UNIVERSITÀ DEGLI STUDI FIRENZE

Istituto Nazionale di Fisica Nucleare

The FAZIA apparatus: status and perspectives

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INFN and University of Florence

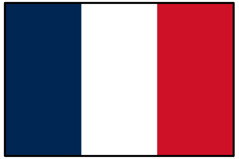
WPCF 2024 - 17th Workshop on Particle Correlations and Femtoscopy
4-8 November 2024, Toulouse

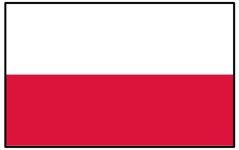
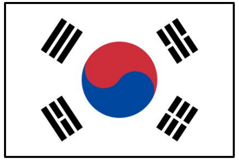
The FAZIA collaboration

FAZIA

Forward **A** and **Z** **I**dentification **A**rray

The FAZIA collaboration is an international research group aimed at operating and maintaining a large modular detector in various nuclear accelerator facilities worldwide.

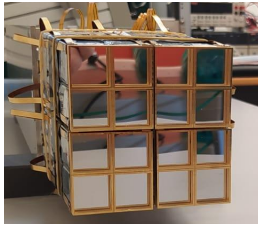



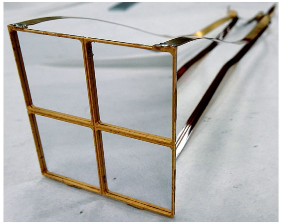
The FAZIA apparatus

Detectors

FAZIA is a modular detector

- **block** - 16 telescopes arranged in 4 quartets to obtain a 4x4 matrix

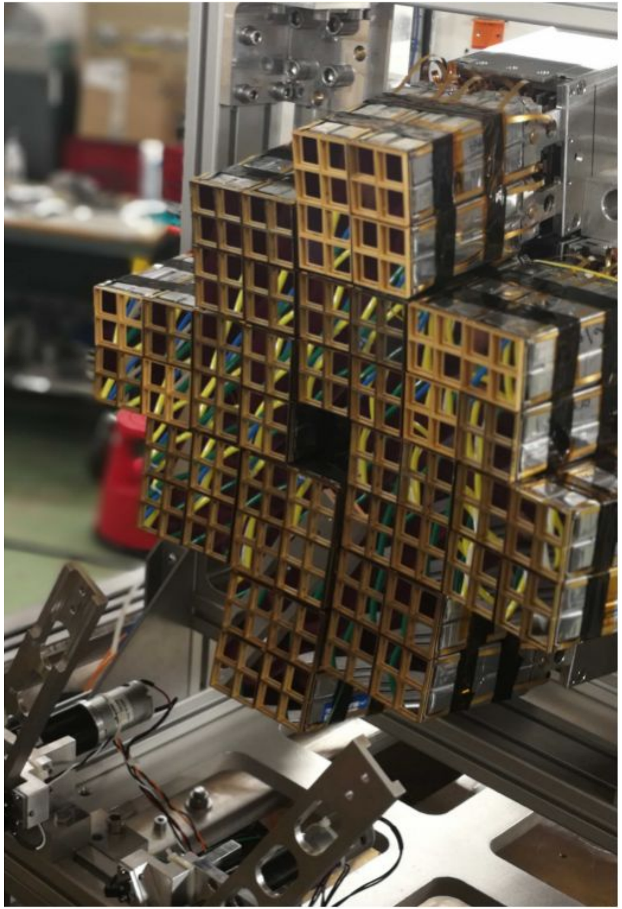




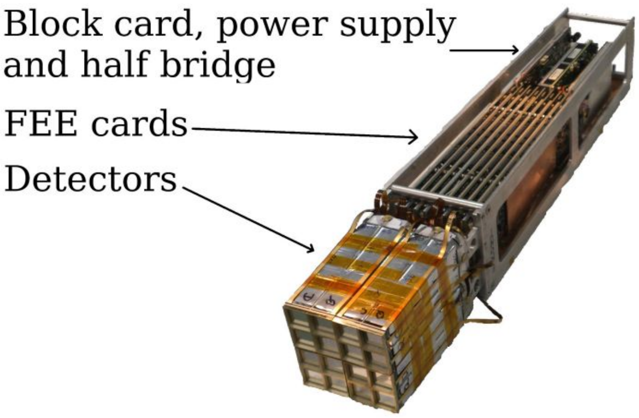
- **telescope** - three layers with active area 20x20 mm^2: **Si (300 μm) - Si (500 μm) - CsI(Tl) (10 cm)**

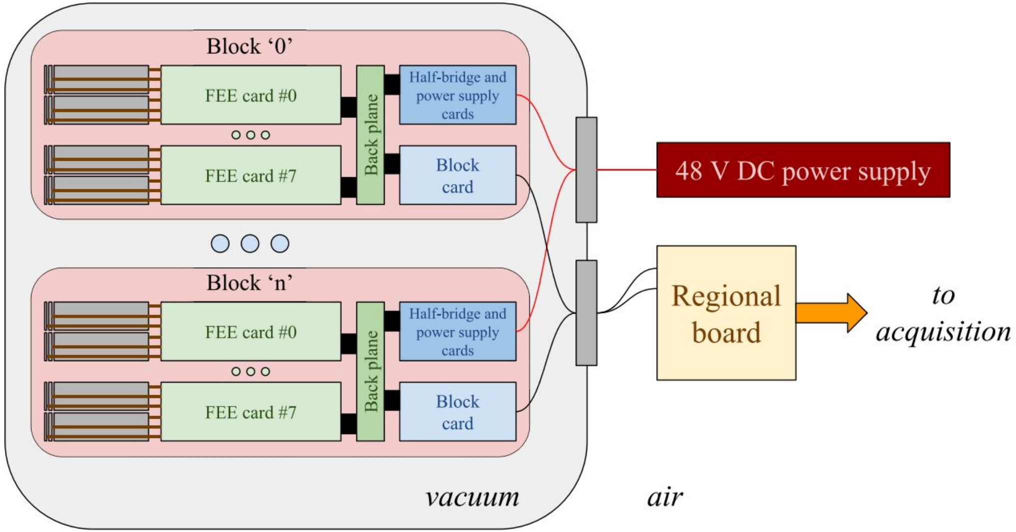
FAZIA "recipe":

- high thickness and doping uniformity
- "random cut" of the Si wafers
- reverse mounting configuration
- monitoring of the silicon reverse current



