Nuclear Physics Mid Term Plan in Italy

LNL – Session

Legnaro (Pd), April 11th-12th 2022

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Nuclear Physics Mid Term Plan in Italy

Nuclear Physics Mid Term PLAN @ LNL

Summary & conclusions

Andrea Gottardo

INFN Istituto Nazionale di Fisica Nucleare

LNL session (11-12 April 2022):

https://agenda.infn.it/event/28738/

- **About 120 researchers** have joined the working groups, about 40% from abroad
- **About 280 researchers attended the meeting**, 82 in presence

Working group (Chair)	Topic	Speaker
Nuclear Astrophysics (R. Depalo)	‣ Nucleosynthesis up to the iron peak ‣ Nucleosynthesis of trans-iron elements ‣ Nuclear astrophysics theory	A. Caciolli T. Kurtukian Nieto S. Cristallo
Nuclear Structure (D. Mengoni)	‣ Shell evolution ‣ Light to medium-mass exotic nuclei ‣ N~Z nuclei and isospin symmetry ‣ Deformation and collective states	A. Gottardo S. Bottoni S. M. Lenzi F. C. Crespi
Nuclear Reactions and Dynamics (T. Marchi)	‣ Physics overview: alpha clustering, dynamics and structure, termodynamics, equation of state, collective motions ‣ Mechanisms/Tools: fusion-evaporation and pre-equilibrium emission ‣ Mechanisms/Tools: transfer, particle spectroscopy ‣ Mechanisms/Tools: fission and sub-barrier fusion	F. Gulminelli & D. Dell'Aquila K. Mazurek & M. Cicerchia L. Gasques & F. Galtarossa M. Caamaño-Fresco & I. Zanon
Applications (G. Pupillo)	‣ Nuclear cross sections measurements and modelling for direct radionuclide production and neutron beam lines at SPES ‣ ISOL and laser applications at the SPES facility ‣ Development, characterization and modifications of materials for applied nuclear physics	L. Mou M. Ballan M. Campostrini

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THE EUROPEAN PHYSICAL JOURNAL PLUS
Regular Article

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Nuclear physics midterm plan at Legnaro National Laboratories (LNL)

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Nuclear Structure

time …

A | B | C

Light and medium mass exotic nuclei

- A: γ decay from near-threshold states
- B: Particle decays from cluster states
- C: γ decay from near-threshold states
- C: Nucleon correlations and molecular orbitals
- C: Isoscalar Giant Monopole Resonance in light deformed nuclei
- C: Proton excitations and 0+ states in Ar isotopes

N~Z nuclei

- A: Isospin symmetry breaking, shape coexistence – lifetime measurements
- B: Fundamental interactions (precision measurement of mirror beta decay branching ratios)
- B–C: T=0 vs T=1 p-n pairing

Shell Evolution

- A–C: New theory developments for shell structure
- A–C: Shell-evolution around N=50: shape coexistence and gap reduction towards 78Ni
- B: Shape coexistence and type II shell evolution around N=60 in Zr, Sr
- C: Lifetimes after transfer reactions for interplay of deformation and single particle
- C: Shell-evolution at N=82 around 132Sn

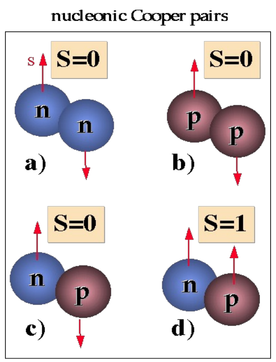
Deformation and Collective modes

- A: GDR/GQR gamma+particle decay, Jacobi shape
- B–C: PDR (alpha scattering inv. kin. with different stable nuclei and SPES beams) and PDR Beta Decay

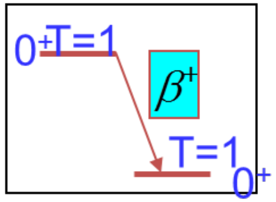
N~Z nuclei and isospin symmetry

N=Z

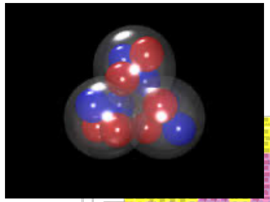
p-n pairing



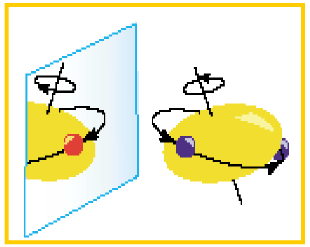
fundamental interactions



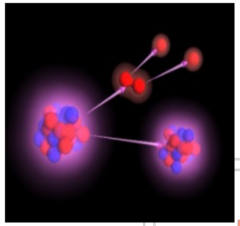
alpha clusterization



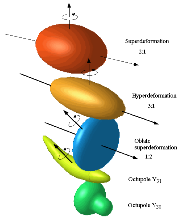
Isospin symmetry breaking

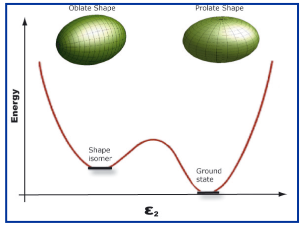


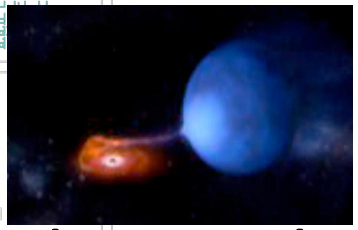
Coupling to the continuum



Nuclear shapes and coexistence







Nuclear Astrophysics

Richness of phenomena and perfect ground for *pn* interaction:

- Short term opportunities with stable beams (quadrupole collectivity); MED+TED
- Short and mid term (T=0 and quartetting)
- Longer term SiC+TiC beam development (FI)

Opportunities at LNL

Measure the B(E2) in isobaric triplets

Reactions with stable beams:

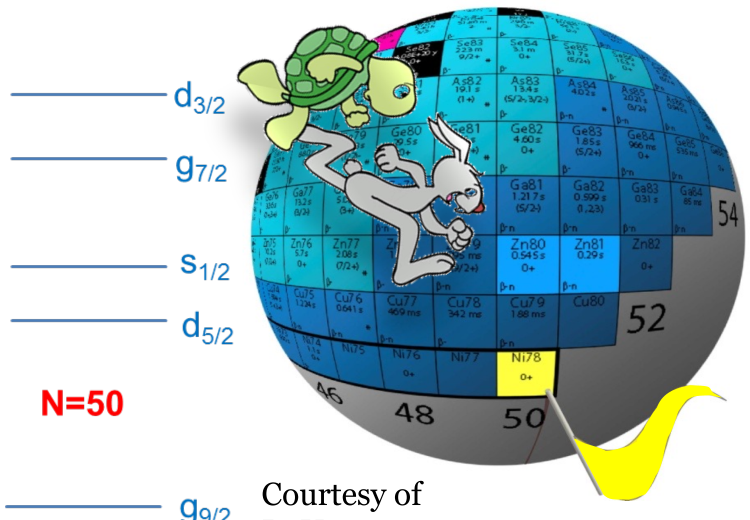
- Fusion-evaporation reactions (-2n evaporation channels)
- Reactions with solid ^{3}He targets (^{3}He,n)
- Selected cases may be done in multinucleon transfer with N=Z beam/target combinations utilizing PRISMA

AGATA: High-efficiency, gamma-gamma capability, position sensitivity (essential for high-velocity reactions and line-shapes)
NEDA: High-efficiency neutron detection

Doppler-shift methods: Lineshape analysis and Plunger-methods

Shell evolution

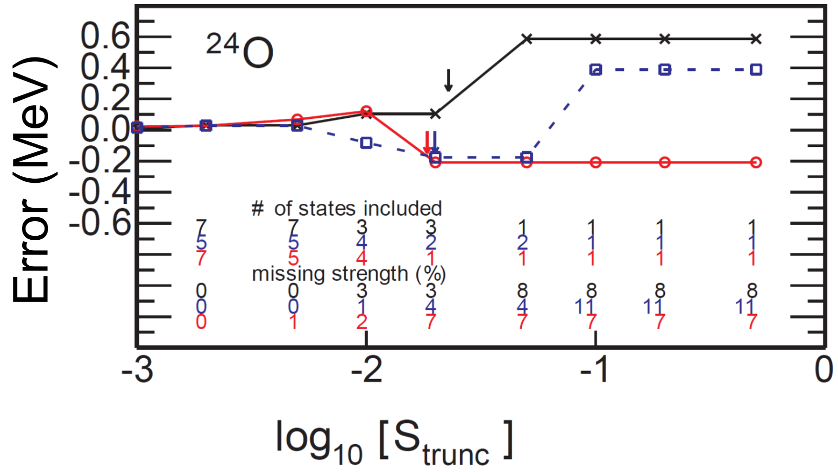
- Shell evolution around 78Ni
- Deformation and shape coexistence
- Shell evolution around 132Sn



Courtesy of
D. Verney

Stable beams (fission): core-coupled states and intruders
1+ SPES beams
q+ SPES beams : lifetime (plunger or DSAM) after transfer (d,p) , (d,t), coulex on intruder states

Limit of observability

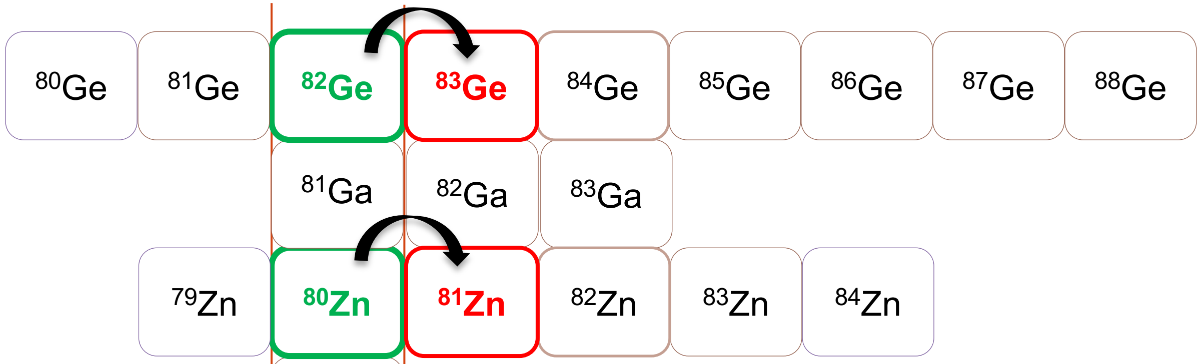


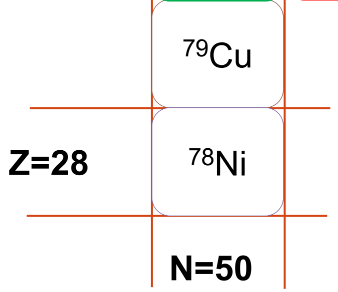
Similar approaches for the the regions around 132Sn (~2 order of magn. more intense than currently available at ISOL facilities) key nucleus for physics and astrophysics purposes

Also with higher-l transfer → alpha transfer

Need for precision measurements ..

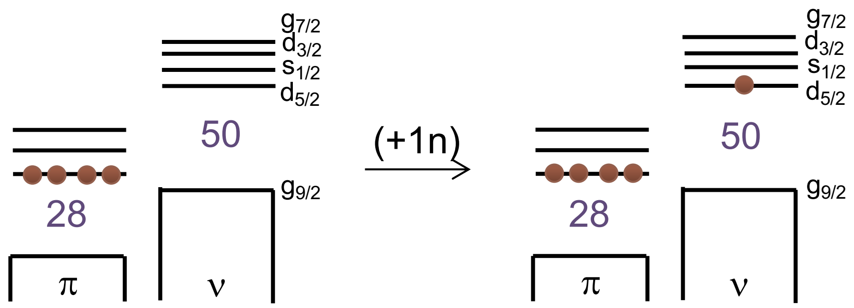
Shell evolution: Neutron Addition at/around N=50





