RIBDCE
Radioactive Ion Beam induced Double-Charge Exchange reactions

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NUSDAF 2025 - 1st Collaboration Meeting on NUclear Structure, Dynamics and Astrophysics at FRIB

Catania, October 22-24, 2025

0νββ decay

Open problem in modern physics:

Neutrino absolute mass scale

Neutrino nature

→ **0νββ** is considered the **most promising approach**

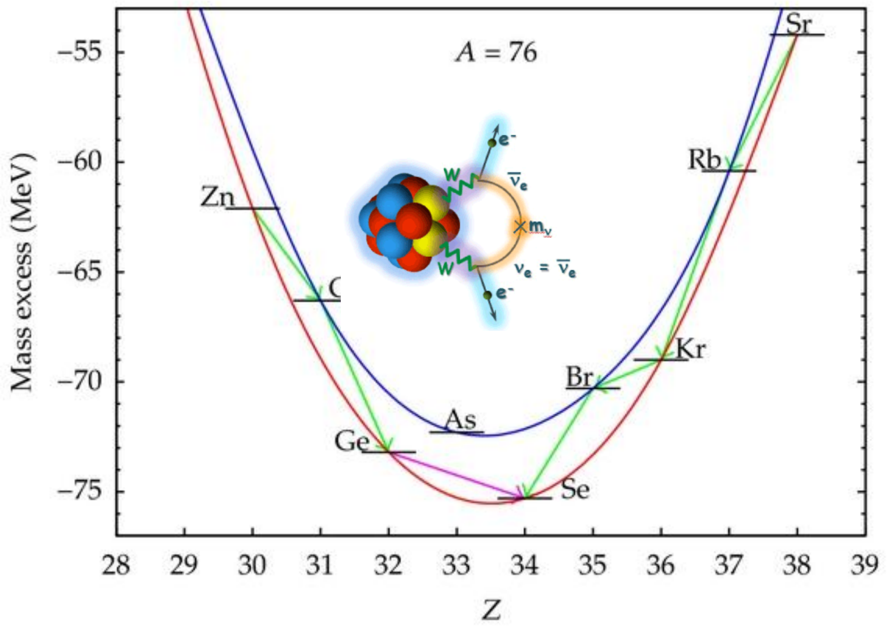
E. Majorana, Il Nuovo Cimento 14 (1937) 171
W. H. Furry, Phys Rev. 56 (1939) 1184

^{75}Se	^{76}Se	^{77}Se	^{78}Se	^{79}Se
^{74}As	^{75}As	^{76}As	^{77}As	^{78}As
^{73}Ge	^{74}Ge	^{75}Ge	^{76}Ge	^{77}Ge

Still not observed

$$^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z+2}Y_{N-2} + 2e^{-}$$

Isobaric nuclear transition where a parent nucleus spontaneously decays into a daughter nucleus changing its charge by two units and leaving the mass number unchanged



- ✓ Mediated by the **weak interaction**
- ✓ Observable in even-even nuclei where the **single β-decay** is energetically **forbidden**

Beyond standard model:

- ➢ Violation of lepton number conservation
- ➢ Probing the Majorana nature of neutrino
- ➢ Access to matter-antimatter asymmetry

*Ejiri, H.; Suhonen, J.; Zuber, K. , Physics Reports **2019**, 1, 797*
*Agostini, M. ; Benato, G.; Detwiler J.A.; Menendez, J.; Vissani, F.; Reviews of Modern Physics **2023**, 95, 025002*

0νββ decay

A worldwide challenge

Intense activities in the **searches for experimental evidence** of this process

0νββ decay rate — Phase space factor — Contains the BSM physics

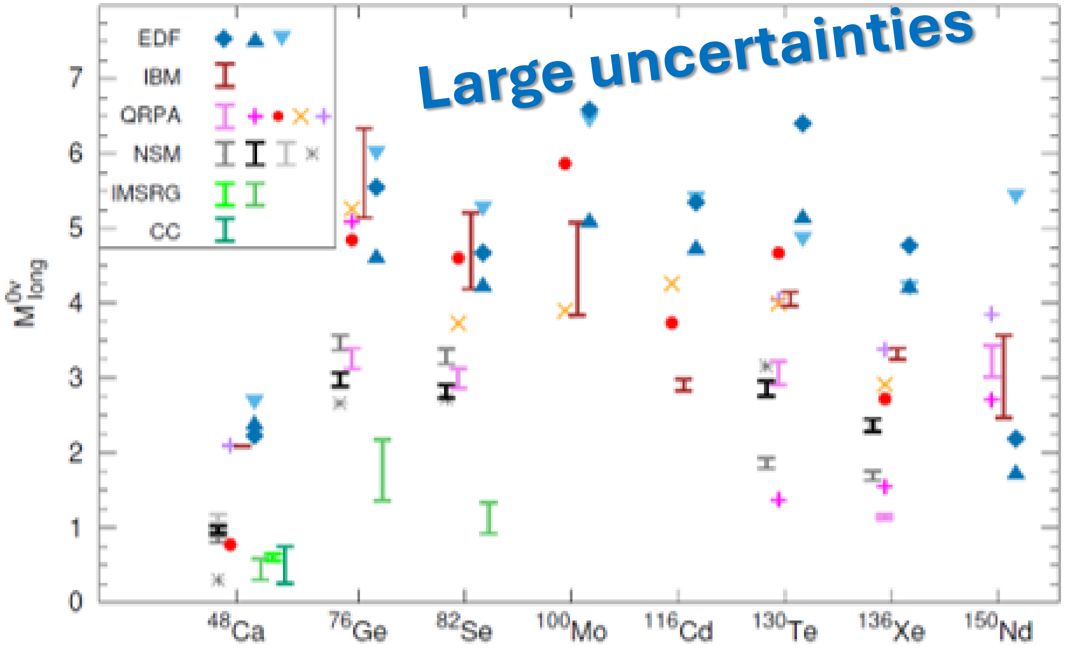
$$\left(T_{1/2}^{0\nu\beta\beta}(0^+ \to 0^+)\right)^{-1} = G_{0\nu\beta\beta}\left|M^{0\nu\beta\beta}\right|^2 \left|f(m_i, U_{ei})\right|^2$$

Nuclear Matrix Element (NME)

$$\left|M_{\varepsilon}^{0\nu\beta\beta}\right|^2 = \left|\left\langle \Psi_f \middle| \hat{O}_{\varepsilon}^{0\nu\beta\beta} \middle| \Psi_i \right\rangle\right|^2$$

