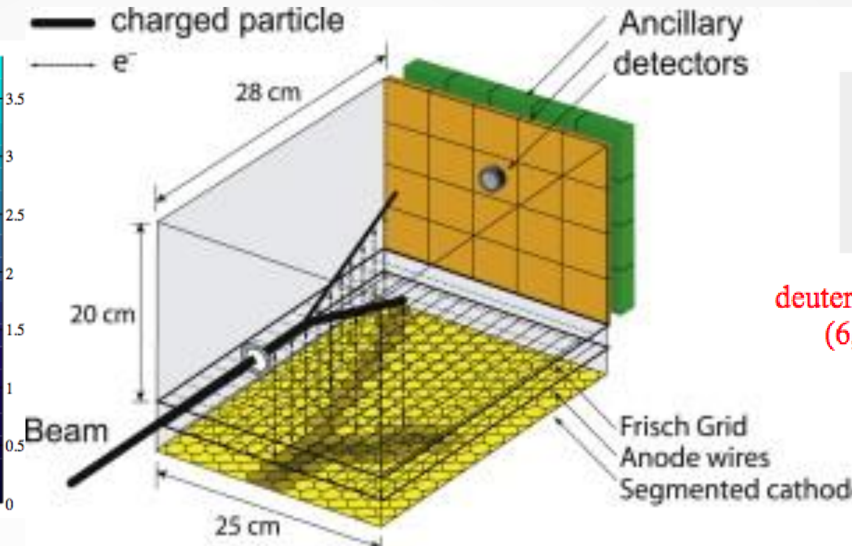
C. Monrozeau et al., Phys. Rev. Lett. 100, 042501 (2008)

Inelastic scattering in inverse kinematics: $^{56}Ni + d \to d' + ^{56}Ni^*$ with active target MAYA

^{56}Ni @ 50 AMeV
$5*10^4$ pps



scattered *d*



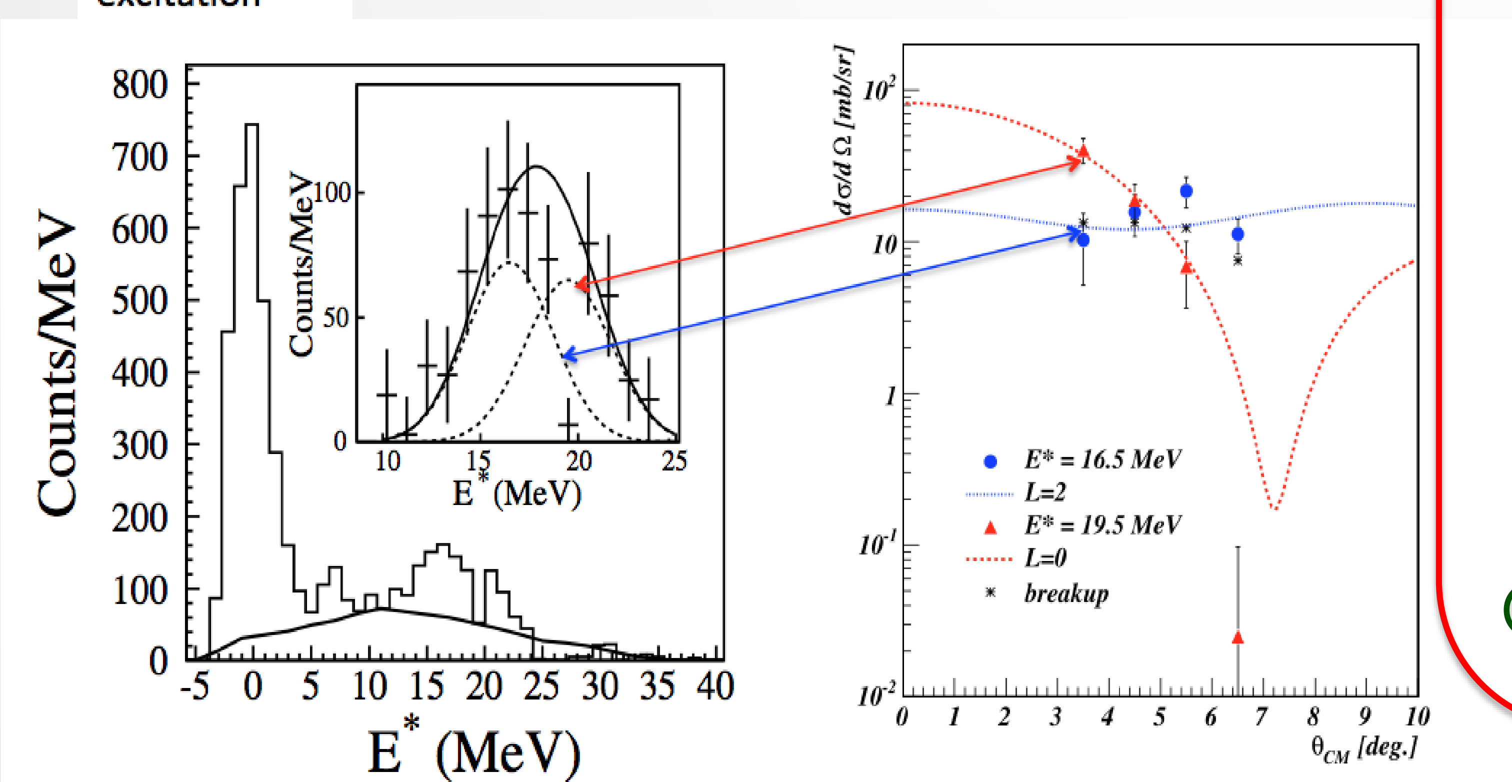
Active target
=
target + detector

deuterium gas : 1,6 mg/cm²
(6,3 mg/cm² CD2)

Time and Charge Projection Chamber

Range et θ
↓
E_{deuton}
↓
Energy excitation

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



Limits of the technique

Deuteron energy from its range and θ

☹ **Energy resolution**

Shielding of the beam = acceptance cut

☹ **Impossibility to measure at 0°**

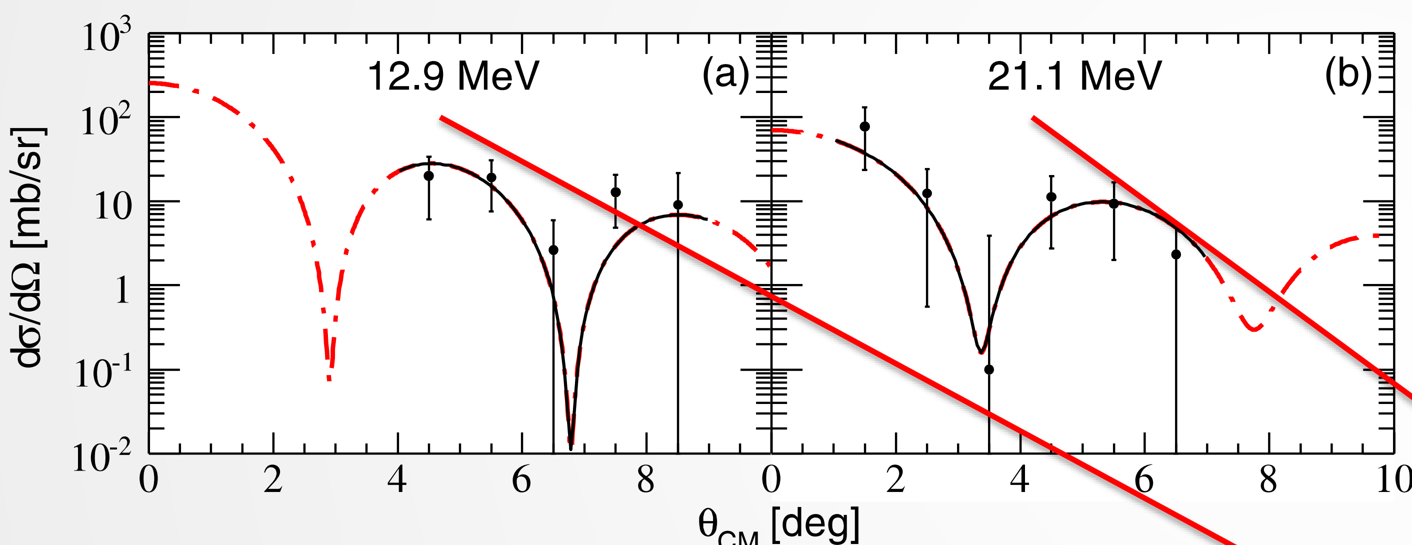
GANIL results II

2ndmeasurement of the Isoscalar Monopole Response in the Neutron-Rich Nucleus : ^{68}Ni@ 50 AMeV at GANIL with active target MAYA. *M.Vandebrouck et al. PRL 113,032504 (2014)*

The **isoscalar monopole response** has been measured in the unstable nucleus **68Ni using inelastic alpha scattering at 50A MeV in inverse kinematics** with the active target MAYA at GANIL.

^{68}Ni(α,α')^{68}Ni*

Angular distribution

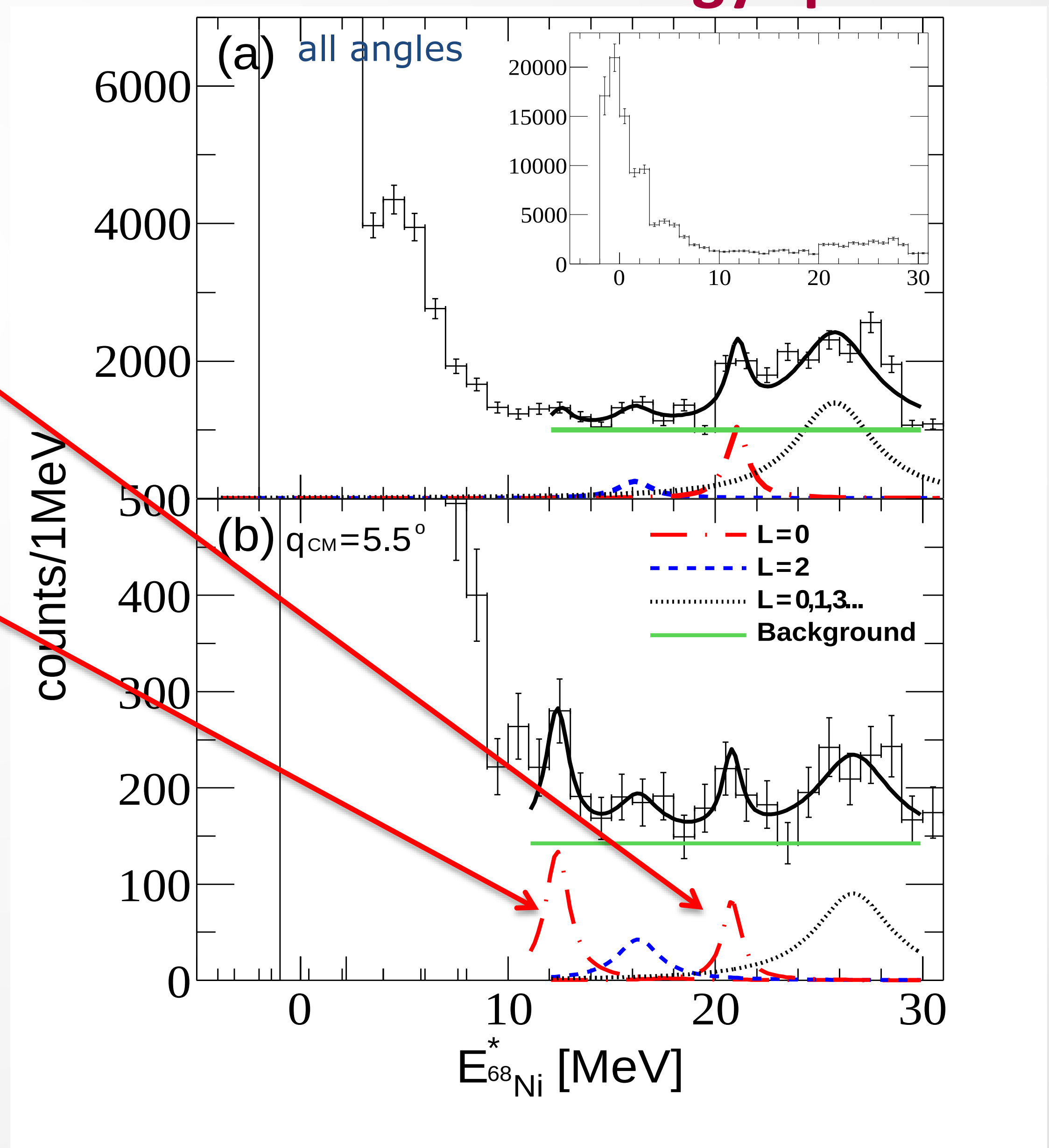


The black solid line corresponds to the fit based on DWBA calculation using microscopic RPA predictions with isoscalar L =0 multipolarity.

Theses predictions are represented in red dot-dashed line.

The angular distributions of the Lorentzians at 12.9 and 21.1 MeV are displayed in Figs. 3(a) and 3(b), and are well reproduced by DWBA calculations assuming an L = 0 multipolarity. Nevertheless, as the angular distributions are less characteristic in the [$\theta_{c:m}$ = 4.5°, $\theta_{c:m}$ = 8.5°] region, L=1 and L = 2 contributions are possible for the low-energy mode, and the present analysis does not allow to disentangle them.

