Activities at the LISE/GANIL facility

(O. Sorlin, GANIL)

Short introduction to the LISE facility and its beam characteritics

Scientific highlights:

Broken mirror symmetries in ^{36}Ca - ^{36}S and magicity at N=16

Spectroscopy and clustering of N=2 nuclei beyond the drip line

Shell evolution due to tensor forces between ^{15}N and ^{19}N

Exotic decay studies with ACTAR-TPC

Campaign 2022 (3 experiments in one):

Coulomb and nuclear excitations of neutron-rich Si isotopes using PARIS-EXOGAM2

Campaigns 2023-2024:

The MUGAST-EXOGAM2 setup

LISE beamline into GANIL environment

BEAMS

- Stable CSS1: CSS2 10- 95 MeV/u
  - -> used directly
  - -> to induce fragmentation
- Spiral1/CIME

Selection

-Stripper at LISE entrance for SP1 beams
- Brho+degrader
- Wien filter (e. g. FULIS)
- Possible to slow-down ions to 15A.MeV A

PHYSICS TOPICS

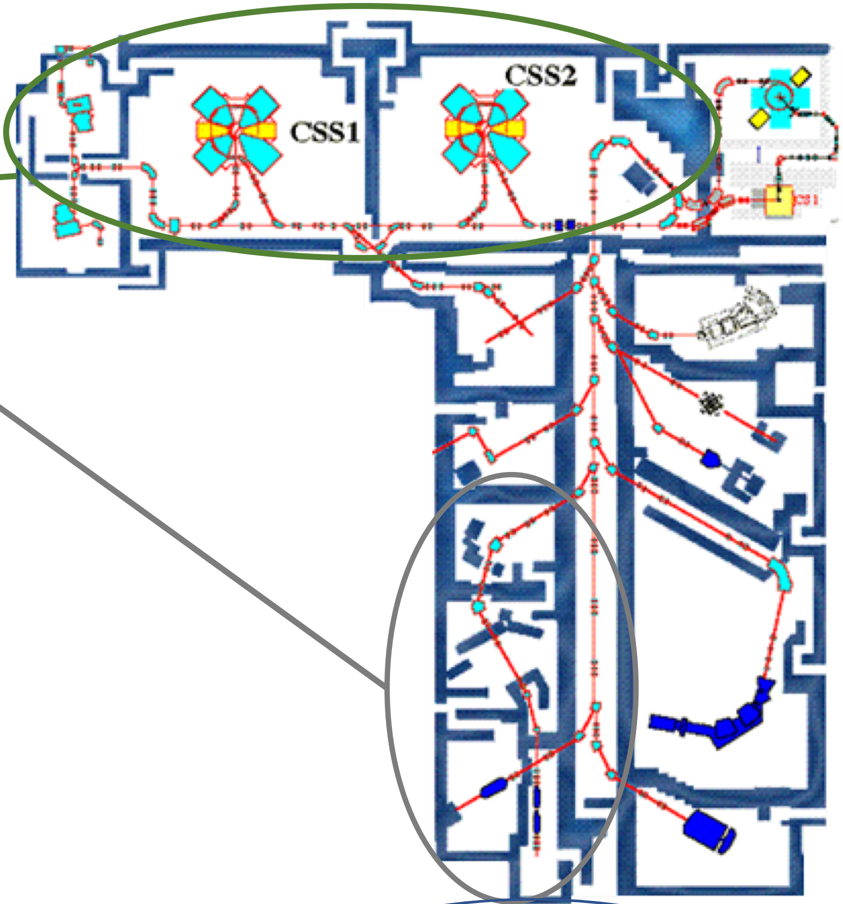
- Exotic decay modes
- Halo and cluster nuclei
- Nuclear astrophysics
- Drip-line studies
- Nuclear structure and nuclear forces
- Giant/soft modes
- Super-heavy nuclei

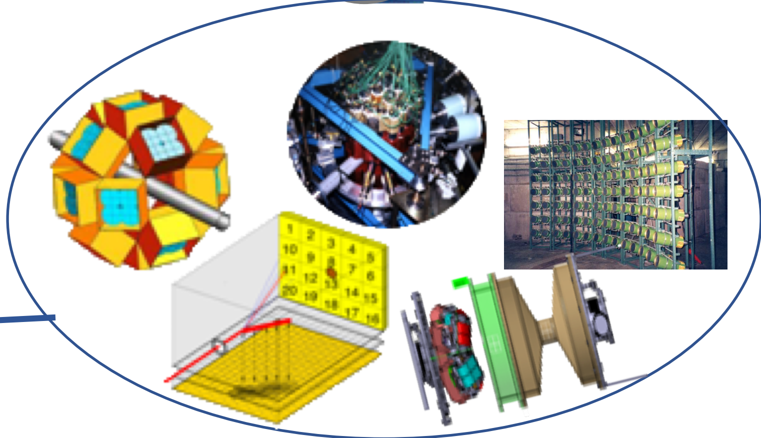
DETECTION

- Exogam 2
- Château de cristal
- Must2/TiaRa / Mugast
- Demon + Nordball

PARIS

ACTAR-TPC





Broken mirror symmetries in ^{36}Ca - ^{36}S, magicity at N=16

L. Lalanne et al. PRL 129 (2022) and to be submitted

MUST 2 array at forward angles

Study of the ^{35}K(p,γ)^{36}Ca reaction

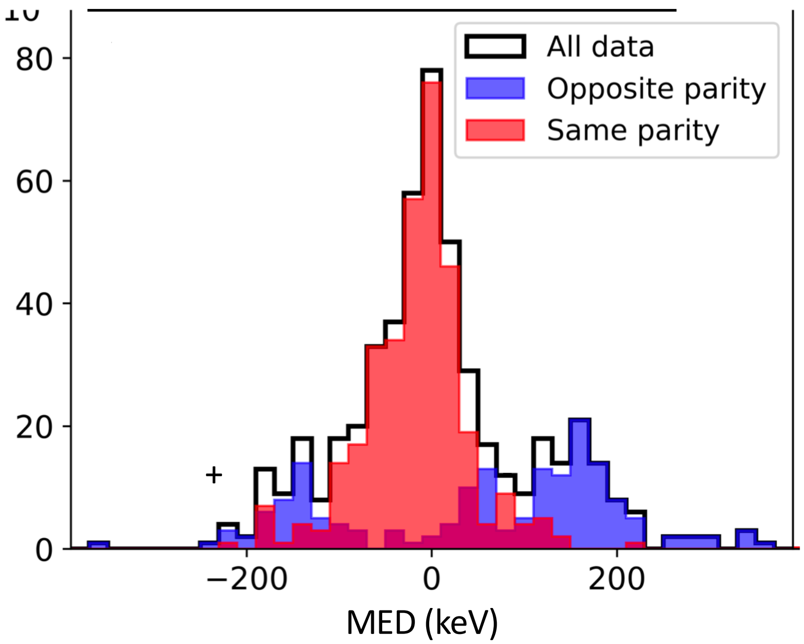
L. Lalanne et al. PRC 103 (2021)

Mirror symmetry and shape coexistence

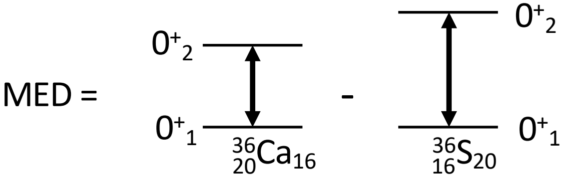
Nuclear spectra between mirror nuclei usually very similar -> Mirror Energy difference very small (MED)

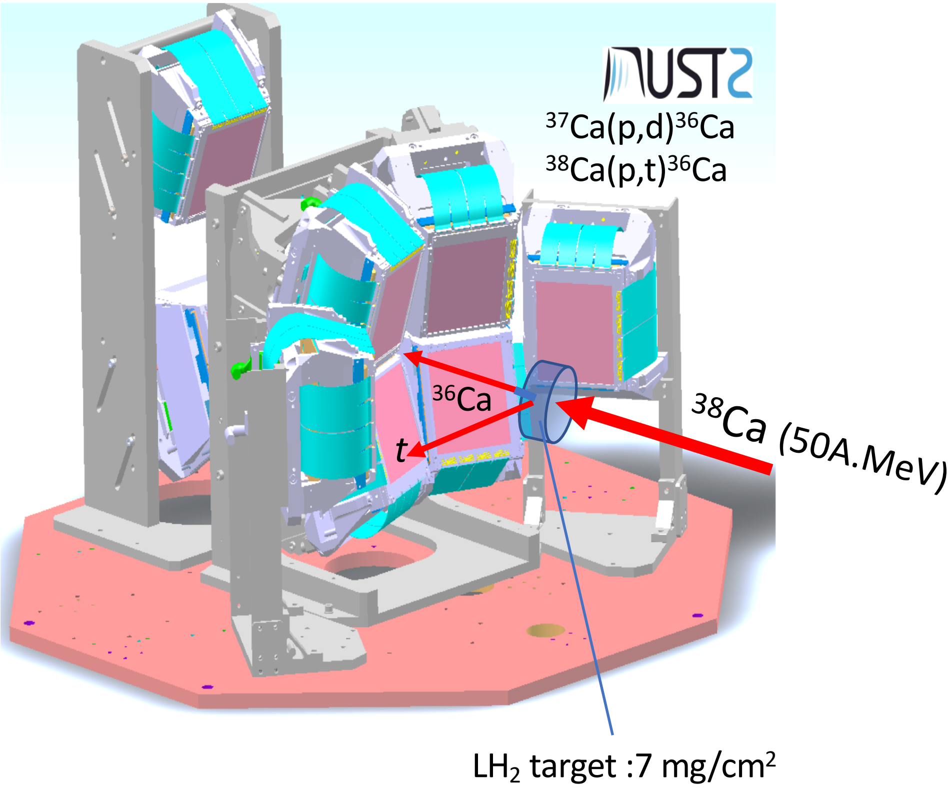
Few exceptions at the dripline (up to 700 keV), e.g. ^{16}F - ^{16}N *I. Stefan et al. PRC 90 (2014).*

