Sesto Incontro Nazionale di Fisica Nucleare

Nuclear physics at LNS: recent results and future perspectives

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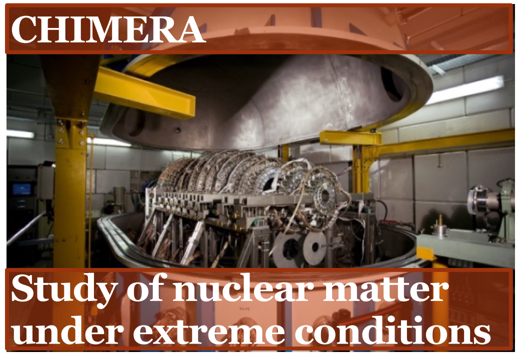
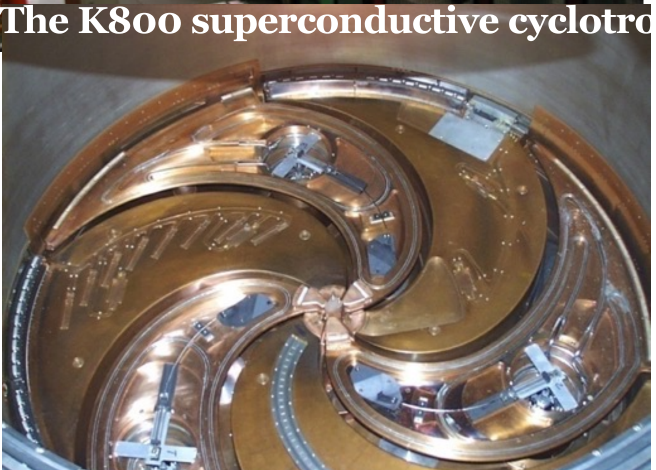
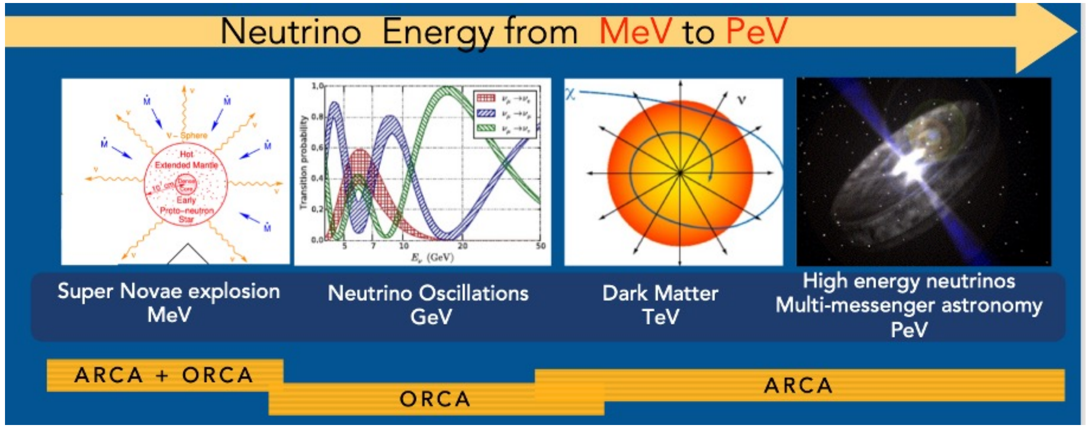
LNS past/present facilities

Thanks to the broad range of available beams and beam energies, LNS research spans a correspondingly broad range of physical problems

- Nuclear structure and dynamics
- Nuclear astrophysics
- Plasma physics
- Medical physics and biophysics
- Astro-particle physics
- Environmental physics
- Applications to cultural heritage





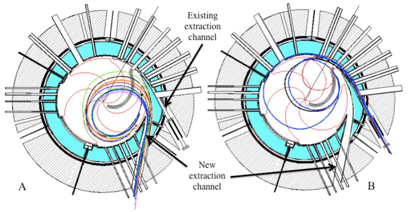


KM3NeT second phase is a research infrastructure housing the next generation neutrino telescopes. KM3NeT will open a new window on our Universe, but also contribute to the research of the properties of the elusive neutrino particles.

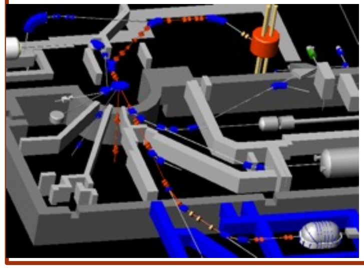
… and the near future

LNS upgrade of their facilities to keep the pace of research in nuclear physics at the international level. After the upgrade, the intensity and variety of beams will increase and new experimental setups will be made available to Users in 2024-25.

The POTLNS project aims at upgrading the LNS CS and beam lines to increase the intensity by about 2 orders of magnitude for ion beams with mass number <= 40 and energies between 15 and 70 MeV/amu.



Extraction by stripping



Applications:

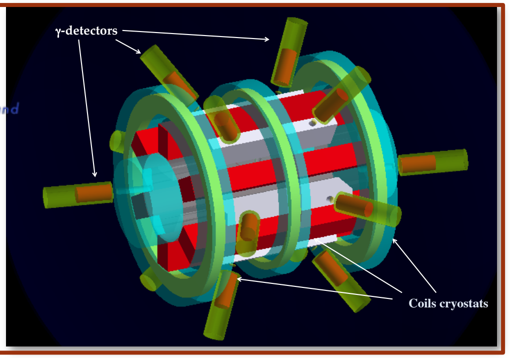
- In flight production of RIBs @ FRAISE
- High intensity beams for the study of $0\nu2\beta$ decay (NMEs)

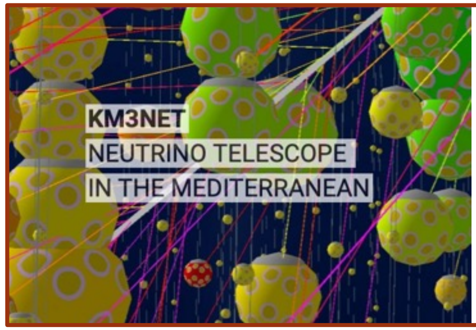
$^{18}O^{6+}$ @ 20 MeV
$^{18}O^{6+}$ @ 25 MeV
$^{18}O^{6+}$ @ 45 MeV
$^{18}O^{6+}$ @ 60 MeV

$^{40}Ar^{13+}$ @ 45MeV
$^{40}Ar^{13+}$ @ 60MeV

PANDORA aims at building an innovative magnetic plasma trap, for interdisciplinary and fundamental physics research, especially the study of β-decays under astrophysical conditions and opacities

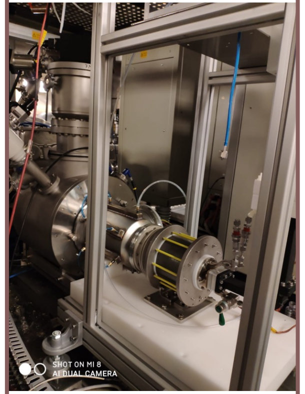
Plasmas for Astrophysics Nuclear Decay Observation and Radiation for Archaeometry





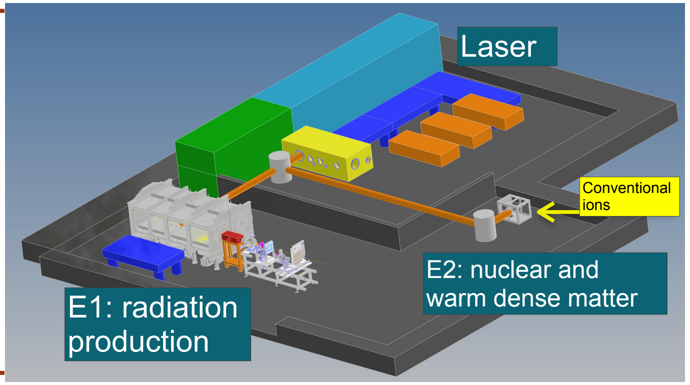
KM3NeT is a research infrastructure housing the next generation neutrino telescopes. KM3NeT will open a new window on our Universe, but also contribute to the research of the properties of the elusive neutrino particles.