Excitation energy spectra



Measure of the ISGMR @ LNS in ^{38}S

Approved by LNS PAC

INFN Istituto Nazionale di Fisica Nucleare

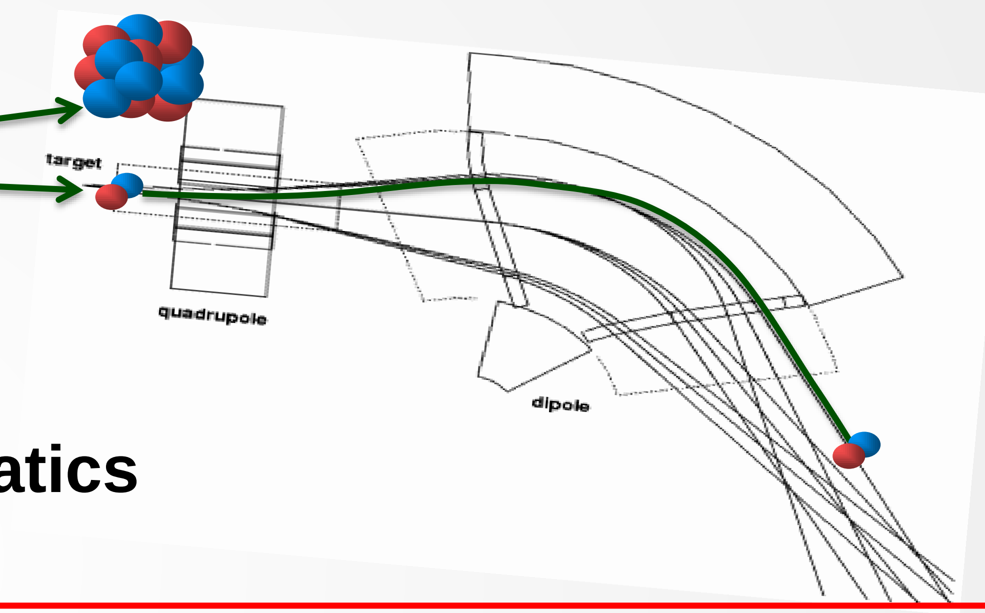
LNS

FRIBS @ LNS + 0^0 measurements with MAGNEX

^{38}S @ 21 AMeV

How….

CD_2 target
1 mg/cm^2 thick



Deuteron inelastic scattering in inverse kinematics

^{40}Ar @ 35 AMeV (100 W) + ^{9}Be 500 µm thick

Why ^{38}S ?

…already produced in the past

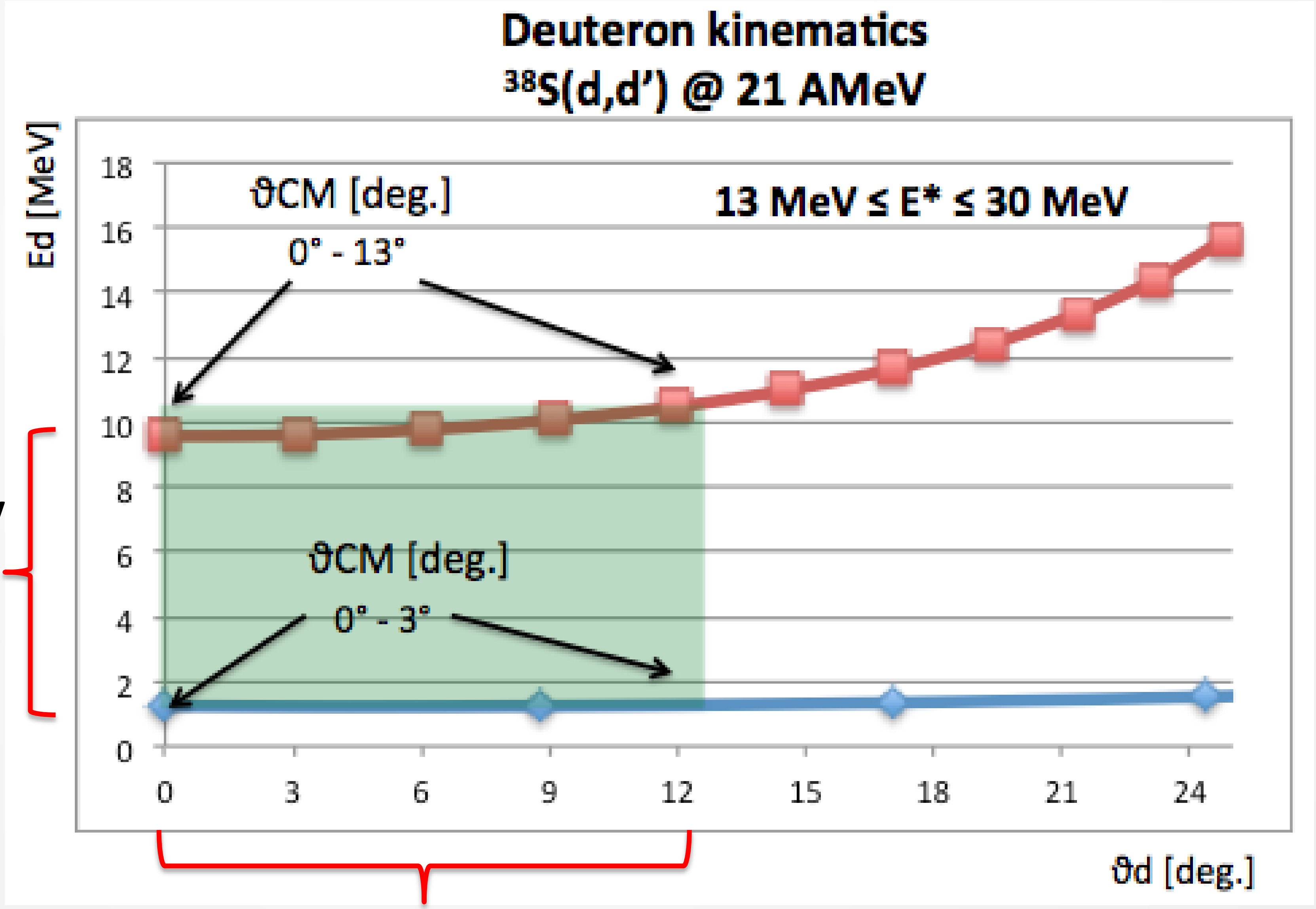
…high intensity primary beam

Other unstable nuclei produced with kHz rates: ^{37}S, ^{34,35}P, ^{31,32}Si, ^{29}Al. Measure GR in many exotic nuclei during the same experiment !

^{32}Ar	^{33}Ar	^{34}Ar	^{35}Ar	^{36}Ar	^{37}Ar	^{38}Ar	^{39}Ar	^{40}Ar	^{41}Ar	^{42}Ar 7.04e-5 0%
^{31}Cl	^{32}Cl	^{33}Cl	^{34}Cl	^{35}Cl	^{36}Cl	^{37}Cl	^{38}Cl 2.44e+0 0%	^{39}Cl 2.42e+3 0.005%	^{40}Cl 1.53e+4 2.945%	^{41}Cl 1.03e+1 0.988%
^{30}S	^{31}S	^{32}S	^{33}S	^{34}S	^{35}S 8.57e+2 0.001%	^{36}S 1.37e+4 0.043%	^{37}S 7.19e+4 0.526%	^{38}S 6.36e+4 1.482%	^{39}S 2.38e+2 0.555%	^{40}S 5.79e-1 0.675%
^{29}P	^{30}P	^{31}P 6.63e+0 0%	^{32}P 9.39e+2 0.002%	^{33}P 1.07e+4 0.026%	^{34}P 3.71e+4 0.202%	^{35}P 3.75e+4 0.619%	^{36}P 1e+4 0.659%	^{37}P 6.29e+2 0.22%	^{38}P 1.04e-1 0.004%	^{39}P 1.32e-7 0%
^{28}Si 7.61e-1 0%	^{29}Si 3.95e+2 0.001%	^{30}Si 6.43e+3 0.012%	^{31}Si 2.82e+4 0.096%	^{32}Si 3.27e+4 0.299%	^{33}Si 1.36e+4 0.453%	^{34}Si 1.83e+3 0.28%	^{35}Si 8.68e+1 0.075%	^{36}Si 7.33e-1 0.005%	^{37}Si 2.89e-5 0%	^{38}Si
^{27}Al 1.64e+3 0.004%	^{28}Al 1.34e+4 0.032%	^{29}Al 2.59e+4 0.126%	^{30}Al 1.74e+4 0.26%	^{31}Al 4.16e+3 0.263%	^{32}Al 4.17e+2 0.144%	^{33}Al 1.71e+1 0.04%	^{34}Al 1.77e-1 0.003%	^{35}Al 2.72e-4 0%	^{36}Al	^{37}Al

Kinematics

Reconstruct the ^{38}S excitation energy spectrum between 13 and 30 MeV measuring deuterons in the 0°-12° angular region with energies between 1-10 MeV



Deuteron energies 1-10 MeV
4 magnetic setting

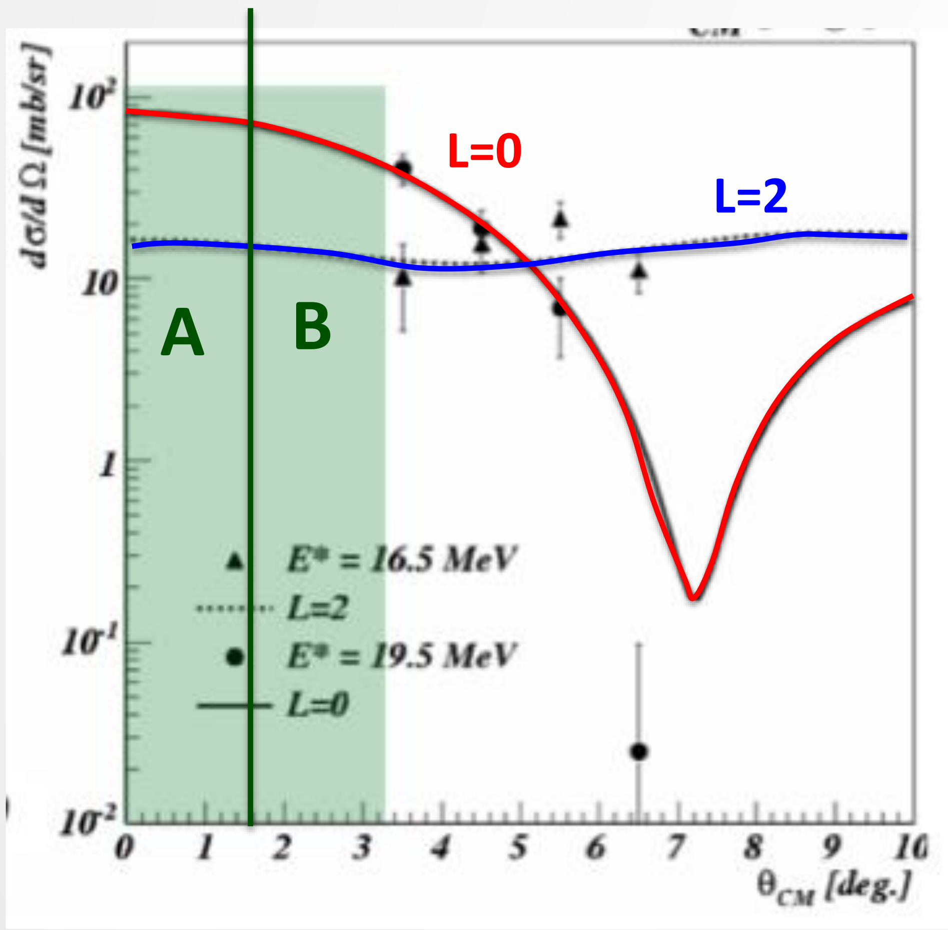
Angle 0° - 12° only one angular setting

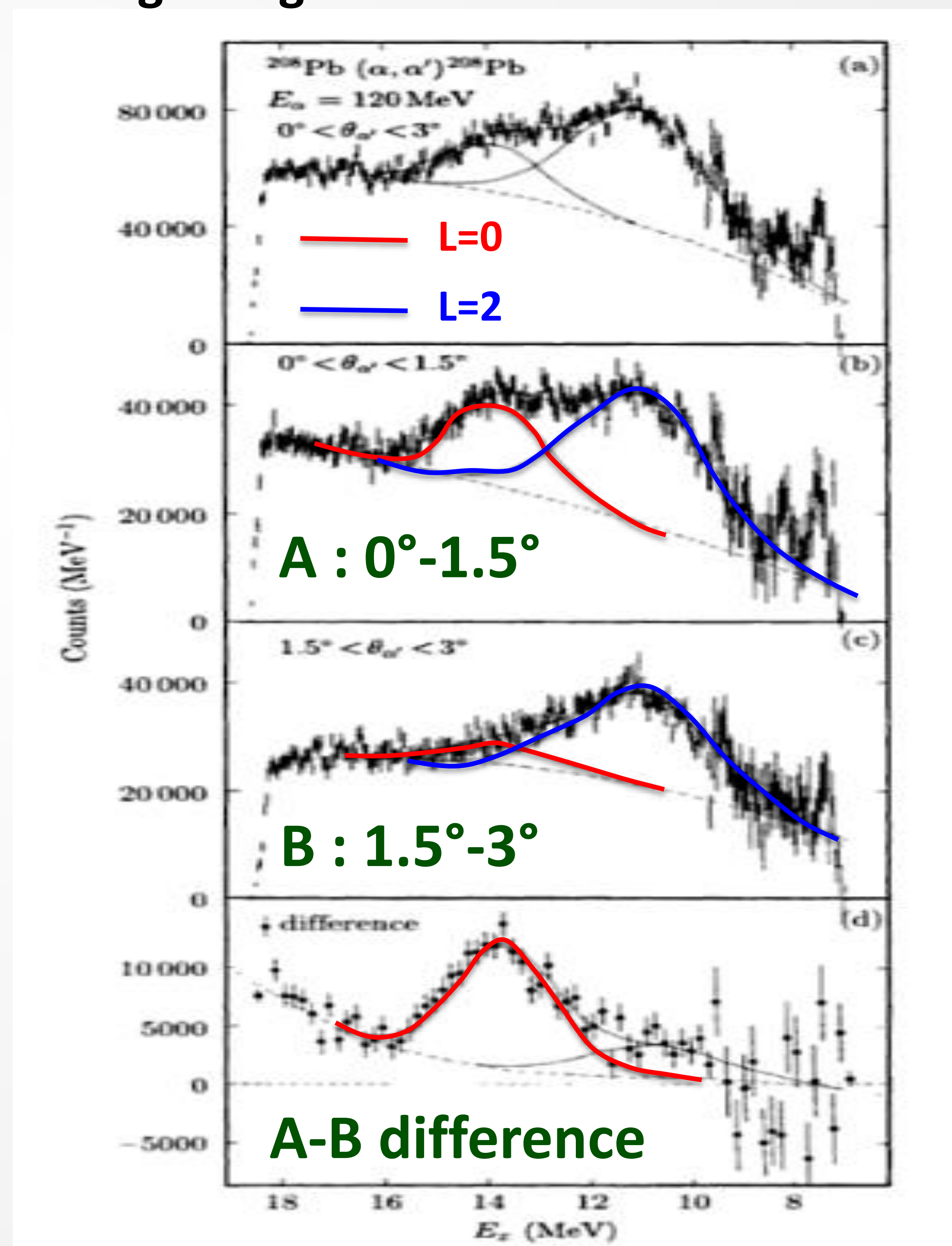
Spectrum subtraction technique

D.H. Youngblood et al., PRC 55 (1997) 2811

The monopole energy spectrum can be directly obtained by subtracting a spectrum taken at a larger angle from the one taken at 0°.

