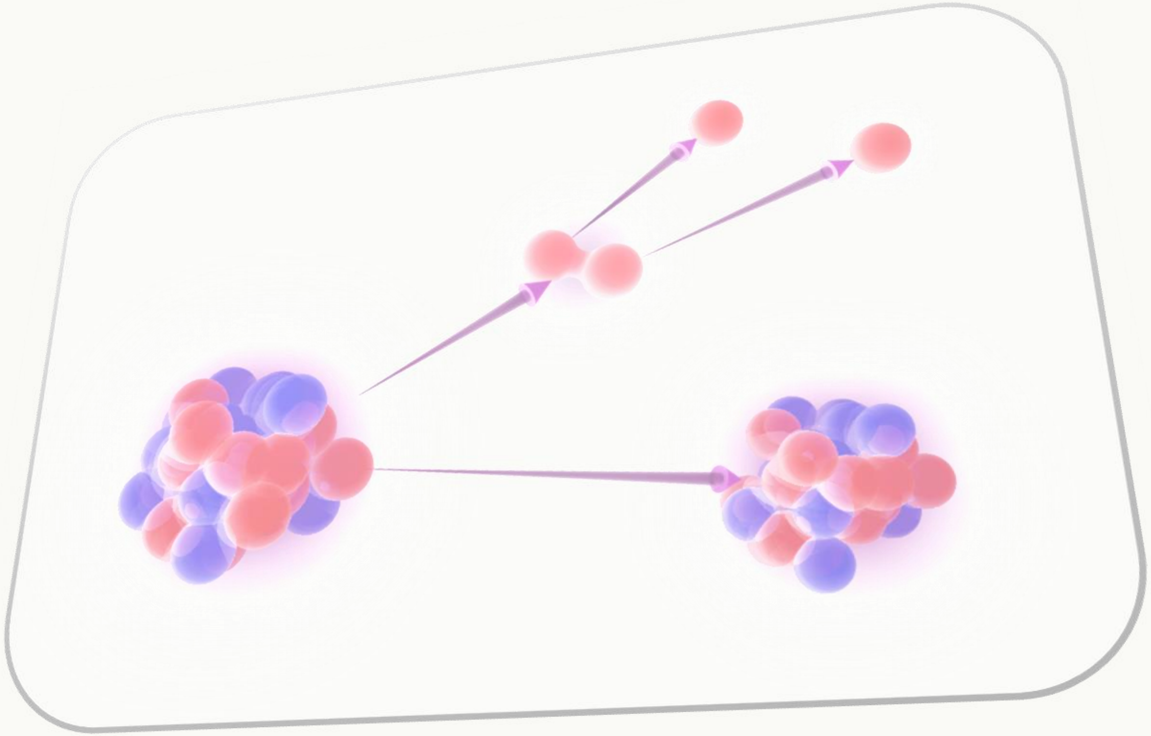
17th Workshop on Particle Correlations and Femtoscopy

WPCF 2024 – Toulouse, France

are
particle correlations in 2-proton radioactivity
really understood ?

J. Giovinazzo – LP2iB (former CENBG) – Bordeaux

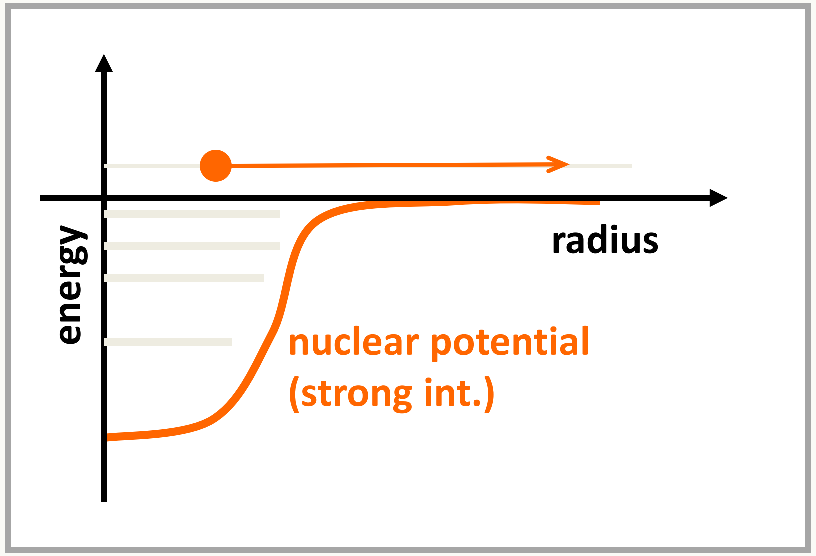
- ▷ 2p radioactivity
- ▷ experiment & theory
- ▷ understanding correlations



LP2i Bordeaux

2-proton radioactivity

beyond the proton drip-line

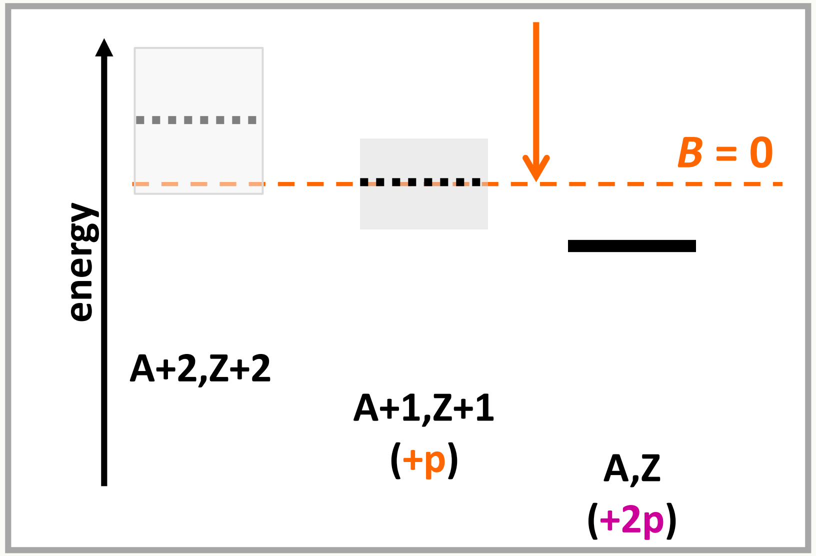


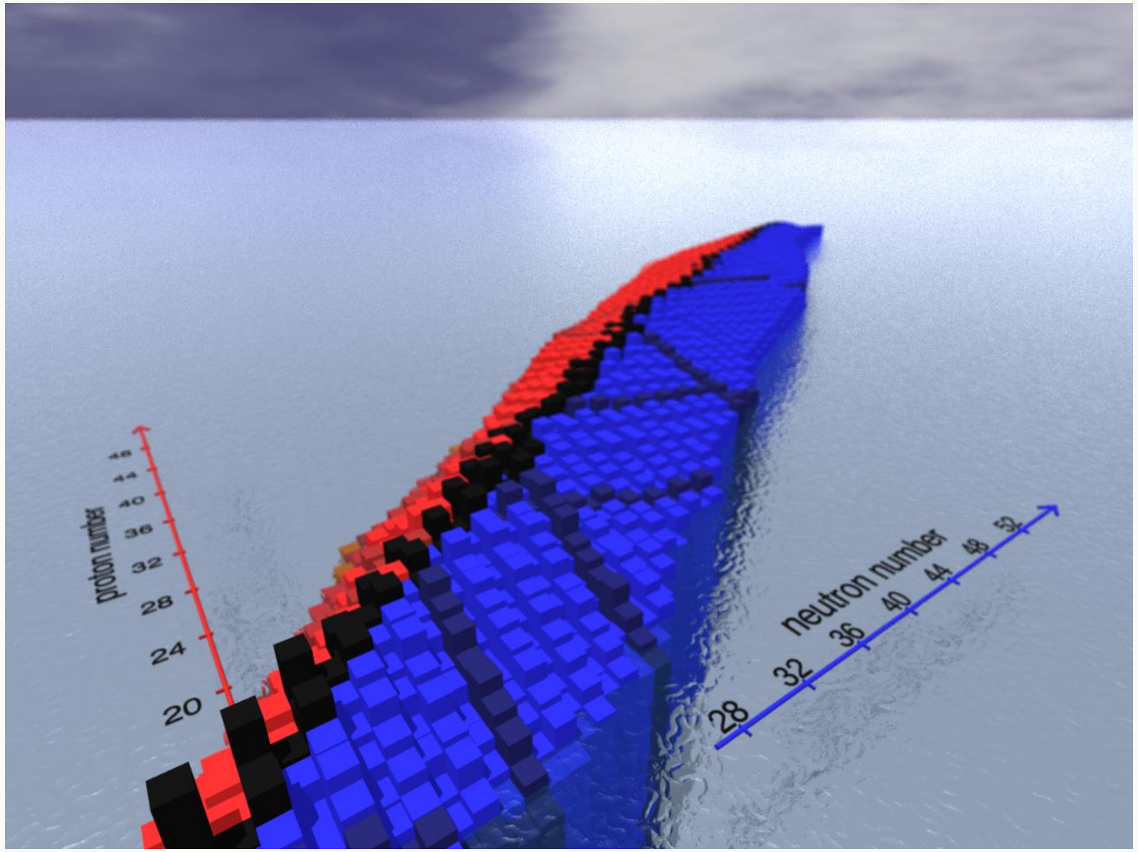
large proton / neutron asymetry

last proton not bound / nuclear strong interaction

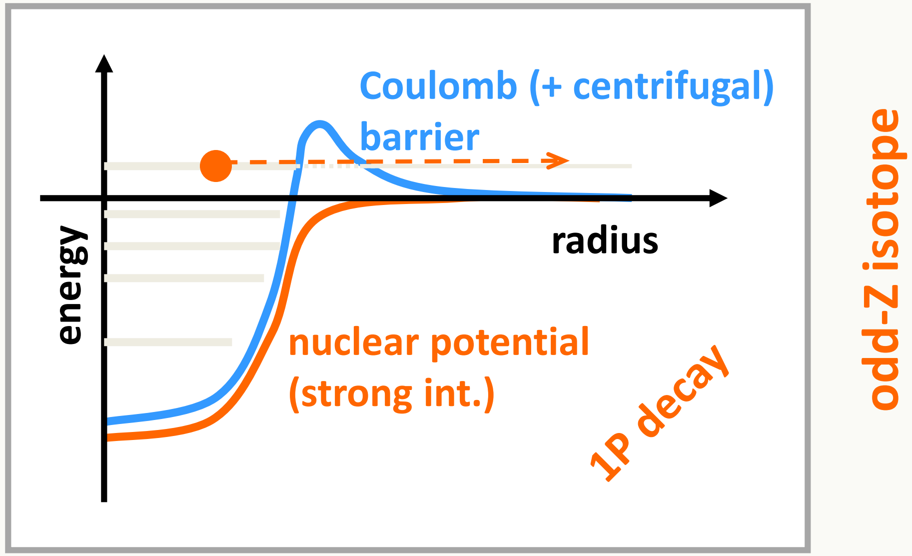
- proton binding energy < 0
  (separation energy > 0)
- time scale of nucleons motion ~10^{-20} s

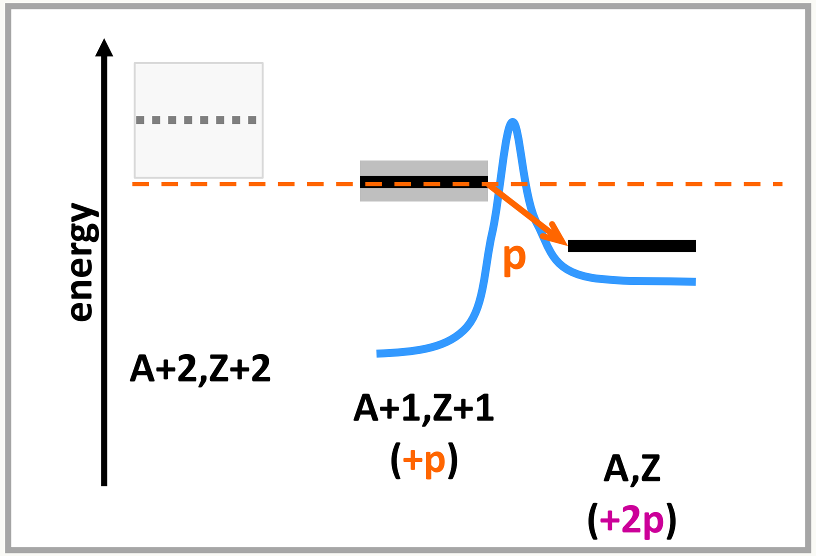
proton drip line
(w/r nuclear interaction)





