Two-proton emitters "reflecting" the halo structure of their mirror neutron-rich nuclei

Ivan Mukha

Motivation. Evolution and limits of existence of proton-unbound nuclei

Mechanisms of 2*p* decays

Recent results: 1*p*, 3*p*, 4*p* emitters studied by tracking products of their decays in-flight: ^{21}Al, ^{20}Al, ^{18}Mg

Prospects at the FRS/Super-FRS:
High-resolution measurement of in-flight decay products at high energy.

International Symposium
Commemorating the 40th Anniversary of the Halo Nuclei
October 12 – 18, Beijing, China

Pioneer Experiments with the BEVALAC
(Discovery of Neutron Halo Nuclei)

VOLUME 55, NUMBER 24 PHYSICAL REVIEW LETTERS 9 DECEMBER 1985

Measurements of Interaction Cross Sections and Nuclear Radii in the Light *p*-Shell Region

I. Tanihata,[a] H. Hamagaki, O. Hashimoto, Y. Shida, and N. Yoshikawa
Institute for Nuclear Study, University of Tokyo, Tanashi, Tokyo 188, Japan

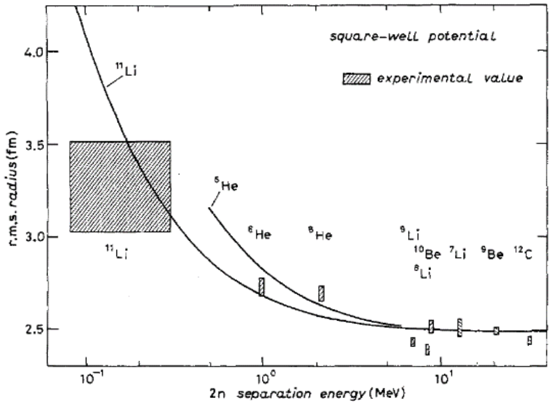
K. Sugimoto,[b] O. Yamakawa, and T. Kobayashi
Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

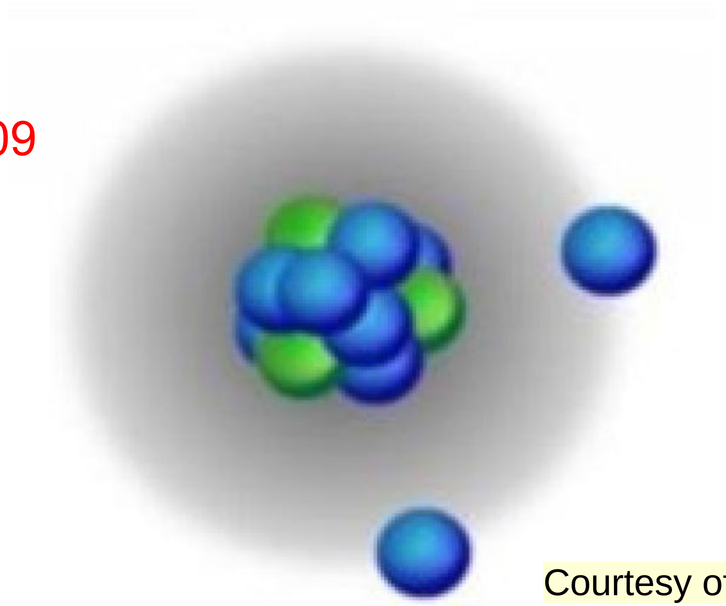
and

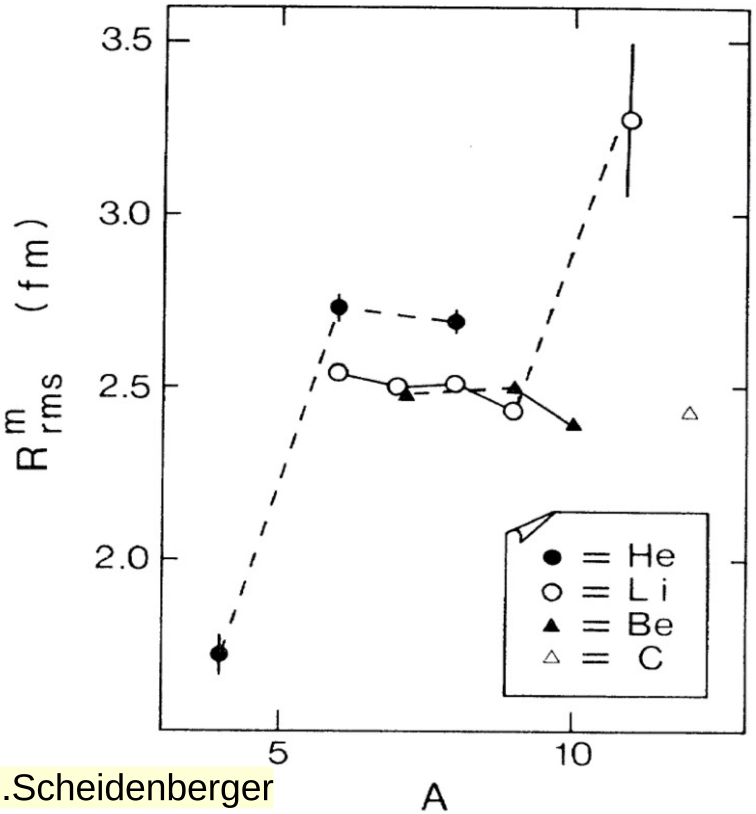
N. Takahashi
College of General Education, Osaka University, Toyor

(Received 11 July 1985; revised manuscript received

P.G. Hansen, B, Jonson
Europhys. Lett. 4 (1987) 409







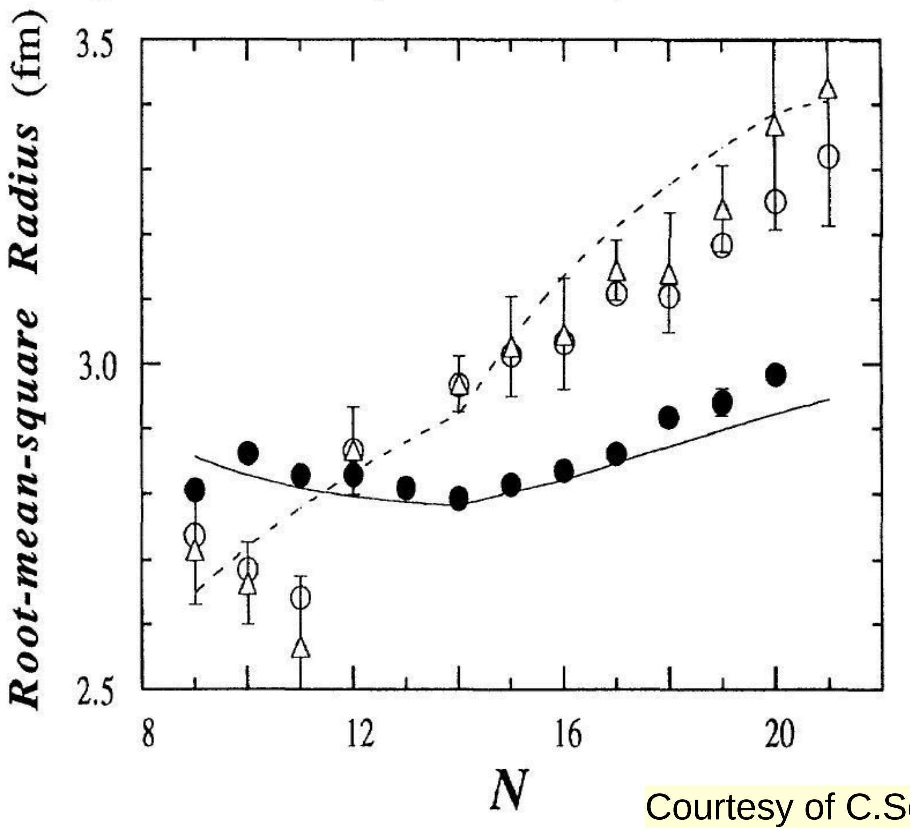
Courtesy of C.Scheidenberger

Discovery of the Neutron Skin in Na Isotopes at GSI

VOLUME 75, NUMBER 18 PHYSICAL REVIEW LETTERS 30 OCTOBER 1995

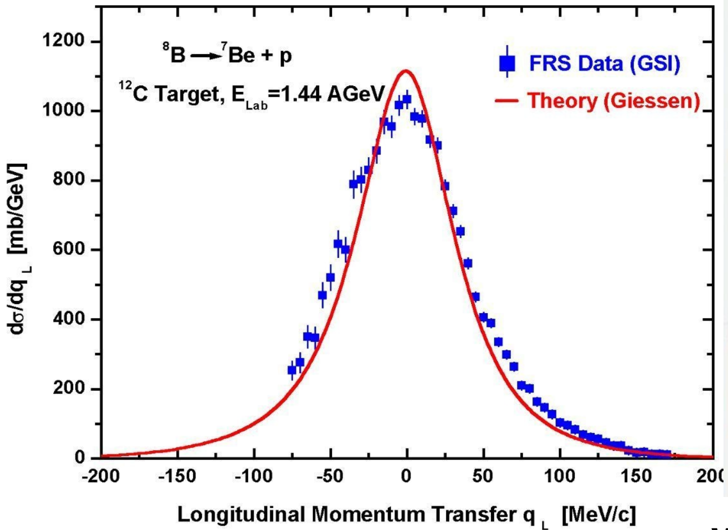
Neutron Skin of Na Isotopes Studied via Their Interaction Cross Sections

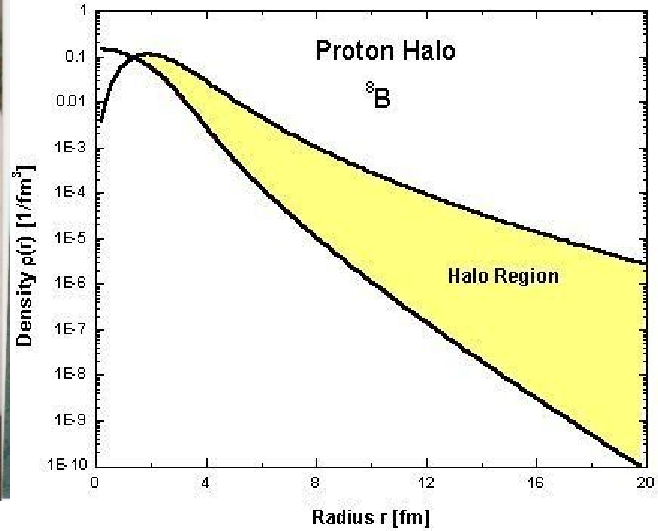
T. Suzuki,[1,2] H. Geissel,[2] O. Bochkarev,[3] L. Chulkov,[3] M. Golovkov,[3] D. Hirata,[1] H. Irnich,[2] Z. Janas,[2] H. Keller,[2] T. Kobayashi,[1] G. Kraus,[2] G. Münzenberg,[2] S. Neumaier,[2] F. Nickel,[2] A. Ozawa,[1] A. Piechaczeck,[2] E. Roeckl,[2] W. Schwab,[2] K. Sümmerer,[2] K. Yoshida,[1] and I. Tanihata[1]



Courtesy of C.Scheidenberger

Discovery of the Proton Halo in ^8B with FRS



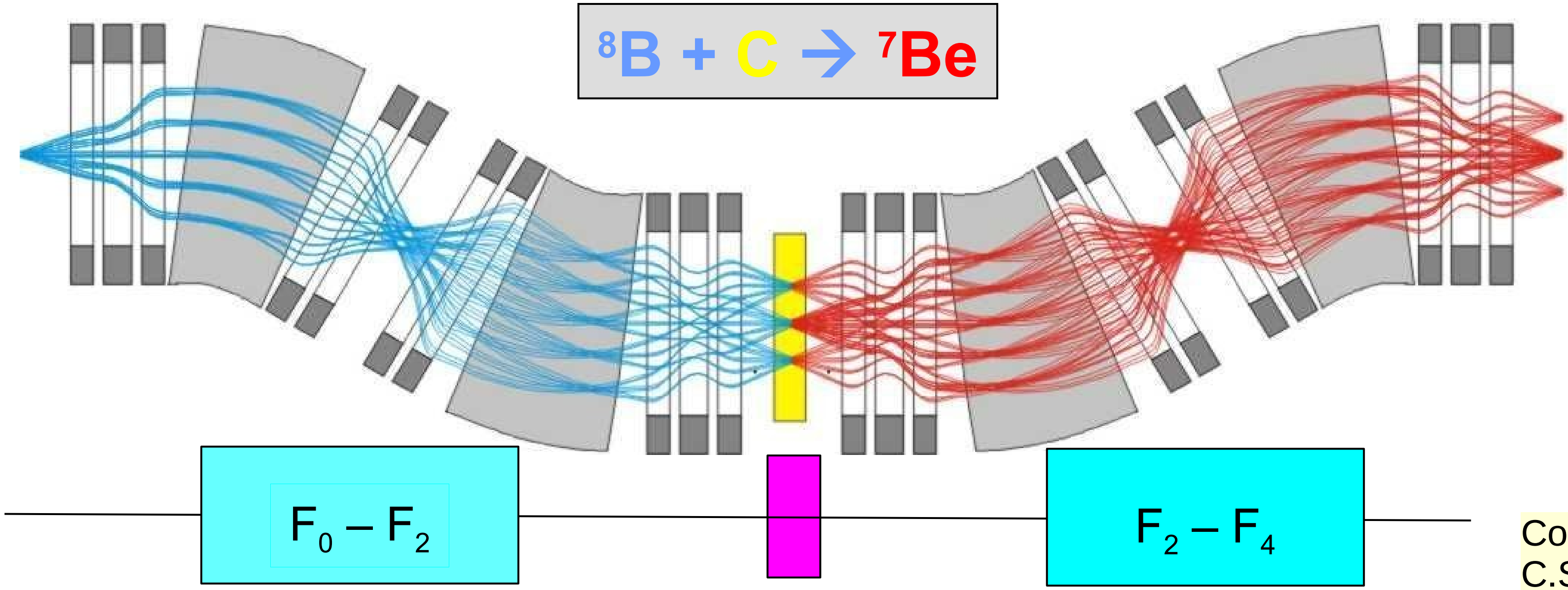


Horst Lenske

W. Schwab et al. Z. Phys. A350, 283 (1995)

$^8B + C \rightarrow {}^7Be$

1500 MeV/u
^{12}C

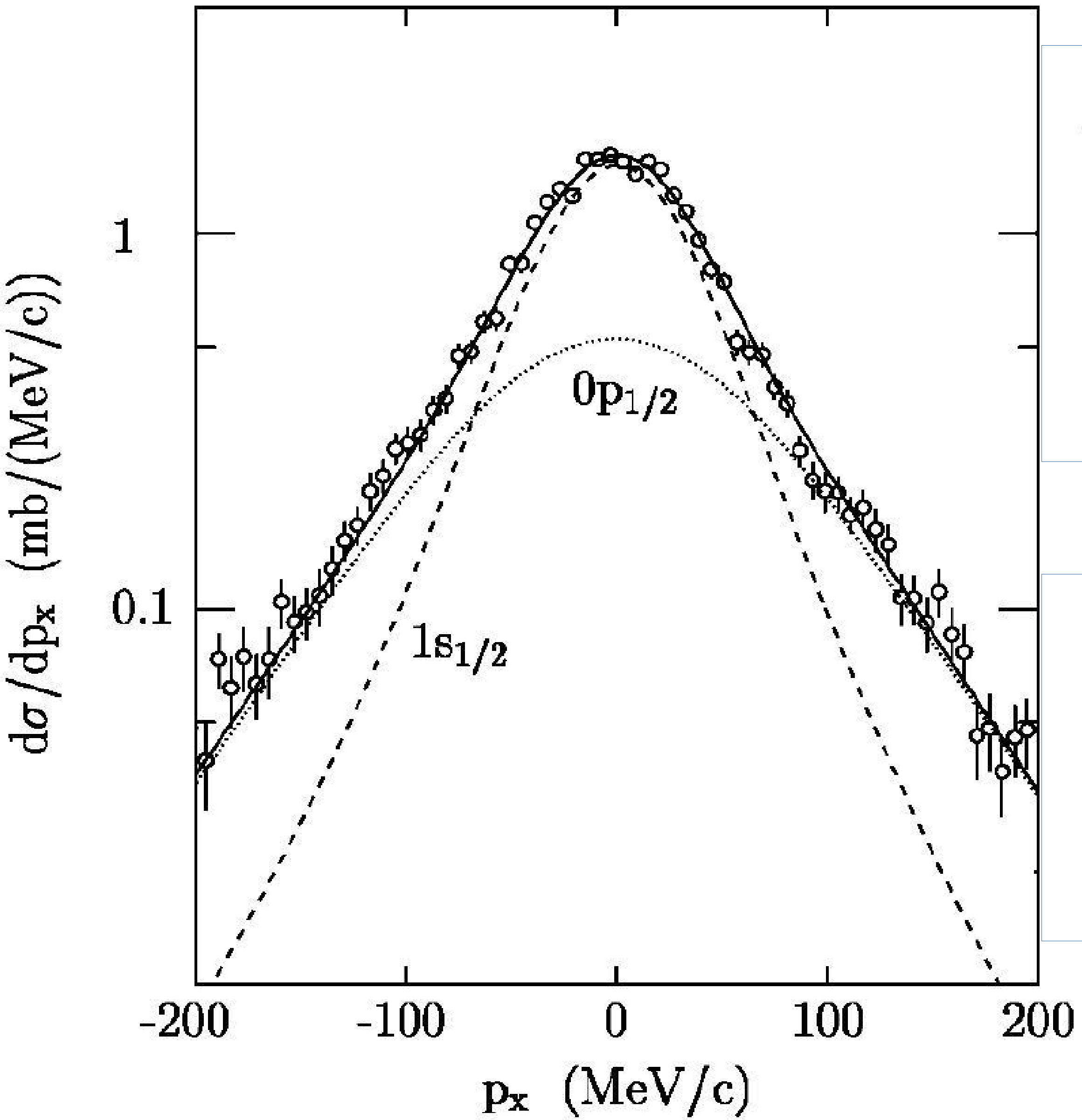


^7Be

FRS in a dispersion-matching mode

Courtesy of C.Scheidenberger

Different parities admixture in ^{11}Li
Experiment with FRS – ALADIN – LAND in 1995