The monopole cross section is strongly peaked near 0° whereas the angular distribution of L=2 is nearly flat at small angles.





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Double Charge Exchange studies @ LNS

Double charge exchange reactions are*characterized*by*the*transfer*of*! $T_z = \pm 2$*,* leaving*the*mass*number*unchanged*

DCE reactions for:

- **Challanging spectroscopic studies of n-rich and p-rich nuclei**
- **Connections to nutrinoless [illegible] decay and its implications for the neutrino mass. The nuclear [illegible]ent involved in the beta decay is connected to the charge ex[illegible] and consequently to the Fermi and/or Gamow-Teller transitions st[illegible]e reaction.**

NUMEN

Drip lines

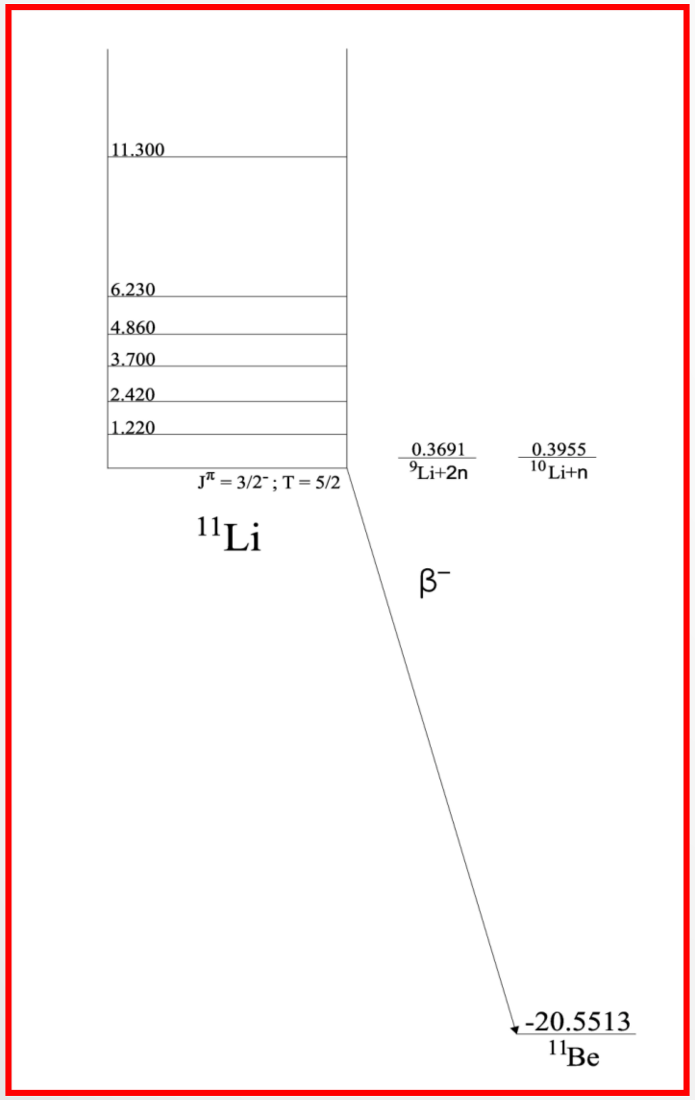
Approved by LNS PAC

We propose to study with MAGNEX spectrometer the poorly known states of ^{11}Li by the simultaneus measurements, at 200 MeV total energy of the reactions:

$^{11}B(^{18}O,^{18}Ne)^{11}Li$

$^{7}Li(^{18}O,^{14}O)^{11}Li$

This could be the first of a series of spectroscopic studies on drip-line neutron rich nuclei using multi transfer technique !



Despite the strong interest to the comprehension of the ^{11}Li structure, very little is known about the excited states of this nucleus.

(*Kelley et al. NPA 880 (2012) 88).*

We looking for resonances on the continuum !

Experimental procedure

A unique magnetic field and angular setting with MAGNEX working in full acceptance mode

4n transfer

$^{7}Li(^{18}O,^{14}O)^{11}Li$

- **^{7}Li target 1 mg/cm^2 thickness**

⬇

energy resolution ≈ 200KeV

- **Excited states up to 18 MeV**
- **Angular range c.m. : from 0^0 to 60^0**

DCE

$^{11}B(^{18}O,^{18}Ne)^{11}Li$

- **^{11}B target 0.2 mg/cm^2 thickness**

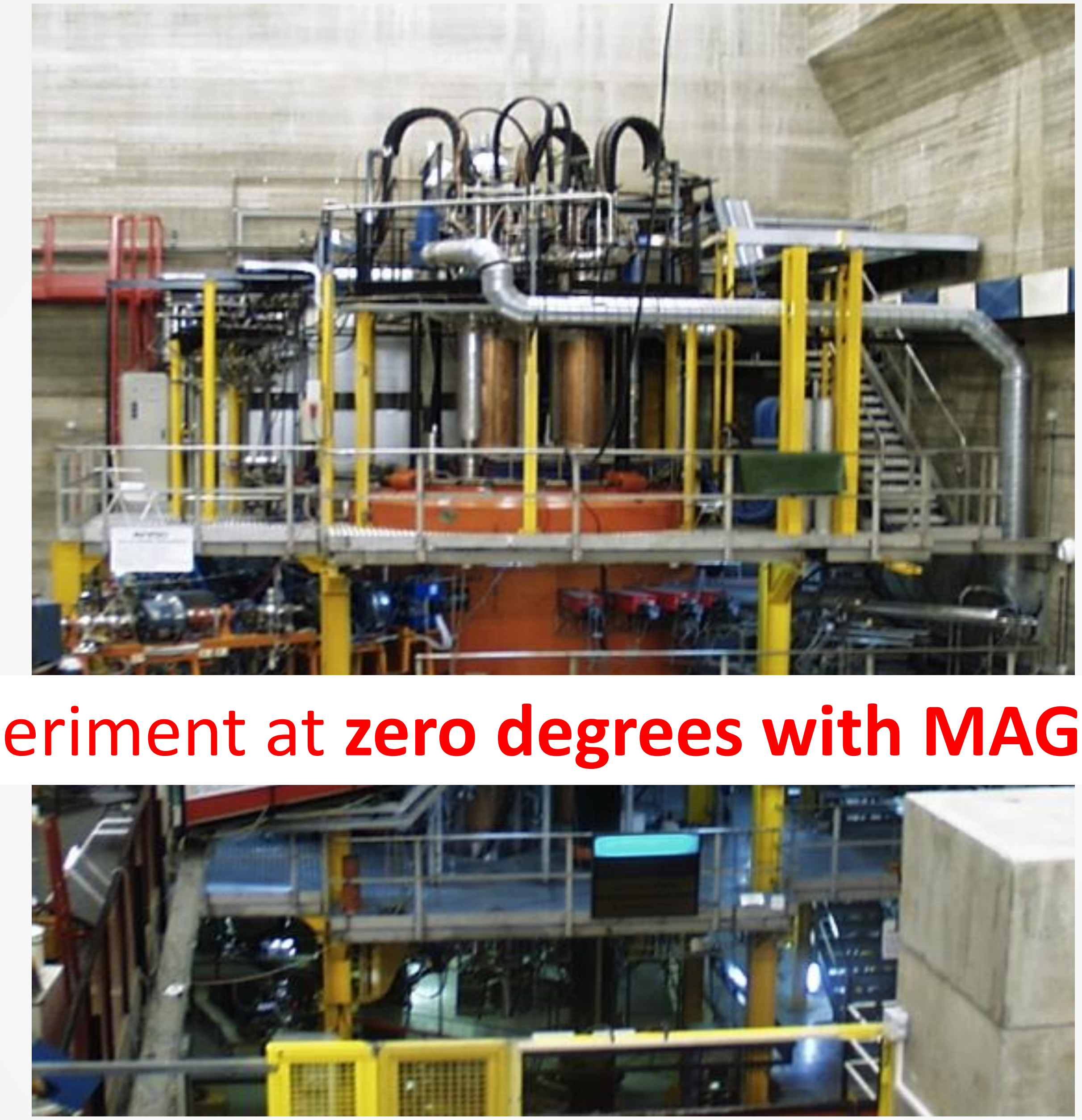
⬇

energy resolution ≈ 350 KeV

- **Excited states up to 30 MeV**
- **Angular range c.m. : from 0^0 to 50^0**

Two reactions for ^{11}Li :
to study with two different reaction mechanisms the same states !

MAGNEX @ CS beams



➢ **2013** first experiment at **zero degrees with MAGNEX @CS**

NUMEN ⟷ **High intensity beams @ CS**

Experimental limits

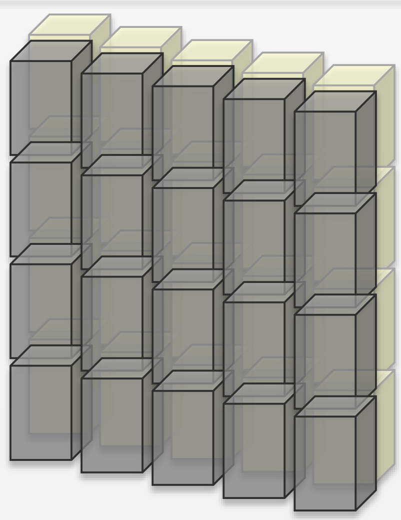
FPD criticity @ high rates

1. **TRACKER : Space charge limits to few kHz**
2. **Silicon detector damaging**

from 1 kHz → to 100 kHz or more

From Multiwire gas tracker → to GEM (or ThickGEM or Micromega) gas tracker
From 7 X 5 cm^2 silicon Wall → to 1x1 cm^2 telescopes wall

- 1x1 cm^2 ΔE-E telescope
- thickness of ΔE stage 100 μm
- thickness of E stage 500-1000 μm
- hard to the radiation damage
- good energy resolution (1-2 %)
- High stability (electric and thermal)



Standard technologies (Si) → new ones (SiC crystals)

From Multiwire gas tracker limited to about 1 kHz

To GEM – like gas tracker to go to 100 kHz

R&D key issue : GEM-based tracker at low pressure and wide dynamic range

Decupling tracking from ion identification

Outlook

- MAGNEX: a magnetic spectrometer with a large acceptance and high energy, mass and angular resolution, allowing 0^0 measurements

    - NUMEN ⟷ HIB @ LNS ⟷ MAGNEX + CS Upgrade

- FRIBS @ LNS for ISGMR in exotic nuclei

- Drip line: spectroscopy studies with tiny cross sections

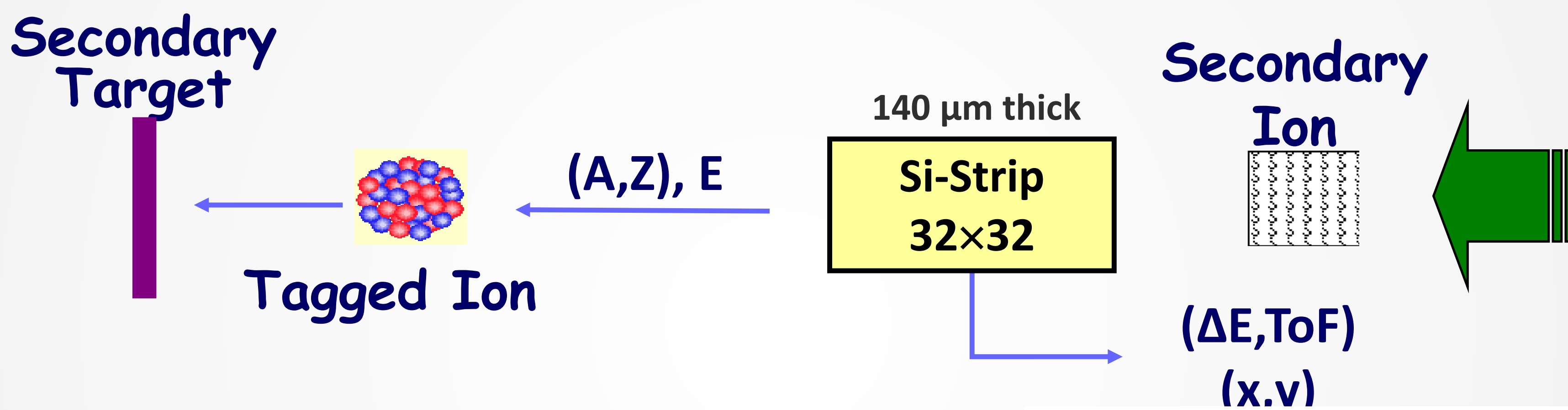
High Intensities CS Beams @ LNS:

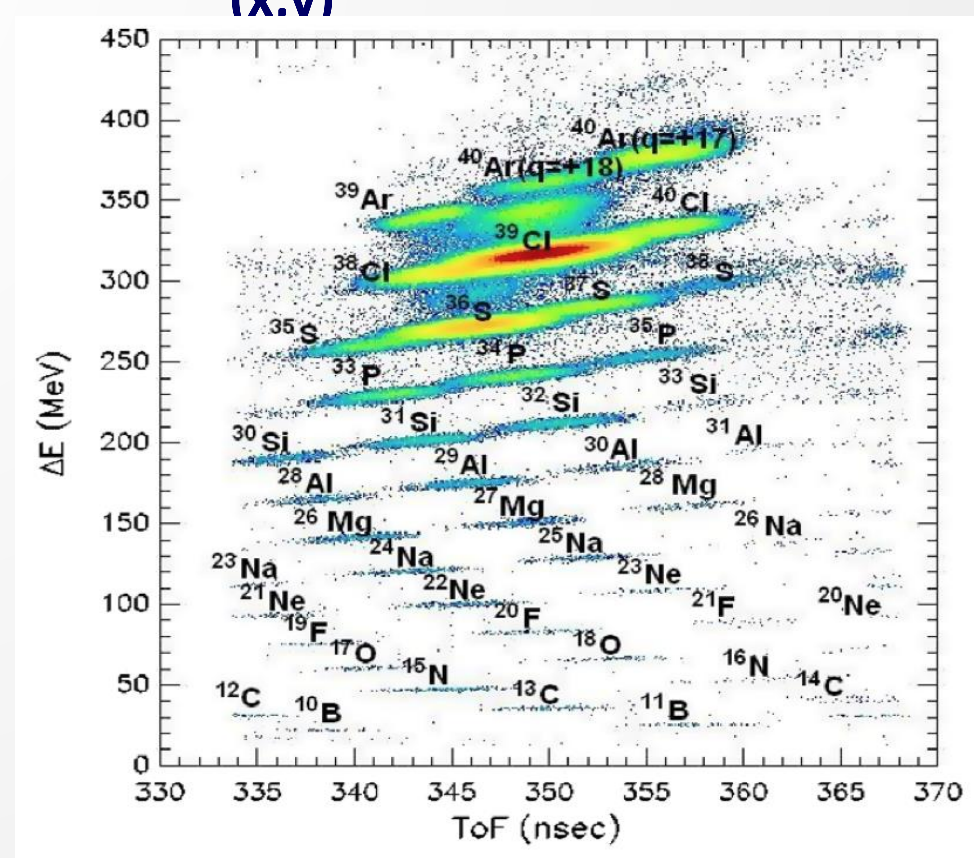
New challanging series of experimental studies !

SPARES

FRIBS @ MAGNEX: tagging + tracking

Identify event-by-event all the fragments of the secondary beam in Z,A and energy before they interact with the reaction target (ΔE-ToF measurement)



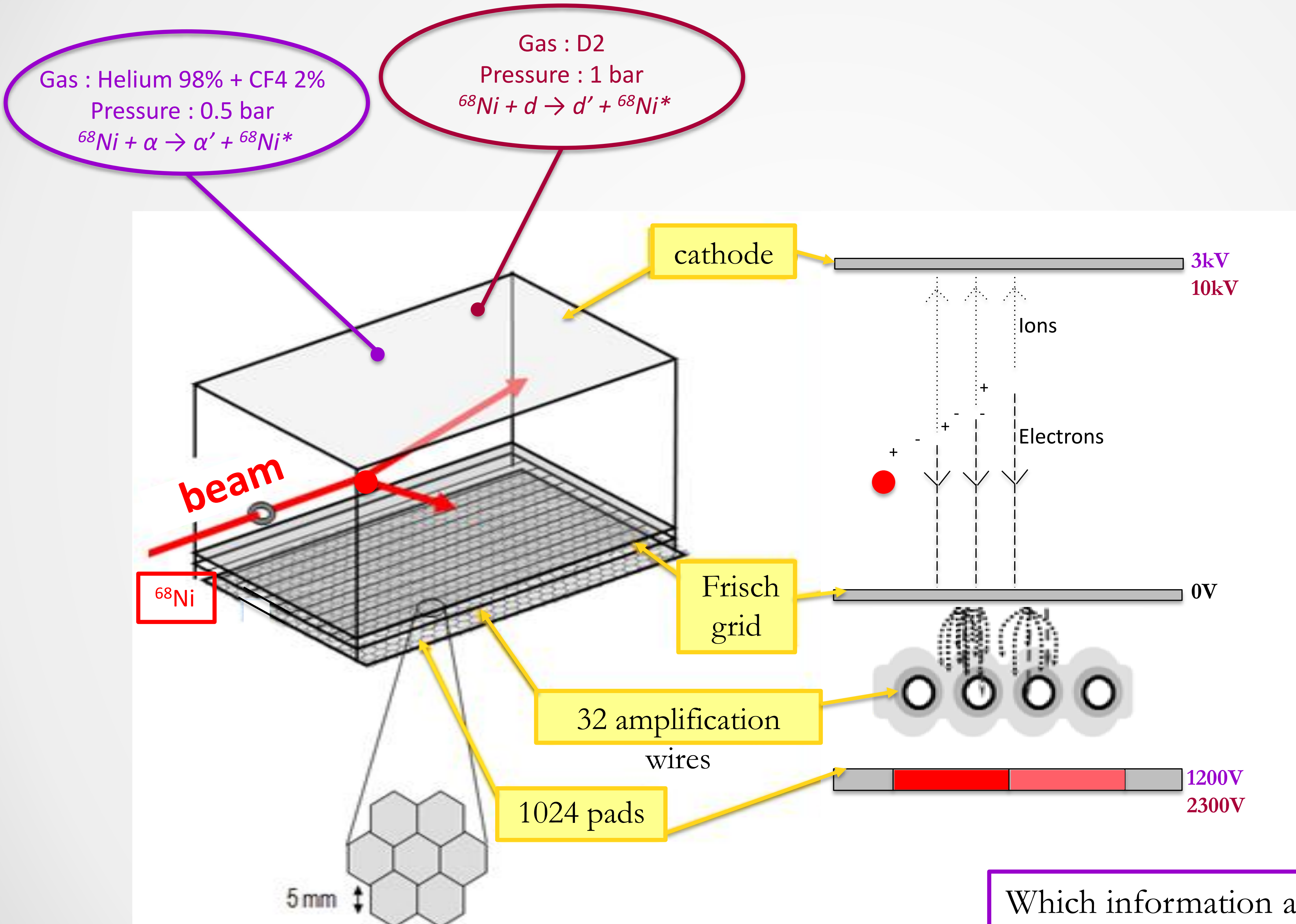


Tracking detector

Measure of the ion direction using a second detector setup few meters before the tagging detector

Setup : the active target MAYA

Principle. The detecto gas also act as a target



Time Projection Chamber (TPC) :

1. The scattered deuteron or α ionizes the gas

2. The electrons drift towards the Frisch grid

3. Amplification on the wires

4. Signal on each pad proportionnal to the amount of electrons collected on the wire above

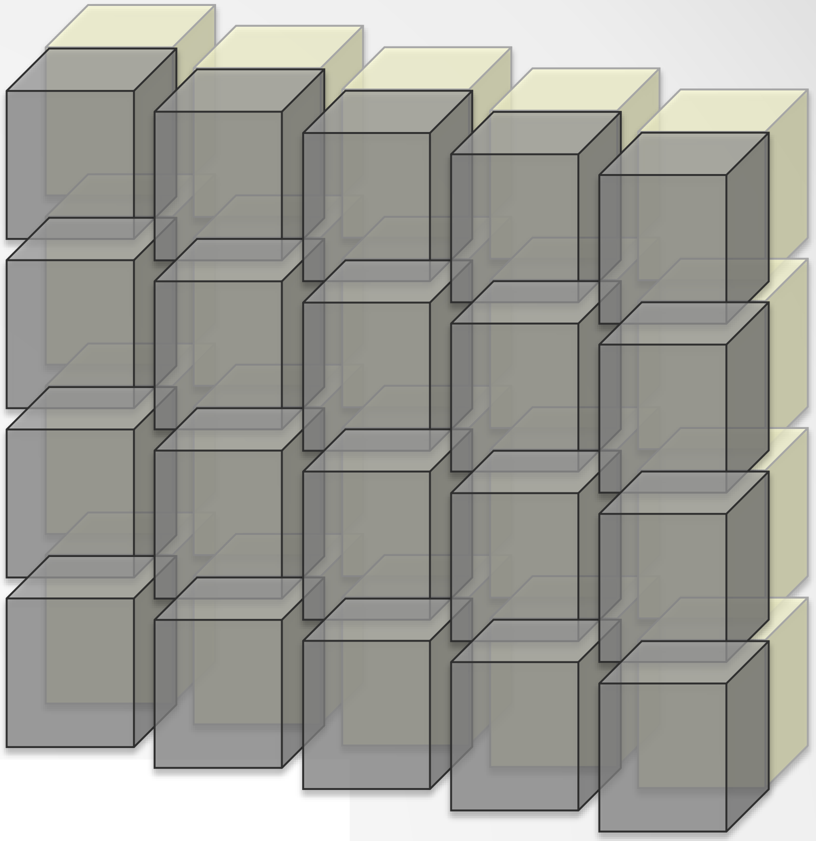
Which information are stored ?
- Time on each wire
- Charge induced on each pad

MAGNEX Upgrade

1. substitution of the present Focal Plane Detector (FPD) gas tracker with a GEM – like tracker system;
2. substitution of the wall of silicon pad stopping detectors with a wall of telescopes based on SiC-CsI detectors;
3. introduction of an array of detectors for measuring the coincident γ-rays;
4. enhancement of the maximum magnetic rigidity.

NUMEN requirements

- ✓ 1x1 cm^2 ΔE-E telescope
- ✓ thickness of ΔE stage 100 μm
- ✓ thickness of E stage 500-1000 μm
- ✓ hard to the radiation damage
- ✓ good energy resolution (1-2 %)
- ✓ High stability (electric and thermal)



RD50 - CERN

Property	Diamond	GaN	4H SiC	Si
E_g [eV]	**5.5**	**3.39**	**3.26**	**1.12**
$E_{breakdown}$ [V/cm]	10^7	$4\cdot10^6$	$2.2\cdot10^6$	$3\cdot10^5$
μ_e [cm^2/Vs]	1800	1000	800	1450
μ_h [cm^2/Vs]	1200	30	115	450
v_{sat} [cm/s]	$2.2\cdot10^7$	-	$2\cdot10^7$	$0.8\cdot10^7$
Z	6	31/7	14/6	14
ε_r	5.7	9.6	9.7	11.9
e-h energy [eV]	**13**	**8.9**	**7.6-8.4**	**3.6**
Density [g/cm3]	3.515	6.15	3.22	2.33
Displacem. [eV]	**43**	**≥15**	**25**	**13-20**

NUMEN

- Wide bandgap (3.3eV)

⇒ lower leakage current than silicon

- Signal (**for MIP !**):
  Diamond 36 e/μm
  SiC 51 e/μm
  Si 89 e/μm

⇒ more charge than diamond Si/SiC≈2

- Higher displacement threshold than silicon

⇒ radiation harder than silicon

Excitation of giant monopole resonance in ^{208}Pb and ^{116}Sn using inelastic deuteron scattering

D.Patel, U.Garg, M.Itoh, H.Akimune et. al.

Physics Letters B 735 (2014) 387–390

The experiment was performed at the ring cyclotron facility of the Research Center for Nuclear Physics (RCNP), Osaka University, Japan. A 196-MeV 2 H+ beam was incident on 10 mg/cm2 -thick, enriched (>95%) isotopic targets of 116Sn and 208Pb.