Transition probability for the **nuclear** process

State of the art NME calculations



M. Agostini et al., Rev. Mod. Phys. 95, 025002 (2023)

- ✓ NMEs are not physical observables (→ calculations)
- ✓ Much work on the **transition operator**, now including all the known short-range weak interaction physics *F.F. Deppisch et al., PRD 102, 095016* (2020)
- ✓ The challenge is the description of the **nuclear many body states**

An interesting experimental tool

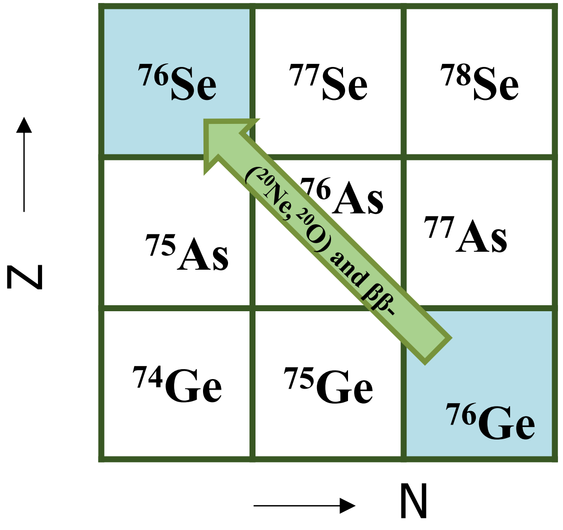
(**NU**clear **M**atrix **E**lements for **N**eutrinoless double beta decay)

F. Cappuzzello et al., EPJ A (2018) 54:72

Heavy-Ion induced Double Charge Exchange reactions (DCE) as a surrogate process of 0νββ to stimulate in the laboratory the same nuclear transition (g.s. to g.s.)

Extraction from measured cross-sections of ***data-driven* information on NME** for all the systems candidate for 0νββ

- **Constraints** to the existing theories of NMEs (nuclear wave functions)
- Model-independent **comparative information** on the sensitivity of 0νββ experiments
- Complete study of the **reaction mechanism**



Heavy-ion induced DCE

Heavy ion DCE can proceed via:

Mean field driven processes

1) Sequential multi-nucleon transfer (TDCE)

J.L. Ferreira et al., PRC 105, 014630 (2022)
J.L. Ferreira et al., PRC 111, 014630 (2025)

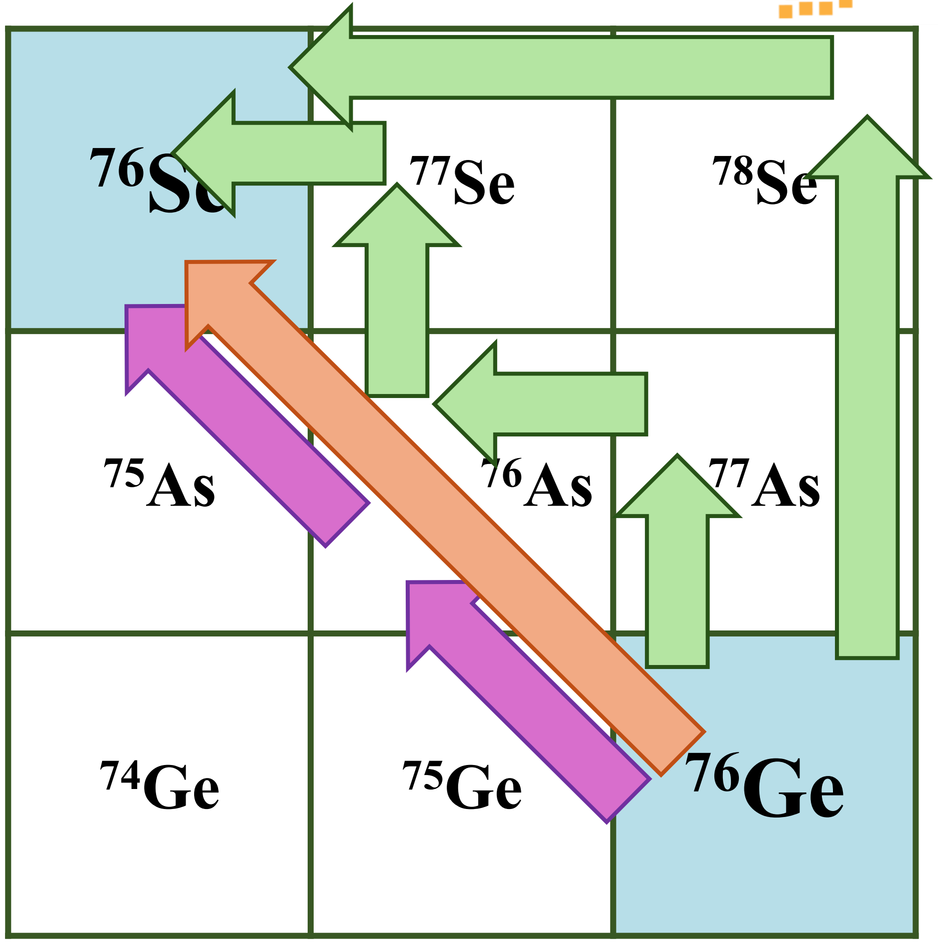
Collisional processes

2) Two-step DCE - Double single charge exchange (DSCE): two consecutive single charge exchange processes, mediated by NN isovector interaction

J.I.Bellone et al., Phys. Rev. C 111, L061602 (2025)
H.Lenske et al., Universe, 7, 93 (2024)

3) One-step DCE - Two-nucleon mechanism (MDCE): relying on short range NN correlations, leading to the correlated exchange of two charged mesons between projectile and target

H. Lenske et al. Progr. Part. and Nucl. Physics 109 (2019) 103716
H. Lenske, Universe (2024) 10, 202



The DCE cross section combines the three different classes of reaction dynamics

F. Cappuzzello et al., Progr. Part. and Nucl. Physics 128, 103999 (2023)

(^3H, 3p) double charge exchange

(^{3}H, 3p) double charge exchange

^{3}H is the **lightest projectile** that can induce a DCE reaction. The transition of the projectile can be treated with **ab-initio methods**, removing uncertainties due to the many-body features of heavy nuclei

