Studies of proton-unbound nuclei by tracking products of their decays in-flight

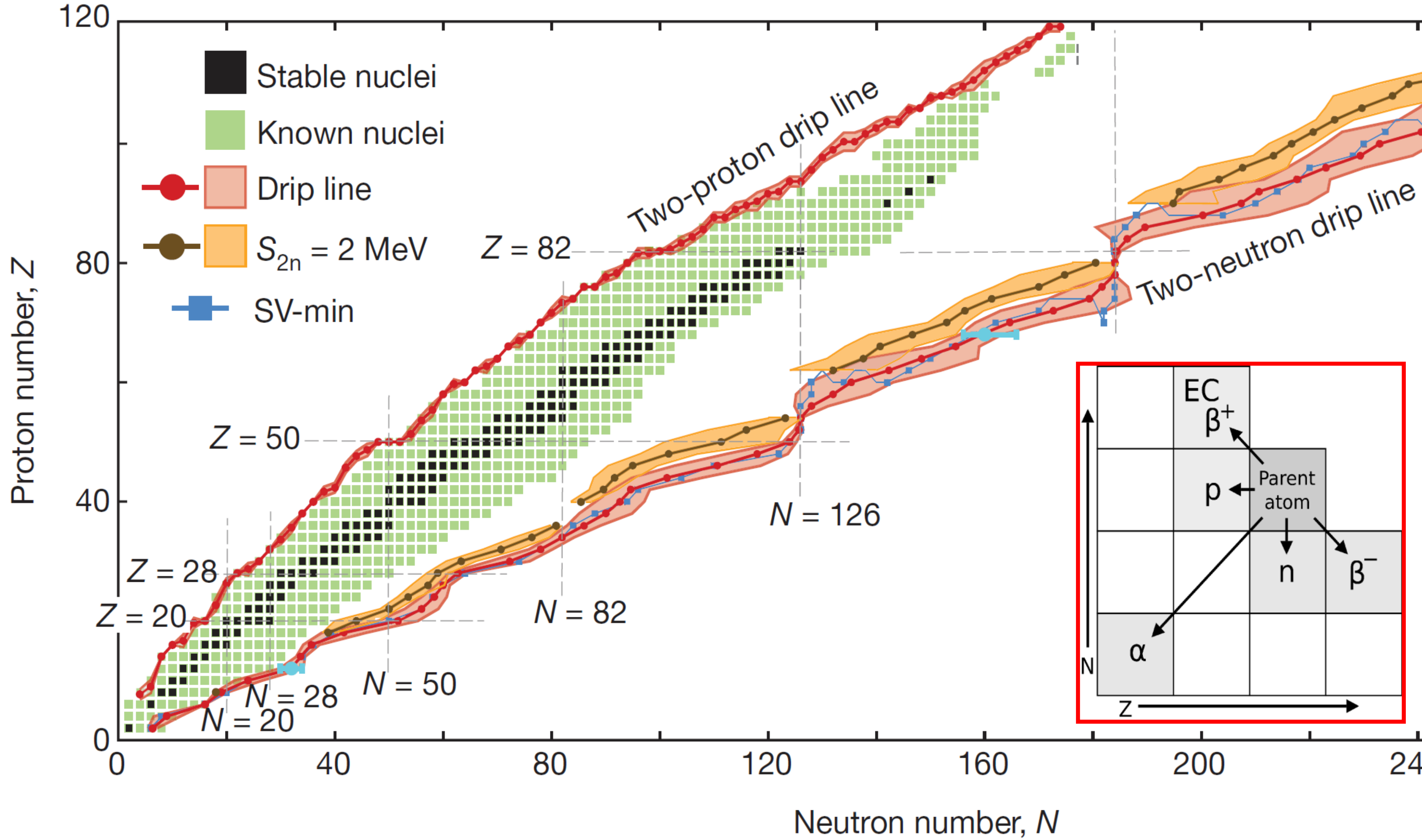
Ivan Mukha

- Predictions of proton radioactivity
- Mechanisms of multi-nucleon emission
- Experimental tracking technique and detectors
- Observation of new isotopes ^{30}Ar, ^{29}Cl, ^{30}Cl and

  of a transition between direct and sequential two-proton decay

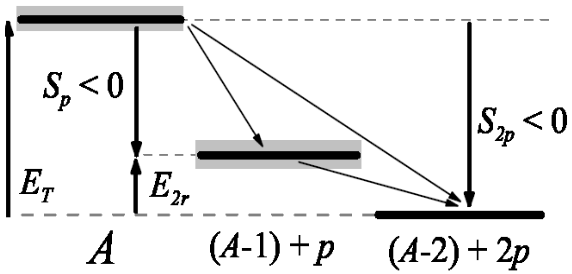
Where is proton or neutron radioactivity ?

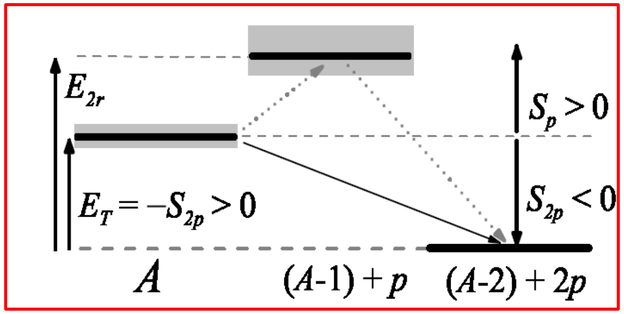
Pushing to limits of nuclear existence

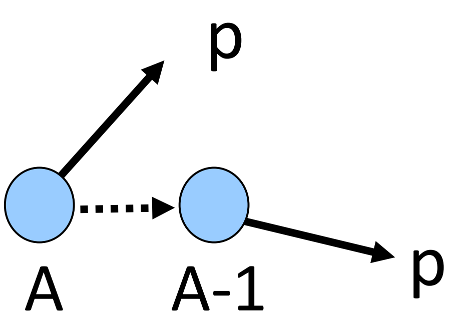


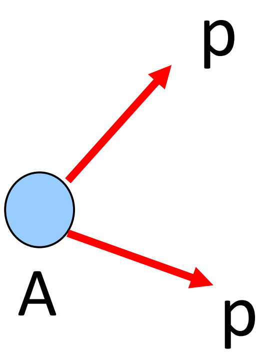
J. Erler *et al.,* Nature **486** (2012) 509

Energy conditions of a genuine 2p decay





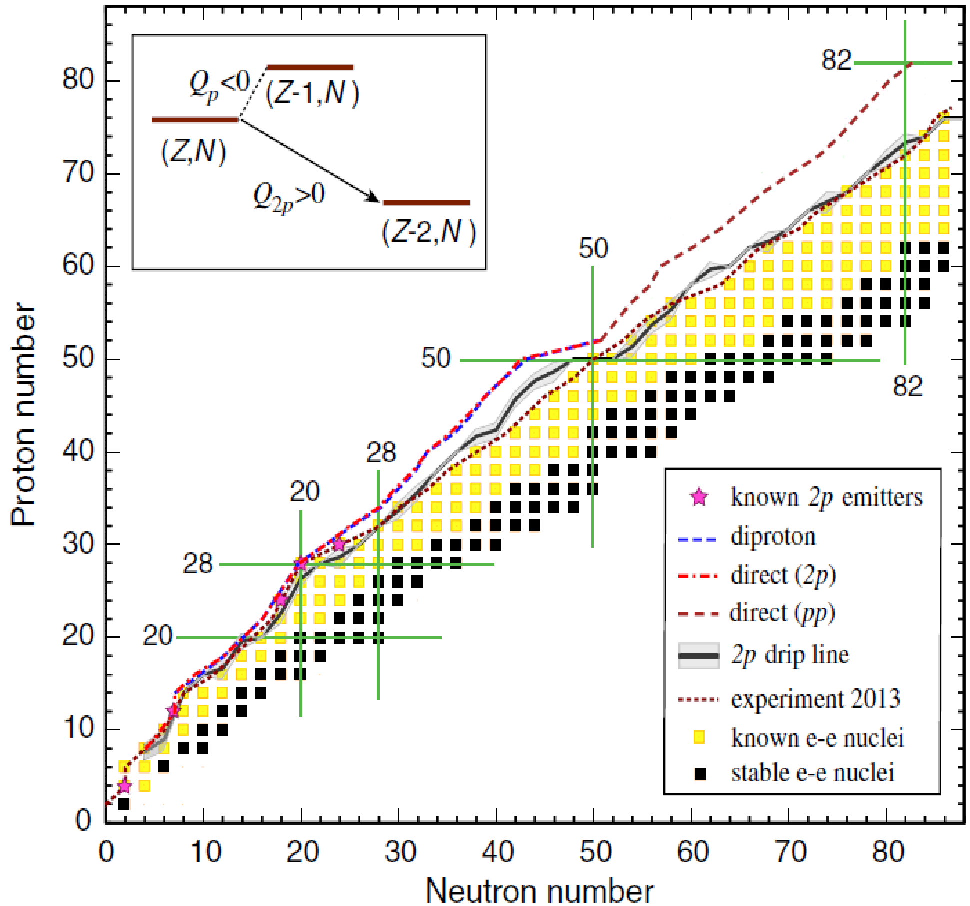




Sequential proton emission

True three-body decay

Landscape of Two-Proton Radioactivity



^{19}Mg, ^{45}Fe, ^{48}Ni, ^{54}Zn, ^{57,58,59}Ge, ^{62,63}Se, ^{66,67}Kr, ^{71}Sr, ^{102,103}Te, ^{73}Zr, ^{77}Mo, ^{81}R u, ^{85}Pd, ^{113}Ce, ^{117}Nd, ^{121}Sm, ^{125,126}Gd, ^{130}Dy, $^{133\text{-}135}$Er, ^{138,139}Yb, ^{151,152}Os, $^{154\text{-}156}$Pt, ^{158,159}Hg, ^{109,110}Ba, ^{114}Ce, ^{127}Gd, ^{131}Dy, ^{144,145}Hf, $^{147\text{-}149}$W

E.Olsen, M.Pfutzner, N.Birge, M.Brown, W.Nazarewicz, and A.Perhac
Phys. Rev. Lett. ***110****, 222501 (2013)*

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

Short-lived nuclei:

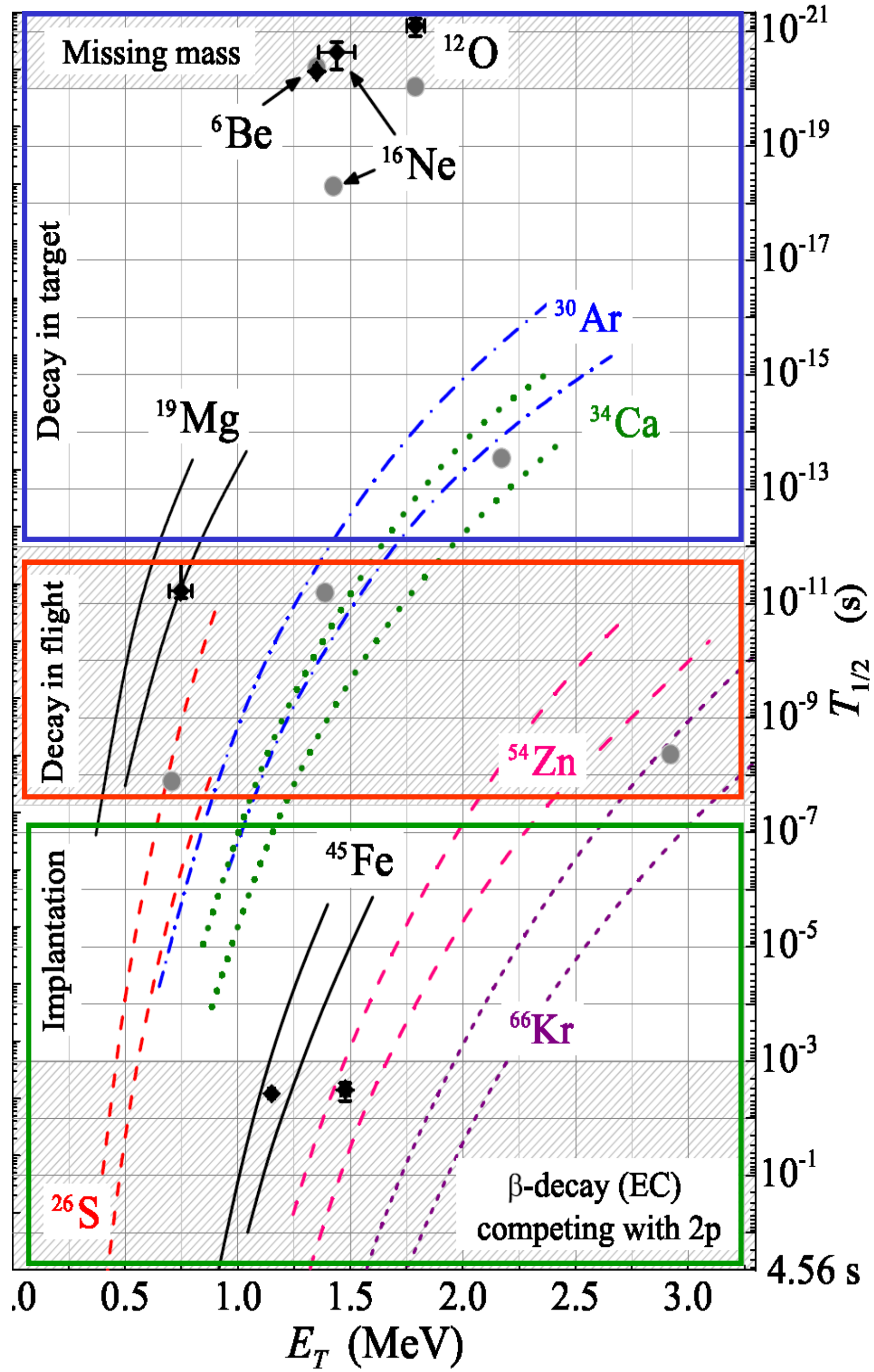
^{6}Be, **^{12}O, ^{16}Ne**, *etc*

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**



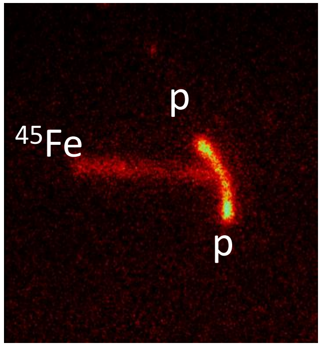
L.V. Grigorenko, I. Mukha, M.V. Zhukov, Proc. PROCON'03 (AIP **681**, NY 2003) 126.

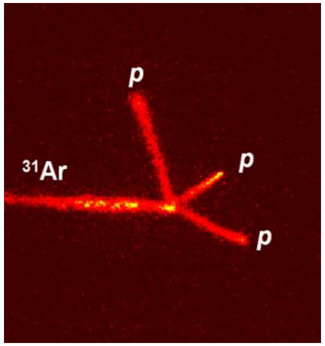
B.A. Brown and F.C. Barker, ibid., p. 118.