Colossal MED (-700 keV) predicted between the 0^+_1 and 0^+_2 states in ^{36}S - ^{36}Ca, *Valiente-Dobon et al., PRC 98 (2018).*



Henderson and Stroberg, PRC 102 (2020) 031303(R)

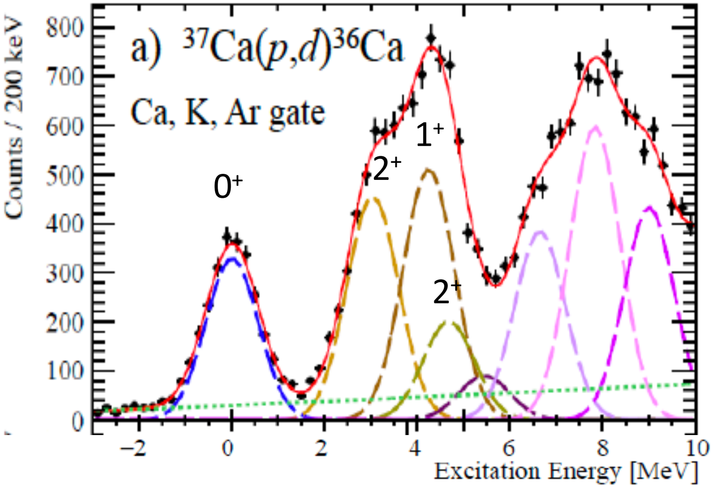


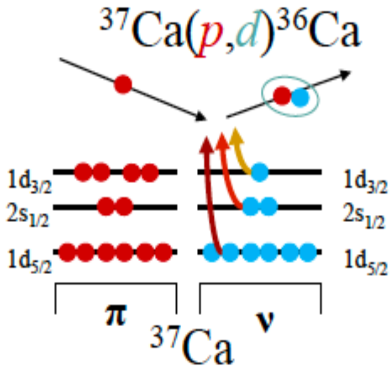


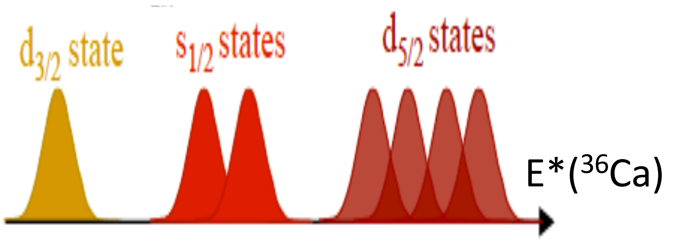
^{37}Ca(p,d)^{36}Ca
^{38}Ca(p,t)^{36}Ca

LH$_2$ target :7 mg/cm^2

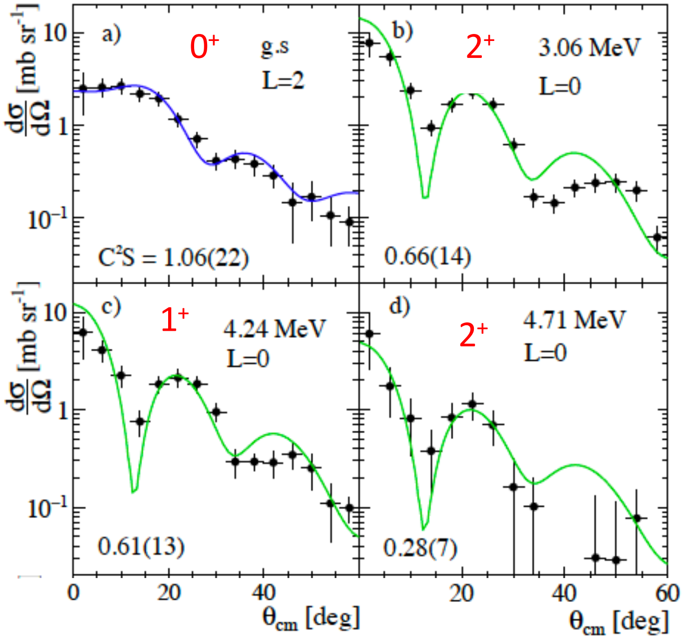
^{37}Ca(p,d)^{36}Ca reaction to probe neutron-hole states

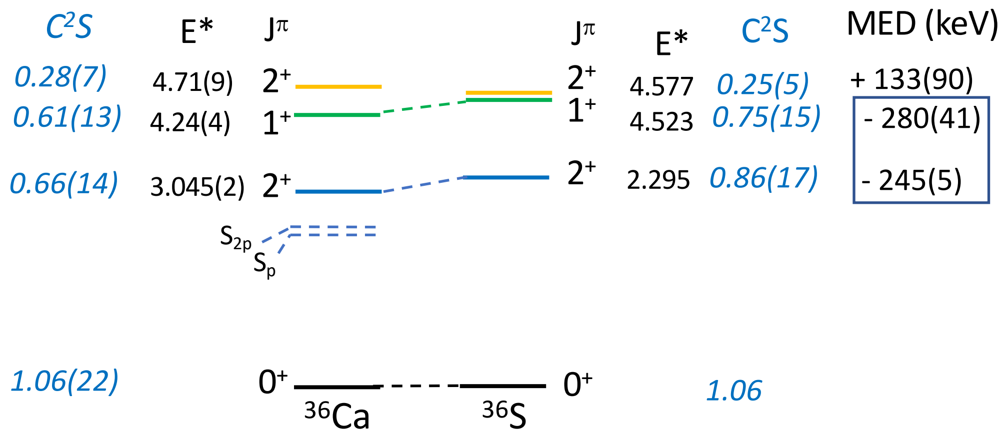






1	2	6	occupancy
0+	1+,2+	1+ - 4+	Jπ
2	0	2	L transfer



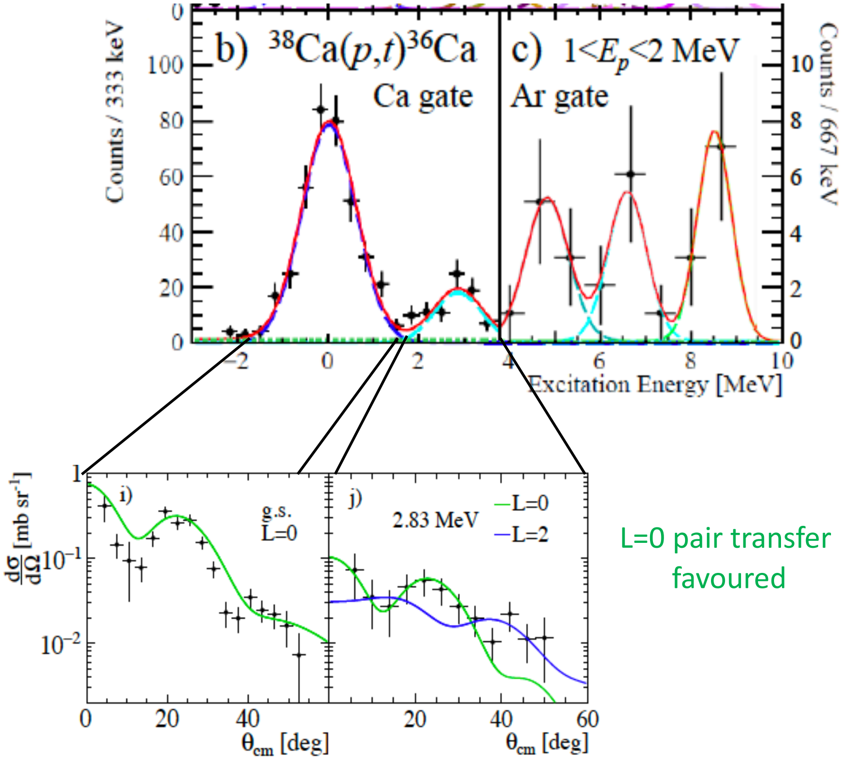


C^2S	E*	Jπ	Jπ	E*	C^2S	MED (keV)
0.28(7)	4.71(9)	2+	2+	4.577	0.25(5)	+ 133(90)
0.61(13)	4.24(4)	1+	1+	4.523	0.75(15)	- 280(41)
0.66(14)	3.045(2)	2+	2+	2.295	0.86(17)	- 245(5)
1.06(22)		0+	0+		1.06	