NESTOR



New beams of $^{4}He^{-}$ and $^{3}He^{-}$, H^{-}, $^{16-18}O^{-}$, $^{14}N^{-}$ … (hopefully ^{20}Ne…)

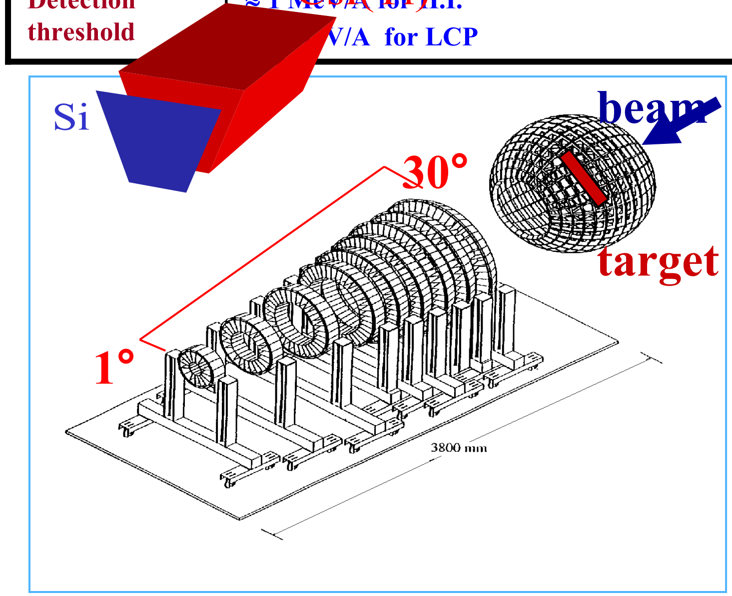
I-LUCE particle acceleration by laser-matter interaction. Laser numbers: 45 TW/23 fs/10 Hz. Accelerated beams: electrons, protons, light ions
Energies: MeV/GeV in broad spectra
Intensities $10^{9} – 10^{12}$
Nuclear reaction studies through Coulomb explosion



Next focus on physics cases
CHIRONE, NUMEN, ASFIN

CHIMERA - **Charge Heavy Ion Mass and Energy Resolving Array**

Granularity	**1192 telescopes** **Si (300μm) +CsI(Tl)**
Geometry	**RINGS: 688 telescopes 100-350 cm** **SPHERE: 504 telescopes 40 cm**
Angular range	**RINGS: 1°< θ < 30°** **SPHERE: 30°< θ < 176° 94% of 4π**
Identification method	**ΔE-E** **E-TOF** **PSD in CsI(Tl)** **PSD in Si (upgrade 2008)**
Experimental observables and performances	**TOF dt ≤ 1 ns** **dE/E LCP (Light Charge Particles) ≈ 2%** **dE/E HI (Heavy Ions) ≤ 1%** **Energy, Velocity, A, Z, angular distributions**
Detection threshold	**≈ 1 MeV/A for H.I.** **V/A for LCP**



Dynamical range : from fusion, fusion-fission to multifragmentation reactions

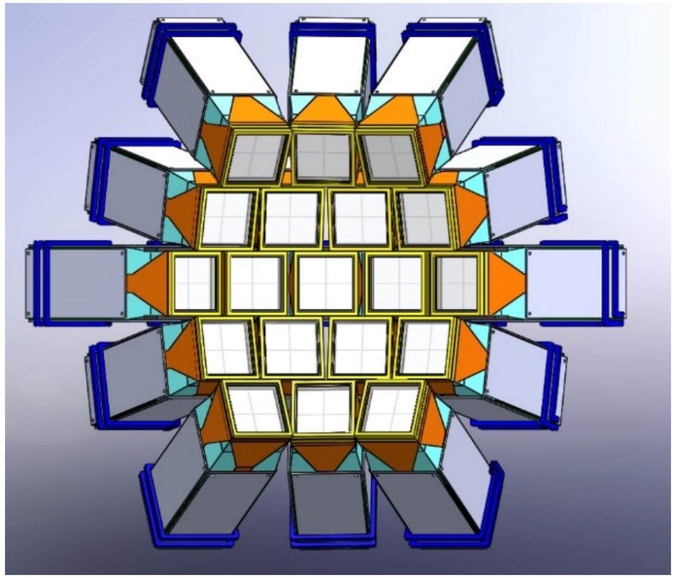
(TANDEM & CYCLOTRON Beams)

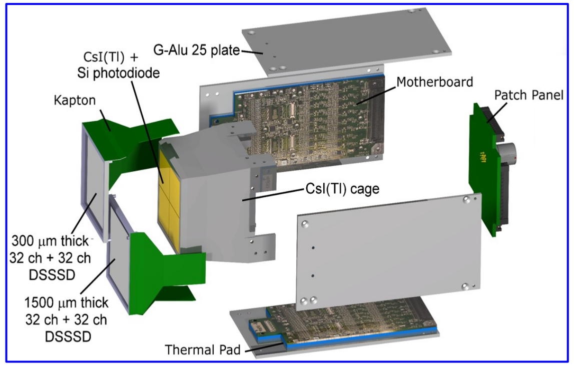
Upgrade activities in progress

- Development of a new tagging system for RIBS based on SIC technology
- New cabling in CHIMERA implementing differential signal transmission

CHIMERA ancillary arrays

FARCOS - Femtoscope Array for COrrelations and Spectroscopy

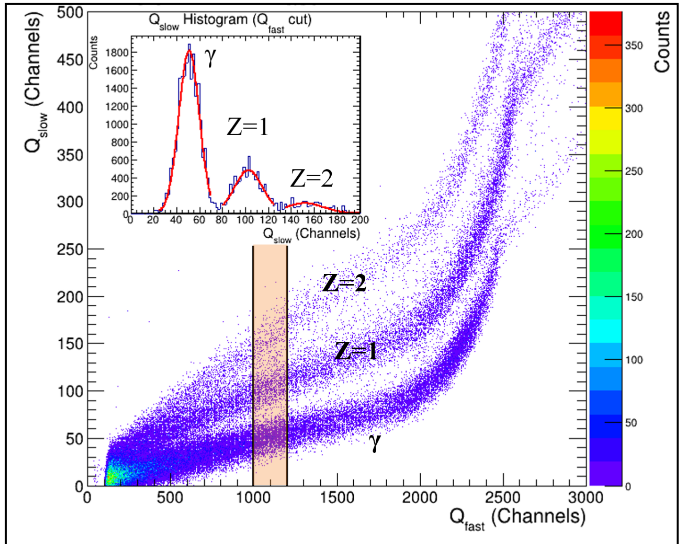




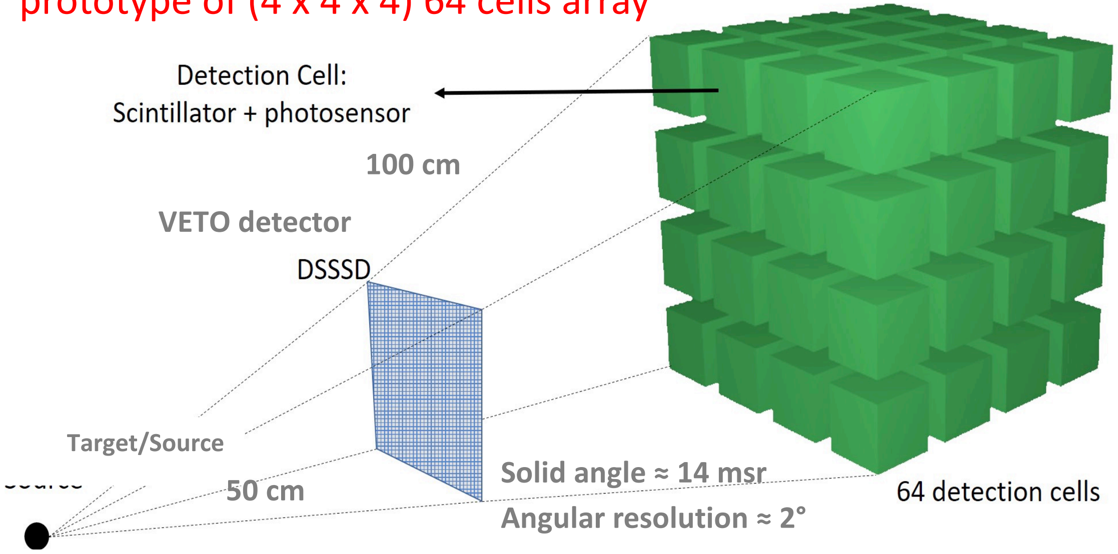
- **High energy and angular resolution (δθ, δϕ<0.1°)**
- **Low thresholds (<1 MeV/A)**
- **Pulse-shape on first Si layer**
- **High counting rate (1KHz)**
- **Large Dynamic range (20MeV to 2GeV)**
- **Flexibility, Modularity, Trasportability: coupling to 4π detectors or spectrometers**
- **Integrated electronics (GET)**
- **DAQ, new digital acquisition system**
- **20 clusters**

Feasibility studies for a new hodoscope for n, gamma and Charged Particles: EJ276(G) read by SiPM

EJ-276G + SiPM



prototype of (4 x 4 x 4) 64 cells array



Esperimento Hoyle-γ

Misura del branching ratio dello stato di Hoyle del ^{12}C e studio del livello a 9.64 MeV