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

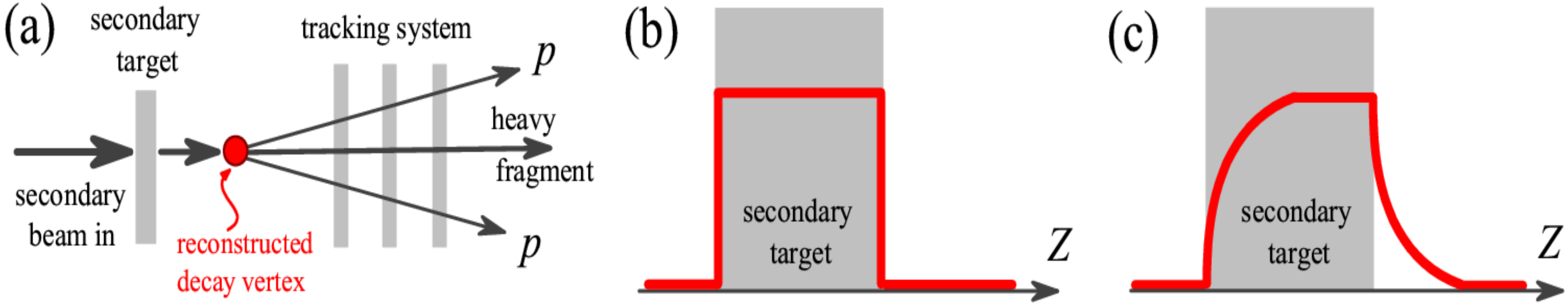
Detection techniques

Implantation-decay measurements of radioactivity. The precursor's half-life $T_{1/2}$ > 100 ns

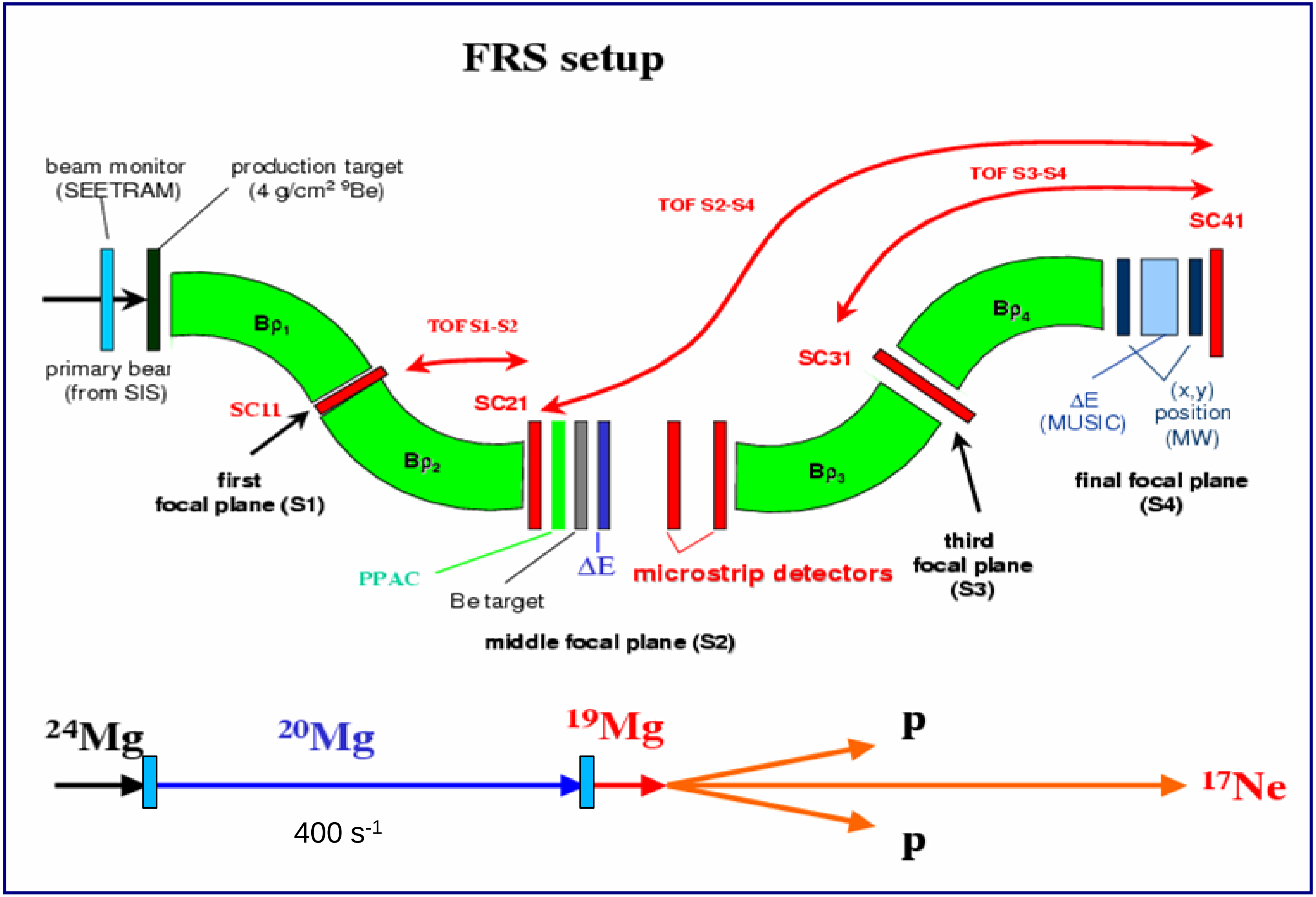




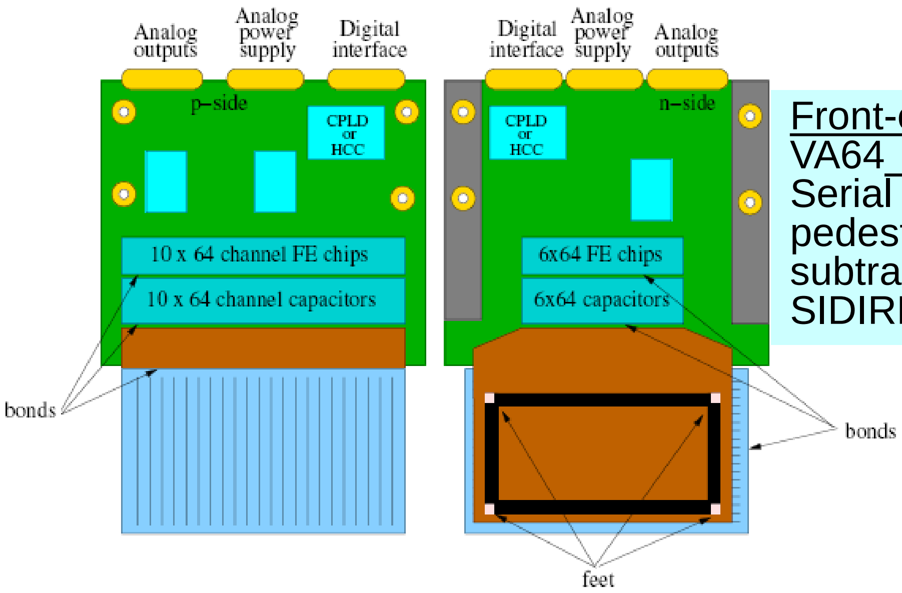
Decay in-flight by tracking method.
The precursor's 100ns > $T_{1/2}$ > 1 ps



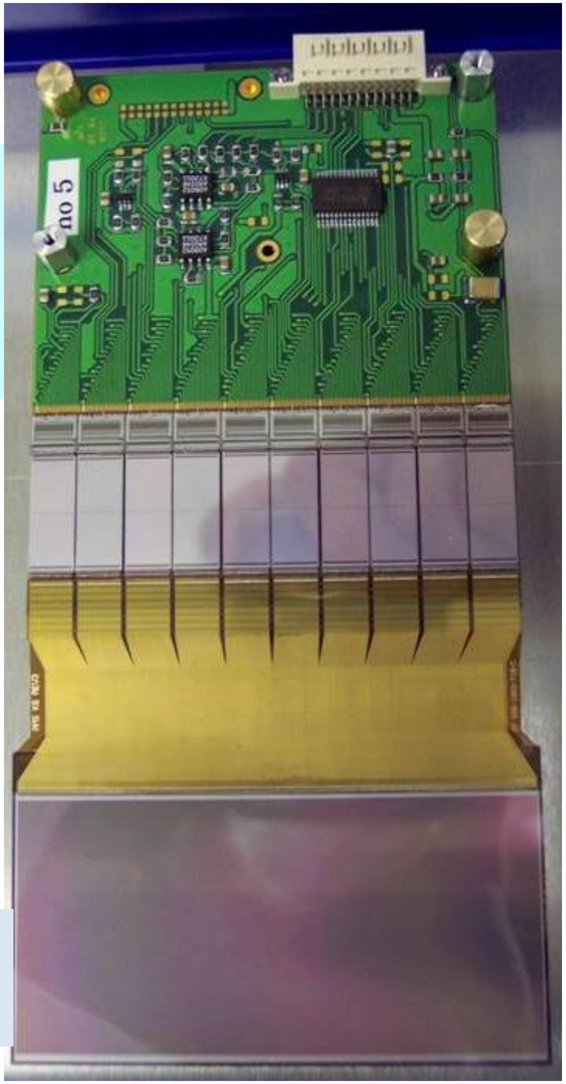
Two-proton radioactivity of ^{19}Mg measured in-flight



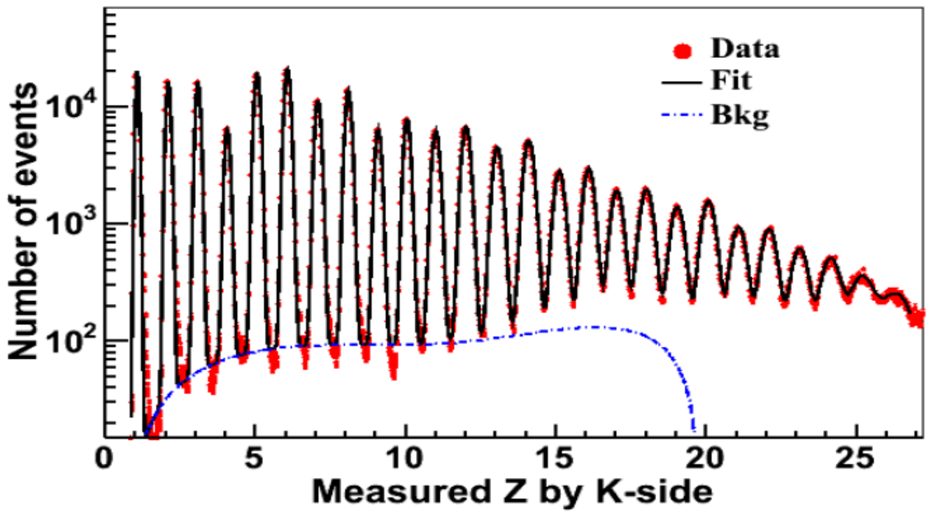
The micro-strip detectors used for tracking



<u>Front-end electronics:</u>
VA64_hdr9 chips from IDE AS.
Serial read-out, digitalization, pedestal and common-noise subtraction made by the SIDIREM electronics modules.



Elements resolved by the AMS02 tracker, the GSI data 2003



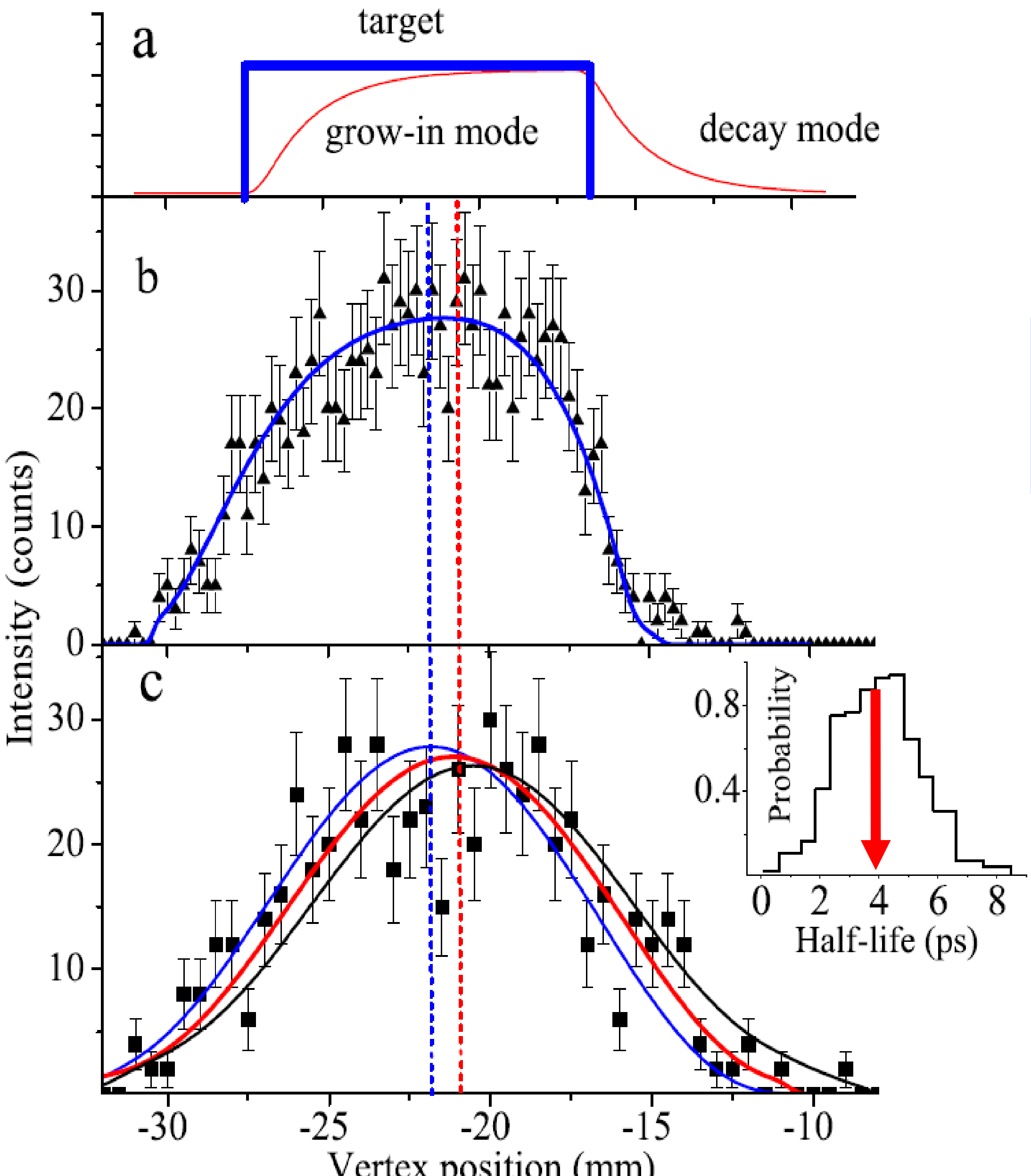
B.Alpat et al.,,

NIM **540** (2005)

Dimensions 70x40 mm^2, 0.1 mm strip pitch,

in total 1000 channels

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 $^{19}Mg_{g.s.}$

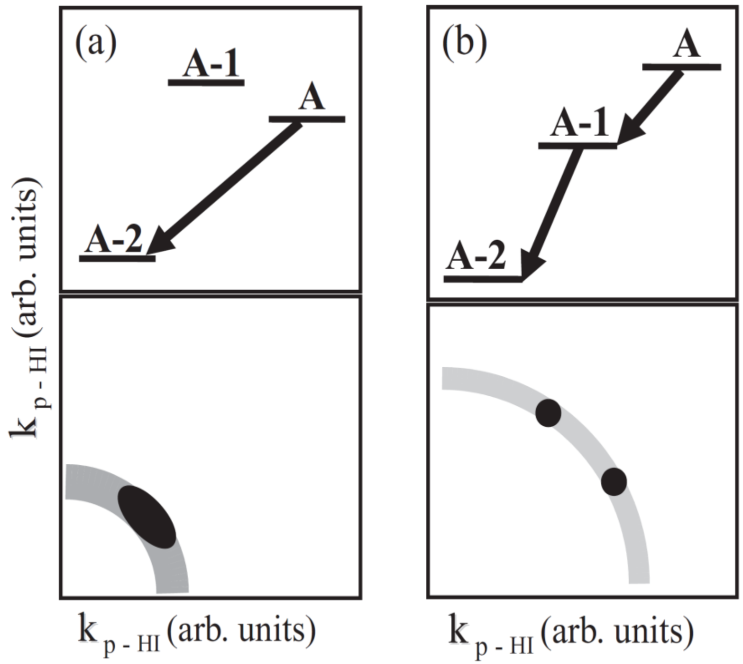
$T_{1/2}$=4.0(15) ps

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

How to identify a reaction channel ?
Momentum and angular correlations of fragments are similar !