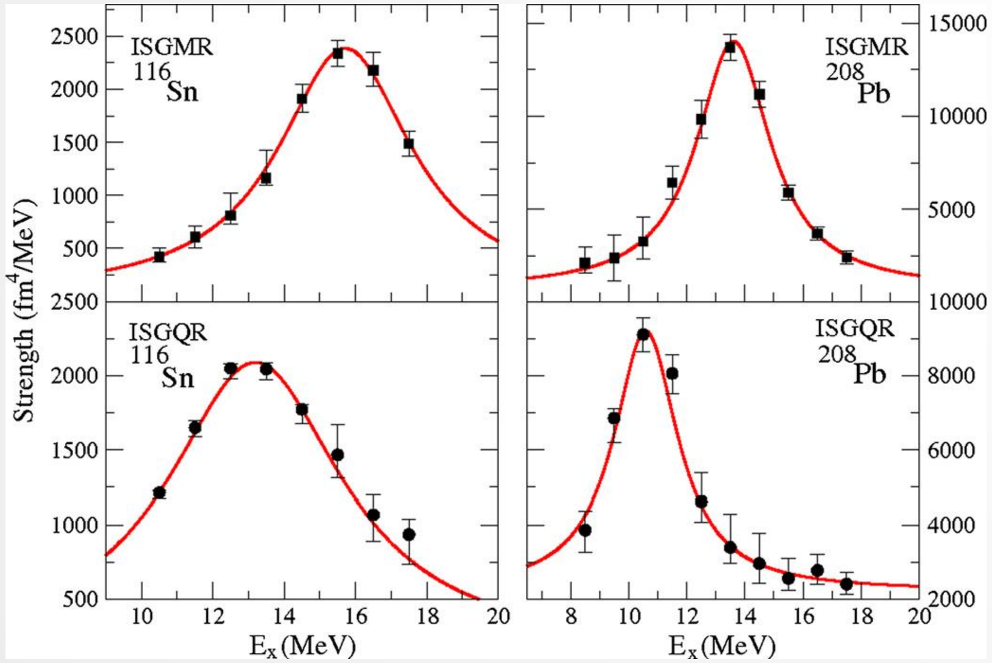
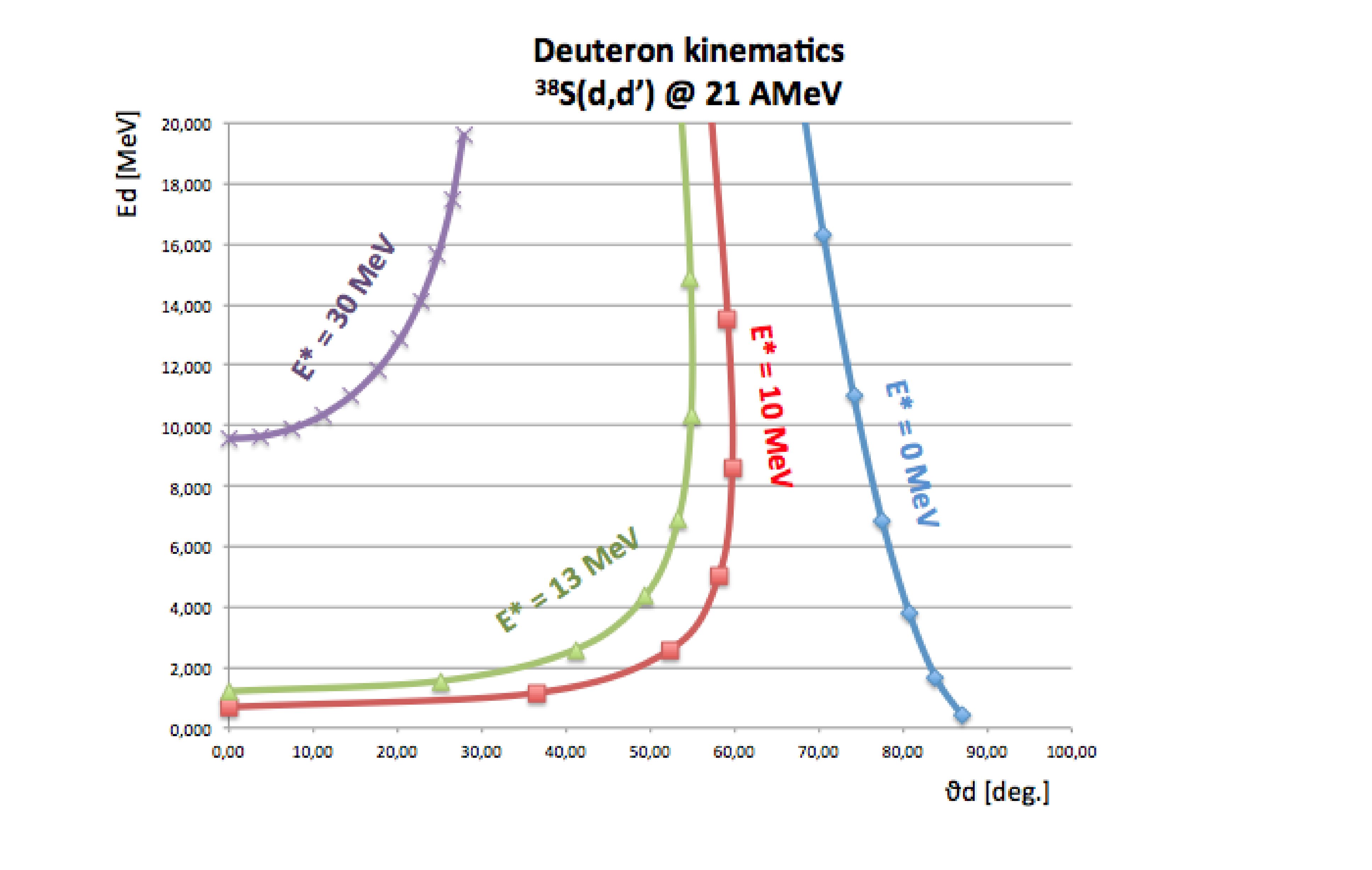


Fig. 4. (Color online.) ISGMR and ISGQR strength distributions for ^{116}Sn and ^{208}Pb obtained in this work. The solid red lines are Lorentzian fits to the data.

	^{116}Sn				
		This work	RCNP [8]	TAMU* [34]	KVI [37]
ISGMR	E (MeV)	15.7 ± 0.1	15.8 ± 0.1	15.85 ± 0.20	15.69 ± 0.16
	Γ (MeV)	4.6 ± 0.7	4.1 ± 0.3	5.27 ± 0.25	3.73 ± 0.39
	% EWSR	73 ± 15	99 ± 5	112 ± 15	101 ± 22
ISGQR	E (MeV)	13.2 ± 0.1	13.1 ± 0.1	13.50 ± 0.35	13.39 ± 0.14
	Γ (MeV)	6.0 ± 1.0	6.4 ± 0.4	5.00 ± 0.30	2.94 ± 0.31
	% EWSR	73 ± 23	112 ± 4	108 ± 12	134 ± 28

Small-angle deuteron inelastic scattering can thus serve for reliable investigation of the ISGMR in nuclei far from stability using inverse-kinematics reacations, making it possible to investigate the properties of ISGMR in the exotic nuclei at the rare isotope beam facilities.

Complete kinematics plot



in searching for ISGMR, it is crucial to populate the excitation energy region where ISGMR are expected, at around 0° in the CMRF. With the proposed kinematics this will be possible. Clearly, we also have the opportunity to reconstruct the 38S excitation energy spectrum between 0 and 13 MeV, moving the spectrometer at larger angles and detecting deuterons with recoiling energies well higher than 1 MeV, as it can be seen from the complete kinematics plot of Fig. 3.

R&D: Ion identification

High rates : standard technologies (Si) vs. new ones (SiC crystals)

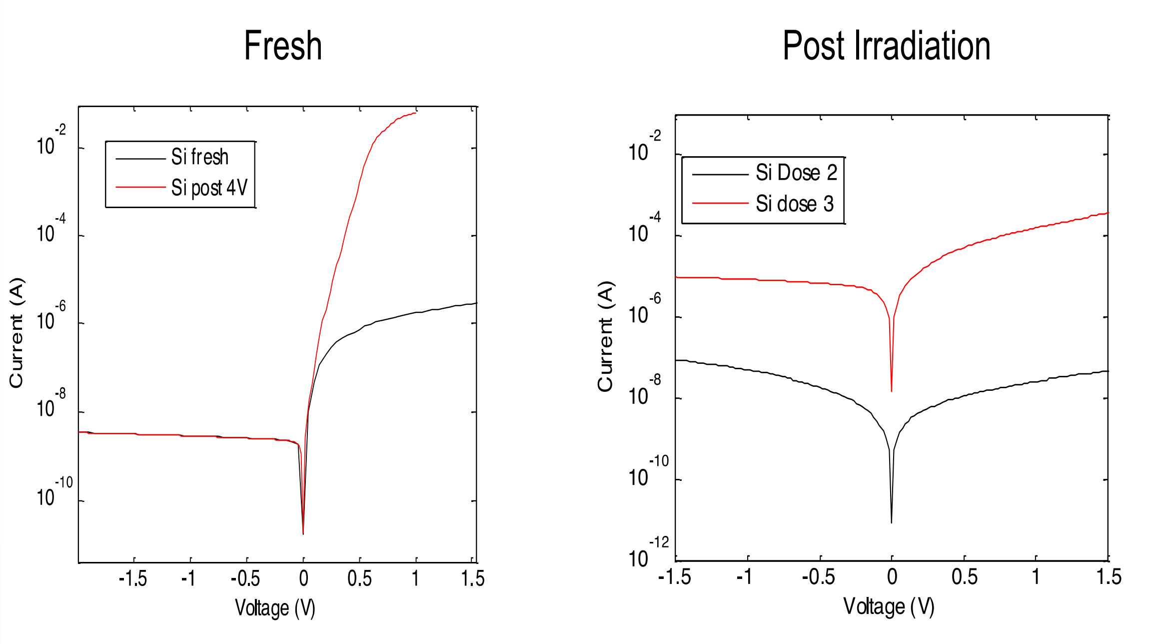
Silicon detectors

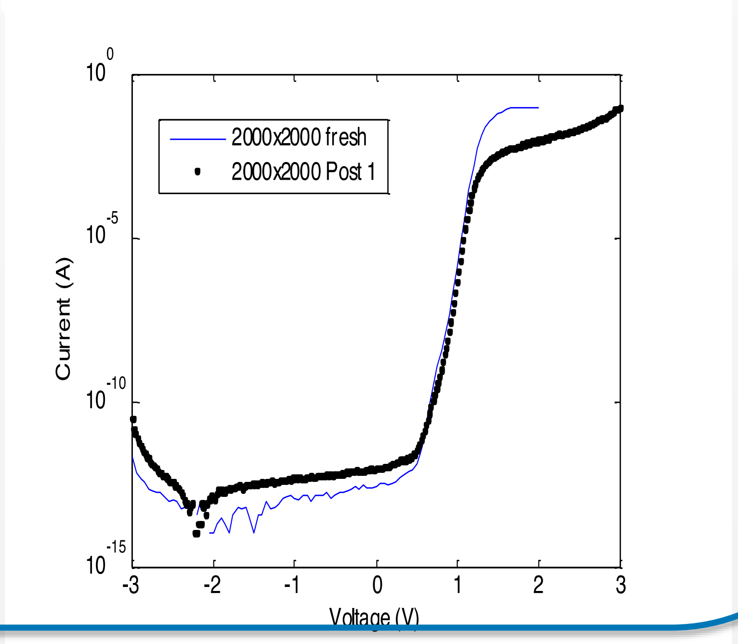
- double hits (high segmentation-high costs)
- radiation hardness at 0^0 rate limit 10^9 ions/cm^2 Si death in few days

SiC crystals

- Preserves good Si properties
- Much harder to radiations
- double hits (high segmentation-high cost

Irradiations tests: around 10^{13} ions ^{12}C @ 62 AMeV at LNS in collaboration with CNR





R&D: to built a realiable number of epitaxial SiC, in order to built a telescopes wall of epitaxial SiC (100 µm and surface of 1cm^2) for energy loss + CsI (1 cm) for residual energy ; decupling tracking from ion identification.

LNS PAC

LNS INFN Istituto Nazionale di Fisica Nucleare

Proposal C164:

GREEN

The committee considers positively this proposal whose goal is very clear. Extending the GMR measurements to exotic nuclei is very interesting. The GANIL (MAYA) result is still debated and this deserves an experimental campaign. The experimental task is not easy when one considers cross-section, FRIBS production tagging. Therefore the full demand is allocated by the committee.

Classification: A

Beam attribution: 52 BTU

PAC APPROVED beamtime

Proposal C156a:

DRIP-LINES.

Last year the committee allocated 4 BTU of 270 MeV ^{18}O in order to test the feasibility of the experiment.

The collaboration realized the test experiment. All questions raised during the 2012-PAC are now answered and a clear estimation of the ^{18}Ne ejectile cross-section has been shown.

The committee allocates 30 BTU.

Classification: A

Beam attribution: 30 BTU (18O 200 MeV)

R&D : exclusive measurements

SCINTILLATORS ARRAY

Detecting **γ-rays in coincidende** with MAGNEX to:

- **improve energy resolution** from the present limit of ≈ 1 MeV for 50 MeV/u heavy ions (1/1000 of 1 GeV ^{18}Ne), mandatory for DCE reactions.

- Work with an **intense flux of γ-rays** and neutrons to **optimize signal-to-noise ratio and reduce spurious** coincidences.