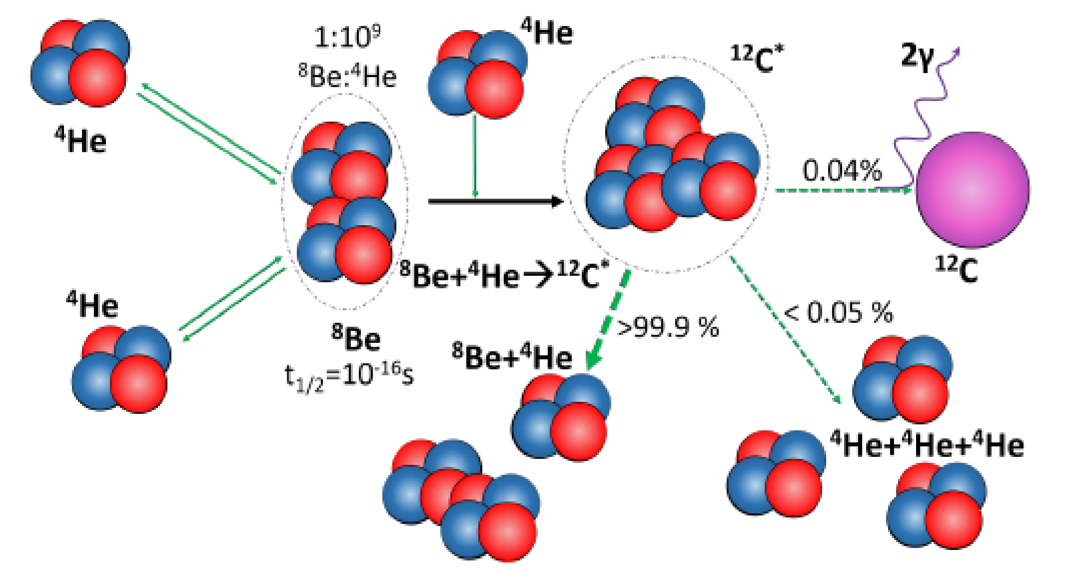
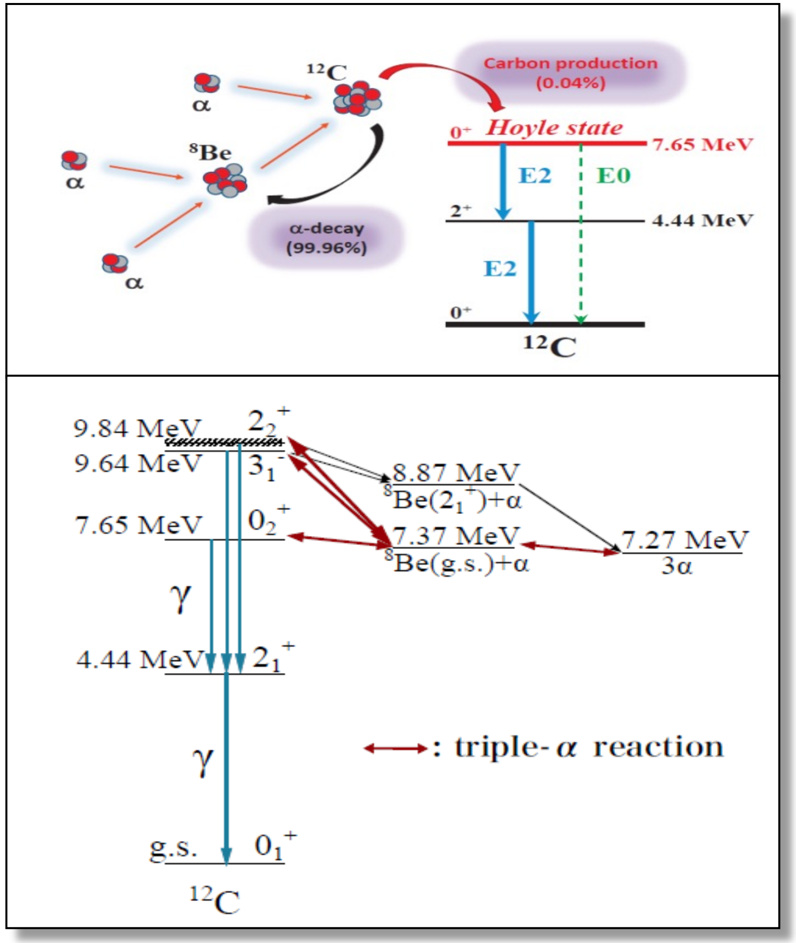


Figure 2.7: Two-step procedure for the triple-alpha process.

A.Raduta et al., PLB 705, 65 (2011)
G. Cardella *et al.*, Nucl. Instr. and Meth. A **799**, 64 (2015)



LNS – CHIMERA&FARCOS

Luglio 2019

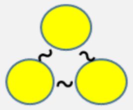
Highlight 2023 – CHIRONE - Study of γ-decay of excited ^{12}C states

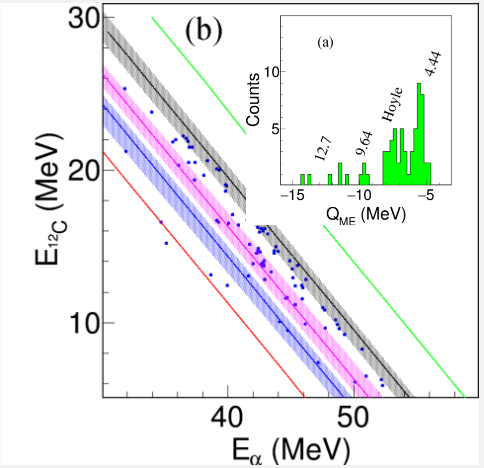
The γ-decay of ^{12}C levels above the particle emission threshold have a crucial role in the production of ^{12}C in astrophysical environments, and the Hoyle state is fundamental for the synthesis of ^{12}C. Despite of the numerous studies in this field, there is still a lot to understand.

The CHIRONE collaboration performed 4 fold coincidence measurements with the results of enhancement in both the 9.64 MeV level and the Hoyle state γ-decay yields. This last result can be explained with the excitation of an Efimov state

Cardella G. et al.,
PRC 104, 064315 (2021)

EFIMOV

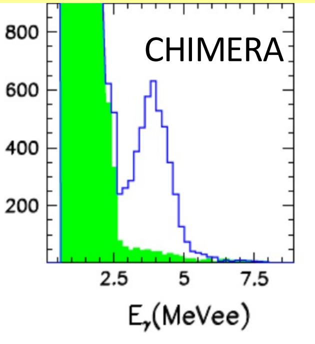




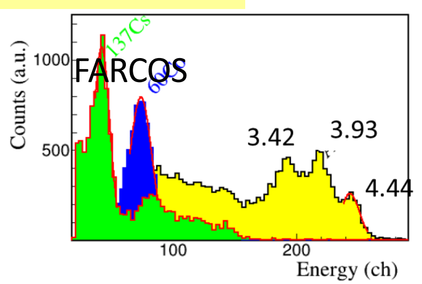
Each couple of α particles has a CM energy like a ^{8}Be - level at **180** keV - **200 keV** below the Hoyle state

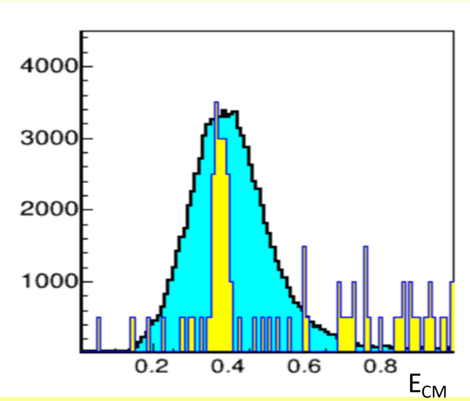
G. Cardella, A. et al.,
Nuclear Physics A 1020 (2022) 122395

We will use α beam @ 40 MeV on ^{12}C **(Tandem @LNS)** measuring both particles and γ rays with FARCOS telescopes



We take advantage of the improved γ-resolution with FARCOS (with respect to CHIMERA) from 1 MeV down to 150 KeV





With FARCOS, we will get a relevant improvement in measuring CM energy for 3-α coincidences (yellow 27 Kev) if compared with CHIMERA (cyan 200 KeV)

New more precise measurements needed to confirm effects on ^{12}C creation in the universe – possible with FARCOS

NUMEN

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

NURE

Extraction from measured cross-sections of *"data-driven"* information on Nuclear Matrix Elements for all the systems candidate for 0νββ
Use of nuclear reactions **(Double Charge Exchange reactions)** to simulate in the laboratory the same nuclear transition occurring in 0νββ

