ATRACT : New Avenue of Transfer Reactions with Active and Cryogenic ^{3}He Targets

Marlène ASSIE (IJCLab) and Thomas Roger (GANIL)

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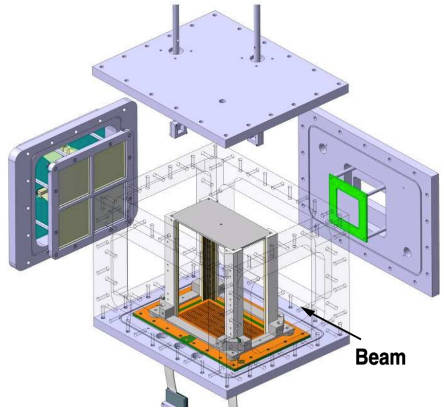
D. Beaumel, Y. Blumenfeld, F. Hammache, N. De Séréville, V. Girard-Alcindor + 1PhD

GANIL: O. Sorlin, J. Pancin + 1 Post-doc



Scientific objectives : transfer reactions in reverse kinematics with an ^{3}He target

Transfer reactions are powerful tools to provide **single-particle and collective properties of nuclear states**, in particular **:**

one-nucleon

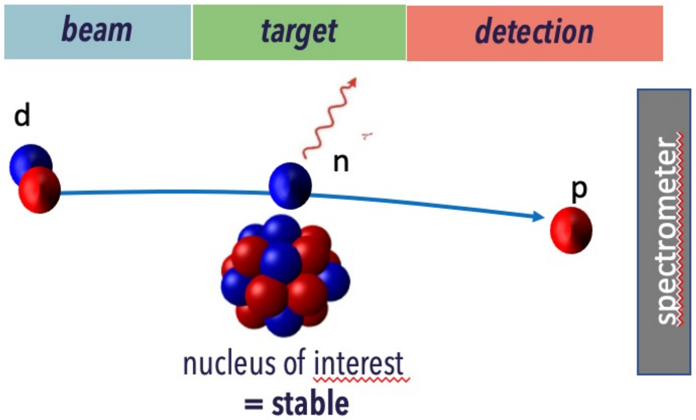
- single-particle states and their mixing, spin-parity, spectroscopic information
- size of gaps and their evolution
- access to the nuclear force (central, spin-orbit & tensor force)
- vacancy and occupancy across the Fermi surface
- unbound states

two-nucleon

- superfluidity in nuclei (np pairing, nn pairing)
- unbound states
- shape coexistence

From direct kinematics for (d,p)….

… to reverse kinematics for (d,p)



all light beams available (p,d, ^{3}He,^{4}He and even t)

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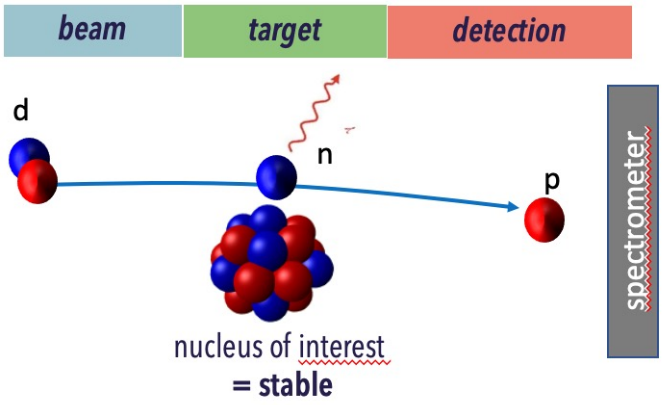

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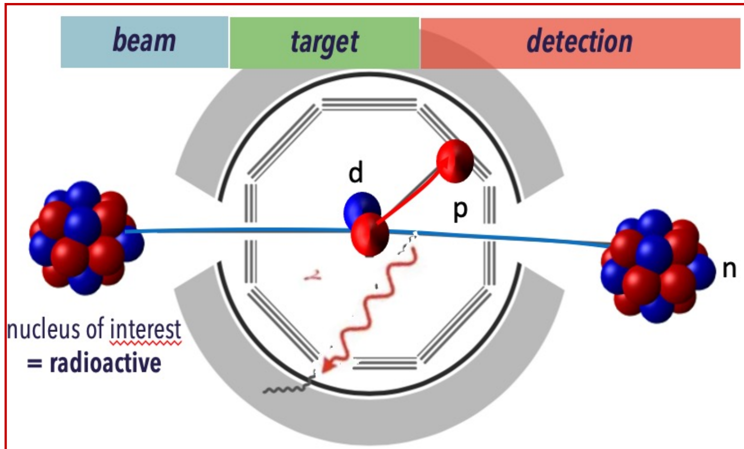

➠ ***Major lock : light targets***

. One- and two-neutron transfer performed with CH_2 and CD_2 targets

(at the expense of background and resolution)

--> boost of neutron WF studies

. Options for proton transfer

- *(d,n) : neutron detection difficult*
- *(d,^{3}He) : identification of ^{3}He (but OK)*
- **(^{3}He,d), (^{3}He,p) : targets availability**

