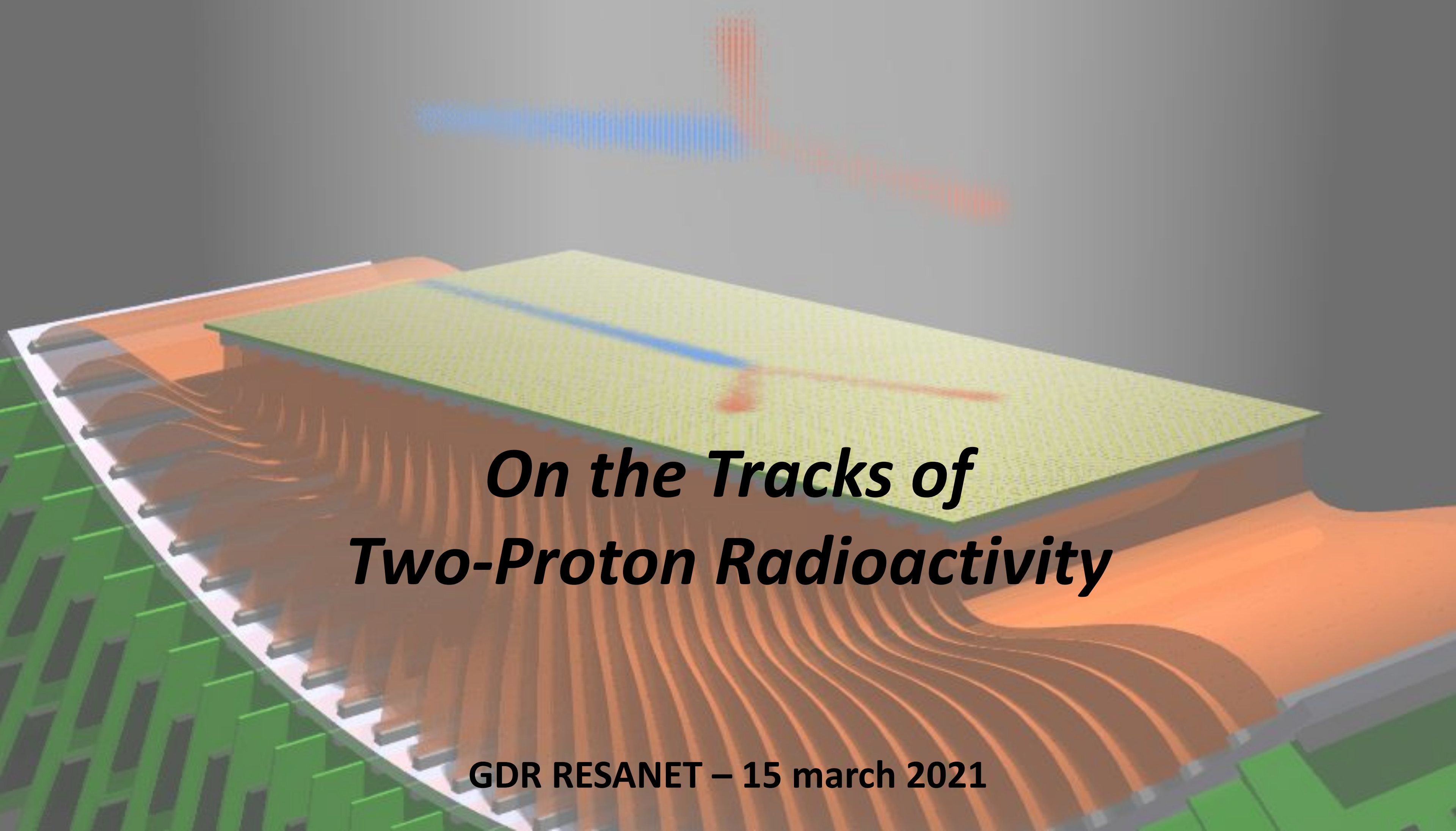
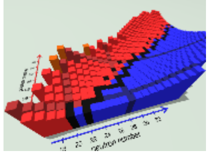
J. Giovinazzo – CENBG / IN2P3



On the Tracks of Two-Proton Radioactivity

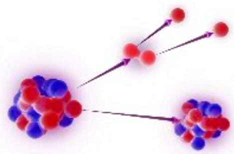
GDR RESANET – 15 march 2021

On the Tracks of Two-Proton Radioactivity

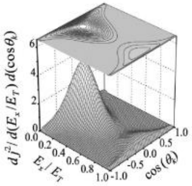


radioactivity on the neutron-deficient side of the table of isotopes

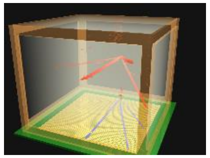
proton-rich



what is two-proton radioactivity?

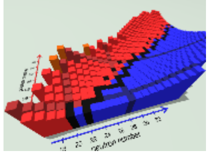


loops between theory and experiment



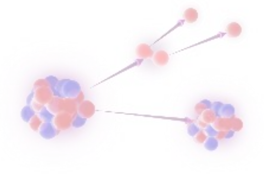
a new tracking device

On the Tracks of Two-Proton Radioactivity

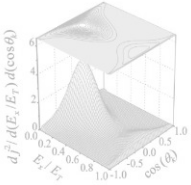


radioactivity on the neutron-deficient side of the table of isotopes

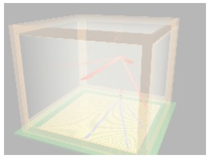
proton-rich



what is two-proton radioactivity?



loops between theory and experiment



a new tracking device

about radioactivity

an story started 120 years ago

1895	discovery of X rays	W. Röntgen
1896	radiation from Uranium	H. Becquerel
1898	**α** and **β** emissions	M. Curie, E. Rutherford
…	development of the atomic nucleus description theory of **β** radioactivity	W. Pauli, N. Bohr, …
1932	discovery of the neutron	J. Chadwick
1934	artificial radioactivity ($\boldsymbol{\beta}^+$)	I. Curie, F. Joliot
1938	spontaneous fission	L. Meitner, O. Hahn, R. Frisch, F. Strassman
…		

webinar from A. Lopez-Martens (30/11/2020)

what is radioactivity?

spontaneous **transformation** of the **atomic nucleus** into a more **stable** system

→ like any system in physics

release of energy ↔ gain of stability

↕

mass

the valley of beta stability

binding energy

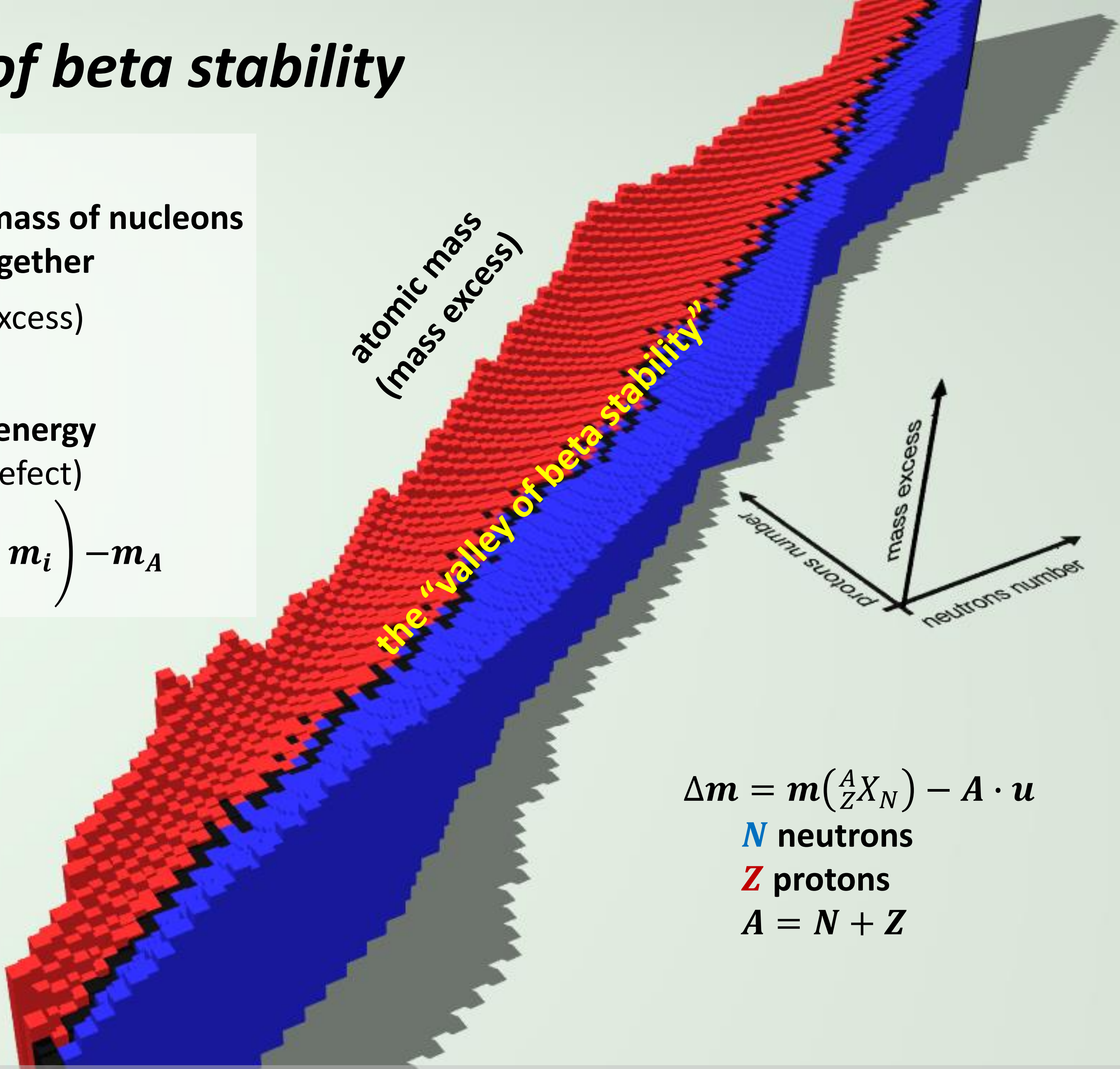
fraction of the mass of nucleons
to bind them together

mass (excess)

⇳

binding energy
(mass defect)

$$B(A) = \left(\sum_{A} m_i\right) - m_A$$



$$\Delta m = m\left({}^{A}_{Z}X_{N}\right) - A \cdot u$$

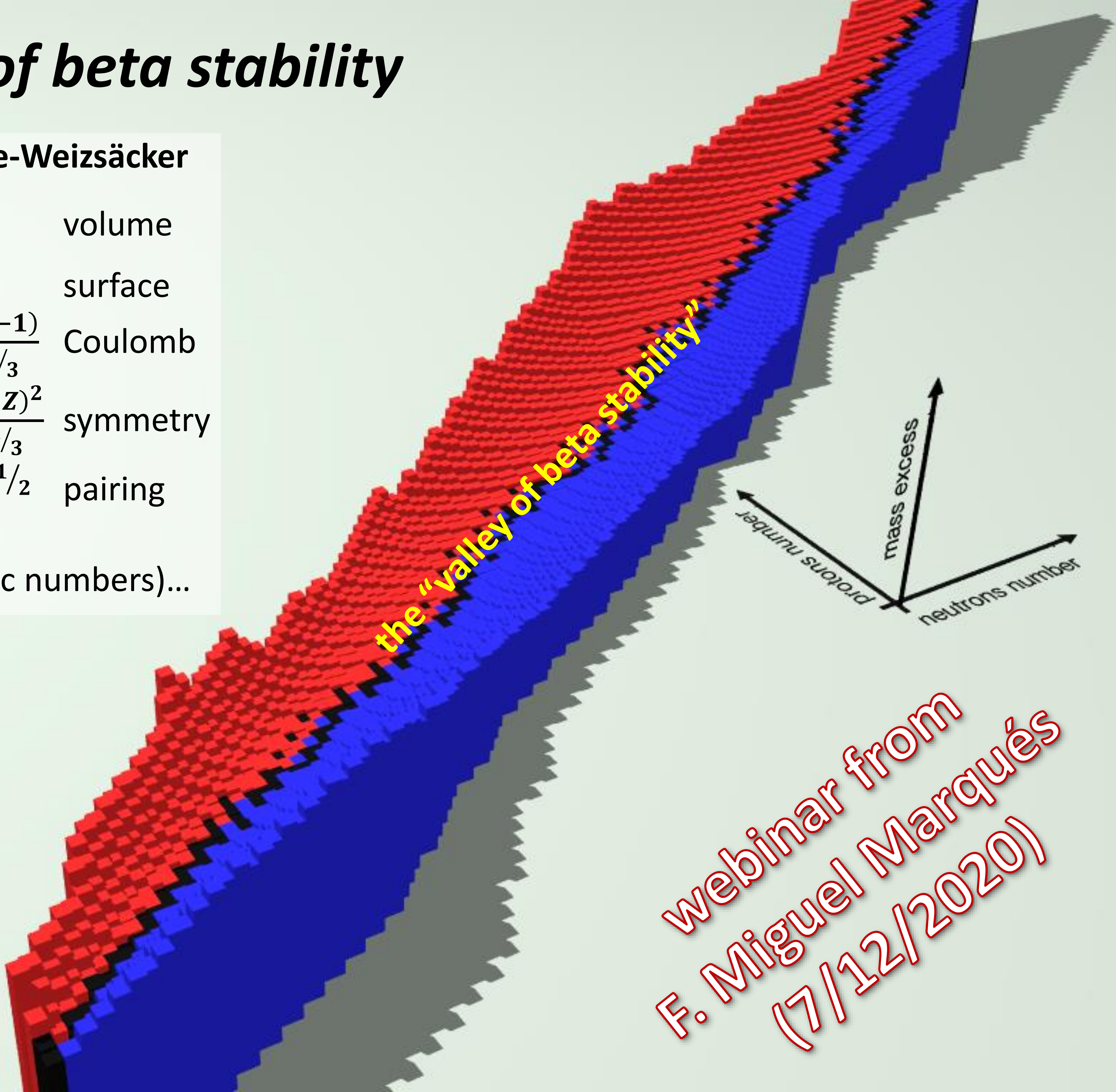
N **neutrons**
Z **protons**
$A = N + Z$

the valley of beta stability

binding energy: Bethe-Weizsäcker

$$\begin{aligned} \boldsymbol{B(A,Z)} &= \boldsymbol{a_v \cdot A} && \text{volume} \\ &- \boldsymbol{a_s \cdot A^{\frac{2}{3}}} && \text{surface} \\ &- \boldsymbol{a_c \cdot \frac{Z(Z-1)}{A^{1/3}}} && \text{Coulomb} \\ &- \boldsymbol{a_a \cdot \frac{(N-Z)^2}{A^{1/3}}} && \text{symmetry} \\ &\pm \boldsymbol{a_p \cdot A^{-1/2}} && \text{pairing} \end{aligned}$$

+ shell effects (magic numbers)…



webinar from F. Miguel Marqués (7/12/2020)

the valley of beta stability

binding energy: Bethe-Weizsäcker

$$\begin{aligned} B(A,Z) &= a_v \cdot A && \text{volume} \\ &- a_s \cdot A^{\frac{2}{3}} && \text{surface} \\ &- a_c \cdot \frac{Z(Z-1)}{A^{1/3}} && \text{Coulomb} \\ &- a_a \cdot \frac{(N-Z)^2}{A^{1/3}} && \text{symmetry} \\ &\pm a_p \cdot A^{-1/2} && \text{pairing} \end{aligned}$$

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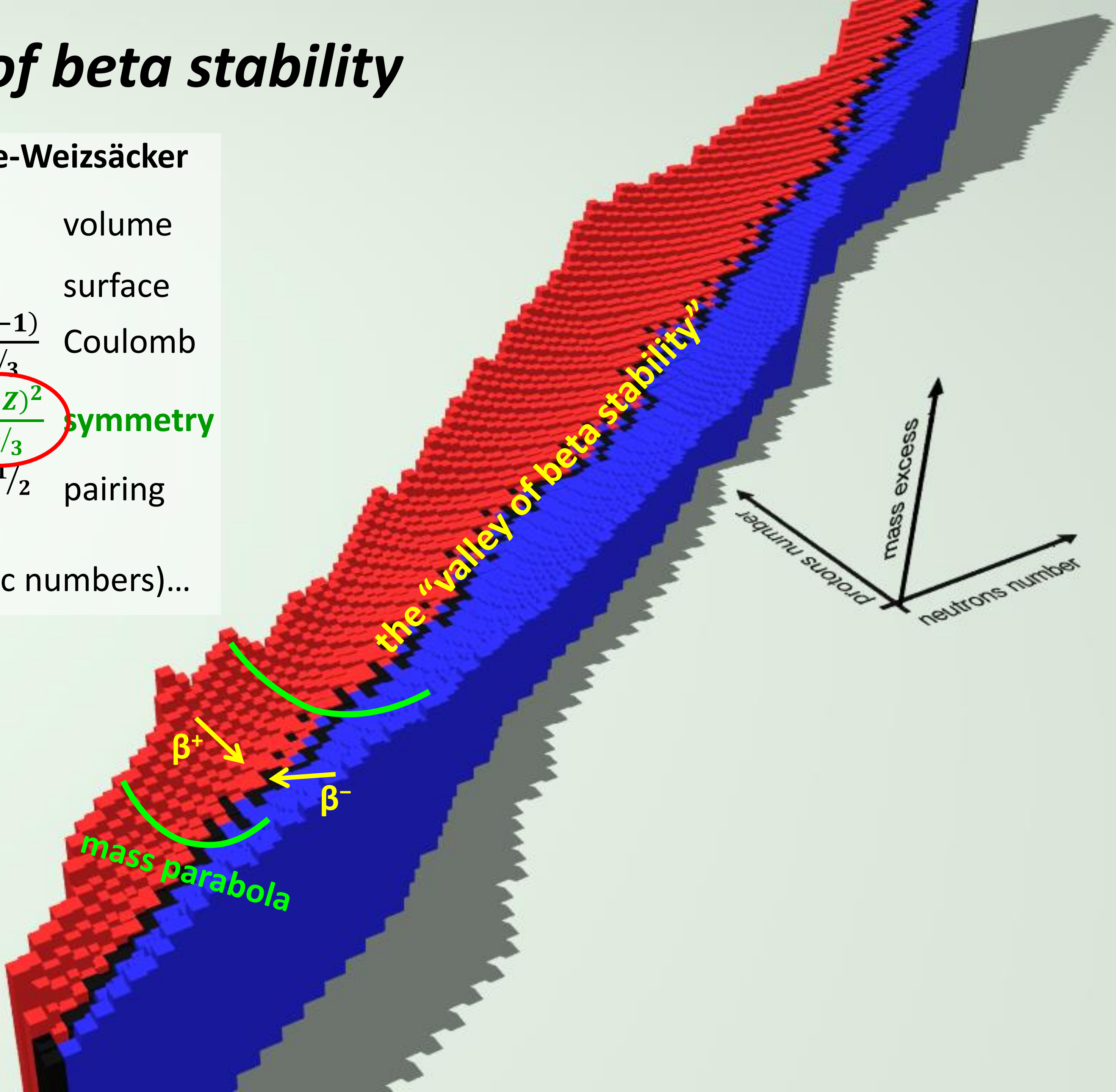
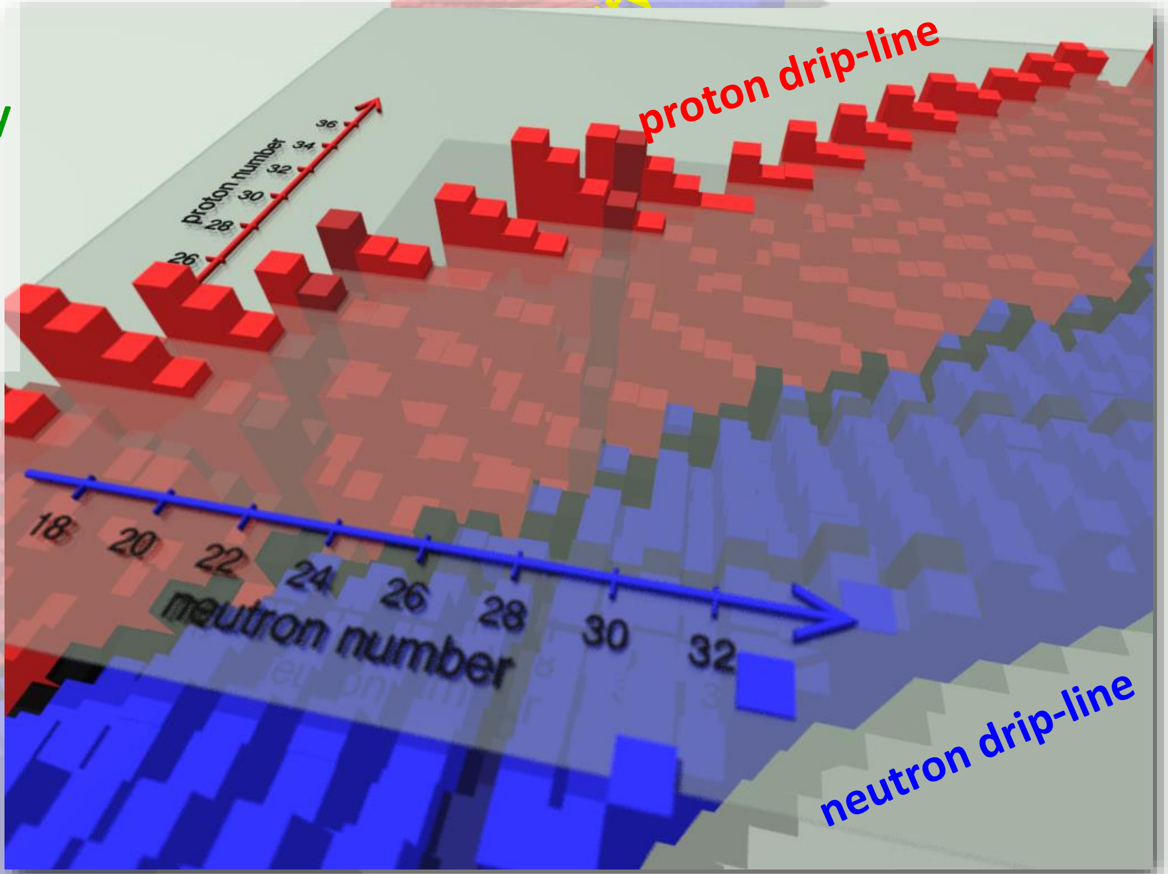


drip-lines: the frontiers of the table of isotopes

binding energy: Bethe-Weizsäcker

$$\begin{array}{lll} B(A,Z) & = a_v \cdot A & \text{volume} \\ & - a_s \cdot A^{\frac{2}{3}} & \text{surface} \\ & - a_c \cdot \frac{Z(Z-1)}{A^{1/3}} & \text{Coulomb} \\ & - a_a \cdot \frac{(N-Z)^2}{A^{1/3}} & \textbf{symmetry} \\ & \pm a_p \cdot A^{-1/2} & \text{pairing} \end{array}$$

+ shell effects (magic numbers)…

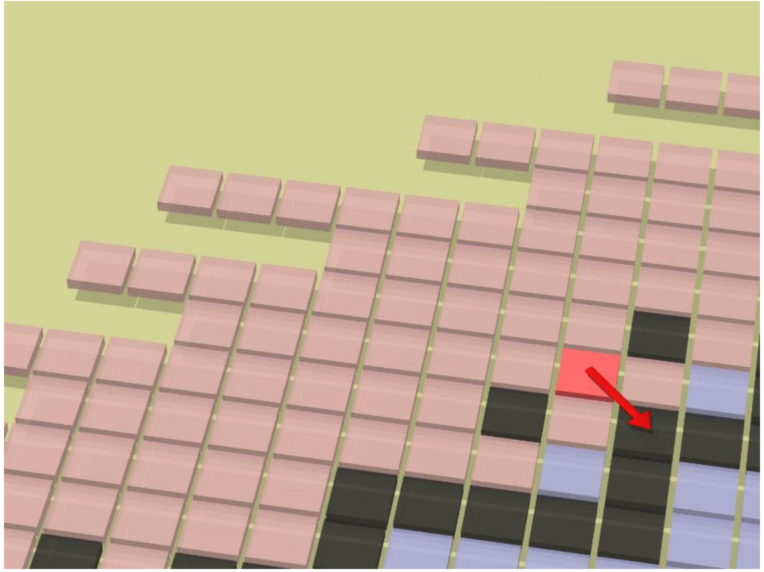


drip-lines

B(*A*,*Z*) < 0

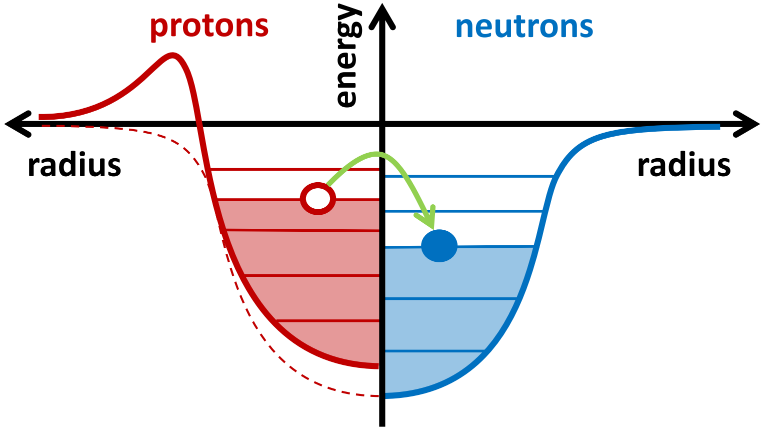
unbound / nuclear force

towards the proton drip-line



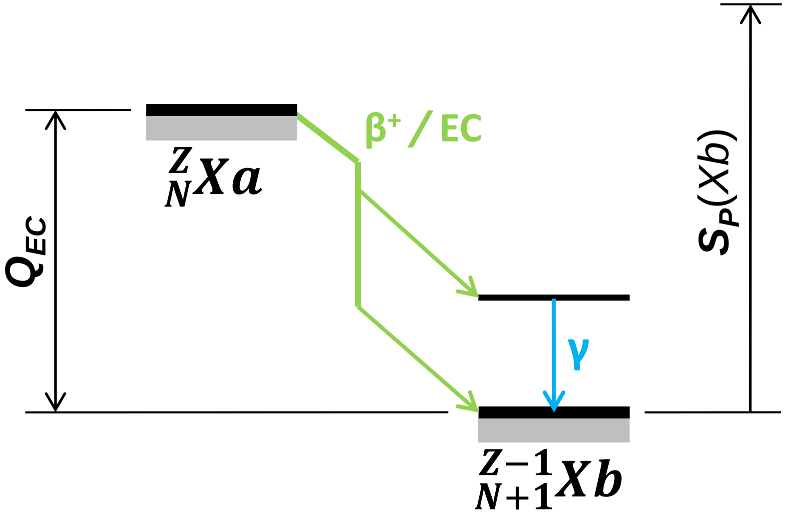
β decay (β^+/EC):

