Studies of Two Proton Radioactivity

GSI

Ivan Mukha

- **Nuclear landscape beyond proton drip line**
- **Basics of two-proton decay and 2p-decay mechanisms**
- **Experiments**

Light nuclei: Reference case of 2p-decay of ^{6}Be
Medium mass: discovery of two-proton radioactivity of ^{45}Fe
Heavy nuclei: Two-proton decay of the high-spin isomer (21^{+}) in ^{94}Ag

Two-proton radioactivity in flight of ^{19}Mg

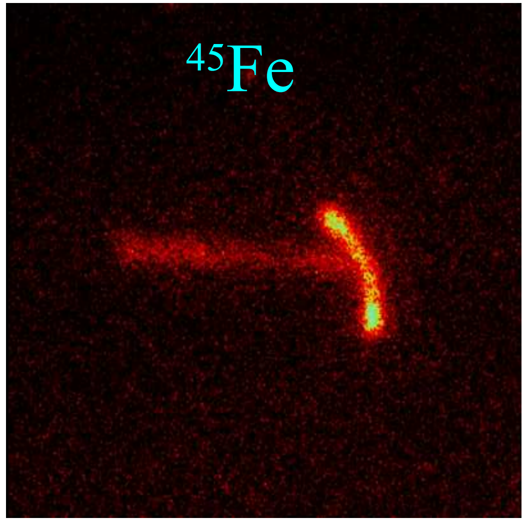
- **Prospective experiments in future**

Historical note

In 1898, Pierre and Marie Curie introduced the term "radioactivity" to describe a phenomenon first observed by Henry Becquerel two years earlier, a spontaneous break-up of elements.

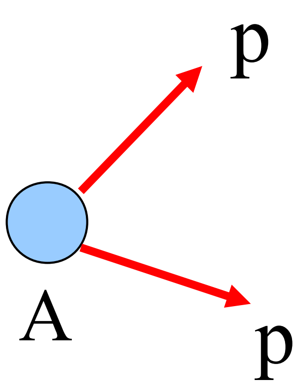
This was a beginning of nuclear physics...

In 1961, V.I.Goldanski predicted two-proton radioactivity of very proton-rich nuclei, which was observed on ^{45}Fe in 2002.

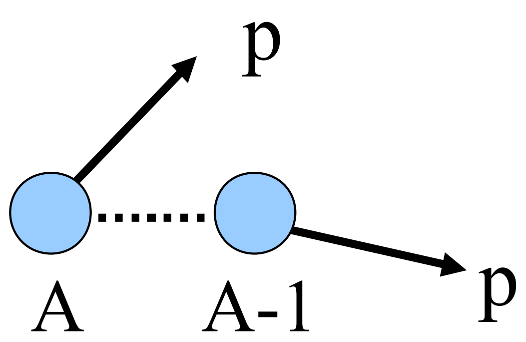


Neutron- or two-neutron radioactivity is not observed yet.

What is two-proton radioactivity ?

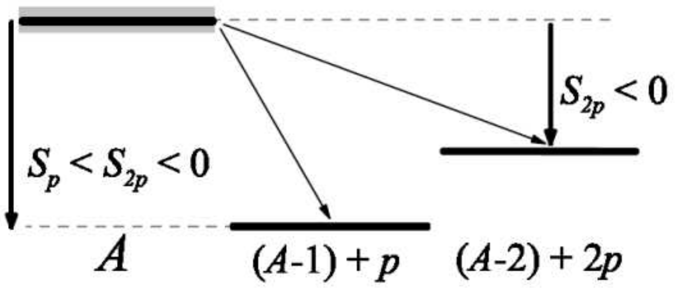


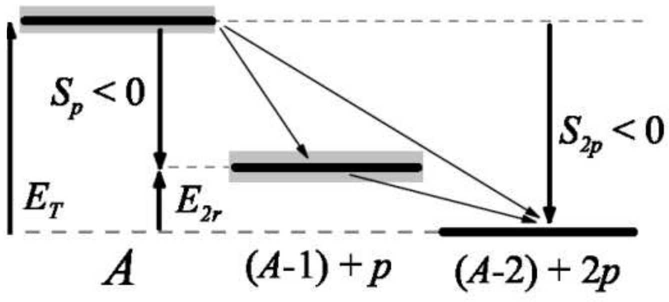
Genuine three-body decay

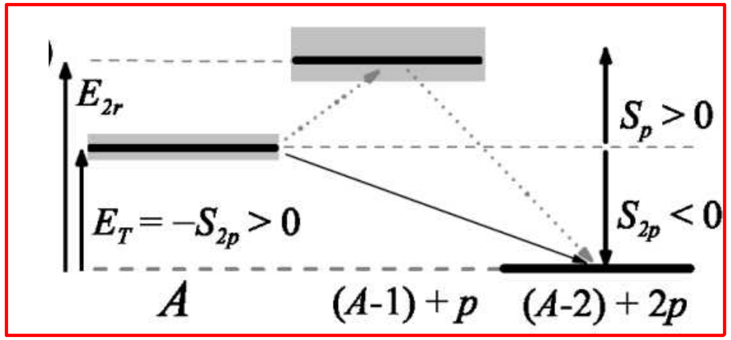


Sequential proton emission

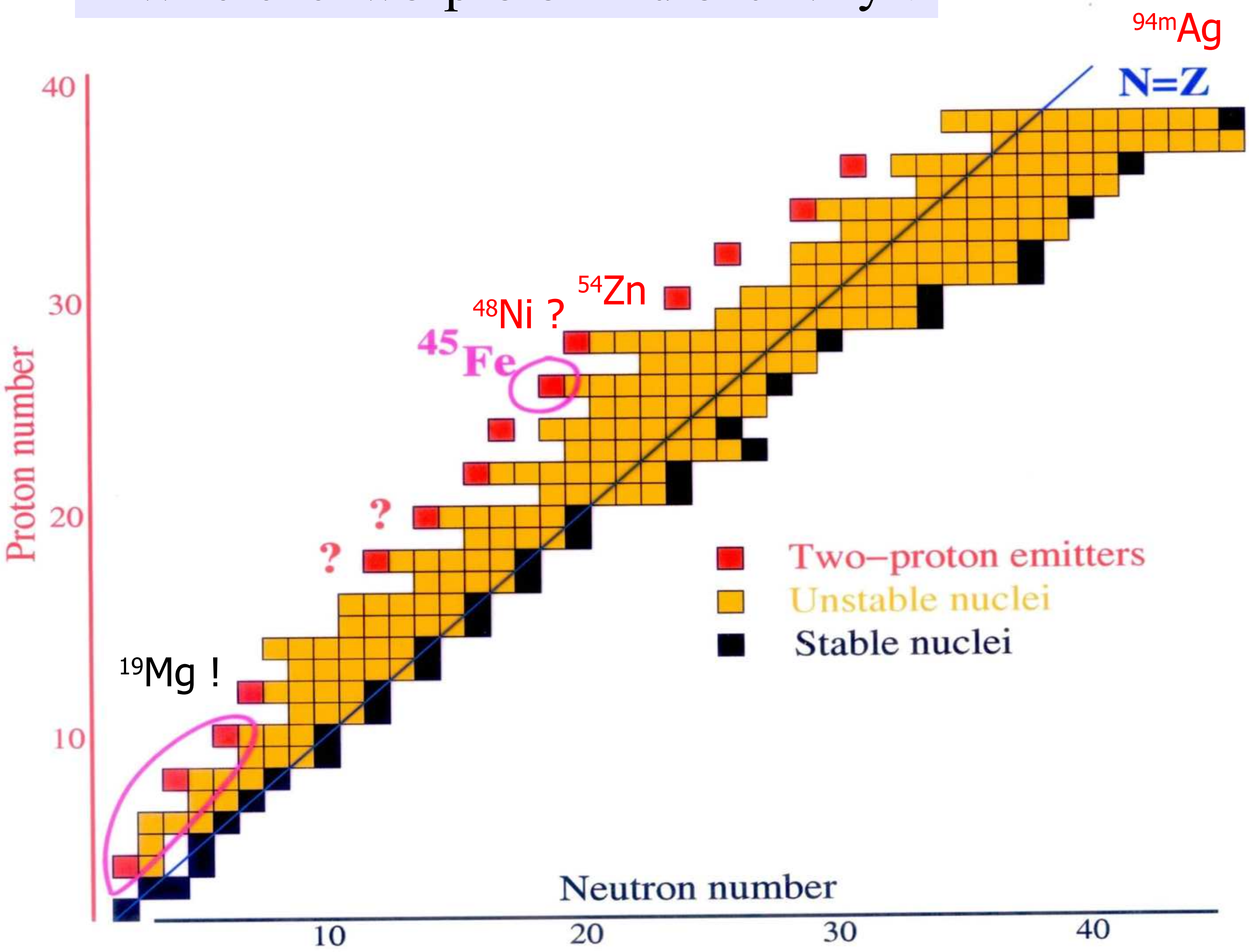
Energy conditions of a genuine two-proton decay







Where is two-proton radioactivity ?



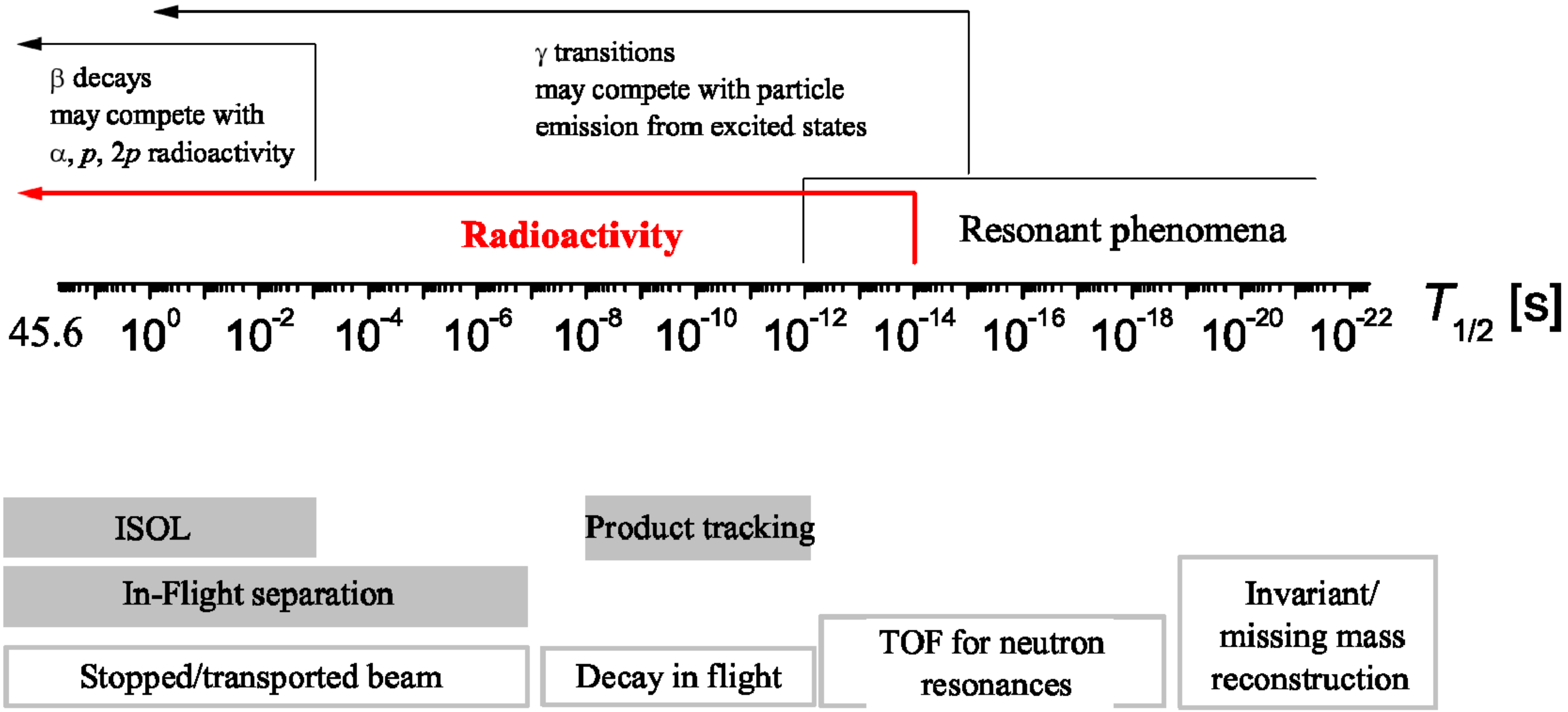
Status of two-proton radioactivity experiments

TABLE III Ground-state $2p$ emitters investigated experimentally.

^{N}Z	E keV	Γ or $T_{1/2}$	Reference
^{6}Be	1371(5)	92(6) keV	(Whaling, 1966)
^{12}O	1820(120)	$400(250)^{a}$ keV	(KeKelis *et al.*, 1978)
	1790(40)	$580(200)^{a}$ keV	(Kryger *et al.*, 1995)
	1800(400)	$600(500)^{a}$ keV	(Suzuki *et al.*, 2009)
^{16}Ne	1350(80)	$200(100)^{a}$ keV	(KeKelis *et al.*, 1978)
	1400(20)	$110(40)^{a}$ keV	(Woodward *et al.*, 1983)
	1350(80)	<200 keV	(Mukha *et al.*, 2008b)
^{19}Mg	750(50)	4.0(15) ps	(Mukha *et al.*, 2007)
^{45}Fe	1100(100)	$3.2^{+2.6}_{-1.0}$ ms	(Pfützner *et al.*, 2002)
	1140(50)	$5.7^{+2.7}_{-1.4}$ ms	(Giovinazzo *et al.*, 2002)
	1154(16)	$2.8^{+1.0}_{-0.7}$ ms	(Dossat *et al.*, 2005)
		$3.7^{+0.4}_{-0.4}$ ms	(Miernik *et al.*, 2007d)
^{48}Ni	1350(20)	$8.4^{+12.8\,b}_{-7.0}$ ms	(Dossat *et al.*, 2005)
^{54}Zn	1480(20)	$3.2^{+1.8}_{-7.8}$ ms	(Blank *et al.*, 2005)

[a] According to theoretical calculations much smaller widths are expected (Barker, 1999, 2001; Grigorenko *et al.*, 2002).
[b] Only one decay event observed.

Detection metods on nuclear de-excitations



Half-life *vs.* decay energy of 2p-radioactivity precursors

Short-lived nuclei:

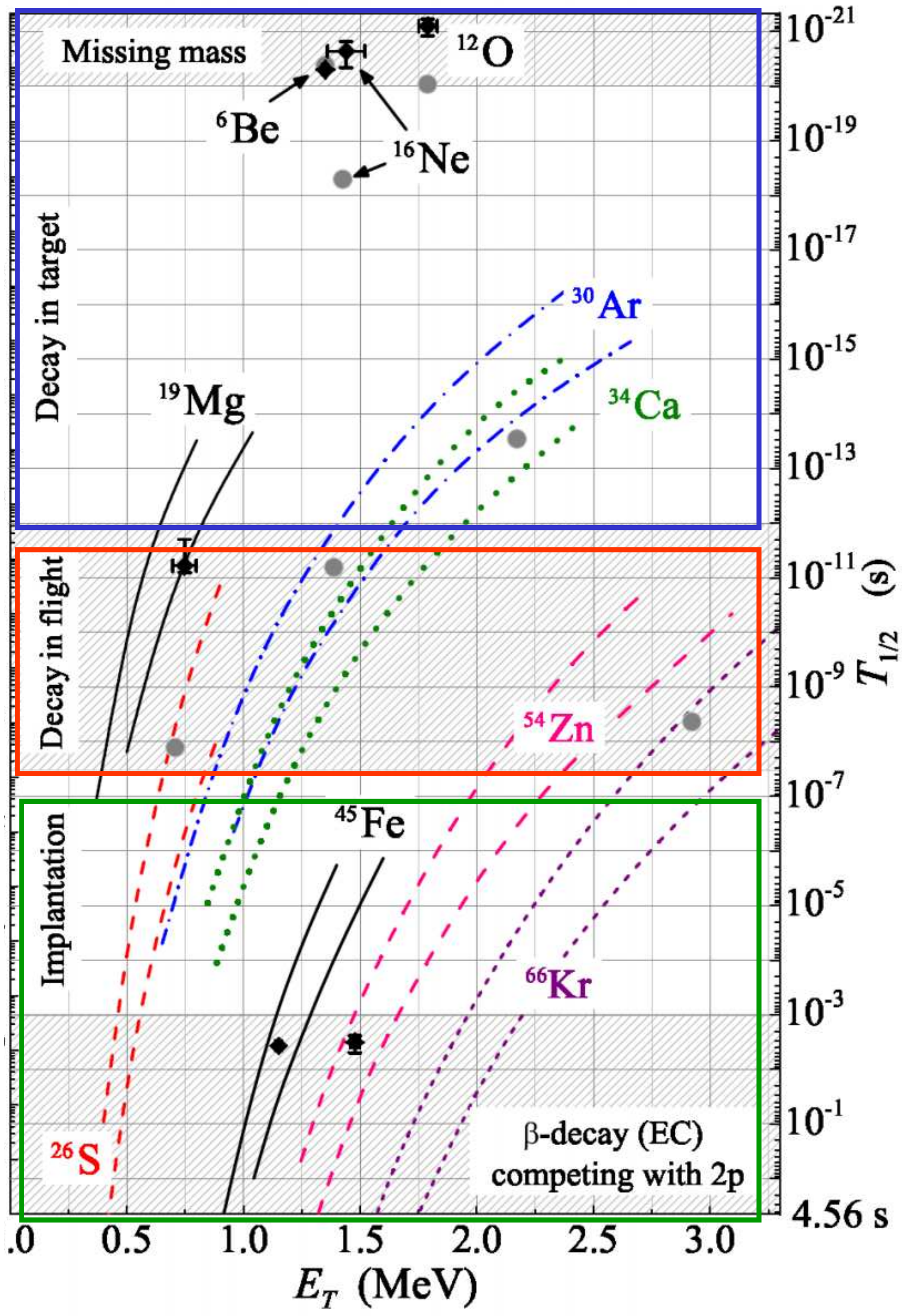
^{6}**Be**, ^{12}**O**, ^{16}**Ne**, *etc*

In-flight decay candidates:

^{19}**Mg**, ^{26}S, ^{30}Ar, ^{34}Ca ^{58}Ge, ^{62}Se, ^{66}Kr

Experiments with stopped ions:

^{45}**Fe**, ^{48}**Ni**, ^{54}**Zn**, ^{59}Ge, ^{60}Ge, ^{94m}**Ag**



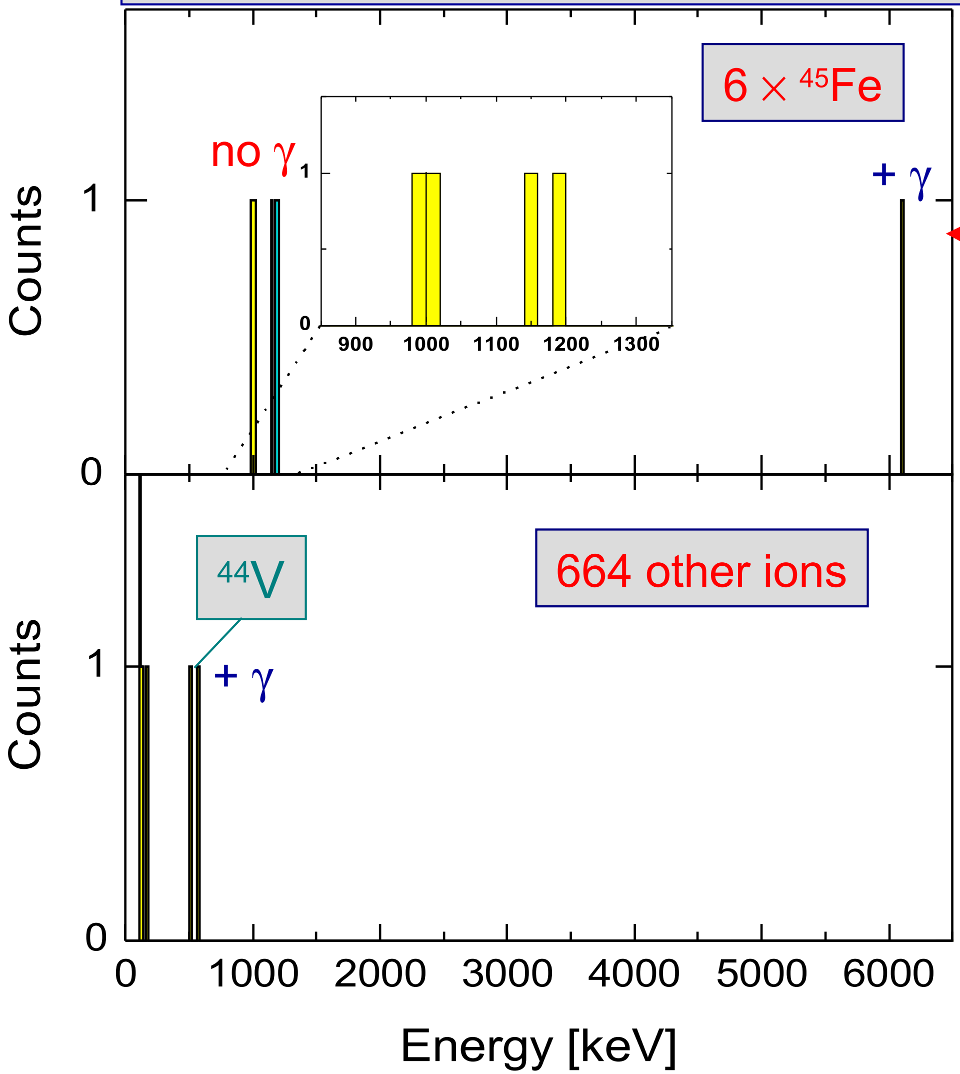
L.V. Grigorenko, I. Mukha, M.V. Zhukov, Proc. PROCON'03 (AIP **681**, NY 2003) 126.

B.A. Brown and F.C. Barker, ibid., p. 118.