- Selective access to few-body **open quantum system** in ab-initio theory (discussion with ab-initio experts already started)

NUCLEAR STRUCTURE

- **^{3}He(^{3}H,3p)3n** allows studying the DCE process in conditions where **distortions** due to ISI and FSI are **suppressed** (more direct access to reaction form factors)
- **^{3}He(^{3}H,3p)3n** could allow the study of the DCE mechanism from "*first principles*" if the 6-body problem in the continuum is faced (discussion with HI-DCE theory experts started)

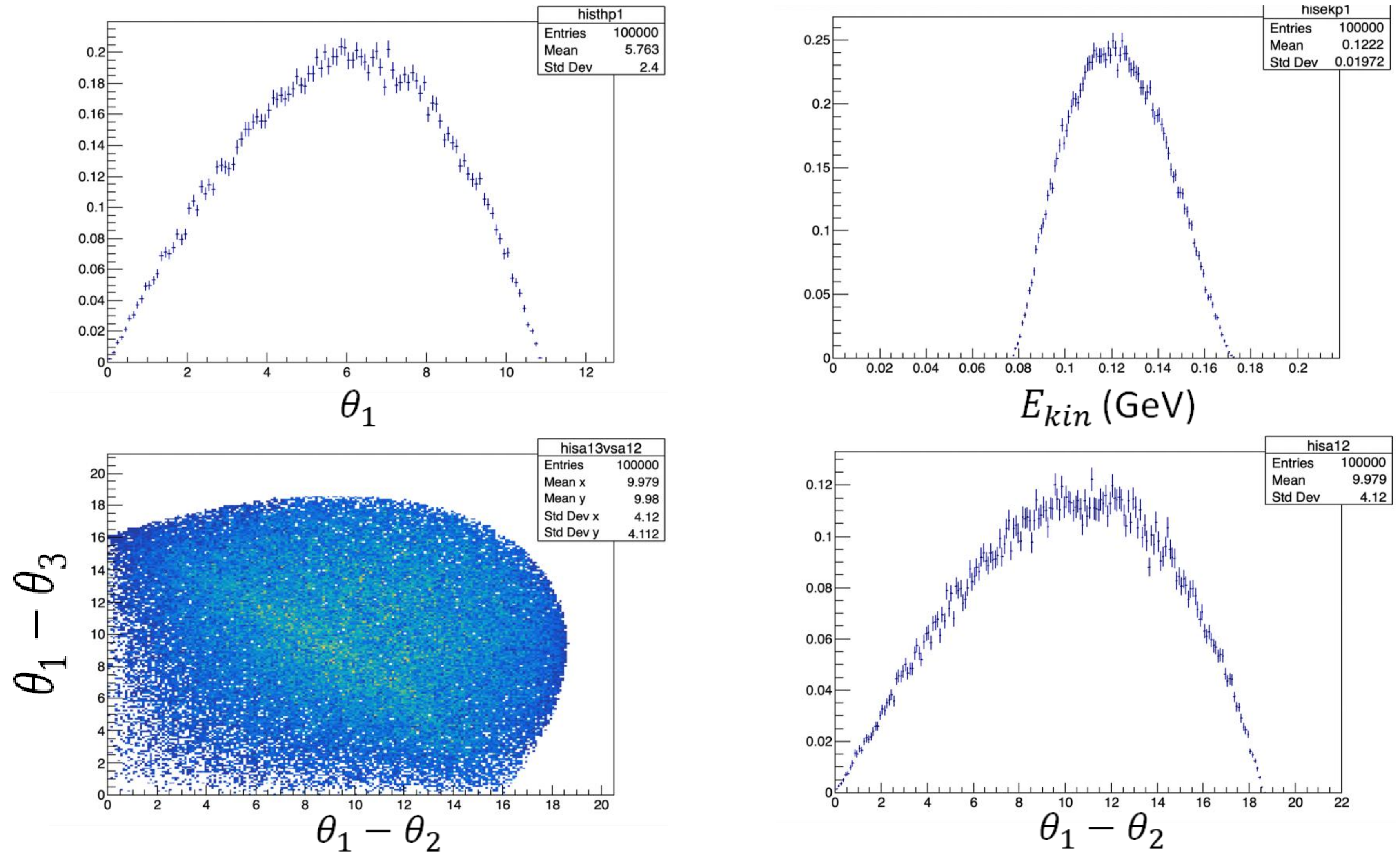
NUCLEAR REACTIONS

- **^{3}He(^{3}H,3p)3n investigates all three-body nuclear systems** (3n, 3p, ^{3}H(pnn), ^{3}He(ppn)) with $|Tz| \leq 3/2$, providing valuable data for direct access to nuclear forces, particularly **three-body forces**, with its relevance to the study of few-body nuclear systems and to the EoS of asymmetric nuclear matter at high densities (**synergy with SYMEOS**)

NUCLEAR INTERACTIONS

Some simulation for the $^3He(^3H,3p)3n$

Simulations of phase-space 3-body distributions of protons in $^3H + {}^3He \rightarrow 3n + 3p$ ($E_{cm,3p}$ = 120 MeV/nucleon)



