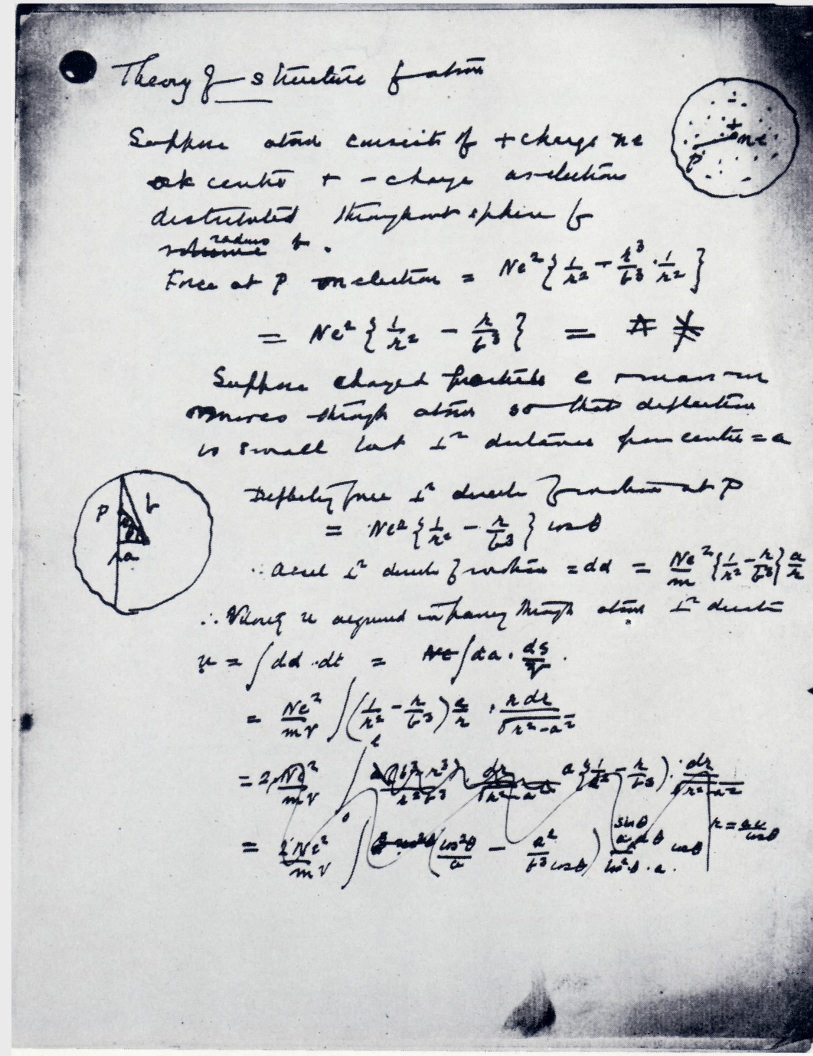
Nuclei at the neutron and proton drip lines

Marek Pfützner
University of Warsaw
Gurgen Ter-Akopian
JINR

JINR in 100 years of the discovery
of the atomic nucleus, Dubna, 10-11.03.2011

100 years ago...

E. Rutherford (1871-1937)

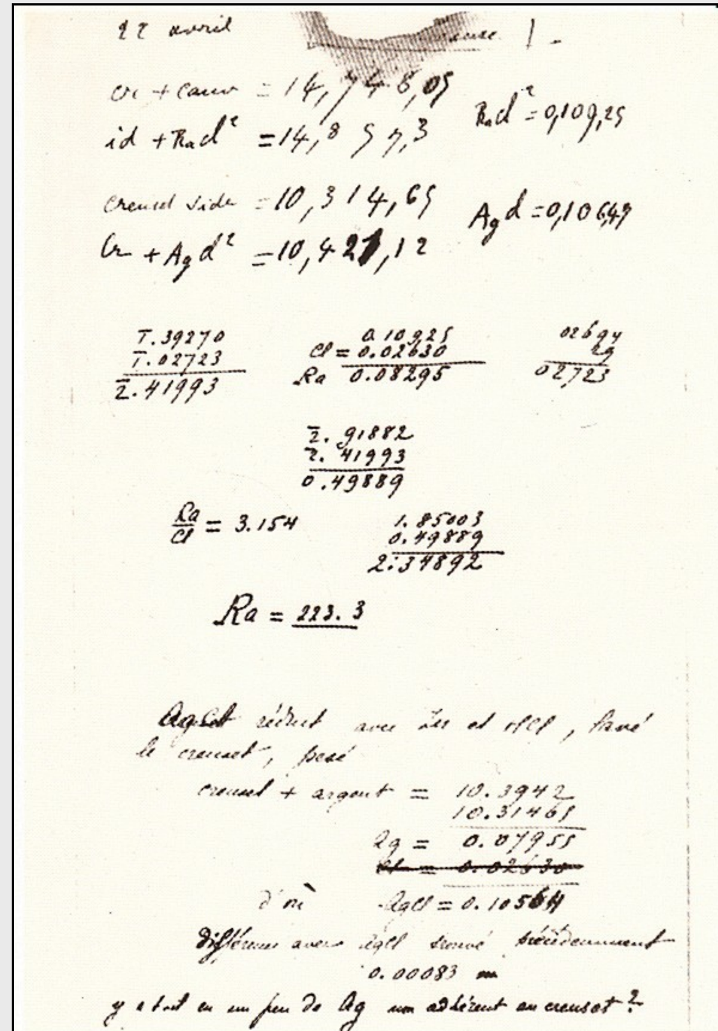


Rutherford's first rough note on the nuclear theory of atomic structure; written, probably, in the winter of 1910–11

2011 – Year of Chemistry

The Nobel Prize in Chemistry 1911 was awarded to Marie Curie *"in recognition of her services to the advancement of chemistry by the discovery of the elements radium and polonium, by the isolation of radium and the study of the nature and compounds of this remarkable element"*.

http://nobelprize.org/nobel_prizes/chemistry/laureates/1911/



T.39270
T.02723
2.41993

Cl = 0.10925
0.02630
Ra 0.08295

1.91882
1.41993
0.49889

Ra/Cl = 3.154

1.85003
0.49889
2.34892

Ra = 223.3

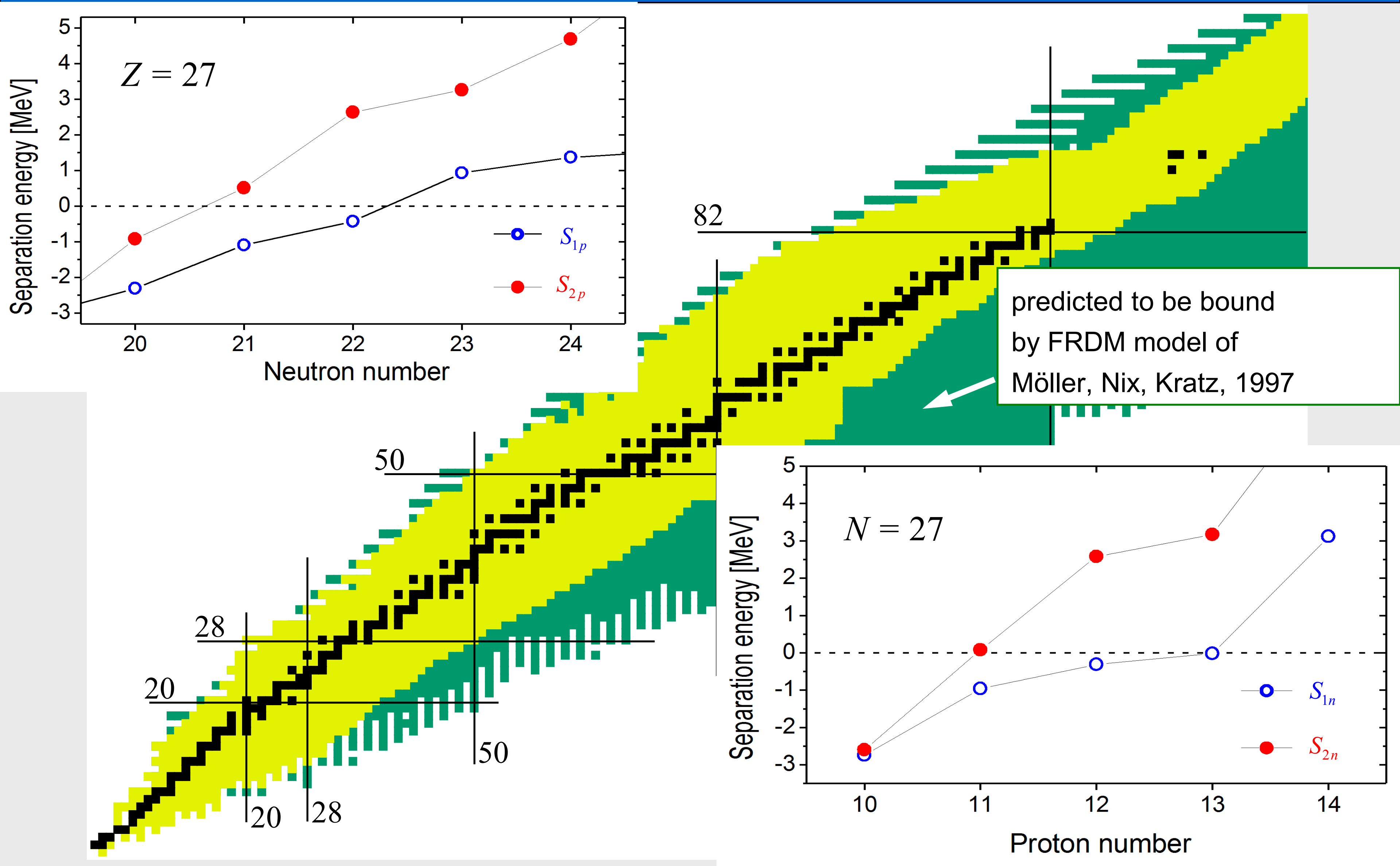
Ag = 0.07955

AgCl = 0.10564

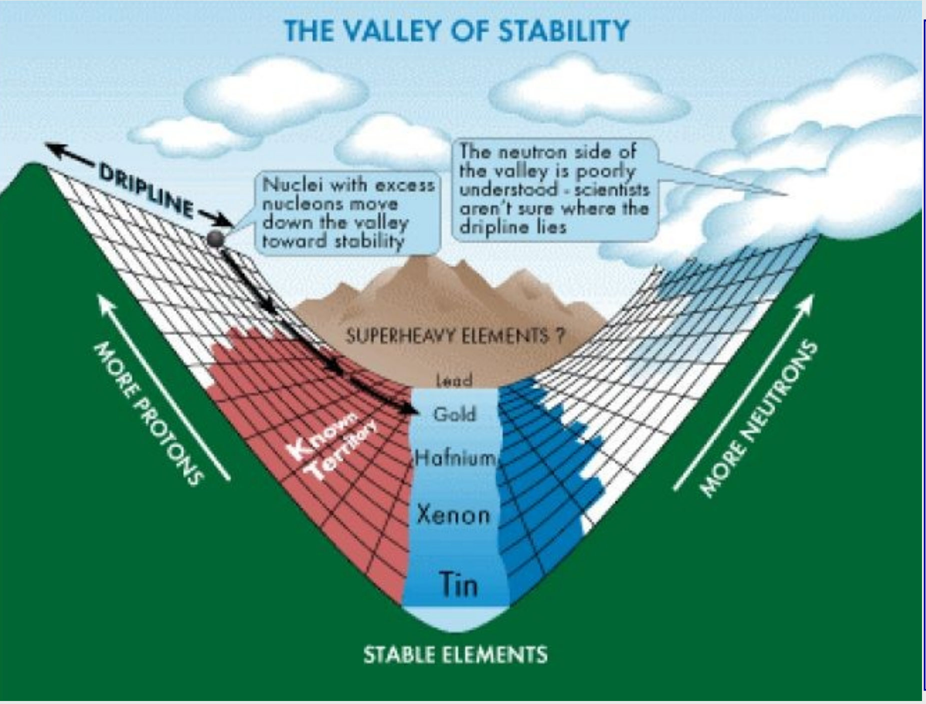
0.00083

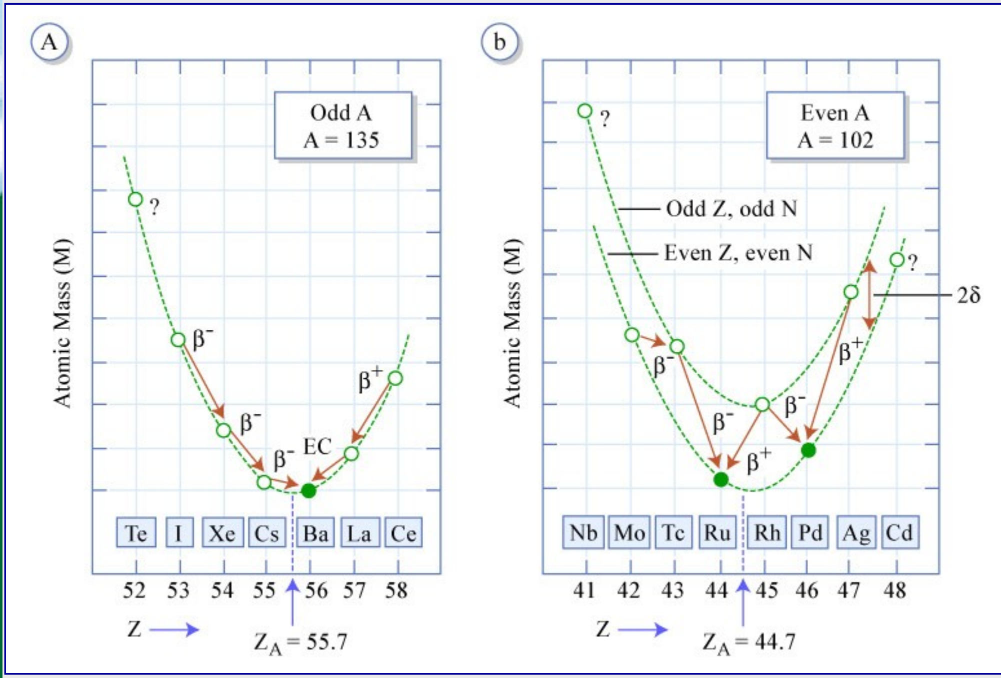
Paris, 11 rue Pierre-et-Marie-Curie

The world of nuclides, 2010



Nuclear valley

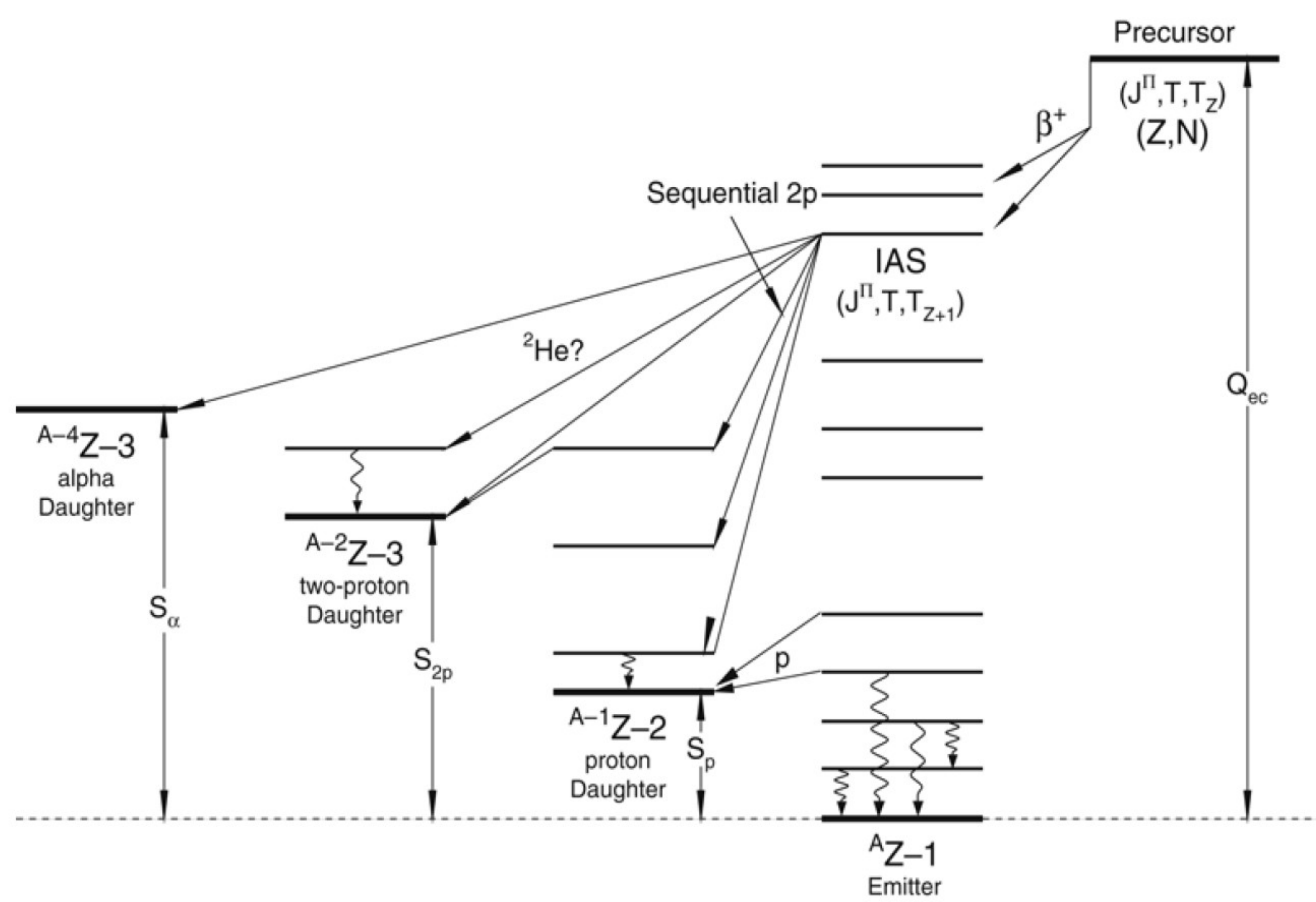




- Masses of isobars ($A = \text{const.}$) lie on parabolas.
  - ➔ β-decay Q values increase toward drip-lines!

β-delayed particle emission

- When the decay energy is large, many exotic decay channels open



B. Blank, M. Borge, Progress in Part. Nucl. Phys. 60 (2008) 403

β-delayed protons

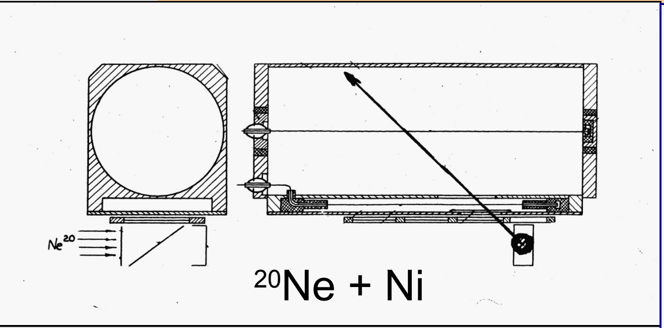
- The first observation of β-delayed protons was achieved by Karnaukhov in Dubna

В.А.Карнаухов, Г.М.Тер-Акопьян, В.Г.Субботин

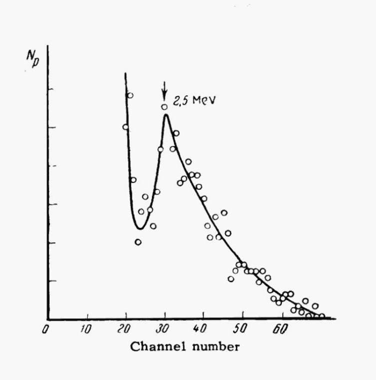
Р-1072

ЭКСПЕРИМЕНТЫ ПО ОБНАРУЖЕНИЮ ПРОТОННОЙ РАДИОАКТИВНОСТИ ЯДЕР

Дубна 1962 год



$^{20}Ne + Ni$



Proceedings of the Third Conference on Reactions Between Complex Nuclei
Held at Asilomar (Pacific Grove, California)
April 14-18,1963

SEARCH FOR PROTON EMITTERS AMONG THE PRODUCTS OF HEAVY ION INDUCED REACTIONS

V.A.Karnaukhov, G.M.Ter-Akopian, V.G.Subbotin
Joint Institute for Nuclear Research
Dubna, USSR

^{17}Ne	$T_{1/2}$	≅	0.1s
^{73}Kr	$T_{1/2}$	≅	25s

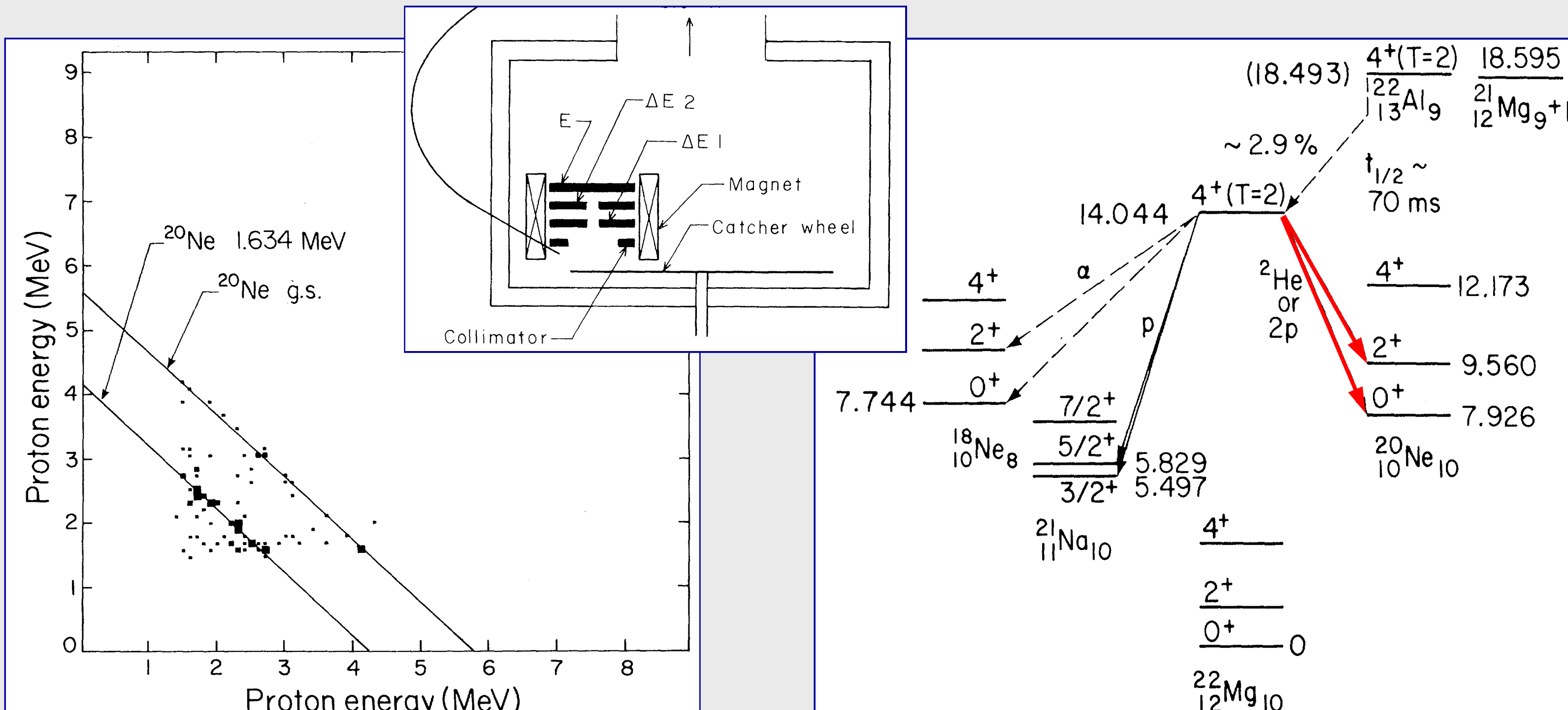
- The first β-delayed proton precursor, ^{25}Si, was identified by
  R. Barton, et al., Can. J. Phys. 41 (1963) 2007
  This work is considered as the first application of Si detector in nuclear physics