- Work done on **HPGe and $LaBr_3$ by other collaborations** that can be used for this purpose;

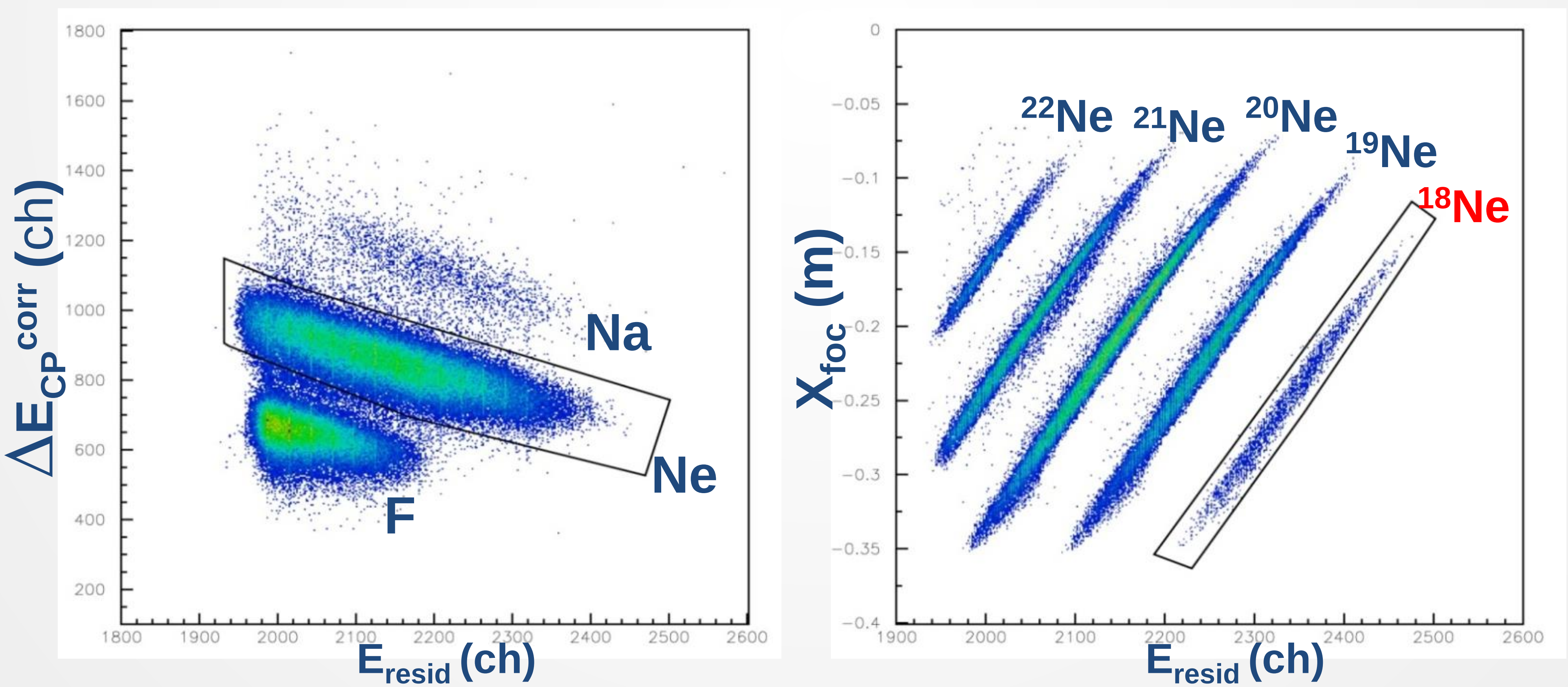
CsI or NaI seems more promising for high rates applications.

- Members of the Italian-Brasilian (INFN-IFUSP-IFUFF collaboration MoU) collaboration are interested to collaborate on this topics with possible in-kind contribution in the future development of NUMEN.

Test run

$^{11}B(^{18}O,^{18}Ne)^{11}Li$ @ 270 MeV $7^0 \leq \theta \leq 19^0$

- **Checked background processes**
- **Selected events corresponding to ^{18}Ne**
- **Established a cross section estimate : ≈ 200 nb/sr**



Clementina Agodi, HIB@LNS - 14-15 dicembre 2015

Present day

magnetic rigidity :

1.8 Tm i.e. 50 MeV/u $^{18}Ne^{10+}$ and ≈ 30 MeV/u $^{20}O^{8+}$

To extend the dynamical conditions

magnetic rigidity :

- 2.8 Tm requires superconducting magnets with present MAGNEX optical layout
- **Power supply upgrade** to obtain 2.1-2.2 Tm i.e. 70 MeV/u $^{18}Ne^{10+}$ and ≈ 42 MeV/u $^{20}O^{8+}$

Q_{opt}

$^{7}Li(^{18}O,^{14}O)^{11}Li$	Q = -34.638 MeV

$^{11}B(^{18}O,^{18}Ne)^{11}Li$	Q = -38.228 MeV

The optimum Q value for multinucleon transfer reaction grow more negative when the incident energy increase

The role of the involved nuclei

- The nucleon transfer reaction cross sections can be deduced from simple dynamic considerations, according to semi-classical arguments, when the incident energy is above the Coulomb barrier.
- Assuming a mechanism where a cluster is transferred: the cross section tends to maximize within a *Q*-window, which depends on the reaction Q_{gg}, on the target, on the projectile radii and on the incident energy.

Brink's matching conditions

D.M. Brink, Phys. Lett. B 40 (1972) 37-40

$$\Delta k = k_0 - \lambda_1 / R_1 - \lambda_2 / R_2 \approx 0$$

$$\Delta L = \lambda_2 - \lambda_1 + \frac{1}{2} k_0 (R_1 - R_2) + Q_{eff} R / \hbar v \approx 0$$

$$l_1 + \lambda_1 = even$$

$$l_2 + \lambda_2 = even$$

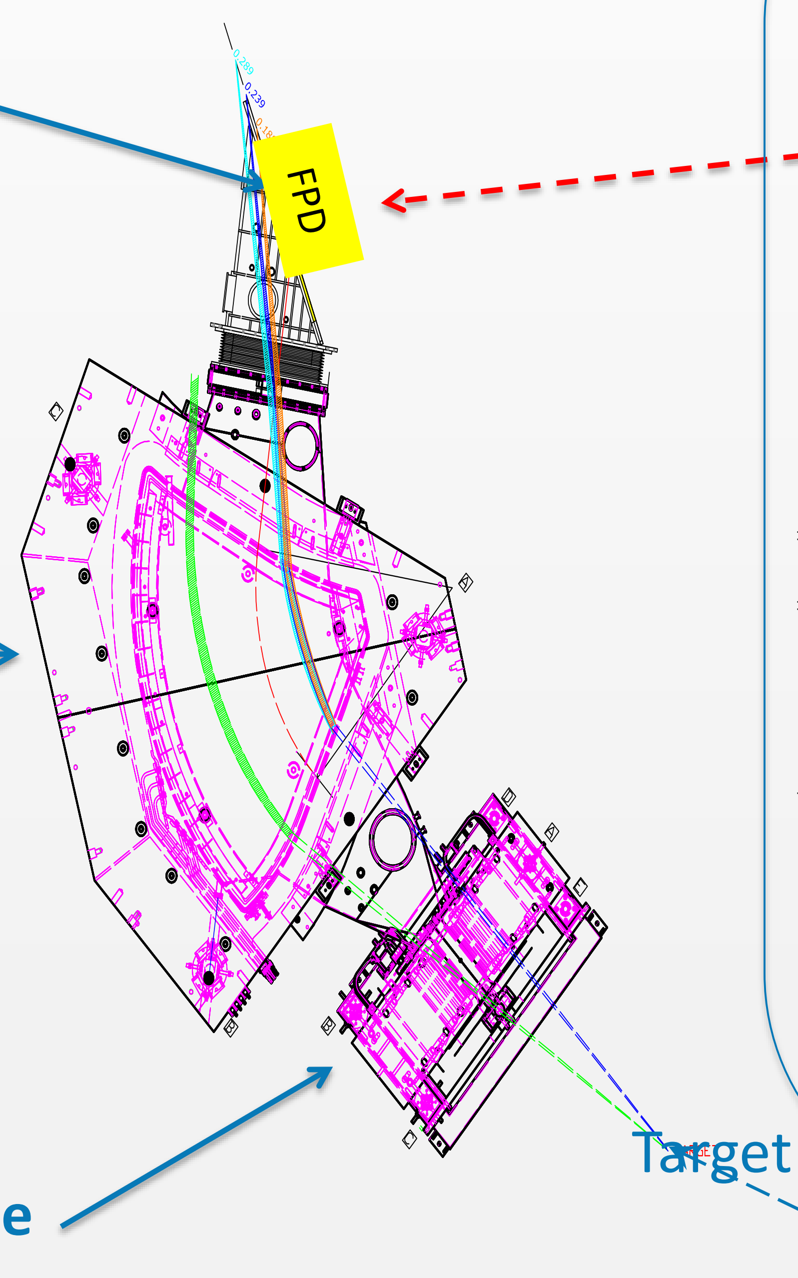
$$k_0 = mv / \hbar$$

$$Q_{eff} = Q - (Z_1^f Z_2^f - Z_1^i Z_2^i)$$

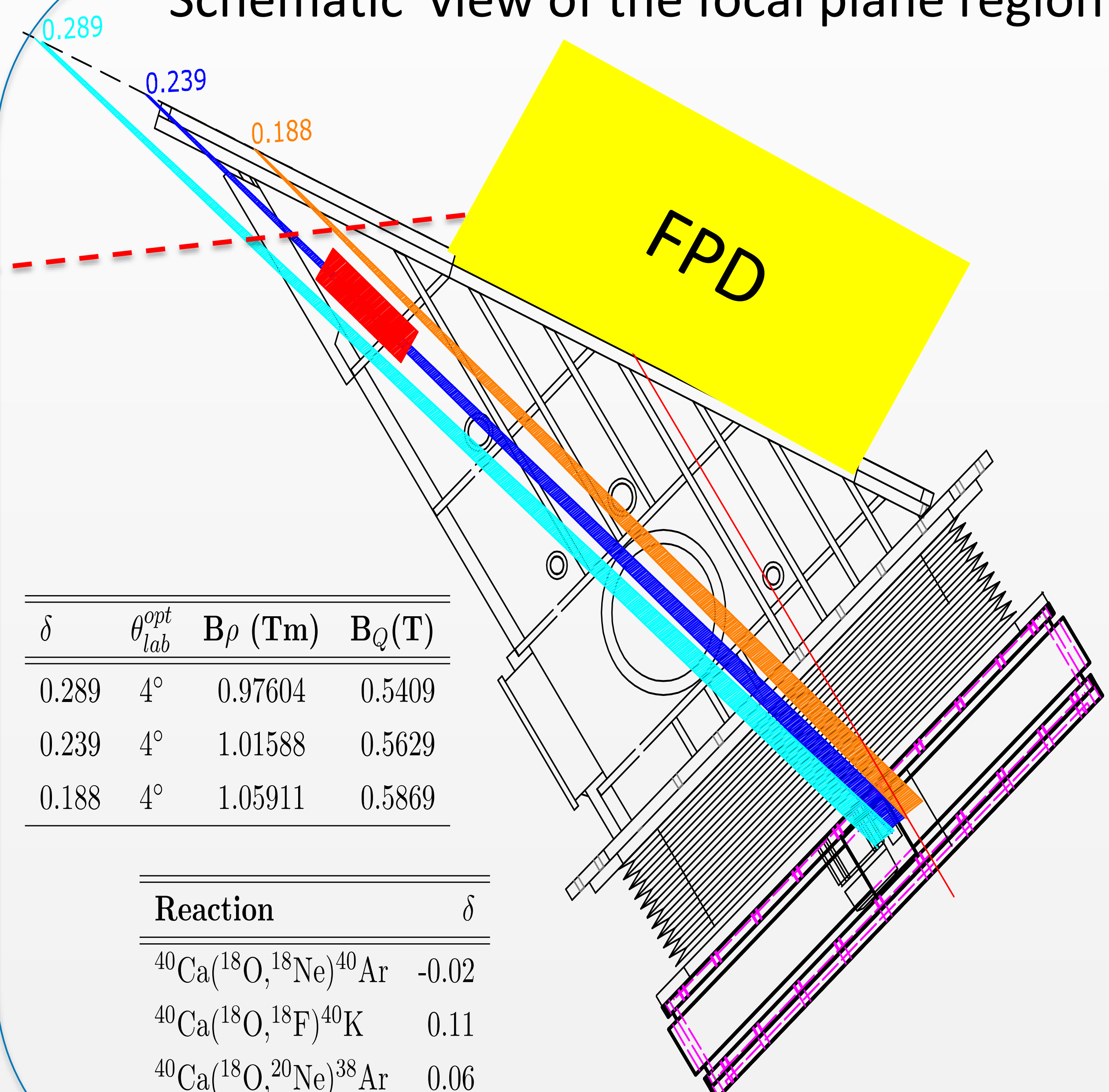
- The survival of a preformed pair in a transfer process is favoured when the initial and final orbitals are the same