0νββ decay half-life

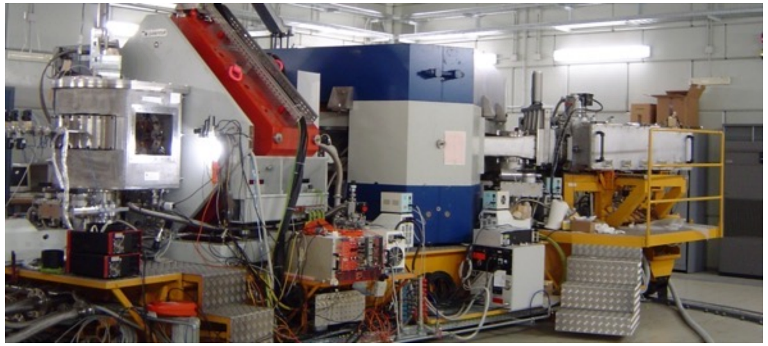
Phase space factor

contains the average **neutrino mass**

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

Nuclear matrix element

K800 Superconducting Cyclotron



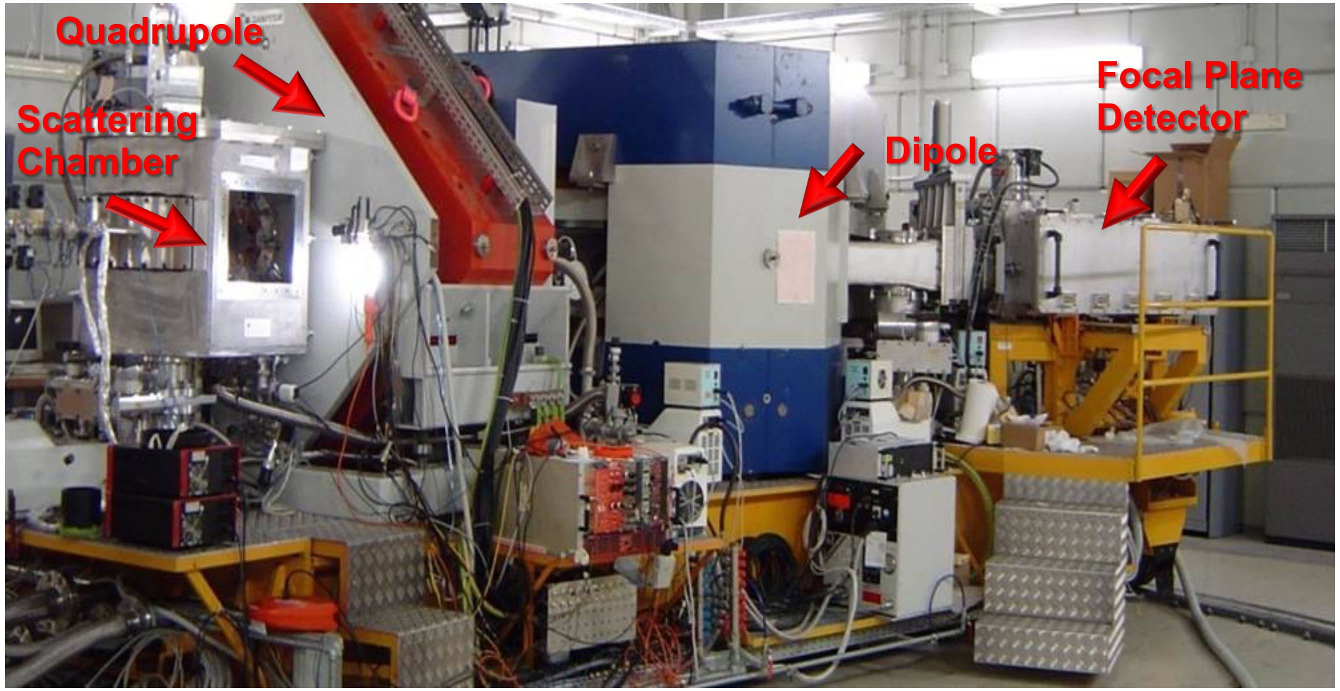
MAGNEX magnetic spectrometer

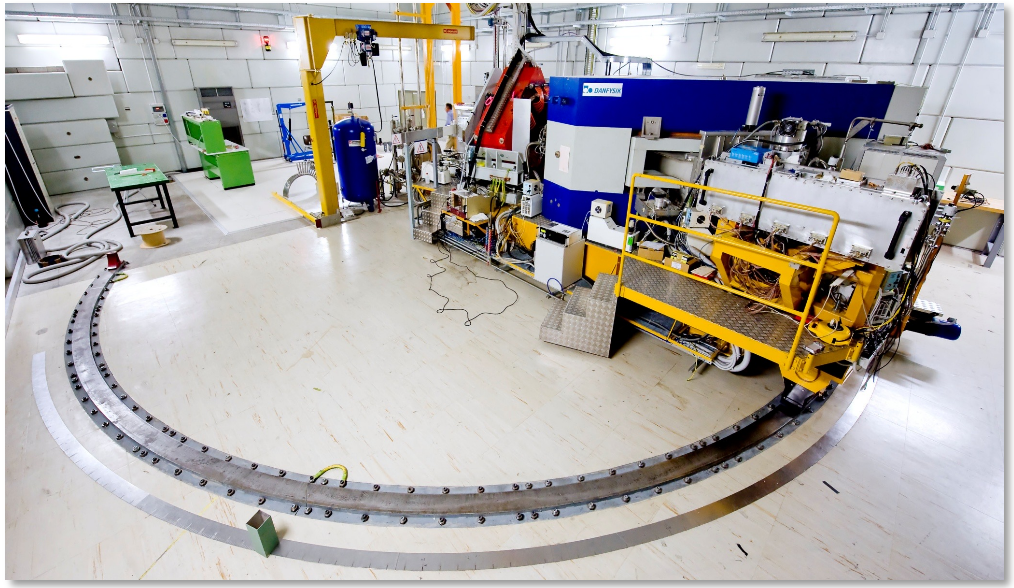
A challenging perspective at LNS in nuclear science

F. Cappuzzello et al., Prog. Part. Nucl. Phys. 128, 103999 (2023)

- 2010 Physics campaigns started

Current MAGNEX configuration



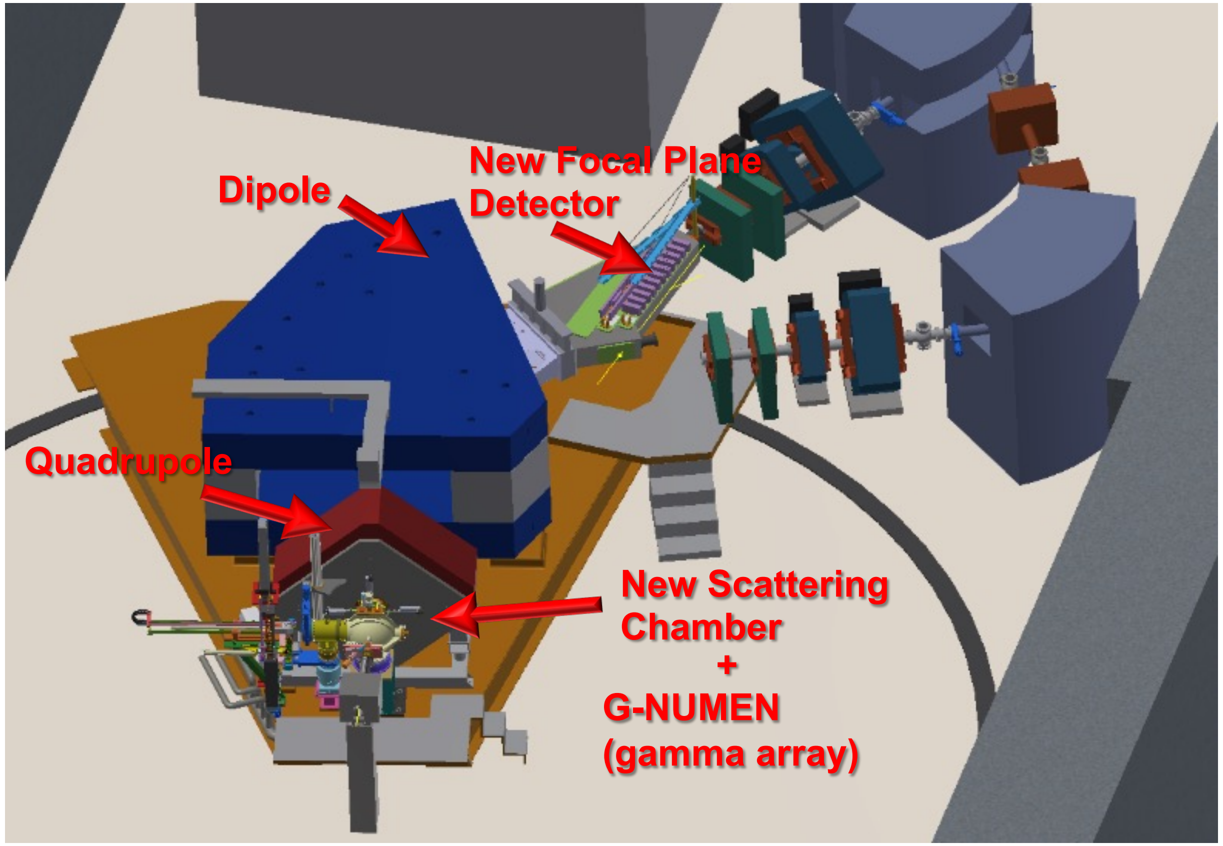


Optical characteristics	Measured values
Maximum magnetic rigidity	1.8 T m
Solid angle	**50 msr**
Momentum acceptance	**-14.3%, +10.3%**
Momentum dispersion for k= - 0.104 (cm/%)	3.68