(a) direct 2p decay,

a three-body decay mechanism

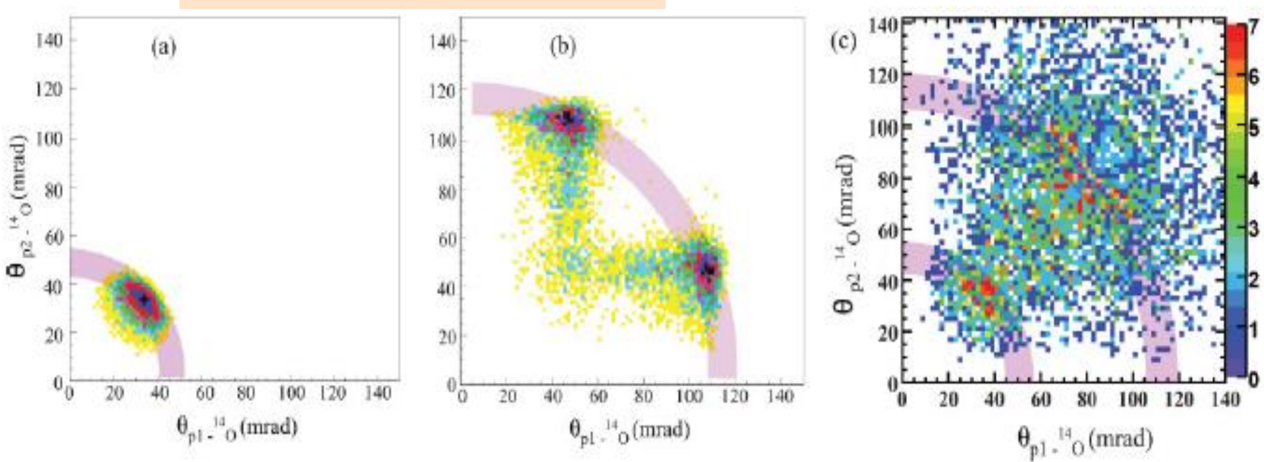


(b) - sequential 2p emission

via an intermediate 1p resonance

Respective simulations

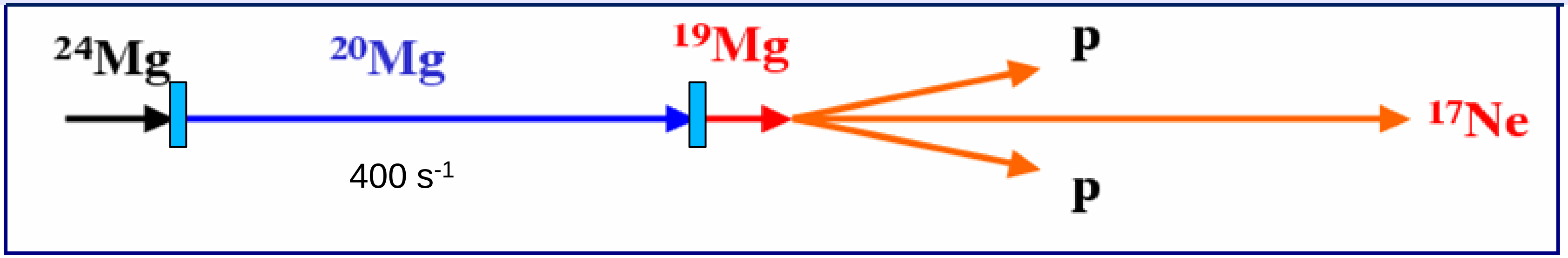
Experiment: $^{16}Ne \to ^{14}O+p+p$



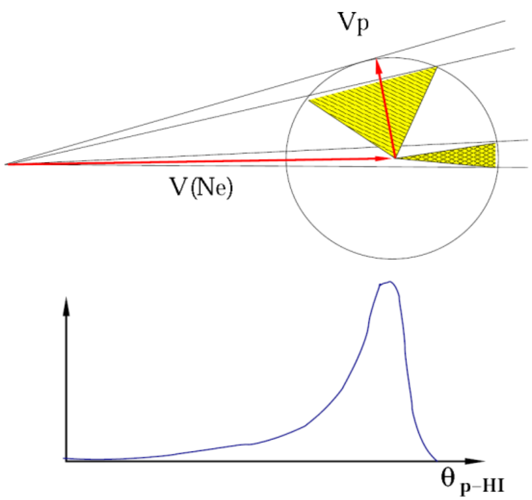
I.Mukha et al.,,

PRC **82** (2010)

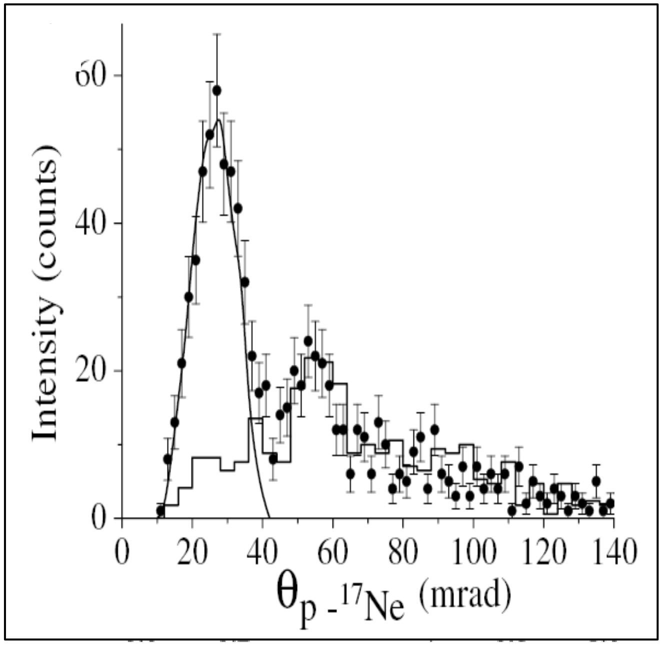
Two-proton radioactivity of ^{19}Mg measured by tracking trajectories of all fragments in-flight

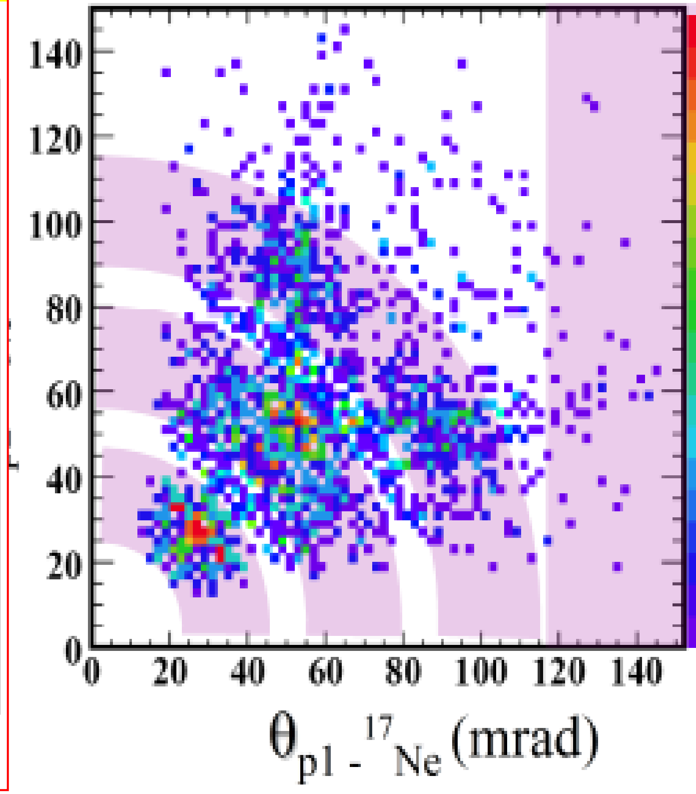


Angular correlations of fragments reflect the decay energy

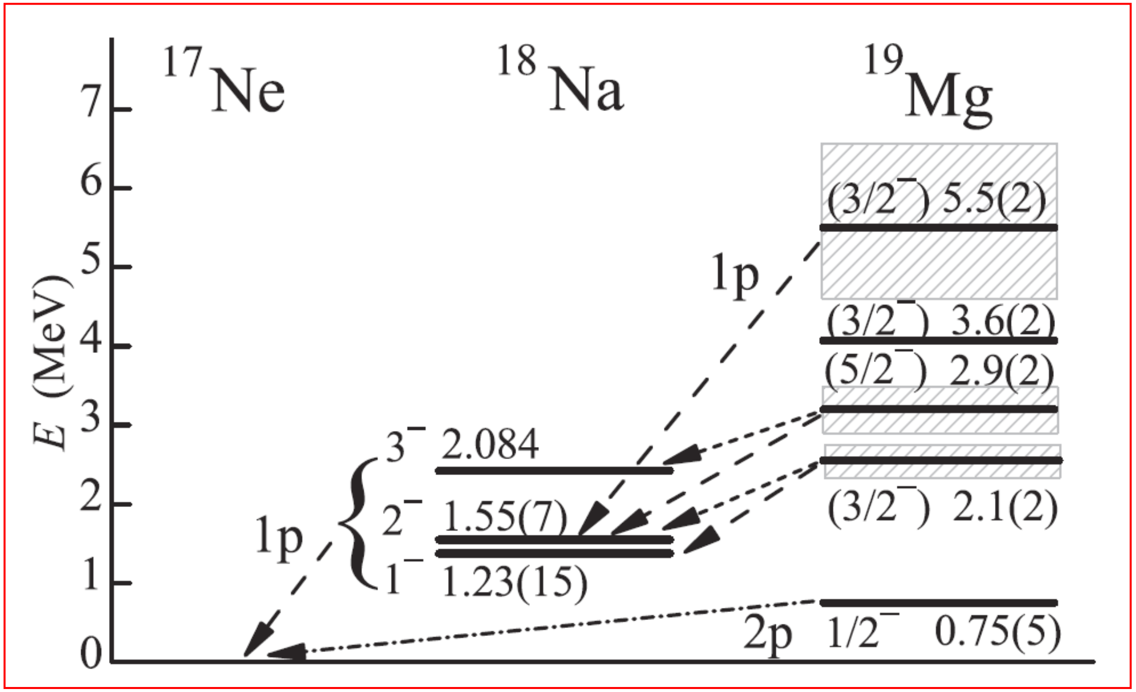


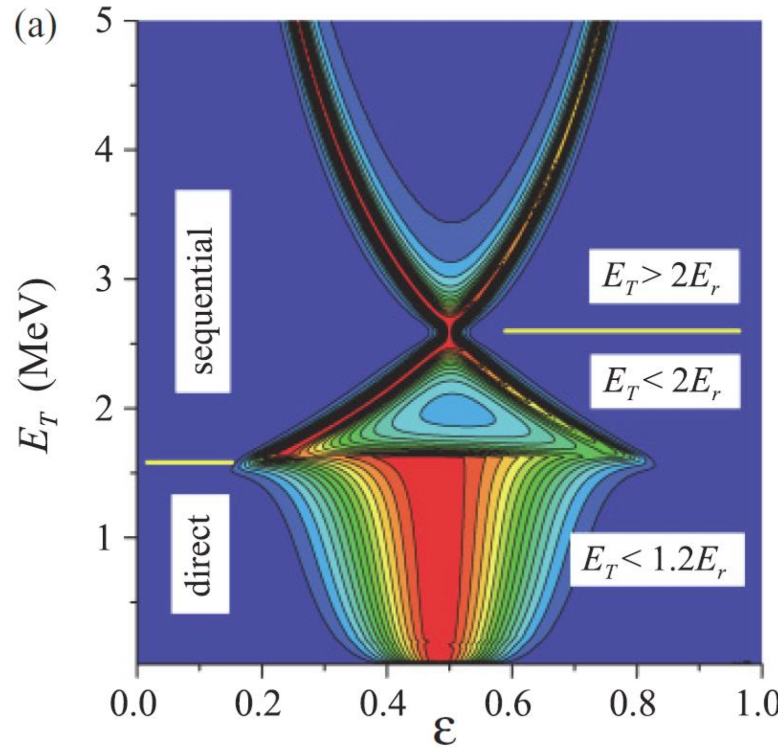
Kinematical enhancement around a maximum angle





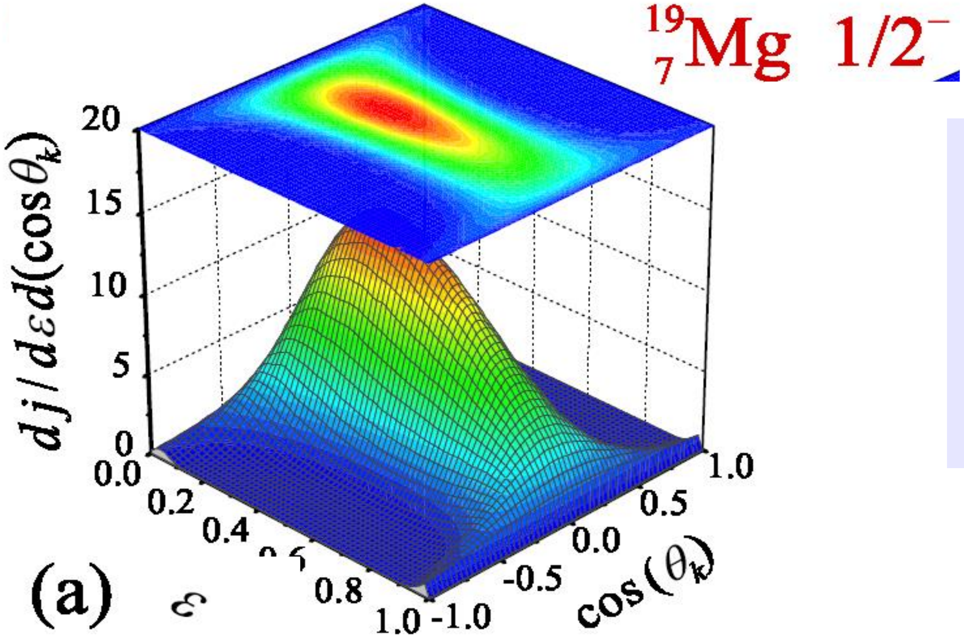
The levels of ^{19}Mg and 2p-decay mechanisms



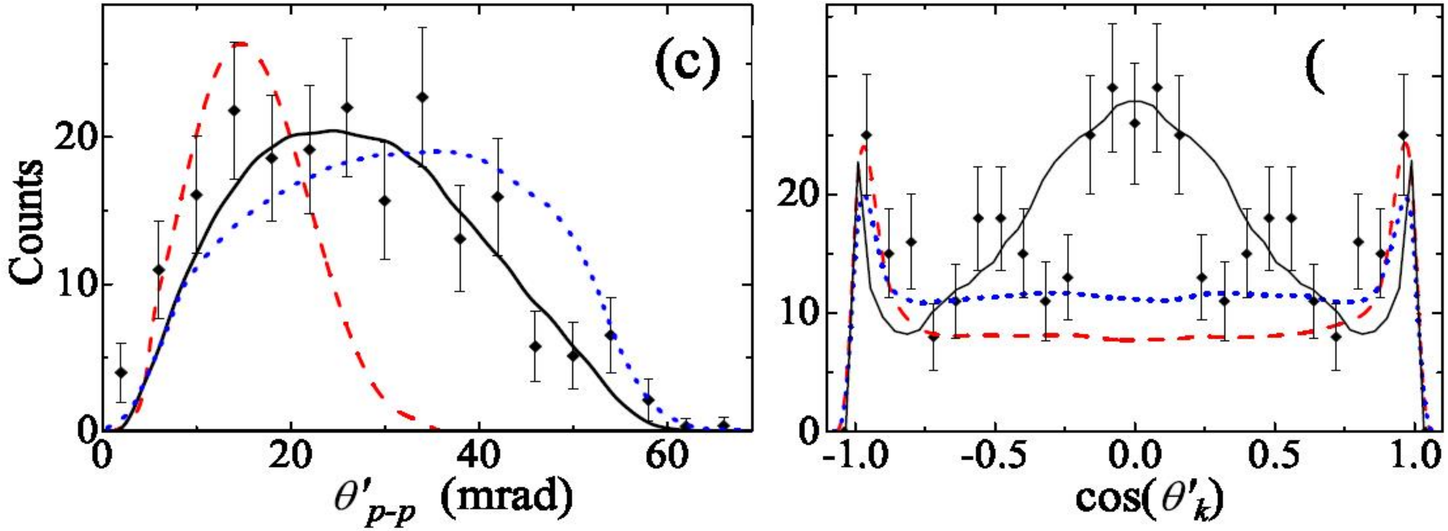


I.Mukha et al.,, PRC **85** (2012)