VOLUME 75, NUMBER 9 PHYSICAL REVIEW LETTERS 28 AUGUST 1995

Study of the Unstable Nucleus ^{10}Li in Stripping Reactions of the Radioactive Projectiles ^{11}Be and ^{11}Li

M. Zinser,[1] F. Humbert,[2] T. Nilsson,[3] W. Schwab,[1] Th. Blaich,[4] M. J. G. Borge,[5] L. V. Chulkov,[6] H. Eickhoff,[1] Th. W. Elze,[7] H. Emling,[1] B. Franzke,[1] H. Freiesleben,[8] H. Geissel,[1] K. Grimm,[7] D. Guillemaud-Mueller,[9] P. G. Hansen,[10,13] R. Holzmann,[1] H. Irnich,[1] B. Jonson,[3] J. G. Keller,[8] O. Klepper,[1] H. Klingler,[7] J. V. Kratz,[4] R. Kulessa,[11] D. Lambrecht,[4] Y. Leifels,[8] A. Magel,[1] M. Mohar,[1] A. C. Mueller,[9] G. Münzenberg,[1] F. Nickel,[1] G. Nyman,[3] A. Richter,[2] K. Riisager,[10] C. Scheidenberger,[1] G. Schrieder,[2] B. M. Sherrill,[12] H. Simon,[2] K. Stelzer,[7] J. Stroth,[1] O. Tengblad,[13] W. Trautmann,[1] E. Waida,[11] and E. Zude[1]

VOLUME 83, NUMBER 3 PHYSICAL REVIEW LETTERS 19 JULY 1999

Direct Experimental Evidence for Strong Admixture of Different Parity States in ^{11}Li

H. Simon,[1] D. Aleksandrov,[2] T. Aumann,[3] L. Axelsson,[4] T. Baumann,[5] M. J. G. Borge,[6] L. V. Chulkov,[2] R. Collatz,[5] J. Cub,[1] W. Dostal,[3] B. Eberlein,[3] Th. W. Elze,[7] H. Emling,[5] H. Geissel,[5] A. Grünschloss,[7] M. Hellström,[5] J. Holeczek,[8] R. Holzmann,[5] B. Jonson,[4] J. V. Kratz,[3] G. Kraus,[5] R. Kulessa,[9] Y. Leifels,[5] A. Leistenschneider,[7] T. Leth,[10] I. Mukha,[2,10] G. Münzenberg,[5] F. Nickel,[5] T. Nilsson,[11] G. Nyman,[4] B. Petersen,[10] M. Pfützner,[5] A. Richter,[1] K. Riisager,[10] C. Scheidenberger,[5] G. Schrieder,[1] W. Schwab,[5] M. H. Smedberg,[4] J. Stroth,[7] A. Surowiec,[8] O. Tengblad,[6] and M. V. Zhukov[2,4]

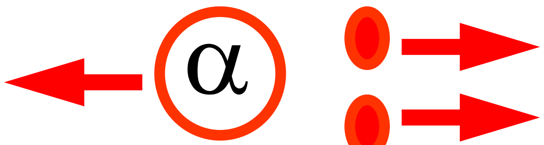
Courtesy of C.Scheidenberger

Nuclear structure reflected in 2*p* decay of ^{6}Be – mirror of ^{6}He

Reference case: ^{6}Be(0+)→ α+p+p

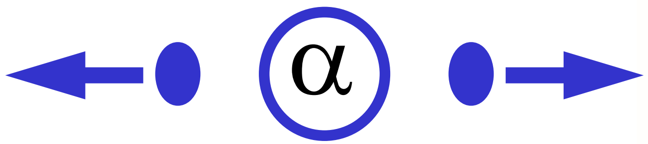
Diproton

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



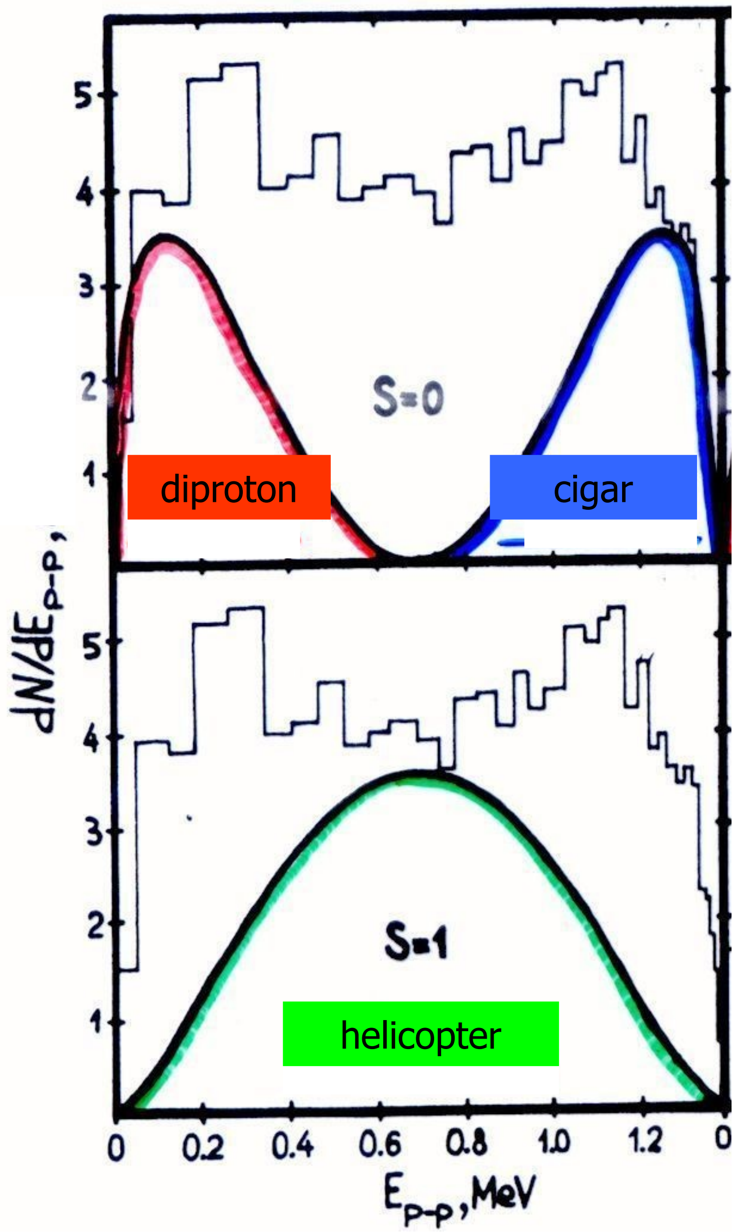
Cigar

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



Helicopter

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

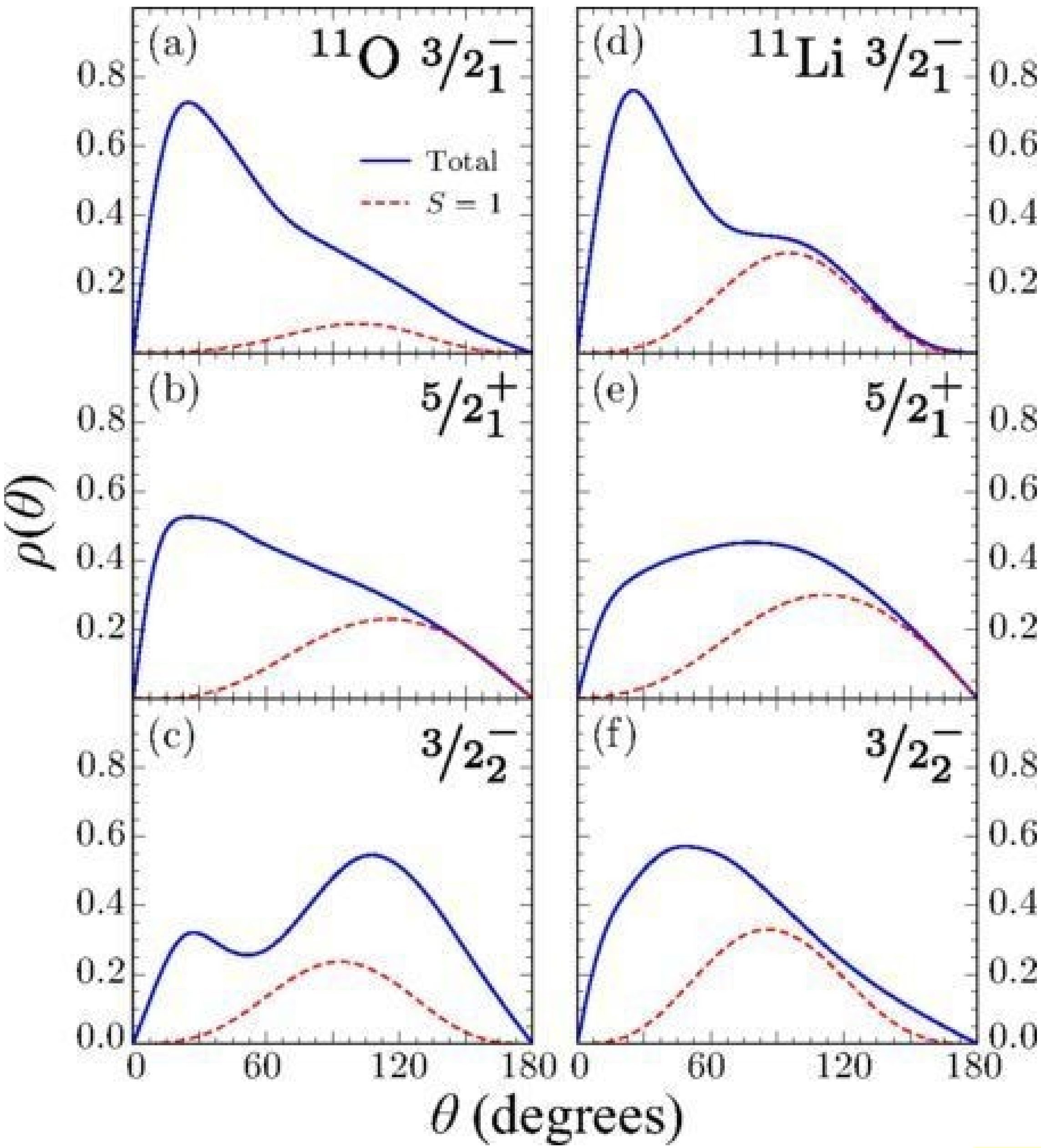


The observed decay modes reflect the ^{6}Be structure,

I.J. Thompson, B.V.Danilin, V.D.Efros, J.S.Vaagen, J.M.Bang, M.V.Zhukov, Phys. Rev. C **61**, 024318 (2000)

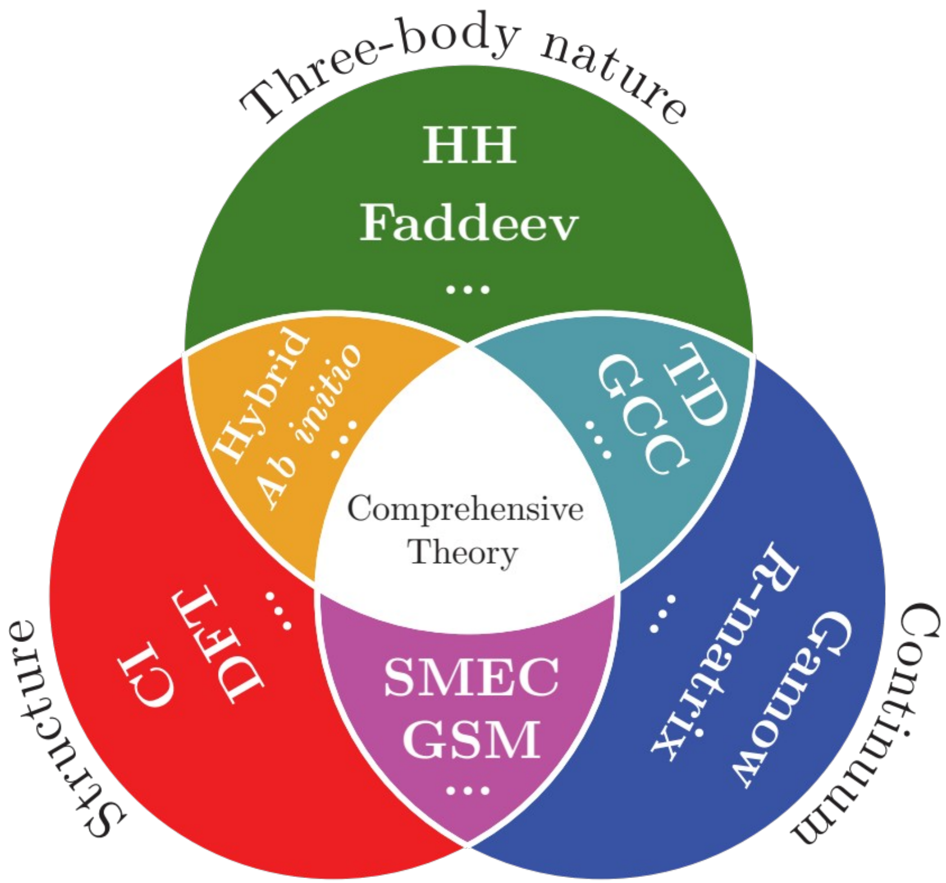
O. Bochkarev *et al.*, Nucl.Phys. **A505** (1989) 215

Nucleon-nucleon correlations in mirror ^{11}Li and ^{11}O states



S.M. Wang, W. Nazarewicz, R.J. Charity, L.G. Sobotka, Phys. Rev. C 99 (2019) 054302

Theoretical aspects of two-proton emission by exotic nuclei



HH: Hyperspherical harmonics

CI: Configuration interaction (shell model)

DFT: Density functional theory

SMEC: Shell model embedded with continuum

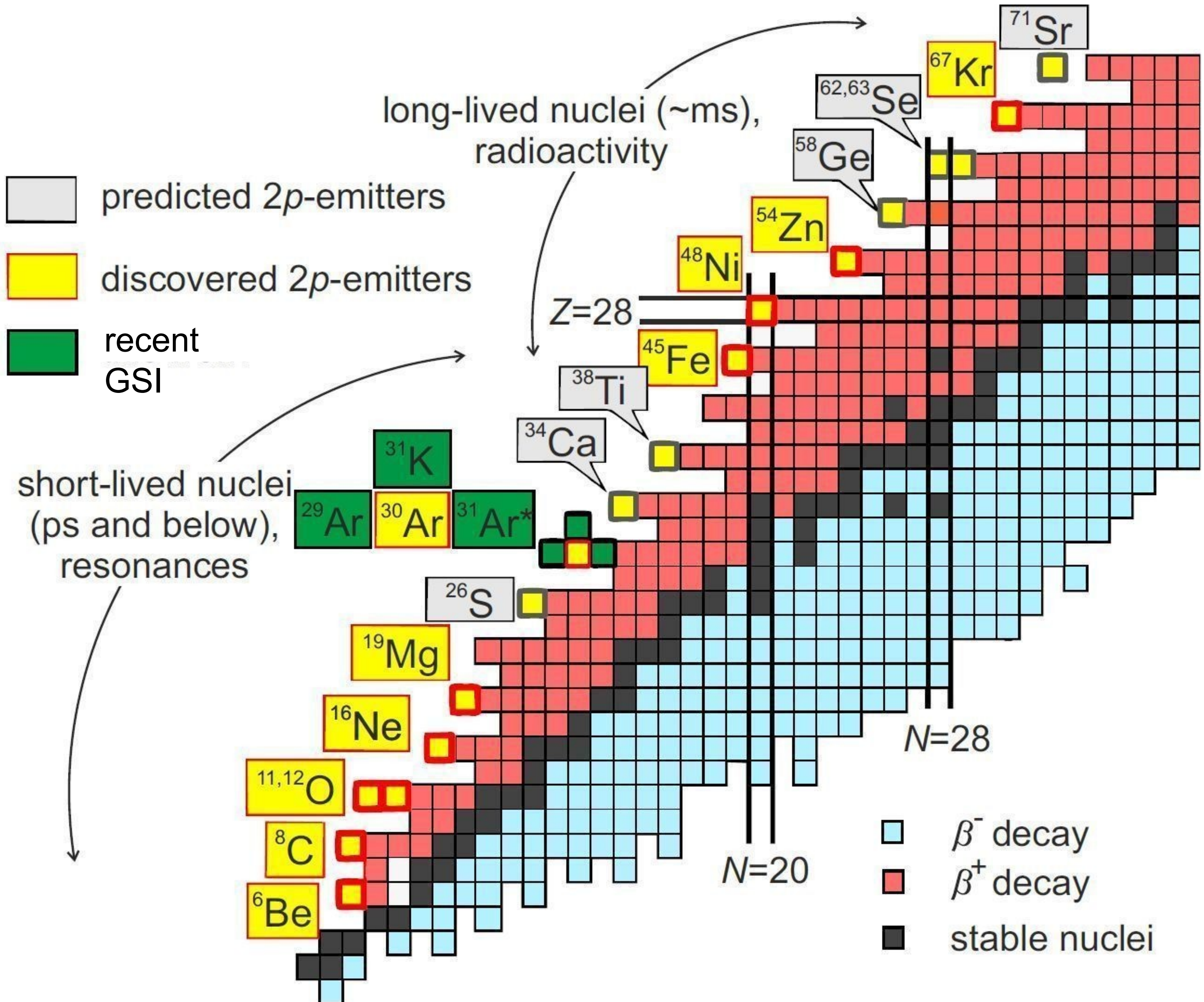
GSM: Gamow shell model

GCC: Gamow coupled channel

TD: Time dependent approach

From recent review by M. Pfützner, I. Mukha, S.Wang, Prog. Part. Nucl. Phys. 132 (2023) 10450

