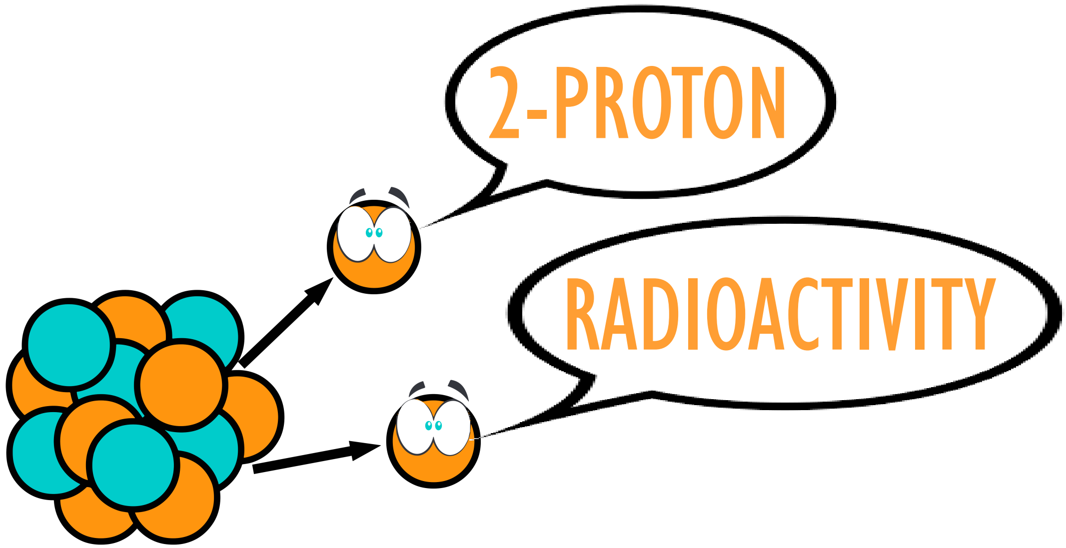
Studies beyond (and close to) the proton drip line in the ^{48}Ni region



Aurora Ortega Moral

LP2i Bordeaux

Haloweek24 – 10 June 2024

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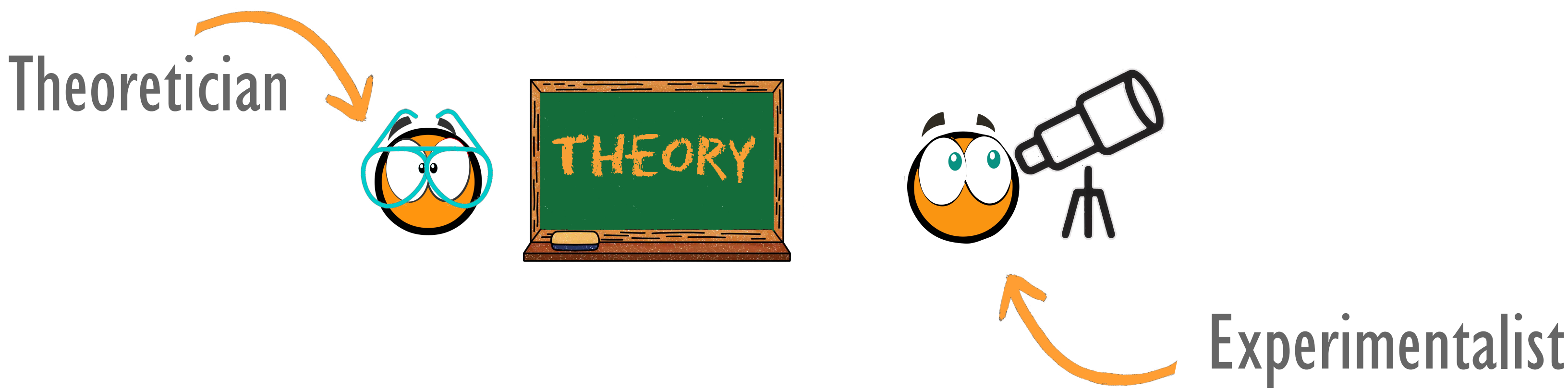

Aurora Ortega Moral

LP2i Bordeaux

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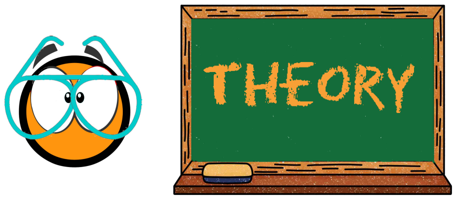

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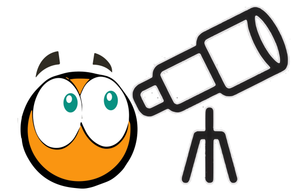
- ^{48}Ni REGION
- 2-PROTON RADIOACTIVITY
- THEORETICAL PREDICTIONS

Discrepancies



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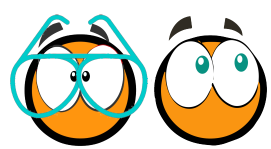
- E791 EXPERIMENT
  - → ACTAR TPC
  - → ANALYSIS
  - → RESULTS



- COMPARISON THEORY-EXPERIMENT
- CONCLUSIONS AND PERSPECTIVES

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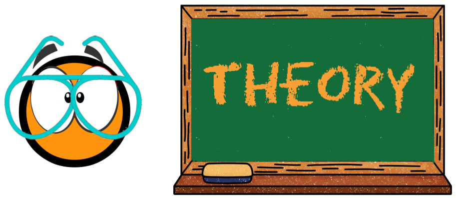

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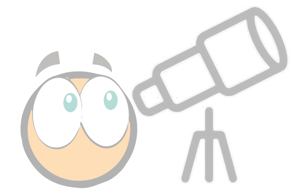

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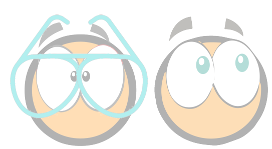

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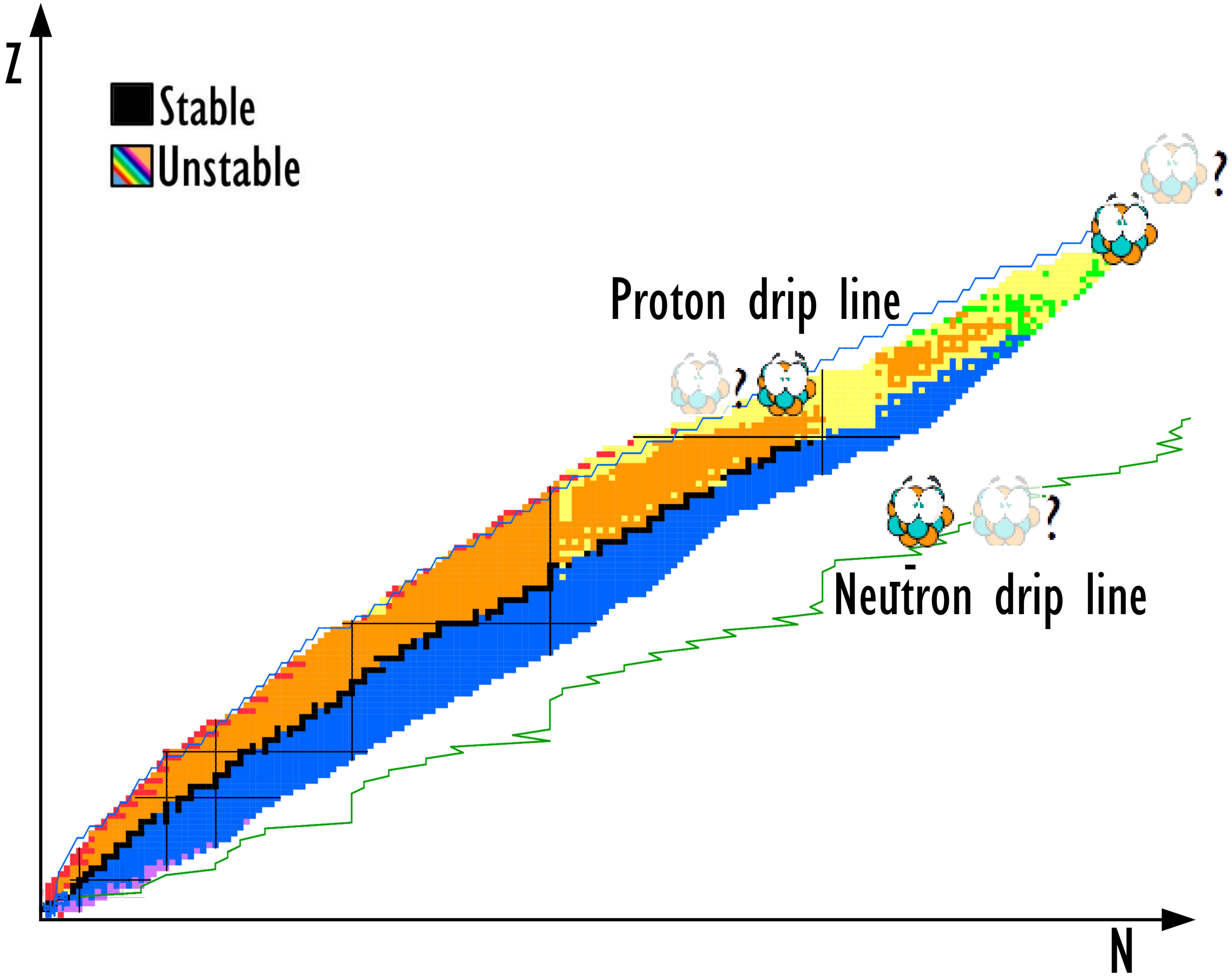
INTRODUCTION UNDERSTANDING NUCLEAR STRUCTURE



HOW?

- Understanding of patterns and symmetries of nuclei

Magic numbers, deformation, pairing, isospin 

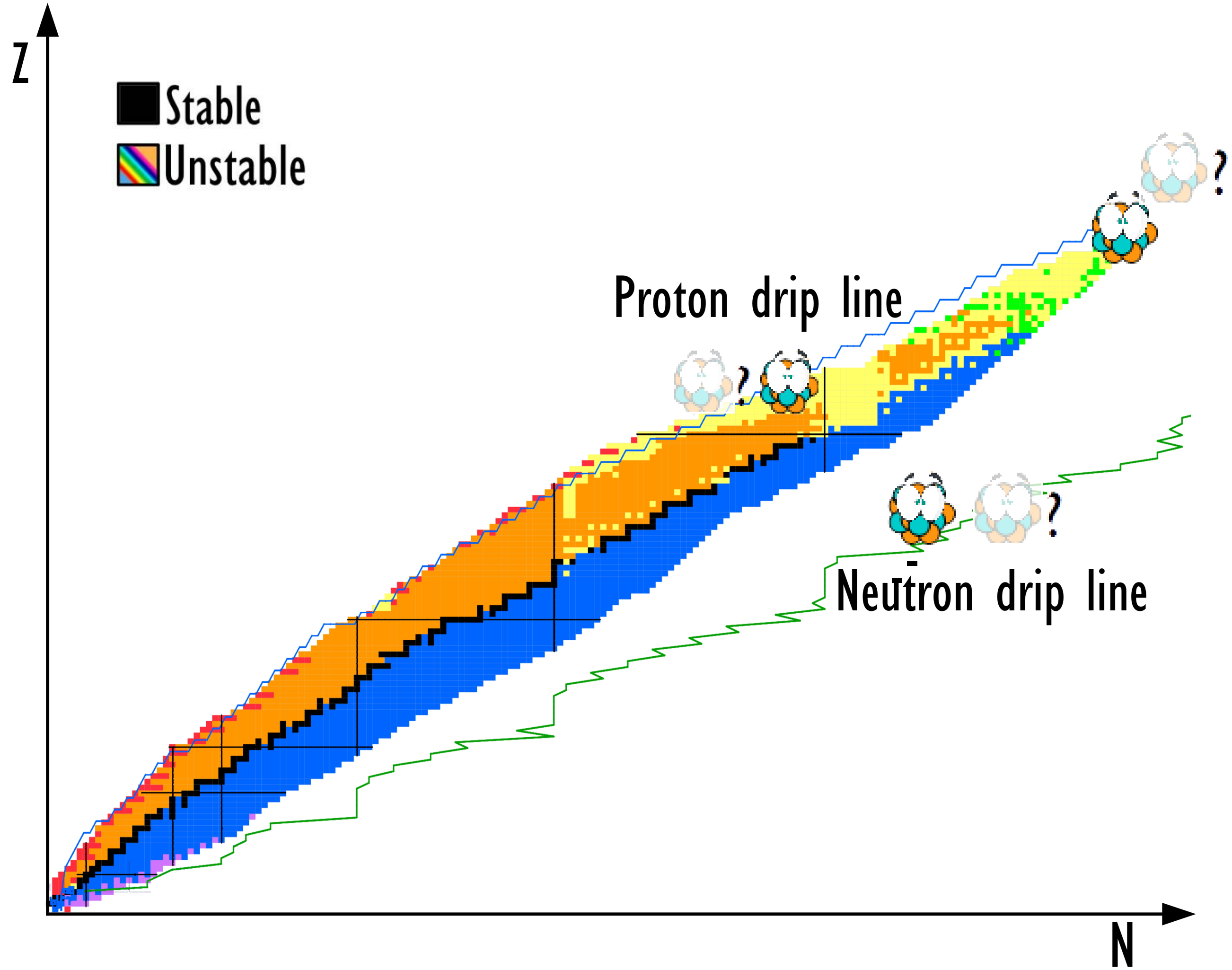
- Evolution of structure

Going away from stability

- Limits of nuclear existence

Drip lines, halo nuclei, binding energies

INTRODUCTION UNDERSTANDING NUCLEAR STRUCTURE



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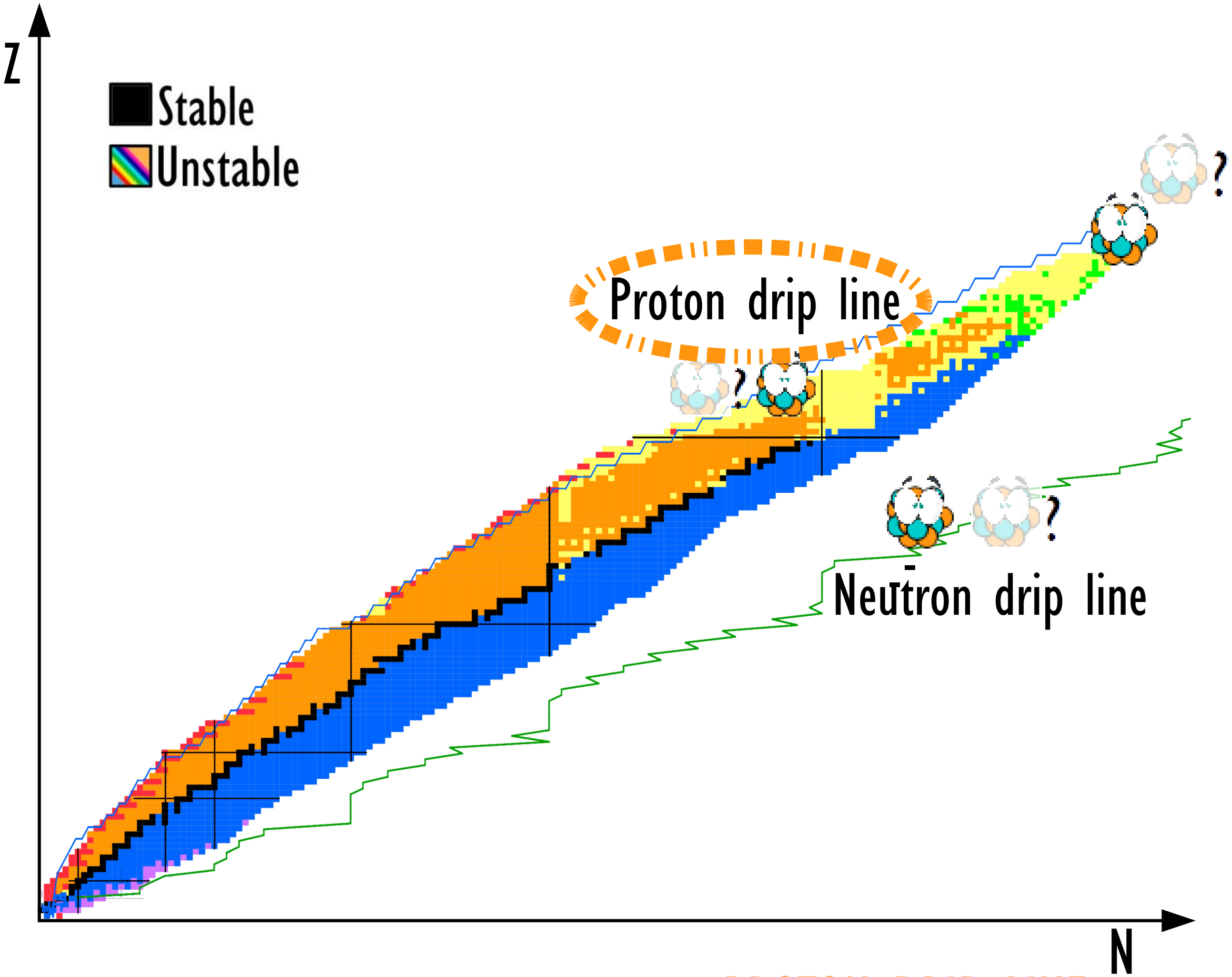
AT PRESENT,NO SINGLE MODEL CAN PREDICT THE STRUCTURE OF ALL NUCLEI

→ New theoretical considerations

→ New experimental inputs

INTRODUCTION PROTON DRIP LINE



PROTON DRIP LINE

HOW?

- Understanding of patterns and symmetries of nuclei

Magic numbers, deformation, pairing, isospin

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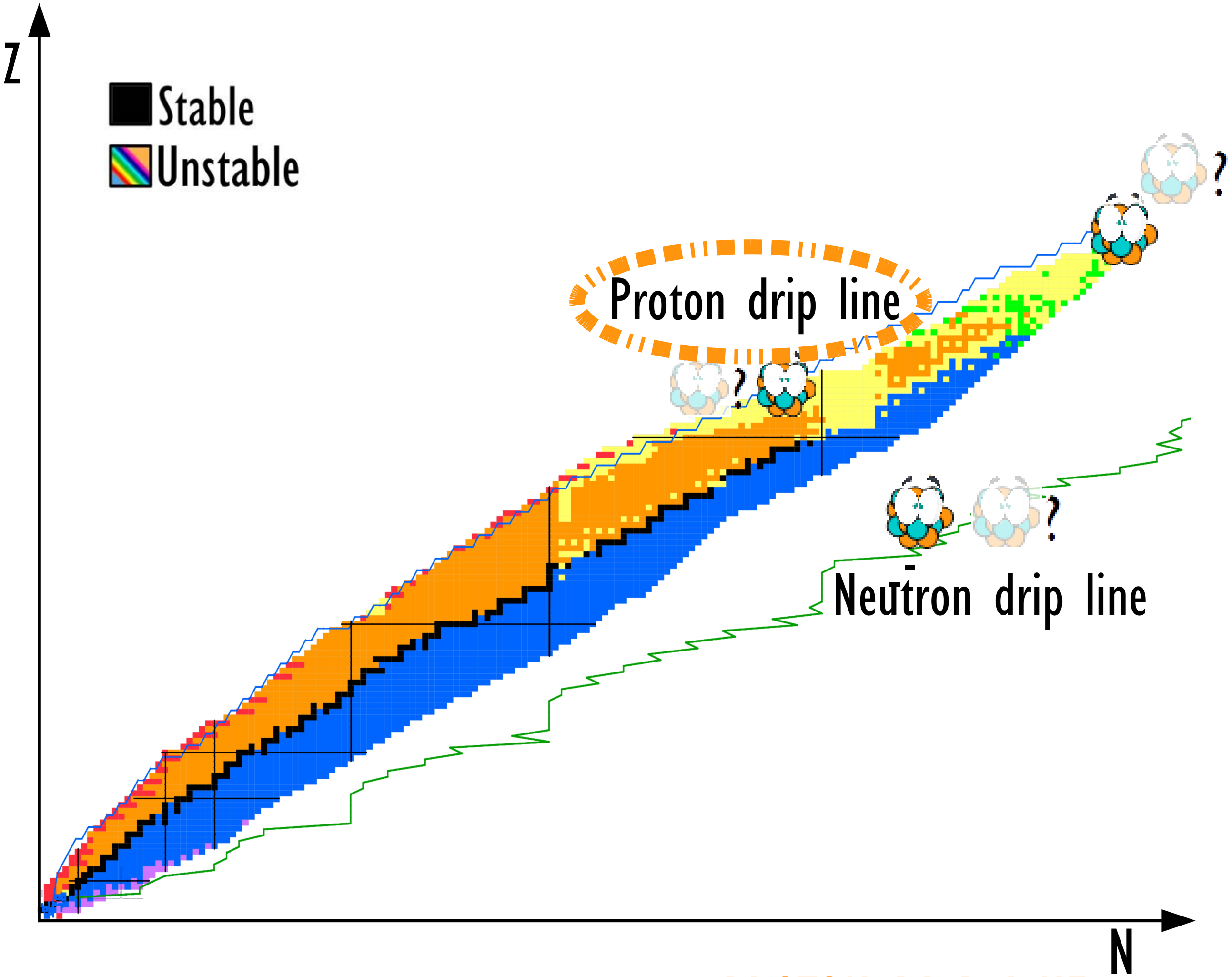
Drip lines, halo nuclei, binding energies