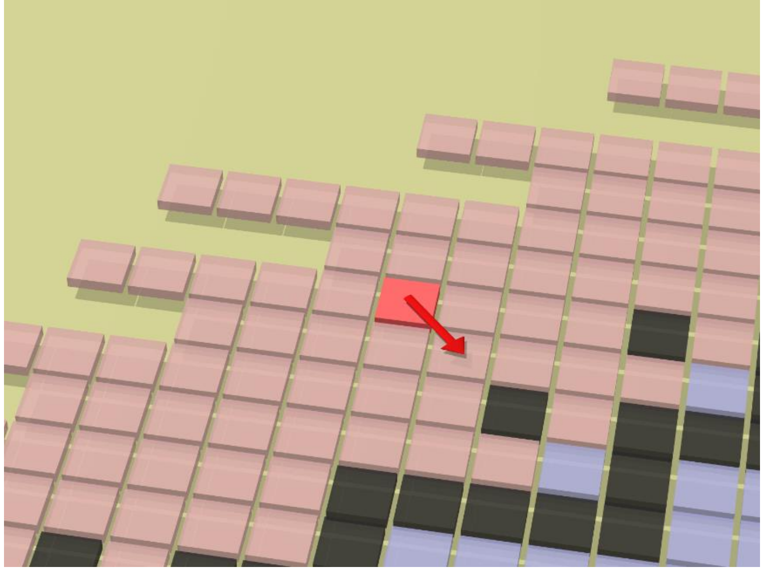
- spectroscopy and nuclear structure

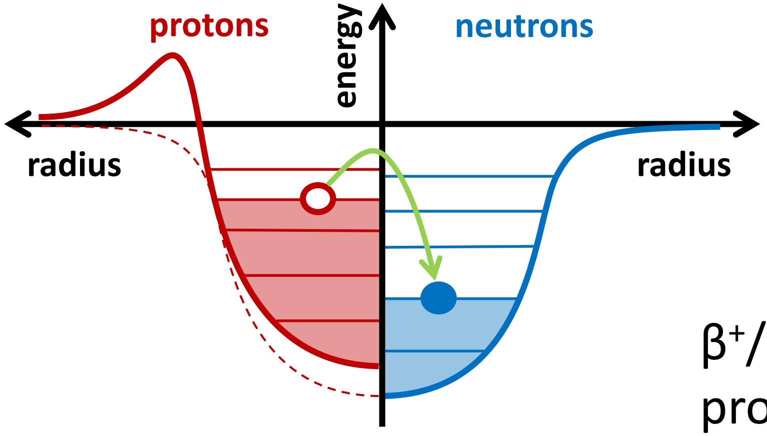


towards the proton drip-line

β and β-γ decays





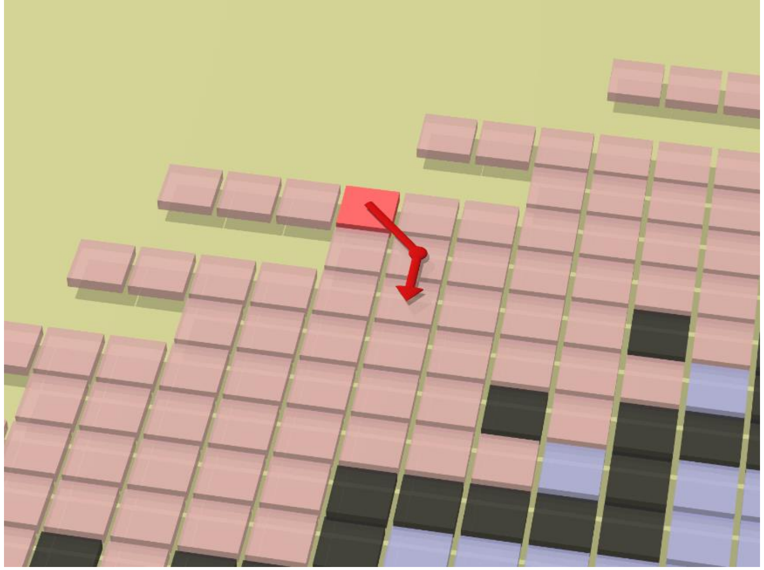


- spectroscopy and nuclear structure
- precision tests of weak interaction

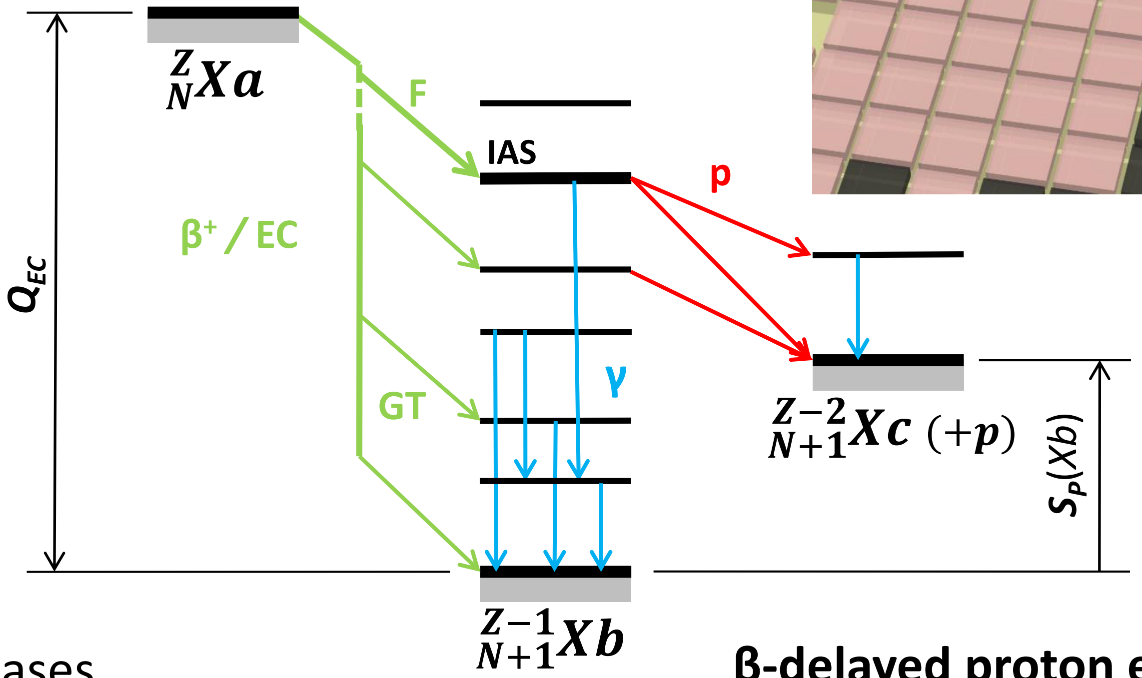
β^+/EC decay energy: $\boldsymbol{Q_{EC}} \sim$ few *MeV*

proton separation: $\boldsymbol{S_P}(Xb) > \boldsymbol{Q_{EC}}$ (*B*/*A* ~8 *MeV*)

towards the proton drip-line



β-delayed proton emission



Q_{EC} increases

$S_P(Xb)$ decreases

β-delayed proton emission:

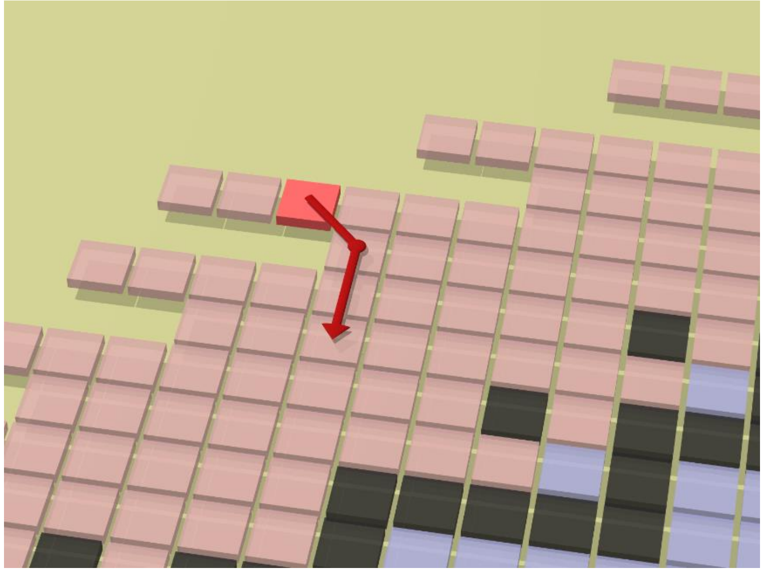
- nuclear astrophysics
- gamma / proton competition

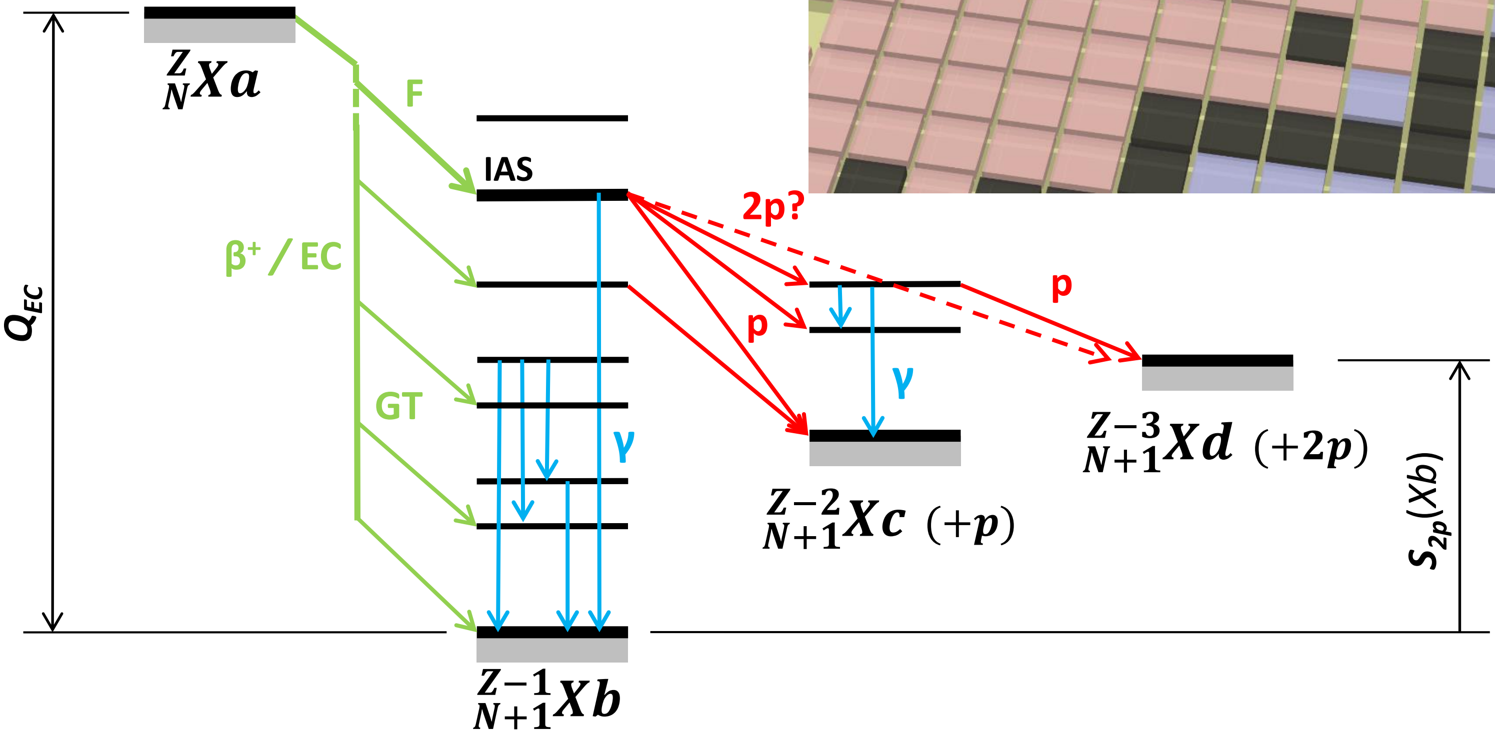
proton transitions: precise probe

towards the proton drip-line

β-delayed multi- proton emission:

- *rp*-process waiting points
- search for direct 2P emission



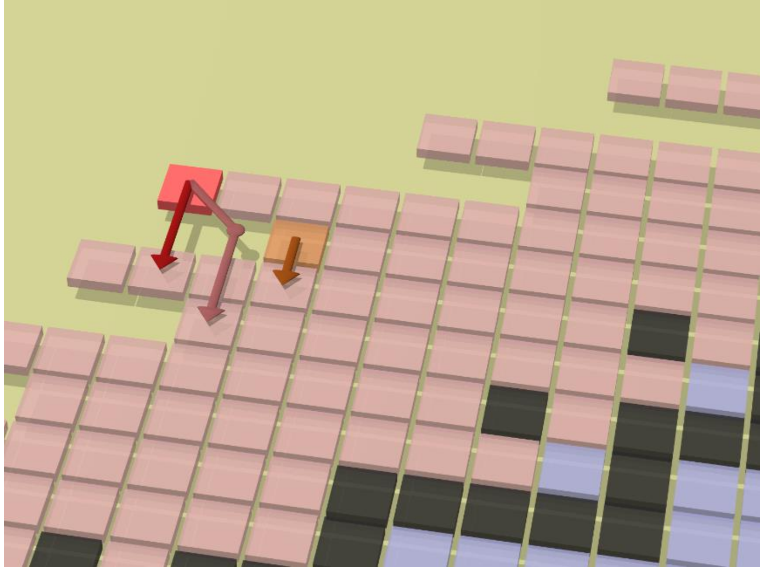


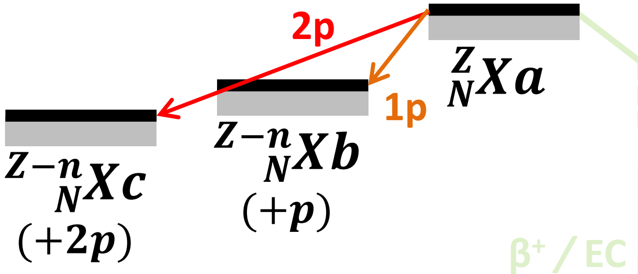
- often the only access to very exotic isotopes
- complex proton emission patterns: level densities & statistical aspects

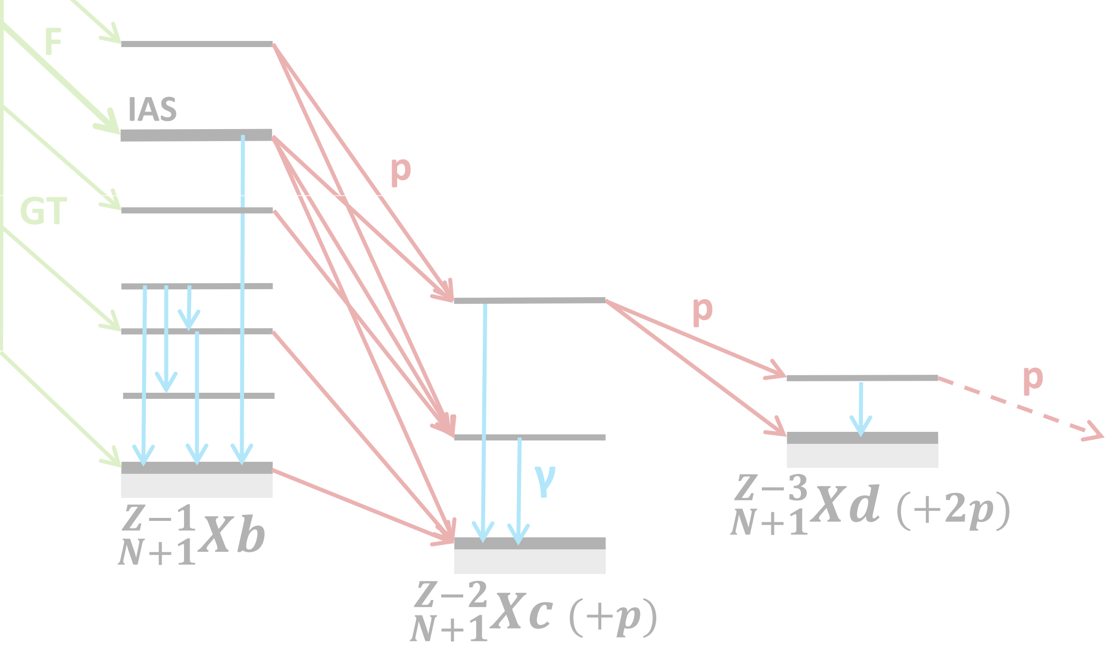
towards the proton drip-line

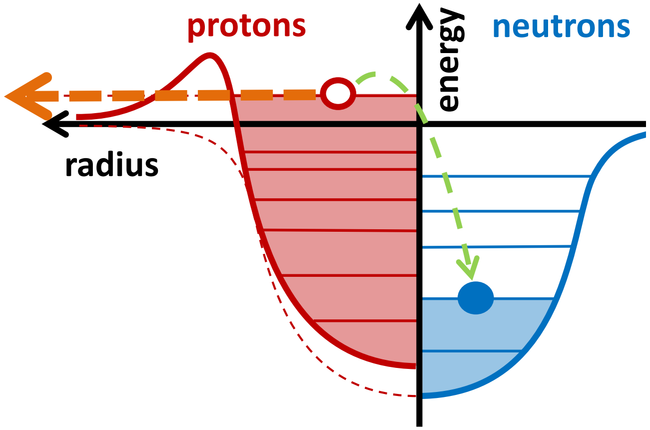
unbound with respect to proton(s) emission

$S_p(Xa) < 0$ and/or $S_{2P}(Xa) < 0$

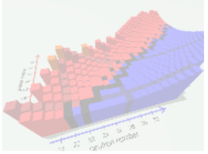






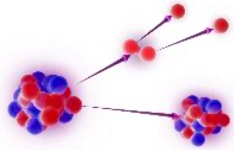


On the Tracks of Two-Proton Radioactivity

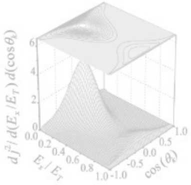


radioactivity on the neutron-deficient side of the table of isotopes

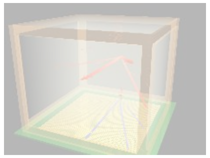
proton-rich



what is two-proton radioactivity?



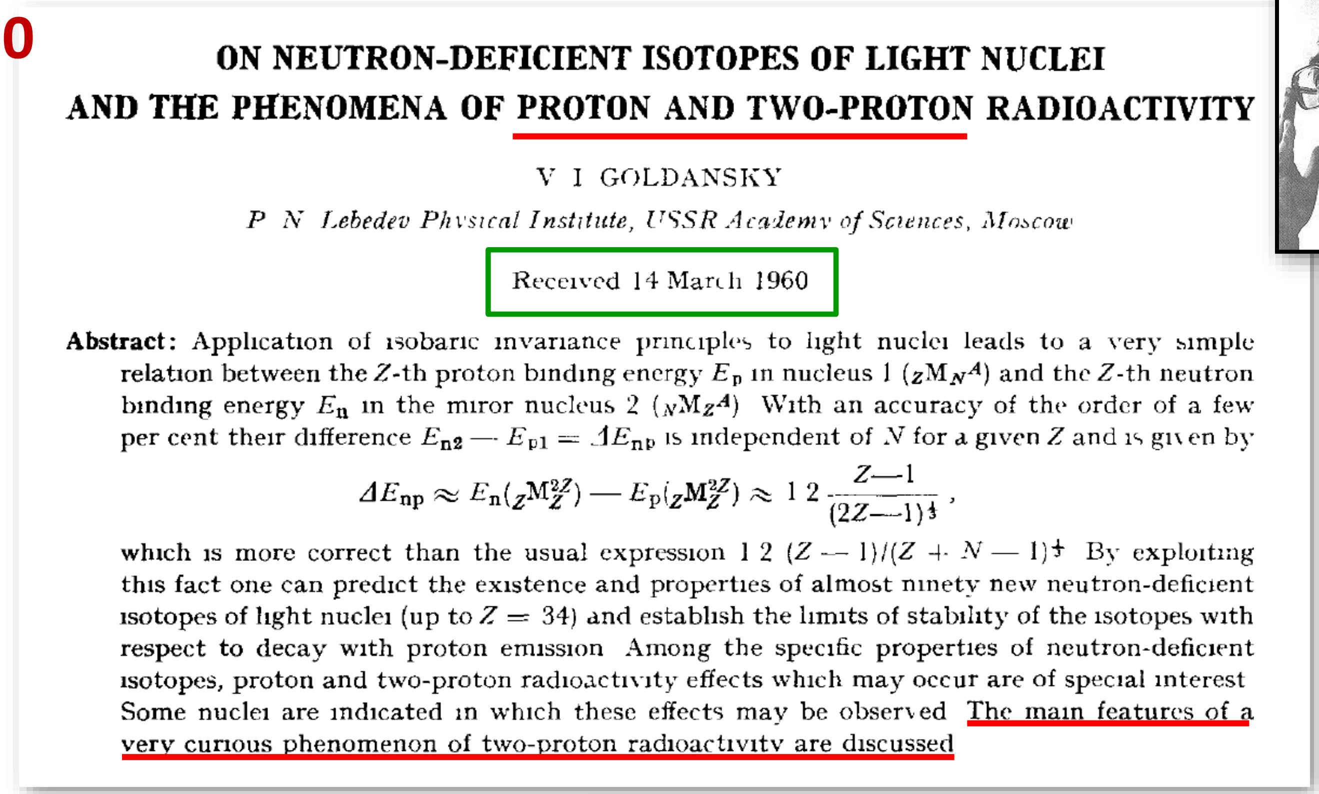
loops between theory and experiment



a new tracking device

first theoretical predictions

1960



ON NEUTRON-DEFICIENT ISOTOPES OF LIGHT NUCLEI AND THE PHENOMENA OF PROTON AND TWO-PROTON RADIOACTIVITY

V. I. GOLDANSKY

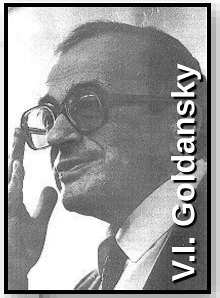
P. N. Lebedev Physical Institute, USSR Academy of Sciences, Moscow

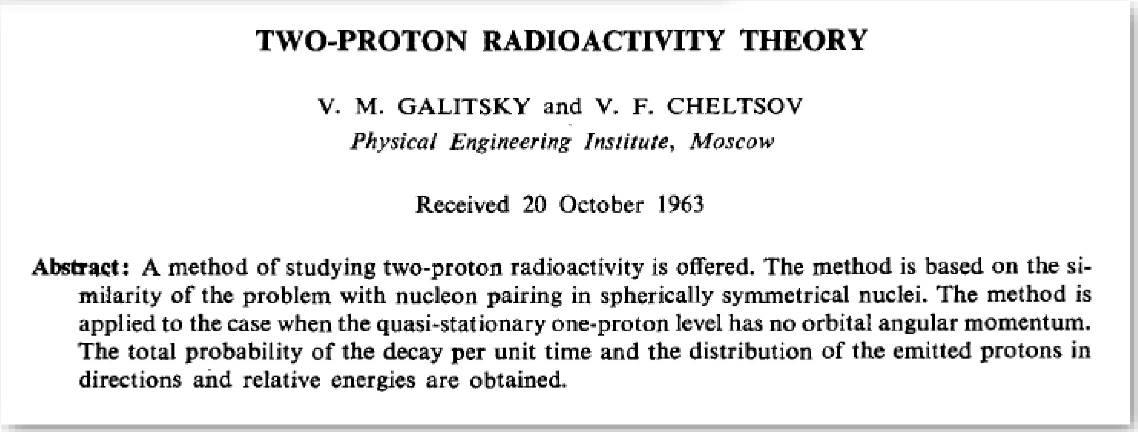
Received 14 March 1960

Abstract: Application of isobaric invariance principles to light nuclei leads to a very simple relation between the Z-th proton binding energy E_p in nucleus 1 (${}_Z M_N{}^A$) and the Z-th neutron binding energy E_n in the miror nucleus 2 (${}_N M_Z{}^A$). With an accuracy of the order of a few per cent their difference $E_{n2} - E_{p1} = \Delta E_{np}$ is independent of N for a given Z and is given by

$$\Delta E_{np} \approx E_n({}_Z M_Z^{2Z}) - E_p({}_Z M_Z^{2Z}) \approx 1.2 \frac{Z-1}{(2Z-1)^{\frac{1}{3}}},$$

which is more correct than the usual expression $1.2\,(Z-1)/(Z+N-1)^{\frac{1}{3}}$. By exploiting this fact one can predict the existence and properties of almost ninety new neutron-deficient isotopes of light nuclei (up to $Z = 34$) and establish the limits of stability of the isotopes with respect to decay with proton emission. Among the specific properties of neutron-deficient isotopes, proton and two-proton radioactivity effects which may occur are of special interest. Some nuclei are indicated in which these effects may be observed. The main features of a very curious phenomenon of two-proton radioactivity are discussed.


V.I. Goldansky



TWO-PROTON RADIOACTIVITY THEORY

V. M. GALITSKY and V. F. CHELTSOV

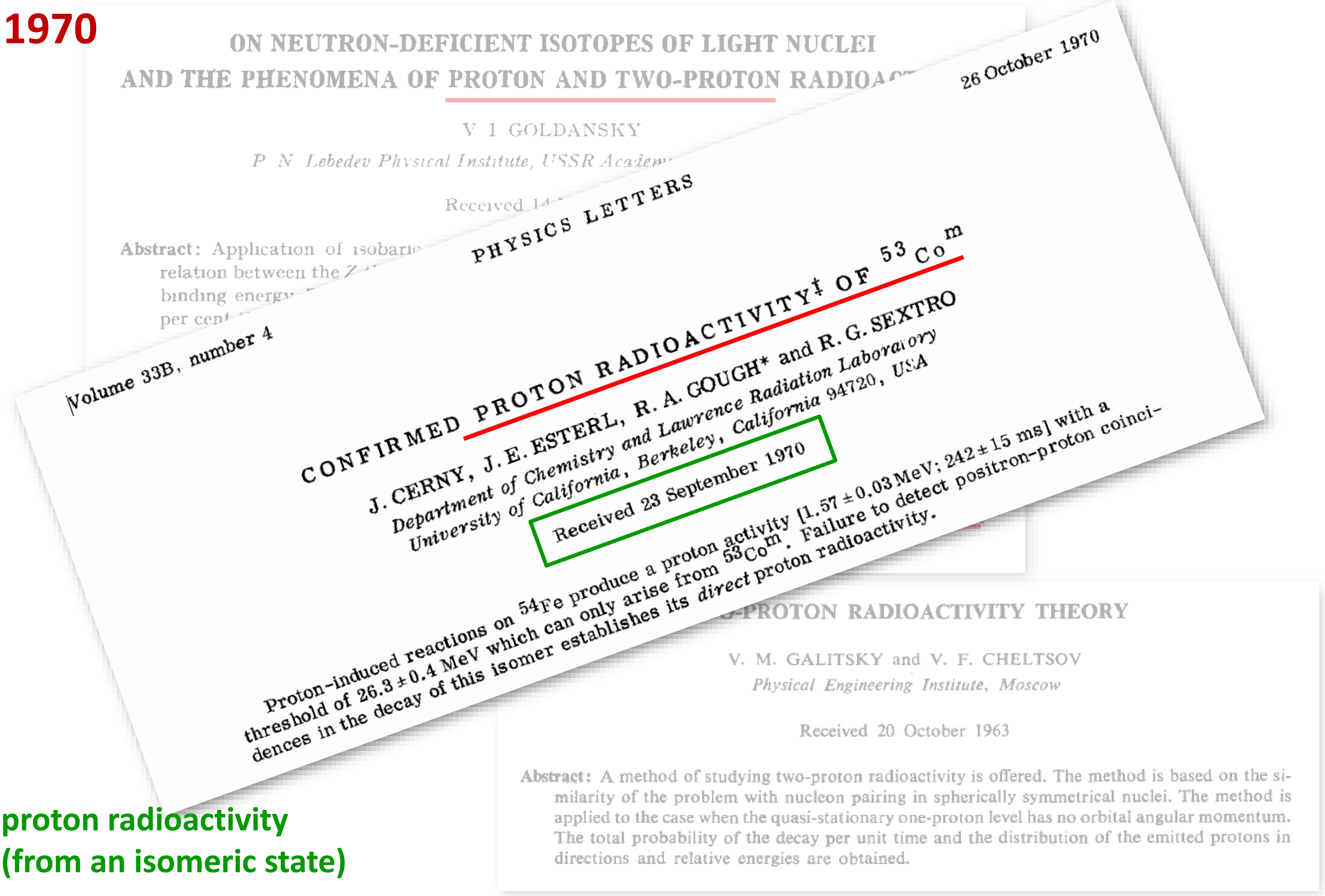
Physical Engineering Institute, Moscow

Received 20 October 1963

Abstract: A method of studying two-proton radioactivity is offered. The method is based on the similarity of the problem with nucleon pairing in spherically symmetrical nuclei. The method is applied to the case when the quasi-stationary one-proton level has no orbital angular momentum. The total probability of the decay per unit time and the distribution of the emitted protons in directions and relative energies are obtained.

first observations

1970



ON NEUTRON-DEFICIENT ISOTOPES OF LIGHT NUCLEI
AND THE PHENOMENA OF PROTON AND TWO-PROTON RADIOA

V I GOLDANSKY

P N Lebedev Physical Institute, USSR Academ

Received 14

Abstract: Application of isobaric
relation between the Z
binding energy
per cent

---

26 October 1970 PHYSICS LETTERS Volume 33B, number 4

CONFIRMED PROTON RADIOACTIVITY‡ OF ^{53}Co^{m}

J. CERNY, J. E. ESTERL, R. A. GOUGH* and R. G. SEXTRO
Department of Chemistry and Lawrence Radiation Laboratory
University of California, Berkeley, California 94720, USA

Received 23 September 1970

Proton-induced reactions on ^{54}Fe produce a proton activity [1.57 ± 0.03 MeV; 242 ± 15 ms] with a threshold of 26.3 ± 0.4 MeV which can only arise from ^{53}Co^{m}. Failure to detect positron-proton coincidences in the decay of this isomer establishes its *direct* proton radioactivity.