The measured and predicted 2*p* emitters



Phenomenon of true two-proton emission

Direct (true) two-proton emission

- expected for even-Z nuclei beyond the proton drip-line

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

- source of valuable information beyond the proton dripline on

  - masses

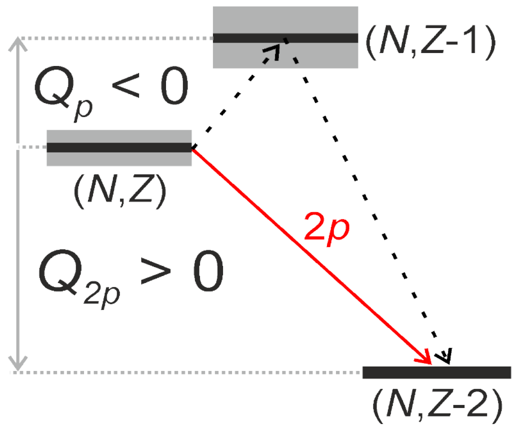
  - nuclear structure

  - nuclear forces

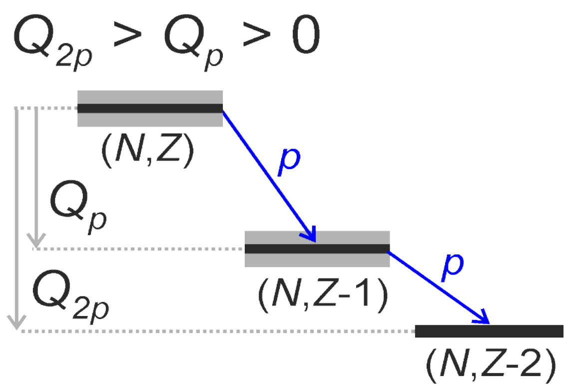
Methods of study:

- implantation and decay
- invariant mass
- **in-flight decay**

Simultaneous (true) 2*p* decay

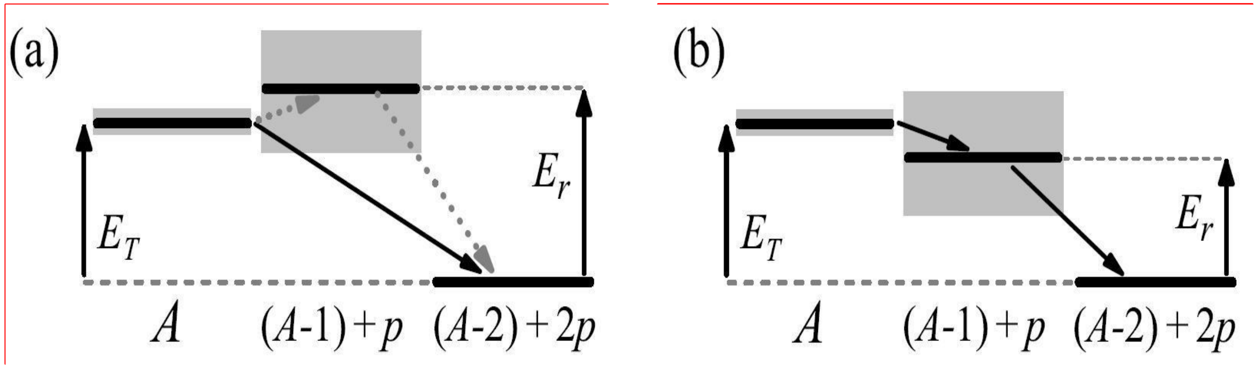


Sequential 2*p* decay



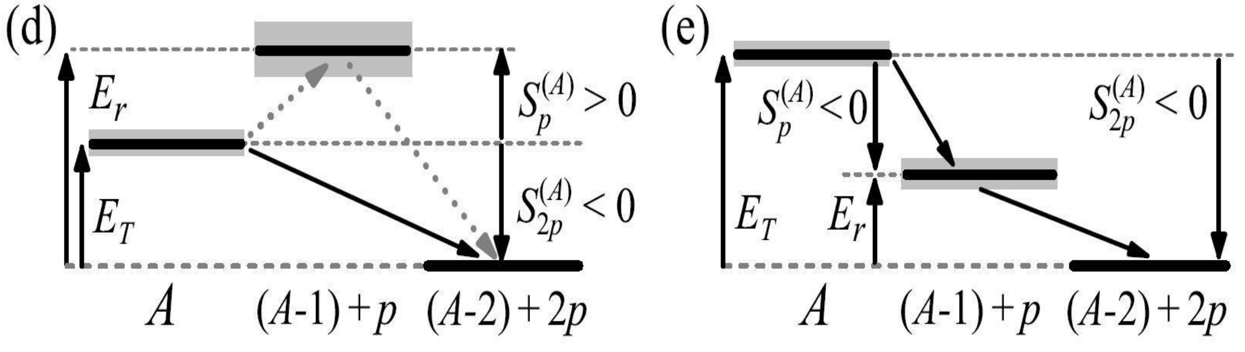
Major 2*p* decay mechanisms:

1) True *2p*,
2) Democratic *2p*
3) Sequential *2p*



Three principal parameters:

$$E_T \quad E_r \quad \Gamma_r$$



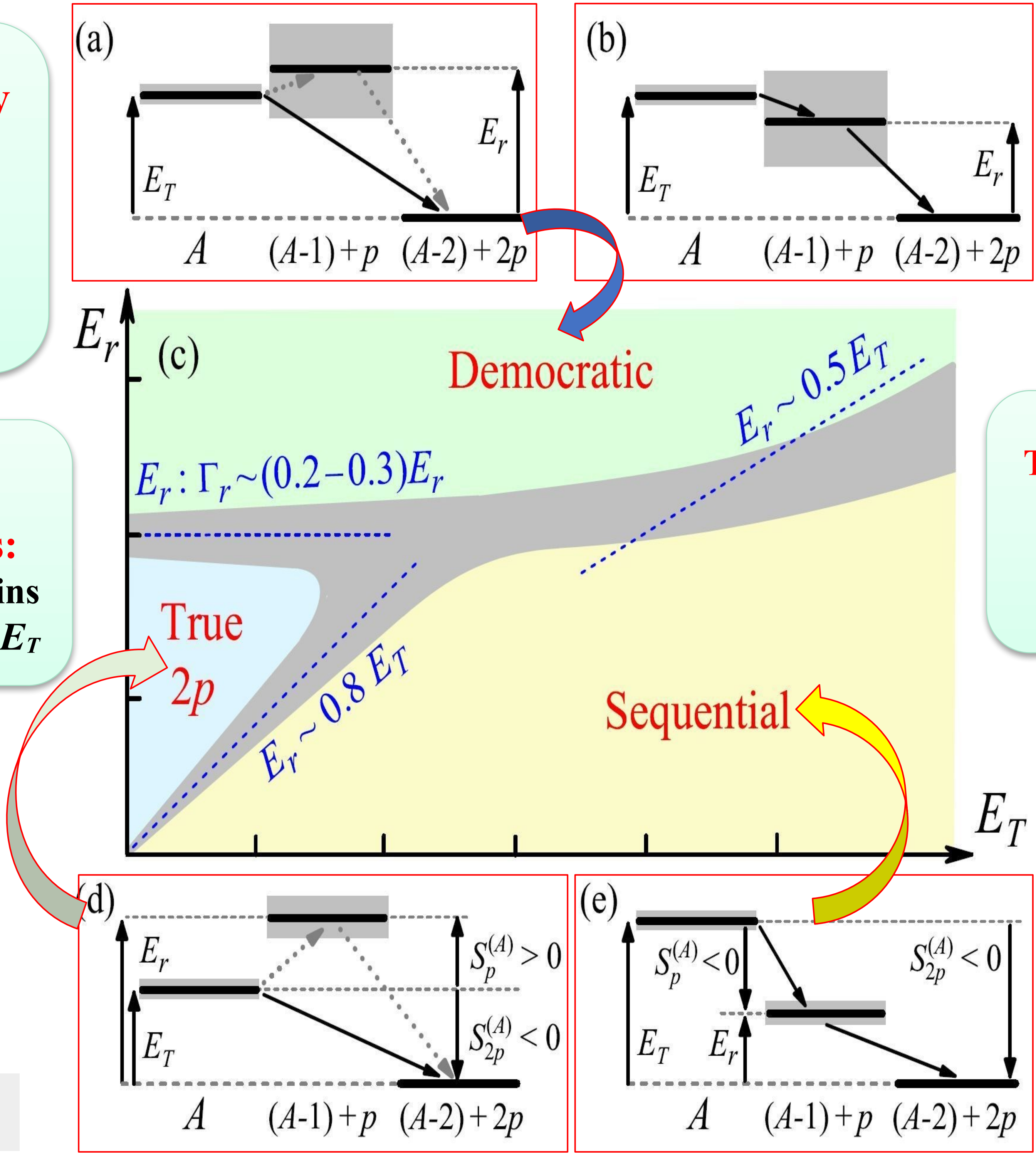
T.A. Golubkova *et al.*,
Phys. Lett. B 762 (2016) 263

Major 2*p* decay mechanisms:

1) True *2p*,
2) Democratic *2p*
3) Sequential *2p*

Evolution of decay mechanisms:

1) g.s. in isotope chains
2) exited states with E_T



Three principal parameters:

$E_T \;\; E_r \;\; \Gamma_r$

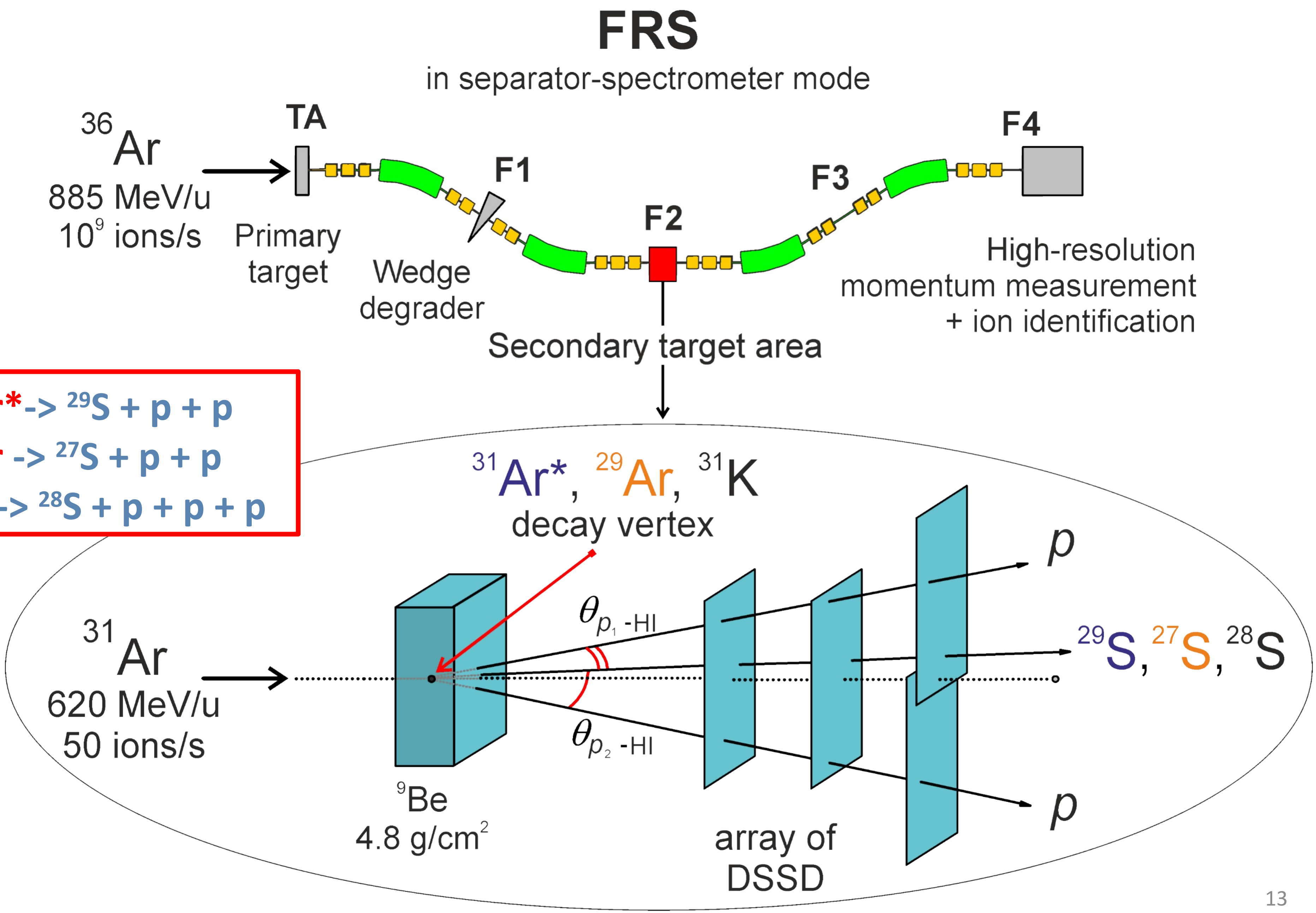
T.A. Golubkova *et al.*,
Phys. Lett. B **762** (2016) 263

Studies of in-flight 2*p* decays by tracking decay products

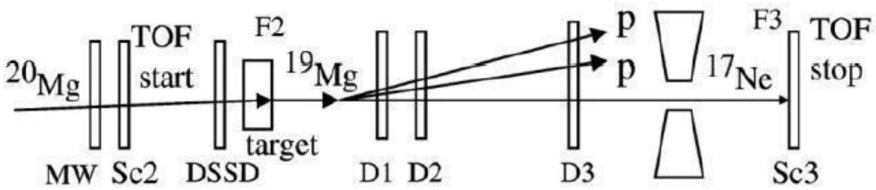
$^{31}Ar^{*} \rightarrow {}^{29}S + p + p$

$^{29}Ar \rightarrow {}^{27}S + p + p$

$^{31}K \rightarrow {}^{28}S + p + p + p$



The in-flight method **does work** for radioactive decays: ^{19}Mg example



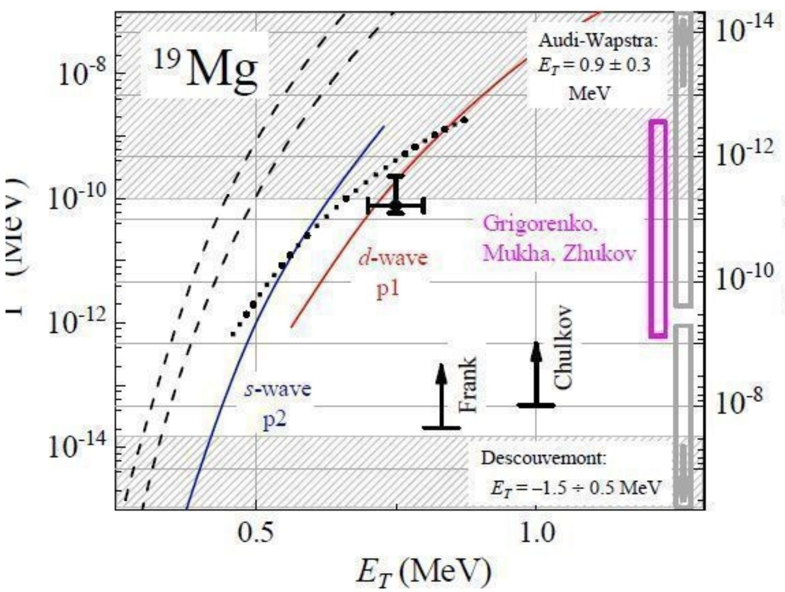
I. Mukha *et al.*, PRL **99**, 182501 (2007)
^{19}Mg 2p radioactivity discovery