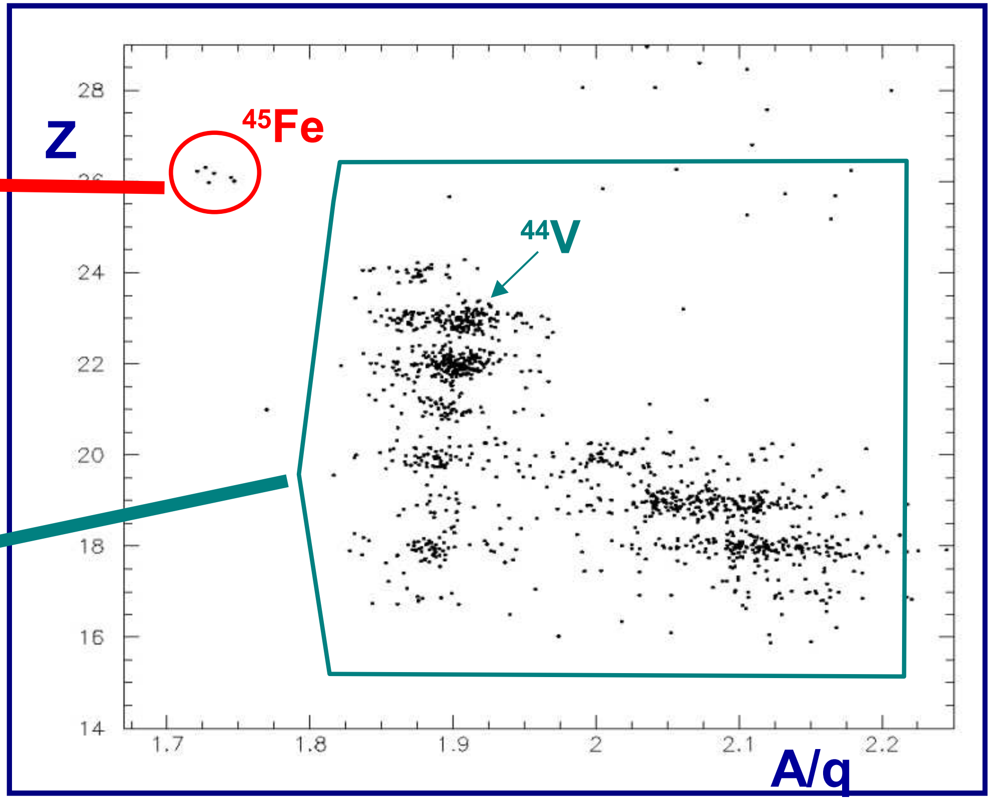
L.V. Grigorenko and M.V. Zhukov, PRC **68** (2003)

Discovery of two-proton radioactivity at GSI

Events correlated with the stopped ions : implantation and decay in the same detector



M. Pfutzner et al., EPJ A **14** (2002)
M. Pfutzner et al., NIM A **493** (2002)



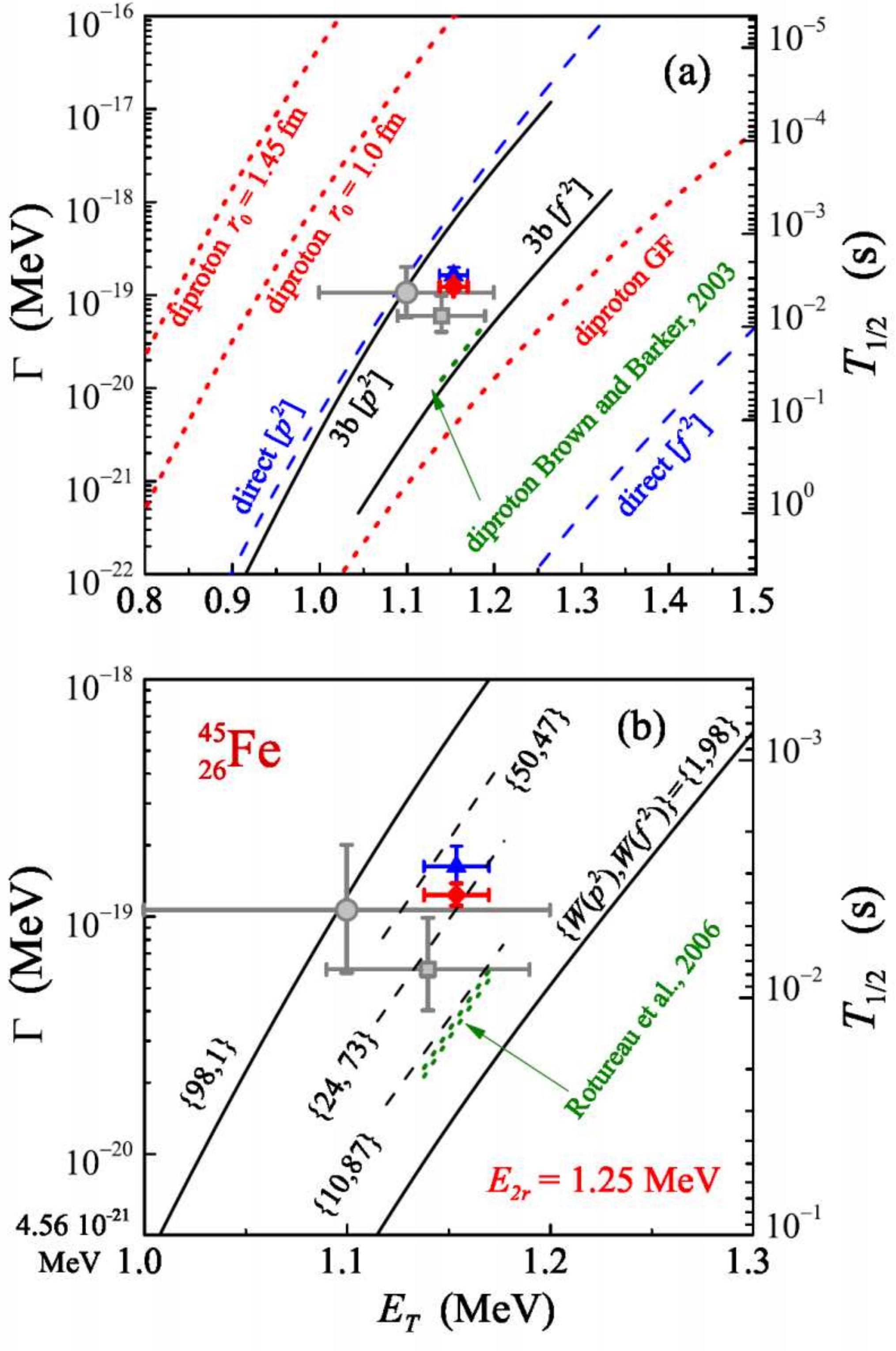
⇨ emission of 2p is the dominant (80%) decay mode of ^{45}Fe :

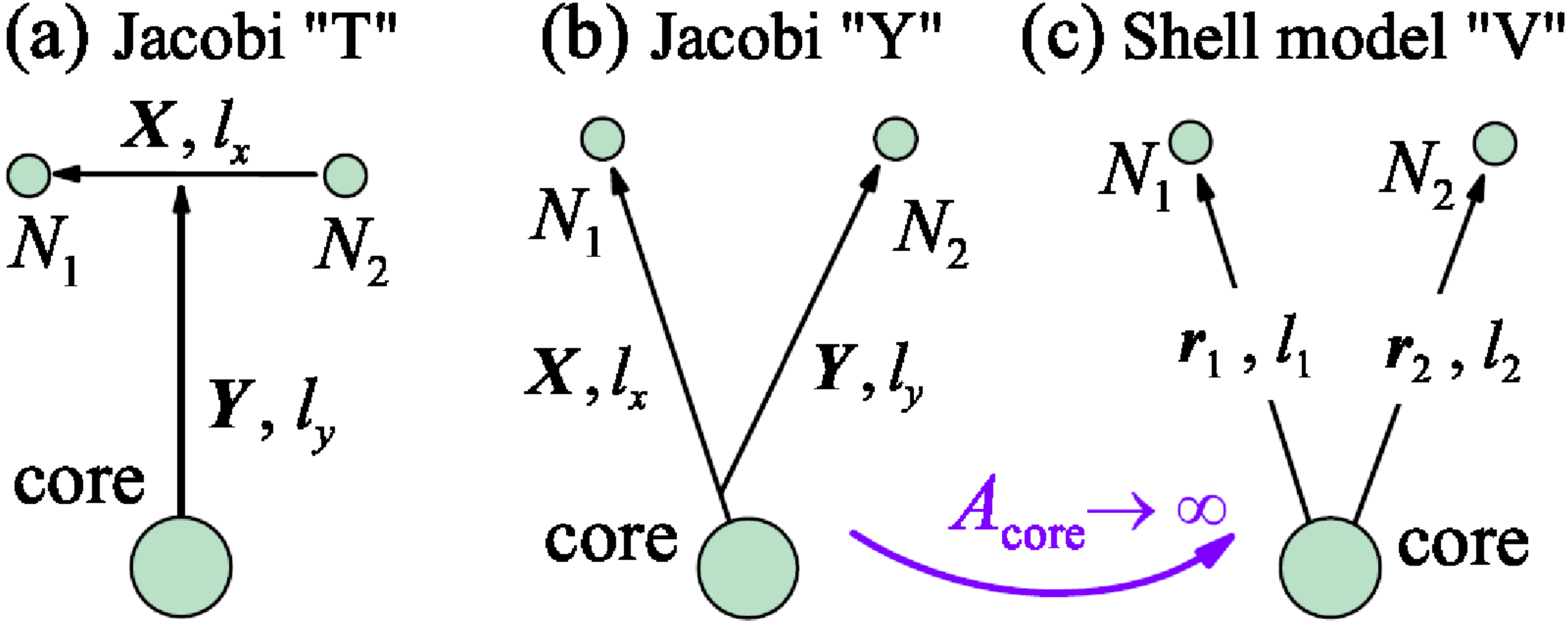
$E_{2p} = 1.1(1)$ MeV

$T_{1/2} = 3.2^{+2.6}_{-1.0}$ ms

ays

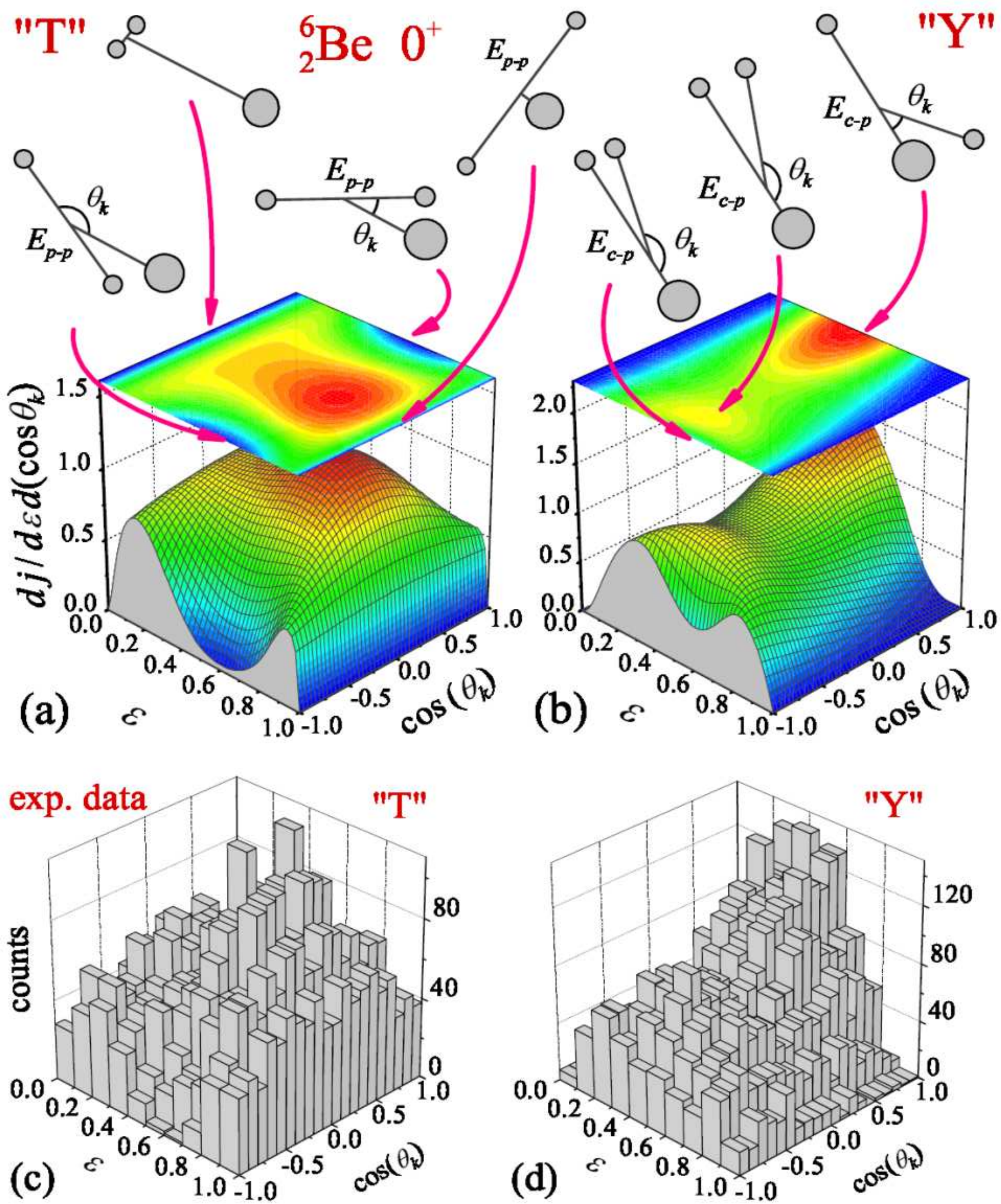
Data on the half-life and decay energy of ^{45}Fe




(a) Jacobi "T"
X, l_x
N_1
N_2
Y, l_y
core
(b) Jacobi "Y"
N_1
N_2
X, l_x
Y, l_y
core
A_core → ∞
(c) Shell model "V"
N_1
N_2
r_1 , l_1
r_2 , l_2
core

Reference case of correlations in 2p decay of ^{6}Be,

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



Old data: Nuclear structure is reflected in a two-proton decay

$^{6}Be(0+) \rightarrow \alpha+p+p$

Diproton

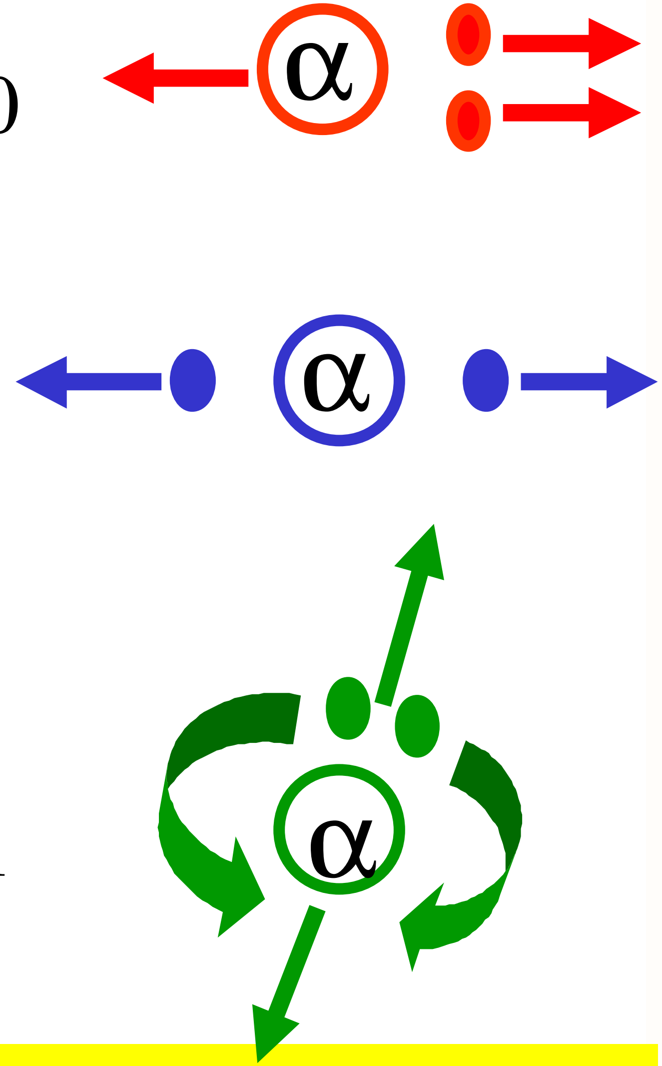
$\ell_{\alpha-pp} = 2, \ell_{pp} = 0$

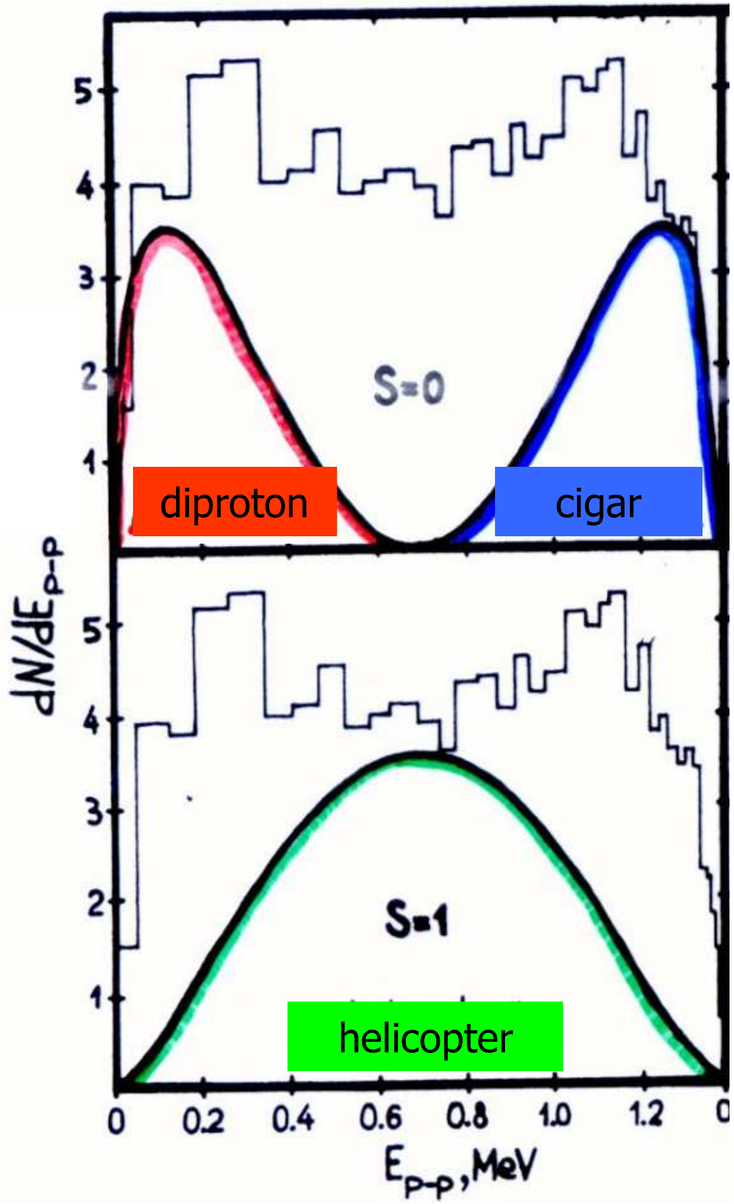
Cigar

$\ell_{\alpha-pp} = 0, \ell_{pp} = 2$

Helicopter

$\ell_{\alpha-pp} = 1, \ell_{pp} = 1$



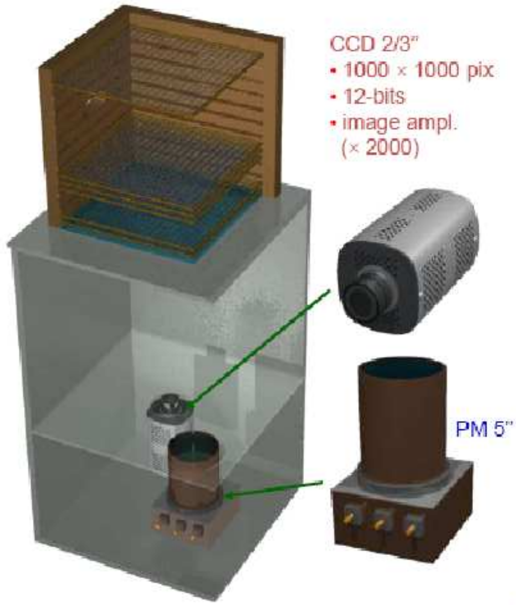


O.Bochkarev, I.Mukha..., Nucl Phys A505 (1989)

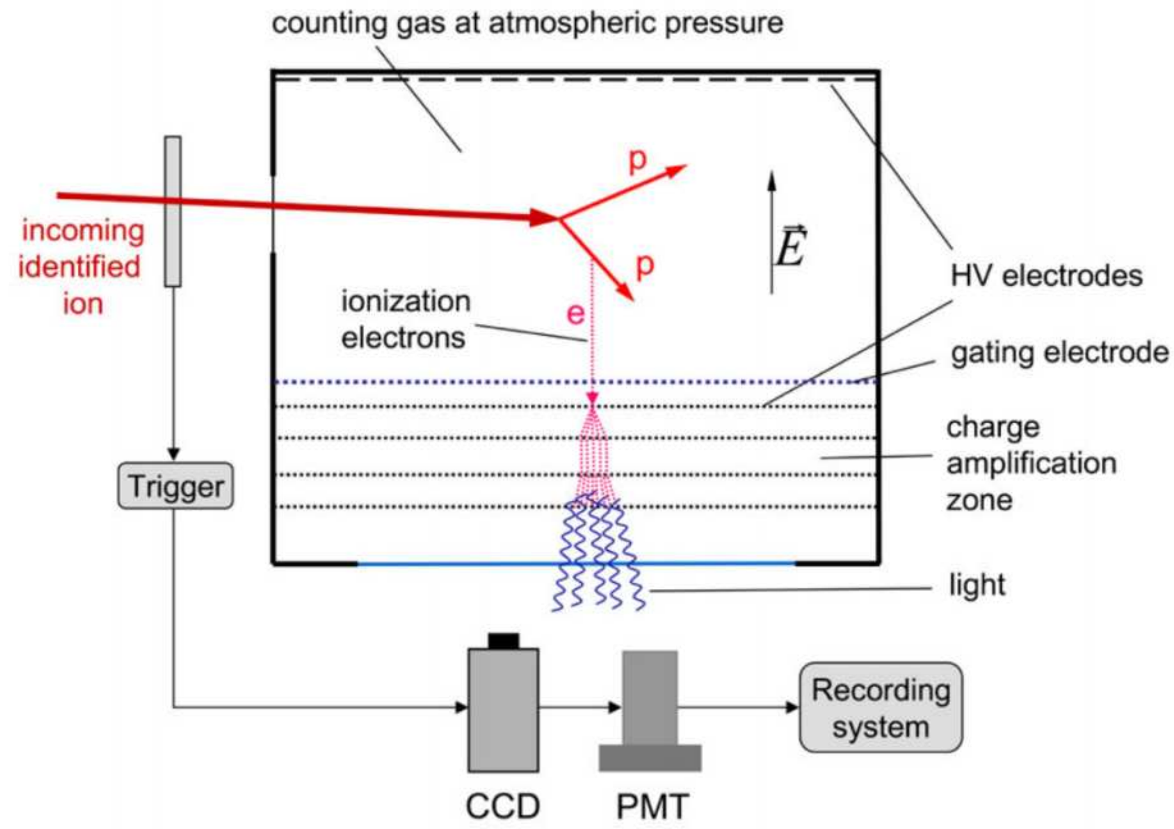
The observed decay modes reflect the ^{6}Be structure,

e.g. I.J.Thompson, B.V.Danilin et al., Phys Rev C **61** (2000)

Optical time projection chamber



M. Ćwiok et al., IEEE TNS, 52 (2005) 2895
K. Miernik et al., NIM A581 (2007) 194



Miernik, K., W. Dominik, H. Czyrkowski, R. Da̧browski, A. Fomitchev, M. Golovkov, Z. Janas, W. Kusmierz, M. Pfützner, A. Rodin, S. Stepantsov, R. Slepniev, *et al.*, 2007a, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **581**(1-2), 194 , ISSN 0168-9002, vCI 2007 - Proceedings of the 11th International Vienna Conference on Instrumentation.