The FAZIA apparatus
Electronics



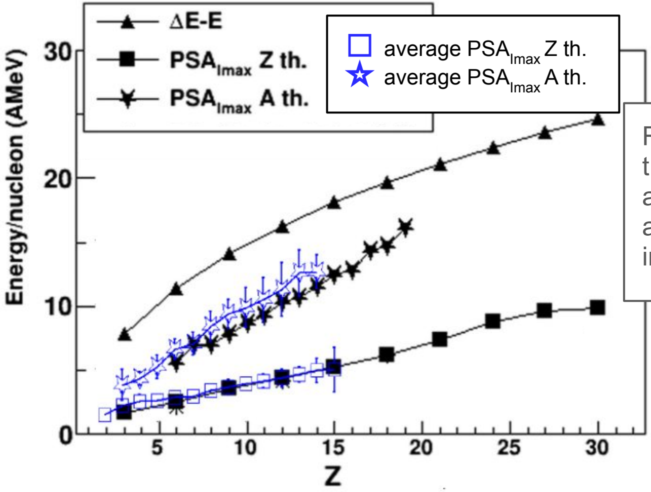


- digital read-out electronics
- placed under vacuum close to the detectors
  - reduce signal distortion and electronic noise
  - minimise the connections needed between the vacuum chamber and outside
- online digital signal processing on the FPGAs of the FEE cards
- ready to be coupled with other apparatuses through timestamp distribution system

The FAZIA apparatus
Identification performances

FAZIA represents the state of the art of ion identification in the Fermi energy domain.

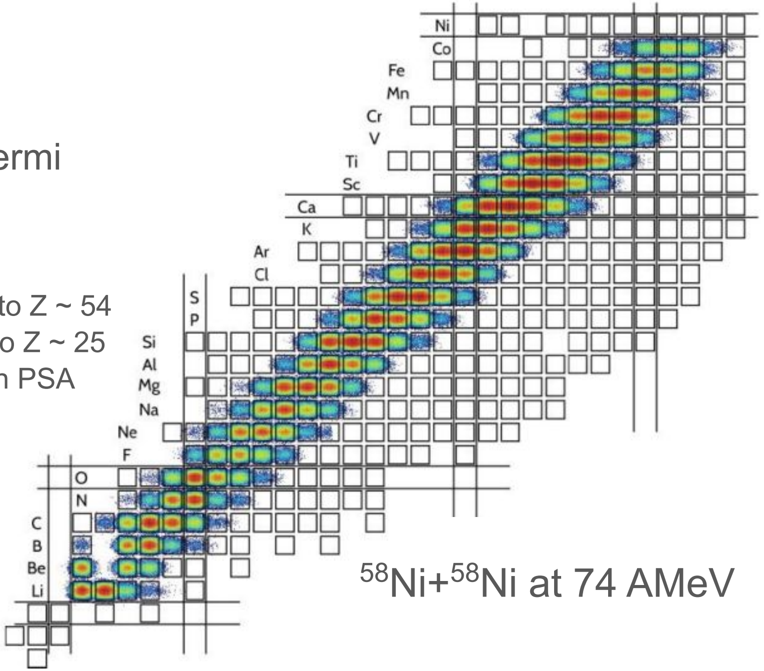
- identification techniques
  - ΔE-E method
  - Pulse Shape Analysis
- identification capabilities
  - charge discrimination up to Z ~ 54
  - isotopic identification up to Z ~ 25 with ΔE-E and Z ~ 20 with PSA



Results obtained from the first experiment and confirmed as average performance in the last experiments

G. Pastore et al., NIMA 860, 42 (2017)

Nuclide chart



$^{58}Ni+^{58}Ni$ at 74 AMeV

- ➔ isospin transport phenomena
- ➔ cluster production
- ➔ spectroscopic studies

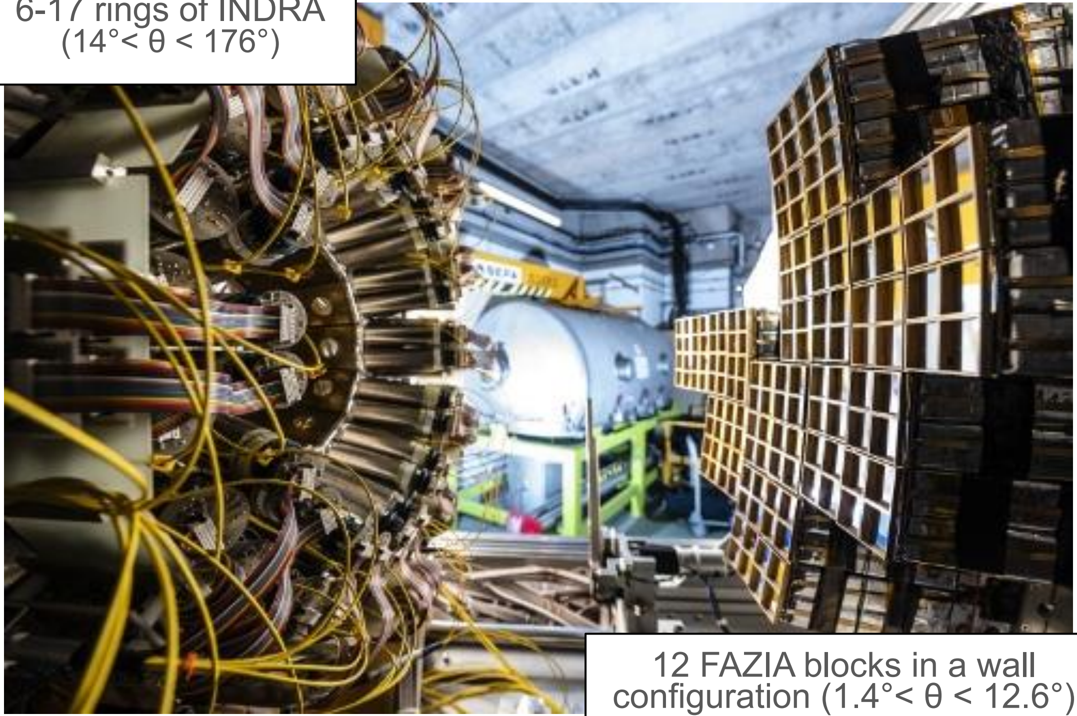
The FAZIA apparatus
History

- 2002-2010: R&D phase which included detectors, identification techniques, electronics, acquisition system
- 2011-2014: test under beam at LNS Catania Italy of the demonstrator (few modules)
- 2015-2018: first experiments at LNS Catania with an increasing number of blocks (from 4 to 6 blocks)
- 2018-2022: construction and operation of 12 FAZIA blocks to be coupled with other devices + 4 additional spare blocks

INDRA-FAZIA at GANIL

In 2019 coupling between FAZIA and INDRA

6-17 rings of INDRA
(14°< θ < 176°)