-PROTON RADIOACTIVITY THEORY

V. M. GALITSKY and V. F. CHELTSOV
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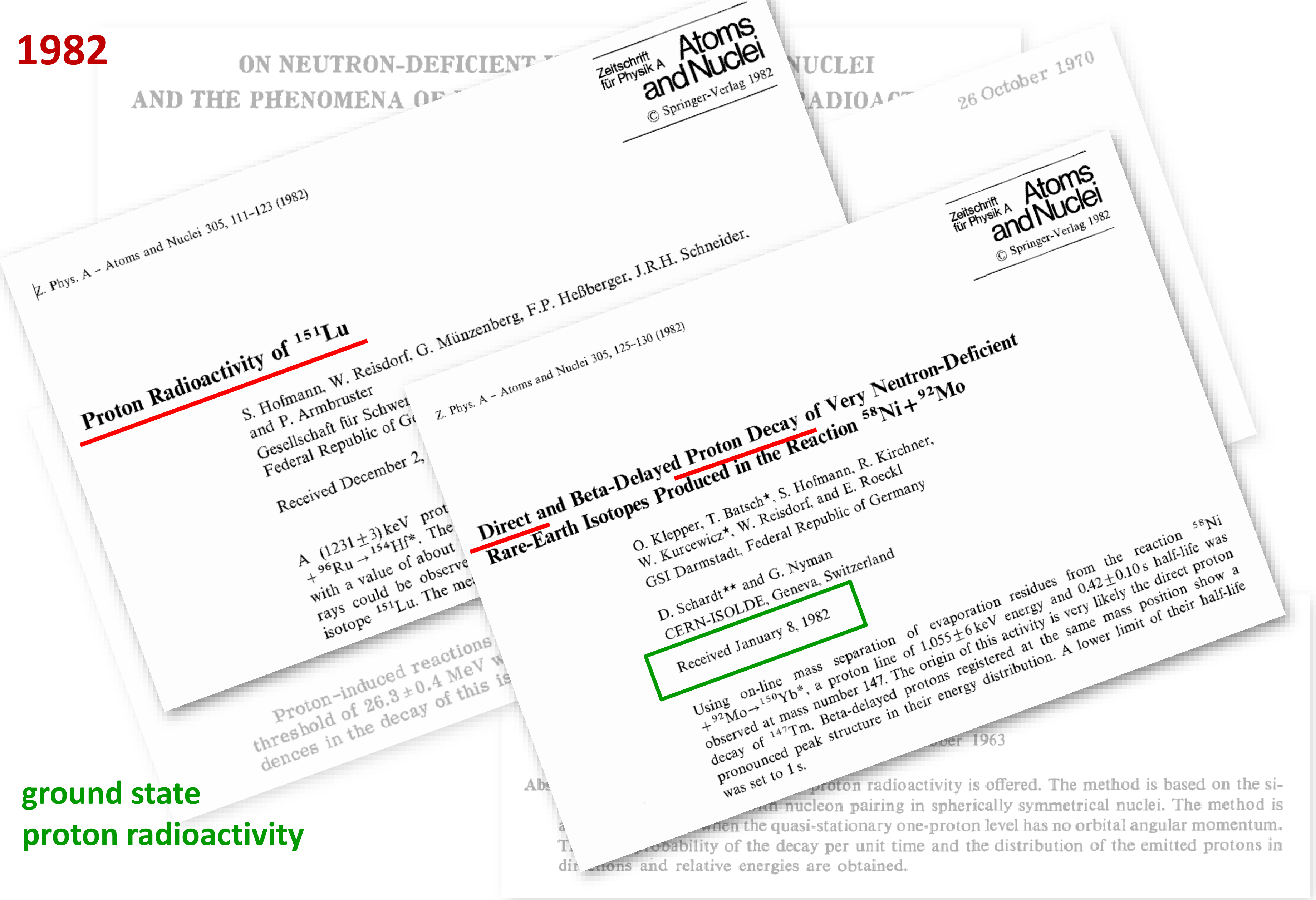
Abstract: A method of studying two-proton radioactivity is offered. The method is based on the similarity of the problem with nucleon pairing in spherically symmetrical nuclei. The method is applied to the case when the quasi-stationary one-proton level has no orbital angular momentum. The total probability of the decay per unit time and the distribution of the emitted protons in directions and relative energies are obtained.

---

proton radioactivity
(from an isomeric state)

first observations

1982



ON NEUTRON-DEFICIENT … NUCLEI
AND THE PHENOMENA OF … RADIOAC…

26 October 1970

Zeitschrift für Physik A
Atoms and Nuclei
© Springer-Verlag 1982

Z. Phys. A – Atoms and Nuclei 305, 111–123 (1982)

Proton Radioactivity of ^{151}Lu

S. Hofmann, W. Reisdorf, G. Münzenberg, F.P. Heßberger, J.R.H. Schneider,
and P. Armbruster
Gesellschaft für Schwer…
Federal Republic of Ge…

Received December 2, …

A (1231±3) keV prot…
+ ^{96}Ru → ^{154}Hf*. The…
with a value of about…
rays could be observe…
isotope ^{151}Lu. The me…

Zeitschrift für Physik A
Atoms and Nuclei
© Springer-Verlag 1982

Z. Phys. A – Atoms and Nuclei 305, 125–130 (1982)

Direct and Beta-Delayed Proton Decay of Very Neutron-Deficient Rare-Earth Isotopes Produced in the Reaction ^{58}Ni + ^{92}Mo

O. Klepper, T. Batsch*, S. Hofmann, R. Kirchner,
W. Kurcewicz*, W. Reisdorf, and E. Roeckl
GSI Darmstadt, Federal Republic of Germany

D. Schardt** and G. Nyman
CERN-ISOLDE, Geneva, Switzerland

Received January 8, 1982

Using on-line mass separation of evaporation residues from the reaction ^{58}Ni + ^{92}Mo → ^{150}Yb*, a proton line of 1,055 ± 6 keV energy and 0.42 ± 0.10 s half-life was observed at mass number 147. The origin of this activity is very likely the direct proton decay of ^{147}Tm. Beta-delayed protons registered at the same mass position show a pronounced peak structure in their energy distribution. A lower limit of their half-life was set to 1 s.

Proton-induced reactions
threshold of 26.3 ± 0.4 MeV w…
dences in the decay of this is…

…ber 1963

Ab… proton radioactivity is offered. The method is based on the si… nucleon pairing in spherically symmetrical nuclei. The method is a… when the quasi-stationary one-proton level has no orbital angular momentum. T… probability of the decay per unit time and the distribution of the emitted protons in dir…tions and relative energies are obtained.

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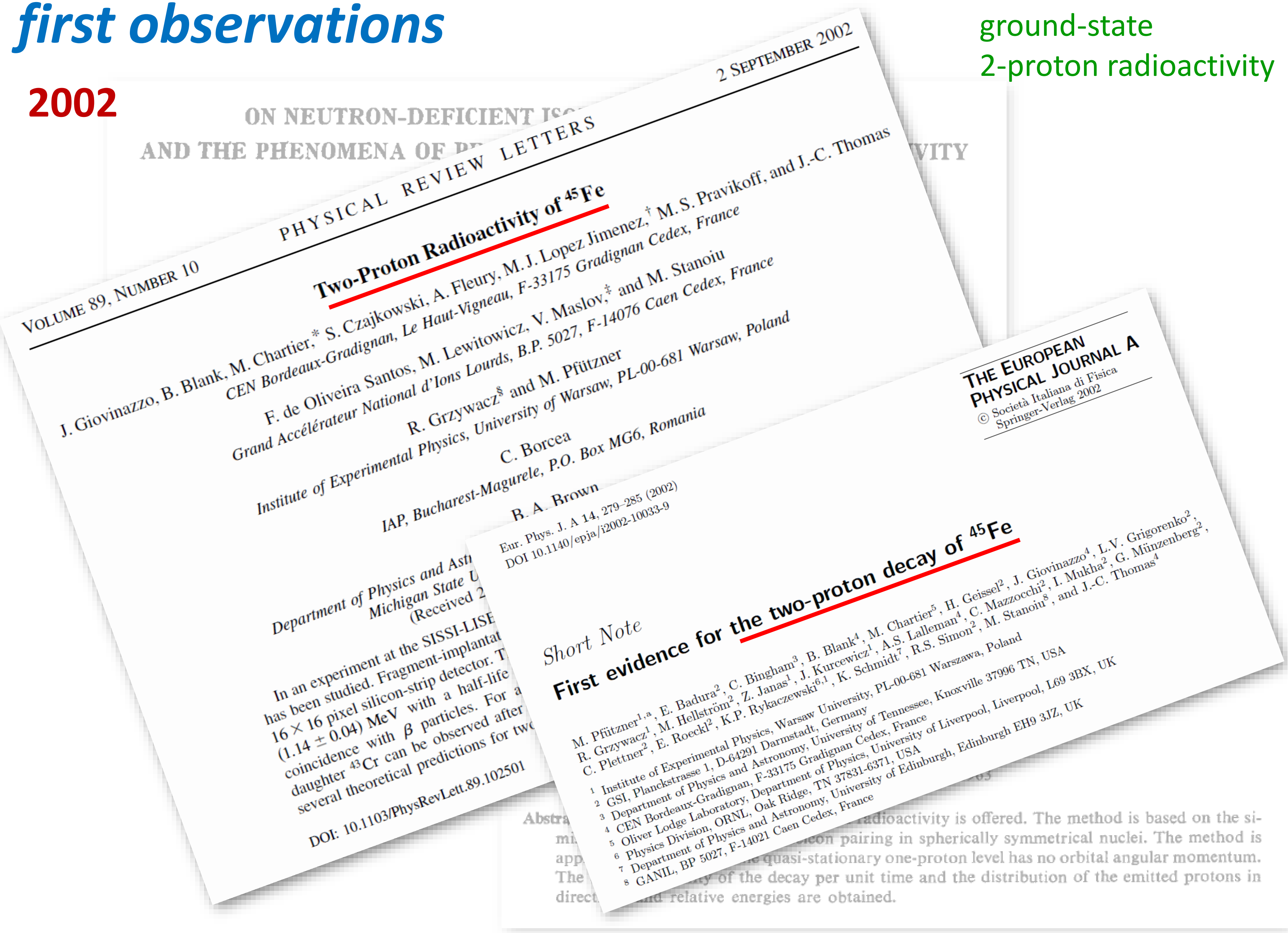
ground state
proton radioactivity

first observations

ground-state
2-proton radioactivity

2002



ON NEUTRON-DEFICIENT IS
AND THE PHENOMENA OF PR VITY

Abstra radioactivity is offered. The method is based on the si-
mi leon pairing in spherically symmetrical nuclei. The method is
app he quasi-stationary one-proton level has no orbital angular momentum.
The ty of the decay per unit time and the distribution of the emitted protons in
direct and relative energies are obtained.

VOLUME 89, NUMBER 10 PHYSICAL REVIEW LETTERS 2 SEPTEMBER 2002

Two-Proton Radioactivity of ^{45}Fe

J. Giovinazzo, B. Blank, M. Chartier,* S. Czajkowski, A. Fleury, M. J. Lopez Jimenez,† M. S. Pravikoff, and J.-C. Thomas
CEN Bordeaux-Gradignan, Le Haut-Vigneau, F-33175 Gradignan Cedex, France

F. de Oliveira Santos, M. Lewitowicz, V. Maslov,‡ and M. Stanoiu
Grand Accélérateur National d'Ions Lourds, B.P. 5027, F-14076 Caen Cedex, France

R. Grzywacz§ and M. Pfützner
Institute of Experimental Physics, University of Warsaw, PL-00-681 Warsaw, Poland

C. Borcea
IAP, Bucharest-Magurele, P.O. Box MG6, Romania

B. A. Brown
Department of Physics and Astr
Michigan State U
(Received 2

In an experiment at the SISSI-LISE
has been studied. Fragment-implantat
16×16 pixel silicon-strip detector. T
(1.14 ± 0.04) MeV with a half-life
coincidence with β particles. For a
daughter ^{43}Cr can be observed after
several theoretical predictions for two

DOI: 10.1103/PhysRevLett.89.102501

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Springer-Verlag 2002

Eur. Phys. J. A 14, 279–285 (2002)
DOI 10.1140/epja/i2002-10033-9

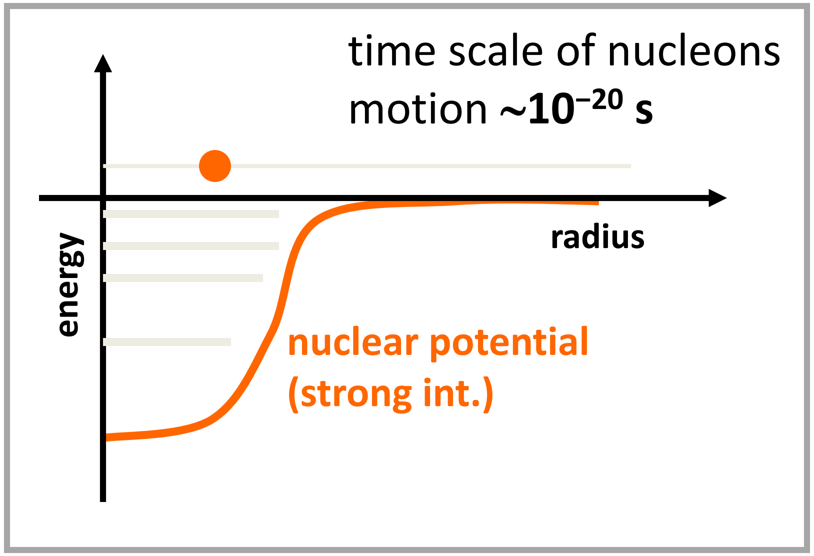
Short Note

First evidence for the two-proton decay of ^{45}Fe

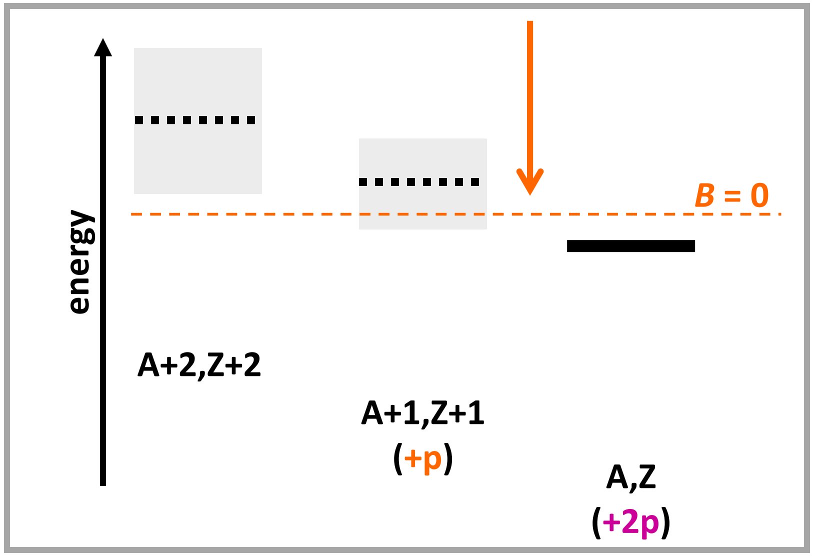
M. Pfützner[1,a], E. Badura[2], C. Bingham[3], B. Blank[4], M. Chartier[5], H. Geissel[2], J. Giovinazzo[4], L.V. Grigorenko[2], R. Grzywacz[1], M. Hellström[2], Z. Janas[1], J. Kurcewicz[1], A.S. Lalleman[4], C. Mazzocchi[2], I. Mukha[2], G. Münzenberg[2], C. Plettner[2], E. Roeckl[2], K.P. Rykaczewski[6,1], K. Schmidt[7], R.S. Simon[2], M. Stanoiu[8], and J.-C. Thomas[4]

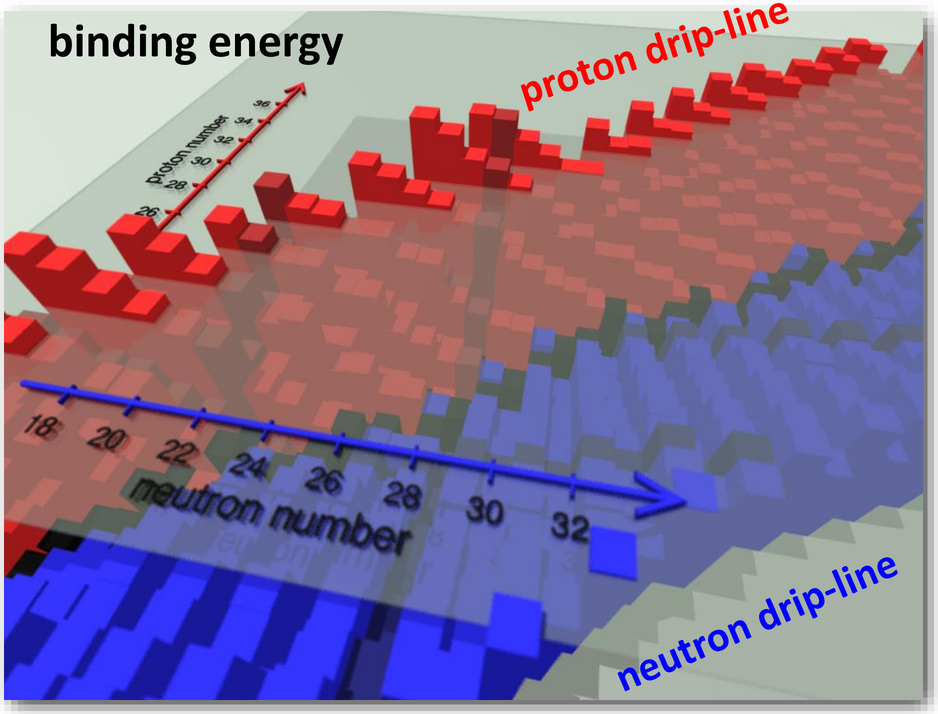
1 Institute of Experimental Physics, Warsaw University, PL-00-681 Warszawa, Poland
2 GSI, Planckstrasse 1, D-64291 Darmstadt, Germany
3 Department of Physics and Astronomy, University of Tennessee, Knoxville 37996 TN, USA
4 CEN Bordeaux-Gradignan, F-33175 Gradignan Cedex, France
5 Oliver Lodge Laboratory, Department of Physics, University of Liverpool, Liverpool, L69 3BX, UK
6 Physics Division, ORNL, Oak Ridge, TN 37831-6371, USA
7 Department of Physics and Astronomy, University of Edinburgh, Edinburgh EH9 3JZ, UK
8 GANIL, BP 5027, F-14021 Caen Cedex, France

quasi-(un)bound nuclei at the proton drip-line

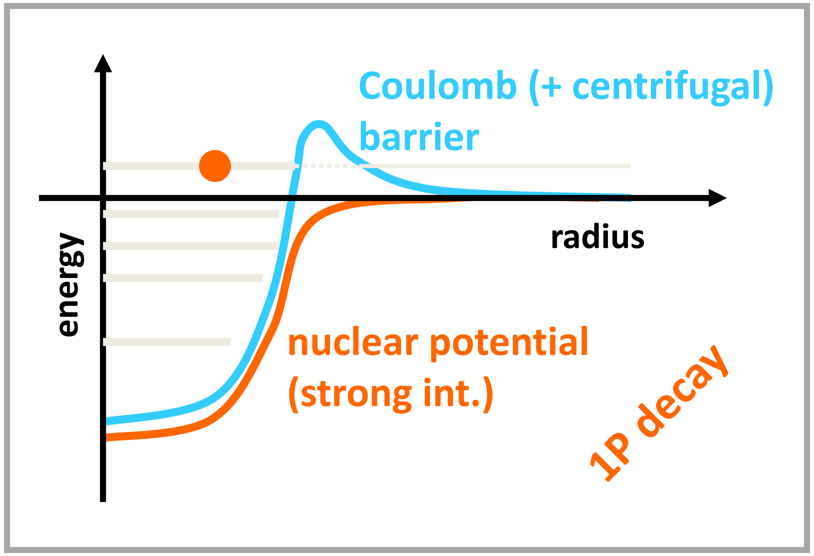


proton drip line
(w/r nuclear interaction)

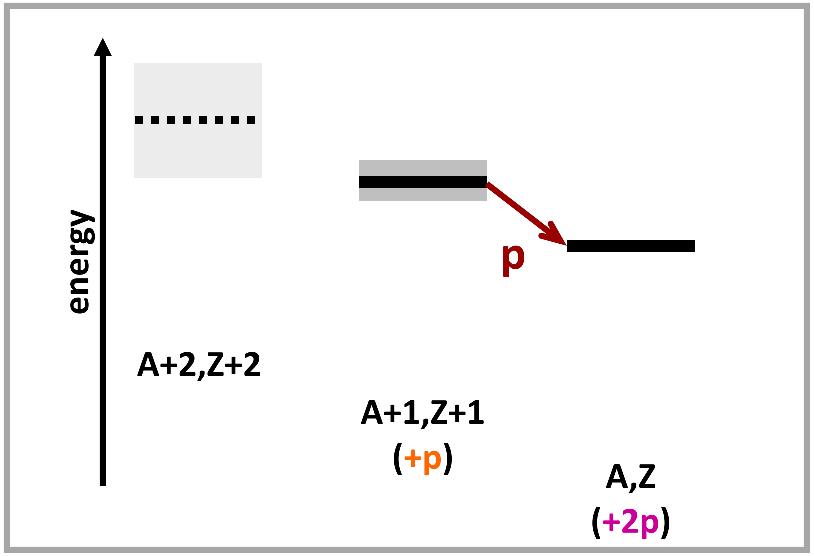




quasi-(un)bound nuclei at the proton drip-line



odd-Z isotope



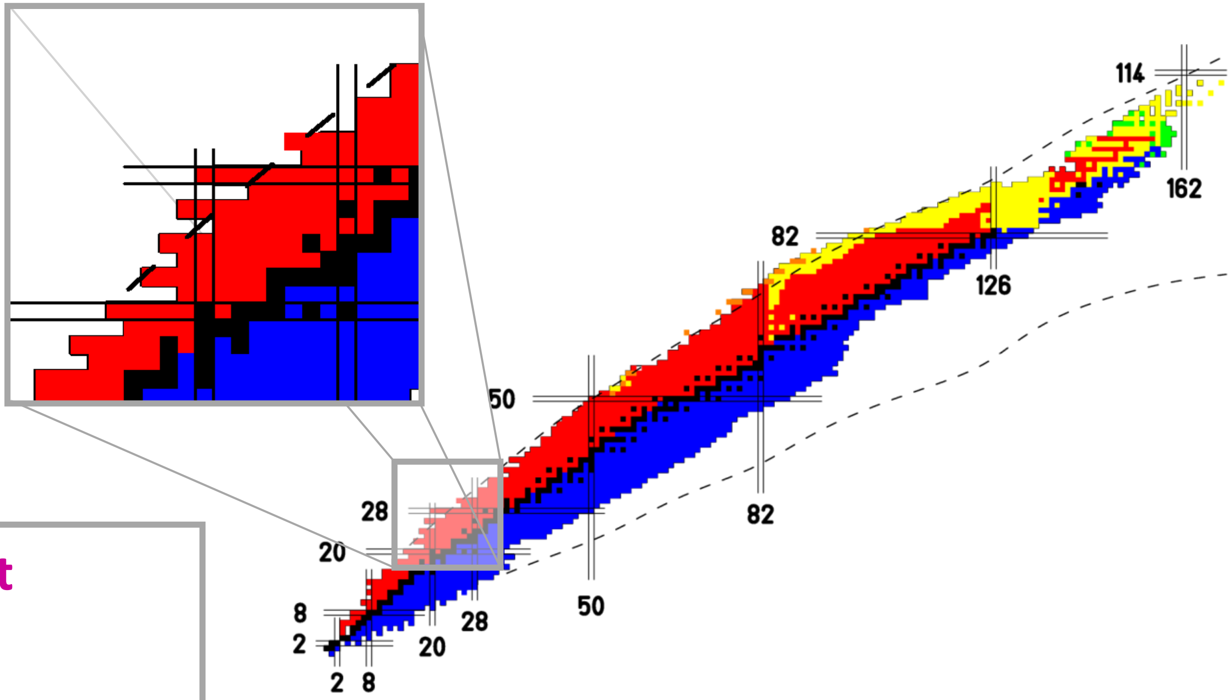
if Coulomb barrier is larger than proton separation energy
→ metastable state

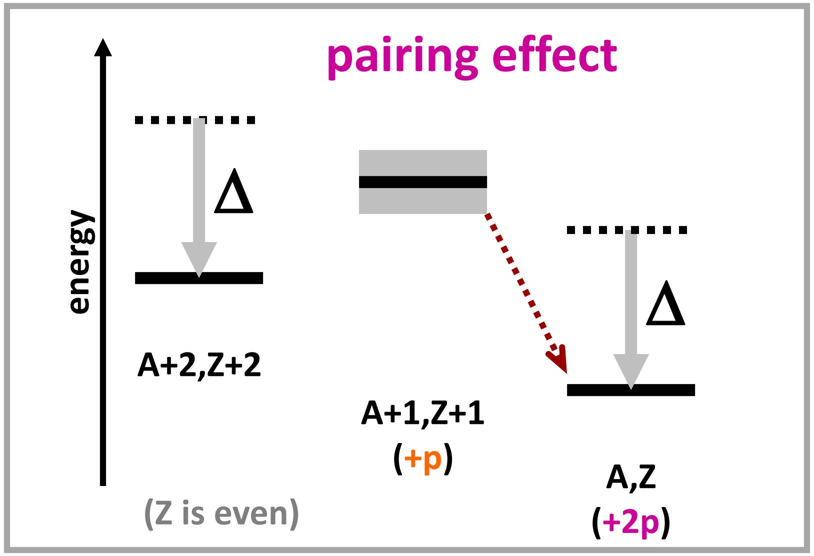
then tunnel effect
→ **1-proton radioactivity**

quasi-(un)bound nuclei at the proton drip-line

illustration of odd – even effect:

- stable isotopes
- drip-lines





pairing effect

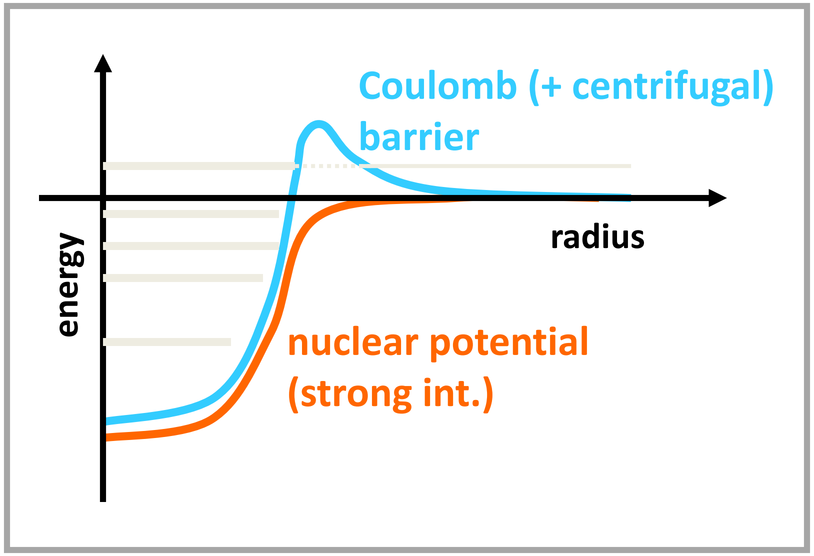
A+2,Z+2

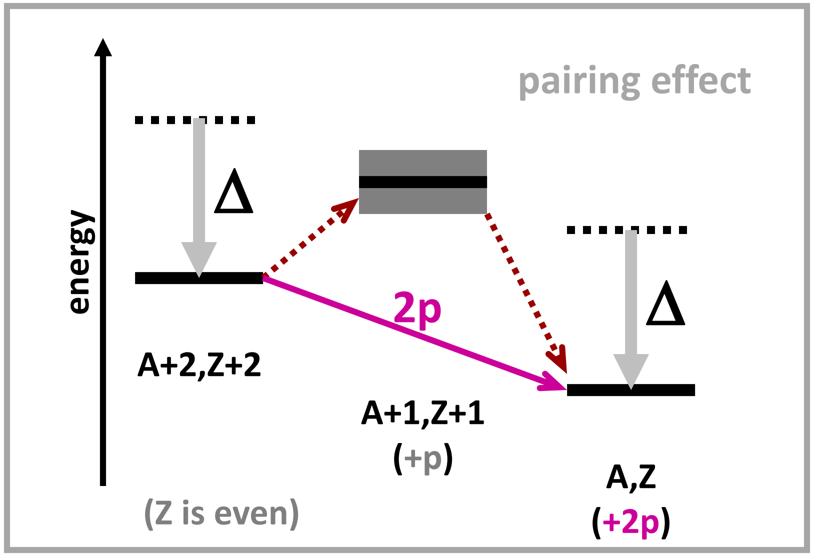
A+1,Z+1
(+p)

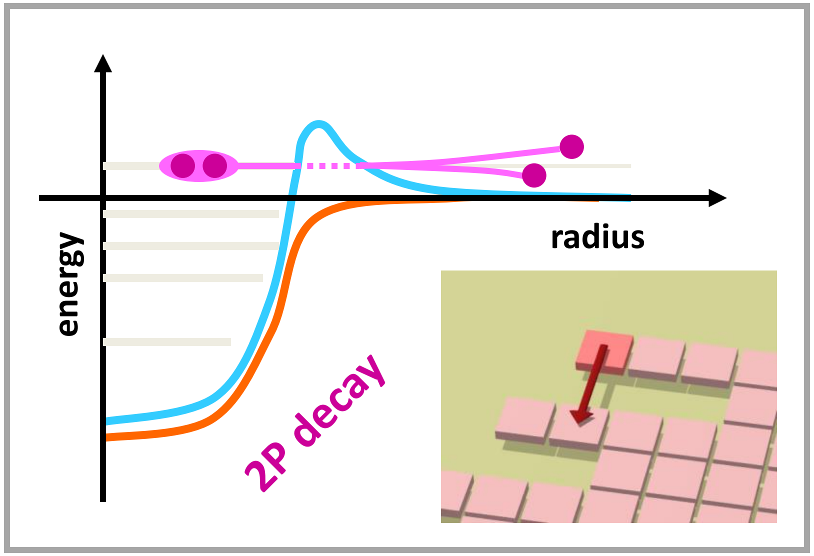
A,Z
(+2p)

(Z is even)

quasi-(un)bound nuclei at the proton drip-line







even-Z isotope

1 proton emission forbidden

(so called “***true***” 2P radioactivity)

why studying this process?

ground-state 2-proton radioactivity

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

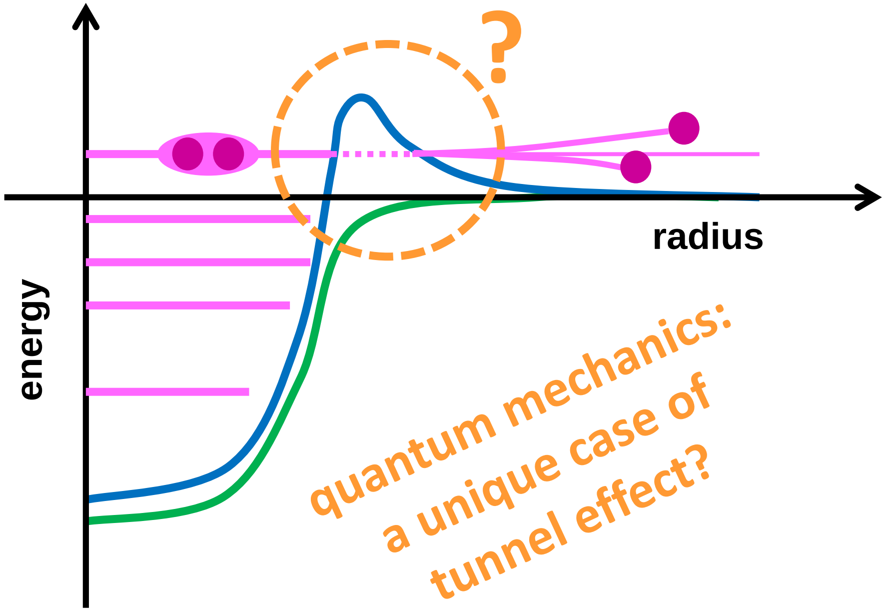
→ **nuclear structure**
energies, half-life, levels configuration

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

→ **tunnel effect**
theoretical descriptions

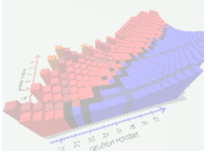
the emitted protons carry information on what's going on inside the nucleus

the 2-proton radioactivity mixes
the **structure** (wave functions)
and the (decay) **dynamics**



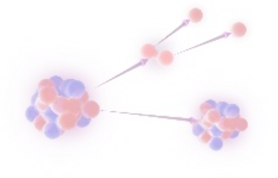
quantum mechanics:
a unique case of
tunnel effect?