beyond the proton drip-line
quasi-bound system





proton charge → Coulomb barrier

if larger than proton separation energy
→ **metastable** state

then tunnel effect
→ **1-proton radioactivity**

beyond the proton drip-line
quasi-bound system

pairing of nucleons
gain of stability for pairs
→ **lower mass** energy

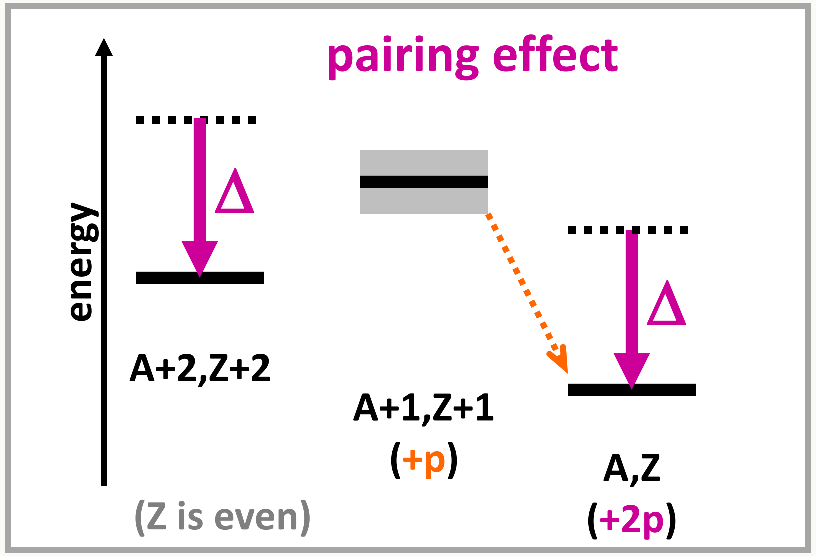
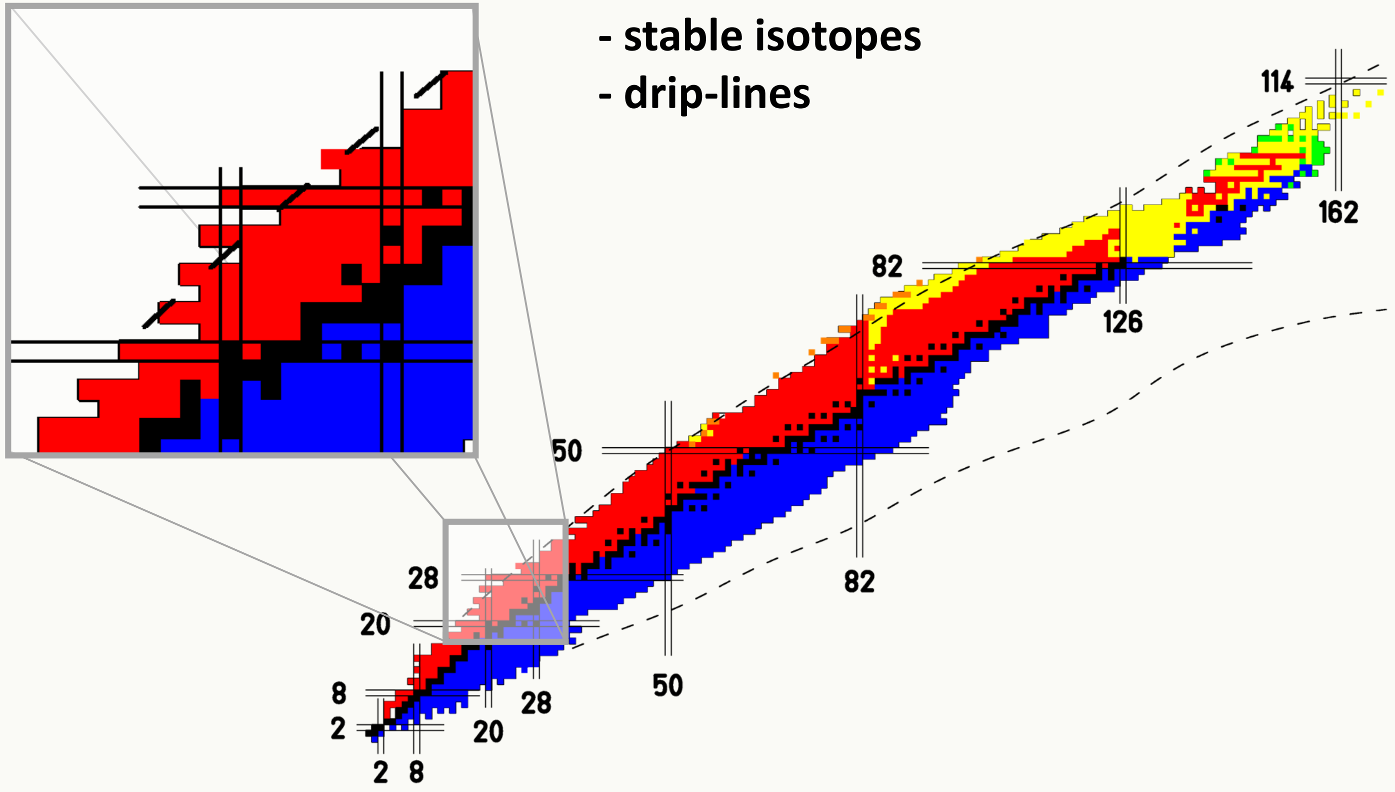


illustration of odd – even effect:
- stable isotopes
- drip-lines



beyond the proton drip-line
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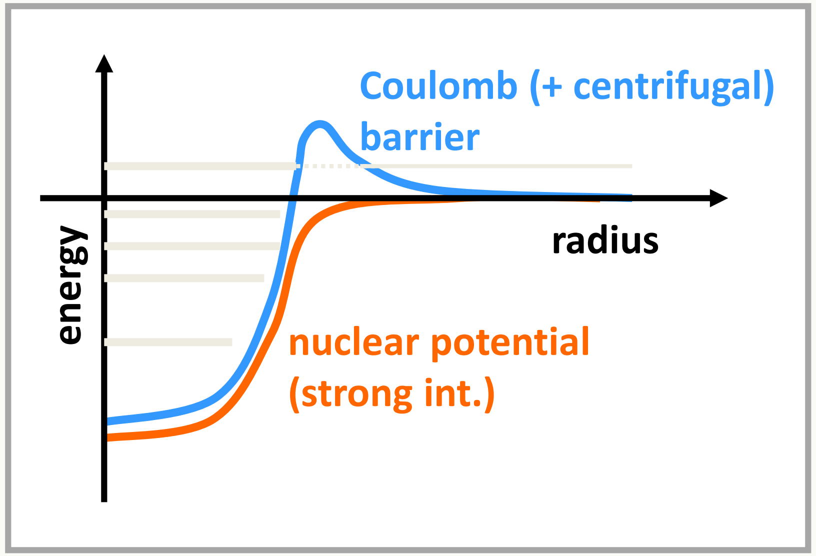
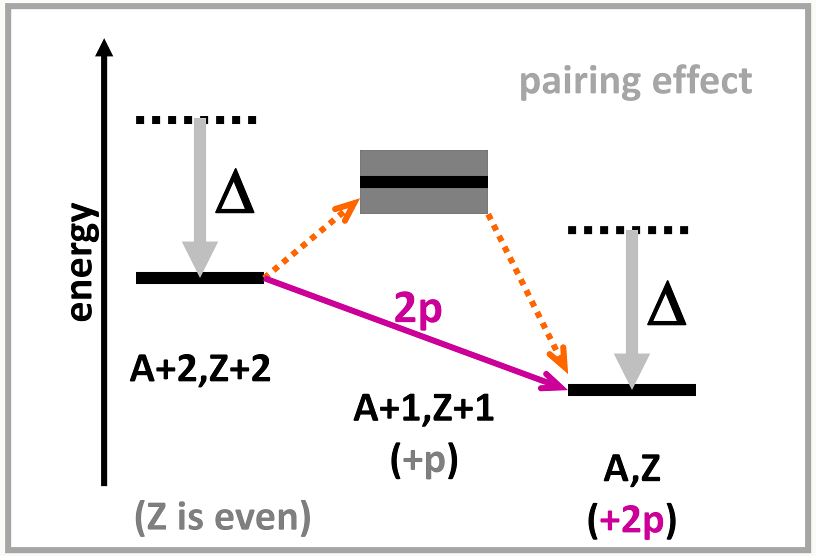
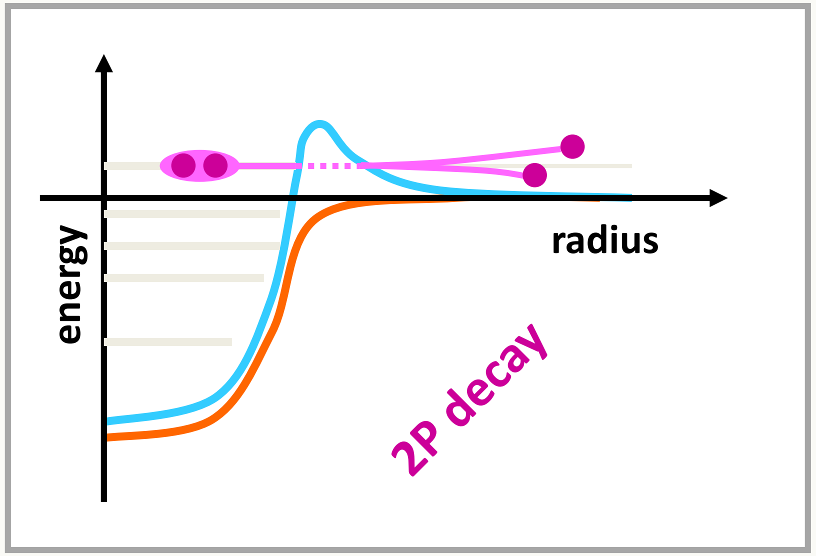




drip-line + Coulomb + pairing
→ 2-proton radioactivity



emitted protons:

- strongly **correlated** inside the nucleus
- **independent** part. oustide

even-Z isotope

1 proton emission forbidden
(so called "***true***" 2P radioactivity)

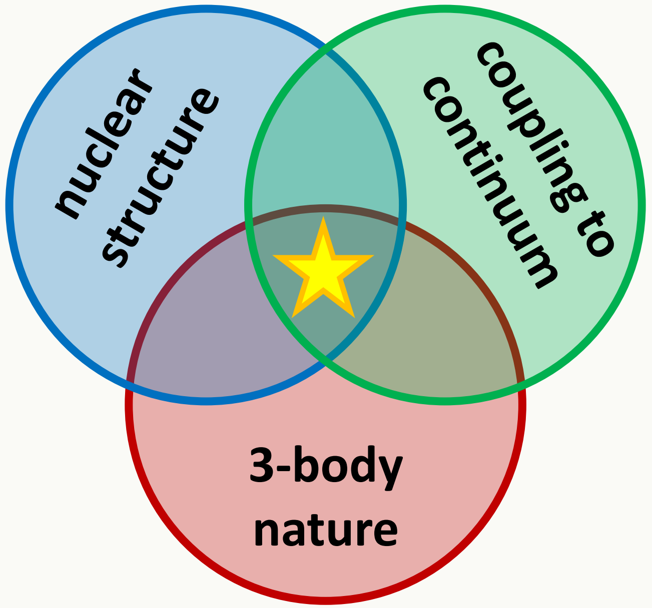
a unique decay process

→ **drip-line and masses** (beyond the « drip-line »)
  transition Q-values

→ **nuclear structure**
  energies, half-life, levels configuration

→ **pairing**
  correlations in energy and angle of emitted protons

→ **tunnel effect**
  theoretical descriptions



adapted from M. Pfützner et al. 2023

complex process for theoretical interpretations / predictions

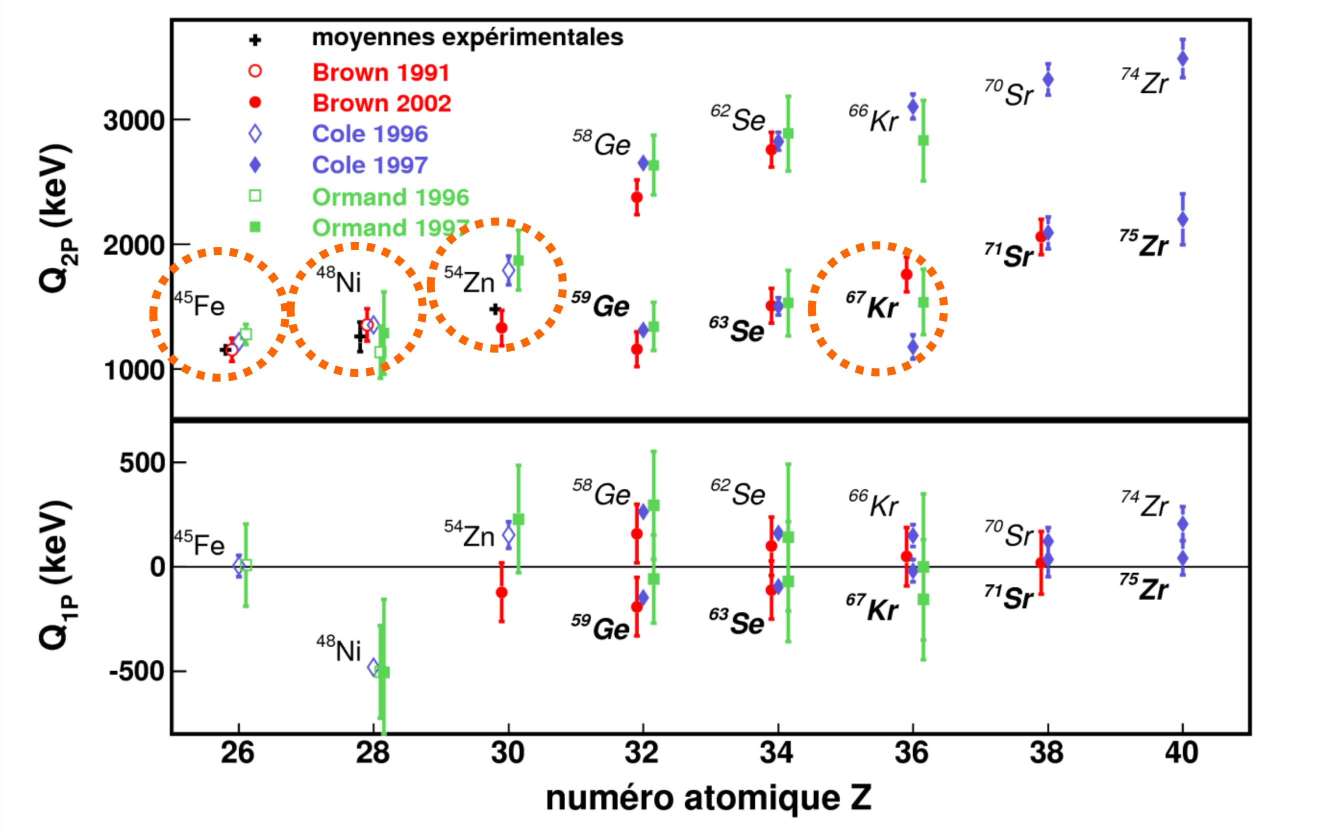
ideally, taking into account:

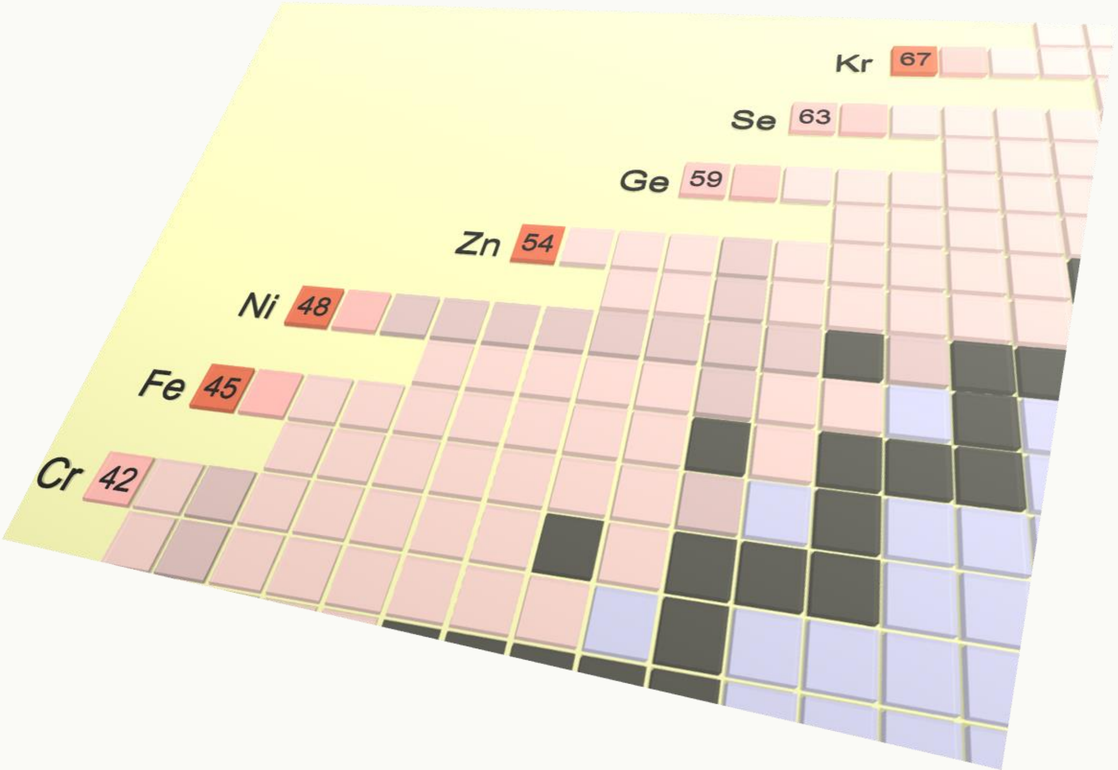
- the 3-body decay dynamics
- the nuclear structure (wave functions)
- the coupling to the continuum

2-proton radioactivity candidates

proposed in ~1960 (by V.I. Goldanskii)

$Q_{2P} > 0$ and $Q_{1P} < 0$
→ mass predictions





observing 2-proton radioactivity

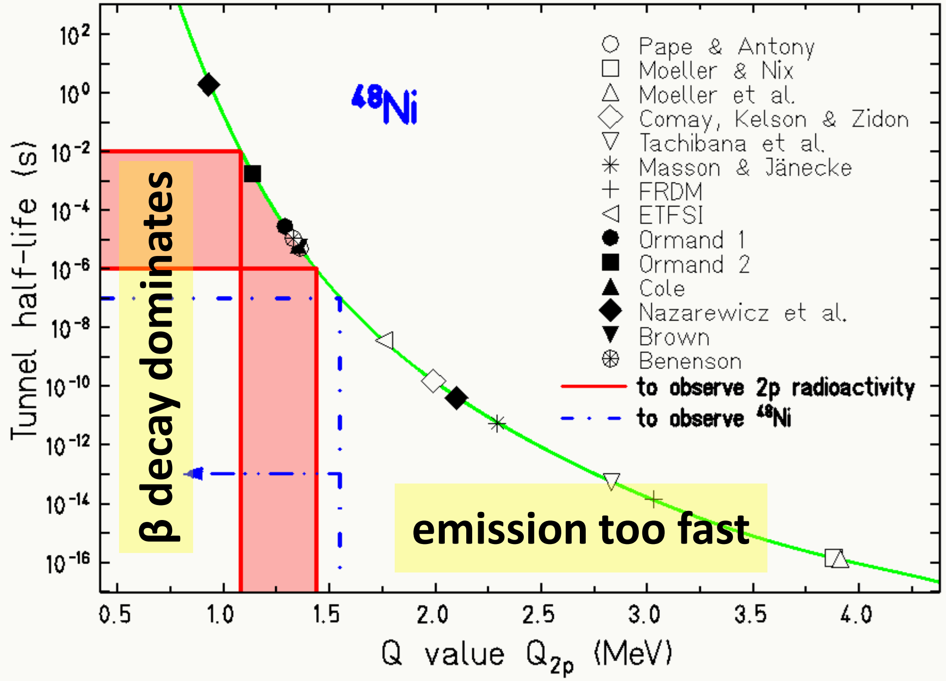
$T_{1/2} = f(Q_{2P})$

competition with beta decay

- small Q_{2P} → slow tunneling → dominated by beta
- large Q_{2P} → too fast for observation

medium mass nuclei

$T_{1/2}(\beta) \sim 10$ ms → observable range 1 µs – 10 ms



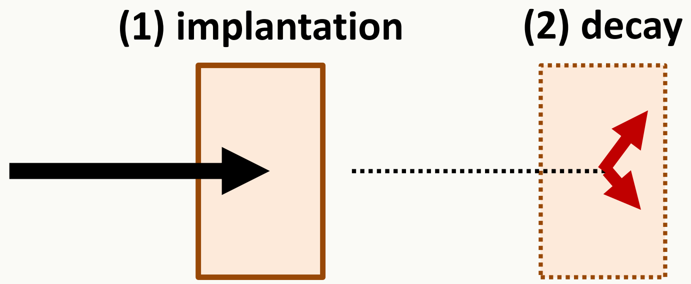
courtesy of B. Blank

possible observation only at fragmentation facilities

(2000's: GANIL/LISE, GSI/FRS, NSCL/A1900; 2010's: RIKEN/BigRips… then: FRIB, FAIR…)

→ fast production / extraction from target

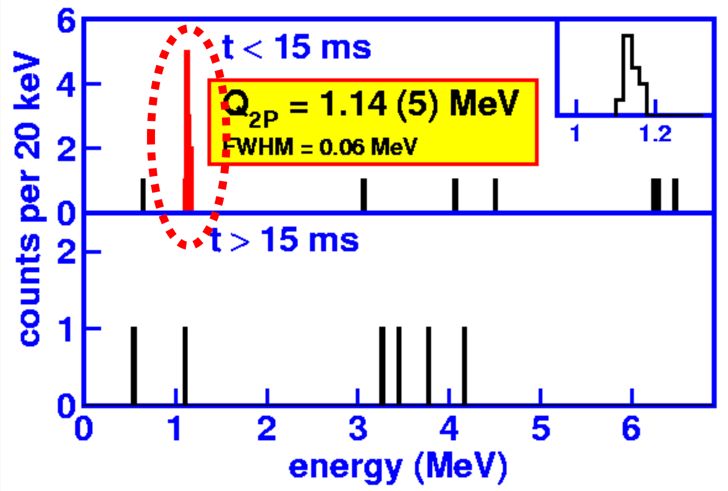
→ implantation in a **thick** **active** **stopper** for decay measurement (few ms after implantation)



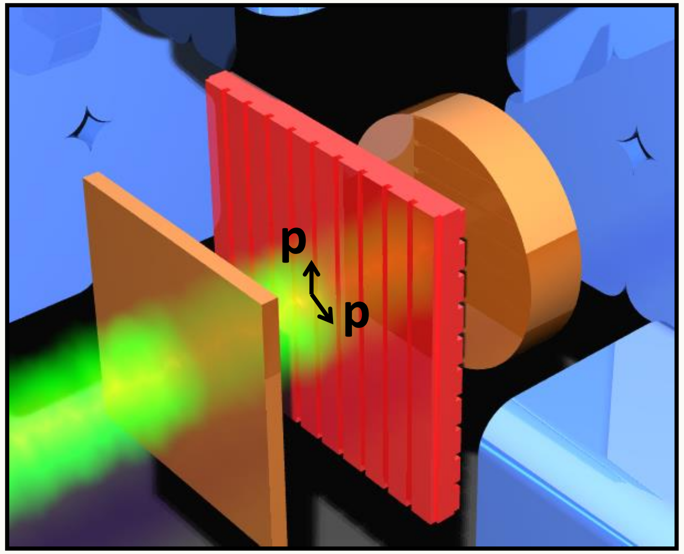
experiments & theory

2-proton radioactivity: experiments

observation: silicon detector experiments



J.G. *et al.* (PRL 2002)



- ^{45}**Fe**: first **indirect** evidence
  (J.G. *et al.* GANIL 2002,
  M. Pfützner *et al.* GSI 2002)
- ^{54}**Zn**: B. Blank *et al*. 2005
- ^{48}**Ni**: indication (B. Blank *et al*. GANIL 2005)
- ^{67}**Kr**: J.G. *et al*. RIKEN 2015
  → half-life problem…

implantation in a silicon detector (DSSD)

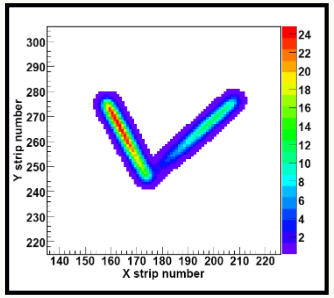
- **protons stopped inside** (full energy)
- **no beta pile-up** (exclude β-p)
- identification of 2nd decay after 2p (**daughter**)

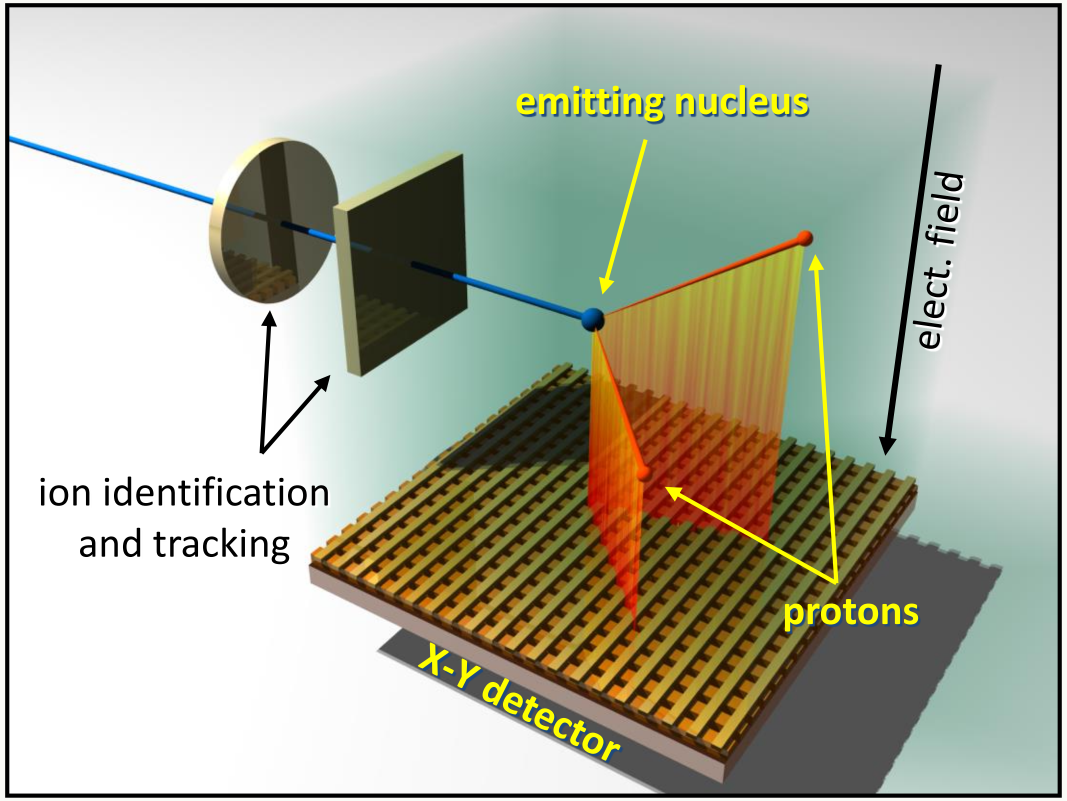
limited exp. information

- $\boldsymbol{T_{1/2}}$ and $\boldsymbol{Q_{2P}}$
- no individual proton info
- limited comp. with models