12 FAZIA blocks in a wall
configuration (1.4°< θ < 12.6°)

INDRA-FAZIA for symmetry energy research

- isotopic identification of forward emitted fragments
- event reconstruction thanks to 80% angular coverage

Experiments:

- E789 (2019) - ^{58,64}Ni+^{58,64}Ni at 32, 52 AMeV
- E818 (2022) - ^{36}Ar,^{58}Ni+^{58}Ni at 74 AMeV

INDRA-FAZIA at GANIL:

E789 experiment: $^{58,64}Ni + ^{58,64}Ni$ at 32 and 52 AMeV

Isospin transport ratio:

F. Rami et al., PRL 84, 1120 (2000)

C. Ciampi et al., PRC 106, 024603 (2022)

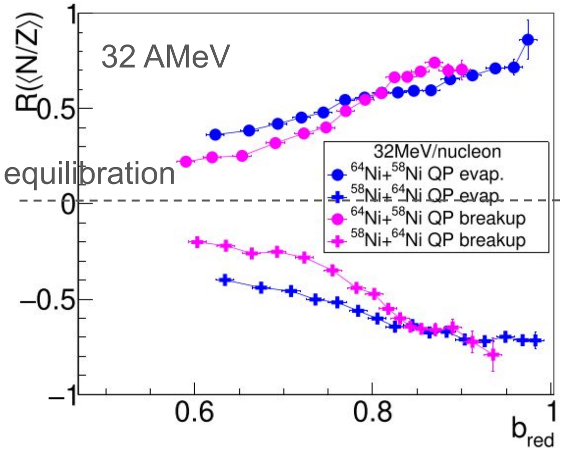
C. Ciampi et al., PRC 108, 054611 (2023)

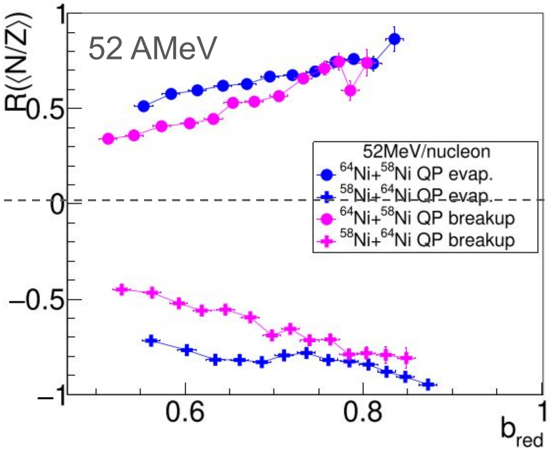
$$R(X_i) = \frac{2X_i - X_{AA} - X_{BB}}{X_{AA} - X_{BB}} \qquad X \equiv N/Z$$

$i = AB, BA$

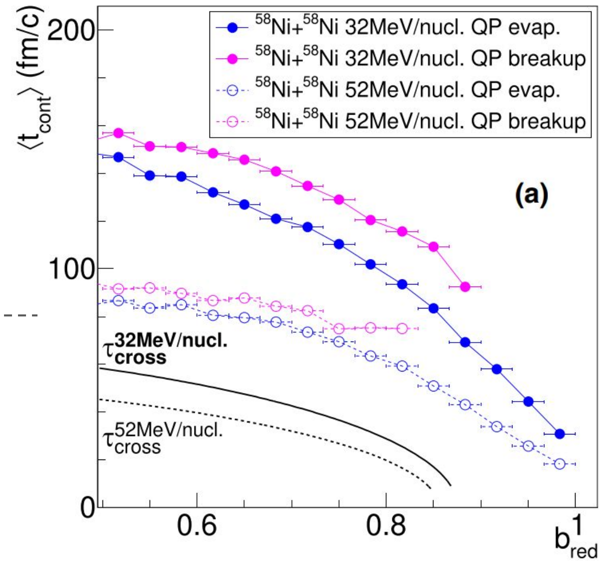
● QP remnant
● QP breakup

equilibration





Contact time extraction from transport models (AMD)



Longer contact time for break-up with respect to the QP remnant → more isospin equilibration

INDRA-FAZIA at GANIL:

E818 experiment: ^{36}Ar,^{58}Ni+^{58}Ni at 74 AMeV

EXTENDING OUR KNOWLEDGE OF WARM DENSE NUCLEAR MATTER IN THE LOW DENSITY REGION.

R. BOUGAULT[1], G. CASINI[2]
FOR THE FAZIA COLLABORATION
AND
F. GULMINELLI[1], H. PAIS[12], C. PROVIDÊNCIA[12]

cluster properties in the warm and low density nuclear matter

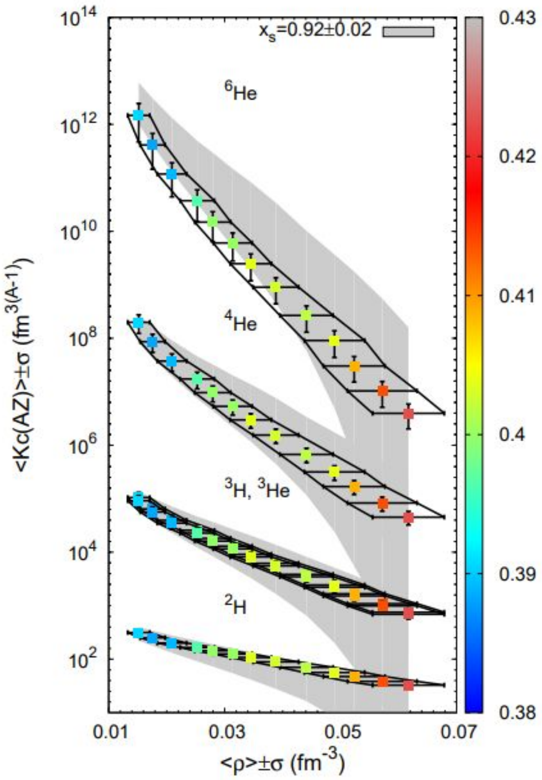
- to extend the in-medium measurements to heavier clusters
- vaporization sources
- FAZIA+INDRA apparatus

Analysis ongoing …

A. Rebillard-Soulié

Chemical equilibrium constants evaluated for mid-rapidity source in ^{124}Xe+^{112}Sn @ 32 AMeV reaction with INDRA.