ATRACT aims at developing ^{3}He targets with > 10^{20} at/cm^2

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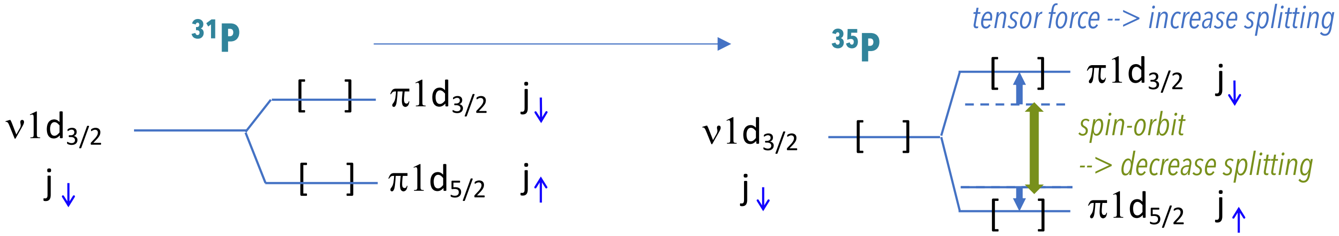
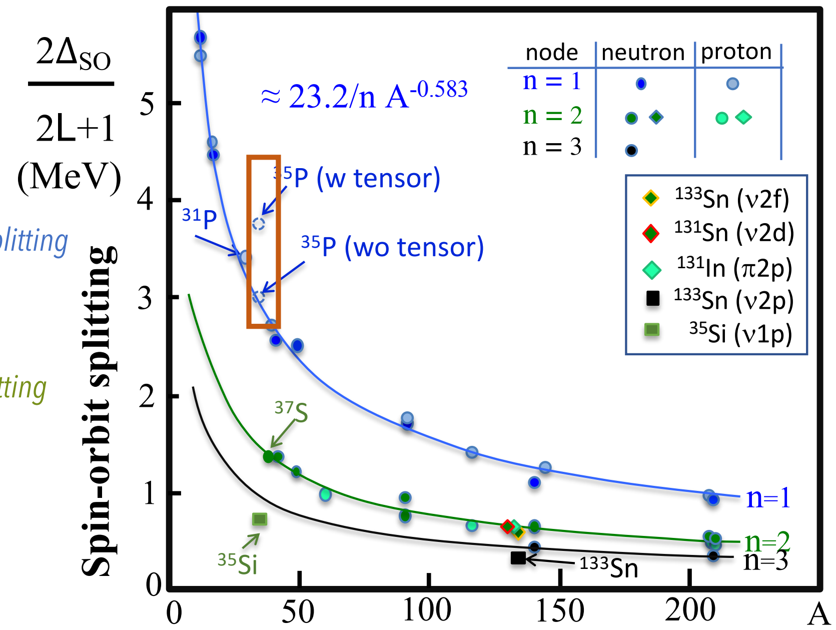
Proton-shell evolution : evolution of the **proton single-particle states along the Si and Ni chains** ➟ evolution of the Z = 16 and Z = 28 shell gaps

➟ role of spin-orbit and tensor forces





Method: **^{34}Si(^{3}He,d)** and ^{34}Si(d,^{3}He) to identify the centroids of each the spin-orbit partners, $j_\downarrow$ and $j_\uparrow$

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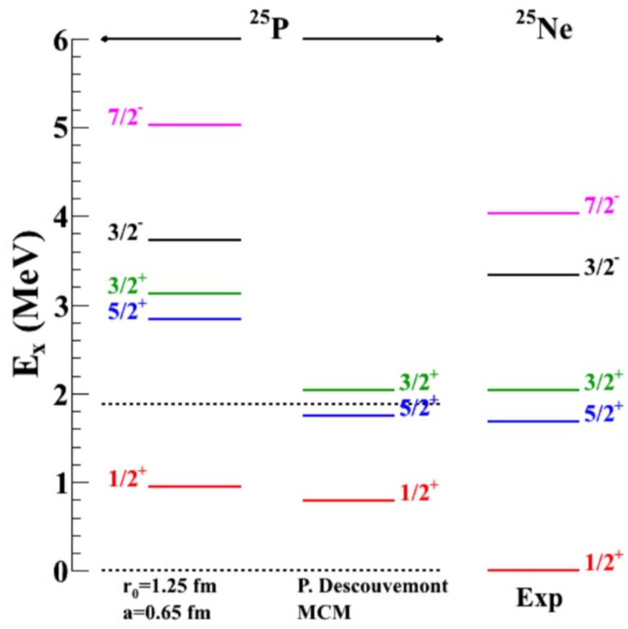
Mirror symmetry and proton-rich unbound nuclei: Case of ^{25}P

➟ **Mirror asymmetry for the low *l*-orbitals (Thomas-Ehrman-shift)** induced by weakly-bound proton (particularly the outermost proton in $s_{1/2}$ state)

→ weakening of Coulomb potential due to the spatial extension of s-wave.

→ New interpretation : the difference in s.p. energies that lead to an asymmetry between the neutron and protons s.p. WF.

Method: ^{24}Si(^{3}He,d) ^{25}P to perform the spectroscopy of ^{25}P



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\+ **Indirectly astrophysically relevant reaction rates**

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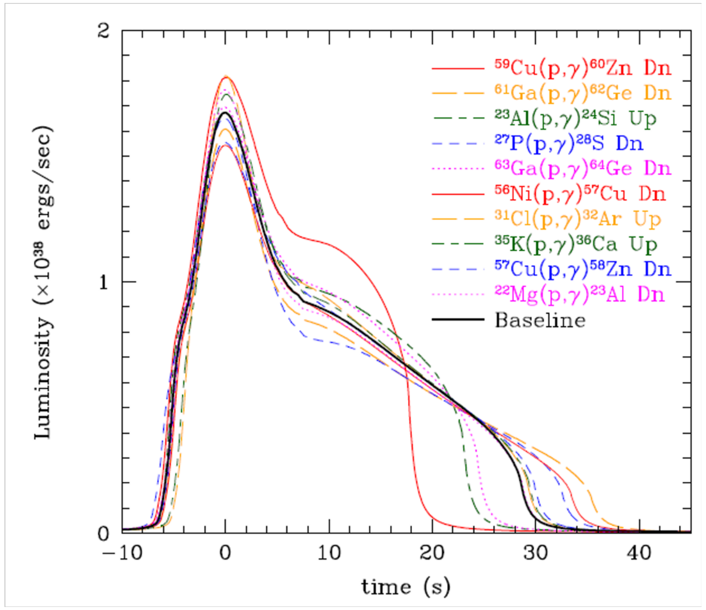
Nuclear astrophysics: Explosive hydrogen burning

. Proton captures during outburst of classical novae and type I X-ray bursts

. Main challenge is to understand the observed light curves

. Sensitive studies give 10 key reactions and particularly : ^{69}Cu(p,γ)^{60}Zn, ^{56}Ni(p,γ)^{57}Cu and ^{57}Cu(p,γ)^{58}Zn

Method: One-proton transfer reactions ^{69}Cu(^{3}He,d)^{60}Zn, ^{56}Ni(^{3}He,d)^{57}Cu and ^{57}Cu(^{3}He,d)^{58}Zn
with low beam intensities, low energy deuterons and γ-ray coincidence needed