2-proton radioactivity: experiments

correlations: time projection chambers (tracking) experiments





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  first **direct** observation (J.G. *et al.* GANIL 2007)
  angular distribution (K. Miernik et al., MSU 2009)

- ^{54}**Zn**: B. Blank *et al.* 2005
  few p-p correlations (P. Ascher et al., GANIL 2011)

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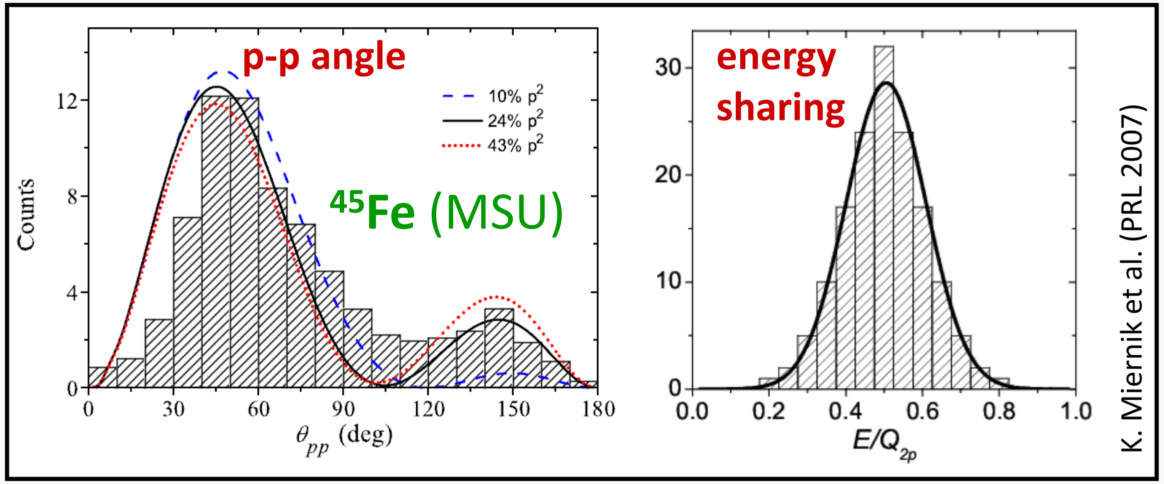
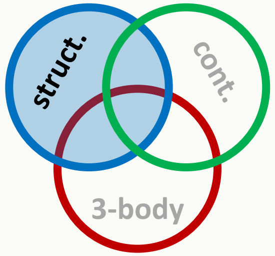
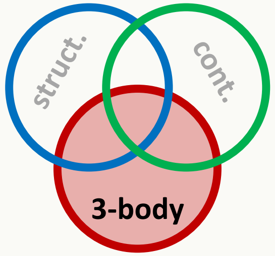


2-proton radioactivity: theoretical interpretations

- **models based on nuclear structure**
  R-matrix formalism, shell model wave functions, p-p resonance (I. Barker & B.A. Brown)
  shell-model embedded in the continuum (SMEC, M. Ploszajczak)
  → no dynamics, limited comparison: $T_{1/2}(Q_{2P})$



- **3-body model**
  core+p+p system (L.V. Grigorenko)
  → emission dynamics (angular & energy correlations), no intrinsic structure prediction
  → good agreement for ^{45}**Fe correlation** patterns

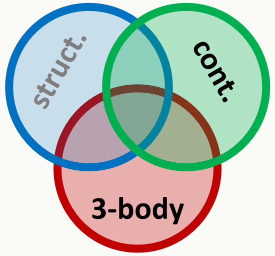


angular & energy correlations

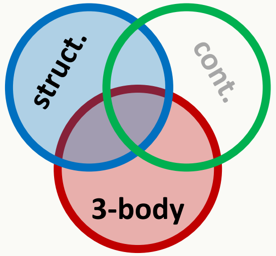
- **recent approaches**

  - **hybrid model** (B.A. Brown)

  - **Gamow Coupled Channels (GCC)** (S. Wang & W. Nazarewicz)



the problem of ^{67}Kr half-life



"hybrid" model

3-body model (L.V. Grigorenko)
good dynamics
$T_{1/2}$ for (s^2,) p^2 and f^2 config.

shell-model (B.A. Brown)
2-proton amplitudes
for (s^2,) p^2 and f^2 config

"Shell model corrected half-lives"
$A = A(f^2) + A(p^2) \rightarrow T_{1/2}(2P)$

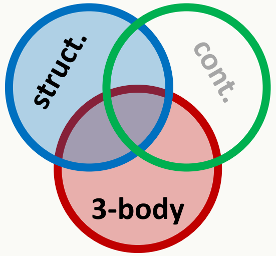
B.A. Brown et al., PRC 2019

	calculation	experiment(s)	
^{45}Fe	1.8 - $5.9\ ms$	$3,6 \pm 0,4\ ms$	OK
^{48}Ni	0.4 - $1.3\ ms$	$4.1 \pm 0,4\ ms$	~OK
^{54}Zn	0.6 - $1.7\ ms$	$1.98^{+0.73}_{-0.41}\ ms$	~OK
^{67}Kr	300 - $900\ ms$	$21 \pm 12\ ms$	!?

B.A. Brown, B. Blank, J.G, PRC 2019

factor 20 to 40 off !!!

the problem of ^{67}Kr half-life



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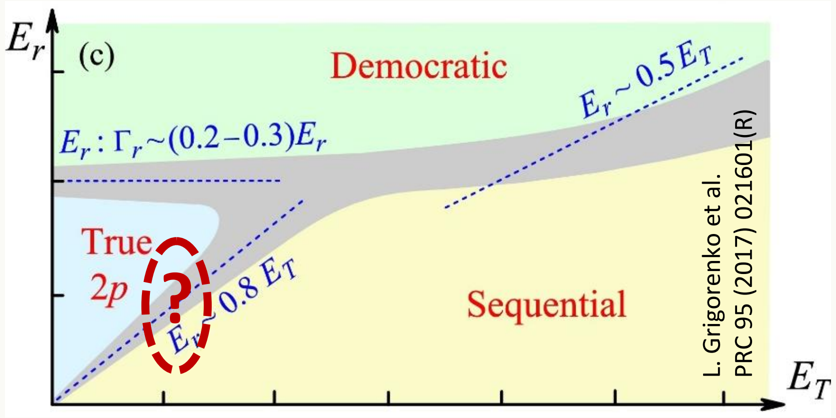
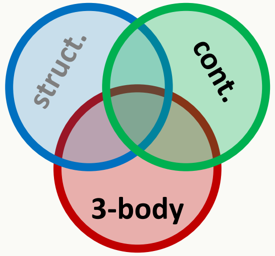
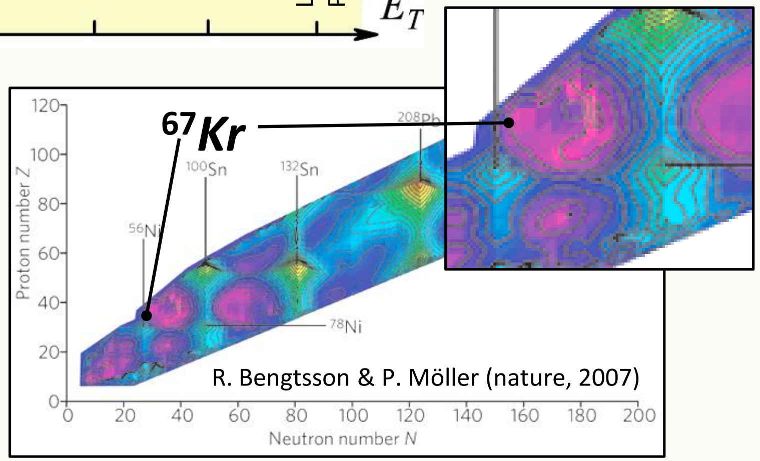


L. Grigorenko et al. PRC 95 (2017) 021601(R)

2 proposed hypothesis

- **transition between direct and sequential 2P emission**
  (L.V. Grigorenko, 2017)
  → **different energy sharing**
- **nuclear deformation**
  Gamow Coupled Channels formalism (GCC)
  (S. Wang & W. Nazarewicz, 2018)
  → **angular distribution prediction**



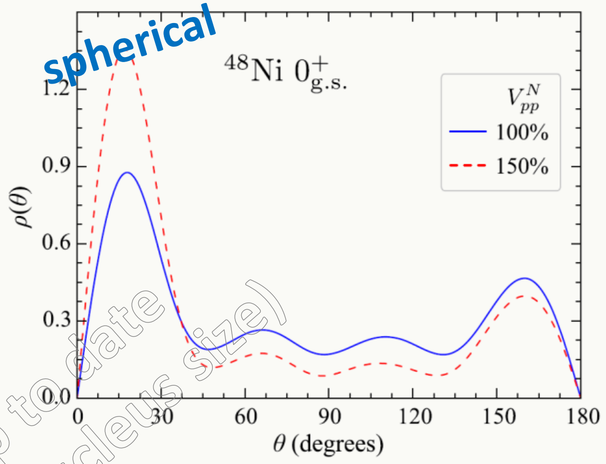


R. Bengtsson & P. Möller (nature, 2007)

need for new measurements (2018 status)

GCC...

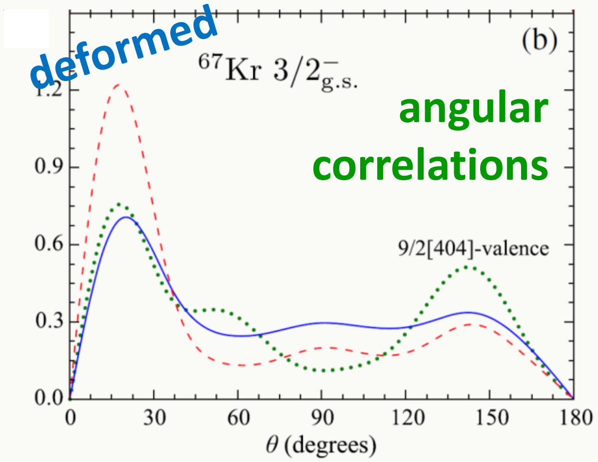
^{48}Ni



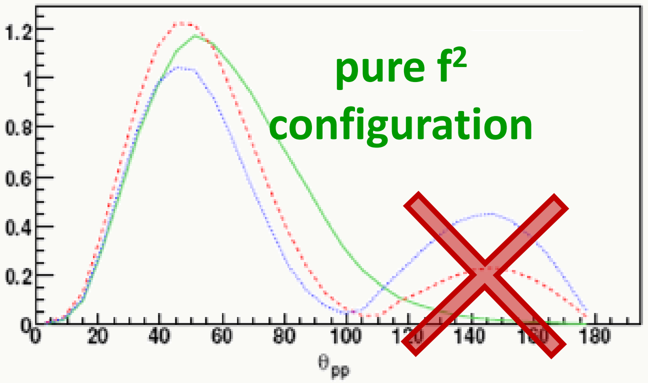
not up to date (limited nucleus size)

consistent structure
and dynamics description

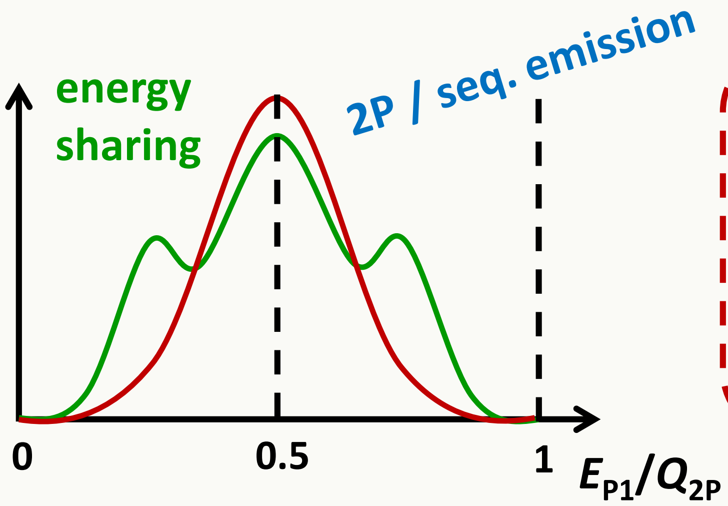
^{67}Kr



3-body model
not available for ^{48}Ni
extrapolation from ^{45}Fe & ^{54}Zn



good agreement
in the case of ^{45}Fe...