The present day experimental set-up @ LNS

Plane view of the MAGNEX magnetic layout



Schematic view of the focal plane region



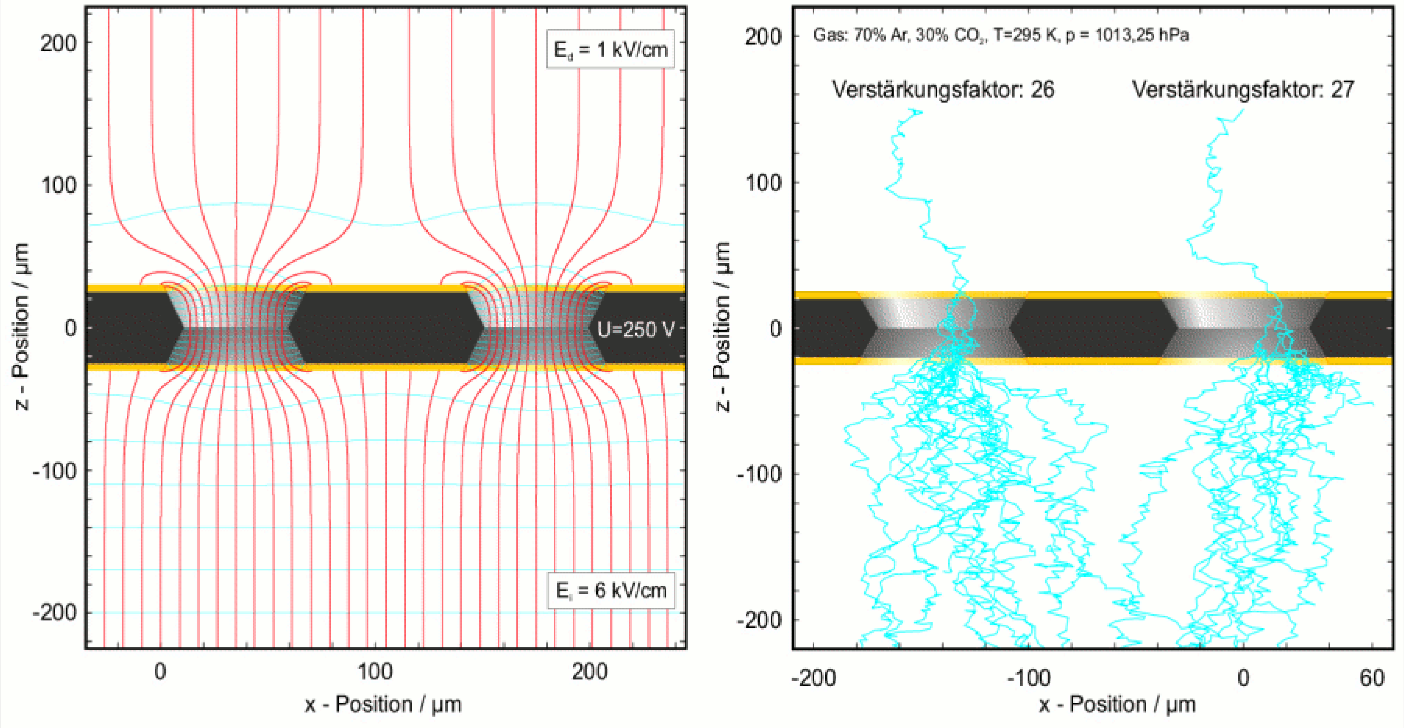
δ	θ_{lab}^{opt}	$B\rho$ (Tm)	B_Q(T)
0.289	4°	0.97604	0.5409
0.239	4°	1.01588	0.5629
0.188	4°	1.05911	0.5869

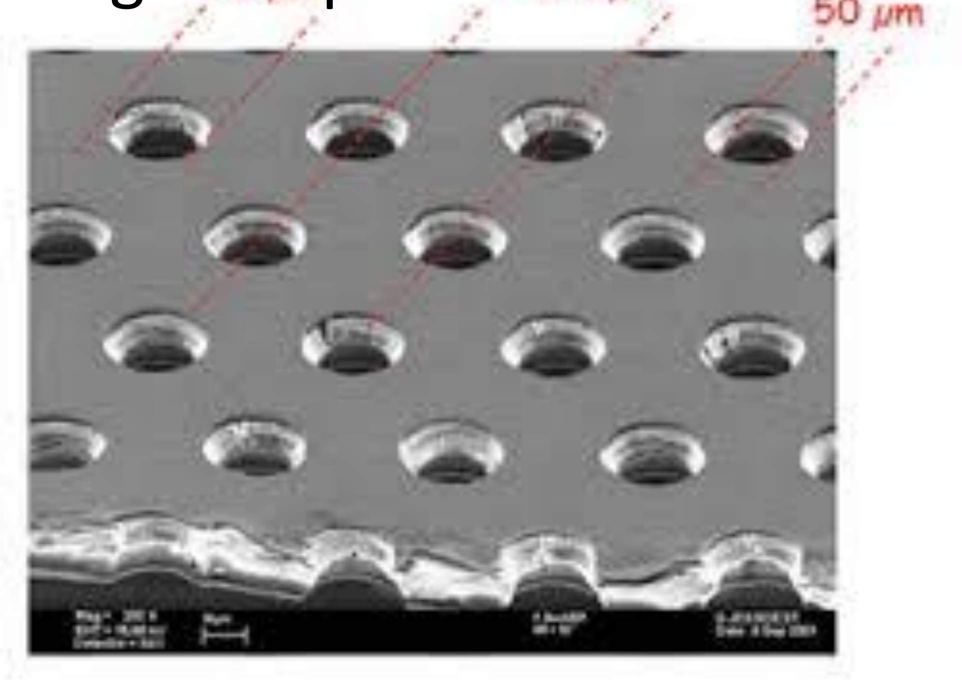
Reaction	δ
^{40}Ca(^{18}O,^{18}Ne)^{40}Ar	-0.02
^{40}Ca(^{18}O,^{18}F)^{40}K	0.11
^{40}Ca(^{18}O,^{20}Ne)^{38}Ar	0.06
^{40}Ca(^{18}O,^{16}O)^{42}Ca	0.18

Micropattern Gas Detector

GEM (Gas Electron Multiplier)

The standard CERN GEMs consist of an insulator made of a **thin Kapton foil** (about 50 µm) which is **coated on both sides with copper layers** (about 5 µm).
This structure is perforated with **holes** (typically **diameter of 70 µm** and pitch of 140 µm).
Between the two copper coatings a voltage of a few 100 V is applied. Since the field lines are focused in the holes, there the resulting **electric field** strength is in the order of some **10 kV/cm** which is high enough for the gas amplification.

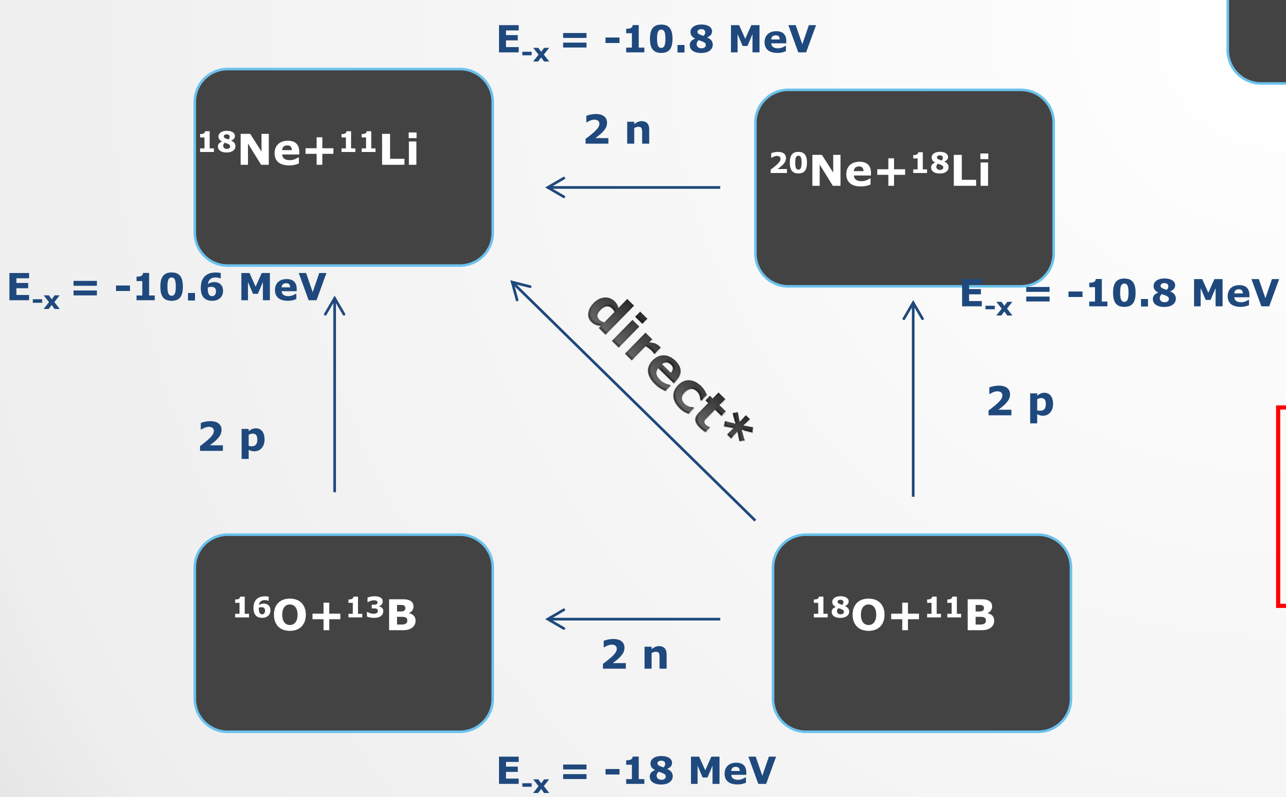




Double Charge Exchange: ^{11}Li

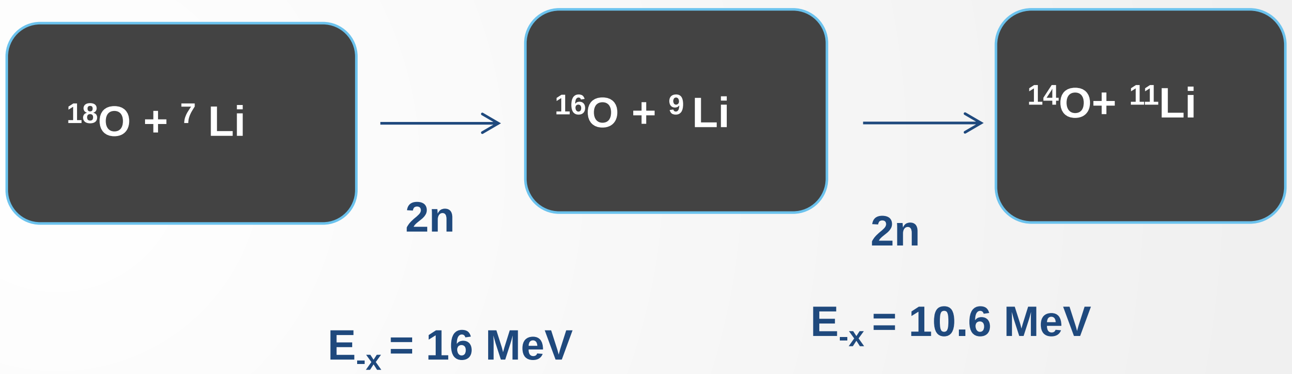
DCE:

^{11}B(^{18}O,^{18}Ne)^{11}Li @ 200 MeV LNS



4n transfer:

^{7}Li(^{18}O,^{14}O)^{11}Li @ 200 MeV LNS



Two different reaction mechanisms to put a signature in ^{11}Li states !

*double Gamow-Teller or double Fermi modes: by the double action of a direct isovector meson exchange operator ^{40}Ca(^{18}O,^{18}Ne)^{40}Ar @ 270 MeV, LNS experiment DoCET, performed in march 2013

NUMEN Project @ LNS

LNS

- An innovative technique to access the nuclear matrix elements entering in the expression of the life time of the $0\nu\beta\beta$ decay by relevant cross sections of double charge exchange reactions is proposed.

- The basic point is the coincidence of the initial and final state wave-functions in the two classes of processes and the similarity of the transition operators.

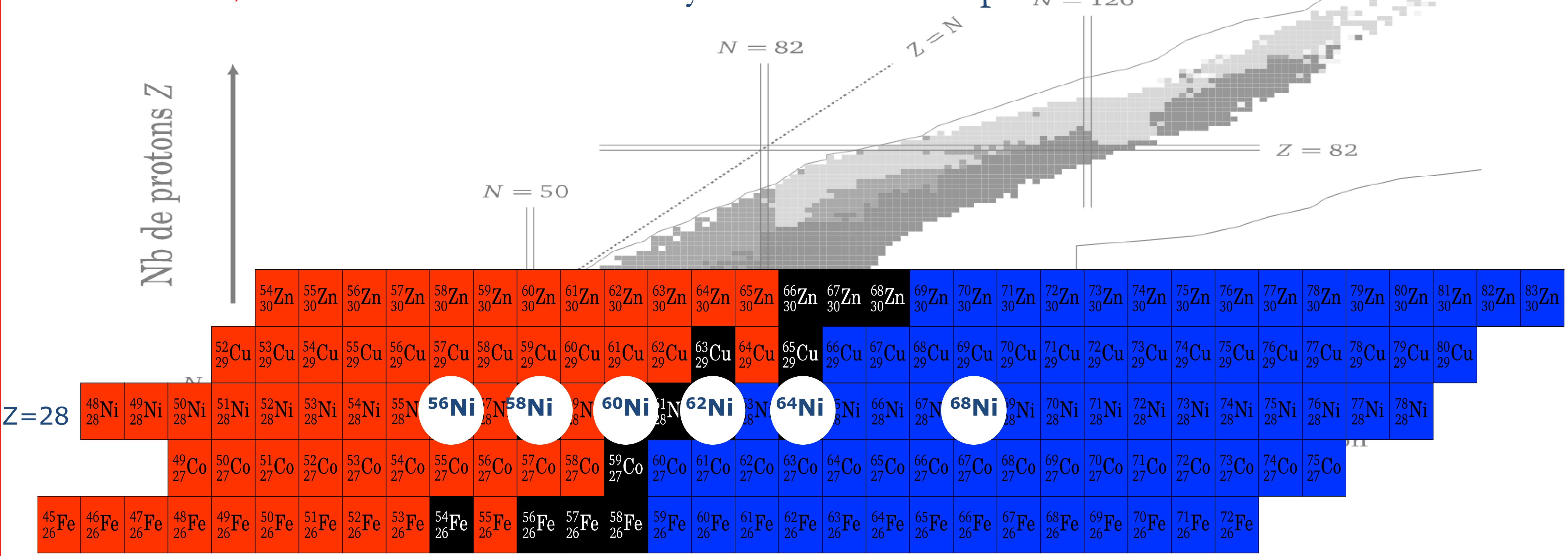
- First pioneering experimental results obtained at the CS beam of NFN-LNS and MAGNEX for the $^{40}Ca(^{18}O,^{18}Ne)^{40}Ar$ reaction at 270 MeV, give encouraging indication on the capability of the proposed technique to access relevant quantitative information.