Cyburt+, ApJ 2016

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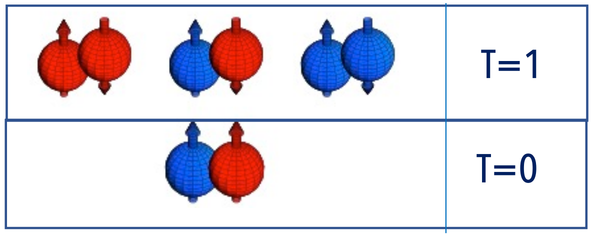
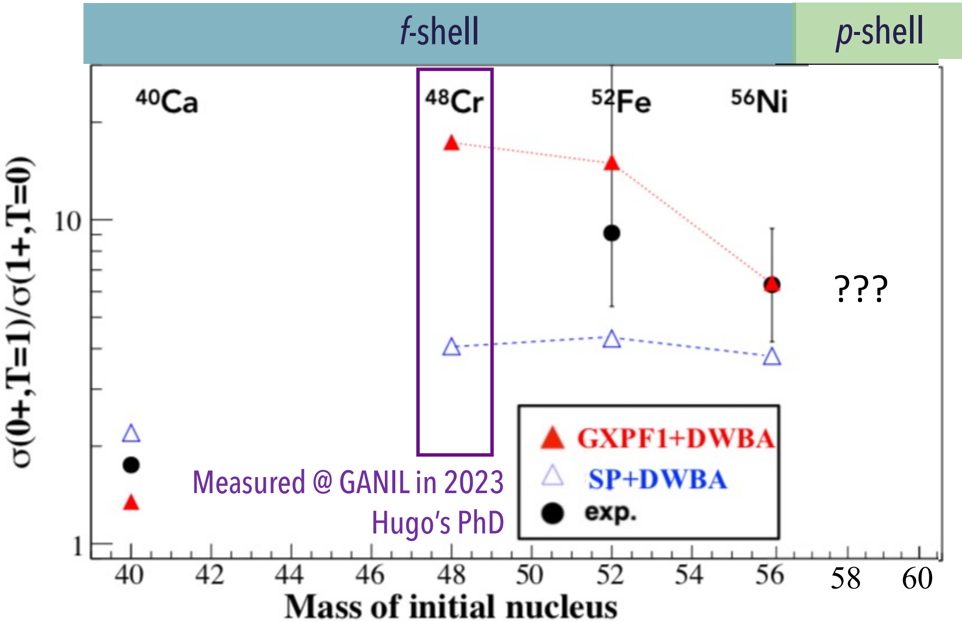
Neutron-proton pairing in the *fp*-shell

Two-nucleon transfer reactions are the best probe for pairing and **(^{3}He,p) and (p,^{3}He)** allows to populate both T=0 and T=1 channel.



Method: **Cross-sections to the first 0+ and 1+ states** for the two-nucleon transfer reaction **^{60}Zn(^{3}He,p) ^{62}Ga** and, simultaneously ^{60}Zn(^{3}He,d)^{61}Ga the intermediate reaction



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Summary of key reactions and specificites:

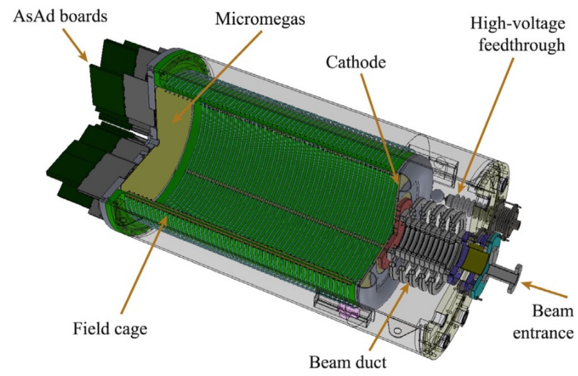
- Proton shell evolution : **^{34}Si(^{3}He,d) @ 20 A MeV**
  --> deuterons recoiling with high energy (few MeV) , gamma-ray needed
  } Cryogenic target
- Unbound proton-rich nuclei : **^{24}Si(^{3}He,d)^{25}P @ 30 A MeV**
  --> low beam intensity, deuterons with very low energy (below 1 MeV)
- Nuclear astrophysics : **^{69}Cu(^{3}He,d)^{60}Zn, ^{56}Ni(^{3}He,d)^{57}Cu and ^{57}Cu(^{3}He,d)^{58}Zn**
  --> low beam intensity, deuterons with very low energy (below 1 MeV), gamma-ray needed
  } Active target
- np pairing: **^{60}Zn(^{3}He,p)^{62}Ga @ 10 A MeV and ^{60}Zn(^{3}He,d)^{61}Ga and ^{60}Zn(^{3}He,^{3}He)**
  --> proton recoiling with high energy ~10 MeV, gamma-ray needed
  } Cryogenic target

Context : available (or close to) « thick » ^{3}He targets

✓✗ **AT-TPC for FRIB**

. Recirculation of ^{3}He designed and tested
. Full volume of ^{3}He already available
. Day1 experiments @ FRIB already approved