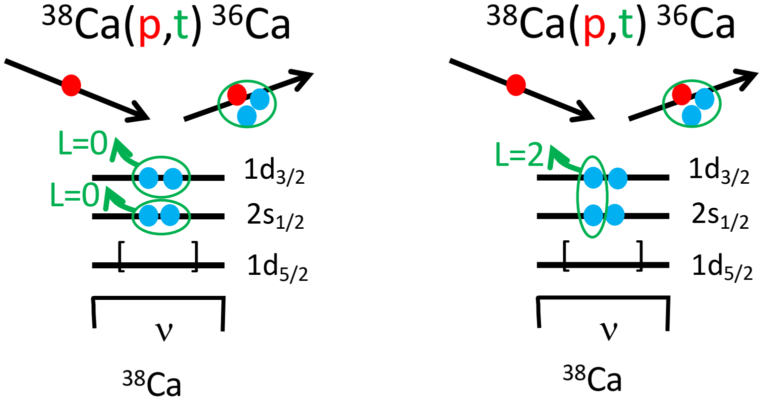
Protons of the (1,2)+ states in ^{36}S have larger Coulomb repulsion than in g.s. *i.e. (ph)* from $2s_{1/2}$ (large r) to $1d_{3/2}$ orbits (smaller r) compared to $(2s_{1/2})^2$

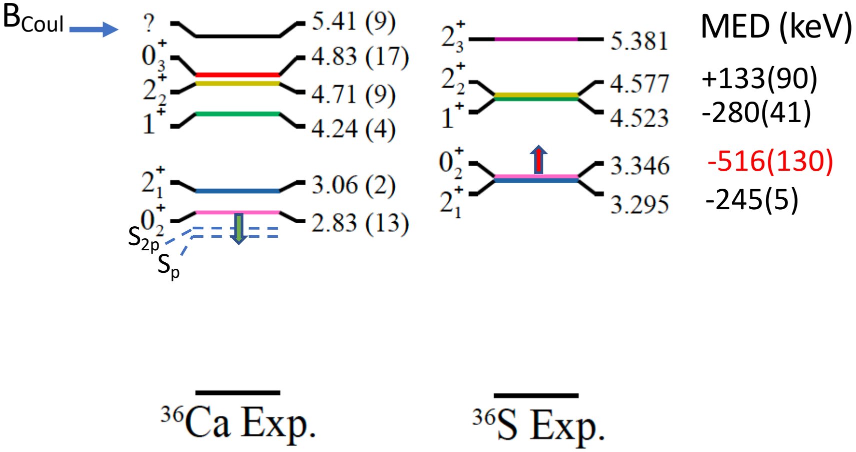
Similar C^2S values between mirror reactions -> same configurations

^{38}Ca(p,t)^{36}Ca reaction to probe 0$^+$ states



L=0 pair transfer favoured





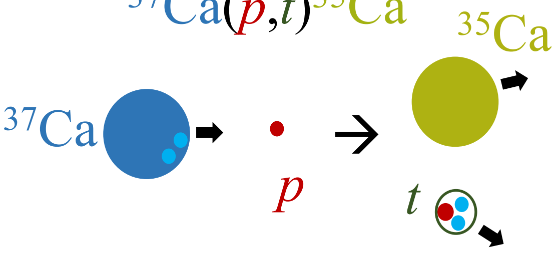
L. Lalanne, O. Sorlin, A. Poves et al., PRL 129 (2022)

Very large MED between the 0^+_2 states -> first excited state in ^{36}Ca
Closed-shell for 0^+_1 and deformed π(2p2h) ⬇ & ν(1p1h) ⬆ for 0^+_2 in ^{36}Ca

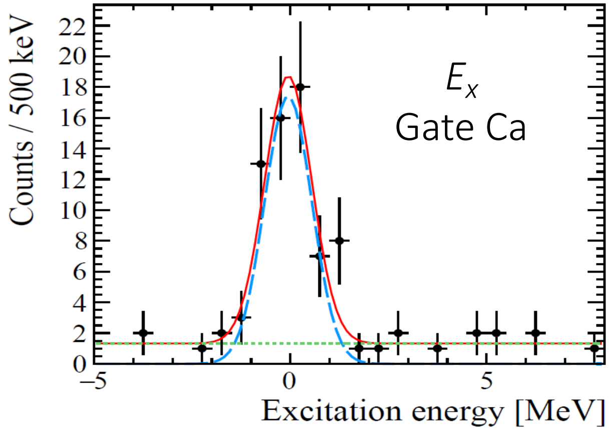
The Coulomb force does not change the structure betweeen mirror states
It highlights their configurations through their observed MED

Study of N=16 magicity in the Ca chain

^{37}Ca$(p,t)^{35}$Ca



Only one bound state in ^{35}Ca



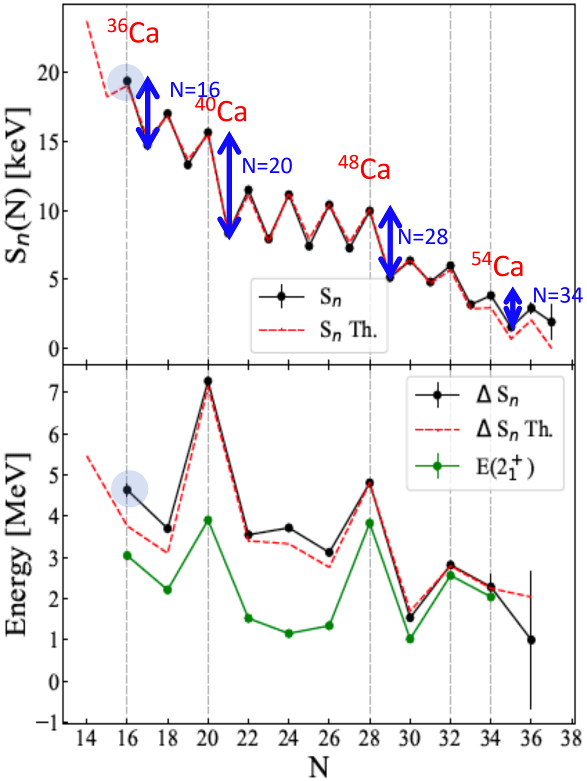
$\Delta M(^{35}$Ca$)$ = -4850 ± 140 keV

→ First mass measurement of ^{35}Ca

Using $\Delta M(^{36}$Ca$)$ - *Longfellow PRC (2021)*

-> $S_n(^{36}$Ca$)$ = 19.36(15) MeV

-> Gap(N=16) = $S_n(^{36}$Ca$) - S_n(^{37}$Ca$)$



Gap (N=16) = 4.60(15) MeV

Gap (N=28) = 4.8 MeV

N = 28 and N = 16 gaps
have comparable sizes
-> N = 16 magic number

Gap(N=34) ≈ 2.28(18) MeV

'Evidence for a new magic number N=34, Magic nature of ^{54}Ca'

Steppenbeck Nature (2013), Michimasa PRL 121 (2018)

Size of shell gaps follow more or less the evolution of 2^+ states

N=16 gap in ^{24}O (4.94 (20) MeV) comparable to that in ^{36}Ca

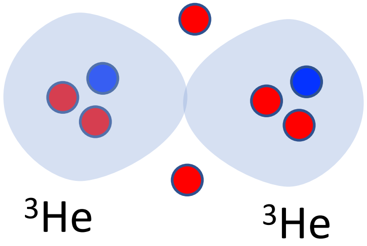
-> magicty at 16 exists at both edges of nuclear stability !

Moreover ^{36}Ca has a small radius, *A.J. Miller et al. Nature Phys. 15 (2019)*

Spectroscopy of N=2 nuclei beyond the drip line

S. Koyama(PhD - RIKEN), D. Suzuki (RIKEN) et al. submitted to PRL

^{8}C

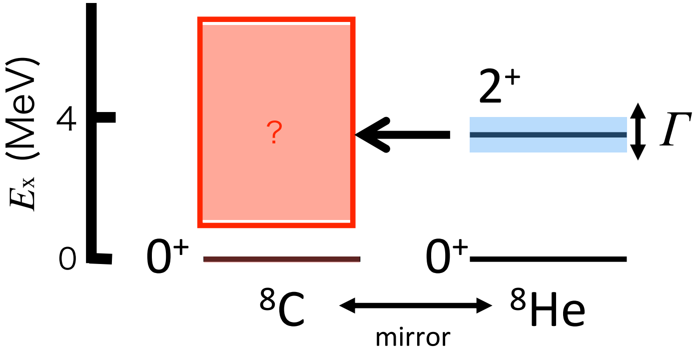


MUST 2 array at forward angles

Mirror symmetry at both edges of stability: ^{8}C and ^{8}He

(S. Koyama, D. Suzuki et al. Submitted to PRL)

M. Michel et al., PRC 84, 044315



^{8}He : g.s. is bound

Resonance 2^+ at 3.54 MeV

2*n* emission, Γ~ 0.8 MeV

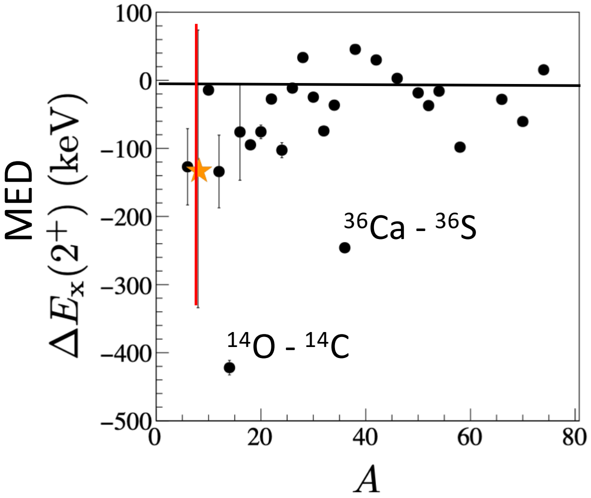
^{8}C : only g.s. is known, unboud by 3.48 MeV