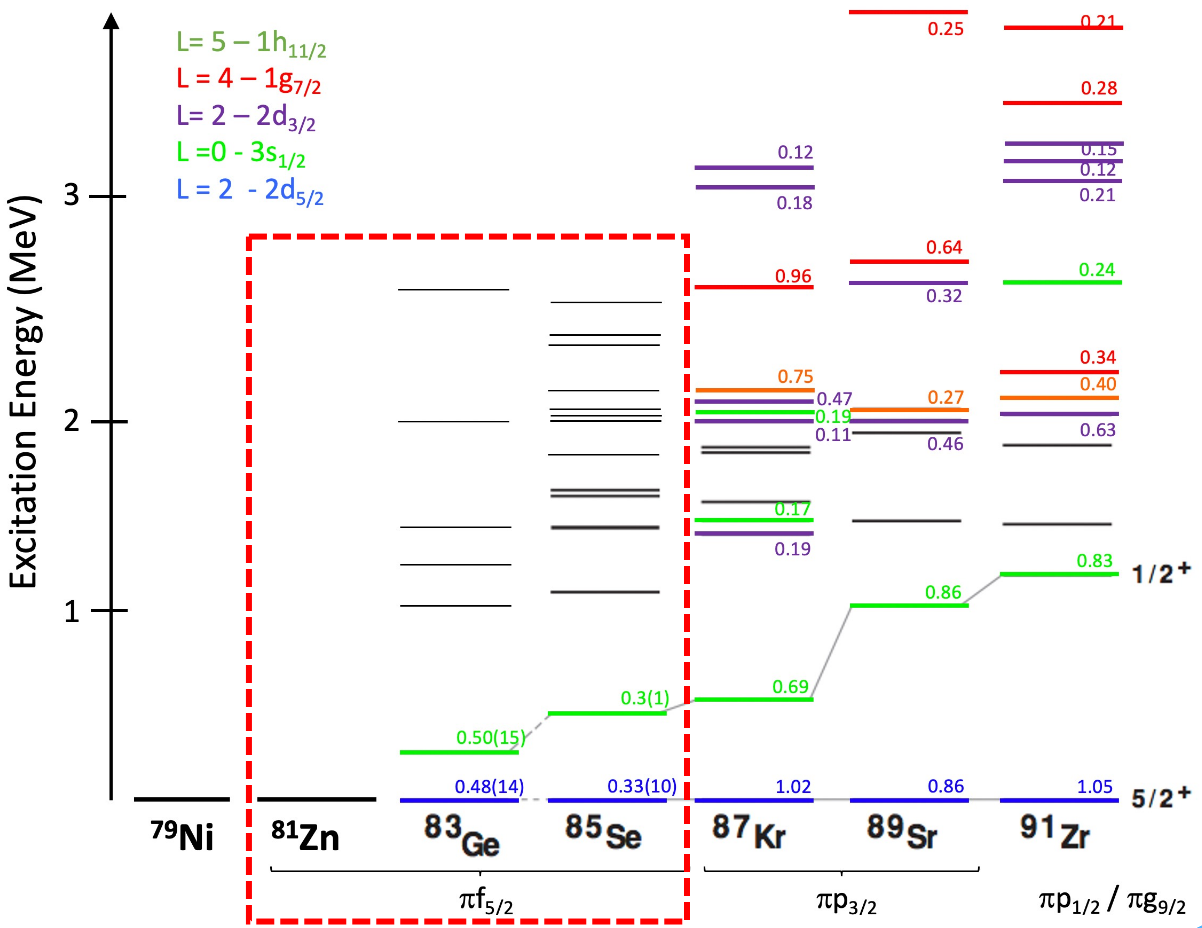
- Selectivity to n(gds)$^{+1}$ states
  - → Natural: from sdg$_7$
- Drift, spread of s.p. strength
  - → Cross sections -> s.p. strength

Neutron addition on N=50 : ^{82}Ge, ^{80}Zn(d,p)



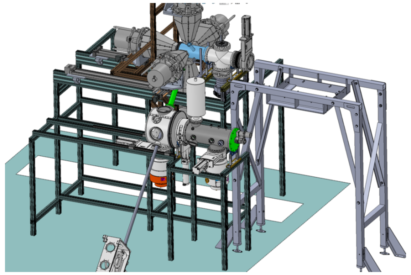
^{82}Ge (gs)

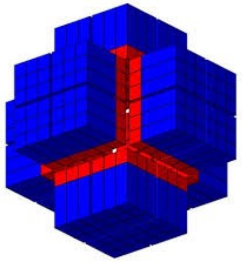
^{83}Ge: sp. states (5/2+,3/2+,7/2+)



Studies enabled by new SPES beams

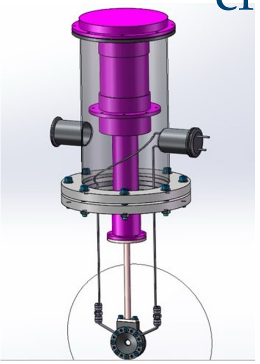
β-decay
station





PARIS
γ-rays

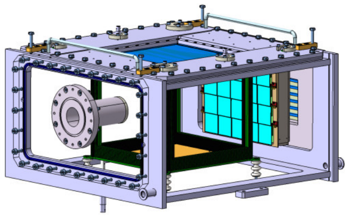
CTADIR
cryogenic
target

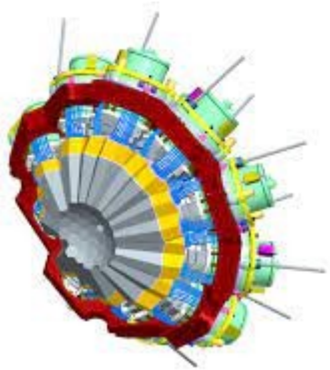


PRISMA
heavy ions

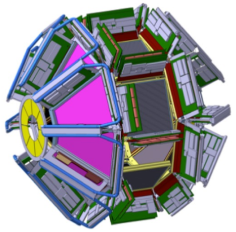
Forefront contemporary nuclear structure needs ground-breaking integrated systems