^{3}He areal density: >10^{20} at/cm^2
limited range of particles



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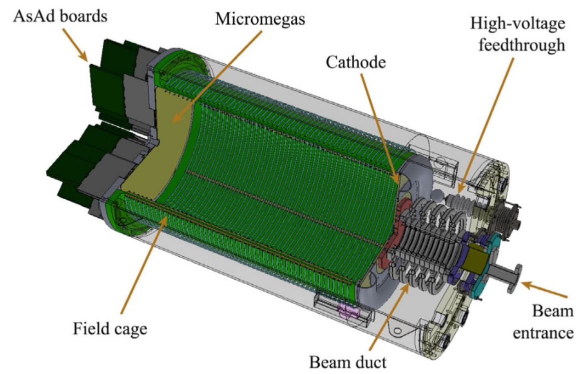
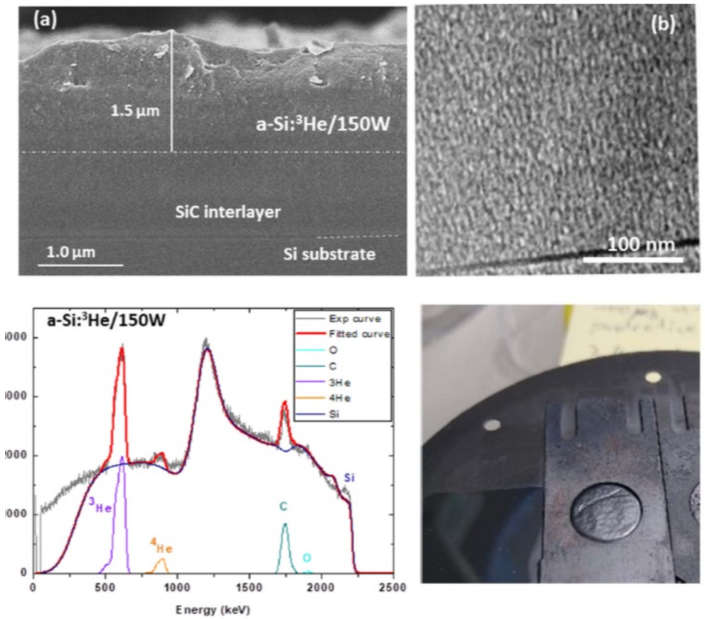


✓✗ **^{3}He implanted targets** on W and Al *(to be tested @ ALTO)*

State-of-the-art implanted ^{3}He target :
- magnetron sputtering technique
- **gas nanobubbles** trapped within a nanoporous solid matrix

^{3}He areal density: ca 5-7 10^{18} at/cm^{2}
Al backing : 7.4 um



Fernández+, Materials and Design 2020

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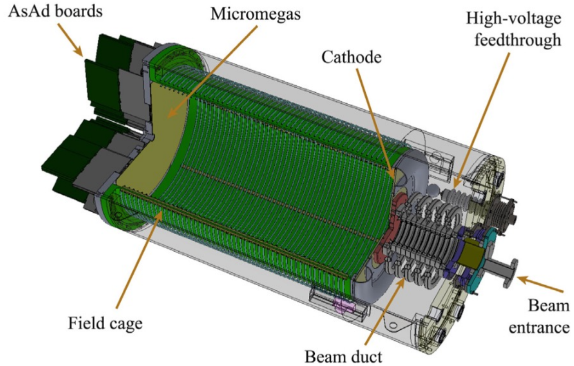

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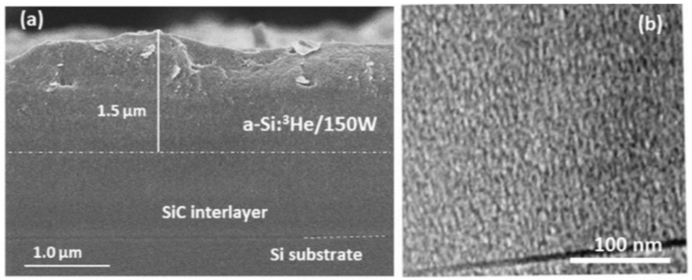
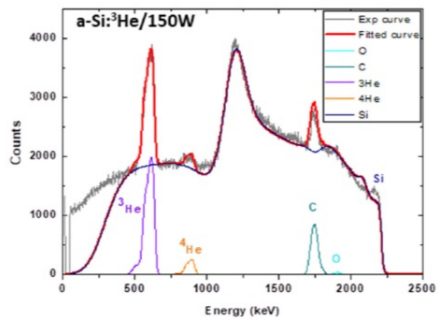


✓ **Cryogenic ^{3}He target**

✓ **HeCTOr** ^{3}He target (M. Assié, M. Pierens et al, IJCLab)
already used during the MUGAST-AGATA-VAMOS campaign

^{3}He areal density: ca 10^{20} at/cm
Havar windows : 3.8 um

F. Galtarossa et al, NIMA (2022)



✓ **CTADIR** ^{3}He target (A. Gottardo et al, INFN)
based on a pulse tube , already tested in beam (2023)

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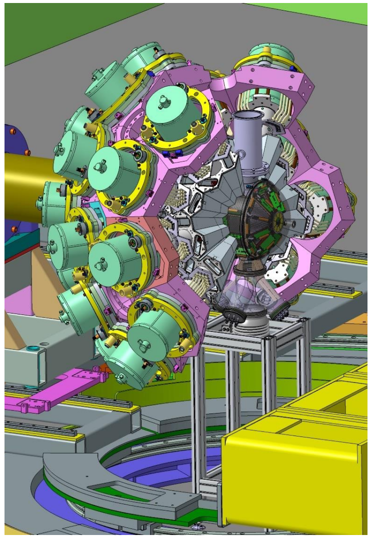
ATRACT aims at developing

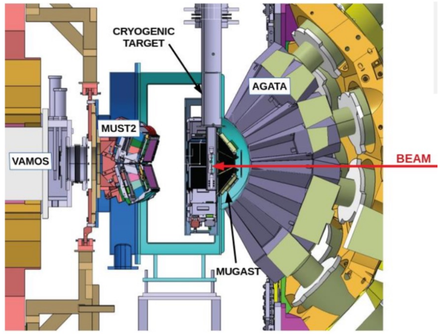
both **cryogenic and active target** with **at least 10^{20} at/cm^2**

and to run experimental campaigns in at GANIL with **Spiral1 beams** and AGATA-GRIT-VAMOS.