GANIL 2021

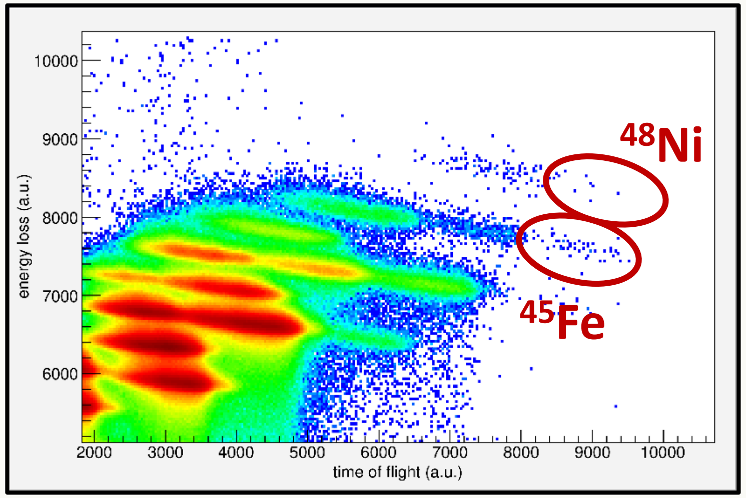
actar TPC

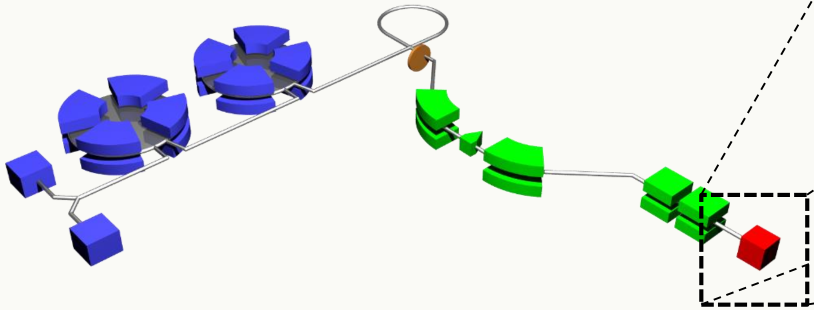
RIKEN future

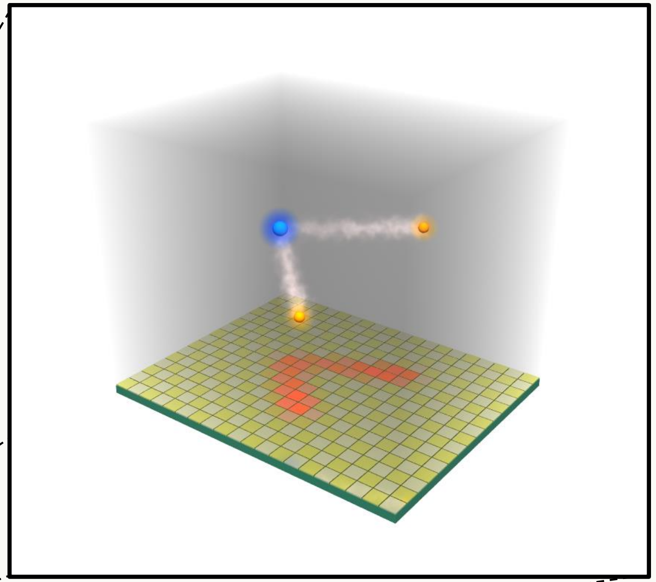
^{48}Ni decay at GANIL / LISE3 with ACTAR TPC

long beam time, high intensity…

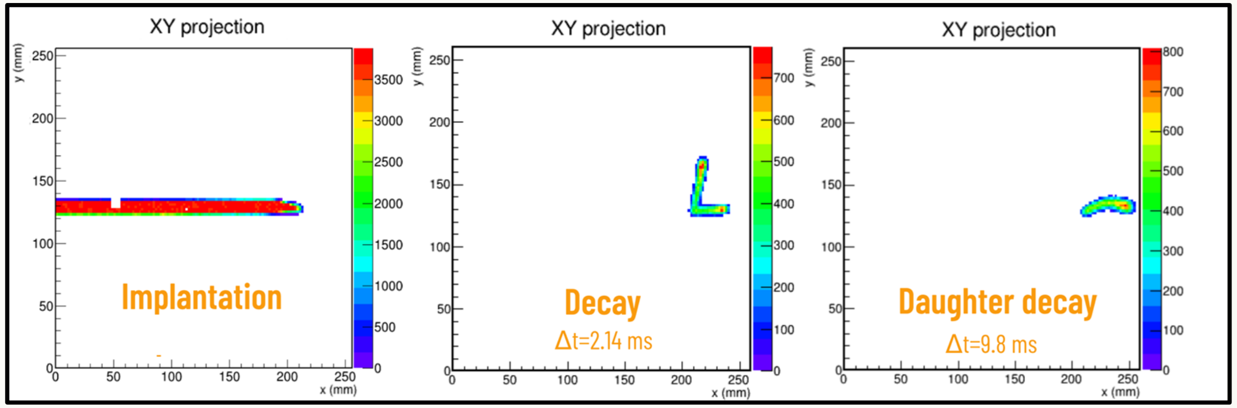
- full acceptance of the spectrometer (→ ident. problems)
- implantation (optimized for ^{48}Ni) in ACTAR TPC







…but very small statistics



	identified	stopped in ACTAR	2p /total decays
^{45}Fe	**80**	**13**(+?)	**6**(+9) / 7(+?)
^{48}Ni	**11**	**6**	**3** / 5

only few 2P decay events (^{48}Ni & ^{45}Fe)

courtesy of A. Ortega Moral

understanding correlations

correlations interpretation

exp. data analysis: **A. Ortega Moral**

proton-proton **relative angles** and **energy sharing**

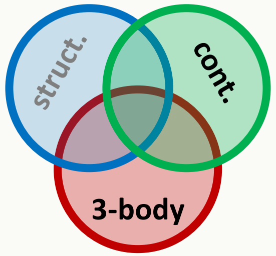
combining ACTAR TPC + O-TPC results

- 15 events for ^{45}Fe + results from K. Mierniek (75 events)
- 3 events for ^{48}Ni + results from M. Pomorski (4 events)

} for angles only (limited energy resol./info. from O-TPC)

GCC calculations: **S. Wang**

new calculations: extended asymptotic region to **500 *fm*** (50 *fm* in 2018 calc.)
→ significant change in angular distributions



variation of proton-proton interaction term V_{pp} in the interaction
(w.r.t. "standard" value ≡ 100%)

previous 3-body model calculations from L.V. Grigorenko
^{48}Ni angular distributions extrapolated from ^{45}Fe and ^{54}Zn

half-life and Q-value

all models fail to reproduce the half-lives with **last measured Q-values**

→ 3-body model:
dominant contribution of $\boldsymbol{p_{3/2}}$ occupancy while expected $\boldsymbol{f_{7/2}}$ (almost 100% for ^{48}Ni)
(it was ok for ^{45}Fe with Q_{2P} from silicon experiments)

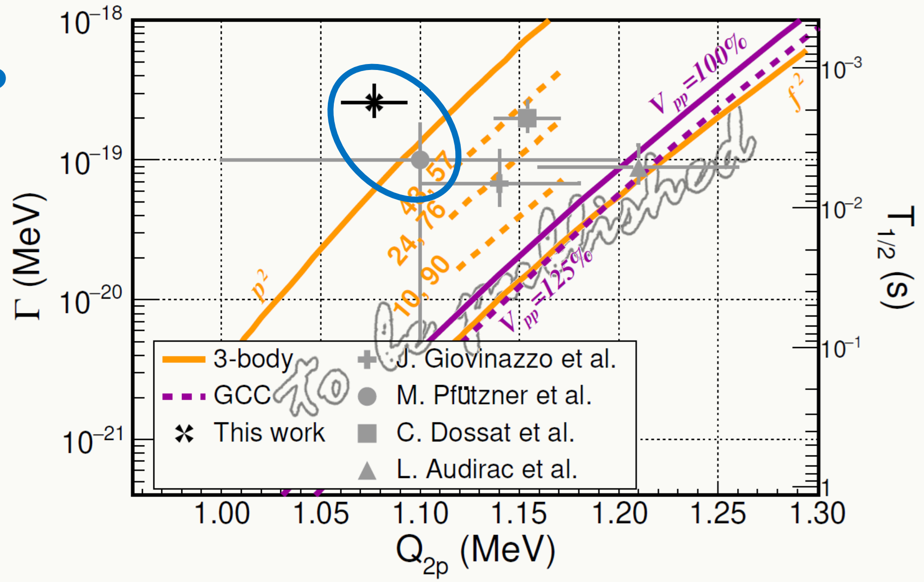
→ GCC framework:
increased $\mathbf{V_{pp}}$ favoured for $\mathbf{^{48}Ni}$, not for $\mathbf{^{45}Fe}$ – but anyway no agreement…

but… **systematic trend: $\mathbf{Q_{2P}}$ values from TPC experiments smaller than from silicon experiments**

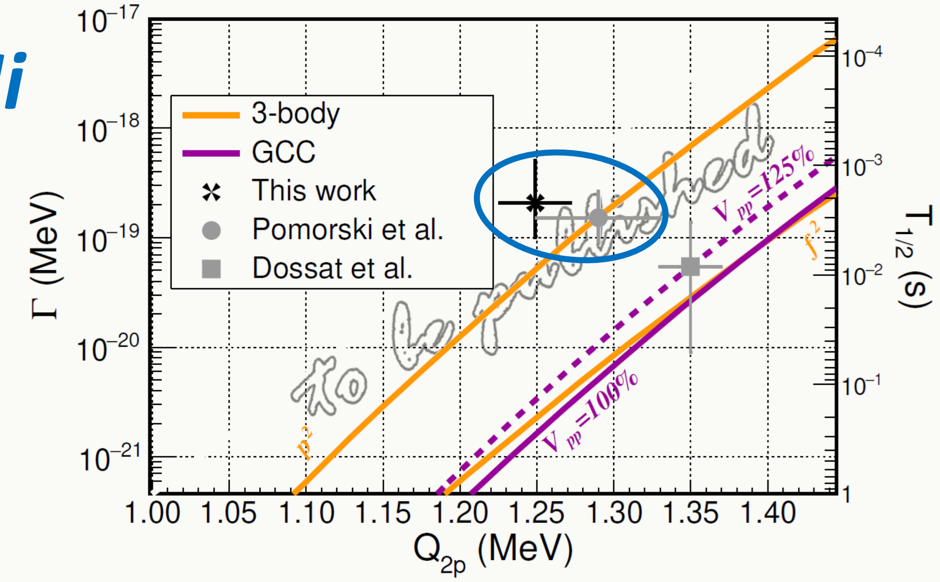
this problem needs to be clarified !!

A. Ortega Moral, S. Wang *et al.*, in preparation

^{45}*Fe*



^{48}*Ni*



angular correlations

very low statistics…

3-body

same conclusions as in Miernik *et al.*
best agreement with ~24% of p^2
no significant change

but similar trend for both models
→ confirmation of the persistence of the shell closure

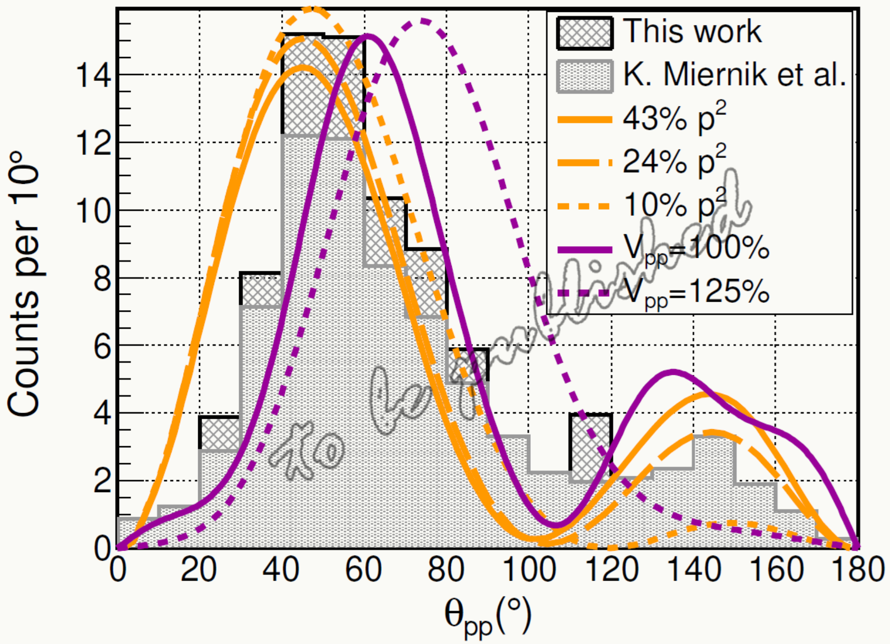
GCC

favours **standard value of V_{pp}**
fairly good agreement with exp.
(χ^2 similar to 3-body)