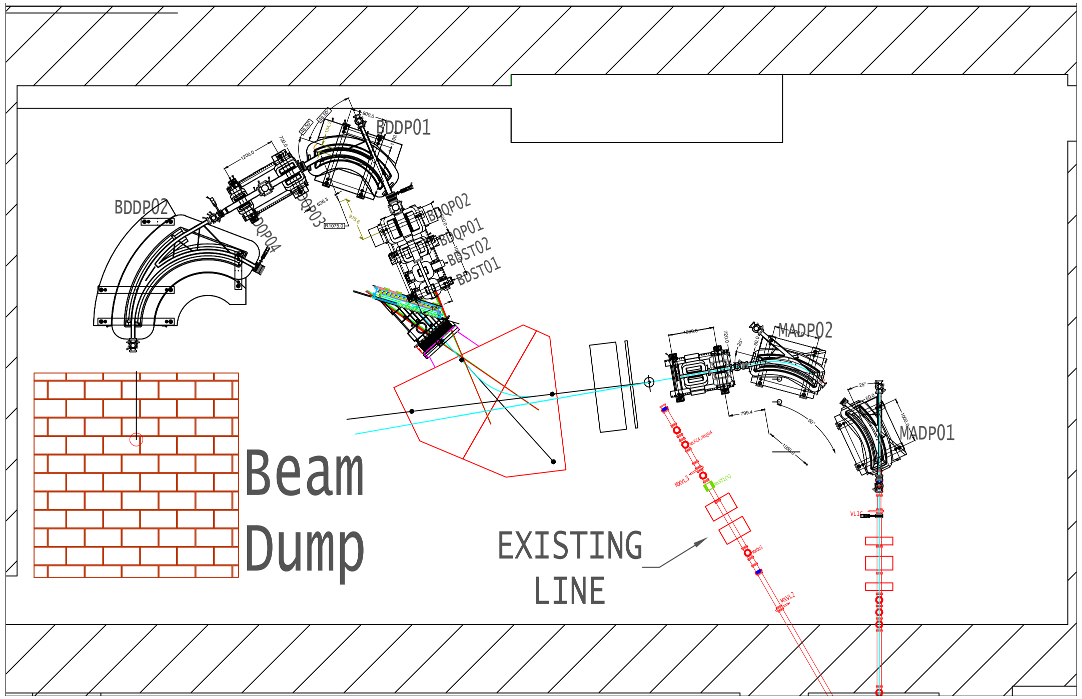
Achieved resolution
Energy $\Delta E/E \sim 1/1000$
Angle $\Delta\theta \sim 0.2°$
Mass $\Delta m/m \sim 1/160$

MAGNEX upgrade to sustain high rates while maintaining the current MAGNEX **resolution and sensitivity**

Future MAGNEX configuration



Future MAGNEX hall

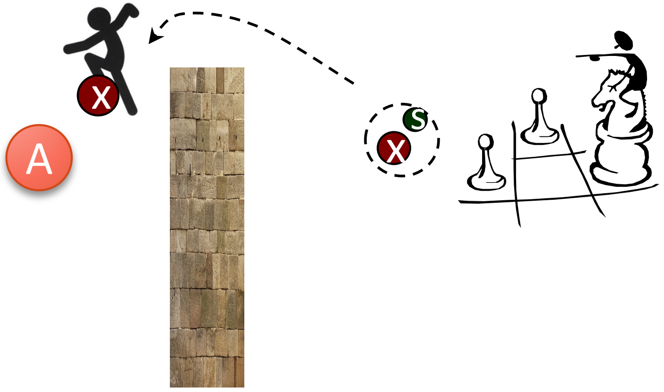


Major upgrades

- New focal plane detector (gas tracker and pid wall)
- New gamma detector array (G-NUMEN)
- New exit beam lines and beam dump (for 0° measurements)
- New power supply to reach higher magnetic rigidity (from 1.8 to 2.2 Tm)
- Suitable targets

Major research field: indirect methods for nuclear astrophysics

Trojan Horse Method



Repulsion wall

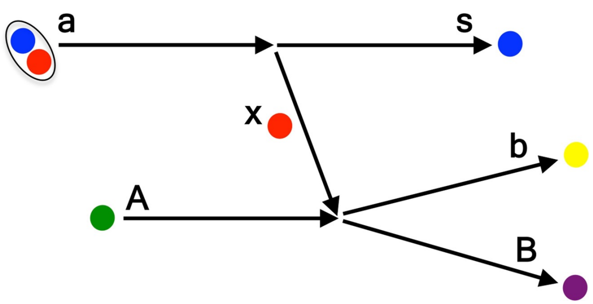
Basic principle: relevant low-energy two-body σ from quasi-free contribution of an appropriate three-body reaction in quasi free kinematics

$$A + a \rightarrow b + B + s \quad \rightarrow\rightarrow\rightarrow \quad A + x \rightarrow b + B$$

a: x $\oplus$ s clusters

Quasi free mechanism

- ✓ only *x* - A interaction
- ✓ *s* = spectator (p_s~0)



$E_A > E_{Coul} \Rightarrow$

NO Coulomb suppression

NO electron screening

$$E_{q.f.} = E_{Ax} - B_{x\text{-}s} \pm \text{(intercluster motion)}$$

plays a key role in compensating for the beam energy

$$E_{q.f.} \approx 0 \quad !!!$$

See for review:

R. Tribble et al., Rep. Prog. Phys. **77** (2014) 106901

A. Tumino et al. Ann. Rev. Nucl. Part. Sci. 71 (2021) 346

THM applied so far to more than 30 reactions, such as $^{6}Li(p,\alpha)^{3}He$, $^{7}Li(p,\alpha)\alpha$, $^{2}H(d,p)^{3}H$, $^{2}H(d,n)^{3}He$, $^{10}B(p,\alpha)^{7}Be$, $^{11}B(p,\alpha)^{8}Be$, $^{17,18}O(p,\alpha)^{14,15}N$, $^{13}C(\alpha,n)^{16}O$, $^{7}Be(n,\alpha)^{4}He$, $^{18}F(p,\alpha)^{15}O$, $^{19}F(p,\alpha)^{16}O$, $^{10}B(p,\alpha)^{7}Be$, $^{11}B(p,\alpha)^{8}Be$, $^{12}C(^{12}C,\alpha)^{20}Ne$, $^{12}C(^{12}C,p)^{23}Na$ ...

Recent result

Article | Open Access | Published: 18 May 2023

Coulomb-free $^1S_0$ $p-p$ scattering length from the quasi-free $p+d \rightarrow p+p+n$ reaction and its relation to universality

Aurora Tumino, Giuseppe G. Rapisarda, Marco La Cognata, Alessandro Oliva, Alejandro Kievsky, Carlos A. Bertulani, Giuseppe D'Agata, Mario Gattobigio, Giovanni L. Guardo, Livio Lamia, Dario Lattuada, Rosario G. Pizzone, Stefano Romano, Maria L. Sergi, Roberta Spartá & Michele Viviani

Charge independence and charge symmetry

After removing the electromagnetic interactions, the NN force between nn, np, pp are almost the same

Charge independence: equality between pp/nn force and np force

Violation: associated to the mass difference between charged and neutral pions

(identical nucleons exchange a neutral pion, a neutron and a proton may exchange both a neutral and a charged pion)

Charge symmetry: equality between pp and nn forces

Charge symmetry breaking: mainly attributed to the up-down quark mass difference

Its validity is supported to some extent by an approximate equality of binding energies of isobar nuclei.