β-delayed two protons

- The β-delayed two-proton emission was predicted by Goldansky in 1980

V.I. Goldansky, Sov. Phys. JETP Lett. 32 (1980) 554

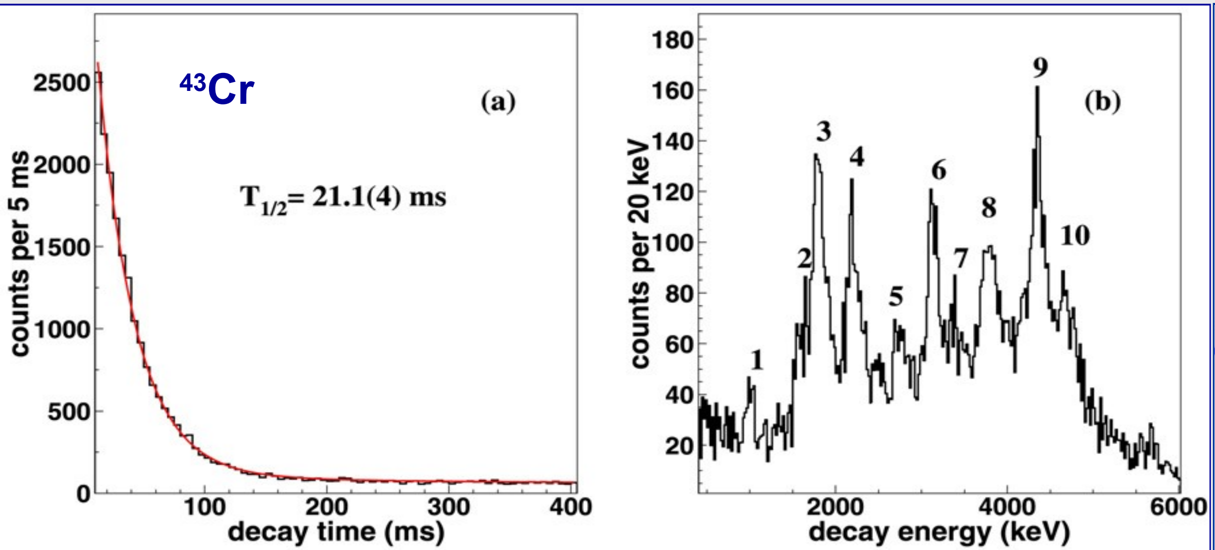
The first observation, for ^{22}Al, at Livermore Berkeley Lab. in 1983

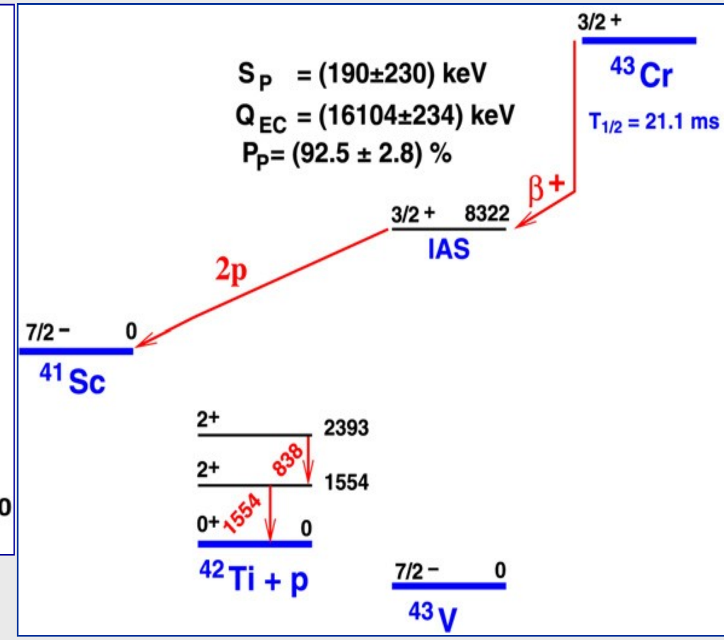


M.D. Cable et al., Phys. Rev. Lett. 50 (1983) 404

βp spectroscopy

Projectile fragmentation at GANIL: ^{58}Ni @ 75 MeV/u + Ni → LISE spectrometer



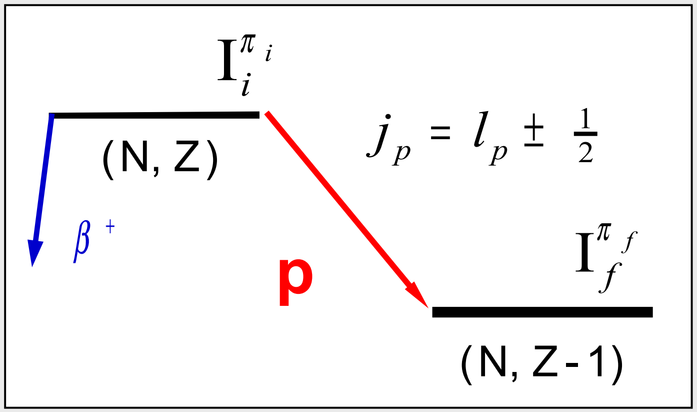


C. Dossat et al., Nucl. Phys. A792 (2007) 18

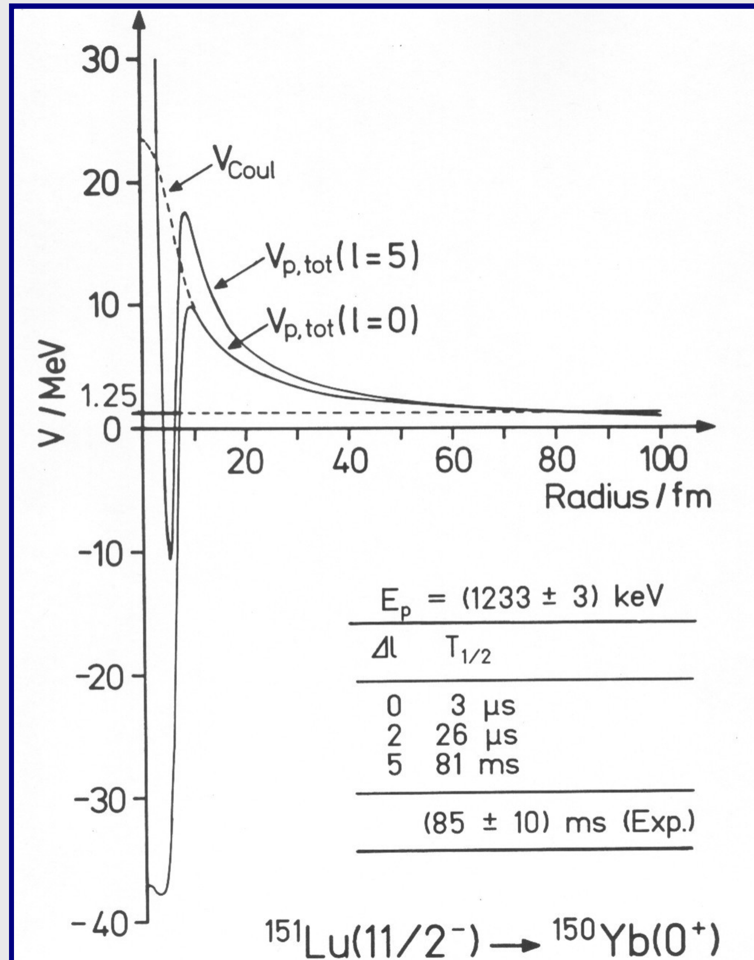
- Today about 160 precursors known, from ^{8}B to ^{183}Hg
- βp spectroscopy provides wealth of information about nuclei far from stability, like β-decay strength distribution, level energies, widths, spins, level densities, etc.

Direct particle emission

- When proton separation energy becomes negative, a proton is no more bound and can be emitted.



- Proton emission always competes with β^+ decay!

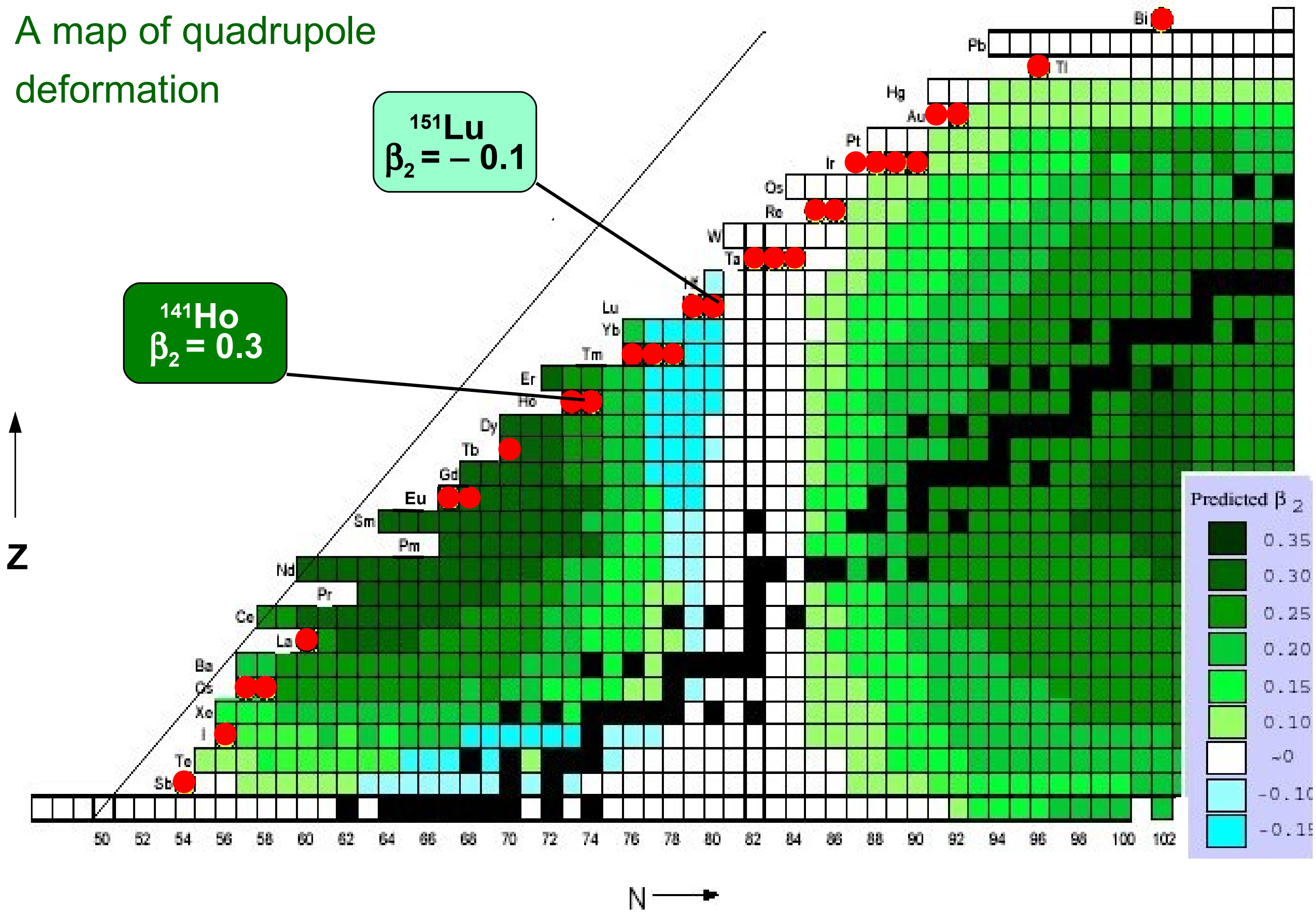


S. Hofmann et al., Z. Phys. A305 (1981) 111

- Today, about 40 proton-emitting nuclear states(g.s. and isomers) are known. All g.s. *p*-emitters between Z = 50 and 82

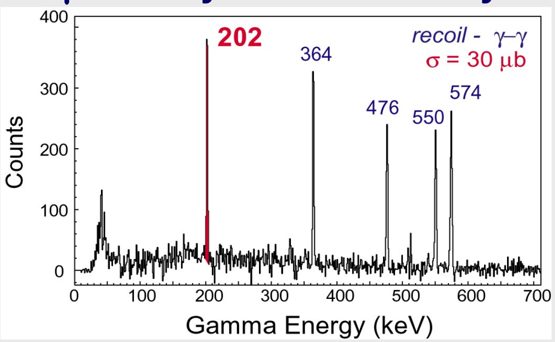
p radioactivity – a recent highlight

A map of quadrupole deformation

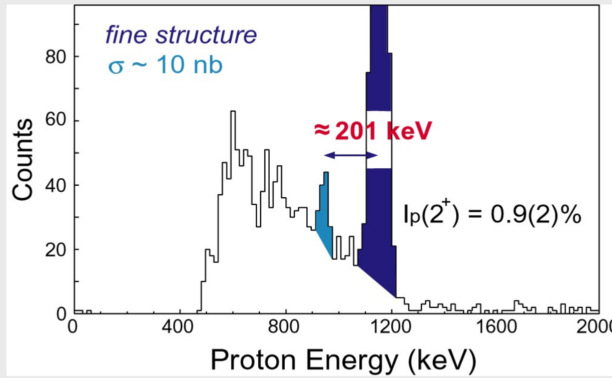


Proton emission from deformed ^{141}Ho

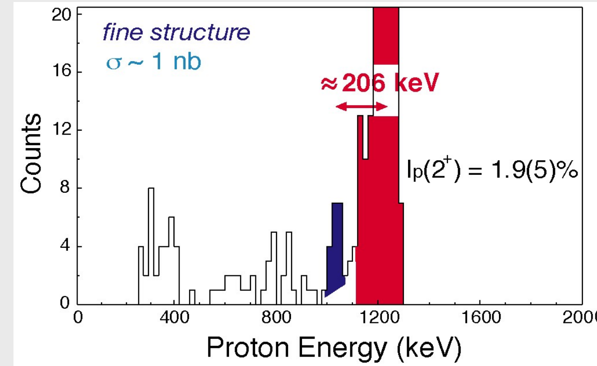
7 μs ^{140m}Dy isomeric decay

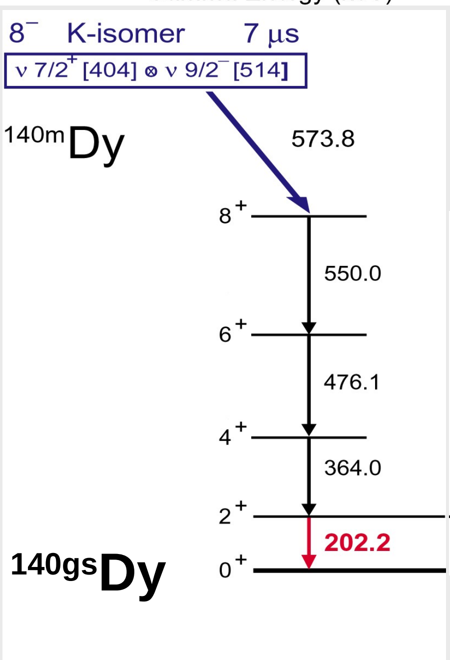


4 ms ^{141gs}Ho proton decay

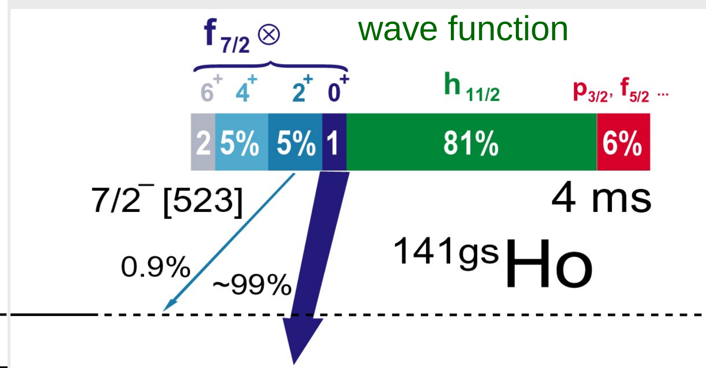


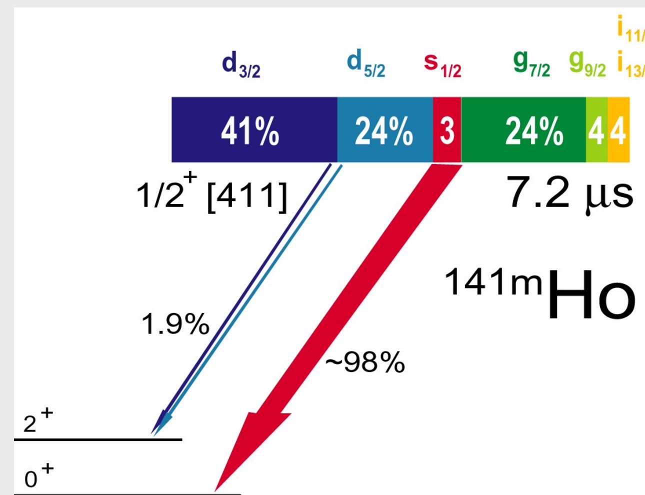
7.4 μs ^{141m}Ho proton decay





Coupled-channels approach
Kruppa et al., PRL 84,4549 (2000)



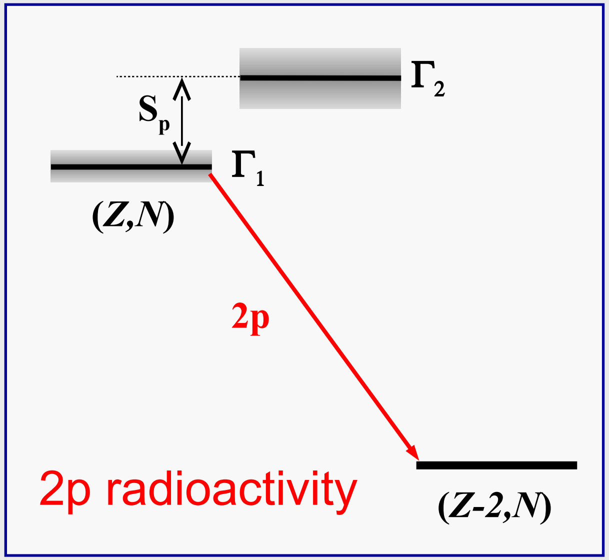


fine structure in proton decay, wave function of ^{141gs}Ho

M. Karny et al., Phys. Lett. B664, 52, 2008

Figures courtesy of K. Rykaczewski (Oak Ridge)

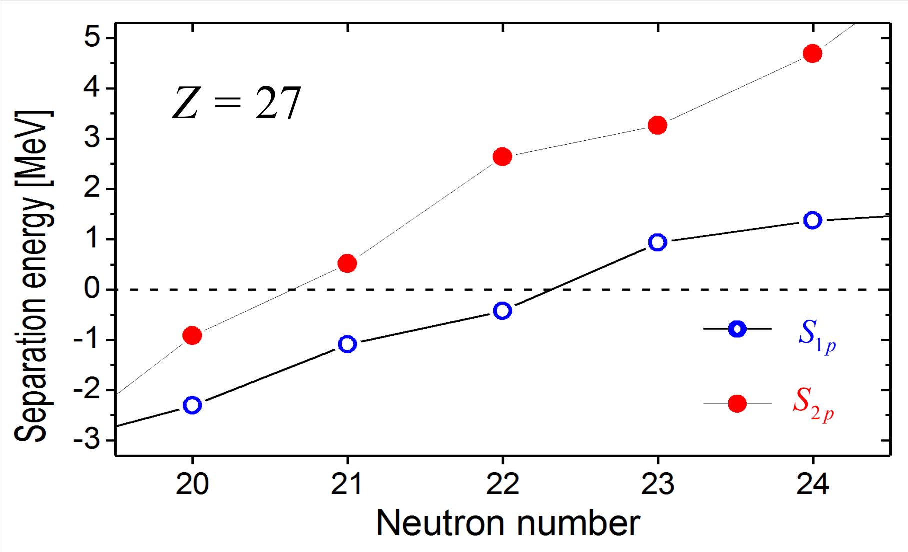
2p radioactivity

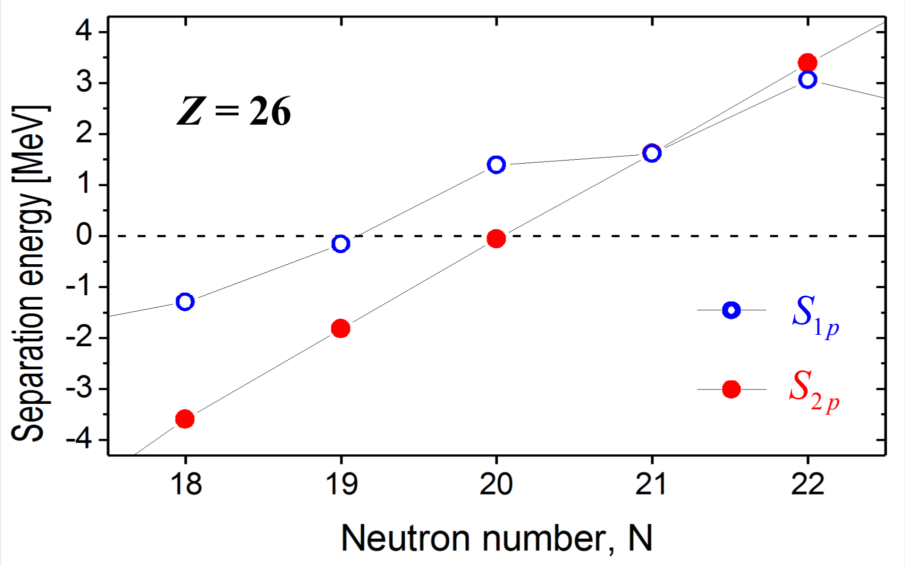


V.I. Goldansky, Nucl. Phys. 19 (1960) 482

- By radioactivity we consider processes with the half-lives longer than 10^{-14} s.