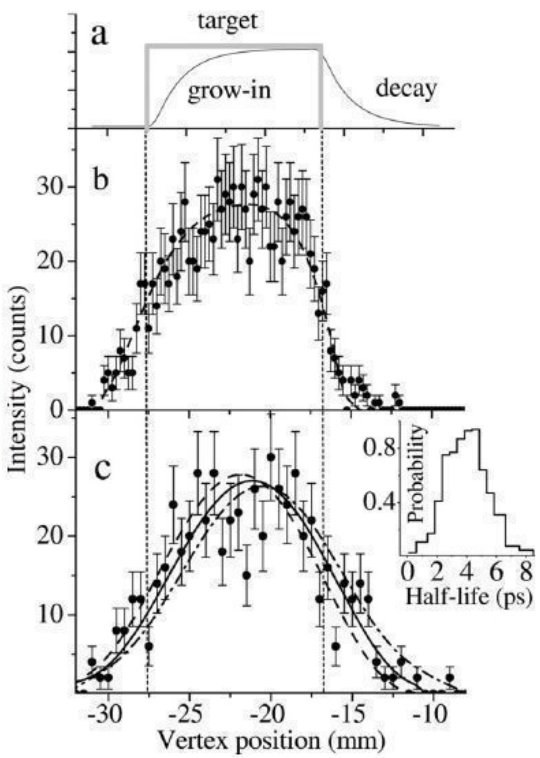
Absolutely independent confirmation

P. Voss et al., MSU, PRC **90**, 014301 (2014):
^{19}Mg lifetime measured by plunger method

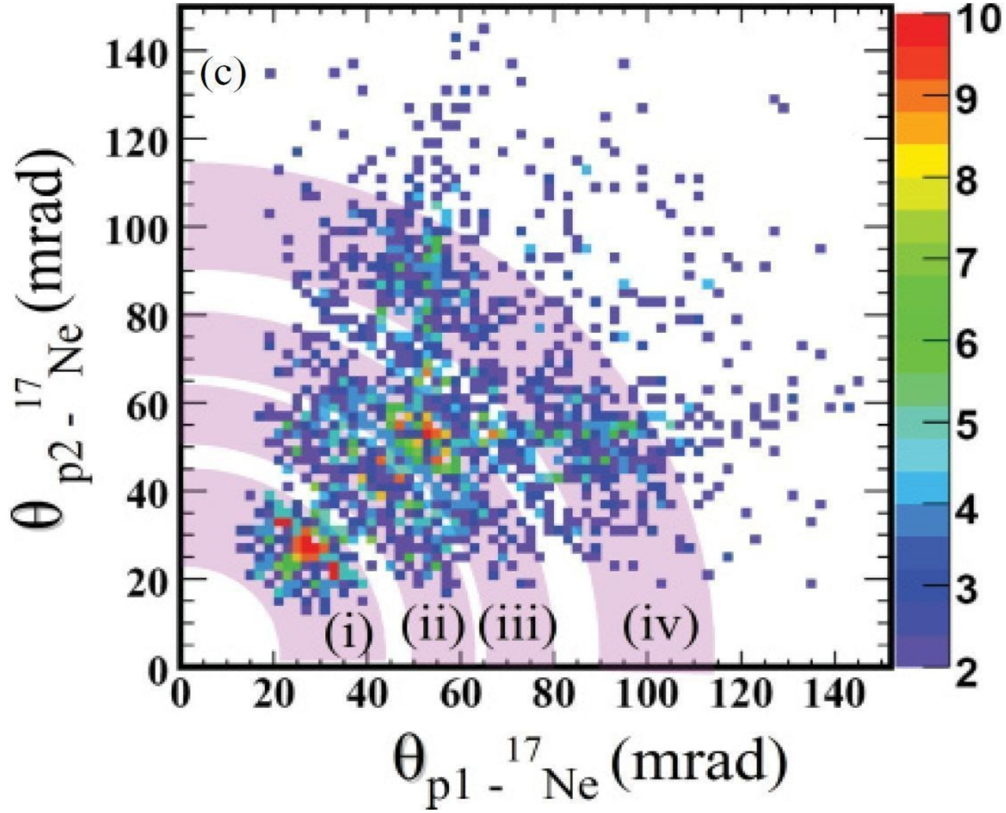
The half-life of ^{19}Mg ranges from
$1.75^{+0.43}_{-0.42}$ ps to $6.4^{+2.4}_{-2.7}$ ps.

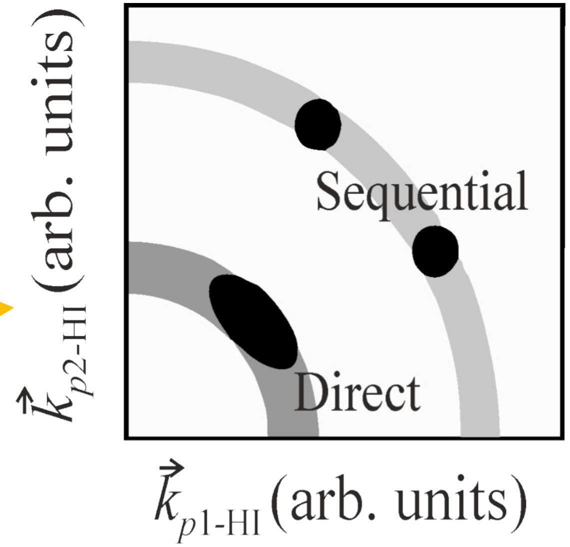
The half-life of ^{19}Mg from the vertex distribution - 4.0(15) ps





Nuclear spectroscopy by in-flight decay technique

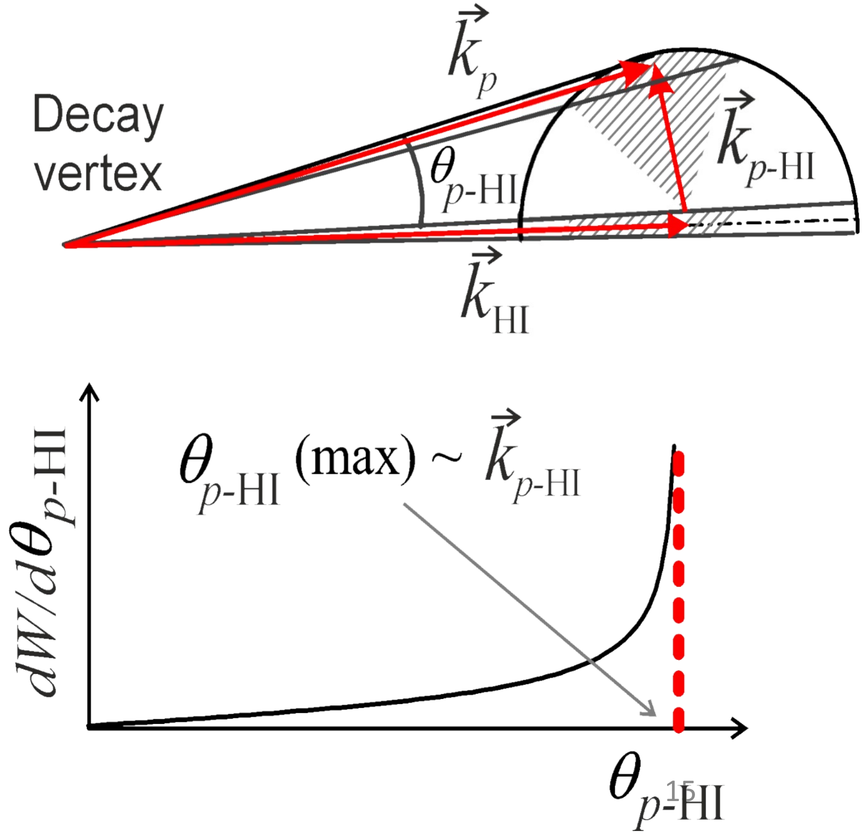




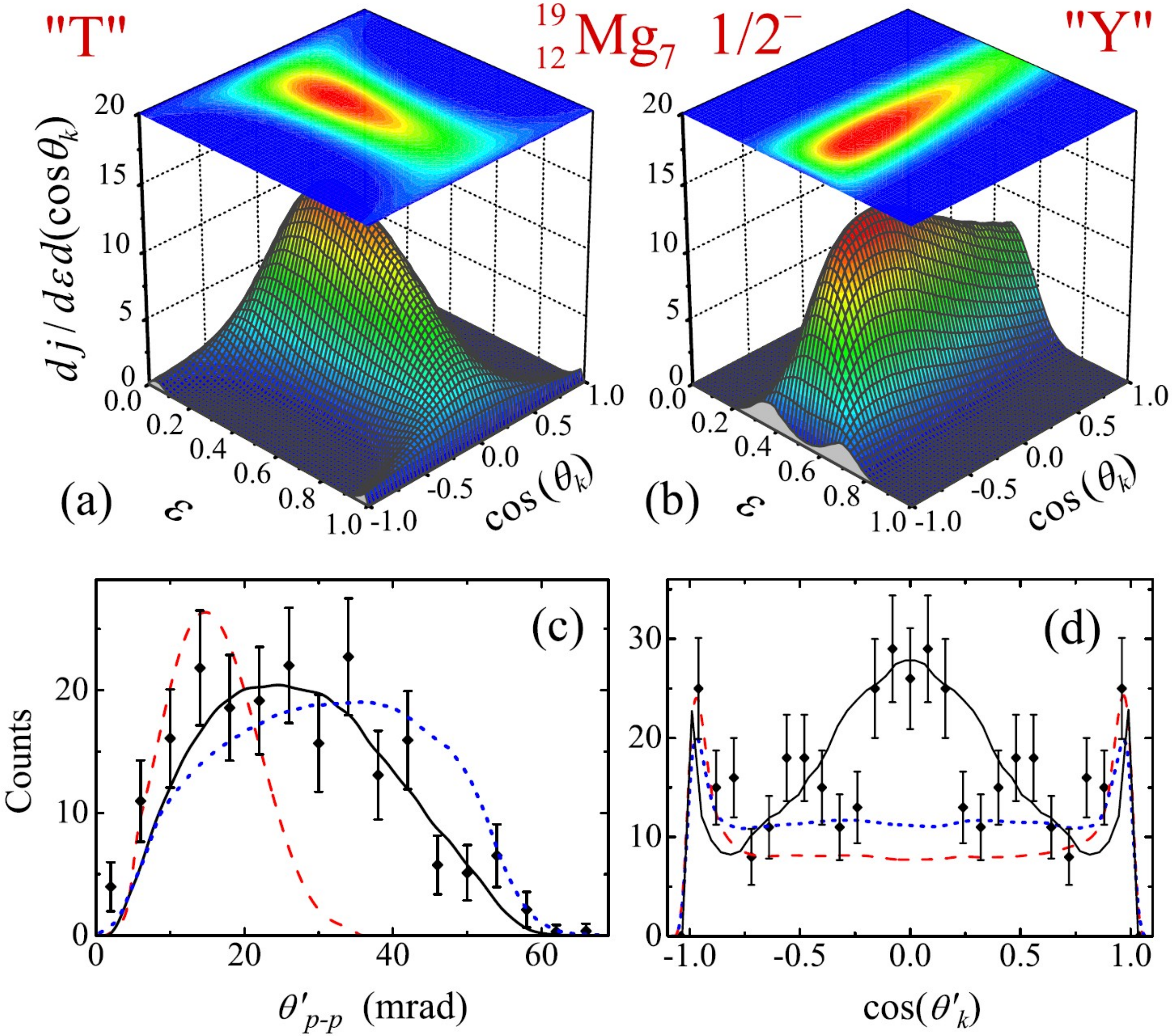
- Angular correlations are in analogy to scatter momentum plot
- Due to enhanced peaks at the maximal angles, one may derive spectroscopic information: **each peak corresponds to decay of a state**

I.Mukha *et al*., Phys. Rev. C **85**, 044325 (2012)

Kinematic focusing effect

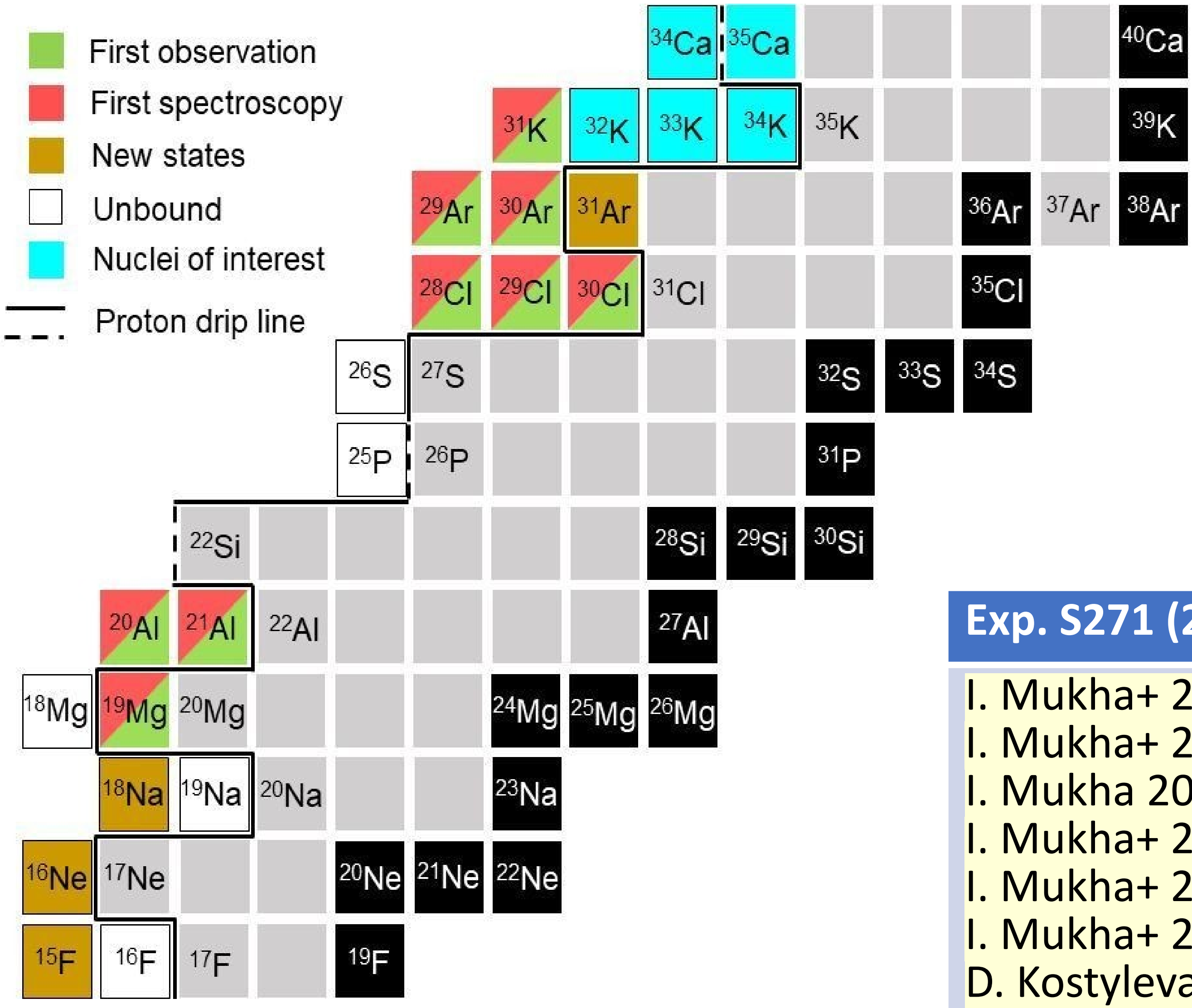


The angular correlation method **does** provide unique results for complicated correlation studies



I. Mukha *et al.*, Phys. Rev. C **77**, 061303 (2008)

Two-proton radioactivity studies with tracking technique at FRS



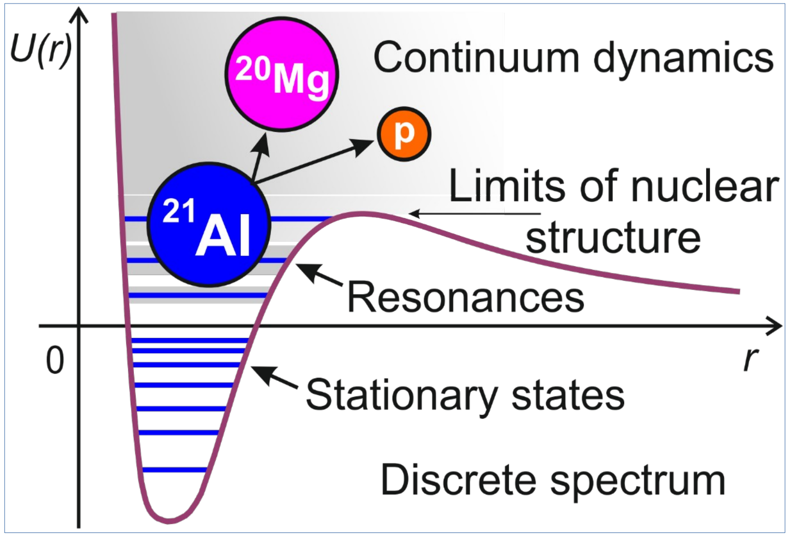
Summary

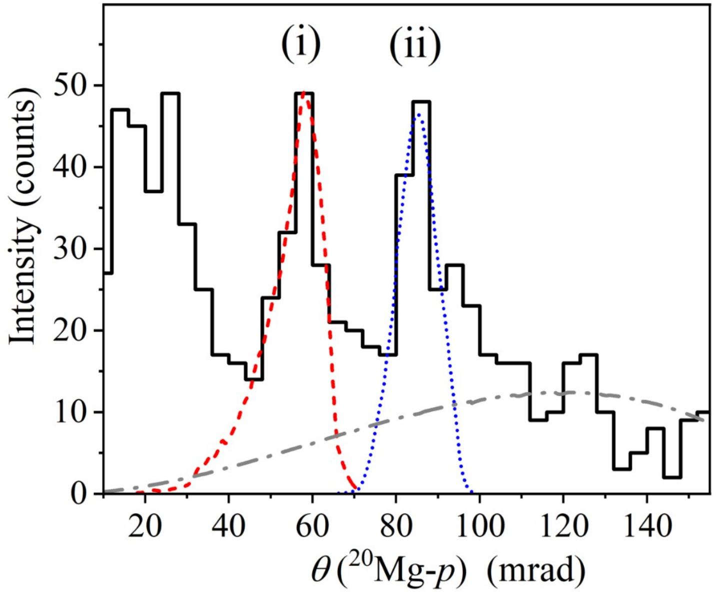
- **Two-proton radioactivity searches**
- First observation and spectroscopy of the most remote isotopes
- Study of exotic **multi-proton decays**