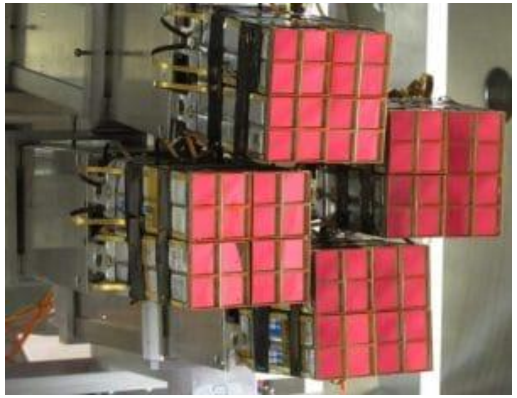
Simulations by G. Verde

Experimental setup for the $^{3}He(^{3}H,3p)3n$

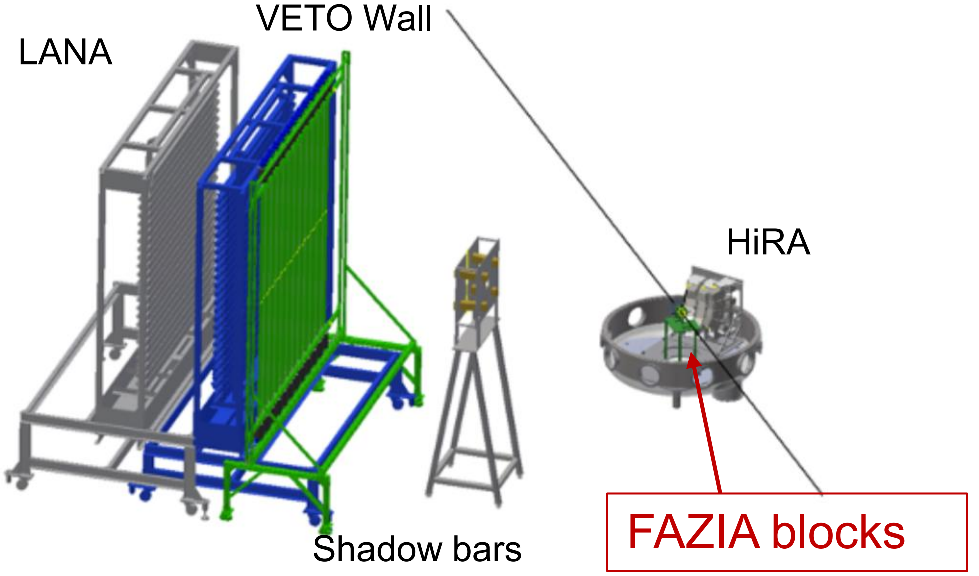
Detecting **3 protons** and measuring their **momentum vectors** to study two- and three-body correlations

- High granularity solid-state detectors arranged in Si-CsI(Tl) telescopes as a possible choice
- Excellent PID, energy and angle measurement of the 3p in coincidence
- Measure at small scattering angles

The telescopes can be the **FAZIA blocks/ HiRA**
Detecting also the 3 neutrons?



Common with SYMEOS



Measurable with FAZIA blocks
- 3 protons with E_{kin}=80-140 MeV and distributed over θ=4°-15° with relative angles of more than 2°...

Challenges for the ^{3}He(^{3}H,3p)3n

- **Cross section estimation** needed to tune beam time request and detector set-up: work started
- **Proton spatial distribution** (impact on detector granularity and angular acceptance): first simulations already done
- **^{3}H beam** as secondary beam with high intensity already discussed with FRIB colleagues
- **^{3}He target** availability at FRIB already discussed
- **Detectors for protons** (and neutrons): exploring availability and detector performances (efficiency, resolution, granularity, …). Discussion started
- **Involvement of few-body theorists** for Ab-initio wave functions: first brainstorming meetings already started

The (^{3}H,3p) in a broader perspective

- **In general, the (^{3}H,3p) is a very promising DCE reaction** due to the possibility of ab-initio methods for studying the reaction mechanism

- In particular, the distortions due to ISI and FSI may be calculated from first principles

- One should expect a steep rise of the cross section due to the weaker absorption compared to heavy-ion DCE

- In addition, thicker target can be used due to the much smaller energy loss and straggling of ^{3}H and protons, thus boosting the DCE yield.

- **The experimental technique** proposed for the case of ^{3}He(^{3}H,3p)3n **may be generalized** to any target of interest for $0\nu\beta\beta$ decay research

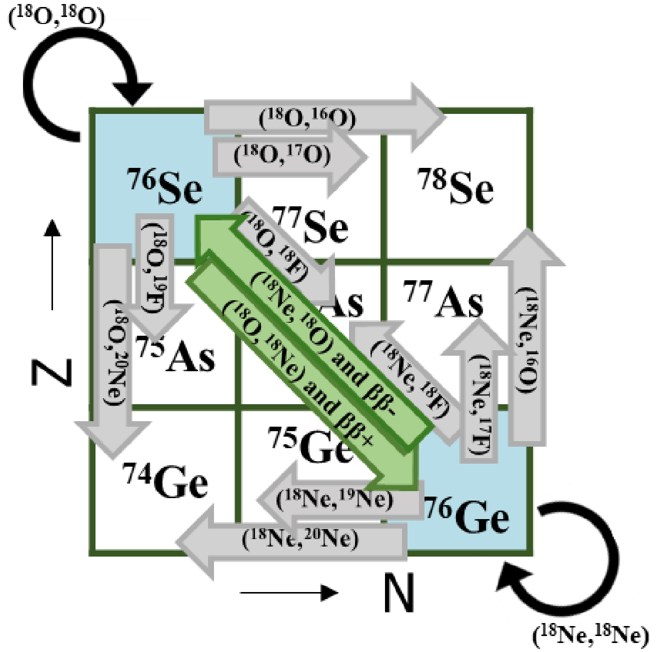
(^{18}Ne,^{18}O) double charge exchange

(^{18}Ne,^{18}O) double charge exchange

- **^{18}Ne radioactive beam** at FRIB

- Both **^{18}O and ^{18}Ne nuclei** are of primary importance for DCE experiments. Indeed, the ^{18}Ne (^{18}O) projectile exhibits a **strong clusterization into ^{16}O + 2p (^{16}O +2n)** in its ground state. The ^{18}Ne (^{18}O) beam offers the closest similarity to a 2p (2n) beam, which would be the most elementary nuclear system that can activate the DCE reaction

- the (^{18}Ne,^{18}O) reactions represent the **time reversal of the (^{18}O,^{18}Ne)** reactions already widely explored (and planned) in NUMEN at INFN-LNS. This will allow tests of time invariance of the NMEs in detail



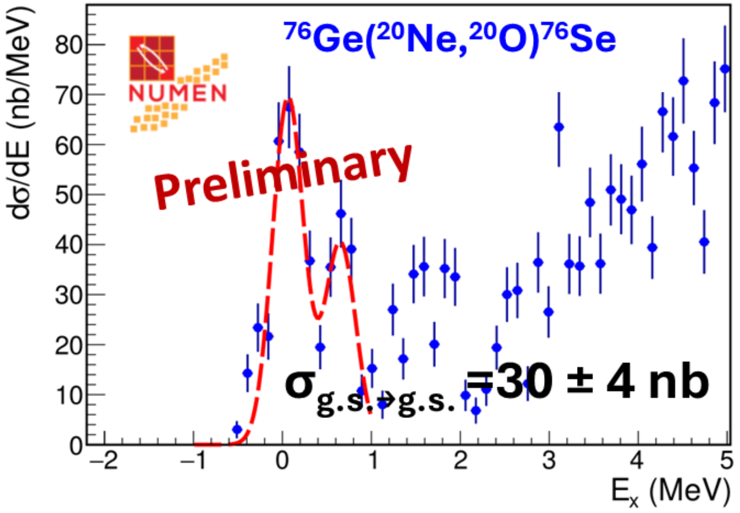
RIBDCE will need to measure:

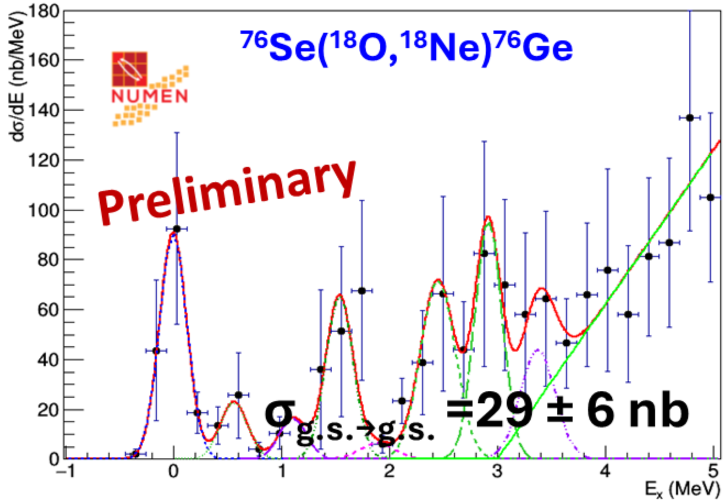
- Z, A and $p^{\rightarrow}$ for identifying the reaction channel (^{18}O, ^{18}F, ...)
- $p^{\rightarrow}$ (with high resolution for energy spectrum measurements)
- differential cross-sections

(^{18}Ne,^{18}O) features and challenges

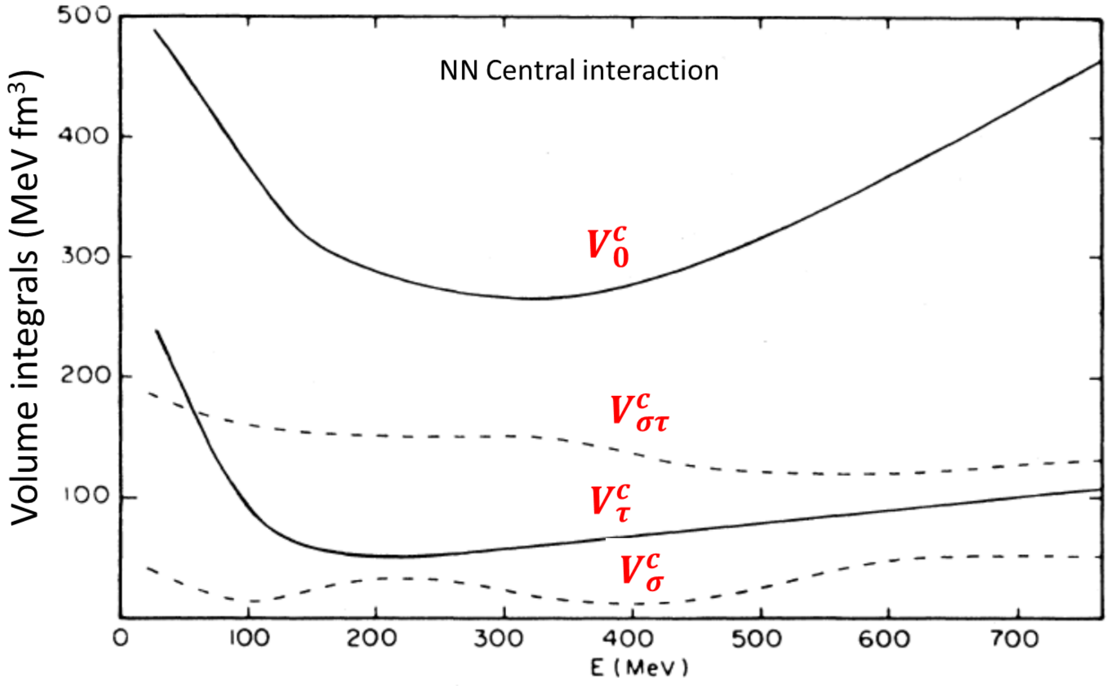
NUMEN data at 15 MeV/u
I_{beam} ~1 pnA, target ~ 300 ug/cm^2
~20 days beam time

$0° < \theta_{lab} < 8°$





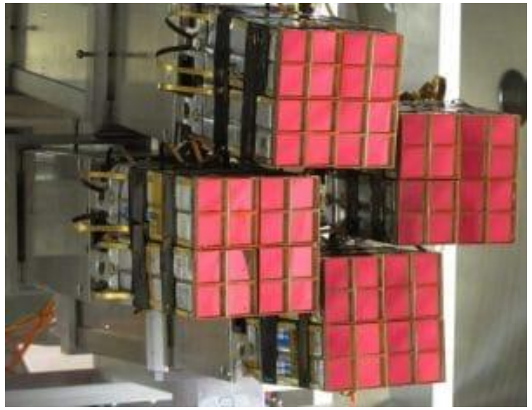
- Larger cross section expected compared to NUMEN at 15 MeV/u, due to reduced absorption
- Possibility to make thicker targets
- Requirement of high energy resolution (500 keV -> 1/10000!)
- Challenging use of gamma-array spectrometer due to expected low yields



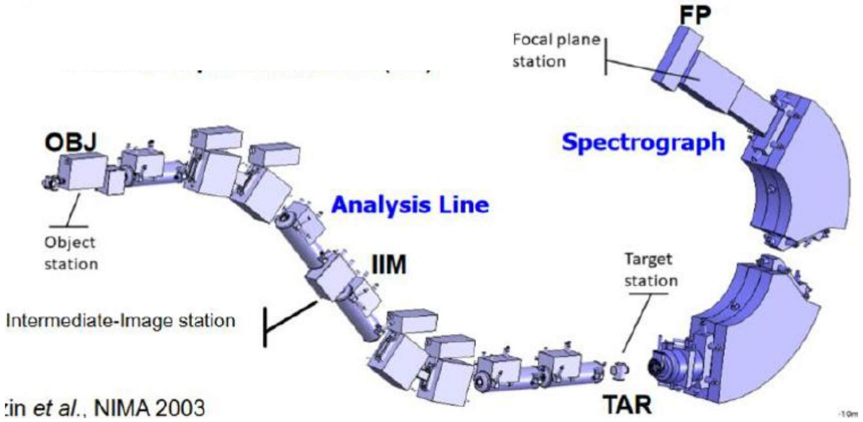
Experimental setup for ^{18}Ne experiments