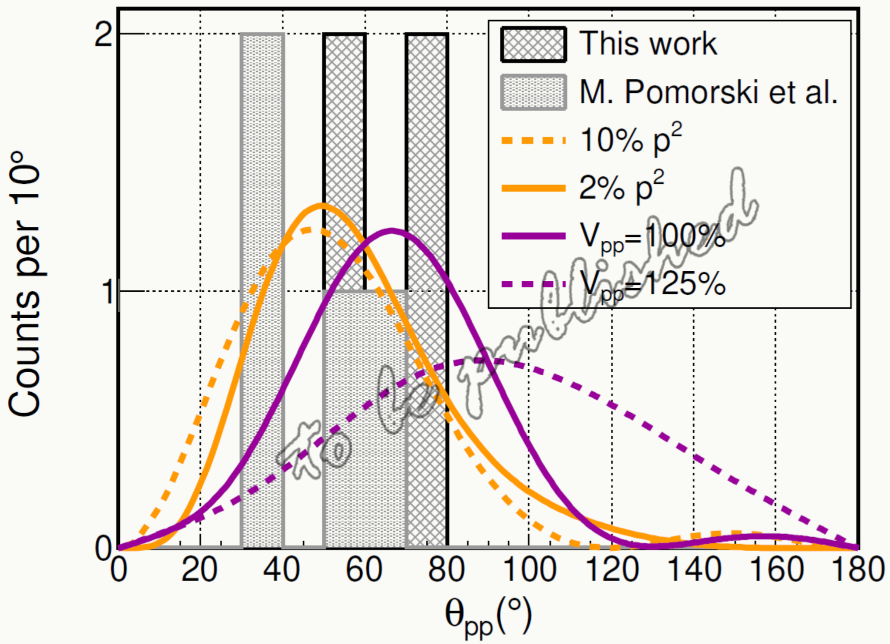
favours **standard value of V_{pp}**
(opposite conclusion than for $T_{1/2}$)

A. Ortega Moral, S. Wang *et al.*, in preparation

^{45}Fe



^{48}Ni



energy sharing

all models (since prediction in the 1960's…) suggest a more favourable equal energy sharing

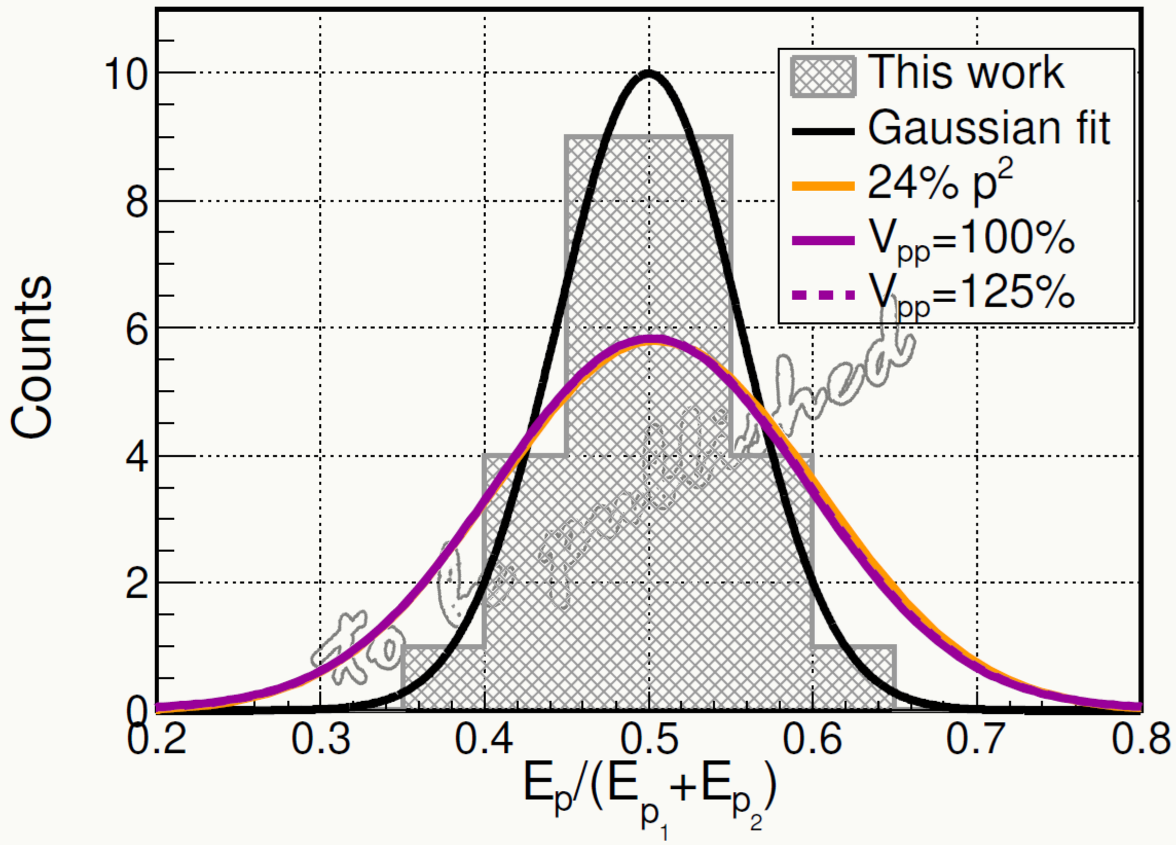
from barrier penetration considerations (non-trivial… ^{2}He / $p+p$ tunnelling)

distribution from calculations larger than experimental ones

3-body model in agreement with data from K. Miernik et al. (2007) with O-TPC → poor energy resolution

GCC calculation: no sensitivity to $\mathbf{V_{pp}}$ (not folded with exp. resol. → worse…)

^{45}Fe



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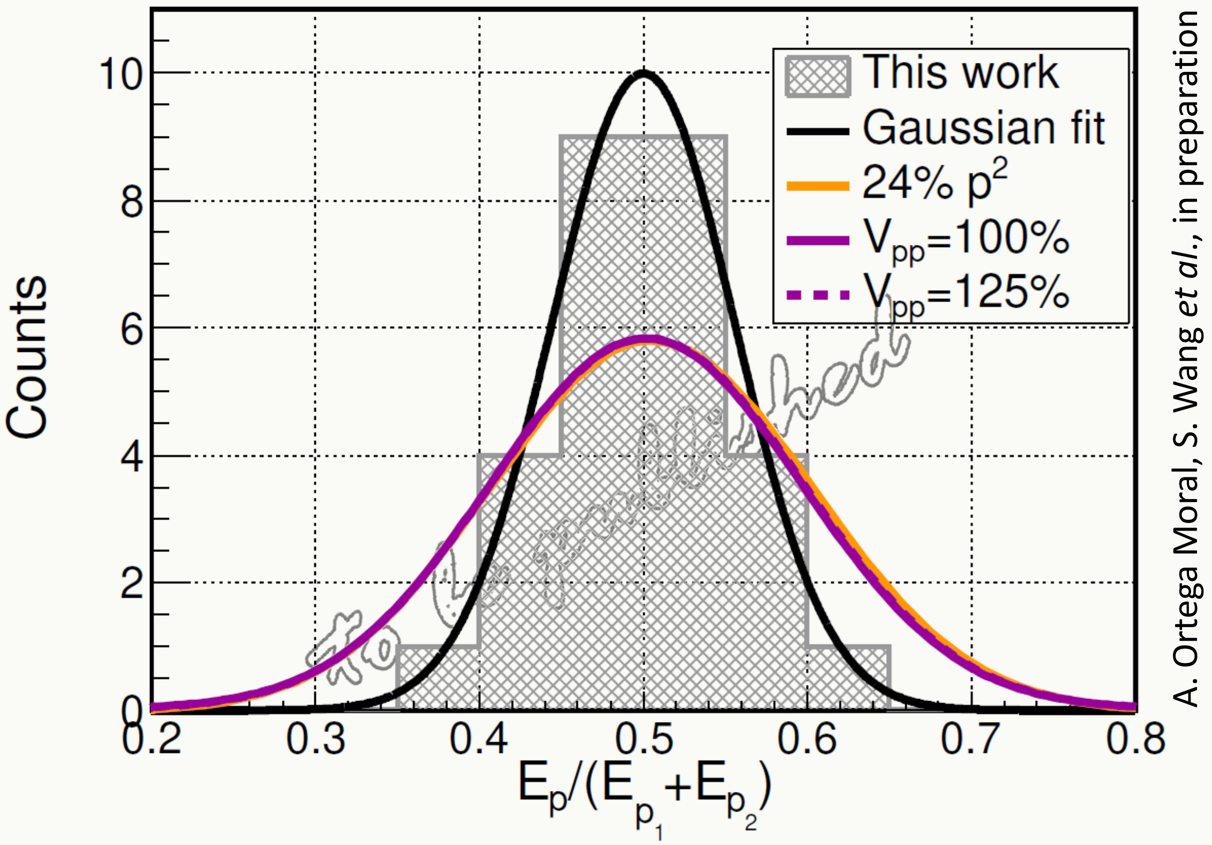
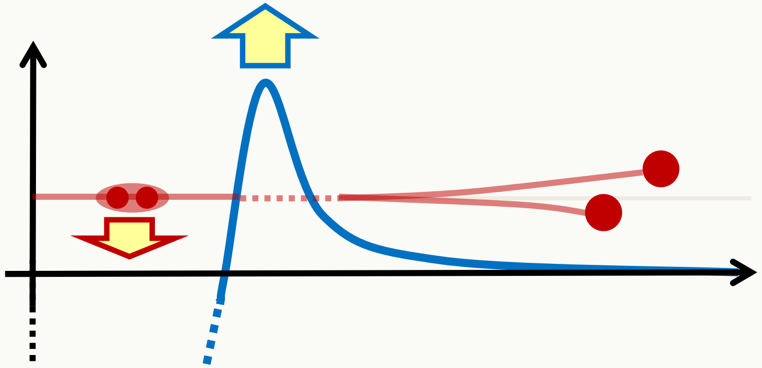


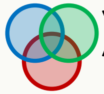


what could influence the distribution width ?

mainly (only ?) the **barrier height**

- ☐ requires significantly **lower Q_{2P}**
  → contradiction with $T_{1/2}$ and exp. TPC/Silicon discrepancy
- ☐ proton pair emitted with angular momentum L_{pp} **> 0** (centrifugal barrier) what reason ?...

concluding remarks

- we (I…) thought a consistent description of all aspects () would give a comprehensive picture
- when **angular and energy correlations** enter the game, we cannot get a satisfying description of experimental observable:
  → contradictory conclusions/trends in models for **half-lives** and **angular distributions**
- open question of the **energy sharing** and the **Q-value**
  → (*in principle*…) experimental data does not lie… but the systematic difference between TPC and silicon experiments (despite large uncertainties) must be clarified
  → comparison with theory suggests the opposite direction

this is (not) the end !...

thank you for your attention

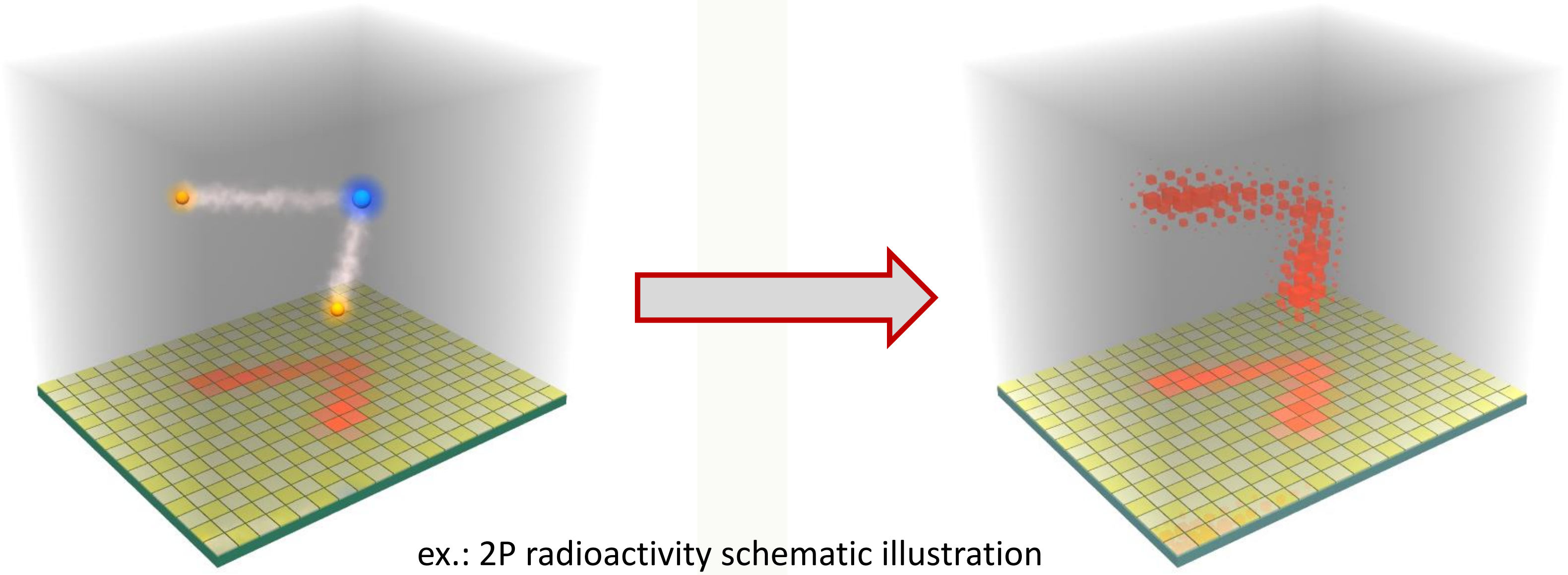
special thanks to A. Ortega Moral and S. Wang
and the E791 collaboration

backup

ACTAR TPC, a 4D detector: tracking and energy

- 2D collection plane (pads/pixels)
- time projection chamber: drift of ionization signal
- time sampling of vertical dimension (ionization drift)