ACTIVE TARGETS

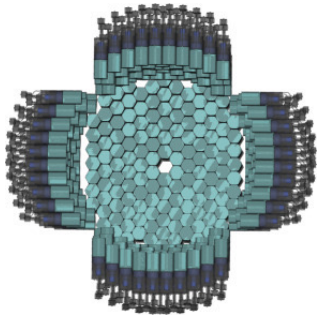




AGATA
γ-rays



GRIT
charged particles



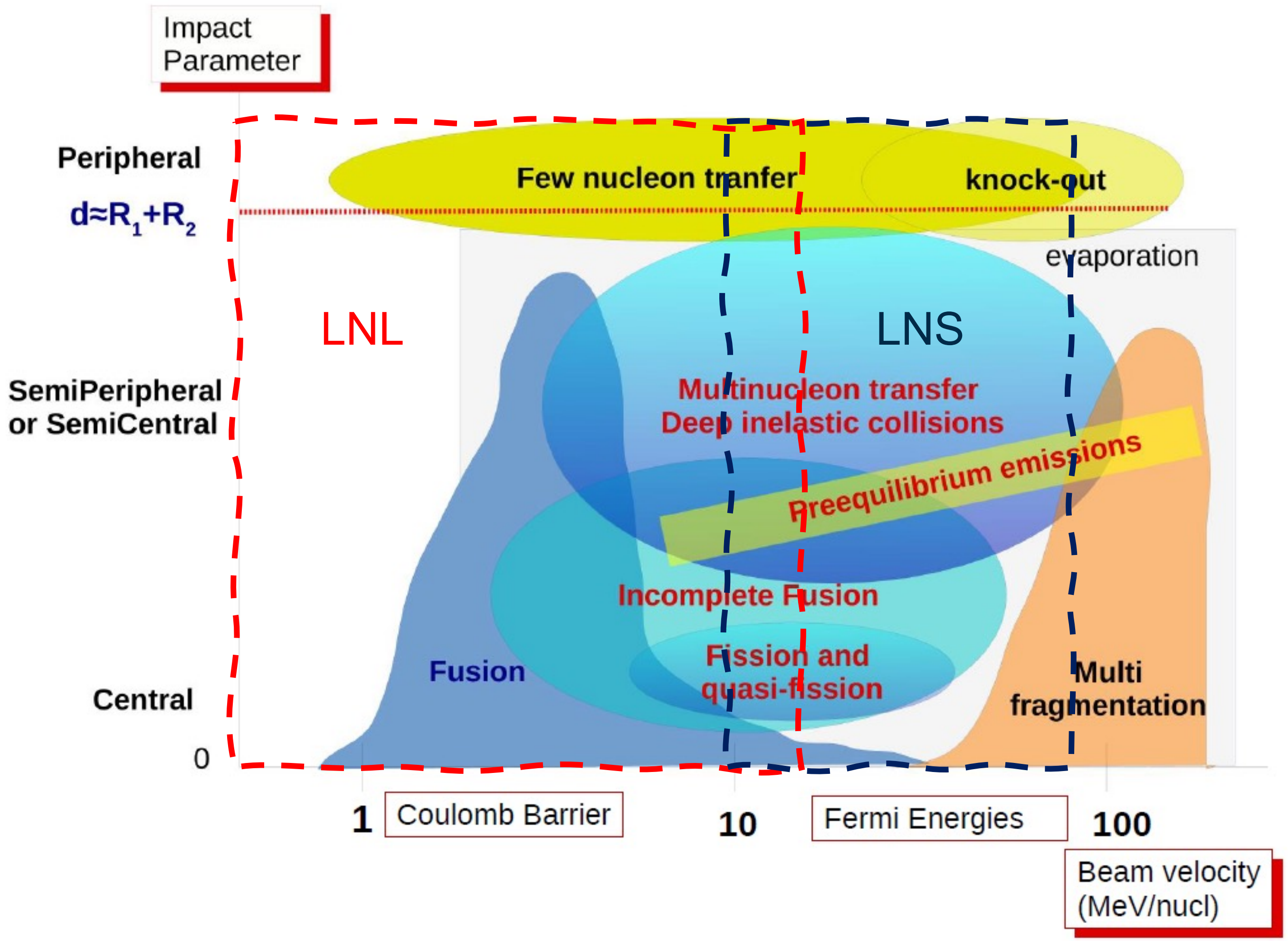
NEDA
neutrons

Nuclear Reactions

Readiness . . .

	A	B	C
Fusion-evaporation and pre-equilibrium emission	**α-correlations and clustering in light and medium mass nuclei**. Beams: $^{16-18}$O at 10 AMeV, light targets.	**Isospin dependence of CN formation and decay.** Beams: Kr, Sr, Sn.	
	onset of pre-equilibrium emission and clustering. Beams: $^{16-18}$O, ^{22}Ne at 18-20 AMeV. **α emission at high spins (deformation).** Beams: Ti, Ni at 10 AMeV. →	**Extension to SPES beams: Sn, Rb**	
		Incomplete fusion, shell effects in quasi-fission	
Direct processes	**Competition between transfer and near-barrier fusion.**	**Links with nuclear structure and astrophysics: Asymptotic Normalization Constants, spectroscopic factors, halos. (also low energy reactions at AN2000 and CN). Future challenges with A.T. and GRIT**	**Future challenges: 6He beams from EXOTIC (12C) 9Be beams**
	MNT1: populating heavy nuclei in the region of Pb		
	MNT2: correlations in transfer (Sn+Ni in progress)		
Fission and sub-barrier fusion	**Scan of neutron deficient systems at high excitation energy.** Beams: Pb.	**Actinides region: shell effects and reaction dynamics at low excitation energy.**	**Isomers measured at the focal plane of PRISMA.**
	The nucleus as a quantum effects with sub-barrier fusion		
	Electron-positron pair spectroscopy		

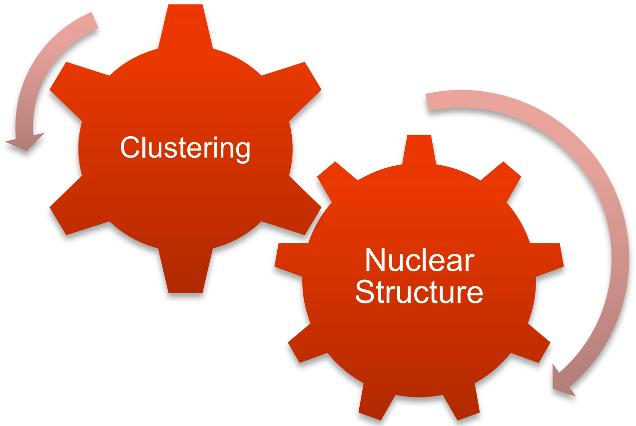
Nuclear Reactions and Dynamics. Highlights.



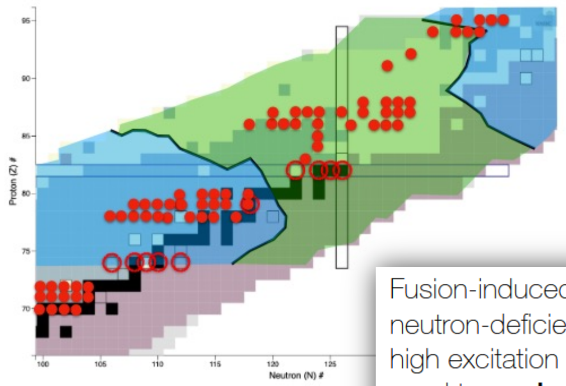
WG1. Fusion-evaporation and pre-equilibrium emission.