  Simultaneous *2p* emission may occur also in faster processes (democratic decays, resonances)





Early considerations

Baz, Goldansky, Goldberg, Zeldovich,
„Light and medium nuclei at the limits of stability, Moscov 1972

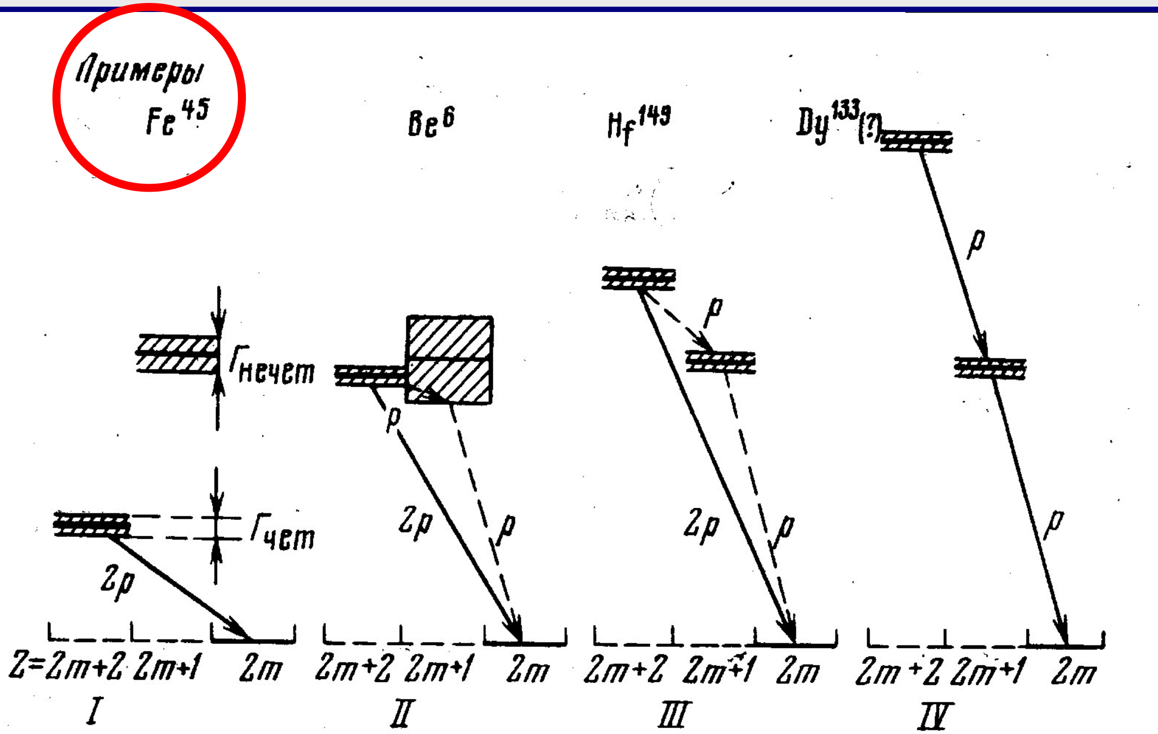
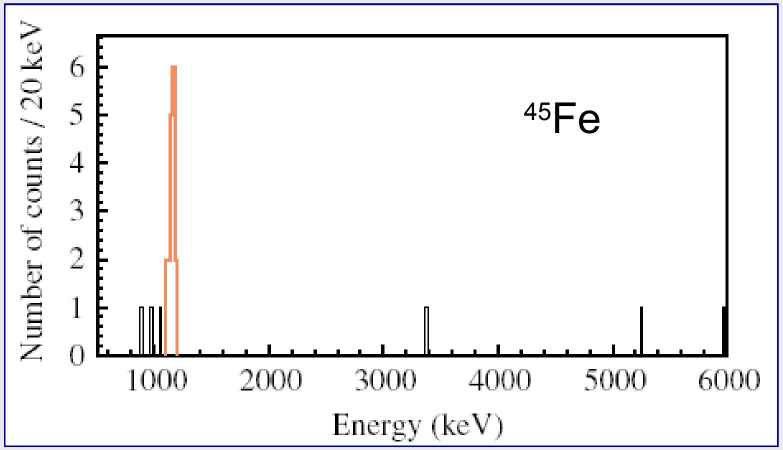


Рис. 48. Различные варианты испускания ядрами пар протонов

Decay of ^{45}Fe

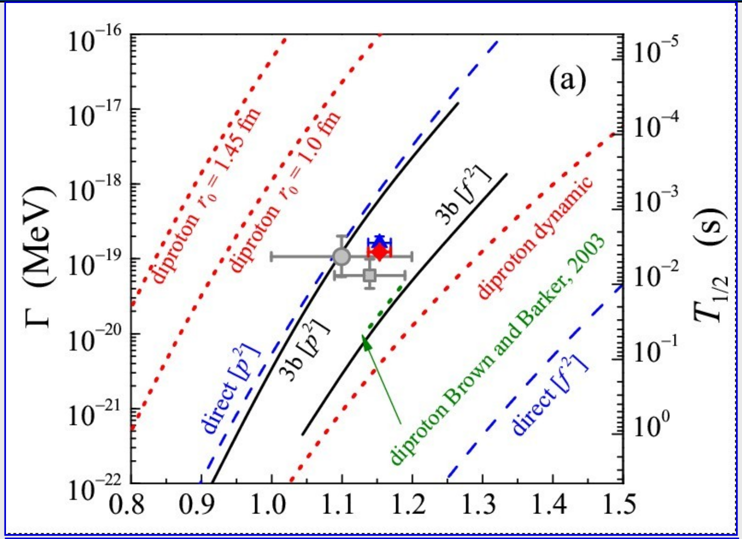


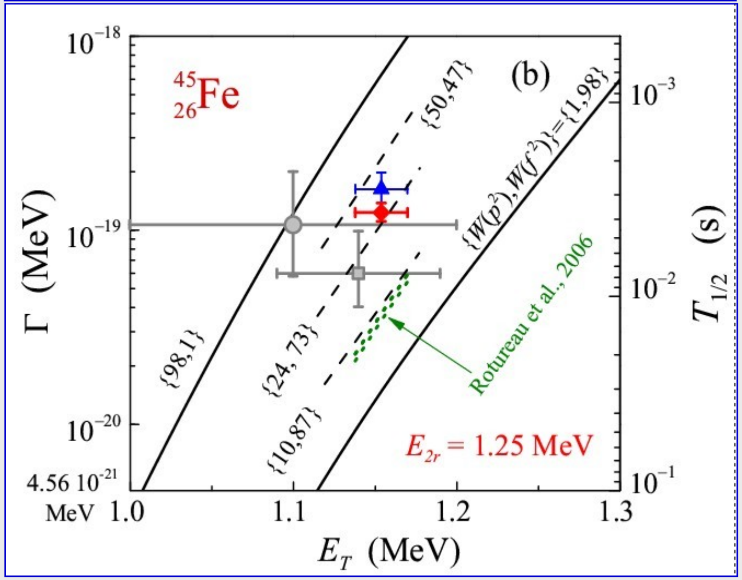
M. P. et al., EPJ A 14 (2002) 279

J. Giovinazzo et al., PRL 89 (2002) 102501

C. Dossat et al., PRC 72 (2005) 054315

- In the first experiments only the decay energy and time were measured!
- A lot of information is still hidden in the correlations between protons !

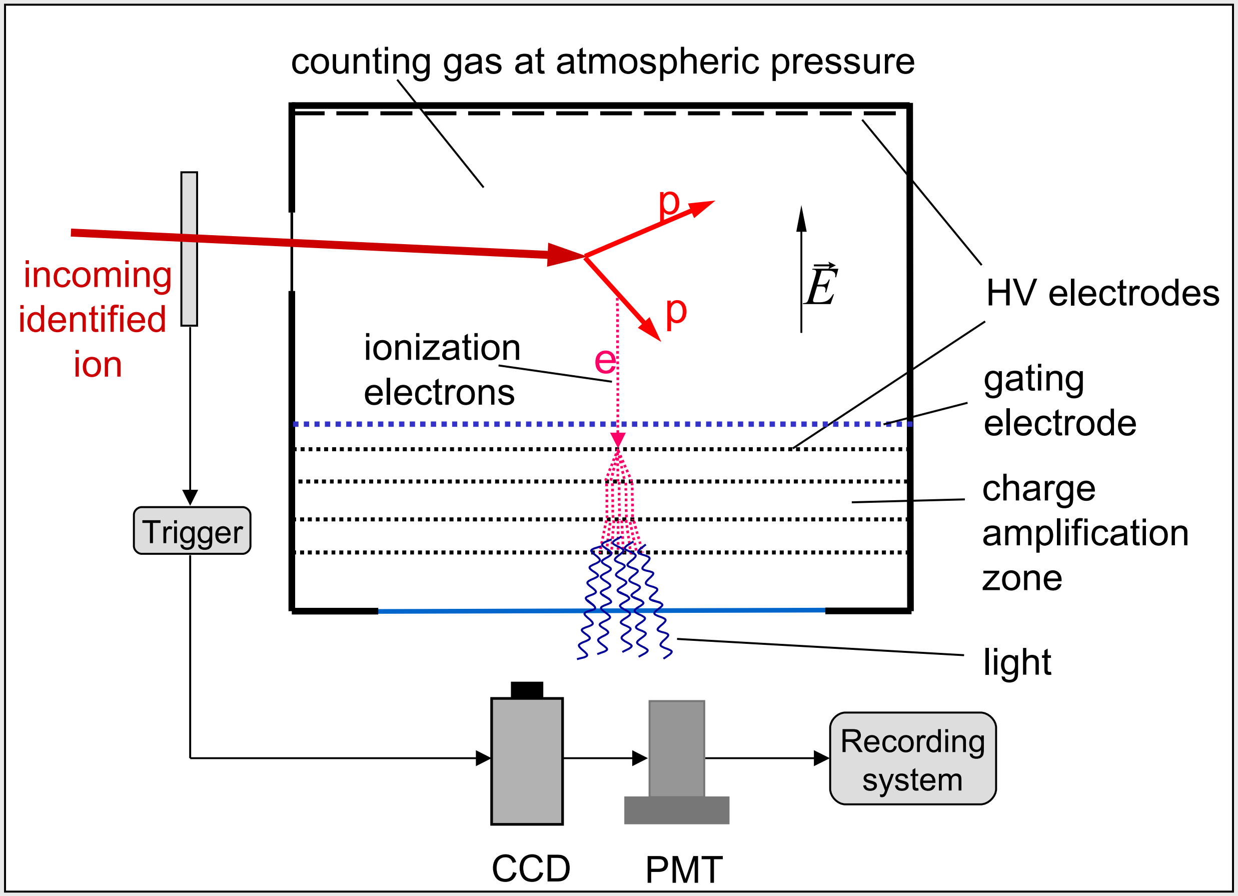


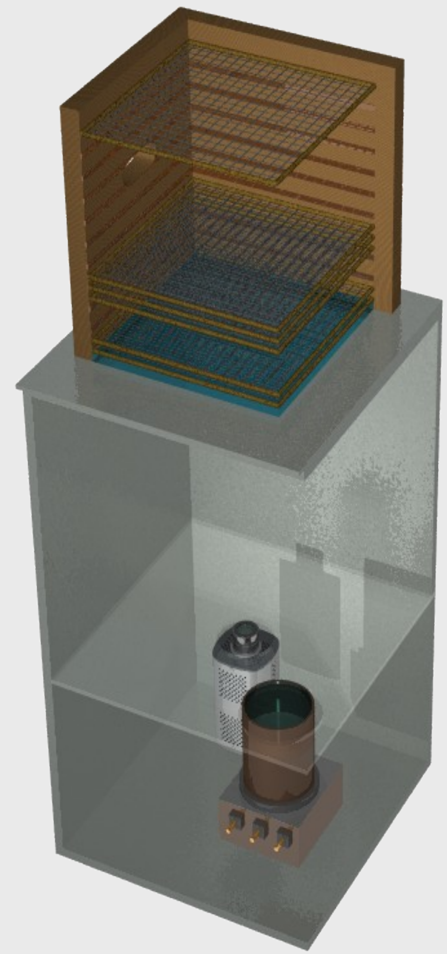


from L. Grigorenko

Optical Time Projection Chamber

- New idea to detect charged particles: an ionization chamber with optical readout

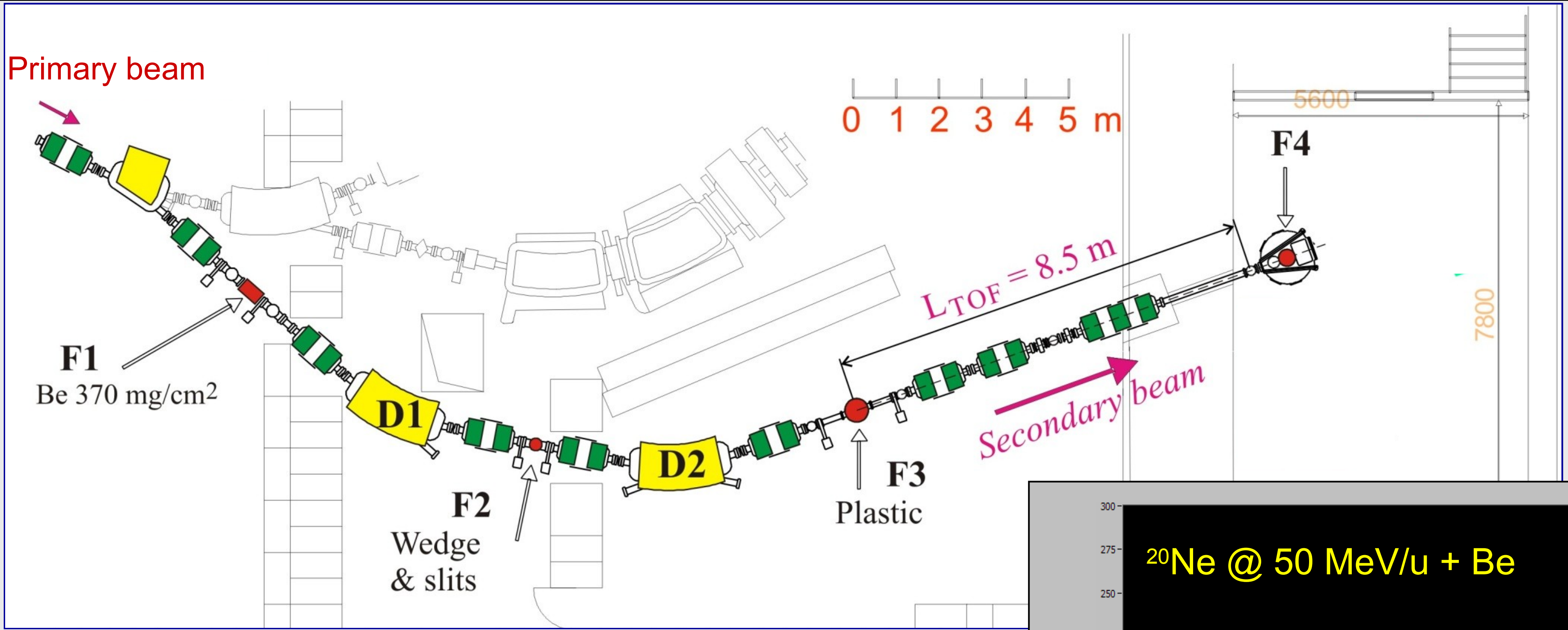


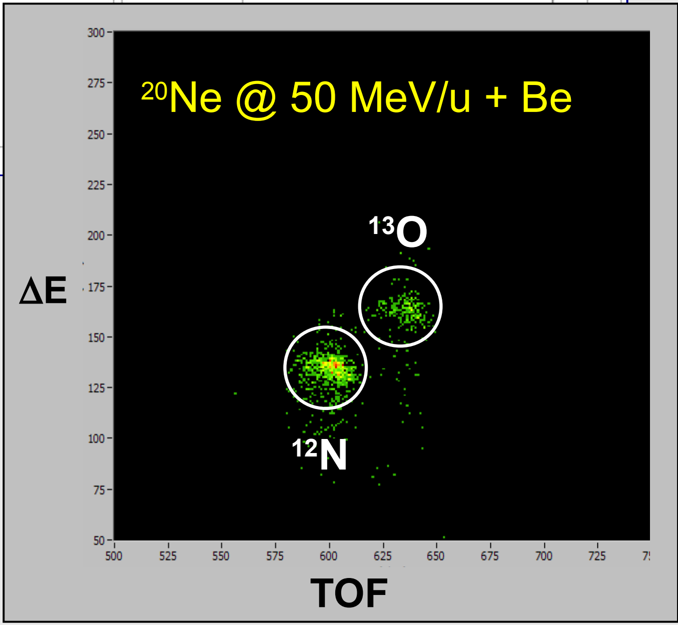


M. Ćwiok et al., IEEE TNS, 52 (2005) 2895

K. Miernik et al., NIM A581 (2007) 194

ACCULINNA @ FLNR, Dubna

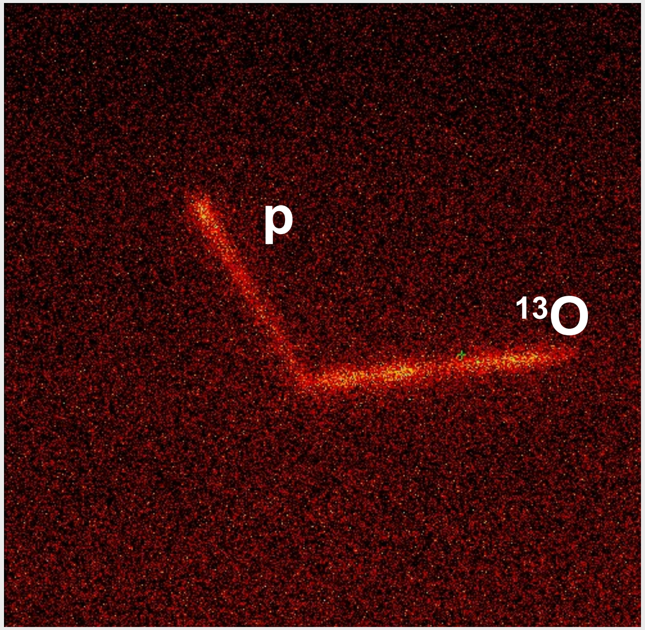




- Low-energy fragment separator, full identification of selected ions by TOF-ΔE method

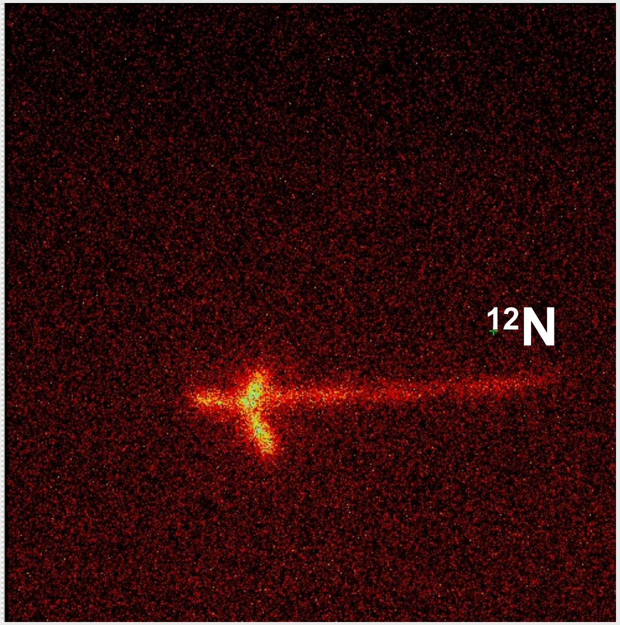
Testing with decays of implanted ions

Acculinna separator, FLNR, JINR, Dubna, 2006 ^{20}Ne (50 MeV/u) + Be →...



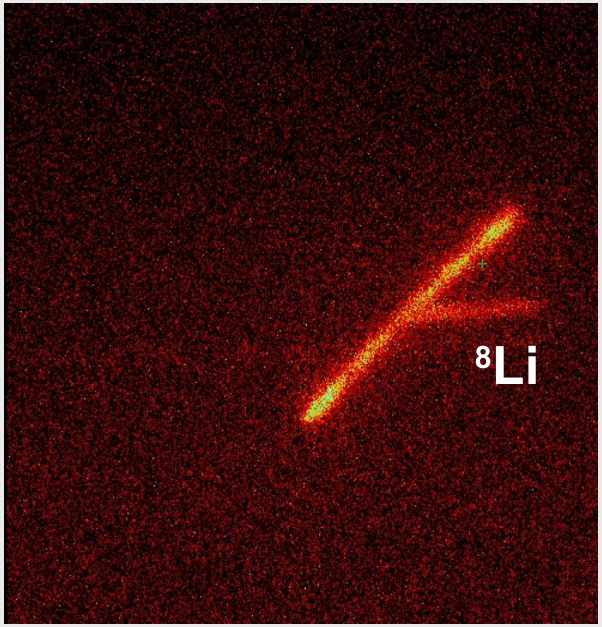
βp emission from ^{13}O

$$^{13}O \underset{8\,ms}{\overset{\beta}{\rightarrow}} {}^{13}N^* \rightarrow {}^{12}C + p$$



$\beta 3\alpha$ decay of ^{12}N

$$^{12}O \underset{11\,ms}{\overset{\beta}{\rightarrow}} {}^{12}C^* \rightarrow 3\alpha$$

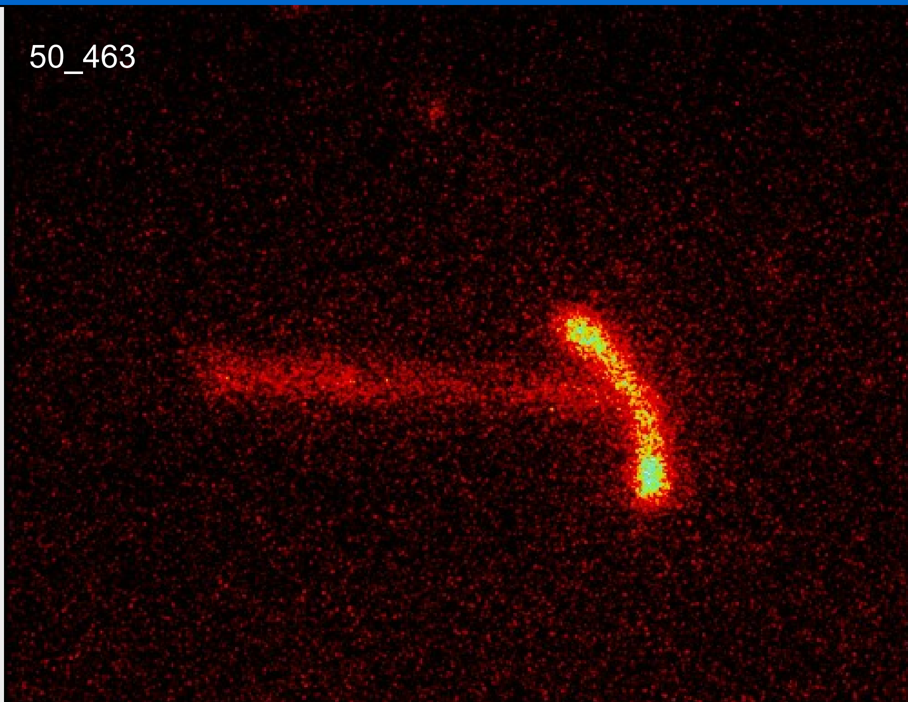


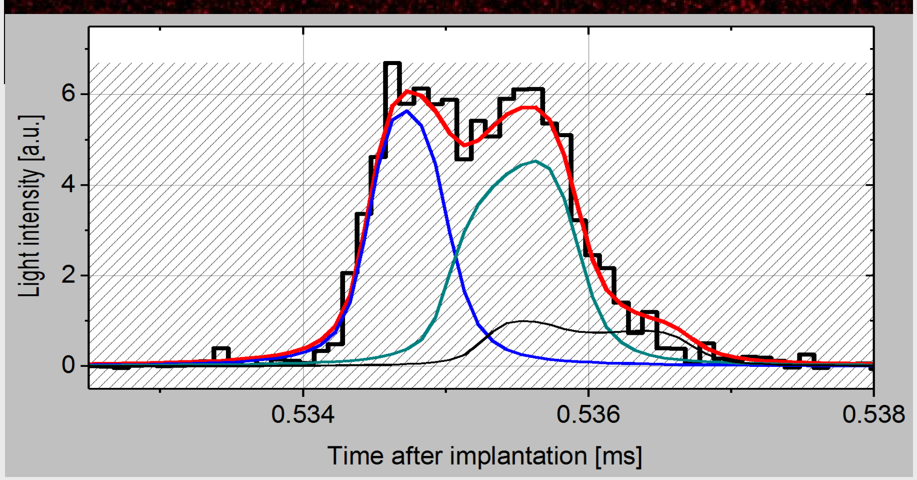
$\beta 2\alpha$ decay of ^{8}Li

$$^{8}Li \underset{840\,ms}{\overset{\beta}{\rightarrow}} {}^{8}Be^* \rightarrow 2\alpha$$