^{45}Fe - correlations

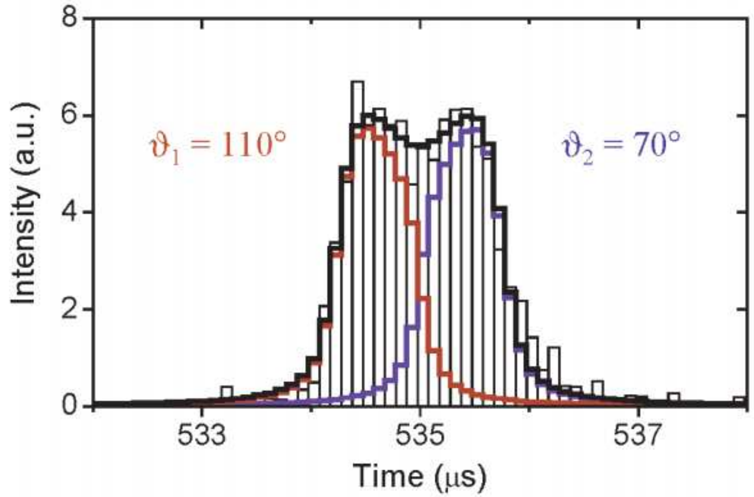
Miernik et al., PRL 99 (2007) 192501

L.Grigorenko et al., PLB 677 (2009) 30

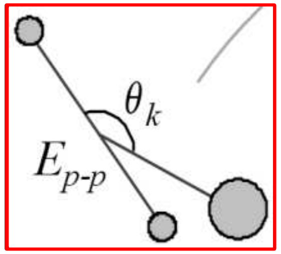
- Precursor stopped in gas
- Special design Optical TPC → nuclear physics "leave video"
- Improved lifetime:

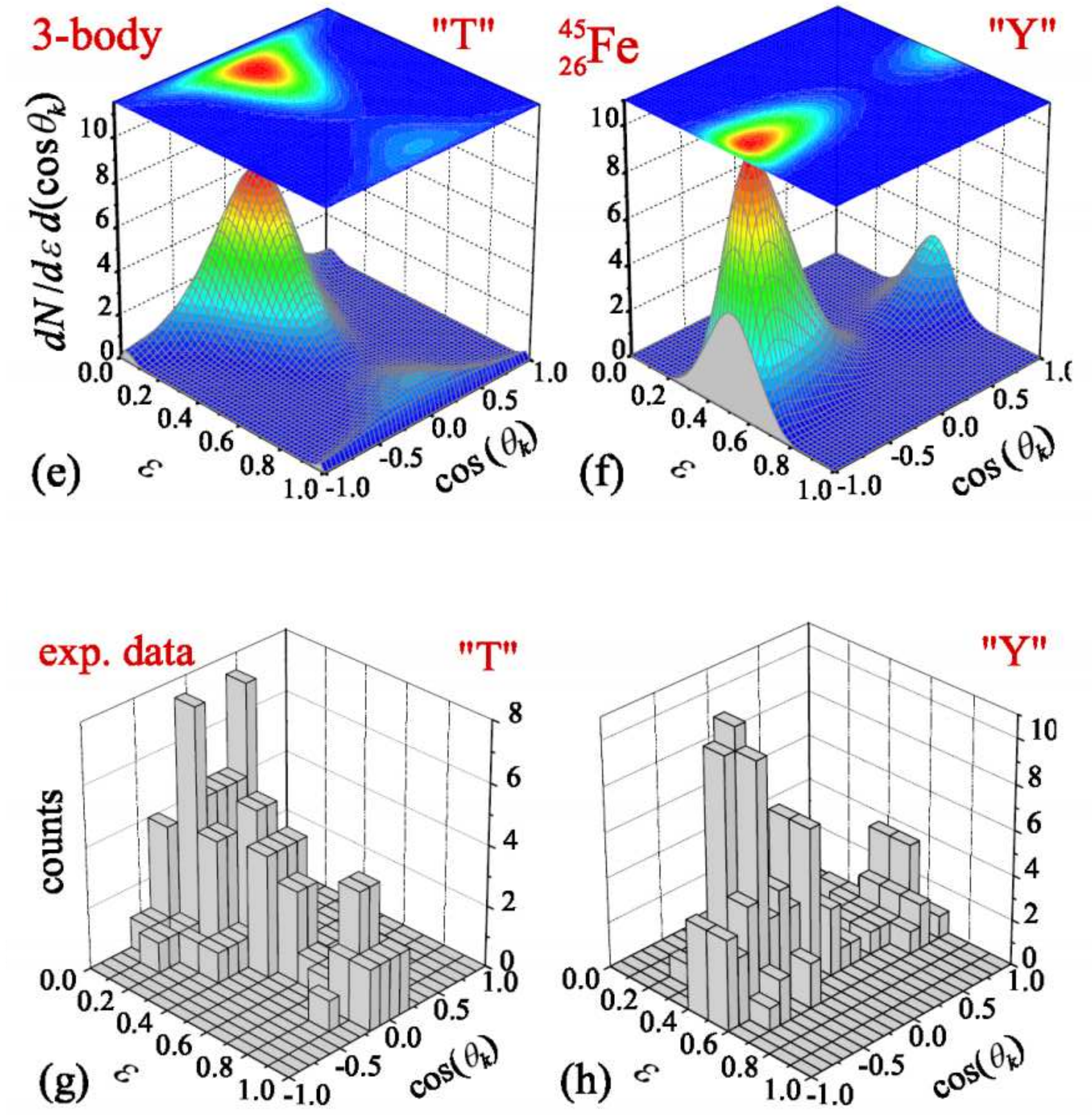
$$\Gamma_{2p} = 1.3^{+0.22}_{-0.16} \times 10^{-19} \quad \text{MeV} \quad T_{1/2}(2p) = 3.5(5) \quad \text{ms}$$

- Complete kinematics reconstructed
- Both lifetime and correlations provide $W(p^2) \sim 30\%$

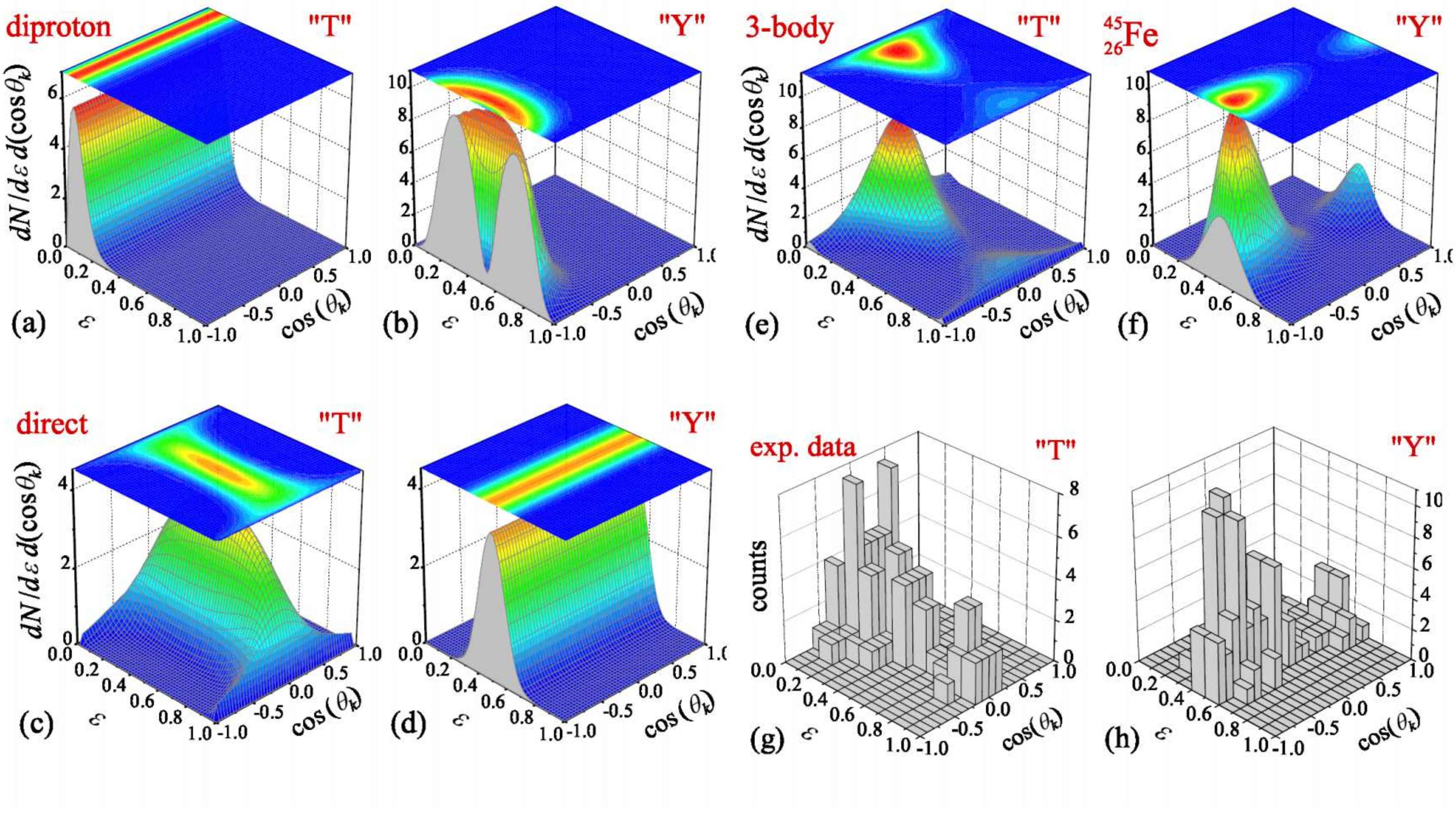


Three-body correlations in 2p decay of ^{45}Fe





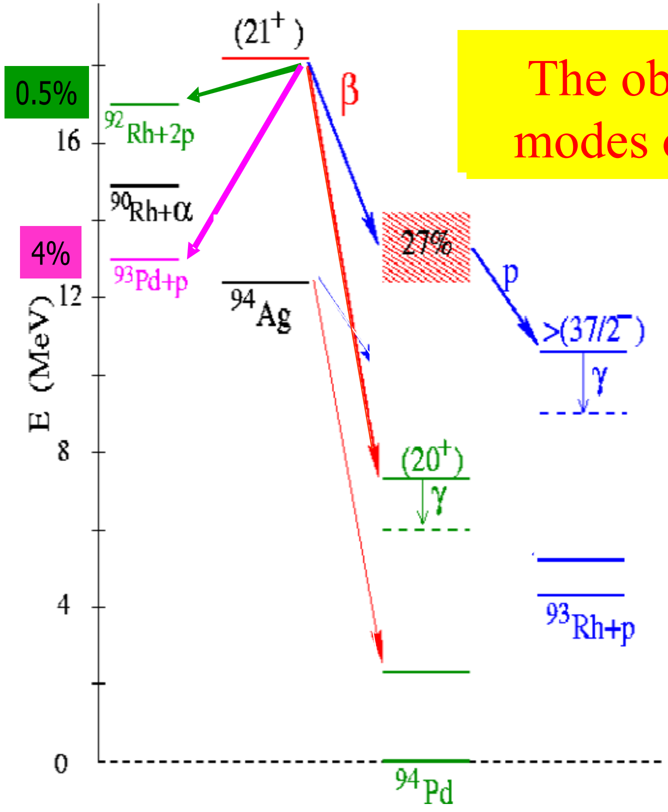
Three-body correlations in 2p decay of ^{45}Fe



The unique observed case of proton and two-proton radioactivity from the same parent state, high-spin isomer (21^+) in ^{94}Ag

Reaction of population: $^{40}Ca(170 MeV) + {}^{58}Ni \rightarrow {}^{98}Gd^* \rightarrow$ 1p3n + $^{94}Ag^m$

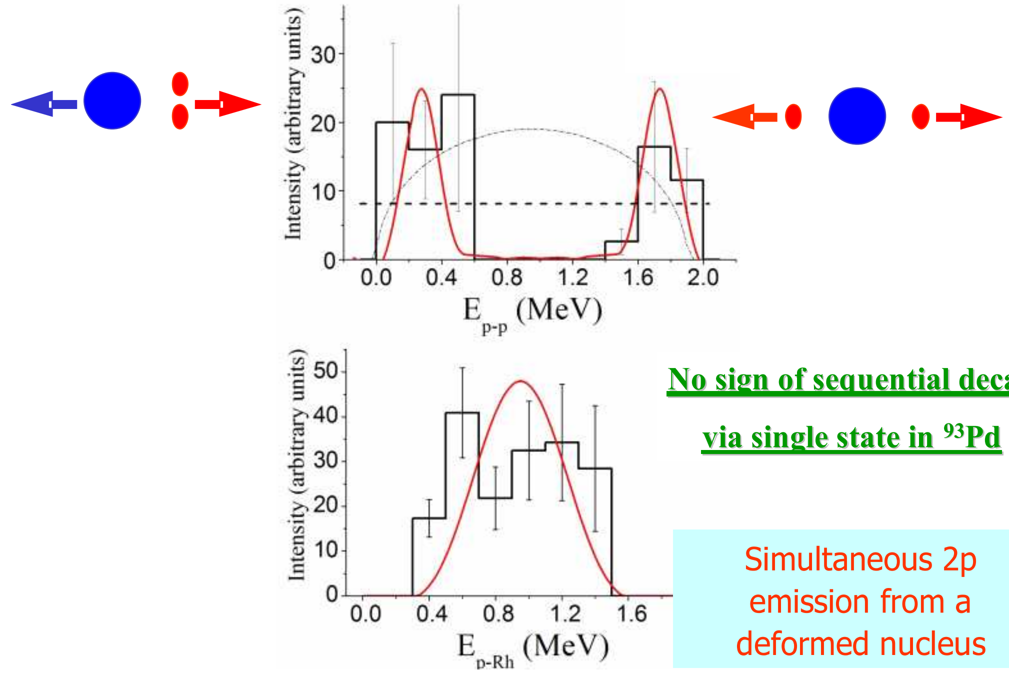
Production rate of 2 atom/s at the GSI ISOL facility



The observed decay modes of $^{94m}Ag(21^+)$

I.Mukha et al., Nature **439** (2006); I.Mukha et al., Phys.Rev.Lett. **95** (2005); I.Mukha et al., Phys.Rev. C**70** (2004); C.Plettner et al., Nucl.Phys. A **733** (2004).

Exclusive data: proton-proton correlations

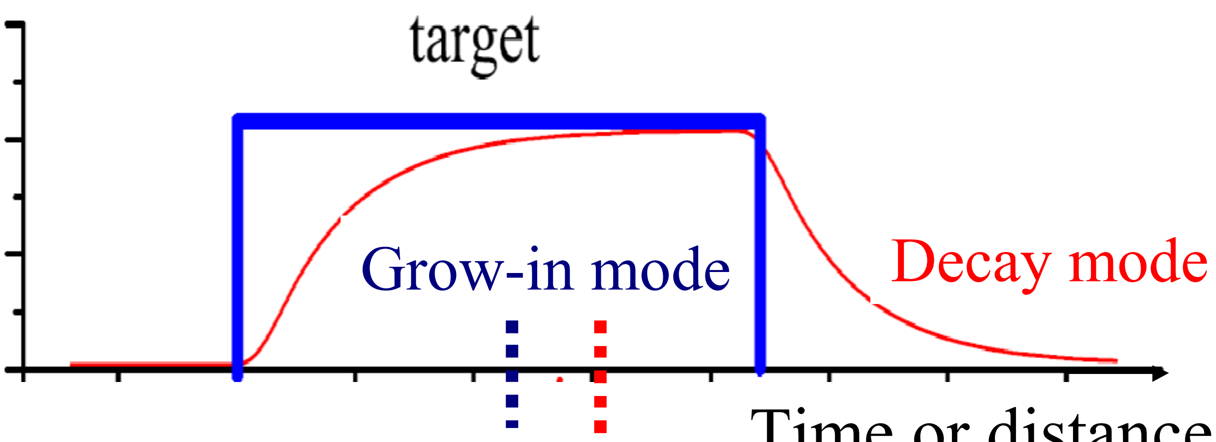


No sign of sequential decay via single state in ^{93}Pd

Simultaneous 2p emission from a deformed nucleus

Future experiments with a laser ion source can be performed *e.g.* at IGISOL-JYFL, the experiment I120 (*I. Mukha, I.Moor et al.*)

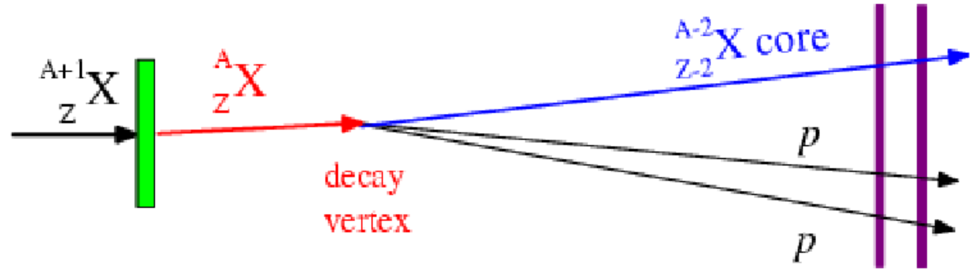
Standard radioactivity experiment:
a time dependence



Decays in flight: spacial distribution of decay vertexes along a beam direction

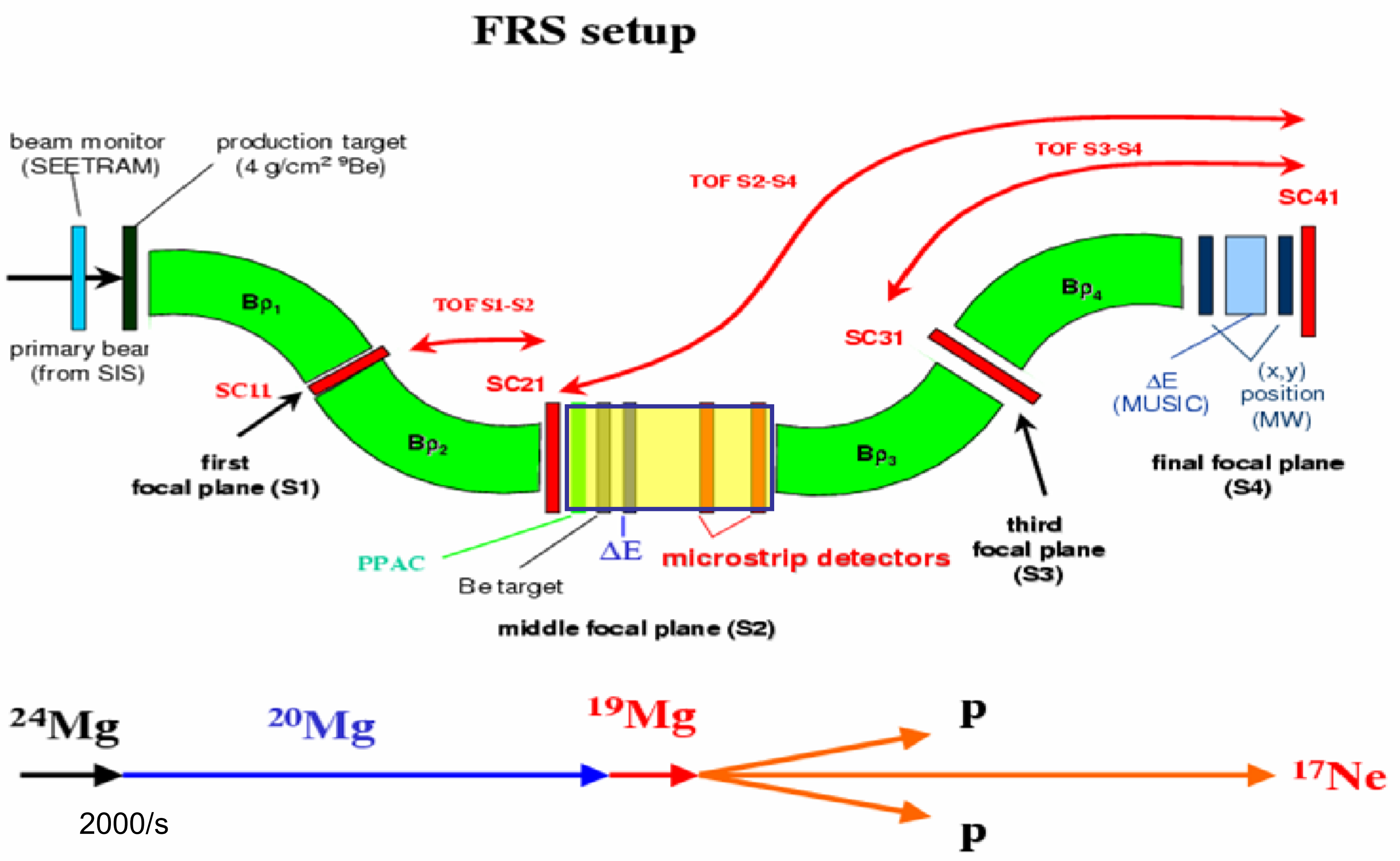
Idea of experiment

Schematic layout

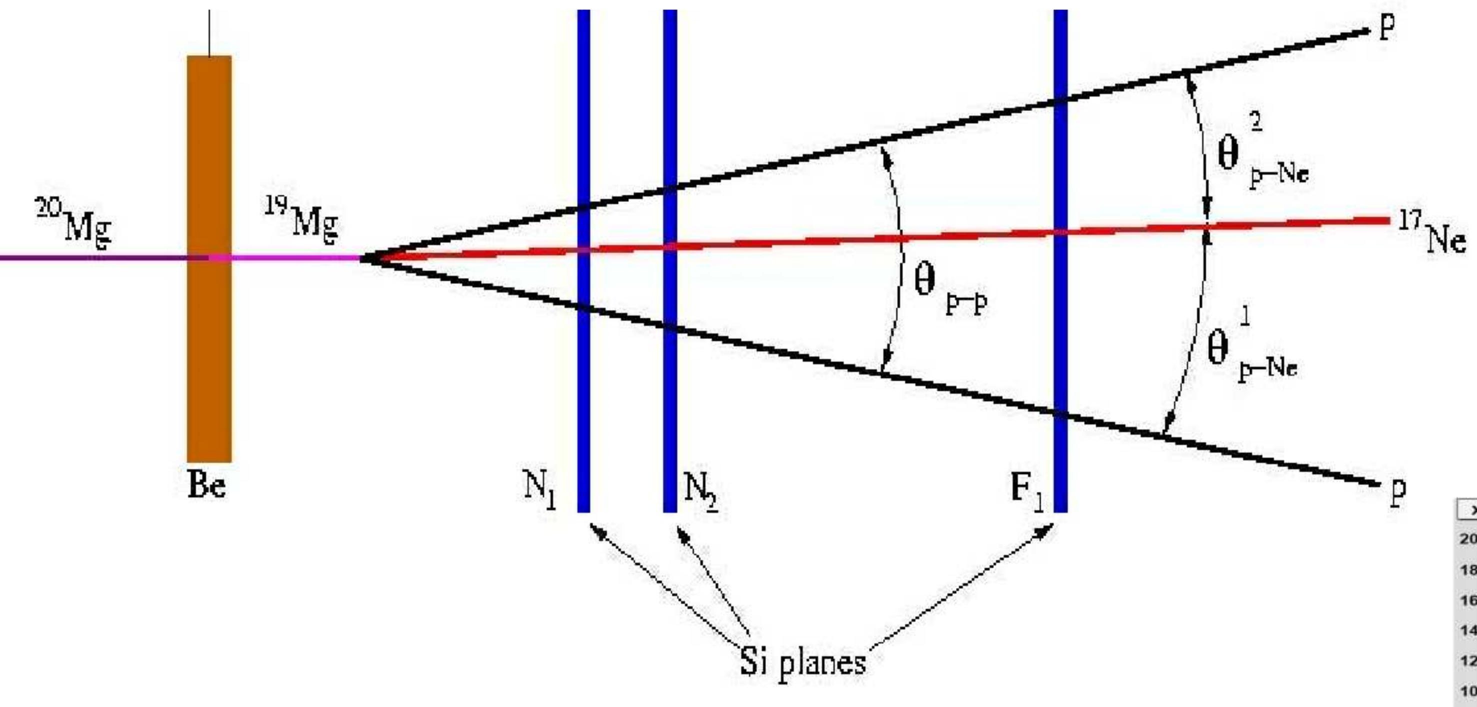


Two-proton events:

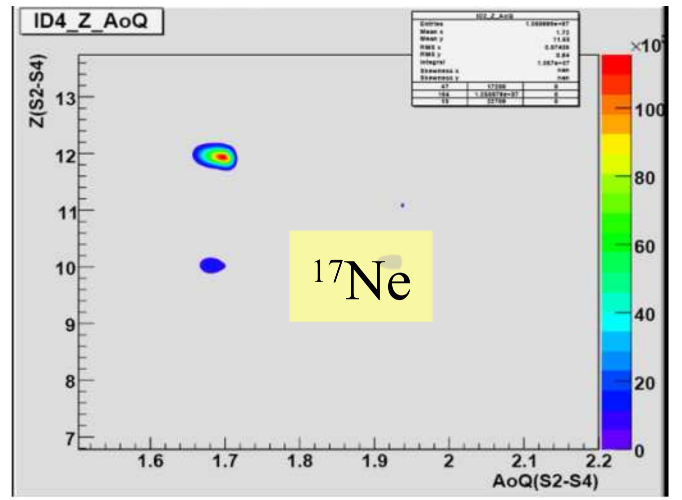
The 2p-decay of ^{19}Mg, the experiment at GSI

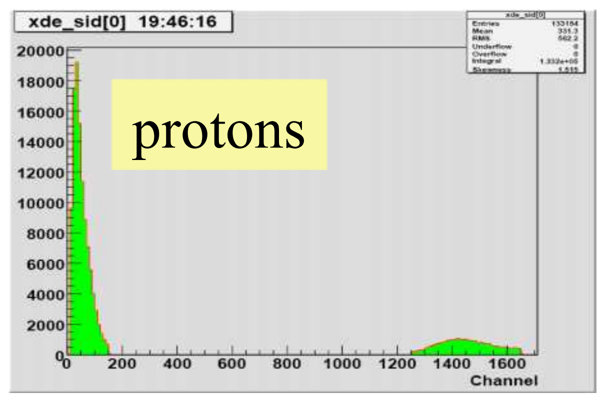


Close-up view



Identification of fragments

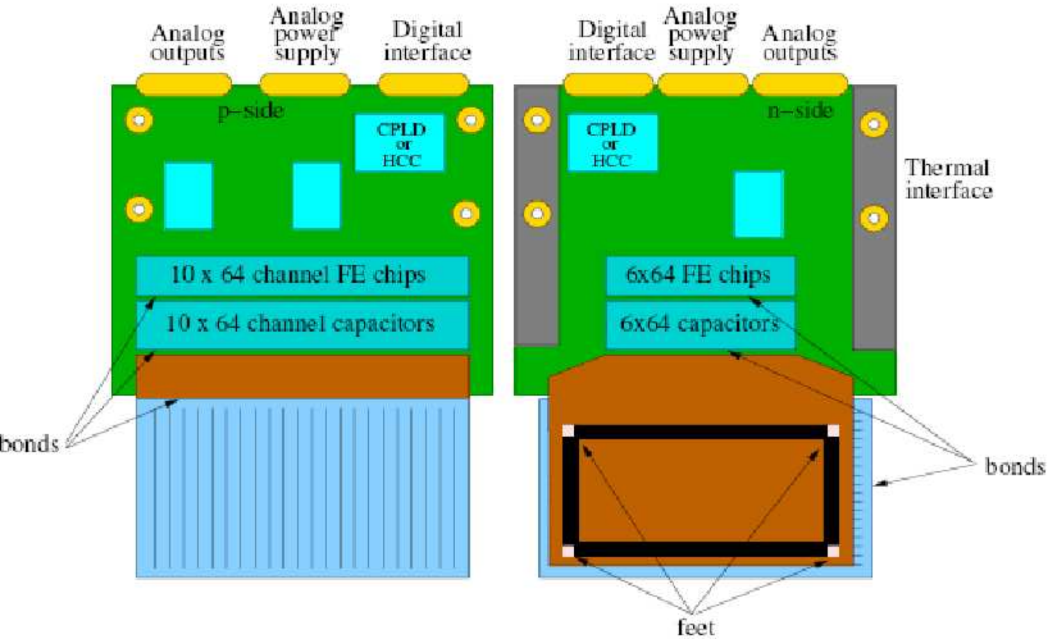


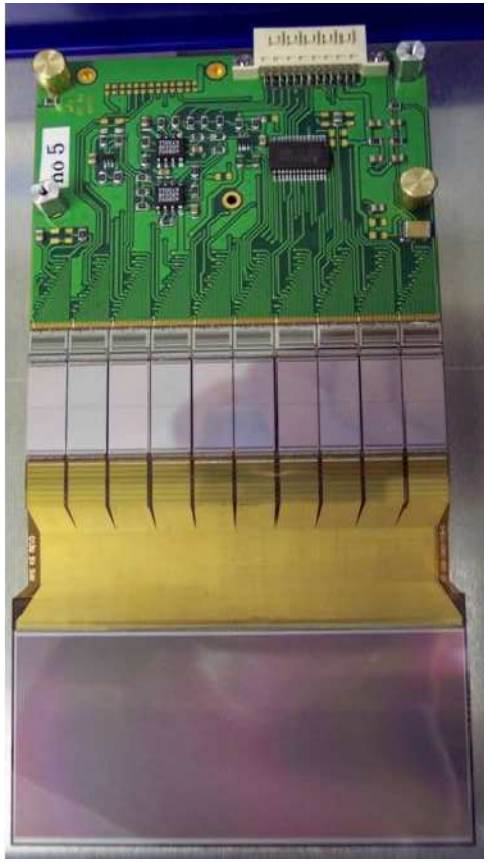


Reaction $^{20}Mg \longrightarrow {}^{19}Mg \longrightarrow {}^{17}Ne+p+p$

Fragmentation $^{20}Mg \longrightarrow {}^{17}Ne+p+p+n$

The micro-strip detectors used for tracking





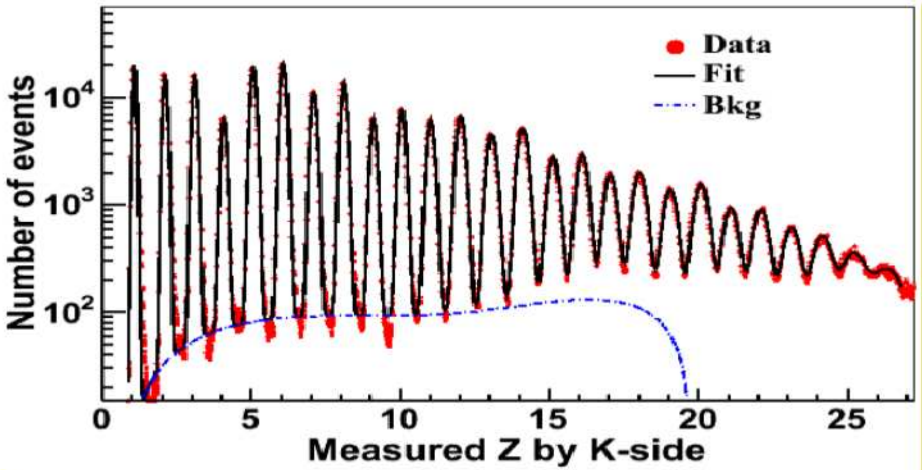
Front-end electronics:
VA64 hdr9 chips from IDE AS.
Serial read-out, digitalization, pedestal and common-noise subtraction made by the GSI electronics modules.

Dimensions 70x40 mm^2, 100m strip pitch,

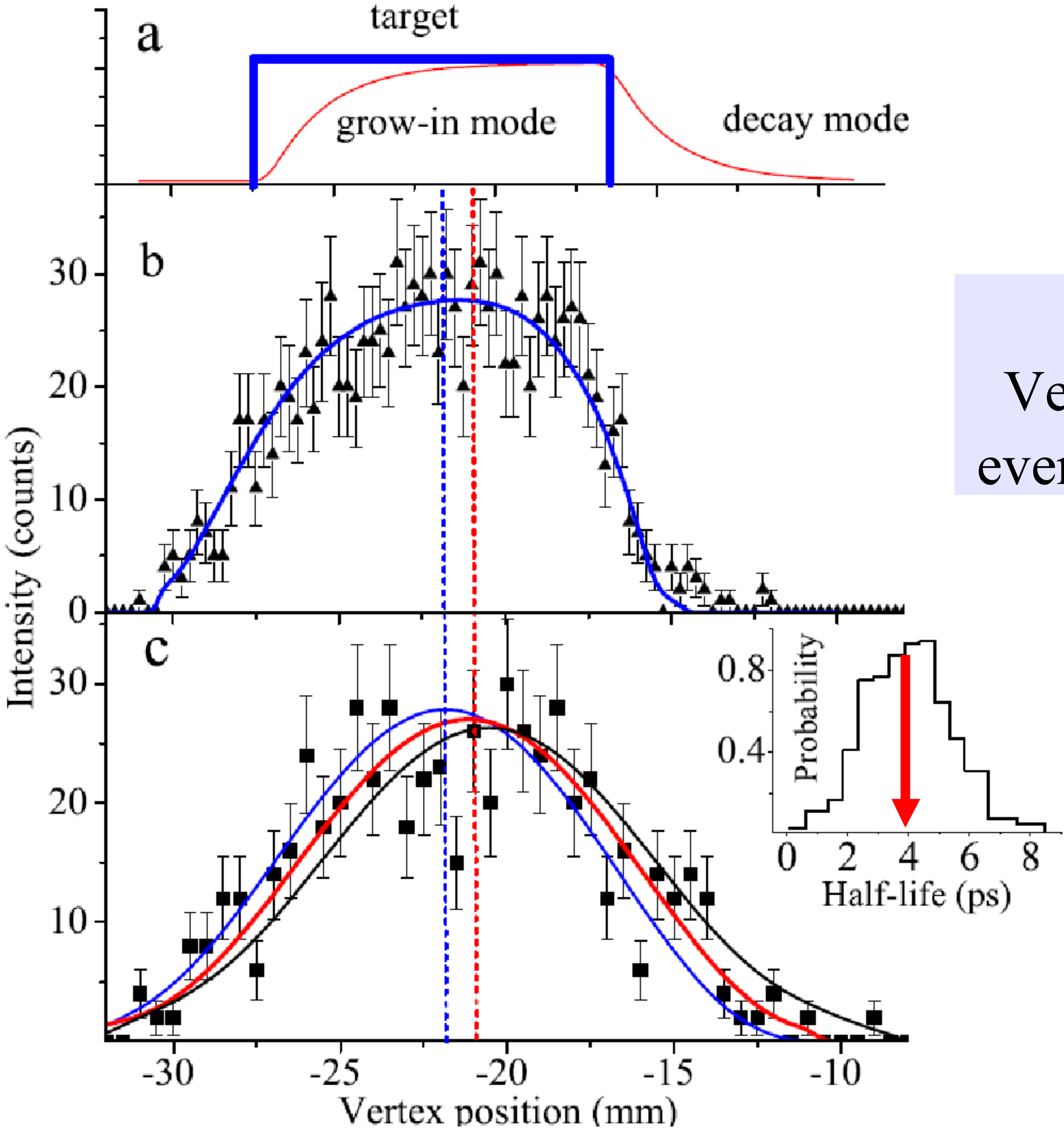
in total 1000 channels

http://dpnc.unige.ch/ams/GSItracker/www/

Elements resolved by the AMS02 tracker, GSI data 2003



Vertex distributions of ^{19}Mg 2p-decays



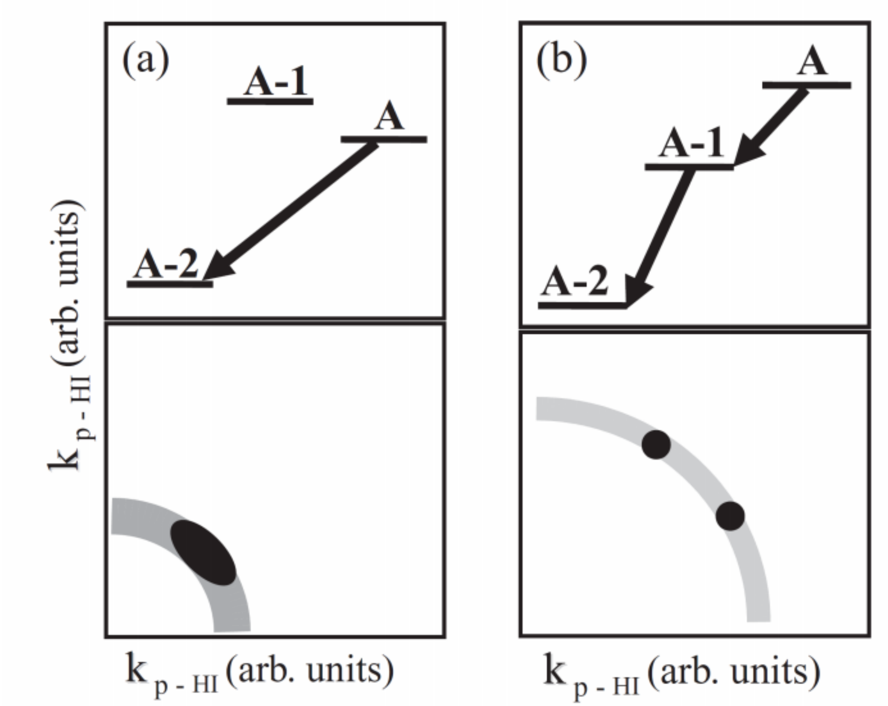
Reference measurement:
Vertex distribution of $^{17}Ne+p+p$ events from short-lived resonances

Half-life value of $^{19}Mg_{g.s.}$

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

How to identify a reaction channel ?

In 2p decays, momentum correlations of fragments are similar to their angular correlations

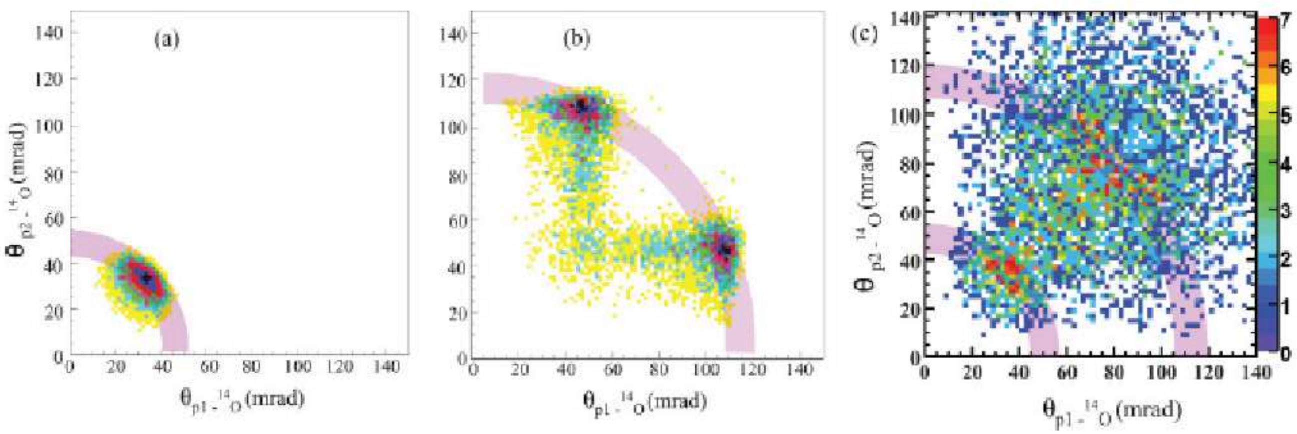


(a) - direct 2p emission,

a three-body decay mechanism

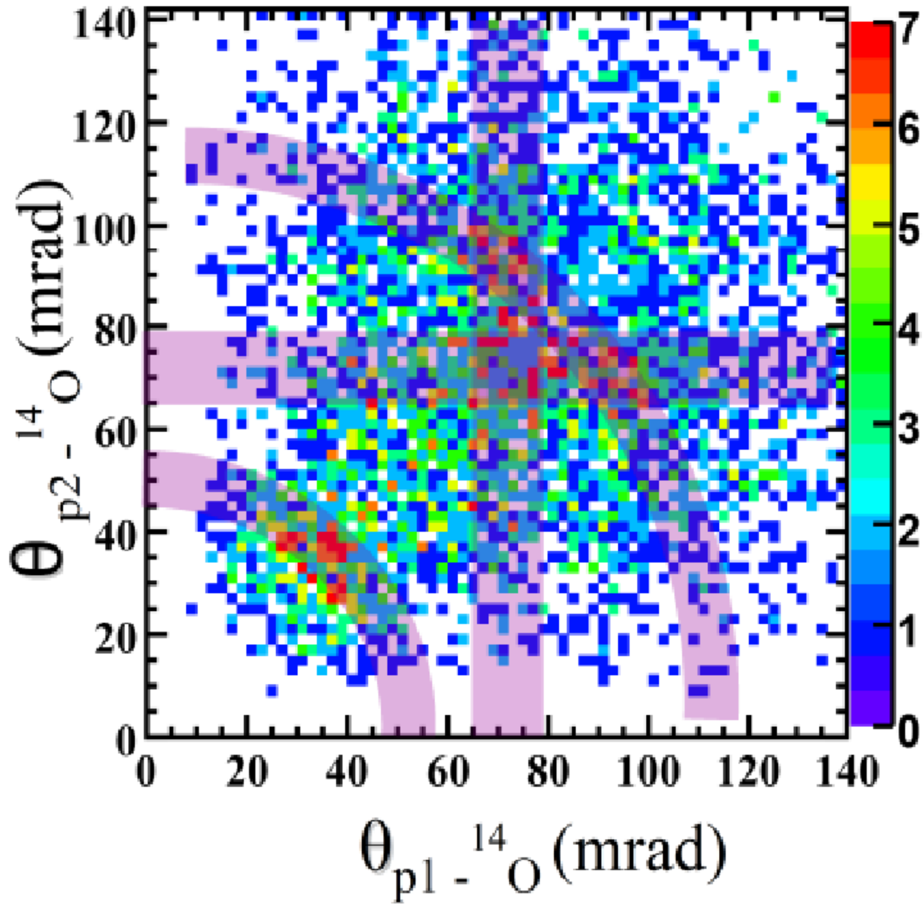
(b) - sequential 2p emission

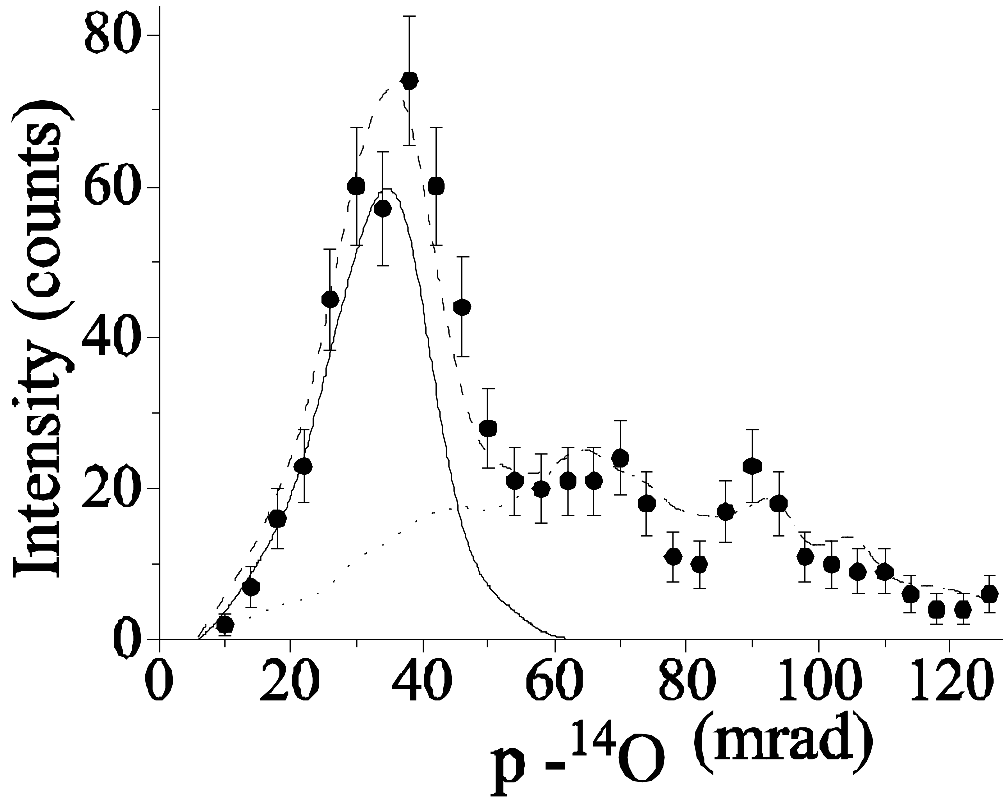
via an intermediate 1p resonance



The reference measurements of the known 2p-decay of ^{16}Ne

Angular correlations from $^{17}Ne \rightarrow ^{16}Ne \rightarrow ^{14}O+p+p$ events

