Large acceptance magnetic spectrometers in nuclear physics: the case of MAGNEX at the INFN-LNS

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Using magnetic fields to learn about microscopic world

\[
\vec{F} = q \vec{v} \wedge \vec{B}
\]

If \( \vec{v} \perp \vec{B} \) and \( \vec{B} \) is uniform

\[
B \rho \Rightarrow \frac{p}{q} \xrightarrow{\text{classically}} \frac{mv}{q}
\]

Macrosopic world \quad Microscopic world

- If \( B \) is known a measurement of \( \rho \) corresponds to a measurement of \( p / q \)
- If also \( q \) is known, by supplemental detectors, one gets information about \( p \) (momentum spectrometry)
- If one also knows the velocity of the particle one directly access its mass (mass spectrometry)
Some historical background

At least 6 Nobel prizes have been awarded to now for studies connected to magnetic spectrometry

Mme Curie 1904 Ph.D thesis
Discovery of different kind of radioactivities

Francis W. Aston 1922 Nobel lecture; Mass spectra and Isotopes

2002: The prize is being awarded with one half jointly to: JOHN B. FENN, and KOICHI TANAKA, for their development of soft desorption ionisation methods for mass spectrometric analyses of biological macromolecules
Main Concepts

- Describing the motion of large numbers of charged particles through complicated magnetic fields
- Average motion and the concept of beam
- Analogy between beam trajectory and light ray
- Optics of charged particle beams
- Phase space and Liouville theorem
Some analogy

Prism

- high frequency
- low frequency

Deflection depending on the frequency

Magnetic dipole

- high p/q
- low p/q

Deflection depending on p/q

Transform frequency or p/q intervals in position intervals

Dispersive elements

May be used as analysers
Some analogy

Convergent and divergent lenses

Magnetic quadrupole

Focus not depending on the frequency

Focus not depending on the p/q

To 1st approximation

Focusing elements

May be used to concentrate intensity
Light spectrometer

Magnetic spectrometer

Focus depends on frequency

Focus depends on p/q
**Large acceptance**

- General optics

High resolution $\rightarrow$ small acceptance

source $\rightarrow$ pointlike image

All the rays have a common focus

Large acceptance $\rightarrow$ aberrations

source $\rightarrow$ broad image

Each ray has its own trajectory: focus not anymore a useful concept
Natural recipes for large acceptance: Human versus fly eyes

- Large acceptance optical devices
- Many small lenses in the fly versus a unique large one for man. **Strong aberrations for us.**
- Aberrations greatly compensated by **brain reconstruction** of the image
- Reconstruction based on neural networks and a **long learning step**
- What about a **“clever”** spectrometer?
Magnetic spectrometry and nuclear reactions

Low bombarding energy

Fusion reactions

Direct reaction

Nuclear reactions produce fragments (charged particles) and radiation ($\gamma$-rays)

Fragments carry the elementary information of the structure of colliding nuclei and of the reaction mechanism
Looking for fragments

- Fragments: what, at what angle and at what energy?
- Magnetic spectrometers can provide extremely clean information about fragments
- Typically one has $10^{9+11}$ nuclei/sec (beam intensity) colliding against $10^{16+18}$ nuclei/cm$^2$ (target thickness)
- Studying a particular reaction is how to look for a needle in a hay stack
- Rare events needs large optical devices not to loose information and effective suppression of unwanted background

Large lenses = large aberrations
Magnetic spectrometers in nuclear physics

- Nuclear physicists initially conceived magnetic spectrometers for accurate energy measurements.

- Soon it was demonstrated that they can detect reaction products at very forward angles, including zero degree, or to measure accurate reaction cross-sections and/or to identify fast heavy ions.

Consequently, magnetic spectrometers quickly became essential tools in nuclear physics laboratories.