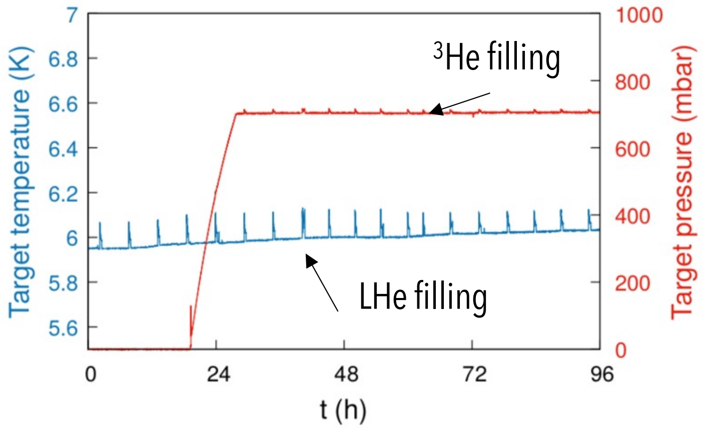


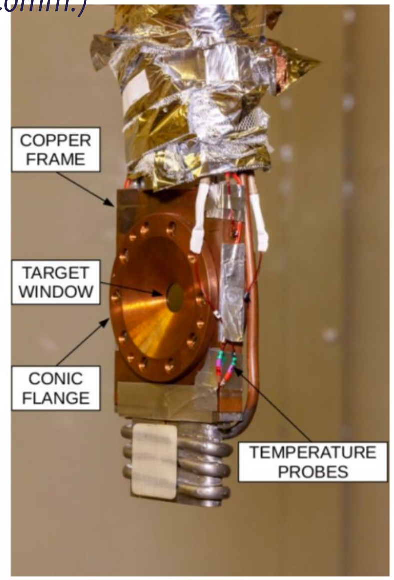
Example with HeCTOr 3He cryogenic target @ MUGAST-AGATA-VAMOS campaign

Is there a problem with protons in N=28 nucleus ^{46}Ar ? *(A. Gottardo, M. Assié, D. Brugnara et al, submitted to Nature Comm.)*



➠ $^{46}Ar(^{3}He,d\gamma)^{47}K$ with MUGAST-AGATA-VAMOS@ GANIL-Spiral1





- Ø 16 mm
- Opening angle: 130 deg.
- Havar windows: 3.8um
- T ~ 6-7 K. / P up to 1 bar
- Equivalent thickness 2 mg/cm^2
- ^{3}He recycling
- LHe open circuit

M. Pierens, V. Delpech,
F. Galet, H. Saugnac (IJCLab)
A. Giret & J. Goupil (GANIL)

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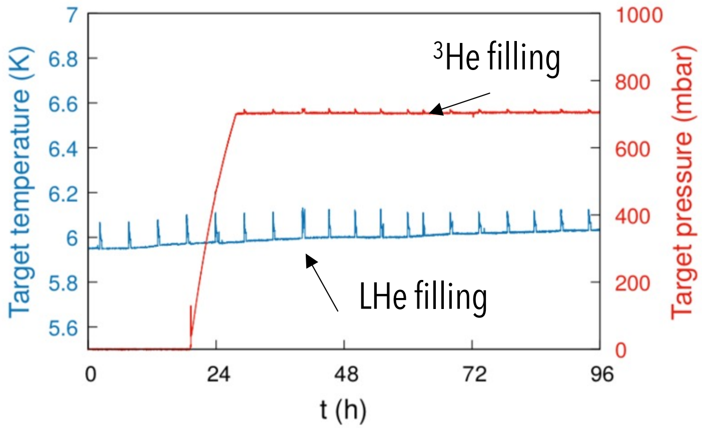
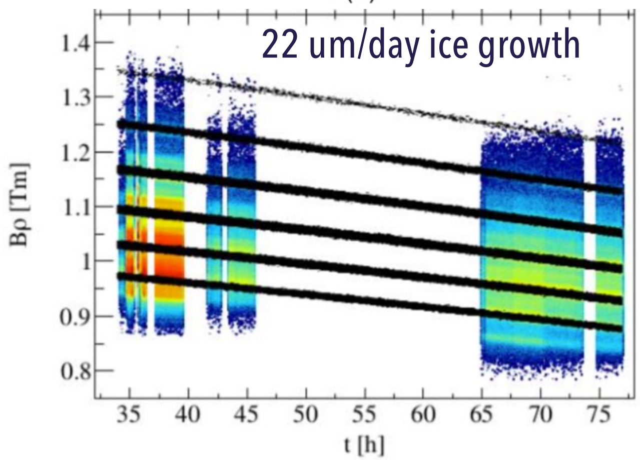
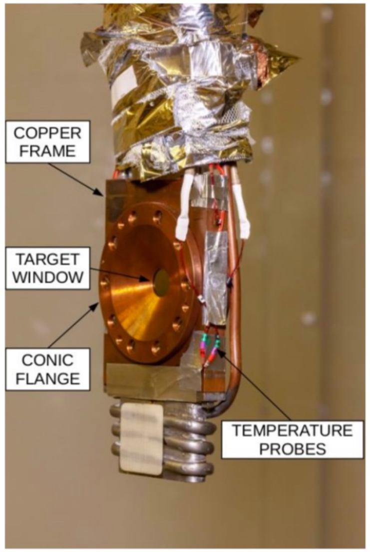
Problems/ Limitations identified with HeCTOr:

1. **Ice growth** : 11 μm/day/window for a vacuum of 10^{-6} mbar.
2. **No reheat and cooling cycles** were not possible due to the LHe consumption.
3. **Deuteron <1.5 MeV do not get out of the target.**
4. Strong background contribution from the **havar** windows
5. and **ice layers** to the **excitation energy resolution** (600 keV each for 3 MeV deuteron and resolution in E*= 3 MeV FWHM).
6. For gamma-ray measurement, depending on the lifetime of the populated state, the **absorption from the target cell and shielding** is quite important.