H. Pais et al. PRL 125 (2020) 012701



INDRA-FAZIA at GANIL:

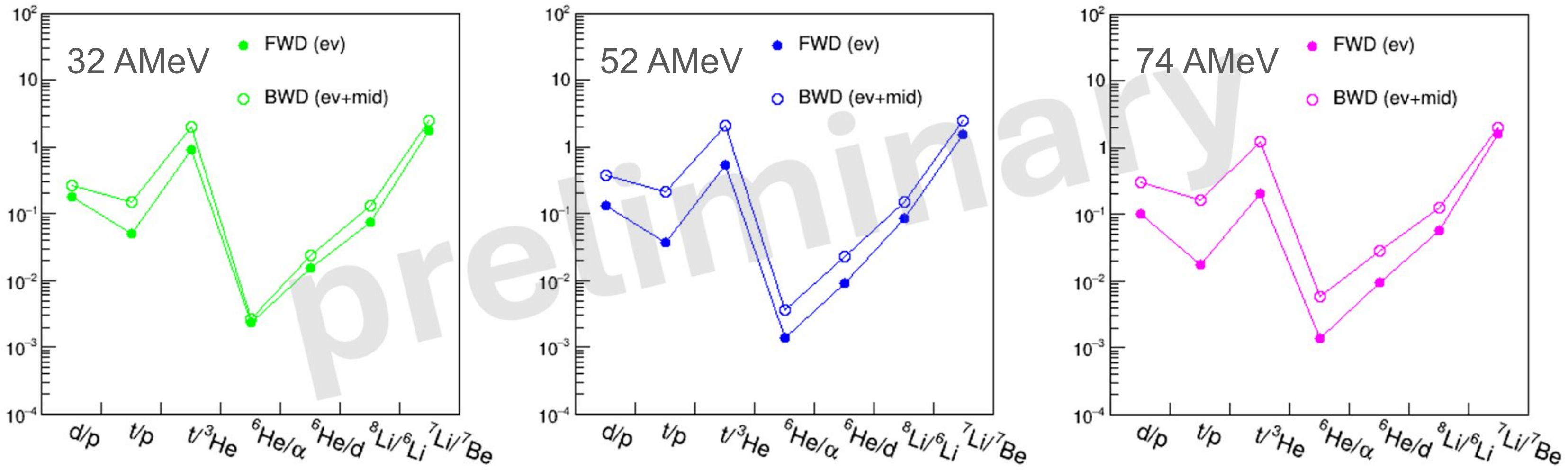
E789 & E818 experiments: ^{58}Ni+^{58}Ni at 32, 52 and 74 AMeV

→ my PhD project: comparison of the ^{58}Ni+^{58}Ni reaction in a broad energy range

- isospin drift
- QP breakup

Analysis ongoing …

Isobaric and isotopic yield ratios



→ clear neutron enrichment in mid-velocity emissions

Next INDRA-FAZIA campaign at Ganil

E884 experiment: $^{70}Zn+^{28}Si,^{70}Zn,^{208}Pb$ at 35 AMeV

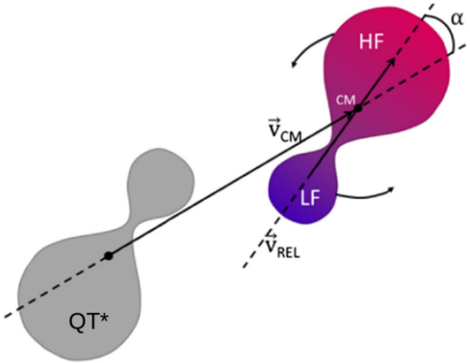
Impact of projectile-target size asymmetry on the isospin equilibration rate extracted from quasiprojectile breakup reactions

C. Ciampi and J. D. Frankland
Grand Accélérateur National d'Ions Lourds (GANIL), CEA/DRF–CNRS/IN2P3, Boulevard Henri Becquerel, F-14076 Caen, France
for the INDRA-FAZIA collaboration

Investigation of isospin transport mechanisms in QP breakup events

- correlation between the α angle and the time scale of the breakup
  - S. Piantelli, PRC 101, 034613 (2020)
  - B. Harvey, PRC 102, 064625 (2020)
- the role of the target
  - K. Brown, PRC 87, 061601(R) (2013)
  - A. Rodriguez Manso, PRC 95, 044604 (2017)

→ investigation of the QP breakup features with a more advanced apparatus in conjunction with a well-controlled characterization of the reaction centrality



A. Jedele et al., PRL 118, 062501 (2017)

Next INDRA-FAZIA campaign at Ganil

E881 experiment: $^{12}C+^{12}C$ at 105 MeV

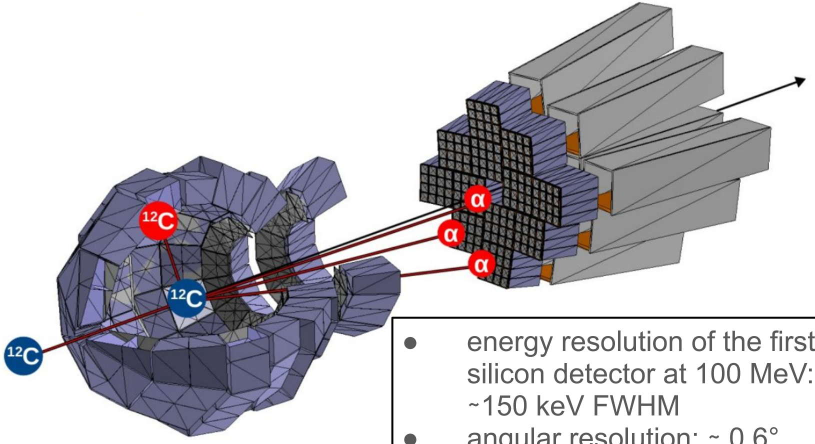
Not only symmetry energy!

Measurement of the ^{12}C Hoyle state radius via double-excitation inelastic scattering

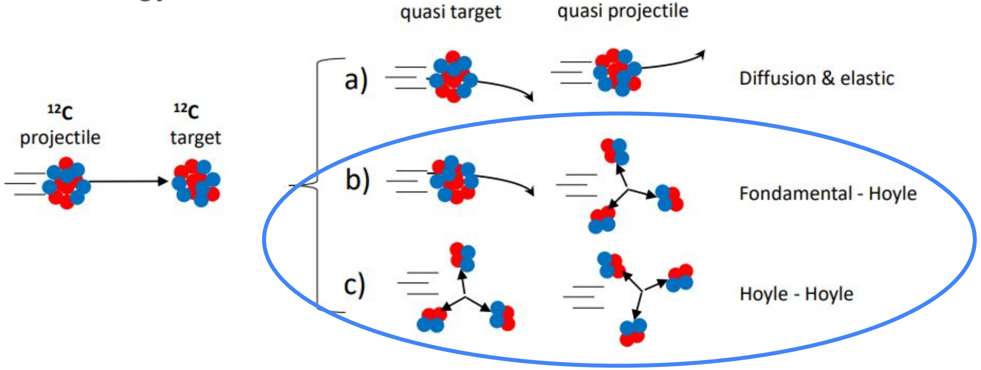
Diego Gruyer*
Université de Caen Normandie, ENSICAEN, CNRS/IN2P3, LPC Caen UMR6534, F-14000 Caen, France