Exp. S271 (2006)	Exp. S388 (2012)
I. Mukha+ 2007 PRL	I. Mukha+ 2015 PRL
I. Mukha+ 2008 PRC	A. A. Lis+ 2015 PRC
I. Mukha 2009 EPJA	T. Golubkova+ 2016 PLB
I. Mukha+ 2009 PRC	X.-D. Xu+ 2018 PRC
I. Mukha+ 2010 PRC	I. Mukha+ 2018 PRC
I. Mukha+ 2012 PRC	L. Grigorenko+ 2018 PRC
D. Kostyleva+ 2024 PRC	D. Kostyleva+ 2019 PRL
X.-D. Xu+ 2025 PRL	D. Kostyleva+ 2019 APPB
X.-D. Xu+ 2025 (in preparation)	

Recent observations of ^{21}Al and ^{20}Al (talk of X.-D. Xu tomorrow)

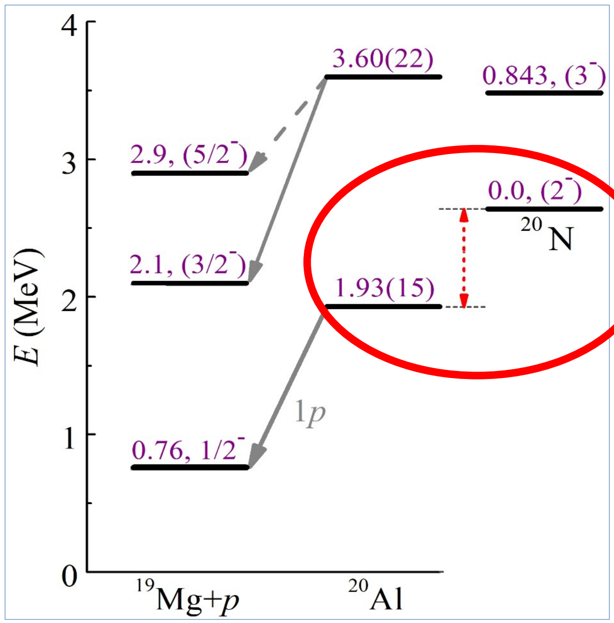
Proton dripline in aluminium isotopes and Borromean feature of ^{22}Si have been established

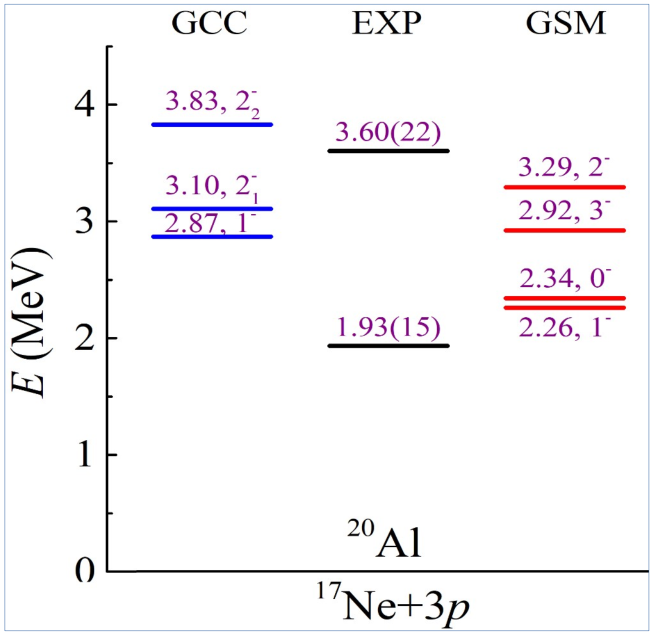




D. Kostyleva, X.-D. Xu *et al.*, Phys. Rev. C **110**, L031301 (2024)

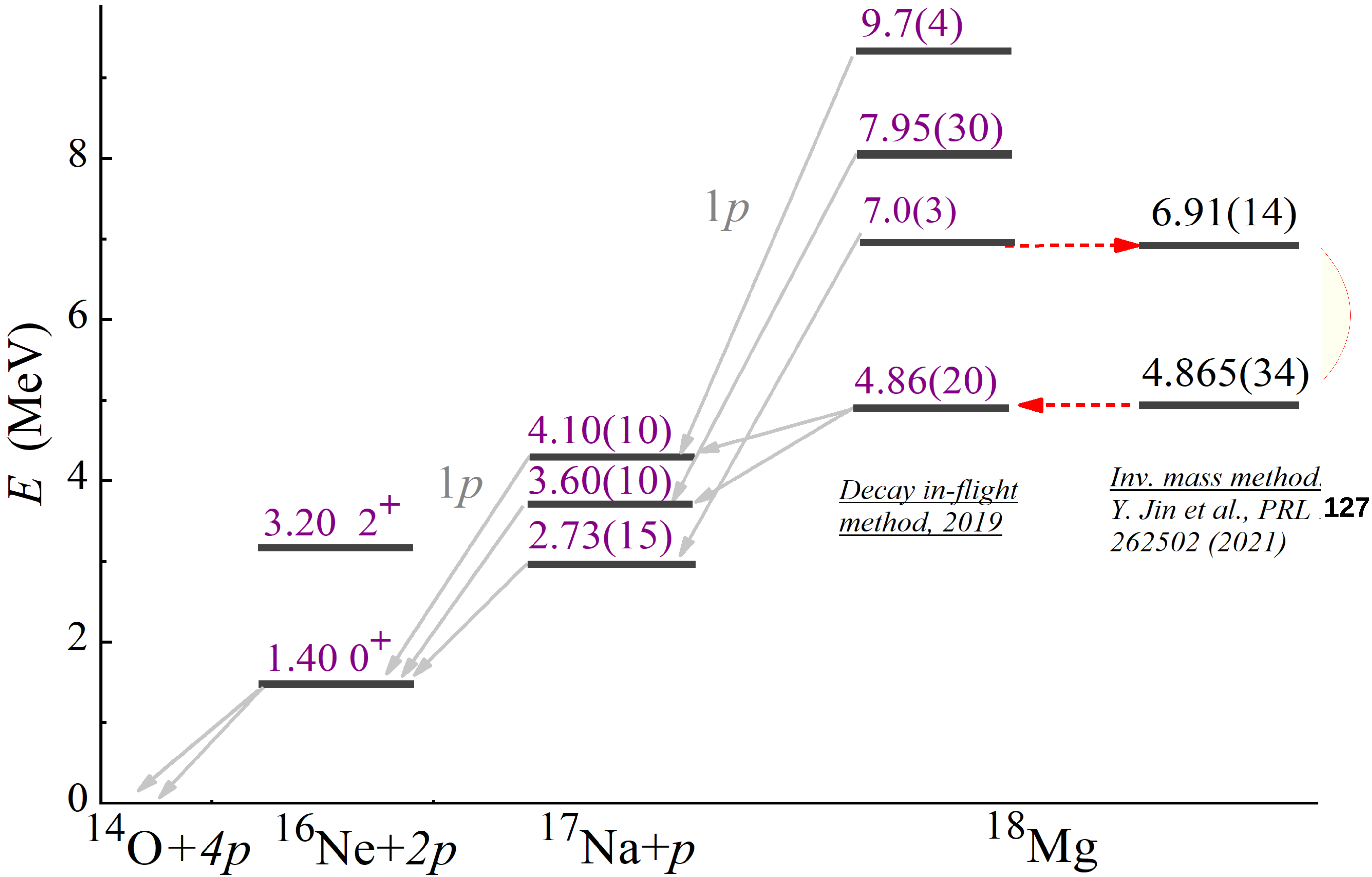
Mirror Symmetry ^{20}Al – ^{20}N Breaking is Disclosed in the Decay of Three-Proton Emitter ^{20}Al





X.-D. Xu, I. Mukha *et al.*, Phys. Rev. Lett., **135,** 022502 (2025)

Levels of 4p-emitter ^{18}Mg have been confirmed



X.-D. Xu *et al.*, in preparation

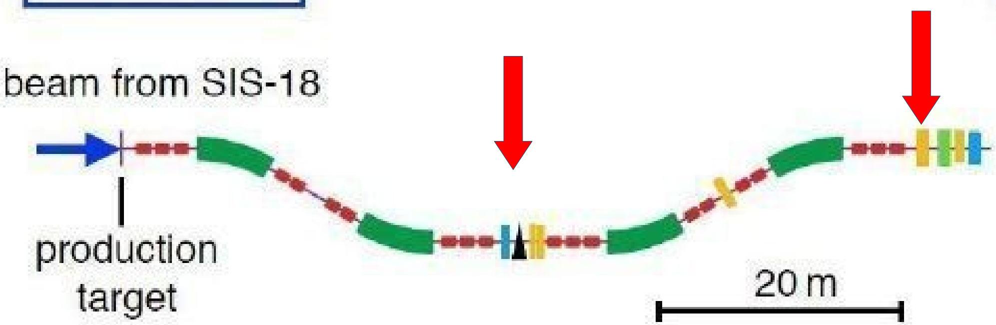
Super-FRS Experiment Collaboration

NUSTAR — Super-FRS EC

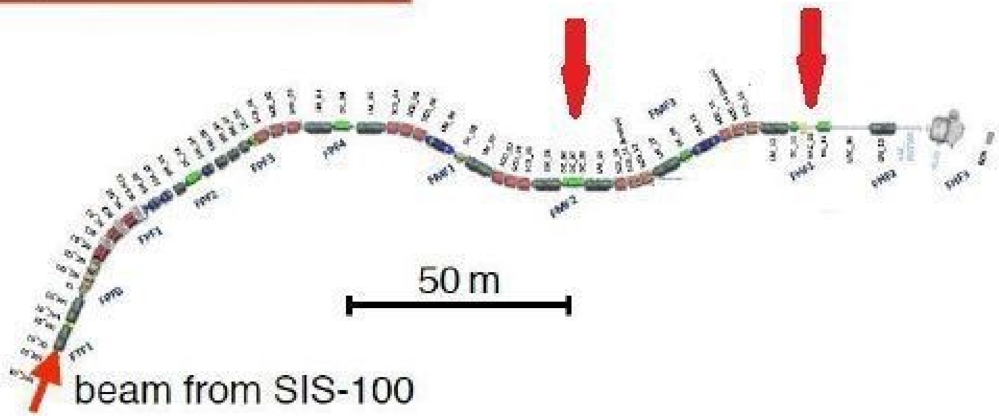
◇ Unique experimental researches with using separator-spectrometer capabilities of FRS at GSI and Super-FRS at FAIR.

- high momentum resolution $\delta P/P \sim O(10^{-4})$
- highly-flexible ion-optical configurations for various experiments

FRS at GSI



Super-FRS at FAIR



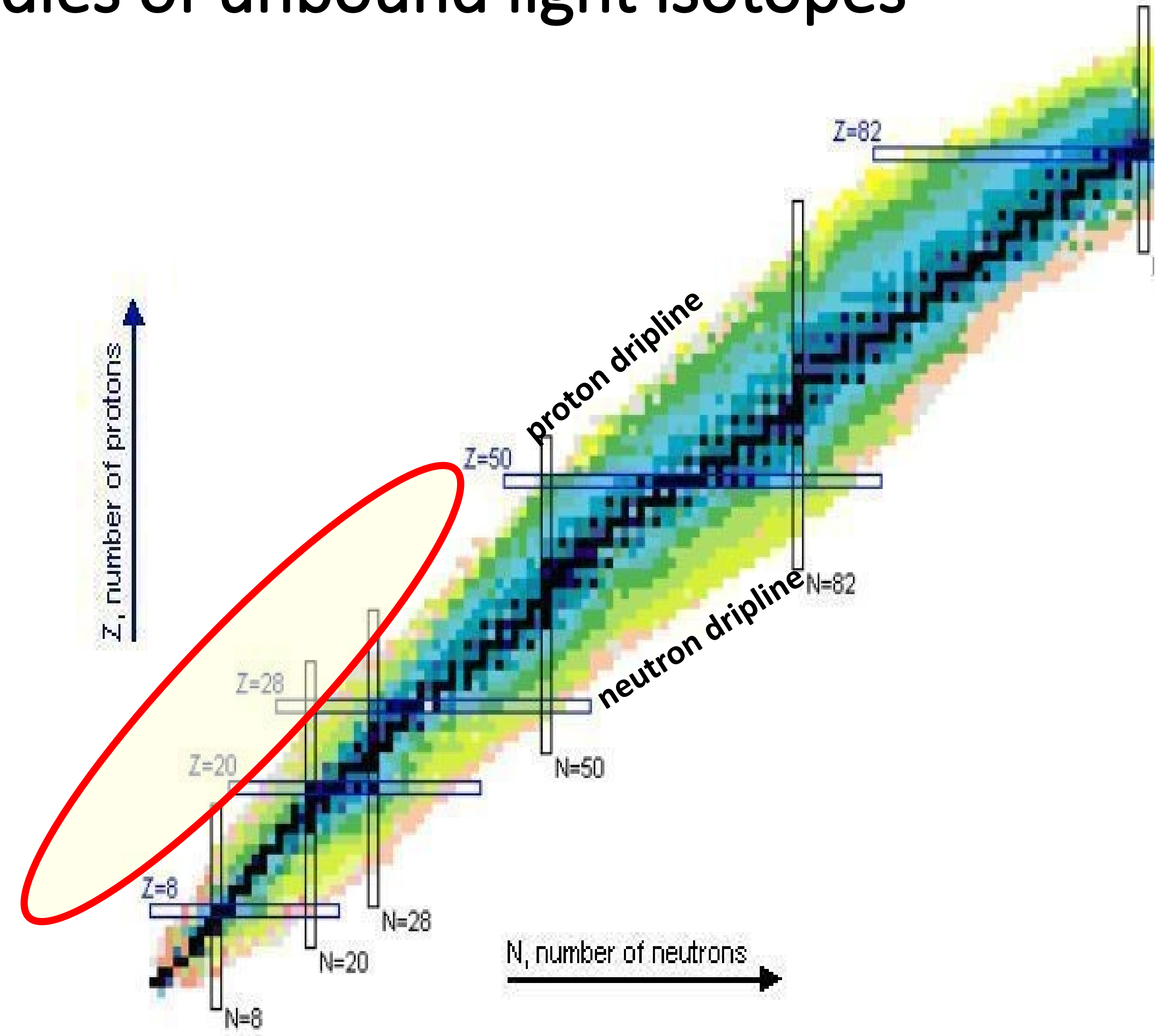
Scientific topics :

- Searches for new isotopes
- Atomic collisions
- Mesic atoms and nuclei
- Hypernucleus
- Tensor force
- Baryon resonances in nuclei
- Nuclear radii and momentum distribution
- **In-flight decays by particle emission**
- Low-q experiments with an active target
- Synthesis of new isotopes and nuclear reaction studies with RIB

Prospects of studies of unbound light isotopes

Deep excursion toward the limits of existence of proton resonances.

Limits of existence of nuclear structure can be explored!



Summary on proton-unbound nuclei

√ 1*p* and 2*p* emitters are beyond the proton dripline by 1-2 atomic mass units

√ 2*p* emitters exhibit three main decay mechanisms and their transition modes

√ The most-remote isotopes have been identified as far as 4 *amu* beyond the proton drip-line and decay by emission of 3 or 4 protons

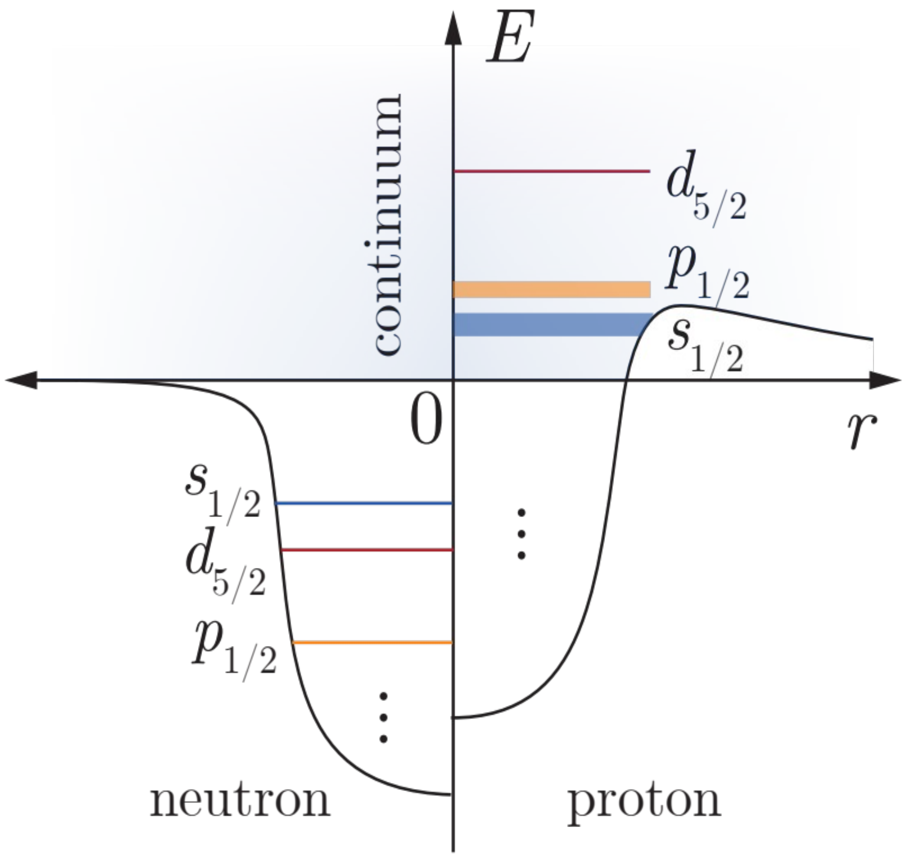
√ The 3*p*- and 4*p*- decay mechanisms are sequential 1*p*-2*p* and 2*p*-2*p* emissions, respectively

√ More multi-proton decay modes are foreseen by emission of 5*p*, 6*p*, ...