To be explored

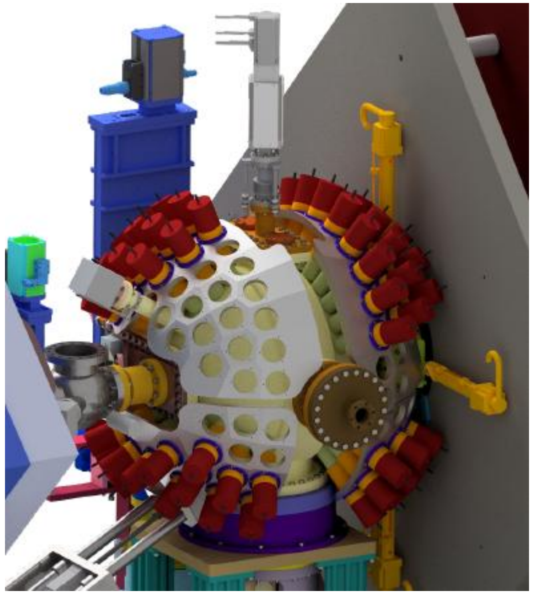
FAZIA-like blocks

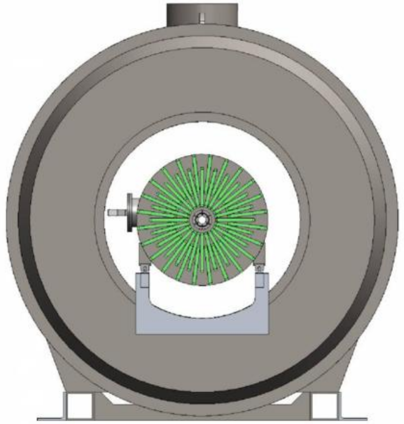


S800



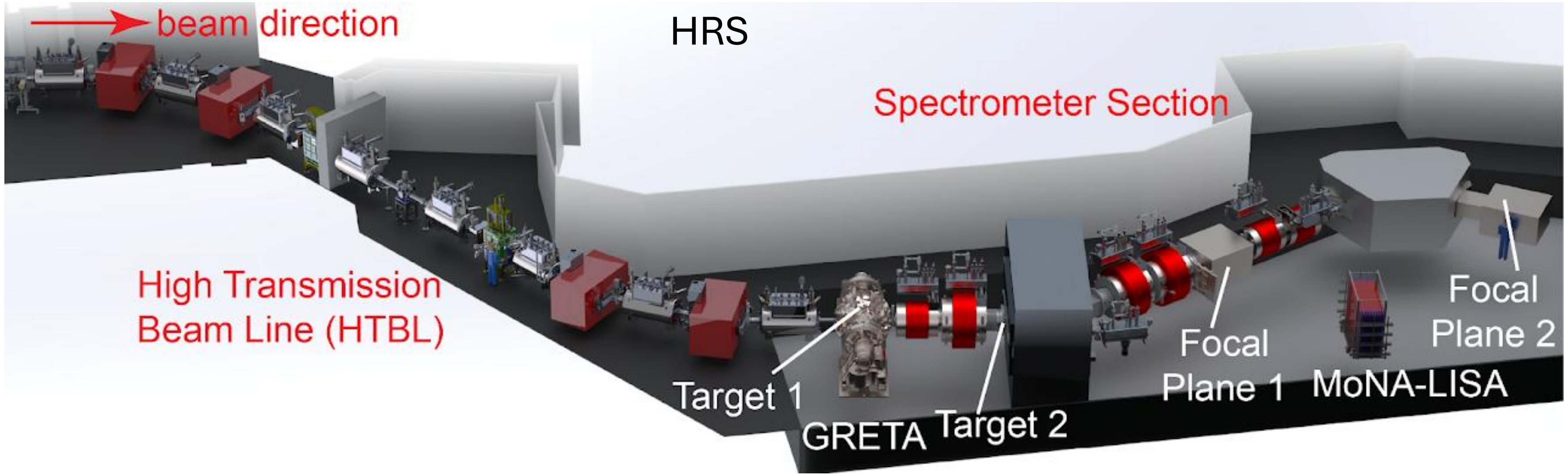
G-NUMEN array of LaBr3(Ce)





Solenoidal TPC

HRS



NUMEN DCE at FRIB

Designing campaigns of measurements at FRIB is a **very promising perspective for the NUMEN collaboration**. Two specific aspects can be outlined:

1. Performing **DCE reactions** with beams that are **complementary** to the ones that will be offered by the upgraded **LNS stable beam facility**, namely beams of radioactive isotopes at 15 to 350 MeV/u

2. The use of a **multi-purpose experimental setup** to be shared with the groups working on EoS and on nuclear astrophysics, thus strongly enhancing the synergic character of the proposed project

Thanks

backup

$t + {}^3He \rightarrow 3p + 3n$

30/05/2023

Why:
- the lightest system to explore short range correlations in Double Charge Exchange (DCE) mechanism
- A direct access to nucleonic 3-body systems and interactions

How:
- Tritium beam and 3He target. It would require the detection of 3 protons at forward angles in coincidence and 3 neutrons in the full solid angle.