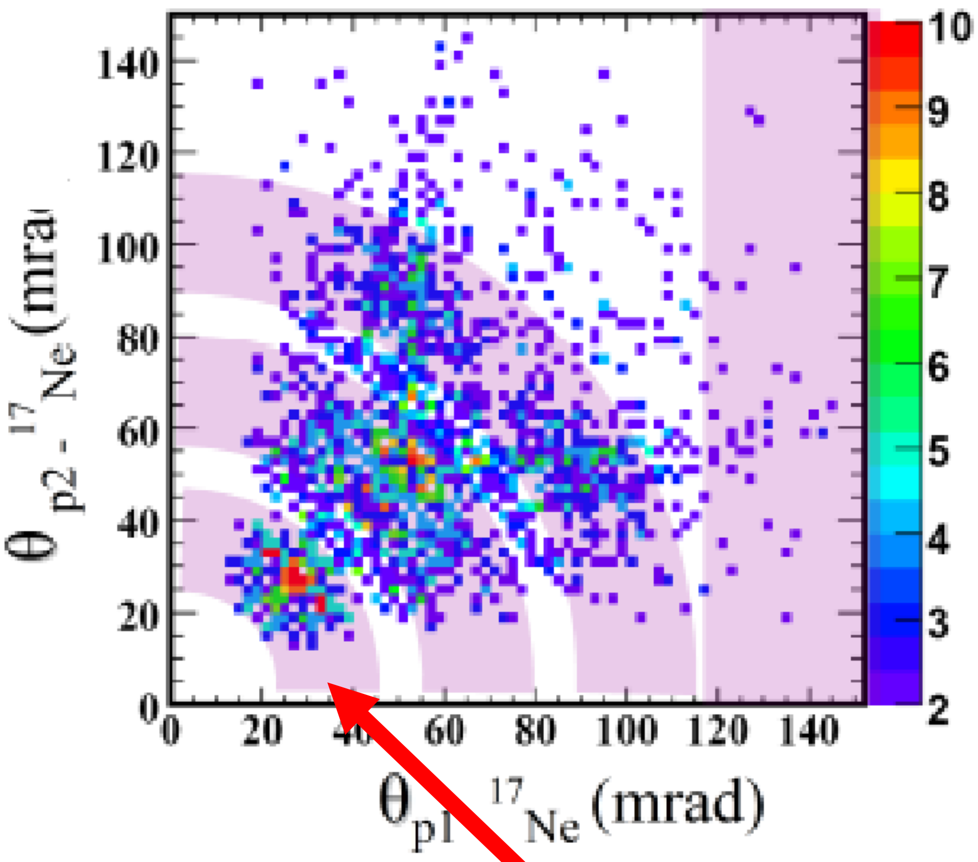


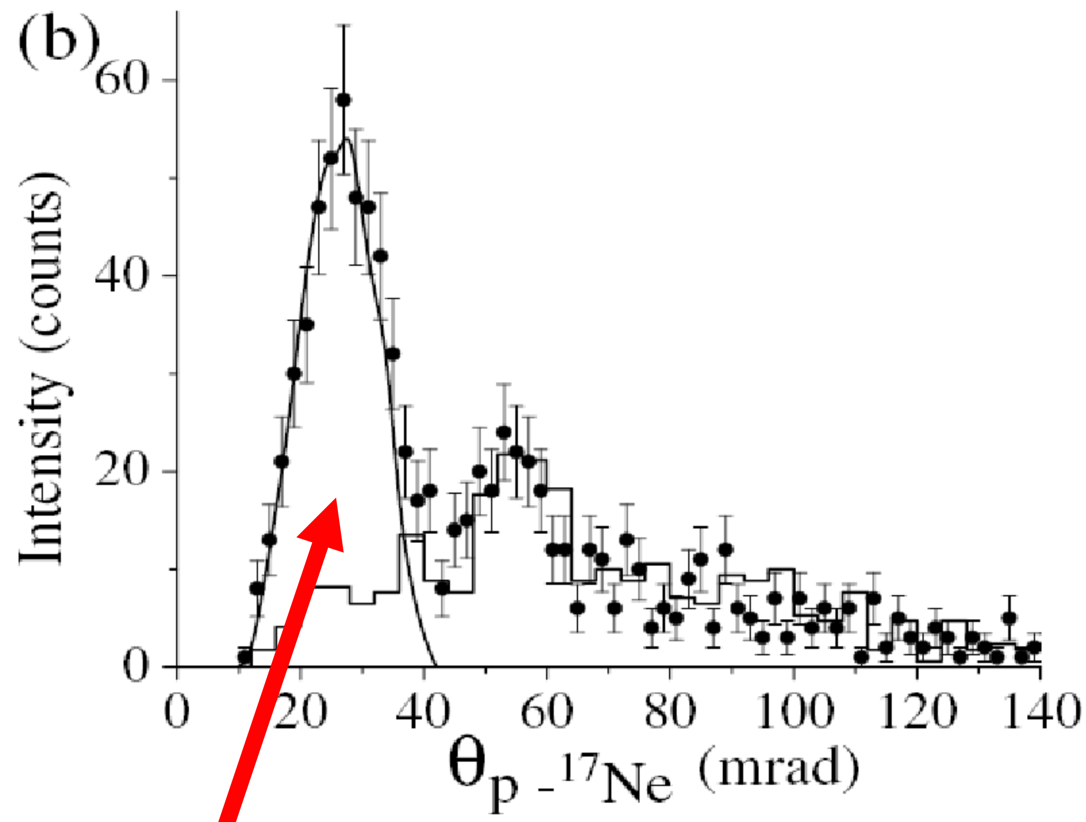


The known Q_{2p}=1.40(10) MeV

The measured Q_{2p}=1.35(8) MeV

States of ^{19}Mg observed in ^{17}Ne+p+p correlations

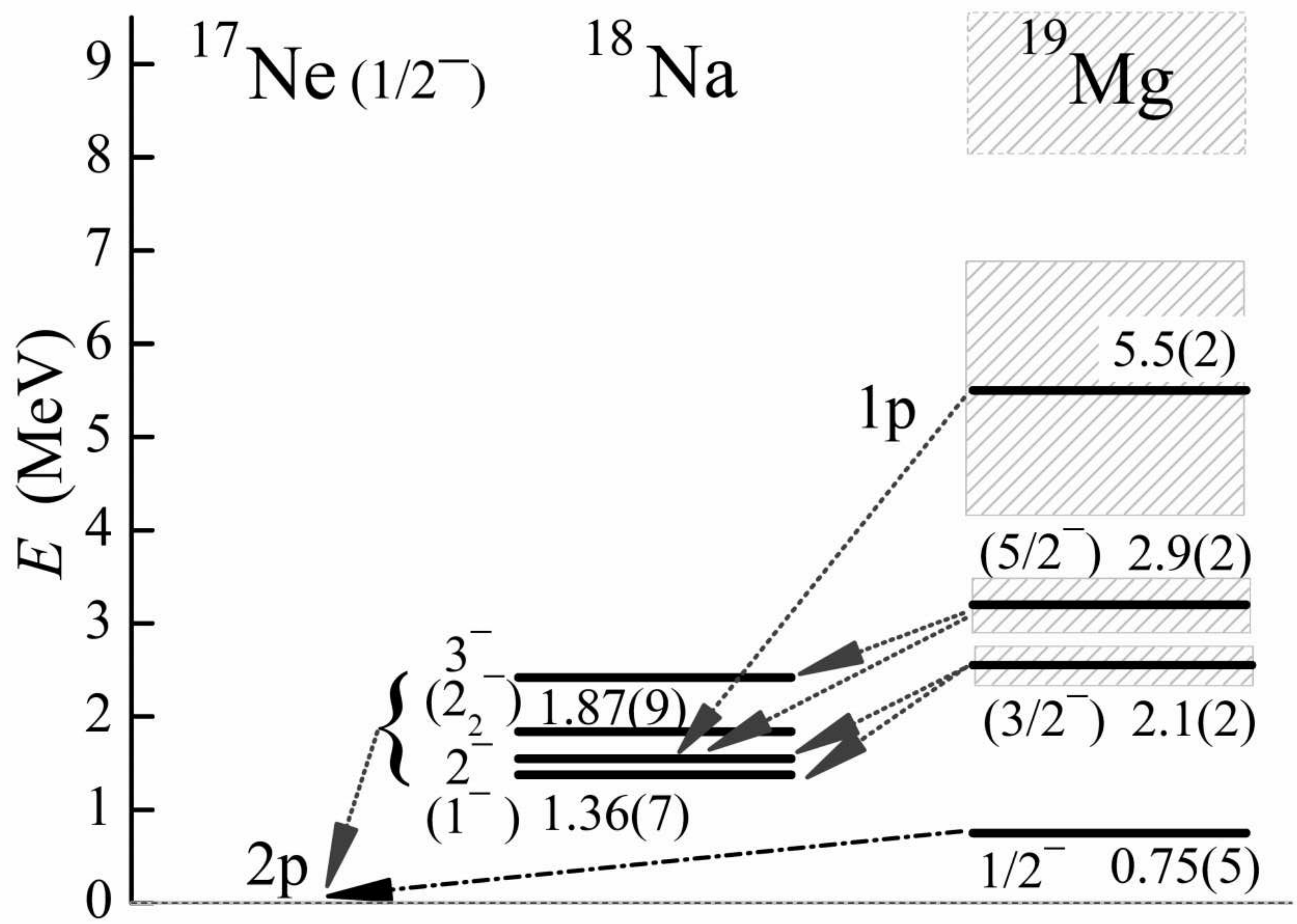




Direct 2p decay of g.s.

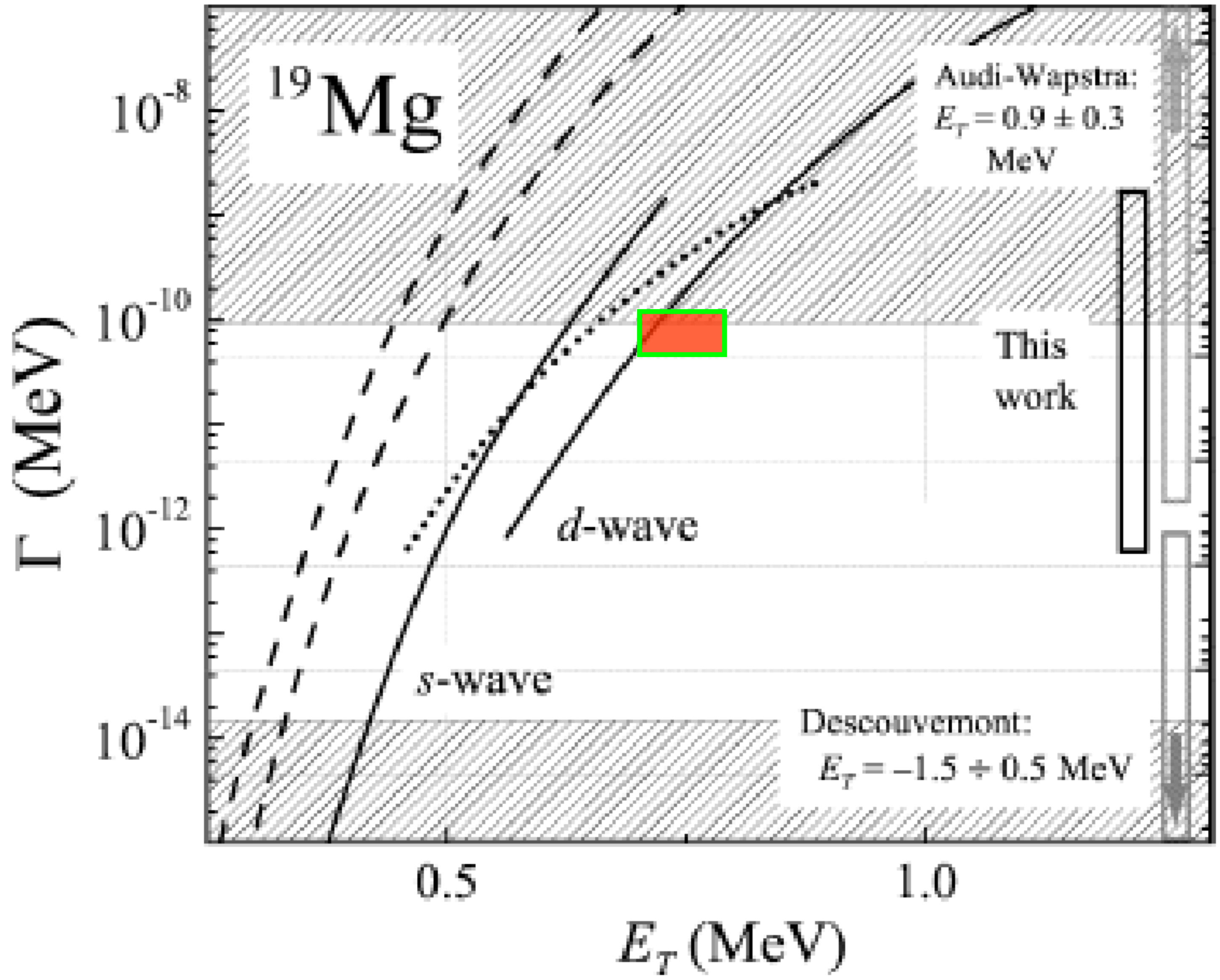
with Q_{2p}=0.75(5) MeV

Scheme of the unknown ^{19}Mg levels



I.Mukha et al., *Phys. Rev. Lett.* ***99***, *182501 (2009); Phys.Rev. C, to be submitted.*

Comparison of the data with the theoretical predictions:



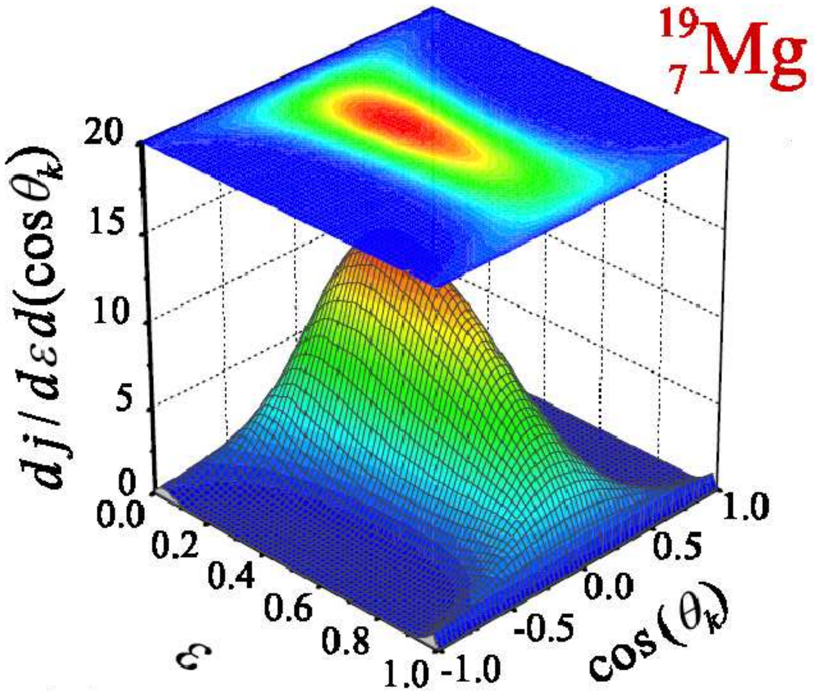
Theory predictions:

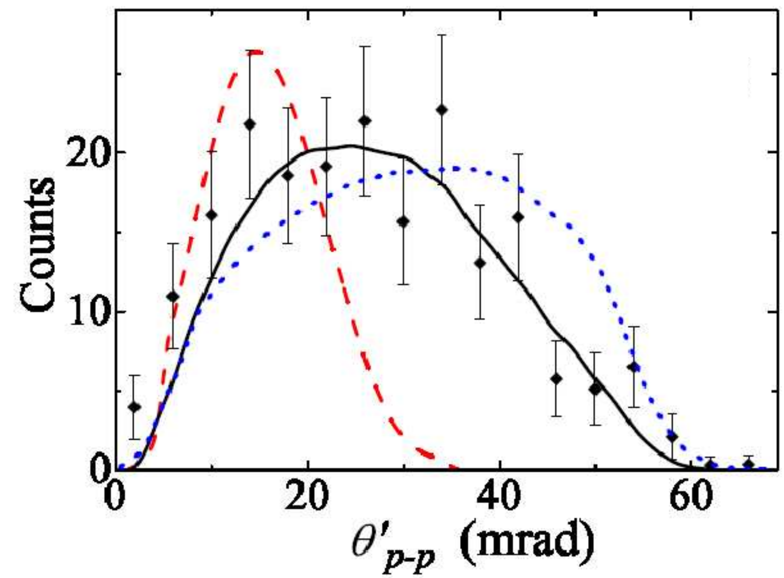
L.V.Grigorenko, I.G.Mukha, M.V.Zhukov, Nucl.Phys. **A** 713 (2003)

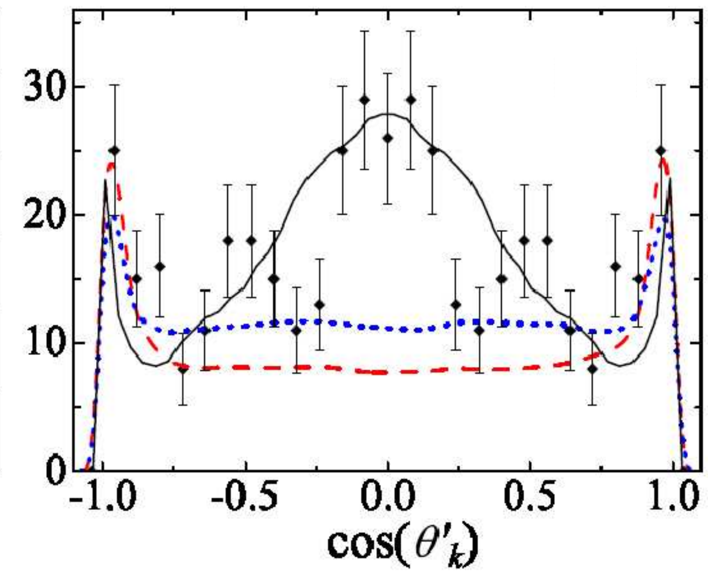
Experiment:

I.Mukha et al., PRL **99**, 182501 (2007)

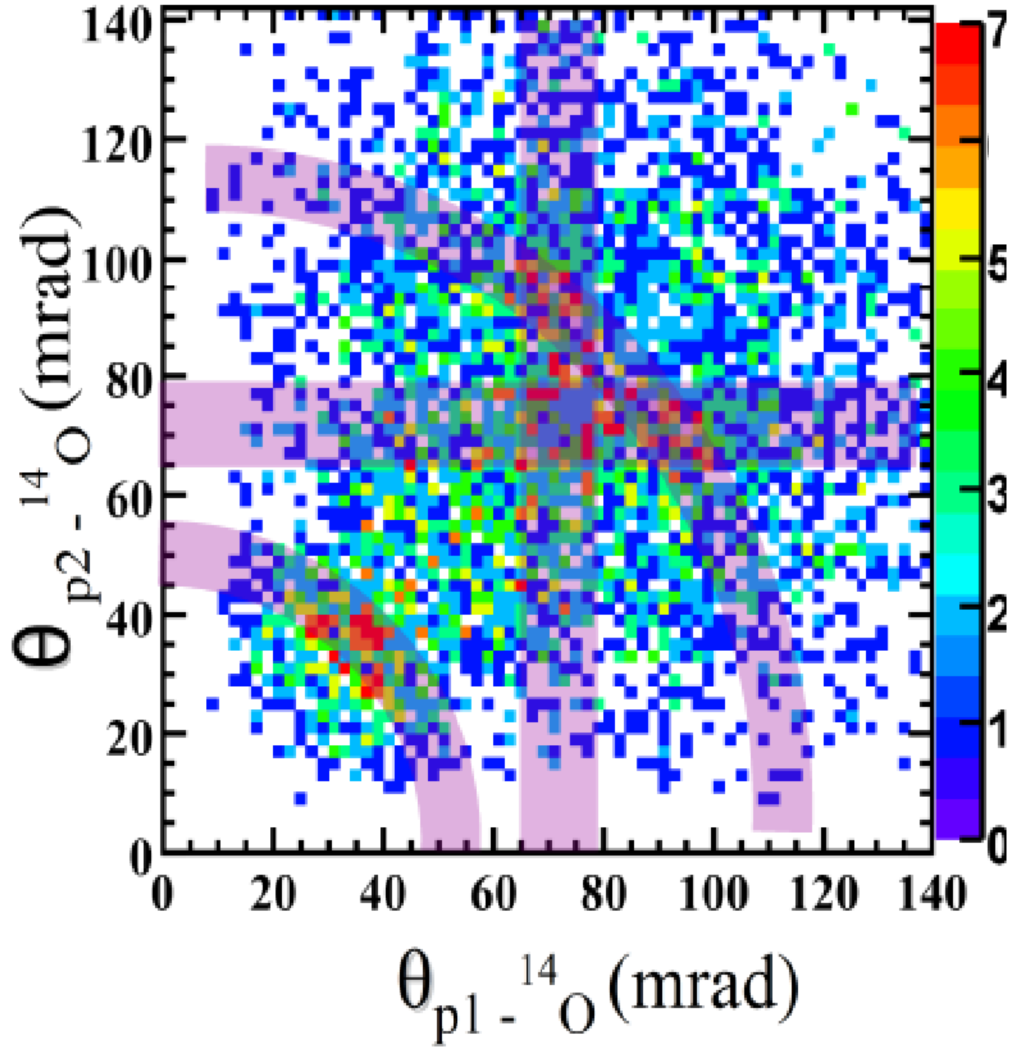
Three-body correlations in 2p decay of ^{19}Mg