Charge symmetry breaking manifested in the s-wave scattering lengths, a_{NN} that determine the low-energy behavior of NN scattering.

a_{np} directly determined from experiments

a_{pp} not directly accessible from experiments because of Coulomb effects → need to remove them theoretically to reveal the strong interaction contribution to the scattering length

a_{nn} not directly accessible from experiments because of the absence of neutron targets.

… we propose an innovative way to determine a_{pp} →

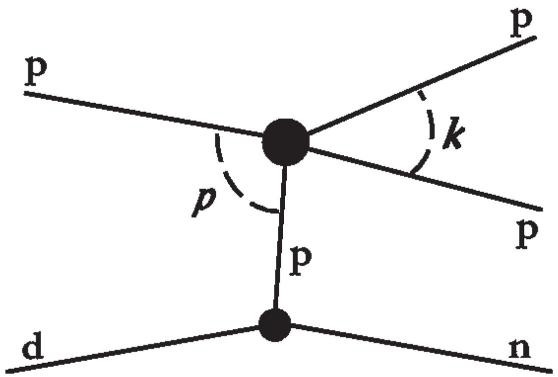
Two-body cross-section from THM data

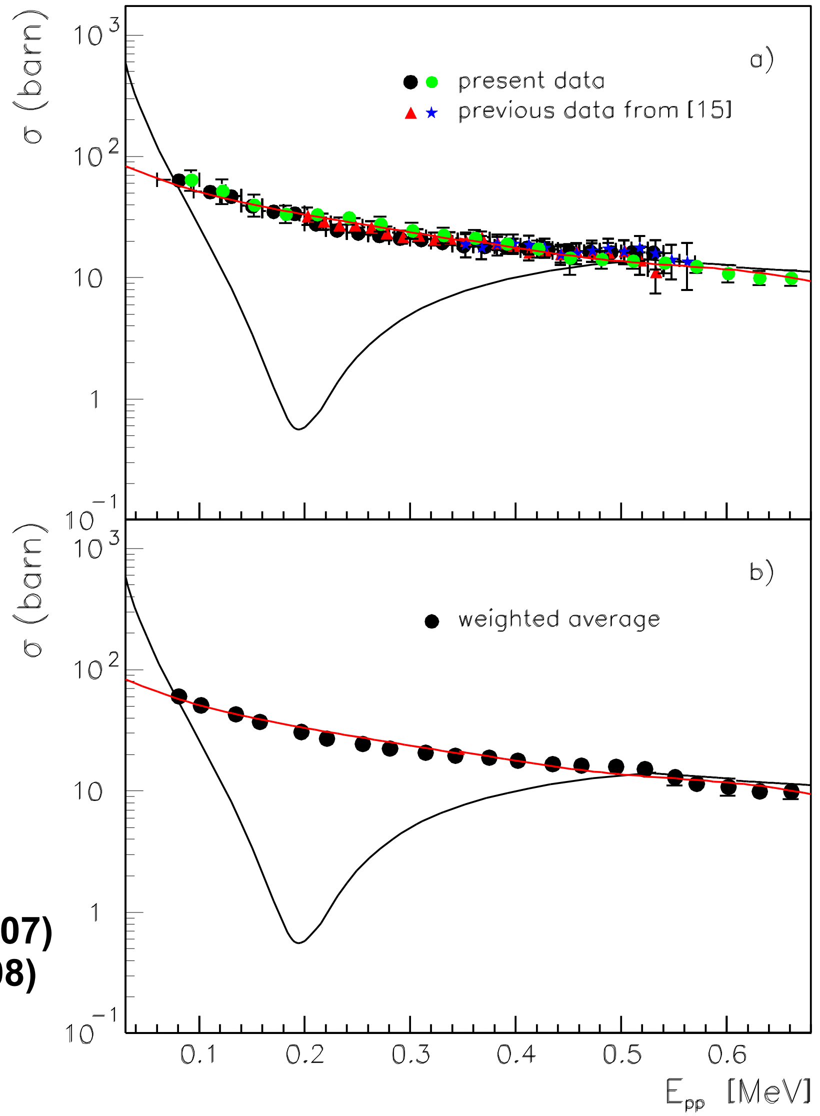
THM p-p cross-section from the p+d→p+p+n quasi free reaction

Coulomb effects appear suppressed

Red line: HOES p-p cross section

Black line: OES p-p cross section





Calculated HOES p-p cross section:

$$\left(\frac{d\sigma}{d\Omega_{\rm c.m.}}\right)^{\rm HOES} = \frac{1}{k^2}\left(\frac{1}{4}\left[\left|2\mu_{pp}\,e^2\,e^{-\pi\eta}\Gamma(1+i\eta)\times\left(\frac{(p^2-k^2)^{i\eta}}{(\mathbf{p}-\mathbf{k})^{2(1+i\eta)}}+\frac{(p^2-k^2)^{i\eta}}{(\mathbf{p}+\mathbf{k})^{2(1+i\eta)}}\right)-2\,T_{CN}(k,p)\right|^2\right] + \frac{3}{4}\left[\left|2\mu_{pp}\,e^2\,e^{-\pi\eta}\Gamma(1+i\eta)\times\left(\frac{(p^2-k^2)^{i\eta}}{(\mathbf{p}-\mathbf{k})^{2(1+i\eta)}}-\frac{(p^2-k^2)^{i\eta}}{(\mathbf{p}+\mathbf{k})^{2(1+i\eta)}}\right)\right|^2\right]\right).$$

A. Tumino et al. PRL 98, 252502 (2007)
A. Tumino et al. PRC 78, 64001 (2008)

nature > communications physics > articles > article

Article | Open Access | Published: 18 May 2023

Coulomb-free $^1S_0$ $p-p$ scattering length from the quasi-free $p + d \rightarrow p + p + n$ reaction and its relation to universality

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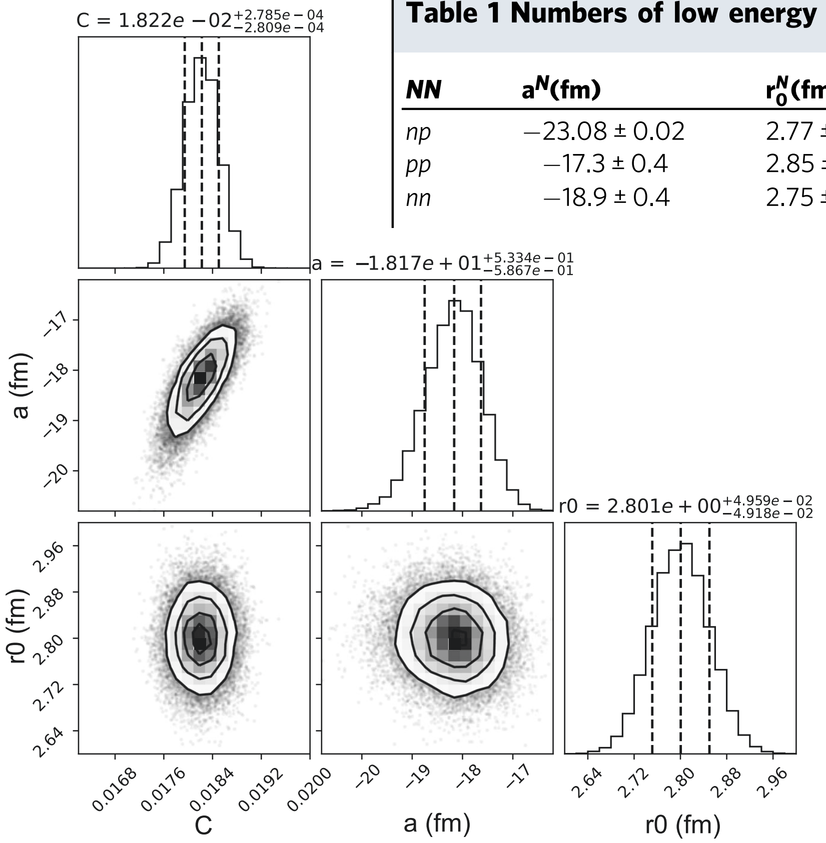
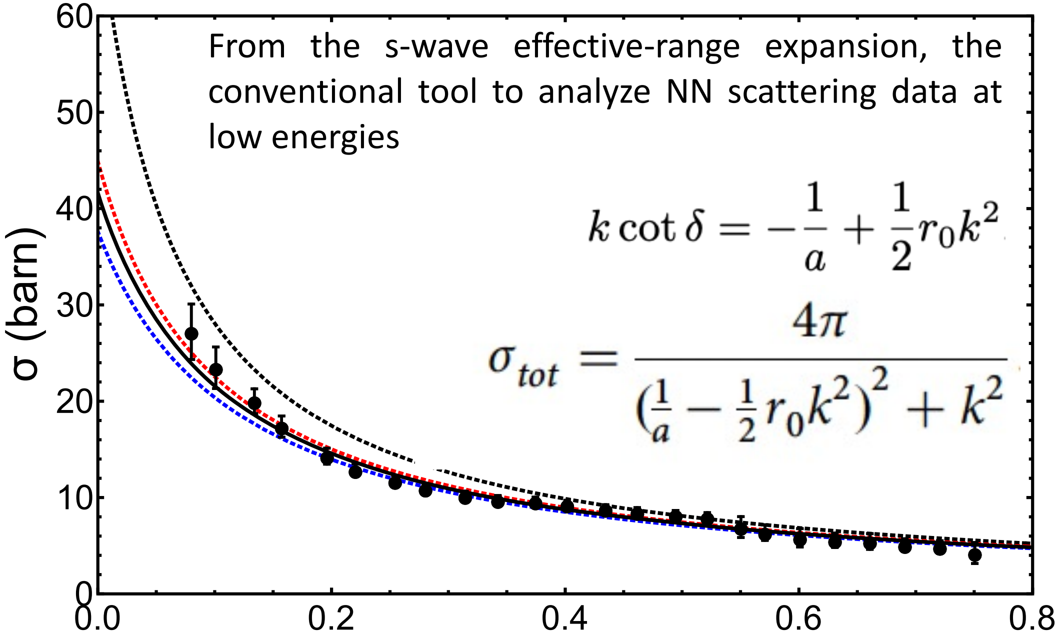
Table 1 Numbers of low energy parameters.