Several important aspects can be explored at once

INTRODUCTION PROTON DRIP LINE



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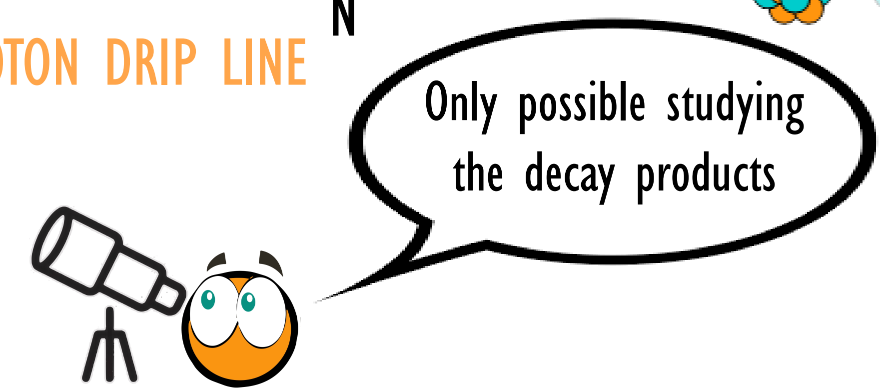
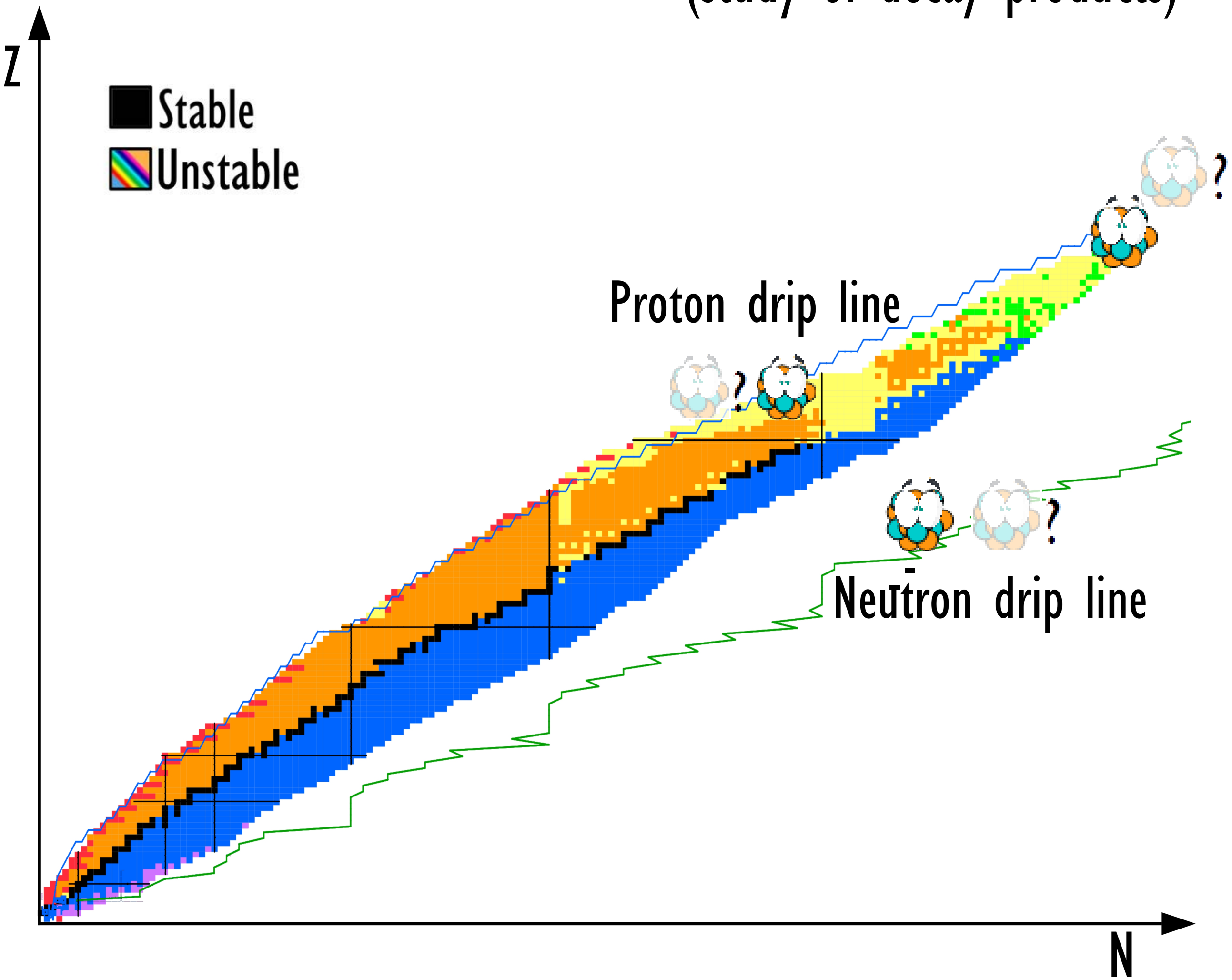
PROTON DRIP LINE

- Low production cross section
- Short half-lives



INTRODUCTION

RADIOACTIVITY
(study of decay products)



Classical radioactivity processes

- 1896 Radioactivity
- 1899 β, α
- 1930 β-α emission
- 1937 Electron Capture
- 1939 β-n emission
- 1940 Spontaneous fission
- 1963 β-p emission
- 1982 Single proton
- 1984 Cluster
- 1987 Double β
- 2002 Two proton
- 2019 Double EC
- 2024 Double α ?

t

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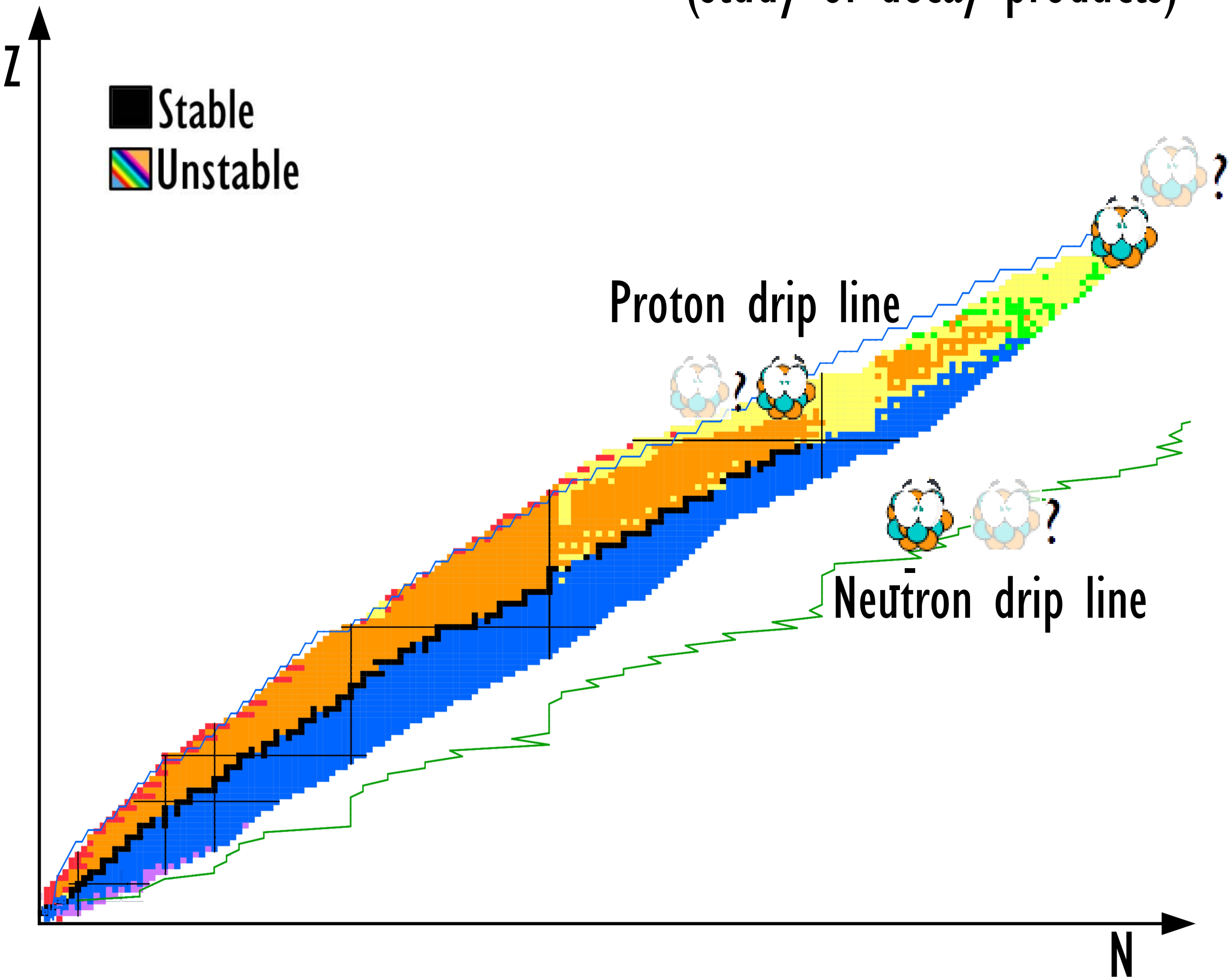
(study of decay products)



Classical radioactivity processes

Exotic radioactivity processes

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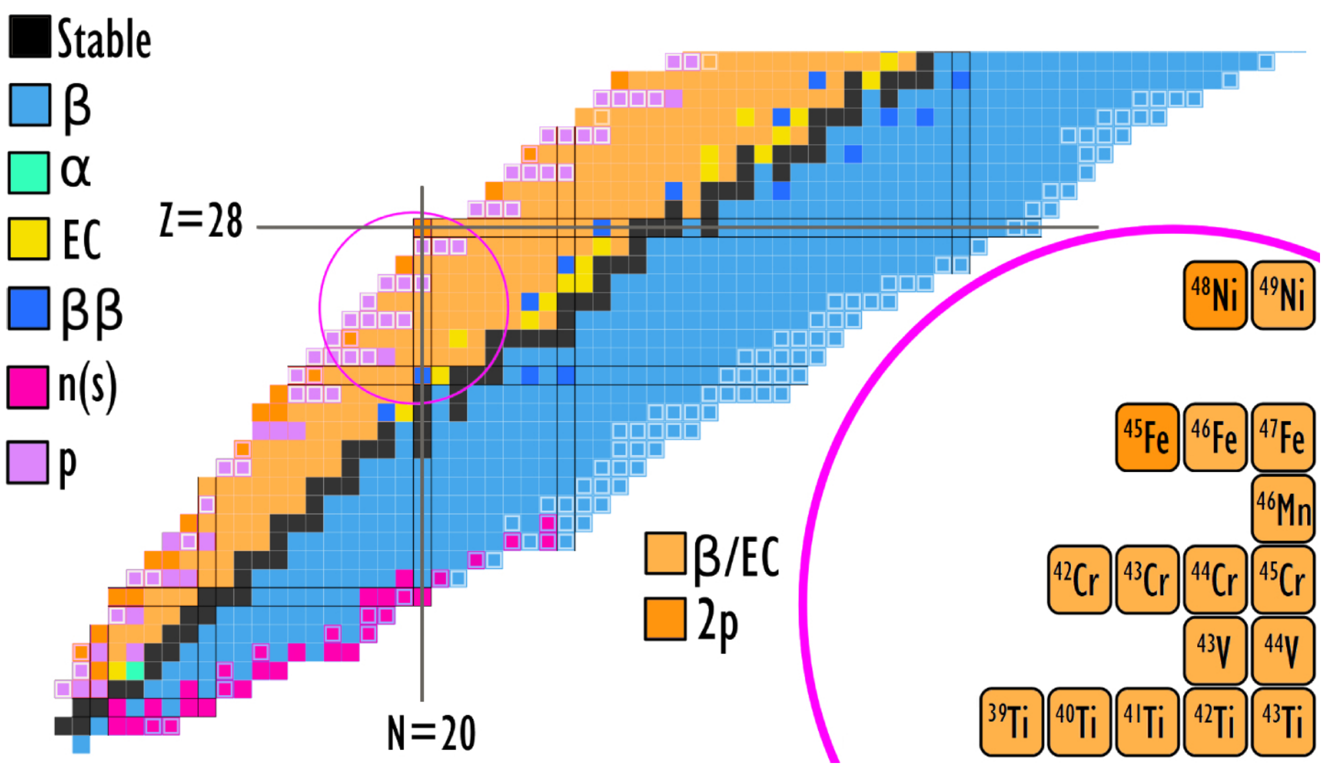
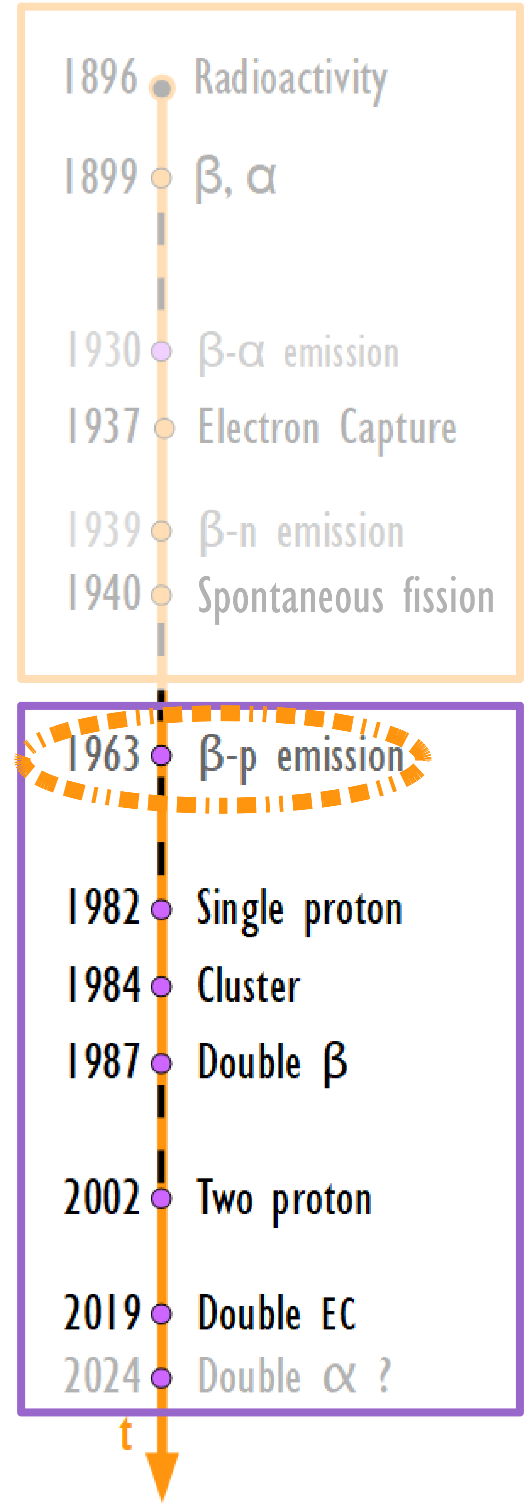
INTRODUCTION REGION OF INTEREST: ^{48}Ni



β-delayed proton(s) emission



● Exotic radioactivity processes

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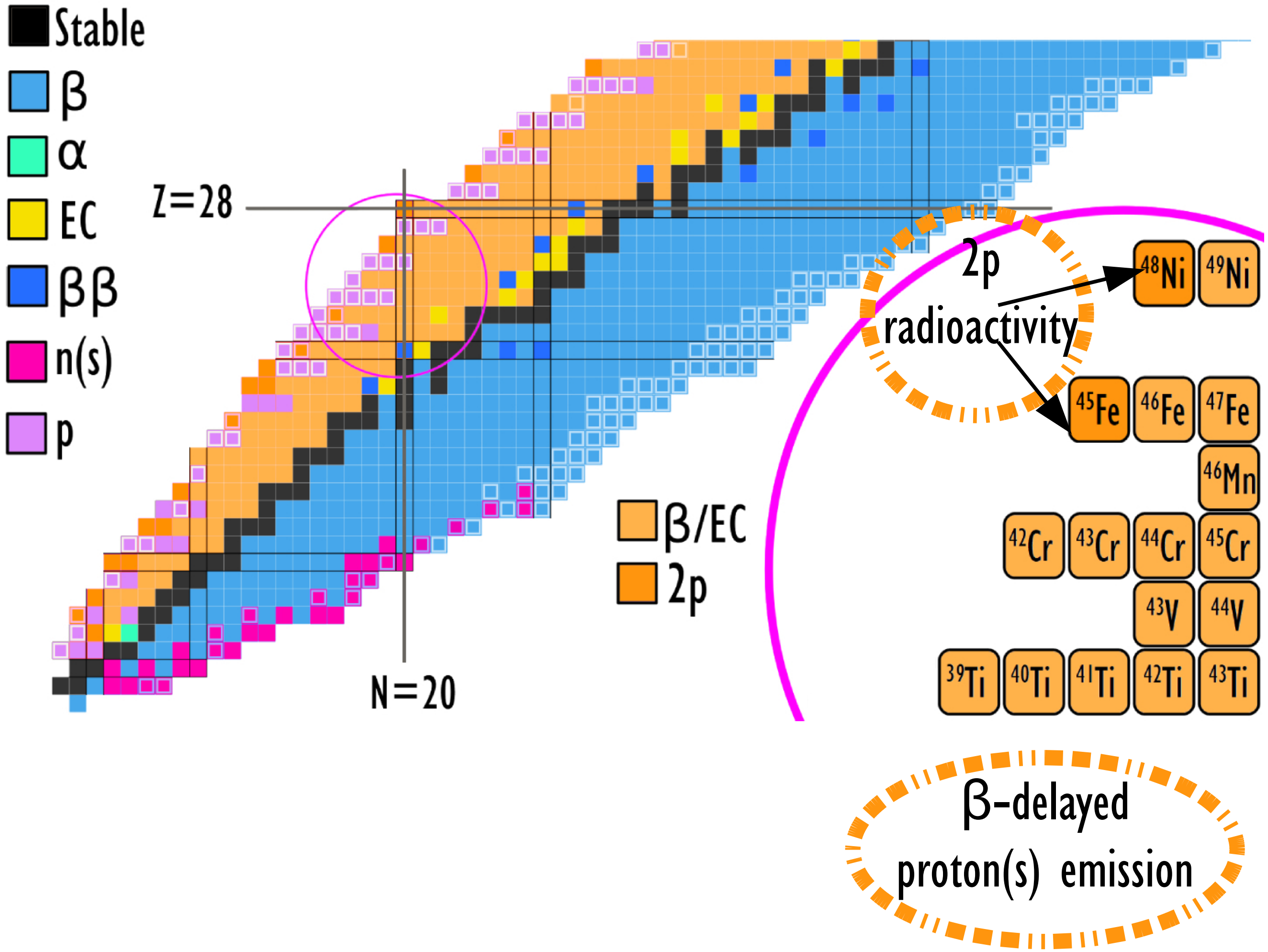

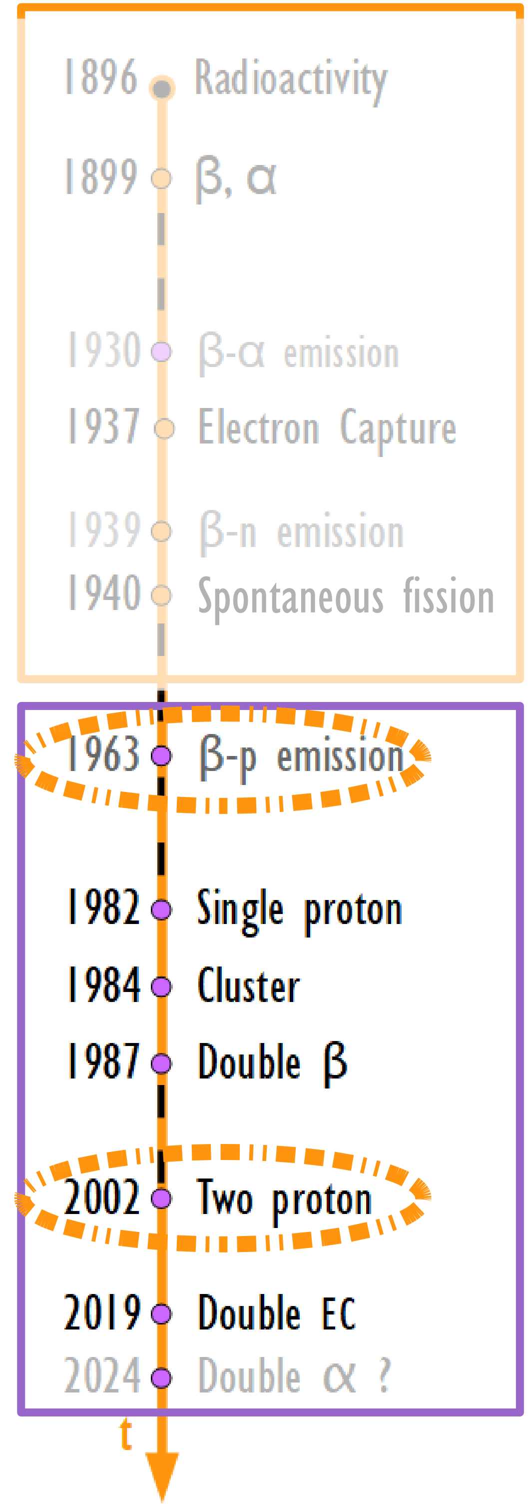

Exotic radioactivity processes

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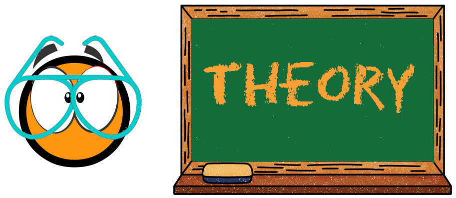

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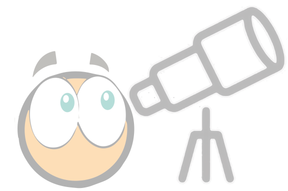

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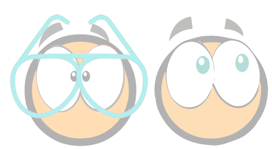

- COMPARISON THEORY-EXPERIMENT
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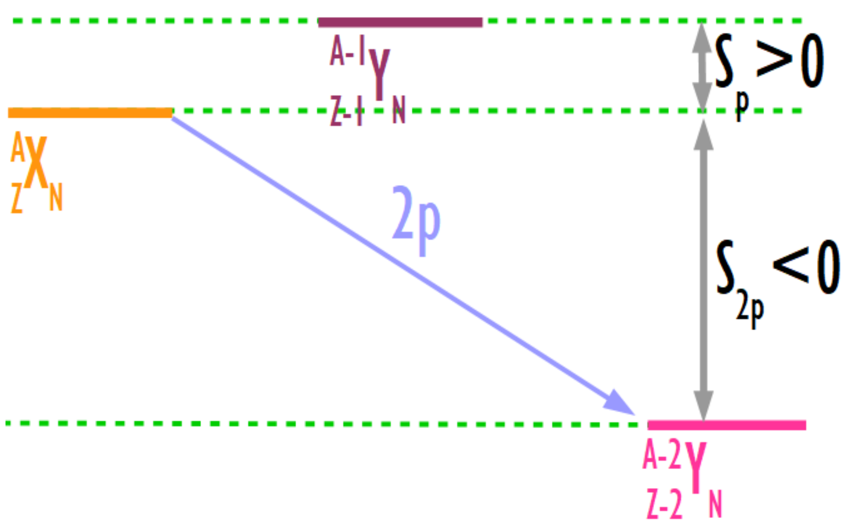
TWO-PROTON RADIOACTIVITY

Predicted in the 60's (Goldanski) → First indirect measurements (2002)

Two proton drip-line: border between the last bound isotope and the first one with a negative value of S_{2P}

$$S_{2P} = B(N, Z) - B(N, Z-2)$$

+Even Z nuclei



- Pairing energy: there is an extra binding energy if the number of protons is even.