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



Correlations by
the three-body model
of L. Grigorenko

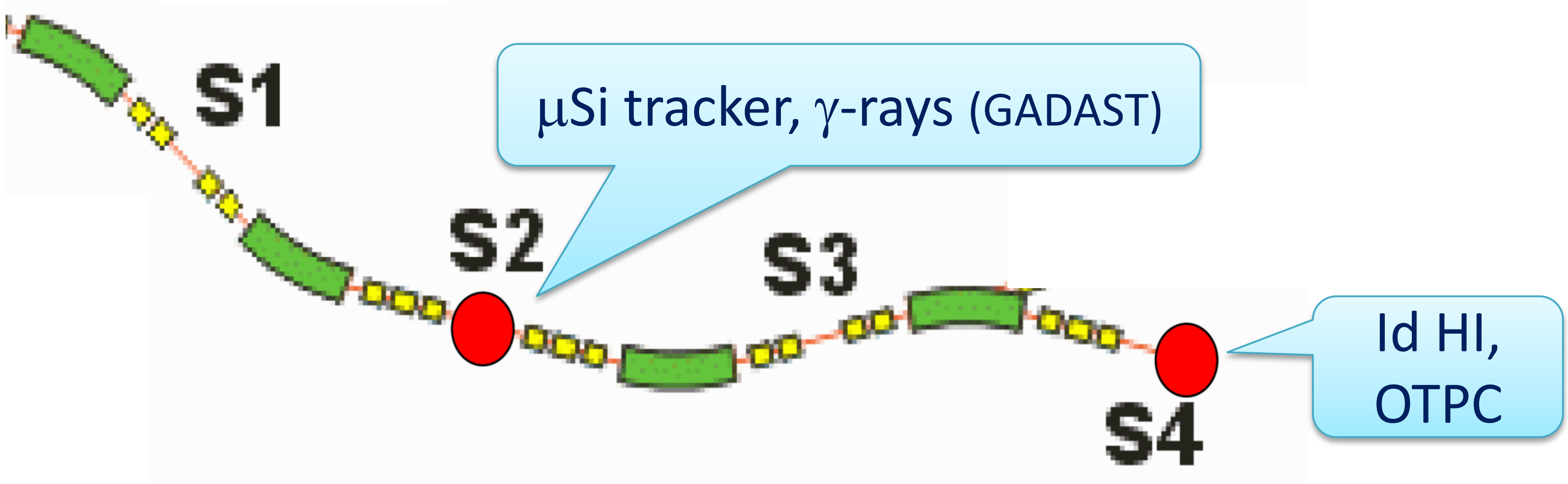


Data *vs.* theory

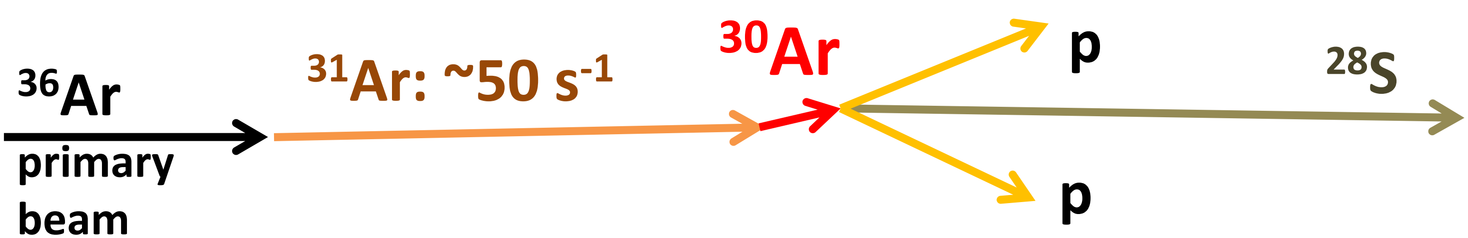
I.Mukha et al.,
PRC **77** (2008)