NN	a^N(fm)	r_0^N(fm)	a^{THM}(fm)	r_0^{THM}(fm)
np	−23.08 ± 0.02	2.77 ± 0.05		
pp	−17.3 ± 0.4	2.85 ± 0.04	$-18.17^{+0.53}_{-0.59}$ fm	2.80 ± 0.05 fm
nn	−18.9 ± 0.4	2.75 ± 0.11		





From the s-wave effective-range expansion, the conventional tool to analyze NN scattering data at low energies

$$k\cot\delta = -\frac{1}{a} + \frac{1}{2}r_0k^2$$

$$\sigma_{tot} = \frac{4\pi}{\left(\frac{1}{a} - \frac{1}{2}r_0k^2\right)^2 + k^2}$$

Notice: the NN s-wave phase shift δ contains all short range effects, including the electromagnetic ones. This means that the present analysis of the HOES cross section allows direct access to the short-range p-p interaction as a whole, with its peculiar a_{pp} and r_0 values.

We propose a new paradigm: to assess the charge symmetry breaking of the short-range interaction as a whole, in line with the current understanding that, at a fundamental level, the charge dependence of nuclear forces is due to a difference between the masses of the up and down quark and to electromagnetic interactions among the quarks.

We can exploit universal concepts to better interpret the results, now that Coulomb effects have been removed from the p-p system.

Notably, in the universal window the dynamics is largely independent of the details of the interaction. It is dominated by the long-range behavior allowing for a description based on few parameters.

We construct a two-parameter Gaussian NN interaction with fixed range, valid for s-wave in the spin singlet channel

$$V_{NN}(r) = V_0 e^{-r^2/r_G^2} + \frac{e_{NN}^2}{r}$$

with NN ≡ nn, np, pp and $e^2_{pp} = e^2$ and zero otherwise

the Gaussian form selected to represent the short-range interaction is not relevant, other choices are acceptable as well

Table 1 Numbers of low energy parameters.

NN	a^N(fm)	r_0^N(fm)	a^{THM}(fm)	r_0^{THM}(fm)	a^{sr}(fm)	r_0^{sr}(fm)	V_0(MeV)
np	−23.08 ± 0.02	2.77 ± 0.05			−23.74 ± 0.02	2.80 ± 0.08	−29.90
pp	−17.3 ± 0.4	2.85 ± 0.04	$-18.17^{+0.53}_{-0.59}$ fm	2.80 ± 0.05 fm	−17.6 ± 0.4	2.85 ± 0.09	−29.08
nn	−18.9 ± 0.4	2.75 ± 0.11			−18.6 ± 0.4	2.85 ± 0.08	−29.22

Current accepted values of a and r_0 parameters, (N superscript stands for “nuclear”) for *n-p*, *p-p* and *n-n* scattering compared with those obtained in this work (“THM” superscript). In the last three columns, the values and the corresponding strength V_0 obtained with the Gaussian characterization are given. The *sr* superscript stands for “short-range” (nuclear + EM).

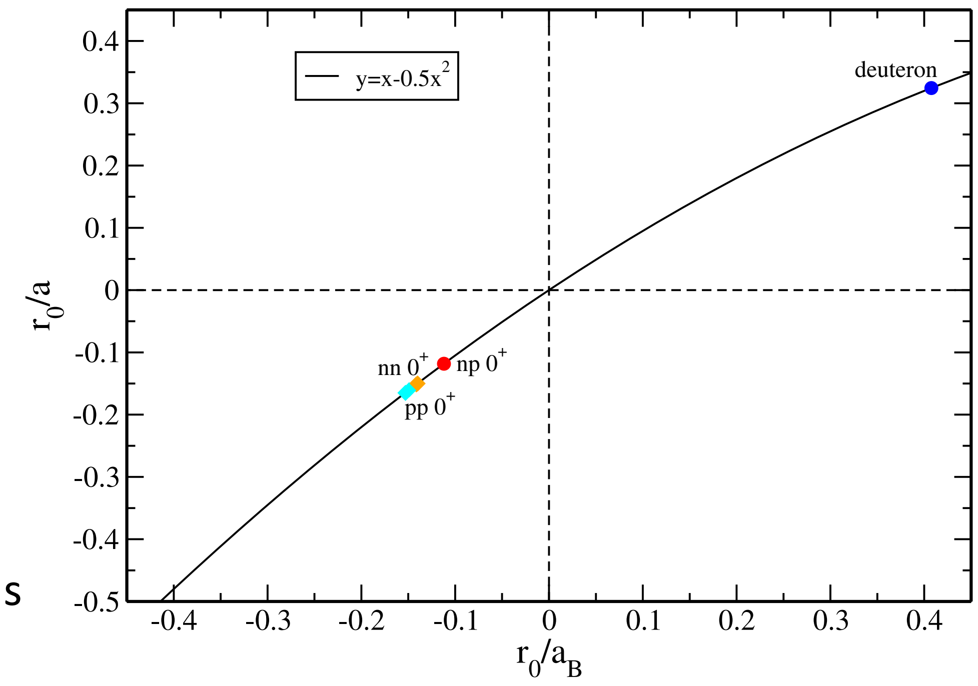
The universal window shows the location of the different NN systems using the numbers here obtained: the coordinates are given by

$[x, y] = [r_0/a_B, r_0/a]$

With a_B given by
$$\frac{1}{a_B} = \frac{1}{a} + \frac{1}{2}\frac{r_0}{a_B^2}$$

From low-energy effective range plus S-matrix pole equation

Interestingly, they lie on the curve $y = x - 0.5x^2$ verifying the correlation as above.



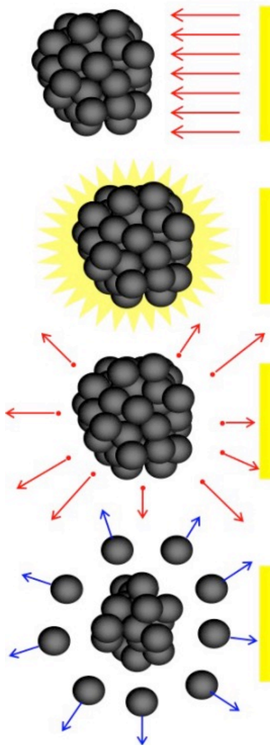
The NN systems are well determined by the corresponding experimental values, and have a precise position along the y(x) curve.

Using the property highlighted here that the systems move along the universal curve, it is possible to reduce the model dependence in the determination of the scattering parameters as produced by the short-range part of the interaction without discriminating between nuclear and electromagnetic.

Laser-cluster scenario

THE COULOMB EXPLOSION PARADIGMA

The interaction of ultra-short laser pulses with an expanding gas mixture at controlled temperature and pressure inside a vacuum chamber causes the formation of plasmas with multi-keV temperature. These energies overlap with the typical temperatures of stellar environments where thermonuclear reactions occur, thus making this paradigm a ***perfect scenario for nuclear astrophysics research***.



Step 1
Clusters are irradiated by high intensity laser pulse ($\sim 10^{16} \sim 10^{18}$ W/cm^2).

Step 2
Laser pulse energy is first absorbed by electrons via heating mechanisms such as rapid collisional heating.