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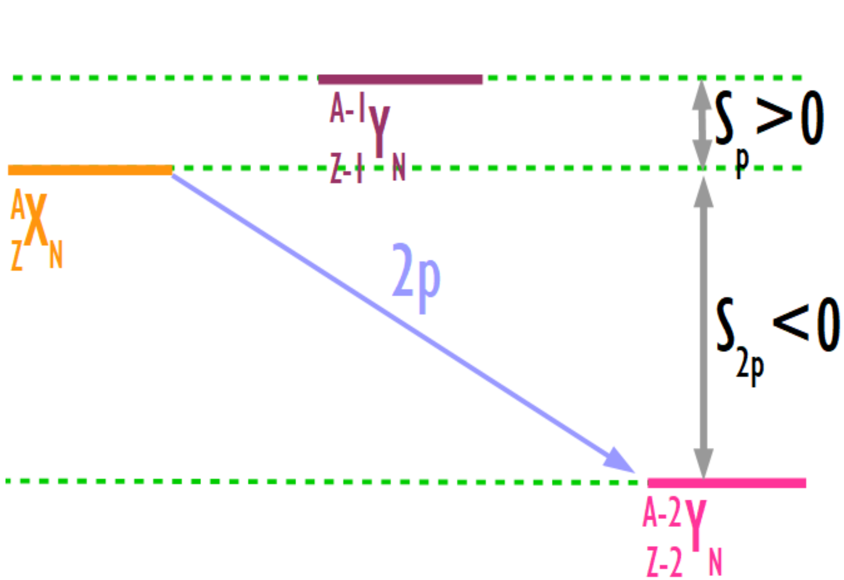
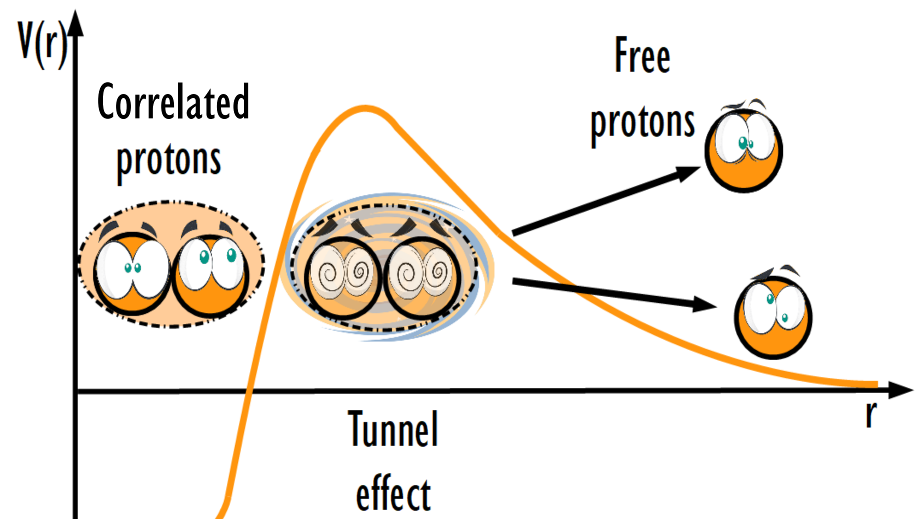




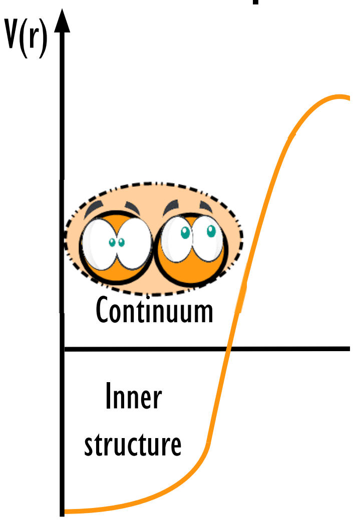
- Pairing energy: there is an extra binding energy if the number of protons is even.
- The nucleus lives for a brief moment until the proton escapes by the tunnel effect.
- Quasi-bound → completely unbound

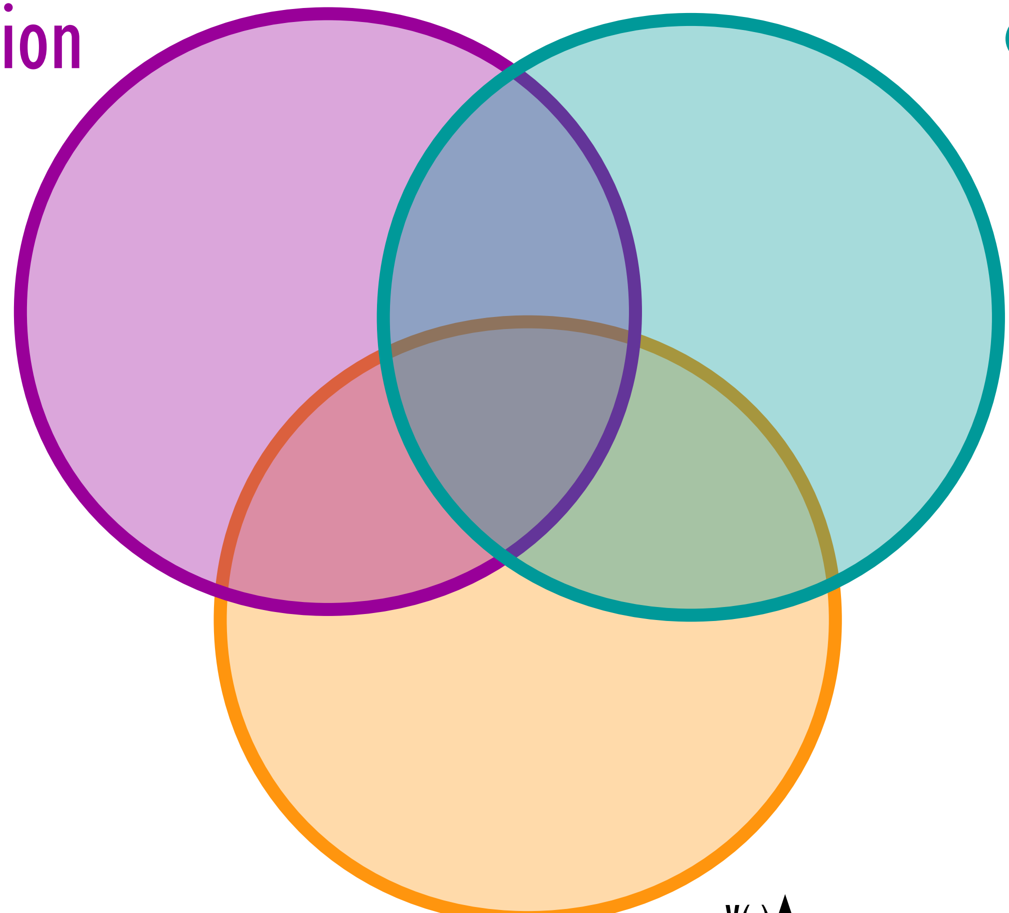
TWO-PROTON RADIOACTIVITY THREE ASPECTS

- Asymptotic region

Unbound system

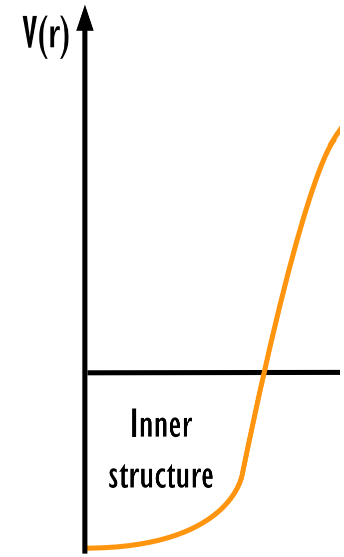
Proton drip line



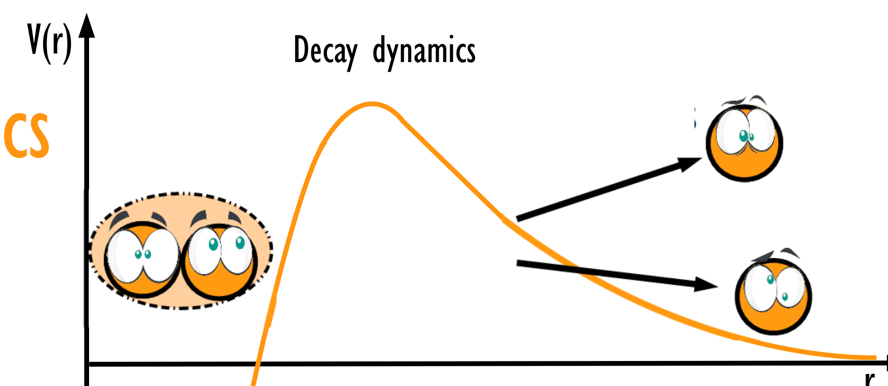


- Inner structure

Far from stability



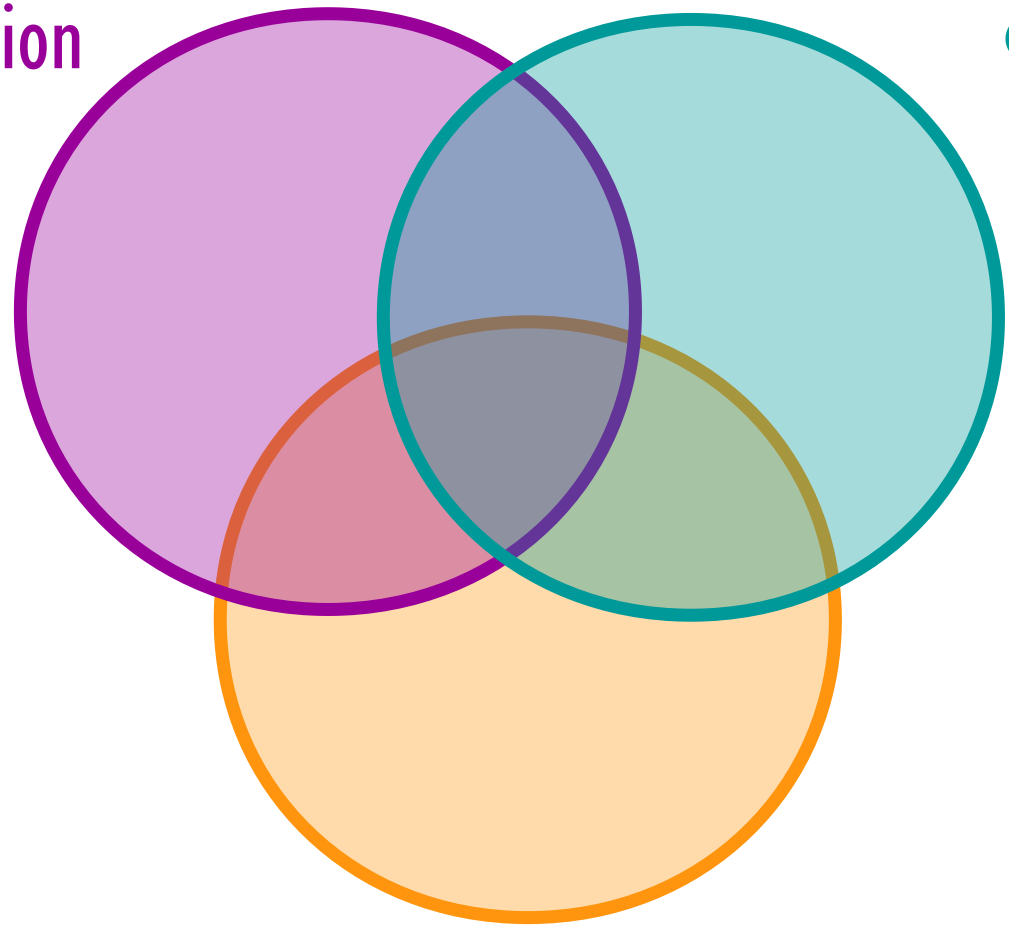
- Decay dynamics



TWO-PROTON RADIOACTIVITY

- **Asymptotic region**

  Open quantum system
  Consistent description of the internal and external wave functions



- **Inner structure**

  (Near-threshold case)
  Experimental input needed to constraint structure

- **Decay dynamics**

  3-body interaction to take into account

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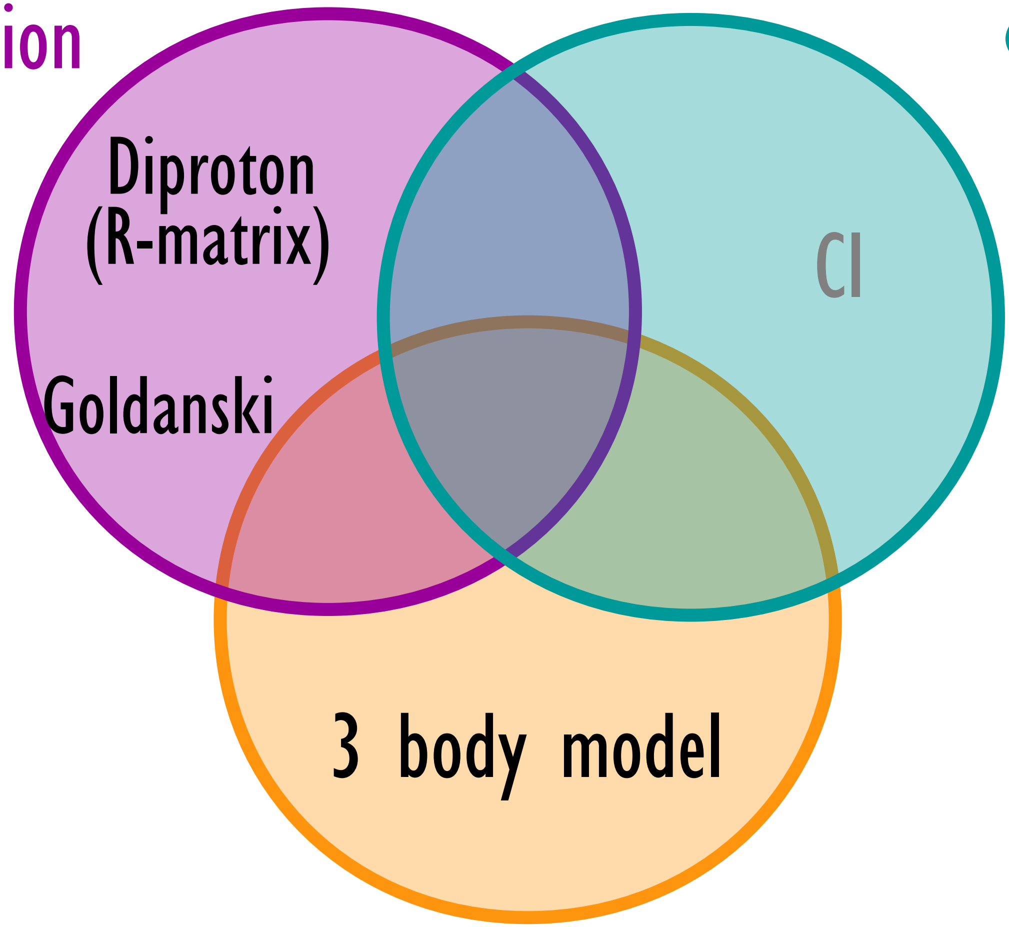

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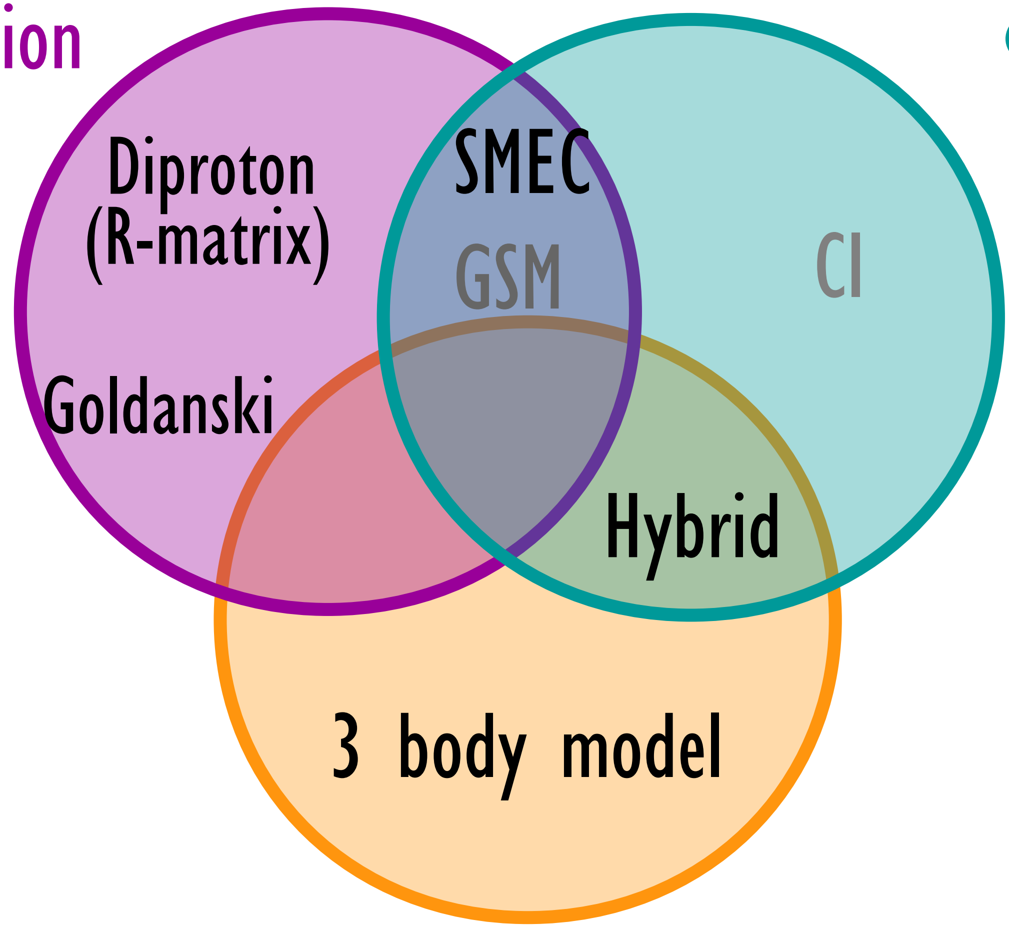

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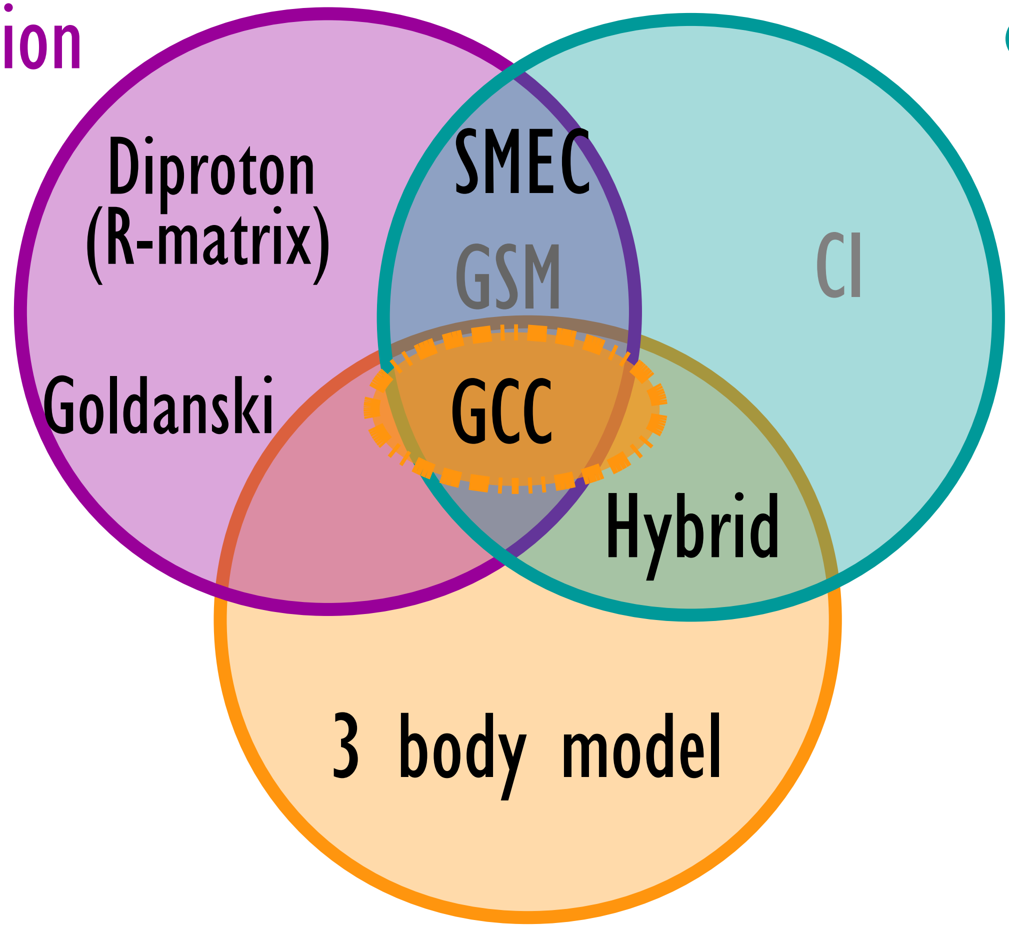

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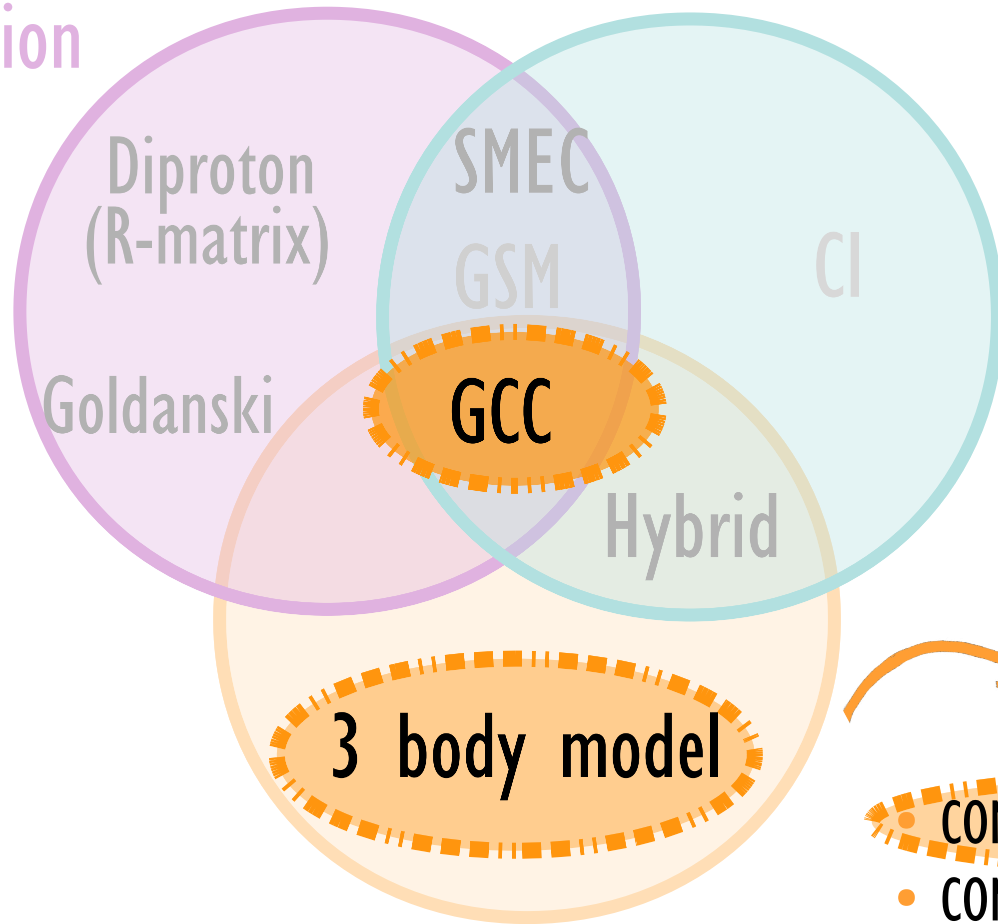

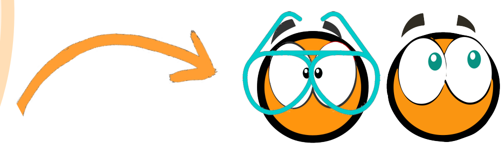

- COMPARISON THEORY-EXPERIMENT
- CONCLUSIONS AND PERSPECTIVES

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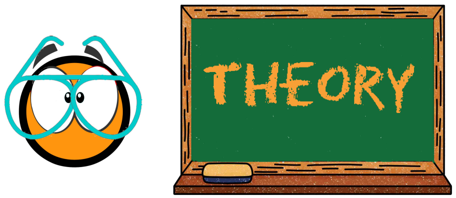

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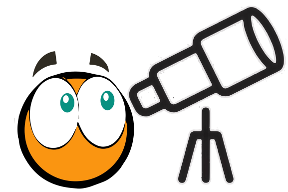

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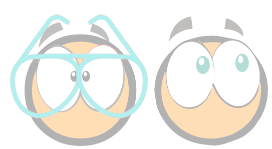

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TWO-PROTON RADIOACTIVITY OBSERVABLES

- Half-life
- Branching ratio
  2p, β-p
- Individual proton
  energies
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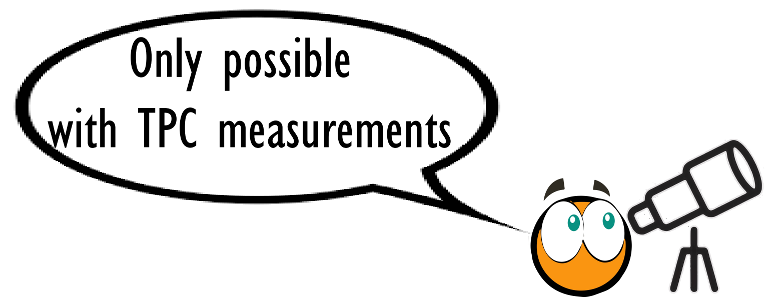

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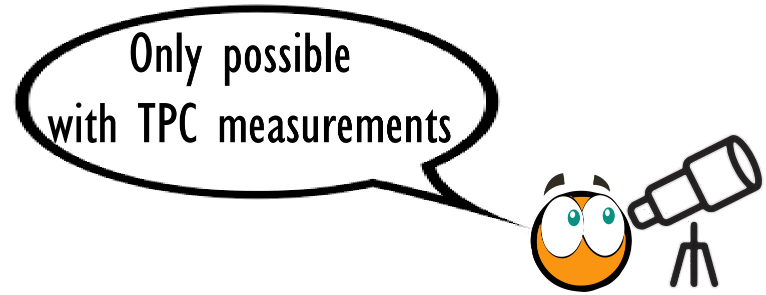

^{45}Fe, ^{54}Zn, ^{48}Ni, ^{67}Kr

First indirect measurements (Si detectors)

^{45}Fe, ^{54}Zn (GANIL 2002,2005)
^{48}Ni (MSU 2011)
^{67}Kr (RIKEN 2016)

Direct measurements (TPC detectors)

^{45}Fe (GANIL, 2007), (MSU, 2008), (GANIL, 2021) — 88 events
^{54}Zn (GANIL, 2011) and (RIKEN, 2019) — 12 events
^{48}Ni (MSU, 2011) and (GANIL,2021) — 7 events

Agreement with theoretical models?