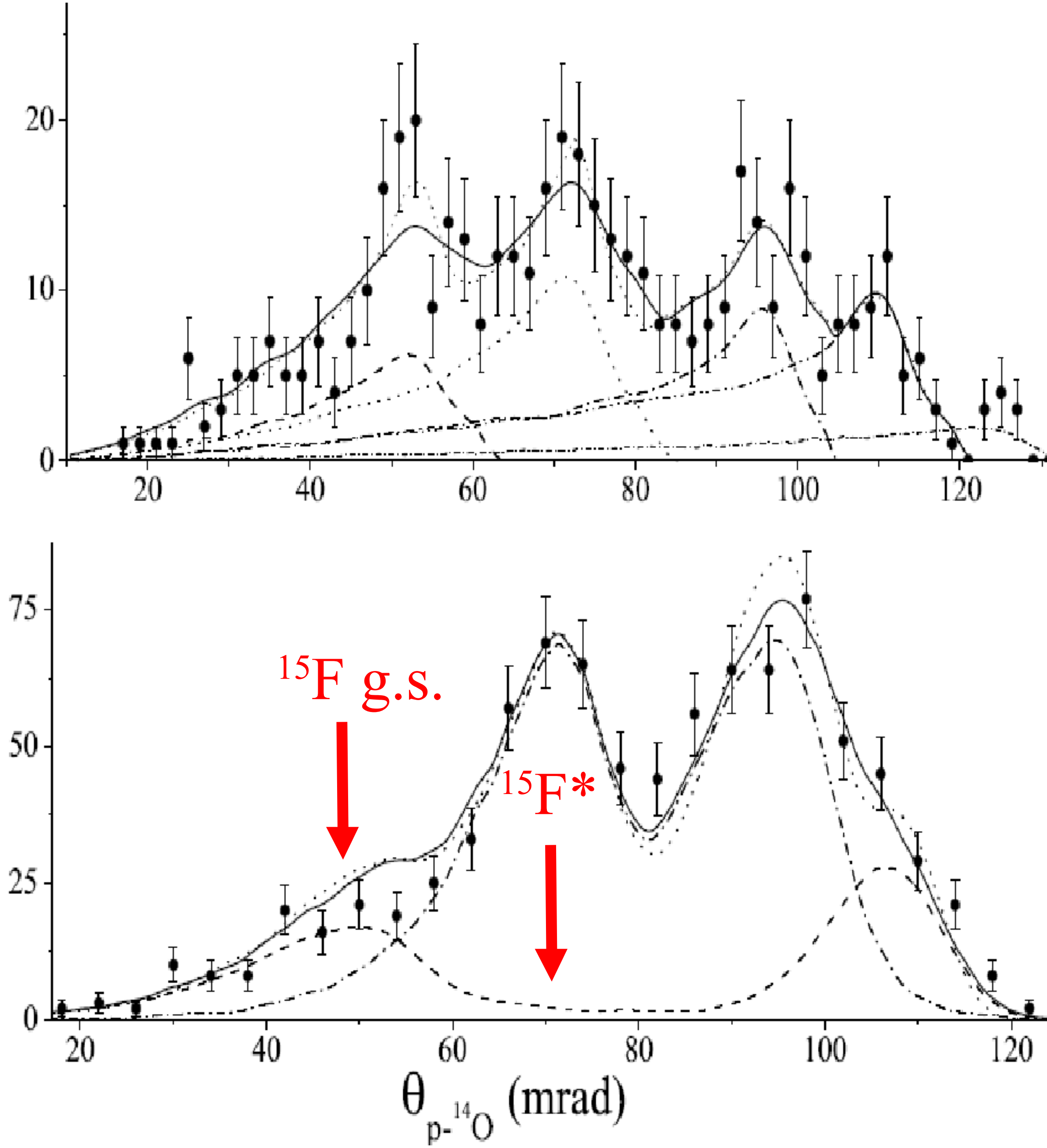




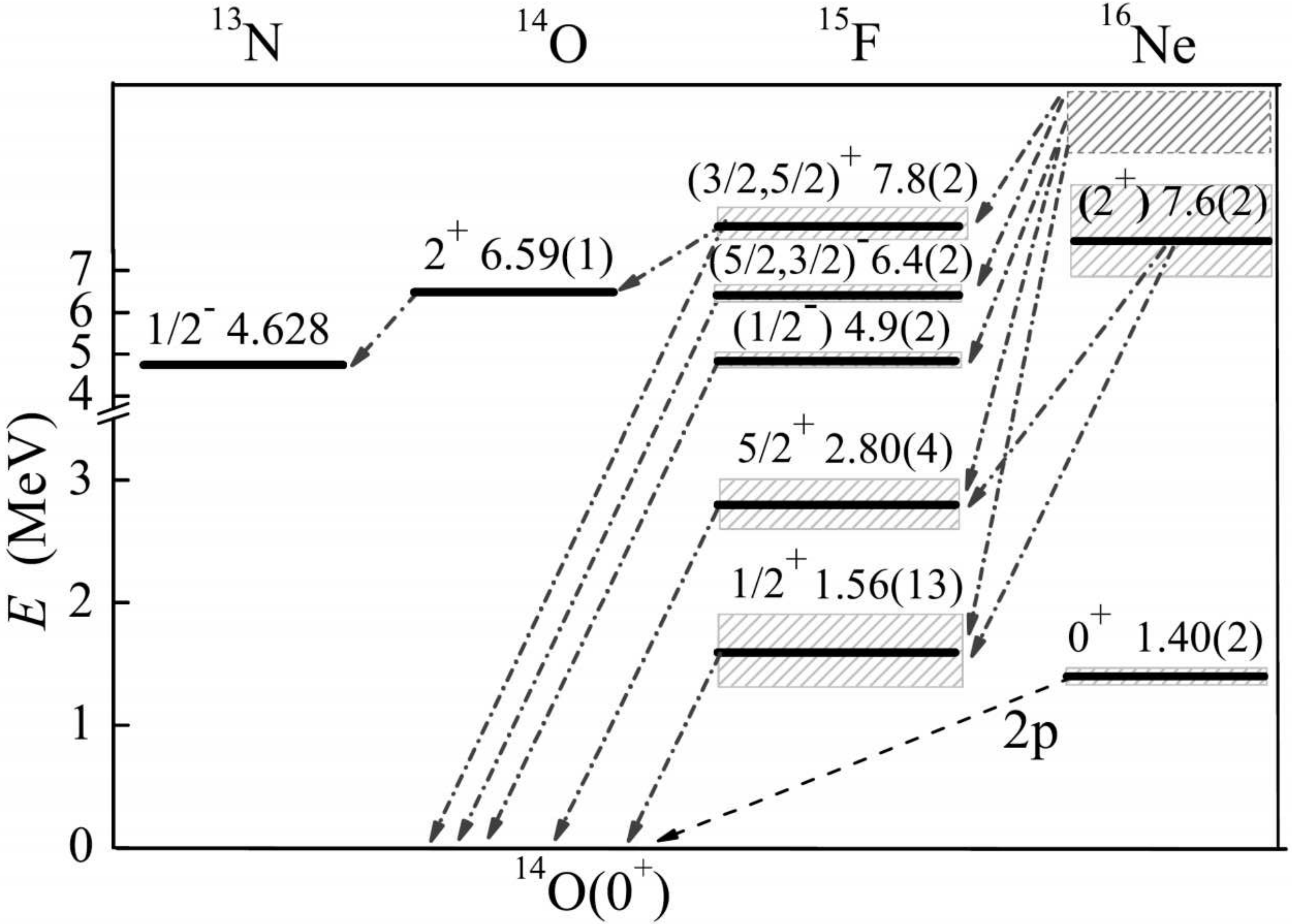


States in ^{15}F observed in $^{16}Ne^*$–> ^{14}O+p+p decays





Level scheme of ^{16}Ne and its decay daughters

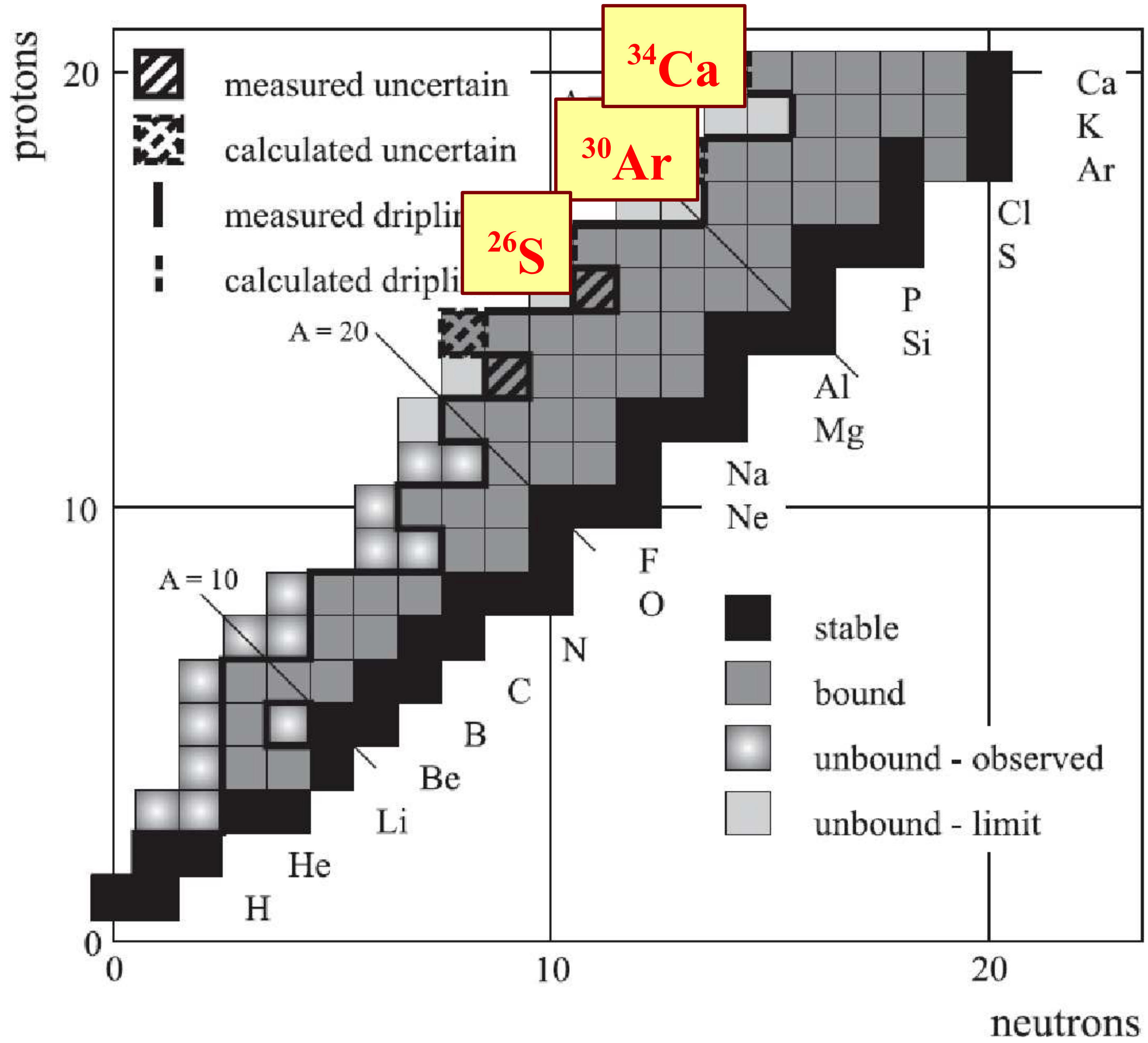


I.Mukha et al., *Phys. Rev. C79 (Rapid Comm.), 0613301 (2009)*

Powerful technique for proton-unbound nuclei study

- Thick (g/cm^2) targets and large-acceptance beams
  - High precision of the measured decay energy
    - Total energy of protons is not required
      - Three-body angular correlations

Two-proton radioactivity candidates: ^{26}S, ^{30}Ar, ^{34}Ca



Future studies of 2p-radioactivity

Invariant-mass experiments:

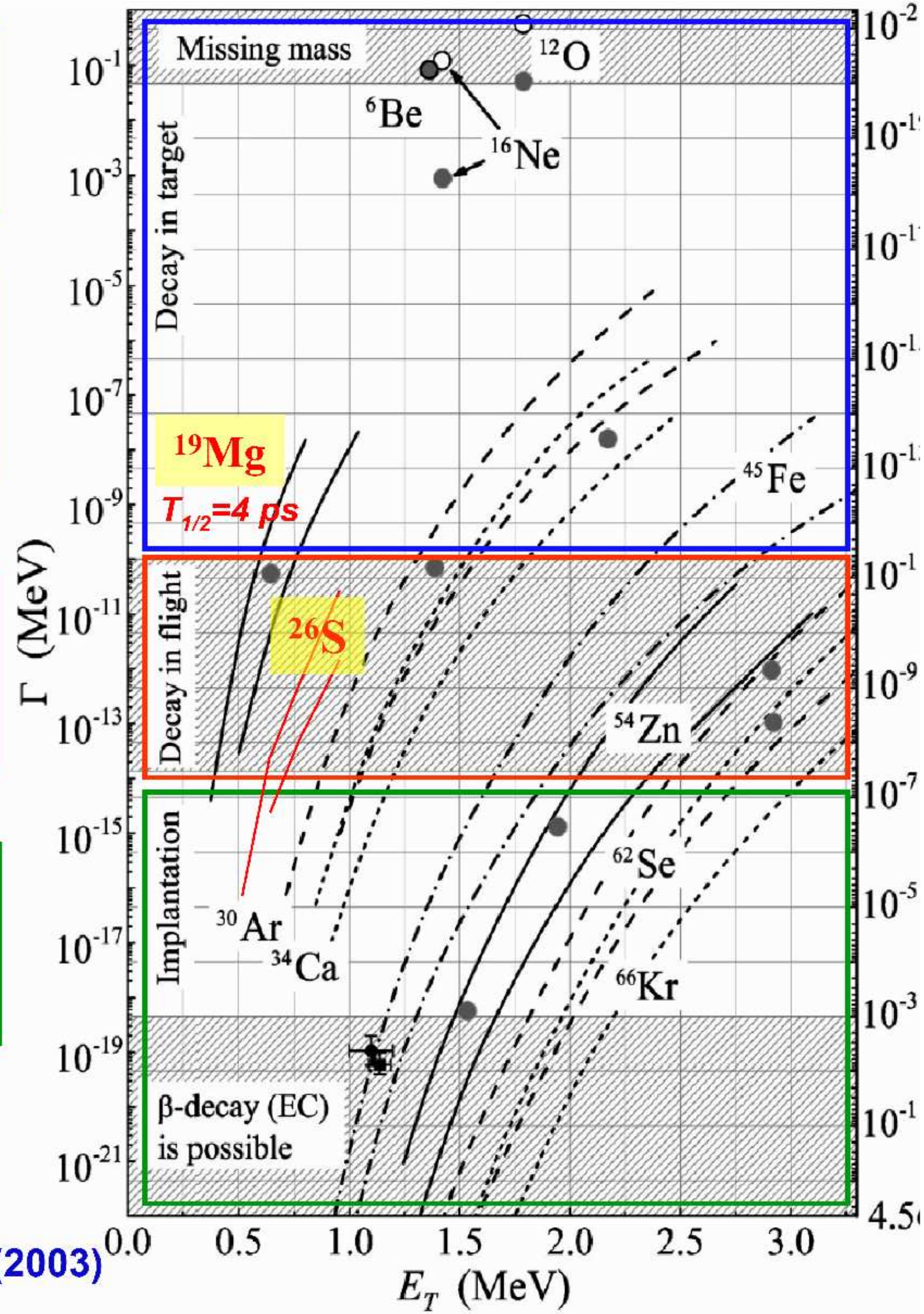
^{6}Be, ^{12}O, ^{16}Ne, ^{34}Ca

In-flight decay candidates:

^{26}S, ^{30}Ar, ^{34}Ca, ^{58}Ge, ^{68}Se, ^{66}Kr

Implantation experiments:

^{45}Fe, ^{48}Ni, ^{54}Zn, ^{58}Ge, ^{62}Se, ^{66}Kr

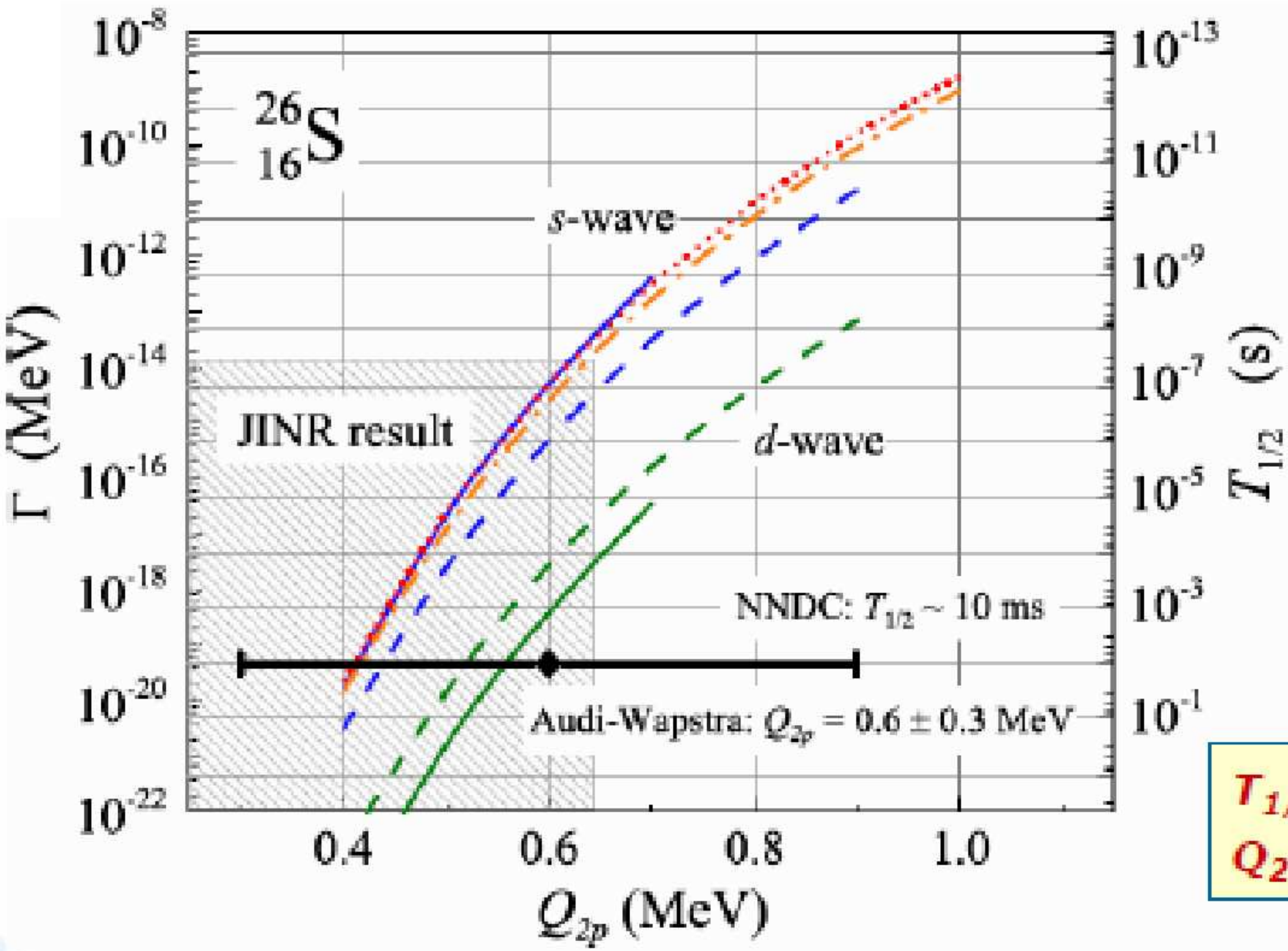


I.G. Mukha, *et al*, PRL 99, 182501 (2007)