Tracking two-proton decays at FRS

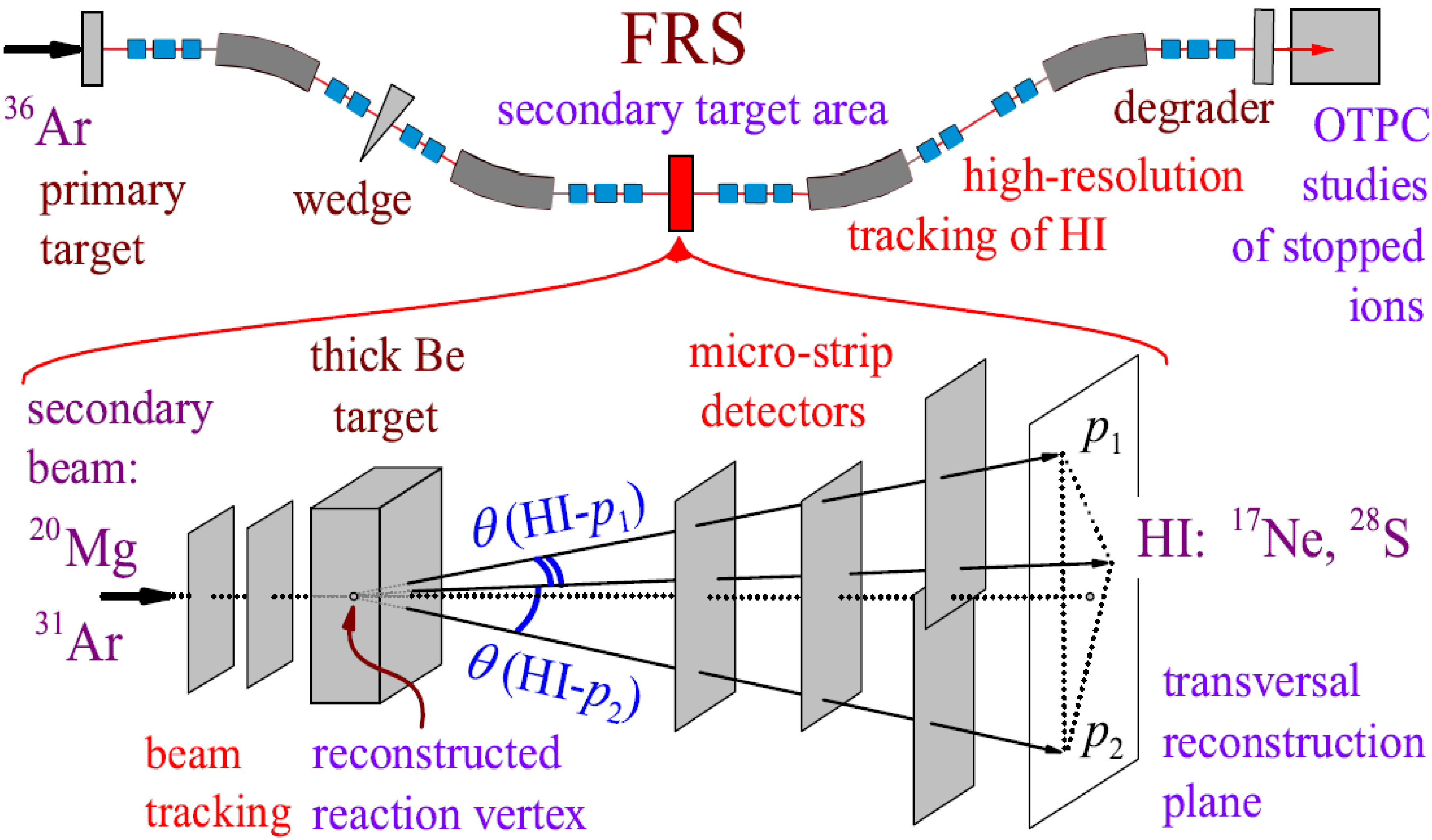
Layout of detection sections



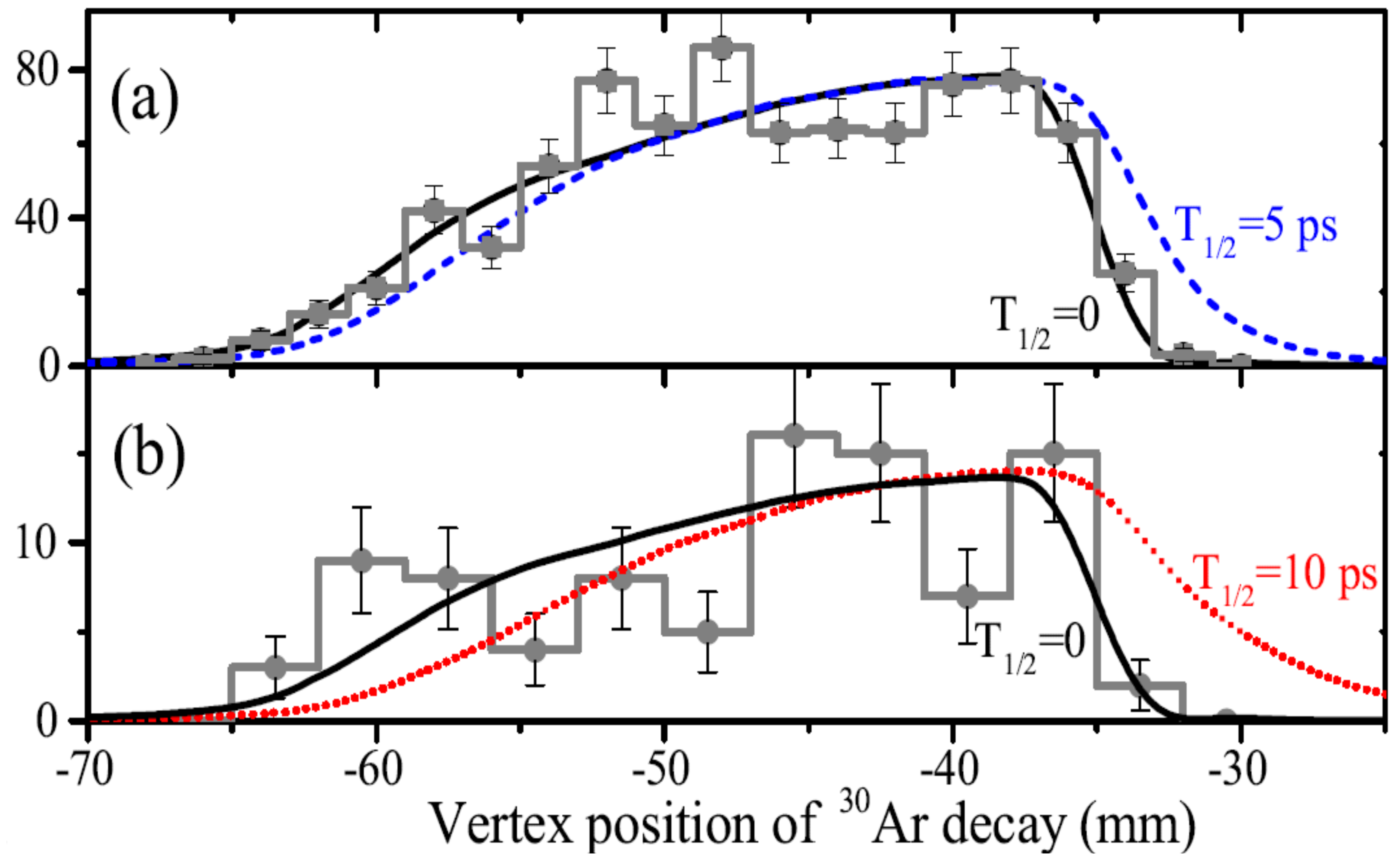
Scheme of reactions



Close-up view



Life-time of ^{30}Ar derived by vertex distribution of ^{28}S+p+p



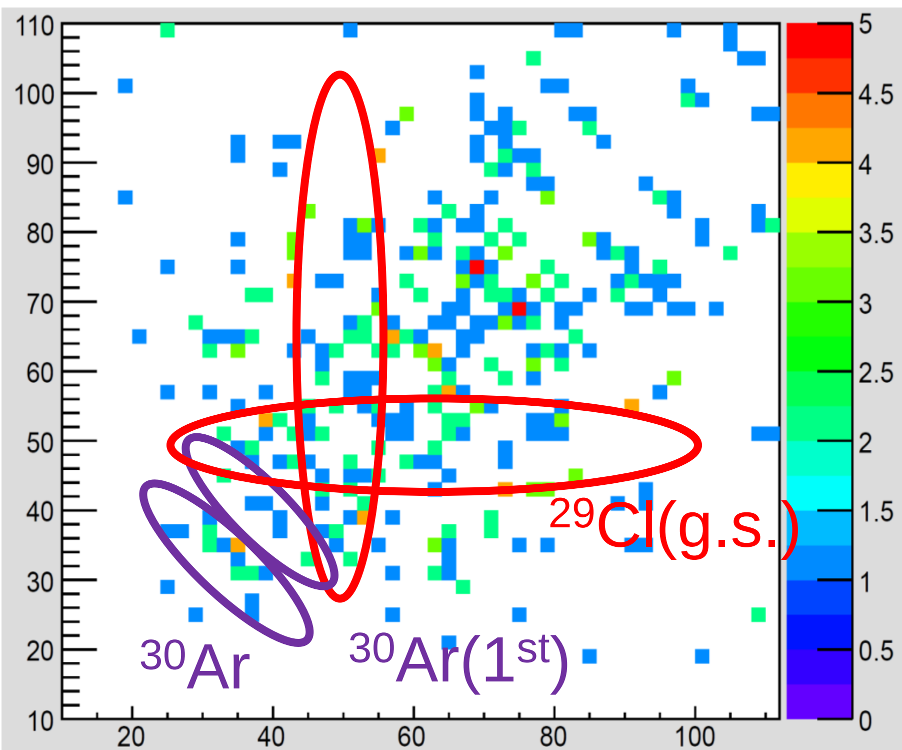
Preliminary results

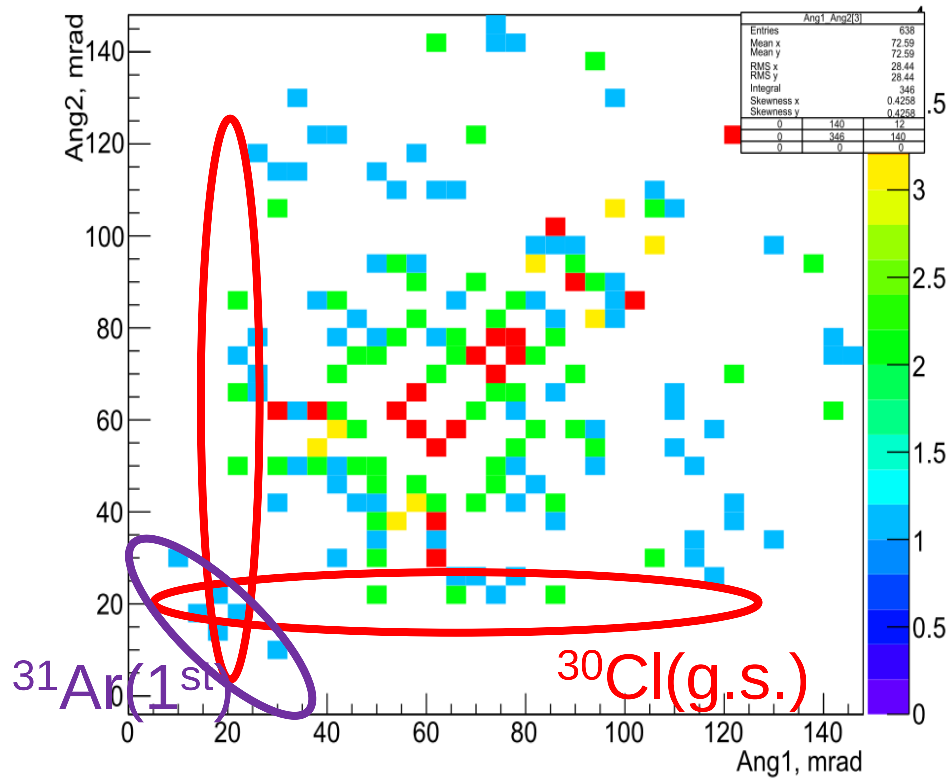
^{31}Ar secondary beam

−p | *inelastic*

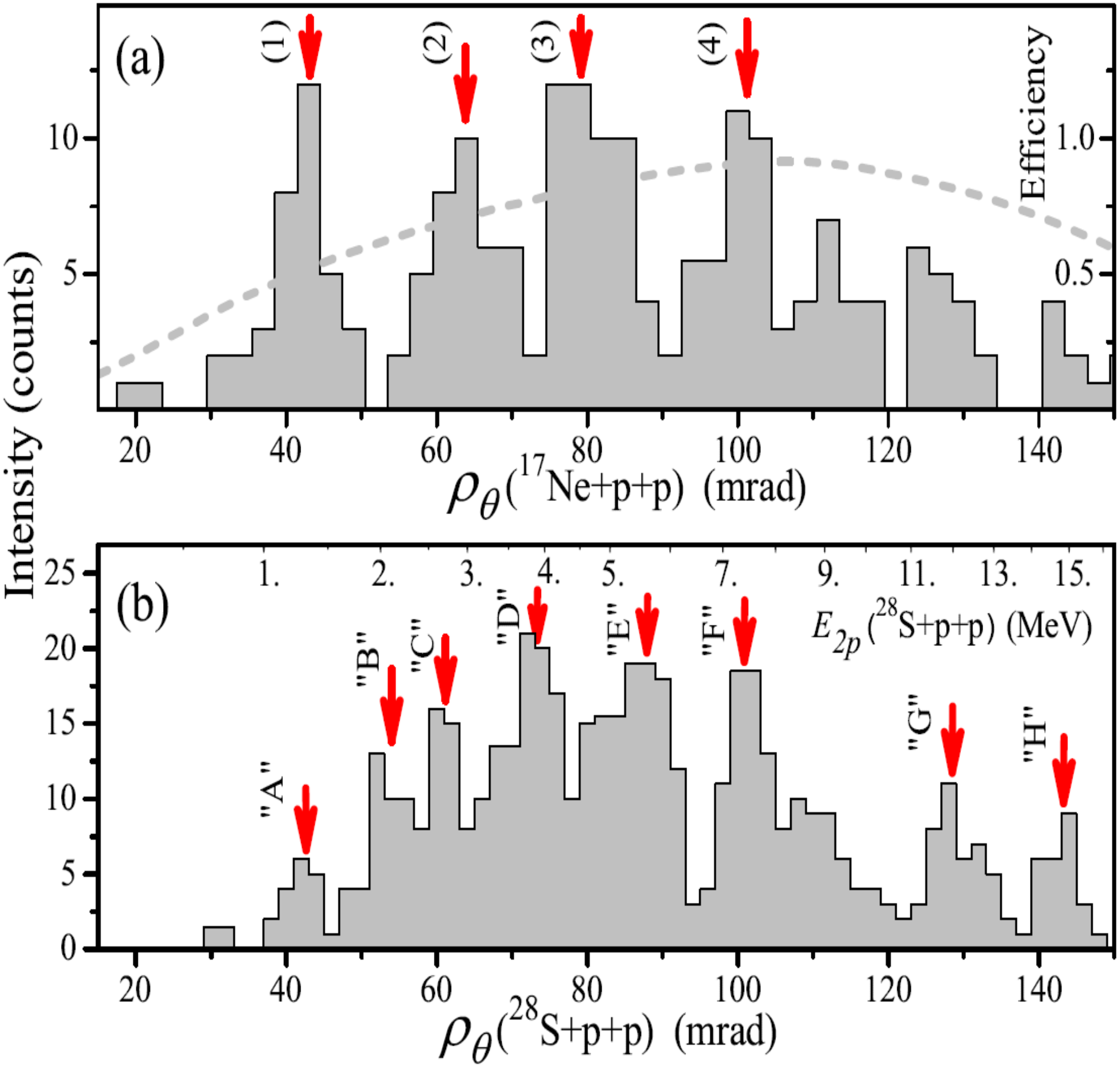
^{30}Ar -> ^{28}S+p+p

^{31}Ar -> ^{30}Cl+p -> ^{29}S+p





Angular correlations of fragments from ^{19}Mg and ^{30}Ar decays



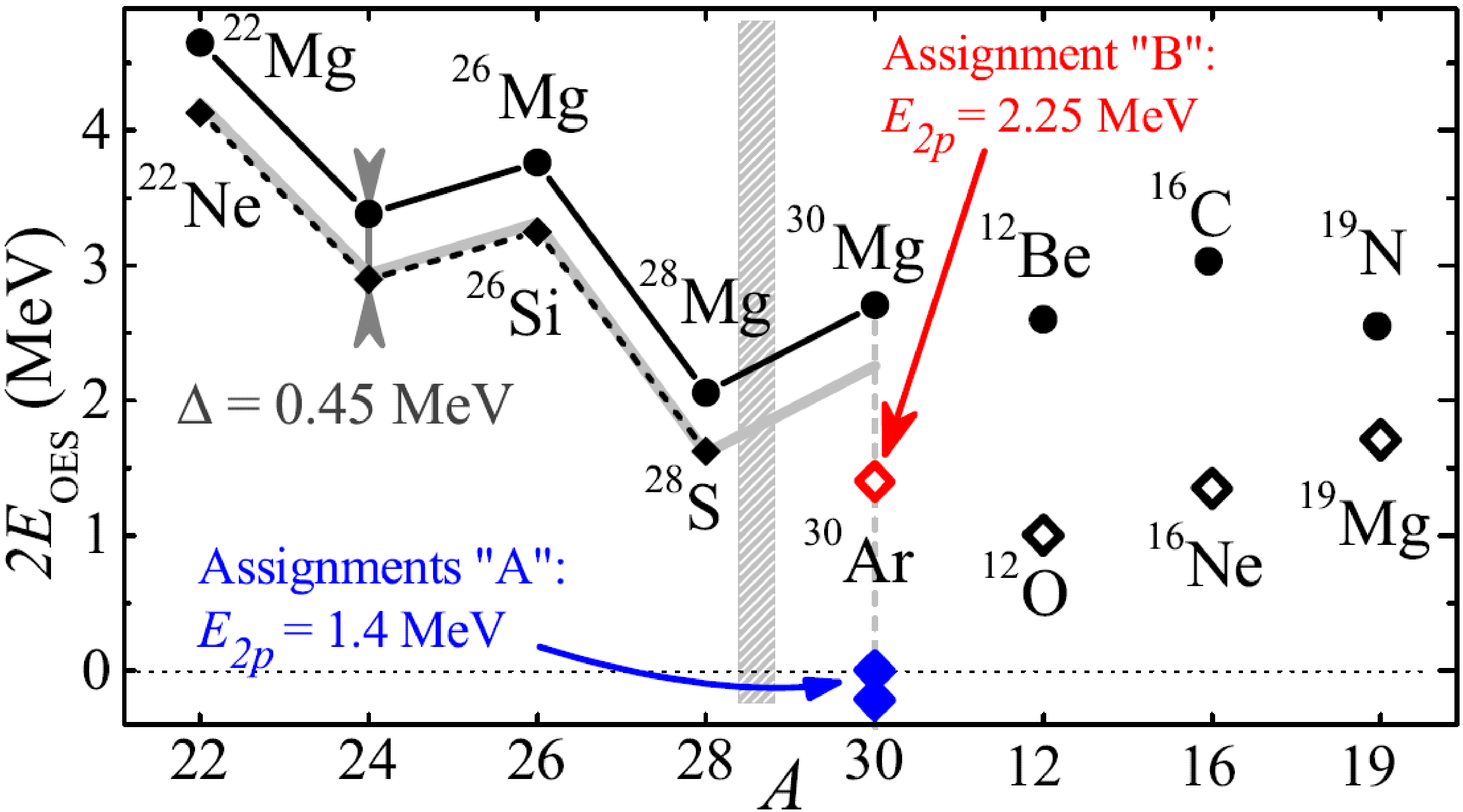
$^{17}Mg+p+p$ correlations

$$\rho_\theta = \sqrt{\theta^2(\text{HI-}p_1) + \theta^2(\text{HI-}p_2)}$$

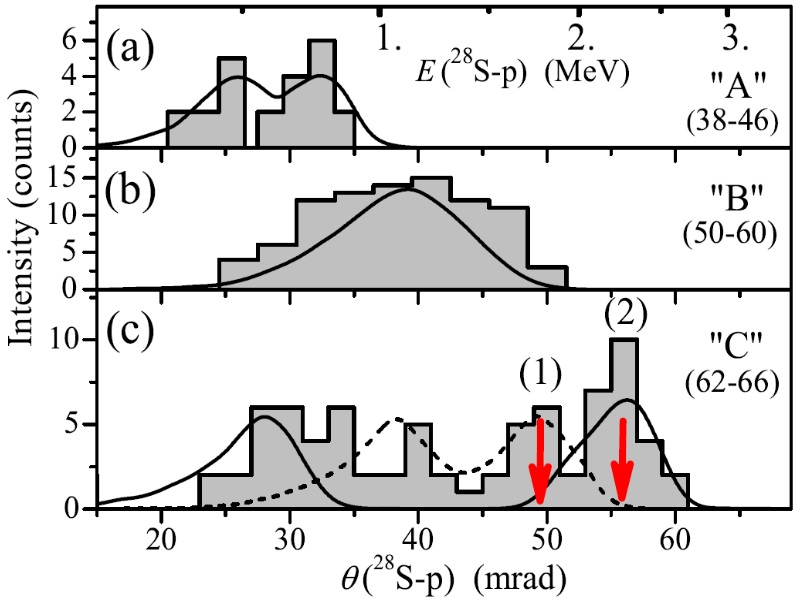
$^{28}S+p+p$ correlations

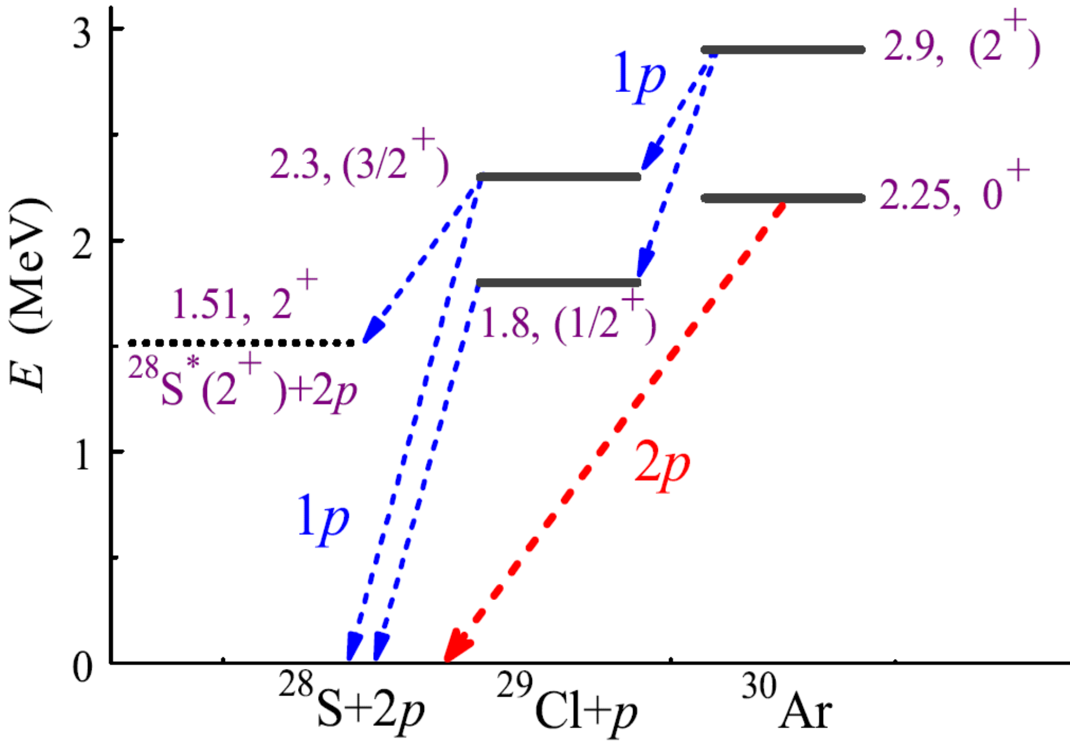
Experimental odd-even staggering energies

$2E_{OES}=2E_p-E_{2p}$; $2E_{OES}=2S_n-S_{2n}$



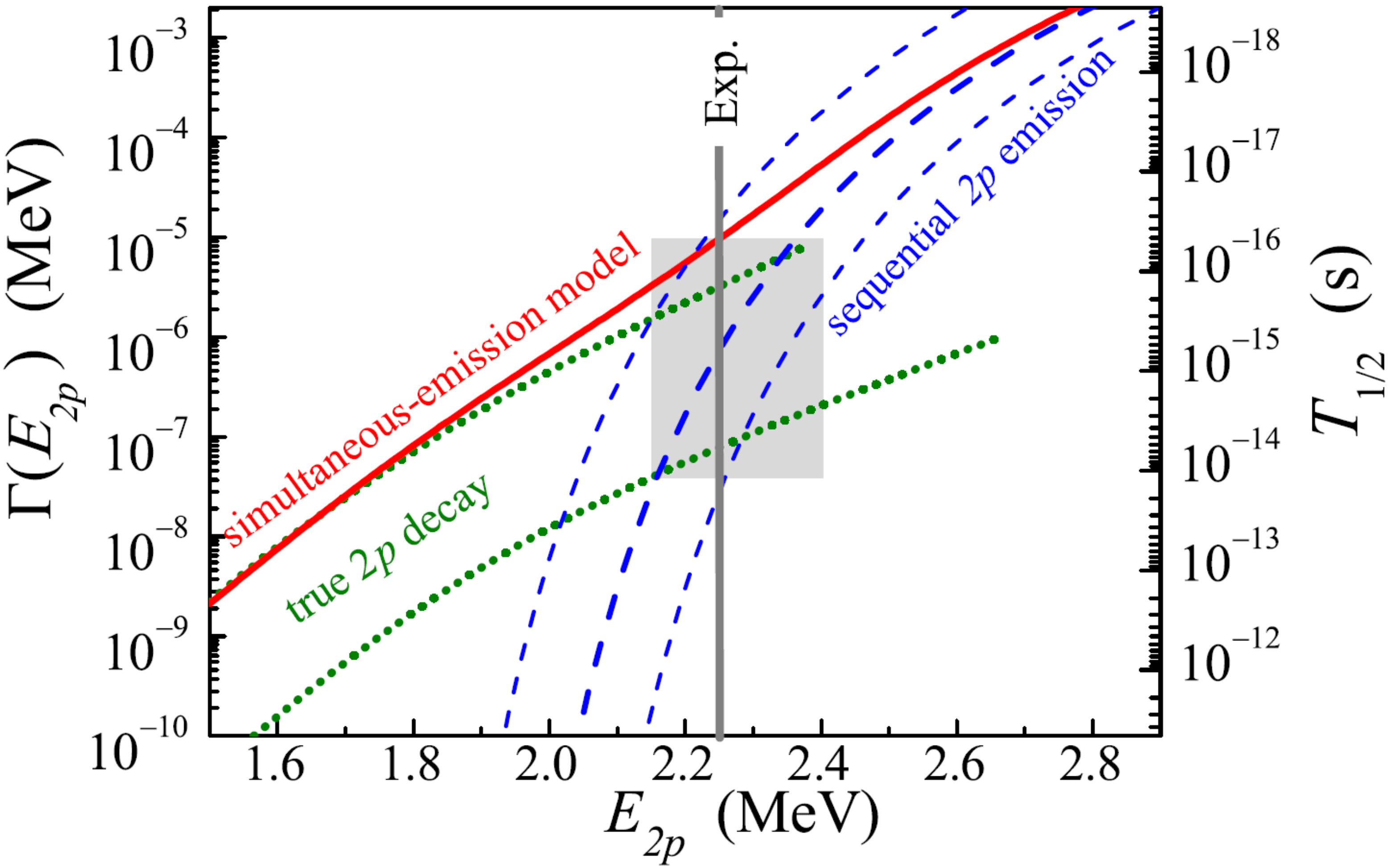
The levels in ^{30}Ar and ^{29}Cl





I.Mukha et al.,, submitted (2015)