WG2. Direct processes, transfer and particle spectroscopy.

WG3. Fission and sub barrier fusion.



Fission



Pb or lighter beams

Fusion-induced fission produces neutron-deficient systems at relatively high excitation energy that can be used to **explore the effect of nuclear structure** and fission dynamics **at high excitation energy**.

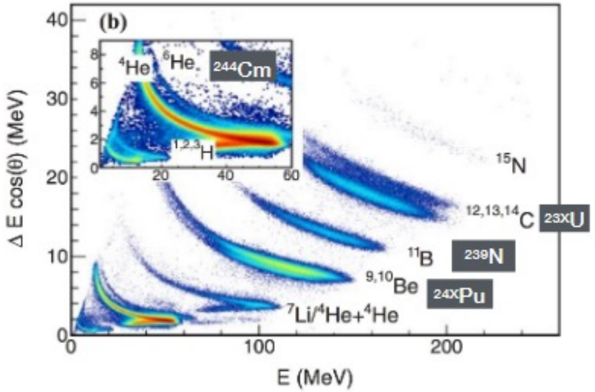
A

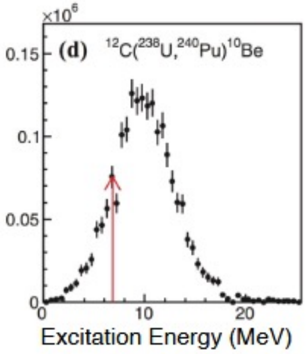
B

- With the upcoming ^{238}U beam and the increase of beam energy, **transfer-induced fission is at hand** for a good set of beam especies.
- Transfer-induced fission can produce **a number of systems with a wide distribution of excitation energy** with a single target and beam combination.

Actinides region: shell effects and dynamics at low excitation energy (transfer-induced-fission, inelastic, etc.).

U beams and dedicated particle detectors are needed





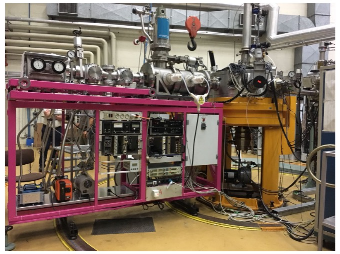
C. Rodríguez. Tajes et al., PRC 89 (2014) 024614

C **Gamma-ray detectors at PRISMA focal plane would allow to study long-lived isomeric states.**

State of the art detectors
for both fission and sbb

The opportunity with PRISMA

The present PISOLO set-up for sub-barrier fusion measurements at LNL



Nuclear Physics Mid Term Plan in Italy
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Nuclear Astrophysics

Phase A | Phase B | Phase C

Nucleosynthesys up to Fe

- Phase A: Indirect study of $^{14}N(p,\gamma)^{15}O$ reaction and the solar composition problem
- Phase A: ^{24}Mg excited states and impact on stellar carbon burning
- Phase B: Abundance of radioactive elements in our Galaxy: Constraining ^{26}Al — $^{26}Al^{m}(n,p)^{26}Mg$, $^{26}Al^{m}(n,\alpha)^{23}Na$, $^{26}Al^{m}(p,\gamma)^{27}Si$
- Phase B–C: Big Bang Nucleosynthesis in the era of precision Cosmology: p+d, d+d, $^{7}Be(d,\alpha)^{5}Li$
- Phase A–C: Investigating the Hoyle state: $^{14}N(d,\alpha)^{12}C$; $^{4}He(^{12}C,^{12}C^{*})^{4}He$; $^{9}Be(\alpha,n)^{12}C$; $^{4}He(2n,\gamma)^{6}He$
- Phase C: $^{16}O+^{16}O$ reaction study at deep sub-barrier energies

Nucleosynthesys beyond Fe

- Phase A: Decay properties of neutron-rich nuclei at the first r-process peak
- Phase A–B: Activation measurements of isotopes of interest for the s-process
- Phase B: Abundances of the elements at the first r-process peak: (α,n) reactions
- Phase B–C: Neutron capture cross sections for i-and r-process nucleosynthesis via surrogate reaction approach
- Phase C: Neutron capture cross sections for s-process via the surrogate reaction approach – batch mode

Theory

- Phase A–B: Sensitivity studies
- Phase B–C: Impact of new results on stellar evolution and nucleosynthesis

Summary on Nuclear Astrophysics

s process

- (n,γ):
  - ^{79}Se, ^{81,85}Kr, ^{86}Rb, ^{65}Zn, ^{121}Sn,
  - ^{64}Cu, ^{108}Ag, ^{109}Pd, and ^{123}Sn and many more

→ collaboration with INFN Pg and INAF Teramo

→ 2 LoIs presented at the 3rd SPES workshop in 2016

→ Tests proposed at LNL

r process

- $^{123,131\text{-}134,131}$In, ^{133}Sb
- Ni, Cu, Zn, Ga, Ge, As

→ Collaboration with ORNL/Rutgers Univ. (exp) and NSCL (theory)

→ 2 LoIs presented at the 3rd SPES workshop in 2016

→ Commissioning tests needed with stable beam

Teresa Kurtukian-Nieto,

LNF session (1-2 December 2022):

https://agenda.infn.it/event/32709/

- **223 researchers attended the meeting**, 80 in presence

Working group (Chair)	Topic
Future possibilities for nuclear physics at DAFNE	▸ Nuclear physics at DAFNE ▸ Femtoscopy at SIDDHARTA and ALICE
Charged particle detectors (G. Pasquali, F. Galtarossa, L. Servoli)	▸ Pulse shape discrimination, silicon carbide detectors, active targets ▸ Segmented silicon detectors, heavy ion detection and spectrometers ▸ Diamond detectors, emulsions and other techniques
Neutron detectors (C. Massimi, A. Gottardo)	▸ Organic scintillators for neutron detection ▸ Detectors for neutron beams and applications ▸ Innovative neutron detectors
Detectors for medical applications (R. Catalano, P. Cardarelli, M. Lunardon)	▸ Treatment monitoring and optimisation ▸ Dosimetry, quality assurance and radiotherapy ▸ X-ray and gamma imaging
Targets development for nuclear physics (M. Cavallaro, S. Corradetti)	▸ Innovative targets for nuclear physics experiments ▸ Innovative targets for new production facilities
Detectors for gamma/X-radiation (A. Scordo, W. Raniero)	▸ X-ray detectors ▸ Gamma detectors
New facilities at LNF, LNL and LNS (A. Di Pietro, A. Gottardo)	▸ New facilities at Laboratori Nazionali di Legnaro ▸ New facilities at Laboratori Nazionali del S [illegible] ▸ New facilities for laser-based activities at [illegible]