$\alpha + 4p$ emission, Γ = 130(50) keV

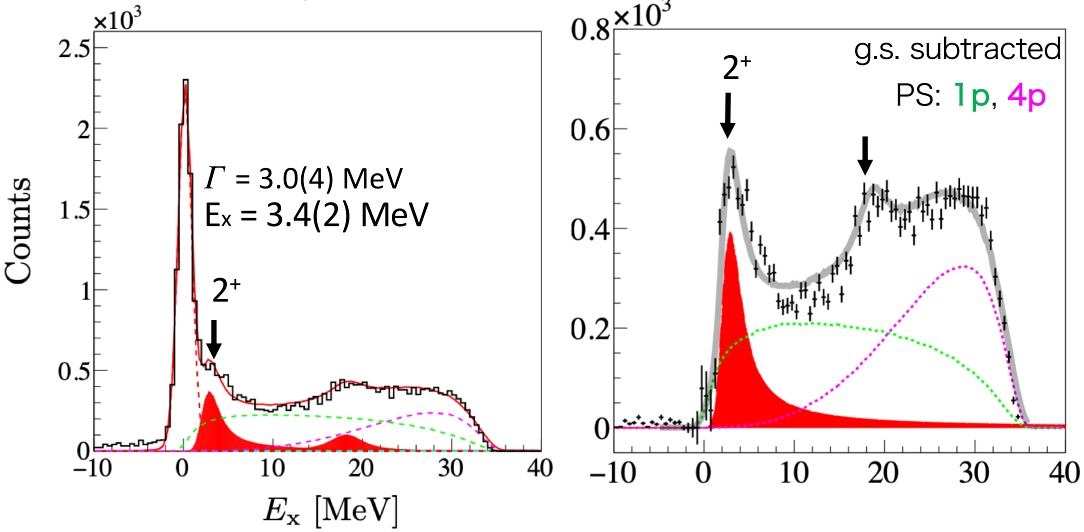
R. J. Charity et al., PRC 84 014320

Search for 2^+ state of ^{8}C (large Γ expected)

-> Mirror energy difference between ^{8}C and ^{8}He ?



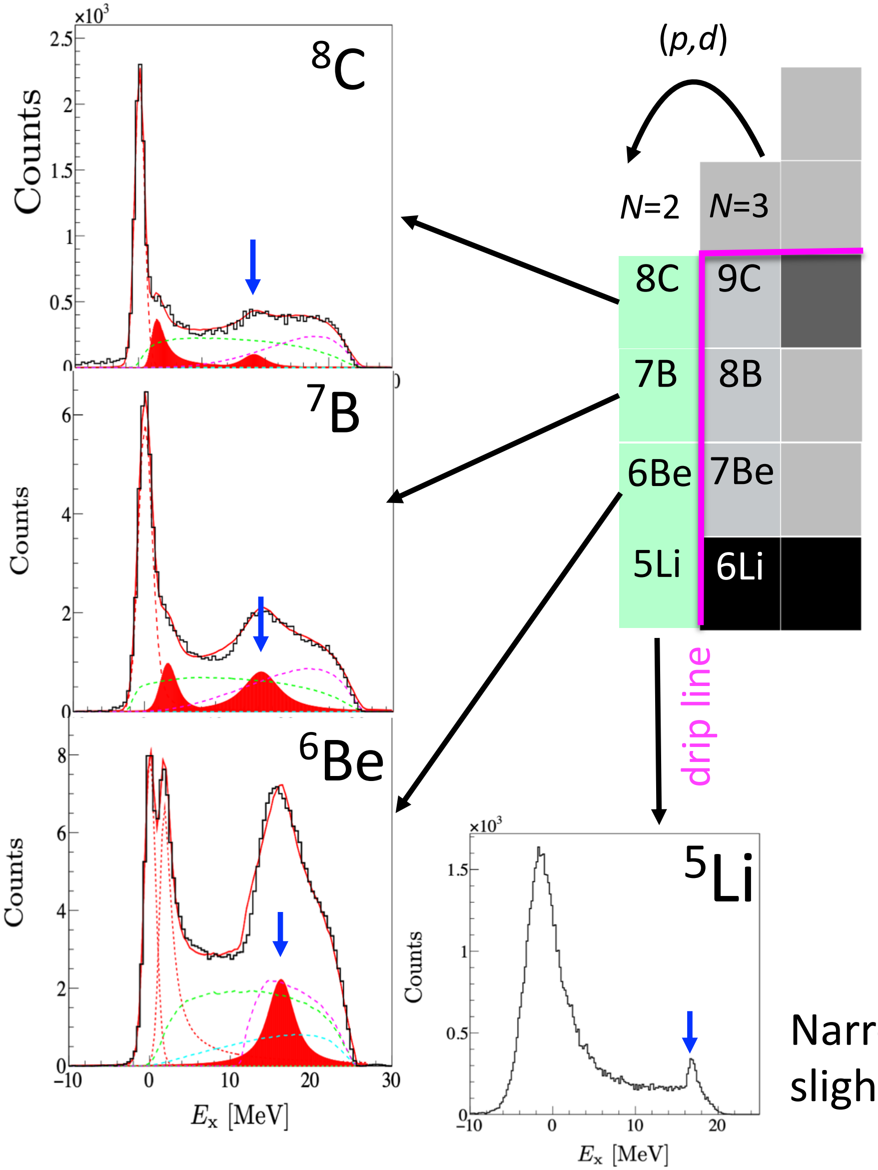
Use of ^{9}C(p,d)^{8}C reaction with MUST2 at 55 A.MeV



Compatible 2^+ energies between the A = 8 mirror states despite the fact that the 2^+ of ^{8}He is unbound by 1.4 MeV and that of ^{8}C by 6.8 MeV

^{3}He-based structure of high-lying states in N=2 isotones ?

(S. Koyama, D. Suzuki et al., to be submitted)



(p,d) reactions from all N=3 isotones

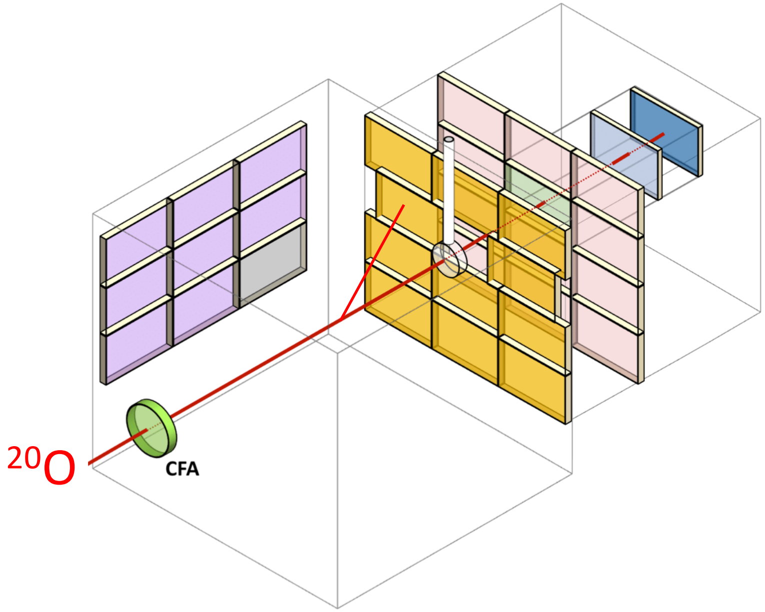
Resonances around 17 MeV in N=2 isotones above ^{3}He+x threshold, e.g. ^{3}He + ^{3}He in ^{6}Be

Persistence of ^{3}He clustering in the N=2 chain, i.e. ^{3}He + ^{3}He +2p in ^{8}C*

Narrow resonance at 16.87 MeV slightly above the ^{3}He+d threshold

Shell evolution between ^{15}N and ^{19}N due to tensor forces

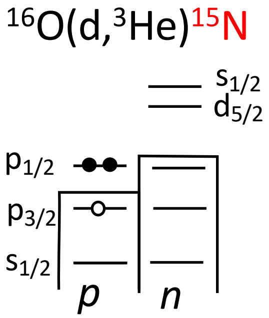
(J.-L. Fuentes, B. Fernandez-Dominguez, T. Roger et al.)