TWO-PROTON RADIOACTIVITY PREDICTIONS vs EXPERIMENTAL RESULTS

Before 2016

3-body model
(L. V. Grigorenko et al.) Good dynamics
Half-lives and angular distributions

Shell-model 2p removal amplitudes
(B.A. Brown) Good Structure
Spectroscopic factors

GOOD agreement with Θpp measurements for ^{45}Fe

Hybrid model

Shell model corrected half-lives (B. A. Brown et al.)
Combination Good Structure + Good Dynamics

GOOD agreement with half-life measurements for ^{45}Fe, ^{54}Zn, ^{48}Ni

TWO-PROTON RADIOACTIVITY PREDICTIONS vs EXPERIMENTAL RESULTS

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Combination Good Structure + Good Dynamics

GOOD agreement with
half-life measurements for
^{45}Fe, ^{54}Zn, ^{48}Ni

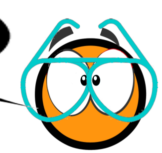
Inconsistency with experimental results $T_{1/2}$ ^{67}Kr (2016)

Transition between Real 2p emission-sequential decay
Semi-analytical R-matrix calculation
L. V. Grigorenko et al. (2017)
Energies of the protons

Deformation of ^{67}Kr

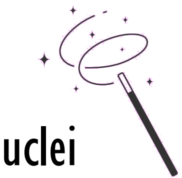
Gamow Coupled Channels (GCC)
S. M Wang & W. Nazarewicz (2018)
Half-lives and angular distributions

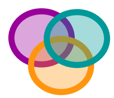
NEW theory inputs!



TWO-PROTON RADIOACTIVITY NEW EXPERIMENTAL INPUTS

Different predictions of angular distributions available

Doubly-magic nuclei 

Spherical nuclei
(benchmark for GCC model) 

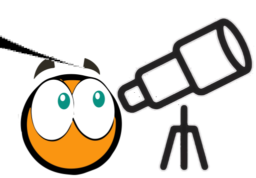
^{48}Ni

Part of the only isotropic chain with three double magic nuclei (^{48}Ni, ^{56}Ni, ^{78}Ni)

Accessible (GANIL)

Only case of double magic nucleus where the mirror nucleus (^{48}Ca) is stable.

Measurement of ^{48}Ni two proton angular distribution



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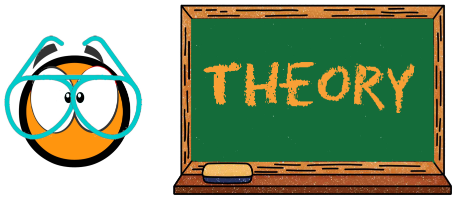

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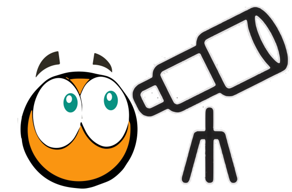
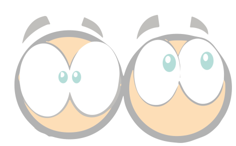


- OBSERVABLES ✓
- E791 EXPERIMENT

GANIL, France (May 2021)



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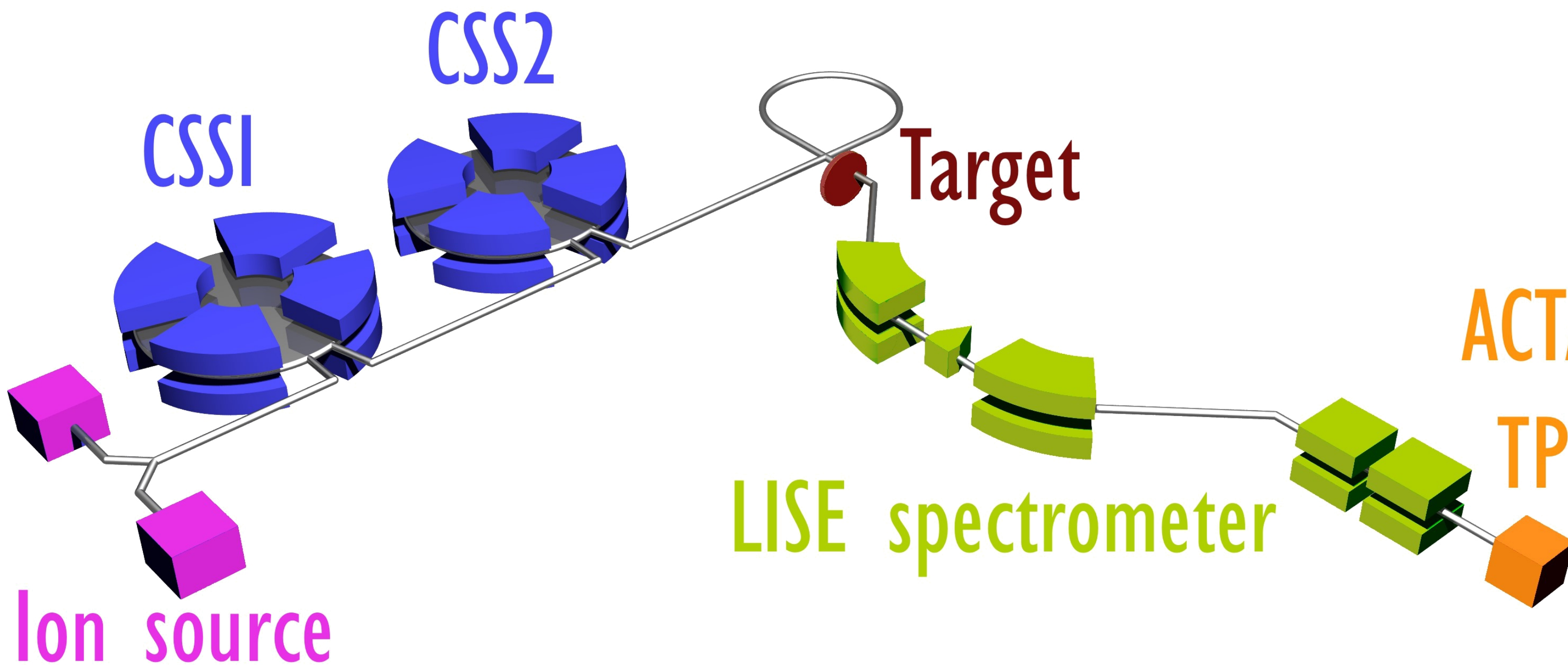
E791 EXPERIMENT PRODUCTION



- Produced by fragmentation by a 74.5A MeV ^{58}Ni beam (5 μA) on a 210 μm thick ^{nat}Ni target
- Exotic fragments selected using the LISE3 spectrometer
- Implantation in ACTAR Ar(90%)+C_4H_{10}(10%) 300-400 mbar

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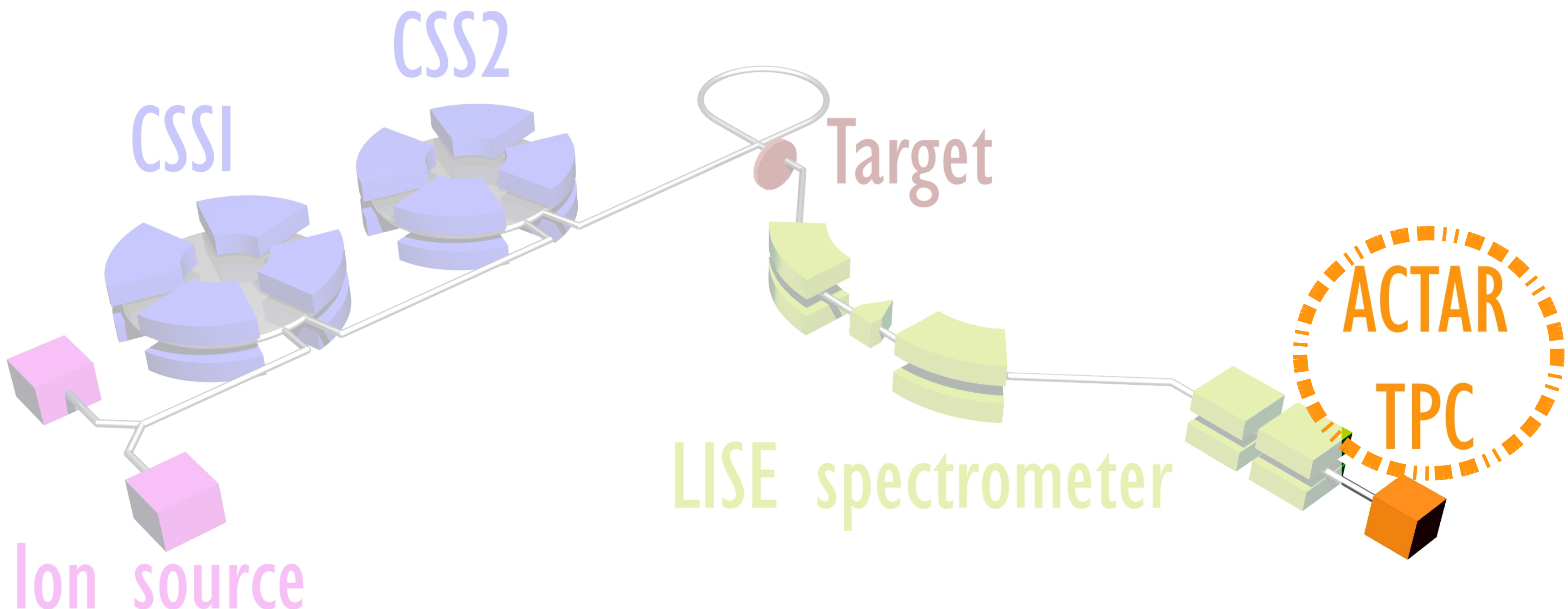

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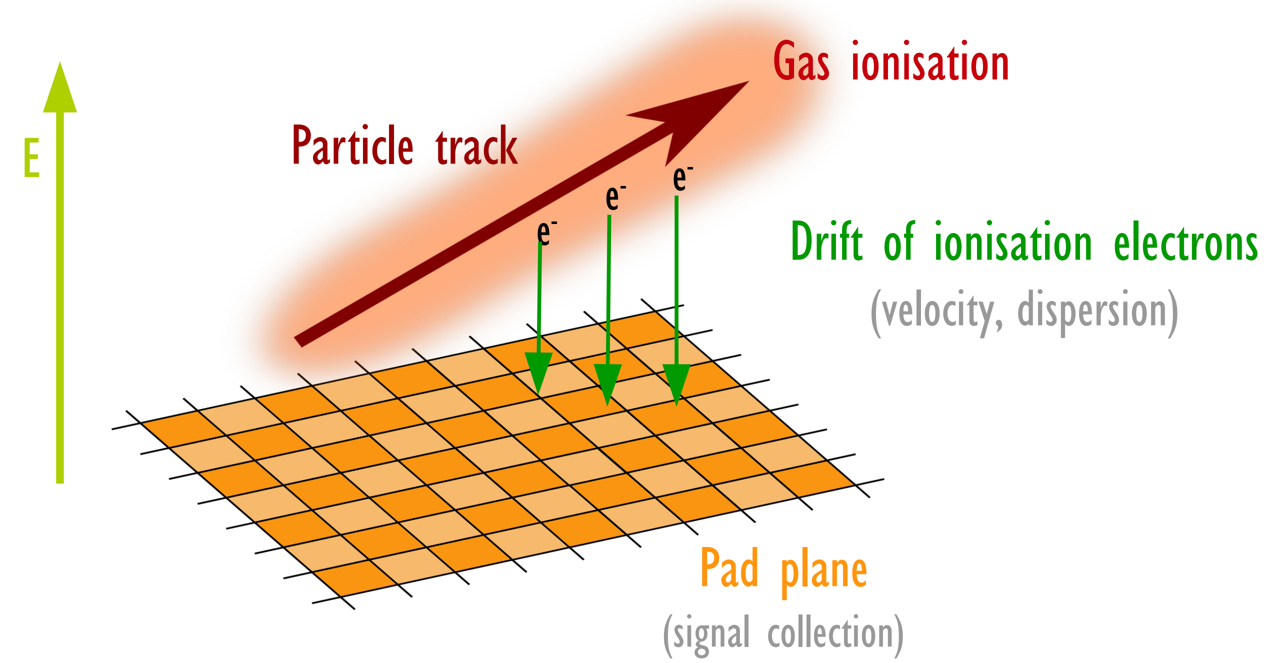
ACTAR TPC: ACtive TARget Time Projection Chamber

(TIME PROJECTION CHAMBER)



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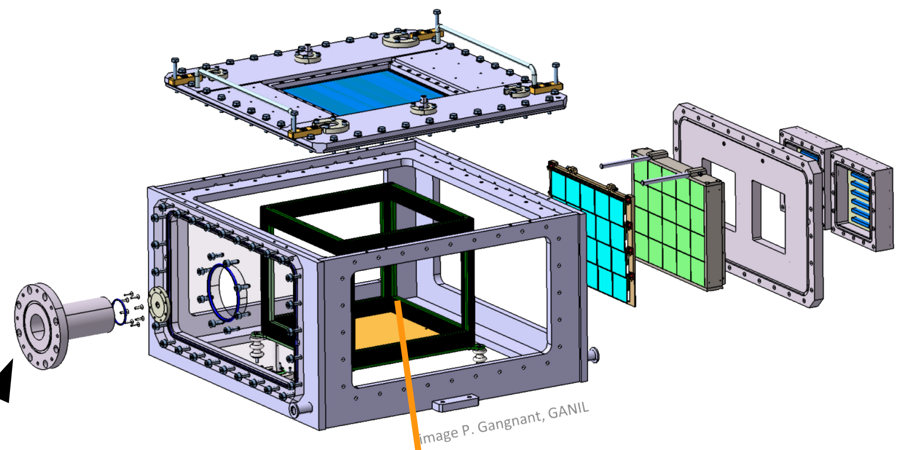


Entrance window

Drift region $25x25x25cm^3$

Homogeneous vertical drift electric field

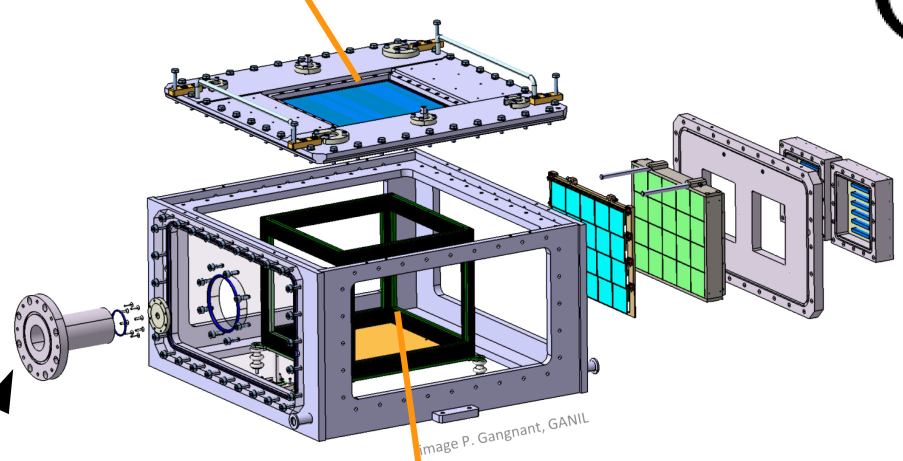
Double-wire field cage

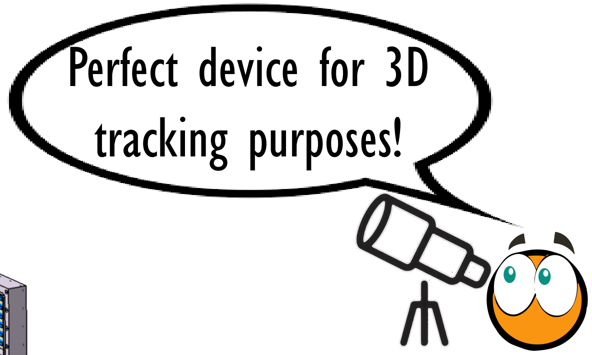
ACTAR TPC: ACtive TARget Time Projection Chamber

Segmented pad plane 128x128 pads x 256 time cells

Direct pad/electronics connection

4 Mvoxel volume sampling





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Drift region 25x25x25cm^3

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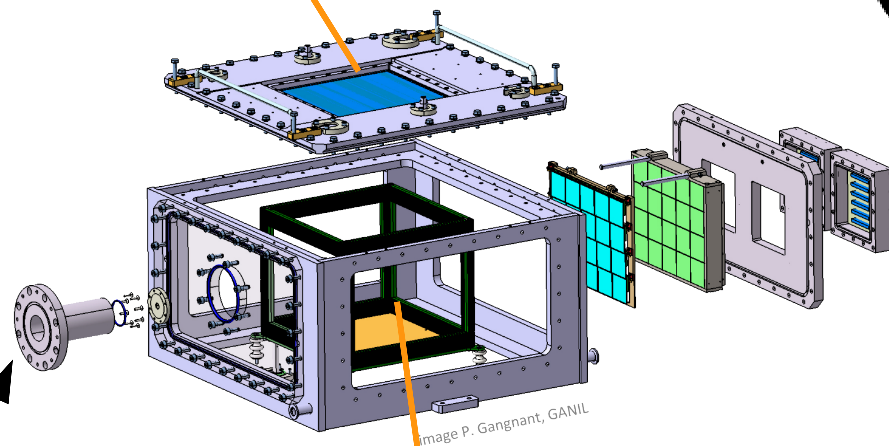
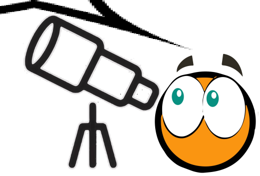


Perfect device for 3D tracking purposes!



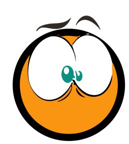
Entrance window

Drift region 25x25x25cm^3

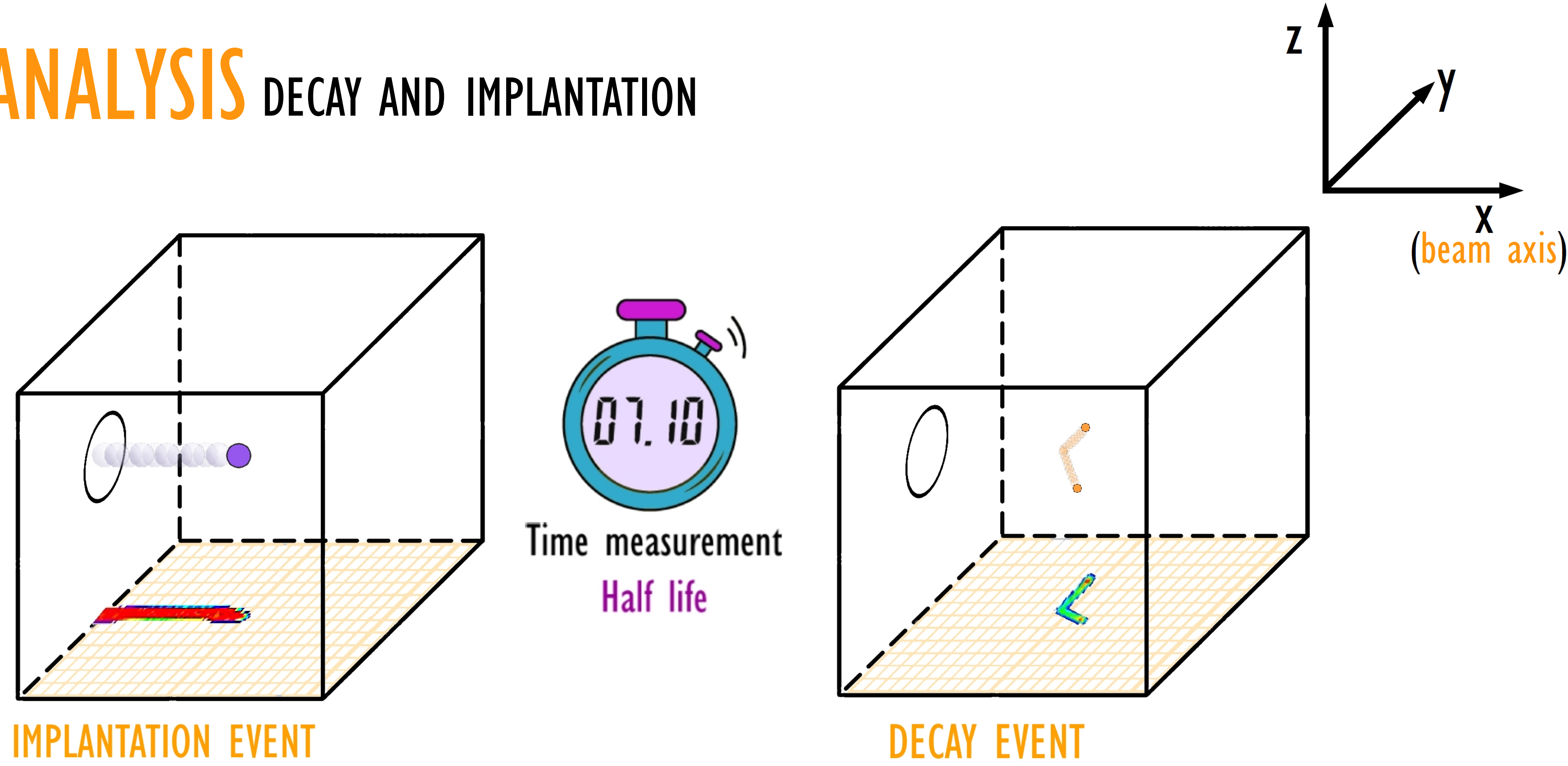
Homogeneous vertical drift electric field