Screenshot

New experimental setups – Low energy

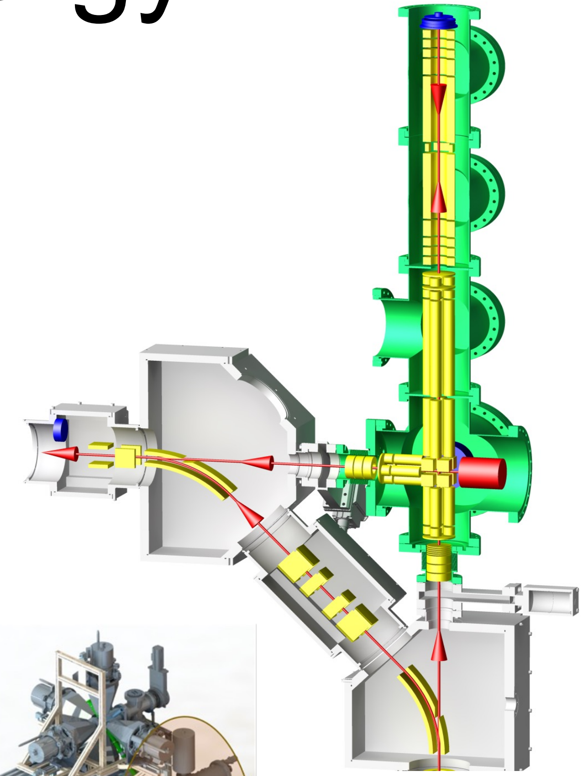
PHASE A : for definition of the item
PHASE B : development of a proposal document.

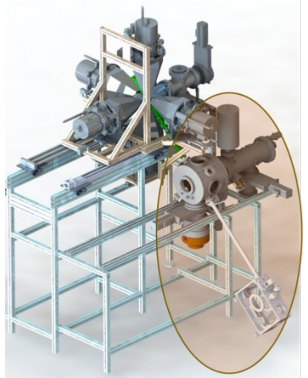
	Sigla	Description	Timeline
LNL-Low01	MR-TOF-MS	MR-TOF trap for mass measurements	A:2025 B:2026
LNL-Low02	Laser	Collinear laser spectroscopy	A:2025 B: 2026 synergy with ALTO @IJCLab
LNL-Low03	NMR	β-NMR e β-NQR	A:2026
LNL-Low04	β-neutron	Resident neutron array for neutron spectroscopy	A:2023 B:2024-25
LNL-Low05	b-DS	upgrade of b-DS and SLICES	A:2023 B:2024

New experimental setups – Low energy

- Setups for determination of ground-state properties
  - Collinear Laser Spectroscopy
  - New equipment for mass measurement (and beam study): MR-TOF-MS

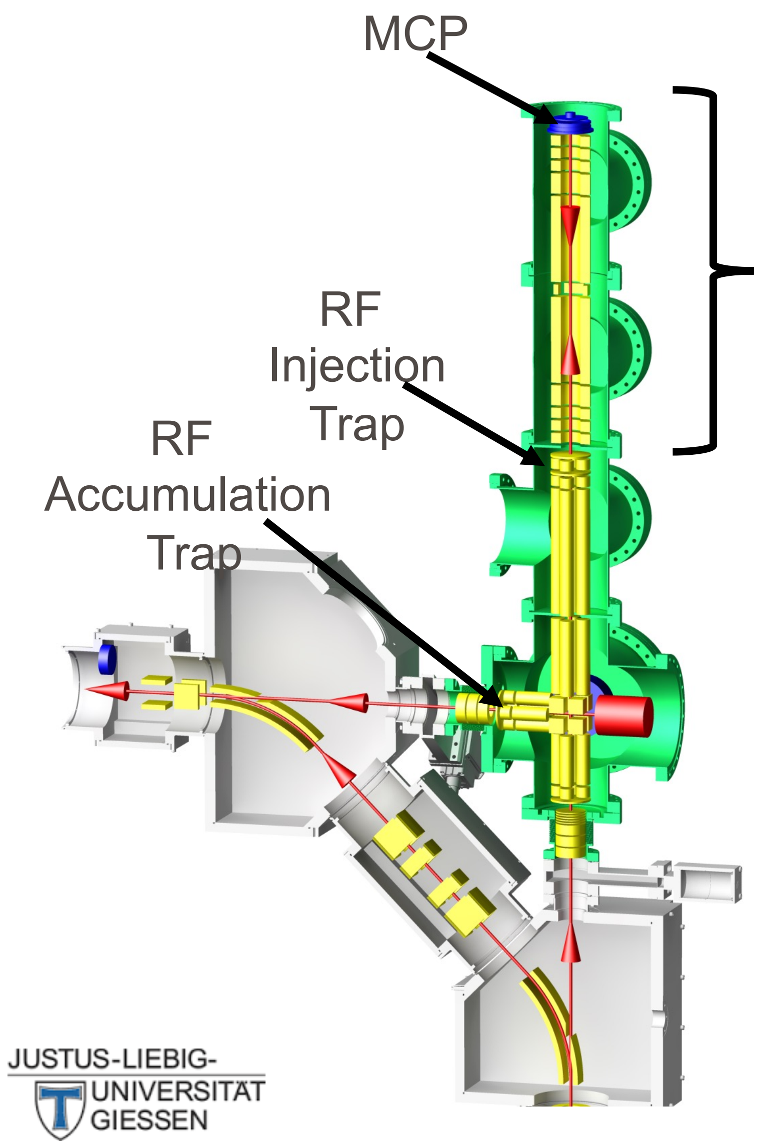
- Setups for β-decay :
  - New equipment for β-decay studies: neutron detection arrays;
  - TAS;
  - Trap-assisted spectroscopy: b-DS after MR-TOF-MS





Multi-Reflection Time-Of-Flight Mass-Separator

Courtesy of T. Dickel



Beam from magnetic dipole → Purification setup (double Penning trap, MR-TOF-MS, RI) → Decay setup