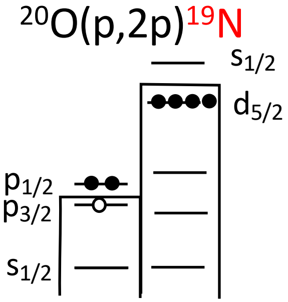
ACTAR –TPC: Active target filled with gas in which a transfer reaction takes place
Vertex reaction identified through Time Projection Chamber
Light particles and tranfer-like nuclei detected in ancillary Si detectors

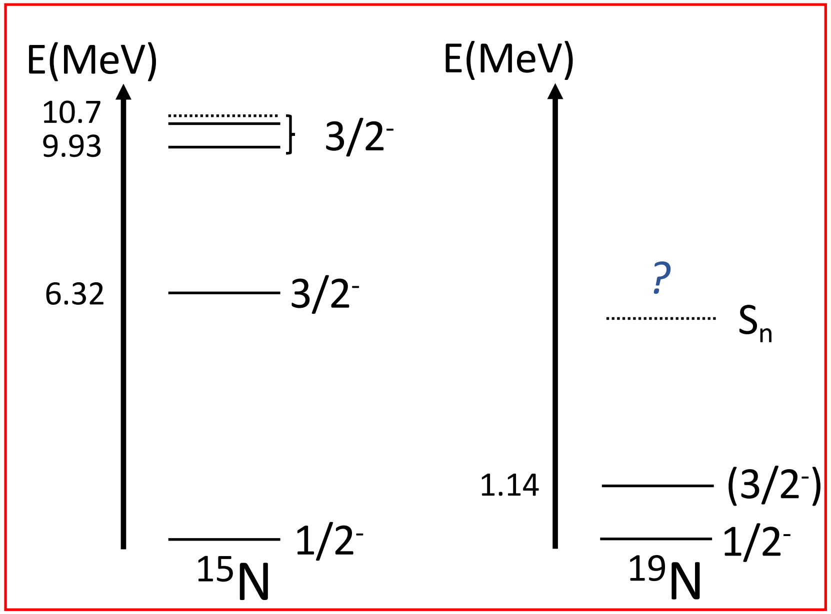
Shell evolution between ^{15}N and ^{19}N due to tensor forces

(J.-L. Fuentes, B. Fernandez-Dominguez, T. Roger et al.)



4 neutrons added ➡

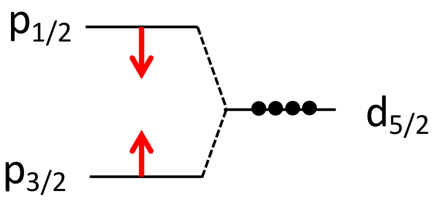




Evolution of the proton $p_{1/2}$-$p_{3/2}$ SO splitting with the filling of the neutron $d_{5/2}$ orbital

The $p_{1/2}$-$p_{3/2}$ splitting expected to be reduced by tensor forces
-> by how much ???

-> Study of $3/2^-$ states in ^{19}N by ^{20}O(p,2p)^{19}N



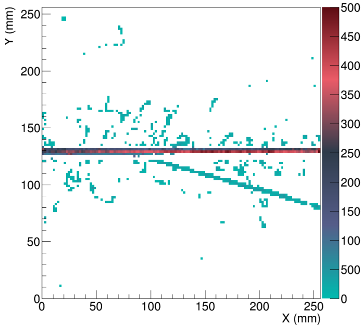
^{20}O (d,t) and (d,^{3}He) Transfer Reactions with ACTAR-TPC

(J.-L. Fuentes, B. Fernandez-Dominguez, T. Roger et al.)

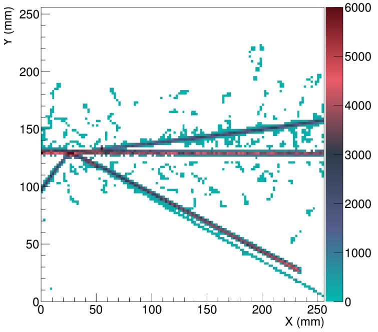
^{20}O at about 30 A.MeV, 3 10^4pps

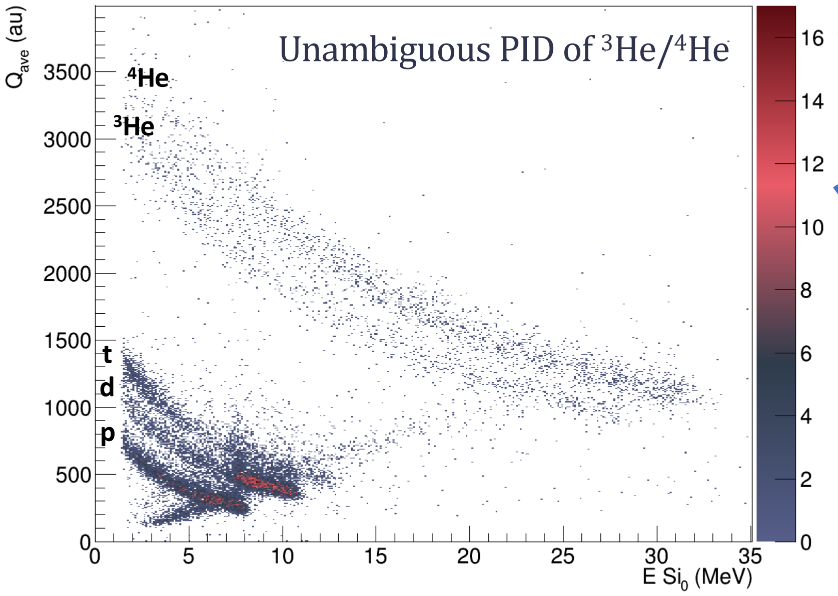
10 mg/cm^2 equivalent CD_2

Binary Reaction

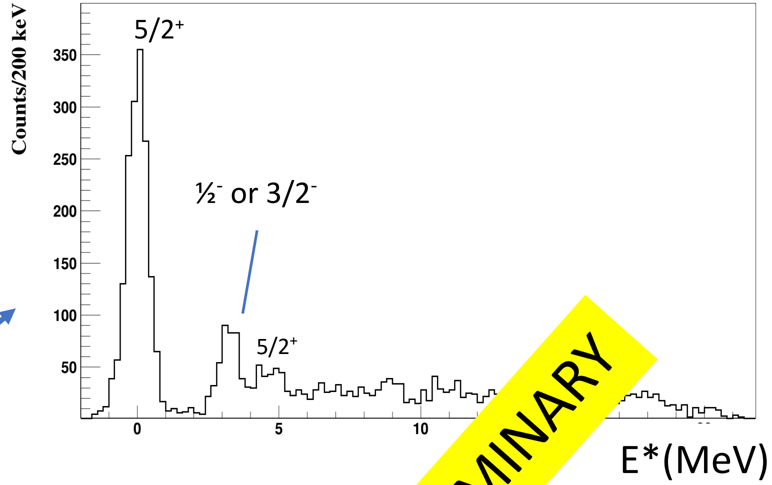


C-induced background

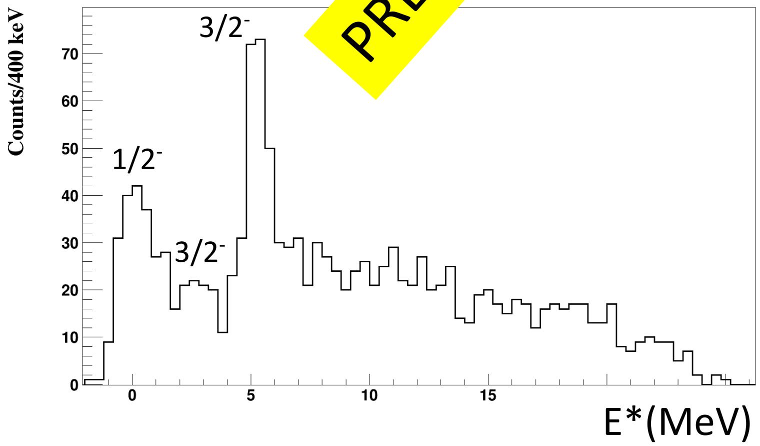




σ ~ 350 keV ^{20}O(d,t)^{19}O



σ ~ 450 keV ^{20}O(d,^{3}He)^{19}N

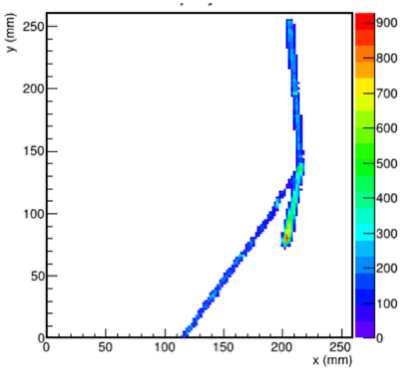


Main 3/2$^-$ component in ^{19}N shifted down by about 1.3 MeV as compared to ^{15}N

Proton radioactivity from ^{54m}Ni and ^{53m}Co isomers

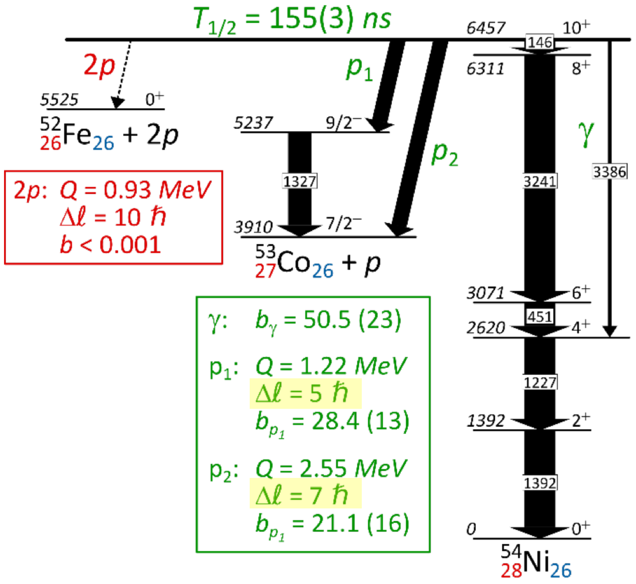
2-proton radioactivity of ^{48}Ni and other exotic decays