√ Multi-proton unbound isotopes are predicted to exist within 5-6 *amu* beyond the proton drip-line

Backup slides

Three-body mechanism of Thomas-Ehrman shift of 2p emitters relative their mirror states (with reversed N, Z)



- Different shell configurations may co-exist in a 2*n*/2*p*-emitter state.
- Each configuration has a respective centrifugal barrier. Different radial dependence.
- Weight of *s*-wave configuration is increased due larger spacial extension thus shifting the level energy down because of less Coulomb repulsion.

- Ground states of 2*p*-emitters are often lower then predictions on basis of isospin symmetry of their mirror states

L.V. Grigorenko, T.A. Golubkova, M.V. Zhukov, ***PRC 91*** *(2015) 024325*

Proton-unbound isotopes in nuclear chart

Sea of unbound nuclei: Isotopes with individual ground states are expe-cted within 5-6 atomic mass units beyond the proton dripline

Region explored: One- and two- proton emitters are located by 1-2 atomic mass units beyond the proton dripline.

Deep excursions to unexplored region with multiple-proton emitters

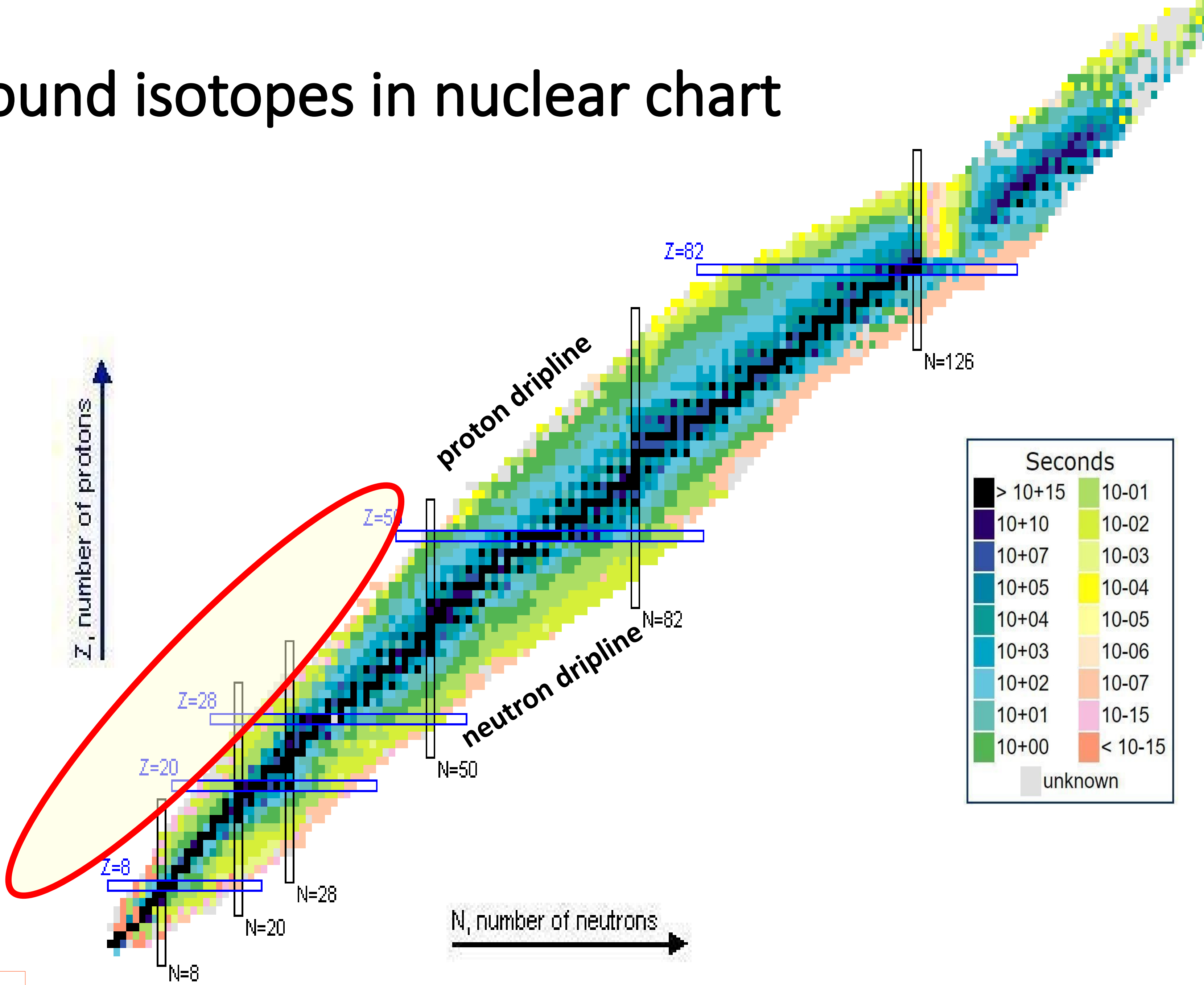
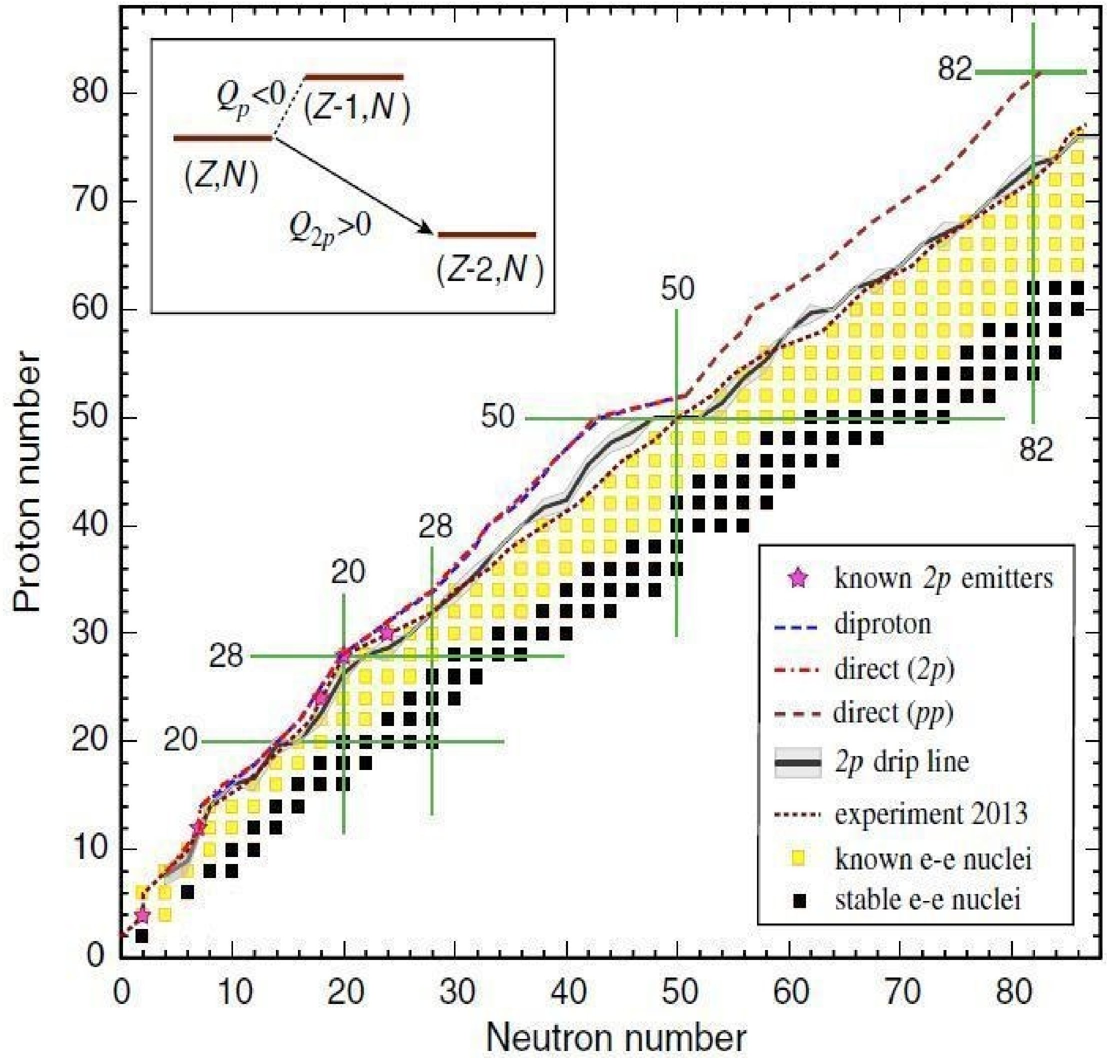


Fig. taken from http://www.nndc.bnl.gov

Proton drip line and two-proton radioactivity

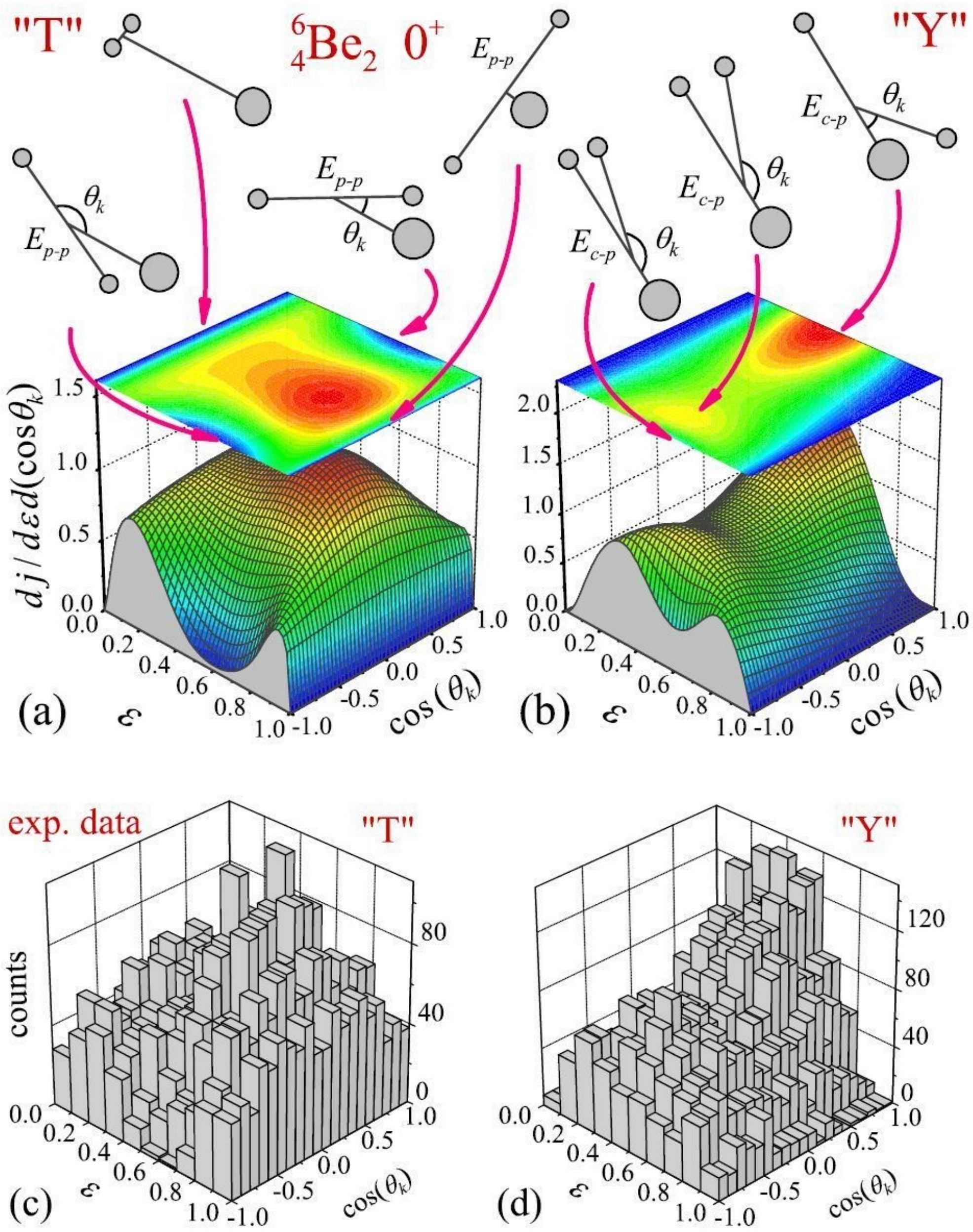
Predicted by nuclear density functional theory,

by *E. Olsen, M. Pfutzner, N. Birge, M. Brown, W. Nazarewicz, A.Perhac, Phys. Rev. Lett.* ***110*** *(2013)*); ***111*** *(2013)*)



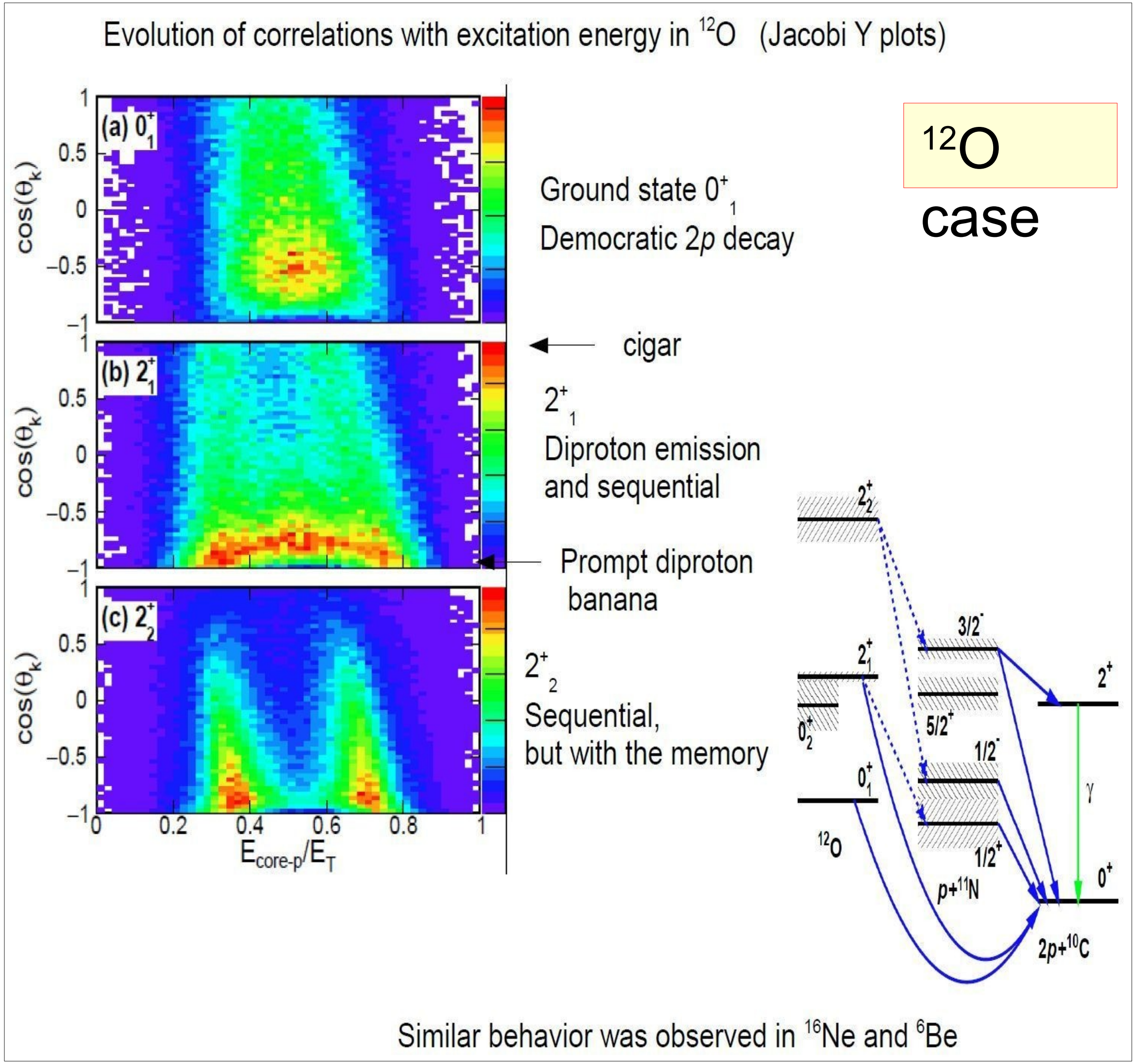
^{19}**Mg,** ^{45}**Fe,** ^{48}**Ni,** ^{54}**Zn**, ^{26}S, ^{57,58,59}Ge, ^{62,63}Se, ^{66,67}**Kr,** ^{71}Sr, ^{102,103}Te, ^{73}Zr, ^{77}Mo, ^{81}Ru, ^{85}Pd, ^{113}Ce, ^{117}Nd, ^{121}Sm, ^{125,126}Gd, ^{130}Dy, $^{133\text{-}135}$Er, ^{138,139}Yb, ^{151,152}Os, $^{154\text{-}156}$Pt, ^{158,159}Hg, ^{109,110}Ba, ^{114}Ce, ^{127}Gd, ^{131}Dy, ^{144,145}Hf, $^{147\text{-}149}$W