K. Miernik et al., NIM A581 (2007) 194

Emission of *2p* from ^{45}Fe

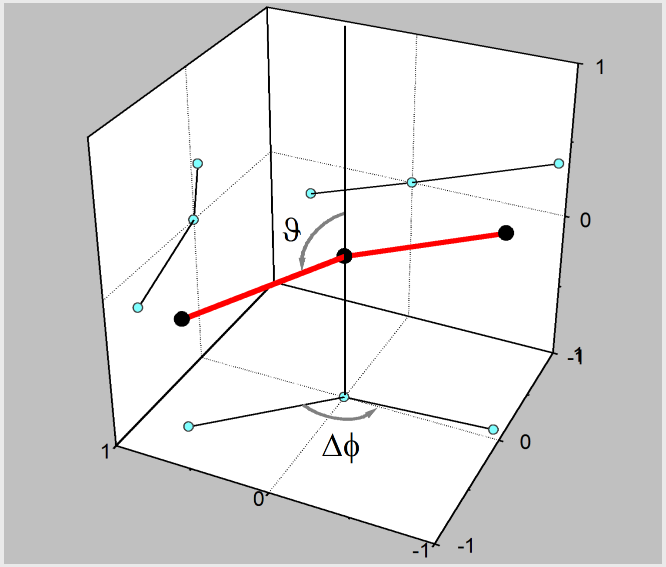




A1900 separator at NSCL/MSU

^{58}Ni at 161 MeV/u + ^{nat}Ni → ^{45}Fe

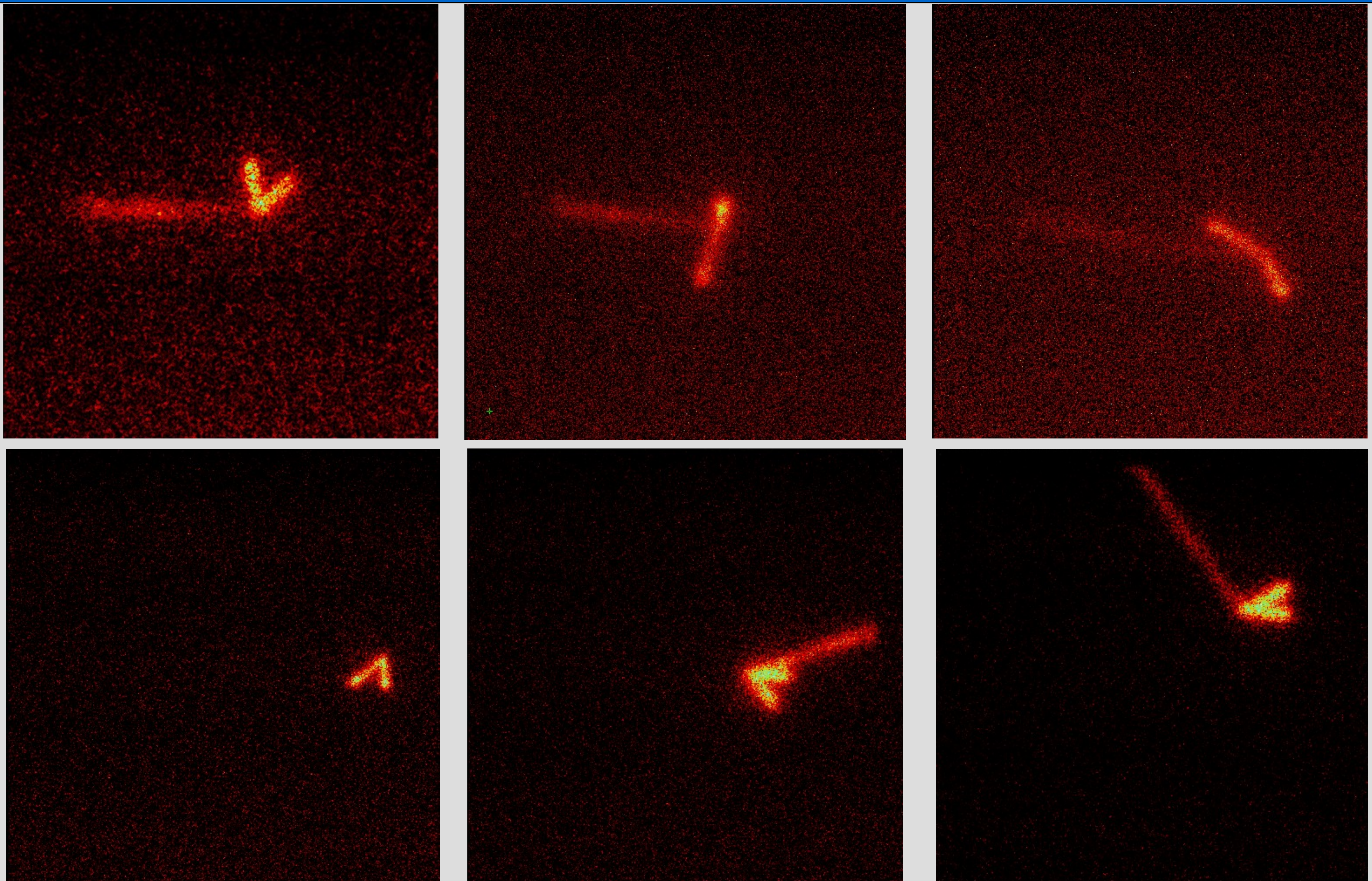
- Full *p-p* corellation pattern could be established



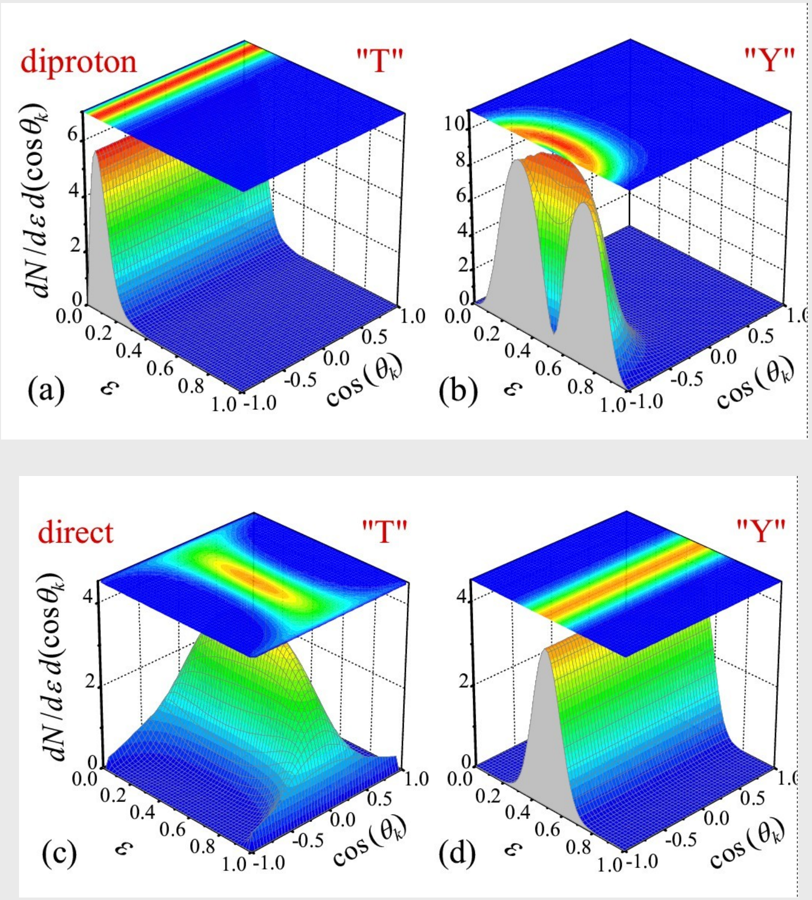
$\vartheta_1 = (104 \pm 2)°$, $\vartheta_1 = (70 \pm 3)°$

$\Delta\phi = (142 \pm 3)°$ → $\theta_{pp} = (143 \pm 5)°$

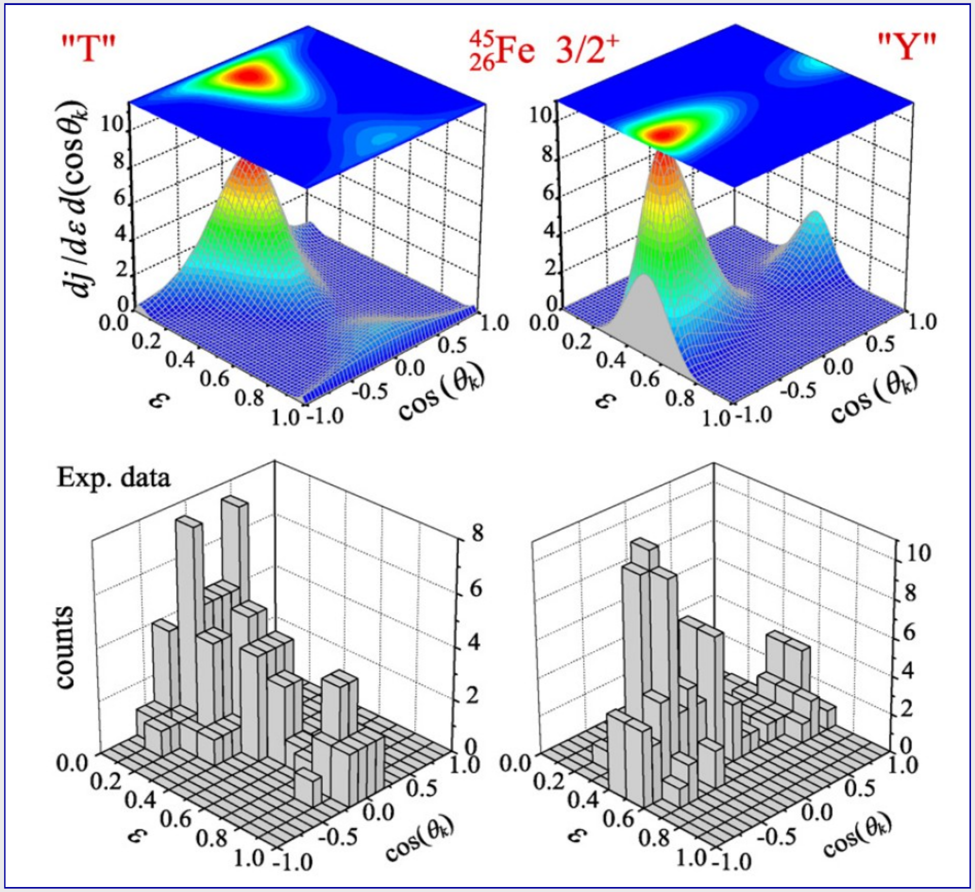
2*p* events from ^{45}Fe



p-p correlations in ^{45}Fe



Three-body model

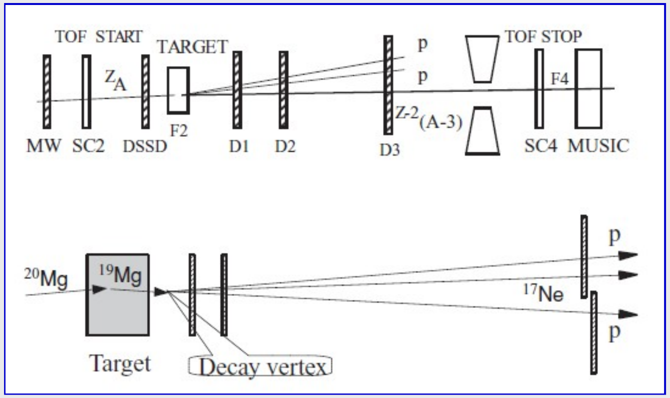


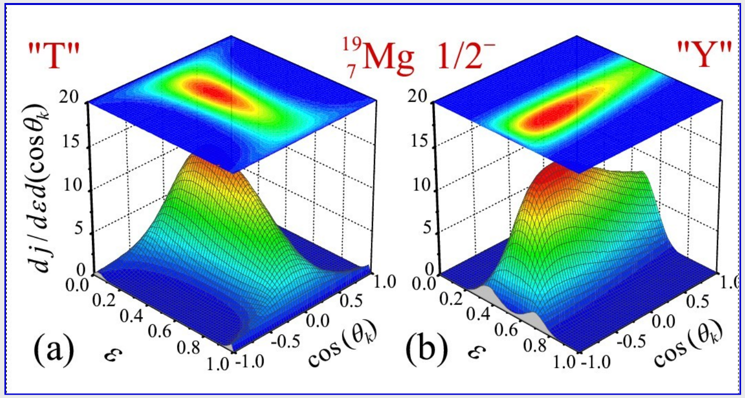
L.V. Grigorenko et al., Phys. Lett. B 677 (2009) 30

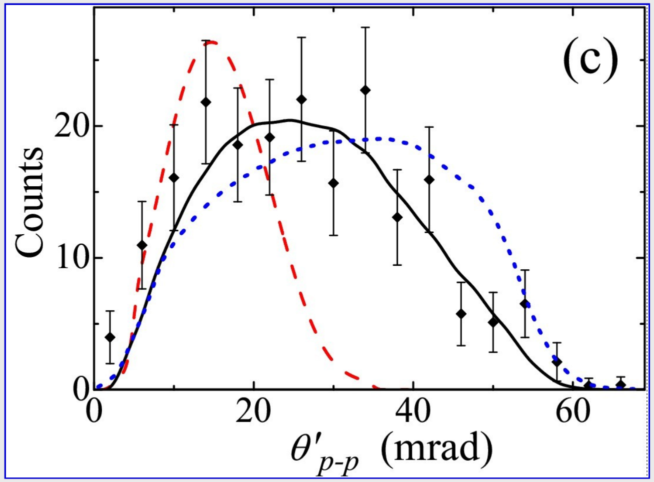
... in ^{19}Mg,...

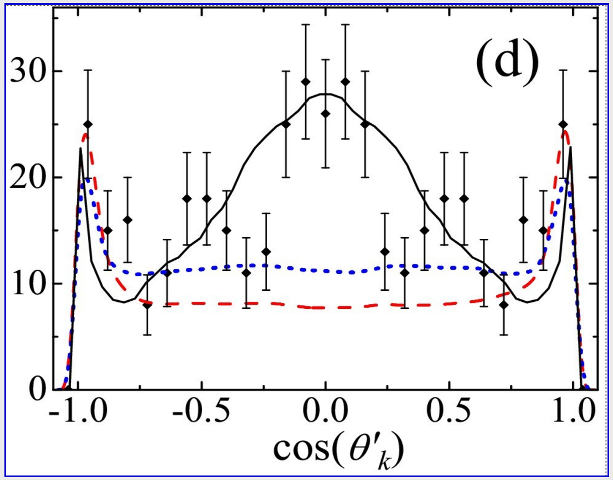
The tracking experiment at GSI/FRS

$T_{1/2}$ = 4.0(15) ps





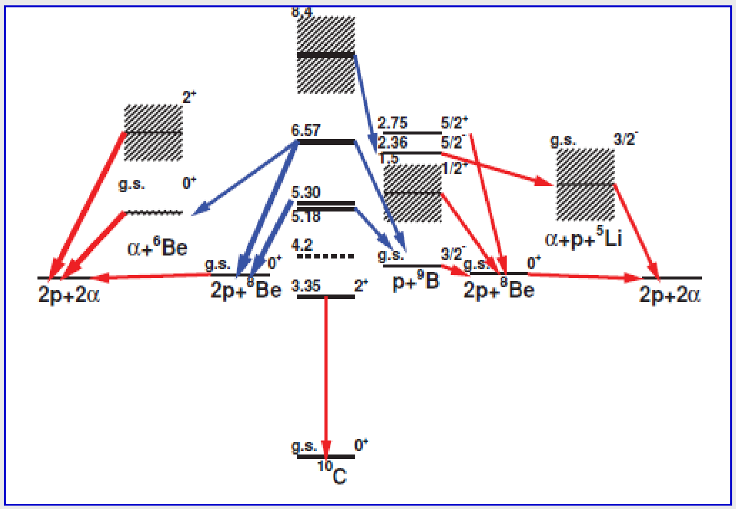


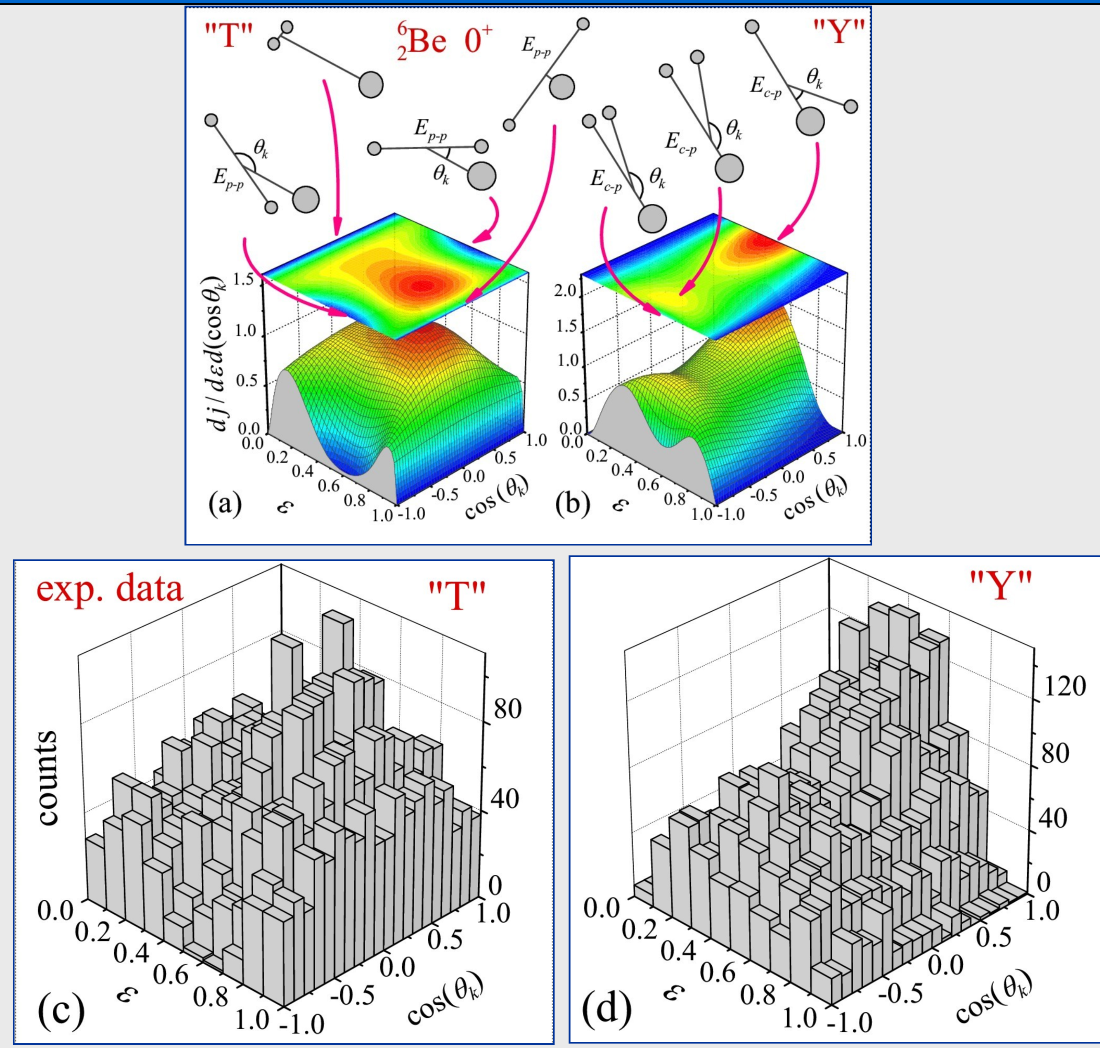


I. Mukha et al., Phys. Rev. C 77 (2008) 061303(R)
I. Mukha et al., Phys. Rev. Lett. 99 (2007) 182501

...and in ^{6}Be

^{10}C inelastic scattering at
Texas A&M University

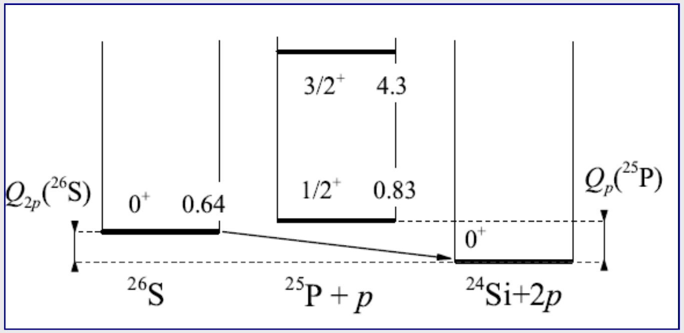


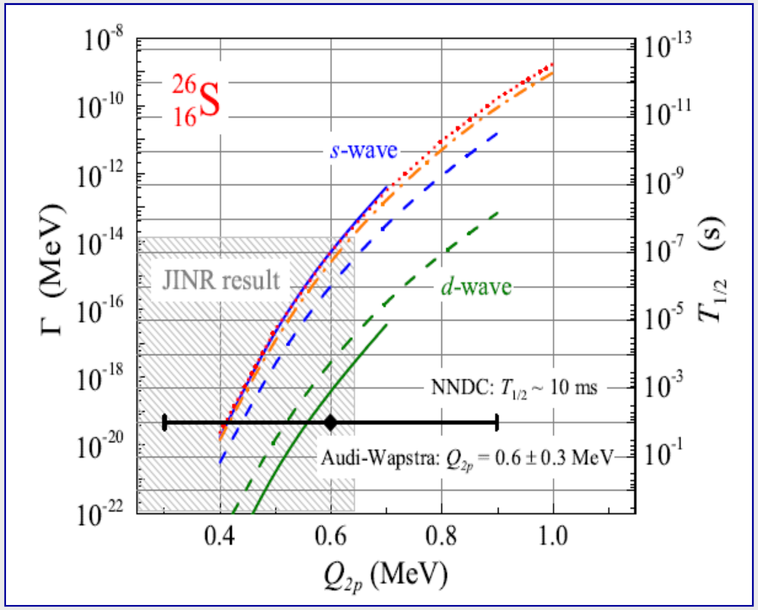


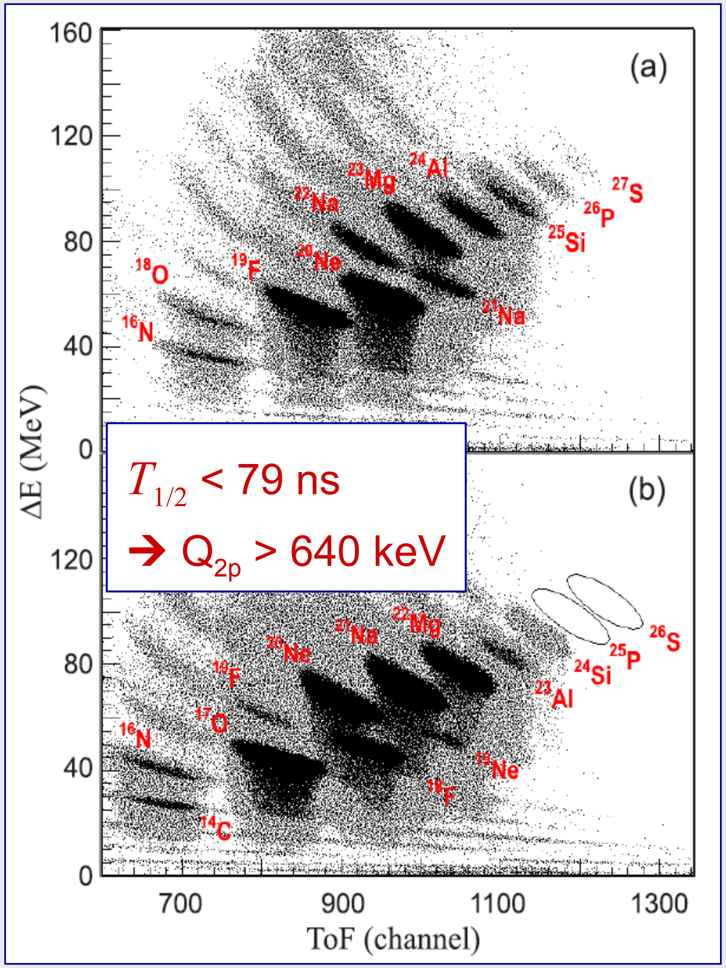
K. Mercurio et al., Phys. Rev. C **78** (2008) 031602(R)
L. Grigorenko et al., Phys. Lett. B **677** (2009) 30