Different layouts have been established, depending on the optimization of one of these functions.
**Clever Spectrometers**

**Tracking instead of focusing**

Possible definition: spectrometer reconstructing a net image by an optically aberrated one

Practically

\[
x_f = F_1(x_i, \theta_i, y_i, \phi_i, l_i, \delta_i)
\]

\[
\theta_f = F_2(x_i, \theta_i, y_i, \phi_i, l_i, \delta_i)
\]

\[
y_f = F_3(x_i, \theta_i, y_i, \phi_i, l_i, \delta_i)
\]

\[
\phi_f = F_4(x_i, \theta_i, y_i, \phi_i, l_i, \delta_i)
\]

\[
l_f = F_5(x_i, \theta_i, y_i, \phi_i, l_i, \delta_i)
\]

\[
\delta_f = \delta_i
\]

inversion

\[
x_i = F'_1(x_f, \theta_f, y_f, \phi_f, l_f)
\]

\[
\theta_i = F'_2(x_f, \theta_f, y_f, \phi_f, l_f)
\]

\[
y_i = F'_3(x_f, \theta_f, y_f, \phi_f, l_f)
\]

\[
\phi_i = F'_4(x_f, \theta_f, y_f, \phi_f, l_f)
\]

\[
\delta = F'_5(x_f, \theta_f, y_f, \phi_f, l_f)
\]

One needs

- **High order inversion algorithms** (especially for large acceptance)
- **Detectors** to measure positions and angles at the focus
- **Detailed knowledge of the magnetic field maps**

Long learning step, i.e. huge calculations
Examples of magnetic spectrometers

• First one designed by Van der Graaff and collaborators

**High resolution**

Grand-Raiden@RCNP, K600@i-Themba Q3D, Split Poles, Elbek ...

**Large acceptance**

MAGNEX@LNS Catania VAMOS@GANIL PRISMA@LNL
The MAGNEX spectrometer

Dipole

Quadrupole

Focal Plane Detector

Target

PSD

Incident beam
MAGNEX: a QD spectrometer

- **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)

- **The surface coils**, located between the dipole pole faces and the inner high vacuum chamber, giving tunable quadrupolar and sextupolar corrections
Software ray-reconstruction

ALGEBRIC RAY-RECONSTRUCTION

1) Detailed knowledge of the geometry and magnetic field

2) Algorithm to transport and invert

3) High resolution measurement at the focal plane (highly performing detectors)

- Solution of the equation of motion for each detected particle
- Inversion of the transport matrix
- Application to the final measured parameters

\[ F : \vec{X}_i \rightarrow \vec{X}_f \]

\[ F^{-1} : \vec{X}_f \rightarrow \vec{X}_i \]
MAGNEX Focal Plane Detector

Section view

60 Silicon Detectors
→ \( E_{res} \)

5 Proportional Wires
→ \( \Delta E \)

4 Induction Strip
→ \( X_1, X_2, X_3, X_4 \)
→ \( X_{foc}, \theta_{foc} \)

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

Ion identification
Ray-reconstruction

• M. Cavallaro et al. EPJ A 48: 59 (2012)
• D. Carbone et al. EPJ A 48: 60 (2012)
MAGNEX technicalities

- Solid angle $\Omega = 50$ msr
- Momentum byte $\Delta p/p \sim 24$
- Zero degree mode
- Energy $\delta E/E \sim 1/1000$
- Angle $\delta \theta \sim 0.2^\circ$
- Mass $\delta m/m \sim 1/160$
- Wide mass range ($A < 100$)
- Wide energy range ($E = 0.5$ MeV - 1000 MeV)
- Wide angular range ($\theta_{\text{lab}} = -20^\circ +90^\circ$)

A tool for multi-user facility with unique features

F. Cappuzzello et al., in: Magnets: Types, Uses and Safety, Nova Publisher Inc., New York, 2011, pp 1-63
MAGNEX: manyfold research lines

- **Pairing correlations**
  - *Italy, France, Brasil*

- **Nuclear break-up**
  - *Greece, Italy, Spain*

- **Pick-up reactions**
  - *Italy, France, Japan*

- **Nuclear rainbow**
  - *Brasil, Italy*

- **α-Clustering**
  - *Brasil, Italy*

- **Giant monopole by FRIBS beams**
  - *Italy*

- **Single and double charge exchange**
  - *Italy, Japan, Brasil, Greece*

- **Ab initio**
  - *Canada, Italy, Brasil, Morocco*

Quick and partial overview today
A mature activity: the research of pairing correlation in \((^{18}\text{O},^{16}\text{O})\) transfer reactions
Main results

Pairing correlations
Italy, France, Brasil


F. Cappuzzello et al. Nature Comm. 6 (2015) 6743


✓ Several experiments performed

✓ Major physics output:
  • Signatures of the GPV
  • Determination of pair spectroscopic factor
  • Superconductivity in few body systems?
MAGNEX + EDEN

EDEN

MAGNEX + EDEN

$E = 30$ keV$(ee)$  
$M = 1.00 \pm 0.03$

$S_n = 1.22$ MeV

$4.21$ MeV

$\gamma$

$n$

Neutron energy (MeV)