Reference case ^{6}Be(0+) $\to \alpha$+p+p measured in complete kinematics



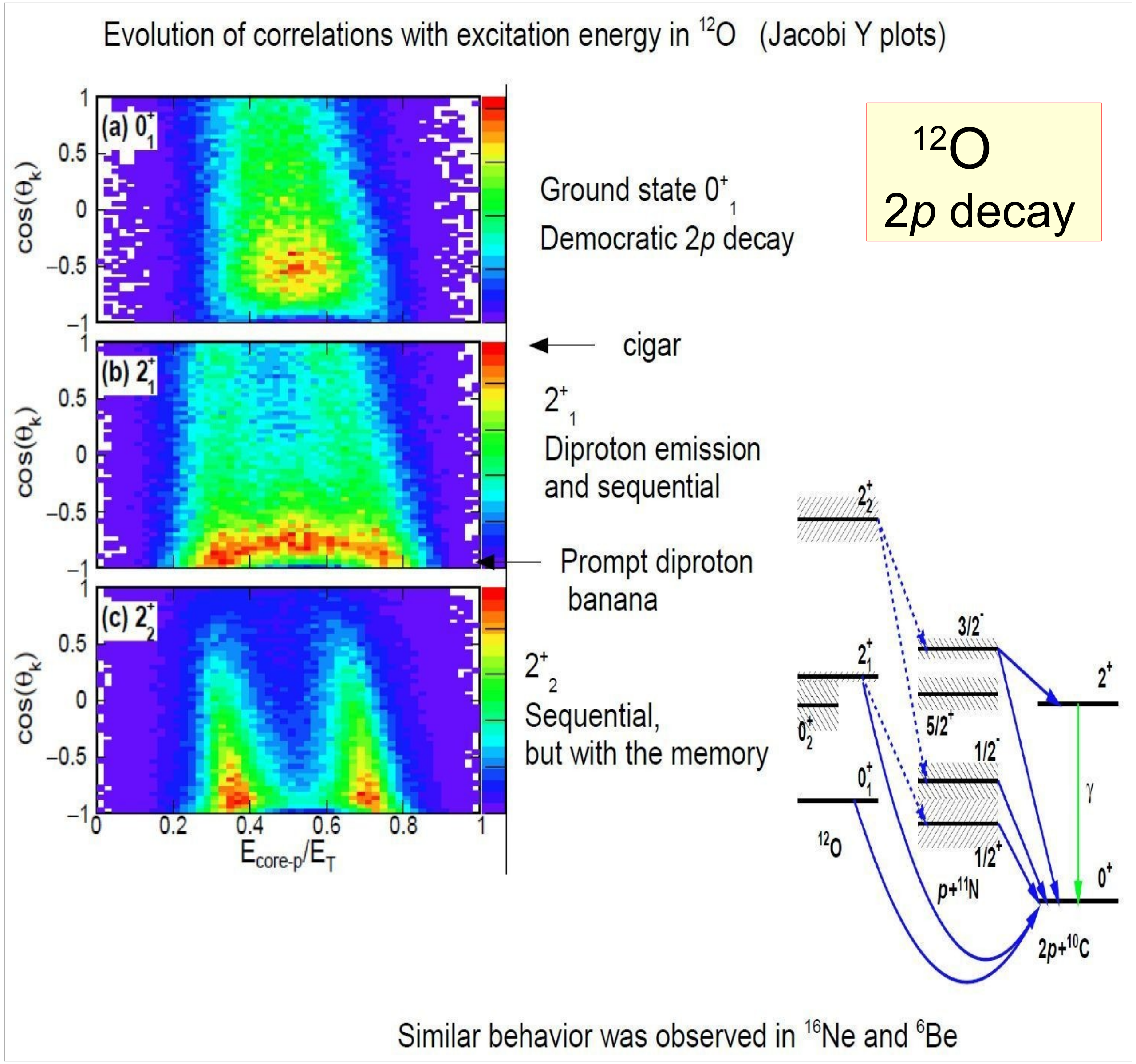
L.V.Grigorenko *et al.*, Phys. Lett. B **677**, 30 (2009)

Evolution of 2*p*- decay mechanisms with excitation energy

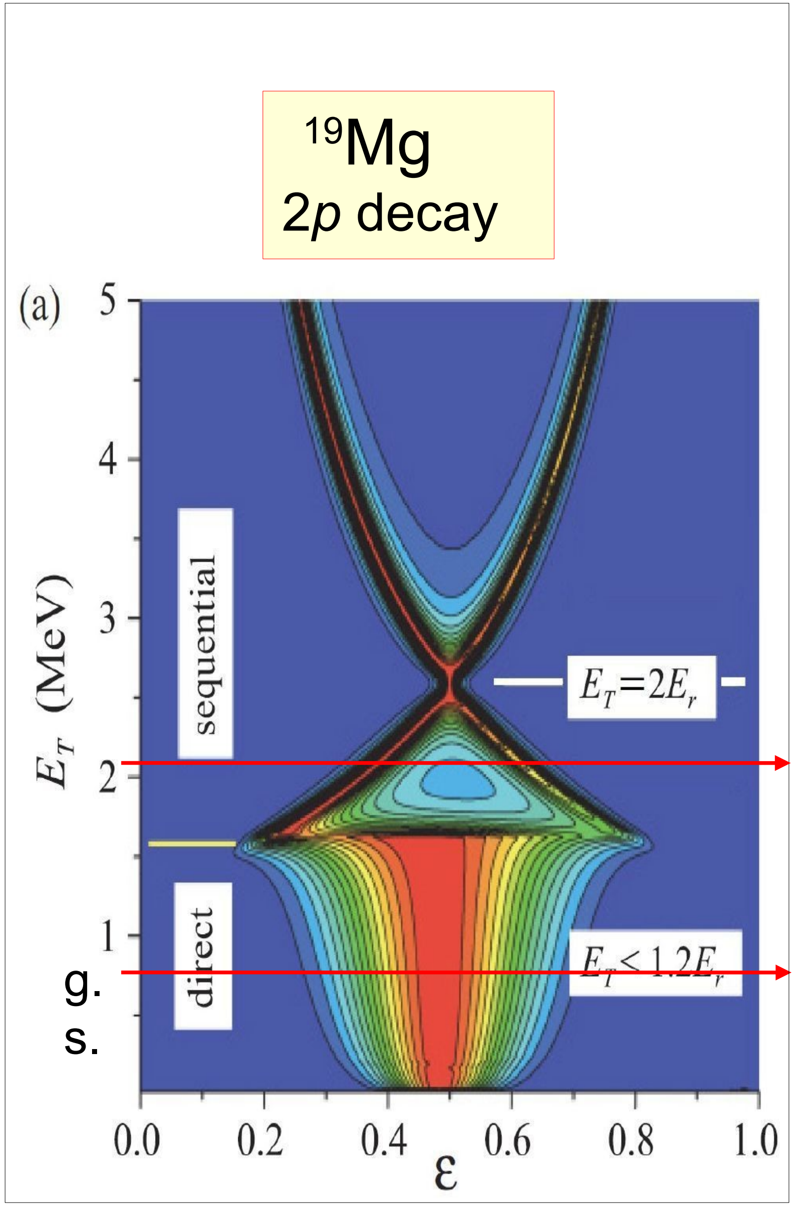


R.J. Charity, Presentation at the PROCON-2019

Evolution of 2*p*- decay mechanisms with excitation energy

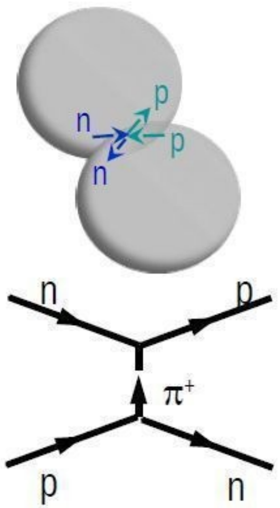


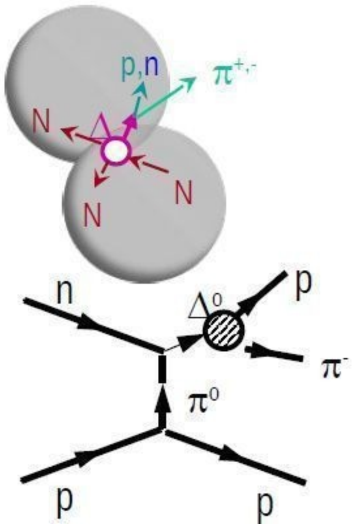
R.J. Charity, Presentation at the PROCON-2019



I. Mukha et al., Phys. Rev. C **85** (2012) 044322

Charge-pickup reactions at high energy





Two processes at high energy:

1. (n,p) charge-exchange via a quasielastic collision
2. Excitation of intermediate Δ resonance

$n \rightarrow \Delta^{o} \rightarrow p + \pi^{-}$ with escaped π^{-}

and de-excitation by emission of neutron(s)

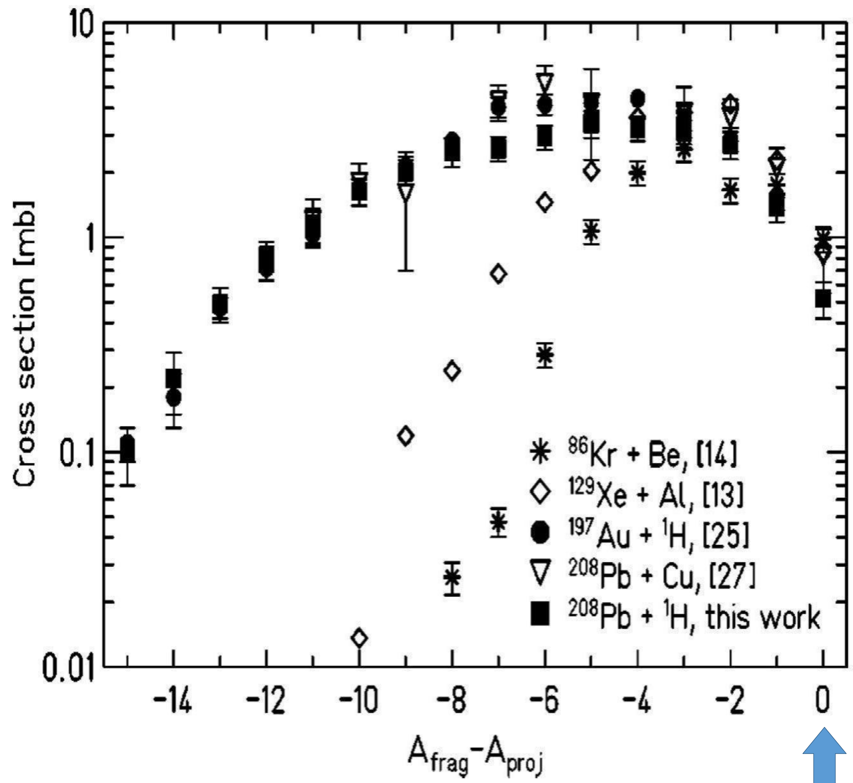
$(Z, A) \rightarrow (Z+1, A\text{-}Xn) + \pi^{-} + Xn;$

At energies of 0.8 GeV/u:

Formation of Δ resonance is confirmed in charge pick-up reactions below 1 Gev/u

K. Sümmerer, et al., Phys. Rev. C 52 (1995) 1106.

Production of fragments by charge-pickup reactions at high energy



Charge-exchange

A. Kelic et al., PRC **70** (2004) 064608

Evolution of nuclear structure of unbound isotopes. Physics goals.

1. **Sketching un-observed isotopes** till limits of their existence.

2. **To test structural changes in proton unbound nuclei in analogy with their neutron-rich mirrrors**

a) Island of inversion (2p-2h intruders in g.s.).
Mirror isotopes ^{31}Ne$\rightarrow$^{31}K have been accessed, other canditates like ^{32}Mg$\rightarrow$^{32}Ca accessible.
Observables: masses and separation energies. Thomas-Ehrmann shifts.
Excitation energy spectra.
Shape co-existence: in mirror pair ^{30}Mg$\rightarrow$^{30}Ar (indication is obtained, to be confirmed).

b) Neutron/proton halos and new N=16,14 magic numbers. ^{11}Li$\rightarrow$^{11}O, ^{22}O$\rightarrow$^{22}Si, ^{26}Mg$\rightarrow$^{26}S.

3. **Isospin symmetry breaking** in proton unbound nuclei. Example: g.s. ^{20}Al(0^+) and ^{20}N(2^+).

4. **Tests of fundamental assumptions** in the most remote nuclear systems, e.g., mean field concept, Pauli principle.

5. **Nuclear forces with T>0** in multi-proton systems. Tetra-, penta- hexa- protons *etc.*

6. **Two-neutron radioactivity.** To test ^{26}O two-neutron decays.

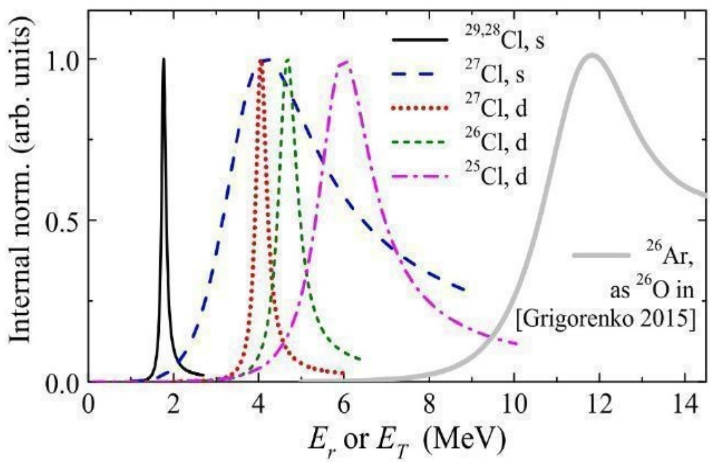
Limits of existence of nuclear structure.
First estimates for 1*p*-, 2*p*- emitters by using their mirror states

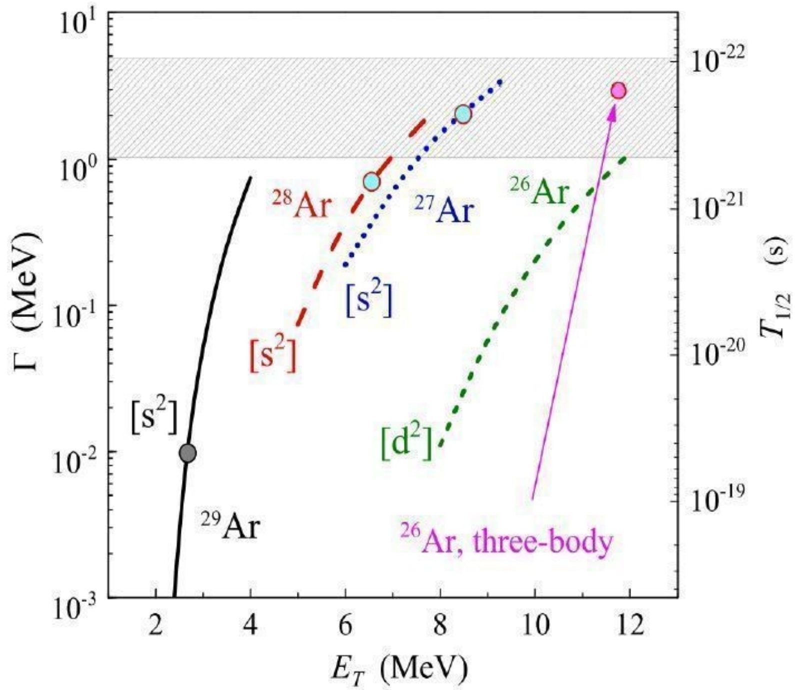
Beyond the proton dripline: quasistationary = stationary for most of purposes

Lifetime as criterium. Γ>3 MeV not a single reflection from the barrier is likely

$$N(E) = \int_0^{r_2} dr\,|\psi(kr)|^2$$

$$\nu = \left(2\int_{r_1}^{r_2}\frac{dr}{v(r)}\right)^{-1} = \left(\int_{r_1}^{r_2} dr\sqrt{\frac{2M}{E-V(r)}}\right)^{-1}$$