Double-wire field cage

Complex and experiment-dependent ANALYSIS needed



ANALYSIS DECAY AND IMPLANTATION



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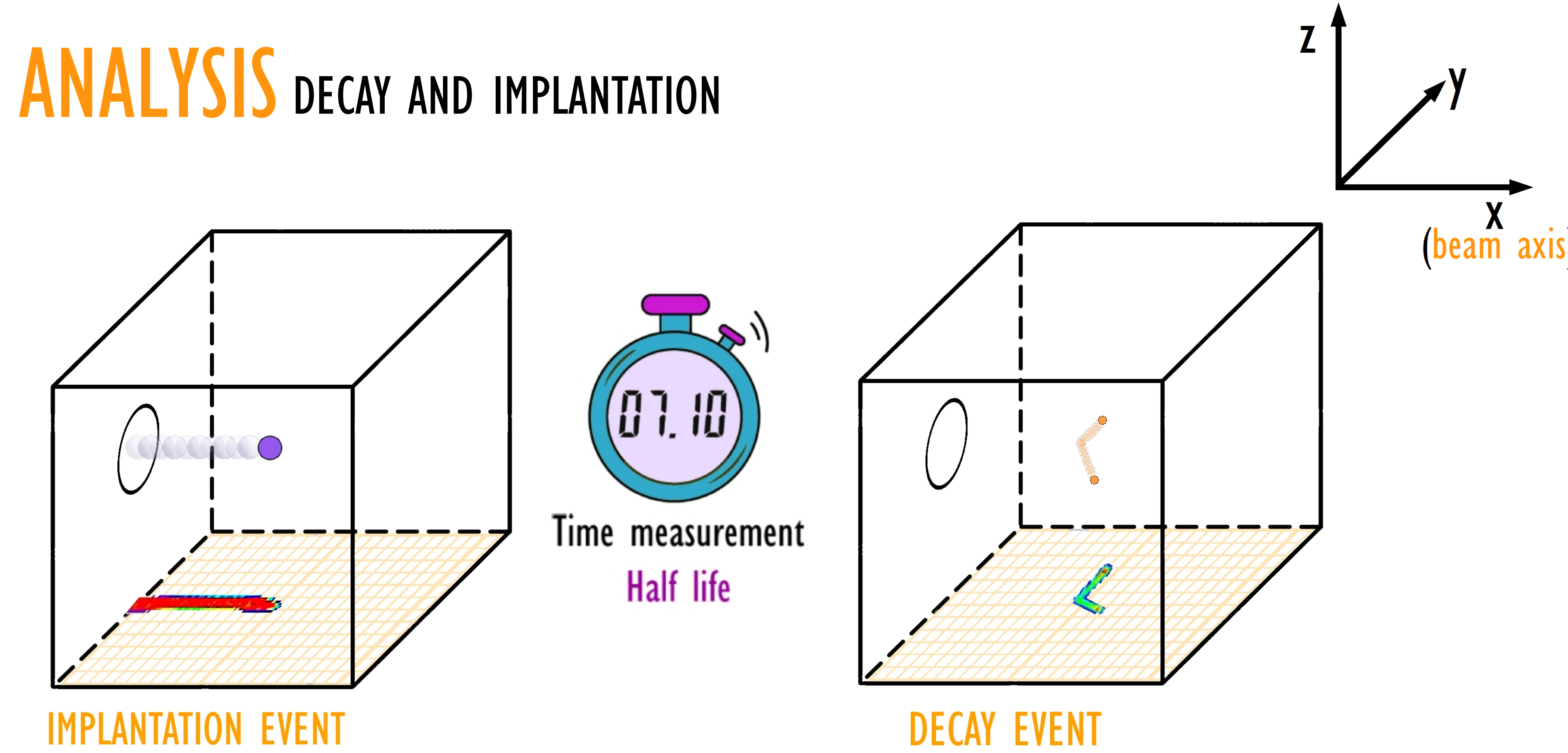
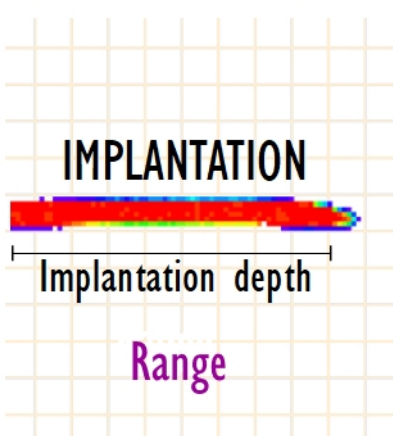
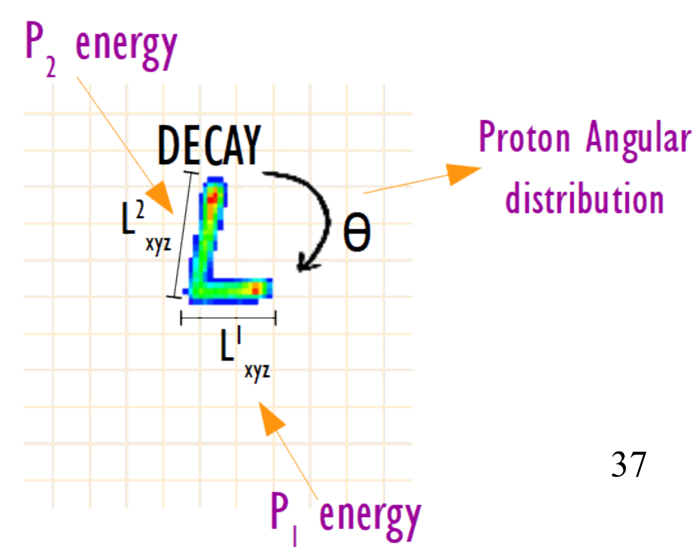






ANALYSIS THREE MAIN DIRECTIONS

- **IDENTIFICATION** (implantation events)

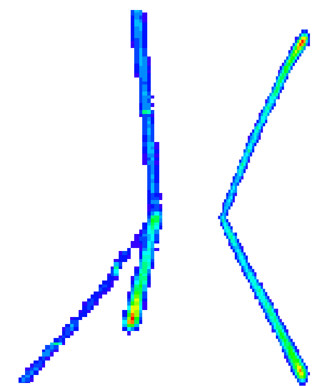
  Use of auxiliary detectors in the beamline

WHO?

- **TRACKING** (decay events)

  Determination of number of protons

  Fitting of tracks (length-energy)



HOW MANY?

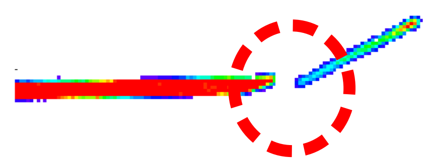
ENERGIES?

ANGLES?

- **IMPLANTATION-DECAY CORRELATION**

  Time window and spatial condition

  between implantation and decay events



EMITTED

FROM WHOM?

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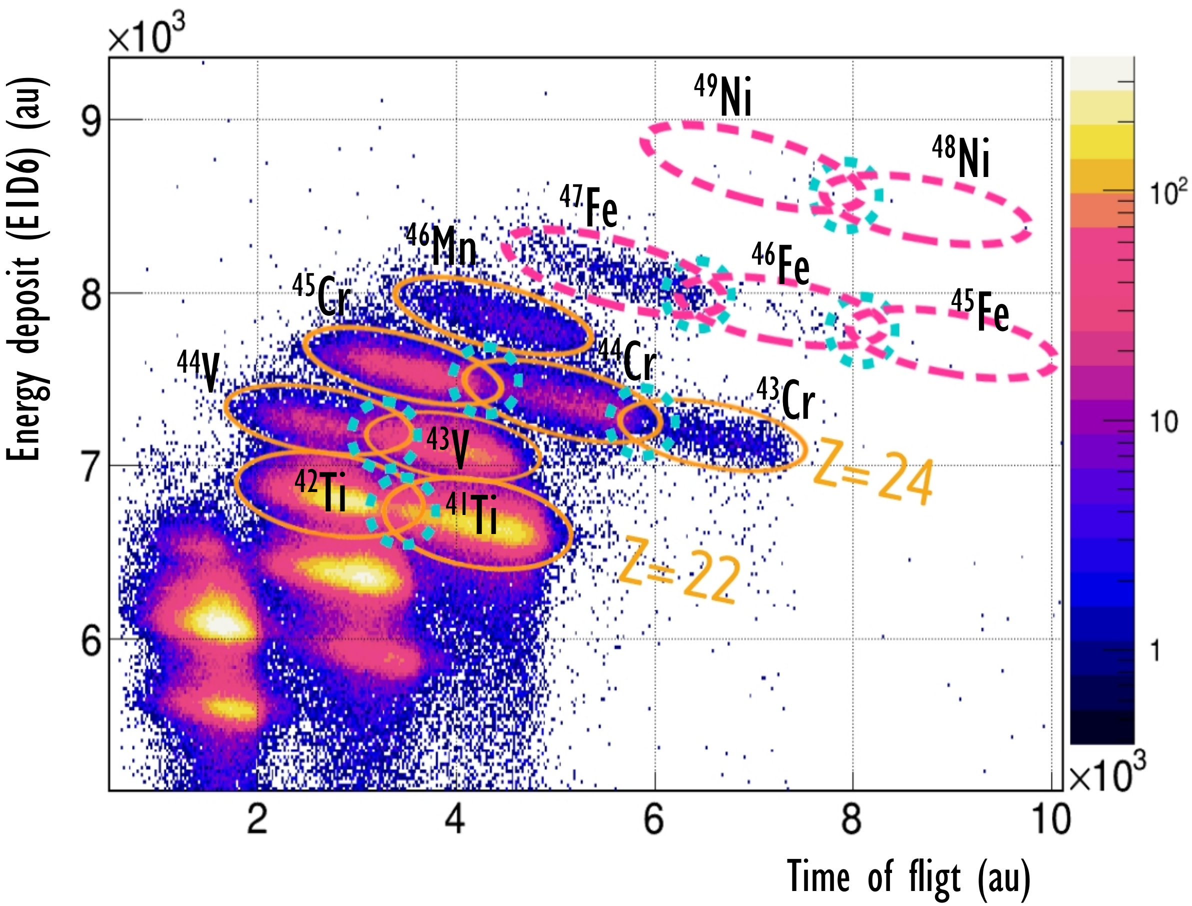

- Extrapolation of contours for the most exotic nuclei

- Multi-parameter analysis (4-D identification matrix)

ANALYSIS THREE MAIN DIRECTIONS

IDENTIFICATION (implantation events)

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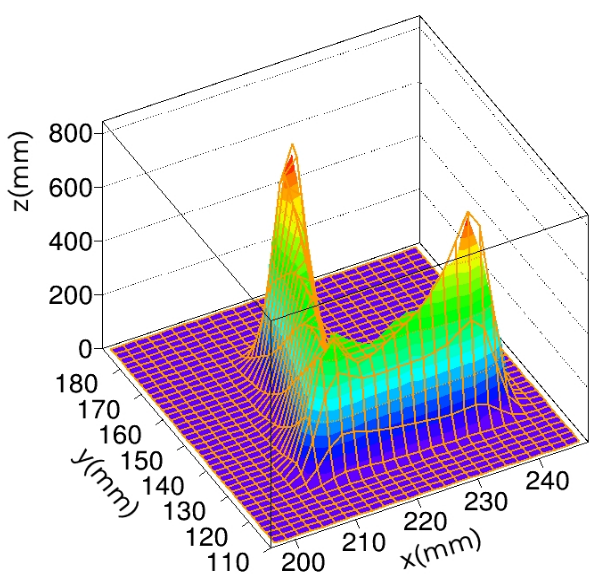

- Signal from more than 16000 independent channels
- Pre-fit (number of tracks, initial parameters)
- Bragg Peak fit (10-14 parameters)
- Lenght-Energy conversion

ANALYSIS THREE MAIN DIRECTIONS

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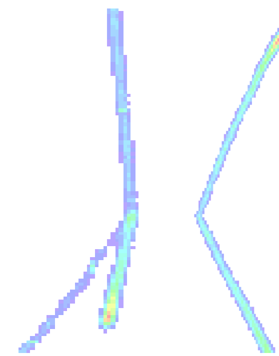

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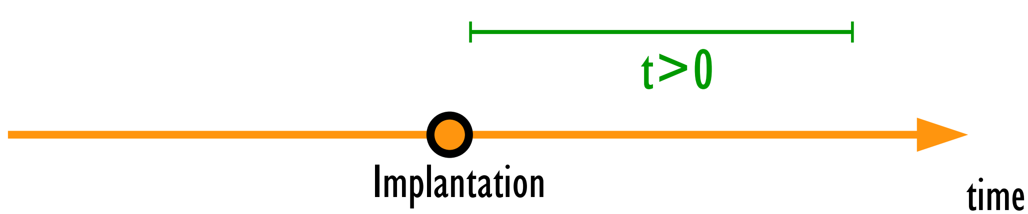
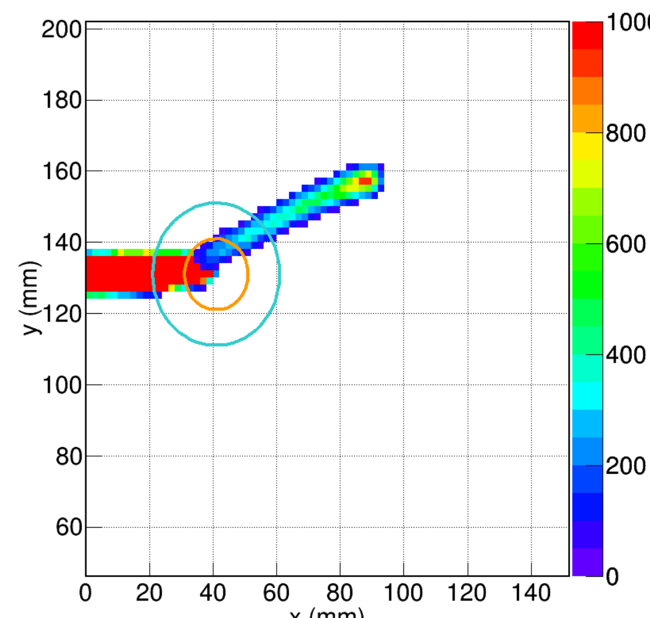
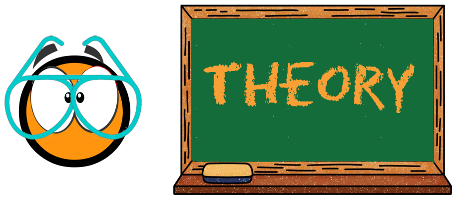


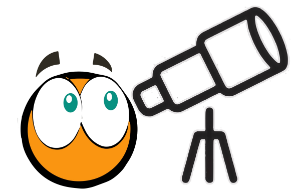


INDEX

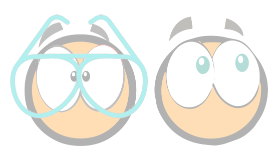


- INTRODUCTION ✓
- ^{48}Ni REGION ✓
- 2-PROTON RADIOACTIVITY ✓
- THEORETICAL PREDICTIONS ✓

Discrepancies

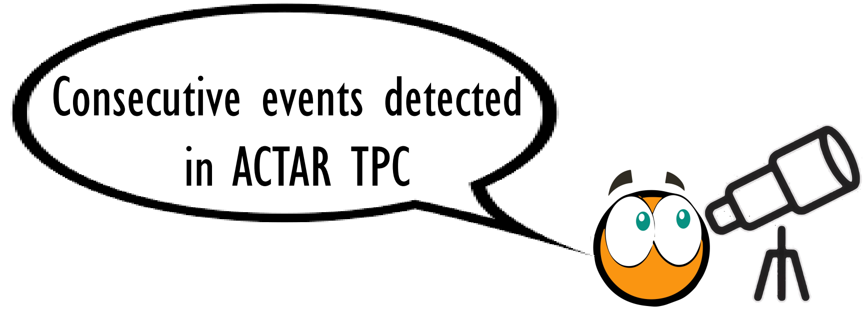


- OBSERVABLES ✓
- E791 EXPERIMENT ✓
  - → ACTAR TPC ✓
  - → ANALYSIS ✓
  - → RESULTS

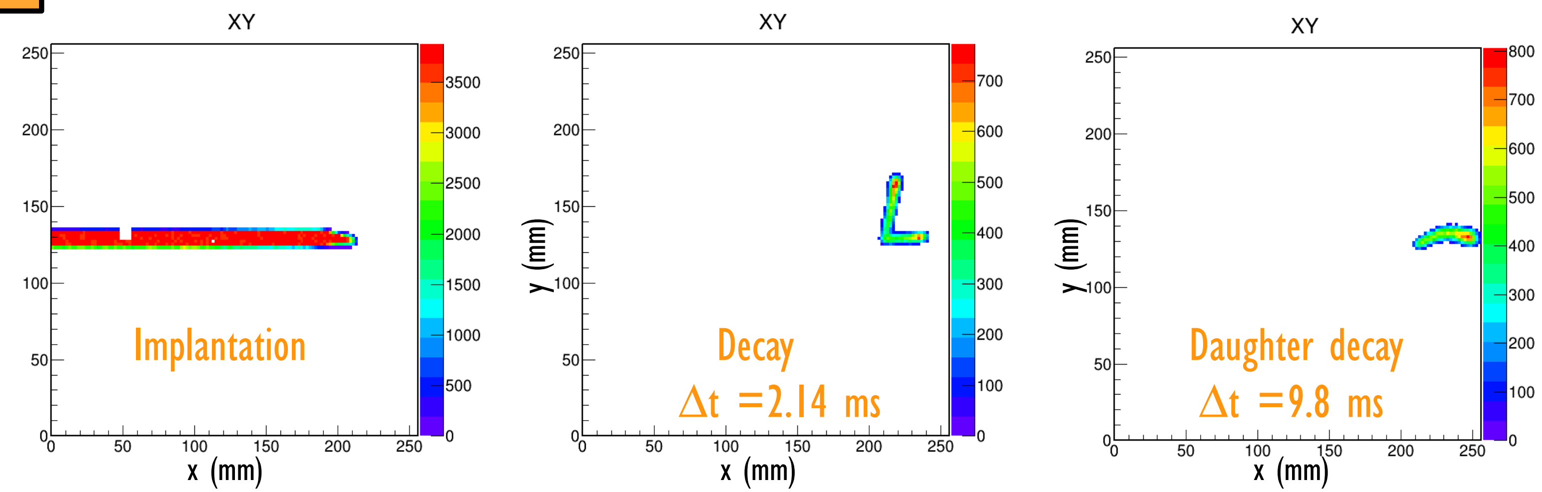


- COMPARISON THEORY-EXPERIMENT
- CONCLUSIONS AND PERSPECTIVES

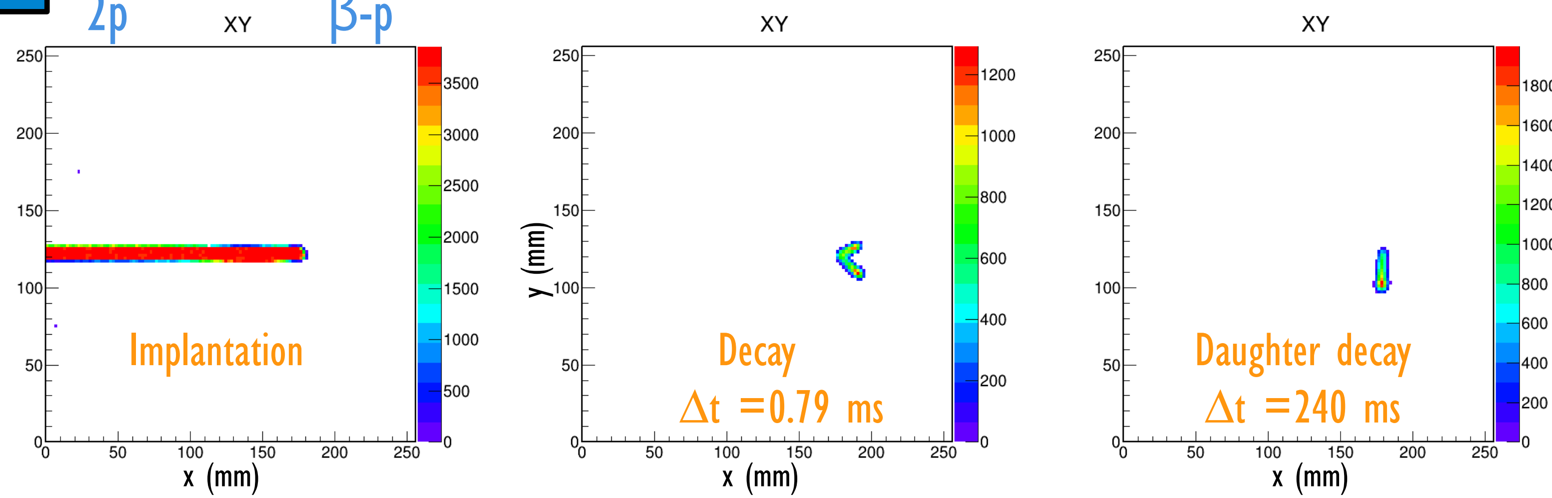
RESULTS



^{48}Ni $\xrightarrow{2p}$ ^{46}Fe $\xrightarrow{\beta\text{-}p}$ ^{45}Cr



^{45}Fe $\xrightarrow{2p}$ ^{43}Cr $\xrightarrow{\beta\text{-}p}$ ^{42}Ti



RESULTS

Two-proton emission

- M. Pomorski et al., (4 events)
- Current work (3 events)

^{48}Ni (6)

- 2 p (3)
- β-p, BR=0.4
  - β-p (1)
  - β-2p
  - β-3p (1)

Decay	BR(%) Current work	BR(%) M. Pomorski et al.
2 p (3)	60^{+25}_{-30}	70(20)
β-p (1)	20^{+32}_{-17}	30(20)
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$T_{1/2}$(ms)

$1.3^{+2.0}_{-1.0}$ $2.1^{+1.4}_{-0.6}$

Q_{pp}(keV)

1249(23) 1290(40)

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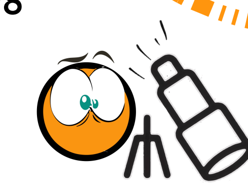
^{45}Fe (11)

Decay	BR(%) Current work	BR(%) M. Pomorski et al.
2 p (6)	75^{+16}_{-24}	70(4)
β-p (2)	25^{+24}_{-16}	19.9(4)

$T_{1/2}$(ms): $0.9^{+2.0}_{-1.0}$ 2.56(2)

Q_{pp}(keV): 1077(18) 1150(15)

Still investigating why



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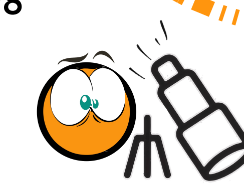