Daniele Dell'Aquila
Dipartimento di Fisica, Università degli Studi di Napoli 'Federico II', Naples, Italy
(INDRA and FAZIA Collaborations)

Measurement of the mean matter radius of the Hoyle state by analyzing the diffraction structure of single- and double-excitation in $^{12}C+^{12}C$ inelastic scattering at 105 MeV beam energy with FAZIA



- energy resolution of the first silicon detector at 100 MeV: ~150 keV FWHM
- angular resolution: ~ 0.6°



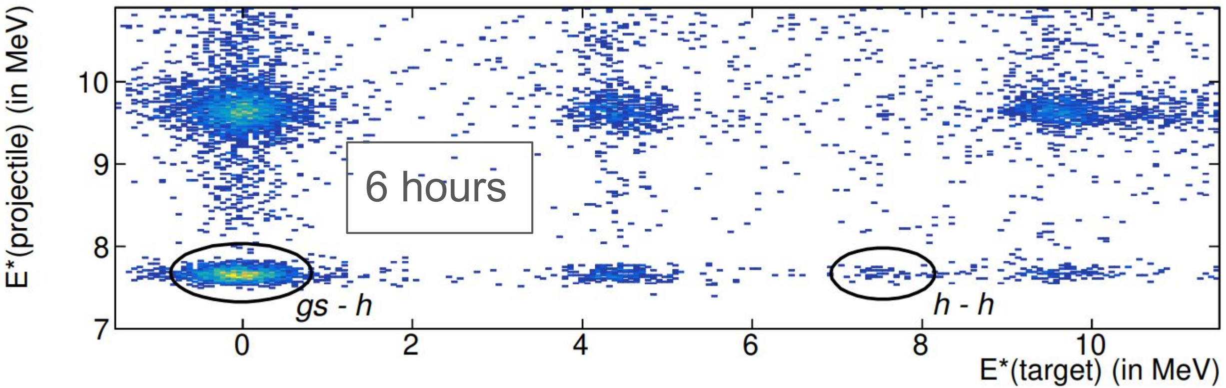
Invariant mass: the $^{12}C(p')$ excitation energy and momentum are reconstructed from the 3α detected in FAZIA.

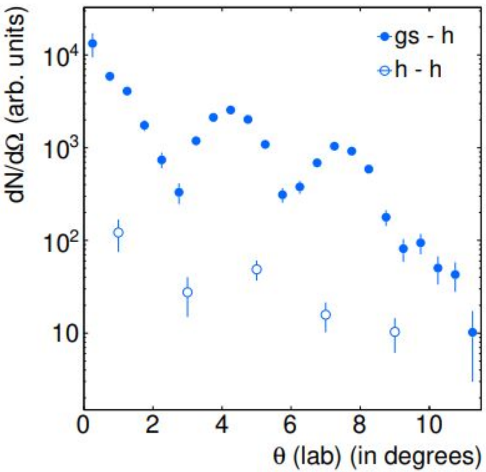
Missing mass: the $^{12}C(t')$ excitation energy can then be deduced from the projectile excitation energy and momentum.

Next INDRA-FAZIA campaign at Ganil

E881 experiment: $^{12}C + ^{12}C$ at 105 MeV

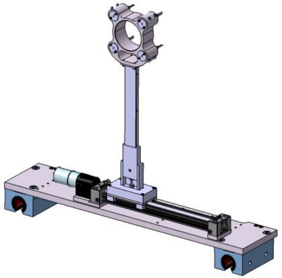
In the E818 experiment, one of the calibration beams was ^{12}C at 8.75 AMeV. After having completed calibrations, we put a ^{12}C target for fun…





Improvements:

- more statistics
- normalization of measured cross-sections using a new beam monitoring device



New opportunities: RAON

Rare isotope Accelerator complex for ON-line experiments

New rare-isotope beam accelerator complex under construction in South Korea

- high intensity RIB by ISOL and IF
  - ISOL: direct fission of ^{238}U by 70 MeV p
  - IF: PF of 200 MeV/u ^{238}U at 8.3 pμA
- high quality neutron-rich beams
  - e.g., ^{132}Sn at 250 MeV/u ~10^8 pps
- more exotic RIBs by combining ISOL and IF

FAZIA activities:

- First phase: testing and experiments with low energy beams (below 20 AMeV)
- Second phase (>2030): very preliminary programs for high energy beams

New opportunities: FRIB

Facility for Rare Isotope Beams
at Michigan State University

Letter of Intent

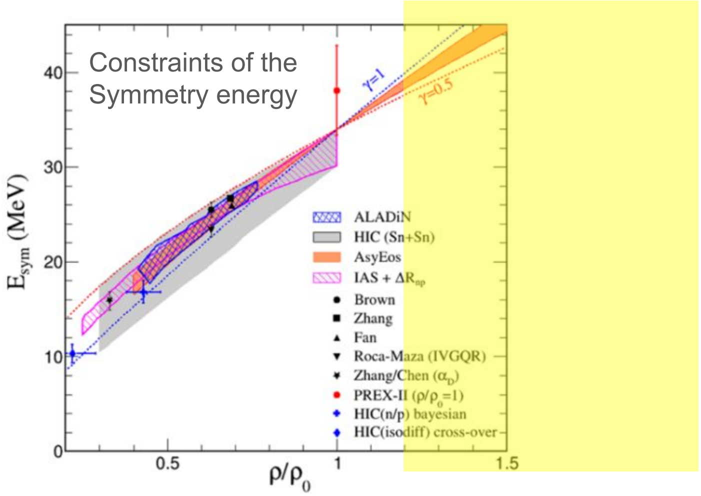
INFN-NUSDAF (INFN - Nuclear Structure, Dynamics and Astrophysics at FRIB)

Giuseppe Verde[1], C. Agodi[2], M. Battaglieri[9], M. Bondì[1], M. Cavallaro[2], M. Colonna[2], D. Gambacurta[2], A. Gottardo[3], L. Lamia[4,2], S. Leoni[5,6], S. Pirrone[1], G. Pizzone[2,4], P. Russotto[2], S. Valdrè[7], J.J. Valiente[3], M. Viviani[8]

on behalf of the ASFIN, CHIRONE, EPIC, GAMMA, JLAB12, NUCL-EX, NUMEN, MONSTRE and NUCSYS groups of INFN (see Appendix 3 for detailed list of institutes)