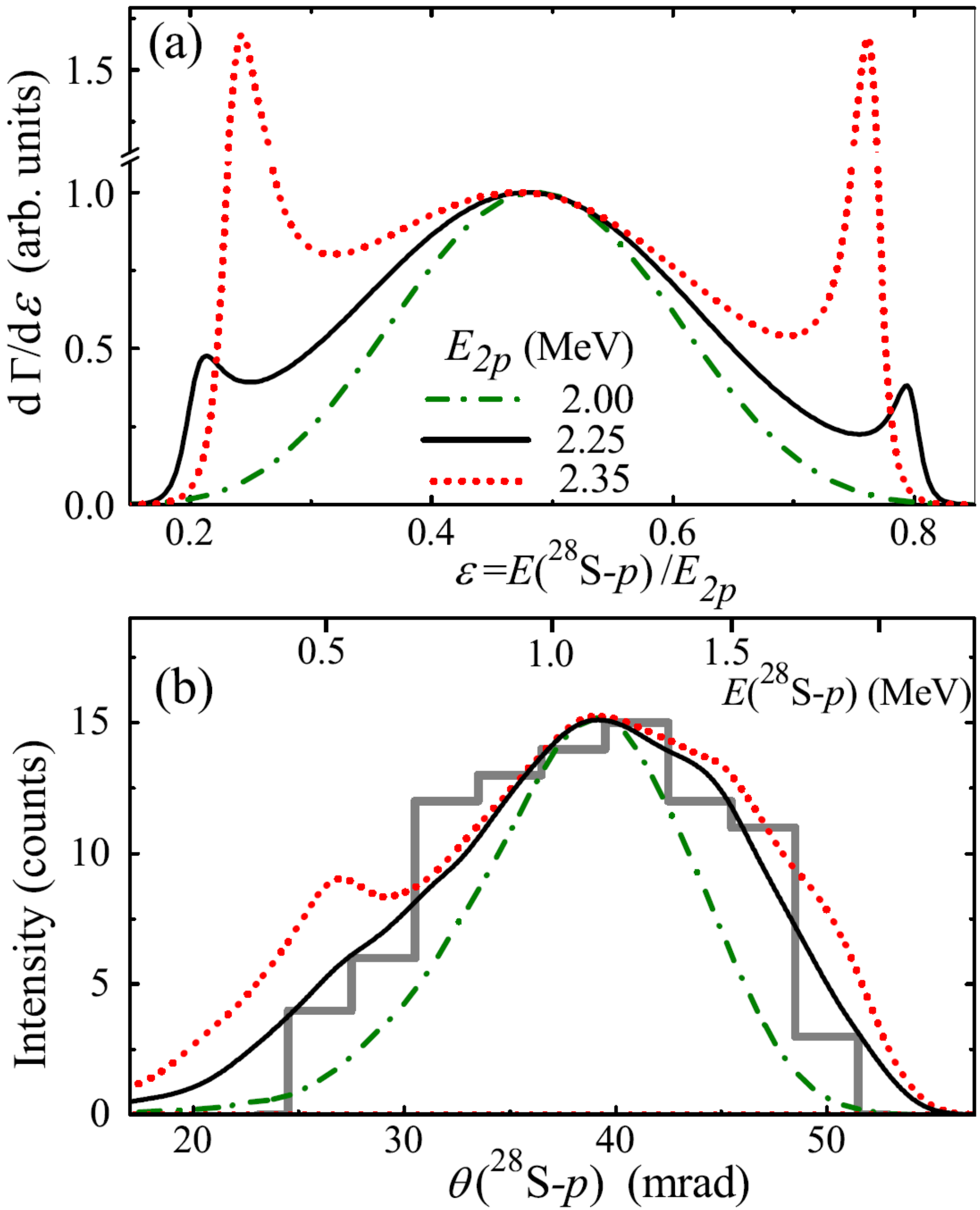
Half-life value of ^{30}Ar g.s.



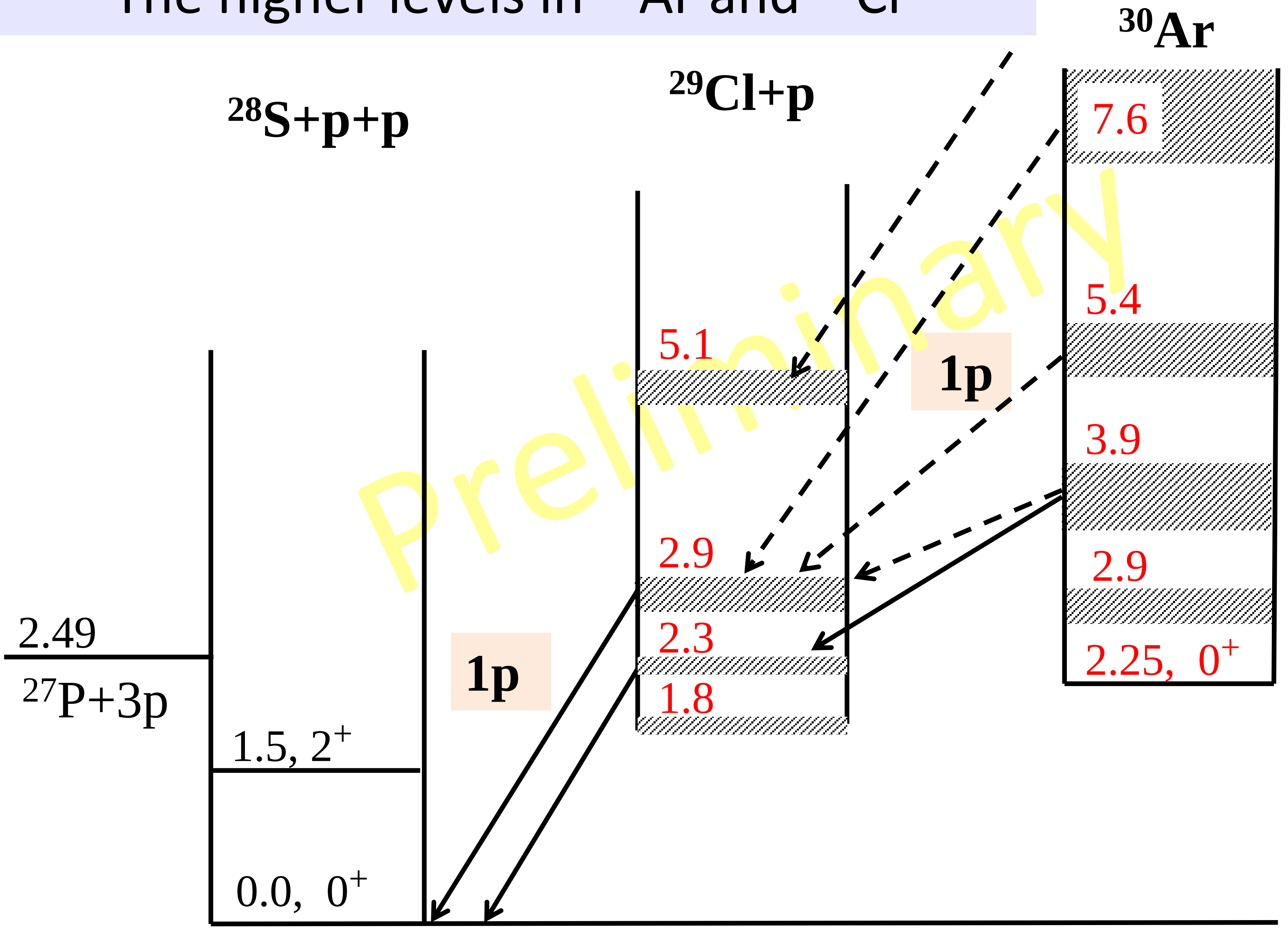
$$\Gamma(E_{2p}) = \frac{E_{2p}\langle V_3\rangle^2}{2\pi}\int_0^1 d\varepsilon\, \frac{\Gamma_{j_1}(\varepsilon E_{2p})}{(\varepsilon E_{2p}-E_{j_1})^2+\Gamma_{j_1}(\varepsilon E_{2p})^2/4} \times \frac{\Gamma_{j_2}((1-\varepsilon)E_{2p})}{((1-\varepsilon)E_{2p}-E_{j_2})^2+\Gamma_{j_2}((1-\varepsilon)E_{2p})^2/4}\,. \quad (1)$$

Simultaneous-emission model of Grigorenko

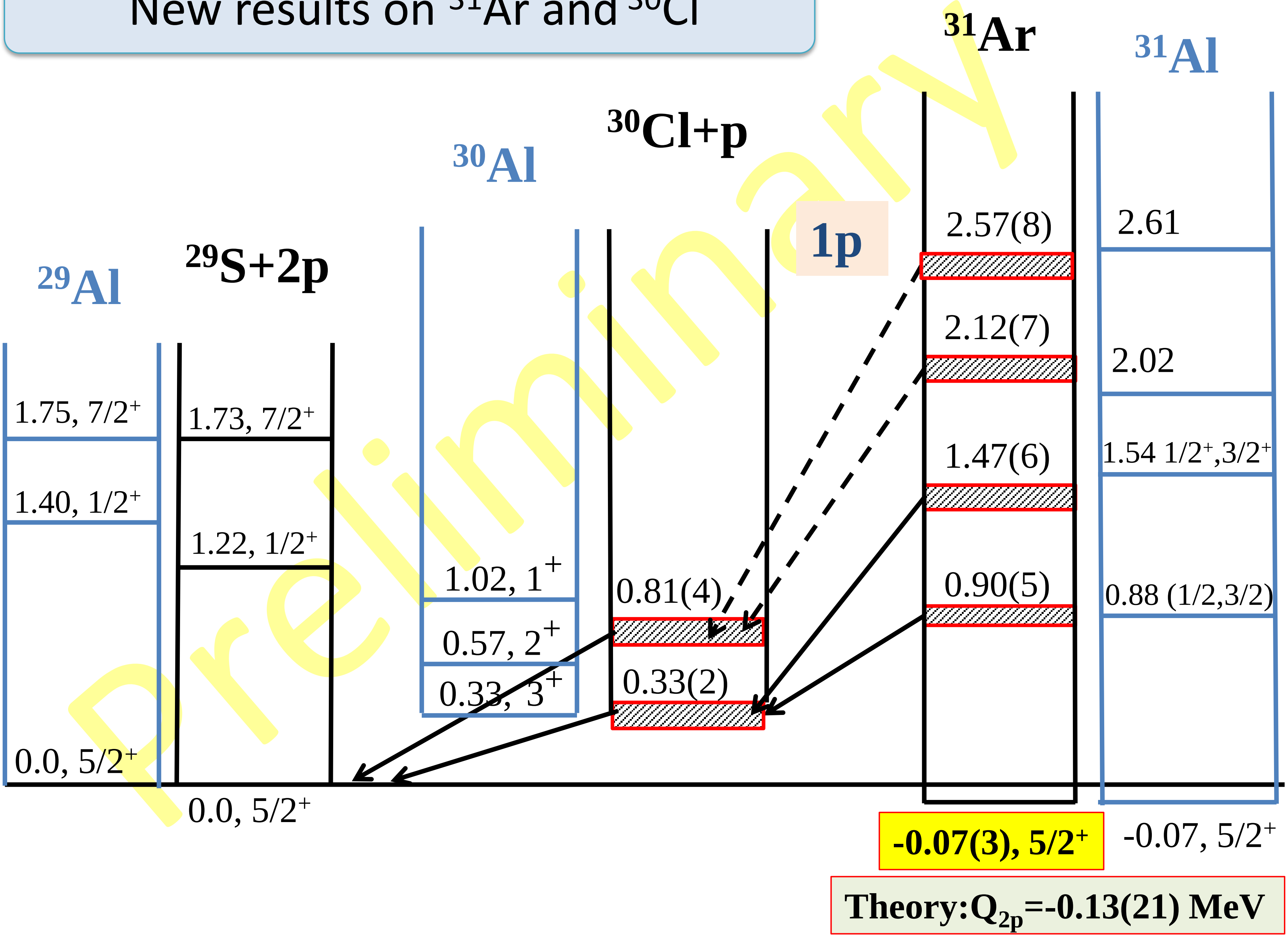
Interplay between true 2p and sequential proton decay mechanisms