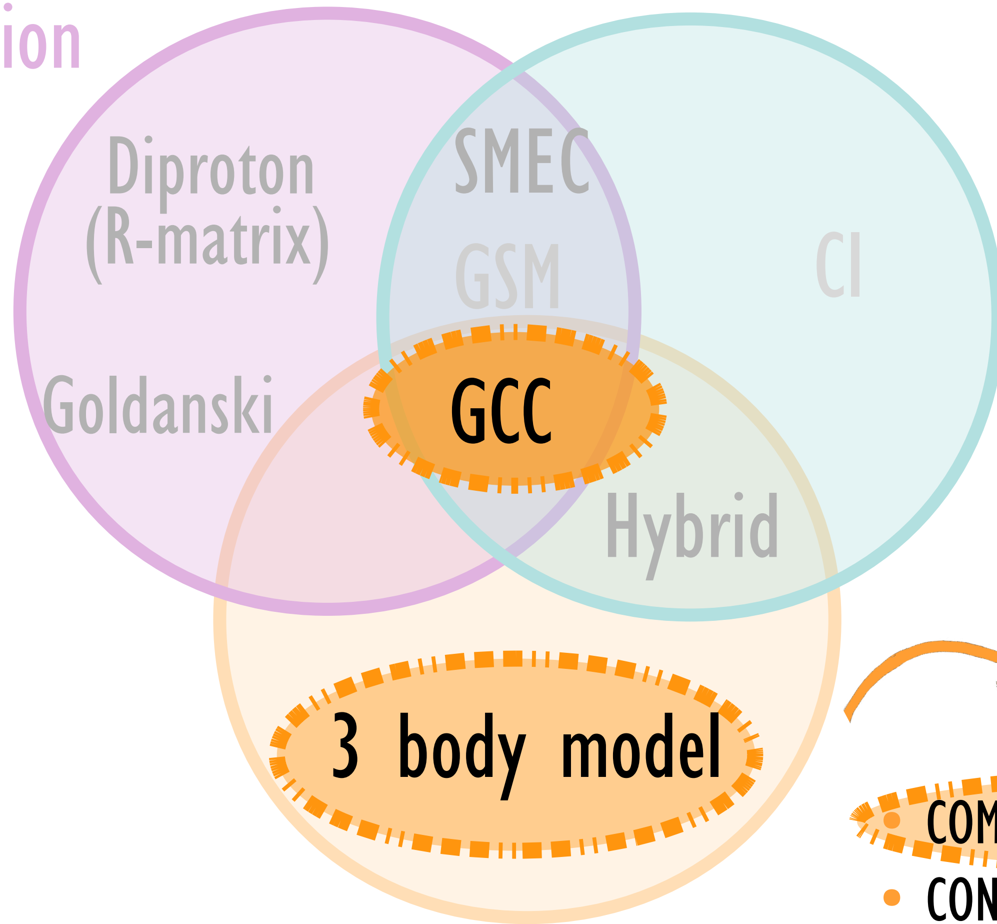
TWO-PROTON RADIOACTIVITY

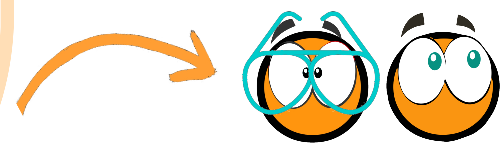
Asymptotic region

Open quantum system
Consistent description of the internal and external wave functions

Inner structure

(Near-threshold case)
Experimental input needed to constraint structure





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Decay dynamics

3-body interaction to take into account

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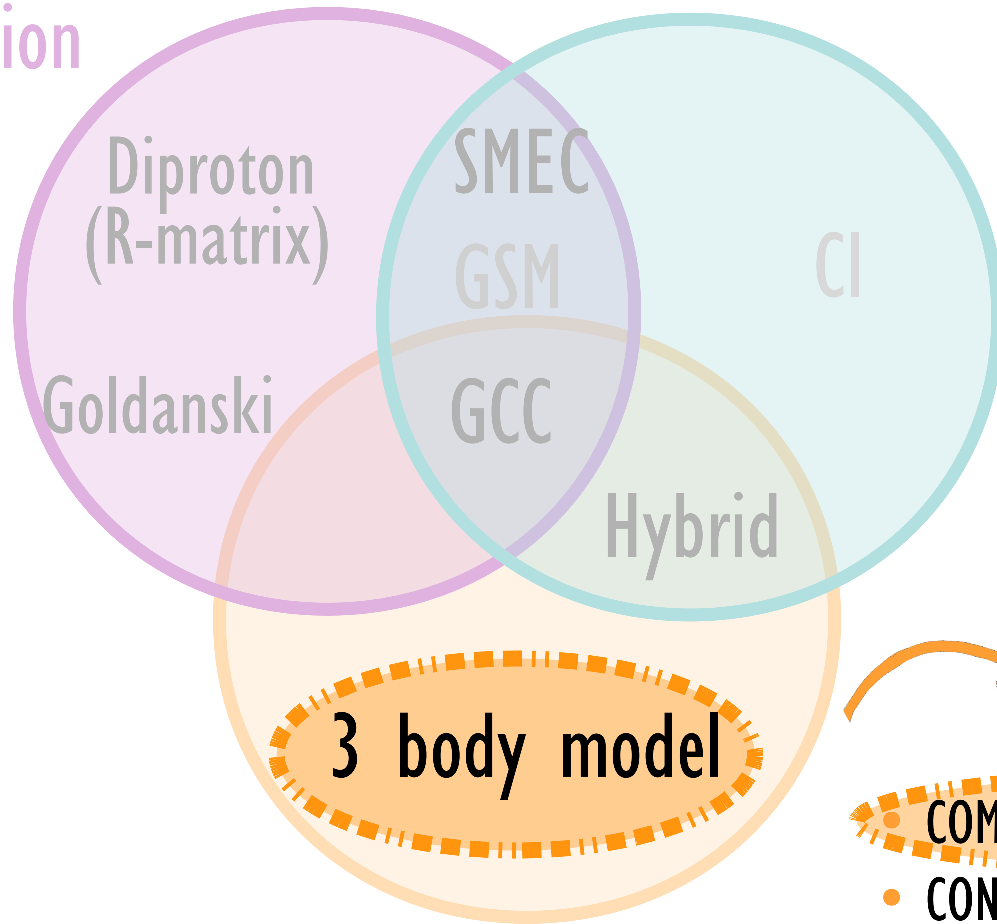

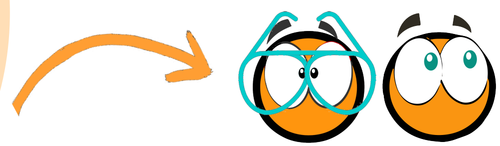

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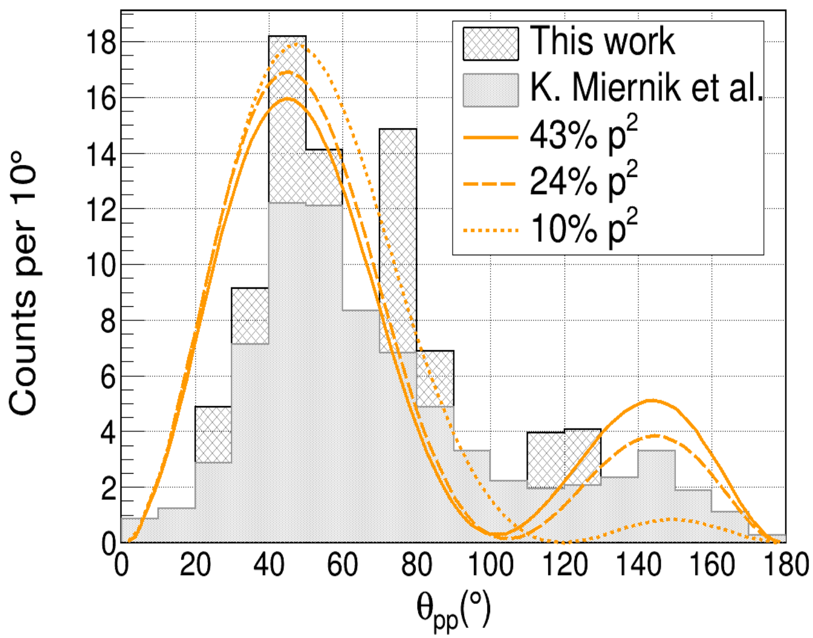
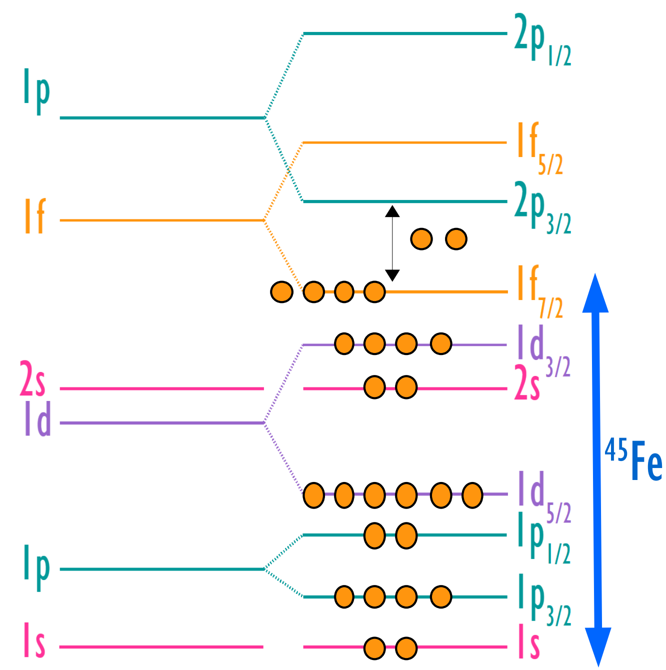
COMPARISON WITH THEORETICAL MODELS

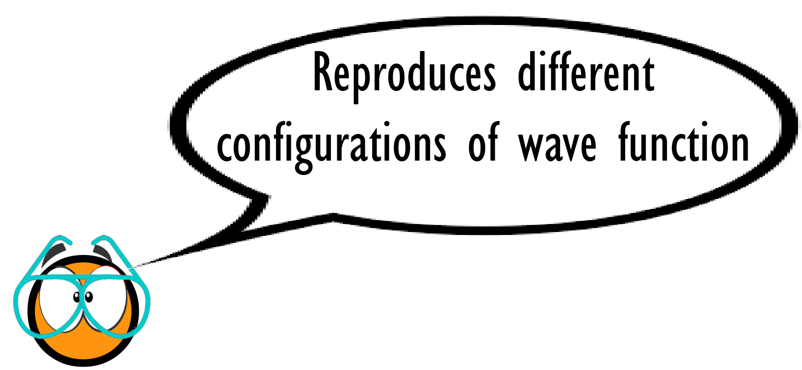
^{45}Fe

- 3-BODY MODEL — L. V. Grigorenko et al.

- ANGULAR DISTRIBUTION







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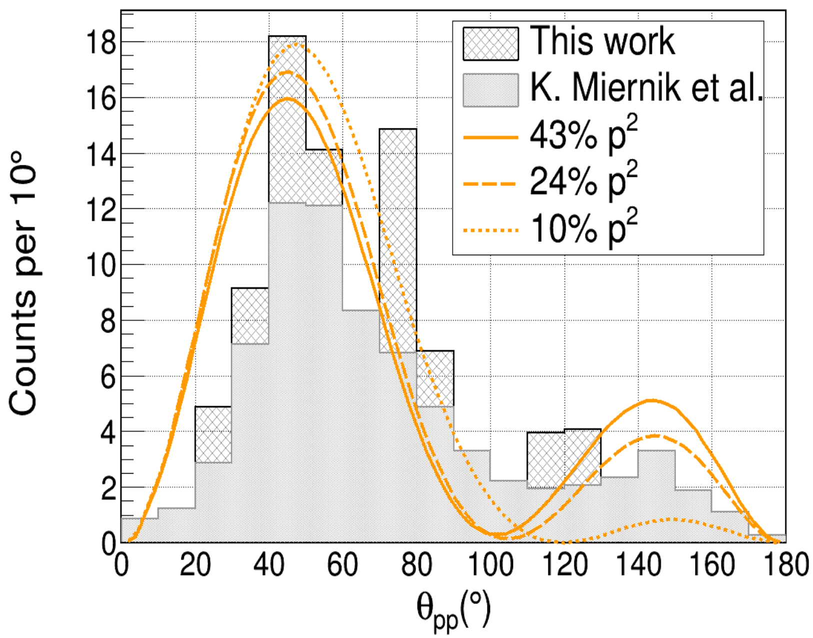

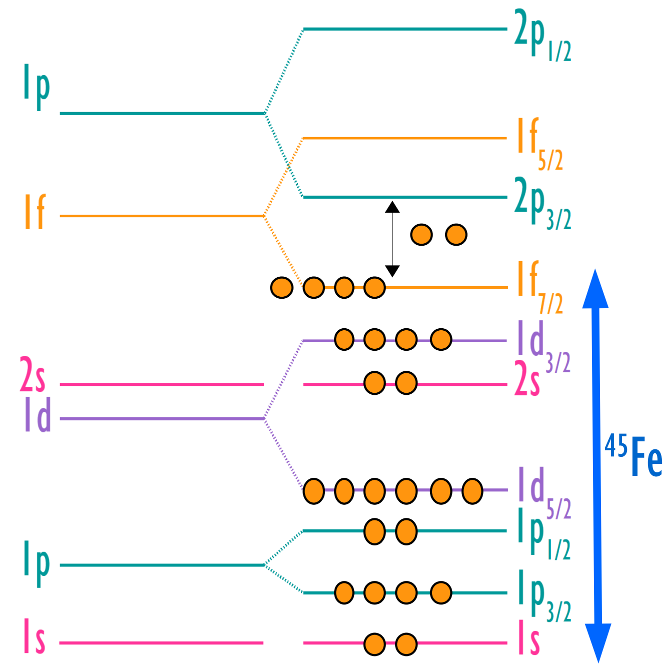

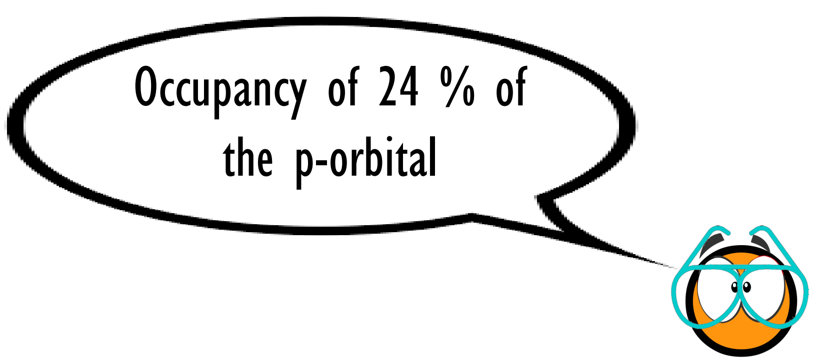

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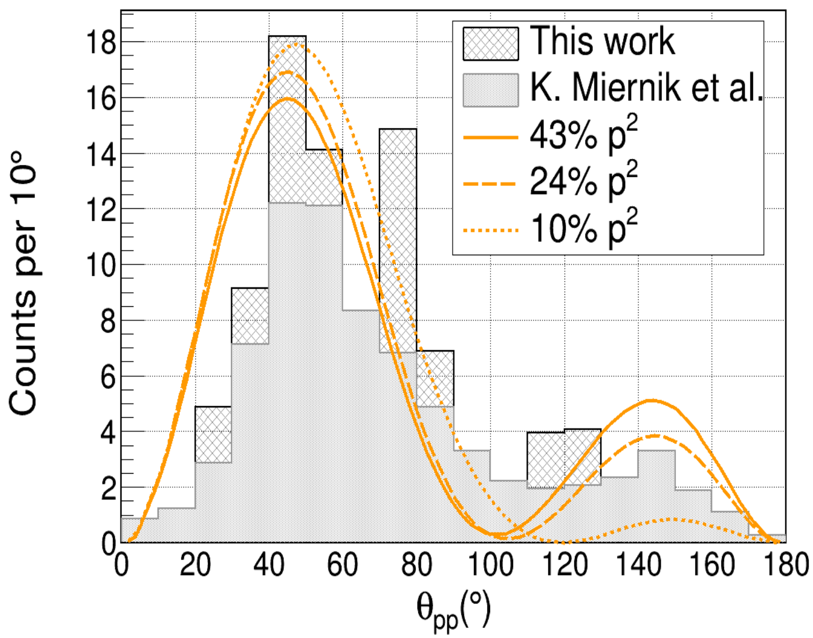
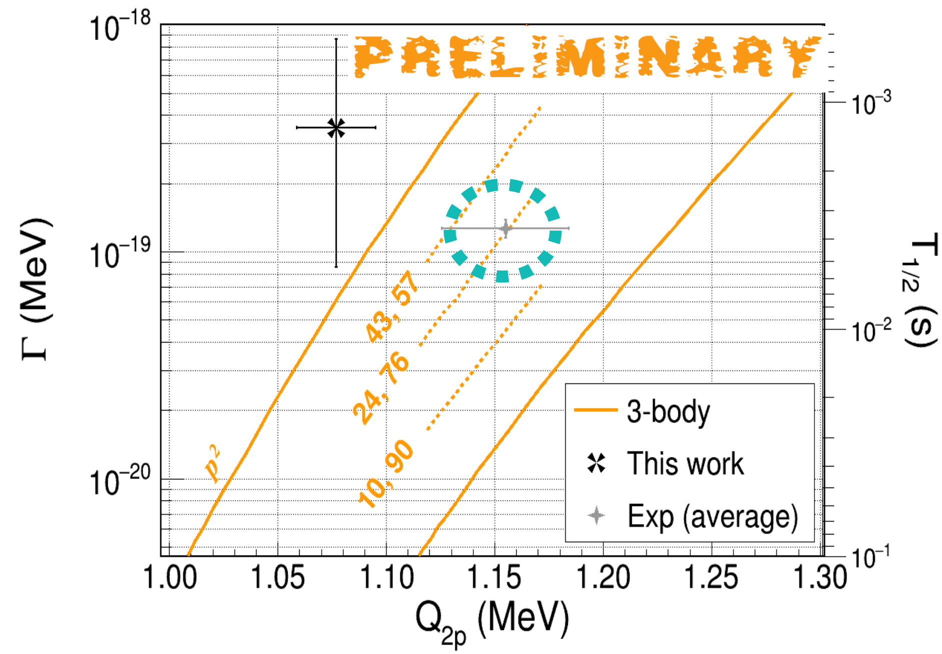
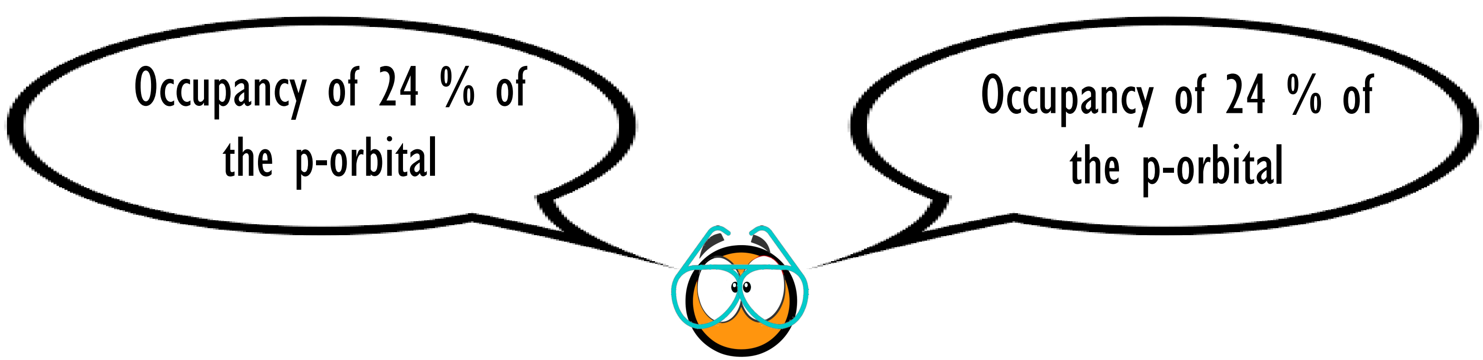


- HALF-LIFE





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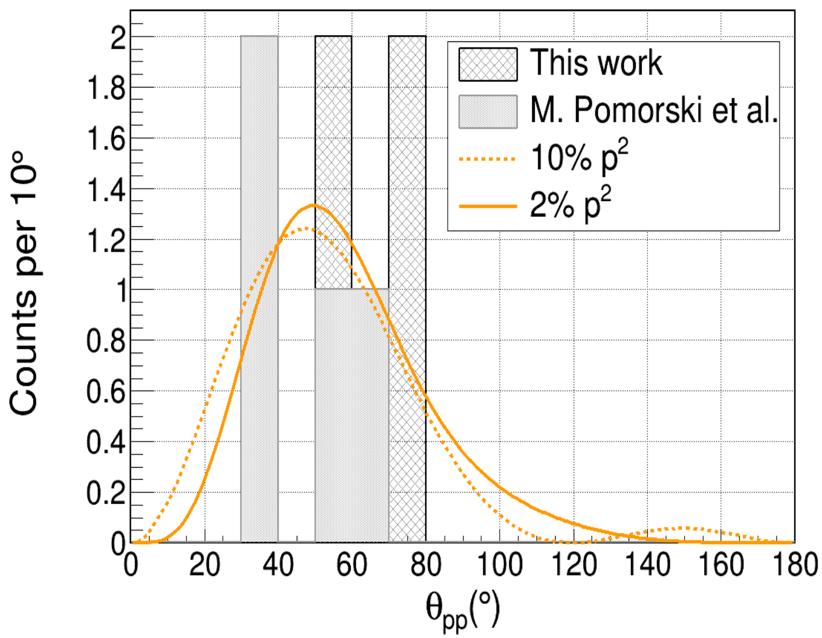

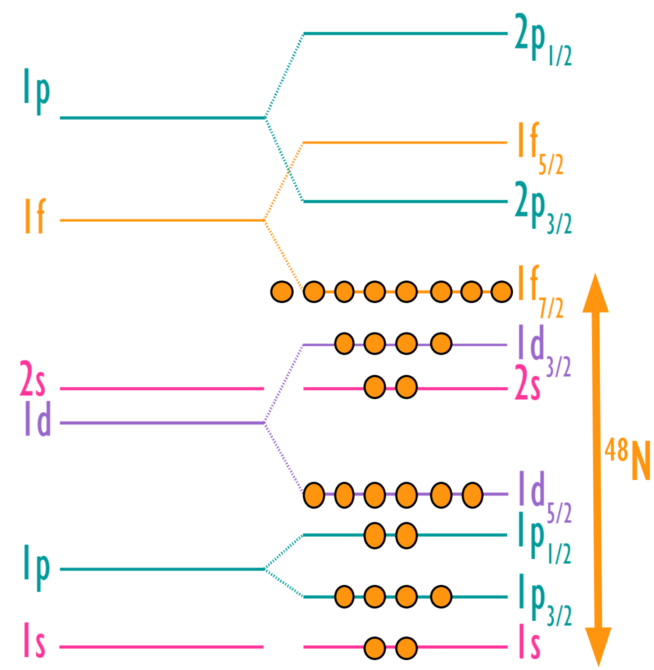

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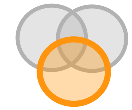
- 3-BODY MODEL  L. V. Grigorenko et al.