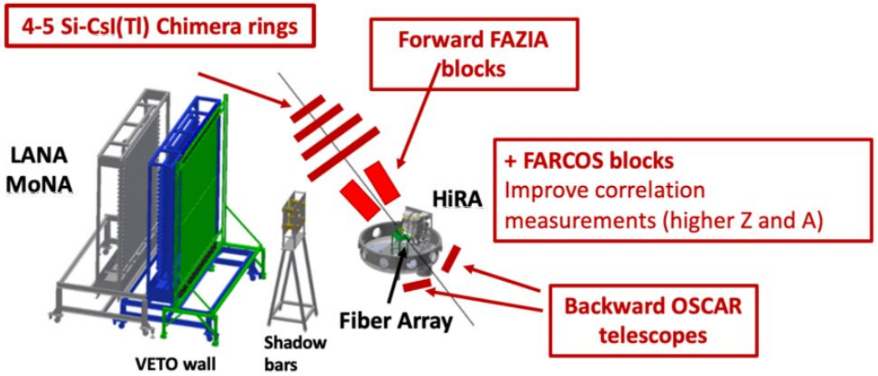
Kyle Brown[10], Giordano Cerizza[10], Zbigniew Chajecki[11], Alexandra Gade[10], Dean Lee[10], Artemis Spyrou[10], Remco Zeger[10]

Local points of contact who agreed to collaborate and support these programs



P. Russotto, et al., Riv. Nuovo Cim. 46, 1 (2023)

Multi-purpose setup



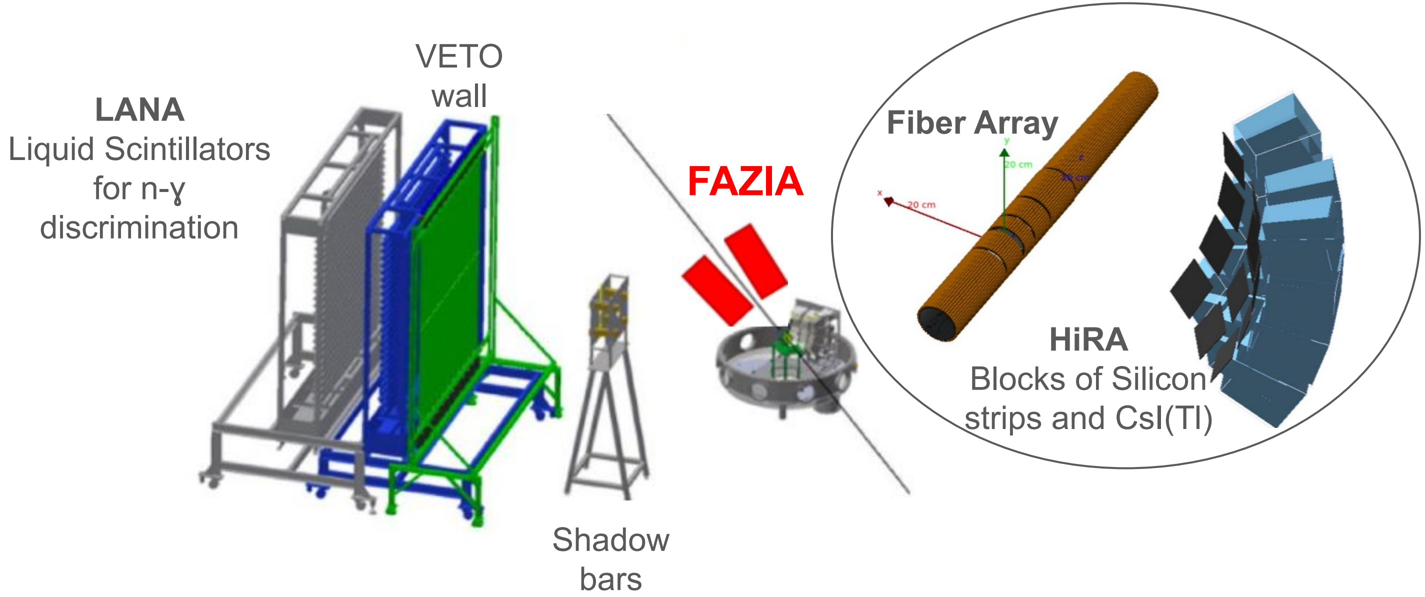
The **SYMEOS (Symmetry Energy and Equation of State)** initiative aims at studying

- the nuclear Equation of State and the Symmetry Energy at densities above saturation, ρ/ρ_0=1.2-2.5
- the Pygmy Dipole Resonances (PDR)
- the particle-particle correlations: Femtoscopy and Invariant Mass Spectroscopy

New opportunities: FRIB

The FAZIA collaboration the next year will participate in the already approved 23058 experiment (K. Brown and Z. Chajecki)

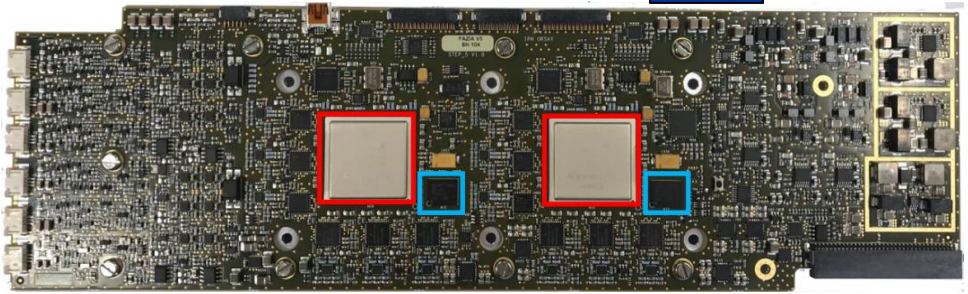
$^{56,70}Ni + ^{58,64}Ni$ at 175 AMeV → measuring the isospin dependence of the nucleon effective mass at supersaturation density



R&D activities for upgrade
Front End Electronics board

Original FAZIA FEE board

S. Valdré, NIMA 930, 27–36 (2019)



Analogue stage | Digital stage | Converters stage

New prototypes - NOTICE South Korea

M. Kweon, NIMB 541, 310–313 (2023)

Renovation of the FEE cards:

- First step: substitution of obsolete components:
  - outdated digital parts were replaced
  - new FPGA chips (Virtex-5 → Kintex-7)
  - new VHDL software developed

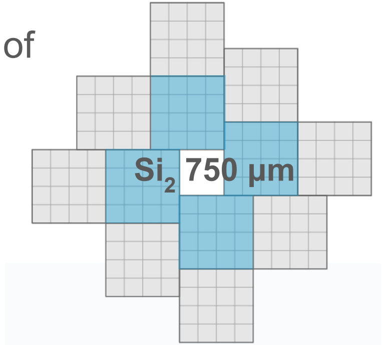
  these new prototypes were tested and validated

- Next step: FEE board more compact and versatile.