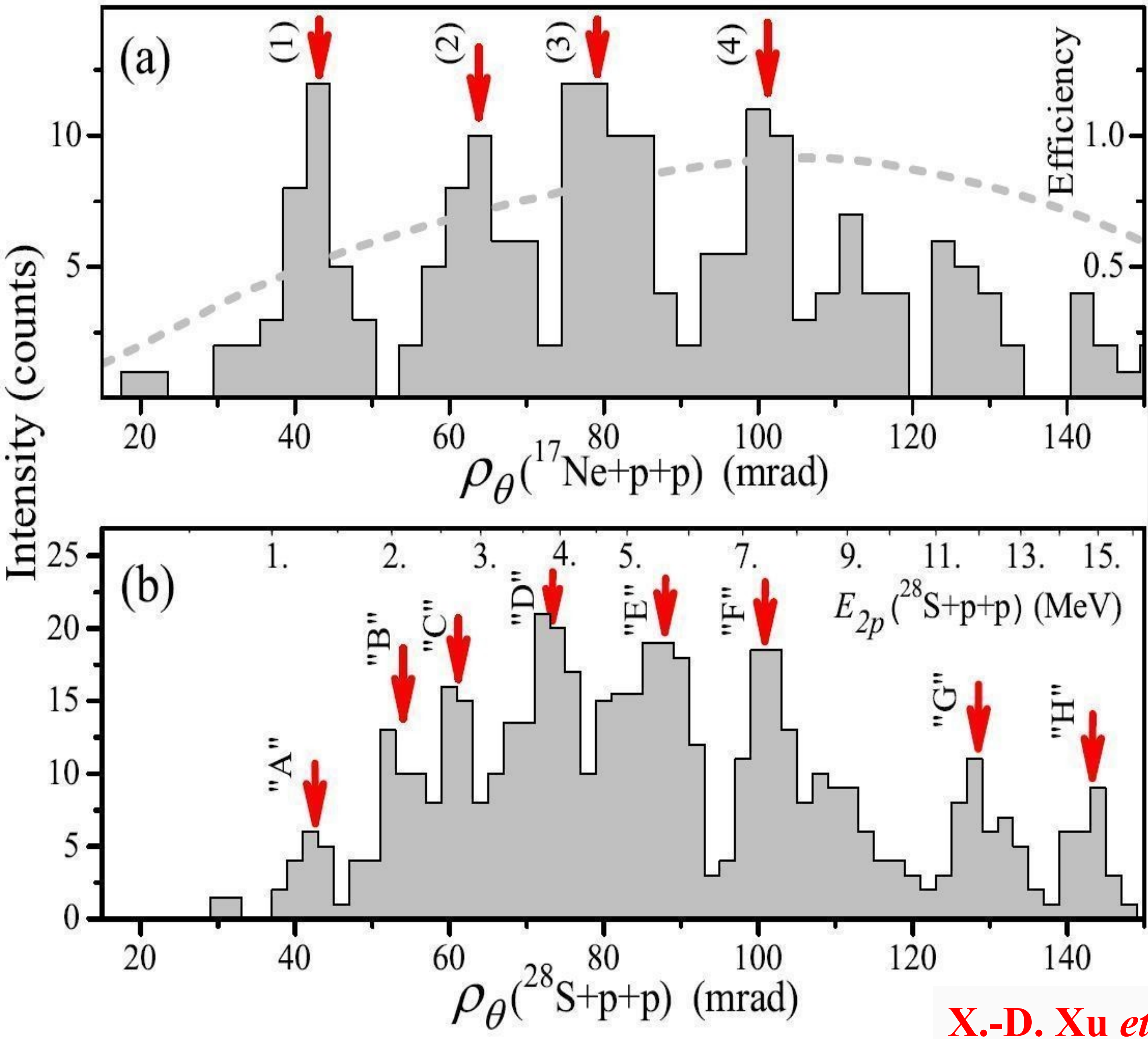




In chlorine and argon isotopic chains the reasonably narrow states can be found down to ^{25}Cl and ^{26}Ar

L.V. *Grigorenko, ...***X.-D. Xu** *et al., Phys. Rev. C 98, 064309 (2018)*

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



^{17}Ne+p+p correlations

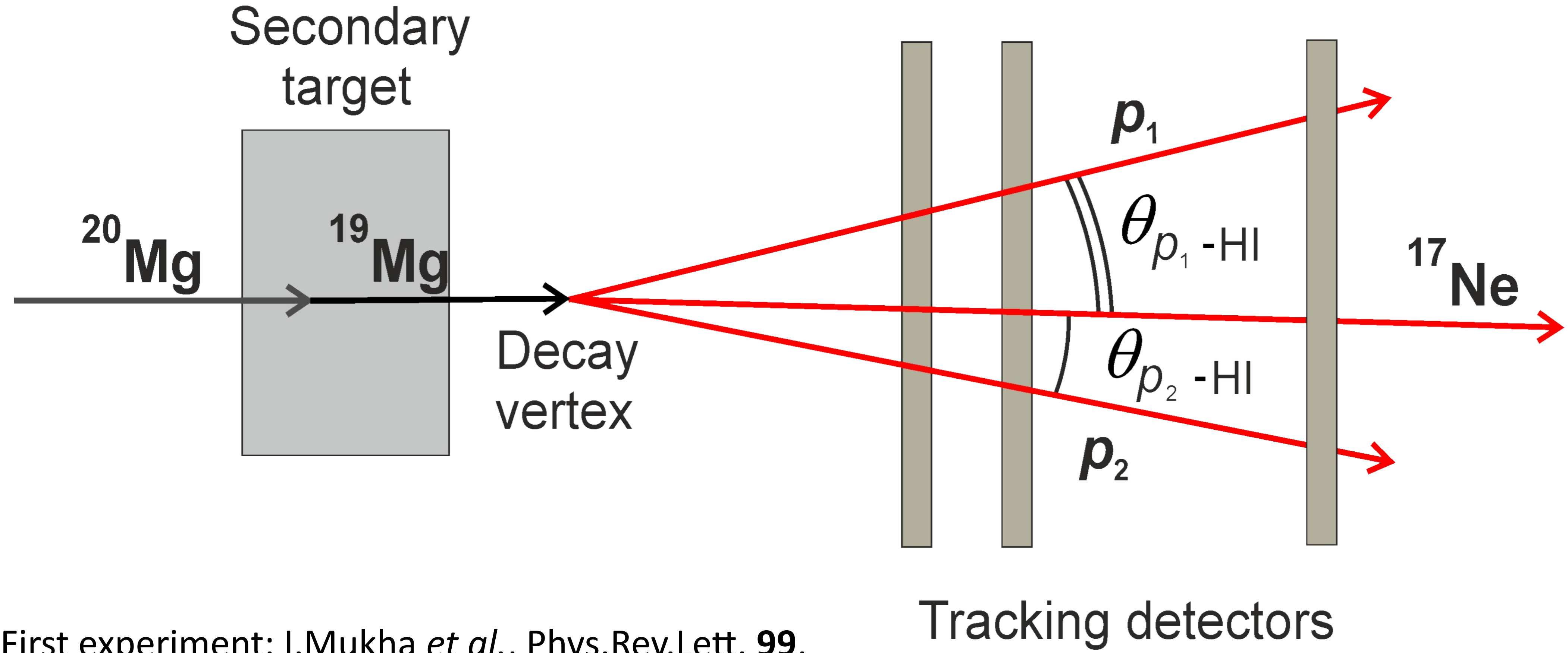
$$\rho_\theta = \sqrt{\theta^2(\mathrm{HI}\text{-}p_1) + \theta^2(\mathrm{HI}\text{-}p_2)}$$

^{28}S+p+p correlations

X.-D. Xu *et al.*, Phys. Rev. C97 034305 (2018)

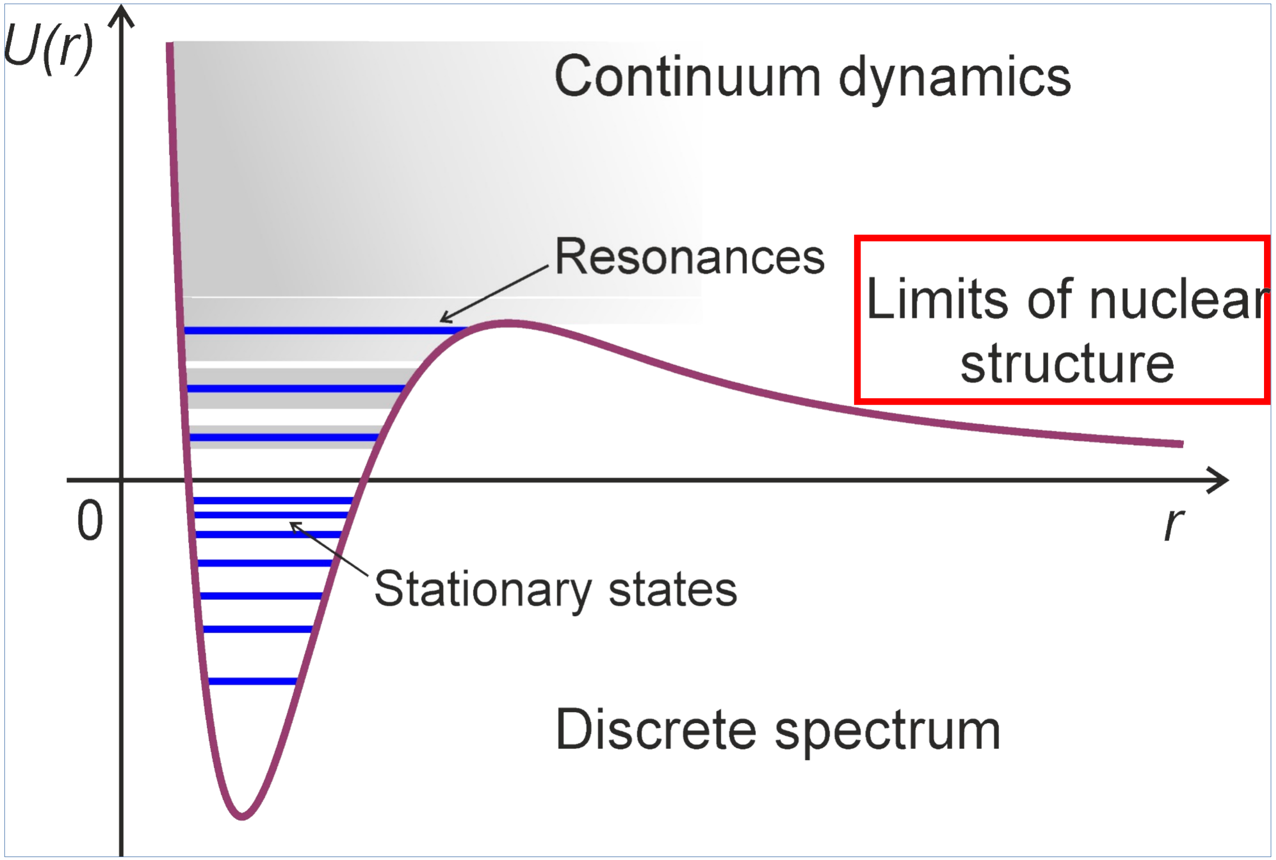
In-flight decay technique

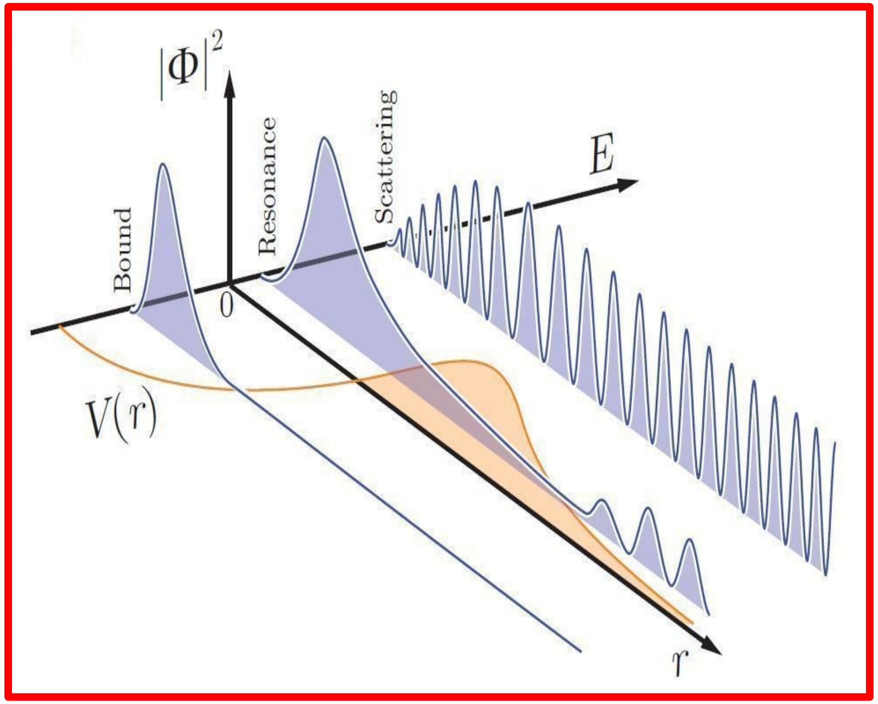
- Studies of proton-unbound nuclei with ns to ps lifetimes
- Measurement of all decay product trajectories
- Unambiguous identification of heavy decay product is required



First experiment: I.Mukha *et al.*, Phys.Rev.Lett. **99**, 182501 (2007)

How far beyond the dripline does the nuclear structure last?





Resonance is when at least one reflection on barrier ($\tau >\sim 10^{-22}$ s), then

$$\Gamma \sim \hbar/\tau \quad \text{~3-5 MeV}$$

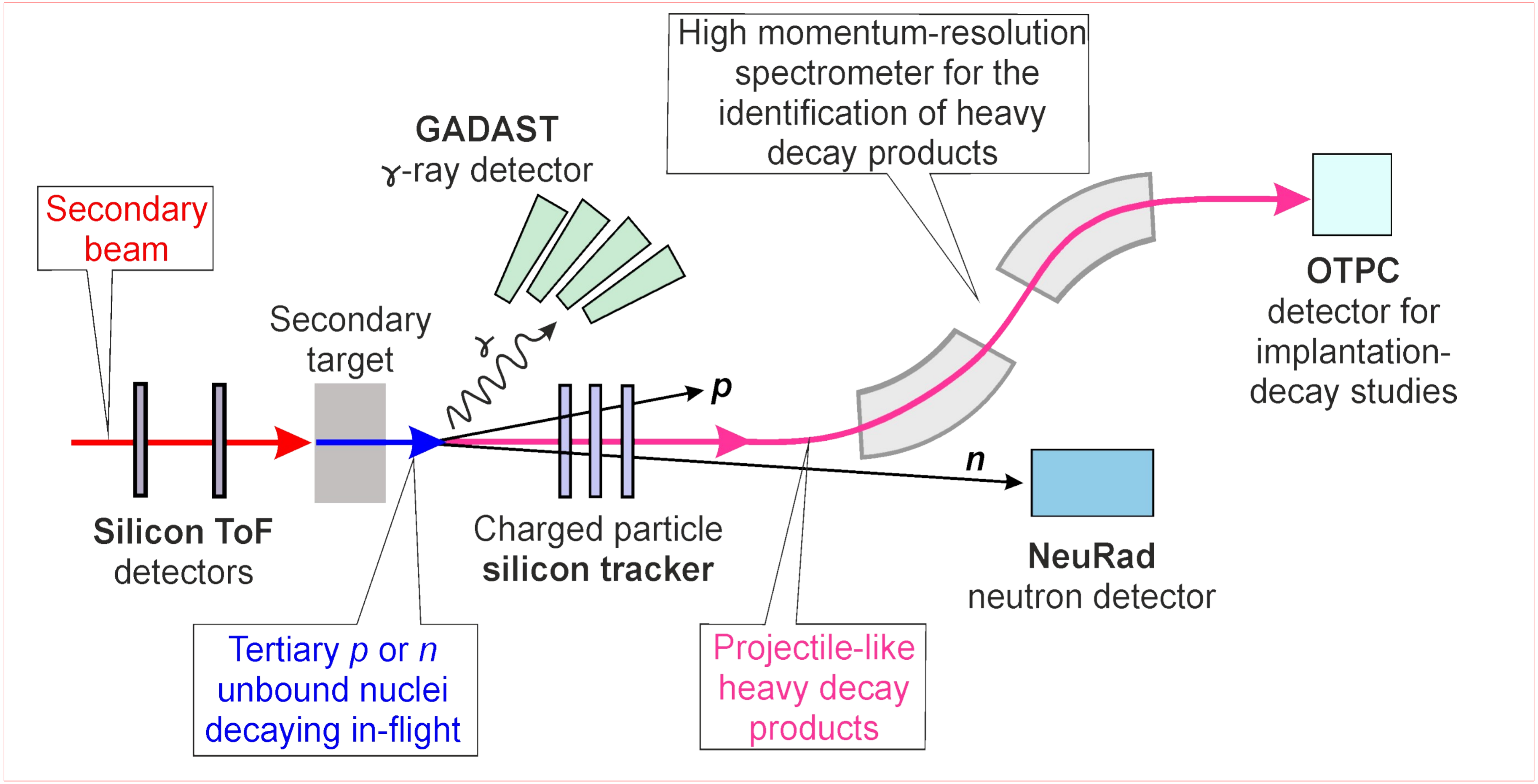
Where are the limits of existence of unbound nuclear systems?
What is beyond?

L.V. Grigorenko, et al., Phys. Rev. C 98, 064309 (2018)
M. Pfützner, I. Mukha, S. Wang, PPNP 132 (2023) 10450

In-flight decay experiments at FAIR

High-energy of 1.5 GeV/u is essential for charge pickup reactions via exitation of barion resonances

EXPERT (EXotic Particle Emission and Radioactivity by Tracking) @ Super-FRS



GSI Halo Collaboration