F. Galtarossa et al, NIMA (2022)







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New design of cryogenic target proposed in ATRACT

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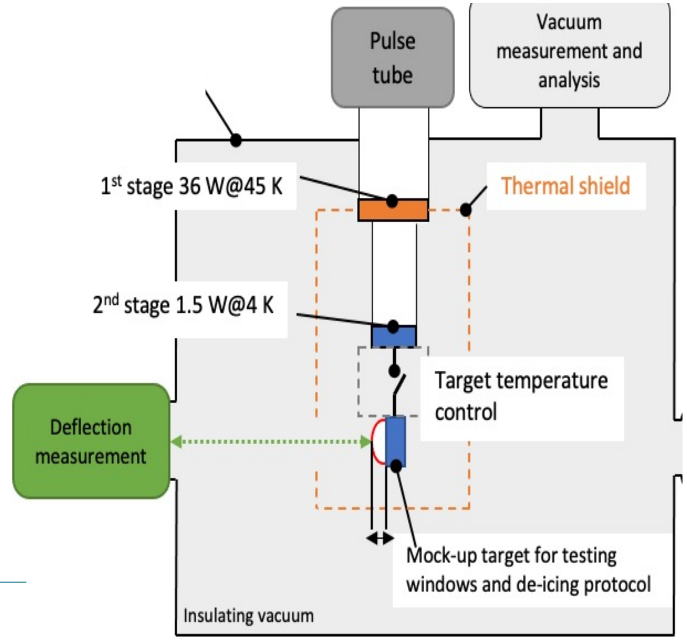
➠ Design of a new cryogenic ^{3}He target

- based on a cryocooler (points 2 & 6) *already bought and tested*
- new window material (points 3 & 4) : *thin synthetic foils (Aramid) and SiN windows to investigate*
- new de-icing protocol (points 1 & 5) *depending on the window chosen*



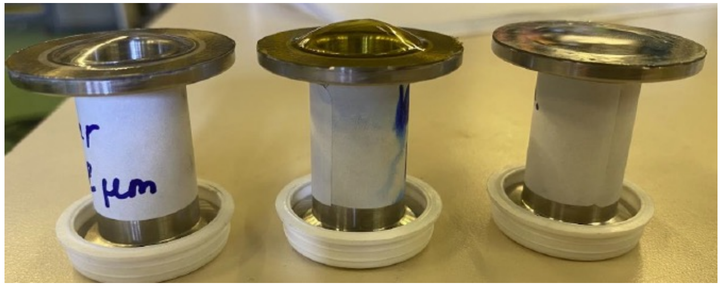
New design of cryogenic target

- Test of new (other) target window (pressure test, deformation)
  - Mylar 12 µm
  - Kapton 8 µm
  - Mylar 50 µm aluminisé 1 face

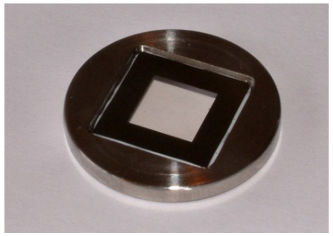
plastic deformation (Mylar 12 µm, Kapton 8 µm)

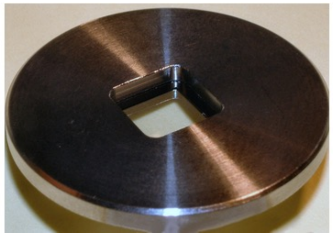
too thick (Mylar 50 µm aluminisé 1 face)

--> Modification of material data --> wrong !!



  - Toray Aramid --> available to be tested
  - SiN windows good properties to be tested (order in progress)

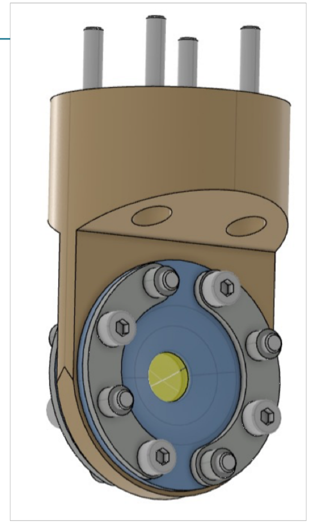




- Target design

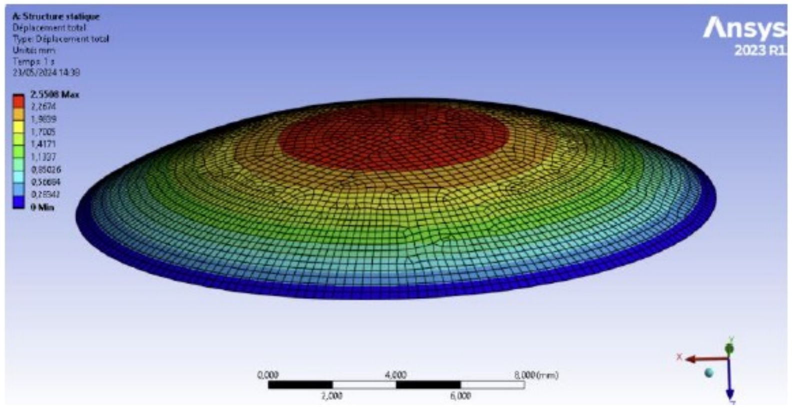
other option considered :

glued windows



- Modelisation of deformation with ANSYS

P. Sebaoun, Ph. Rosier, J. Blivet (IJCLab)
M. Pierens, P. Duthil (IJCLab)



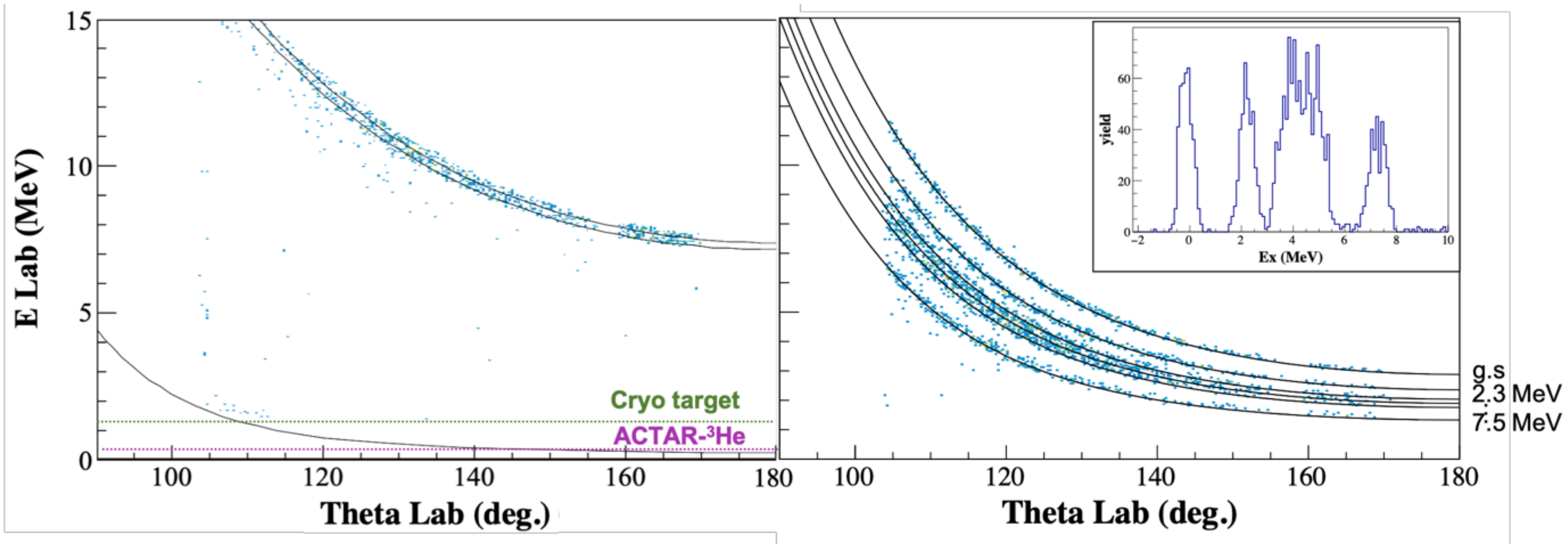
Physics simulations for the new design of cryogenic target proposed in ATRACT