On the Tracks of Two-Proton Radioactivity

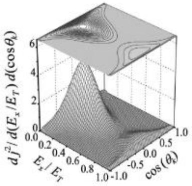


radioactivity on the neutron-deficient side of the table of isotopes

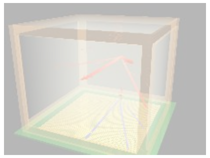
proton-rich



what is two-proton radioactivity?

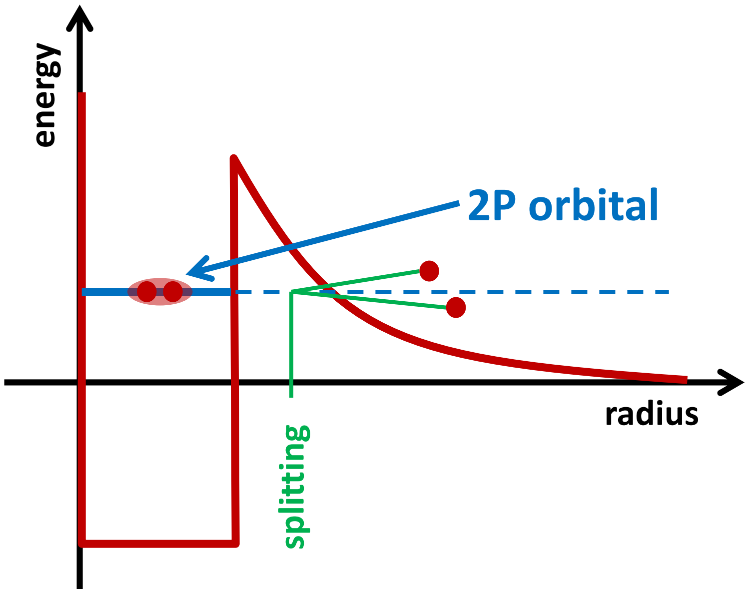


loops between theory and experiment



a new tracking device

initial predictions



First calculation by V.I. Goldanskii (1960s)

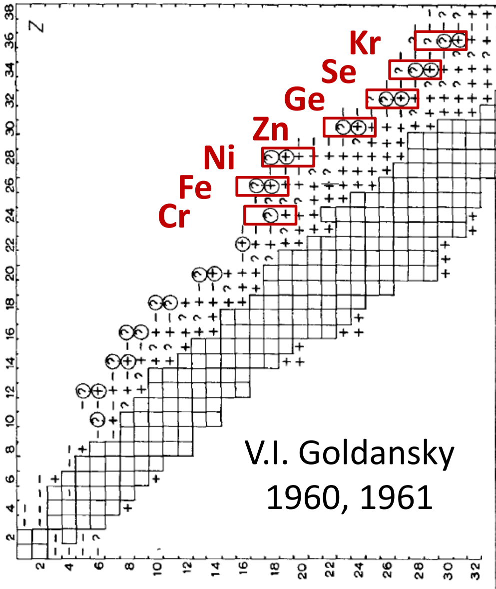
→ **simple potential model**

→ **based on masses differences**
(mass predictions)

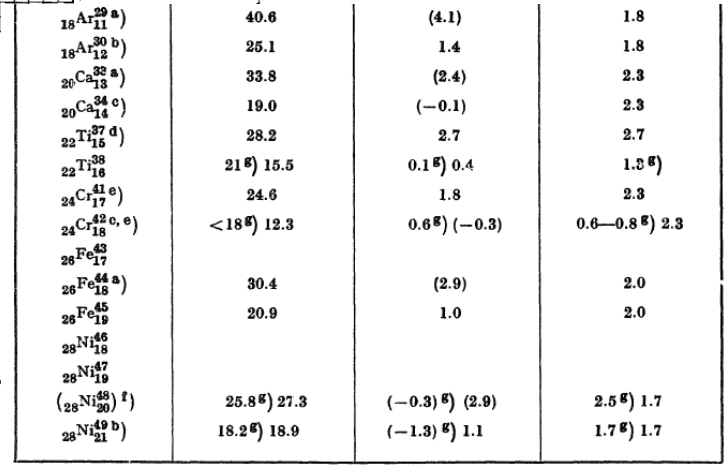
→ **tunnel effect**
barrier penetration of a ^2He particle vs. simultaneous emission of 2 protons

energy sharing
→ equal sharing between protons

discussion of the splitting of ^2He into 2 protons along r axis



V.I. Goldansky
1960, 1961



$_{18}Ar^{29}_{11}$ a)	40.6	(4.1)	1.8
$_{18}Ar^{30}_{12}$ b)	25.1	1.4	1.8
$_{20}Ca^{32}_{13}$ a)	33.8	(2.4)	2.3
$_{20}Ca^{34}_{14}$ c)	19.0	(−0.1)	2.3
$_{22}Ti^{37}_{15}$ d)	28.2	2.7	2.7
$_{22}Ti^{38}_{16}$	21 g) 15.5	0.1 g) 0.4	1.3 g)
$_{24}Cr^{41}_{17}$ e)	24.6	1.8	2.3
$_{24}Cr^{42}_{18}$ c, e)	<18 g) 12.3	0.6 g) (−0.3)	0.6—0.8 g) 2.3
$_{26}Fe^{43}_{17}$			
$_{26}Fe^{44}_{18}$ a)	30.4	(2.9)	2.0
$_{26}Fe^{45}_{19}$	20.9	1.0	2.0
$_{28}Ni^{46}_{18}$			
$_{28}Ni^{47}_{19}$			
($_{28}Ni^{48}_{20}$) f)	25.8 g) 27.3	(−0.3) g) (2.9)	2.5 g) 1.7
$_{28}Ni^{49}_{21}$ b)	18.2 g) 18.9	(−1.3) g) 1.1	1.7 g) 1.7

mass region A ≈ 50 already foreseen as the most promising

search for candidates

$Q_{2P} > 0$ and $Q_P \leq 0$

(mass differences)

most exotic nuclei

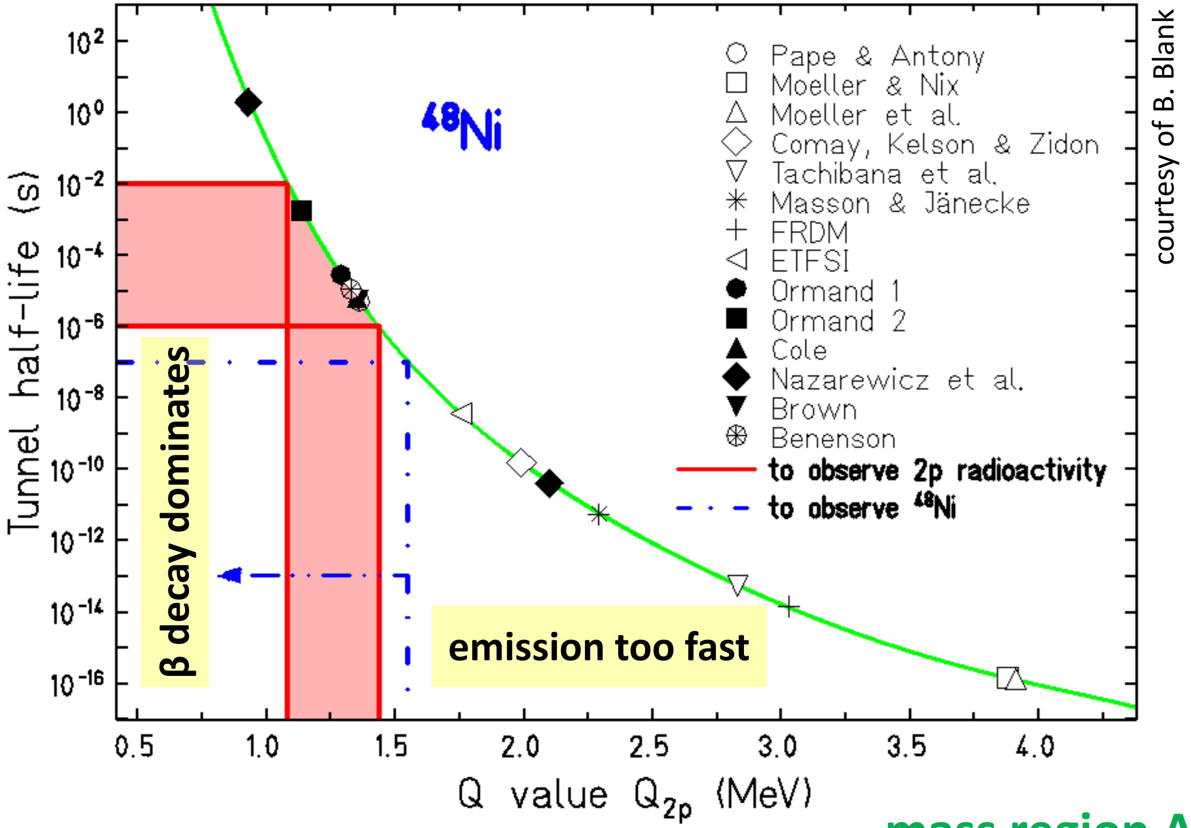
nothing is known !

$\Downarrow$

only mass predictions

search for candidates

simple ^{2}He tunneling model



⇨ $T_{1/2} = f(Q_{2P})$

if Q_{2p} too high

⇨ too short $T_{1/2}$

if Q_{2p} too small

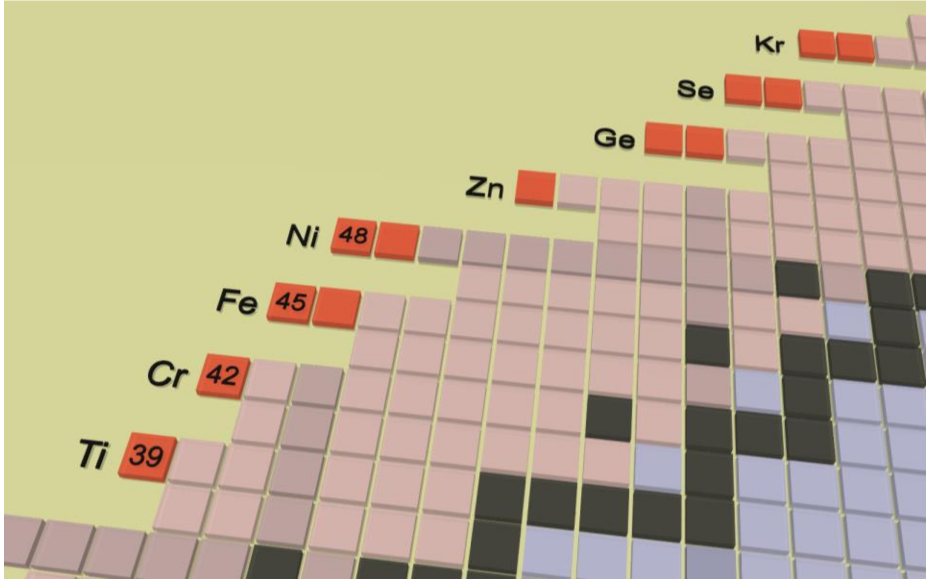
⇨ tunneling too slow:
β^+ dominates the decay

mass region A~50

(already foreseen by Goldanskii)

- **Coulomb barrier high enough ($Z \approx 20$ to 30)**
- **half-life 1 μs ~ 10 ms**

a difficult experimental access to the drip-line



→ very exotic nuclei

→ very short half-lives (~*ms*)

how to produce nuclei far from stability?

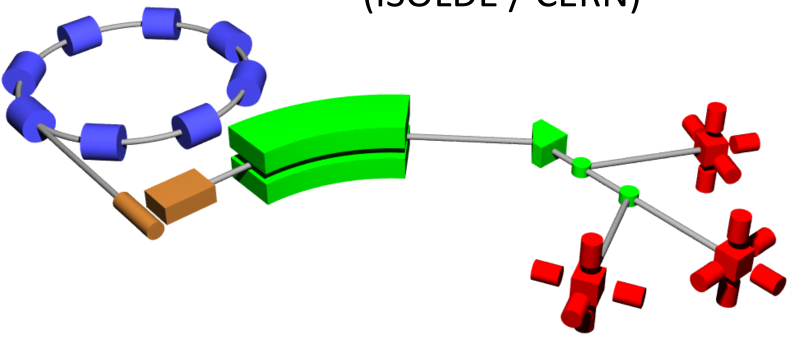
transfer, charge exchange
fusion-evaporation
induced fission

out of reach

target spallation + ISOL separation

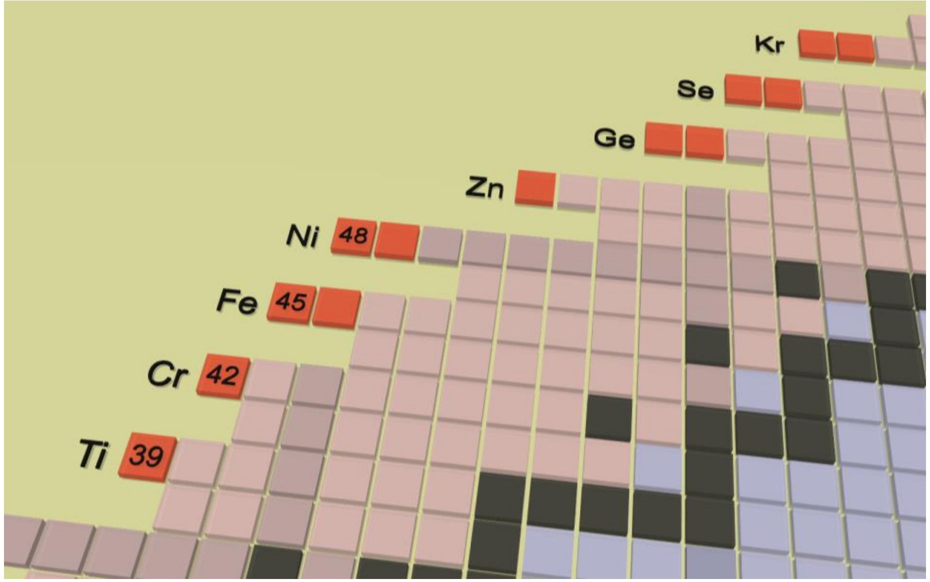
- high energy projectile (proton)
- thick target → extraction from target
- separation & purification
- collection & detection

too slow



(ISOLDE / CERN)

a difficult experimental access to the drip-line



→ very exotic nuclei
→ very short half-lives (~*ms*)

how to produce nuclei
far from stability?

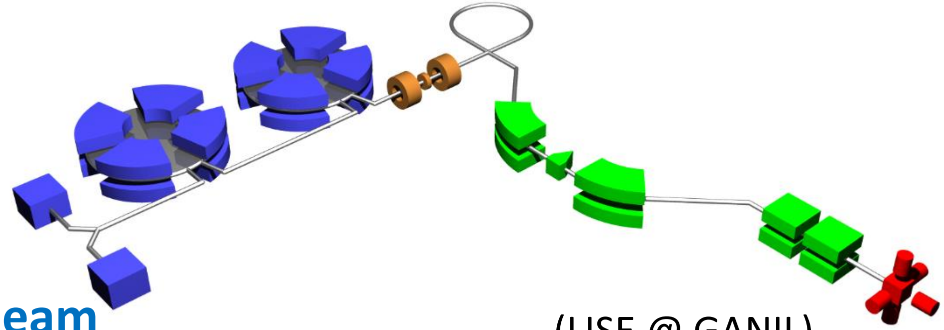
~~transfer, charge exchange~~
~~fusion-evaporation~~
~~induced fission~~

~~target spallation + ISOL separation~~

projectile fragmentation

ok!

high energy and intensity ion beam
projectile fragmentation in a thin target
fragment separator (charge and mass)
implantation identification & decay

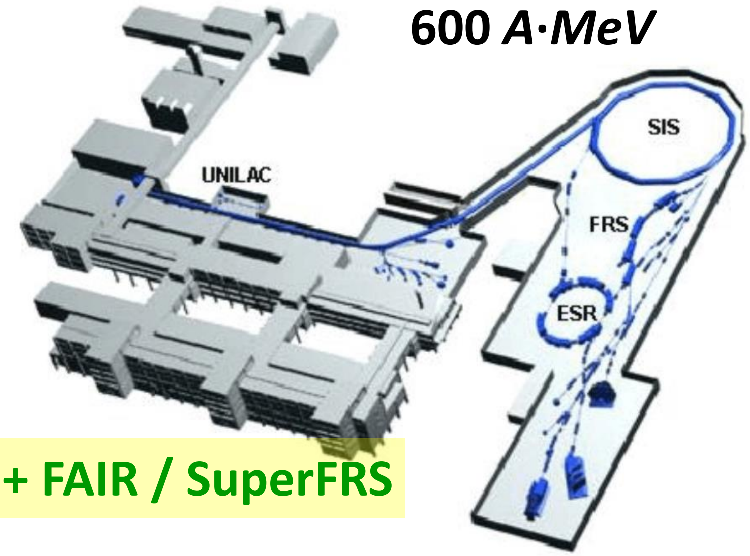


(LISE @ GANIL)

projectile fragmentation facilities in the 1990's & 2000's

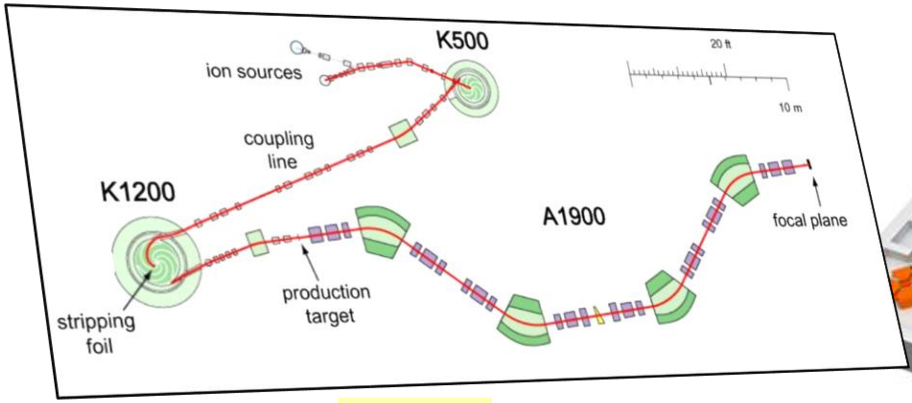
GANIL / LISE
95 *A·MeV*

GSI / FRS
600 *A·MeV*



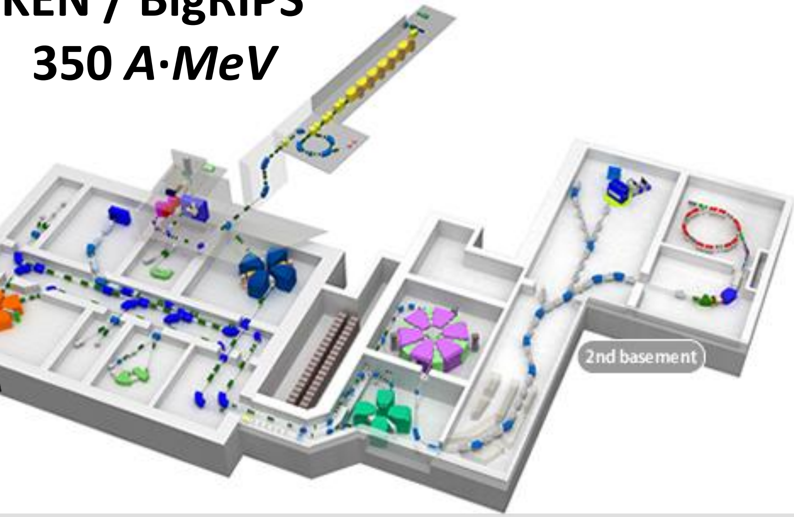
+ FAIR / SuperFRS

NSCL / A1900
160 *A·MeV*

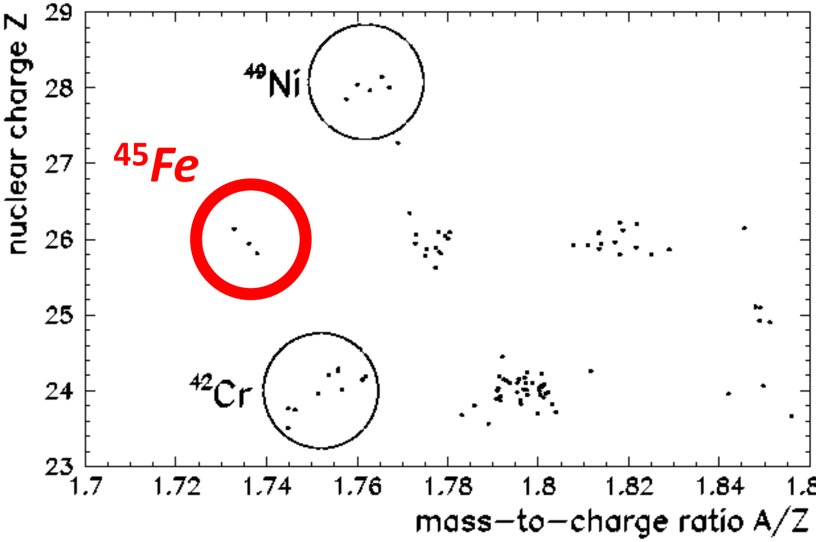


+ FRIB

RIKEN / BigRIPS
350 *A·MeV*



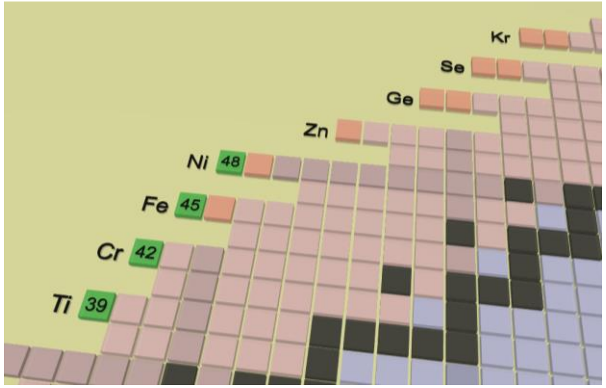
experimental exploration…

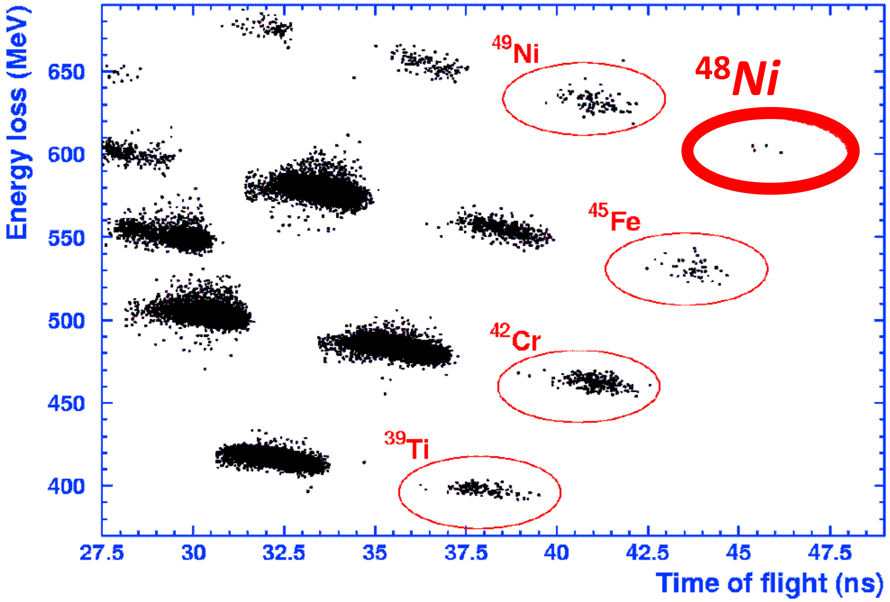


B. Blank *et al.* PRL77 (1996)

first observation of ^{45}*Fe*

GSI / FRS (1996): 3 events





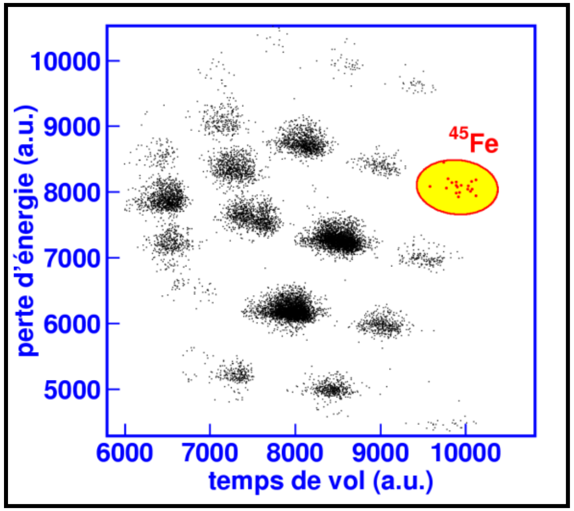
B. Blank *et al.* PRL84 (2000)

first observation of ^{48}*Ni*

GANIL / LISE (1999): 4 events

no measurement of the decay modes…

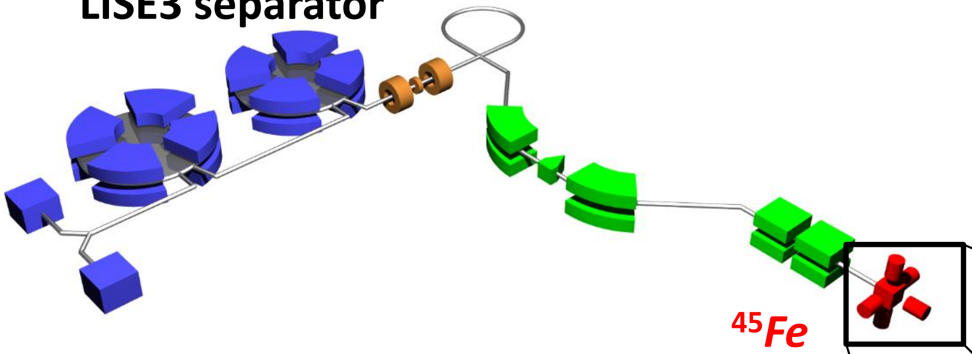
first observation: the case of ^{45}Fe



at GANIL

high intensity primary ^{58}Ni beam: 5 *pμA*

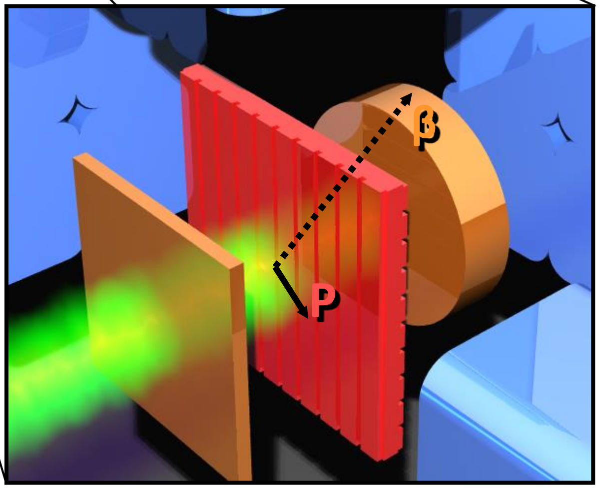
LISE3 separator



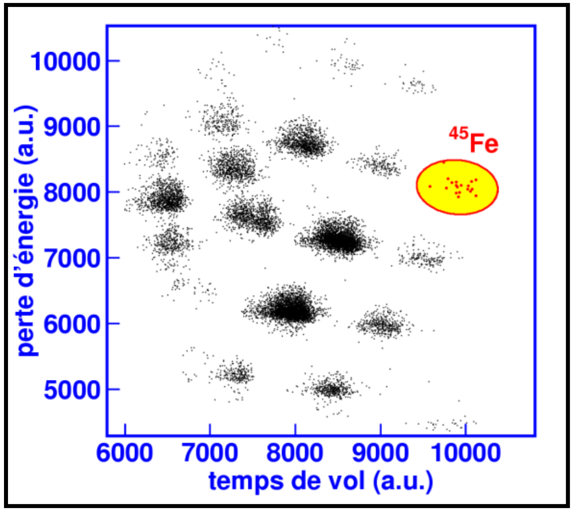
implantation in a thick silicon detector

decay after few milliseconds

- proton(s) stopped in impl. detector
  - → full energy deposit
- beta particles escape
  - → partial energy loss
  - → possible signal in other Si detectors