J. Giovinazzo (CENBG), A. Ortega Moral (CENBG), T Roger (GANIL) et al.



ACTAR-TPC

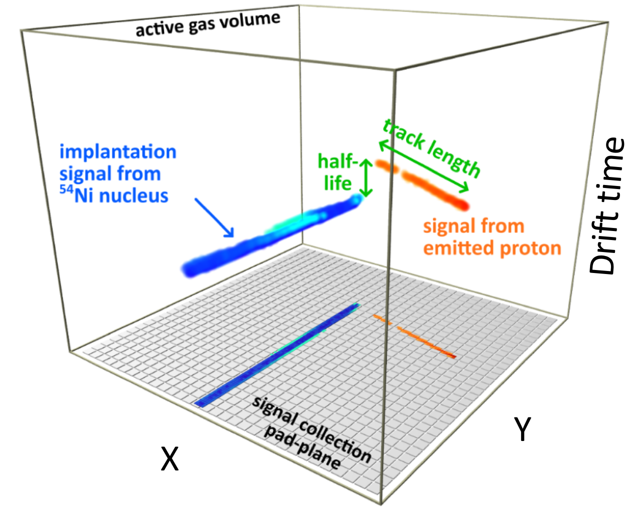
Proton radioactivity from ^{54m}Ni



Structure of the isomer due to $\nu(f_{7/2})^{-2}\ \pi(f_{7/2})^{-1}\ (fp)^{+1}$ configuration

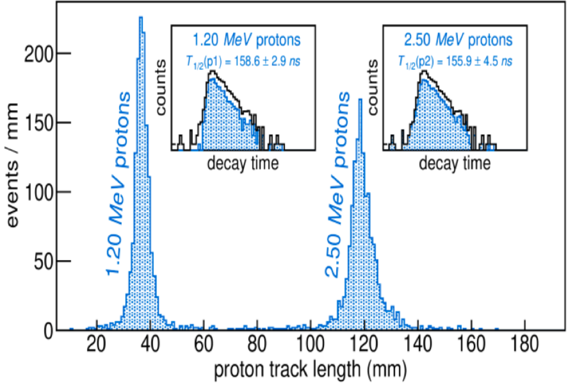
Competition between γ & p decay(s)

Implantation-decay in ACTAR TPC:



J. Giovinazzo et al. Nature Comm. (2021)

Two different branches clearly observed



A p signal of 1/1000 of the beam intensity detected soon after implantation

Identification of both tracks, time delay corresponding to the $T_{1/2}$ of the isomer

The proton decay occurs through very tiny components from high-L orbits

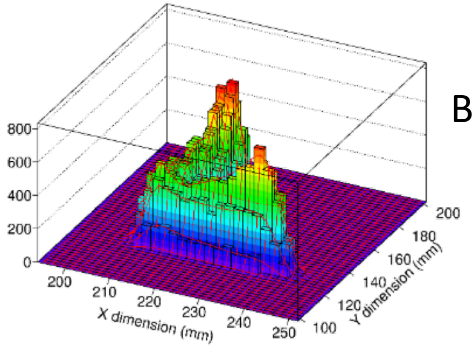
To come : proton radioactivity of ^{53m}Co *(T. Roger et al.)*

→ full proton decay, with **ℓ = 7** and **ℓ = 9** protons !

→ longer half-life (220 ms): separated implantation and decay events

^{48}Ni decay: ACTAR TPC @ GANIL/LISE (2021)

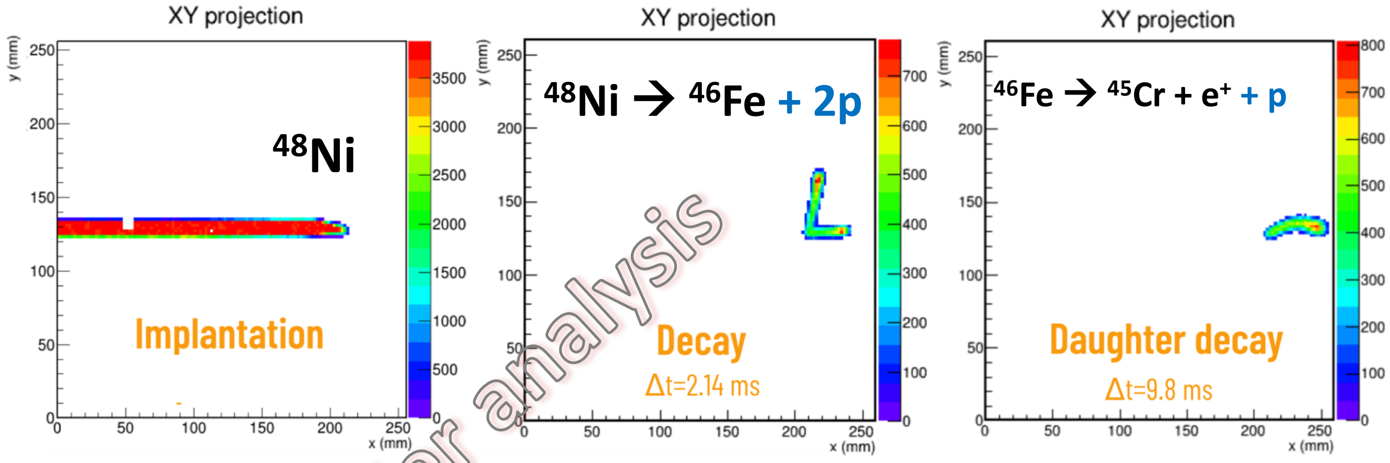
few observed events of ^{48}Ni 2-proton radioactivity



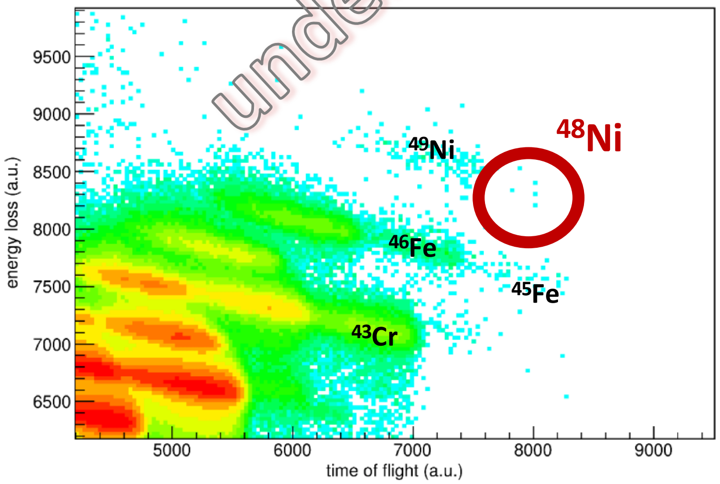
Bragg peak signal
for a 2p event

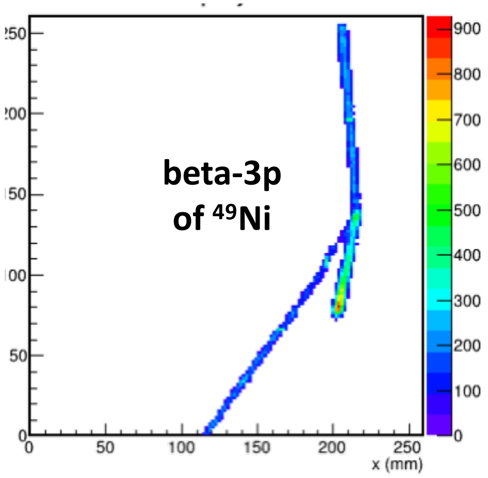
^{48}Ni

decay registered	**8**
β-(*x*)p decay	**4**
2-p decay	**4**



many (new) β-(*x*)p deca
in the mass region
^{49}Ni, ^{47,46}Fe, ^{46}Mn,
^{43}Cr, ^{41,40}Ti…