Hypothesis:

- 2.2 mm thickness of the cell with deformation
- 10^{20} atoms/cm^2
- Toray Aramid windows of 4 um thickness

^{60}Zn(^{3}He,p)^{62}Ga (g.s.) and ^{60}Zn(^{3}He,d)^{61}Ga (g.s) at 10 MeV/u

^{34}Si(^{3}He,d) assuming equal population of states in ^{25}P



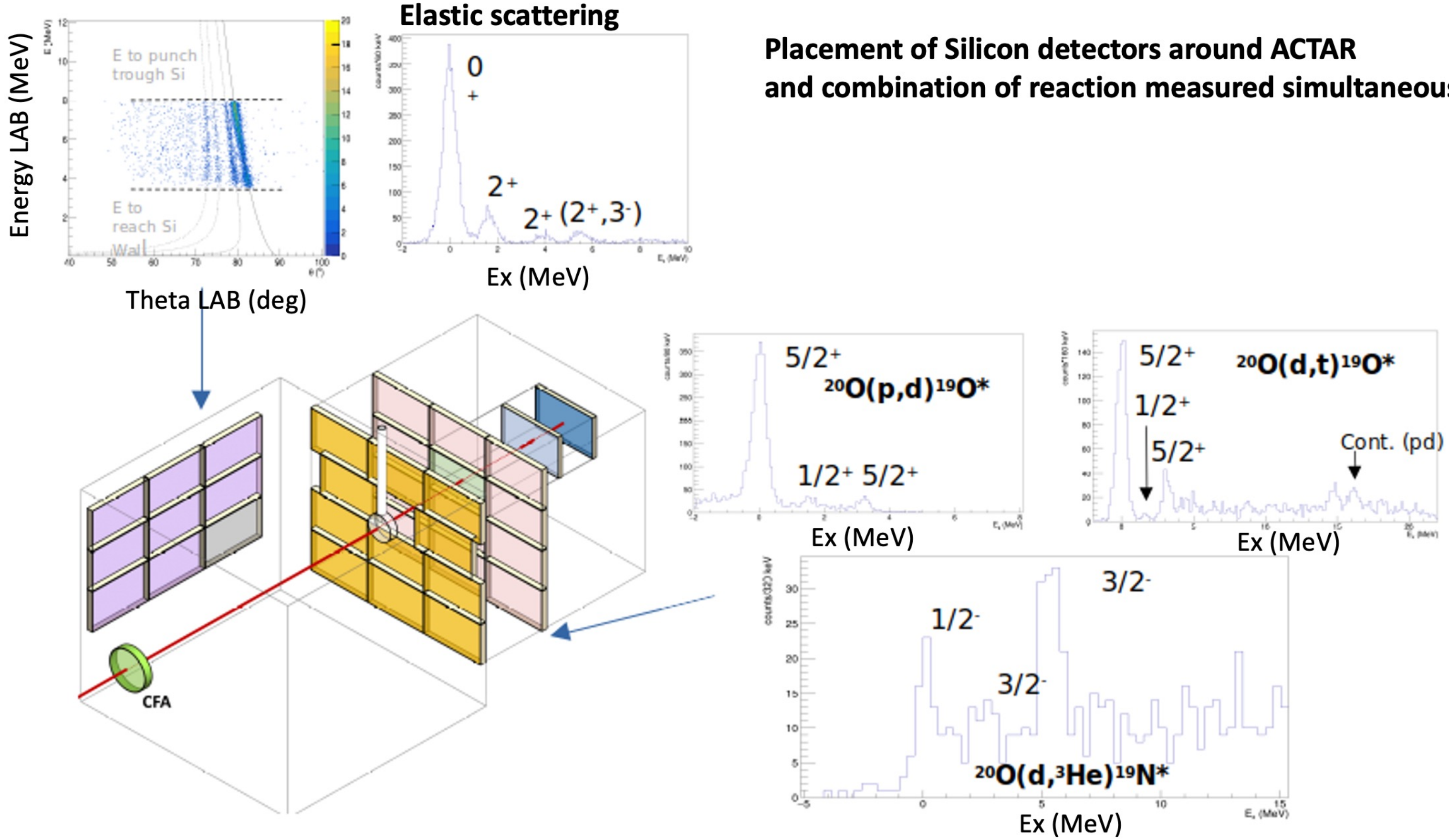
E* Resolution : 420 keV with Aramid
505 keV with Havar

New active 3He-target proposed in ATRACT: ACTAR-3He

Very few direct reactions have been measured up to now with active targets, this is just the beginning….