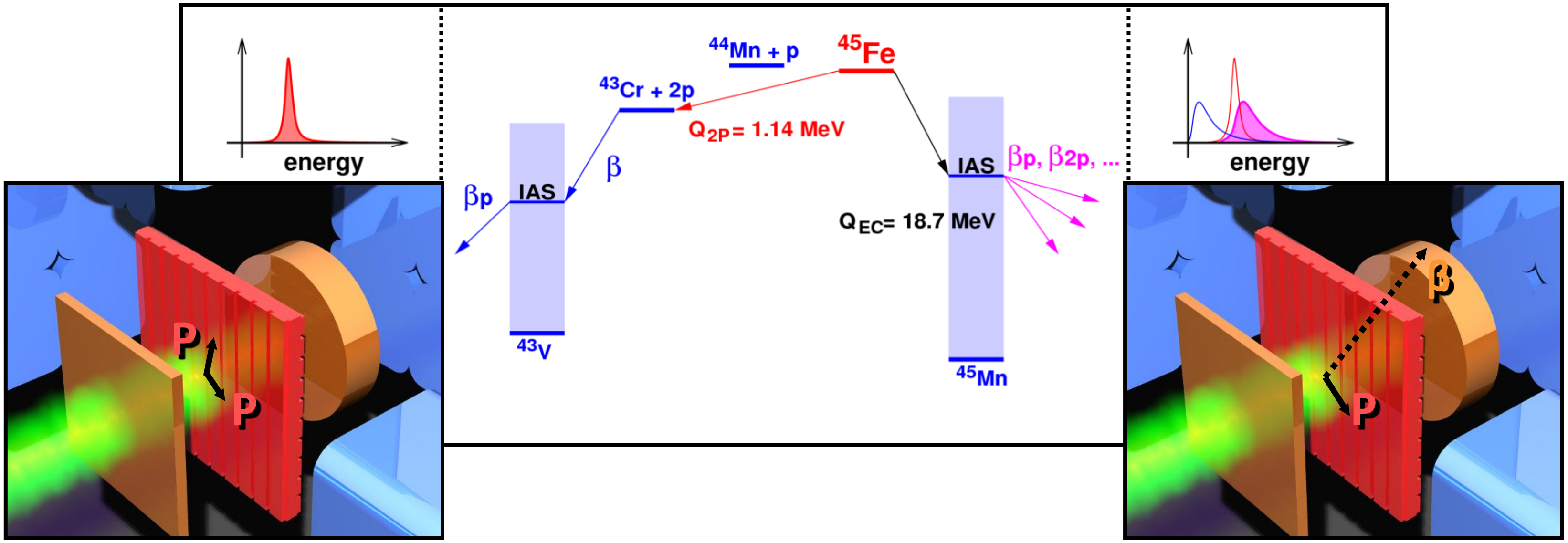


first observation: the case of ^{45}Fe



competition of decay modes

2 proton emission ↔ β-proton(s) emission



first observation: an indirect signature

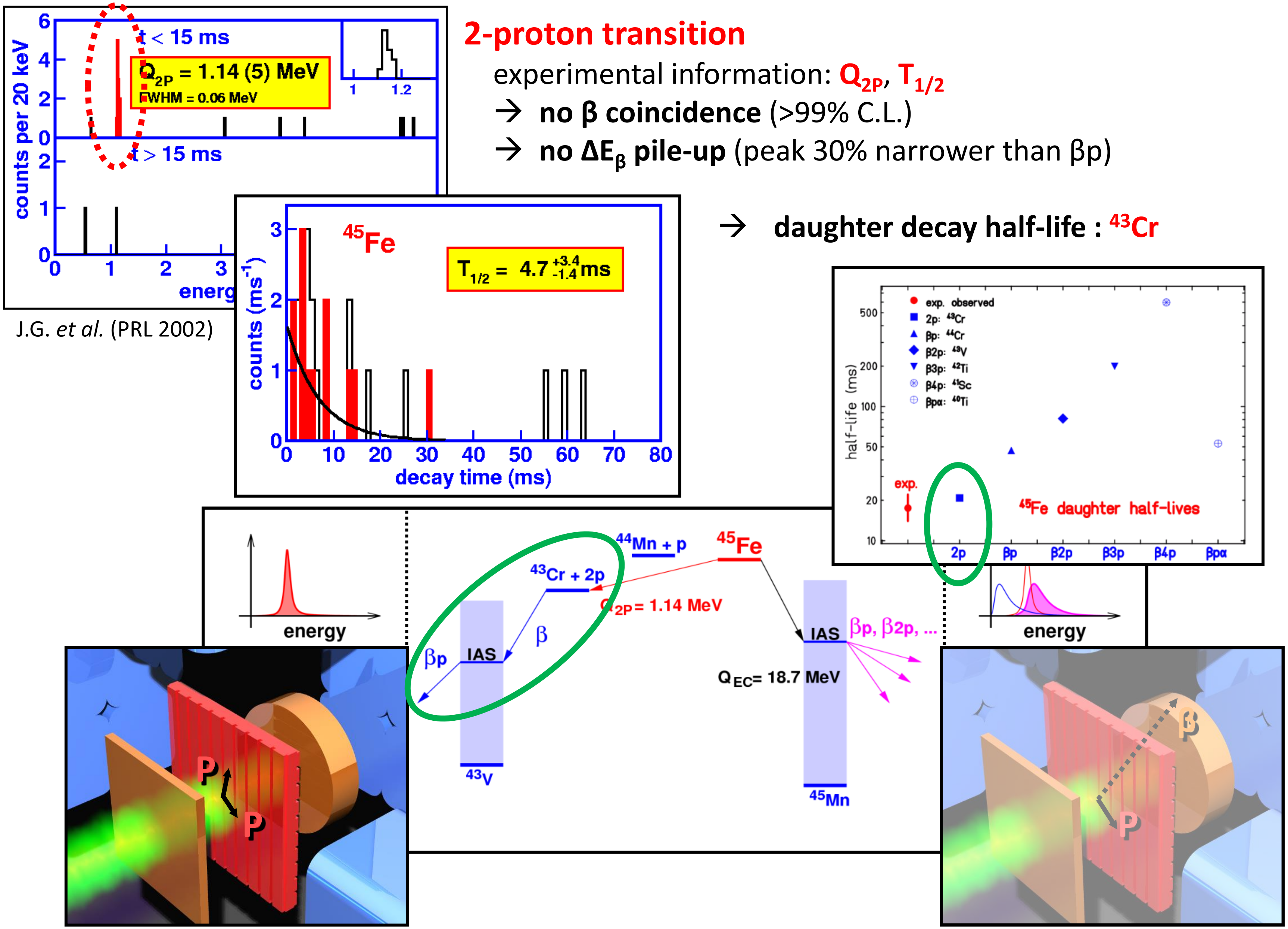
2-proton transition

experimental information: Q_{2P}, $T_{1/2}$

→ **no β coincidence** (>99% C.L.)

→ **no ΔE_β pile-up** (peak 30% narrower than βp)

→ **daughter decay half-life : ^{43}Cr**



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

experimental confirmation of the 2-proton radioactivity

indirect signature: no observation of individual protons
only scenario explaining the measurement

2002 2P decay of ^{45}Fe: at GANIL / LISE and GSI / FRS

2-proton radioactivity
is found…

not enough for
understanding
the process

experimental confirmation of the 2-proton radioactivity

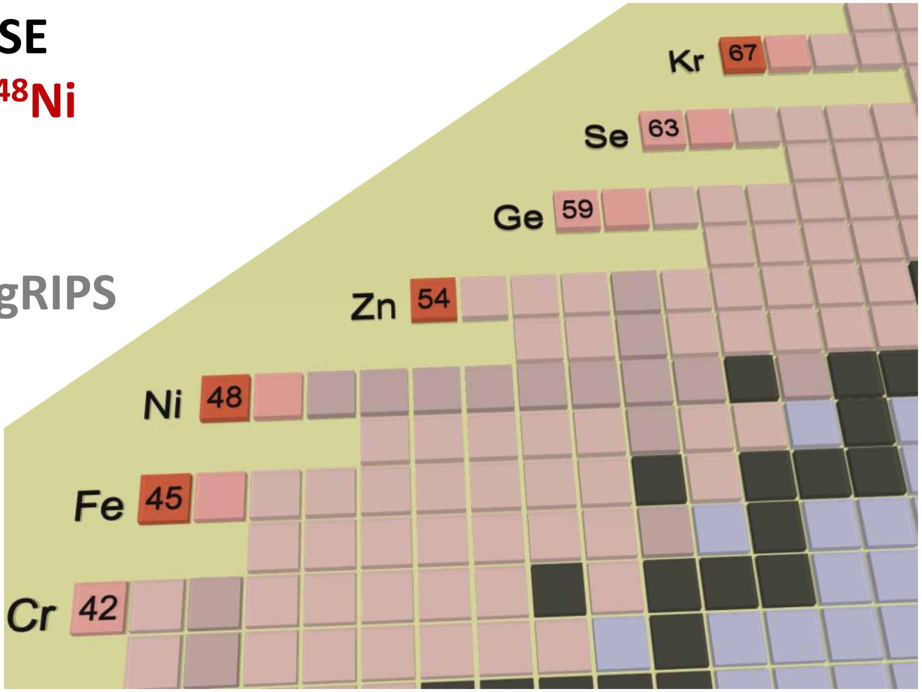
indirect signature: **no observation of individual protons**
only scenario explaining the measurement

2002 **2P decay of ^{45}Fe: at GANIL / LISE and GSI / FRS**

based on the same experimental technique
(indirect observation)

2005 **2P decay of ^{54}Zn at GANIL / LISE**
indication of the 2P decay of ^{48}Ni
(confirmed later…)

2016 2P decay of ^{67}**Kr** at RIKEN / BigRIPS



a very limited information for theory…

experiment: half-life ($T_{1/2}$) and transition energy (Q_{2P})

models based on nuclear structure

R-matrix formalism

- Barker & Brown approach
- include ***p-p*** resonance
- shell model wave functions

shell model embedded in the continuum (SMEC)

- tentative approach from Ploszajczak & Rotureau

difficult task…

→ unbound system
role of states in the continuum

→ 3 body system
(core + p + p)

a very limited information for theory...

experiment: half-life ($T_{1/2}$) and transition energy (Q_{2P})

models based on nuclear structure

R-matrix formalism

- Barker & Brown approach
- include ***p-p*** resonance
- shell model wave functions

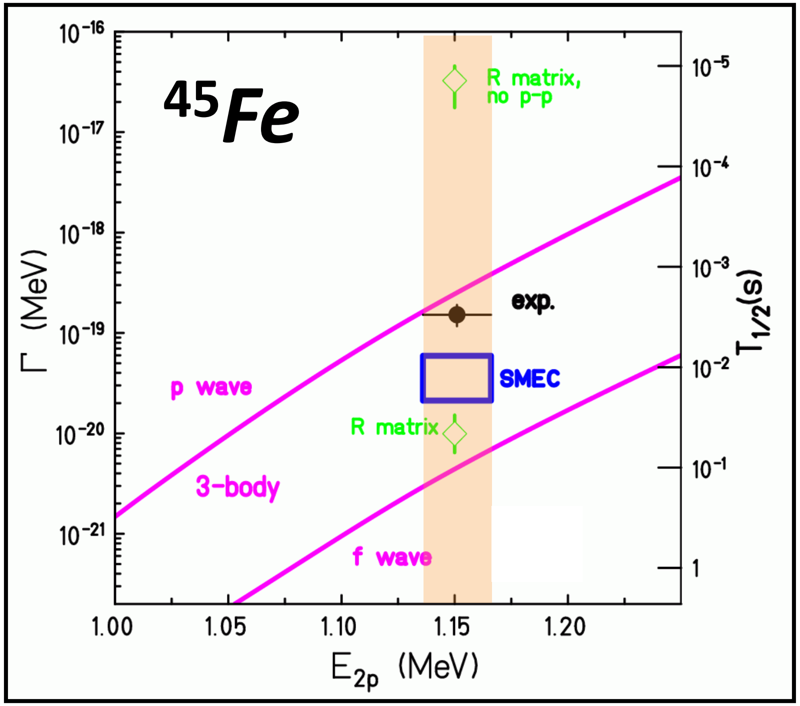
shell model embedded in the continuum (SMEC)

- tentative approach from Ploszajczak & Rotureau

⇨ **no dynamics**

limited comparison: $T_{1/2}(Q_{2P})$

(with Q_{2p} taken from experiments !)



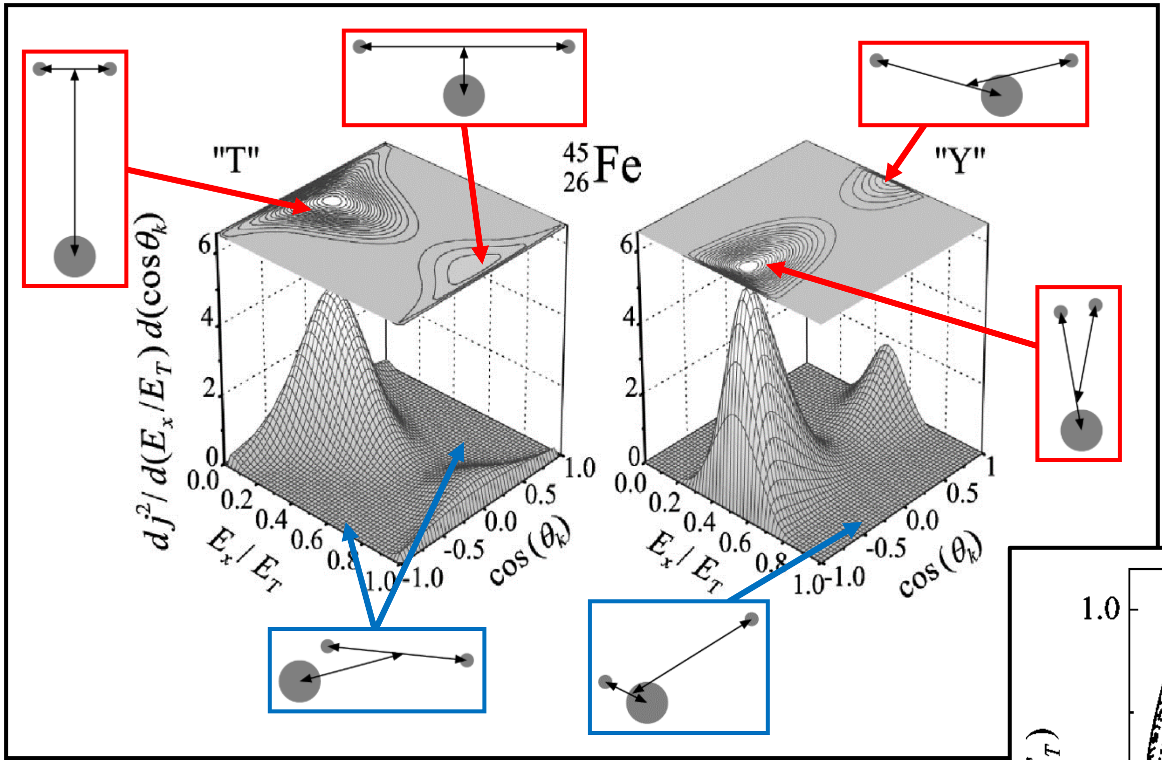
$$T_{1/2} = f(Q_{2P})$$

3-body model

- **core+p+p** system (hyperspherical harmonics)
- good dynamical description
- no intrinsic structure prediction

3-body model: correlations predictions

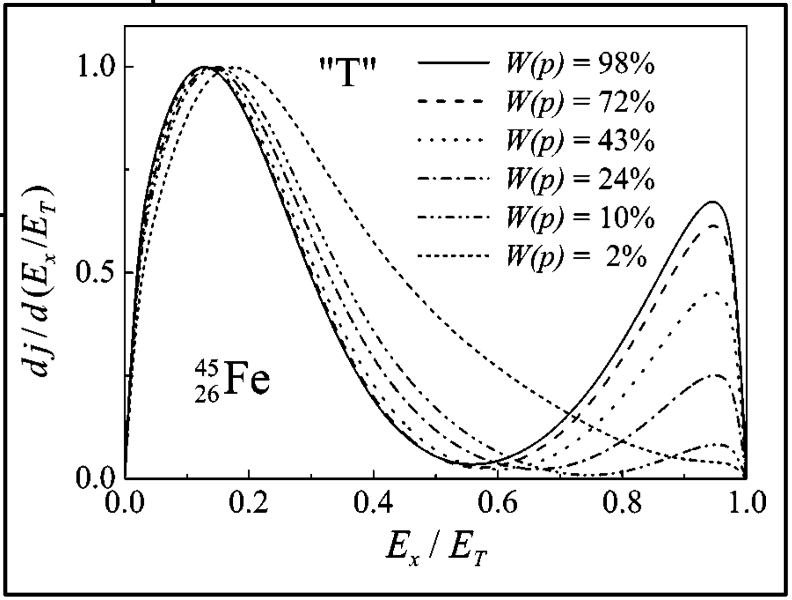
developed by M.V. Zhukov & L.V. Grigorenko



L.V. Grigorenko

3-body Schrödinger equation

solved in *hyper-spherical harmonics* basis



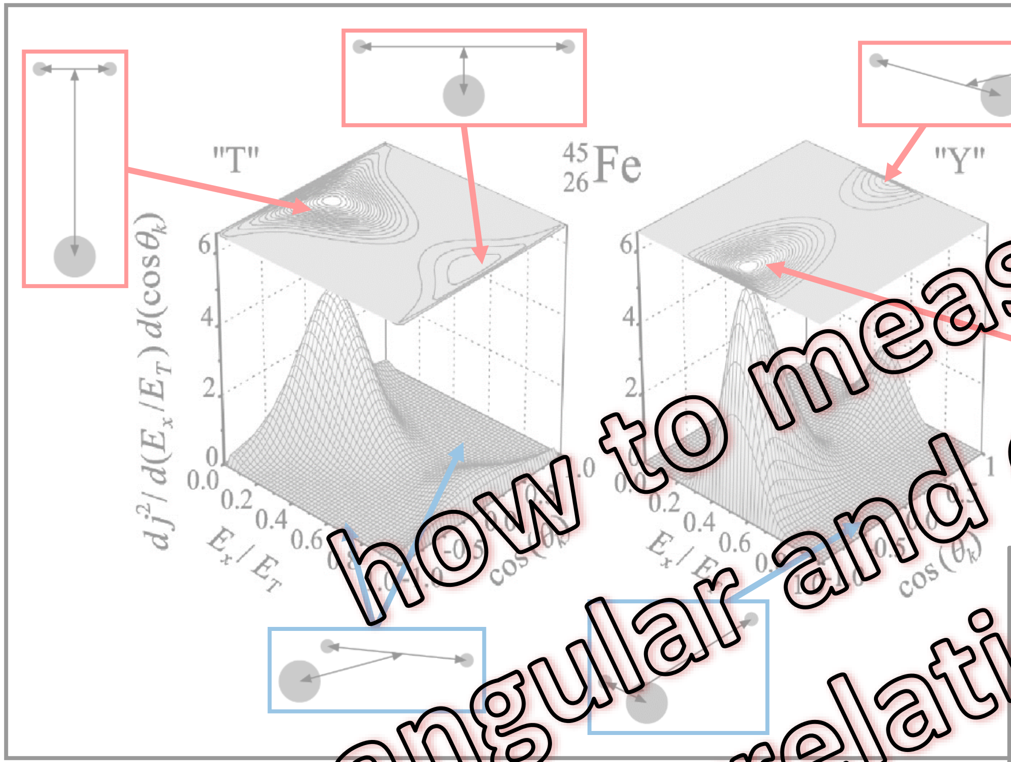
prediction of distributions for

- **energy sharing between protons**
- **proton-proton angular correlations**

sensitive to involved orbitals

3-body model: correlations predictions

developed by M.V. Zhukov & L.V. Grigorenko



3-body Schrödinger equation

solved in *hyper-spherical harmonics* basis

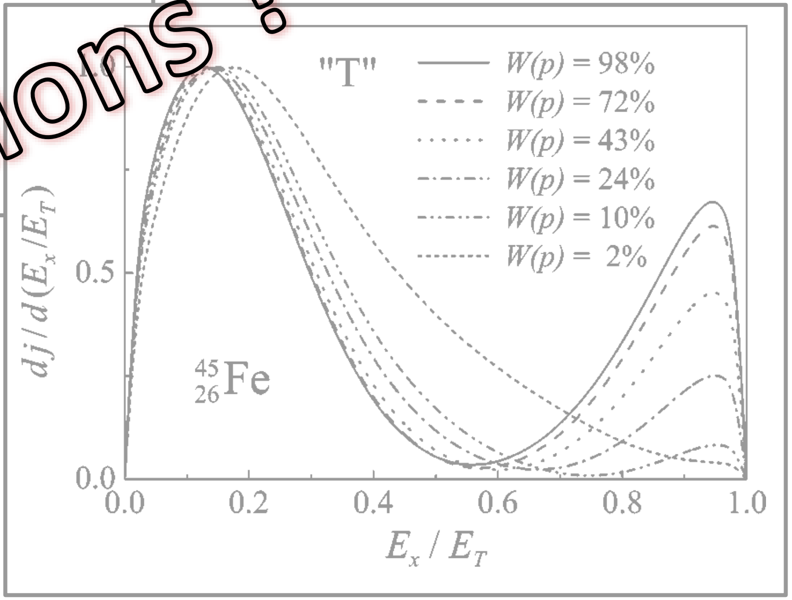
L.V. Grigorenko

how to measure angular and energy correlations ?

prediction of distributions for

- energy sharing between protons
- proton-proton angular correlations

sensitive to involved orbitals



a new experimental step: tracking experiments

standard (silicon) experiments

- **limited experimental information: $T_{1/2}$, Q_{2P} & BR_{2P}**
- **limited comparison with theoretical interpretations**

purpose of tracking experiments

- **measure proton-proton correlations**
  angular distribution and energy sharing

- **compare with 3-body model** (kinematics)

- **extract structure information**

a new experimental step: tracking experiments

development of gas detectors

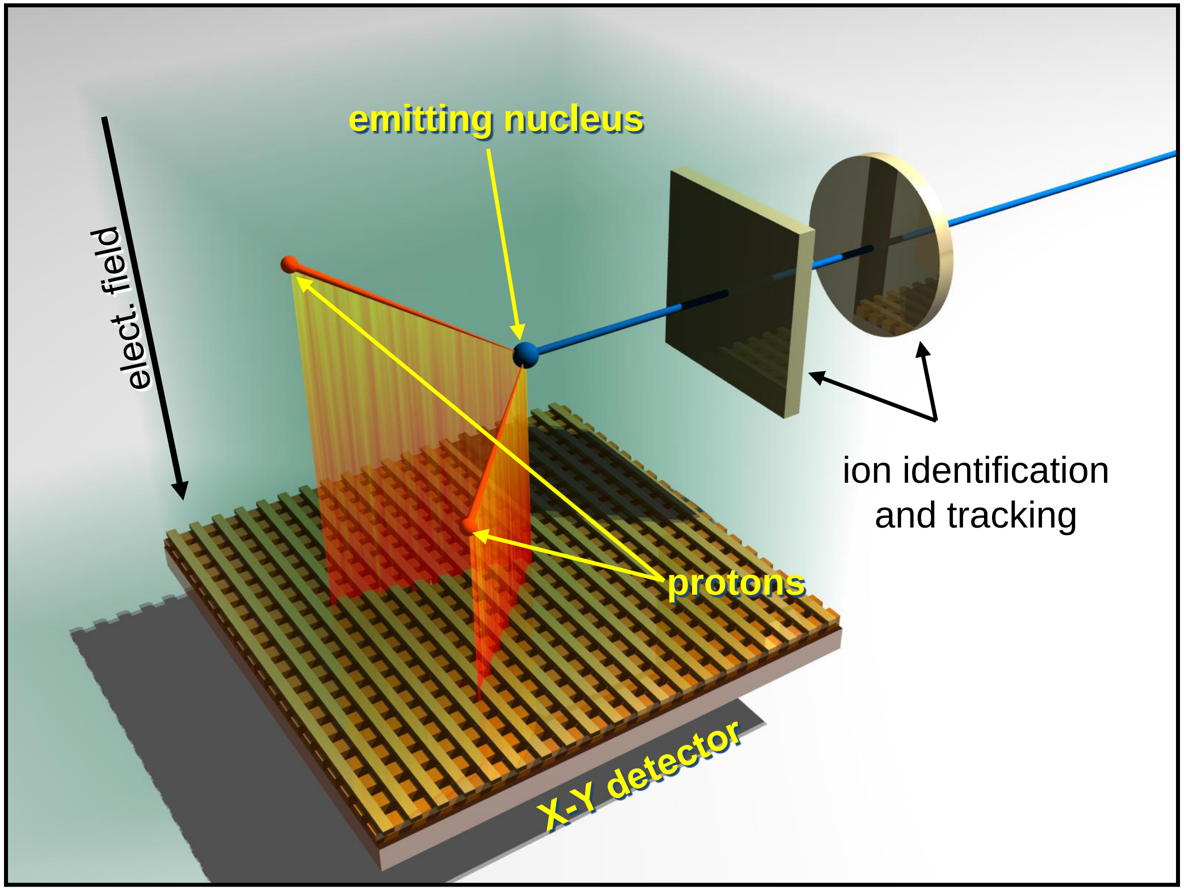
Time Projection Chambers for tracking of particles

charged particles slow down in a **gas volume**

ionisation electrons drift to a 2D detector

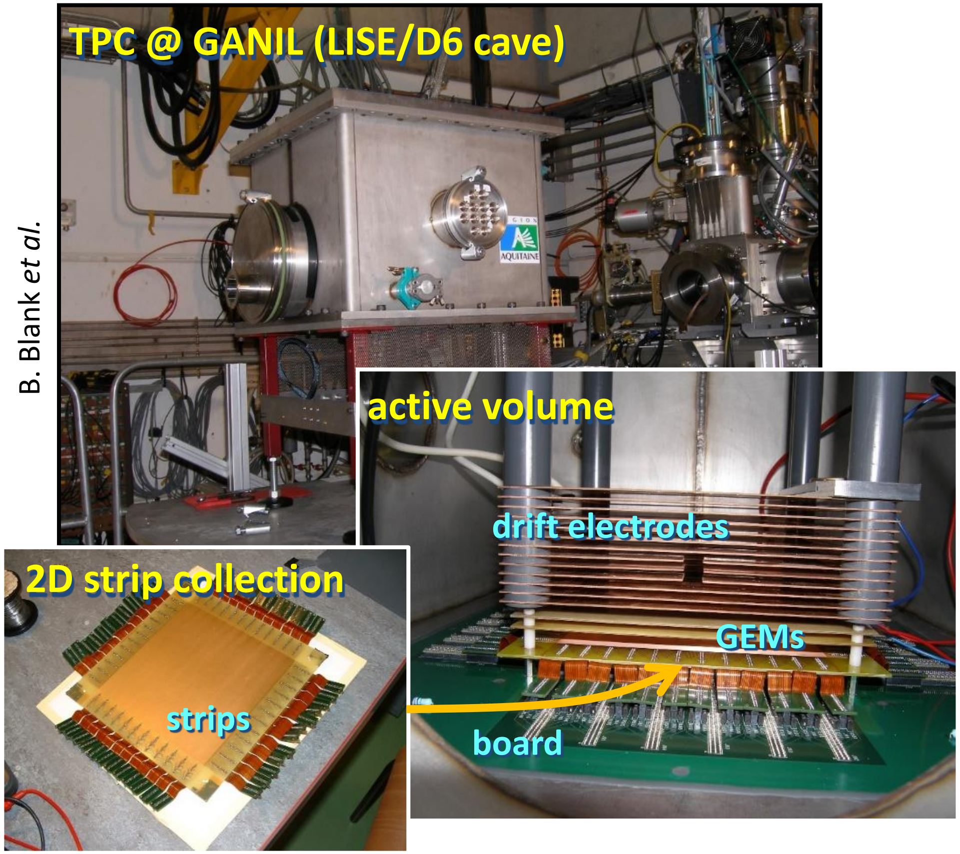
the **2D detector** registers the **tracks projection**

the **drift time** measures the **3rd dimension**



a new experimental step: tracking experiments

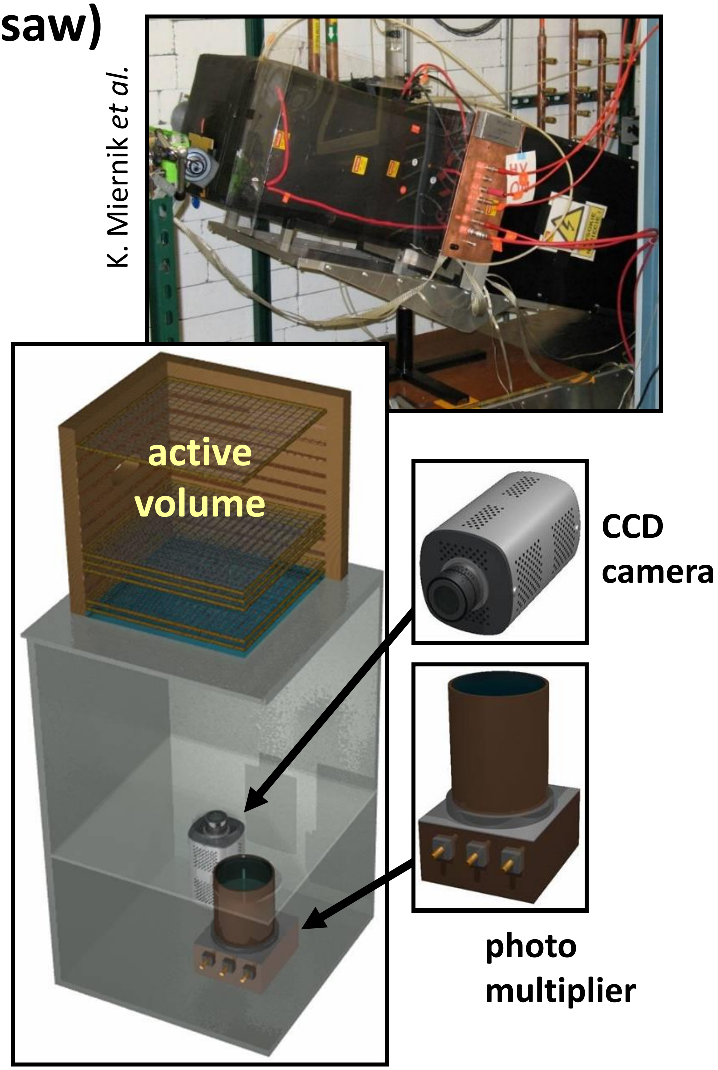
X-Y strips projection readout TPC (CENBG)