Search for *2p* decay of ^{26}S @ FLNR

- ^{32}S @ 50 MeV/u + Be → ACCULINNA

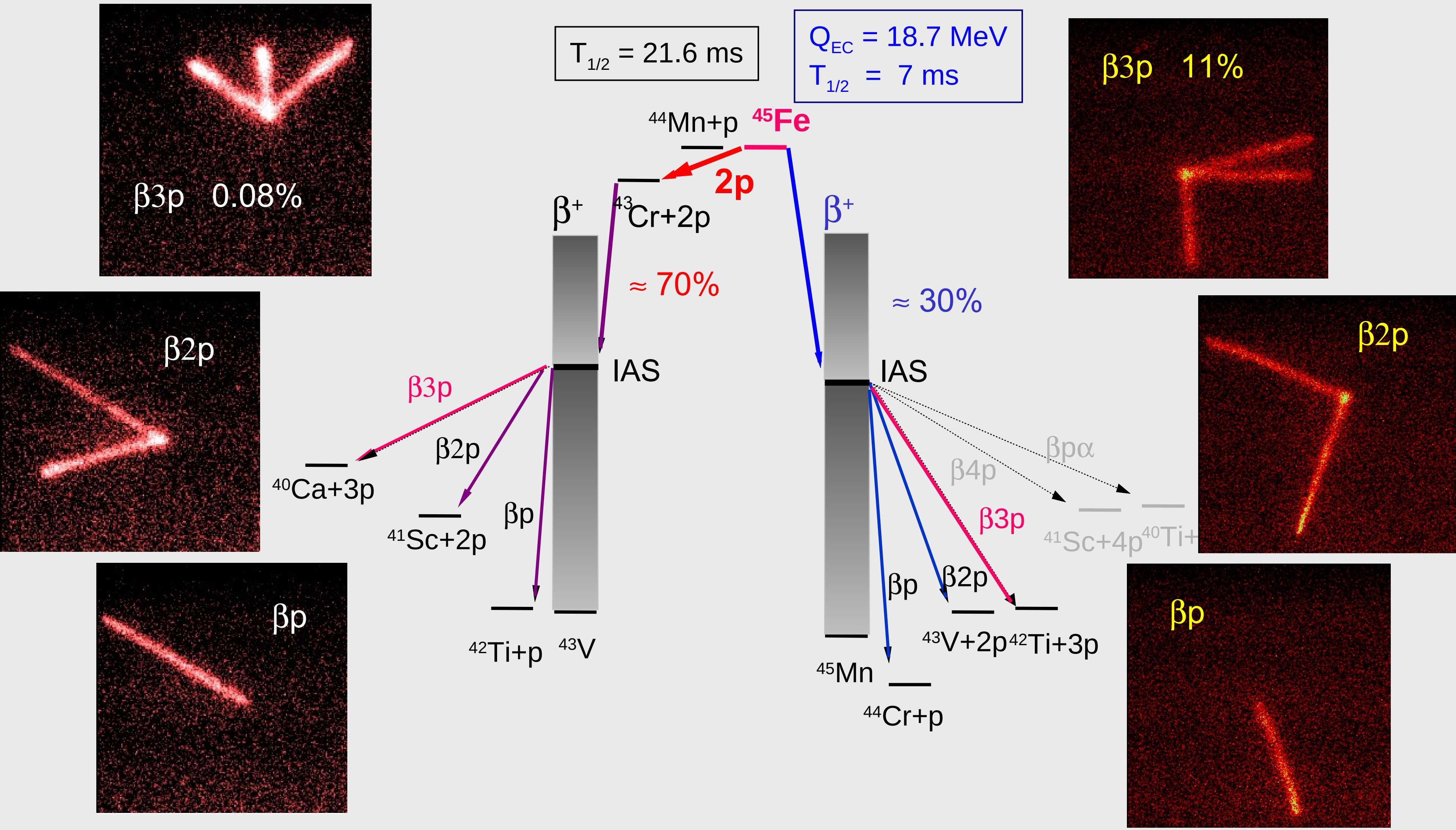






A.S. Fomichev et al., to be published

Decays of ^{45}Fe and ^{43}Cr



M. Pomorski et al., Phys. Rev. 83 (2011) 014306

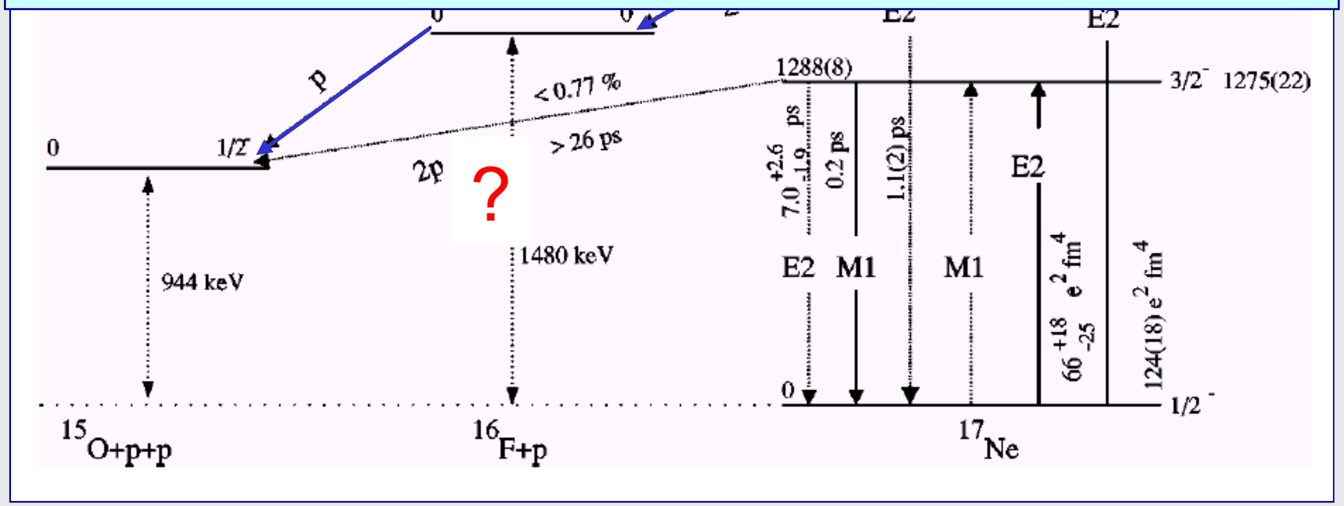
K. Miernik et al., Eur. Phys. J. A 42 (2009) 431

β2p from excited state – ^{17}Ne

- COULEX of 59 AMeV ^{17}Ne on Au target (NSCL/MSU)

ACCULINNA proposal:

→ search for the small *2p* decay branch from the 3/2⁻ state, populating it by $^{1}H(^{18}Ne,d)^{17}Ne$ reaction

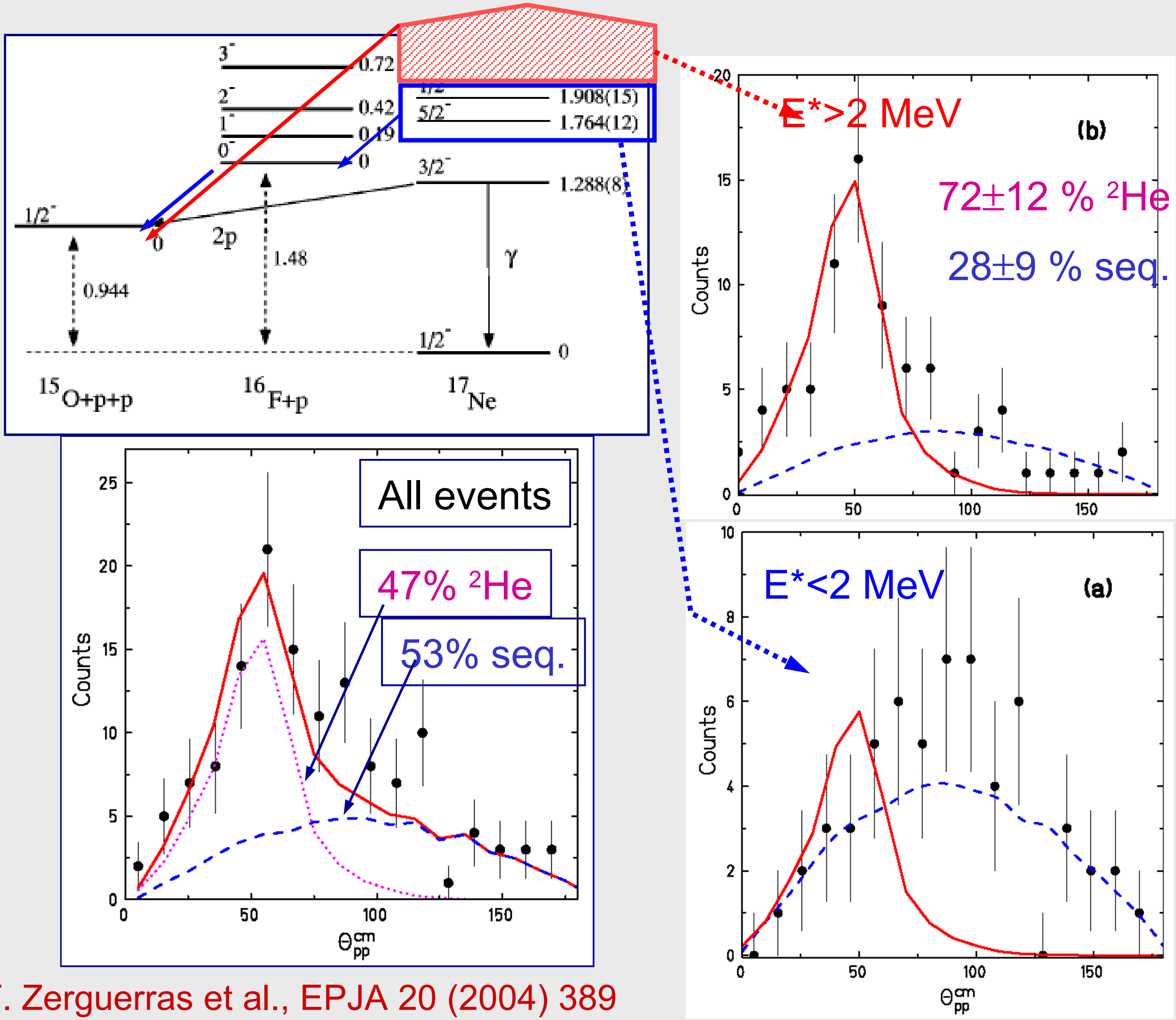


- Sequential 2p emission from the 5/2⁻ state was observed
- No evidence for the 2p branch from the 3/2⁻ state obtained

M.J. Chromik et al., PRC 66 (2002) 024313

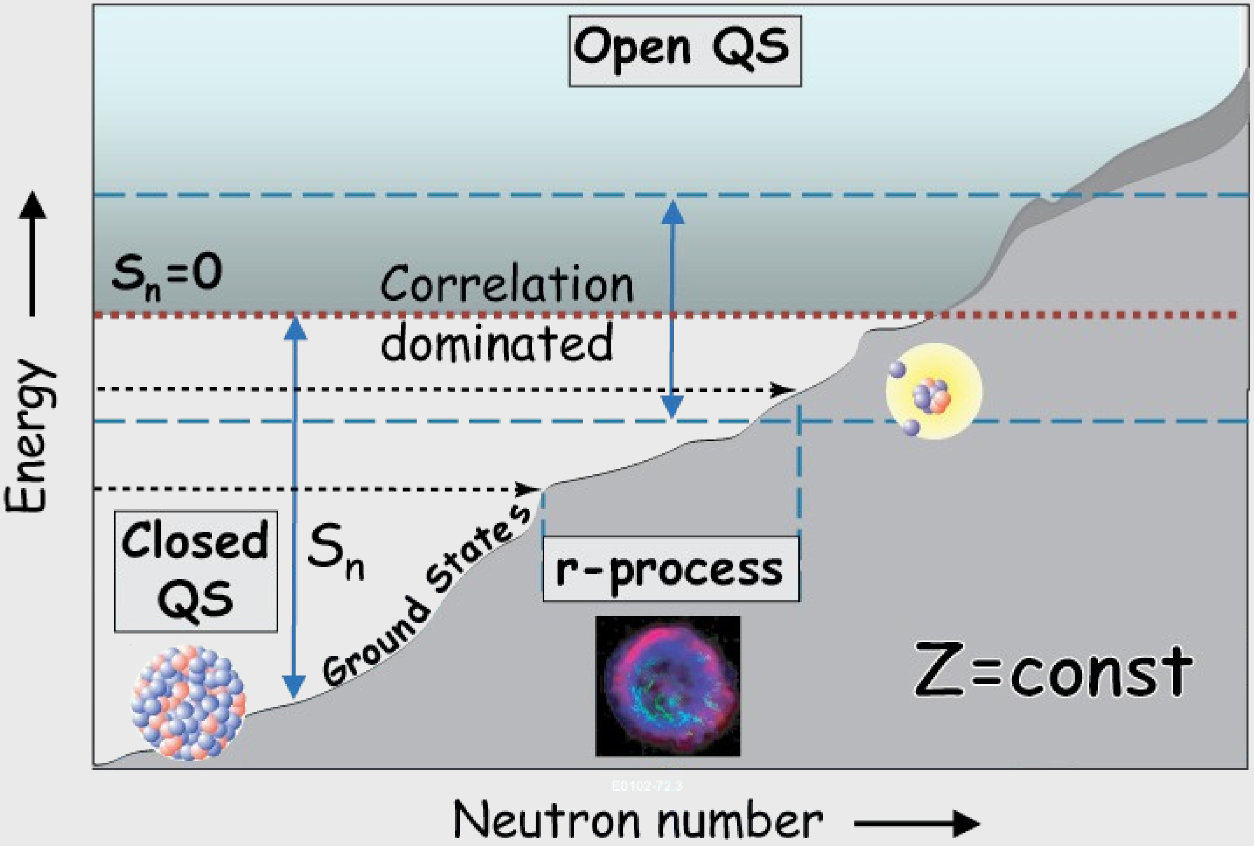
Evidence for the di-proton ?

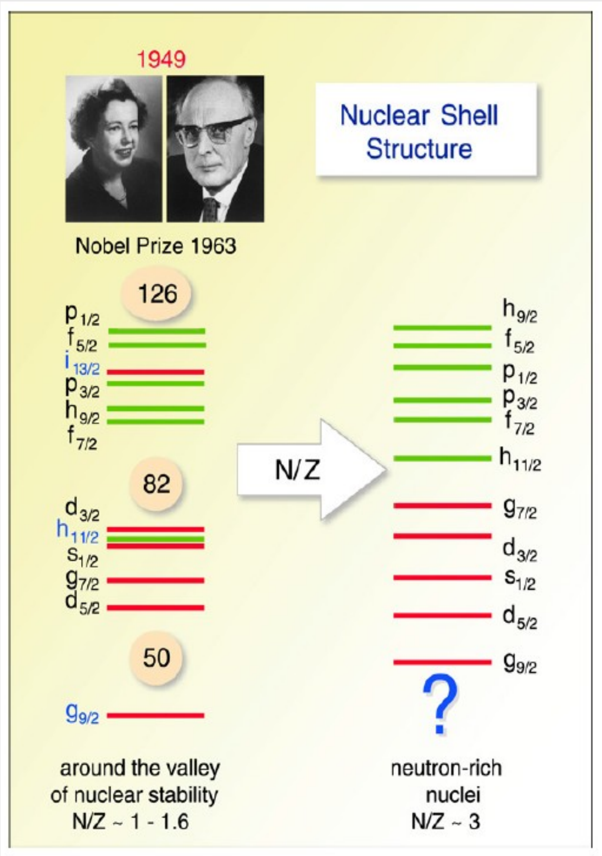
1n stripping from 36 AMeV ^{18}Ne (GANIL) → ^{17}Ne* → ^{15}O + 2p



T. Zerguerras et al., EPJA 20 (2004) 389

Towards neutron drip-line

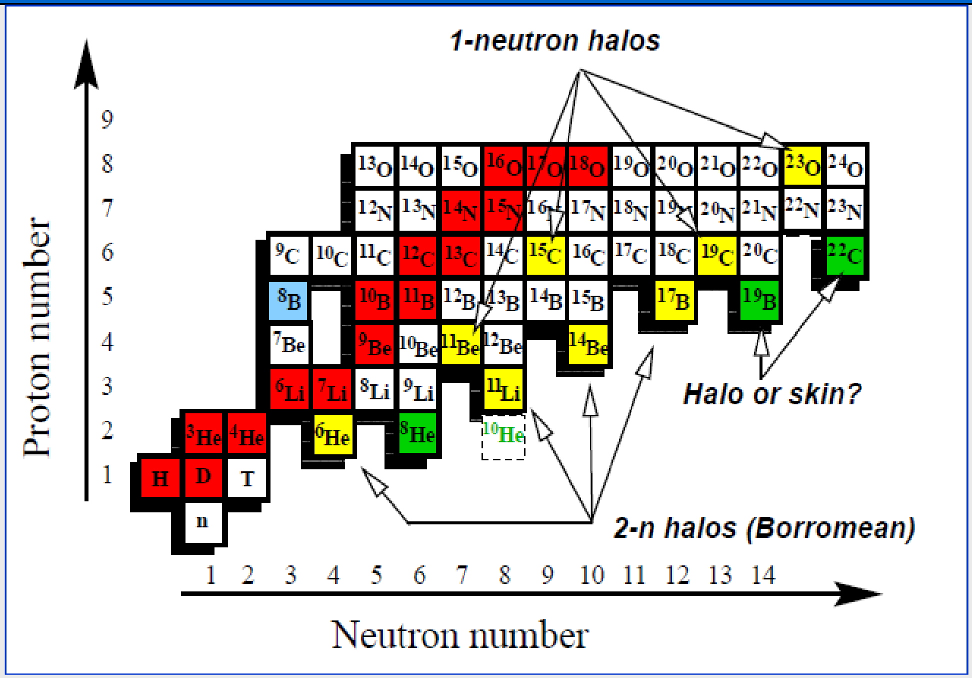


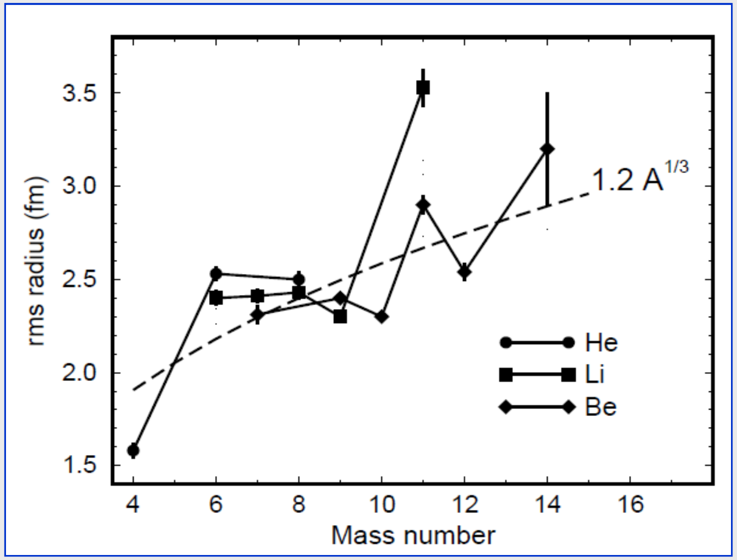


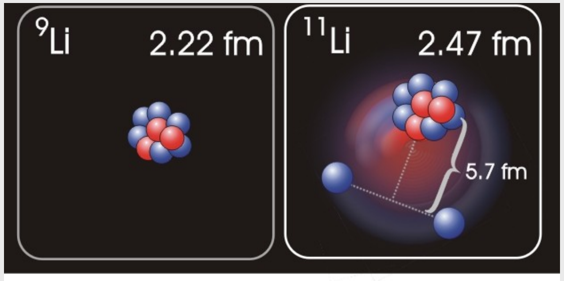
N. Michel et al., J. Phys. G 36 (2009) 013101

J. Dobaczewski et al., Prog. Part. Nucl. Phys. 59 (2007) 432

Neutron halos

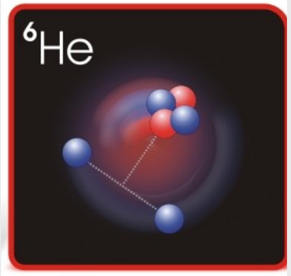


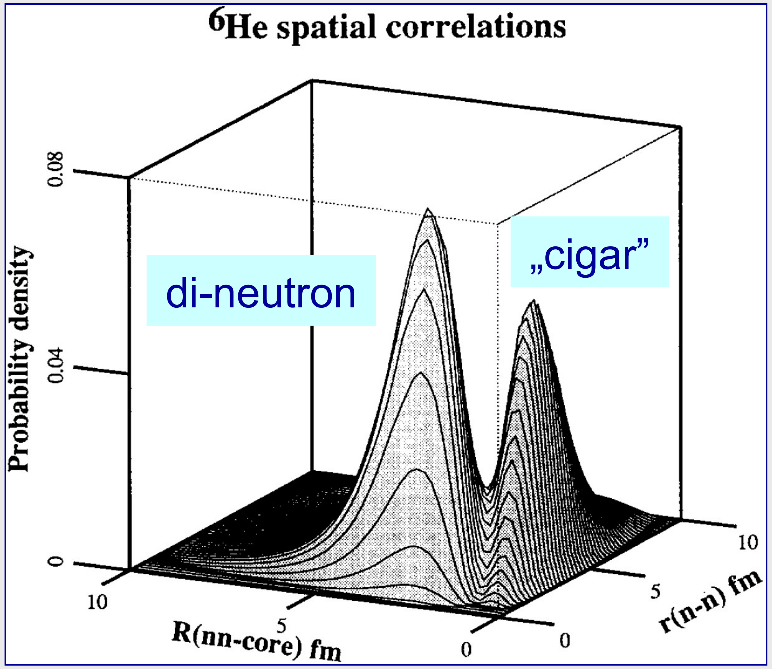




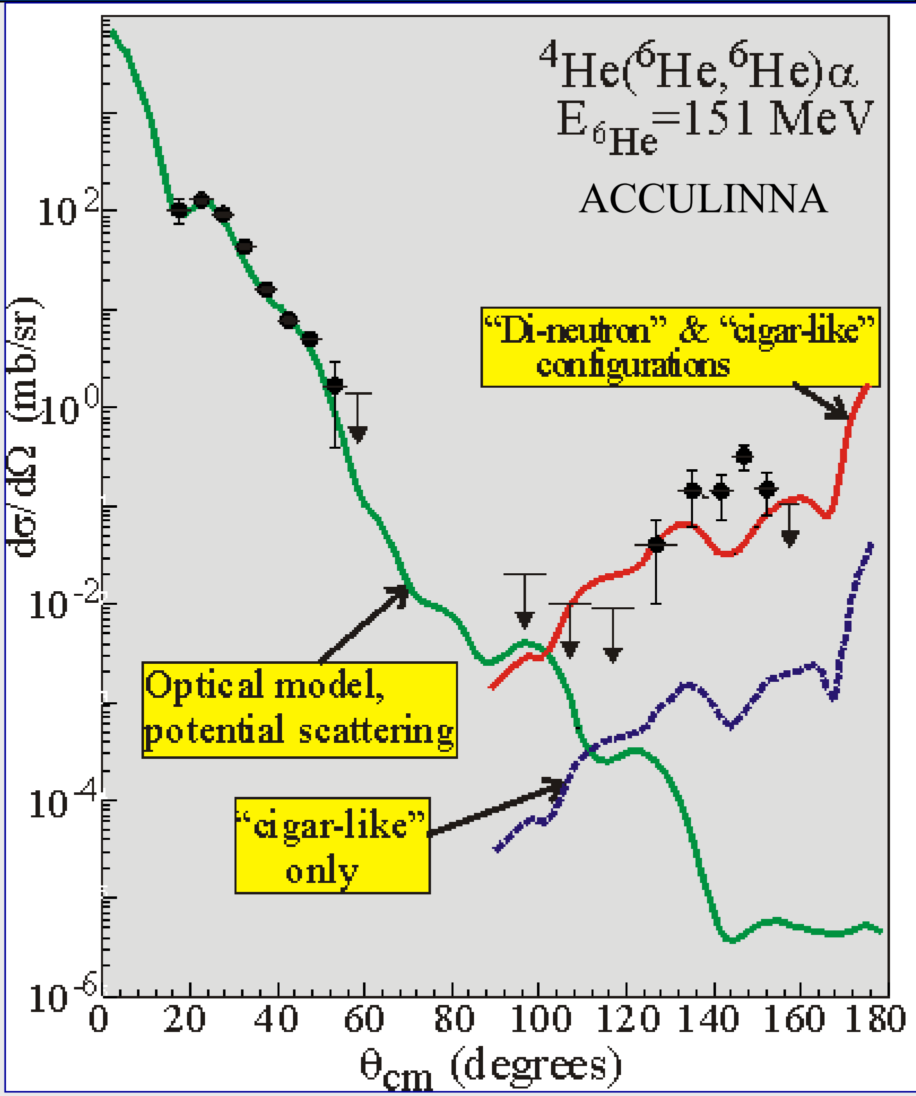
- Neutron halos – strange nuclear systems:
  - large spatial extension (more than 50% outside classical region)
  - clasterization (core × valence neutrons)