First transfer reaction measurement performed with ACTAR :

One-neutron transfer $^{20}O(p,d)^{19}O$ and $^{20}O(d,t)^{19}O$ + elastic



Courtesy of B. Fernandez-Dominguez

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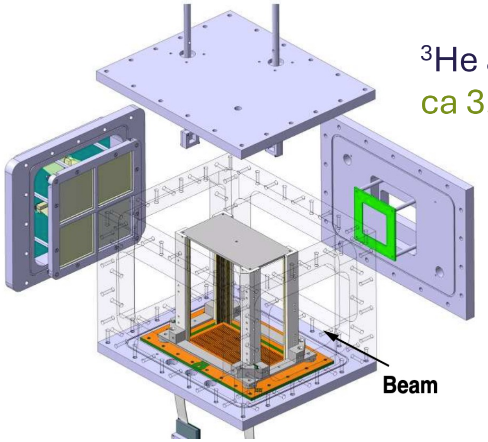
✓✗ **ACTAR-3He demonstrator (-> SMACTAR) will be used**

➠ **Improvements required:**

- Recirculation/purifying system, to not waste the 3He
- New multiplication stage, to improve the gain of the system (only micromegas not enough)
- Si detector all around, to cover the full range of the ejectile

➠ **So far:**

- Gas system in close-loop was studied and developed @GANIL [*NIM A 1069 (2024) 169866]*. Expertise acquired on the subject
- Preliminary tests with triple THGEM performed with 4He in SMACTAR. Very promising results were obtained in term of gain
- New THGEM under construction, to have a more homogeneuus drift field
- Pad plane sent to CERN because too noisy
- 15l of 3He have been bought



^{3}He areal density:
ca 3.10^{20} at/cm^2

➠ **What next:**

- Recirculation system has to be designed and tested on SMACTAR.
- Lekeage rate of SMACTAR has to be measured
- Test new THGEM and pad plane (when they will be delivered)
- Look for electronics indepedent from ACTAR

➠ **And then commissioning of ACTAR-3He:**

- with pure ^{4}He (LoI for NFS submitted to the November 2024 PAC)
- with pure ^{3}He

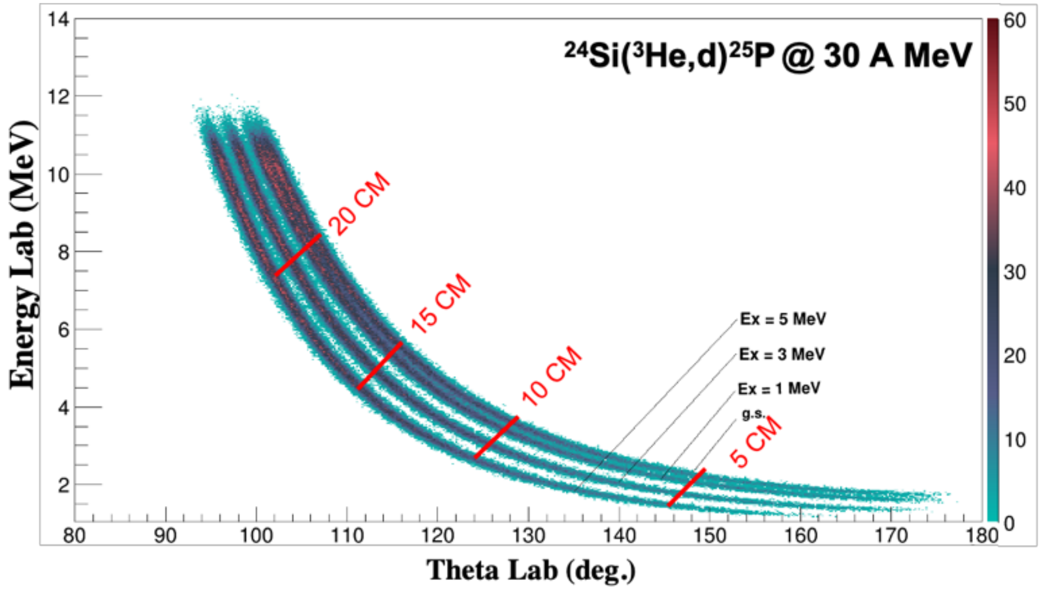
Physics simulations for ACTAR-3He proposed in ATRACT

Hypothesis:

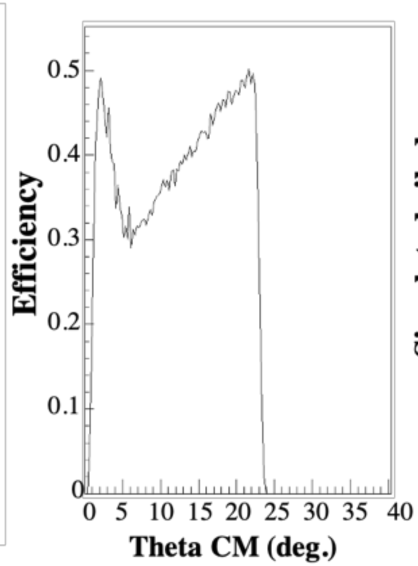
- ACTAR demonstrator 500 mbar pure ^{3}He
- $3.2\ 10^{20}$ atoms/cm^2
- $5\ 10^4$ pps --> 1000 counts for one week

Expected energy resolution : **300 keV**
with the cryogenic target it would be 940 keV (with the same equivalent target thickness)

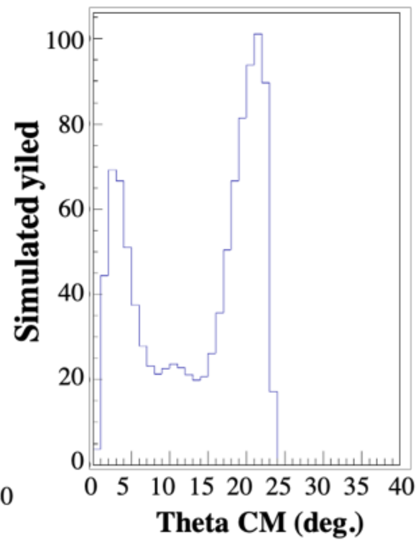
$^{24}Si(^{3}He,d)$ at 30 A MeV for the population of the ground state and three excited states at 1, 3 and 5 MeV.



Efficiency in the center-of-mass



Expected yield as a function of center-of-mass angle.



Timeline for ATRACT