B. Blank *et al.*

optical TPC (Warsaw)

K. Miernik *et al.*



M. Pfützner, K. Miermik, et al., 2007

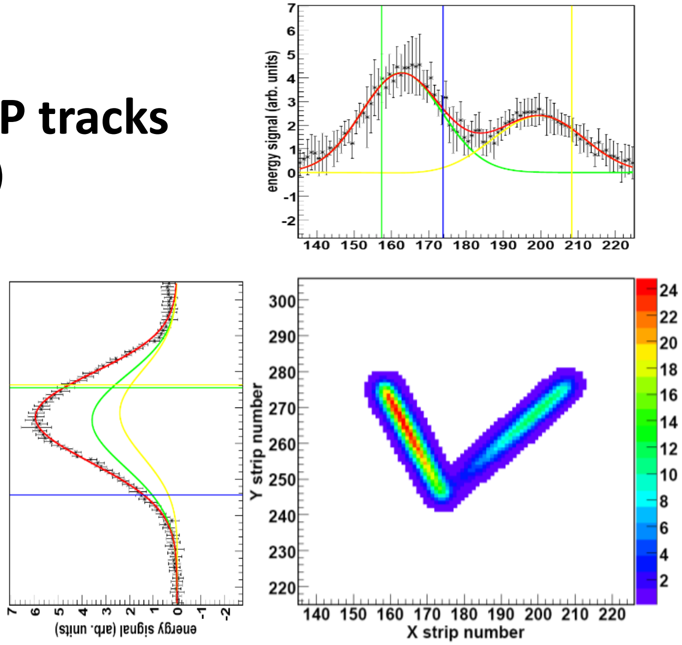
direct observation

^{45}Fe

first 2P tracks

(GANIL)

J.G. *et al.*, PRL 2007



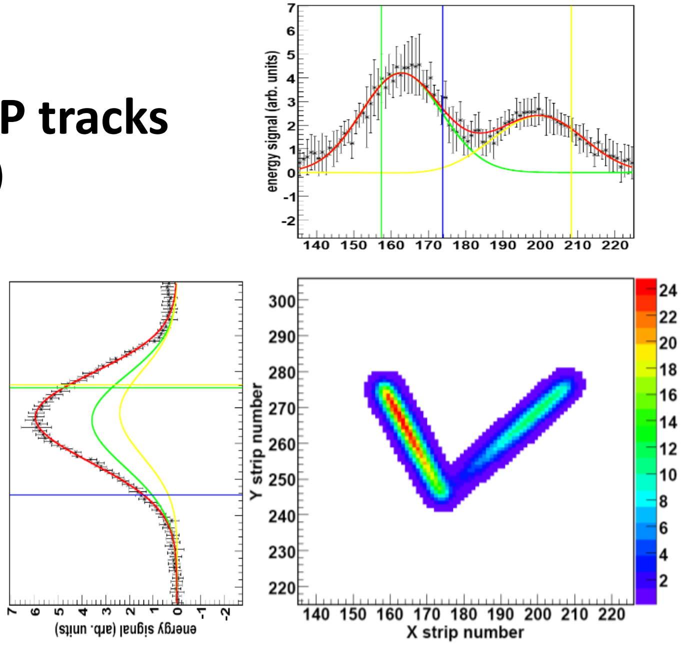
first direct observation

direct observation

^{45}*Fe*

first 2P tracks

(GANIL)

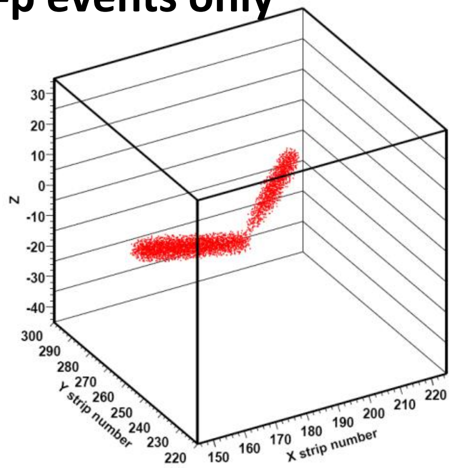


J.G. *et al.*, PRL 2007

^{54}*Zn*

(GANIL)

7 p-p events only



P. Ascher *et al.*, PRL 2011

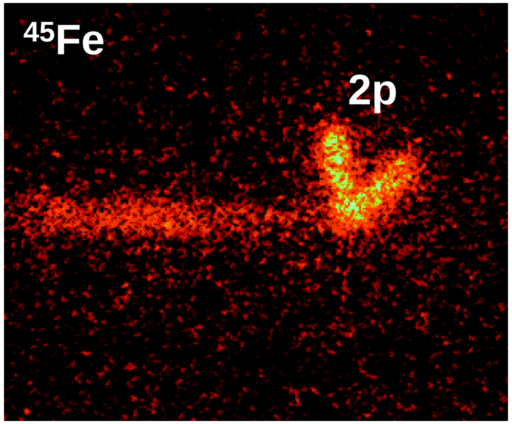
^{48}*Ni*

confirmed as 2P emitter

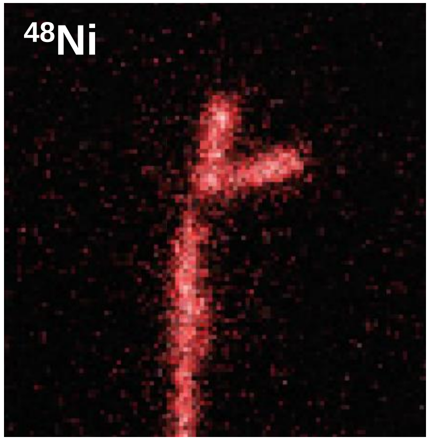
4 p-p events

experiment @ NSCL

→ 75 counts of p-p correlations



K. Miernik *et al.*, PRL 2007

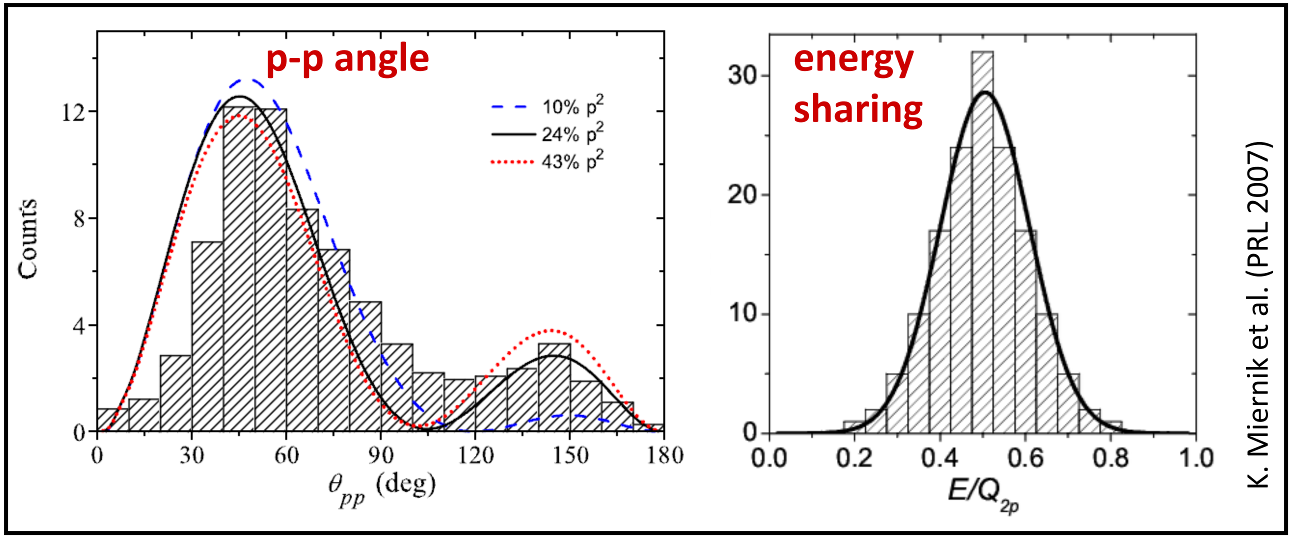


M. Pomorski *et al.*, PRL 2011

tracking experiments results

first angular distribution: good agreement with **predictions** from the 3-body model

^{45}Fe (MSU)

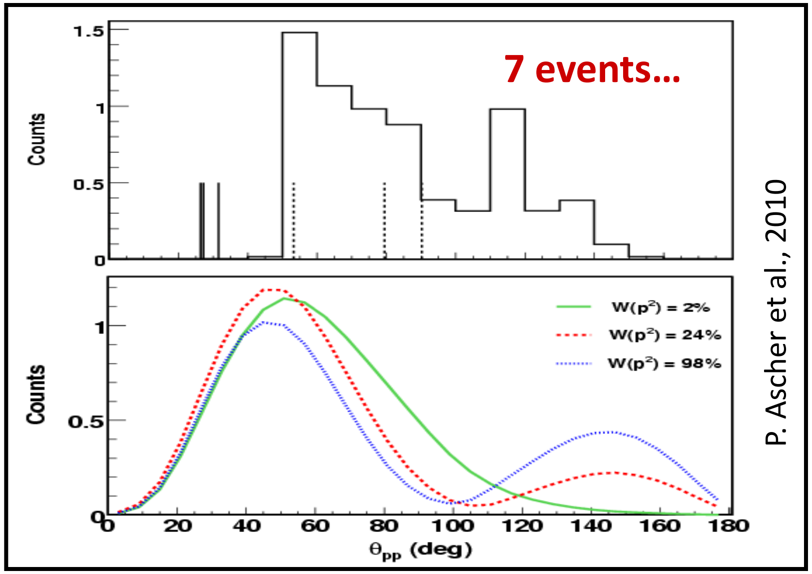


K. Miernik et al. (PRL 2007)

pioneering experiments

→ **opening structure studies** at the drip-line
→ angular distribution probes the **wave function** content (single particle states)

requires more statistics
other cases to test the models descriptions

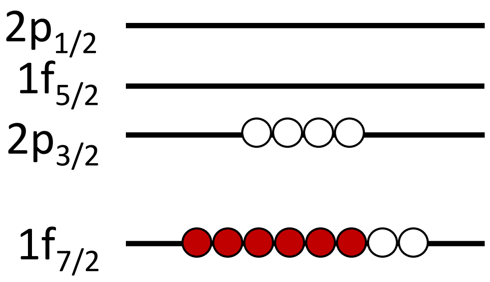


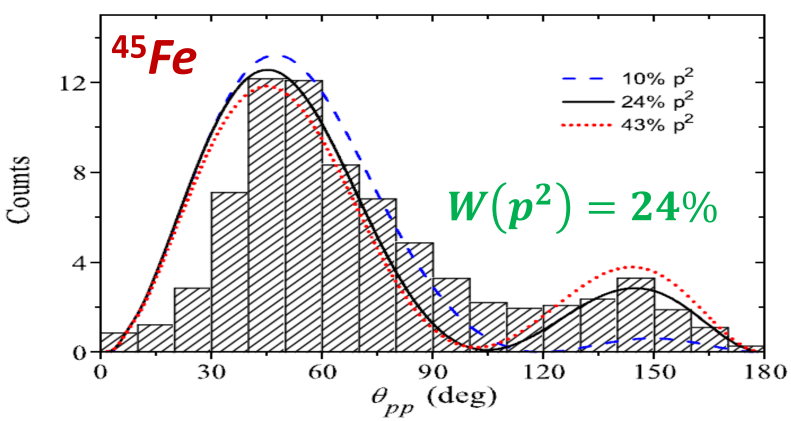
P. Ascher et al., 2010

^{54}Zn (GANIL)

probing structure beyond the drip-line

^{45}*Fe* : 26 protons



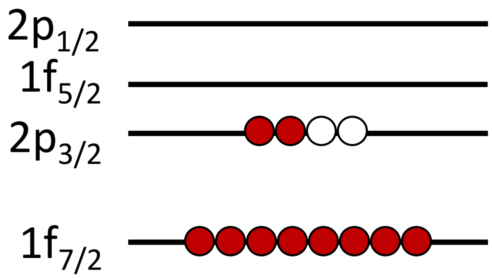


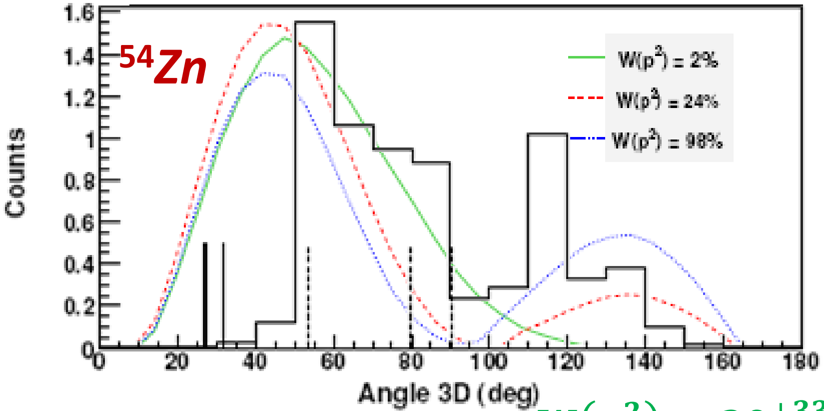
$W(p^2) = 24\%$

K. Miernik *et al.*, EPJA (2009)

proton-proton angular distribution → orbitals configuration

^{54}*Zn* : 30 protons

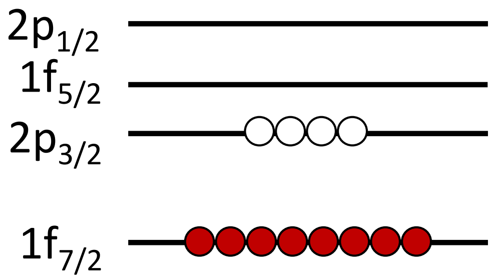




P. Ascher *et al.*, PRL (2011)

$W(p^2) = 30^{+33}_{-21}\%$

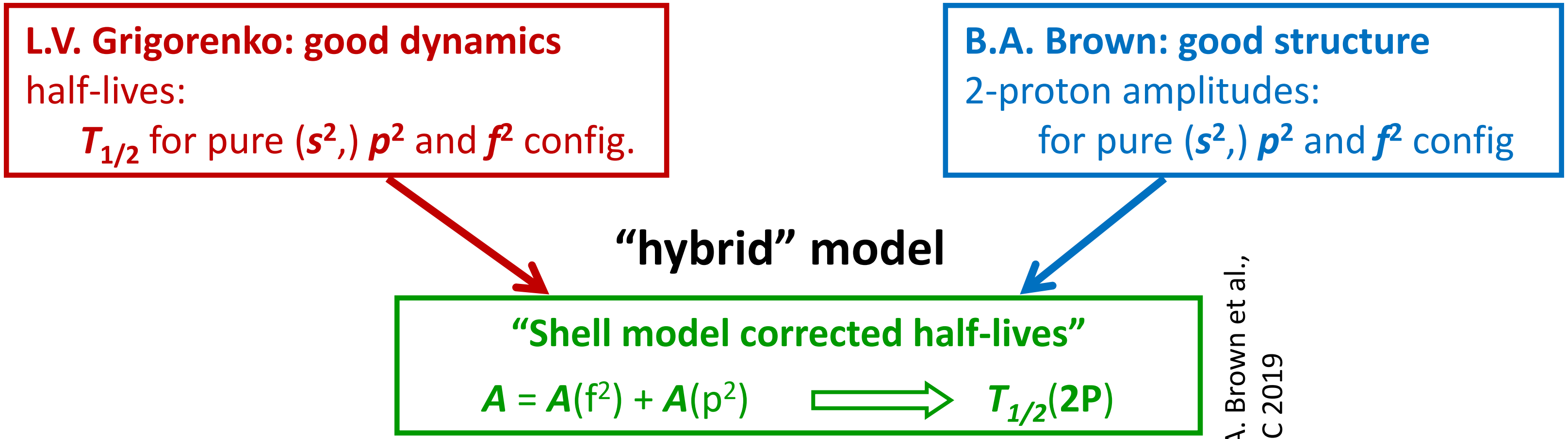
^{48}*Ni* : 28 protons



^{48}Ni ??

doubly magic → pure configuration ?

mixing structure and dynamics



L.V. Grigorenko: good dynamics
half-lives:
$T_{1/2}$ for pure (s^2,) p^2 and f^2 config.

B.A. Brown: good structure
2-proton amplitudes:
for pure (s^2,) p^2 and f^2 config

"hybrid" model

"Shell model corrected half-lives"

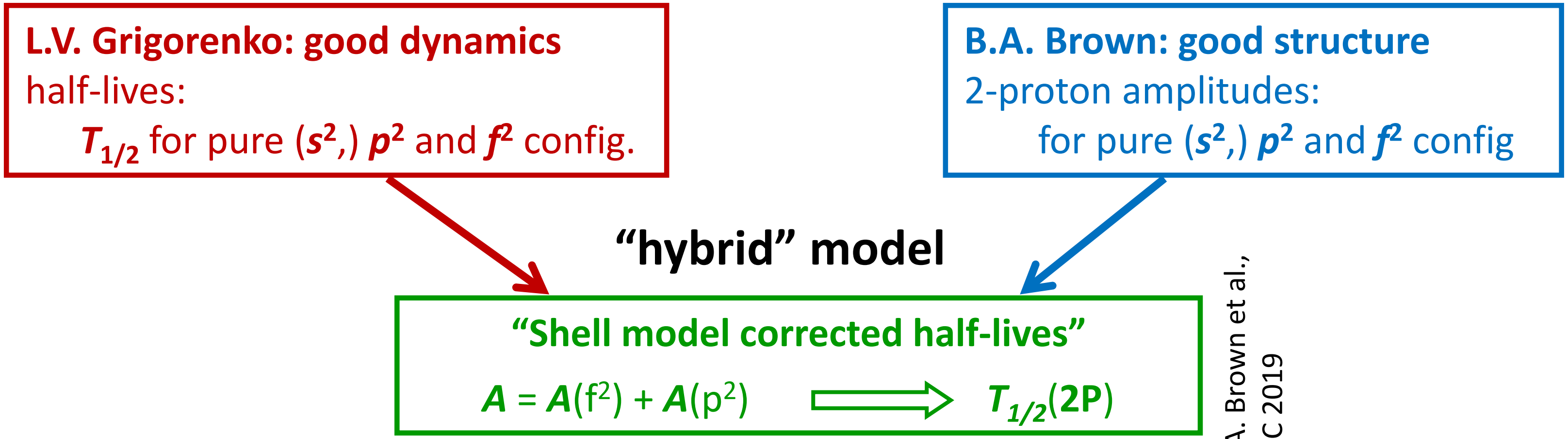
$A = A(f^2) + A(p^2) \Longrightarrow T_{1/2}(2P)$

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**

happy end ?...

mixing structure and dynamics



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B.A. Brown et al.,
PRC 2019

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^{54}Zn	0.6 - 1.7 *ms*	$1.98^{+0.73}_{-0.41}$ *ms*	~OK
^{67}Kr	300 - 900 *ms*	21 ± 12 *ms* (Goigoux et al., PRL 2016)	!?

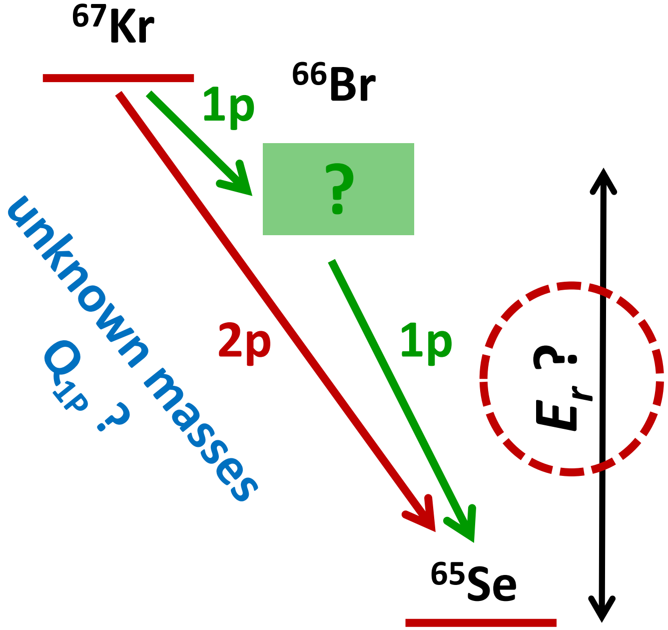
2016

factor 20 to 40 off !!!

"puzzling two-proton decay of ^{67}**Kr" ?**

(title from Wang & Nazarewicz, PRL 2019)

first hypothesis: transition from 2P *to* sequential *decay ?*



^{67}Kr

^{66}Br

1p

?

2p

1p

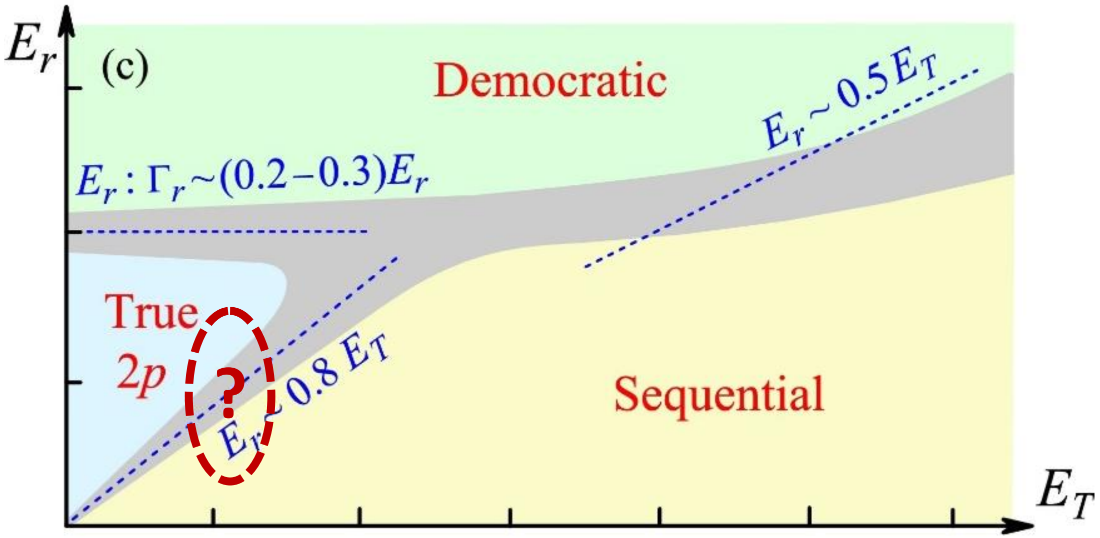
^{65}Se

unknown masses

Q_{1P} ?

E_r ?