EDEN installed in the MAGNEX hall
• New electronics from INFN-Mi (BaFpro)
• Neutron energy from ion trajectory reconstruction

First physics output:
• Study of neutron decay
• Neutron branching ratios

M. Cavallaro, et al., NIM A 700 (2013) 65–69
M.Cavallaro, et al, PRC 93 (2016) 064323
The NUMEN perspective at INFN@LNS
The NUMEN project

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\[ \frac{1}{T^{0\nu}} \left( 0^+ \rightarrow 0^+ \right) = G_{01} \left| M_{\beta\beta 0\nu} \right|^2 \frac{\langle m_\nu \rangle^2}{m_e} \]
Double $\beta$-decay

$$\frac{AX}{Z} \rightarrow Z-2Y_{N+2} + 2e^- + (2\bar{\nu})$$

- Process mediated by the **weak interaction** occurring in even-even nuclei where the single $\beta$-decay is energetically forbidden

- The role of the **pairing force**
Double $\beta$-decay

**Two-neutrino double beta decay**

Observed in 11 nuclei since 1987

- Within standard model
- $T_{1/2} \approx 10^{19}$ to $2 \times 10^{21}$ yr

\[
1 / T^{2\nu}_{1/2} (0^+ \rightarrow 0^+) = G_{2\nu} |M^{\beta\beta 2\nu}|^2
\]

**Neutrinoless double beta decay**

Still not observed

- Beyond standard model
- Access to effective neutrino mass
- Violation of lepton number conservation
- CP violation in lepton sector
- A way to leptogenesis and GUT

\[
1 / T^{0\nu}_{1/2} (0^+ \rightarrow 0^+) = G_{0\nu} \left| M^{\beta\beta 0\nu} \right|^2 \left( \langle m_\nu \rangle / m_e \right)^2
\]

M. Goeppert-Mayer, Phys Rev. 48 (1935) 512

E. Majorana, Il Nuovo Cimento 14 (1937) 171

W. H. Furry, Phys Rev. 56 (1939) 1184
New physics for the next decades

but requires

Nuclear Matrix Element (NME)!

\[ |M_{\epsilon}^{\beta\beta0\nu}|^2 = \left| \langle \Psi_f | \hat{O}_{\epsilon}^{\beta\beta0\nu} | \Psi_i \rangle \right|^2 \]

✓ Calculations (still sizeable uncertainties): QRPA, Large scale shell model, IBM, EDF, ab-initio ..... 

✓ Measurements (still not conclusive for 0νββ):
  \( (\pi^+, \pi^-) \)
  single charge exchange (\(^3\)He,t), (d,\(^2\)He)
  electron capture
  transfer reactions
  muon capture ...

✓ A new experimental tool: heavy-ion Double Charge-Exchange (DCE)
State of the art NME calculations

\[ M^{(0\nu)} = M_{GT}^{(0\nu)} - \left( \frac{g_V}{g_A} \right)^2 \left( M_F^{(0\nu)} + M_T^{(0\nu)} \right) \]

Courtesy of Prof. F. Iachello
Heavy-ion DCE

- Induced by strong interaction

- Sequential nucleon transfer mechanism 4\textsuperscript{th} order:
  

- Meson exchange mechanism 2\textsuperscript{nd} order

- Possibility to go in both directions

Tiny amount of DGT strength in low lying states

Sum rule almost exhausted by DGT Giant Mode
$^{40}\text{Ca}(^{18}\text{O},^{18}\text{Ne})^{40}\text{Ar} @ 270 \text{ MeV}$


Pauli blocking about 0.14 for F and GT
The role of the transfer reaction and the competing processes

Very weak

$^{40}\text{Ca}(^{18}\text{O},^{16}\text{O})^{42}\text{Ca}$
$3^\circ < \theta_{\text{lab}} < 6^\circ$

Extracted $B(\text{GT}) = 0.087$

$B(\text{GT})$ from $(^{3}\text{He},t) = 0.083$

Y. Fujita

Less than 1% effect in the DCE cross section

2p-transfer

$^{2p}\text{-transfer}$

2n-transfer

$^{2n}\text{-transfer}$

Single charge exchange

$x$-section ($2\text{MeV} < E_x < 3\text{MeV}$)