Separation in Z guaranteed (can be isomerically purified)

+ Pure beams
+ Better determination of mother nuclei spin and parities
+ Better spin-parity assignment using GT selection rules

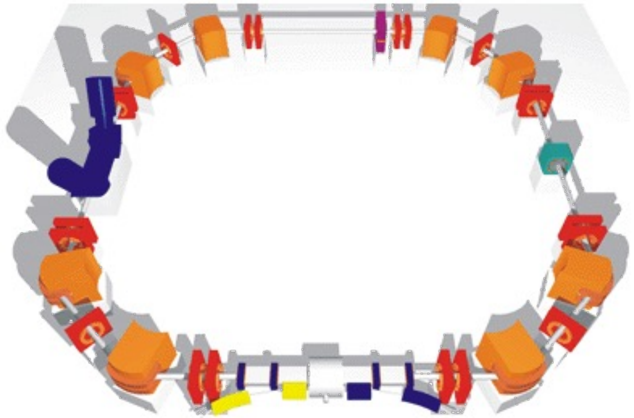
- Lower transmission
- Pulsed beam

E. Leistenschneider et al., PRL 120 (2018) 062503
M.P. Reiter et al., PRC 98 (2018) 024310

New experimental setups – Accelerated beams

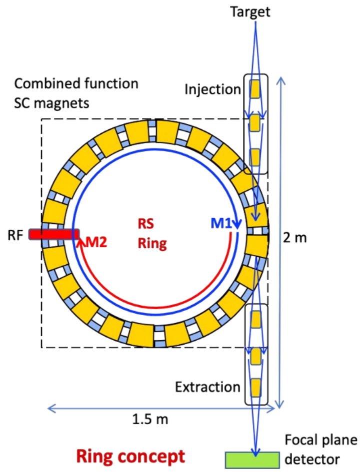
PHASE A : for definition of the item
PHASE B : development of a proposal document

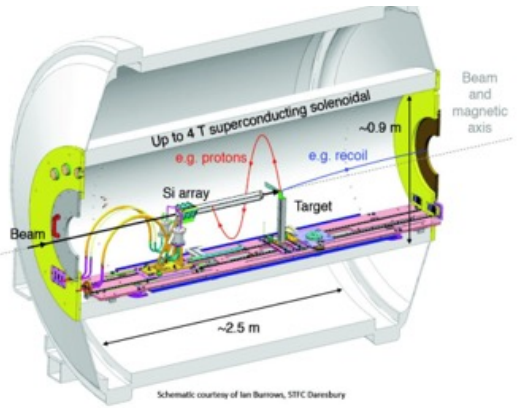
	Sigla	Description	Timeline
LNL-Acc01	GammaRIB	New resident γ-ray array	A:2023/24 B:2024/25
LNL-Acc02	PRISMA gas filled	Gas-filled spectrometer	A:2024 B:2025
LNL-Acc03	Solenoid	Solenoid for light particles after transfer reactions	A:2027 B:2028
LNL-Acc04	SCHIR	SC Heavy ion recoil spectrometer	A:2028 B:2029
LNL-Acc06	Ring	Accumulation ring for exotic nuclei	A:2028 B:long range

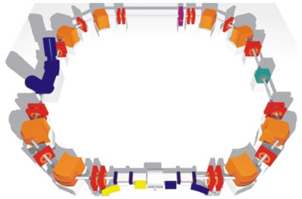


New experimental setups – Accelerated beams

- Resident γ-ray array
  - Galileo Phase III
- Setups for heavy ions
  - Prisma Gas-Filled
  - Heavy-ion SC separator ring
- Setup for light ions
  - SC solenoid
- Setup for exotic ion storage :
  - Storage ring







Upgrade of the LNL resident γ-ray array

Present Configuration (Phase II):

- 25 Compton-suppressed HPGe
- 10 triple-cluster CS
- ε_γ = 4.5%, P/T ≈ 50%, no position sensitivity
- Fixed geometry

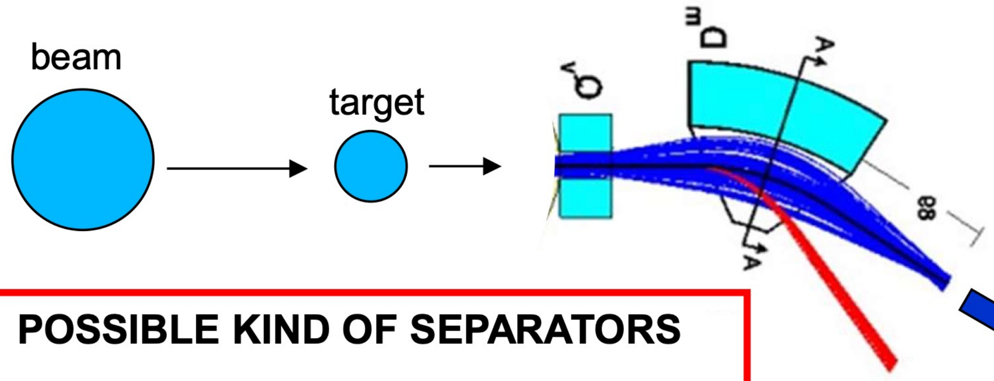
Desired upgrade (Phase III):

- Variable geometry
- Position sensitivy 5-10 mm
- ε_γ ≈ 10%, P/T ≈ 40 − 50

How to do it? Discussion on going (new detectors, detectors from GAMMAPOOL, geometry to be carefully studied via GEANT4, founding agencies, …)