R&D activities for upgrade
Silicon detectors

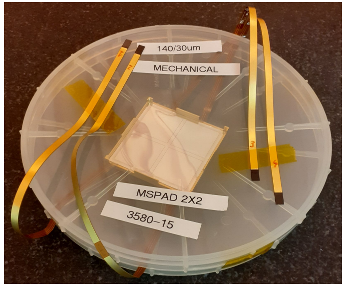
To extend the employment of the FAZIA detector within a broader energetic range, to lower and higher beam energies, available at radioactive ion beam facilities:

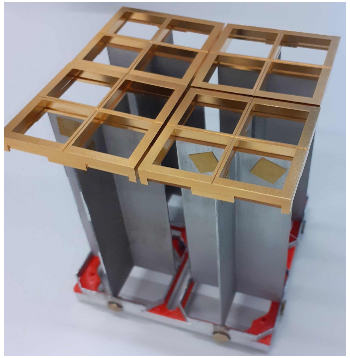
- thicker detectors to advance higher energy physics
    - 750 µm thick silicon sensors as second layer already used in the E818 experiment
    - production and testing of new sensors with thickness from 100 to 1000 µm undergoing



- ultrathin ΔE silicon stage (25 µm) for low-energy ion spectroscopy

Test of the demonstrator block featuring the ultrathin “custom” sensors as first Si foreseen for 2025 at LNL





Conclusions

- The FAZIA collaboration obtained high-quality experimental data at Fermi Energies to investigate the EOS and the fragment/cluster formation and decay
- Activity at GANIL to be continued next years
- New opportunities given by the RAON and FRIB exotic beams also at supersaturation density
- R&D efforts ongoing

Thank you for your attention

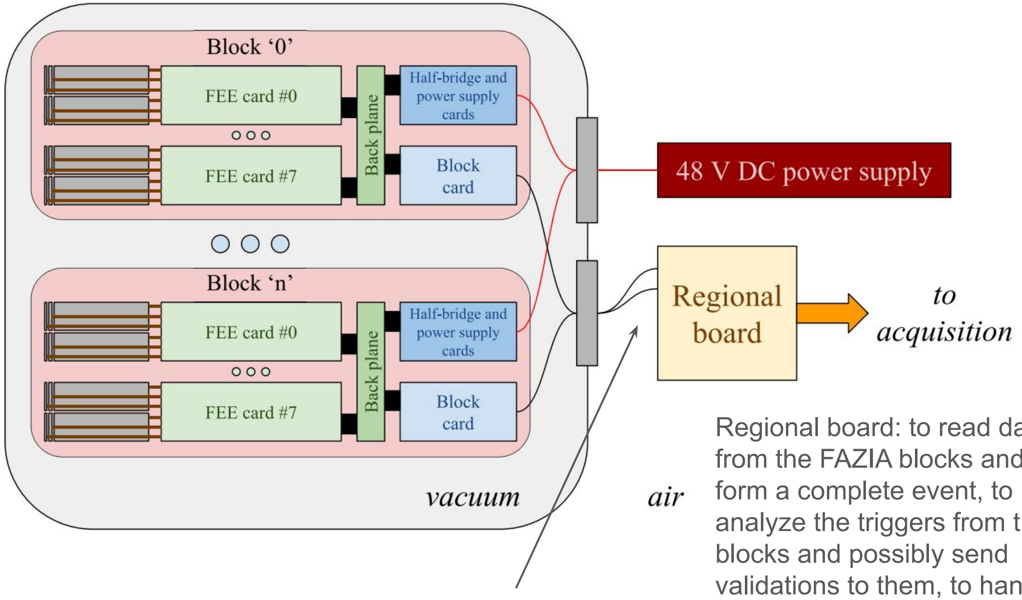
Backup

The “FAZIA recipe”

- **High thickness uniformity** (better than ±1%) → to reduce the dependence on the impact point of the ΔE released by a particle punching through the silicon pad
- **High doping uniformity** (and therefore resistivity homogeneity, ~ 3%) → to achieve a good result with the PSA method
- **“Random cut” of the Si wafers** → to reduce the channeling effect.
- **Reverse mounting configuration**: all silicon detectors are mounted with the low field side facing the target → to enhances the PSA identification performance of the setup, without affecting the ΔE-E method
- **Monitoring of the silicon reverse current** during measurements and correction for the associated voltage drop over the bias resistor, in order to keep the detector bias voltage constant → obtain a constant electric field in the depletion region of the detector

The FAZIA apparatus
Electronics

- FEE: feature, among other components, charge sensitive pre-amplifiers, ADCs, Si bias voltage regulators, and FPGAs for data handling
- Block Card: devoted to handle I/O operations and to merge data coming from the FEE cards.
- Power Supply and Half Bridge cards: produce and monitor the voltages needed to the other boards on the block.



optical link used to transfer data, to synchronize the clocks, to send triggers, and to manage any block parameter via slow control.

Regional board: to read data from the FAZIA blocks and form a complete event, to analyze the triggers from the blocks and possibly send validations to them, to handle slow control requests from many PCs and eventually to communicate with acquisition servers.

FAZIA SUD

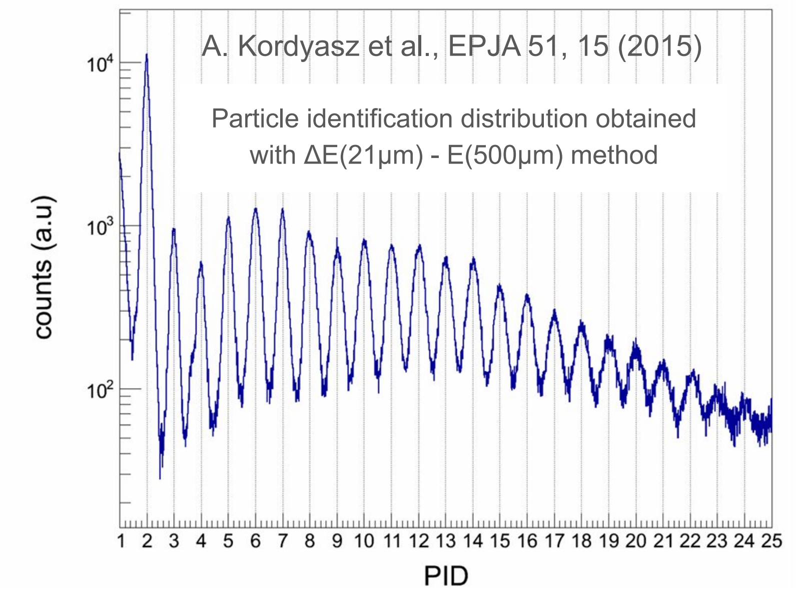
2015-2018: the FAZIA collaboration performed a series of experiments at the INFN Laboratori Nazionali del Sud (LNS) with a FAZIA demonstrator made by four, up to six, blocks.