^{6}He wave function





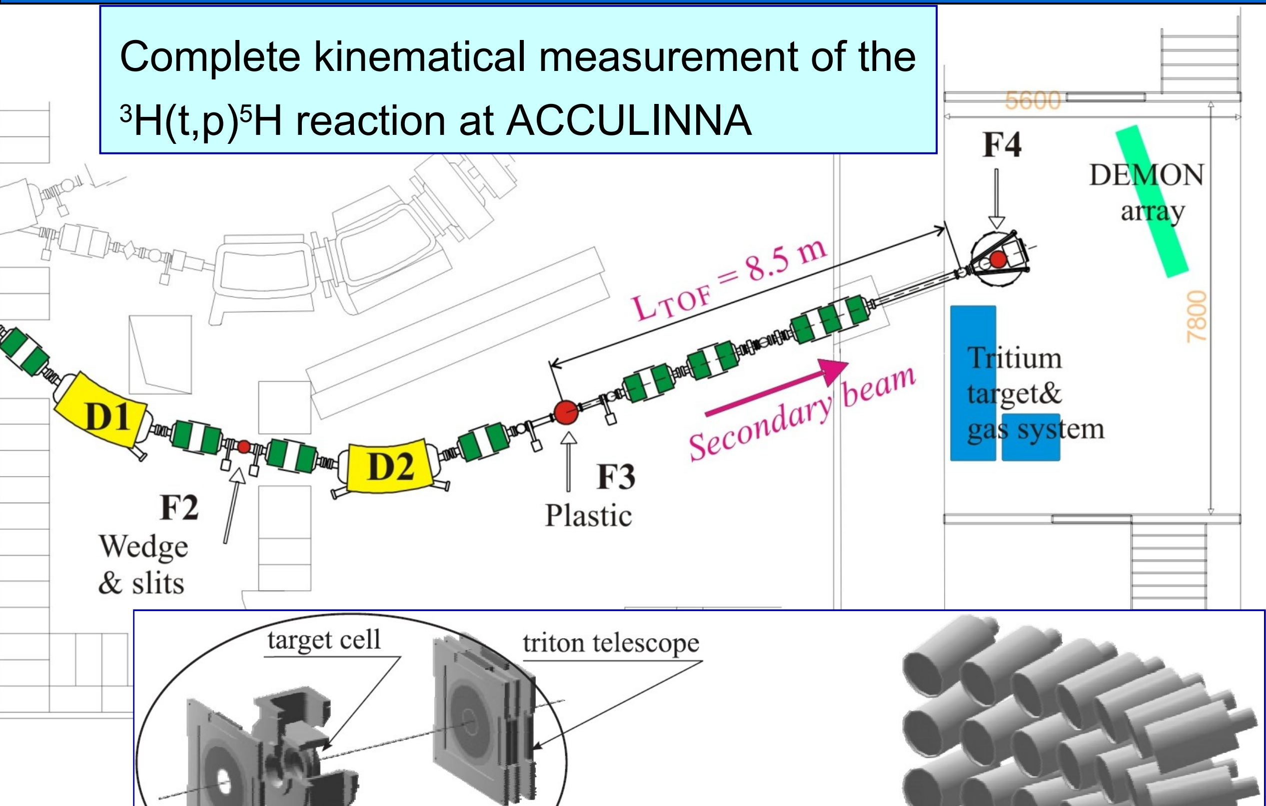
M.V. Zhukov et al., Phys. Rep. 231 (1993) 151

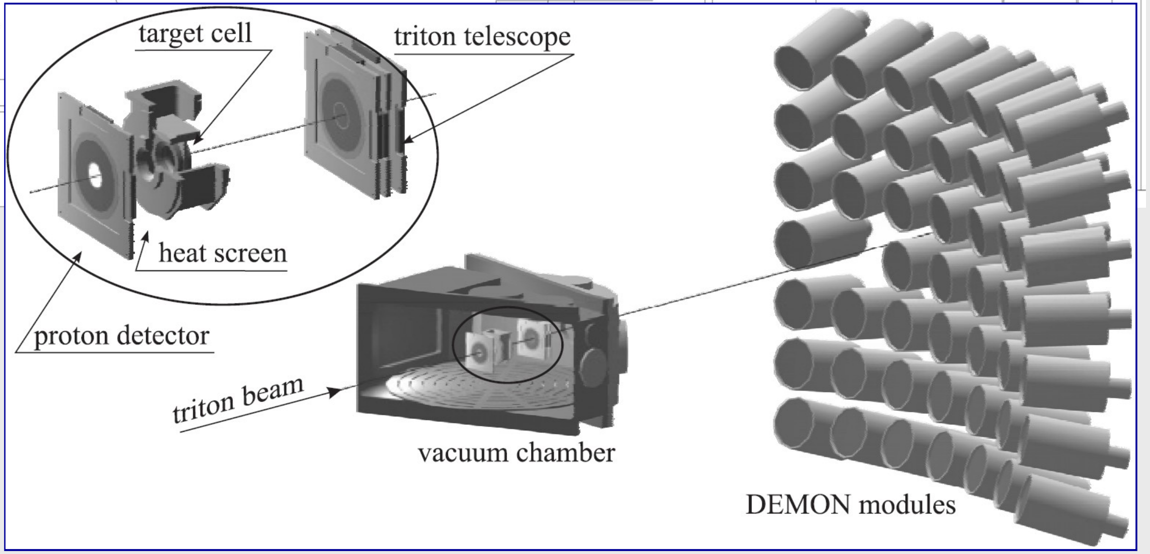


G.M. Ter-Akopian et al,, Phys. Lett. B 426 (1998) 251

Study of ^{5}H

Complete kinematical measurement of the $^{3}H(t,p)^{5}H$ reaction at ACCULINNA



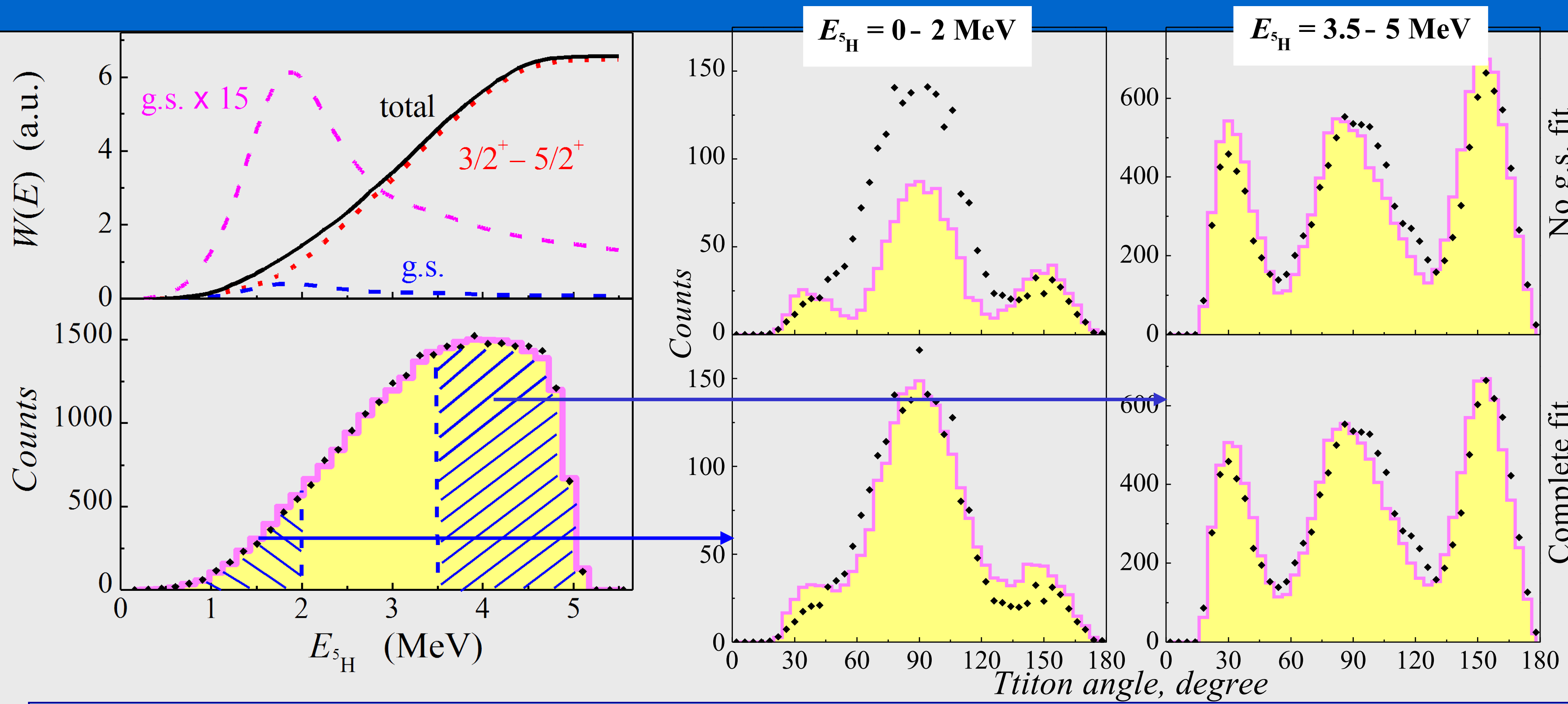


❶ Slow protons registered in the backward direction (E_{5H} < 5 MeV).

❷ Fast tritons registered in the forward telescope.

❸ Threefold *t-p-n* and fourfold *t-p-n-n* coincidences provide the complete kinematics.

Study of ^{5}H



Correlation analysis yields following conlusions:

a) Continuum above 2.5 MeV is a mixture of energy degenerate broad $3/2^+$ and $5/2^+$ states.

b) Continuum below 2.5 MeV results from interference of $3/2^+$– $5/2^+$ doublet and $1/2^+$ g.s.

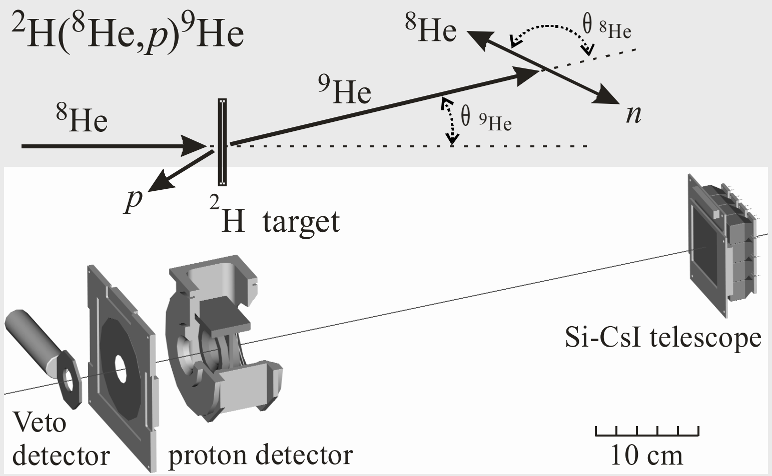
c) Ground-state properties of ^{5}H .: E_R = 1.8 MeV, Γ = 1.3 MeV.

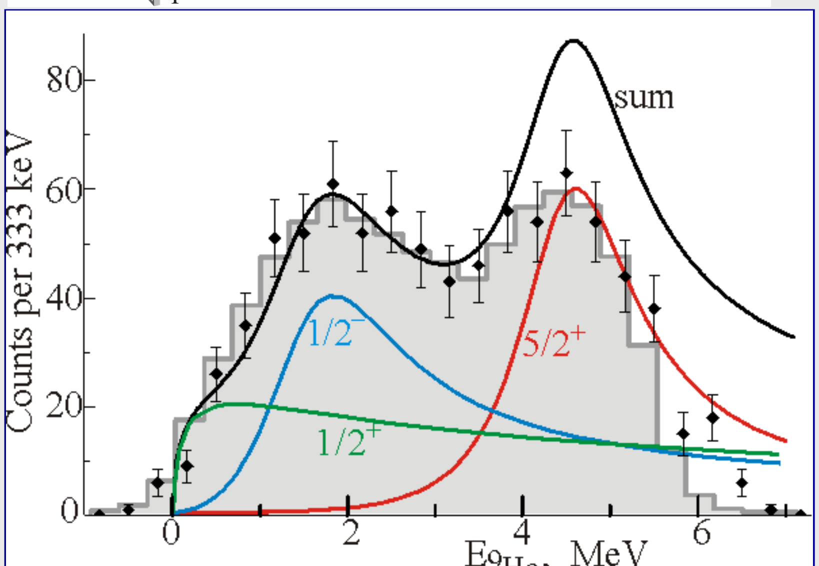
M. Golovkov *et al.*, PRL 93 (2004) 262501

M. Golovkov *et al.*, PRC 72 (2005) 064612

Study of ^{9}He

Complete kinematical study of the $^{2}H(^{8}He,p)^{9}He$ reaction at ACCULINNA





❶ ^{9}He spectrum shows two broad overlapping peaks at 2.0 and 4.2 MeV.

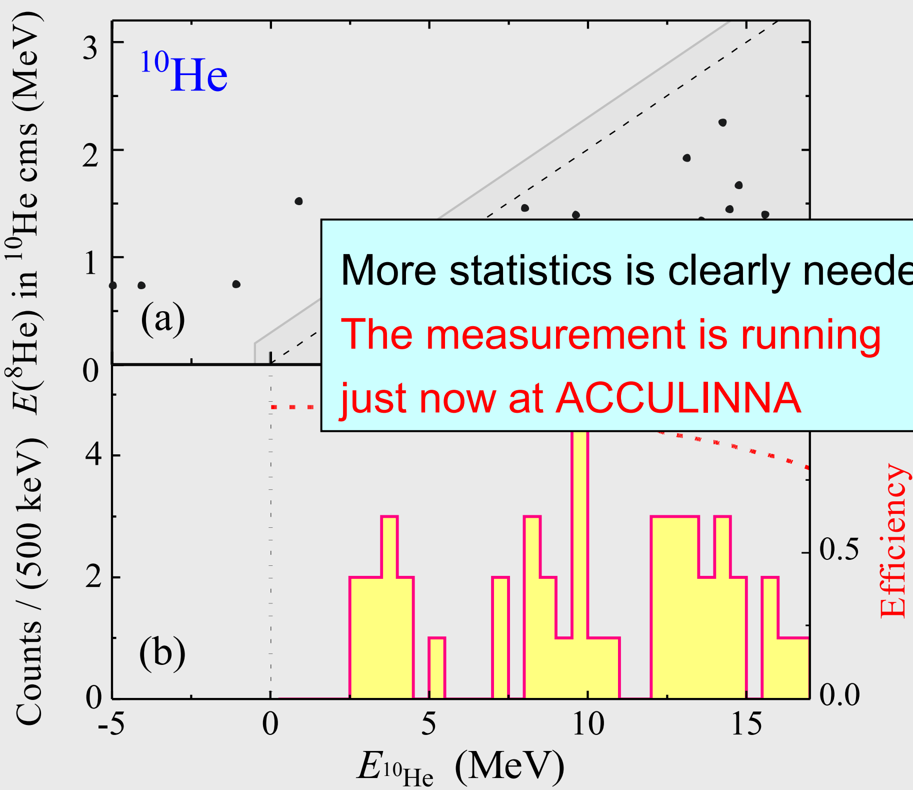
❷ There is a contribution of the *s*-wave state at the ^{8}He+n threshold. The scattering length for this state is $a > -20$ fm.

❸ These states are assigned as $s_{1/2}$, $p_{1/2}$, $d_{5/2}$

❹ The data are well described in a simple single-particle potential model. The ^{8}He with the closed $p_{3/2}$ subshell is a "good" core for ^{9}He.

... and ^{10}He

Reaction ^{3}H(^{8}He,^{10}He)p (E_{8He} = 27.4 MeV/amu , θ_{cm} = 2° – 12°)

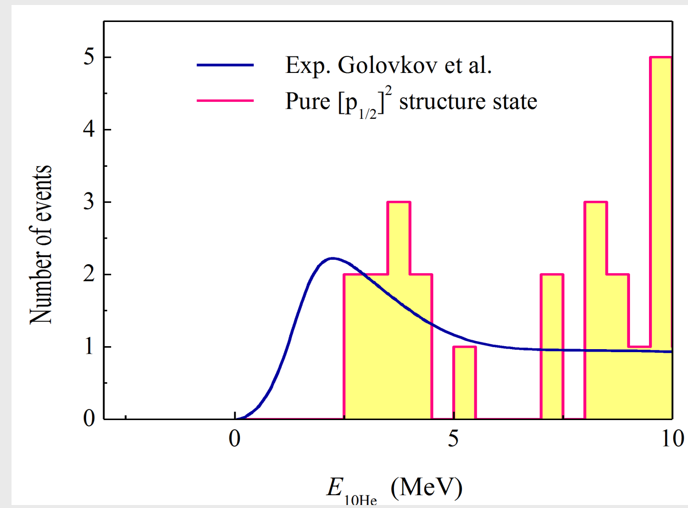


More statistics is clearly needed.

The measurement is running just now at ACCULINNA

M.S. Golovkov et al., Physics Letters B 672 (2009) 22

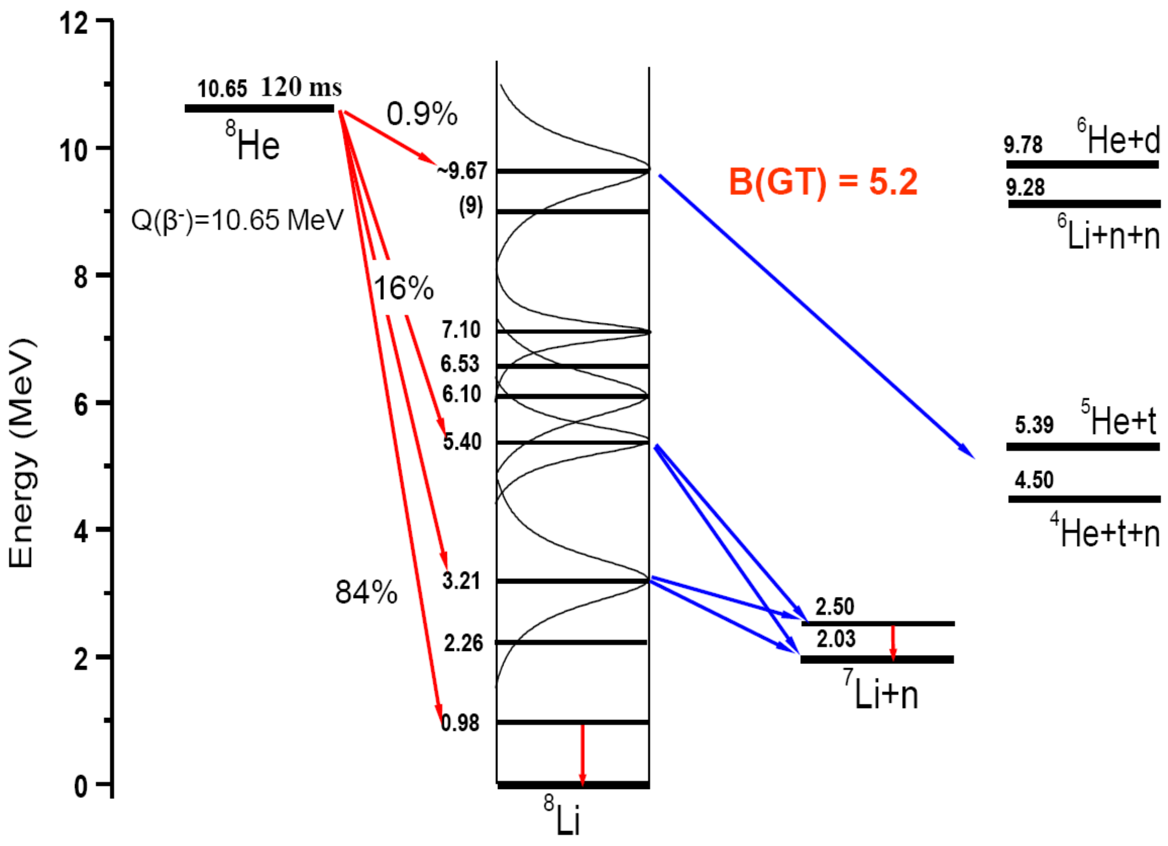
L. Grigorenko and M. Zhukov, PRC 77, 034611 (2008)



The population cross section of the 3 MeV peak in ^{10}He σ_{10} = 140(30) mb/sr is consistent with the estimated resonance cross section for the population of the ^{10}He 0^+ state with the $[p_{1/2}]^2$ structure.

Decay of ^{8}He

^{8}He – the most neutron-rich, particle-stable nucleus, attracts lot of interest (NNDC/NSR Data Base shows 225 papers!)



D. R. Tilley et. all, Nucl. Phys. A 745 (2004)

β-delayed t emission measured

$$^{8}\mathrm{He} \rightarrow \; ^{8}\mathrm{Li}^{*} \rightarrow \; \mathrm{t} + \alpha + \mathrm{n}$$

$$b_t = (8.0 \pm 0.5) \times 10^{-3}$$

→ $B_{GT} \geq 5.2$, $\log ft = 2.9$!

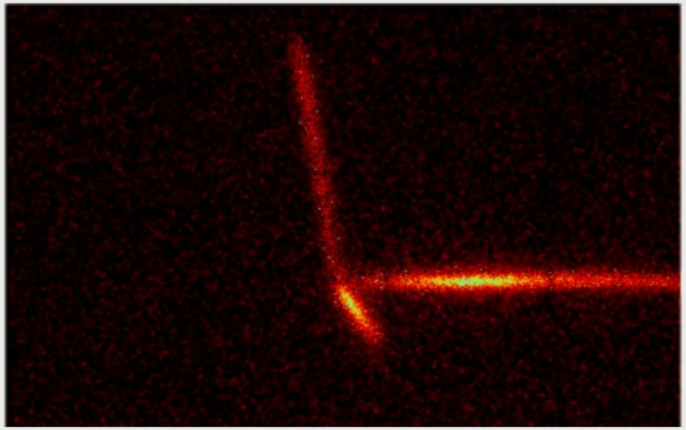
ISOLDE (1992)

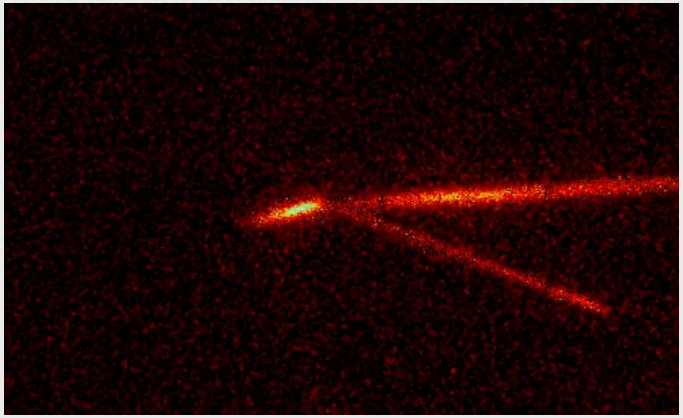
M. Borge et al., NP A 560 (1993) 664

^{8}He decay study @ JINR, Dubna

We see the tritium channel

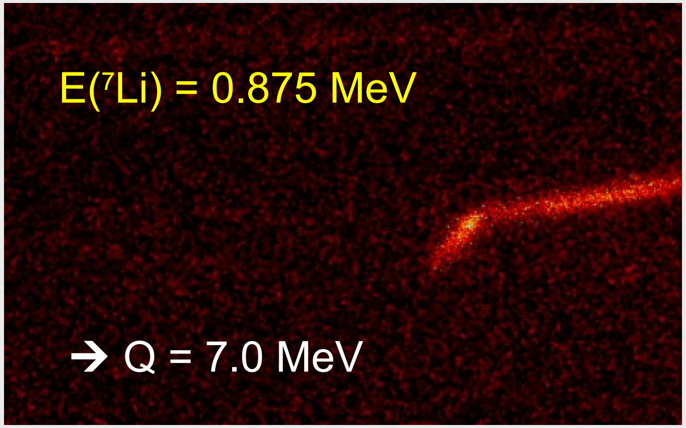
$$^8He \rightarrow {}^8Li^* \rightarrow \alpha + n + t$$

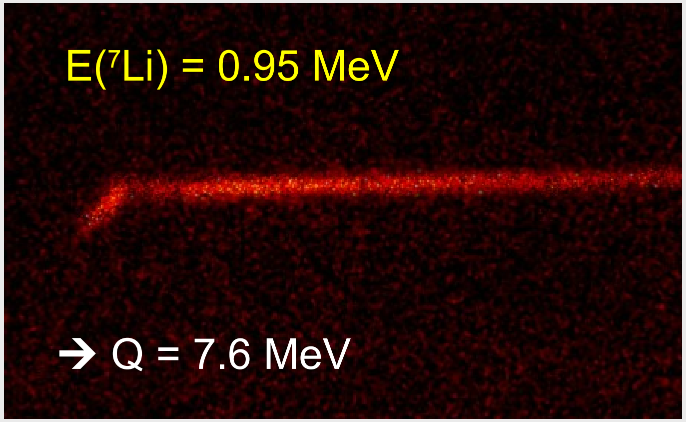




but also the recoil of ^{7}Li !