→ **full 3D “voxelization” of the energy loss distribution**
(for tracks analysis)



ex.: 2P radioactivity schematic illustration

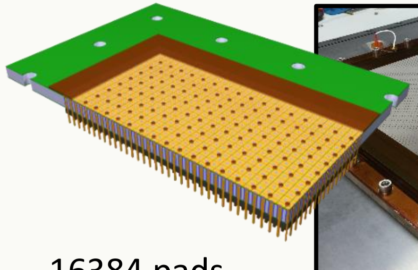
a versatile detector

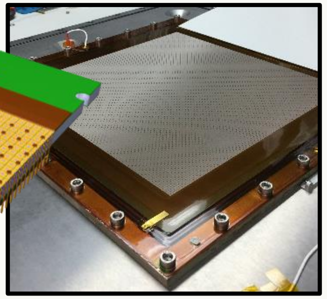
Active Target mode: inelastic scattering, transfer,…

Decay TPC mode: implantation-decay experiments

the ACTAR TPC device

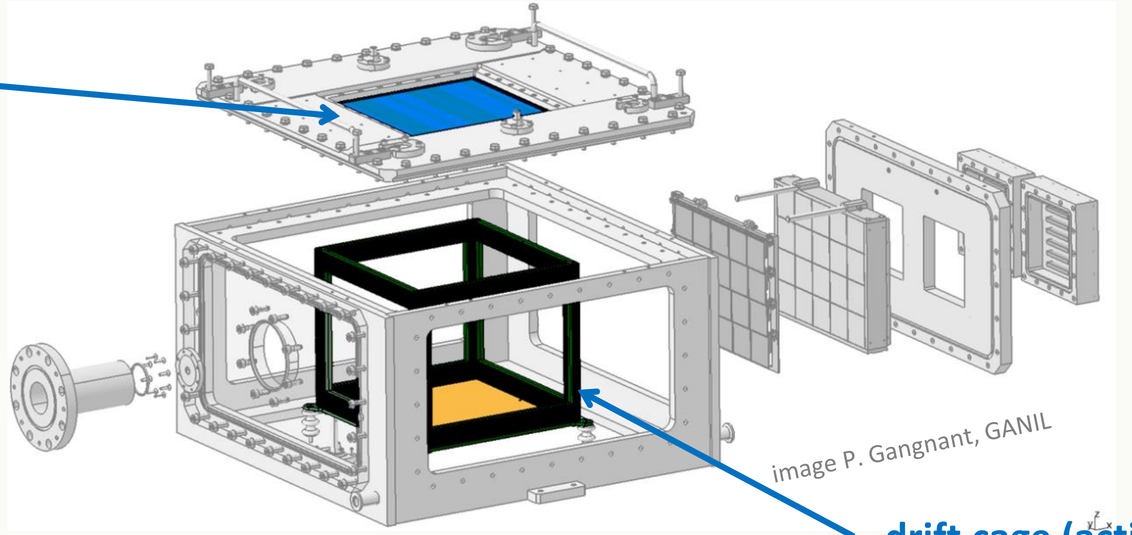
collection plane (pads)





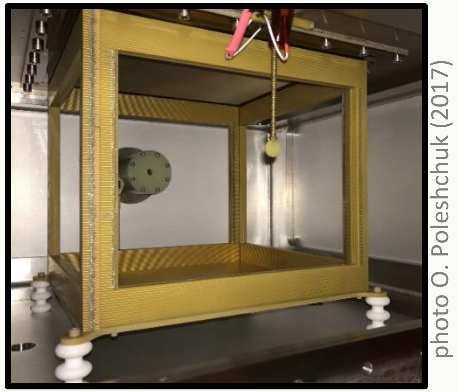
16384 pads
(128×128; 2×2 mm²)

metal-core or
multi-layer PCB

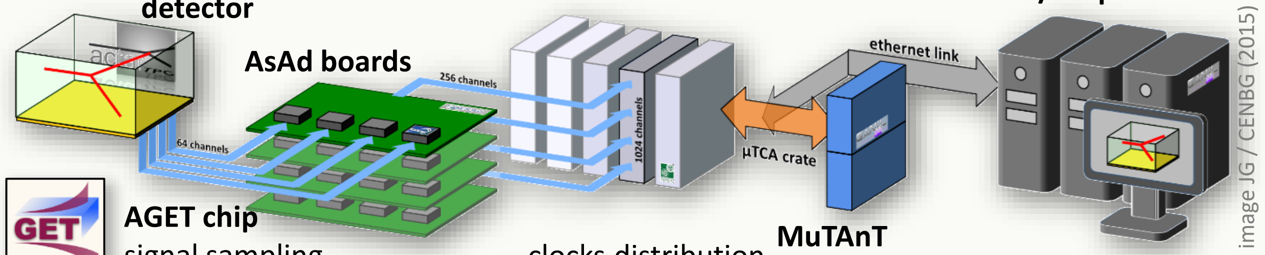


drift cage (active volume)

+ flexible PCB connection to readout electronics



readout electronics



AGET chip
signal sampling
512 @ 1-100 *MHz*

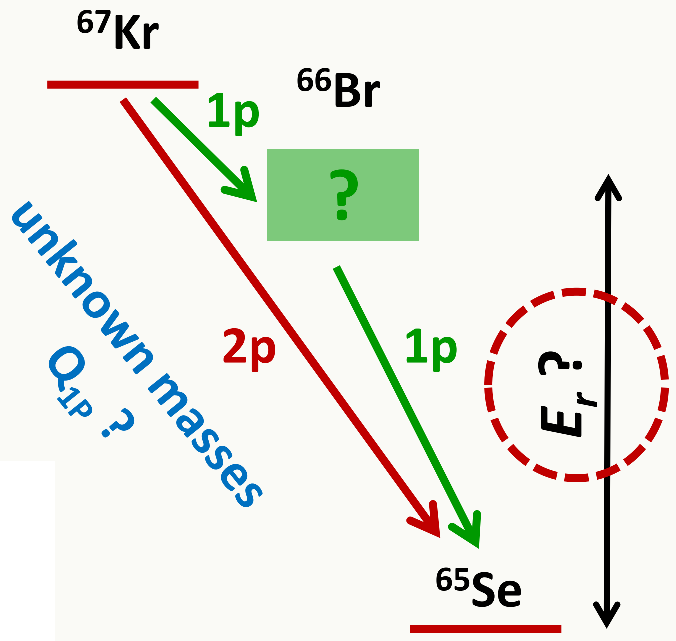
clocks distribution
and data concentration

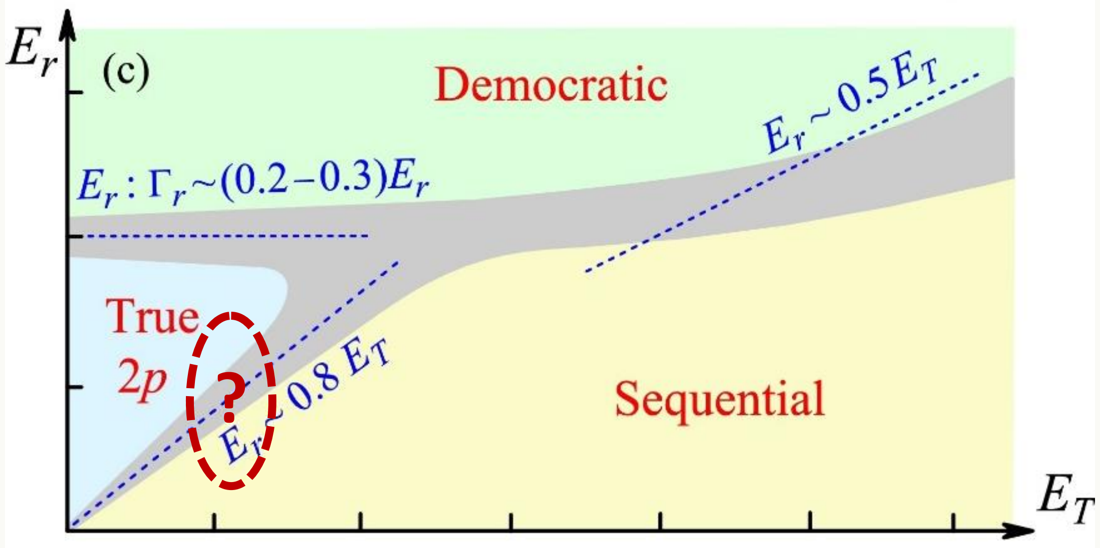
decay experiments (GANIL/LISE)

2019: proton radioactivity of ^{54m}Ni and isospin symmetry (^{54m}Fe)
2021: 2-proton radioactivity of ^{48}Ni & other exotic decays

first hypothesis: transition from 2P to sequential decay ?

- **possible transition region depending on intermediate state position**





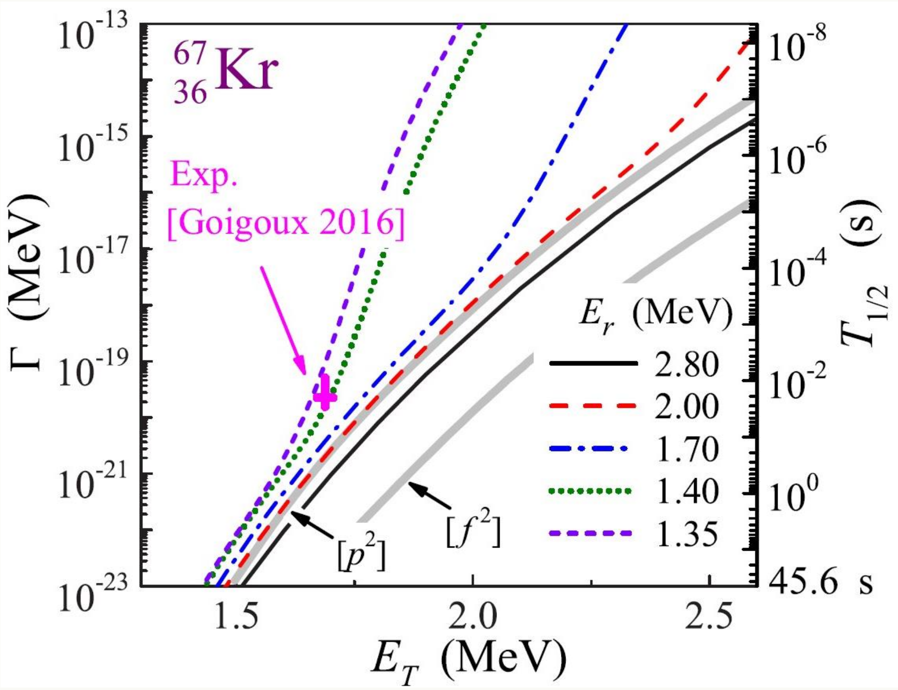
L. Grigorenko et al.
PRC 95 (2017) 021601(R)

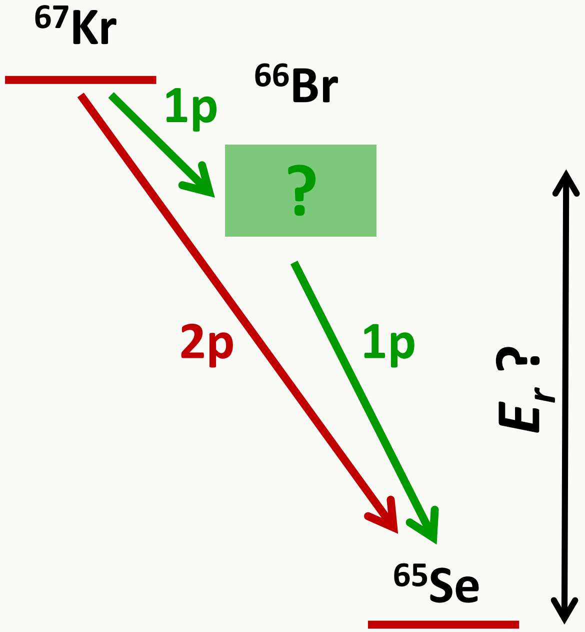
first hypothesis: transition from 2P to sequential decay ?