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

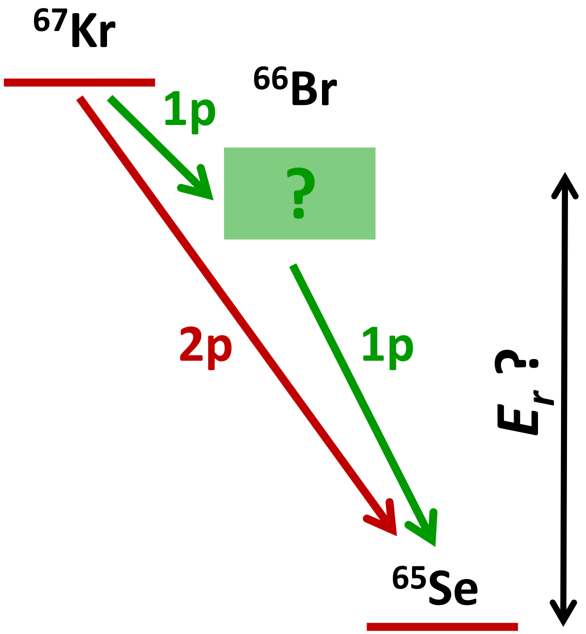


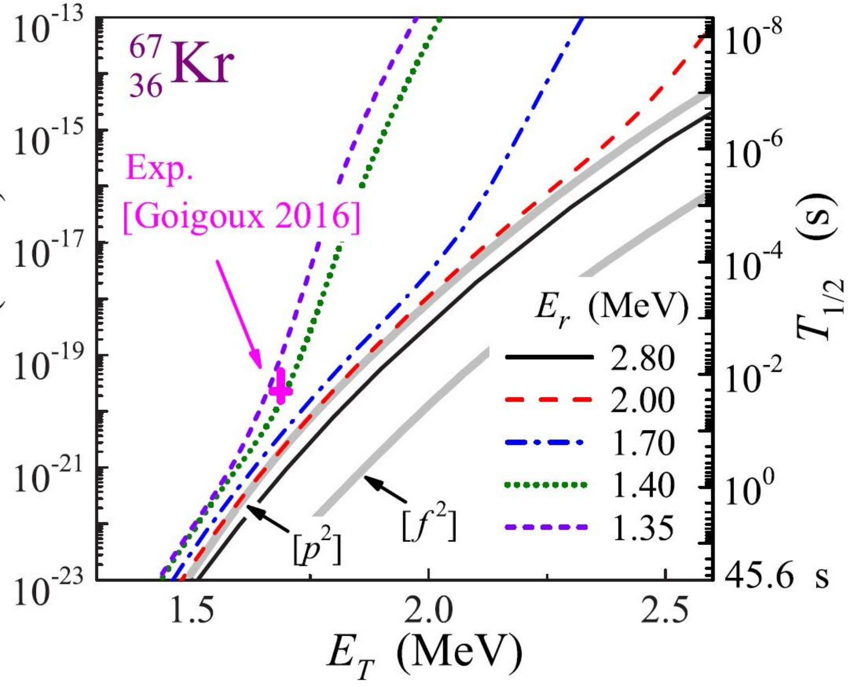
L. Grigorenko et al.
PRC 95 (2017) 021601(R)

first hypothesis: transition from 2P *to sequential decay ?*

(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*

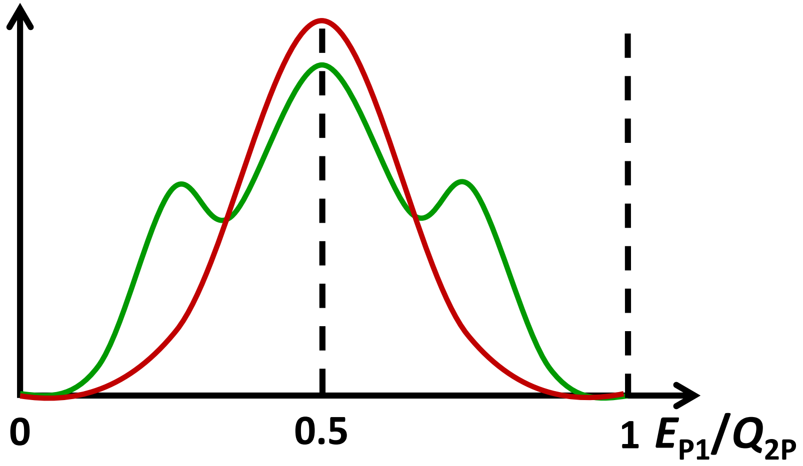




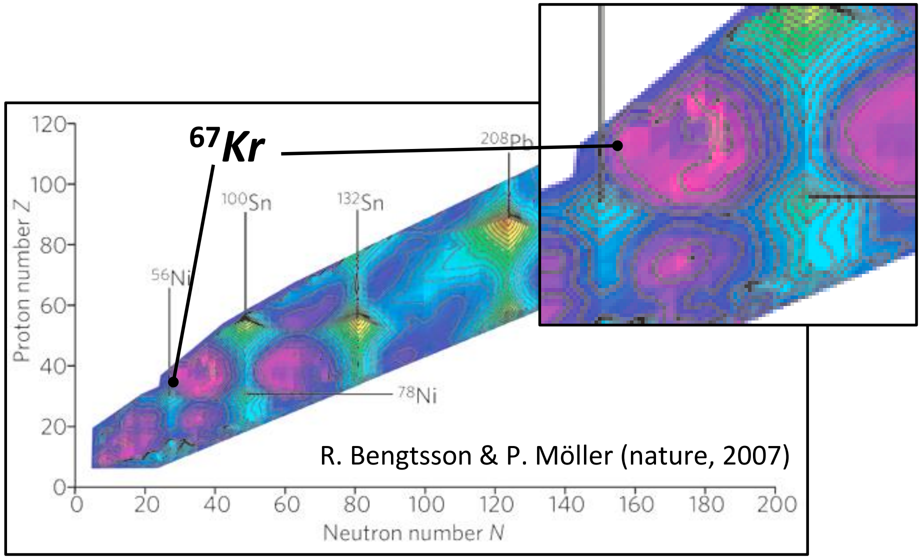
L. Grigorenko et al.
PRC 95 (2017) 021601(R)

2017

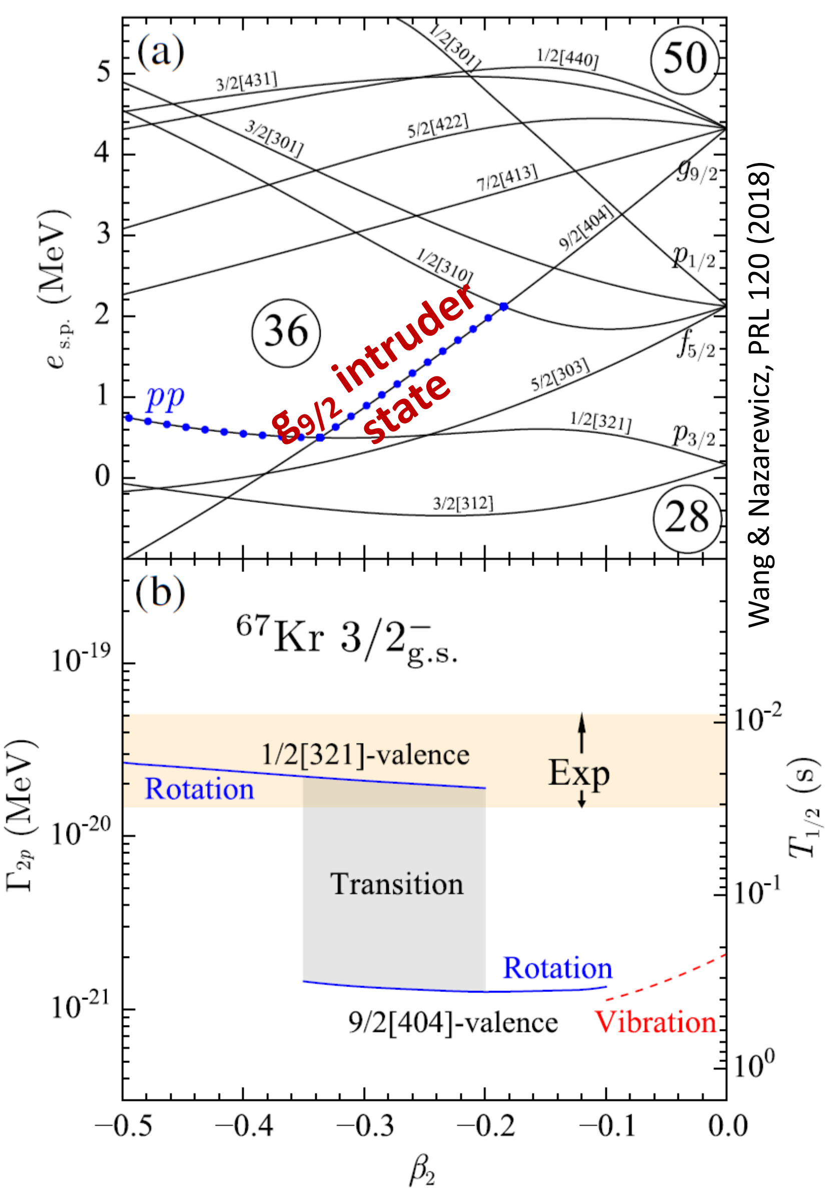
energy sharing pattern
(correlations)



second hypothesis: influence of deformation ?



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



Wang & Nazarewicz, PRL 120 (2018)

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

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

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

agreement with exp. !

2018

second hypothesis: influence of deformation ?

angular correlation prediction

recent work by Wang & Nazarewicz, PRL 120 (2018)
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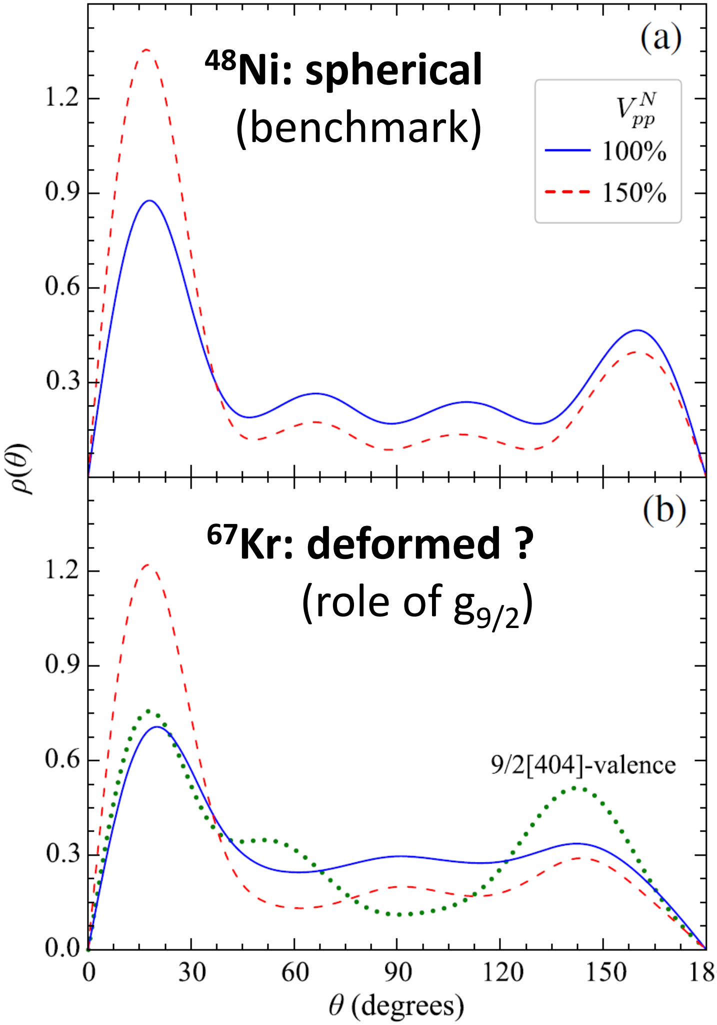


^{48}Ni: spherical
(benchmark)

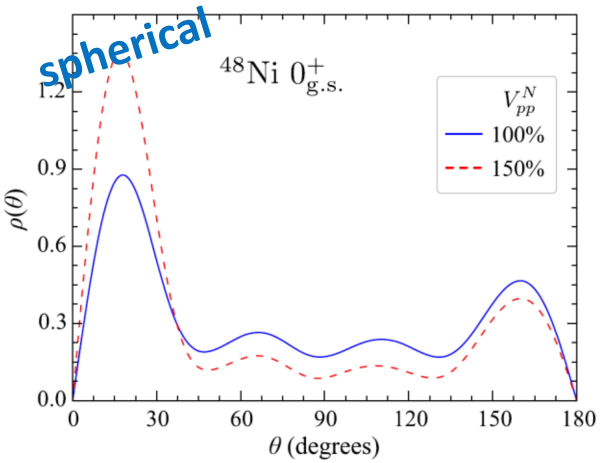
^{67}Kr: deformed ?
(role of $g_{9/2}$)

Wang & Nazarewicz, PRL 120 (2018)

time for new measurements

^{48}Ni

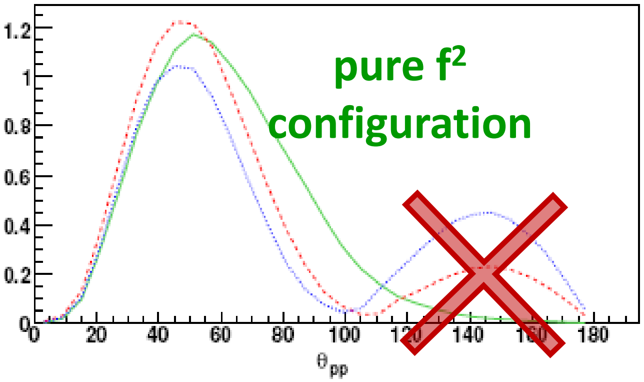
GCC…



3-body model

not available for ^{48}Ni

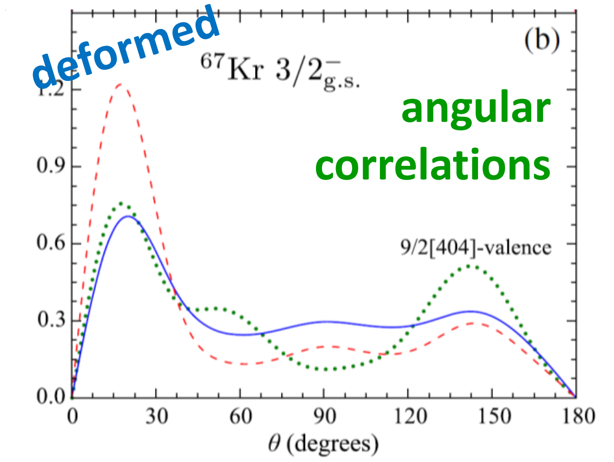
extrapolation from ^{45}Fe & ^{54}Zn

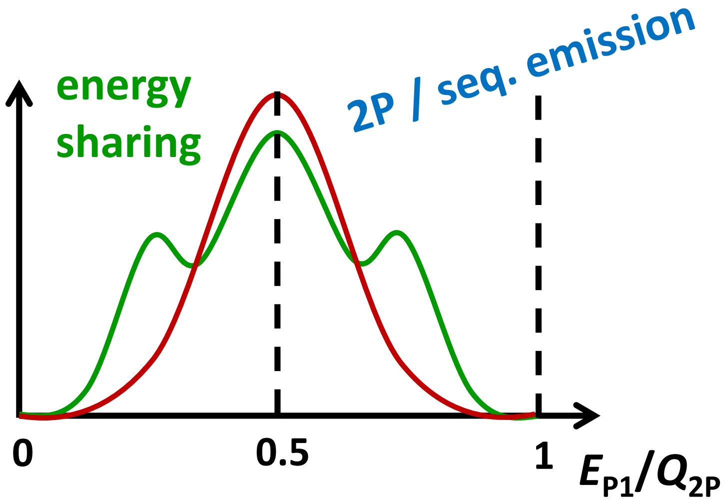


consistent structure and dynamics description

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

^{67}Kr





time for new measurements

GCC…

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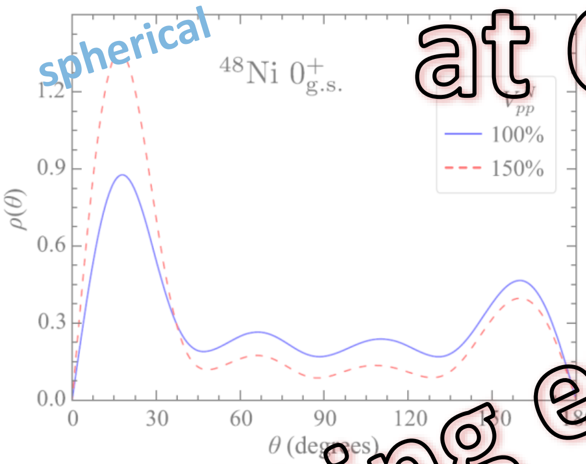
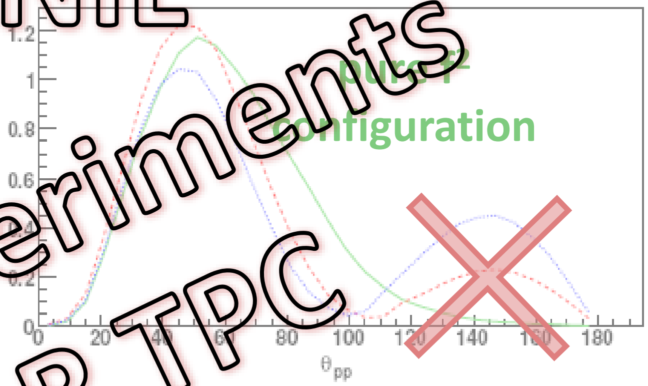
at GANIL

^{48}*Ni*





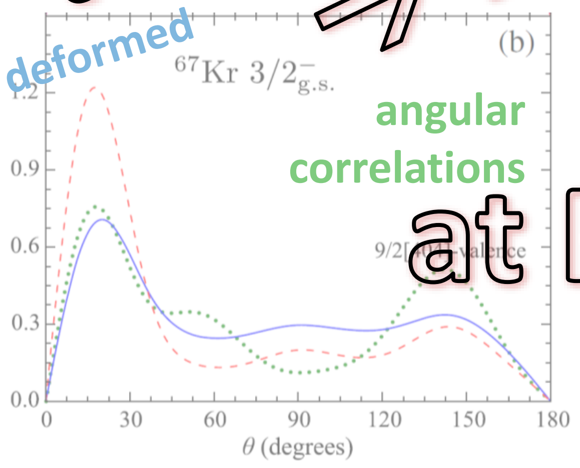
tracking experiments

→ ACTAR TPC

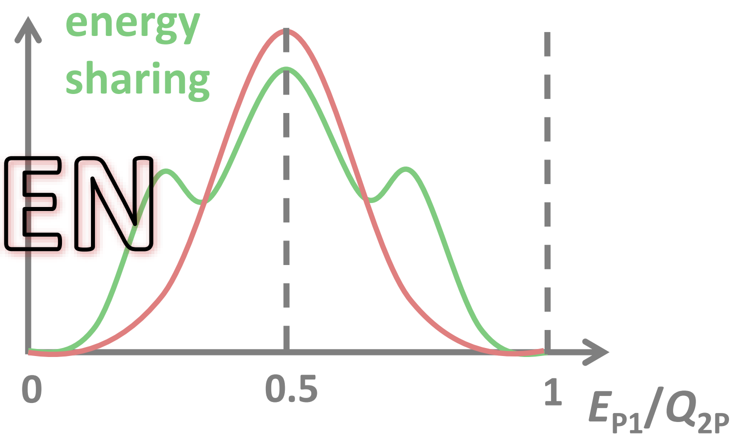
consistent structure and dynamics description

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

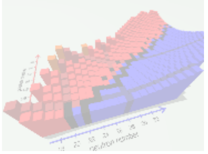
^{67}*Kr*



at RIKEN

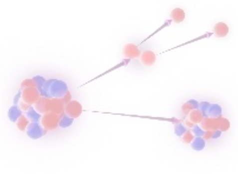


On the Tracks of Two-Proton Radioactivity

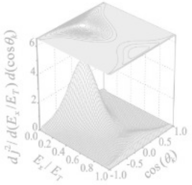


radioactivity on the neutron-deficient side of the table of isotopes

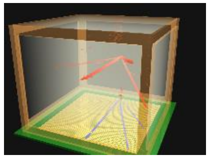
proton-rich



what is two-proton radioactivity?



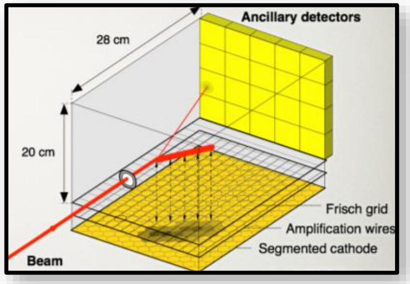
loops between theory and experiment



a new tracking device

ACTAR TPC collaboration

ACtive TARget & Time Projection Chamber

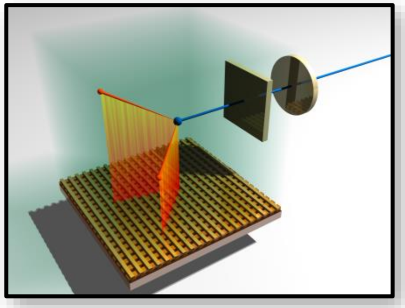


MAYA

(GANIL and coll.)

nuclear reactions

pads (hex): 2D proj.
wires: drift time

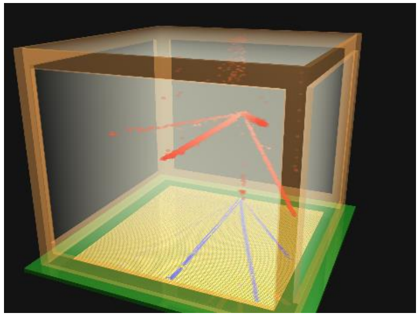


CENBG TPC

ions stopping and decay

X-Y strips
energy & time:
2x 1D proj.

development of a new TPC
for a large (nuclear) physics case



GANIL, CENBG,
Leuven, Santiago de C.,
IPNO, Legnaro

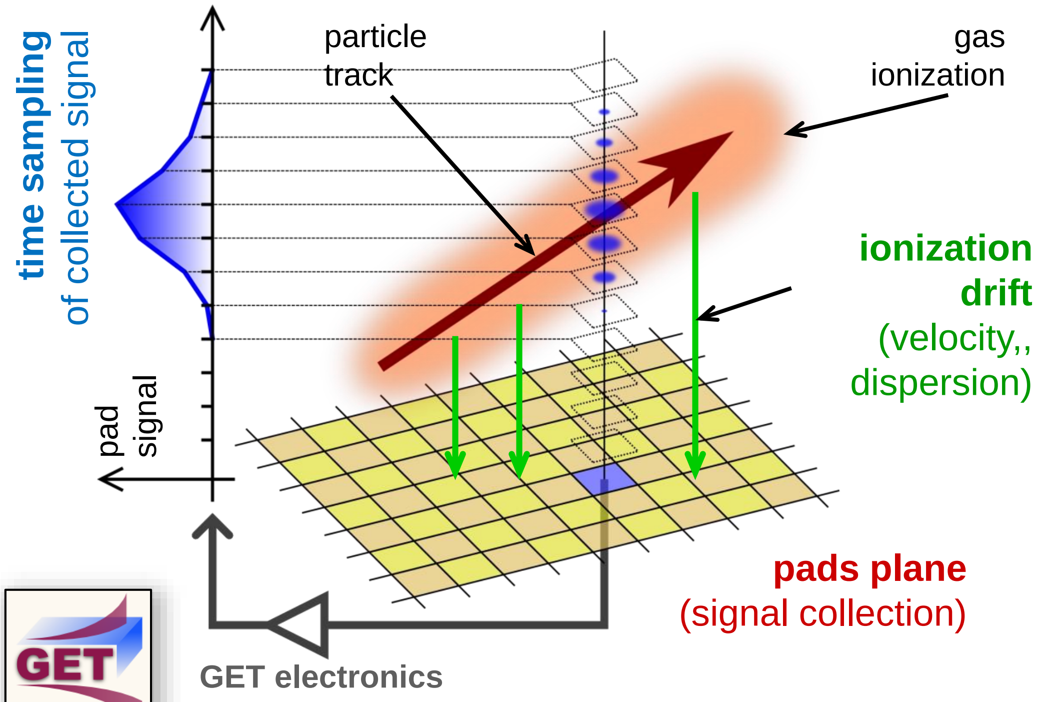
a 4D detector: tracking and energy

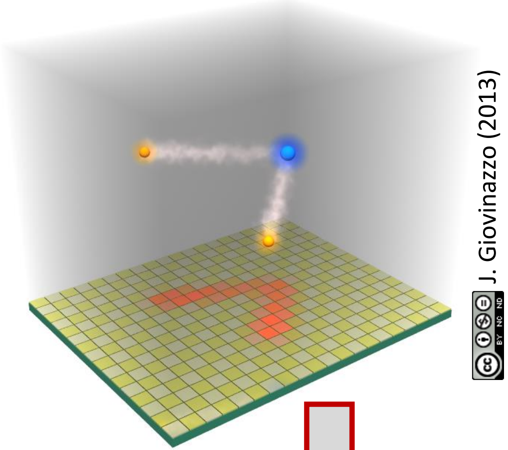
pads plane
(signal collection)
2D digitization

TPC principle
$z \Leftrightarrow t$

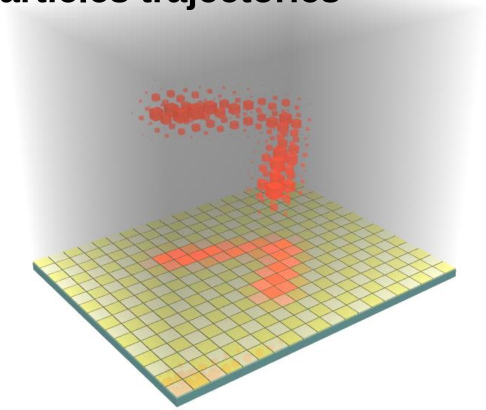
time sampling of signal
3D digitization

$$\Delta E(x,y,z) \Longleftrightarrow \Delta E[x_i,y_j](z) \Longleftrightarrow \Delta E[x_i,y_j](t) \Longleftrightarrow \Delta E[x_i,y_j,t_k]$$



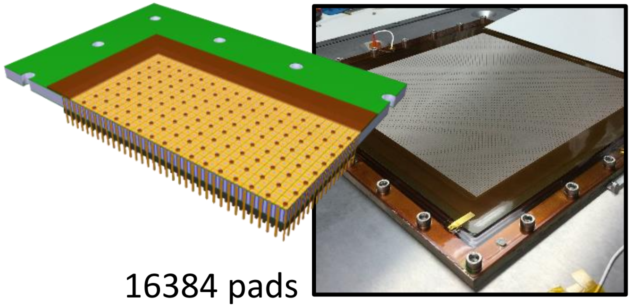


3D reconstruction of ionizations charges along the particles trajectories



ACTAR TPC: main elements

metal-core PCB



16384 pads
(128×128; 2×2 mm^2)

collection plane (pads)

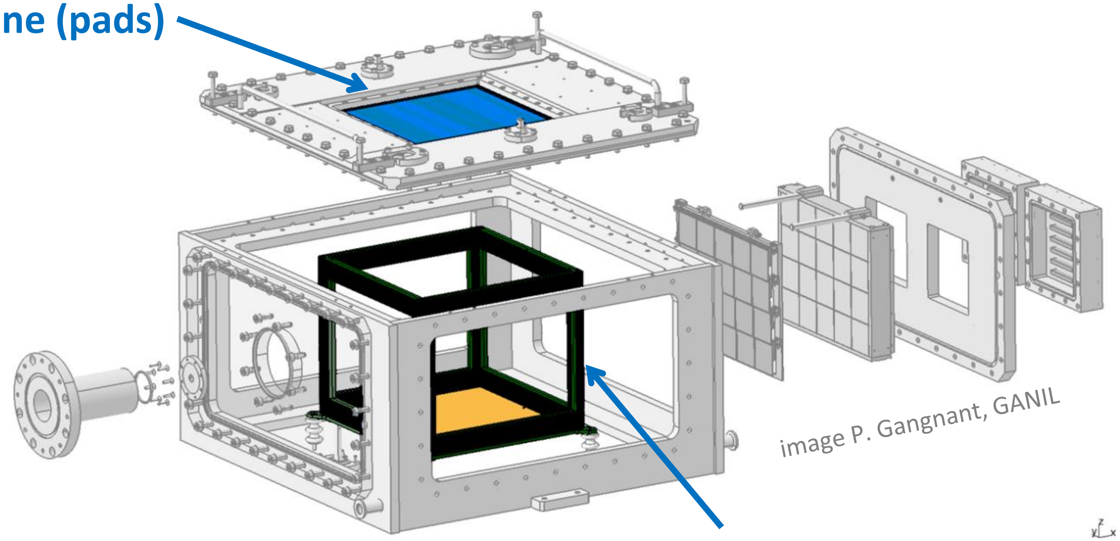
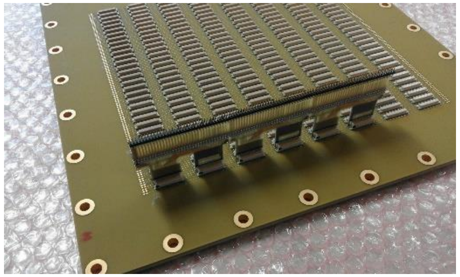


image P. Gangnant, GANIL

drift cage (active volume)

multi-layer PCB



GANIL 2019

+ flexible PCB connection to read. elec.