K. Miernik, *et al*, EPJ. A 42, 431 (2009)

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

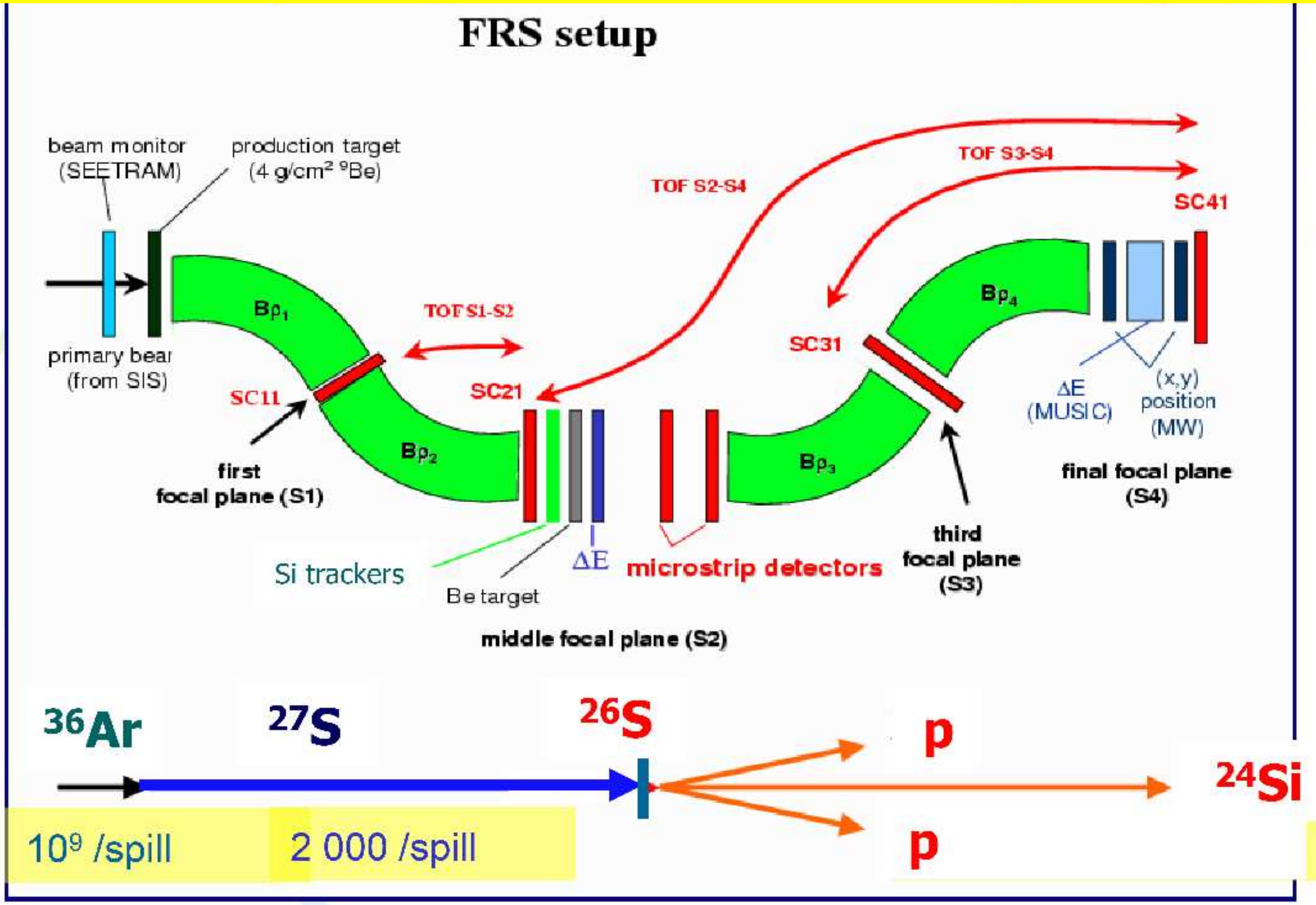
A.Fomichev et al., IJMPE, in print (2011)



$T_{1/2}$ < 79 ns
Q_{2p} > 640 keV

Width of the ^{26}S ground state as a function of the 2*p* decay energy.
Solid and dashed curves correspond to the quasiclassical simultaneous emission model and to the three-body "*1* 2" model, respectively. The RMF-assisted threebody model based on RH and on the complete RH+BCS results are shown by the dotted and by the dash-dotted curves, respectively.
{RH+BCS = Relativistic Hartree + Bardeen-Cooper-Schrieffer approximation}

Experiments S414 and S388 on ^{26}S and ^{30}Ar



- ☻ wide range for $T_{1/2}$: from 0.1 ps up to 10 ps
- ☼ correlations between two protons and core-proton
- ☼ decay mechanism and structure of ^{26}S

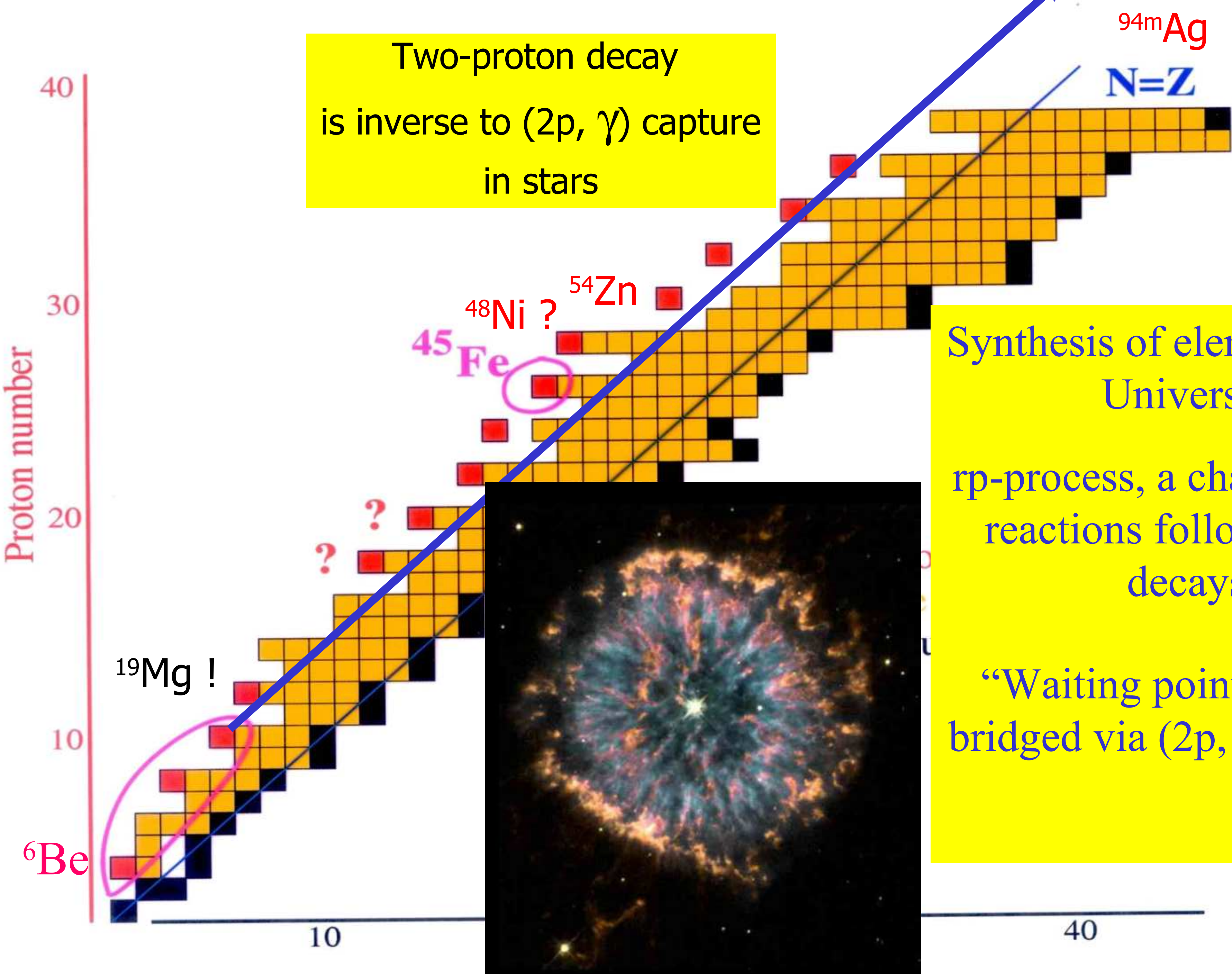
ys

Impact on nuclear astrophysics

Two-proton decay

is inverse to (2p, γ) capture

in stars

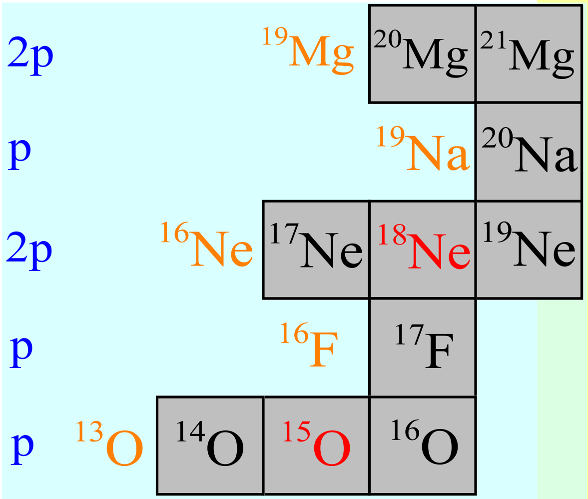


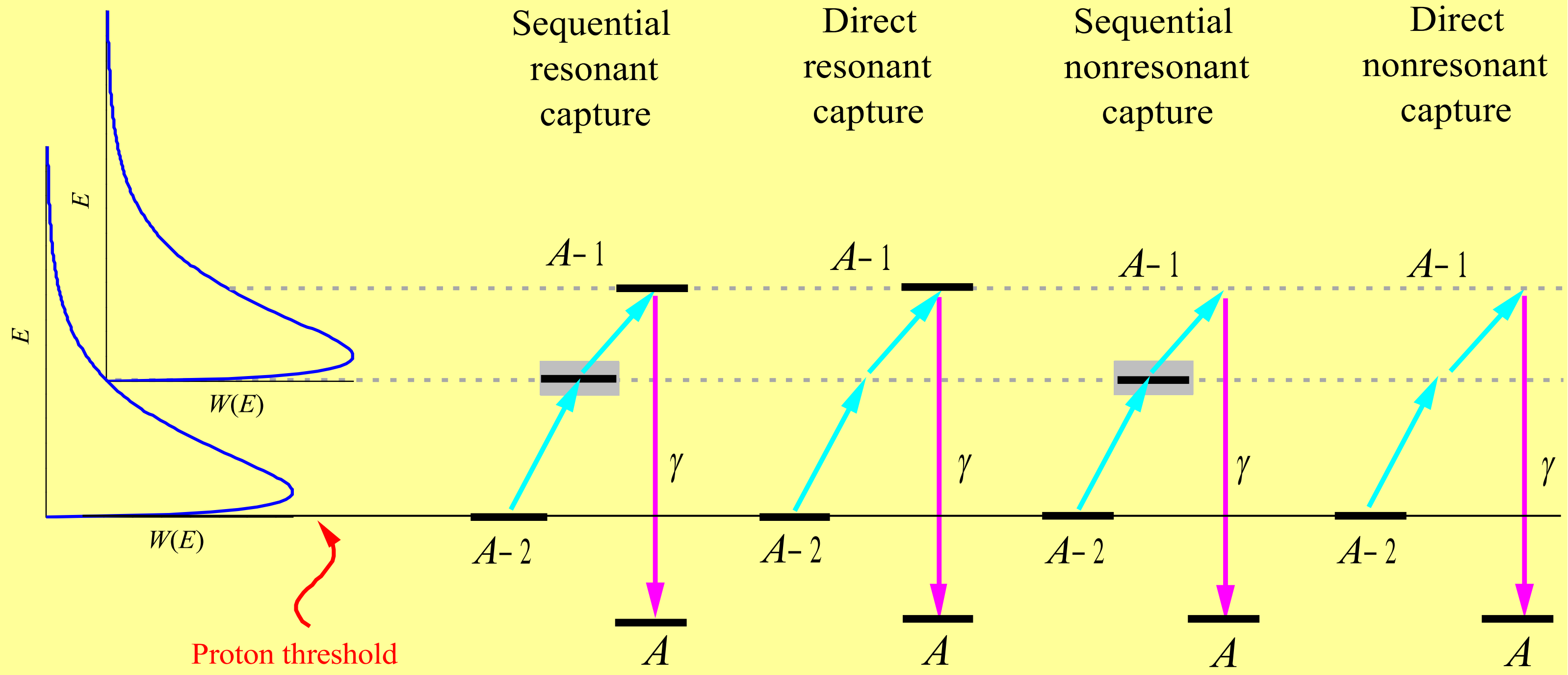
Synthesis of elements in the Universe:

rp-process, a chain of (p,γ) reactions followed by β decays.

"Waiting points" can be bridged via (2p, γ)

Nuclear astrophysics. Modes of two-proton radiative capture.

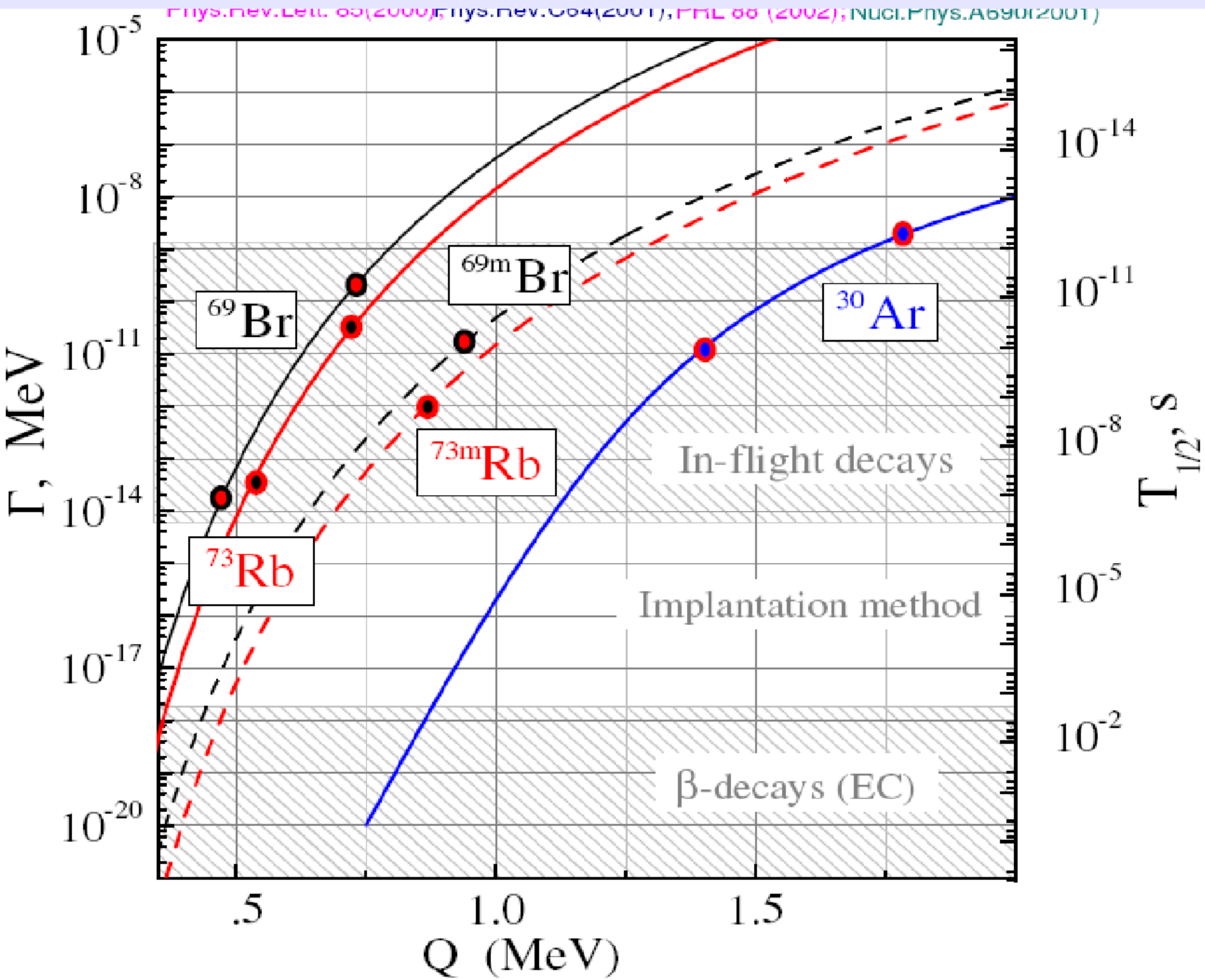




- *rp*-process at high temperature and density.
- Could be important in the regions of nuclear chart, where there are "ridges" connected with paring and intermediate system is not proton-bound. Inverse process to direct 2p emission.
- ^{15}O, ^{18}Ne, ^{38}Ca : *J.Gorres, M.Wiescher, and F.-K.Thielemann, PRC **51** (1995) 392*.
- **^{68}Se, ^{72}Kr,** … ,^{96}Cd : *H.Schatz et al., Phys. Rep. **294** (1998) 167.*

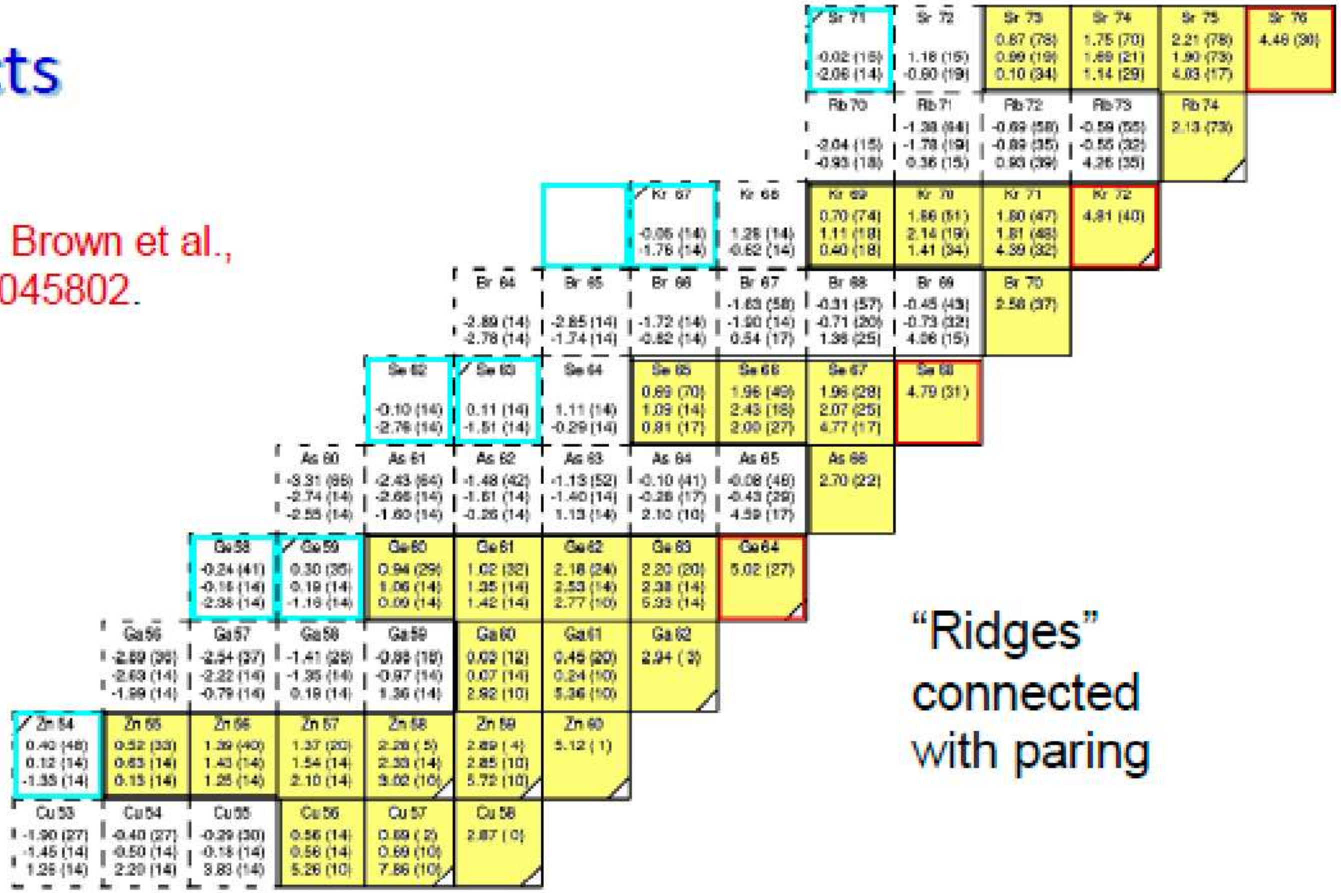
Theory developments: L. Grigorenko, K. Langanke, N. Shulgina, M. Zhukov

Predicted half-lives of ^{69}Br, ^{73}Rb, ^{30}Ar



Prospects

Illustration: B.A. Brown et al., PRC 65 (2002) 045802.