The higher levels in ^{30}Ar and ^{29}Cl



New results on ^{31}Ar and ^{30}Cl



Experiment summary

Physics information obtained from limited data

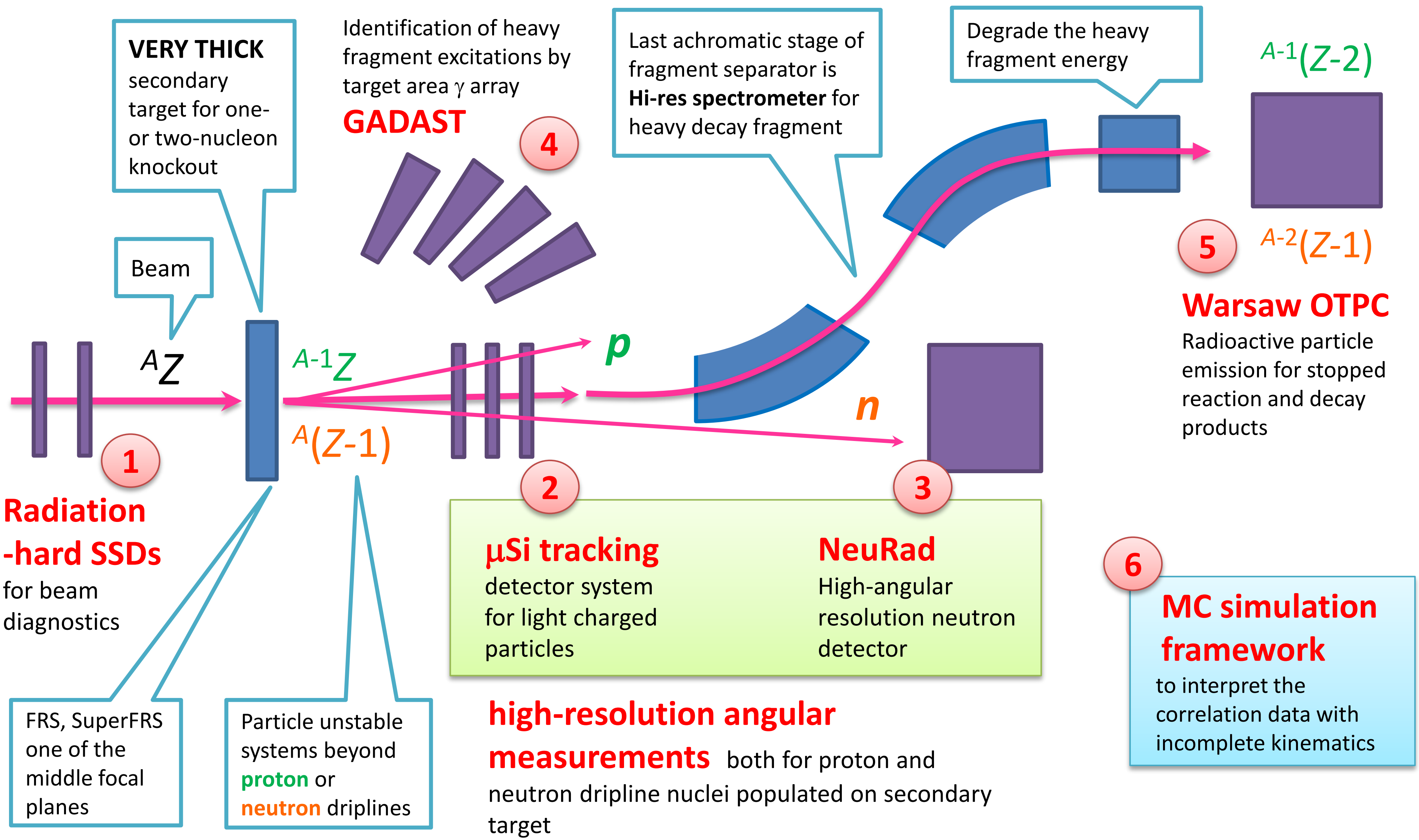
New isotopes ^{29}Cl, ^{30}Cl, ^{30}Ar discovered

First spectroscopy of ^{31}Ar, ^{30}Ar, ^{29}Cl, ^{30}Cl

Intermediate two-proton emission mechanism for ^{30}Ar g.s. identified with the lifetime predicted to be in fs range

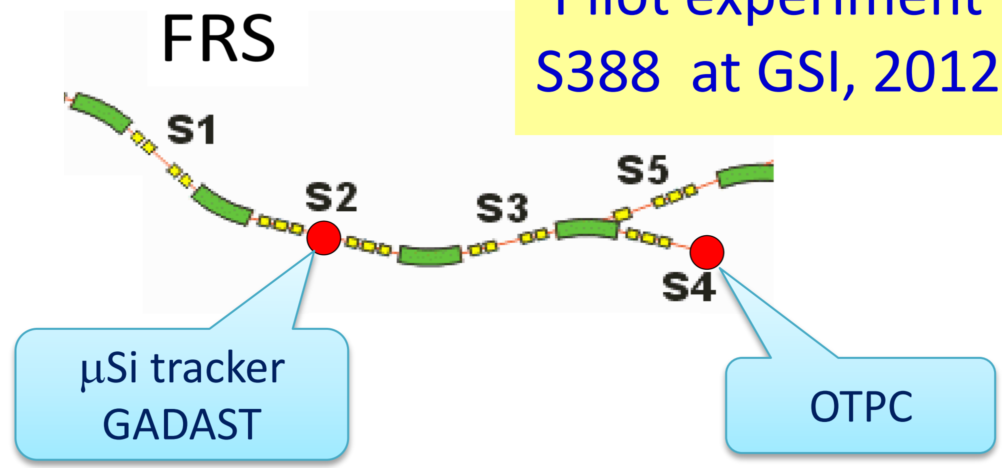
Thomas-Ehrman shift and level ordering in ^{29}Cl $(1/2^+,3/2^+)$ vs. ^{29}Mg $(3/2^+,1/2^+)$

Project EXPERT in the Super-FRS Collaboration of FAIR: (**EX**otic **P**article **E**mission and **R**adioactivity by **T**racking)

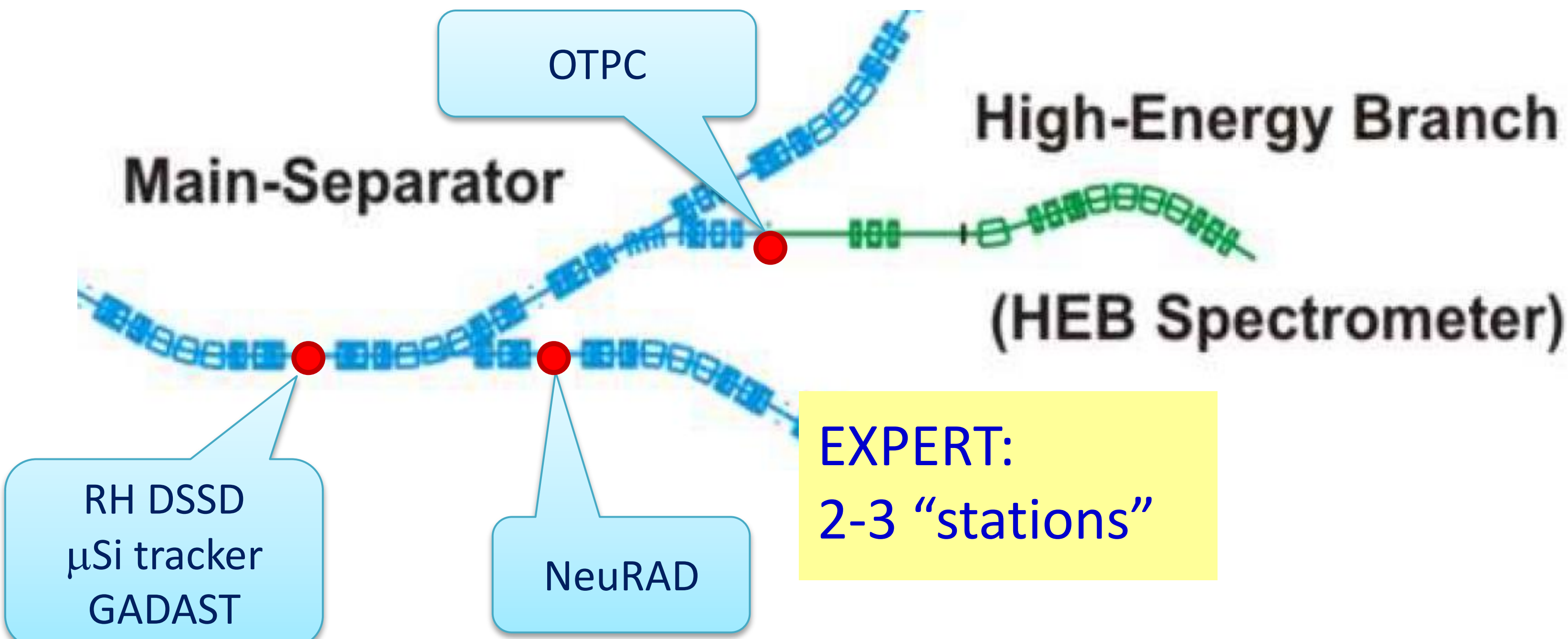


The EXPERT layout

Pilot experiment
S388 at GSI, 2012

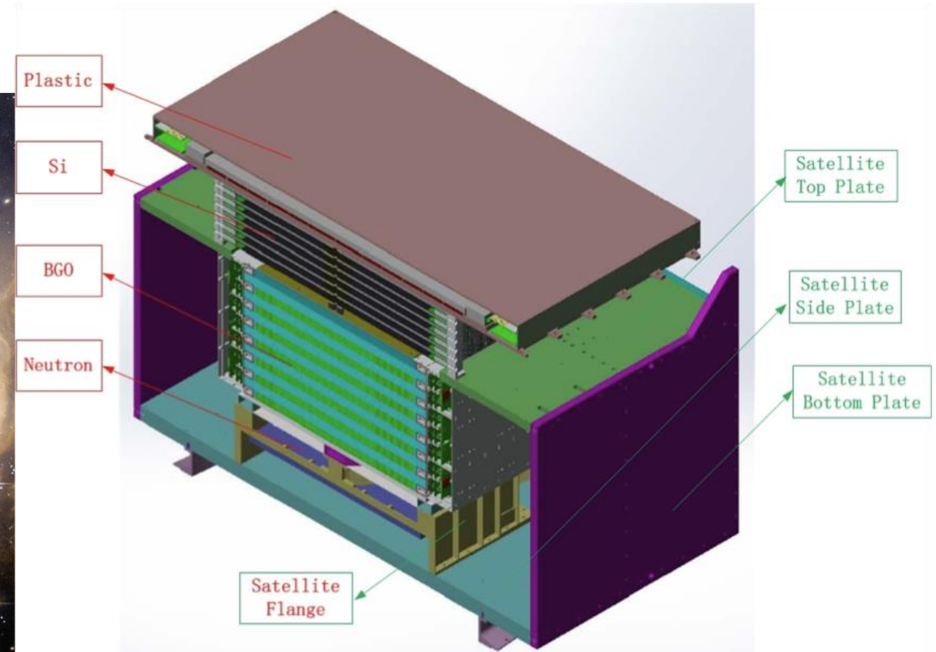


At Super-FRS



EXPERT:
2-3 "stations"

Si trackers by DAMPE (Dark Matter Particle Explorer)



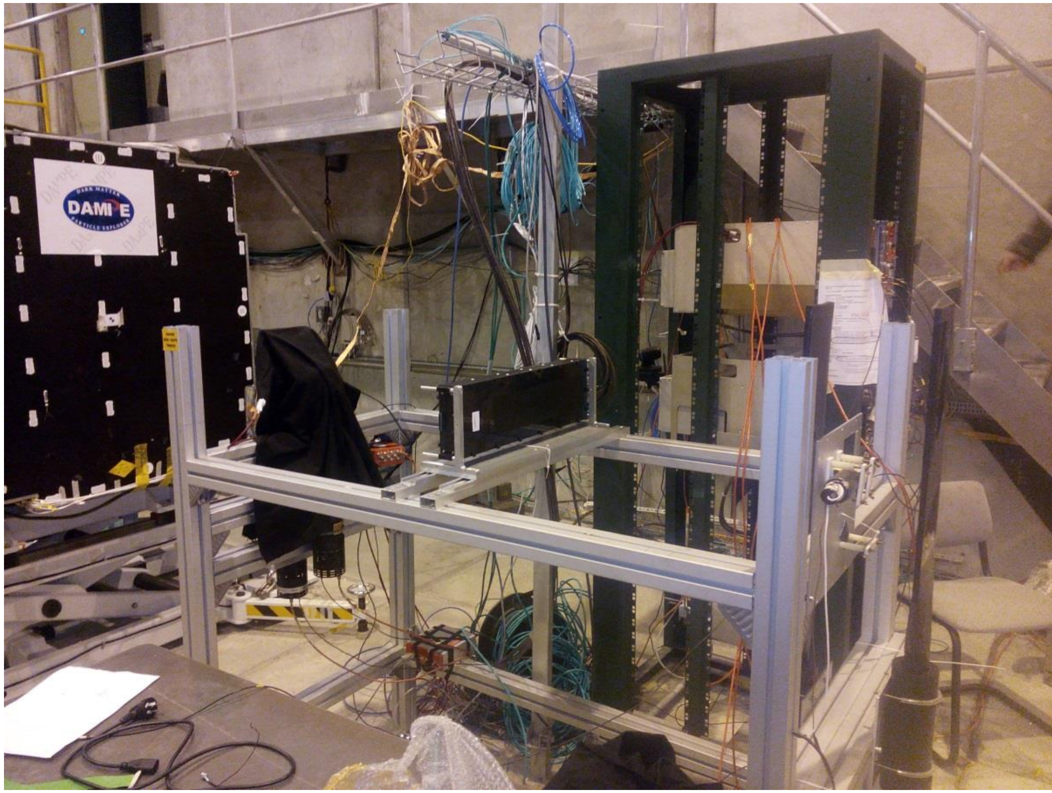
- Dark matter search apparatus
- Planned to be launched in 2015 – 2016 within the Chineese **Strategic Priority Research Program in Space Science**
- Different Si detectors but similar electronics as last generation of our detectors
- ***Synergy with astrophysics progects – AMS and DAMPE***

Courtesy of O.Kiselev

Test setup with DAMPE at SPS CERN

March 16 – April 1 2015

Detectors installed:
Beam trigger scintillators
Up to 6 our DSSDs
Two AMS ladders with DSSDs
Full DAMPE detector



- ^{40}Ar primary beam @ 30, 40 and 75 GeV/u
- Intensity: 5 – 1000 pps
- „Proton“ and „Secondary-ion“ runs

Courtesy of O. Kiselev

Test setup at SPS

- 4 or 6 detectors (X, Y) form a beam telescope
- Tracking through 3 (5) detectors allows testing one detector
- Full energy measurement by DAMPE provides $\Delta E - E$ correlation

Courtesy of O.Kiselev

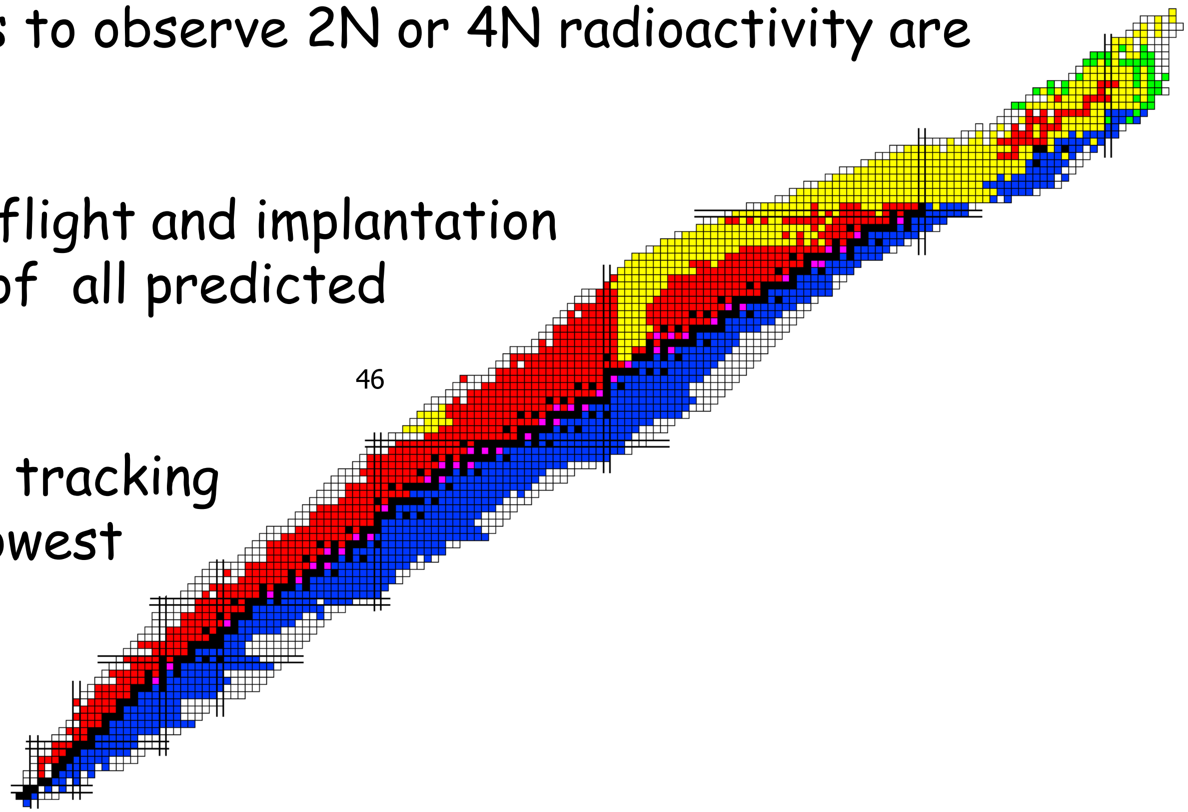
Summary

- One-, two- and four- proton decays limit the nuclear landscape beyond the drip-lines in nuclear landscape.