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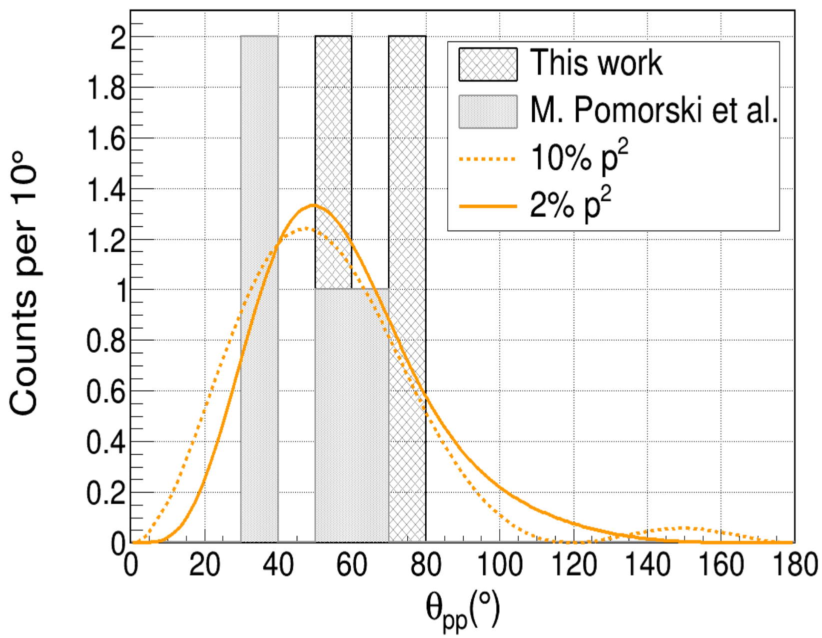

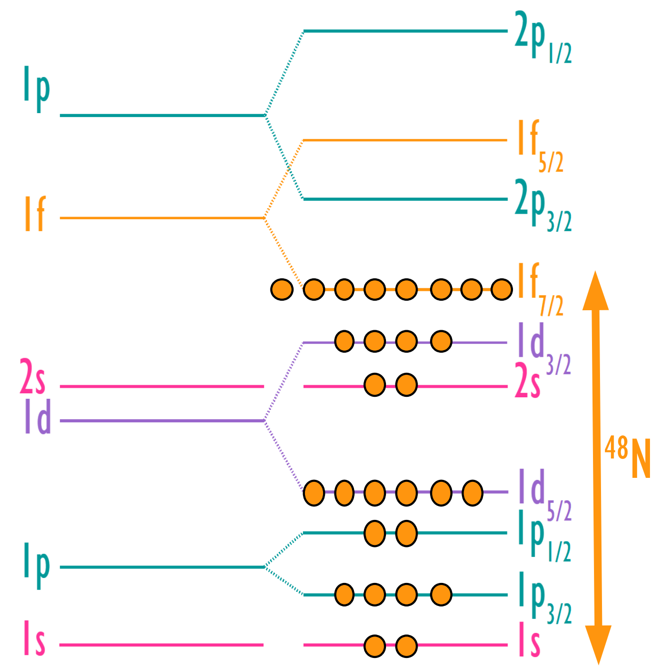

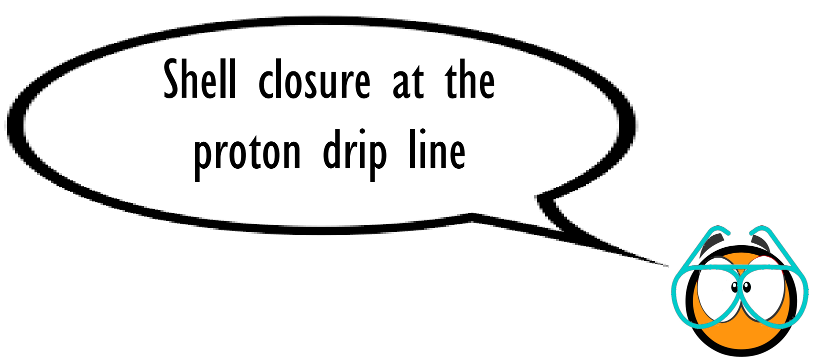

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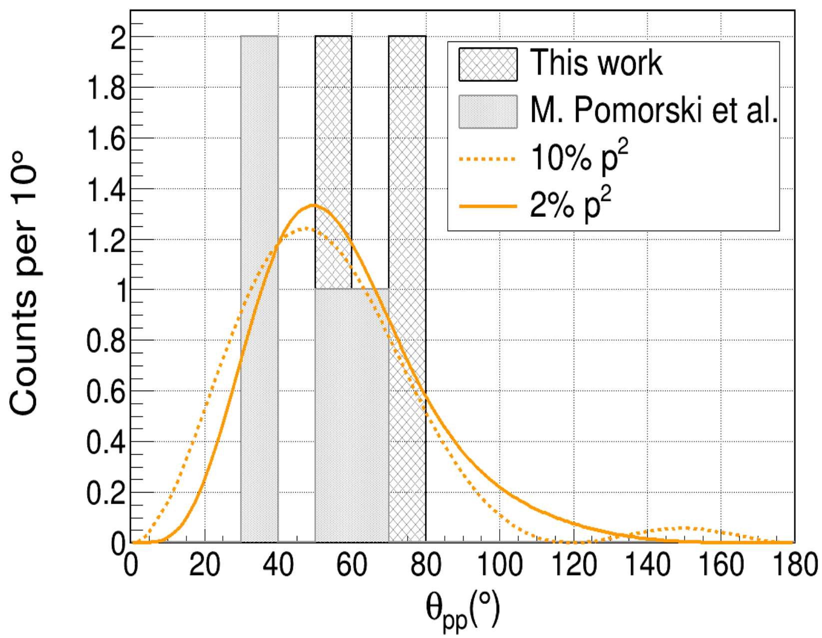

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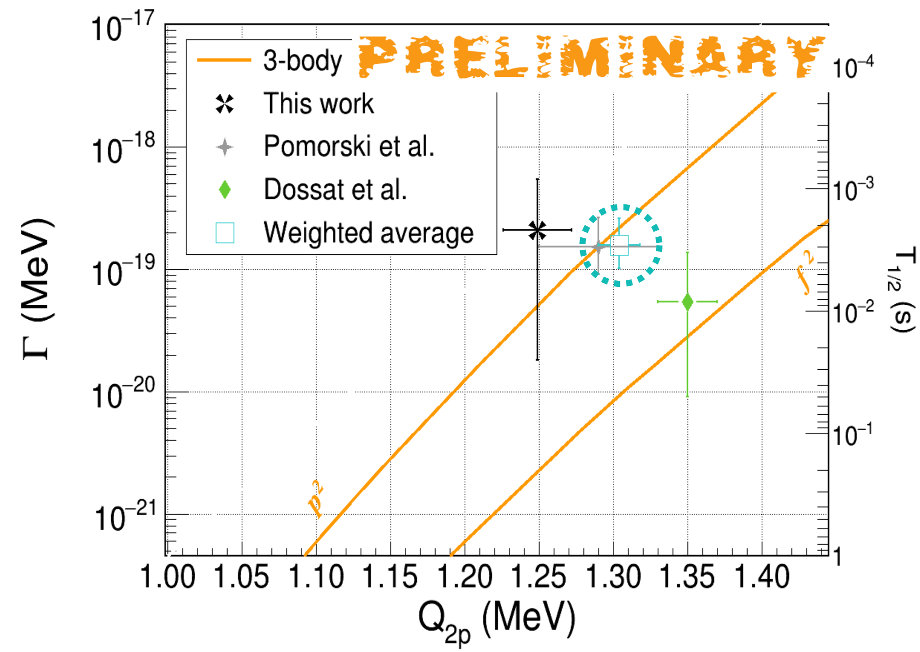
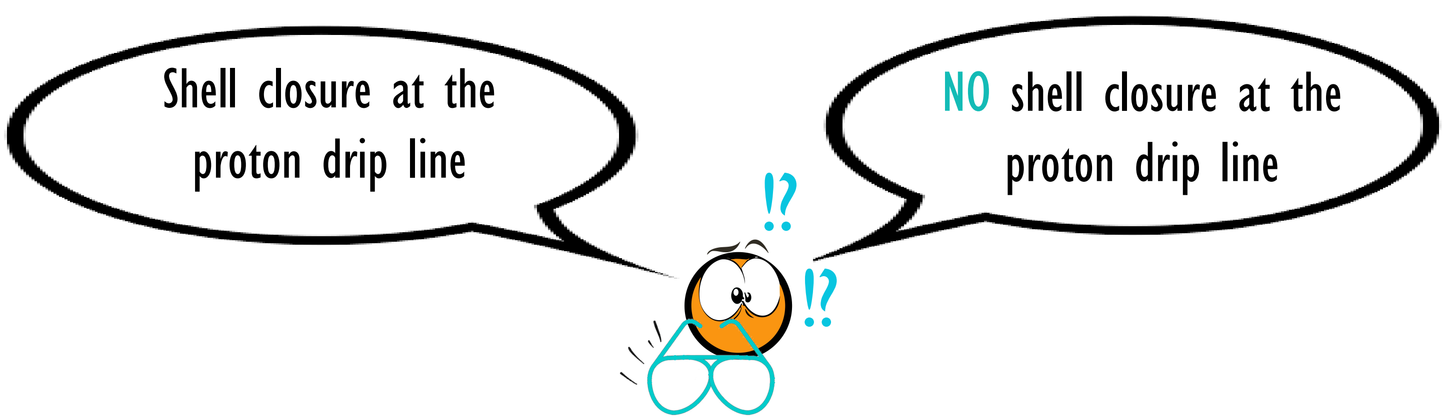
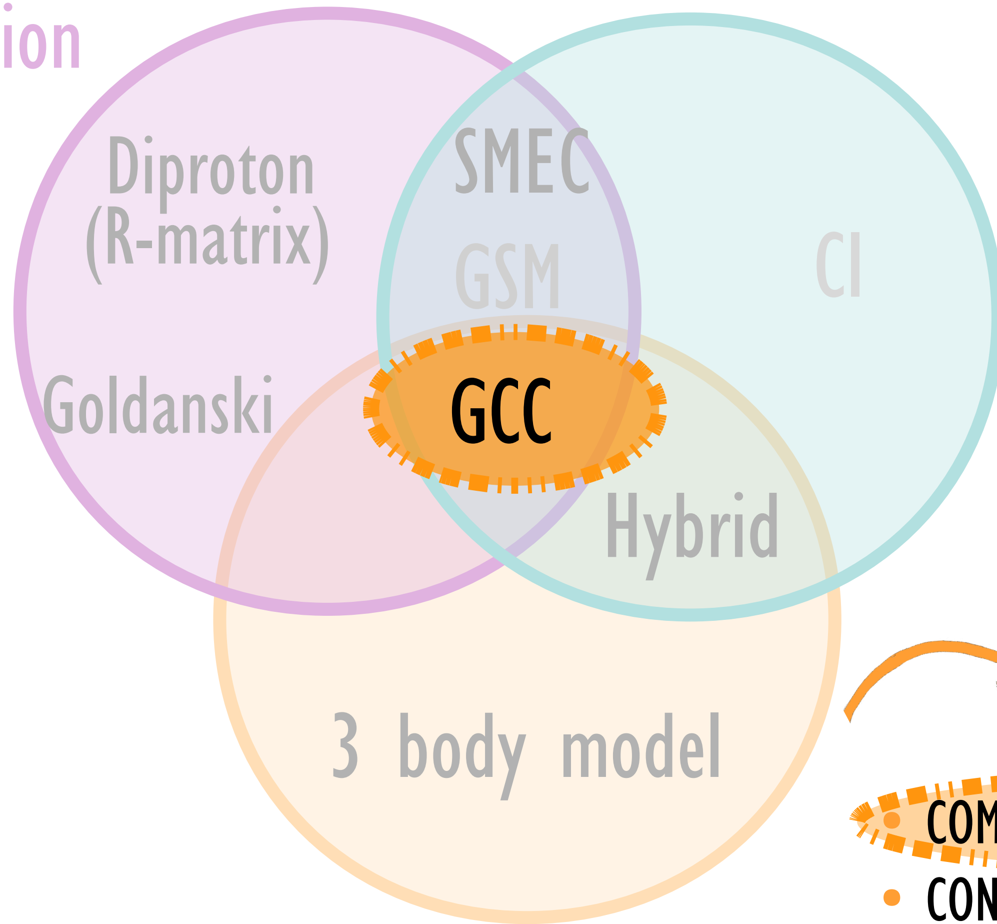




TWO-PROTON RADIOACTIVITY

- **Asymptotic region**

Open quantum system
Consistent description of the internal and external wave functions



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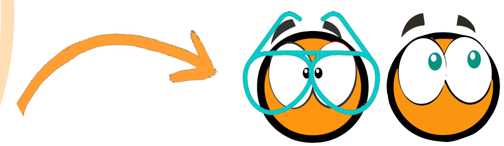

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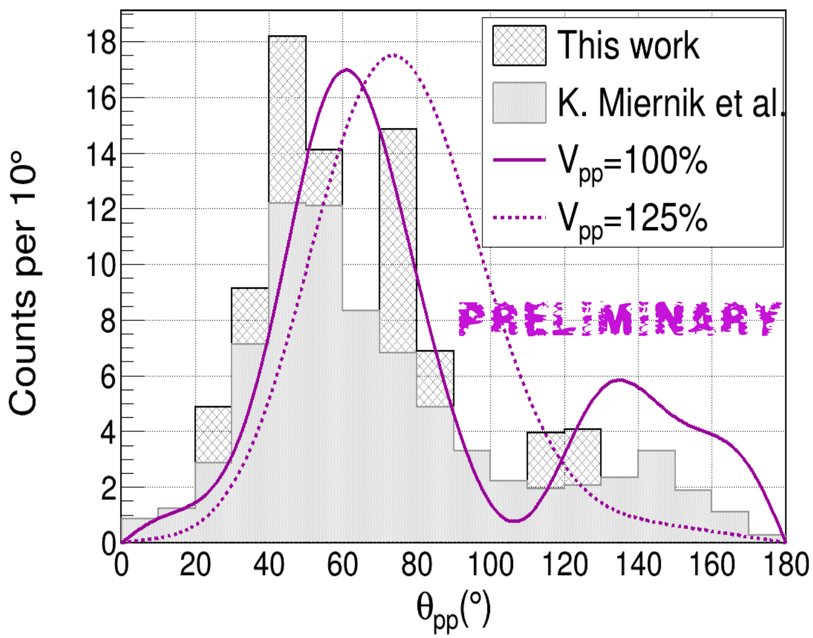

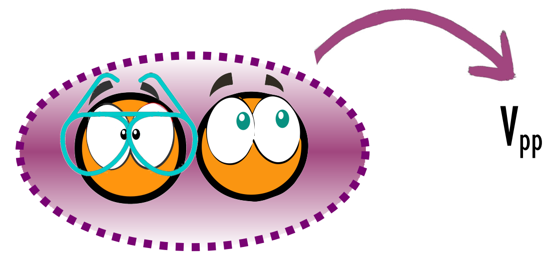

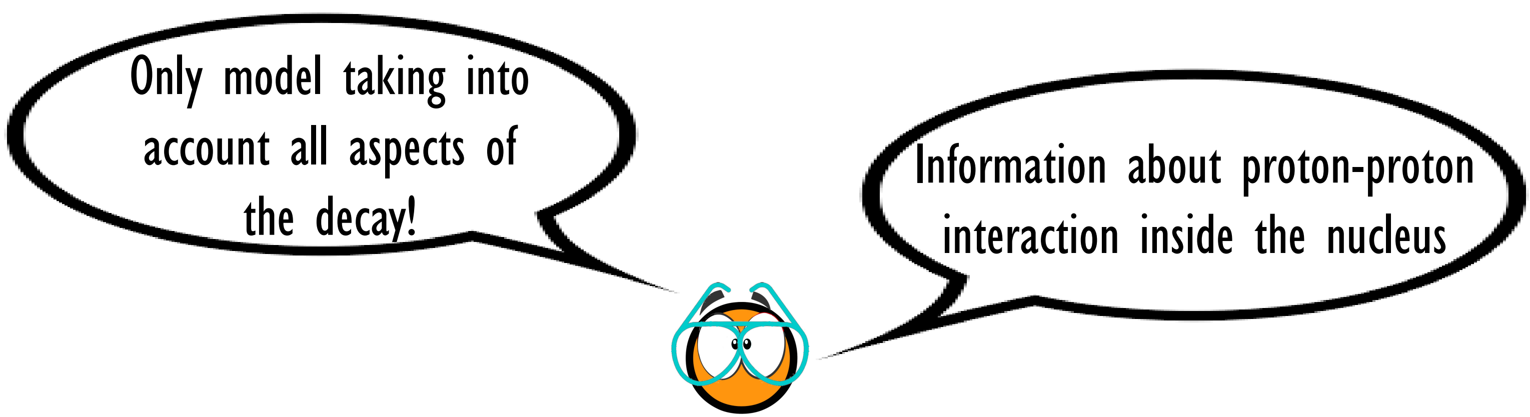

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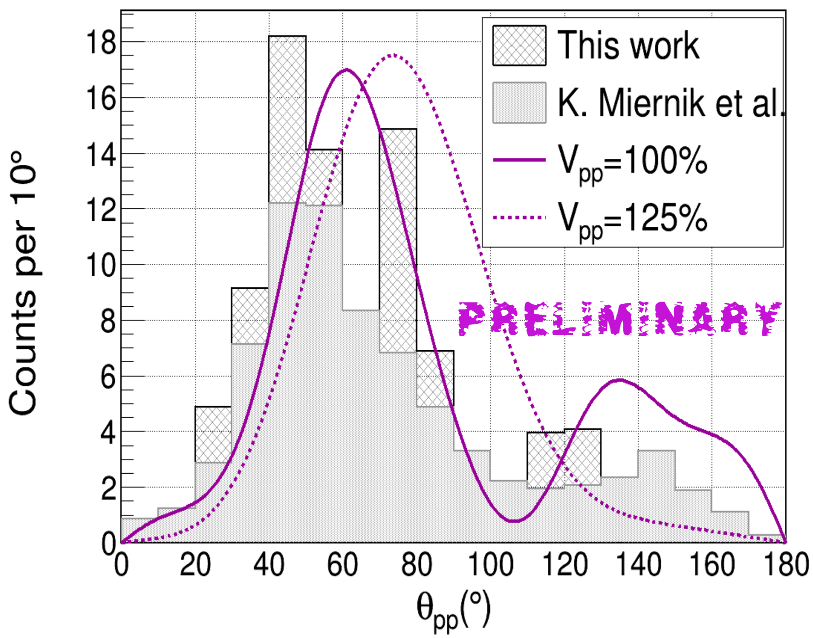
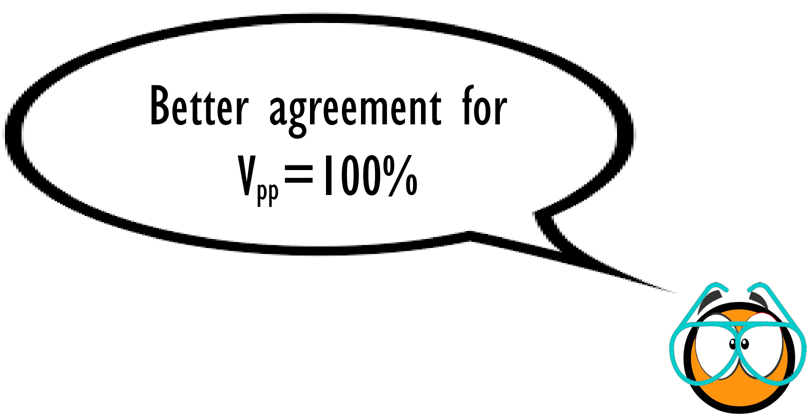