Where:
- FRIB facility at MSU seems the best place

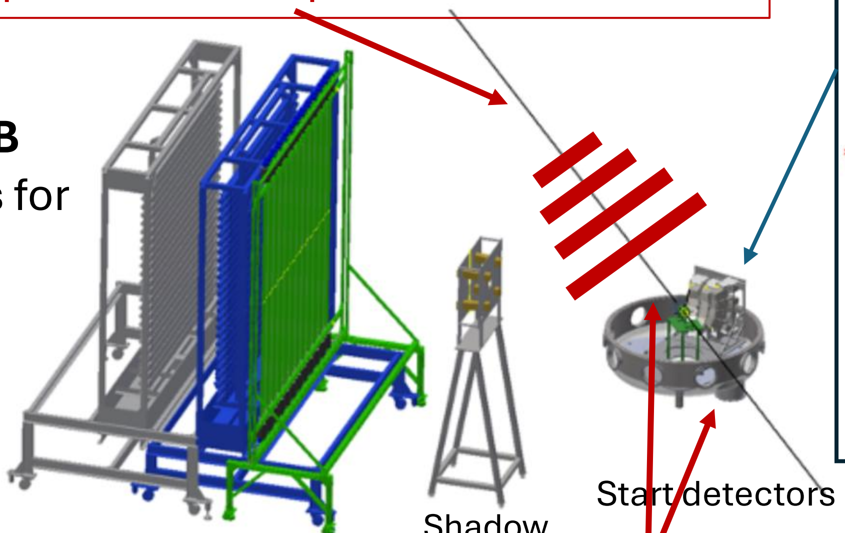
Issues:
- Cross section estimation needed to tune beam time and detector setup
- Proton spatial distribution (impact on detector granularity and angular acceptance)
- t beam as secondary beam with high intensity. Energy? Intensity?
- 3He target. Availability? Liquid? Gas? Thickness?
- Detectors for protons and neutrons. Availability, Efficiency, resolution
- Involvement of few-body theorists for Ab-initio wave functions?

When
- Call for proposal?

SYMEOS campaigns of measurements

+ 4-5 Si-CsI(Tl) Chimera rings
Improve reaction plane and b

LANA n det @ FRIB
Liquid Scintillators for
n-γ discrimination



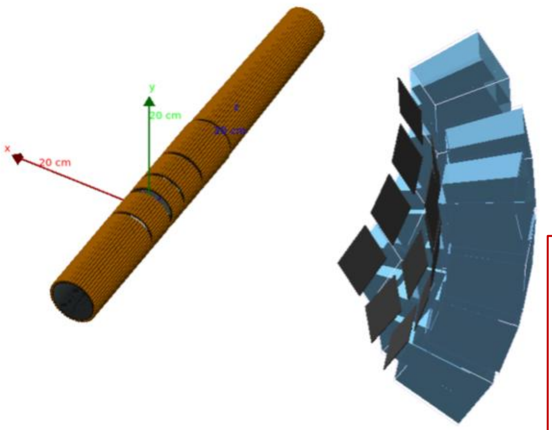
VETO wall

Shadow
bars

Start detectors

+ FAZIA forward & backward
N/Z in spectators and participants (OSCAR?)

Fiber Array @ FRIB

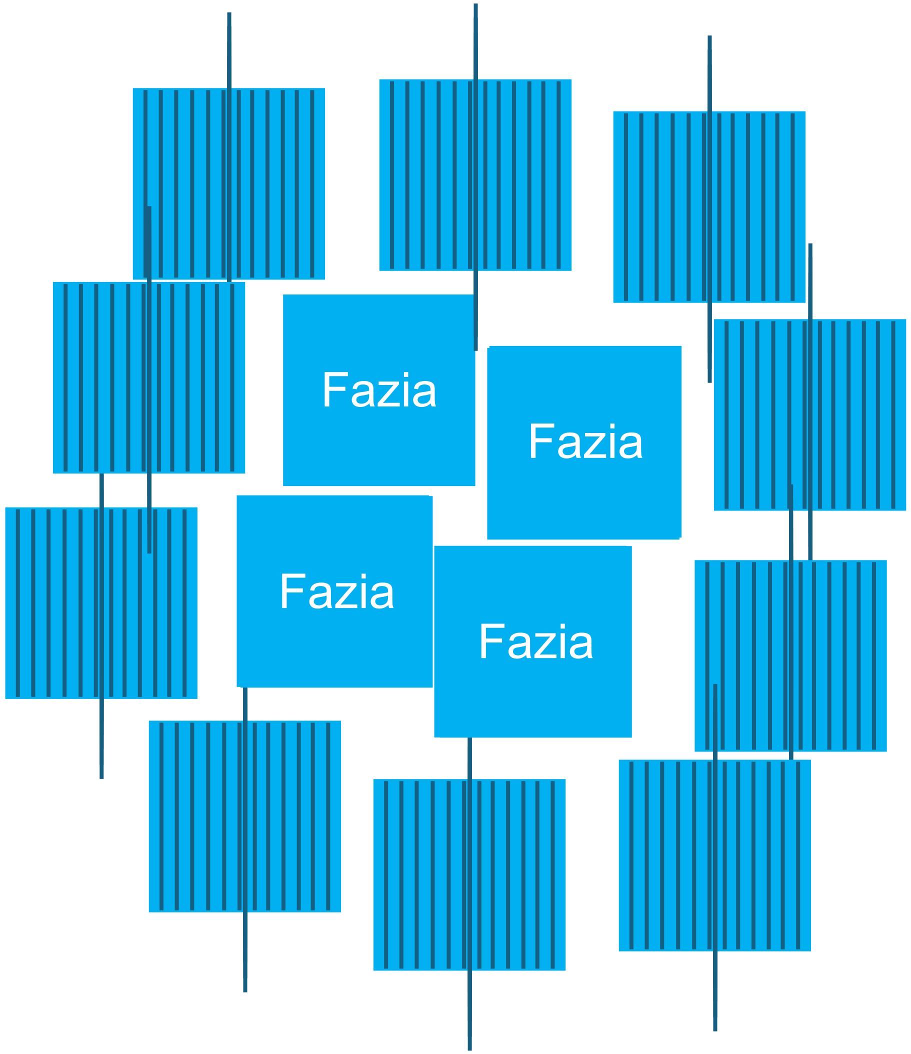


HiRA
Blocks of Silicon strips and CsI(Tl)

+ FARCOS
Increase correlators
(Silicon strips and CsI(Tl))

- Heavy-ion collision campaigns at E/A=120-400 MeV
  ^{56,70}Ni + ^{58,64}Ni, ^{104,132}Sn +^{112,124}Sn, etc.... towards FRIB400
- Interest in TPC phase 1 (solenoidal) and phase 2 (HRS)

FAZIA-HiRA/Farcos for other physics cases



Possible configuration FAZIA-HiRA to increase solid angle coverage
- FAZIA at forward angles and at 1 m distance from the target
- HiRA at large angles and closer to the target

Homogeneous angular resolution as particles are detected at larger polar angles (useful for correlations)