$$^8He \rightarrow {}^8Li^* \rightarrow {}^7Li + n$$



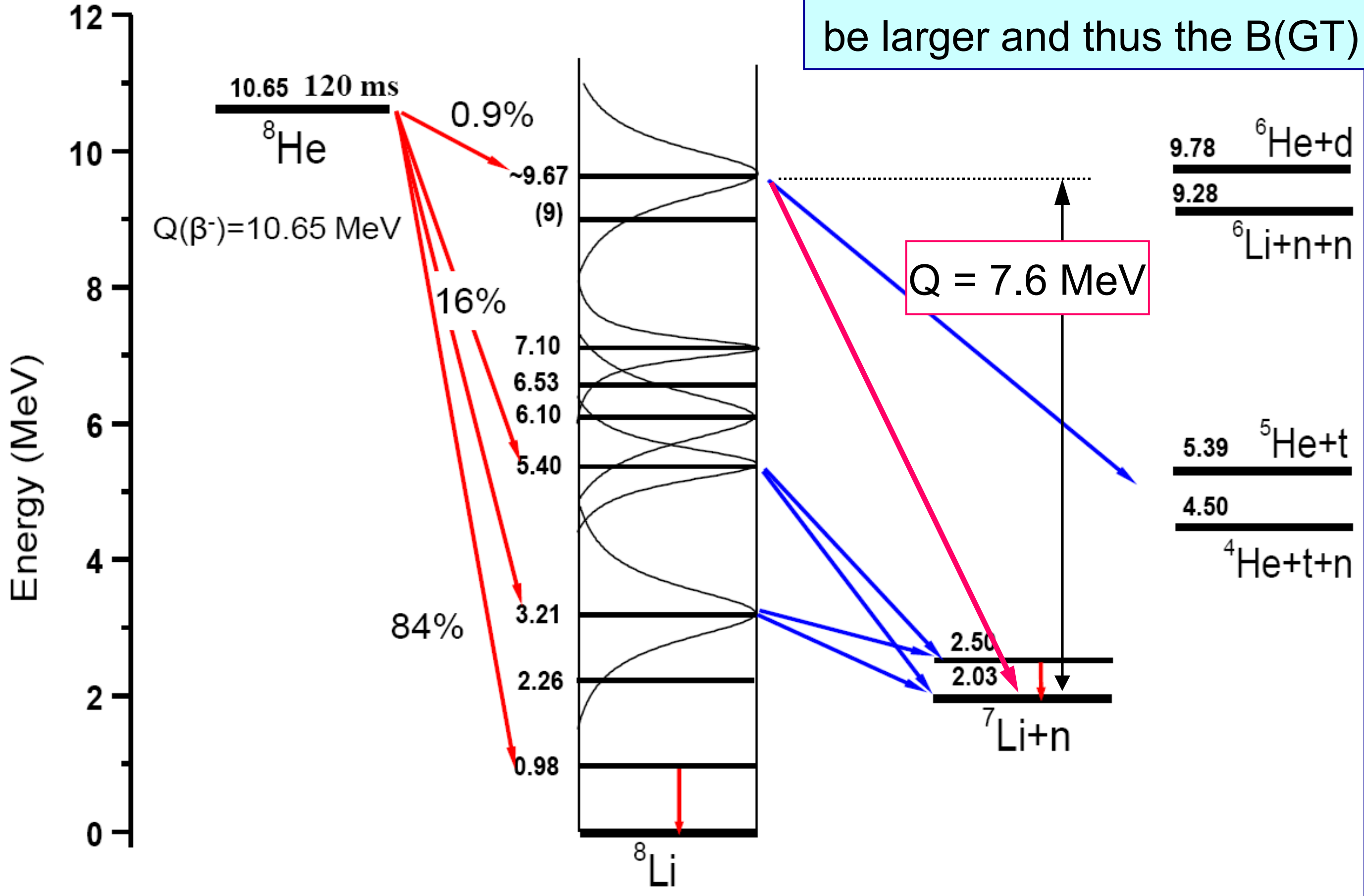


S. Mianowski et al., Acta. Phys.Pol. B41 (2010) 449

A new decay branch

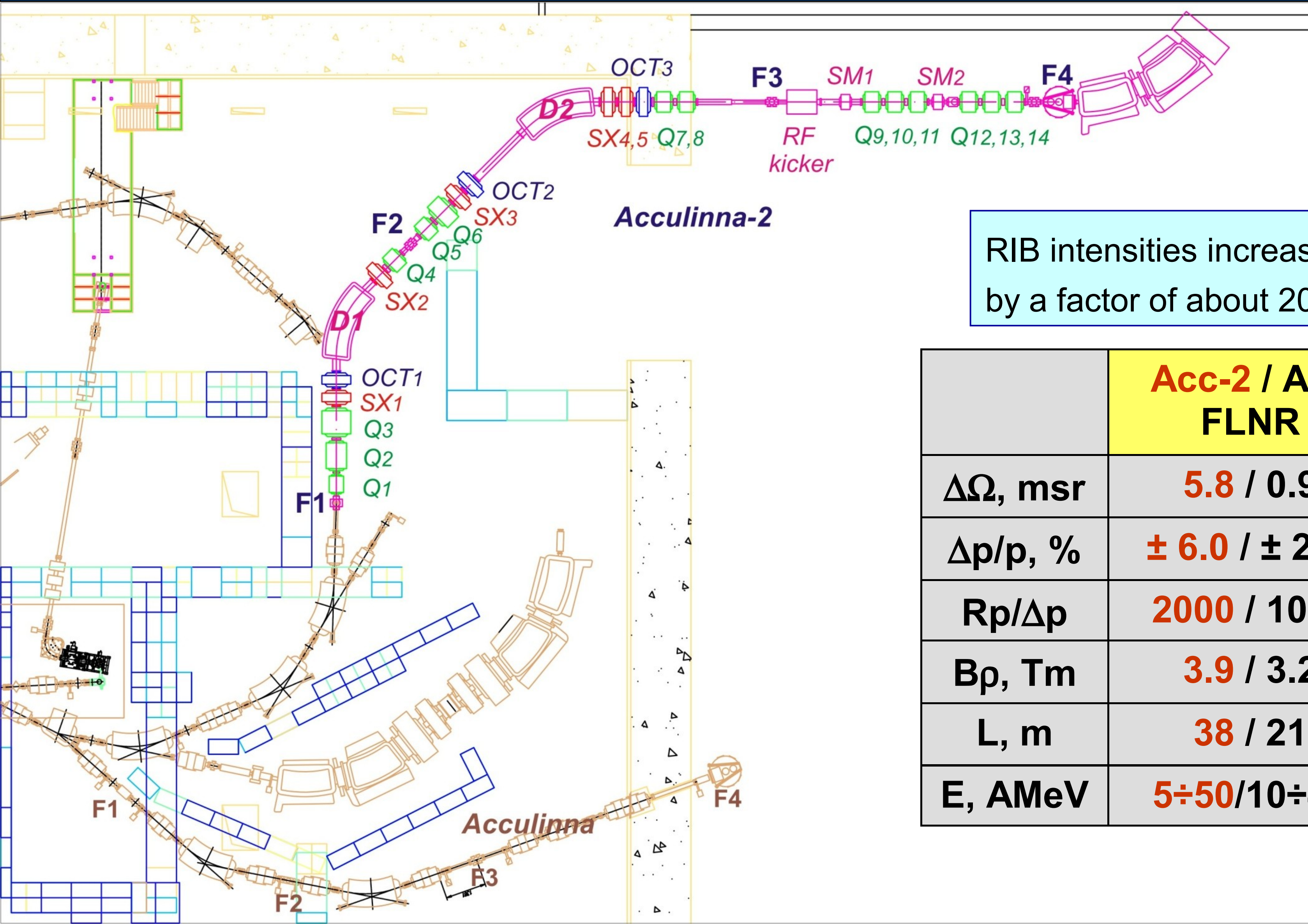
preliminary!

Branching to the 9.67 MeV state must be larger and thus the B(GT) too!



D. R. Tilley et. all, Nucl. Phys. A 745 (2004)

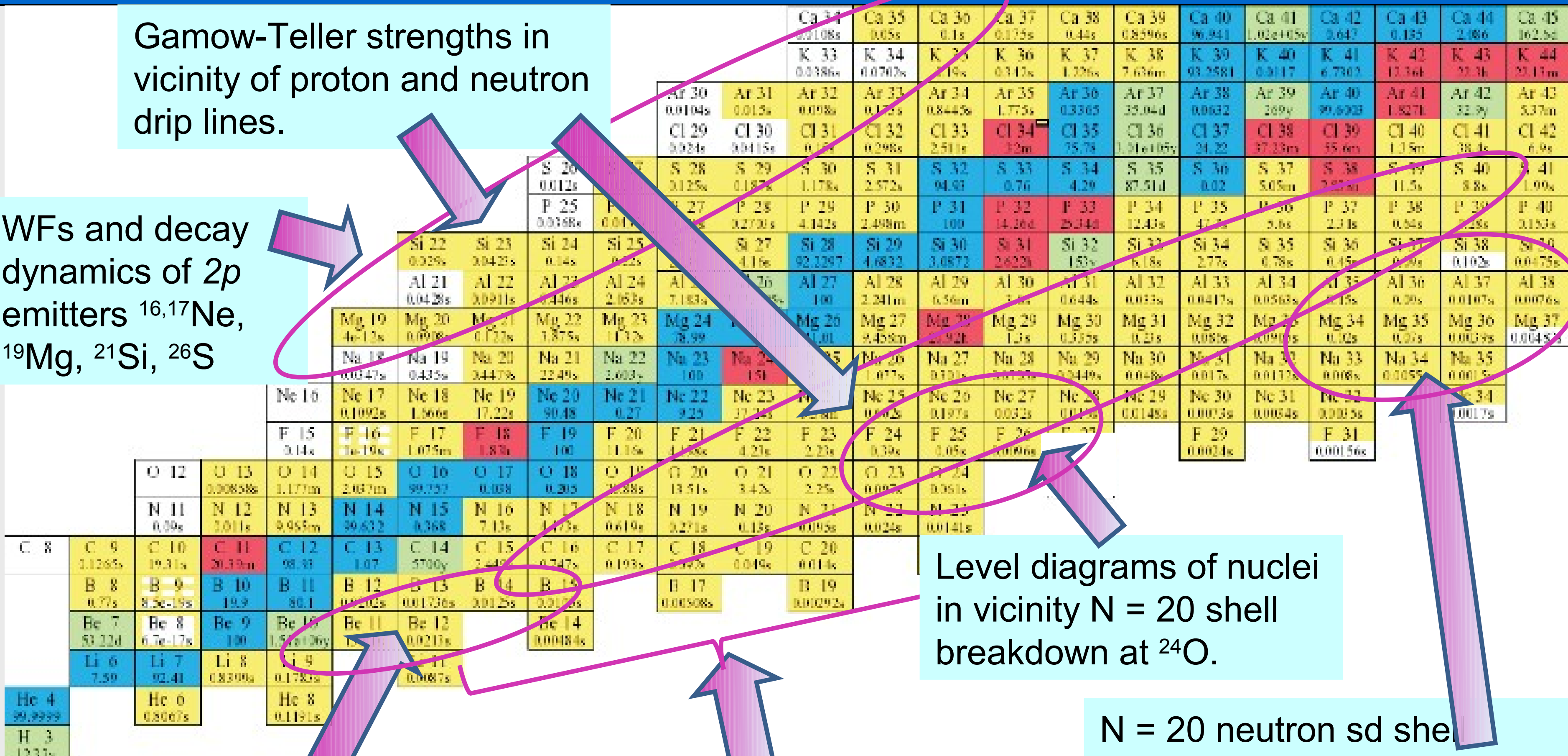
New project: ACCULINNA-2



RIB intensities increase by a factor of about 20

	Acc-2 / Acc FLNR
ΔΩ, msr	**5.8 / 0.9**
Δp/p, %	**± 6.0 / ± 2.5**
Rp/Δp	**2000 / 1000**
Bρ, Tm	**3.9 / 3.2**
L, m	**38 / 21**
E, AMeV	**5÷50/10÷40**

Research plans at ACCULINNA-2



Gamow-Teller strengths in vicinity of proton and neutron drip lines.

WFs and decay dynamics of *2p* emitters ^{16,17}Ne, ^{19}Mg, ^{21}Si, ^{26}S

Level diagrams of nuclei in vicinity N = 20 shell breakdown at ^{24}O.

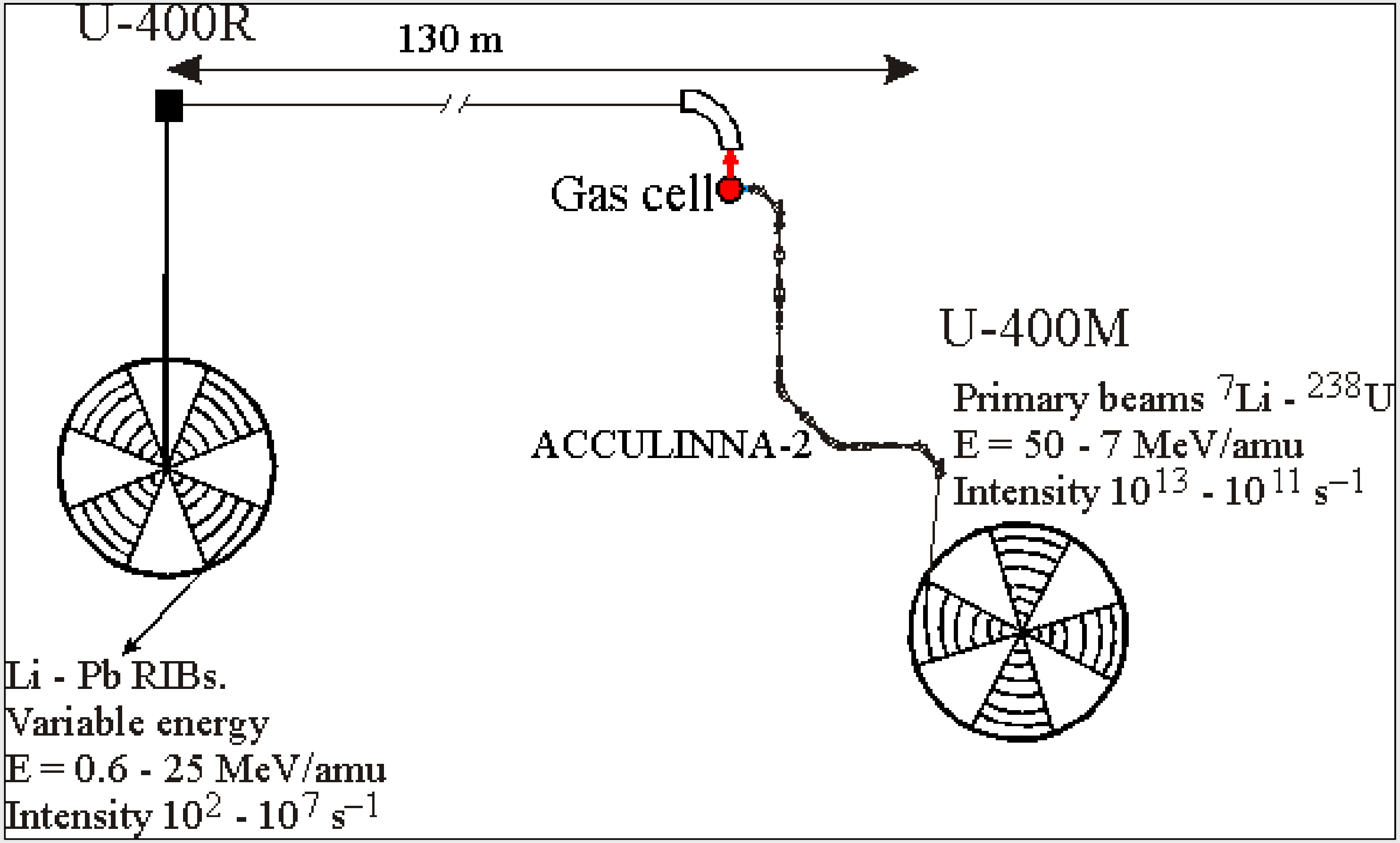
1s-0d intruder states in the drip-line He, Li, Be nuclei.

Missing mass spectra and ground-state WFs of drip-line nuclei in the neutron halo region.

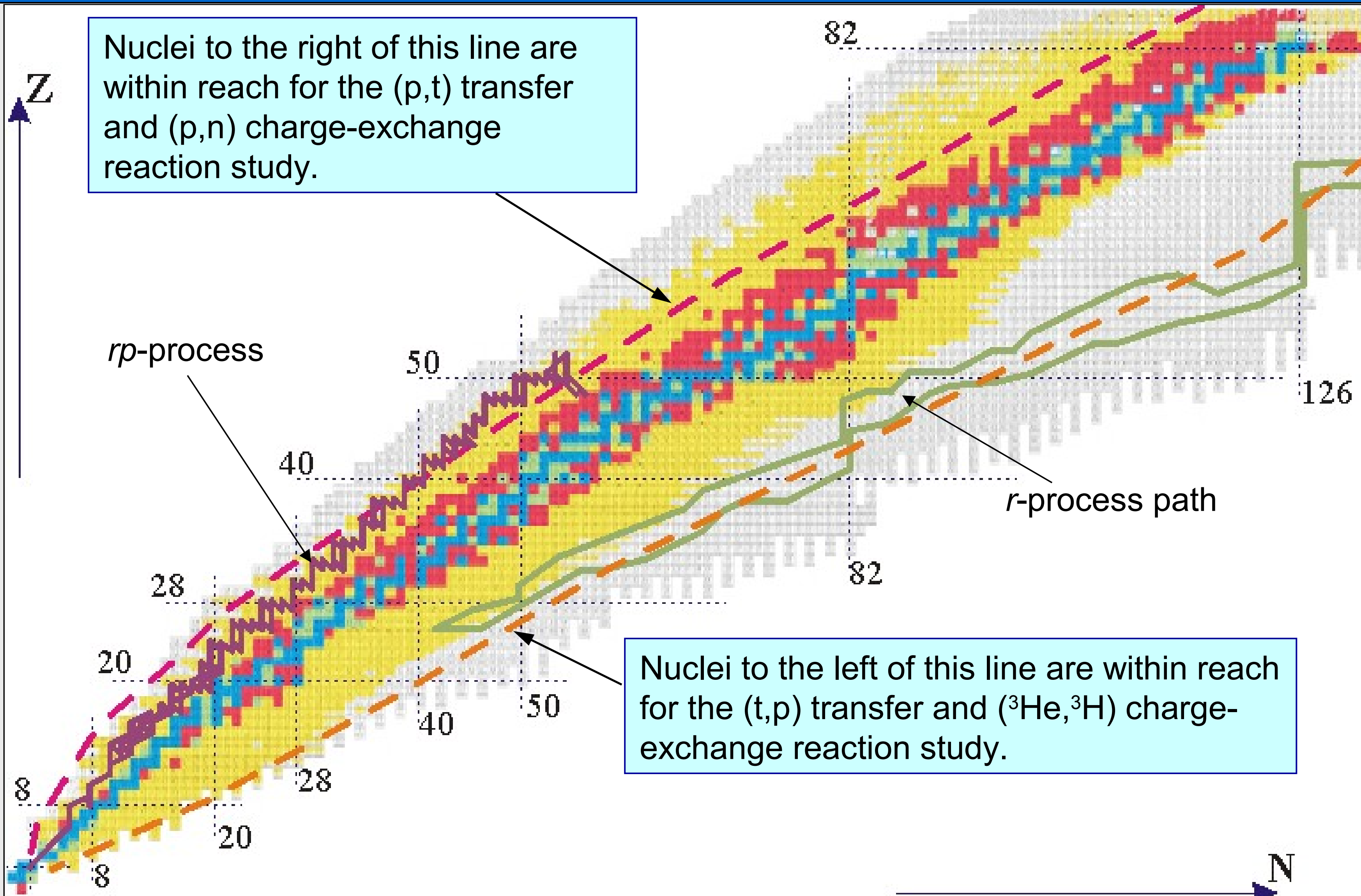
N = 20 neutron sd shell closure in ^{32}Ne and possible filling of the neutron $f_{7/2}$ intruder orbit for Z < 14 nuclei in the region.

Further dreams: DRIBS-3

- RIB products from ACCULINNA-2 can be stopped and thermalized in a gas catcher, to form a high-quality, low-energy RI beam to be injected into U400R for the reacceleration.



Exotic nuclei accesible at the DRIB-3



Summary

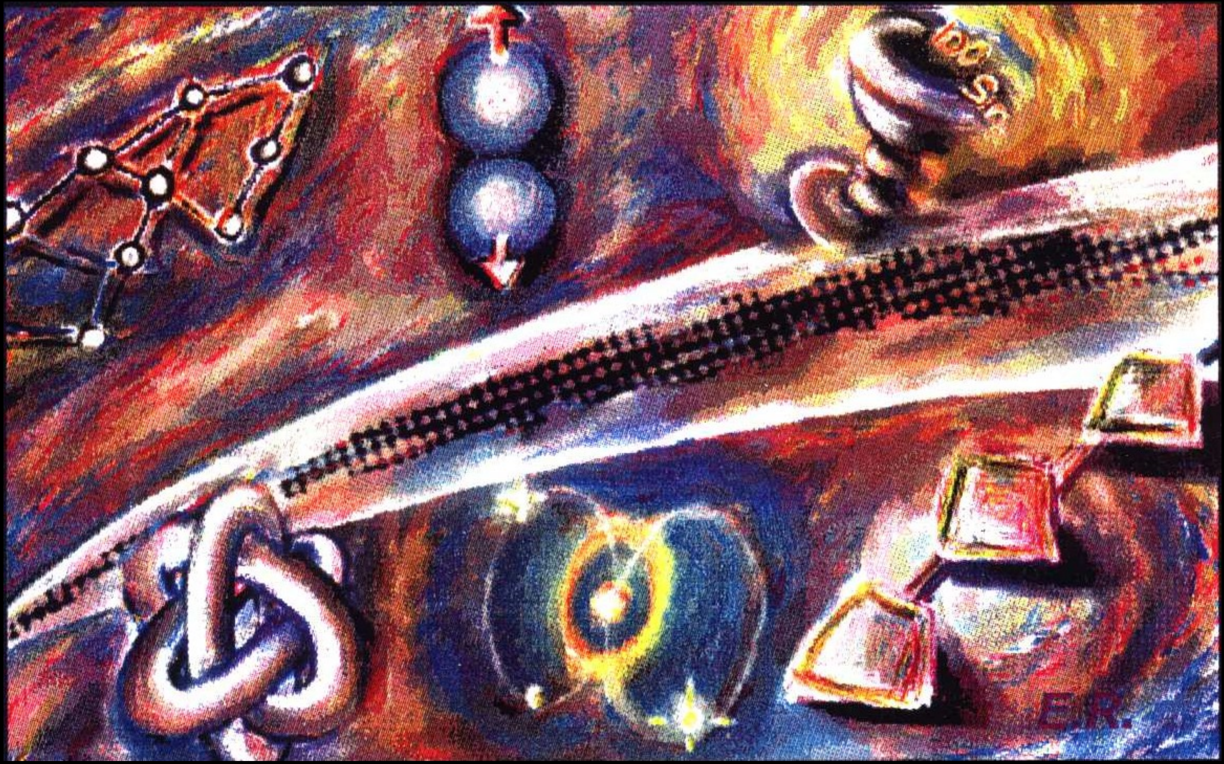
- There is a continuous progress in reaching nuclei far from β stability.
  In the last three decades the number of known nuclides increased
  from about 2200 in 1981 to about 3000 in 2006 → 32 new nuclei/year!
- Proton drip-line reached up to $Z = 91$ except for even $Z \in (32,64)$ and $Z > 82$
  Neutron drip-line reached up to $N = 27$ except for N=10, 14 and even N>21
- New phenomena at the limits of stability: β-delayed (multi)particle emission,
  p and *2p* radioactivity, neutron halo, shell migration,...
- New technique employing digital photograpy provides complementary data
  to classical methods based on Si detectors (angular correlations, branching ratios)
- Separator ACCULINNA @ FLNR offers first-class conditions for studies of light
  nuclei at the limits of stability. Its particular feature is a cryogenic tritium target.
- Proposed upgrade ACCULINNA-2 will largely increase the experimental possibilities
  and represent the key facility worldwide for light and medium mass RIB.