- ISO-FAZIA: $^{80}Kr+^{40,48}Ca$ at 35 AMeV → isospin transport phenomena
- FAZIA-SYM: $^{40,48}Ca+^{40,48}Ca$ at 35 AMeV → isospin transport phenomena
- FAZIACOR: $^{32}S,^{20}Ne+^{12}C$ at 25 and 50 AMeV → cluster production
- FAZIA-PRE: $^{40,48}Ca+^{12}C$ at 25 and 40 AMeV → QP breakup channel
- FAZIA-ZERO: $^{12}C+^{12}C$ at 62 AMeV → cross section measurements

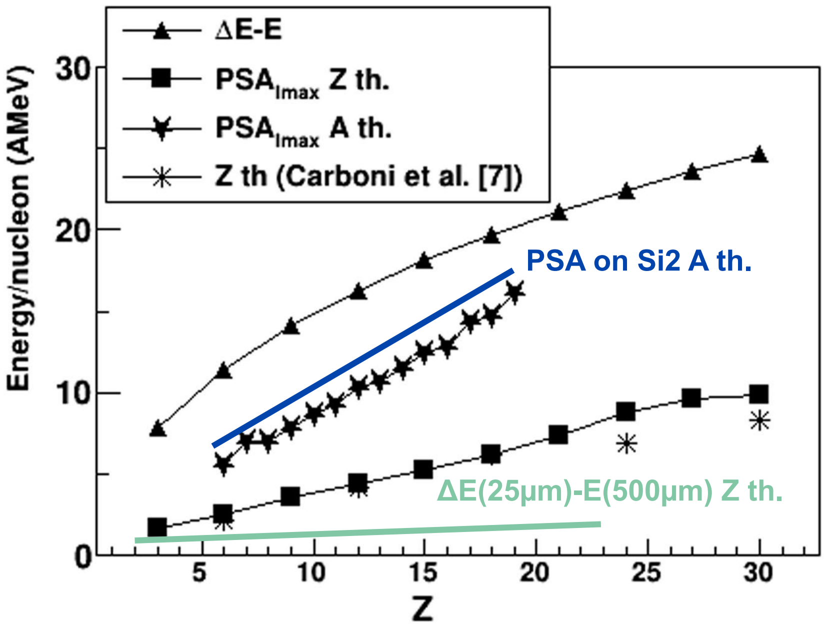
Ultrathin ΔE silicon stage

In 2015 first test of a single FAZIA telescope with a thin silicon sensor as first ΔE stage (21 μm)

- high thickness homogeneity
- ΔE-E method
    - good charge identification for Z=2-24
    - energy threshold 1.1-2 AMeV



G. Pastore et al., NIMA 860, 42 (2017)



- ΔE(25μm)-E(500μm): very low **thresholds for Z identification** up to Z=20-25, comparable to those of an ionisation chamber
- isotopic separation can be achieved by exploiting PSA on Si2 → **thresholds for A identification** should be slightly higher (<1 AMeV) than those of PSA on Si1

Particle correlation studies

^{40,48}Ca + ^{12}C at 25 and 40 AMeV with six FAZIA blocks

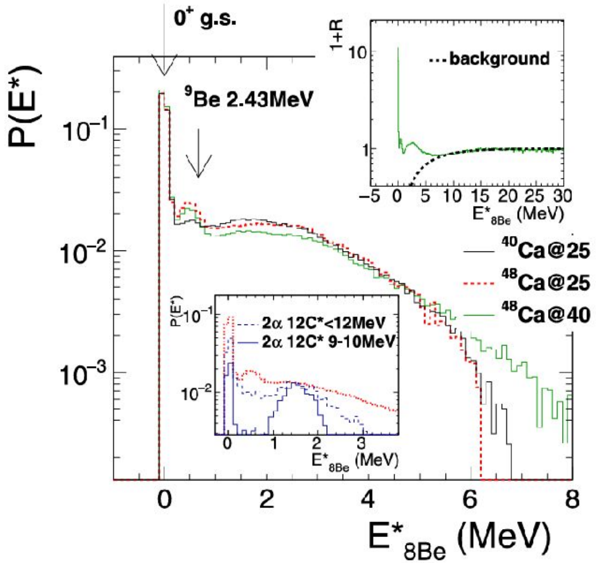
S. Piantelli, PRC 107,044607 (2023)

Particle-particle correlation technique

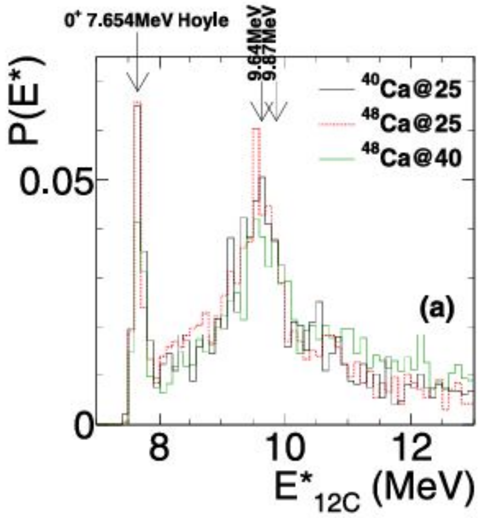
$$1 + R(E_{rel}) = C \frac{\sum Y_{12}(\vec{p}_1, \vec{p}_2)}{\sum Y_{12}^{unc}(\vec{p}_1, \vec{p}_2)}$$

uncorrelated yields estimated by means of the event mixing technique

^{8}Be* reconstructed from two-α correlations



^{12}C* reconstructed from three-α correlations, two of them ascribed to ^{8}Be ground state



study of breakup channel performed both on detected fragments and on some resonances

- phase space analogy for detected cold and resonant BU fragments
- same BU process as origin
- further studies to more quantitative results

E818 experiment: $^{12}C+^{12}C$ at 8.75 AMeV

$^{12}C(p')$ excitation energy:
The excitation energy spectrum starts above the 3 alpha threshold. It shows two narrow resonances and a broader «background»

$^{12}C(t')$ excitation energy:
The excitation energy spectrum covers all ^{12}C states, including the ground state. Most ^{12}C states are visible with some background.

Resolution:
The E* resolution using invariant mass increases with increasing E* from 130 keV to 280 keV FWHM. For the missing mass method the resolution is almost constant around 900 keV FWHM.