courtesy of A. Ortega Moral

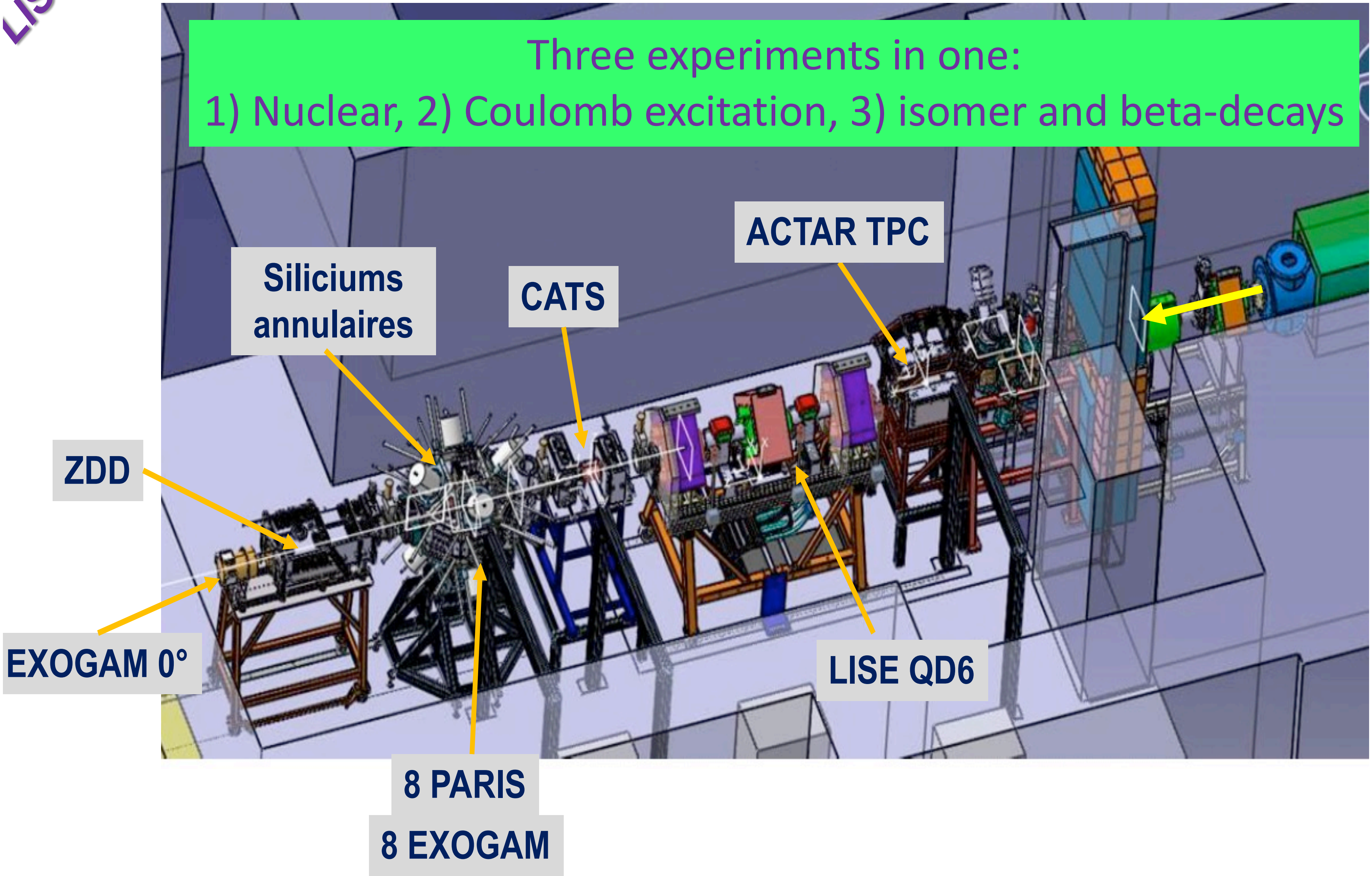
Nuclear and Coulomb excitation of Si isotopes (campaign2022)

Q. Delignac, S. Grévy et al.
R. Lica, S. Calinescu et al.

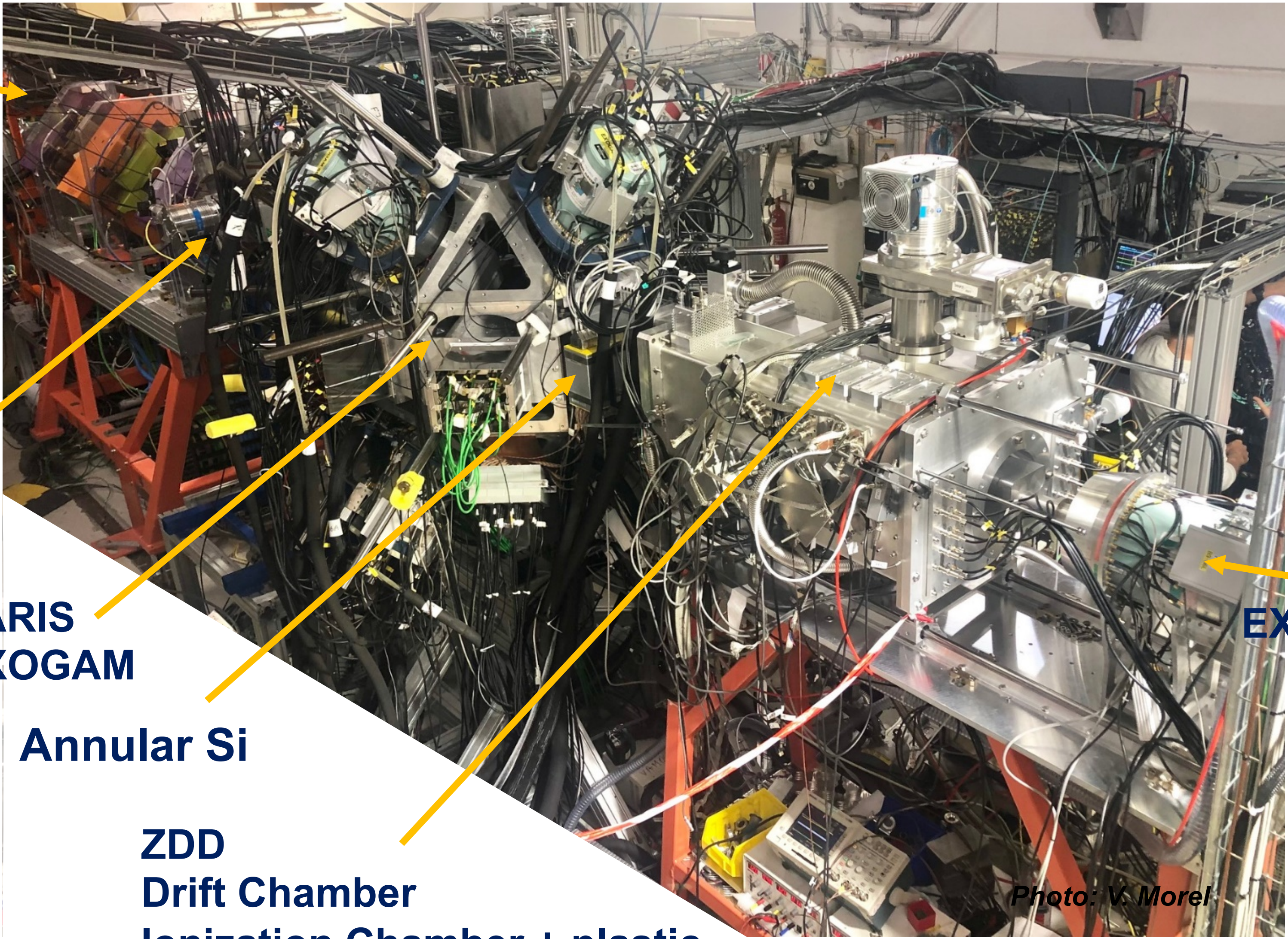
LISE

C. Barthe-Dejean, P. Gangnant, V. Morel

Three experiments in one:
1) Nuclear, 2) Coulomb excitation, 3) isomer and beta-decays



Experimental setup (campaign 2022)



ACTAR TPC

CATS

8 PARIS
8 EXOGAM

Annular Si

ZDD
Drift Chamber
Ionization Chamber + plastic

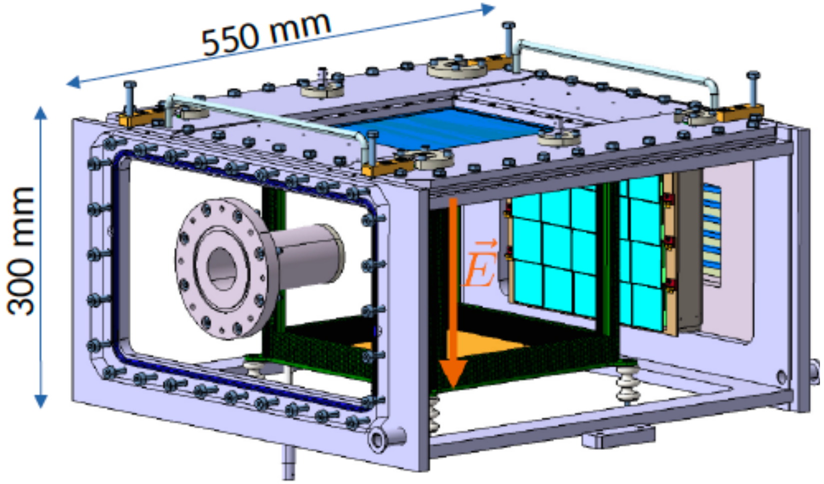
EXOGAM 0°

Photo: V. Morel

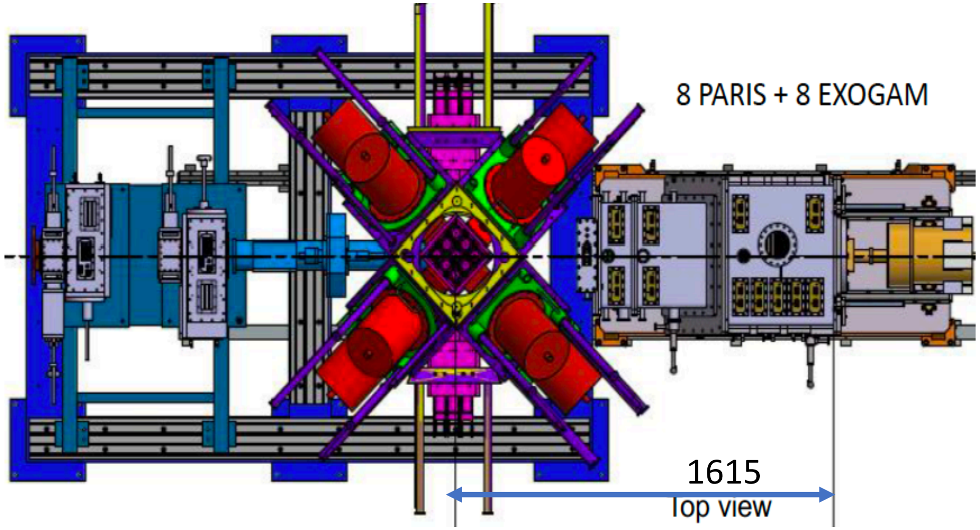
First achievement wordlwide: 3 experiments in one !