Step 3
Electrons escape from the cluster and leave positive charge build-up on the cluster.

Step 4
The cluster "explodes" and deuterons acquire multi-keV kinetic energy.

deuterium ions
Kinetic Energy < 10^2 keV
Density ~ 10^{18} atoms/cm^3
10^5-10^7 neutrons per shot

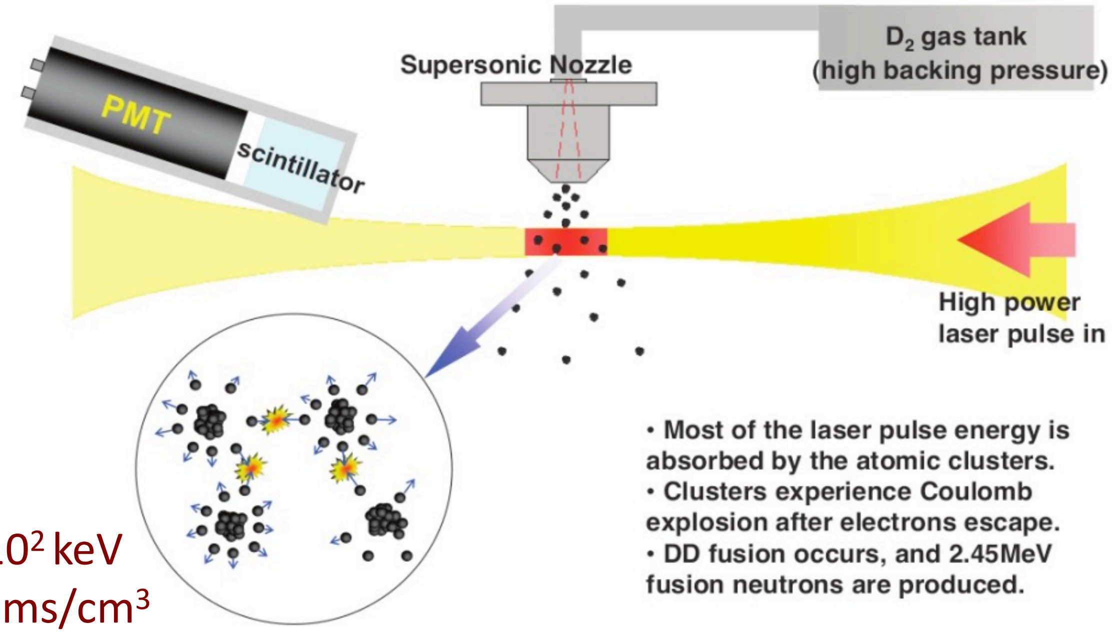
Example: deuterium-deuterium fusion

$$d + d \rightarrow {}^3\text{He}(0.82MeV) + n(2.45MeV)$$

$$d + d \rightarrow p(3.02MeV) + t(1.01MeV)$$

$$d + {}^3\text{He} \rightarrow p(14.7MeV) + {}^4\text{He}(3.6MeV)$$

Nuclear fusion from laser-cluster interaction



Deuterium-deuterium fusion

PHYSICAL REVIEW C
covering nuclear physics

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Model-independent determination of the astrophysical *S* factor in laser-induced fusion plasmas

D. Lattuada, M. Barbarino, A. Bonasera, W. Bang, H. J. Quevedo, M. Warren, F. Consoli, R. De Angelis, P. Andreoli, S. Kimura, G. Dyer, A. C. Bernstein, K. Hagel, M. Barbui, K. Schmidt, E. Gaul, M. E. Donovan, J. B. Natowitz, and T. Ditmire

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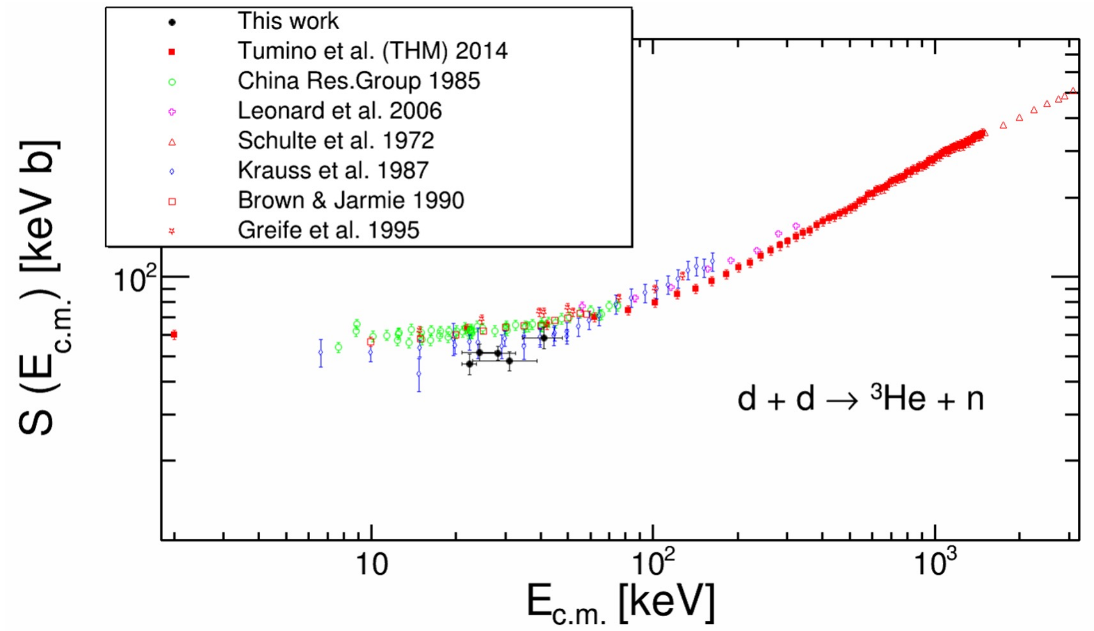
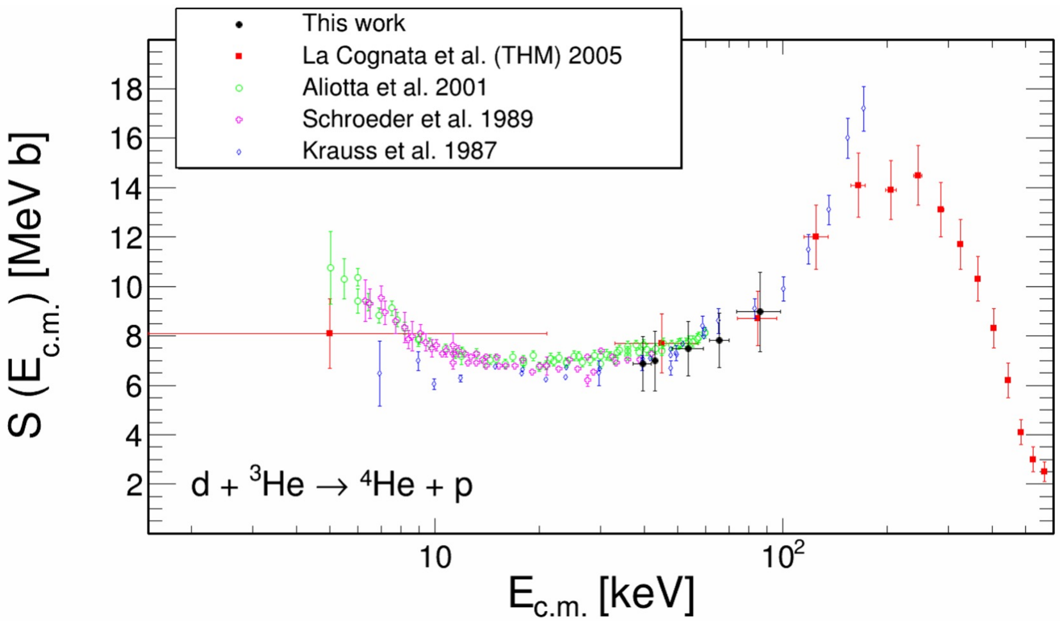
This method will open the way for a new approach to study nuclear astrophysics reactions such as:

- deuterium- deuterium
- deuterium-^{3}He
- proton-lithium
- proton-boron
- ^{12}C-^{12}C
- ^{16}O-^{16}O
- and much more….





SUMMARY

- Nuclear physics at LNS covers a broad range of physical cases
- Many experiments (CHIRONE, NUMEN, ASFIN) are focused on the CS and on the TANDEM
- Nuclear astrophysics is a key research fields, from dark matter to multimessenger astronomy, with a strong connection with international laboratories
- Waiting for the CS beams, the Tandem program for the next years is very broad and full of exciting and highly competitive physical cases

THANK YOU FOR YOUR ATTENTION