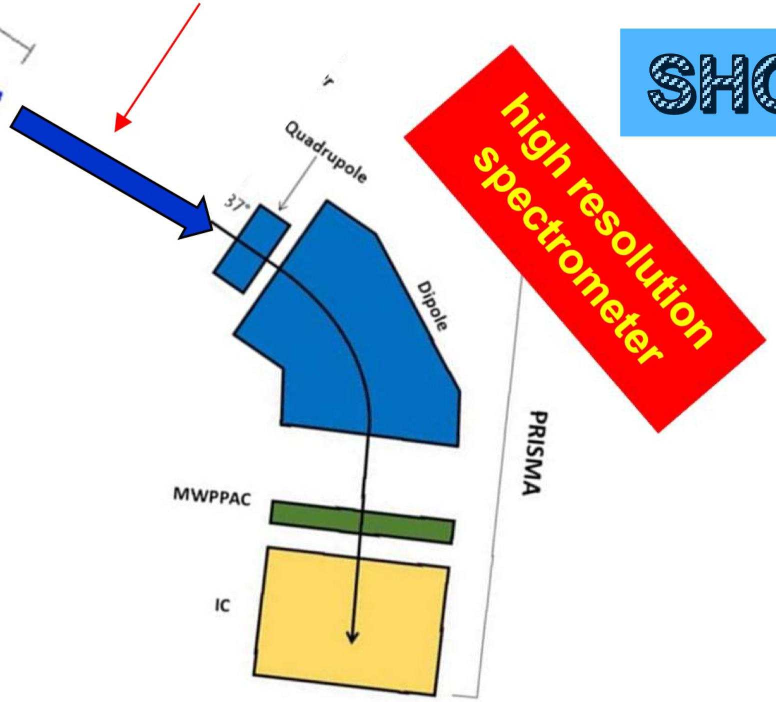
Courtesy of M. Rocchini

Options to be investigated for ion detection at very forward angles



if primary beam rejection and an acceptable focusing of selected ion species can be achieved one can then inject nuclei into a high resolution spectrometer

SHORT / MID - term



POSSIBLE KIND OF SEPARATORS

Gas filled magnetic system (it can be also used for tagging and decay studies)

Radiofrequency device (an electromagnetic filter which could reject, at least partially, the primary beam)

Solenoid (it can be also used for ion detection and for partial primary beam rejection)

Courtesy of L. Corradi

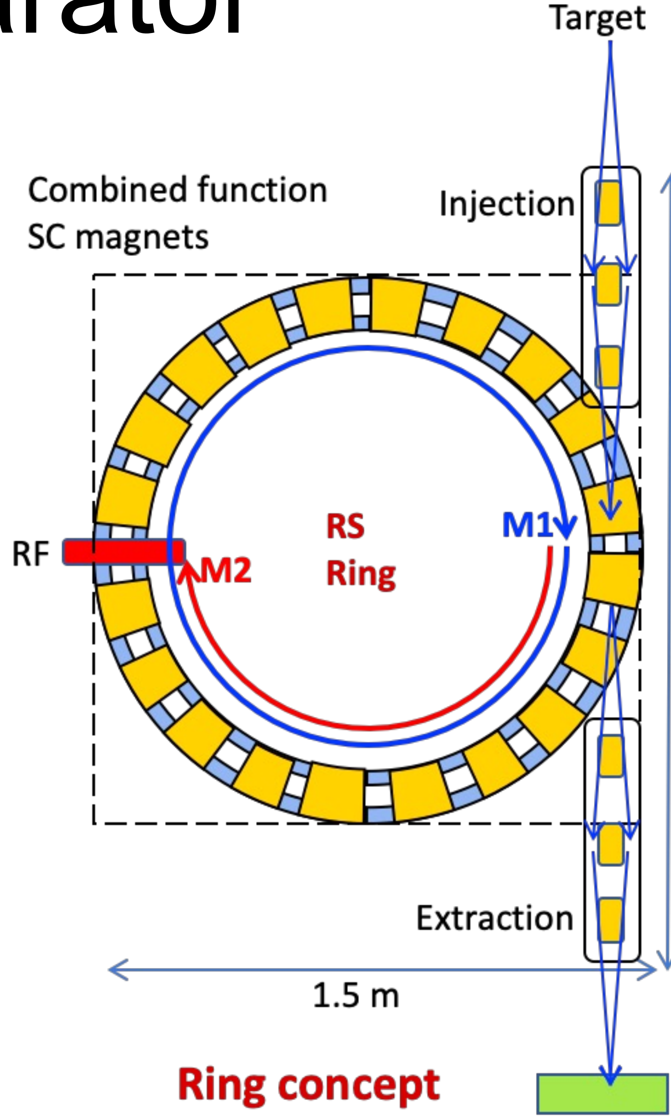
Heavy ion recoil separator

LONG - term

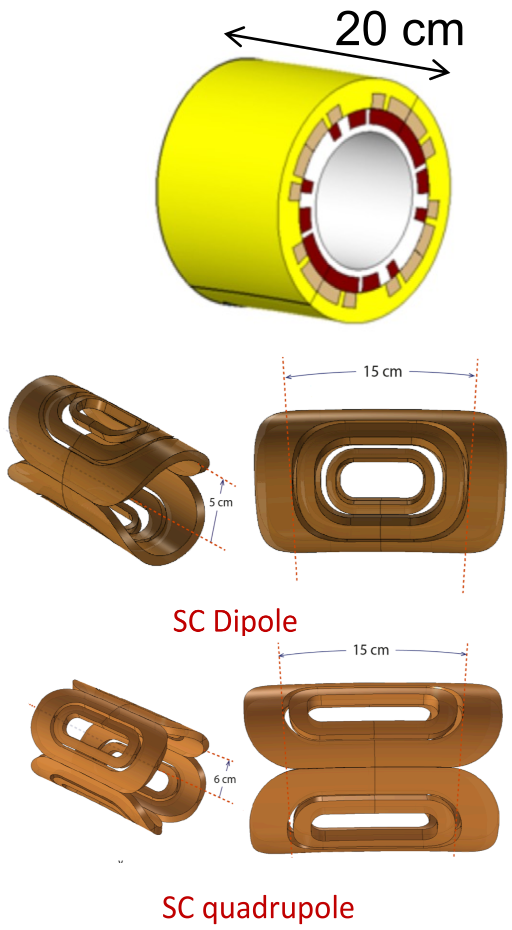
- 100 % transport efficiency
- Mass resolution > 1/300
- Large acceptance ~ 100 mrad
- Gas-filled mode

Focal plane detector:

- Position sensitivity ~ 1 mrad (scattering angle)
- Particle identification (A, Z)
- Eloss, Time of Flight, Pulse shape
- Time resolution ~ ns
- Energy resolution < 100 keV



Ring concept



Courtesy of I. Martel

Conclusions: Physics domain with SPES

SPES Low-Energy and Post-Accelerated Physics Program, thanks to existing or short-term set-ups, is wide and has an impact in bridging towards next generation radioactive-beams facilities

Short-to-Mid Term (<2026) opportunities in enlarging the scope of the set-ups are already being developed

Mid-to-Long Term (>2026) proposed activities will complete the facility and introduce new physics to LNL (ground state properties)

Longer-term (>2030) projects to be evaluated to enrich further the physics program

However …. Time is running