- Life-times of 2N, 4N precursors are much longer in comparison with 1N precursors, thus prospects to observe 2N or 4N radioactivity are more hopeful.

- Invariant-mass, decay-in-flight and implantation techniques allow studies of all predicted radioactivity precursors

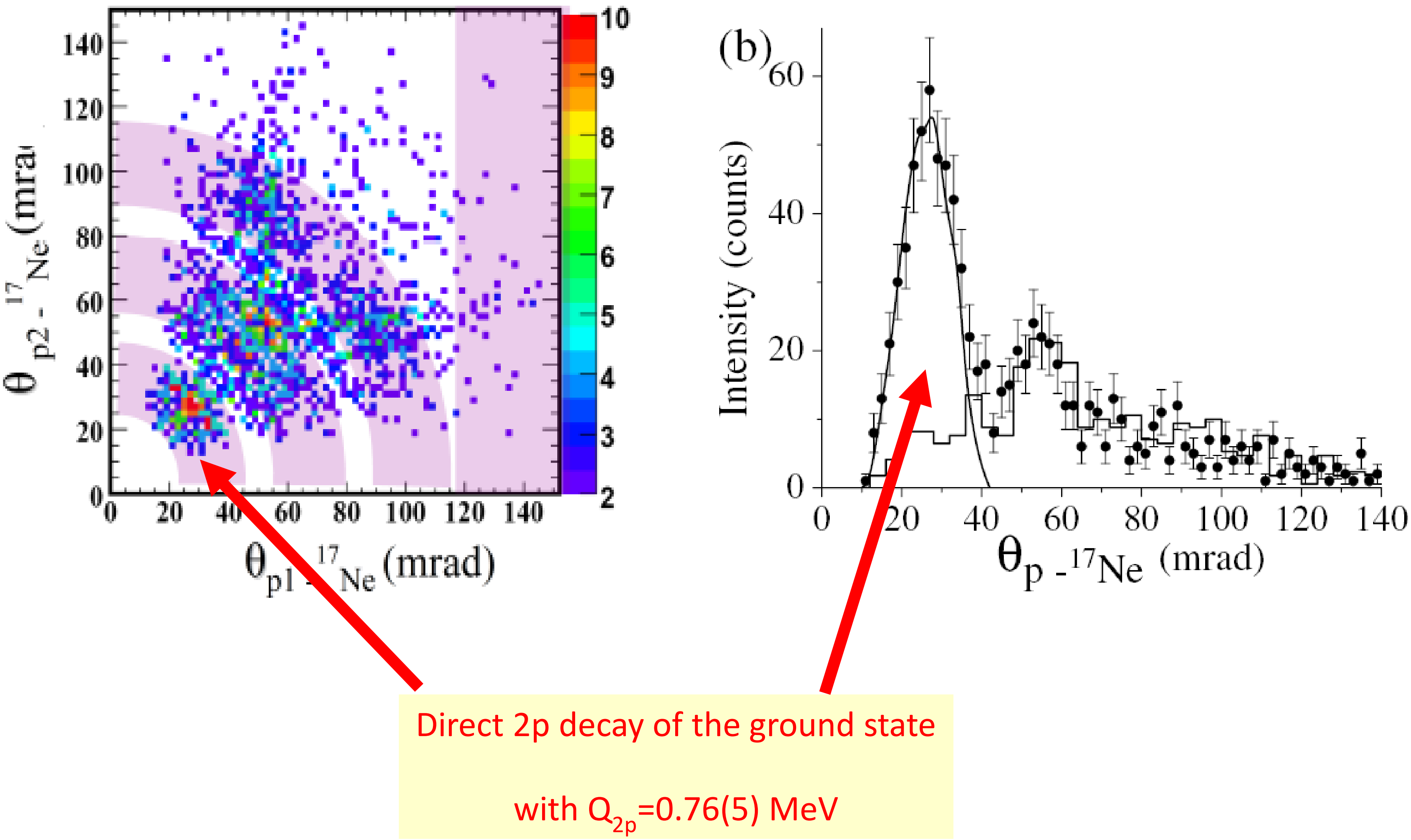
- Decay-in-flight method by tracking technique is best at the lowest decay energies



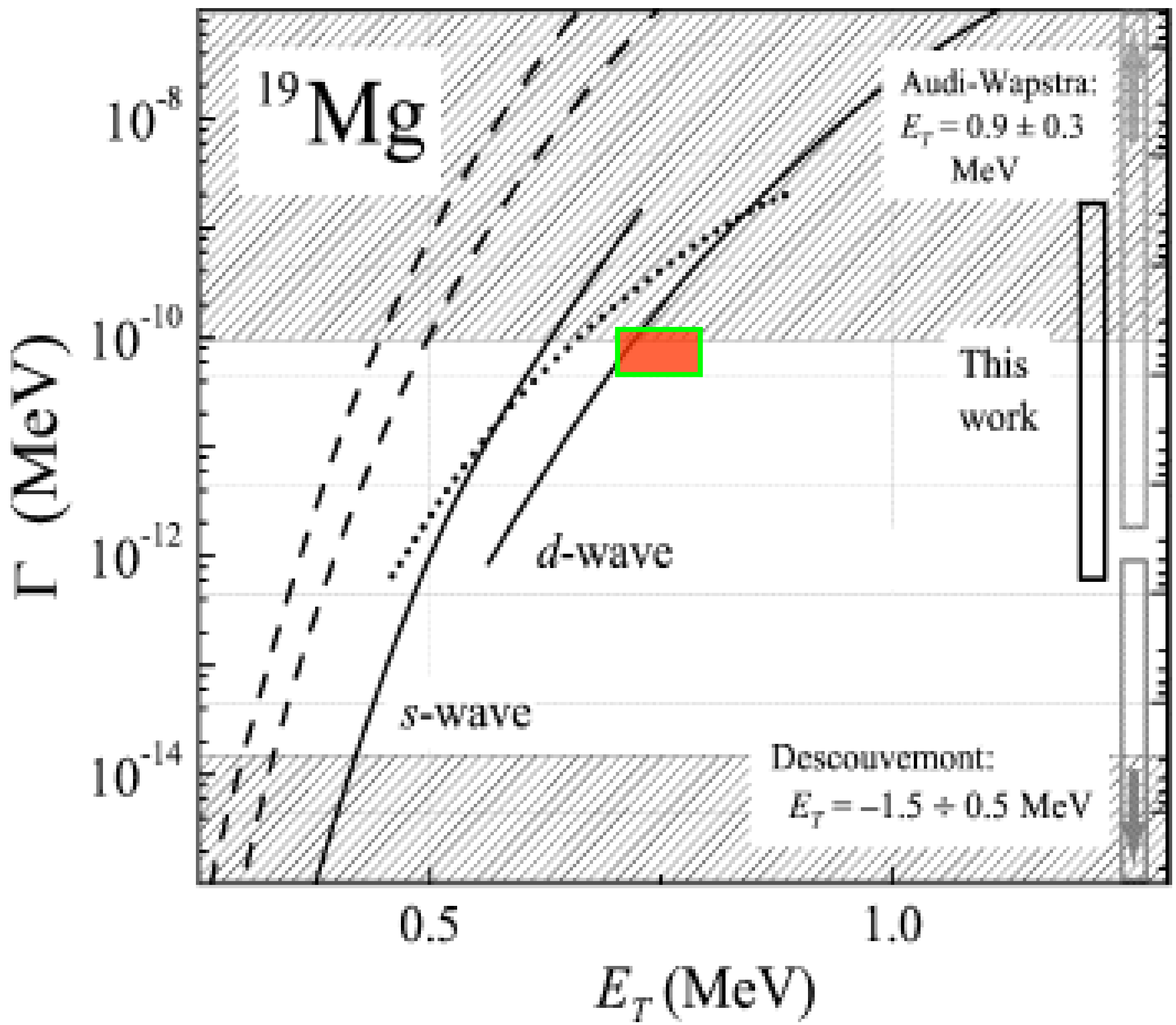
I. Mukha,[1,2] L.V. Grigorenko,[3,4,2] X. Xu,[5,1,6,*] L. Acosta,[7,8] E. Casarejos,[9] A.A. Ciemny,[10] W. Dominik,[10] J. Duénas-Díaz,[11] V. Dunin,[12] J. M. Espino,[13] A. Estradé,[14] F. Farińon,[1] A. Fomichev,[3] H. Geissel,[1,5] T.A. Golubkova,[15] A. Gorshkov,[3] Z. Janas,[10] G. Kamiński,[16,3] O. Kiselev,[1] R. Knöbel,[1,17] S. Krupko,[3] M. Kuich,[18,10] Yu.A. Litvinov,[1] G. Marquinez-Durán,[11] I. Martel,[11] C. Mazzocchi,[10] C. Nociforo,[1] A. K. Ordúz,[11] M. Pfützner,[10,1] S. Pietri,[1] M. Pomorski,[10] A. Prochazka,[1] S. Rymzhanova,[3] A.M. Sánchez-Benítez,[11] C. Scheidenberger,[1,5] P. Sharov,[3] H. Simon,[1] B. Sitar,[19] R. Slepnev,[3] M. Stanoiu,[20] P. Strmen,[19] I. Szarka,[19] M. Takechi,[1] Y.K. Tanaka,[1,21] H. Weick,[1] M. Winkler,[1] and J.S. Winfield[1]

[1] *GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany*
[2] *National Research Centre "Kurchatov Institute", Kurchatov sq. 1, 123182 Moscow, Russia*
[3] *Flerov Laboratory of Nuclear Reactions, JINR, 141980 Dubna, Russia*
[4] *National Research Nuclear University "MEPhI", 115409 Moscow, Russia*
[5] *II.Physikalisches Institut, Justus-Liebig-Universität, 35392 Gießen, Germany*
[6] *School of Physics and Nuclear Energy Engineering, Beihang University, 100191 Beijing, China*
[7] *INFN, Laboratori Nazionali del Sud, Via S. Sofía, 95123 Catania, Italy*
[8] *Instituto de Física, Universidad Nacional Autónoma de México, México, D.F. 01000, Mexico*
[9] *University of Vigo, 36310 Vigo, Spain*
[10] *Faculty of Physics, University of Warsaw, 02-093 Warszawa, Poland*
[11] *Department of Applied Physics, University of Huelva, 21071 Huelva, Spain*
[12] *Veksler and Baldin Laboratory of High Energy Physics, JINR, 141980 Dubna, Russia*
[13] *Department of Atomic, Molecular and Nuclear Physics, University of Seville, 41012 Seville, Spain*
[14] *University of Edinburgh, EH1 1HT Edinburgh, United Kingdom*
[15] *Advanced Educational and Scientific Center, Moscow State University, 121357 Moscow, Russia*
[16] *Institute of Nuclear Physics PAN, 31-342 Kraków, Poland*
[17] *Justus-Liebig-Universität, 35392 Gießen, Germany*
[18] *Faculty of Physics, Warsaw University of Technology, 00-662 Warszawa, Poland*
[19] *Faculty of Mathematics and Physics, Comenius University, 84248 Bratislava, Slovakia*
[20] *IFIN-HH, Post Office Box MG-6, Bucharest, Romania*
[21] *University of Tokyo, 113-0033 Tokyo, Japan*

Decay energy of ^{19}Mg measured by ^{17}Ne+p+p correlations



Comparison of the data with the theoretical predictions:



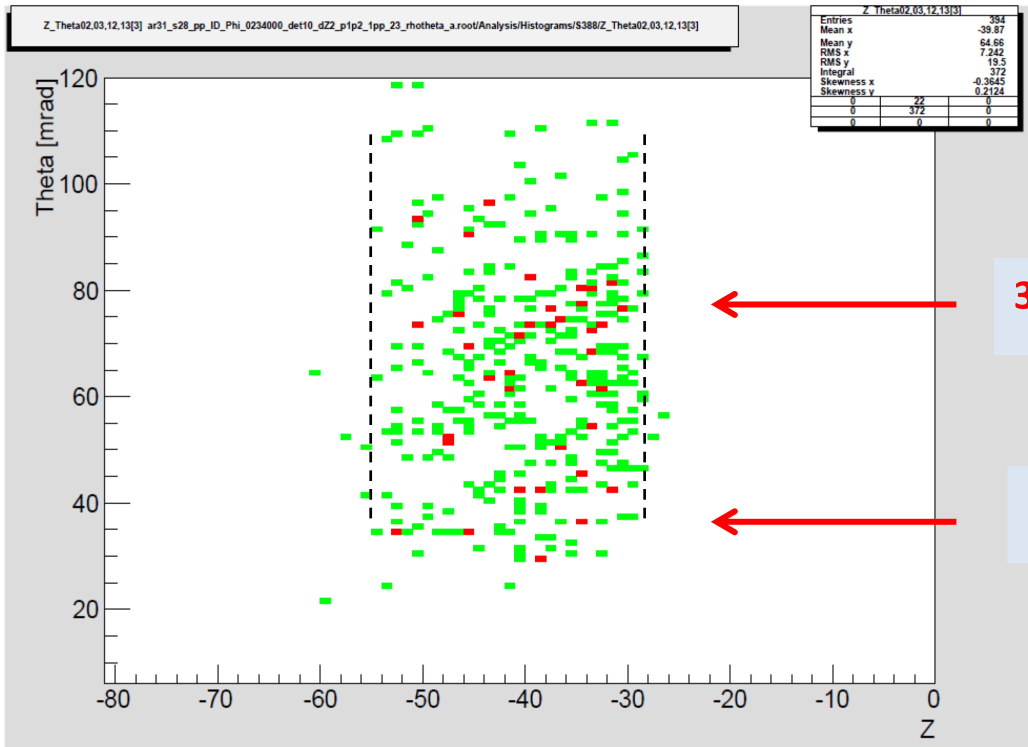
Theory predictions:

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

Experiment:

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

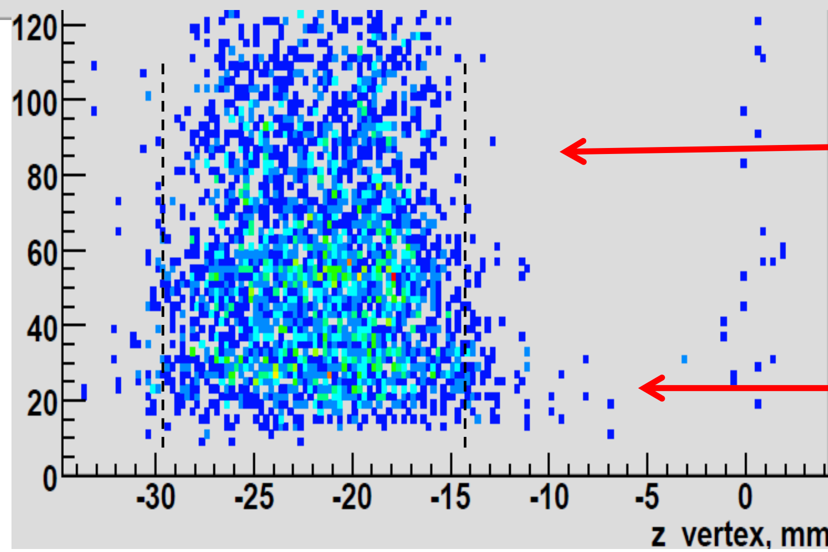
Life-time of ^{30}Ar derived by vertex distribution of ^{28}S+p+p



^{30}Ar exc. states

^{30}Ar ground state

Reference case: ^{19}Mg



^{19}Mg exc. states

^{19}Mg ground state