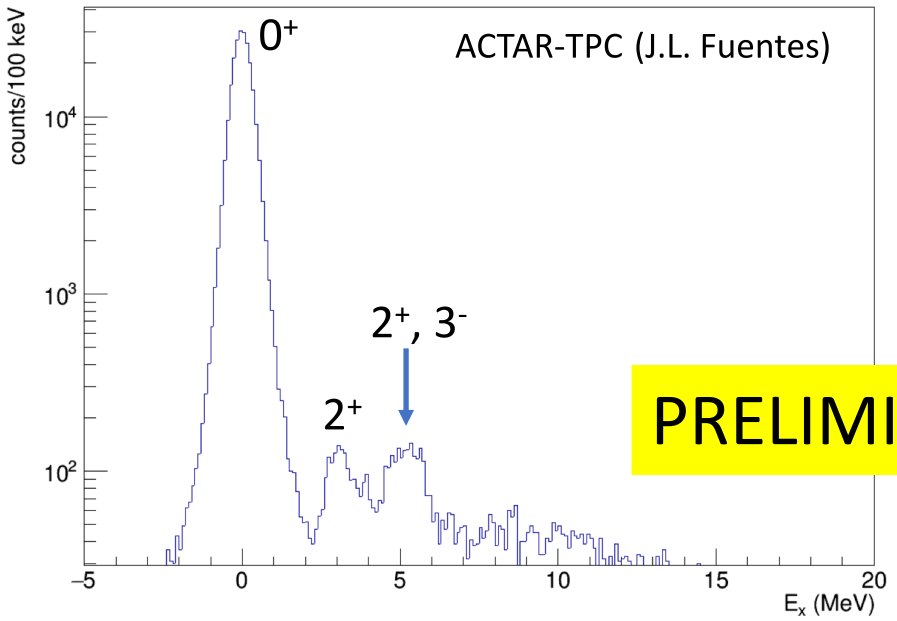
Probe the doubly magic structure and the PDR in ^{34}Si (R. Lica, 2022)

^{34}Si(p,p’) inelastic scattering
Mostly sensitive to neutron excitations

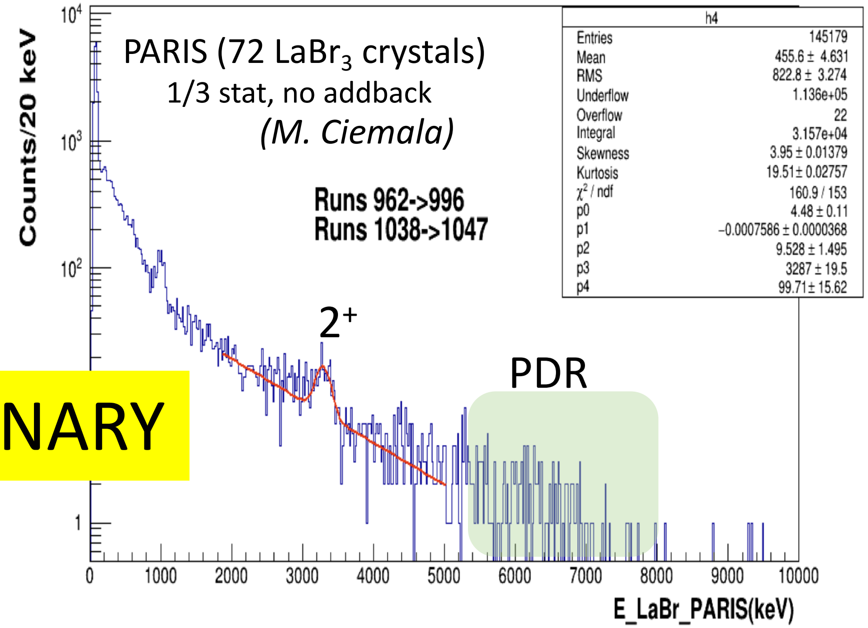


^{34}Si + ^{197}Au Coulomb excitation
Mostly sensitive to proton excitations

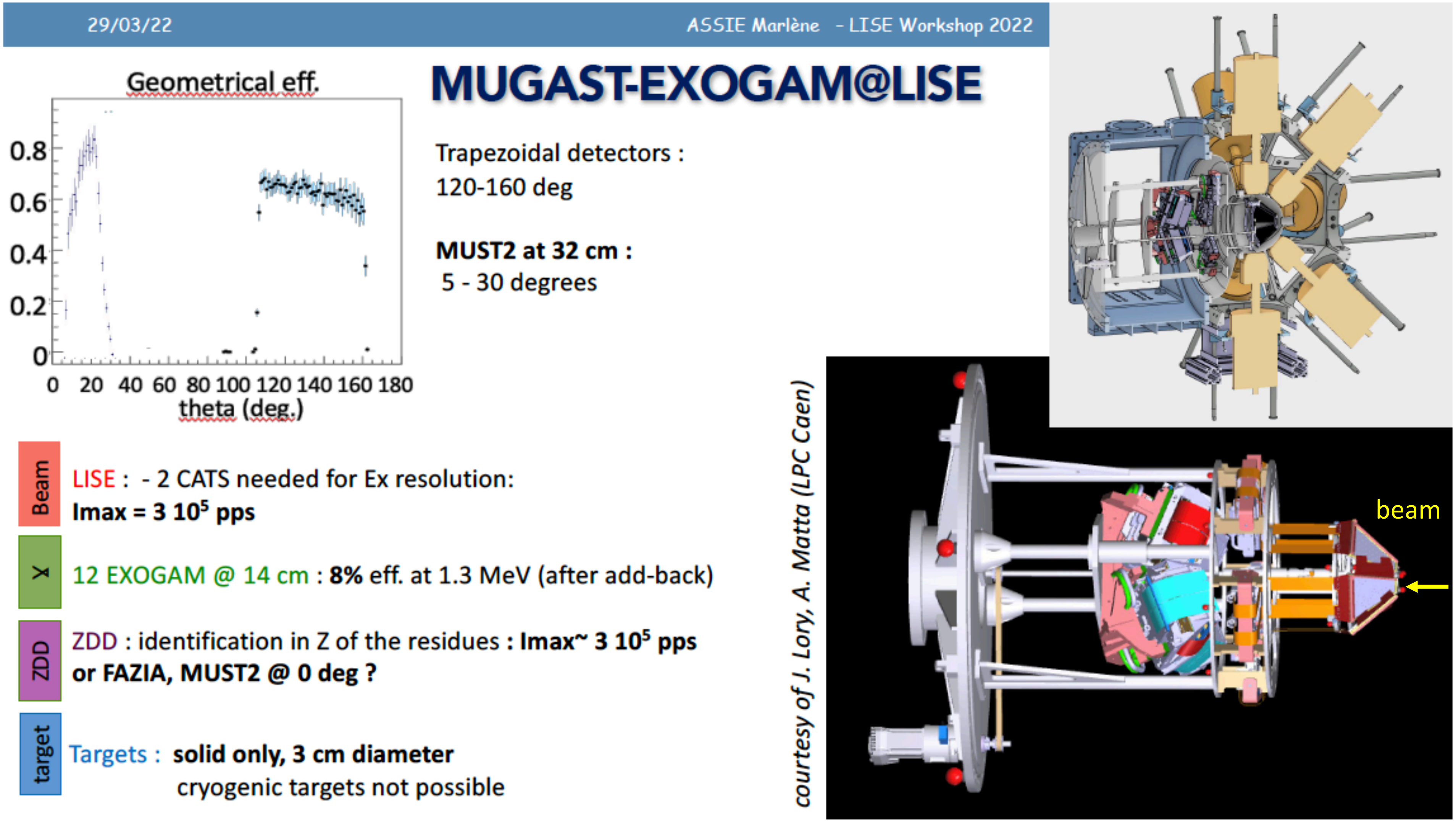




PRELIMINARY



Campaign (2023-2024): Transfer reactions with MUGAST - EXOGAM2



29/03/22 ASSIE Marlène - LISE Workshop 2022

MUGAST-EXOGAM@LISE

Trapezoidal detectors :
120-160 deg

MUST2 at 32 cm :
5 - 30 degrees

Beam — LISE : - 2 CATS needed for Ex resolution:
Imax = $3\ 10^5$ pps

γ — 12 EXOGAM @ 14 cm : **8%** eff. at 1.3 MeV (after add-back)

ZDD — ZDD : identification in Z of the residues : **Imax~ $3\ 10^5$ pps**
or FAZIA, MUST2 @ 0 deg ?

target — Targets : **solid only, 3 cm diameter**
cryogenic targets not possible

courtesy of J. Lory, A. Matta (LPC Caen)

Experimental program (under evaluation):

Shell evolution, Rotation of halo nucleus, Study of triton clustering, Breakout of the hot CNO cycle, Study of pn pairing