Slide by G. Verde

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When
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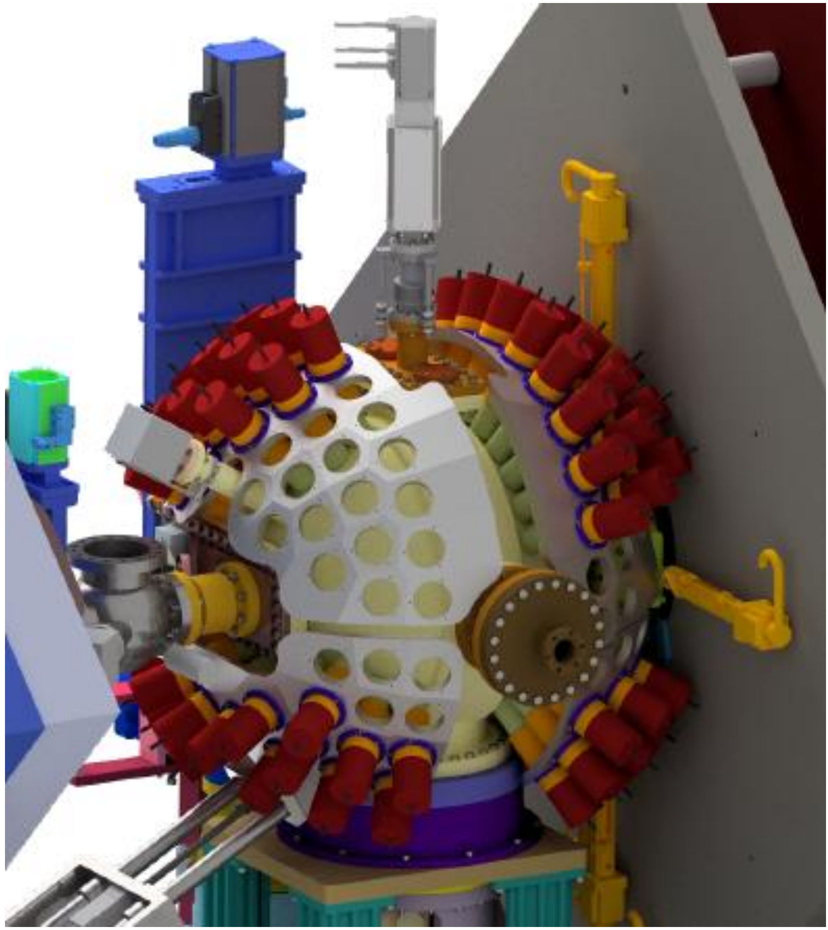
The G-NUMEN array

110 Single LaBr3(Ce) crystals (size 38 mm diameter and 50 mm length)

Demonstrator (15 crystals) already available at LNS

Expected performances

- Total photopeak efficiency of 4% at 1.3 MeV
- Energy resolution of 2.8% (6.4%) at 662 (122) keV
- Time resolution better than 1 ns
- Observational limit 0.3 x 10^{-9} (σ_{DCE} = 1 nb/state for σ_R = 3 b)
- Radiation tolerance up to 10^{10} neutrons/cm^2 (need of new data)



G-NUMEN array of LaBr3(Ce) in coincidence measurements will **improve the energy resolution** of the measured spectra populated via DCE reactions, allowing to separate ground state transition from the transitions to the excited states of ejectiles and residual nuclei. The modularity of the G-NUMEN array will allow its coupling with various detectors and setups in different configurations, with **possible applications also to other physics cases**.

G-NUMEN: The γ array detector

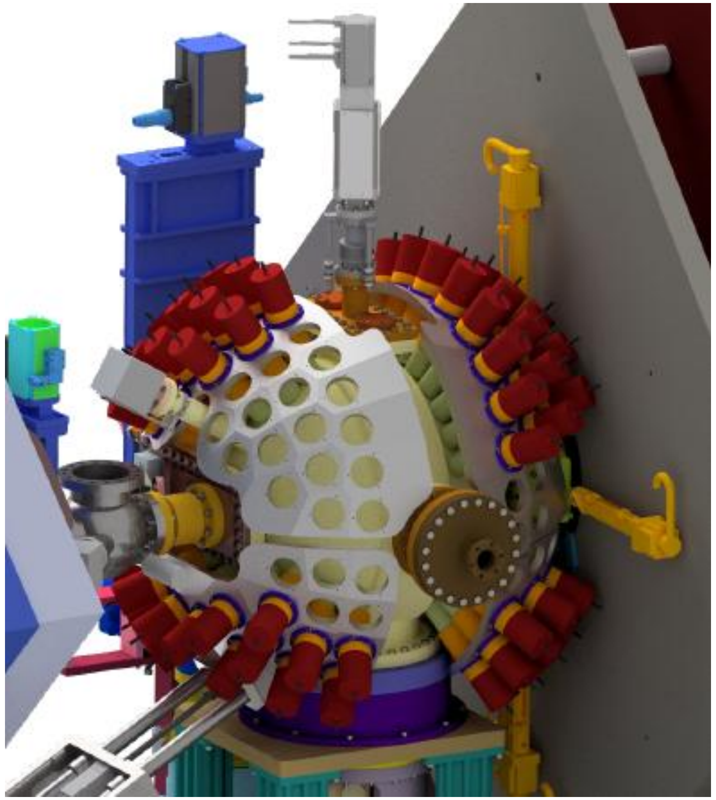
Mesurement of γ transitions in coincidence (or anti-coincidence) with DCE events in the Focal Plane Detector when the energy resolution in MAGNEX is not sufficient to resolve between states of the reaction products such as for deformed target-nuclei ^{110}Pd, ^{150}Nd and ^{160}Gd, and in all cases, at high reaction energies.

Requirements for **G-NUMEN**

- **Observational limit** $\sigma_{DCE}/\sigma_R < 10^{-8}$
- **Energy resolution** to separate g.s from excited states in DCE events
- **Time resolution** better than 2-3 ns
- **Radiation Tolerance** at 10^{11} fast neutrons/cm^2
- **Stability of the output pulse** with the **count rate** (up to 300 kHz)
- **Good linearity of the output pulse charge** with **energy**

G-NUMEN: 110 $LaBr_3$(Ce) scintillators coupled with Hamamatsu R6231PMT-type tubes purchased by the EPIC crystal company.

- Single crystal size 38 mm diameter and 50 mm length
- 24 cm distance from the target
- Total solid angle coverage = 20%



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Challenge: distinguish γ rays from DCE events (very few) in the region of interest, in experimental conditions dominated by a **very high rate** of events coming from the projectile-target interactions-> **G-NUMEN demonstrator (15 detectors)**