Legacy of Maria Skłodowska-Curie – 100 years after discovery of atomic nucleus,

September 11 – 18, 2011, Piaski, POLAND

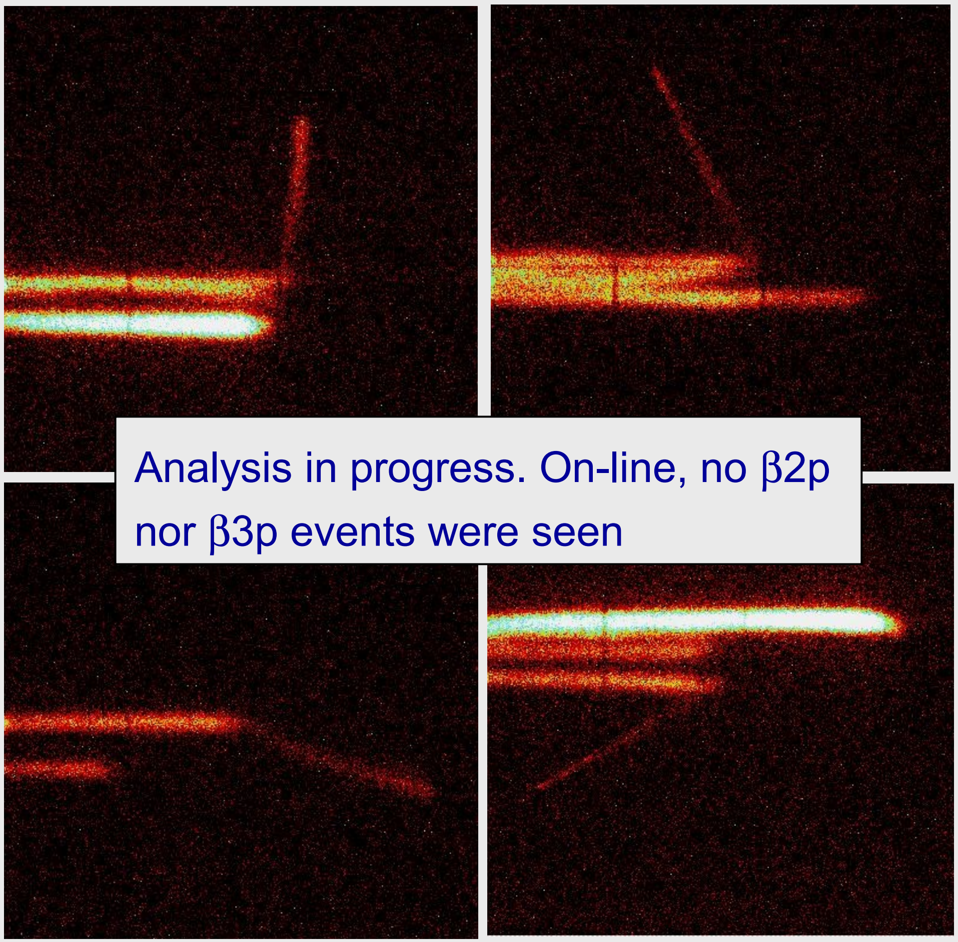
➤ www.mazurian.fuw.edu.pl

Thank you for attention!

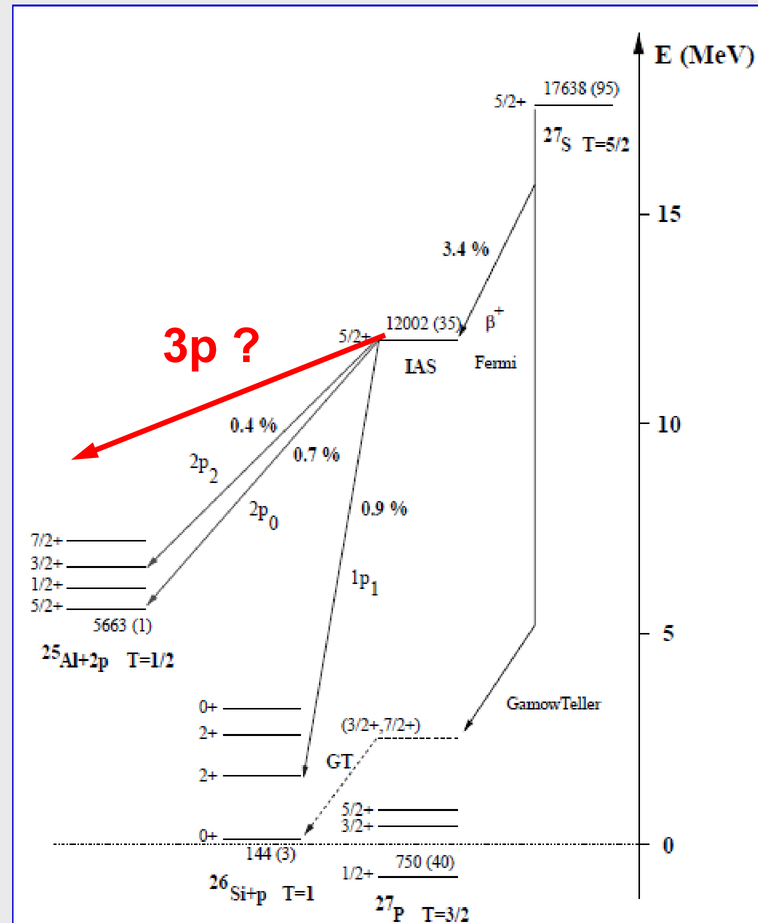


Search for β3p in ^{27}S @ FLNR

- ^{32}S @ 50 MeV/u + Be → ACCULINNA → ^{27}S (December 2010)



Analysis in progress. On-line, no β2p nor β3p events were seen



The scattering of the α rays...

The first public announcement of the atomic nucleus:

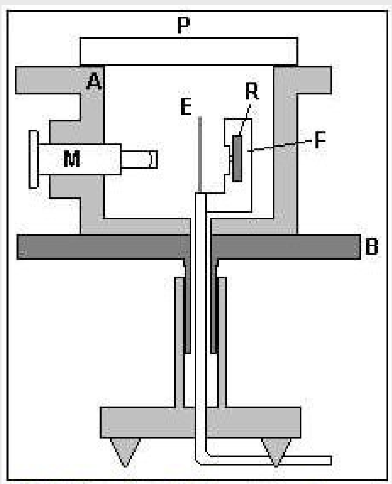


Fig1. Marsden-Geiger experiment.

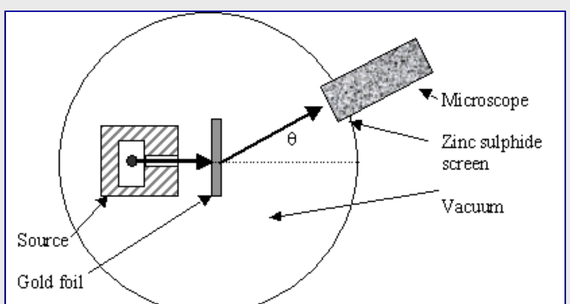
The Scattering of the α and β Rays and the Structure of the Atom

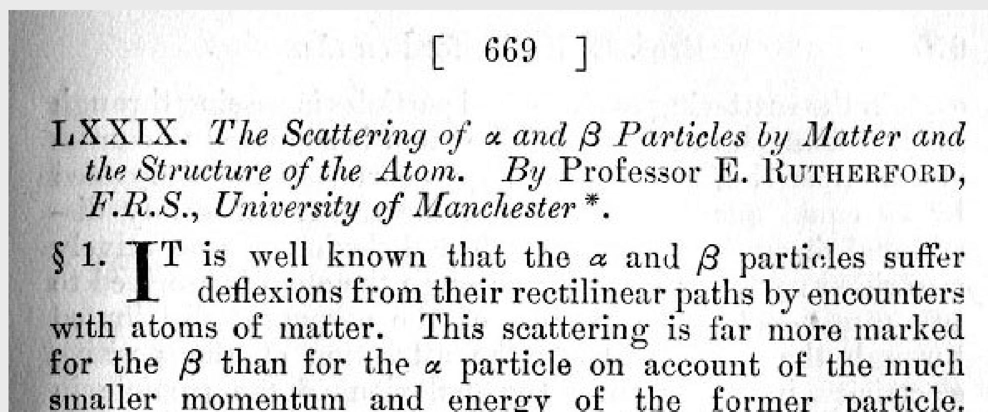
by Professor E. Rutherford, F.R.S.

Proc. of the Manchester Literary and Philosophical Society, IV, 55, pp.18-20.

presented on March 7, 1911

$$P(\theta) \propto \frac{1}{\sin^4 \theta/2}$$





[669]

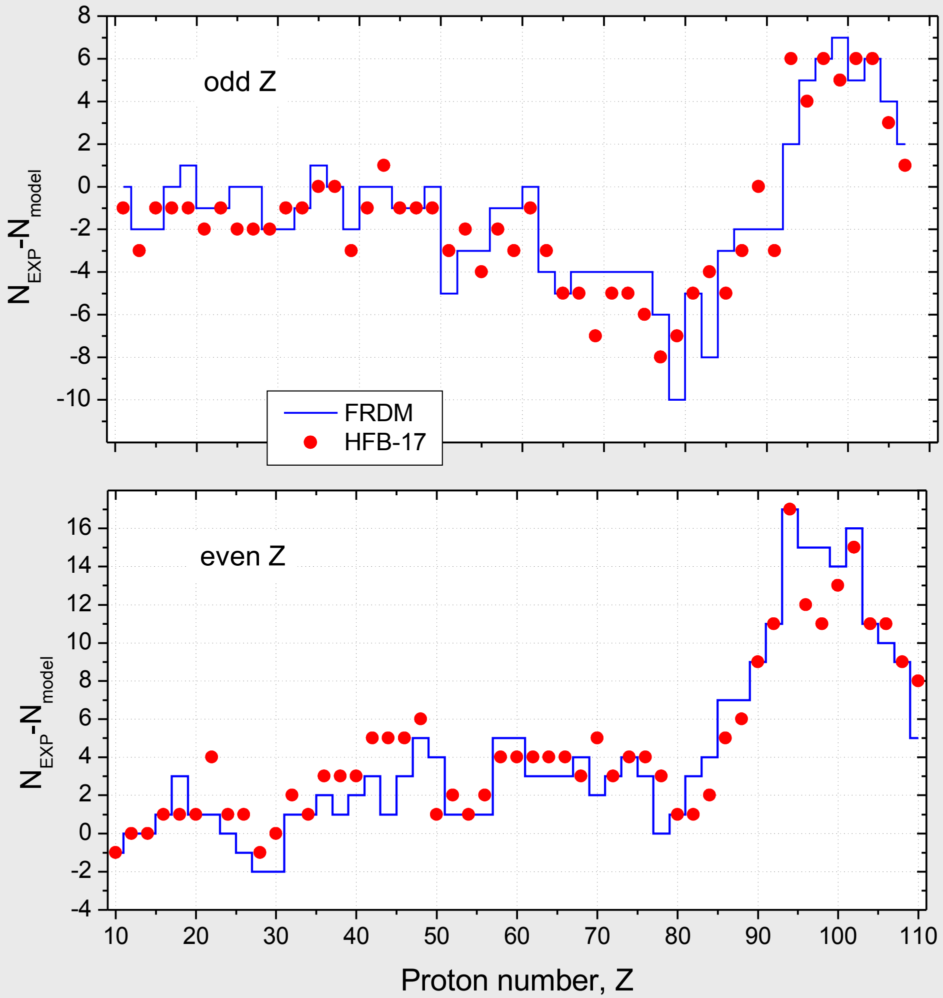
LXXIX. *The Scattering of α and β Particles by Matter and the Structure of the Atom.* *By* Professor E. RUTHERFORD, *F.R.S., University of Manchester* *.

§ 1. IT is well known that the α and β particles suffer deflexions from their rectilinear paths by encounters with atoms of matter. This scattering is far more marked for the β than for the α particle on account of the much smaller momentum and energy of the former particle.

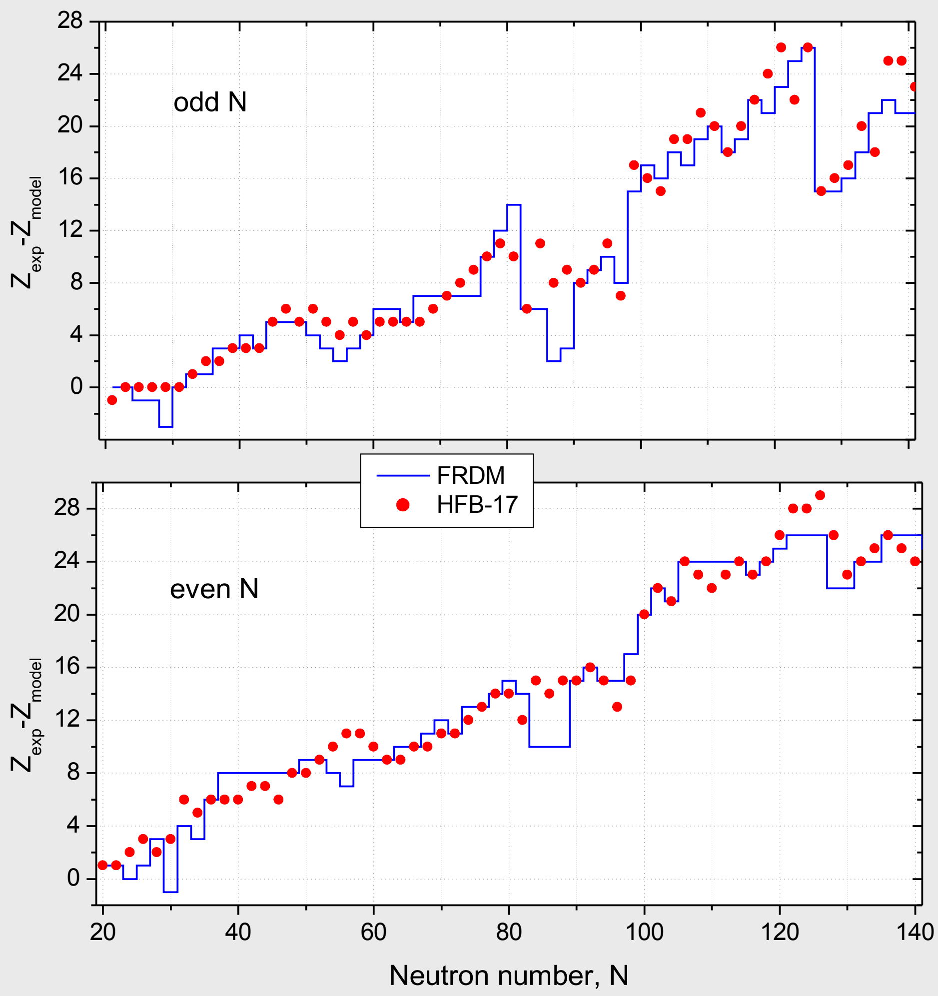
Philosophical Magazine, May 1911, ser.6, xxi, pp.669-88

Drip lines

proton drip-line



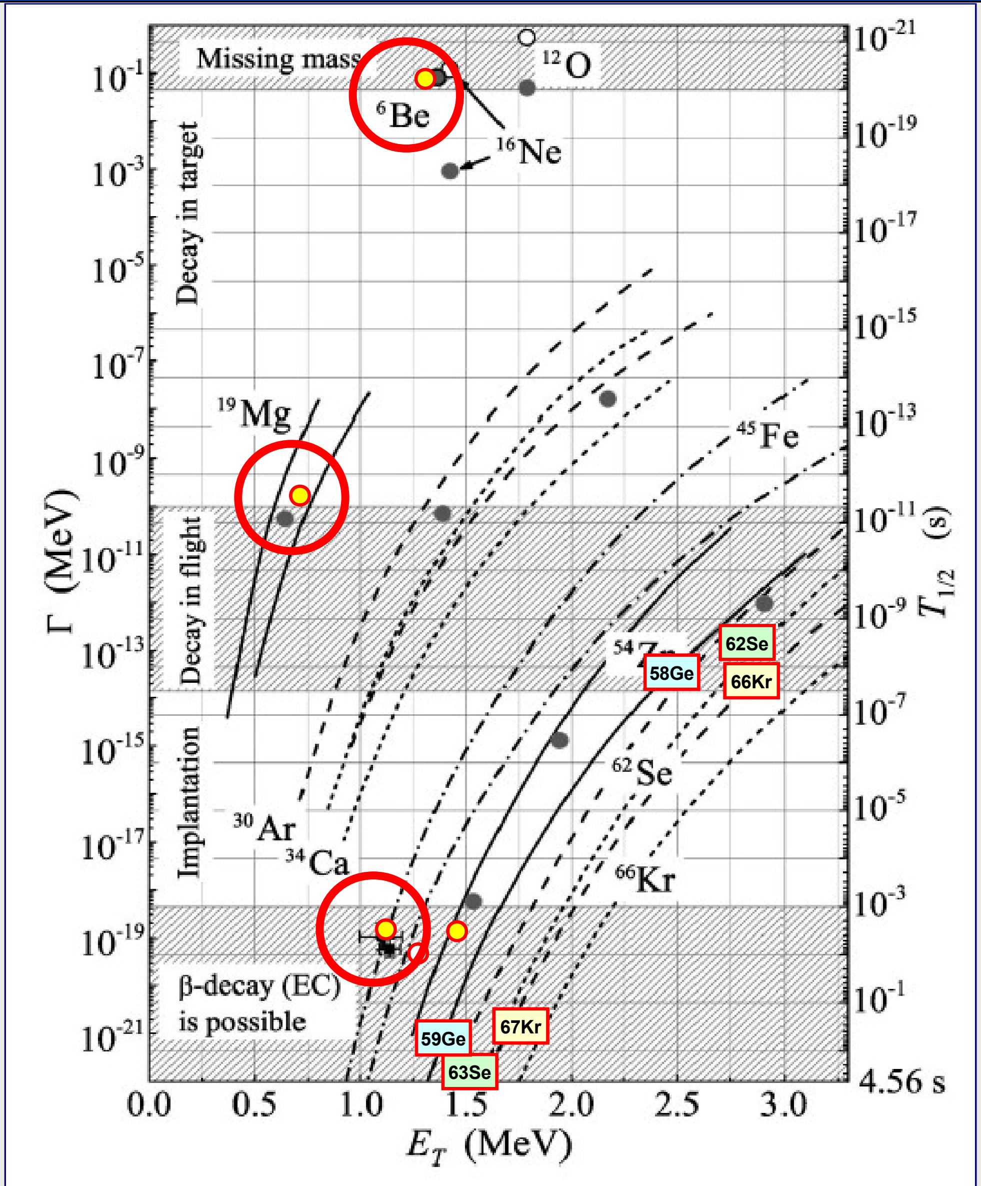
neutron drip-line



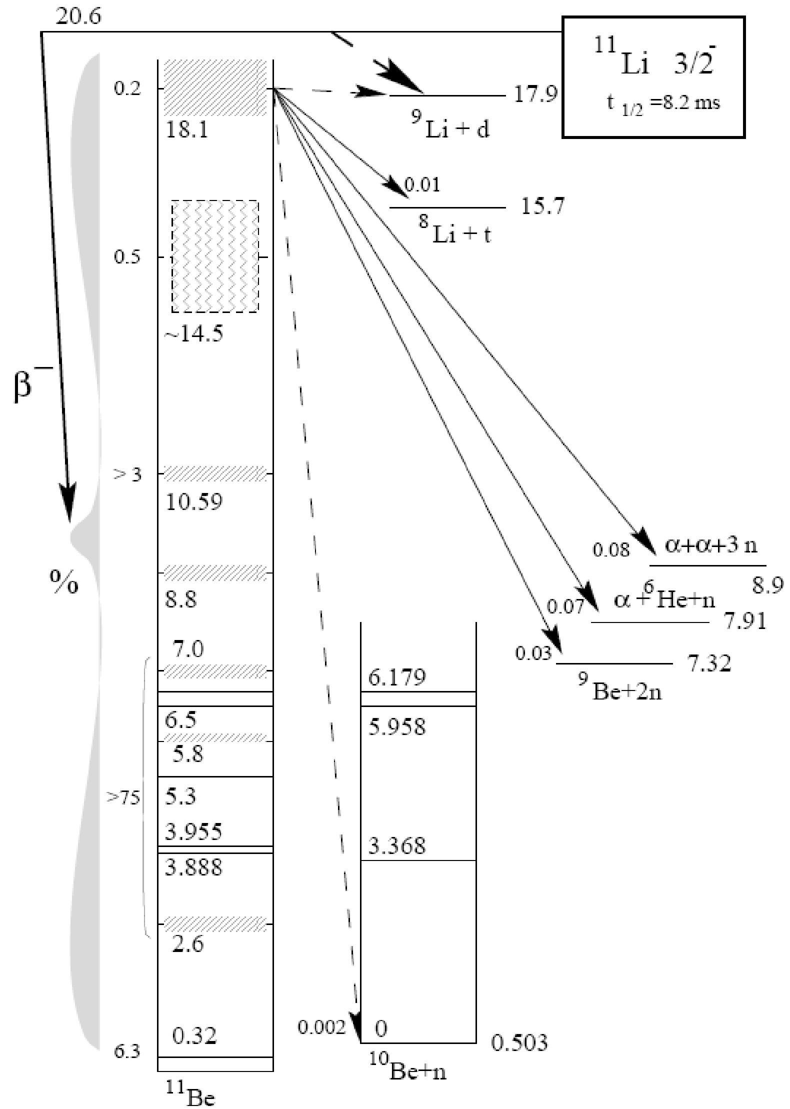
Three lifetime regimes

- Invariant mass method for broad resonanses
  $T_{1/2} \leq 10^{-19}$ s
- In-flight decays
  $T_{1/2}$ = 5 ps – 50 ns
- Implantation method
  $T_{1/2}$ > 50 ns

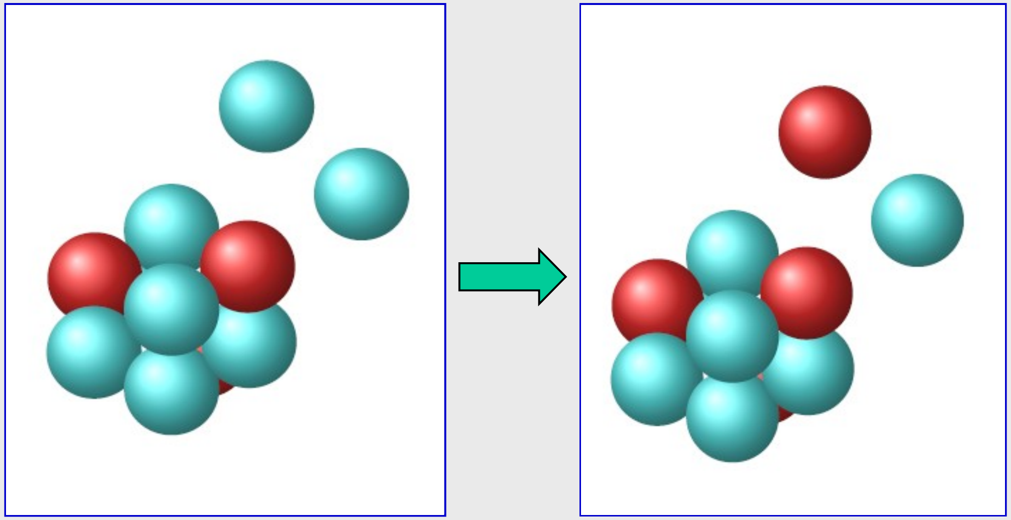
L.V. Grigorenko and M.V. Zhukov, PRC 68 (2003) 054005



β-delayed *d* emission from ^{11}Li



K. Riisager et al., NPA 616 (1997) 169c



$B.R. = 1.30(13) \times 10^{-4}$
"large" value only possible
if core has a small contribution
⇒ decay essentially in the halo

Jeroen Büscher at ENAM'08

R. Raabe et al., PRL 101 (2008) 212501