(L.V. Grigorenko, semi-analytical R-matrix calculation)

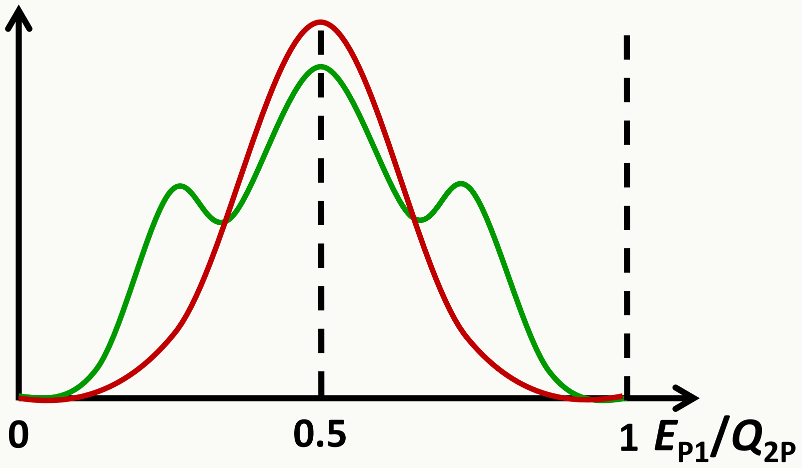
- indication of a 1p channel opening ?
- possible transition from 2P to seq. emission
  transition region: S_p = [−340 ; −270] *keV*

L. Grigorenko et al.
PRC 95 (2017) 021601(R)

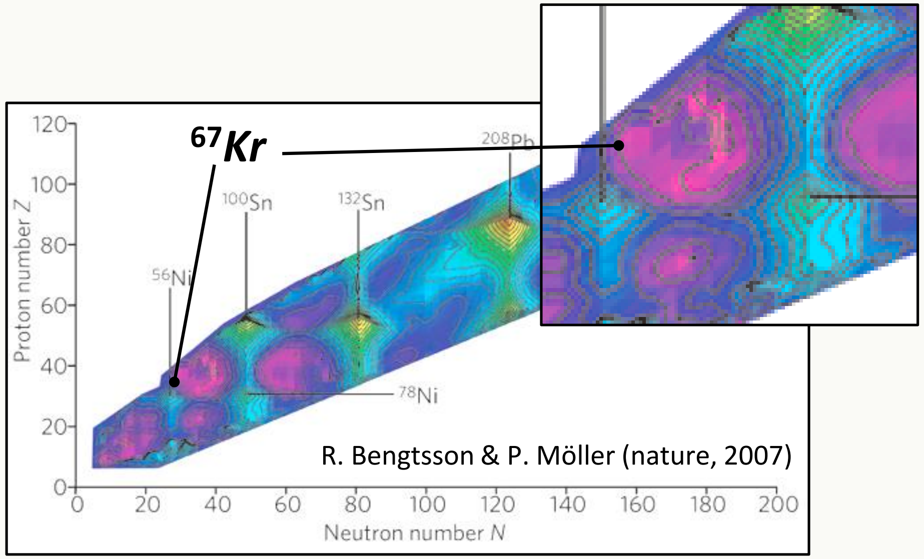


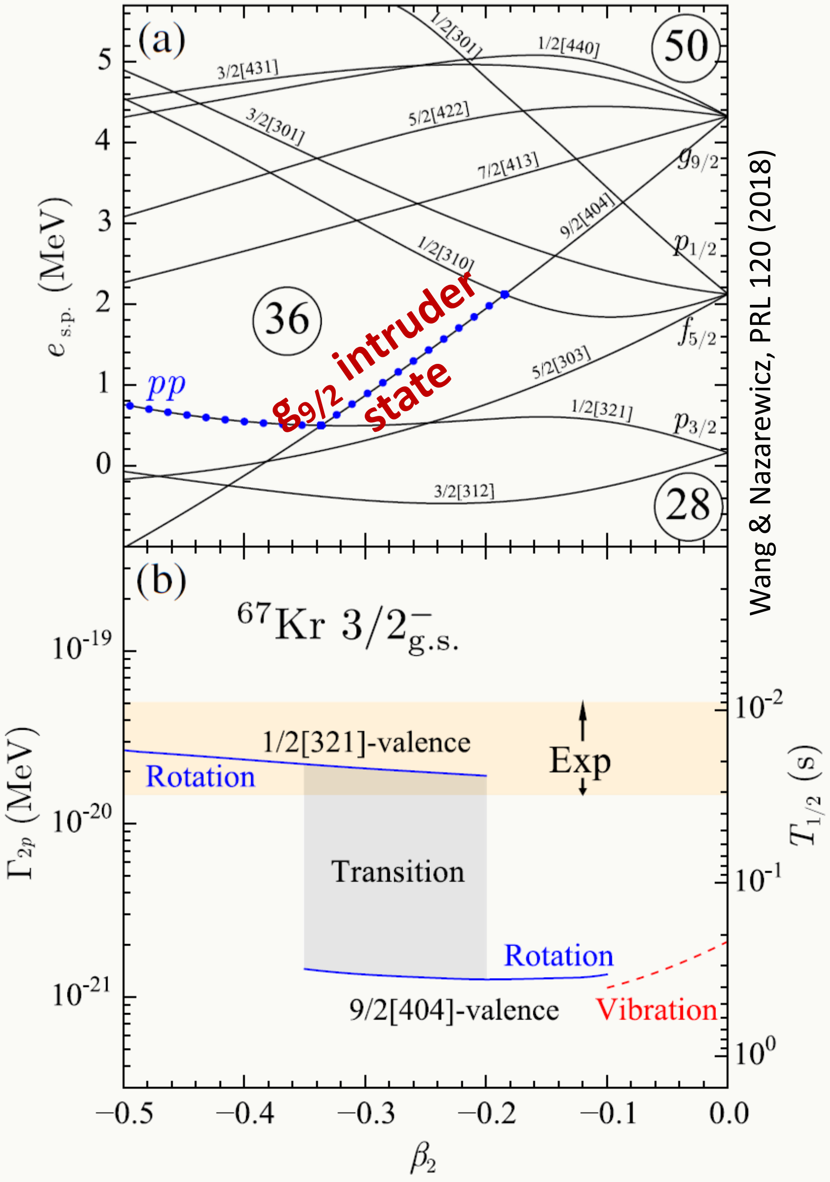


energy sharing pattern
(correlations)



second hypothesis: influence of deformation ?





calculations by Wang & Nazarewicz, PRL 120 (2018)
(**Gamow Coupled Channels + coupling to core exc.**)

with $|\boldsymbol{\beta_2}| < \mathbf{0.1}$ → $\boldsymbol{T^{2P}_{1/2}} > \mathbf{220}\ ms$

with $\boldsymbol{\beta_2} = \mathbf{-0.3}$ → $\boldsymbol{T^{2P}_{1/2}} = \mathbf{24^{+10}_{-7}}\ ms$
agreement with exp. !

+ angular correlation prediction
(consistent treatment of structure and emission dynamics)

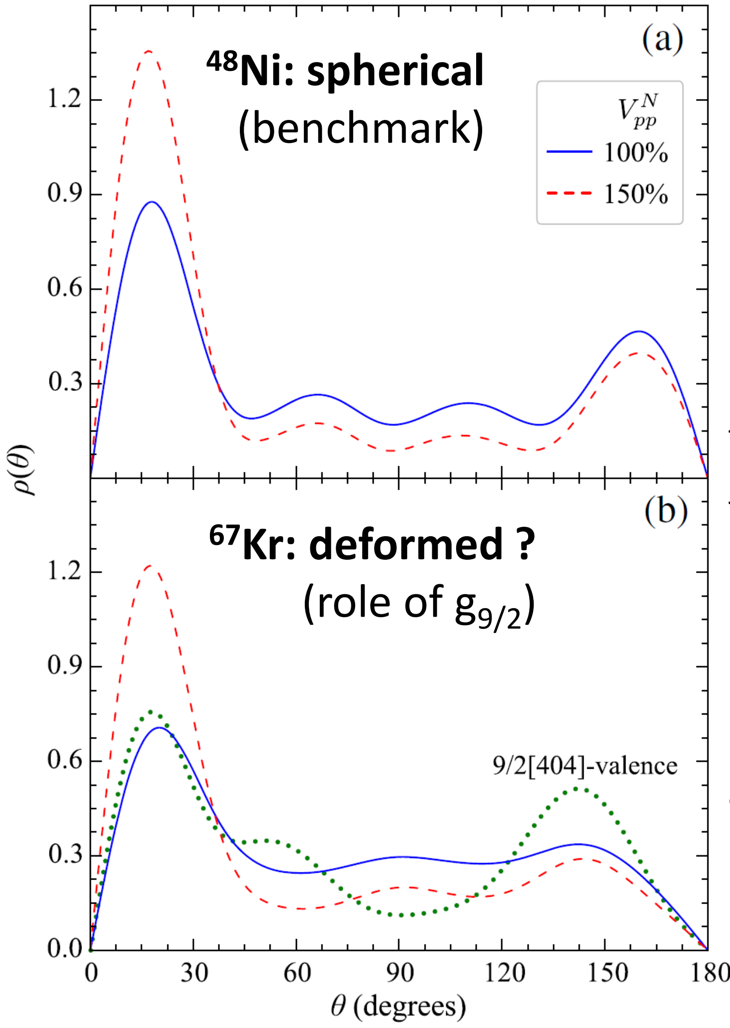
second hypothesis: influence of deformation ?

angular correlation prediction

recent work by Wang & Nazarewicz, PRL 120 (2018)
(**Gamow Coupled Channels + coupling to core exc.**)

with $|\boldsymbol{\beta}_2| < \mathbf{0.1}$ → $\boldsymbol{T}^{2P}_{1/2} > \mathbf{220}\ ms$

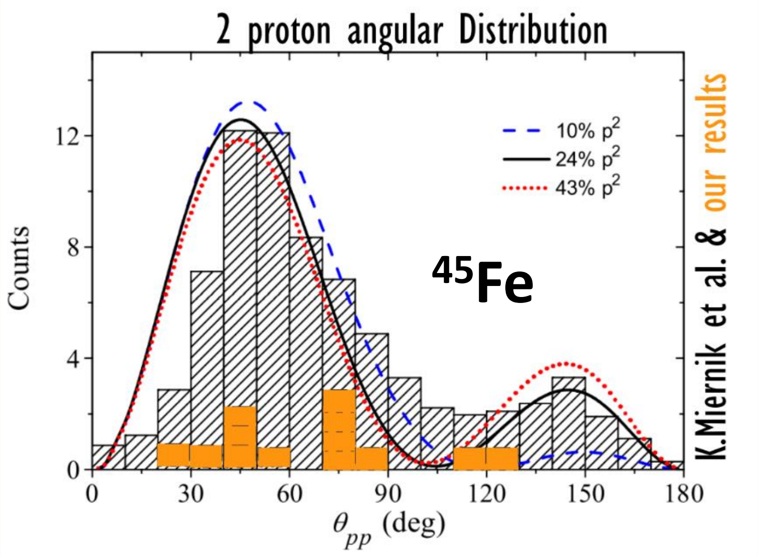
with $\boldsymbol{\beta}_2 = -\mathbf{0.3}$ → $\boldsymbol{T}^{2P}_{1/2} = \mathbf{24}^{+10}_{-7}\ ms$
agreement with exp. !

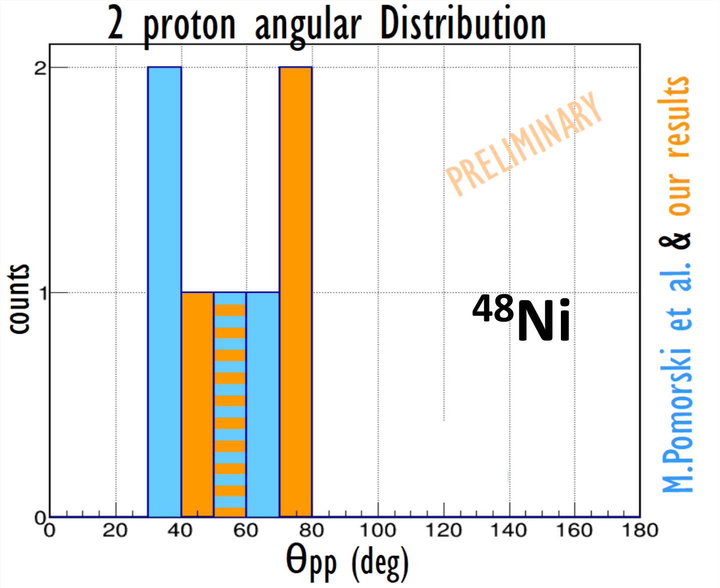


Wang & Nazarewicz, PRL 120 (2018)

2-proton radioactivity events

courtesy of A. Ortega Moral





low additional statistics

^{45}Fe

agreement with previous distribution

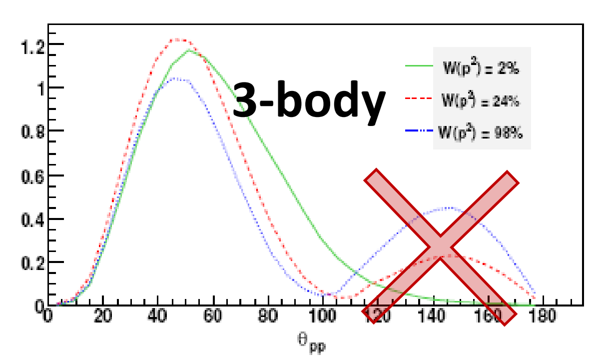
no significant change

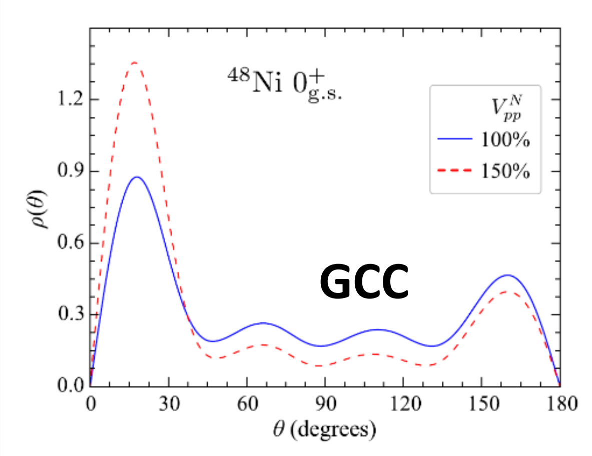
side product of the experiment

^{48}Ni

limited comparison with theory

but…





measurement for ^{67}Kr required !

(→ RIKEN)