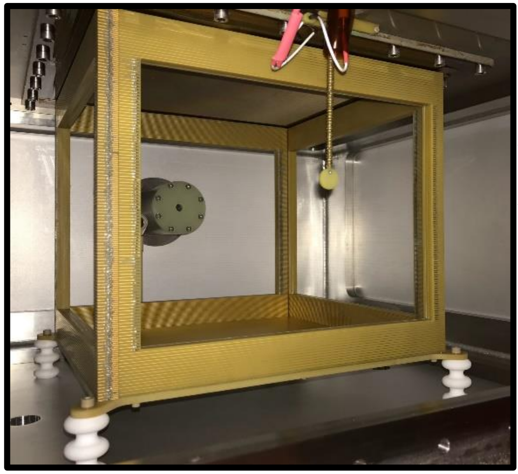
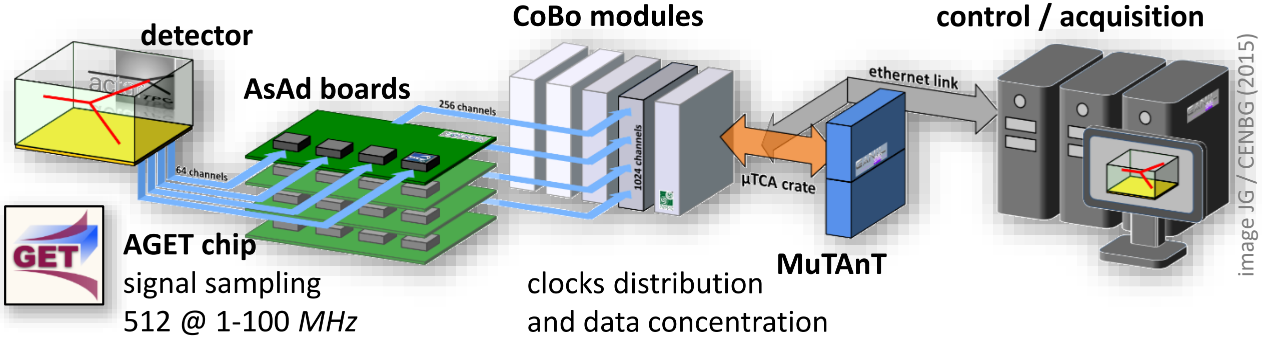


photo O. Poleshchuk (2017)

readout electronics



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

clocks distribution
and data concentration

image JG / CENBG (2015)

beginning of the scientific program

2017 commissioning experiment

active target mode

resonant reaction $^{1}H(^{18}O,^{15}N)^{4}He$

(T. Roger, B. Mauss)

2019 first physics campaign

- **active target mode**

  giant resonance $^{68}Ni(\alpha,\alpha')$

  (R. Raabe, M. Vandebrouck)

- **implantation-decay mode**

  proton radioactivity of

  ^{54m}Ni (10^{+}, 150 *ns*)

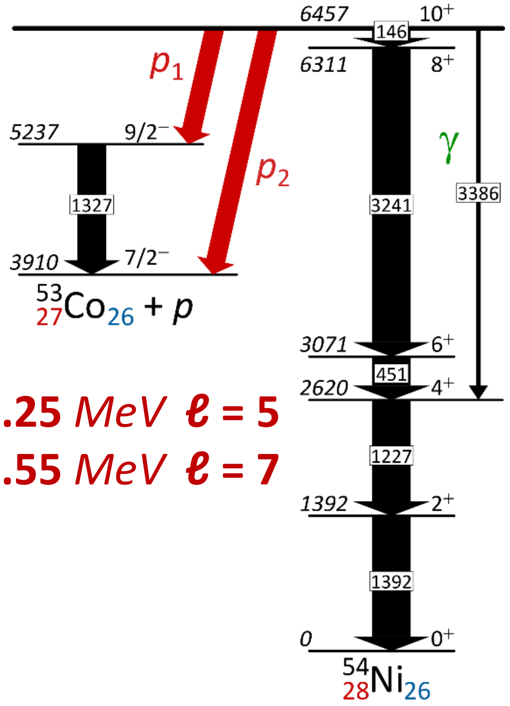
  ^{53m}Co ($19/2^{-}$, 220 *ms*)

  (D. Rudolph, B. Blank)

first ACTAR TPC campaign (GANIL 2019)

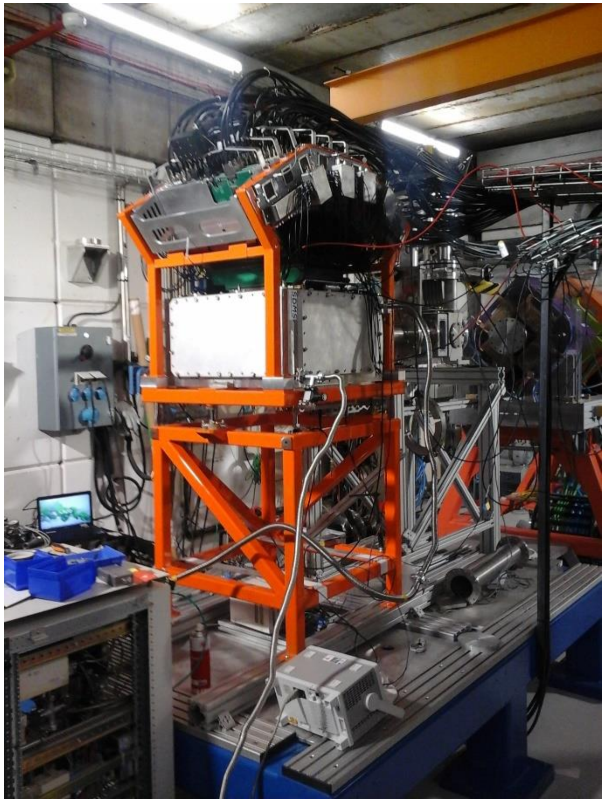
proton radioactivity of ^{54m}Ni

$T_{1/2}$ = 155(3) *ns*



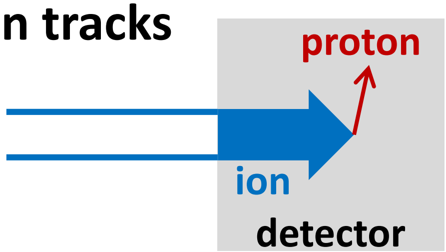
1.25 *MeV* ℓ = 5
2.55 *MeV* ℓ = 7

- → **isospin symmetry**
- → **structure around *N* = 28**
- → ***fp* shell model coupled to continuum**



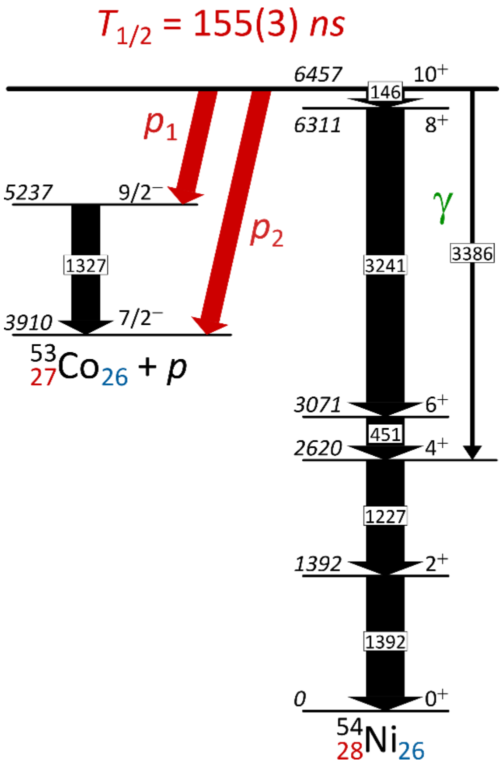
(very) short half-life:

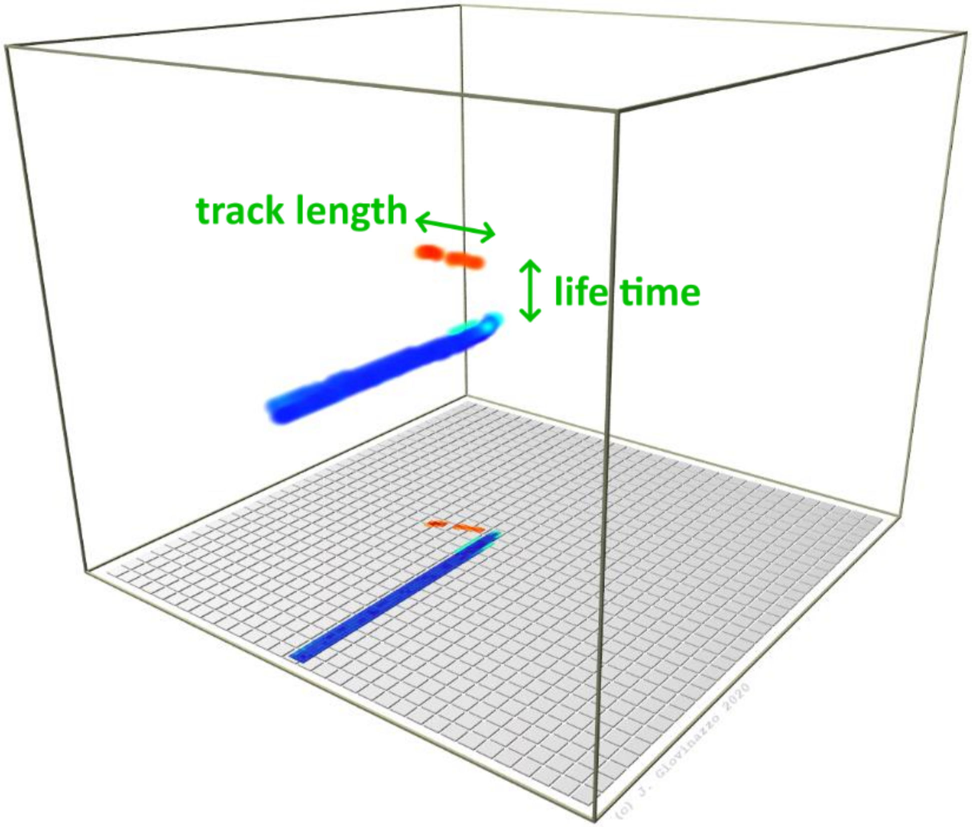
- **detection impossible in solid stopping detector ion signal hides proton signal**
  (1:1000 energy deposit)
- **TPC: separated ion and proton tracks**



\+ **proton radioactivity of ^{53m}Co** (220 *ms*)
ℓ = 7 and **ℓ = 9**

proton radioactivity of ^{54m}Ni



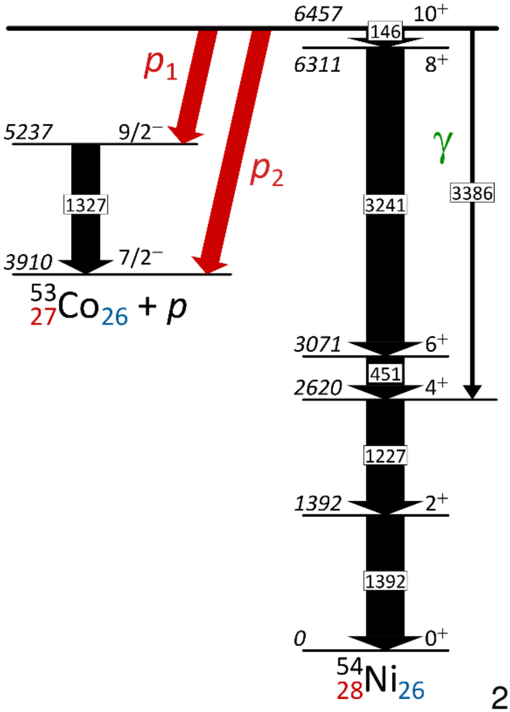


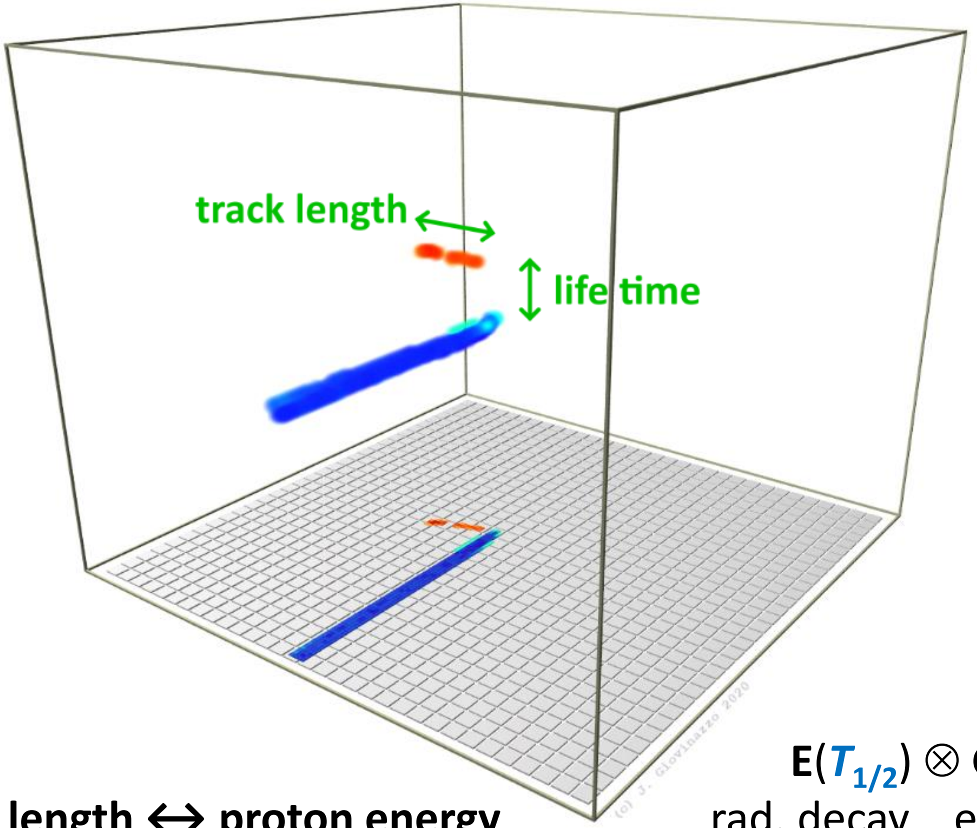
4D imaging of proton decay

principle of the measurement:
3D tracking
+ decay time

proton radioactivity of ^{54m}Ni

$T_{1/2}$ = 155(3) *ns*

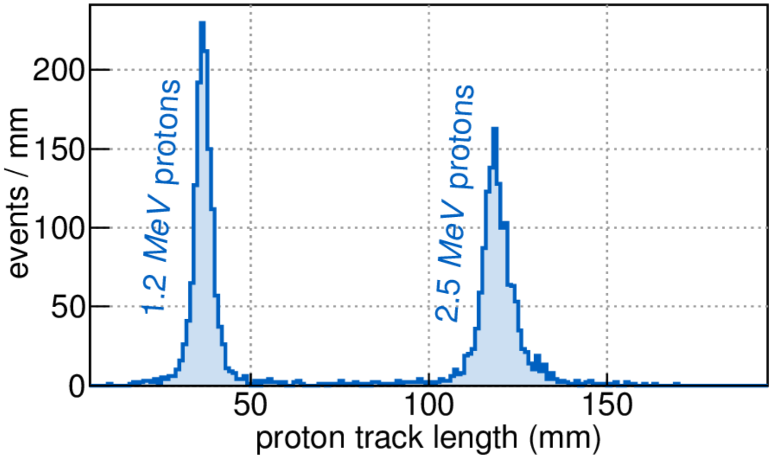


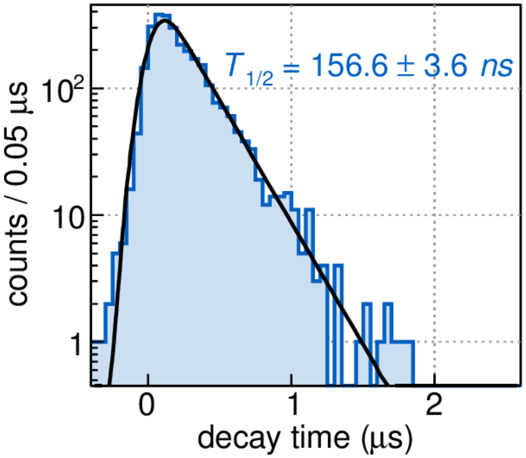


track length ↔ proton energy

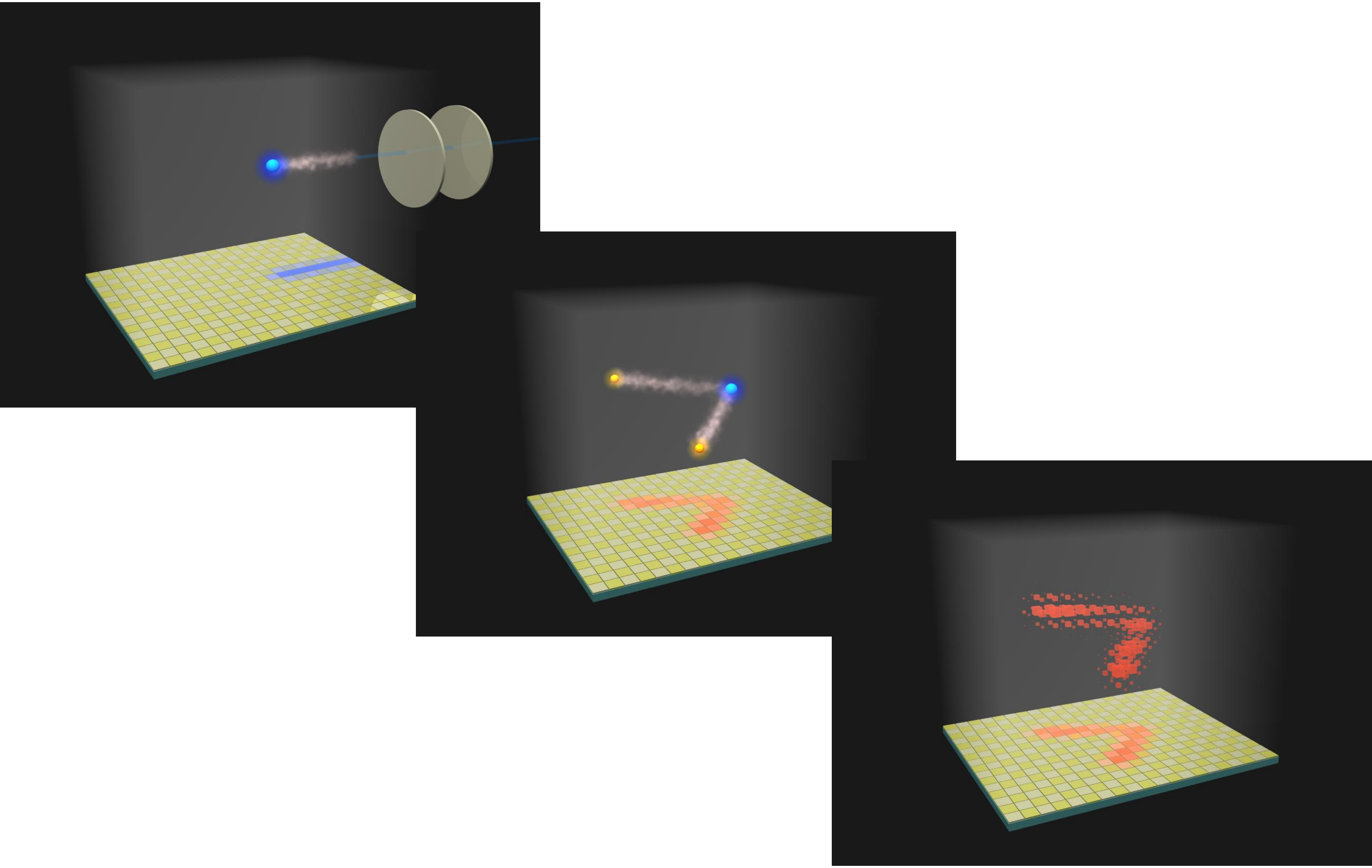
E($T_{1/2}$) ⊗ G(σ_T)

rad. decay exp. resol.

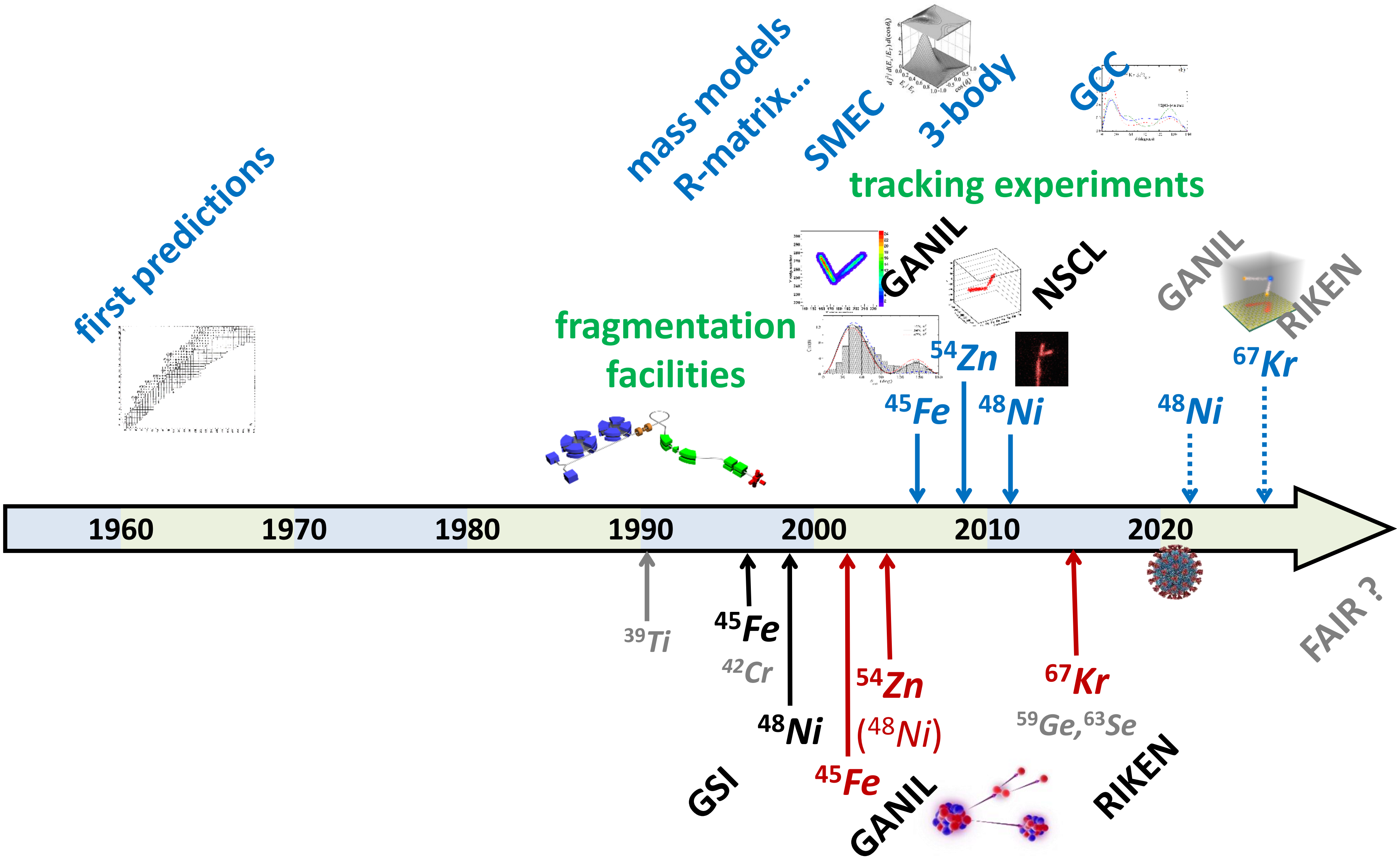




correlation measurements for ^{48}Ni and ^{67}Kr with ACTAR TPC



timeline of the 2-proton radioactivity



first predictions

fragmentation facilities

mass models

R-matrix…

SMEC

3-body

GCC

tracking experiments

GANIL

NSCL

GANIL

RIKEN

^{45}*Fe*

^{54}*Zn*

^{48}*Ni*

^{48}*Ni*

^{67}*Kr*

1960 1970 1980 1990 2000 2010 2020

^{39}*Ti*

^{45}*Fe*

^{42}*Cr*

^{48}*Ni*

GSI

^{45}*Fe*

^{54}*Zn*

(^{48}*Ni*)

GANIL

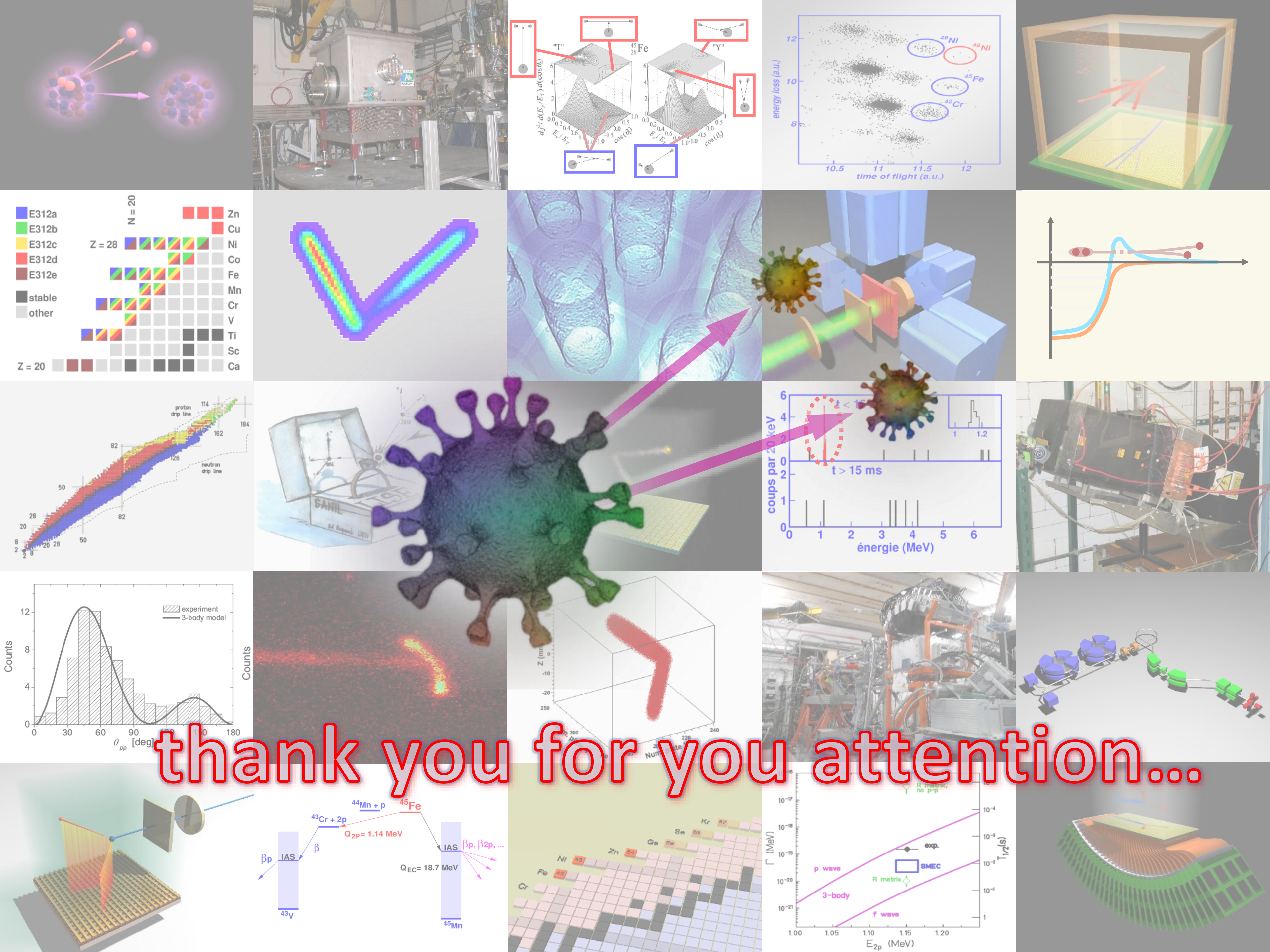
^{67}*Kr*

^{59}*Ge*,^{63}*Se*

RIKEN

FAIR ?

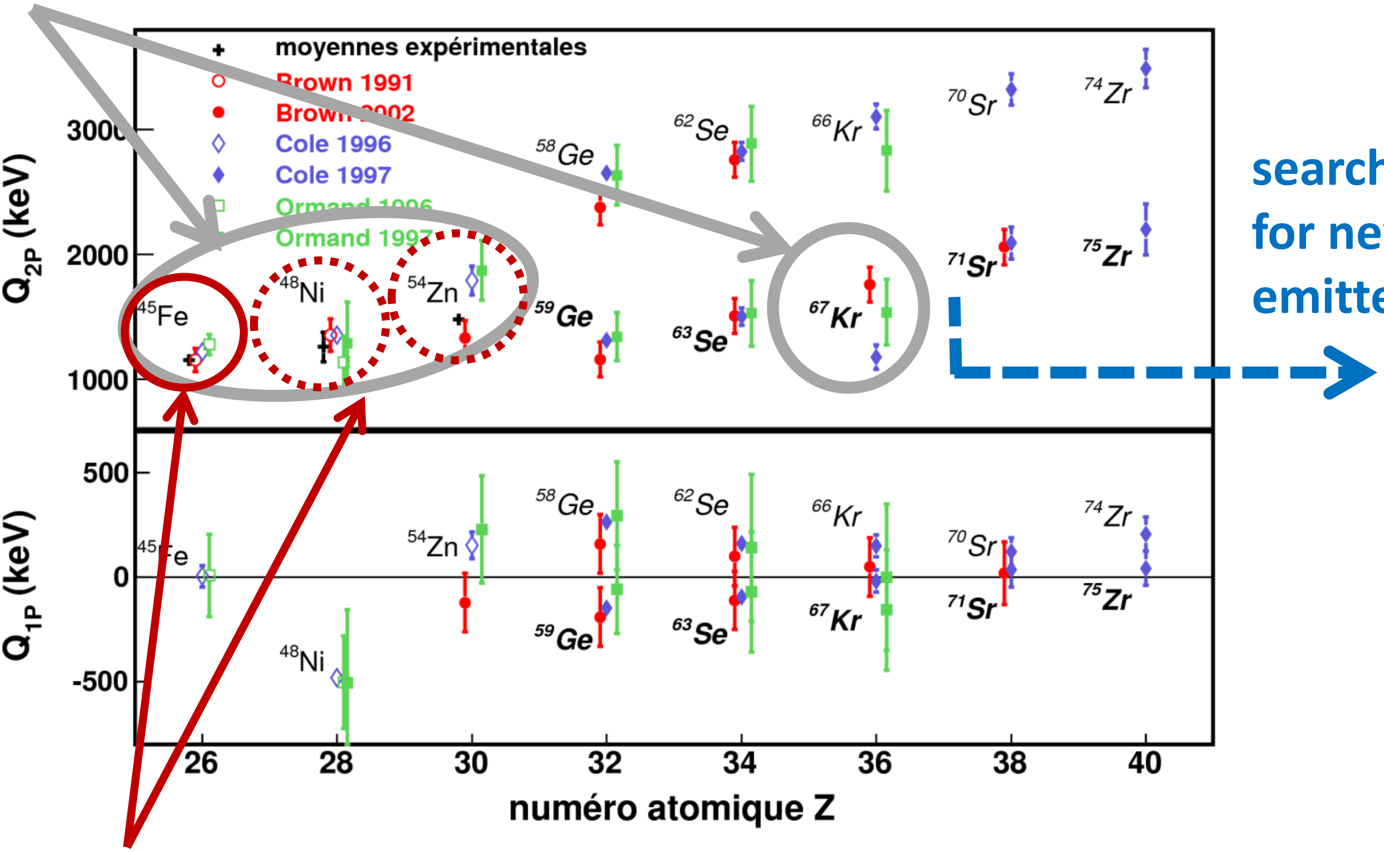
indirect observation



thank you for you attention...

further studies

known cases



search for new emitters ?

direct observations

→ future (short term) tracking / correlation experiments: ***^{48}Ni, ^{54}Zn, ^{67}Kr***

further studies, new candidates ?

larger set of nuclei with different structure configurations
between closed shells Z = 28 and Z = 50

- opportunities **FRS / Super-FRS @ GSI / FAIR**

rate estimates (courtesy of B. Blank)
(**5 × 10^{11} pps** of primary beam, **600 MeV/A**,
4 sec per pulse, 4 g/cm^2 of Be)

beam	frag.	rate (1/day)
^{58}Ni	^{48}Ni	70
^{78}Kr	^{67}Kr	200
^{92}Mo	^{71}Sr	100
	^{70}Sr	5
	^{75}Zr	60
	^{79}Mo	10
^{124}Xe	^{98}Sn	10

~50 × more | GANIL
~20 × more | RIKEN