“Ridges” connected with paring

- Lifetimes: ^{64}Ge $T_{1/2}$ = 63.7 s, ^{68}Se $T_{1/2}$ = 35.5 s, ^{72}Kr $T_{1/2}$ = 17.2 s, ^{76}Sr $T_{1/2}$ = 8.9 s
- Lifetimes of the nearby drip line nuclei are typically tens of milliseconds
- To calculate astrophysical capture rates leading to nuclei in the “ridges” at high temperatures we need to know at least the 2p and gamma width of the excited states
- For temperatures below 0.1-1 GK the nonresonant calculations may become important

Medium-range future. The FAIR project in Darmstadt, Germany

FAIR Countries	Total declared Contribution
Austria	5.000
China	12.000
Finland	5.000
France	27.000
Germany	705.000
Great Britain	8.000
Greece	4.000
India	36.000
Italy	42.000
Poland	23.740
Romania	11.870
Russia	178.050
Slovenia	12.000
Slovakia	6.000
Spain	19.000
Sweden	10.000
Total	1.104.660
Firm Commitments	1.038.660

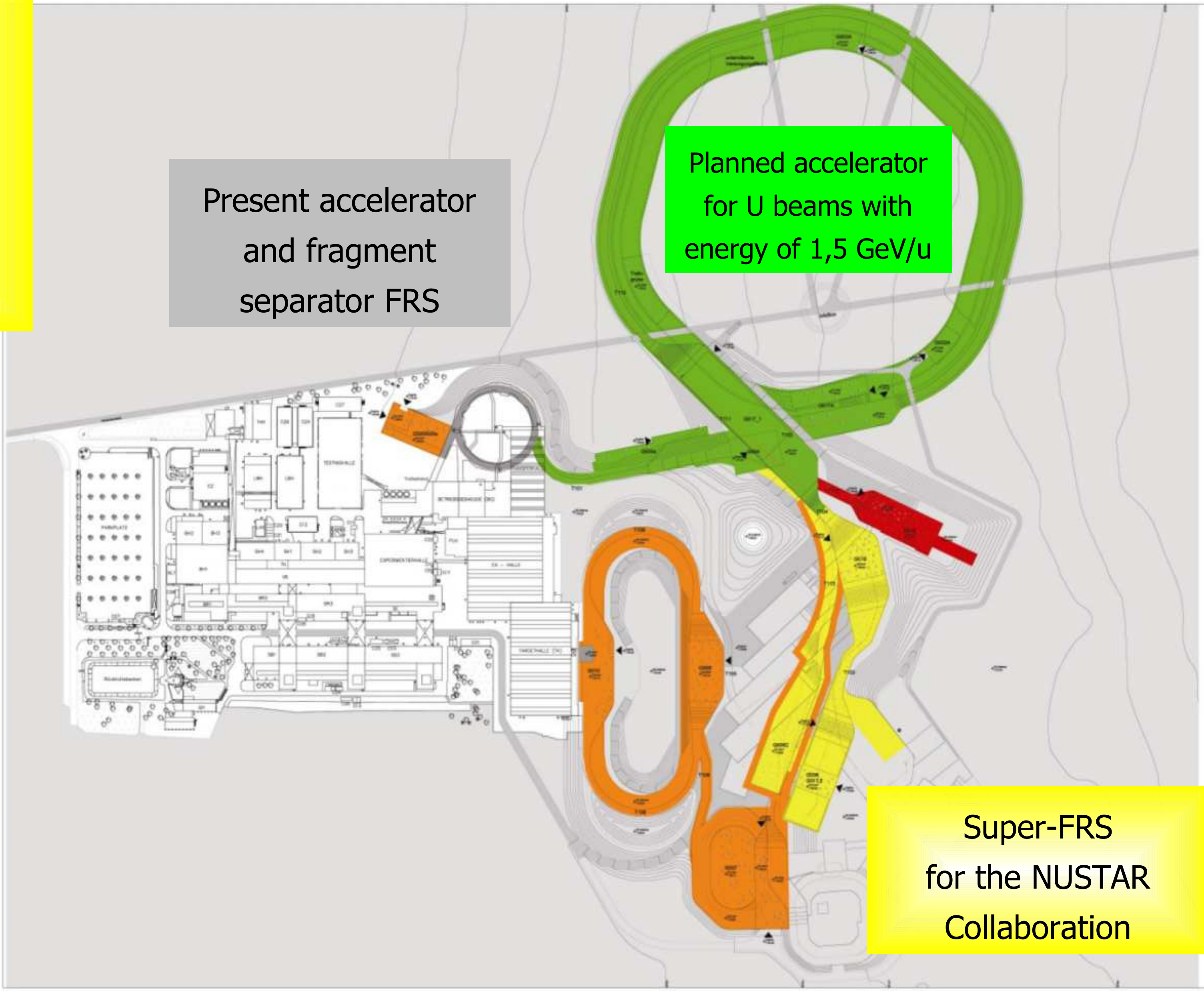
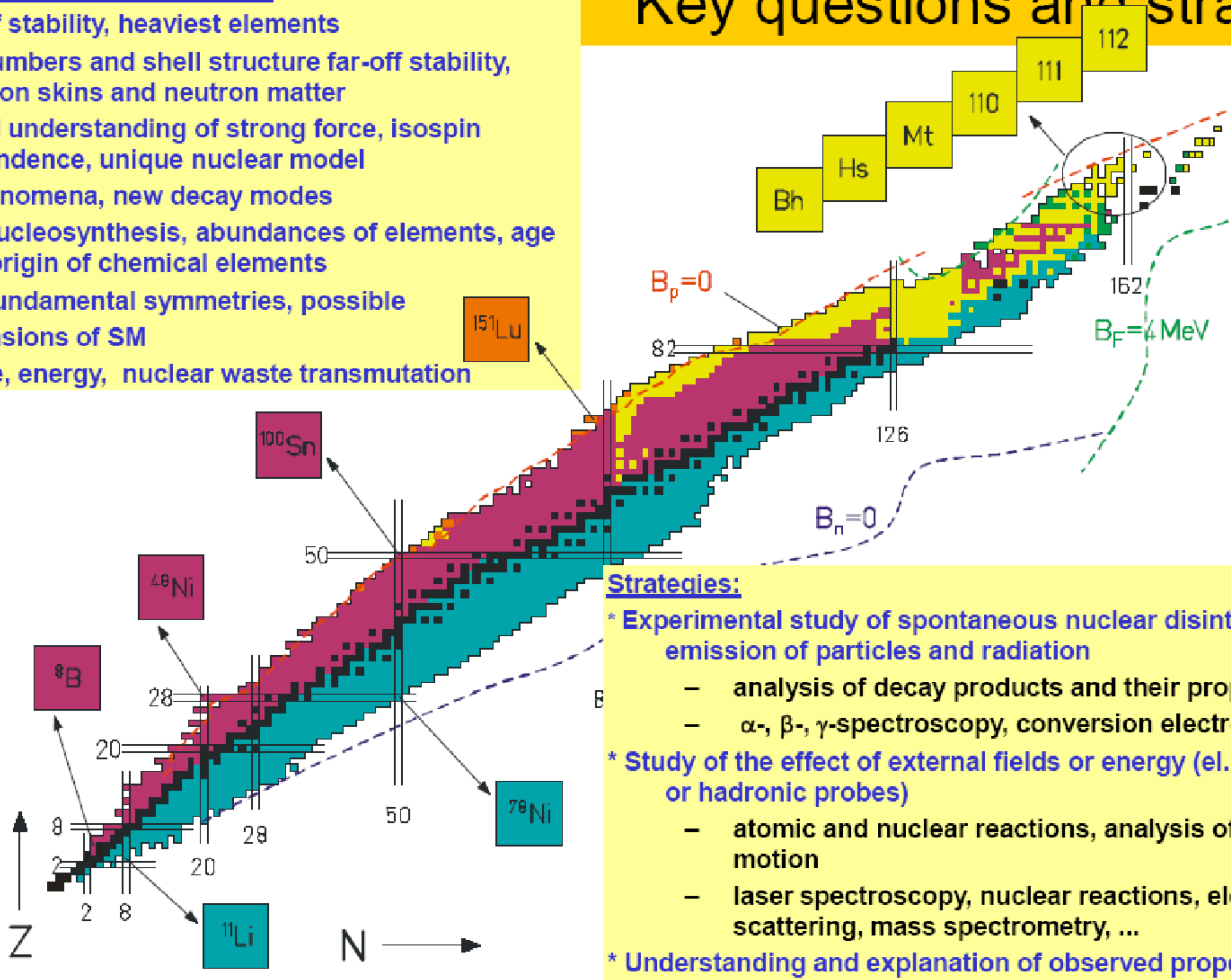


Figure 1: The FAIR Modularized Start Version. Colouring of modules: 0 – green; 1 – red; 2 – yellow; 3 – orange. The Modules 4 and 5 are not marked in colour. Not shown is the additional experimental area above ground, which is part of Module 1. On the left hand side of the figure, the existing GSI facility is

Key questions and strategy

Key questions and applications:

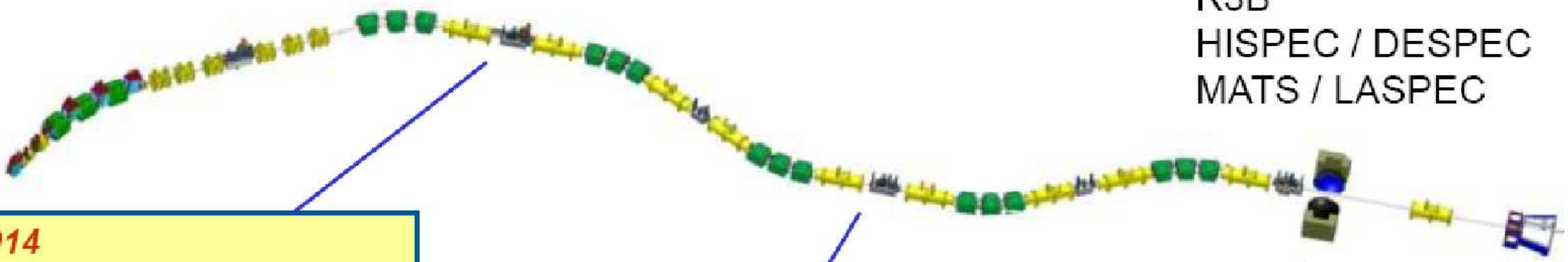
- * Limits of stability, heaviest elements
- * Magic numbers and shell structure far-off stability, neutron skins and neutron matter
- * Detailled understanding of strong force, isospin dependence, unique nuclear model
- * New phenomena, new decay modes
- * Stellar nucleosynthesis, abundances of elements, age and origin of chemical elements
- * Test of fundamental symmetries, possible extensions of SM
- * Medicine, energy, nuclear waste transmutation



Strategies:

- * Experimental study of spontaneous nuclear disintegration and emission of particles and radiation
  - – analysis of decay products and their properties
  - – α-, β-, γ-spectroscopy, conversion electrons,...
- * Study of the effect of external fields or energy (el.-mag., leptonic or hadronic probes)
  - – atomic and nuclear reactions, analysis of particle motion
  - – laser spectroscopy, nuclear reactions, elektron scattering, mass spectrometry, ...
- * Understanding and explanation of observed properties and phenomena, predictions
  - – hypothesis, models, phenomenological, analytical and

Stepwise installation and commissioning of Super-FRS



R3B
HISPEC / DESPEC
MATS / LASPEC

Year 2014
- Pre-Separator commissioning
- Test of separation quality
- New isotope production
- beta-decay measurements

Year 2015
- Reaction studies, momentum measurements
- New skin and halo nuclei
- Total interaction cross section measurements

Year 2016
- Comissioning of main separator
- Spectroscopy experiments
- r-nuclides half-lives
- Kinematical complete experiments

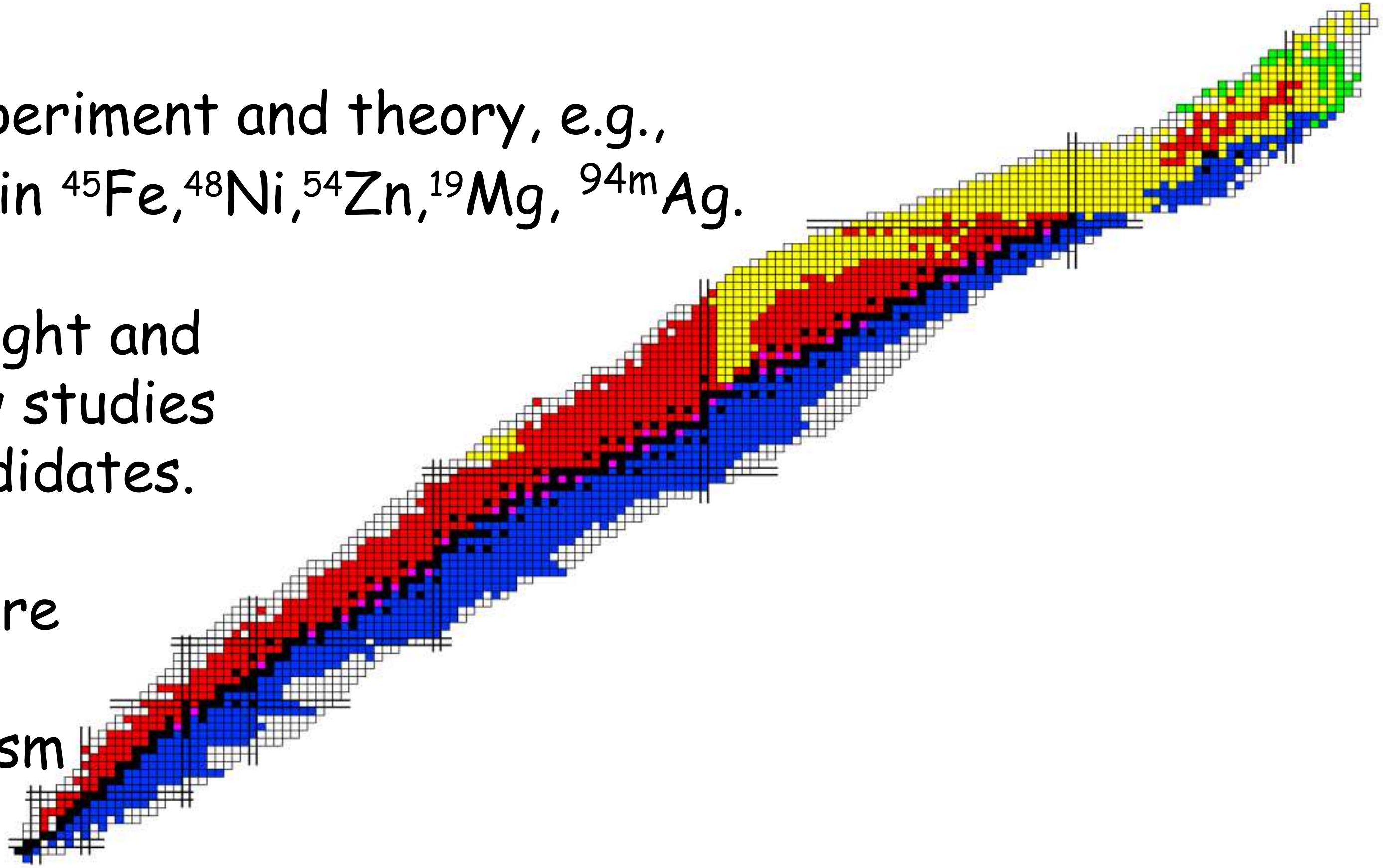
Outlook

- Two-proton decays limit nuclear landscape beyond the proton drip-line and are expected to influence elemental abundances in nature.

- Recent breakthroughs in experiment and theory, e.g., 2p radioactivity is observed in ^{45}Fe, ^{48}Ni, ^{54}Zn, ^{19}Mg, ^{94m}Ag.

- Invariant-mass, decay-in-flight and implantation experiments allow studies of all predicted 2p-decay candidates.

- Proton-proton correlations are crucial in future experiments establishing 2p-decay mechanism and nuclear structure.



Prospective 2p-decay candidates: ^{26}S, ^{30}Ar, ^{34}Ca, ^{58}Ge, ^{62}Se, ^{66}Kr.

L.Grigorenko, I.Mukha, M.Zhukov, Nucl. Phys. A**714** (2003); Phys.Rev.Lett. **85** (2000)

Many-body structure of 2p precursors

p+p+"core" model $\Psi_3^{(+)} = \sum_i X_i [l_i^2]_0$ Probability of 2p decay, $P_{2p}=1$

Many-body structure $\left(\frac{A!}{2!(A-2)!}\right)^{1/2} \langle \Psi_A | \Psi_{A-2} \rangle = \sum_i \tilde{X}_i [l_i^2]_0$ $P_{2p} \neq 1$

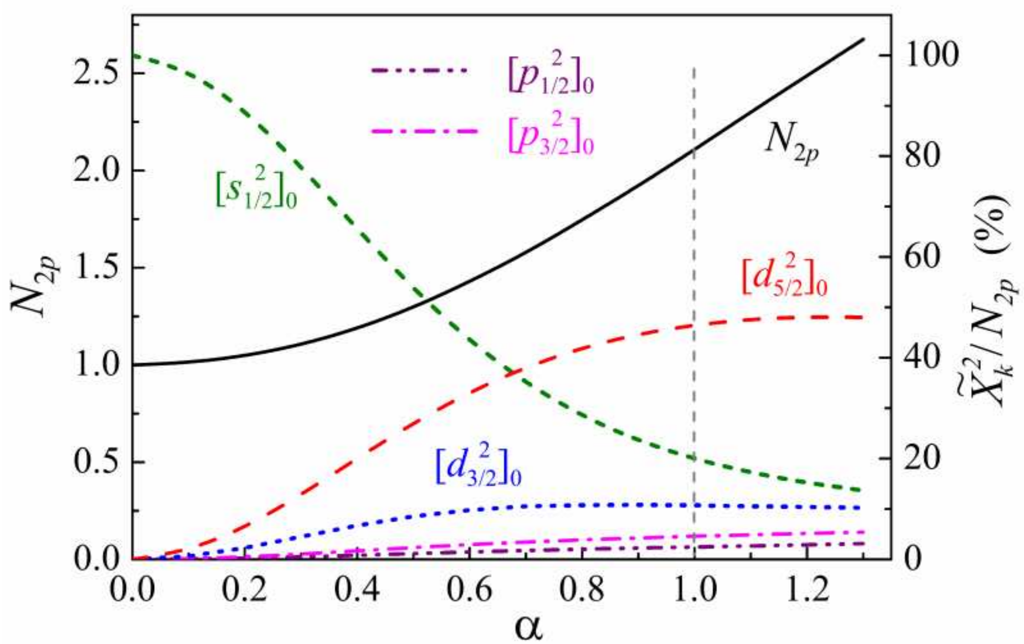
Width to be re-normalized $\Gamma(\{X_i^2\}) \rightarrow N_{2p} \Gamma(\{\tilde{X}_i^2 / N_{2p}\})$

Example of ^{26}S 2p-decay

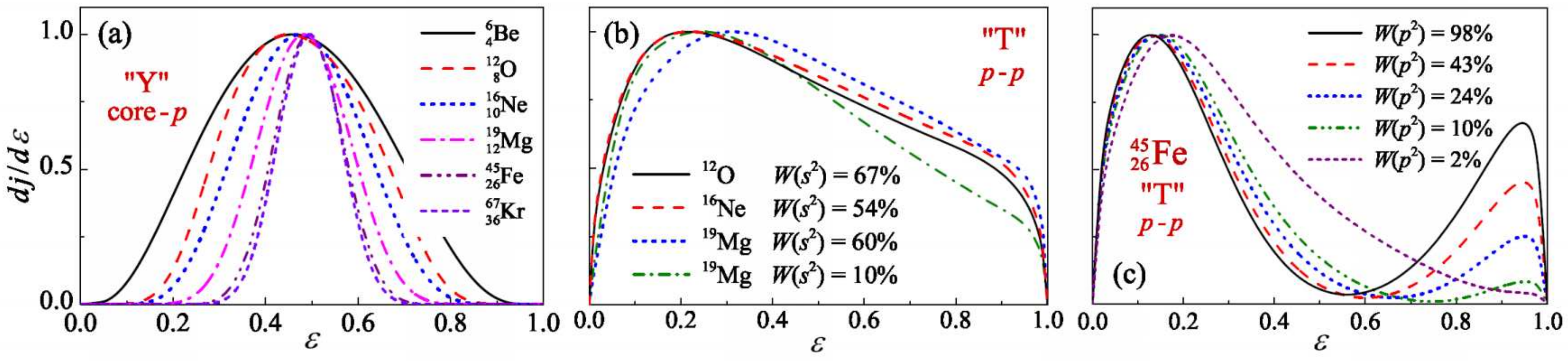
LIFETIME OF ^{26}S AND A LIMIT FOR ITS 2p DECAY ENERGY

A.S. FOMICHEV,[1,*] I.G. MUKHA,[2,3] S.V. STEPANTSOV,[1] L.V. GRIGORENKO,[1,2,4] E.V. LITVINOVA,[2,5] V.CHUDOBA,[1,6] I.A. EGOROVA,[7] M.S. GOLOVKOV,[1] A.V. GORSHKOV,[1] V.A. GORSHKOV,[1] G. KAMINSKI,[1,8] S.A. KRUPKO,[1] YU.L. PARFENOVA,[1,9] S.I. SIDORCHUK,[1] R.S. SLEPNEV,[1] G.M. TER-AKOPIAN,[1] R. WOLSKI,[1,8] M.V. ZHUKOV[10]

IJMP E (2011) in print

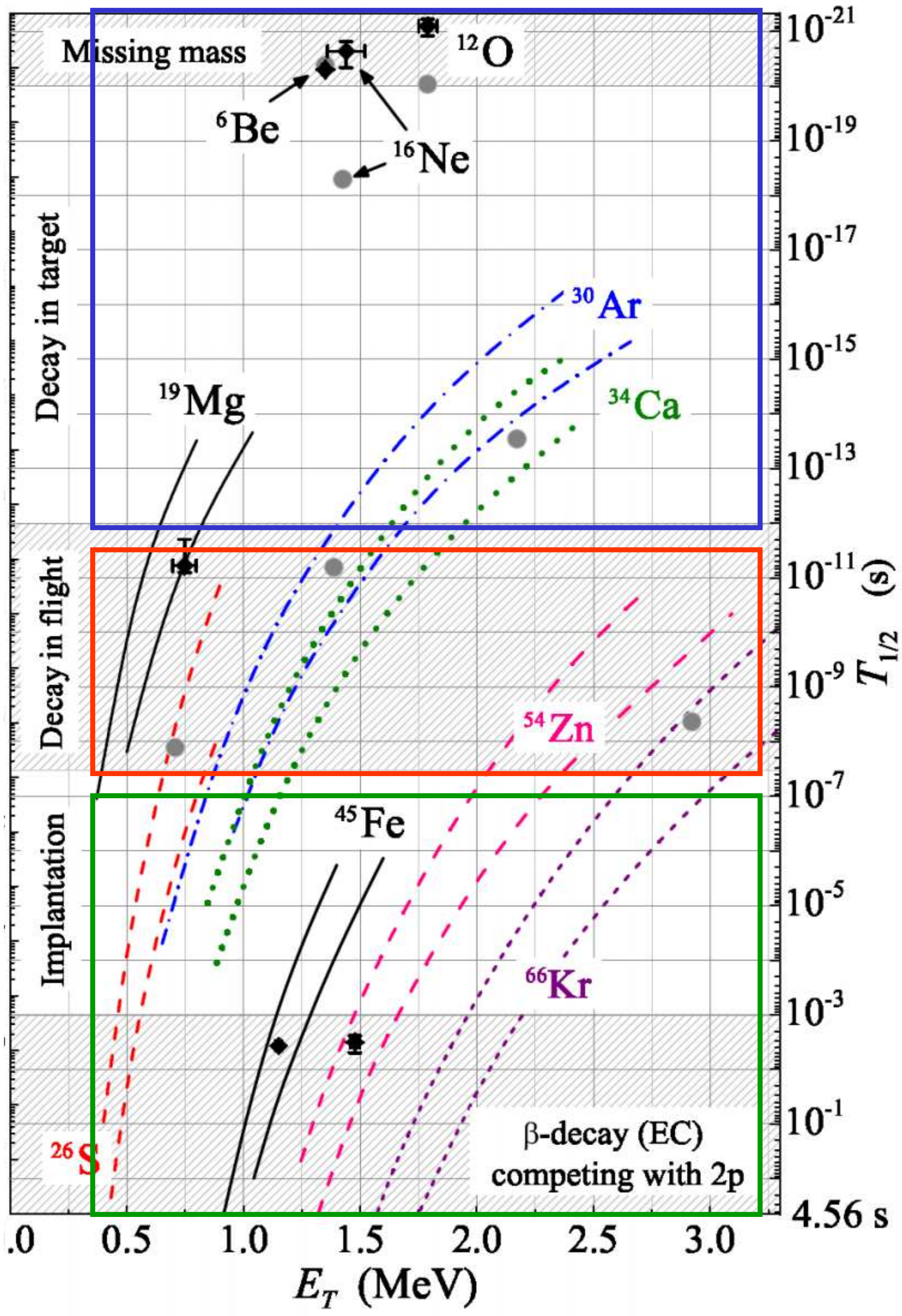


Structure of ^{45}Fe reflected in p-p correlations



L.Grigorenko, privet communication.

Half-life *vs.* decay energy of prospective 2p-radioactivity precursors



In-flight decay candidates:

^{26}S, ^{30}Ar, ^{34}Ca, ^{58}Ge, ^{62}Se, ^{66}Kr

L.V. Grigorenko, I. Mukha, M.V. Zhukov, Proc. PROCON'03 (AIP **681**, NY 2003) 126.

B.A. Brown and F.C. Barker, ibid., p. 118.

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