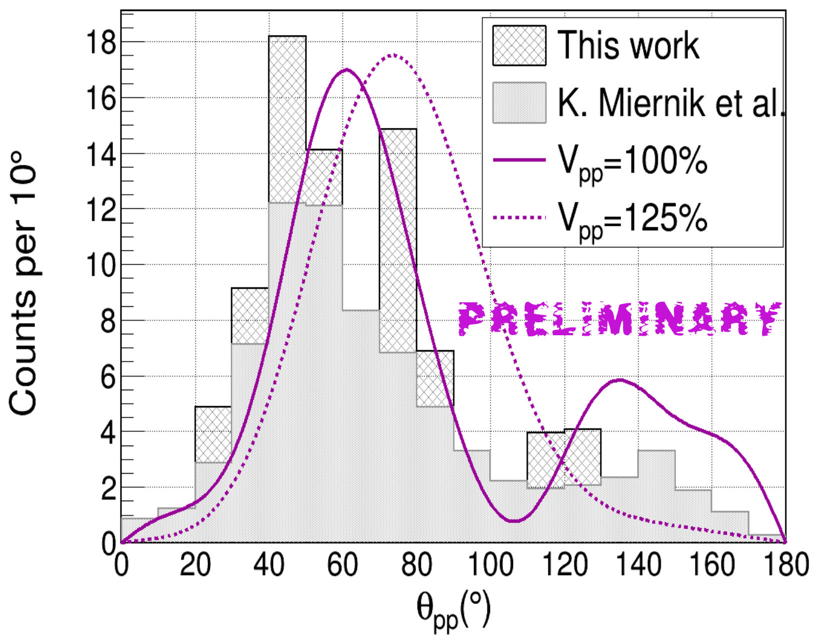


COMPARISON WITH THEORETICAL MODELS

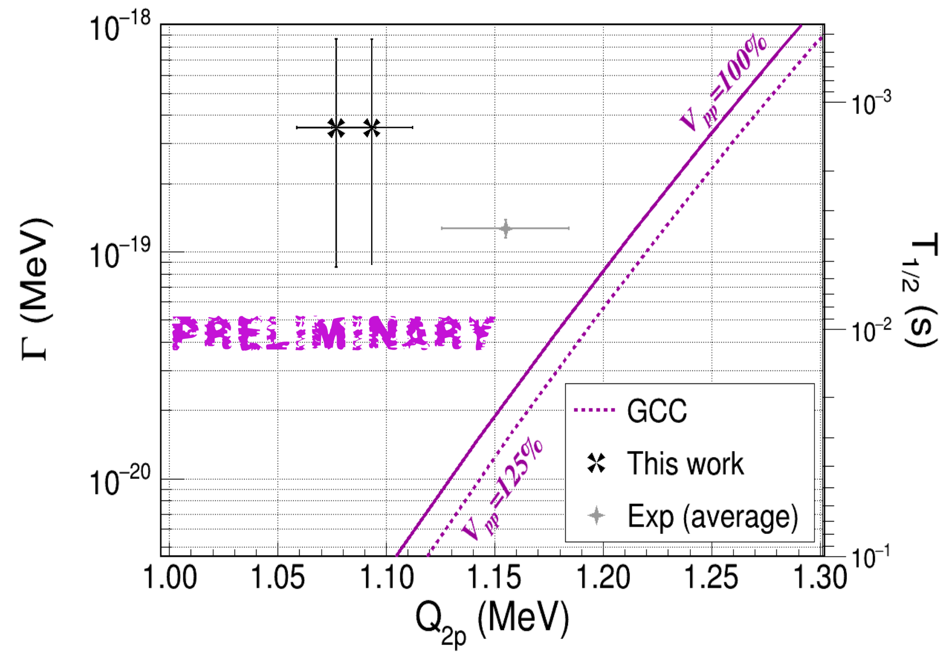
^{45}Fe

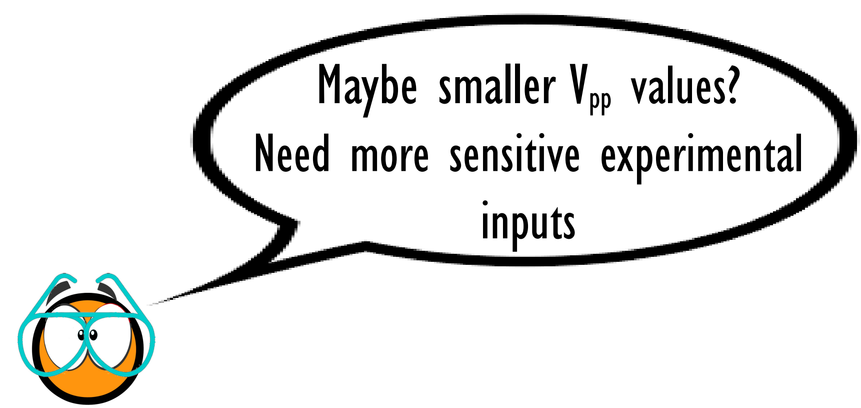
- GCC — Novel calculations from S.Wang

- ANGULAR DISTRIBUTION



- HALF-LIFE



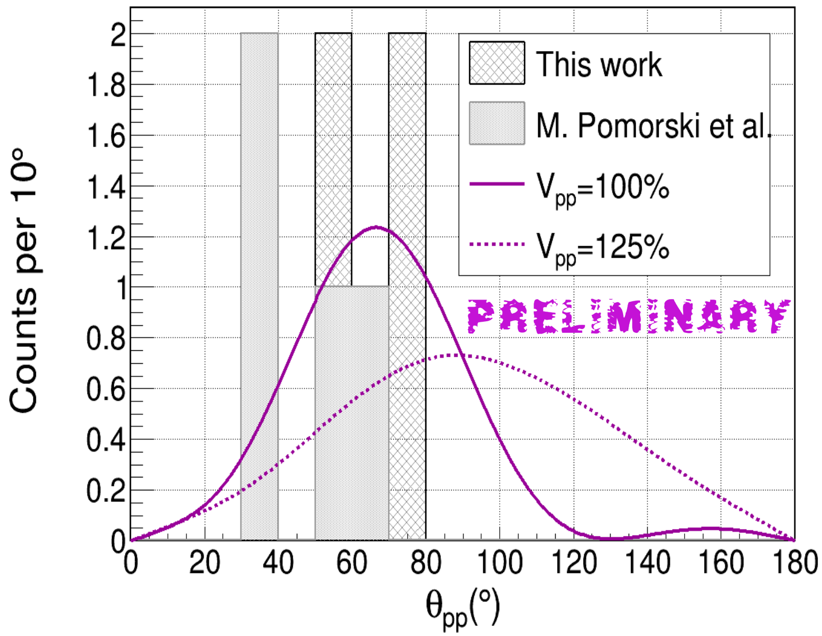


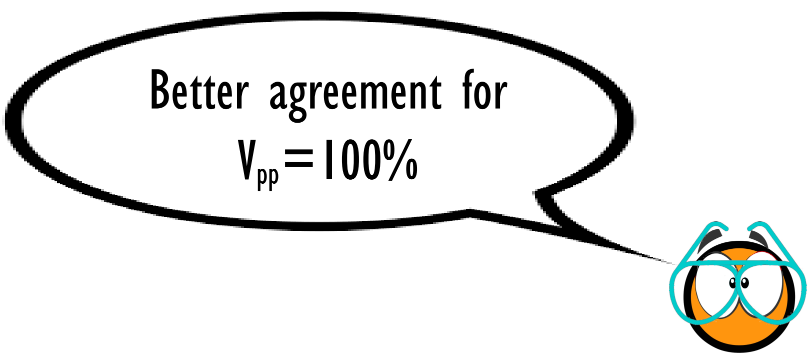
COMPARISON WITH THEORETICAL MODELS

^{48}Ni

- GCC Novel calculations from S.Wang

- ANGULAR DISTRIBUTION





COMPARISON WITH THEORETICAL MODELS

^{48}Ni

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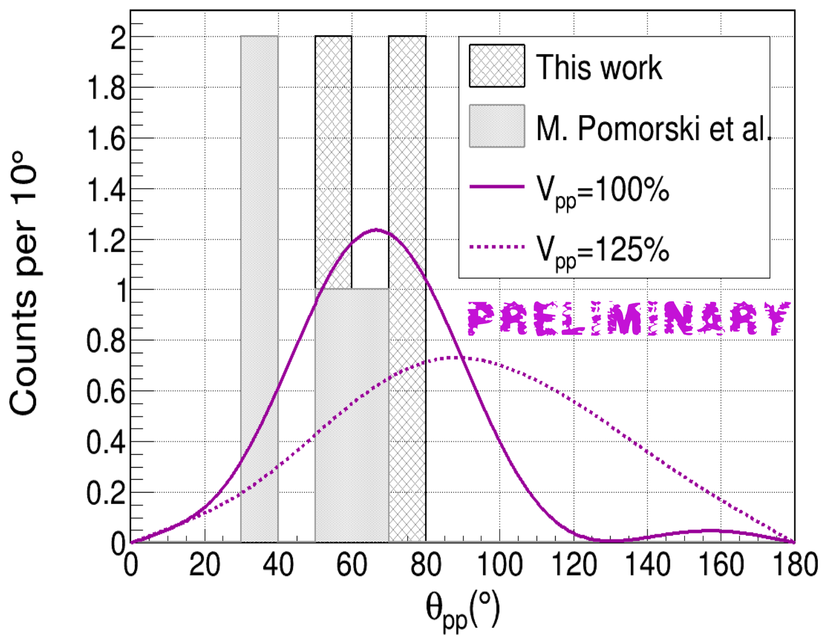
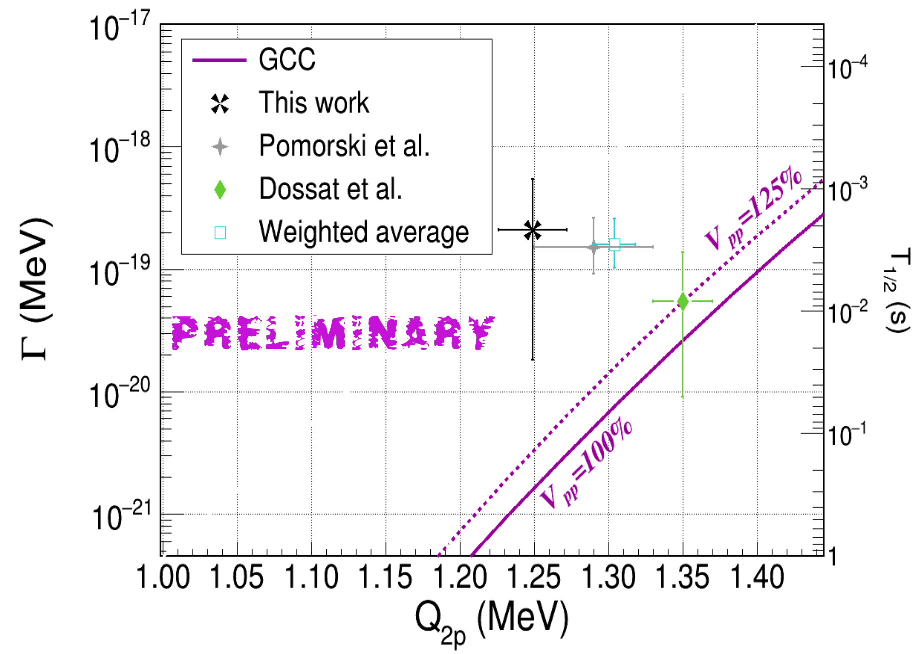
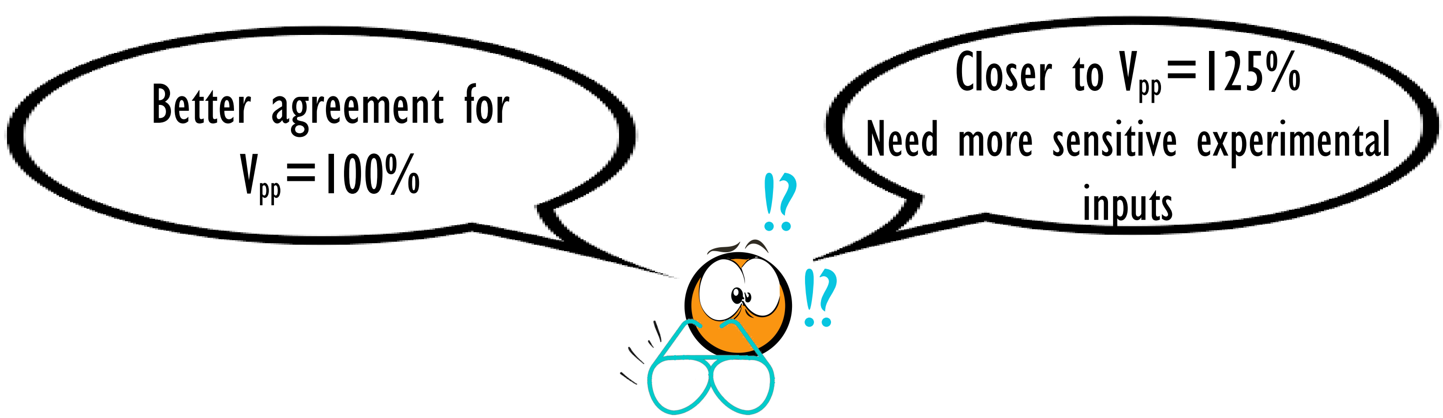
- ANGULAR DISTRIBUTION

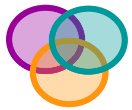


- HALF-LIFE



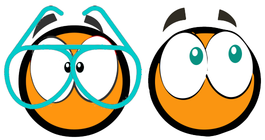


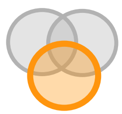
SUMMARY



GCC

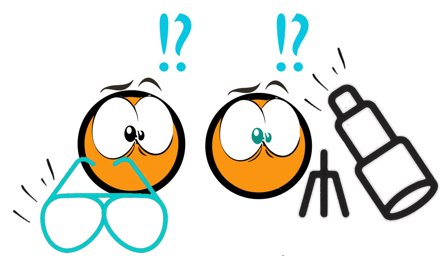
The comparison of angular distributions with GCC novel calculations confirms the characterization of V_{NN} for ^{48}Ni and ^{45}Fe.





3-BODY MODEL

The comparison with existing 3-body model angular distribution predictions indicates the shell closure of the $f_{7/2}$ orbital (^{48}Ni) and an occupancy of 24% of the p-orbital for ^{45}Fe.



Interpretation and experimental discrepancies are found when studying the other observables for ^{48}Ni and ^{45}Fe respectively, showing once more the complexity of the description of the two-proton emission process.

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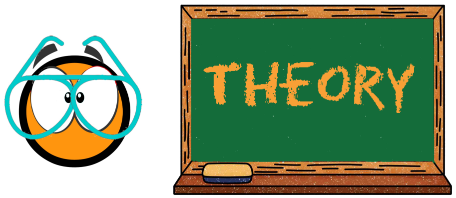
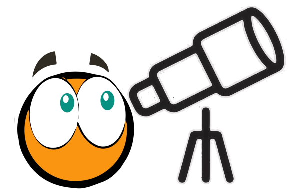
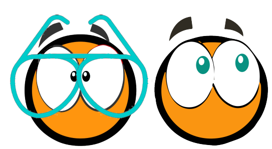


- INTRODUCTION ✓
- ^{48}Ni REGION ✓
- 2-PROTON RADIOACTIVITY ✓
- THEORETICAL PREDICTIONS ✓

Discrepancies

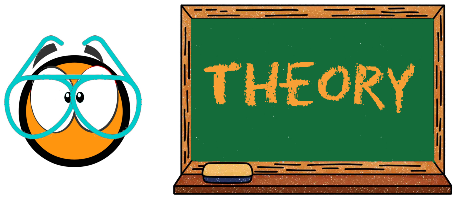


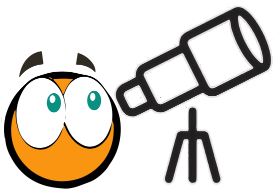
- OBSERVABLES ✓
- E791 EXPERIMENT ✓
  - → ACTAR TPC ✓
  - → ANALYSIS ✓
  - → RESULTS ✓



- COMPARISON THEORY-EXPERIMENT ✓
- CONCLUSIONS AND PERSPECTIVES

CONCLUSION AND PERSPECTIVES





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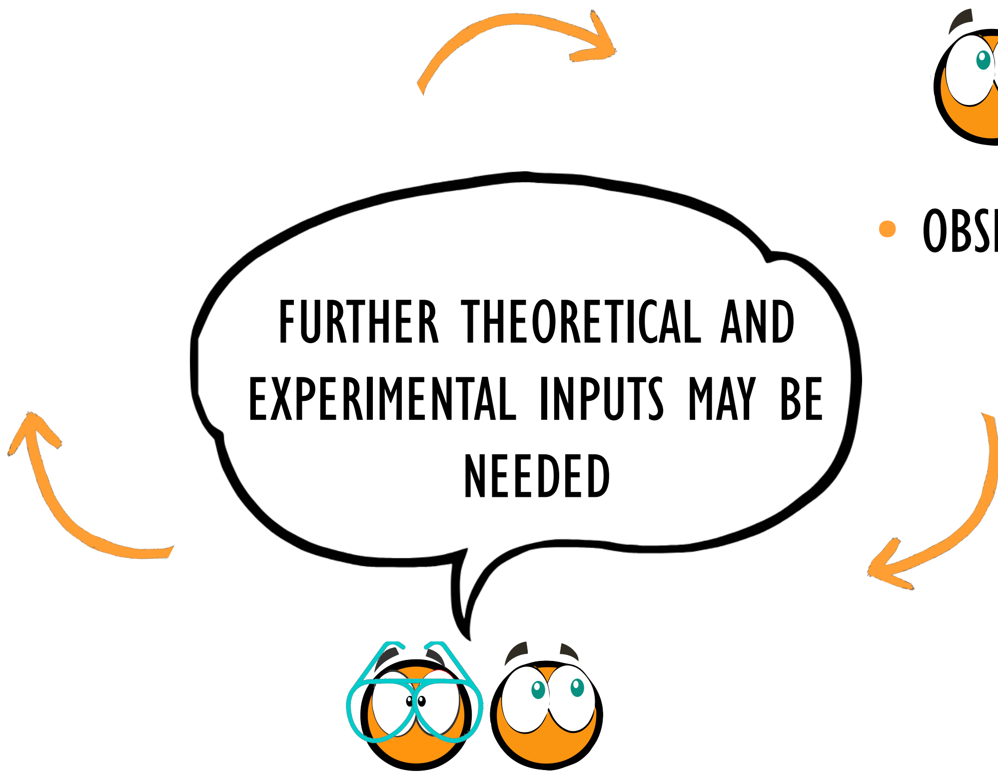

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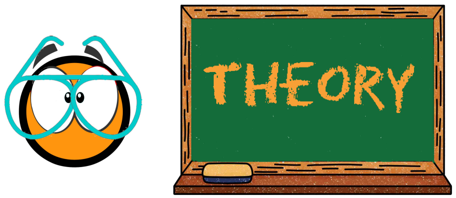
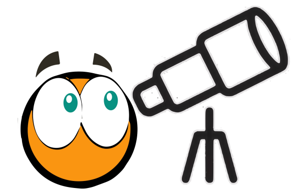
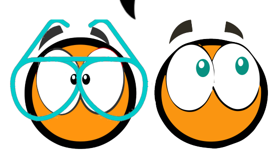
CONCLUSION AND PERSPECTIVES





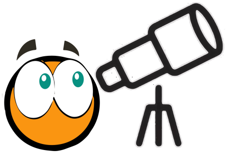
- OBSERVABLES

FURTHER THEORETICAL AND EXPERIMENTAL INPUTS MAY BE NEEDED



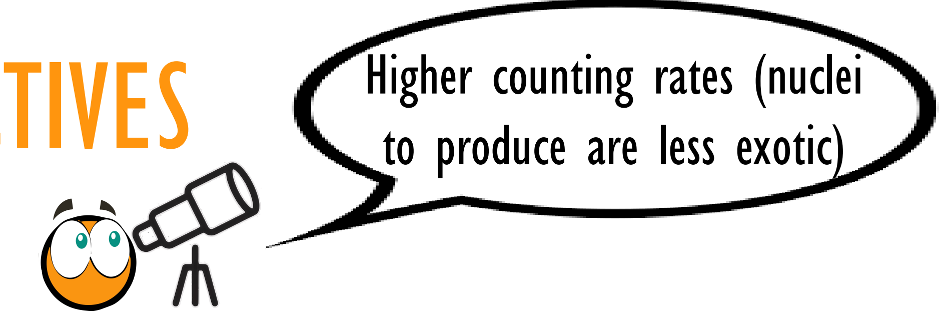
- COMPARISON THEORY-EXPERIMENT

(EXPERIMENTAL) PERSPECTIVES



- Further measurements for ^{48}Ni
- Two proton radioactivity of ^{67}Kr (Accepted experiment at RIKEN with ACTAR TPC)
- Two proton radioactivity for other candidates in future (^{100}Sn region)
- Two proton radioactivity from excited states

(EXPERIMENTAL) PERSPECTIVES



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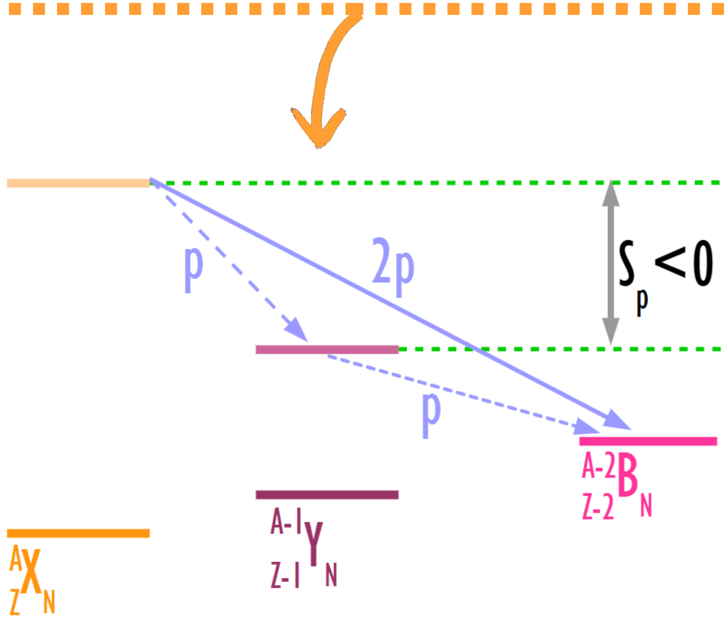
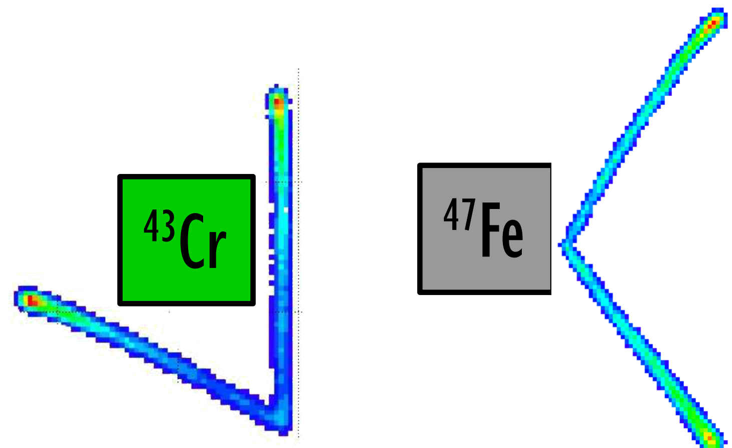
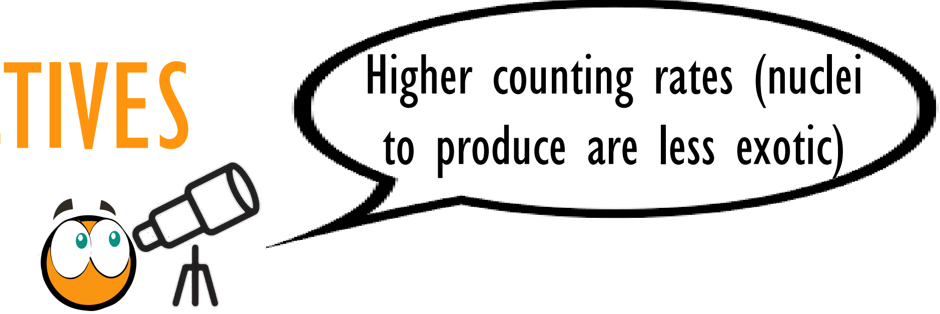




Candidates for β direct two-proton emission (E791 experiment)

- Feeding by β decay
- Population by reaction

(EXPERIMENTAL) PERSPECTIVES



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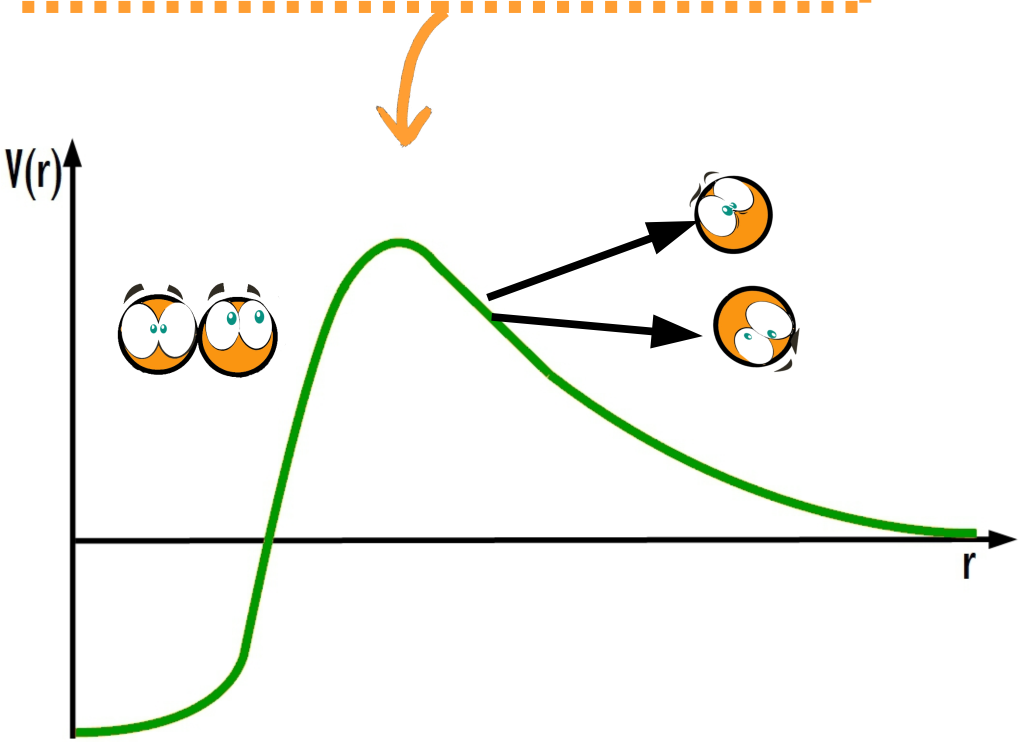

- **Help for the understanding of two-proton emission from ground state**

Are the protons correlated in the same way in the nucleus?

What is the influence of the Coulomb barrier in the angular correlation?

Do the proton share the energy in the same way?

Young two-proton-experimentalist-theoretician collaboration: A.Ortega Moral[a], Simin Wang[ij]

Special thanks: J.Giovinazzo[a], T.Roger[b], J.Lois Fuentes[c], J.Pancin[b], B.Blank[a]

Experiment Collaboration: A.Ortega Moral[a], P. Ascher[a], B.Blank[a], C.Borcea[d], L.Cáceres[b], M.Caamaño[c], F.De Oliveira[b], A.De Roubin[f], B.Fernández[c], D.Fernández[c], J.Lois Fuentes[c], M.Gerbaux[a], J.Giovinazzo[a], S.Grevy[a], M.Hukkanen[g], A.Husson[a], O.Kamalou[b], T.Kurtukian-Nieto[a], J.Michaud[a], J.Pancin[b], J.Piot[b], M.Pomorski[b], D.Regueira[c], T.Roger[b], A.M.Sánchez Benitez[g], O.Sorlin[b], M.Stanoiu[d], C.Stodel[b], J-C.Thomas[b], M.Vandebrouck[h]

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Thanks!

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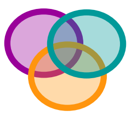
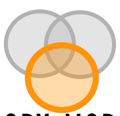
SUMMARY

- The main observables of the 2-proton emission decay process: half-life, total energy of the decay and energy and angular correlations have been measured for ^{48}Ni and ^{45}Fe recently in an experiment at GANIL 2021 using ACTAR TPC



Simin Wang

- The comparison of angular distributions with GCC novel calculations confirms the characterization of V_{NN} and the predominant diprotonlike structure of the emission.



- The comparison with existing 3-body model angular distribution predictions indicates the shell closure of the $f_{7/2}$ orbital and an occupancy of 24% of the p-orbital for ^{48}Ni and ^{45}Fe, respectively.

- Interpretation and experimental discrepancies are found when studying the other observables for ^{48}Ni and ^{45}Fe respectively, showing once more the complexity of the description of the two-proton emission process.

FURTHER THEORETICAL AND EXPERIMENTAL EFFORTS MAY BE NEEDED

- Further measurements for 2-proton ground state (confirmed) emitters ^{48}Ni, ^{54}Zn, ^{67}Kr and higher masses candidates
- Complementary studies from two-proton emission from excited states