- High beam intensity is the new frontier for these studies with a substantial change in the technologies used : CS upgrade + MAGNEX upgrade

Status of the GR measurement in unstable nuclei

- Understand these excitation modes from stable to exotic nuclei : the IVGDR/PDR has been measured in ^{68}Ni, neutron rich Oxygen and Tin isotopes at GSI, in ^{26}Ne at Riken
- 1st measurement of the ISGMR and ISGQR in unstable nuclei ^{56}Ni : *^{56}Ni(d,d')^{56}Ni**
  Monrozeau *et al., Phys. Rev. Lett.* **100,** 042501 (2008)

⇨ Study of the ISGMR and ISGQR in a neutron rich Ni :
⇨ **^{68}Ni** Continue the study of the Ni isotopic chain



Study of the ISGMR and ISGQR by inelastic scattering *^{68}Ni(a,a')^{68}Ni** and *^{68}Ni(d,d')^{68}Ni**

M. VANDEBROUCK et al. @ GANIL

Isoscalar Giant Resonances

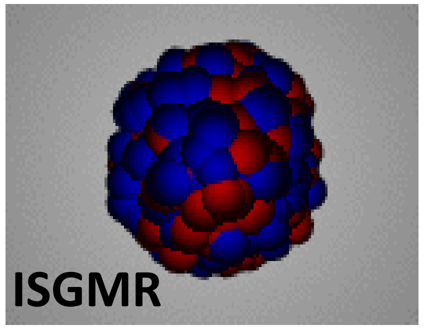
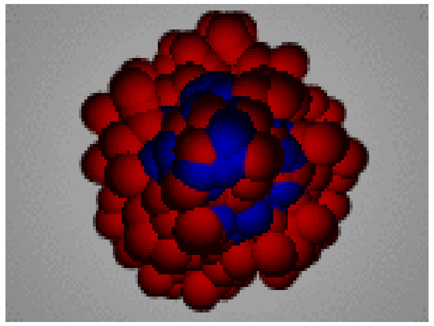
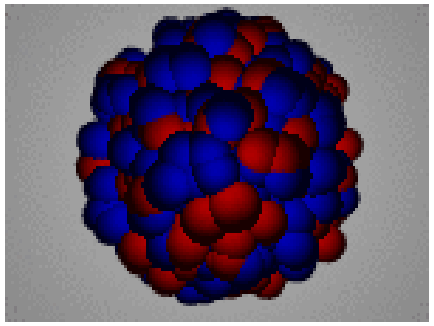
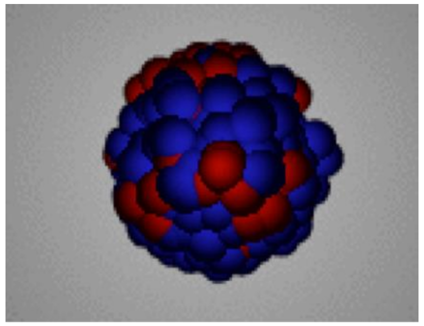
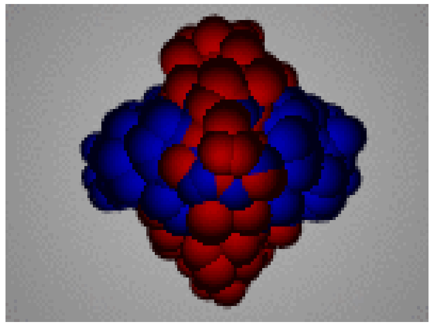
What are giant resonances ?

- **Collective excitation mode**

- Feature :
  - Important cross section (100 mb)
  - Exhaust a large part of the EWSR
  - Properties change smoothly with the number of nucleons

- Quantum number of the excitation :
  - Spin ***S***
  - Isospin ***T***
  - Multipolarity ***L***

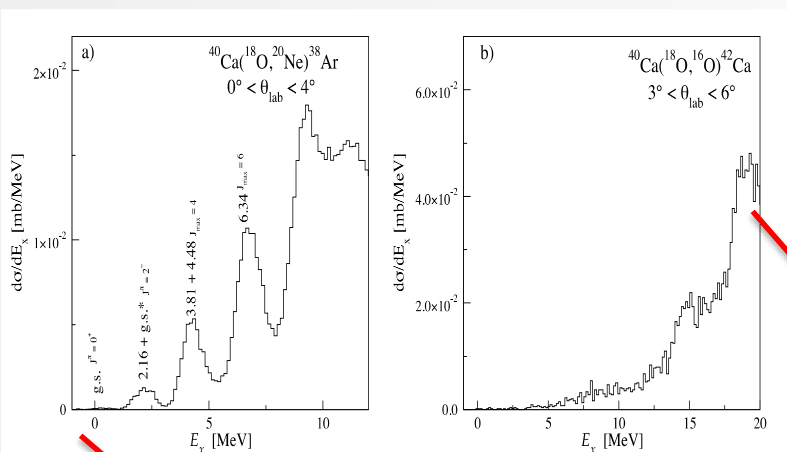
Electric GR :

	T = 0 isoscalar	***T*** = 1 isovectorial
$L = 0$ monopole (GMR)		
$L = 1$ dipole (GDR)		
$L = 2$ quadrupole (GQR)		

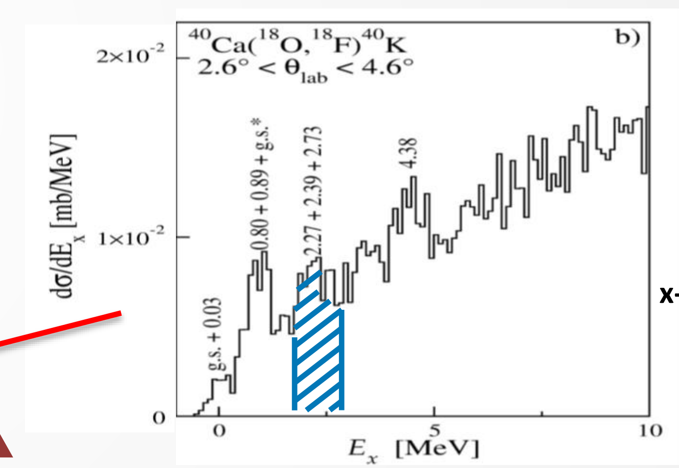
The pilot experiment: $^{40}Ca(^{18}O,^{18}Ne)^{40}Ar$@LNS

- $^{18}O^{7+}$ beam from LNS Cyclotron at **270 MeV (10 pnA)**
- ^{40}Ca solid target of 300 μg/cm²
- Ejectiles detected by the MAGNEX spectrometer
- Angular setting

$$q_{opt} = 4° \longrightarrow \boxed{-2° < q_{lab} < 10°}$$



2n-transfer:
^{16}O)^{42}Ca @ 270 MeV



x-section (2MeV < E_x < 3MeV) ≈ 0.5 mb/sr

Extracted B(GT) = 0.087

B(GT) from (^{3}He,t) = 0.083
Y. Fujita

$^{16}O + ^{42}Ca$

$^{18}O + ^{40}Ca$

$^{40}Ca(^{18}O,^{18}F)^{40}K$

$^{18}F + ^{40}K$

$^{18}Ne + ^{40}Ar$

2p-transfer:
$^{40}Ca(^{18}O,^{20}Ne)^{38}Ar$ @ 270 MeV

$^{20}Ne + ^{38}Ar$

Measured

Not measured

R&D : exclusive measurements

INFN LNS Istituto Nazionale di Fisica Nucleare

SCINTILLATORS ARRAY

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- **improve energy resolution** from the present limit of ≈ 1 MeV for 50 MeV/u heavy ions (1/1000 of 1 GeV ^{18}Ne), mandatory for DCE reactions.
- Work with an **intense flux of γ-rays** and neutrons to **optimize signal-to-noise ratio and reduce spurious** coincidences.
- Work done on **HPGe and LaBr$_3$ by other collaborations** that can be used for this purpose;

CsI or NaI seems more promising for high rates applications.

- Members of the Italian-Brasilian (INFN-IFUSP-IFUFF collaboration MoU) collaboration are interested to collaborate on this topics with possible in-kind contribution in the future development of NUMEN.

R&D: increase the magnetic rigidity

Present day

magnetic rigidity :

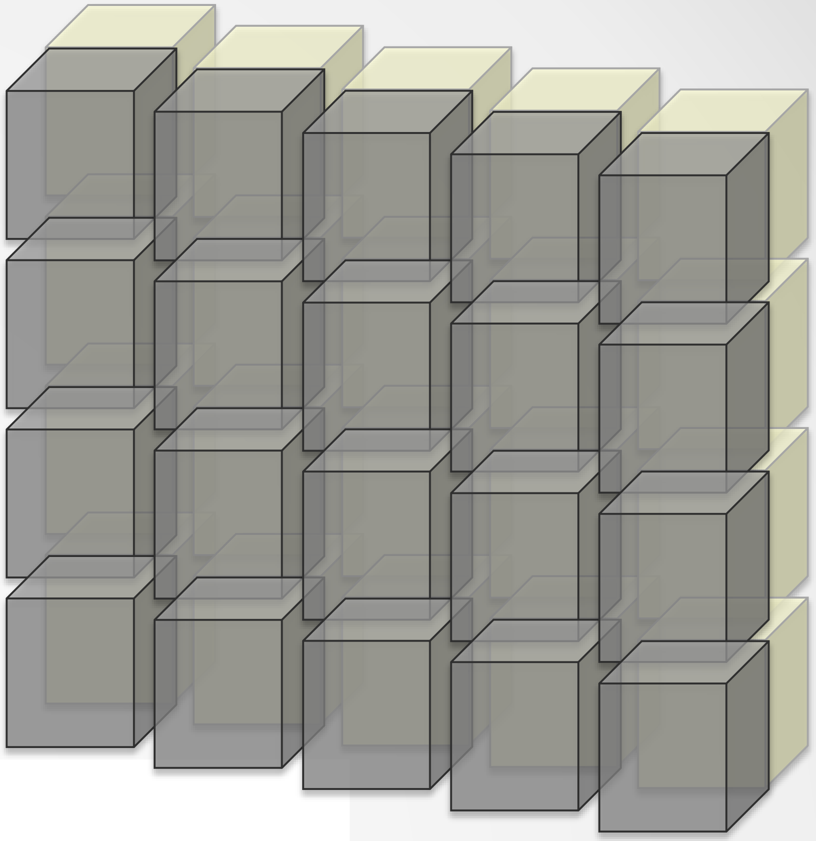
1.8 Tm i.e. 50 MeV/u $^{18}Ne^{10+}$ and ≈ 30 MeV/u $^{20}O^{8+}$

To extend the dynamical conditions

magnetic rigidity :

- 2.8 Tm requires superconducting magnets with present MAGNEX optical layout
- **Power supply upgrade** to obtain 2.1-2.2 Tm i.e. 70 MeV/u $^{18}Ne^{10+}$ and ≈ 42 MeV/u $^{20}O^{8+}$

NUMEN requirements



- ✓ 1x1 cm^2 ΔE-E telescope
- ✓ thickness of ΔE stage 100 μm
- ✓ thickness of E stage 500-1000 μm
- ✓ hard to the radiation damage
- ✓ good energy resolution (1-2 %)
- ✓ High stability (electric and thermal)

RD50 - CERN

Property	**Diamond**	**GaN**	**4H SiC**	**Si**
E_g [eV]	**5.5**	**3.39**	**3.26**	**1.12**
$E_{breakdown}$ [V/cm]	10^7	$4\cdot10^6$	$2.2\cdot10^6$	$3\cdot10^5$
μ_e [cm^2/Vs]	1800	1000	800	1450
μ_h [cm^2/Vs]	1200	30	115	450
v_{sat} [cm/s]	$2.2\cdot10^7$	-	$2\cdot10^7$	$0.8\cdot10^7$
Z	6	31/7	14/6	14
ε_r	5.7	9.6	9.7	11.9
e-h energy [eV]	**13**	**8.9**	**7.6-8.4**	**3.6**
Density [g/cm3]	3.515	6.15	3.22	2.33
Displacem. [eV]	**43**	**≥15**	**25**	**13-20**

NUMEN

- Wide bandgap (3.3eV)

⇒ lower leakage current than silicon

- Signal (**for MIP !**):
  Diamond 36 e/μm
  SiC 51 e/μm
  Si 89 e/μm

⇒ more charge than diamond Si/SiC≈2

- Higher displacement threshold than silicon

⇒ radiation harder than silicon

An energy resolution of 400 keV (fwhm or sigma?) is quoted.

The quoted value of 400 keV is an estimation of the final uncertainty in the reconstructed excitation energy spectrum at E*=20 MeV, i.e. about 2%. It has been calculated as the square root of the sum of the squares of the single uncertainties, originating from different sources. Among them, the two that contribute most are:

- **Energy loss of the deuterons in the target. In case of reactions occurring in the middle of the target, this effect contributes for ∼200 keV.**

- Energy resolution of the Si strip. The beam energy is reconstructed, event-by-event, from the measured energy loss in the Si-strip tagging detector. The latter has an energy resolution of about 1% (FWHM). Due to this energy resolution, the beam energy is reconstructed with an uncertainty of ∼20 MeV. However, due to the favorable (in this case) inverse kinematics condition, this value is responsible for an uncertainty of only ∼300 keV in the excitation energy spectrum.

The contributions of other less-critical sources, like the deuteron energy and angular straggling and the beam angular straggling have been estimated using the SRIM code. These are ∼90 keV, ∼30 keV and ∼40 keV, respectively.