$\approx 0.5 \text{ mb/sr}$

$^{40}\text{Ca}$

$^{42}\text{Ca}$

$^{38}\text{Ar}$

$^{40}\text{K}$

$^{40}\text{Ca}$

$^{40}\text{K}$
The $(^{18}\text{O},^{18}\text{Ne})$ reaction is particularly advantageous, but it is of $\beta^+\beta^+$ kind;

None of the reactions of $\beta^-\beta^-$ kind looks like as favourable as the $(^{18}\text{O},^{18}\text{Ne})$. $(^{18}\text{Ne},^{18}\text{O})$ requires a radioactive beam $(^{20}\text{Ne},^{20}\text{O})$ or $(^{12}\text{C},^{12}\text{Be})$ have smaller $B(\text{GT})$

The reaction $Q$-values are normally more negative than in the $^{40}\text{Ca}$ case

In some cases gas or implanted target will be necessary, e.g. $^{136}\text{Xe}$ or $^{130}\text{Xe}$

In some cases the energy resolution is not enough to separate the g.s. from the excited states in the final nucleus → Coincident detection of $\gamma$-rays

Much higher beam current is needed
Major upgrade of LNS facilities: The CS accelerator

- The **CS** accelerator current (from 100 W to 5-10 kW);

- The **beam transport line** transmission efficiency to nearly 100%

**Project approved by INFN (~10M€)**
A challenging beam dump inside the MAGNEX hall

Present MAGNEX hall

Possible MAGNEX hall
Major upgrade of LNS facilities: the MAGNEX spectrometer

- The **MAGNEX focal plane** detector rate (from few kHz to several MHz)

  - From multi-wire tracker
  - To micro-pattern tracker

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

- INFN-LNS (M. Cavallaro), collaboration with INFN-CT, UNAM

- From wall of 60 Si pad
- To wall of 2500 SiC-SiC-SiC pad telescopes

  - A big challenge!
  - 0.9 M€ call approved by INFN CSN5 (SICILIA)
  - P.I. S.Tudisco, collaboration with CNR, STM, FBK
SiC detectors: state of art

The Schottky diodes are fabricated by epitaxy onto high-purity 4H–SiC n-type substrate.

**Limits**

- Thickness of EPI-Layer ≈ 80 μm
- Detection surface
- Substrate Thickness ≈ 200 μm

**Target**

- p-n junctions
- Schottky diodes

**Major upgrade required by NUMEN**

- 1x1 cm² ΔE-E telescope
- thickness of ΔE stage 100 μm
- thickness of E stage 500-1000 μm
Front-end and read-out electronics

ELECTRONICS PROTOTYPES (D. LoPresti)

1) ASIC front–end chip:

for FPD chip **VMM2(3)** in collaboration with Brookhaven National Laboratory (8x10^4 transistor/channel for 64 channels)

2) Read – out: new generation of **FPGA** and System On Module (**SOM**)  

Number of channels

- Gas tracker ~ 2000 ch  
- SiC-SiC ~ 7500 ch  
- γ-ray calorimeter ~ 2500 ch

Tot ~ 12000 ch
Other upgrades

• The **MAGNEX** maximum magnetic **rigidity** (from 1.8 Tm to 2.2 Tm)

• An **array of detectors for γ-rays** measurement in coincidence with MAGNEX (in collaboration with IFUSP and IFUFF (J. de Oliveira))

• The **target** technology for intense heavy-ion beams (developed by Poli Torino and INFN (D.Calvo))

• **Nuclear reaction theory** (formal development and calculations) coordinated by INFN CSN-IV (M. Colonna) in collaboration with H. Lenske.

• **Data Acquisition** (L. Pandola)

• **Data Reduction** (D. Carbone)
The Phases of NUMEN project

- **Phase 1**: The experimental feasibility
- **Phase 2**: “hot” cases optimizing the experimental conditions, getting first results and complete the tender for the new accelerator and detector (approved)
- **Phase 3**: The facility Upgrade (Cyclotron, MAGNEX, beam lines, ….):
- **Phase 4**: The systematic experimental campaign

### Time table

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Conclusions and Outlooks

- MAGNEX is a **multipurpose** facility for **multi-user** based activities in low energy nuclear physics
- It presents very interesting properties making it a **unique tool in many cases**
- It has played and plays an important role for **attracting worldwide researchers at the LNS**
- The **NUMEN perspective** for the future of LNS in nuclear science turns around the MAGNEX and the Cyclotron upgrade